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Review

Review of Crucial Problems of Underwater Wireless Power Transmission

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Abstract: In order to solve the problem of energy supply for underwater equipment, wireless power transmission technology is becoming a new way of underwater power transmission. It has incomparable technical advantages over traditional power supply method, and can effectively improve the safety, reliability, convenience and concealment of power supply for underwater equipment. The WPT has a natural electrical isolation between the primary and secondary sides to ensure safe charging in an underwater environment. This breakthrough technology greatly facilitates power transmission in the deep sea. However, current transmission power and efficiency levels are not at the level of WPT systems in air. Based on the analysis of the development status of underwater wireless power transmission technology, this paper firstly puts forward the challenges of underwater wireless power transmission, and summarizes the electromagnetic coupler structure, underwater docking mode, compensation topology, control method and eddy current loss. The current research hotspots in the field of underwater wireless power transmission are summarized and analyzed. Finally, according to the development trend of technology, the urgent technical problems in underwater wireless power transmission are expounded.

Keywords: WPT; electromagnetic coupler structure; docking mode; compensation topology; eddy current loss

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1. Introduction

The ocean is rich in biological resources, mineral resources and renewable energy, which is an important part of the global life support system and a valuable asset for the sustainable development of human society [1]. With the development and utilization of marine resources, autonomous underwater vehicles (AUVs) have been rapidly developed [2,3]. Wireless power transmission technology is applied in the marine field, which can improve the charging safety, reliability, flexibility and concealment of underwater equipment, and enhance the working capacity of underwater equipment, but its endurance and charging problems restrict the maneuverability of underwater unmanned vehicles [4]. The typical process of charging these electronic devices is time-consuming, resulting in service interruptions and limited operating range. In order to solve such problems, scholars at home and abroad have conducted extensive research on underwater robots. Research focuses include compensation topology [5,6], coil optimization [7–11], foreign body detection [12–14], biological contamination [15], and safety issues [16]. In these areas, coil optimization is critical to increasing the overall efficiency of WPT systems and minimizing the size, weight, and cost of WPT systems, especially for receivers with limited requirements. Below we summarize the various challenges faced by underwater wireless power transfer (UWPT):

(1) What is the effect of highly conductive water dielectrics on the electrical parameters of WPT systems? What is the effect on the coil radiation resistance?

(2) Underwater WPT systems are susceptible to current disturbances, extreme temperature and pressure conditions. What is the electromagnetic coupling structure required for underwater applications?
(3) The fluctuation of the coupler gap distance caused by the actual underwater environment has an impact on the stability of the transmission efficiency, so how to achieve maximum power and efficiency tracking?

In addition to these challenging factors, due to the dynamic nature of seawater, migration will occur in WPT systems, and how to better achieve underwater docking of AUVs to suppress this possible change is particularly important. Another influencing factor is the high loss of the seabed and the high dielectric constant. The dielectric constant and permeability parameters of an underwater medium are different from those of an air medium. The control technologies involved in WPT systems in air media can record changes in system parameters with a communication link, but these techniques are not suitable for underwater wireless power transfer (UWPT). Therefore, it is essential that there is no control mechanism for any communication link. It is foreseeable that the ongoing rapid research will bring a promising revolution to this technology [17]. In view of the above problems, Zhou et al. [18] unified the expressions of eddy current loss and attenuation of electromagnetic waves in seawater, and discussed the influence of seawater as a transmission medium on WPT systems. Duan [19] designed a cylindrical coil for energy transmission in two-way wireless power transmission under seawater, due to water current disturbances and other factors that cause the electromagnetic coupler coil to rotate relatively or even shift in position. Fu Yibo [20] preliminarily studied the effect of changes in seawater pressure on the performance and stability of system power transmission. Tae-Dong Yeo et al. [21] proposed a maximum efficiency tracking control scheme for closed-loop wireless charging (WPC) systems for wireless charging of mobile devices. Other studies [22,23] give a good introduction to the theory of high-resonance wireless power transmission (WPT) technology, emphasizing key system concepts such as frequency splitting [24–26], ideal operating distance (critical coupling), and the behavior of the system when over-coupled and under-coupled. Aiming at the magnetic over-coupling problem existing in WPT, YuE-Long Lyu [27] adopted two non-identical resonant coils as wireless power transmitter and receiver, respectively, to suppress or completely eliminate frequency division and achieve uniform power output.

In this paper, the basic structure and working principle of WPT technology are firstly introduced. According to the particularity of WPT technology in marine environments, the structure of electromagnetic coupler, underwater docking mode, compensation topology, control method and eddy current loss of seawater are reviewed. Finally, the key problems to be solved and the development trend of this technology are analyzed, including power transmission mechanism, electromagnetic coupler design, marine environment adaptability of the system, electromagnetic compatibility and the application of new materials. The research aims to provide reference for the development and application of underwater WPT technology.

2. Underwater Wireless Power Transmission Technology and Principle

2.1. Classification Definition

Wireless power transfer (WPT) technology, also known as contactless power transfer (CPT) technology, refers to electrical energy transformed by an emitting device into other forms of energy, such as electric field, magnetic field, microwave, laser, waves, etc., in the space of the non-contact transmission distance, and then through the receiving device again transferring the other forms of energy into electricity, realizing the wireless transmission of power, and implementing the complete electrical isolation between the power and electric equipment.

Broadly speaking, any system not directly connected to the supply and receiving electric power by contact transmission belongs to the category of wireless power transmission (WPT) technology. According to the implementation of the power transmission mechanism, wireless transmission technology in general can be divided into magnetic field, electric field, microwave, laser, and ultrasonic technology [28].

- Magnetic field technology. Based on the principle of electromagnetic induction coupling, it is a wireless power transmission technology that realizes the wireless transmission of electric energy through the non-contact mode between power acquisition equipment and power supply by integrating modern power electronic energy conversion technology, magnetic field coupling technology and modern control theory [29]. High-frequency alternating current is passed through the transmitting coil, the transmitting coil generates a high-frequency magnetic field, the receiving coil close to the magnetic field induces the electromotive force, and the non-contact transmission of electric energy is realized by inductive coupling. Power transmission from milliwatts to several hundred kilowatts can be realized through resonant capacitor compensation, and the transmission efficiency can reach more than 90%. Today, WPT has been commercially used to charge electric vehicles [30], electronic products [31] and biomedical systems [32–34]. The advantages of wireless charging are safety, convenience and reliability, and the charging process is fully automated.
- Electric field technology. Capacitive coupling to tube lighting by Tesla in 1891 was the first public testing of WPT to power a load [35,36]. Capacitive wireless power transfer (CWPT) has been well studied [37] since then. The biggest advantage over the magnetic field technology is that the medium between the metal plates can also be metal. Therefore, it has certain advantages in some cases where electricity is transmitted through metal. The electric field is used for energy transmission, and the transmission distance is short. The transmission medium between plates and a small change of transmission distance will greatly affect the stability of power transmission [38]. Compared with magnetic field technology, the plate voltage is higher, and there is a strong electric field around the plate. Its environmental safety is also a problem to be solved.
- Microwave technology. Wireless power transfer using microwaves has been investigated since the 1950s [39]. Microwave technology [40,41] can transmit hundreds of kilowatts of power within the scale distance of hundreds or even thousands of kilometers. The key problems limiting its application at present are low transmission efficiency and only linear transmission with no other obstacles within the linear range. In recent years, people are increasingly interested in RF energy collection technology, and microwave wireless energy transmission [42] is being actively studied. However, due to the low efficiency of long-distance energy transmission, the feasibility of microwave wireless energy transmission in applications such as AUV charging is still under discussion.
- Ultrasonic technology. This technology has been recently proposed in [43–46]. Ultrasonic technology uses efficient electro-acoustic energy conversion, transducer and circuit matching, acoustic matching, and acoustic energy convergence to carry out long-distance wireless power transmission [47]. Due to the high frequency and short wavelength of ultrasonic wave, the transmission direction is good. This method does not produce electromagnetic interference, and also is not affected by electromagnetic interference, but the transmission power is small, and needs a certain transmission medium such as air, water.
- Laser technology. Optical power transfer based on laser sources was first introduced for the application of solar power satellites [48]. The laser technology [49] consists of a laser transmitter and a laser-electric energy conversion component. This method has good direction and high energy density. However, the technology is still not mature enough because it requires high precision and low efficiency.

It can be seen that the AUV under seawater can be charged wirelessly with the charging platform at close range, so compared with other wireless power transmission modes, the magnetic field coupling mode has inherent advantages in underwater wireless power transmission. By analyzing the system loss model under seawater conditions, selecting the appropriate topological structure, optimizing the working frequency and selecting a reasonable control mode, the wireless charging demand of AUV under seawater can be met and the ideal use effect can be achieved.

2.2. Magnetic Field Coupled Wireless Power Transmission

Magnetic field coupled radio energy transmission technology has become a hot topic in recent years. In the field coupled radio energy transmission, there are two main technologies: induction and magnetic coupled resonance. Both of them use the principle of electromagnetic induction and are two different manifestations of the same technology. Inductive wireless power transfer (IWPT) is based on the transformer principle, and its transmission distance is small, only millimeters. Magnetically coupled resonant wireless power transfer (MCR-WPT) systems can achieve high power and efficient transmission of electric energy at both short and medium distances, and are especially suitable for electrical energy supply of underwater vehicles and other electromechanical equipment in marine environments. The basic structure and working principle of underwater MCR-WPT technology are introduced as an example.

2.2.1. Basic Structure

The typical topology of an MCR-WPT system is shown in Figure 1. It is mainly composed of a power frequency alternating current, rectifier filtering, high-frequency inverter, primary side compensation, electrical energy transmission coil, electric energy receiving coil, secondary side compensation, rectifier filter, buffer control circuit, and load. After the electrical energy of the submarine base station undergoes high-frequency inversion, the output is sent to the transmitting coil, and under the action of magnetic coupling resonance, the receiving coil and the transmission coil produce coupling resonance, and the received electrical energy can be used for battery charging and other electrical energy replenishment requirements after rectification filtering, so as to realize the contactless transmission of electrical energy from the submarine base station to the underwater vehicle.

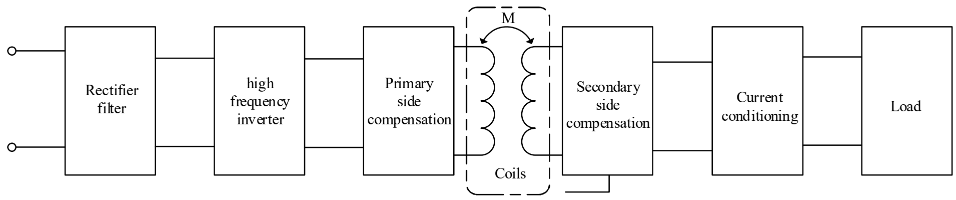

Figure 1. Basic structure of MCR-WPT system.

A typical MCR-WPT system is a two-coil structure consisting of a power transmission coil and a power receiving coil. Krus et al. [50] proposed a four-coil structure consisting of two resonant coils, one power supply excitation coil connected to the power supply, and one load coil connected to the load. This structure can perform power supply matching and load matching, and realize the isolation of power supply and power transmission coil, and the isolation of load and receiving coil. In [51], a three-coil structure is used in an underwater MCR-WPT system: a resonant relay coil is added to the energy transmission and receiving coils. The transmission distance is effectively improved by adding an auxiliary coil to the coil gap, which is more demanding on the installation and use of the structure, but provides a new idea to solve this problem.

2.2.2. Working Principle

In an MCR-WPT system, the power supply is used to send electrical energy when the frequency of the coil is the resonant frequency of the system; resonance will occur on one side of the sending coil, which will generate a large current in the coil and establish a strong magnetic field. Due to resonance, the electric field energy stored in the capacitor on one side of the sending coil is constantly exchanged with the magnetic field energy in the inductor coil. On one side of the receiving coil, the alternating magnetic field induces current in the receiving coil because the magnetic fields of the receiving and sending induction coils are coupled with each other. When one side of the receiving coil also resonates, the magnetic field energy of the induction coil and the electric field energy in the capacitor constantly exchange energy, thus realizing the wireless transmission of electric energy from the sending end to the receiving end and then to the load. The power transmission principle of the system in the four-coil structure and the three-coil structure is similar.

Since the permeability of seawater and the permeability of vacuum are extremely close, it can be considered that the coupling ability of the transmission coil of the coupled system in the two environments of air and seawater is consistent, but at the same time it should be noted that the conductivity of the air is extremely small, and it can be approximated that the air is not conductive, so there is no eddy current loss problem. When seawater is used as the transmission medium, seawater has good conductivity and large conductivity, and a high-frequency alternating magnetic field generates a vortex electric field in seawater, which in turn produces vortex current and eddy current loss, and part of the energy is absorbed by seawater. Therefore, in order to accurately describe the electromagnetic induction system under the seawater medium, ref. [51] adds an additional equivalent resistance and equivalent capacitance to the air-to-air model as shown in Figure 2, which reflects that the actual seawater medium changes the impedance value of the coupler coil at the air gap and produces additional active power loss. However, at the same time, it is also seen that the seawater medium only changes the numerical size of the parameters in the system, and does not change the transmission mechanism of the original system.

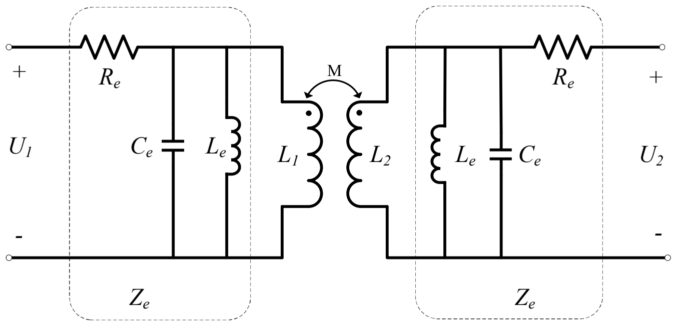

Figure 2. Equivalent circuit model for transport in a seawater environment.

3. Research on Key Technologies

3.1. Magnetic Couplers Based on Loosely Coupled Transformer Principle

In wireless power transfer systems, magnetic couplers are important because they determine power transfer performance and magnetic field distribution [52]. At present, loose coupling transformers with or without magnetic cores, can be divided into four different structures: the primary side coil has a magnetic core and a secondary core without a core, the secondary side coil has a magnetic core, the primary and secondary coils have a magnetic core, and the primary and secondary side coils have no cores [53]. In the design of electromagnetic couplers, it is necessary to consider their performance, but also to consider their installation, docking and other needs and anti-current impact interference and other factors [54]. Therefore, in recent years, scholars at home and abroad have continuously optimized the design of the magnetic coupling mechanism so that it can meet the use of underwater vehicles as much as possible in all aspects. He et al. [55] proposed a three-dimensional omni-directional underwater wireless power transfer system (Figure 3a). Although its output power and transmission efficiency have been improved, its coil structure is difficult to achieve in AUV wireless charging. Kojiya et al. [56] have developed a conical coil that can improve power and efficiency (Figure 3b), which has strong anti-offset characteristics, ensuring the transmission efficiency of the system and strengthening the adaptability of the system. Cheng et al. [57] proposed a novel underwater LCT semi-closed core structure (Figure 3c). This structure can effectively increase the coupling coefficient and reduce electromagnetic radiation. It has been experimentally verified that 10 kW of power can be transmitted in an air gap of 25 mm with a maximum transmission efficiency of 91%. Zhou et al. [58] proposed a PM-type magnetic coupler (Figure 3d) that transmits 300 W underwater with a DC-DC efficiency of 85%. Neither the PM type magnetic coupler nor the semi-enclosed magnetic coupler considered compatibility with the AUV housing. This may disrupt the streamlined structure of the AUV and increase the friction of the AUV's travel. To match the casing of the AUV, Wang et al. [59] designed a ring magnetic coupler (Figure 3e) and made a miniature prototype to validate the scheme. However, on the one hand, the weight of the ring ferrite core is a huge burden for the AUV, and it is difficult to sinter because of its material properties, on the other hand, through the analysis of the magnetic field distribution of the ring ferrite core, it will produce greater electromagnetic interference to the internal electronic device of the AUV. Tianze Kan et al. [60] studied the magnetic field distribution of the ring magnetic coupler (Figure 3f) and proposed a three-phase system containing multiple segmented ferrite rods, which had less adverse effect on the existing electronics in the AUV. However, on the one hand, the installation of the ferrite rod is not suitable, which may occupy more space in the AUV cabin. On the other hand, such systems are very sensitive to rotational imbalance and therefore require advanced mechanical systems, which increase costs. The underwater environment is not as stable as the ambient air conditions, and when the AUV is wirelessly charged in the docking station, rotation misalignment always occurs. In response to this situation, Tianze Kan et al. [61] then proposed an electromagnetic coupler with an inverse winding receiver (Figure 3g) that has good fault tolerance for the change in transmission power caused by rotational misalignment. However, the above systems will produce large electromagnetic interference to the equipment. In order to reduce the impact of electromagnetic interference, Yan et al. [62] proposed an underwater wireless power transmission system with a spiral coil structure to adapt to the cylindrical symmetrical housing of autonomous underwater robots (AUVs) (Figure 3h). Cai et al. [63] proposed a magnetic coupler based on dipole coils (Figure 3i), which has a good effect not only in terms of magnetic field distribution, but also in reducing the air gap and the weight of the magnetic coupler. Although these electromagnetic couplers can meet the wireless energy supply needs of underwater vehicles of specific structures, they generally have only one advantage, and their comprehensive performance is often not optimal. It is particularly urgent to determine how to form a set of electromagnetic coupler system design theory methods, which, combined with the actual application needs, optimizes the electromagnetic coupler to achieve the best comprehensive performance.

From Table 1, it can be seen that most of the current IWPT systems are used in the electromagnetic coupling mechanism with a magnetic core, and its transmission efficiency is higher than that of the core. This is because the core plays a role in strengthening the magnetic field, and the high permeability of the core can concentrate most of the high-frequency alternating magnetic field generated by the primary side coil in the magnetic circuit formed by the two coils, and the coupling coefficient of the system is enhanced to ensure the efficient transmission of the system energy. The magnetic induction intensity of the entire magnetic field space without a magnetic core is significantly smaller than that of the magnetic induction with a magnetic core, and the magnetic induction intensity is more, and the distribution of its magnetic field lines in the space is more chaotic, and a large part of the magnetic field generated by the primary side coil does not pass through the secondary side coil to form a closed loop but diverges around or after spatial propagation; it returns to the primary side coil and itself to produce a closed loop, and cannot achieve the same effect of efficient energy transmission as the electromagnetic coupler with the core. Therefore, although the permeability of the soft magnetic material will be changed in the seawater environment due to the deep sea high pressure environment, the transmission performance of the soft magnetic material will be affected, but the core cannot be directly removed, and the presence of the core can ensure that the system can transmit energy at a higher efficiency.

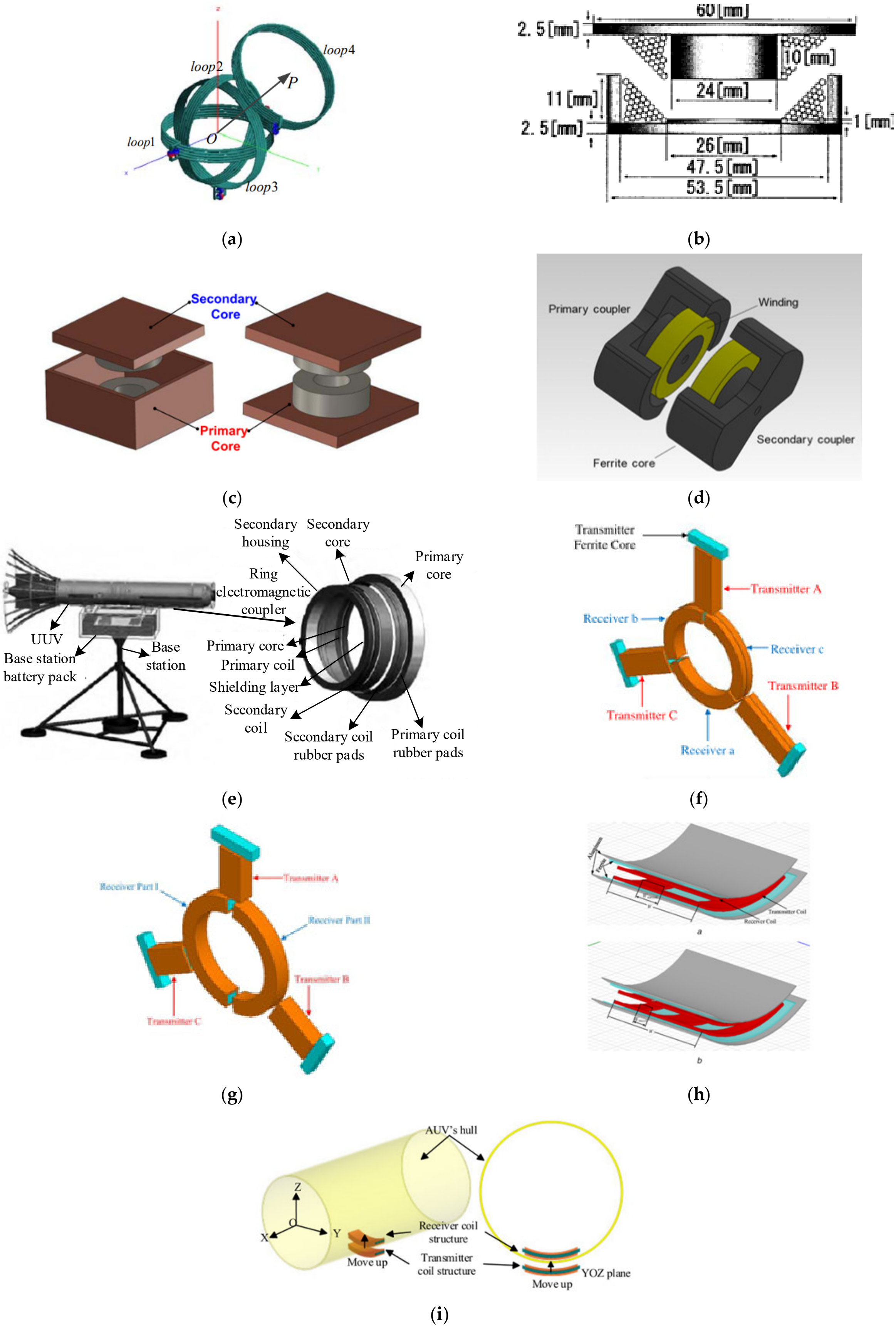

Figure 3. Types of electromagnetic couplers. (**a**) Three-phase coils; (**b**) Special electromagnetic coupler and tapered coils. (**c**) LCT semi-enclosed electromagnetic coupler; (**d**) PM type electromagnetic

coupler. (**e**) Ring magnetic coupler; (**f**) Three-phase electromagnetic coupler; (**g**) Improved three-phase electromagnetic coupler; (**h**) Coiled coil electromagnetic coupler; (**i**) Dipole coil electromagnetic coupler.

Table 1. Comparison of various IWPTs using resonant coils.

Literature	Type of Magnetic Coupler	With or Without Iron Core	Power (w)	Efficiency (%)	Frequency (kHz)	Coupling Coefficient (k)	Distance (mm)
Kojiya et al. [56]	Tapered coil	Yes	500	93.1	100	N/A	2
Cheng et al. [57]	LCT type	Yes	10,000	91	21	0.68	25
Zhou et al. [58]	PM type	Yes	300	85	147	0.64	5
Wang et al. [59]	Three-phase coil	Yes	745	86.19	471.8	N/A	N/A
Kan et al. [61]	Three-phase coil	Yes	1000	92.41	465	0.43	5
Cai et al. [63]	Dipole coil	Yes	630	89.7	50	N/A	N/A
Askari et al. [64]	coil	No	N/A	80	20	N/A	75
Shi et al. [65]	EM type	No	45	84	167	0.74	N/A
Bana et al. [66]	coil	Yes	75	85	118	N/A	N/A
McGinnis et al. [67]	Coaxial coupler	Yes	240	70	50	N/A	2
Li et al. [68]	EM type	Yes	400	87	94	N/A	2
Wang et al. [69]	EC type	Yes	500	88	98.6	N/A	6
Yan et al. [70]	EE type	Yes	N/A	82	100	0.43	5

3.2. AUV Underwater Docking Method

Compared with the initial and secondary connection, separation, and fixation of wireless power transmission systems on land, it is basically impossible to rely on personnel under sea conditions, and equipment such as manipulators must be relied on. Therefore, the structure of the underwater wireless power transfer system needs to be carefully designed to adapt to the complex working environment underwater. At present, the docking structure of underwater power pickup equipment and charging platforms mainly has the following three structures [71]:

1. Snap docking;

Snap-type docking refers to the capture device to capture the rope, rod and other positioning targets on the docking device, and move towards the docking device to complete the device docking. In 2000, the "Odyssey-II.B" underwater docking system [72] jointly developed by the Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology in the United States proposed a system based on an acoustic ultrashort baseline system shown in Figure 4. The system allows the AUV to approach the dock from any direction, direct the craft to the dock, mechanically connect itself to the dock, align the induction cores for data and power transmission, and leave the dock at the start of a new mission.

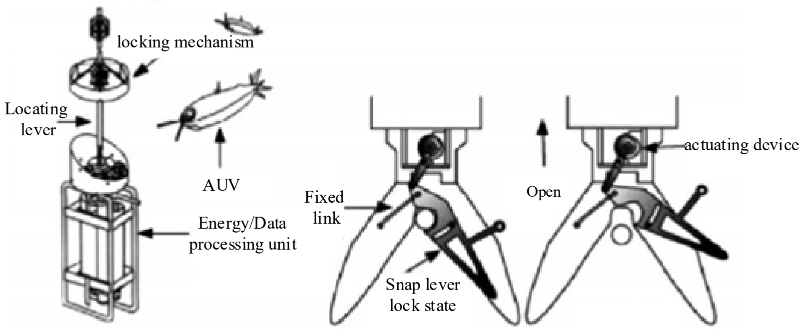

Figure 4. Underwater capture docking device.

2. Inclusive docking;

Inclusive docking refers to the underwater electric energy pickup device entering the pair of takeovers or docking box cages to complete the docking device. The docking device in the inclusive docking generally adopts the shape of the horn mouth, and the underwater electrical equipment enters the predetermined track inside it through the guidance of this structure to achieve docking, and the REMUS underwater docking system in the United States in Figure 5 and the underwater docking system developed by the MBARI Research Institute in Figure 6 are representative inclusive docking devices [73,74]. The REMUS docking system developed by Woods Hole Ocean Research Institute adopts a horn-shaped guide port, and after the underwater cable inspection robot enters the docking device, it is treated by watertight technology for electrical energy replenishment and information exchange. The Bluefin underwater inclusive docking system was developed by MBARI research and is basically similar to the REMUS docking system. The underwater docking base station adopts USBL to guide the AUV docking, and after successful docking, the AUV is locked by the locking mechanism, and the AUV can be exchanged wirelessly and charged underwater after locking. It is stated in [75] that funnel docking is attractive because it allows for a larger capture aperture that allows the AUV to be completely enclosed to protect the AUV and simplify power transmission. However, in [76] it is pointed out that another disadvantage of using this docking platform is that it can only support a specific type of REMUS AUV, and AUVs with larger or smaller hull diameters cannot be charged with this platform.

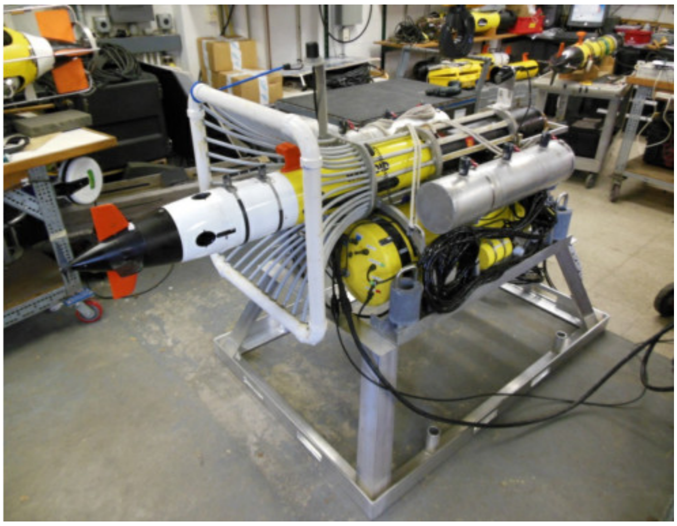

Figure 5. REMUS docking station.

Figure 6. Bluefin underwater docking base station.

3. Platform docking.

Platform docking refers to the underwater electric energy pickup equipment landing on the docking platform, and then using a capture mechanism to capture it to complete the docking. Japan's Marine-bird is a typical underwater platform docking system. In 2003 Fukasawa et al. [77,78] developed a new capture-type experimental AUV called the "Marine-Bird" with a new underwater docking and charging system, shown in Figure 7. When the AUV approaches the gripping point, it releases the hooks of the two gripping arms, drags them, and uses the grippers to snap the V-shaped rails onto the base. The positioning accuracy of this docking method is higher, and the success rate is also high; the disadvantage is that the electric energy pickup equipment is required to have a good self-conduction system and power system, and it is necessary to add a set of capture mechanisms and lock mechanisms, and the changes to the electric energy pickup equipment will also be larger, and it is easy to be affected by the disturbance of the submarine ocean current.

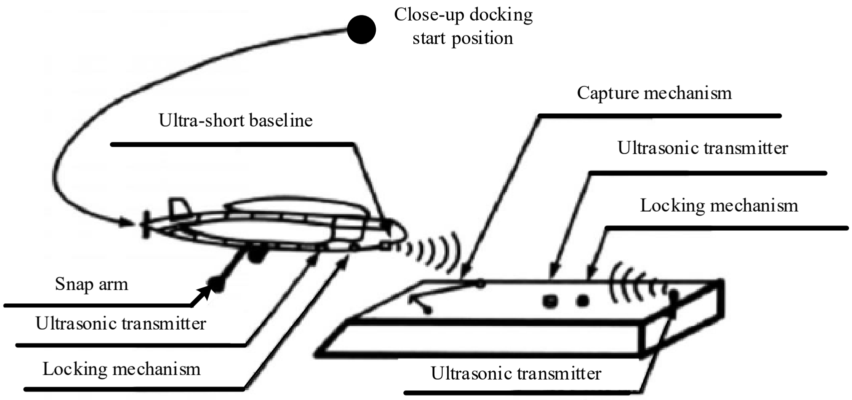

Figure 7. Marine-bird underwater docking platform.

3.3. Control Mode

The power flow in the WPT system can be controlled by the main controller, the deputy controller or the two controllers, and there may or may not be communication [79] between units. Among them, the two-sided control of closed-loop communication is beneficial to obtain ideal power control and maximum efficiency. Two-way WPT charging of AUV or underwater sensor requires communication to identify the transmitter and receiver. Some requirements for bi-directional power transfer are defined in the article [80]. At present, underwater wireless power transmission control technology is mainly divided into three control modes: primary side control, secondary side control and bilateral control [81]. Primary-side control is a type of voltage that controls the voltage at the load end by ensuring a constant current of the primary-side coil to generate a constant alternating magnetic field. However, maximum efficiency of control is not possible and control of the load output is limited. The secondary side control is generally added to the Buck converter after the rectifier circuit, and the duty cycle of the switching device is adjusted in combination with a certain algorithm to achieve load output control. This method can realize constant current, constant voltage or maximum efficiency charging of energy storage equipment, but it requires accurate modeling. As shown in Figure 8, Li et al. [82] proposed a maximum efficiency point tracking (MEPT) control scheme that maximizes system efficiency while adjusting the output voltage. Taofeek Orekan et al. [83] proposed a new maximum power efficiency tracking (MPET) method that uses k-neighbors to estimate the coupling coefficient of the system and track peak efficiency by adaptive converter control (>85%). Simulation and experimental test results verify the effectiveness and robustness of MPET to achieve maximum WPT efficiency in dynamic and uncertain subsea environments.

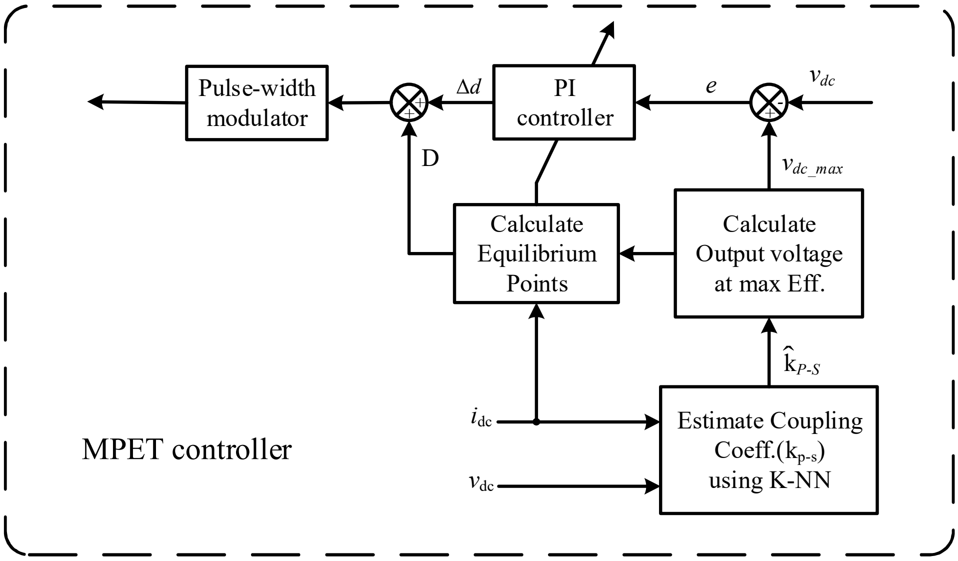

Figure 8. MPET control block.

Zheng et al. [84] use the nonlinear function approximation characteristics of BP-ANN-PID to track the optimal output voltage according to the actual output voltage and achieve MET control, shown in Figure 9. Experimental results show that when the coupling coefficient and load conditions change dynamically, the control method can correctly calculate the optimal output voltage, quickly and accurately adjust the output voltage, and achieve the maximum efficiency of the wireless power transmission system. Bilateral control is divided into two ways: bilateral non-communication and communication control. The classic bilateral non-communication control mode, has its primary side component by the full bridge structure, and an LCL resonance network composition. The control method used to ensure the constant current output of the transformer primary side coil is through the frequency conversion control mode. The secondary side component of the parallel compensation structure adjusts the load energy through the uncontrolled rectifier and boost converter. The bilateral communication control method is to combine the original and secondary sides and propose a closed-loop control method based on operating frequency modulation and bilateral wireless communication to achieve wireless charging. This method can realize the synchronous control of power and maximum efficiency, but the real-time performance is poor, and it is difficult to achieve wireless communication on the seabed.

3.4. Compensation Topology

3.4.1. Low-Order Compensation Topology in WPT

The WPT system uses a resonant compensation network to compensate coil reactive power. It results in higher power transmission capacity with reduced device stress. The compensation network also determines the constant voltage (CV) or constant current (CC) output characteristics and the soft switching behavior of the switch [85]. Therefore, the selection of the compensation network is based on the operating frequency, the load dependent requirements of the output, the coil current and the soft switching requirements of the switch.

The compensation topology selected in different WPT systems has these basic configurations and their combined control. The basic compensation topology used in WPT systems includes series–series (SS), series–parallel (SP), parallel–series (PS) and parallel (PP) second-order LC compensation, as shown in Figure 10. The characteristics of these topologies are documented in many available publications [52,79,86], as shown in Table 2. The PS topology is excluded because it is not normally used.

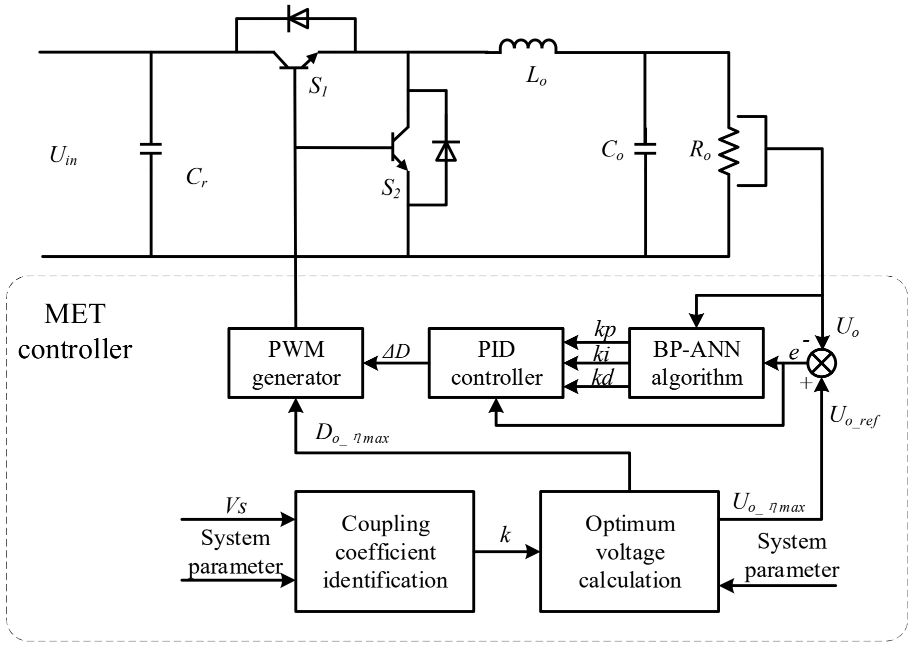

Figure 9. Block diagram of buck converter with the proposed control system.

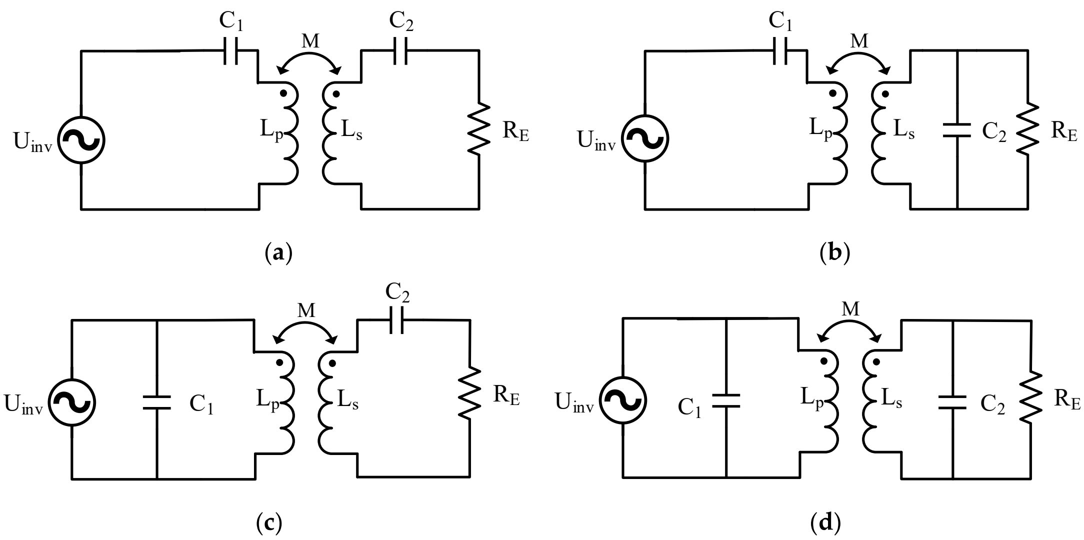

Figure 10. Basic LC compensation topologies. (**a**) S-S Compensation structure; (**b**) S-P Compensation structure; (**c**) P-S Compensation structure; (**d**) P-P Compensation structure.

It is worth noting that the SS topology driven with constant voltage can produce a constant output current, and driven with constant primary current can produce a constant output voltage. Its dual role occurs in the SP topology, which produces a constant voltage output if driven by a constant voltage source, and a constant current output if driven by a constant primary current [86].

In underwater WPT, SS and SP are mainly used, among which SS topology is the most used [61,83]. Typically, they are driven by a constant voltage source, producing a constant current output to charge the AUV battery. However, if the load needs a constant voltage to supply power, we can modify the circuit topology. SS topology is also popular because it requires only capacitive filters, while SP topology requires LC filters at the output. To reduce system volume, some underwater WPT systems do not use compensation for the second stage [65]. This is possible in underwater WPT because of smaller clearances and higher coupling. However, this is limited to lower power designs.

The main advantage of the SS configuration is that the value of primary capacitance does not depend on the variation of the coupling coefficient [87,88]. The major drawback occurs under light load condition, and when the receiver is not present and the equivalent impedance seen is zero at the primary resonance frequency, with only the parasitic impedance of the capacitor and inductor limiting the current [88–90]. Therefore, the voltage transferred to the secondary is very high. This makes the terminal voltage across the load very high, leading to an unsafe condition. The transmission impedance of PS and SS configurations is the same [87]. The main advantages are high efficiency and high power factor under the conditions of relatively low mutual inductance and relatively large load and mutual inductance variation range [87,91,92]. A major disadvantage is that it requires a current source input to avoid any instantaneous changes in voltage [87].

Table 2. Basic LC Compensations in WPT.

Topologies	Characteristics
• Series-Series (SS) [93–95] • Series-Parallel (SP) [96–98] • Parallel-Parallel (PP) [99]	• Lower compensation tank volume. • Simpler design, high reliability and efficiency. • SS is inoperable at no-load, SP and PP are no-load capable. • SS has resistive reflected impedance when operated. At resonance, which is not available for the others. • Higher tank harmonics with the series compensations. • Voltage-fed inverter with series primaries, current-fed inverter with parallel primaries. • SS good for high-power, SP and PP good for low to medium power.

For the SP topology, if the receiver or load is not present, the primary side will still short-circuit at the resonant frequency [87,88]. Therefore, the current-limiting control must still be carried out on the primary side. In PP compensation, the transfer impedance of the original side is the same as that of SP compensation. The disadvantages of this configuration are low power factor, high voltage of the parallel secondary load and large requirements for the parallel primary current source [85,90]. Due to these shortcomings, this configuration has not been extensively studied [88,90].

3.4.2. Higher-Order Topology in WPT

The traditional resonant compensation network is generally connected in series or parallel for LC components, but simple low-order resonant networks have inevitable disadvantages, such as the parallel structure of the primary and secondary sides and the inability of the DC component to play an obstructive role. Furthermore, the primary and secondary sides are used in series parallel structure, although the DC component plays a barrier role, but the capacitor is connected into the circuit, and the current stress and voltage stress of the capacitor are very high. The LCC-type high-order hybrid resonant compensation structure is improved on the low-order string and resonance structure, so that the overall performance of the system is greatly improved.

As shown in Figure 11, LCC-type high-order hybrid resonance compensation structures are generally divided into LCC-S, LCC-P, S-LCC, P-LCC and LCC-LCC. In addition, some of their characteristics are summarized in Table 3. Tang [100] designed an integrated coil LCC-S dynamic wireless charging system, which has the advantages of strong offset resistance, low electromagnetic radiation, small energy loss and high safety. A dual-coupled inductor-capacitor-capacitor and series (LCC-S) compensated wireless power transfer (WPT) system with a compact receiver size is proposed in the paper [101] to improve the misalignment performance and achieve fault tolerant operation as well as a stable output power. It is proved that the WPT system can be used for wireless charging of autonomous underwater vehicles. The performance of the proposed coil structure is evaluated experimentally in [102] on a LCC-S compensated WPT prototype. The S-LCC compensation topology was studied in [103,104]. Ref. [105] studies the LCC-P compensation topology to achieve a compact receiver for AUVs. Unlike the SS compensation topology, the LCC-P topology retains the advantages of the double-sided LCC topology and has a more compact receiver than the double-sided LCC topology with fewer elements used on the receiver side. Zhao [106] Considering the current stress and voltage stress of the compensation components, the series parallel structure of the basic compensation circuit is improved, the LCC-LCC type high-order resonant compensation circuit structure is designed, the mutual inductance equivalent model of the resonant compensation circuit is established, the voltage-current relationship is derived, and the output constant current characteristics and impedance characteristics of the LCC-LCC high-order resonant compensation circuit are obtained. Literatures [107,108] also carried out the characteristic research on bilateral LCC compensation network successively. Yan et al. [62] performed experimental analysis on the SS topology and the LCC-LCC topology, and the results showed that the coil current of the former was distorted, and the structural topology of the latter could maintain relative sinusoidal. In [109], a novel circulating current controller for serial-parallel-tuned LCL pickers is proposed. In addition, in EV DWPT systems, a constant current, mainly a sinusoidal current, is usually required to pass through the primary electrode. LCL compensation requires two identical inductors. Therefore, the size of the inductor is large; in order to reduce the size and cost of the system LCC compensation network are reported in [110–112]. Moreover, by tuning LCC compensation, zero current switching (ZCS) can be achieved. Also, LCC pickup can compensate the reactive power at the secondary side to form a unity power factor pickup. Other advantages are independence of the coupling coefficient and load conditions, with ensured ZVS for MOSFETs [111,112]. In the literature, double-sided LCC compensation is most popular as it can reduce the current stress in the inverter, it has high misalignment tolerance and load independence characteristics [111,112]. To this end, refs. [113,114] developed LCCL-based high-order compensation. Primary LCCL compensation helps to produce a constant primary coil current. However, LCCL compensation can also optimize the low pulsation power profile of the inverter with power factor lag, which is helpful for soft switching [115,116].

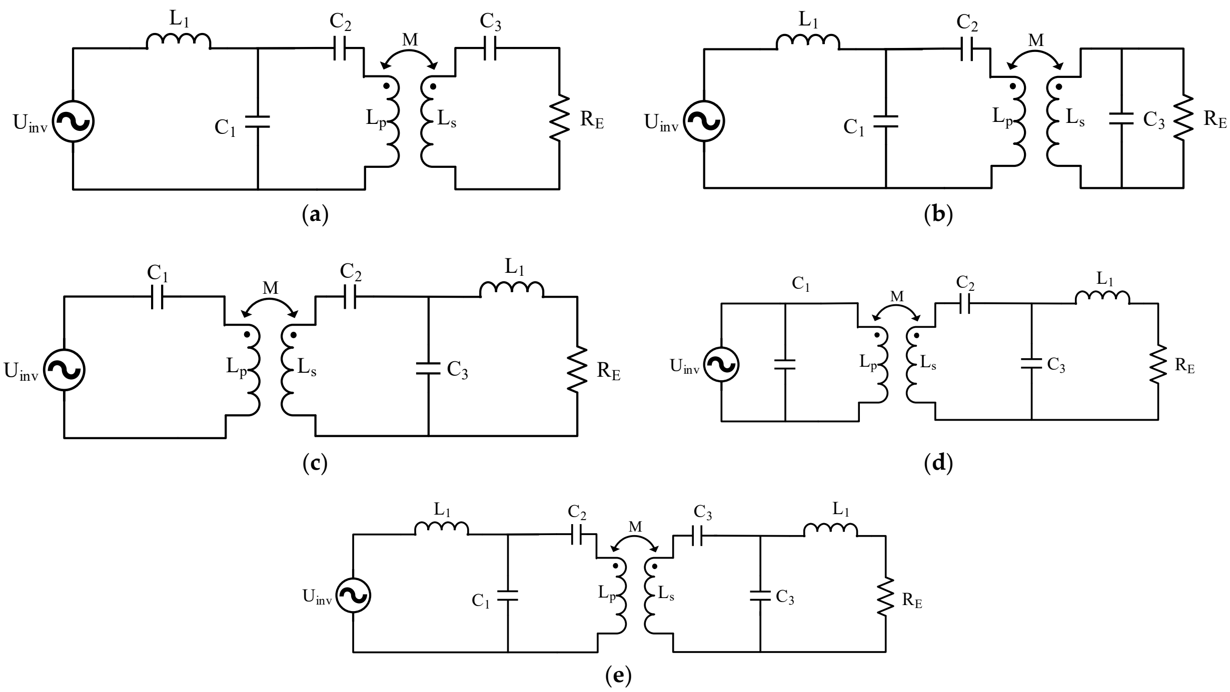

Figure 11. LCC type high-order hybrid resonance compensation structure. (**a**) LCC-S Compensation structure; (**b**) LCC-P Compensation structure; (**c**) S-LCC Compensation structure; (**d**) P-LCC Compensation structure; (**e**) LCC-LCC Compensation structure.

Table 3. Basic LCC compensations in WPT.

Topologies	Characteristics
• LCC-S • S-LCC • LCC-P • P-LCC • LCC-LCC	• Higher order filtering of current harmonics. • Improved control over primary current. • High reliability and high design flexibility. • Higher compensation tank volume and lower efficiency compared to LC compensations. • Best applied for low to medium power • Applications. • Reduce voltage and current stress and switching loss of switching tube, improve efficiency.

To sum up, both low- and high-order compensation networks can to some extent determine the output voltage or current independent of the load. Table 4 summarizes the characteristics of different compensation topologies with voltage source input, and all have their own advantages and disadvantages. Current underwater research results show that most of them are low-order compensation, but the newly emerged high-order compensation is also constantly applied to underwater wireless charging systems, providing a reference for future research on WPT systems.

Table 4. Main characteristics of common compensation networks.

Compensation Topology	Load Characteristic	Compensation Independent on k	Operation at k = 0
S [63,83,84,93–95]	Load-independent output voltage/current	Yes	Not allowed
P-S	Load-independent output voltage	No	Allowed
S-P [96–98]	Load-independent output voltage/current	No	Not allowed
P [99]	Load-independent output current	No	Allowed
LCC-S [100–102]	Load-independent output voltage	No	Allowed
S-LCC [103,104]	Load-independent output voltage/current	No	Not allowed
LCC-P [105]	Load-independent output current	No	Allowed
P-LCC	Load-independent output current	No	Allowed
LCC-LCC [62,106–108]	Load-independent output voltage/current	No	Allowed

3.5. Calculation of Eddy Current Loss in Seawater under Magnetically Coupled Resonance

The main properties of the Leeds coil for underwater WPT include its AC resistance and inductance. The total AC resistance of the underwater WPT coil consists of three losses: skin effect loss, proximity effect loss and seawater eddy current loss, which is usually expressed as the additional AC loss of the coil [117].

Detailed modeling of the Litz coil for AC resistance estimation [118] and approximation methods [119] are available in the literature. In [120] an analytical method for size and electrical specification optimization of underwater IWPT system based on Litz wire coil is proposed. Therefore, if an appropriate Litz line is selected, the loss caused by skin effect in the coil and proximity effect in the winding strand can be ignored [121]. Therefore, eddy current loss is mainly considered in the magnetic coupling resonance underwater loss.

In the marine environment, for magnetic coupling resonant electrical energy transmission mode, alternating current produces an alternating magnetic field, and the alternating magnetic field will produce a vortex electric field in seawater; because seawater has high conductivity, the resulting eddy current loss is larger, which will reduce the efficiency of electrical energy transmission in seawater and increase the complexity of the system. The electrical parameters of seawater as a transmission medium are very different from those in the air, as shown in Table 5. Yan et al. [118] proposed a calculation model for eddy current losses of underwater transverse eccentric WPT systems based on Maxwell's equations, and verified the proposed calculation model by using the finite element analysis (FEA) method. Subsequently, an analytical model of eddy current loss in coreless WPT systems in seawater was established by using Maxwell's equations [122], and the expressions of electric field strength and eddy current loss were derived, and the eddy current losses under different conditions were analyzed. Zhou et al. [18] used eddy current loss theory and electromagnetic attenuation theory to study the effect of seawater on WPT systems, gave expressions of eddy current losses, and discussed the effect of seawater as a transmission medium on WPT systems. In the context of the UICPT system, the rapidly changing magnetic field of the electromagnetic coupler causes eddy current losses in seawater between the AUV's shell and coil. Therefore, in order to evaluate the impact of eddy current on system performance, finite element analysis software ANSYS was used to establish a simulation model in reference [65].

Table 5. Conductivity and dielectric constants of several gap media.

Medium	Relative Dielectric Constant	Electrical Conductivity
Air	1.0006	0 s/m
Purified Water	81	0.0002 s/m
Tap Water	81	0.01 s/m
Seawater	81	4 s/m

Currently, there is less research on modelling based on seawater media. Zhou [51] fully considers the electrical characteristics of the seawater medium, and through the calculation and analysis of the eddy current loss between the couplers in the seawater environment, it is concluded that the power loss is positively correlated with the electric field strength of the eddy current, and the greater the electric field strength of the eddy current, the greater the power loss. Furthermore, the power loss generated by the eddy current increases with the increase in the excitation current. Zhang et al. [123] proposed a $1 \times 1 \times 1$ coil structure in which the eddy current loss caused by the emitter coil can be reduced to about half of the eddy current loss in a 1×1 structure. Experimental results show that the power transfer efficiency from transmitter to receiver is increased by nearly 10%. Zhang et al. have studied the field of eddy current loss in WPT seawater relatively extensively, and proposed an equivalent eddy current loss impedance [124] and an improved mutual inductance circuit model for underwater WPT systems [125]. The mutual inductance circuit model is used to analyze the detuning effects caused by eddy current losses and seawater. By introducing equivalent eddy current loss impedances on the primary and secondary sides, a modified mutual inductance circuit model of the underwater WPT system is obtained.

4. Key Issues to Be Solved and Development Trend

The basic transmission principle and system structure of underwater and air WPT are roughly the same. Although some achievements have been made in the development of underwater WPT in recent years, there are still many key problems to be solved due to the electrical conductivity of seawater, the particularity of the marine environment and the uniqueness of application fields.

4.1. Technical Principle of WPT in Seawater

The mutual inductance circuit model is no longer suitable for developing a seawater WPT mechanism. For example, the full mutual inductance model [126] and modified mutual inductance model [127] are only suitable for partial circuit analysis, and cannot describe seawater WPT power transmission mechanisms comprehensively and systematically. In terms of the study of seawater turbine losses, the current studies are all targeted at specific electromagnetic couplers, and the results are not universal, and the accuracy of the theoretical study and numerical simulation of eddy current losses needs to be improved, which makes it difficult to provide theoretical guidance for the optimization of key performance such as power transmission efficiency and power of the system. Therefore, we need to form a comprehensive and systematic circuit model, on this basis, from the theoretical derivation, numerical simulation, experimental test, and accurate quantitative analysis of eddy current loss, eddy current loss mechanism, and influence factors of WPT to accurately describe the seawater system power transmission mechanism, providing the theoretical basis to improve system performance in power transmission.

4.2. IWPT System Implementation on an AUV

The IWPT system integration to an AUV without affecting the AUV shape and hydrodynamic performance is challenging. The hull is made up of mechanically strong and lightweight, but conductive materials, such as aluminum and titanium. In [76], the secondary coil was placed inside the AUV's aluminum hull, which has drastically reduced the power transfer efficiency compared to the case without the hull. Some of the earlier designs [67,68,128,129] have modified AUV shapes with projections outside the AUV hull, which can affect the hydrodynamic performance of the AUV. The coaxial coil design in [65] utilizes a thin secondary coil mounted on the AUVs hull, which does not affect the shape of the AUV, but it generates higher magnetic flux inside the AUV.

4.3. Communication and Data Transfer

The power flow in an IWPT system can be controlled using the primary, the secondary, or dual-side controls, with or without communication between units [79]. Out of these, dual-side control with closed-loop communication is advantageous in terms of obtaining desired power control and maximum efficiency. Bidirectional WPT charging of AUVs or underwater sensors requires communication to determine the identity of the transmitter and the receiver. Some of the requirements for bidirectional power transfer are defined in [80]. A communication link between the primary and secondary units is required to initiate or terminate the charging process and to exchange the control information (the details of the power transfer, battery state of charge (SOC), voltage and current levels, etc.). The same communication link can be employed to transfer the data collected between two charging sessions. Establishing a reliable communication with low latency and low BER is a challenging task in an underwater environment, and acoustic and radio frequency (RF) data transfer methods are generally used for that purpose at short distances. However, the distance at which RF waves can be used in an underwater environment is significantly reduced due to higher losses. Some researchers have demonstrated accurate and high-speed data transfer using the same IWPT hardware [128,130]. Others (see [67,131–133]) have communicated the information by modulating the secondary parameters and sensing their effect on the primary side. This method eliminates the requirement for additional hardware for data transfer, but it requests additional circuitry for load modulation and detection.

4.4. Adaptability to the Marine Environment

In the marine environment, ocean current impact, pressure and magnetic effect caused by deep-sea high pressure, seawater salinity, temperature, microbial attachment and other disturbances can cause the change of parameters of underwater WPT system and affect the stability of power transmission. The influence of high hydrostatic pressure on the efficiency of IWPT systems was studied in [68]. The experimental results show that the system efficiency decreases significantly when the pressure is 40 MPa and the water depth is 4 km. This is because under the action of high pressure, the magnetic permeability of the core is reduced and the magnetization inductance is reduced. The effect of salinity on WPT systems was studied in [56,134]. Both studies show that the efficiency of the WPT system decreases with increasing salinity, and the trend of efficiency decline accelerates when salinity exceeds 10%. Seawater is a cooling medium, thus increasing the thermal limit of the coil; as shown in [79], the cooling effect increases the maximum power of the coil from 600 W in air to 1 kW in water. The potting material also affects the dissipation of heat generated in the coil. During heat dissipation tests on polyurethane and epoxy materials [135], polyurethane coils were damaged due to low thermal conductivity. The research in literature [20,51,126,136] lacks depth and a systematic approach. The measures proposed to enhance the adaptability of the Marine environment of the system have not been tested and verified, so they do not have universal adaptability.

At present, the research on environmental variable disturbance mostly focuses on a single variable, such as coupling angle problems, horizontal shift change, temperature, salinity, etc., while the researches on multi-environmental variable disturbance are very few and not in-depth. Based on the study of single variables, comprehensive simulation of the disturbance of multiple environmental variables can be carried out, and a multi-field coupling simulation model of electromagnetic field, temperature field, stress field, and fluid field can be established based on finite elements to simulate the dynamic marine environment, and the variation rule of system performance under disturbance of multiple environmental variables can be obtained.

4.5. Electromagnetic Compatibility

The sending coil and receiving coil in the underwater WPT system generate strong high-frequency alternating electromagnetic fields to launch the system, making it easy for marine electrical and mechanical equipment such as underwater vehicle navigation and sonar, fuses, and electronic components to produce interference, affecting its normal function, and even causing misoperation or damage. In military applications, the electromagnetic field of the underwater WPT system radiates outward, which will seriously reduce the electromagnetic stealth performance of underwater vehicles. On the other hand, the high-order harmonics generated by the working electronic and electrical components of the marine electromechanical equipment will also cause interference to the underwater WPT system. When the high-order harmonics are close to the resonant frequency of the system, the interference is the most serious, which will lead to a serious decline in the power transmission efficiency of the system. Therefore, it is necessary to solve the electromagnetic compatibility problem of underwater WPT systems, taking effective measures to reduce the electromagnetic interference of the system in the outside world, and enhance the anti-external electromagnetic interference ability of the system. At present, researchers have not paid enough attention to this problem, and only Kan et al. [137] studied the electromagnetic interference of WPT system in electronic components of underwater vehicles by using numerical simulation method. Li Zesong [126] found that the metal shell of the electromagnetic coupler can play the role of electromagnetic shielding, but the magnetic flux leakage between the magnetic core gap will produce eddy current loss in the metal shell, reducing the efficiency of the system. By adding a thin copper skin between the metal shell and the magnetic core as a shielding layer, the eddy current loss can be reduced, and the electromagnetic shielding effect can be achieved at the same time. Lu [138] proposed that by optimizing the coupling coil layout and adding coil shielding, stray magnetic fields can be effectively reduced without affecting the power transmission efficiency of the system. Syahroni [139] adopted electromagnetic and acoustic absorbing materials for underwater vehicles, which can effectively improve electromagnetic stealth performance. Attention should also be paid to the electromagnetic environment safety of WPT systems in underwater application, as summarized by Zhou Hong [140]. The can-shaped magnetic core used in [141] can reduce the magnetic interference to the outside world when the coil is working, but it cannot form an effective protection for the electric equipment itself. In a word, there are few research results at home and abroad, and there is no clear research conclusion and design method, which is worthy of in-depth study by researchers.

4.6. Application of New Materials

The copper loss caused by the power transmitting coil and the receiving coil in underwater WPT system is the main system energy loss. Superconducting materials with zero resistance can effectively reduce the copper loss of the system under certain conditions. Chung et al. [142] used superconducting material to make power transmission coils. Compared with ordinary coils, the power transmission efficiency of superconducting material coils is significantly higher. Metamaterials, generally artificial composite materials, are materials with extraordinary, special physical properties that ordinary natural materials do not have. Electromagnetic metamaterials with special electromagnetic properties, such as negative dielectric constant and magnetic permeability, can be used in WPT technology. Through experiments and tests, Wang [143] found that the application of electromagnetic metamaterials in the WPT system can increase the coupling between coils, establish uniform current distribution, enhance the magnetic field, and greatly improve transmission efficiency. In view of the low transmission efficiency of the WPT system caused by the high loss of electromagnetic waves in seawater, Kangle et al. [144] proposed to use electromagnetic metamaterial to "magnify" vanishing waves, so as to enhance the energy density of electromagnetic wave and significantly improve the transmission efficiency of the system.

5. Conclusions

The diversity of AUV applications in ocean exploration and military missions is growing rapidly. The concept of inductive wireless charging has been proposed in recent years to overcome the limitation of navigation range and autonomous ability of underwater vehicles due to their limited carrying capacity. This paper firstly introduces several energy transmission modes of wireless charging, and finds that magnetic field mode is more advantageous for the underwater environment. Then, the magnetic coupling structure, docking method, IWPT system control method, and compensation network of underwater vehicles are comprehensively reviewed. The realization method, control, and power transfer of underwater wireless charging are discussed. Finally, the key and difficult points in this field are summarized, including principle, environment, electromagnetic interference, and the use of new materials. Due to the conductivity of seawater, serious eddy current loss occurs during the transmission of electrical energy, resulting in a significant reduction in the power transmission efficiency of the system. The influence of the seawater environment on the performance of wireless charging system parameters needs to be described by a more accurate model. Wireless charging is not a static process due to ocean currents. The impact of the ocean current will cause the vehicle and the charging station to roll and shift relative to the axial direction, resulting in the change of the mutual inductance of the coupling coil, making the resonance frequency shift, affecting the stability of the power transmission. Furthermore, the high voltage of the seabed will change the coupling parameters of the system coil, making the system deviate from the best performance. Therefore, it is necessary to select a suitable compensation topology, design a magnetic coupling coil with anti-offset characteristics, and use anti-disturbance control strategy to improve the transmission performance of the system. Although some achievements have been made in the development of underwater WPT in recent years, there are still many key problems to be solved due to the electrical conductivity of seawater, the particularity of marine environment, and the uniqueness of application fields.

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