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Review

Review on Development and Research of Underwater Capacitive Power Transfer

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Abstract: Wireless power transfer (WPT) technology applied to underwater environments has the advantages of no electrical contact, high safety, and high applicability. Underwater capacitive power transfer (UCPT) technology shows great potential in the field of underwater wireless power transfer as it has more advantages compared to underwater inductive power transfer (UIPT) technology. This paper begins with the system principles of UCPT and explains the advantages of UCPT technology for underwater applications. It then reviews the coupler and equivalent circuit models currently used for UCPT in various underwater environments, which indicates the direction for the design of underwater couplers in the future. In addition, compensation networks currently applied in UCPT systems are summarized and compared. Furthermore, different application examples of UCPT are introduced, and the key factors constraining UCPT development are pointed out. Research directions for future development of UCPT technology are also investigated.

Keywords: wireless power transfer; capacitive power transfer; underwater; coupler; compensation network

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1. Introduction

Marine resources have gradually developed and expanded over time, driven by advancements in technology, growing environmental awareness, and increasing demand for sustainable products. Underwater unmanned equipment, important for underwater resource exploration and military patrol, has recently become a research hotspot in the field of marine engineering and has a wide range of economic, scientific and military values [1,2]. According to the industry research and market prospect forecast of underwater robots, it is predicted that by 2029, the global market scale of autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs) will reach 4.77 billion US dollars, and the compound annual growth rate (AGR) will be 9.9%, as shown in Figure 1. However, in the special underwater environment, the metal cables used for conductive power supply limit the flexibility and operating range of the underwater electromechanical devices, and there is also potential risk of electric leakage. The power supply uses batteries with limited energy, which limits the endurance of the underwater electromechanical devices [3]. To solve the bottleneck problem of energy supply for underwater unmanned equipment, capacitive power transfer (CPT) technology is becoming a new underwater power transfer mode. Power transfer via non-physical connection has solved a series of problems, such as difficult sealing, complicated docking operations, electrical ignition, and the mechanical wear of conventional electrical connection points, in the underwater environment [4–7]. It can effectively improve the flexibility and endurance of underwater electromechanical devices and improve operating efficiency [8,9]. Underwater power capacitive transfer (UCPT) technology is of great significance to the exploration, development, and utilization of underwater resources, and it is also an important means of solving the energy problem of underwater equipment, with promising development and application prospects.

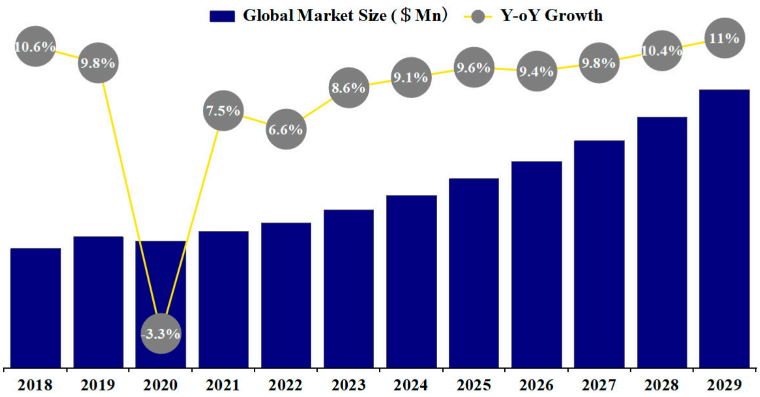


Figure 1. Global market size prediction of AUVs and ROVs.

Underwater wireless power transfer can be divided into underwater inductive power transfer (UIPT) and underwater capacitive power transfer (UCPT). UIPT technology also faces some challenges. Previous research has clearly shown that when the transmitter and receiver exchange energy through high-frequency electromagnetic fields, eddy currents caused by seawater, a good conductor, result in energy loss [10,11]. In addition, UIPT systems typically require relatively complex coupler structures, including coils, ferrites, and shielding, which are difficult to seal in underwater environments. In particular, the high-pressure environment of the deep ocean decreases ferrite permeability and affects system transmission parameters [12]. UCPT technology is a better choice for wireless charging in underwater environments than UIPT technology, which uses a high-frequency electric field instead of a magnetic field to transfer power, eliminating eddy current losses [13]. Capacitive couplers are usually constructed of metal plates, and the coupler is very easy to seal and robust in underwater environments. Insulation of the coupler requires only a layer of insulating material on the surface of the metal plate, which is low cost. In addition to this, the relative dielectric constant of water can reach 81, which can significantly increase the coupling capacitance between the metal plates, thus improving the power transfer capability of the system, and reduce the size of the compensation inductor, further improving the power density of the system and facilitating later integration [14–16]. Therefore, UCPT has a very great potential for development and represents an interesting research direction.

WPT technology effectively solves the problems of limited equipment flexibility and potential safety hazards caused by traditional wired power access methods. It has broad application prospects in electric vehicles, industrial production, biomedicine, aerospace, underwater environment, and other fields [17,18]. Compared with wireless power transfer in the air, UCPT system faces more challenges because of its complicated underwater environment. At the same time, the existing review on CPT technology is mainly an overview of almost the whole field of CPT technology research [19,20], where the applications of this technology in the underwater wireless power transfer field are only briefly summarized as one of the chapters [20]. In conclusion, in the existing literature, there is no general review of the UCPT technology in a concrete and elaborate sense. In this paper, the development and research status of UCPT technology are systematically and comprehensively summarized for the first time. Compared with the traditional CPT system, the biggest particularity of UCPT technology lies in its different working environment. On the one hand, there are significant differences between water and air in terms of electrical conductivity and relative dielectric constant, and the relative dielectric constant of water is large, which leads to a larger coupling capacitance of the metal plate in a certain area than that of the metal plate air. The different electrical conductivity of water mainly affects the establishment of an equivalent model of the coupler; there will be water flow in the underwater environment and the coupler will shift. Moreover, special problems, such as pressure, corrosion, and plankton attachment in the underwater environment, need further consideration, so the coupler and resonance compensation network need to be improved. This paper also analyzes the development problems of the current UCPT technology and proposes solutions and development directions to overcome these problems. The general framework diagram of this paper is shown in Figure 2.

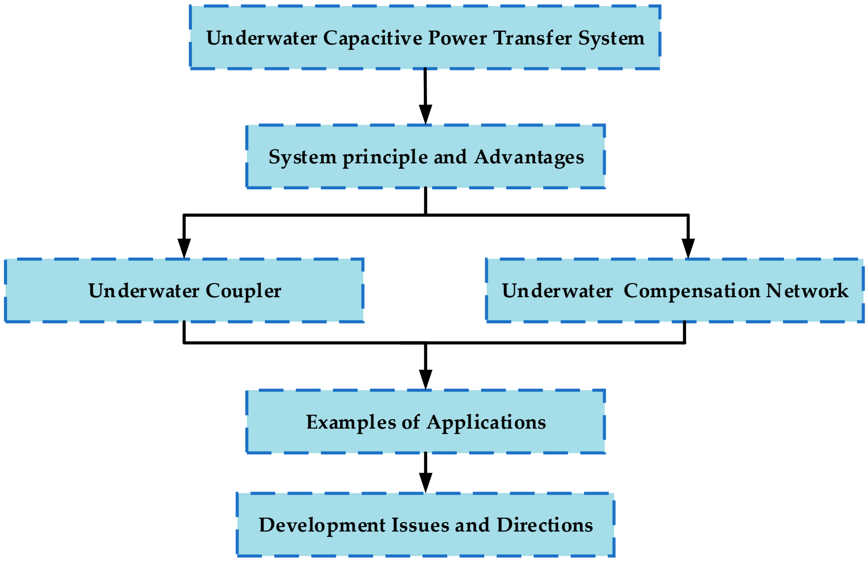


Figure 2. Overall framework of this paper.

2. Principles and Advantages of UCPT Systems

2.1. Working Principle of UCPT Systems

As early as 1966, there was a brief introduction to the UCPT system in the literature [21] presented by an American electrical engineer named Paul C. His proposed UCPT system mainly consists of a signal generator, a high-voltage generator, a coupler, and a signal detector. The metal plate of the coupler is separated from the seawater by an insulating material, and the seawater is used as the dielectric of the coupler, which increases the equivalent capacitance value of the coupler. This system only proves the feasibility of UCPT. Corresponding research on operating frequency, efficiency, and coupler design are not included. The UCPT system was not developed due to technical limitations at that time.

A typical UCPT system is illustrated in Figure 3, which contains a DC power supply, a high-frequency inverter, a primary compensation network, a coupler, a secondary compensation network, a rectifier filter, and load. At the primary side, the high-voltage DC power supply is used to power the system. The DC voltage is converted into high-frequency AC voltage by the high-frequency inverter. The high-frequency AC voltage passes through the compensation network composed of LC components to provide the coupler with high-frequency and high-voltage AC excitation. When the flat capacitor begins to charge, high-frequency and high-voltage excitation will establish an electric field between the two metal plates of the capacitor, resulting in the accumulation of charges on the metal plates. According to the concept of "displacement current" in Maxwell's equations, the change of electric field will produce "displacement current" inside the capacitor. When the flat capacitor discharges, the energy stored in the electric field begins to be released, and the intensity of the electric field decreases, resulting in the change to the displacement current. The direction of the displacement current is opposite to that of charging to reflect the decrease in electric field intensity [22]. At the secondary side of the system, the electrical power is rectified and converted into the direct current required by the load [23].

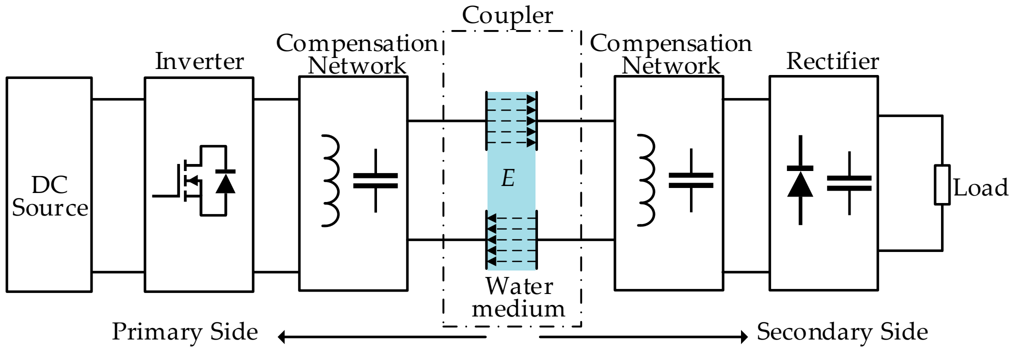


Figure 3. A typical UCPT system.

"Displacement current" is the integral of the change rate of electric displacement vector with time to the surface; it is proportional to the change rate of the electric field between capacitor plates. During the charging and discharging process of the planar capacitive coupler, the "displacement current" is not directly converted into actual power transmission but is related to the electromagnetic field changes inside and outside the capacitive coupler, which reflects the process of storing and releasing the energy of the capacitive coupler. "Displacement current" plays a key role in the storage and propagation of electromagnetic energy, but its relationship with system efficiency is indirect and there is no quantitative relationship; it needs to be evaluated in combination with specific applications and system design.

2.2. Advantages of UCPT Technology

In terms of the application of WPT in underwater environments, the performance comparison between UCPT technology and UIPT technology is shown in Table 1. UCPT is a better choice than UIPT for wireless charging because of the following advantages [24,25]:

1. UCPT technology uses a high-frequency electric field to transfer electrical energy instead of a magnetic field, which reduces eddy current loss in water.
2. UCPT technology has minimal electromagnetic interference with electrical equipment and can transfer energy through metal obstacles.
3. The coupler of UCPT technology uses metal plates with a simple structure, which can adapt to situations involving high pressure in deep water. When used underwater, it only needs to be covered with an insulating layer on the surface.
4. For UCPT technology, the coupling capacitance between the metal plates is a key factor in energy transfer. The relative permittivity of water is 81, which greatly increases the coupling capacitance between the metal plates, which is beneficial for increasing the transmission power and efficiency of the system [14].
5. An increase in coupling capacitance means that smaller inductors can be used for compensation, further reducing the size of the system and lowering its cost, which is beneficial for increasing the power density of the system.

Table 1. Comparison of UCPT and UIPT.

Underwater Inductive Power Transfer (UIPT)	Underwater Capacitive Power Transfer (UCPT)
Magnetic field	Electric field
Cannot travel through metal	Can travel through metal
With eddy current loss in water	Without eddy current loss in water
High-frequency Leeds line; has high cost	Metal plates; has low cost
Ferrite core is needed, which is heavy and has "piezomagnetic effect" in deep sea	Water medium has a high relative dielectric constant
The coupler takes up a lot of space, and the coil heats obviously	The space occupied by coupler is small, and the heating of metal plate is low
Working frequency is several hundred kHz	Working frequency is MHz
Further research stage	Preliminary research stage

3. UCPT Coupler

The gap of the coupler in the underwater environment is filled with a water medium, and reasonable and effective modeling of the coupler of the UCPT system is the key to analyzing the underwater transmission performance. As shown in Figure 4, distilled or purified water contains very little impurity, and its conductivity is about 1.0 to 10.0 µS/cm. This type of water medium basically has no conductivity. Natural fresh water contains more conductive ions and impurities, with a conductivity of about 125 to 1250 µS/cm, while mineralized water has a conductivity of about 500 to 1000 µS/cm. This type of water medium has a certain degree of conductivity. Seawater contains a large number of conductive ions and impurities, and its conductivity can reach 30,000 µS/cm and above, further enhancing its conductivity. There are significant differences in the electrical conductivity of other insulating media, such as air, when compared to water medium, and these differences will affect the working characteristics of the UCPT coupler, which will change the output characteristics of the UCPT system [26].

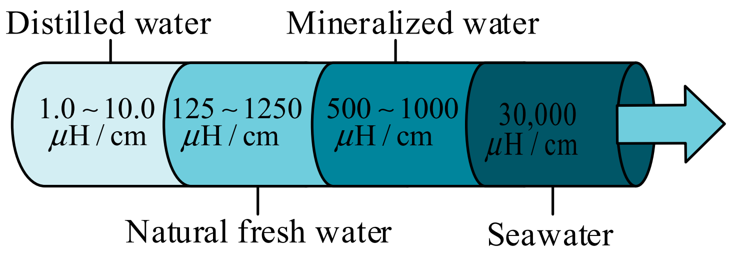
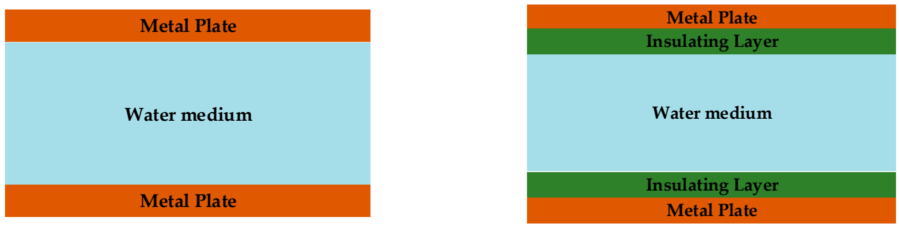


Figure 4. Conductivity of different water mediums.

The coupler of the UCPT system is composed of several metal plates, and the metal plates are generally made of materials with high conductivity, which can reduce the resistance loss and improve the transmission efficiency. However, considering the cost and availability, most of the UCPT system metal plates studied at present choose copper or aluminum materials. At present, the majority of UCPT systems have an insulating layer applied to the surface of the coupler [27]. Insulated UCPT couplers offer four advantages compared to uninsulated couplers: first, the insulated coupler provides better safety performance; second, the insulated coupler can limit direct current in the circuit, thereby reducing the potential direct current bias in the alternating current resonant circuit; third, the insulating layer can prevent potential electrical breakdown of the dielectric material (such as water) between the metal plates, ensuring safe operation for a long time; fourth, the insulating layer can prevent corrosion of the metal when working in water for a long time, helping to extend the service life of the charging system in a water environment.

3.1. Underwater Two-Plate Coupler

UCPT systems in the underwater environment that only use a pair of metal plates to transfer energy are called two-plate couples. The capacitive coupler consists of two metal plates, which are, respectively, the transmitting and receiving plate. The surface of the metal plate can be optionally covered with a layer of insulating material between the two metal plates by the water dielectric for the filling of the composition of the capacitive coupler. So, the two-plate coupler is divided into two kinds, i.e., those with and without insulating layer [16,28–30], as shown in Figure 5a,b.

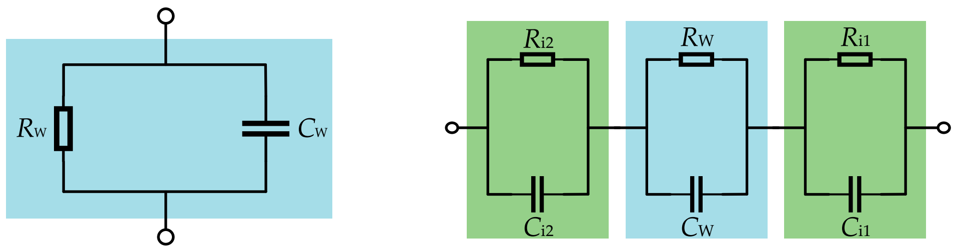


(a) (b)

Figure 5. Two-plate capacitive coupler without and with insulating layer. (**a**) Two-plate capacitive coupler without insulating layer. (**b**) Two-plate capacitive coupler with insulating layer.

Depending on the conductivity, the water medium can be considered as either a non-conducting medium or a conducting conductor. When the medium is fresh water, the conductivity of fresh water is relatively low, so both the equivalent resistance and the equivalent capacitance should be considered in the equivalent circuit model of the freshwater medium [26,27]. The equivalent circuit model of the uninsulated and insulated two-plate coupler is shown in Figure 6. R_w and C_w are the equivalent resistance and capacitance of the water medium, respectively; R_{i1} and R_{i2} are the equivalent resistance of the insulating layer and the equivalent capacitance of the C_{i1} and C_{i2} insulating layers, respectively. Therefore, the equivalent capacitance and equivalent resistance of a two-plate insulated capacitive coupler in a freshwater environment can be defined as follows.

$$R_{eq1} = R_w + R_{i1} + R_{i2}, C_{eq1} = \frac{1}{\frac{1}{C_w} + \frac{1}{C_{i1}} + \frac{1}{C_{i2}}}, \quad (1)$$



(a) (b)

Figure 6. The equivalent circuit model of the uninsulated and insulated two-plate coupler. (**a**) The equivalent circuit model of the uninsulated two-plate coupler. (**b**) The equivalent circuit model of the insulated two-plate coupler.

However, the conductivity of seawater is quite large compared to fresh water. This means that the R_W is so small in seawater that seawater can act as a conductor; a current is generated between the metal plates; and a high-frequency electric field cannot exist inside the conductor. Therefore, neither equivalent capacitance C_w nor equivalent resistance R_w can be formed [31,32]. Thus, the equivalent capacitance and equivalent resistance of a two-plate insulated coupler in seawater can be defined as follows:

$$R_{eq2} = R_{i1} + R_{i2}, C_{eq2} = \frac{1}{\frac{1}{C_{i1}} + \frac{1}{C_{i2}}}, \quad (2)$$

Due to the high conductivity of seawater, the coupling metal plates in seawater need to be insulated. In this case, the equivalent capacitance of the UCPT coupler is only related to the area of the metal plate, the thickness of the insulating material, and the relative permittivity of the insulating material but not to the transfer distance and the relative permittivity of the water medium [33].

In addition, Cai C. and other scholars established the equivalent circuit model of the two-plate capacitive coupler in the seawater environment with due consideration to the fact that seawater contains a large number of free ions and a variety of species. When the voltage is applied to the metal plate, it is assumed that it carries a positive charge. Due to the presence of an insulating layer, the positive charge cannot be lost. Under the electrostatic force of the positive charge on the metal plate, the cations in the ocean will move away from the metal plate. The anions will approach the metal plate and gather at the solid–liquid interface of the insulating medium to form an anion layer opposing the positive surface charge of the metal plate such that a diffuse double layer can be formed between the charged insulated metal plates in seawater [34,35]. The equivalent circuit model of the under-seawater two-plate capacitive coupler is shown in Figure 7, where C_{M1} and C_{M2} denote the double capacitance formed between the metal plate and the seawater; R_{S1} and R_{S2} denote the dielectric loss and internal resistance of the insulating medium; and R_{sea} is the seawater resistance. However, the equivalent model of electric double layer of the coupler is not applicable under all conditions. With the increase in working frequency, it will be difficult to form the electric double layer, so we should fully consider its existence conditions when establishing the equivalent model of circuit.

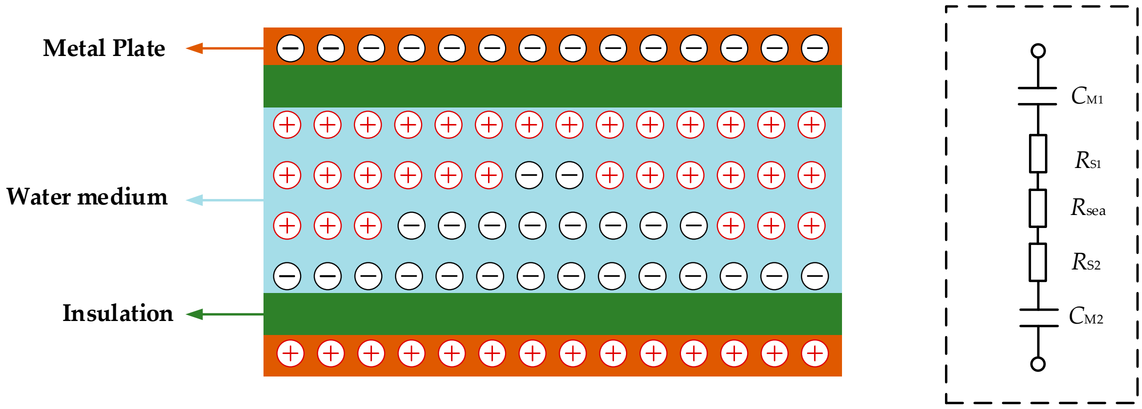


Figure 7. Two-plate capacitive coupler and its equivalent circuit model.

Above all, the ion concentration in the water medium will affect its conductivity and then affect the establishment of the equivalent model of the UCPT coupler. The current is mainly conducted by ions in the solution. Distilled water contains almost no ions, so the conductivity of distilled water is relatively low. According to Ohm's law, the resistivity is inversely proportional to the conductivity. In a certain space, the lower the resistivity, the greater the resistance value. Capacitance and conductance can exist between metal plates at the same time, and the insulating layer will also bring additional capacitance. Therefore, when modeling the underwater capacitive coupler, it is necessary to fully consider the conductivity of the actual underwater environment and the influence of different working frequencies on the equivalent capacitance and equivalent conductance of the water medium so as to obtain a more simplified and accurate equivalent model of the UCPT coupler.

In addition, the UCPT system can be designed according to the influence of water with different levels of conductivity with respect to coupler energy transfer. First, the higher the conductivity of a dielectric, the greater the energy loss caused by the movement of charge carriers (such as electrons or ions) inside it. In the coupled capacitor energy transmission system, this kind of loss mainly appears in the form of heat, which leads to the reduction of energy transmission efficiency. Secondly, the conductivity of dielectric can be regarded as a part of the equivalent series or of the parallel resistance of the capacitor, and the establishment of equivalent model of the coupler should be considered comprehensively [17]. Finally, the quality factor Q of the coupler is the parameter used to measure its energy loss, which is defined as the ratio of stored energy to lost energy. Dielectric with high conductivity will reduce the Q value of capacitance because more energy is lost [36,37].

3.2. Underwater Four-Plate Coupler

Four-plate couplers can be divided into parallel and vertical two types, although the four-plate coupler structure is simple, the coupling capacitance is large; the coupling coefficient is high and has been widely researched [38–47]. However, in the face of complex underwater environments, couplers still face challenges when using parallel and vertical arrangements. For example, when arranged in parallel, the coupler is prone to edge effects, resulting in uneven distribution of the electric field and a large degree of electric field dissipation. In order to obtain large coupling capacitance values for efficient power transfer, parallel and vertical plates may require large physical dimensions, which can be a challenge in space-constrained applications. The parallel arrangement of the couplers cannot overcome the cross-coupling problems caused by the rotation process, which will reduce the stability and transmission efficiency of the system. In an underwater environment, it is very difficult to maintain precise alignment between the transmitter and receiver due to water flow, water pressure, and other dynamic factors, which may require complex circuit design and control strategies.

According to the current research, it is known that the placement of the metal plate of the UCPT coupler in the water is roughly divided into two categories: one is that the metal plates are fully immersed in the water [10–35,38,39], and the other is that the water only exists in the middle of the metal plates; the backs of the metal plates are in the air environment [42–47]. In actual scenarios, the metal plates are generally close to the surface of the base station and the charging equipment casing, and the air environment is inside the base station and the equipment. So, the water area, which only exists between the metal plates, is closer to the actual situation. Therefore, as shown in Figure 8, there are two four-plate insulated couplers for the water that only exists between metal plates.

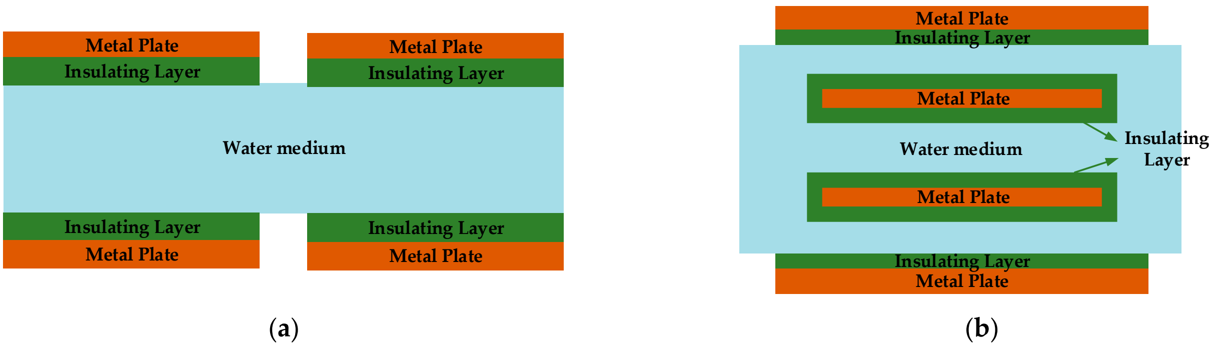


Figure 8. Underwater four-plate insulated coupler: (**a**) parallel coupler; (**b**) vertical coupler.

Currently, in research on UCPT technology, the four-plate coupler often adopts the equivalent method of the traditional six-capacitance model, as shown in Figure 9. For example, ref. [31] modeled the UCPT by directly ignoring the conductance of seawater between the metal plates and only considered the water's capacitance. In ref. [48], the insulated coupler is equated using the insulation layer capacitance and the freshwater capacitance in series, and the conductance of the water is not considered. Ref. [42] investigated the insulated coupler in water with different conductivities and analyzed the effect of conductivity change on the coupling capacitance, but again, the conductance of the water was neglected in the modeling. Therefore, the six-capacitance equivalent model is only suitable for simple theoretical analysis, and it is unreasonable to directly adopt the six-capacitance equivalent model in different underwater environments. The capacitance and conductivity characteristics of water media should be fully considered.

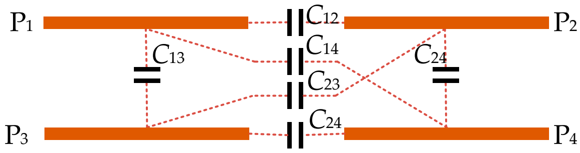


Figure 9. Equivalent six-capacitor model for four-plate coupler.

In Figure 9, there is a coupling capacitance between each pair of metal plates, resulting in a total of six capacitors, where C_{13} and C_{24} are defined as the main coupling capacitance; C_{14} and C_{23} are defined as the cross coupling capacitance; and C_{12} and C_{34} are defined as the self-coupling capacitance. This six-capacitance coupling model is more effective and accurate than the traditional coupling model. Different from directly ignoring the conductance of the waters, the research scholars Lu F. of Drexel University, USA, propose that the equivalent model of the freshwater capacitive coupler needs to consider the parasitic resistance [27]. The resistances are defined as R_{12}, R_{13}, R_{14}, R_{23}, R_{24}, and R_{34}. The equivalent model of the four-plate capacitive coupler, considering parasitic resistance, is shown in Figure 10. Considering the equivalent capacitance and conductance of the water medium at the same time will lead to the increase in the equivalent parameters of the coupler and further increase the analysis difficulty, but the equivalent method is more reasonable and accurate. The conductance of the coupling is defined as follows:

$$\begin{aligned} Y_{12} = j\omega C_{12} + \tfrac{1}{R_{12}}, Y_{13} = j\omega C_{13} + \tfrac{1}{R_{13}}, Y_{14} = j\omega C_{14} + \tfrac{1}{R_{14}}, \\ Y_{23} = j\omega C_{23} + \tfrac{1}{R_{23}}, Y_{24} = j\omega C_{24} + \tfrac{1}{R_{24}}, Y_{34} = j\omega C_{34} + \tfrac{1}{R_{34}}. \end{aligned} \quad (3)$$

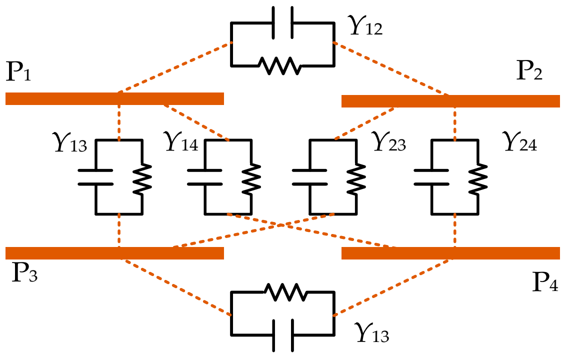


Figure 10. Equivalent six-admittance model of the four-plate coupler.

Unlike pure capacitive models, parasitic resistance increases the complexity of the system. More parameters need to be considered to simplify the topology. Lu F.'s research team pointed out that when the four metal plates of the UCPT coupler are of the same size, the main capacitors C_{13} and C_{24} and the cross-capacitors C_{14} and C_{23} of the UCPT coupler are approximately equal. At this time, the equivalent mutual capacitance of the UCPT coupler is extremely small, which is not conducive to the transmission of electrical energy. In order to increase the equivalent mutual capacitance of the underwater coupler, this team designed an asymmetric UCPT coupler, as shown in Figure 11. By reducing the area of a pair of metal plates, thereby increasing the gap between the main capacitance and cross capacitance of the UCPT coupler, they ultimately achieved an increase in the equivalent mutual capacitance of the UCPT coupler. The coupler of this design uses an insulating material to isolate the metal plates from the water medium. However, the water medium selected in the study has a low conductivity of only 2 μS/cm [27].

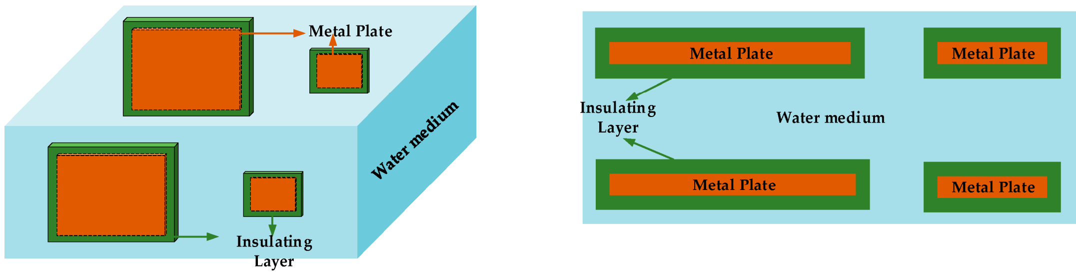


Figure 11. Underwater parallel asymmetric four-plate insulated coupler.

Ref. [49] points out that in the case of a seawater medium, because seawater is a conductor, the metal plates soaked inside seawater produce effects similar to a short circuit, so it is necessary to isolate the ipsilateral metal plates to transfer power. Capacitance is generated only in the insulating layer, and seawater generates resistance between each pair of metal plates. To avoid C_M equaling zero, C_{13} and C_{24} should be larger than C_{14} and C_{23}. The Japanese scholar Tamura M. first proposed a double-cavity coupler in a seawater environment; the insulating plate divides the whole structure into two cavities such that the four-plate structure turns into two two-plate structures, as shown in Figure 12 [36].

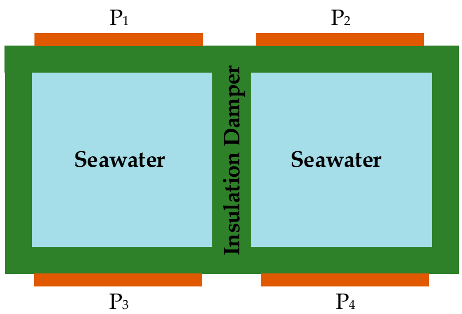


Figure 12. Double-cavity coupler for seawater environments.

3.3. Underwater Six-Plate Coupler

The four-plate UCPT coupler has strong electric field radiation, which has two disadvantages: first, it is a safety hazard to nearby organisms and equipment; second, it is susceptible to outside interference and becomes a source of interference. The six-plate coupler provides a good electric field shielding solution. It has four power transfer plates and two shield plates. The power transfer plates are connected to the transmitter and receiver circuits, respectively, while the shield plates are not connected to electricity [50].

As for the six-plate coupler, with the increase in the distance between the shield plates and the power transfer plates, the self-capacitance of the coupler decreases significantly, and the mutual capacitance increases, which makes the coupling coefficient of the coupler improve, and this is helpful in achieving higher efficiency [37].

Rong E.'s research team first proposed an underwater six-plate insulated coupler [37], as shown in Figure 13. Since there is an admittance between each pair of metal plates, the fifteen-admittance model of the coupler is proposed. Compared with ref. [27], this model is more complex, with further increases in parameters, and the water medium is close to distilled water, which is quite different from the level of conductivity in practical application scenarios. Based on ref. [37], the team further proposes a new type of six-plate and hybrid-dielectric insulated coupler, as shown in Figure 14. Specifically, water is used as the dielectric between the transmitting metal plates and the receiving metal plates, while air is used as the dielectric between the same-side power transfer metal plates and the shielding metal plates [51]. Since the dielectric constant of water is higher than that of air, this choice of material greatly reduces the ratio of the self-capacitance to the mutual capacitance of the coupler, greatly improving the coupling coefficient of the six-plate coupler. Compared with the traditional stacked and parallel plate coupler in underwater environment, the underwater six-plate and hybrid-dielectric coupler greatly reduces the leakage of electric field emission and greatly improves the safety of the system. However, there are many equivalent parameters of the coupler, which increases the analysis difficulty of the system, and the design of the coupler in practical application is complicated and takes up a lot of space.

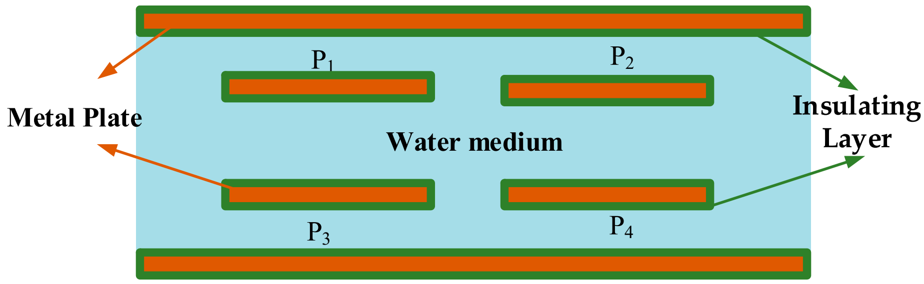


Figure 13. Underwater six-plate insulated coupler.

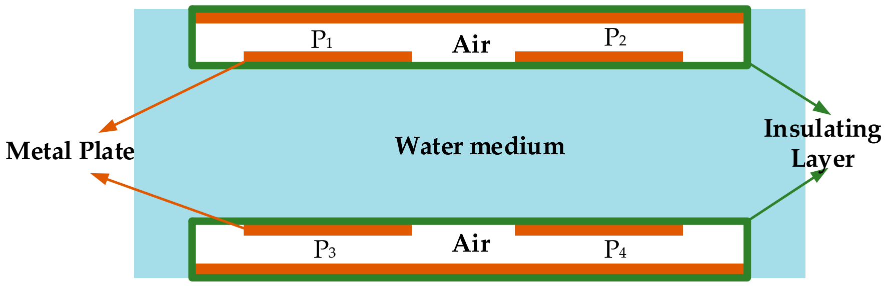


Figure 14. Underwater six-plate and hybrid-dielectric coupler.

3.4. Underwater Rotary Coupler

The plate-type coupler will cause cross-coupling problems during rotation and will also reduce its own equivalent coupling area. Therefore, the plate-type coupler cannot be used in a rotating scenario [52]. To meet the requirements of underwater rotating equipment, ref. [53] proposes an underwater disc-type insulated coupler as shown in Figure 15. This coupler consists of two pairs of disc structures, which are coaxially arranged. During the rotational motion along this axis, the area of the two pairs of discs facing each other remains constant, avoiding the problems associated with the plate-type coupler in rotating scenarios.

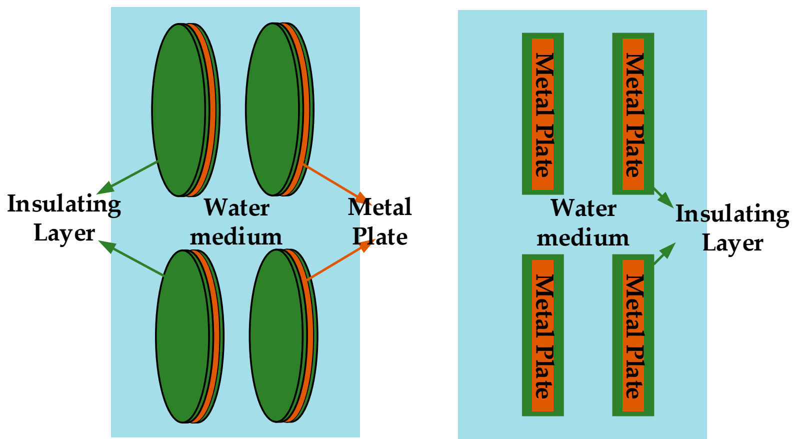


Figure 15. Underwater disc-type insulated coupler.

Compared with the disc-type coupler, in order to increase the coupling capacitance of the coupler within a certain space, ref. [48] takes the application of the wireless power supply to the rotating equipment using capacitive coupling in fresh water as an example and proposes a rotating cylindrical coupler that takes into account the insulating layer, as shown in Figure 16. The anti-offset effect of this coupler in an underwater environment is better than that in air.

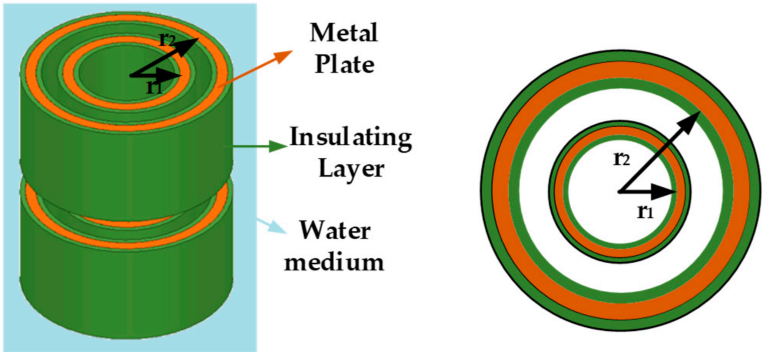


Figure 16. Underwater cylindrical insulated coupler.

Although the underwater cylindrical insulated coupler can be applied to rotation, it also reduces the flexibility of the receiving device and increases the difficulty of aligning the operation between the receiver and the transmitter. Therefore, in order to adapt to underwater rotating applications, a new coupler with strong applicability relative to a cylindrical structure is proposed in [54], as shown in Figure 17.

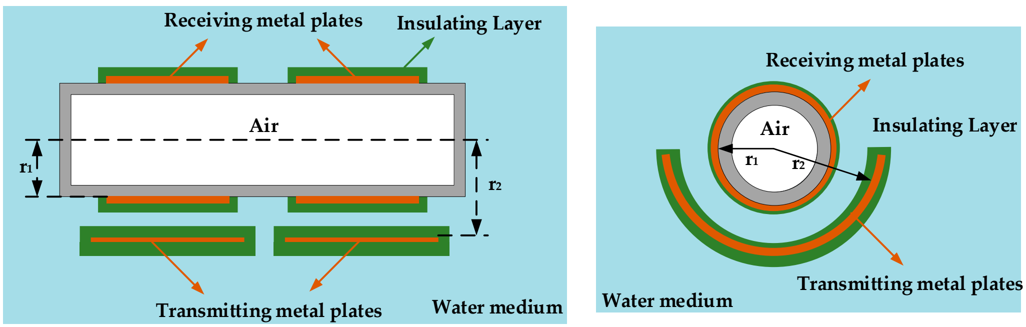


Figure 17. Underwater semi-cylindrical insulated coupler.

Compared with underwater plate-type coupler, the cylindrical coupler can not only be used in rotating environment; it can also increase the equivalent capacitance per unit area, attain a stronger anti-offset ability, and reduce electric field dissipation, but its structure is more complicated.

3.5. Other Underwater Couplers

Figure 18 shows an underwater spherical insulated coupler, which is composed of two metal balls. It is suitable for WPT in all directions in three-dimensional space. The transmitting end and receiving end can be rotated arbitrarily, which increases the wireless charging range of the electrical equipment and greatly increases the flexibility of system power supply [55]. Therefore, this coupler can be widely used in scenarios with high flexibility or multi-load charging, for example, the wireless power supply between surface-monitoring buoys and between monitoring buoys and surface sensors.

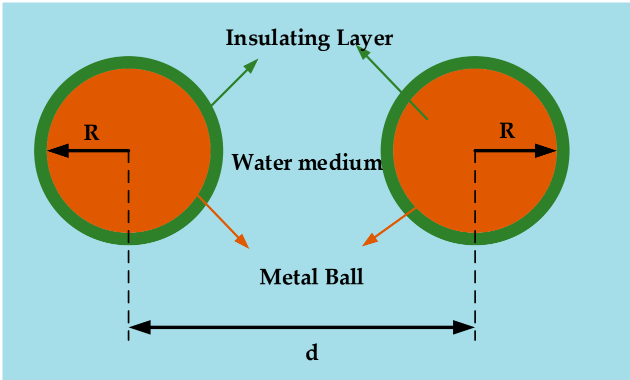


Figure 18. Underwater spherical insulated coupler.

Feng D. described an underwater multi-layer stacked insulated coupler, as shown in Figure 19. The transmitting side and the receiving side are both composed of three layers of metal plates with insulation, and the metal plates on the same side have the same voltage potential. If there are no space constraints, the number of stacked layers can theoretically be increased indefinitely. With the same metal plate area and the same transfer distance, this coupler significantly improves the coupling capacitance. However, the circuit model of the multi-layer stacked coupler is more complicated. The insulating layer of each metal plate is equivalent to a parallel combination of coupling capacitance and resistance [56].

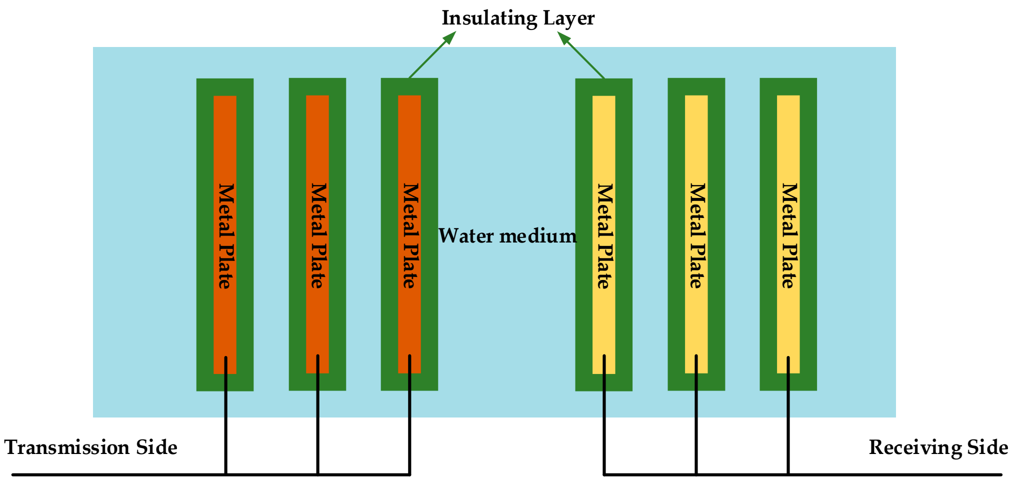


Figure 19. Underwater multi-layer stacked insulated coupler.

The parameters and performances of the above underwater couplers are summarized in Table 2. The traditional couplers in the UCPT system are mainly divided into three types: flat coupler, disc coupler, and cylindrical coupler. To meet the requirements of various underwater environments, more applicable coupler types need to be proposed in the future. For example, to address the issue of the low power transfer capability of underwater couplers, multi-transmitter single-receiver couplers can be taken into consideration. Given the situation of there being weak resistance to the offset effect in traditional underwater couplers, designing large-to-small or rectangular array couplers can be considered.

Table 2. Parameter comparison of various underwater capacitive couplers.

Type	Water Medium	Size	Transfer Distance	Power	Efficiency	Reference
Two-plate coupler	Fresh water	170 × 50 mm	5 mm	0.0198 W	76.7%	[16]
Parallel four-plate coupler	Seawater	170 × 100 × 5 mm	100 mm	100 W	50%	[31]
Parallel four-plate coupler	Fresh water	125 × 205 × 1.6 mm	20 mm	400 W	90%	[40]
Asymmetric four-plate coupler	Fresh water	200 × 200 × 1 mm, 200 × 100 × 1 mm	500 mm	220 W	60.17%	[14,27]
Vertical four-plate coupler	Seawater	150 × 150 × 30 mm	500 mm	48 W	54%	[57]
Double-cavity coupler	Seawater	150 × 150 × 2 mm	100 mm	200 W	70.1%	[49]
Double-cavity coupler	Seawater	250 × 125 × 1.6 mm	20 mm (150 mm)	1018 W	94.5% (85.3%)	[36]
Cylindrical coupler	Fresh water	Outside radius 82 mm, inside radius 72 mm	10 mm	311 W	87.4%	[48]
Six-plate insulated coupler	Fresh water	200 × 200 mm	50 mm	3300 W	75.9%	[37]
Six-Plate and hybrid-dielectric coupler	Fresh water	200 × 200 mm	60 mm	5000 W	87.24%	[51]
Disc-type coupler	Seawater	Radius 51 mm, thickness 3 mm	2 mm	0.125 W	-	[33]
Semi-cylindrical insulation coupler	Fresh water	Outside radius 138 mm, inside radius 125 mm	10 mm	471 W	44%	[54]
Spherical insulating coupler	Fresh water	Radius 50 mm, thickness 2 mm	700 mm	53.3 W	40.9%	[55]

The structure and size of the coupler determine the coupling capacitance and directly affect the transmission power capacity of the system.

1. The area of the coupler is proportional to the coupling capacitance. Increasing the area can improve the power transmission capacity of the UCPT system.
2. The distance between couplers is inversely proportional to the coupling capacitance. Reducing the spacing can improve the power transmission capacity of the UCPT system.
3. The shape of the coupler will affect the distribution of electric field. Ideally, the shape of the coupler should make the electric field as uniform as possible and reduce the edge effect to improve the energy transmission efficiency of the coupler.
4. The structure and size of the coupler directly affect the coupling coefficient, that is, the energy transfer efficiency of the coupler.
5. In different underwater environments, the structure and size of the coupler need to be adjusted according to different environmental parameters to maintain high power and high efficiency of the system.

The impact of the structure and size of the coupler on the power and efficiency of the system in a changing underwater environment is manifold. Factors such as coupling capacitance values, coupling field distributions, figure of merit, coupling coefficients, and physical and environmental constraints need to be considered. The shape and size of the coupler needs to be determined based on the specific application needs, environmental conditions, and cost–benefit analysis. Through simulation and experimental testing, the design is further optimized to achieve the best power and transmission efficiency.

4. Underwater Compensation Network

The compensation network, as an important part of the UCPT system, determines the power capability, efficiency, and frequency characteristics of the system under specific input and output conditions. The main purpose of adding the compensation network is to reduce the reactive power, increase the output power and efficiency, and achieve different load characteristics, such as constant voltage or constant current characteristics, etc. [58–61]. The complexity of the underwater environment puts higher requirements on the UCPT system. The underwater environment has the influence of water current, which requires the compensation network to have certain anti-offset characteristics and to be able to operate stably in an environment of high underwater pressure. At present, the research into UCPT technology is still in the primary stage; most of the research on UCPT technology is theoretical, so the compensation network design for the complex environment of the UCPT system is not rich enough, but this paper provides a summary of the compensation network of the UCPT system and points out the problems of the current compensation network.

4.1. Power Amplifier Based Compensation Network

Aiming at the problems of the low output power, small resonant capacity, and large frequency drift of single-stage LC resonant UCPT system, ref. [62] designed a UCPT system that was more suitable for the water environment. As shown in Figure 20, this system is based on the CLC-L tuning network, which combines the advantages of high efficiency with a high-frequency class E amplifier to achieve the power output. The UCPT system adopts a π-S type compensation network, and compared with the LC series resonant circuit, the CLC type resonant network with higher order has the role of voltage pumping, which makes the voltage of the coupler higher than the output voltage of the inverter network and effectively solves the contradiction between the low-voltage demand of the MOSFET tubes of the E-class inverter and the high-voltage excitation demand of the coupler, which both reduces the voltage level of the switching tubes and ensures a higher transfer power [1].

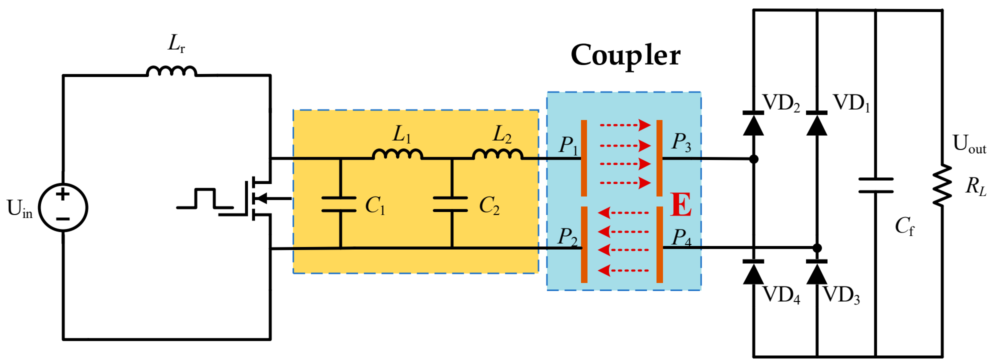


Figure 20. CLC-L compensation network based on class E amplifiers.

Since the class E amplifier has a smaller number of switching tubes, it is smaller and less costly. In addition, the class E amplifier can achieve soft switching with high conversion efficiency and low conduction loss. However, it requires higher resonance accuracy and is more sensitive to changes in resonance circuit parameters, so there are greater implementation difficulties [63,64].

4.2. Compensation Network Based on Full-Bridge Inverter

A full-bridge inverter is an effective method of supplying AC excitation to the UCPT system. The inverter is a key component for supplying AC excitation to the compensation network. The primary-side inverter consists of four MOSFET switch tubes driven by a PWM signal. The system power can be adjusted by adjusting the switching frequency and duty cycle. On the secondary side, a diode rectifier is used to supply DC current to the load. UCPT technology has now developed a variety of compensation networks using a full-bridge inverter to achieve capacitive power transfer.

4.2.1. Double-Sided L Compensation Network

The most basic compensation network in the UCPT system is single-inductor compensation [13,31,57]. The advantage of this compensation network is that it is simple and economical, and only one inductor is used on the primary and secondary sides to complete the resonant compensation function, as shown in Figure 21. Although the equivalent coupling capacitance in the UCPT system is relatively large, the value of the resonant inductor used for compensation is still large considering the voltage of the coupler metal plate and the power level of the system. Therefore, single-inductor compensation networks are more suitable for low-power and high-frequency scenarios.

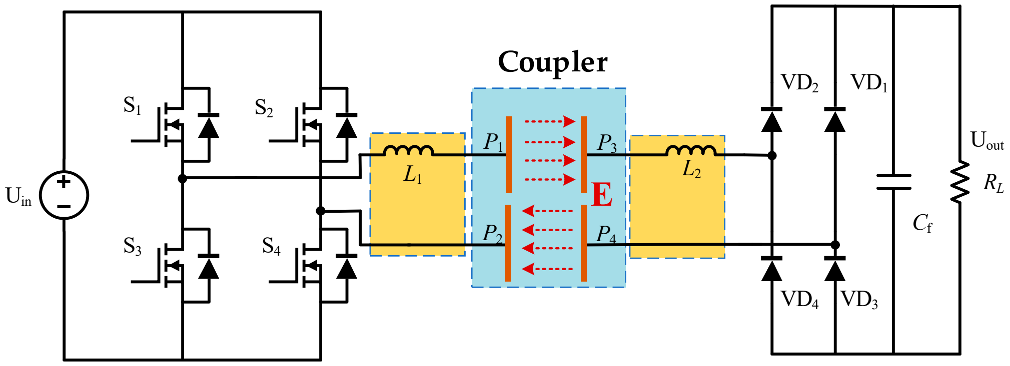


Figure 21. UCPT system with double-sided L compensation network.

4.2.2. Double-Sided LC Compensation Network

LC compensation networks are widely used due to their simplicity. As shown in Figure 22, a double-sided LC compensation network can be formed by connecting a compensation capacitor in parallel at each end of the coupler, which can significantly reduce the resonant inductance parameter. Since the compensation capacitor is much larger than the equivalent coupling capacitor, when the coupling capacitor experiences a shift in capacitance due to external factors, the total shunt capacitance of the system can still maintain a small change, thereby improving system stability and anti-offset capability [48,49]. When this compensation network is used underwater, scholar Zhu Y. also considered the effect of seawater insulation corrosion. Based on the double-sided LC compensation network, a variable capacitor is connected in series with the coupler to maintain a zero-phase angle input and a constant current output for the UCPT system.

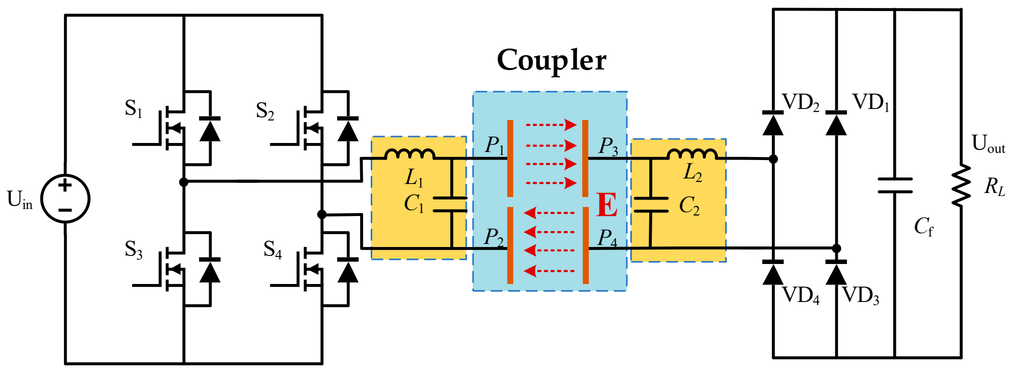


Figure 22. UCPT system with double-sided LC compensation network.

The double-sided LC compensation network can provide constant voltage and constant current outputs independently of the load and can boost or buck the output according to parameters. The SS compensation network can provide constant current output. In current research on UCPT systems, the SS topology is widely used, but the application of other double-sided LC topologies in underwater environments is yet to be studied. In addition, the double LC compensation network is suitable for low power output. When the output power increases, especially when the input voltage increases, the input current of the system and the withstand voltage of the components will increase significantly, the risk of electric breakdown of the metal plate is increased [65].

4.2.3. LC-CLL Compensation Network

The compensation networks of the existing UCPT system are relatively simple; it mostly adopts a double-sided L or double-sided LC compensation network. Only with the zero-phase angle can it achieve zero reactive power and load-independent constant current output or constant voltage output, but it cannot achieve constant current and constant voltage output at the same time. Therefore, to address the above problems, ref. [54] proposed an LC-CLL compensation network, as shown in Figure 23. This is a kind of compensation network for the UCPT system under freshwater conditions, which can achieve output constant AC voltage and constant AC current at two operating frequencies, respectively. In other words, this compensation network can meet the different demands of loads for output constant AC voltage or constant AC current, which improves the practicality and flexibility of the UCPT system.

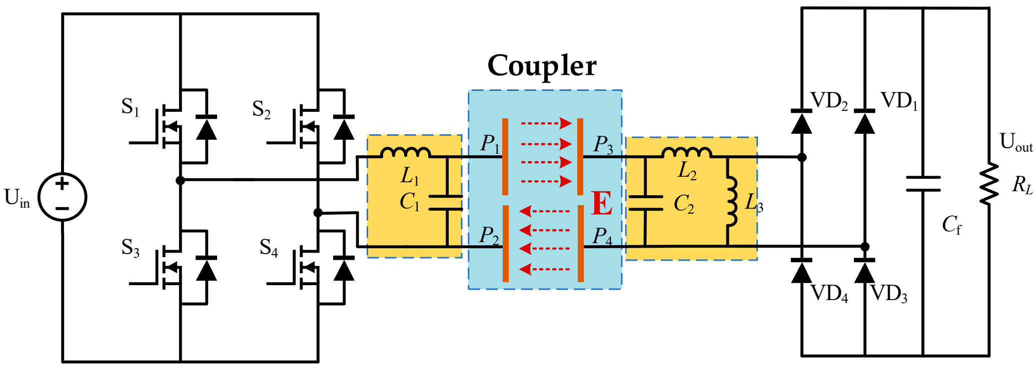


Figure 23. UCPT system with LC-CLL compensation network.

4.2.4. M-M Compensation Network

In order to achieve high-power transmission of the UCPT system, a high-order compensation network is required [58]. Rong E.'s team used an M-M compensation network in their research on high-power UCPT systems under freshwater conditions, as shown in Figure 24. This compensation network can resonate with the coupler to increase the metal plate voltage and compensate for reactive power loss, thereby improving the power and efficiency of the system [37,51]. The UCPT system uses an M-M compensation network, which has a constant current output characteristic and a high degree of design freedom [66]. Compared with other high-order compensation networks, the M-M compensation network is more compact. The inductance of the coupling improves the flexibility of system design and provides additional isolation. However, the addition of a transformer will cause electromagnetic interference to a certain extent. At the same time, the transformer's iron core will also increase the weight of the system [67–69].

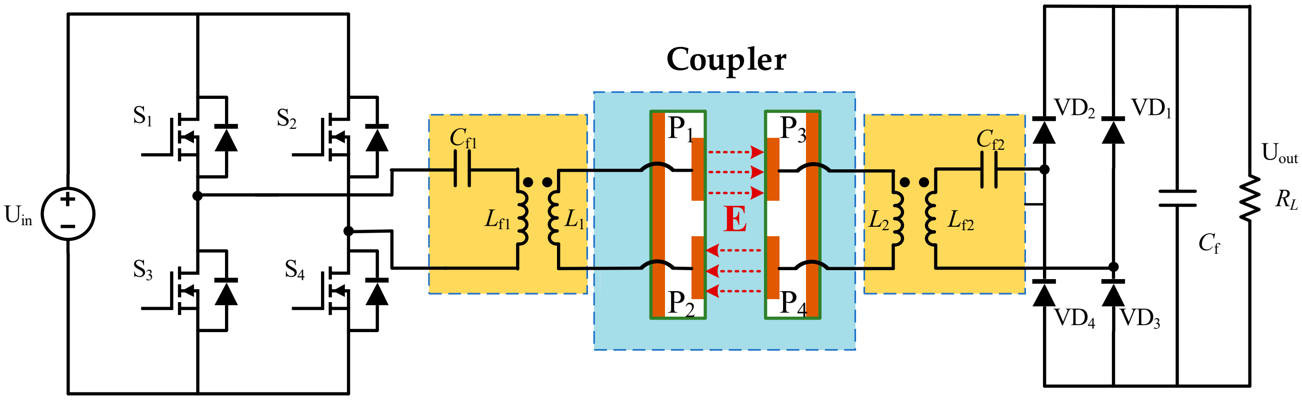


Figure 24. UCPT system with M-M compensation network.

4.2.5. Double-Sided LCLC Compensation Network

The advantage of a double-sided LCLC compensation network is that it can achieve a constant current output regardless of the load. Both the output current and output power are positively correlated with the coupling coefficient [44]. After the T-type LCL structure is boosted, the coupled metal plates can form high voltages to meet the requirements of high-power scenarios, overcoming the limitations of double-sided LC and double-sided LCL compensation networks.

The UCPT system proposed by Yang L.'s team adopts two H-bridge inverter networks to achieve bidirectional power transmission, as shown in Figure 25. The H-bridge circuit is built on GaN devices, which can achieve high switching frequencies and low power losses [70]. The two LCLC compensation networks are used on the transmitter and receiver sides, respectively. The disadvantage of the double-sided LCLC compensation network is its complex structure. As there are eight passive components in the compensation network, the system cost and weight increase accordingly. In addition, more components lead to additional power loss in the system, thereby reducing system efficiency [71,72].

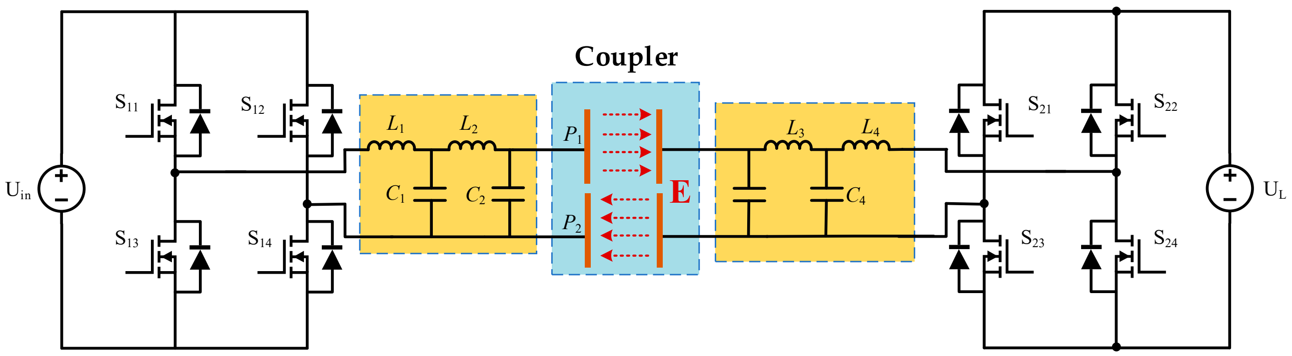


Figure 25. UCPT system with double-sided LCLC compensation network.

Most of the UCPT systems we summarized and analyzed above are built in the laboratory for principle analysis and experimental verification as shown in Table 3, i.e., without considering the influence of underwater working depth or scope. The underwater environmental parameters (temperature, ocean current, pressure, etc.) are different at different working depths, so considering the adaptability of UCPT system at different underwater depths is also anticipated to be one of the research hotspots in the future.

Table 3. A summary of the compensation network applicable to the UCPT system.

Category	Compensation Network	Water Medium	Transfer Distance	Frequency	Power	Efficiency	References
Class E power amplified	CLC-L	Seawater	2 mm	500 kHz	0.125 W	-	[62]
Full-bridge inverter	Double-sided L	Seawater	400 mm	500 kHz	100 W	50%	[31]
	Double-sided L	Seawater	500 mm	516 kHz	48 W	54%	[57]
	Double-sided LC	Seawater	20 mm (150 mm)	6.78 MHz	1018 W	94.5% (85.3%)	[36]
	Double-sided LC	Seawater	100 mm	1 MHz	200 W	70.1%	[49]
	Double-sided LC	Fresh water	500 mm	1 MHz	220 W	60.17%	[14,27]
	Double-sided LC	Fresh water	20 mm	107.7 MHz	400 W	90%	[40]
	LC-CLL	Fresh water	10 mm	839 kHz (950 kHz)	47 W (16.4 W)	44% (36%)	[54]
	M-M	Fresh water	50 mm	1 MHz	3300 W	75.9%	[37]
	M-M	Fresh water	60 mm	1 MHz	5000 W	87.2%	[51]
	Double-sided LCLC	Seawater	150 mm	625 kHz	100 W	80.15%	[45]

5. Examples of UCPT Applications and Future Development

Currently, underwater electromechanical devices mainly include autonomous underwater vehicles (AUVs), buoy monitoring systems, underwater wireless sensors, electric unmanned ships, etc. Most of these devices need to work for a long time in the water environment and have high requirements for the battery life of the device itself [73]. The traditional method of recharging the power of underwater electromechanical devices is problematic. Therefore, the application of WPT technology to the special scenario of the underwater environment can just solve the power supply problem of underwater electromechanical facilities, thereby improving the working efficiency and battery life of underwater equipment [74,75].

5.1. Research on UCPT for AUVs

The endurance of autonomous underwater vehicles (AUVs) is limited by the onboard energy storage system, which is mainly a battery system. In order to improve the cruising range and autonomy of AUVs, various underwater charging methods have been adopted. At present, the contact underwater charging technology requires high-precision docking of the AUV, and it is prone to electrical safety problems. To overcome these limitations, many scholars have explored UCPT technology for AUVs in recent years.

The UCPT system of the AUV is shown in Figure 26. In the context of wireless charging of AUVs, ref. [76] designed an underwater disc-type coupler, which was immersed in salt water with a conductivity of 40 mS/cm to simulate the seawater environment for experiments. Due to the high conductivity of seawater, the coupler composed of metal plates has strong conductive coupling. Therefore, based on the maximum efficiency of seawater UCPT coupler, ref. [36] analyzes in detail the specific influence of the parameters of the two-chamber coupler on the maximum transmission efficiency of the coupler and verifies the rationality of the design method. Using this method, a double-chamber coupler is designed in UCPT system in seawater environment in reference [49]. The insulating plate is used to separate the metal plates on the same side. Choosing a material with low dielectric constant and small loss tangent as the insulating board can effectively reduce the penetration of electromagnetic field and energy loss. Because the insulation board is thick enough and has good insulation within the charging station and AUVs, it eliminates the effects of cross-capacitance between different sides of the coupling metal plate and self-capacitance between the same side. When the transmission distance is 100 mm, the output power of the system reaches 200 w, and the transmission efficiency reaches 70.1%. However, this solution requires the bottom of the AUV to be tightly attached to the insulation board of the power transmitter to achieve the barrier effect on seawater, which is difficult to achieve on a seabed with a strong current.

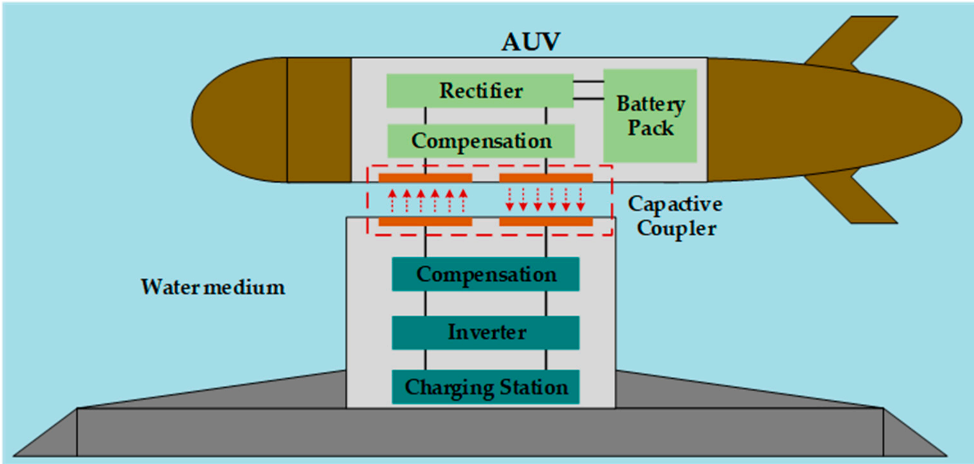


Figure 26. The UCPT system of the AUV.

Ref. [45] proposed a bidirectional underwater capacitive wireless power transfer (BD-UCWPT) system for AUVs. In the proposed BD-UCWPT system, two H-bridge circuits are used to achieve bidirectional power transfer. The application of BD-UCWPT technology in multi-vehicle underwater systems can significantly improve work efficiency, reliability, and task duration [77,78], including unmanned underwater vehicles (UUVs), autonomous underwater vehicles (AUVs), and remotely operated submersibles (ROVs). There is no practical application case of BD-UCWPT technology at present. We can refer instead to the research of BD-UIWPT and design a bidirectional inductive power transmission system for unmanned underwater vehicles [78] and propose an integrated structure for the magnetic coupler and cockpit. Finally, an 800 W BD-UIWPT system is implemented. The forward energy transfer efficiency is 82.18%, while the reverse efficiency is 73.63%. BD-UCWPT technology has broad application prospect in the future work of intelligent marine systems. For example, several UUVs are jointly carrying out underwater exploration missions, and one UUV consumes more electricity than expected. This means that an underwater robot can charge through the UWPT station and release its stored energy to other underwater robots or seabed sensors. The research of a two-way underwater capacitive wireless power transmission (UCWPT) system will promote the application of UCPT technology in intelligent marine energy systems.

In addition, in order to study the application principle of UCPT technology in AUVs, ref. [40] designed a UCPT system suitable for freshwater environments. Their coupler can contribute to the development of underwater robotics technology for structure health monitoring in various infrastructures, i.e., from power plant installation to bridges and dams. The research summary of underwater robot UCPT technology is shown in Table 4.

Table 4. A summary of the research on UCPT technology for AUVs.

Year	Water Medium	Coupler	Compensation Network	Distance	Frequency	Power	Efficiency	References
2018	Fresh water	Four-plate	Double-sided LC	20 mm	107.7 MHz	400 W	90%	[40]
2019	Seawater	Disc-type	CLC-L	2 mm (10 mm)	420 kHz	0.055 W (0.021 W)	12.3% (7.8%)	[76]
2019	Seawater	Four-plate	Double-sided LCLC	150 mm	625 kHz	100 W	80.15%	[45]
2020	Seawater	Four-plate	-	60 mm	6.78 MHz	275 W	50%	[29]

Table 4. *Cont.*

Year	Water Medium	Coupler	Compensation Network	Distance	Frequency	Power	Efficiency	References
2021	Seawater	Four-plate	Double-sided L	400 mm	500 kHz	100 W	50%	[31]
2021	Seawater	Double-cavity	Double-sided LC	20 mm (150 mm)	6.78 MHz	1018 W	94.5% (85.3%)	[36]
2022	Fresh water	Semi-cylindrical	LC-CLL	10 mm	839 kHz (950 kHz)	47 W (16.4 W)	44% (36%)	[54]
2023	Seawater	Double-cavity	Double-sided LC	100 mm	1 MHz	200 W	70.1%	[49]

5.2. Research on UCPT for Electric Ships

At present, pure electric ships mainly use the wired charging method of shore power cables or return to the base for manual power supply (plug or battery replacement). The above charging methods require human participation, which reduces the work efficiency of unmanned ships. When the ship docks for charging, the process of plugging and unplugging the cable increases the workload of the crew and takes up a lot of time. There are also problems such as the contact port being prone to aging and insufficient flexibility. Manually plugging and unplugging the charging cable may cause electric sparks and electric shock accidents caused by poor electrical contact [79,80]. The structure of the UCPT system for electric ships is shown in Figure 27.

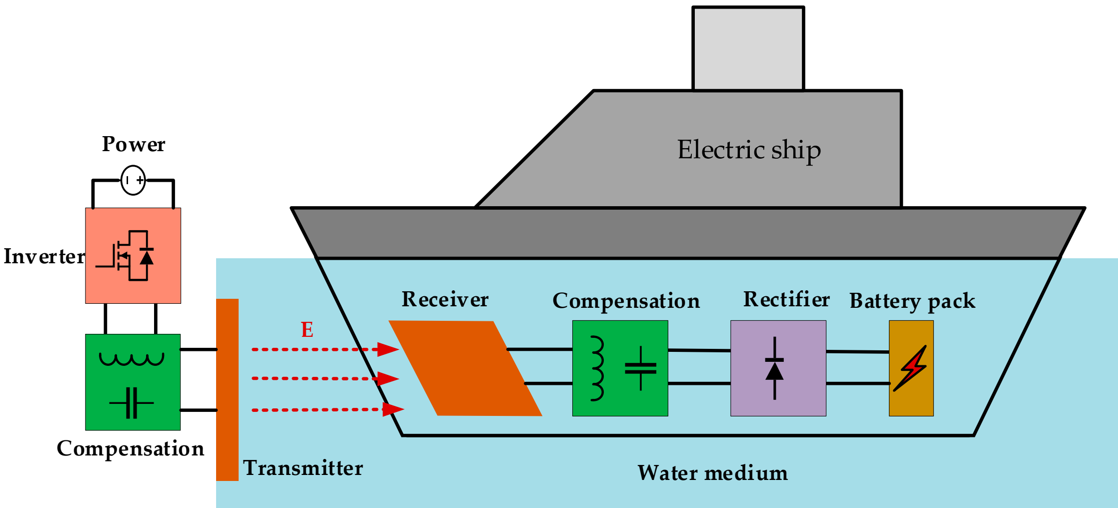


Figure 27. The UCPT system of the electric ship.

Drexel University scholars have studied the application of UCPT technology in the charging of electric ships [14]. An equivalent model of the coupler in a freshwater underwater environment was established, and a freshwater UCPT system with relatively high-power transmission over long distances and high efficiency was proposed. An asymmetric underwater four-plate coupler was adopted to widen the gap between the main capacitance and cross capacitance of the capacitive coupler, ultimately achieving an increase in the equivalent mutual capacitance of the UCPT coupler and thereby increasing the transmission power of the system.

Rong E.'s research team further improved the output power level and transmission efficiency of the system by improving the coupler and compensation network of the UCPT system [37]. The team established an experimental platform for a UCPT system with a six-plate coupler and an M-M compensation network. Compared with high-power CPT systems in the air [81–83], the metal plates are smaller in size; and compared with other UCPT systems [14,37], the research provides a prototype in the kW range. The team also proposed an underwater six-plate and hybrid-dielectric coupler. As a result, the coupling coefficient of the six-plate coupler is improved, thereby increasing the power and efficiency of the system while maintaining the electric field shielding. It also provides a new idea for our follow-up research on underwater capacitive couplers for electric ships.

In addition, Mahdi H.'s research team provided a cheap, lightweight, and well-collimation-tolerant charging scheme for UCPT systems for unmanned vehicles at sea [57]. A mathematical model for the maximum achievable efficiency of the UCPT system, considering dielectric permittivity losses, is proposed and validated. The effects of separation distance and switching frequency on the transfer power and total efficiency are also investigated using series compensation.

During the charging period of electric ships, the ship will sway due to wind, waves, currents, etc. The swaying of the ship makes the transfer distance and effective coupling area between the transmitter and receiver of the wireless power transfer system change, thus affecting the transfer performance of the system. Therefore, the UCPT system of the electric ship requires strong anti-offset and high fault tolerance for large position changes.

Table 5 is a summary of the research on UCPT technology of electric ships at present.

Table 5. A summary of the research on UCPT technology for electric ships.

Year	Water Medium	Coupler	Compensation Network	Distance	Frequency	Power	Efficiency	References
2019	Fresh water	Four-plate (asymmetrical)	Double-sided LC	500	1 MHz	220 W	60.17%	[14,27]
2023	Seawater	Four-plate (vertical)	Double-sided L	500 mm	516 kHz	48 W	54%	[57]
2023	Fresh water	Six-plate	M-M	50 mm	1 MHz	3300 W	75.9%	[37]
2024	Fresh water	Six-plate and hybrid-dielectric	M-M	60 mm	1 MHz	5000 W	87.2%	[51]

5.3. Research on Underwater Capacitive Communication Technology

In most power transfer systems, in addition to power transfer, the transfer of primary and secondary information is also required to achieve feedback closed-loop control, status monitoring, command interaction, and other functions to ensure the safety and efficiency of charging [84,85]. Underwater equipment also needs a reliable and safe communication method so that they can send the collected information and receive new control commands with the base station in time; therefore, it is very necessary to establish communication between the primary and secondary sides in the underwater environment. Inductive coupling is a key method in underwater wireless power and data transfer (UWPDT) which uses magnetic fields to transfer power and data. This method provides a viable solution for short-range applications. However, there are several challenges to the application of inductive coupling in an underwater environment. With the magnetic field strength decaying rapidly [86–88], the power transfer efficiency and signal-to-noise ratio (SNR) will decrease significantly with distance. In addition, the presence of conductive seawater will cause additional losses, which will further affect the overall efficiency and data gain of the system [89].

Given that capacitive coupling power and signal parallel transfer technology has the characteristics of penetrable conductive materials and strong misalignment resistance, it is expected to be an effective means to solve the difficulties of power supply and communication in underwater environments. Therefore, ref. [34] takes the double-plate seawater capacitive coupling device and T-LCL based compensation network as the research object and investigates the modeling of the seawater capacitive coupling channel, the topology and parameter design of the T-LCL-based compensation network, the feasibility of the seawater environment capacitive coupling power and signal parallel transmission, and the output characteristics of the system. A half-duplex signal transmission system was constructed, and the parallel transmission and demodulation of energy and 100 kHz signals were accomplished using a 5 MHz carrier wave at 10 V and 50 V, respectively, to verify the feasibility of the parallel transmission of power and signal in a seawater medium, as shown in Figure 28.

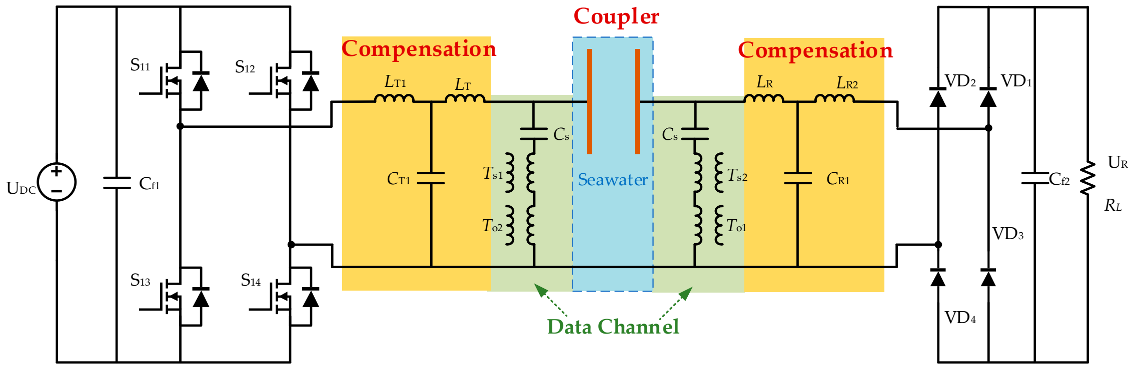


Figure 28. Seawater CCPT system with a bilateral T-LCL compensation network system.

Li T. and other scholars used the principle of single capacitor coupling to transfer data under seawater and proposed a synchronous underwater wireless power and data transmission system. This system used inductive power transmission and capacitive communication mode, thereby reducing the crosstalk between the power channel and the communication channel. The system used the self-capacitance and stray capacitance of the coupling plate to form a complete loop. Finally, the system achieved full-duplex communication of 1 Mbps with 1.2 kW of parallel transmission power [90].

C. Da and other scholars followed suit and proposed a synchronous wireless power and data transmission system with a single-layer capacitive coupling underwater, as shown in Figure 29. The synchronous wireless power and data transmission system with a single-layer capacitive coupling underwater forms a complete circuit through the coupling capacitance between metal plates, the parasitic capacitance of metal plates to the reference ground or infinity, and the parasitic capacitance of the primary and secondary devices to the reference ground or infinity. The system can simultaneously achieve a power transmission of 300 W and a two-way communication rate of 500 kb/s in seawater, with a transfer distance of 100 cm [91].

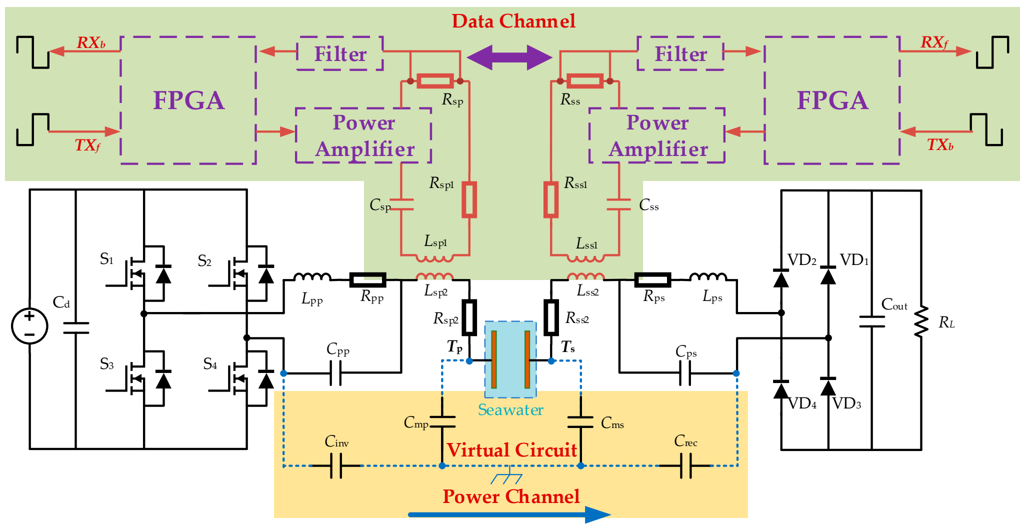


Figure 29. Underwater single capacitive coupled simultaneous wireless power and data transfer system.

5.4. Development Issues and Directions of UCPT Technology

5.4.1. Considerations for the Underwater Environment

Due to the complexity of the underwater environment, higher requirements are placed on UCPT technology. Water is a liquid dielectric with strong fluidity, so the UCPT system is susceptible to the influence of disturbances from environmental variables in the seawater environment. The transmission performance of the UCPT system is related to various environmental variables such as the conductivity, temperature, water pressure, and flow rate of the water. Any one of these environmental variables may lead to changes in the transmission power and efficiency of the system. Therefore, the complexity of the underwater environment must be considered when researching UCPT technology [92].

Current research focuses only on the impact of a single variable on system performance [93,94], such as the quality factor, normalized frequency, transmission distance, and different couplers. Complex seawater parameters such as water pressure and water temperature have not yet been considered when considering the conductivity of water. If the wireless power supply of underwater electrical equipment is completed through an underwater base station in the actual underwater environment, the impact of variables such as shell-attached microorganisms and seawater corrosion on the UCPT system also needs to be considered.

In addition, frequency splitting occurs under seawater conditions, which reduces the output power. To improve the efficiency of the underwater wireless power transfer system, the optimal operating frequency under seawater is also one of the research priorities in the future.

5.4.2. Trade-Off Between Transfer Distance, Power, and Efficiency of UCPT System

At present, the research of UCPT technology is still in the primary stage, and the transfer distance, power, and efficiency of UCPT system still need to be improved. The coupler should consider a variety of influencing factors for different water media in the future and continue to improve its equivalent circuit model, and we should conduct in-depth research on the impact of the complex underwater environment on the coupler, explore the fundamentals of the coupler medium loss, and further design the UCPT coupler with strong anti-offset and large coupling capacitance. The influence of the insulation layer of the coupler also needs to be further investigated to analyze, in detail, the influence of the type of insulating material, thickness, and attachment method on the coupling capacitance [95].

In terms of compensation topology, a variety of compensation networks analogous to CPT systems in air should be studied [96]. According to different underwater environments, output demands, power and efficiency requirements, and topological networks applicable to UCPT systems are further investigated. While meeting the requirements, the feasibility of the system, weight, volume, and power density should also be taken into account [97,98].

Therefore, in the future, the research on the coupler and compensation network of UCPT system should be the fundamental, and further research on the long-distance, high-power, and high-efficiency UCPT system applicable to different underwater environments should be carried out [99].

5.4.3. Control of UCPT System in Underwater Complex Environment

In order to adapt to the complex underwater environment, the controllability of UCPT system is also one of the hot spots in future research. The typical WPT system control strategy can be modulated from four perspectives, including inverter control, compensation network control, rectifier control, and DC converter control. These control theories are consistent with the UCPT system. Comparatively speaking, the UCPT system needs to pay more attention to system efficiency and reliability control, that is, maximum efficiency tracking and anti-disturbance control. The specific control scheme needs to be designed according to the actual operation of UCPT system and the charging parameter requirements of lithium battery load [100,101].

GaN device has the characteristics of low resistance and high switching frequency, which is helpful in improving the efficiency of the UCPT system. The GaN device can drive signals with higher frequency, thus enhancing the penetration ability of the electromagnetic field by increasing the resonance frequency, which may help to increase the transmission distance. In an underwater environment, the volume and weight of the system are key factors. The high-power density of GaN devices allows for the design of smaller and lighter power supplies and converters, which is beneficial to reduce the size and weight of the whole UCPT system. The UCPT system needs to adapt to different transmission distances and water depths. The fast-switching ability of GaN devices can support a wider tuning range, thus adapting to different operating conditions.

5.4.4. Safety of UCPT Systems

The development of underwater UCPT technology must consider the safety of underwater organisms. In UCPT systems, the transmission capacity of the system is related to the power density; the higher the power density of the capacitive coupler, the larger the electric field emitted to the surroundings [102]. In the case of high-power charging, electric field emission is a critical issue. For human safety reasons, the IEEE C95.1 standard requires that the exposure to high-frequency electric fields at 1 MHz should be less than 614 V/m. The safety of electric field emission is even more important in long-distance UCPT systems. In addition, the fringing field between parallel plates increases significantly with voltage and distance; as the power of the system increases, both the voltage and the fringing electric field on the metal plate increase, which can easily lead to dielectric breakdown. Therefore, when designing UCPT systems to achieve high power densities, consideration should be given to the emission of electric fields into the surrounding environment and to the safety of the system structure itself [103,104].

6. Conclusions

Underwater capacitive power transfer (UCPT) technology has developed rapidly in recent years because of its safety, convenience, concealment, and suitability for unmanned operation. It is considered as one of the effective solutions with which to address power supply and voyage anxiety in autonomous underwater vehicles. This paper first discusses the working principle of the UCPT system, comparing it with underwater inductive power transfer (UIPT) in terms of principles and performance, and explains the unique advantages of CPT in underwater environments. Subsequently, the impact pattern of water media with different degrees of conductivity on UCPT couplers is summarized, and a detailed introduction to the equivalent circuit models of capacitive couplers is provided. Based on the summary of current UCPT development issues, UCPT couplers and compensation networks in various underwater environments are analyzed in detail. The optimization design methods for couplers and compensation networks to enhance the power transfer capability and offset resistance characteristics of UCPT are also summarized. In terms of practical applications, UCPT case studies for AUVs, electric ships, and underwater capacitive communication are indicated. Finally, this paper discusses the current issues that need to be addressed and the future development trends of UCPT. In summary, UCPT technology has certainly made progress. However, due to the complexity of the underwater environment, many theoretical, performance, and application challenges remain to be overcome.

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