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Review Article

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Design considerations for contact-less underwater power delivery: a systematic review and critical analysis

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Abstract

Wireless power transfer (WPT) has attracted attention from academia and industry in recent years. WPT has natural electrical isolation between primary and secondary side, which ensures safe charging in an underwater environment. This breakthrough technology greatly facilitates the deep-sea power transmission. However, at the current stage the transferred power and energy efficiency level are not up to that of the WPT system in the air. The major concerns include the attenuation is seawater, extreme temperature and pressure conditions, disturbance of ocean currents, and bio-security. Three questions are answered in this paper: first, the expressions of eddy current loss and attenuation of electromagnetic wave in seawater are unified, and the influence of seawater as transmission medium on the WPT system is discussed. Second, the evolution of electromagnetic coupling structure suitable for underwater applications is studied. Third, the loss and heating effects of an underwater WPT system and the corresponding bio-fouling phenomenon are investigated. The questions above were addressed through analysis of electrical properties, coupler structures, and bio-fouling effects of the underwater WPT system. This paper will facilitate the study and research on underwater WPT applications.

Introduction

As the development of submarine observation technology, an underwater power supply system is gaining more and more attention from both academia and industry. A traditional power supply system connects the load and power source through wet plugging. The jack socket is squeezed and water is drained out to obtain the safe charging environment. After a long operation period, the interface will be worn and the danger of leakage will thus be increased.

As an epoch-making technique, wireless power transfer (WPT) realized energy migration in a contact-less way and this technique has changed our traditional utilization patterns of energy in various applications, such as electrical vehicles, portable electronic devices, implanted medical devices, the autonomous underwater vehicle (AUV), and so forth. The reason why WPT technologies are so crucial in an underwater environment is regarding to two fundamental problems – short endurance mileage of battery and the lack of mobility of connection stations.

Take unmanned underwater vehicle (UUV) as an example, a typical 150 kg 1.8 m-long UUV is able to travel 20–40 km, which significantly restricts the exploration range of deep-sea activities. On the other hand, the endurance mileage can be extended by increasing the number of batteries installed, but the corresponding weight and cost will become in-affordable for the UUV.

Meanwhile, before the battery runs out, the UUV needs to go to the connection station at a certain position. All these excuses significantly restrict the cruising range of the UUV. While by utilizing the WPT technique, the UUV can harness wireless power from electromagnetic field and then charge its batteries. The charging process can even be realized in the moving state when power is taken from a submarine (usually powered by nuclear). This novel charging technology is able to fundamentally solve the problems of short endurance mileage due to limitation of batteries and the lack of mobility due to stationary charging stations.

Despite all the facts above, contact-less underwater power delivery does not deliver the same amount of power with comparable efficiency as the WPT system in the air (see Fig. 1). The major concerns include the attenuation is seawater, extreme temperature and pressure conditions, disturbance of ocean currents, and bio-security.

This paper attempts to address three challenging questions:

(1) Firstly, the influence of seawater on the WPT system was mainly carried out using eddy current loss theory and electromagnetic attenuation theory, can the expressions of eddy

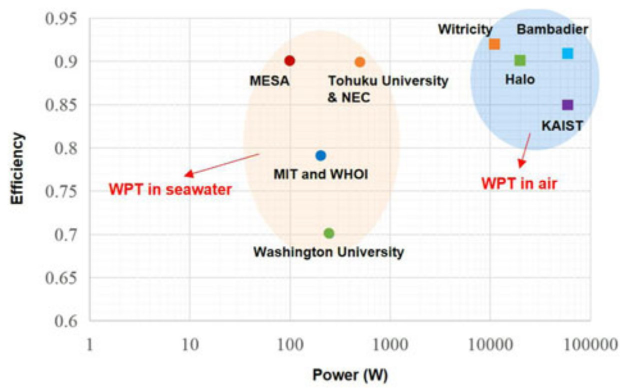

Fig. 1. Comparison of the transferred power and efficiency of the WPT system in air and in seawater.

current loss and attenuation of the electromagnetic field in seawater be unified? What is the quantified evaluation of effects of seawater on WPT system?

(2) Secondly, the underwater WPT system is vulnerable to ocean current disturbance, extreme temperature, and pressure conditions. What is the desired electromagnetic coupling structure for underwater applications?

(3) Thirdly, system loss makes the power transmission device a hotter spot compared with environmental temperature. Is this a severe problem considering the bio-fouling effects?

The questions above were addressed through analysis of electrical properties, coupler structures, and bio-fouling effects of the underwater WPT system.

Challenges

Attenuation in seawater

The fundamental distinction of the underwater WPT system is brought by the application environment – seawater. In seawater, the behavior of the electromagnetic field is different from that in air because of its high conductivity and high relative permittivity, and the comparison is made in Table 1.

According to Maxwell equations, the propagation of electromagnetic wave in seawater is written as:

$$\begin{cases} \nabla \times H = J + \dfrac{\partial D}{\partial t} \\ \nabla \times E = -\dfrac{\partial B}{\partial t} \\ \nabla \cdot D = \rho \\ \nabla \cdot B = 0 \end{cases} \tag{1}$$

In which, H is the magnetic field intensity, B is the magnetic flux density, E is the electric field intensity, D is the dielectric flux density, and J is the electric current density.

The linear and isotropic medium also satisfies the following equations:

$$D = \varepsilon E, B = \mu H, J = \sigma E$$

where ε is the dielectric constant, μ is the permeability, and σ is the conductivity.

Table 1. Comparison of relative permittivity and conductivity in air, fresh water, and seawater

Medium	Relative permittivity	Conductivity (s/m)
Air	1.0006	0
Fresh water	81	0.01
Seawater	81	4

In a passive conducting medium, the Maxwell equations are transferred into:

$$\begin{cases} \nabla \times H = \sigma E + jw\varepsilon E \\ \nabla \times E = -jw\mu H \\ \nabla \cdot H = 0 \\ \nabla \cdot E = 0 \end{cases} \tag{2}$$

In a uniform conducting medium,

$$\nabla \times H = \sigma E + jw\varepsilon E = jw\left(\varepsilon - j\frac{\sigma}{w}\right)E = jw\varepsilon' E \tag{3}$$

Furthermore,

$$\nabla \cdot E = \frac{1}{jw\varepsilon'} \nabla \cdot (\nabla \times H) = 0 \tag{4}$$

So in the uniform conducting medium, even though the electric current density $J \neq 0$, but the free charge density is zero, i.e. $\rho = 0$. The values of H and E meet the Helmholtz equations, as in homogeneous and non-lossy media:

$$\begin{cases} \nabla^2 E + k^2 E = 0 \\ \nabla^2 H + k^2 H = 0 \end{cases} \tag{5}$$

In which, $k^2 = w^2\mu\varepsilon - jw\mu\sigma$

In the air, $\sigma = 0$, $k^2 = w^2\mu\varepsilon$ is the real number; while in seawater, $\sigma \neq 0$, so k^2 is the complex number.

Assume the uniform plane wave propagates in the $+z$ direction, and the electric field only has E_x component, the electromagnetic wave is a function of z and x. The electric field in Equations (5) is:

$$E_x = E_0 e^{jwt - \gamma z} \tag{6}$$

In which, $w = 2\pi f$ is the angular frequency, $\gamma = jk$ is the propagation constant of electromagnetic wave in seawater, $\gamma^2 = jw\mu\sigma - w^2\mu\varepsilon$

Assume $\gamma = \alpha + j\beta$, expand the real part and imaginary part,

$$\alpha = w\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1 + \left(\frac{\sigma}{w\varepsilon}\right)^2} - 1\right]} \tag{7}$$

$$\beta = w\sqrt{\frac{\mu\varepsilon}{2}\left[\sqrt{1 + \left(\frac{\sigma}{w\varepsilon}\right)^2} + 1\right]}$$

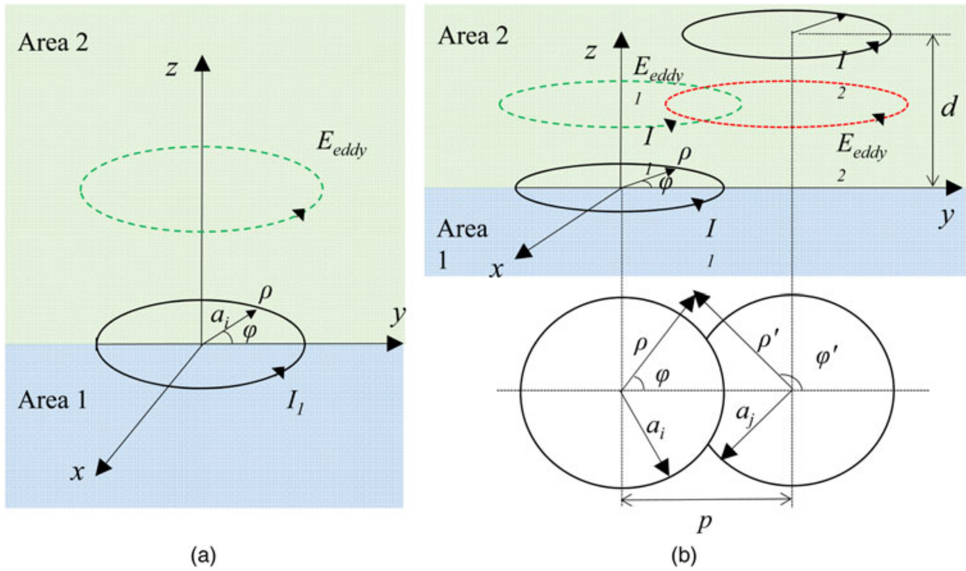

Fig. 2. Calculation model: (a) single-turn coil and (b) two single-turn coils with misalignment.

Apply to Equation (6), the expression of the electric field of plane wave is:

$$E_x = E_0 e^{-\alpha z} e^{-j\beta z} e^{jwt} \tag{8}$$

The factor $e^{-\alpha z}$ demonstrates the amplitude of electric field decays exponentially as the increase of transfer distance z, α is the decay coefficient. The factor $e^{-j\beta z}$ reflects the relationship between the phase and distance, β is the phase coefficient.

Seawater is a good conductor of electromagnetic wave, so in the low-frequency range, we obtain the following relationship:

$$\sigma / w\varepsilon >> 1 \tag{9}$$

As a result, the amplitude and phase coefficients can be simplified as:

$$\alpha \approx \beta \approx \sqrt{f\pi\mu\sigma} \tag{10}$$

Bring the expressions of α and β back to Equation (14),

$$E_x = E_0 e^{jwt - \sqrt{f\pi\mu\sigma}(1+j)z} \tag{11}$$

E_x is the electric field intensity incurred by the current in primary coil, the induced voltage in secondary coil is thus calculated as:

$$U_s = N \oint E_x dl \tag{12}$$

U_s is a complex number and can be written in the form of:

$$U_s = U_s' e^{j\theta} \tag{13}$$

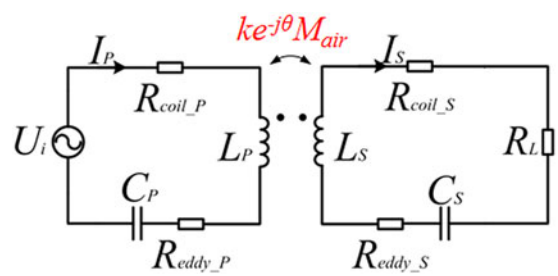

Fig. 3. Modified mutual inductance model of the WPT system in seawater.

In the form of the mutual inductance model, the induced voltage in secondary coil in seawater can be expressed as:

$$U_s = -jwM_{air} I_p e^{j\theta} \tag{14}$$

Other literature studied the effects of seawater on the WPT system based on eddy current loss theory. In the underwater WPT system, the eddy current loss tends to be non-negligible as the increase of frequency and current. The expression of the electric field excited by circular current in coils is deduced with Maxwell equations, which is relative to the current frequency f, the root-mean-square value of current I, and coil turns N [1].

The electric field intensity $E(\rho,\Phi,z)$ at an arbitrary point (ρ,Φ,z) is given as follows [1]:

$$E(\rho, \varphi, z) = -jw\mu\alpha_p I_p N_p \cdot \int_0^\infty \frac{\lambda}{u} J_1(\lambda\alpha_p) J_1(\lambda\rho) e^{-u|z|} d\lambda e_\varphi \tag{15}$$

J_1 and Y_1 are the first and secondary species first-order Bessel function, u is a function of variable λ, permittivity ε, conductivity σ, and permeability μ, which is expressed as:

$$u = \sqrt{\lambda^2 - \omega\mu(\omega\varepsilon - j\sigma)} \tag{16}$$

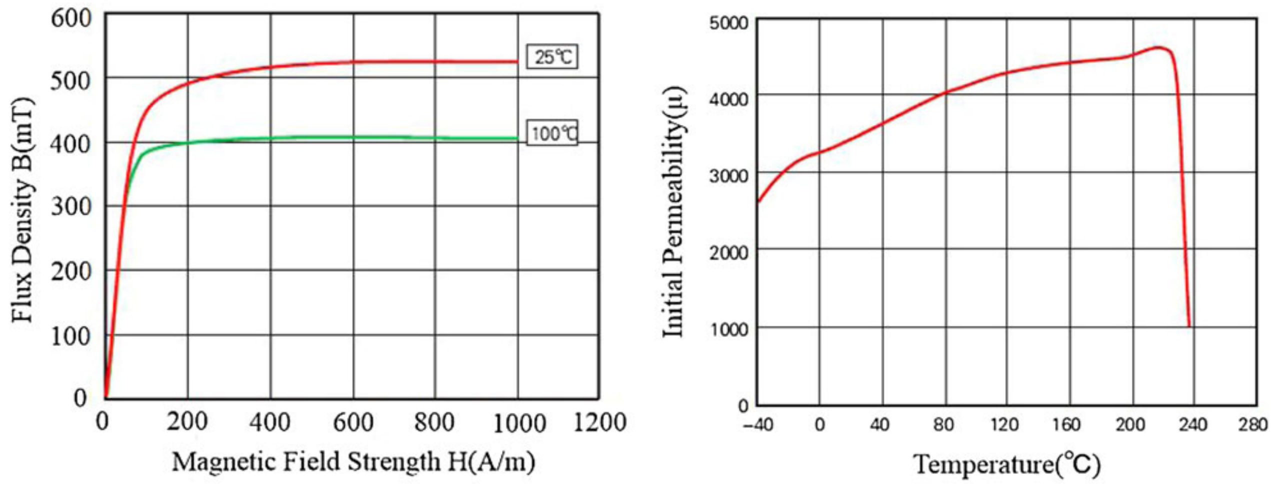

Fig. 4. B–H curve of ferrite at different pressures and temperatures.

N_p is the number of turns of $\mathrm{Coil}_{\mathrm{Tx}}$.

The eddy current loss is then analyzed under different frequencies, in aligned and misaligned positions, shown in Fig. 2 [2].

Due to the attenuation in seawater, the traditional mutual inductance circuit model in air cannot be used directly to describe WPT systems in seawater applications. By introducing the equivalent eddy current loss impedance, a modified mutual inductance circuit model of an underwater WPT system was obtained [3], as shown in Fig. 3, where k is defined as a ratio of the amplitude of induced voltage in secondary coil in seawater and air and θ is defined as the phase difference of the phase of the induced voltage in secondary coil in seawater and air. The modified model can be used to analyze the eddy current loss and detuning effect incurred by seawater.

Comparing with Equation (14), the expressions of eddy current loss agree well with the attenuation of the electromagnetic field in seawater. And the effects of seawater can be quantified by adding a coefficient on the mutual inductance based on the basic WPT model.

To conclude, both the electromagnetic model and eddy current loss model have been utilized in theoretical analysis for the underwater WPT system. The electromagnetic model focuses on the propagation and attenuation of electromagnetic wave in seawater according to Maxwell equations, while the eddy current loss model calculates the eddy current loss in seawater, as that tends to be non-negligible as the increase of frequency and current. This paper found out that these two models have a similar expression on the mutual inductance circuit model of the WPT system, and the expression can be unified.

For a WPT system in the air, there is an optimum resonant frequency, for a higher frequency leads to a larger induced voltage, but will result in larger coil losses simultaneously. However, the optimum resonant frequency will be shifted because of the eddy current loss in the sea water [4–6]. Frequency splitting happens in the over-coupling region [7, 8]. Furthermore, the phase difference between the currents in the primary coil and secondary coil is not 90°, which results in detuning of the WPT system [9, 10].

Evolution of coupling structure

In deep sea applications, such as a seafloor observation network, the wireless charging system suffers from high pressure and low temperature, which affects the behavior of ferrite and causes unexpected saturation. Extra protection must be taken to shield and support the magnetic coupler and power modules. On the other hand, the ocean currents may affect the precise positioning of stationary charging, clamping and fixing equipment are always included to maintain stable power transmission between the transmitter and receiver.

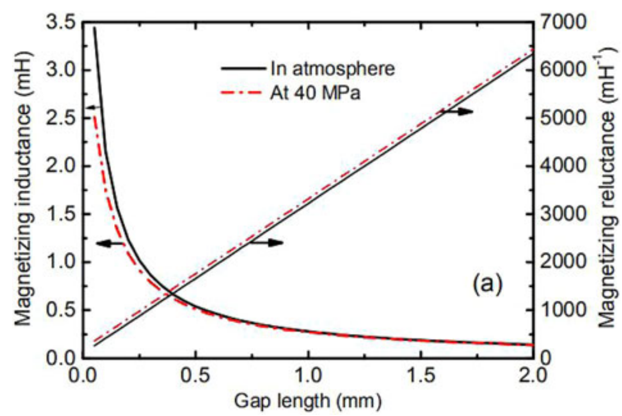

Fig. 5. Gap effects on the electromagnetic coupler [13].

Temperature and pressure

Soft magnetic ferrite is a promising candidate material for the WPT system, due to its superior magnetic properties, low temperature sintering, and high-frequency characteristics, which are technologically important for achieving high power transfer efficiency in the WPT system.

Submarine temperature generally decreases with increasing depth, which is also subject to periodic changes and irregular changes. Temperature stability of ferrite is defined by temperature coefficient. The temperature coefficient is given by the change in permeability between two fixed temperatures.

$$\alpha_\mu = \frac{\mu_2 - \mu_1}{\mu_1} \bullet \frac{1}{\theta_2 - \theta_1} \tag{17}$$

μ_1 is the permeability at temperature θ_1

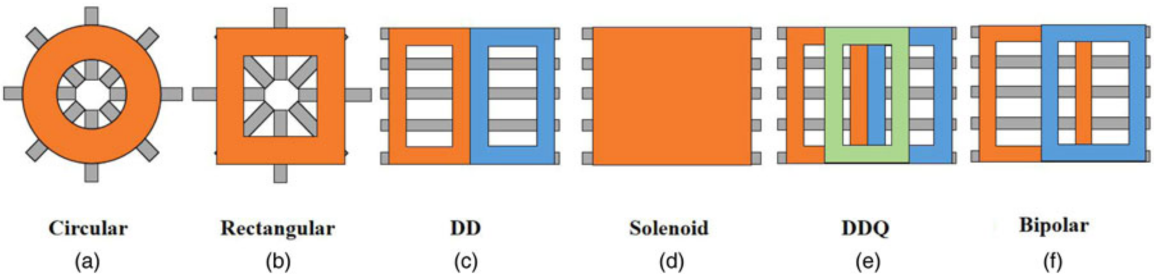

Fig. 6. Traditional structures of the WPT coupler.

μ_2 is the permeability at temperature θ_2

The B–H curve and initial permeability of ferrite at different temperatures are shown in Fig. 4.

On the other hand, the undersea pressure increases by one atmosphere with 10 m increase in depth. In deep-sea applications, the magnetic core is exposed to sea water with a pressure up to 40 MPa, its relative permeability is reduced to about 1400 [11]. The high pressure leads to a reduction in the magnetic permeability of ferrite, because of the material's piezomagnetic property. The relationship between initial permeability and pressure is described using the following equation (18) [12].

$$\frac{\mu_{rc}(0)}{\mu_{rc}(P)} = \frac{1}{1 + c\mu_{rc}(P) \cdot P'} \tag{18}$$

where $\mu_{rc}(0)$ and $\mu_{rc}(P)$ are the relative permeability of the ferrite core in an atmosphere and at pressure P, c is a constant of the ferrite. As shown in Fig. 5, with an increase in pressure, the magnetizing inductance L_m will decrease and the reluctance will increase correspondingly. If a large gap exists between the transmitter and receiver, the gap reluctance becomes dominant and the effective permeability is mainly determined by the gap length. As a result, the magnetizing inductance will be little affected by high pressure [13].

Ocean current disturbance

Traditional structures of WPT coupling include circular pads, rectangular, DD pads, and solenoid structure, as is shown in Fig. 6. However, typical coil structures are vulnerable to ocean current disturbance, additional fixing devices are obligatory, which adds to the complexity and cost of the system. As a result, an evolution of the coupling structure is taking place in order to adapt to the effects of ocean current disturbance. The new coupling structure evolves to fit into the application scenario.

As to the torpedo-shaped UUV, the power supply transmitter can be incorporated into the docking cage, so when the UUV comes to the docking place, the transmitter and receiver coil are in the aligned position. Power can be transferred to the UUV in an efficient way.

As shown in Fig. 7, the inductive power transfer (IPT) system is composed of two coaxial solenoids, where the transmitter side is wound on the submerged base station and the receiver coil is assembled to the AUV's hull [14, 15]. In the AUV docking process, the secondary winding is inserted into the primary winding. The electric power could be transferred from the submerged base station to AUV [16].

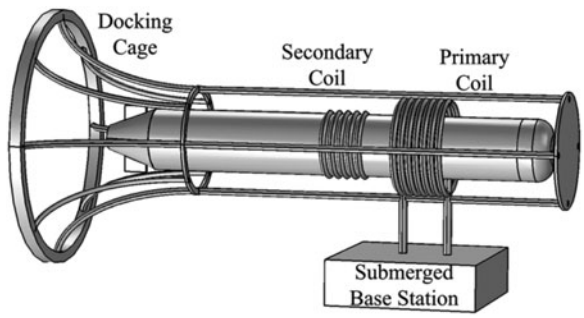

Fig. 7. Fixed configuration of the concentric circular ring structure for AUV's IPT system [17].

However, a problem incurred by this coil structure is the electromagnetic interference (EMI) inside the receiver coil, which may affect the operation of electronics devices in the UUV.

In order to solve the EMI problem, a rotation-free WPT system for charging of AUVs is proposed [17], as shown in Fig. 8. The two receivers are reversely wound, so the magnetic flux directions of the two receivers are perpendicular to each other. The two receivers are thus decoupled and the mutual inductance remains constant under rotational misalignment. An overall 92% dc–dc efficiency can be achieved at around 600 W [17, 18]. This coil structure is further improved into a three-transmitter two-receiver system. And the receiver is sectioned into three parts, to reduce the mutual inductance fluctuation as rotational misalignment increases.

As shown in Fig. 9, the generated magnetic field is concentrated in the outer ring within the coil structure itself, which has fewer adverse effects on the existing electronics devices in the AUV.

Loss, heating, and bio-fouling

A unique challenge in the maritime environment is bio-fouling. Temperature elevation near the WPT coils, along with the increased mission duration, can exacerbate marine microbial growth [19].

Concerning the loss map in an underwater WPT system, the distribution of power losses in the underwater WPT system is shown in Fig. 10. The total loss in the system includes the copper loss caused by coil resistance, the magnetic loss in ferrite, the eddy current loss in seawater, the loss in compensation capacitors, and switching loss in the inverter and rectifier.

As eddy current loss in seawater has been discussed in the previous section, and the heat generated in seawater can be easily

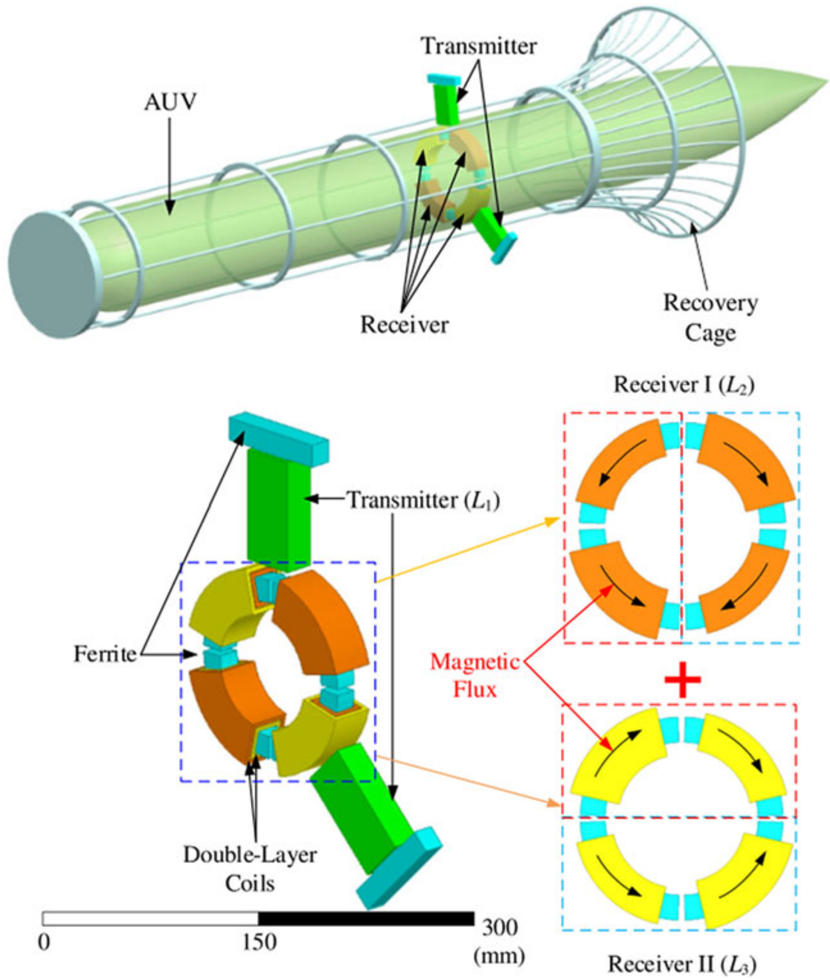

Fig. 8. (a) General overview of the WPT system for AUVs. (b) Proposed rotation-free coil structure.

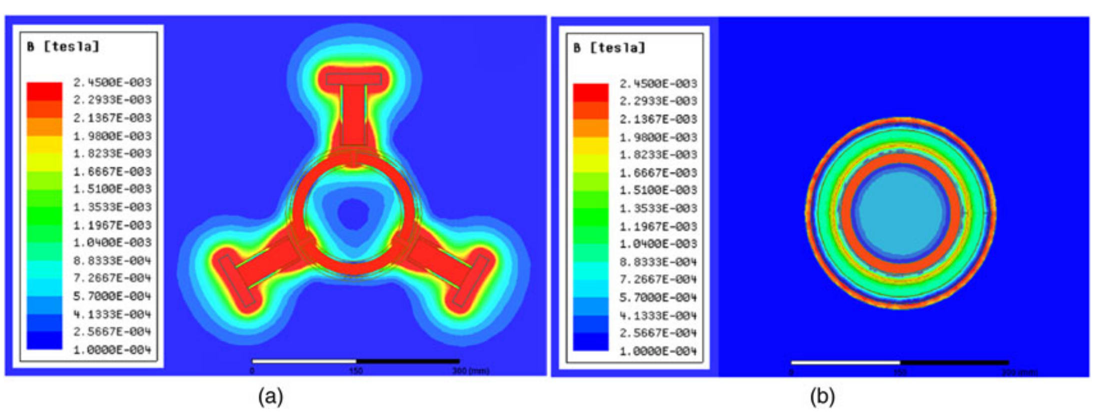

Fig. 9. Magnetic flux densities: (a) proposed coil structure and (b) coaxial coil structure [18].

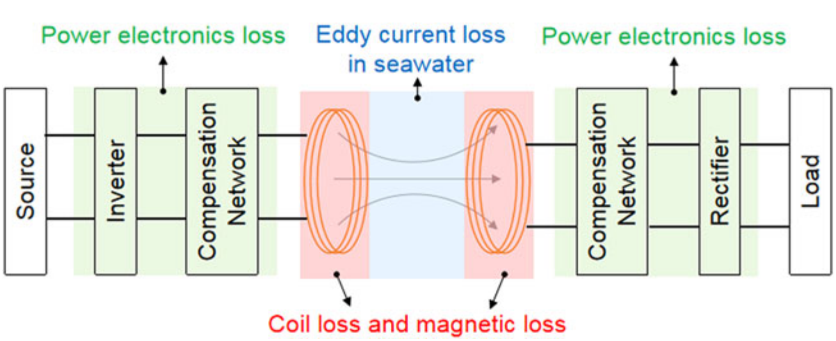

Fig. 10. Distribution of power losses in the underwater WPT system.

Fig. 11. Bottom of control coils (no Anti Foul) after 45 days [19].

dissipated. The effects of power electronic losses is minimum as it only accounts for 1~2% of total loss. Copper loss can be obtained by multiplying the square of the current effective value with resistance, in low frequency situations. As the frequency increases, the skin effect happens and current tends to concentrate on the surface area, which will increase the resistance of the conductor and incurs additional loss.

Copper loss can be effectively reduced using Litz wire, and coaxial winding leads to an even current distribution and copper loss reduction.

When the soft magnetic material is in a weak alternating field, on the one hand, energy is stored by magnetization; on the other hand, the loss is generated because B is lagged behind H. The magnetic loss can be roughly calculated using Steinmetz equations.

$$P_{core} = C_m f^{\alpha} B^{\beta} \cdot V_e \tag{19}$$

Heat generation in a WPT system is closely related to the transferred power, system efficiency, and operation duration. The higher power level, the longer operation time, the more heat generated. A WPT system with higher efficiency is always desirable, as low efficiency results in more loss in the system.

Handling the heat dissipation should be a priority concern when implementing a high power underwater WPT system. The coils used in WPT experience elevated temperatures due to resistive losses in the wire [20].

Unchecked microbial growth (shown in Fig. 11) introduces the risk of misalignment or greater stand-off distances between the inductive coils, which can severely reduce their transfer efficiency. The coating material functioning as isolation against seawater should be a good heat dissipation medium.

Applications

Sea-floor base station or mother ship charge to AUV

MIT and WHOI pioneered the idea of applying wireless charging to the underwater vehicle in submarine sampling network AOSN. In 2001, Feezor and Sorrell developed an underwater wireless charging system, in which the underwater robot MIT/WHOI Odyssey II is charged in a seafloor base in a wireless way. The system works in the 2000 m deep ocean, and transfers 200W power with 79% efficiency [21, 22]. Soon afterwards, Underwater Vehicle REMUS 100, REMUS 600, and Bluefin 21 all accomplished underwater wireless charging experiment [23, 24]. The charging platform for REMUS 100 and Bluefin 21 is shown in Fig. 12.

Kawasaki shipbuilding company, belonging to Kawasaki Heavy Industries designed an UUV named "Marine Bird". When the UUV docks in the underwater platform, the underwater base station provides power to the UUV using an electromagnetic induction principle [25, 26].

In 2004, Tohuku University and NEC company jointly developed a contact-less charging system for AUV, as shown in Fig. 13. The system is able to transfer 500 W power with 90% efficiency, meanwhile, the system is stable and not vulnerable to disturbance [27, 28].

Ocean observation network

Prof. McGinni in Washington University designed a WPT system for the ALOHA-MARS seabed observation system, as shown in Fig. 14. The transferred power of the system is 250 W with 70% efficiency.

MESA company in Germany has developed a rotatable underwater wireless charging equipment, which provides power to sensors, lighting devices, electric motors, microprocessors etc. Power and data transfer can be transferred simultaneously. MESA has developed INPUD CAN series wireless charging products in shoal waters and INPUD DON series products in the deep-water region. INPUD DON100HE30 is shown in Fig. 15. The system is able to transfer 100 W with 90% efficiency, 2500 rpm rotary speed is allowed [29].

Beside, Japan TRITON Company developed a buoy system which realized simultaneous transfer of power and data, which is able to provide 180 mW power to underwater devices. Tianjin University studied the IPT scheme fed by solar energy, which supplies power to underwater sensors through two couplers tied by the steel cable [31].

A comparison of underwater WPT systems is shown in Table 2.

Future research

Underwater WPT technology derives from the WPT technique in the air, and inherits a similar transmission principle and coupling structure. However, because of the special characteristics of seawater as the transmission medium, and the unique application background of deep-sea devices, underwater WPT technology is confronted with many exclusive problems. As far as the authors concerns, future research lies in the following aspects:

Transmission distance

Considering the complicated working environment and induced eddy current loss in seawater, the transmission distance underwater is usually limited to several millimeters, while the transmission distance in the air is 20–30 cm for electric vehicles. After the waterproof and pressure resistance package, the distance between the transmitter and receiver is further reduced. When a larger transmission distance is compulsory, the radius of the coil has to be increased as compensation. However, deep-sea devices usually have a compact design, and the increase of the coil radius will occupy the precious volume. It remains a research difficulty, how to increase the transmission distance without increasing the device volume.

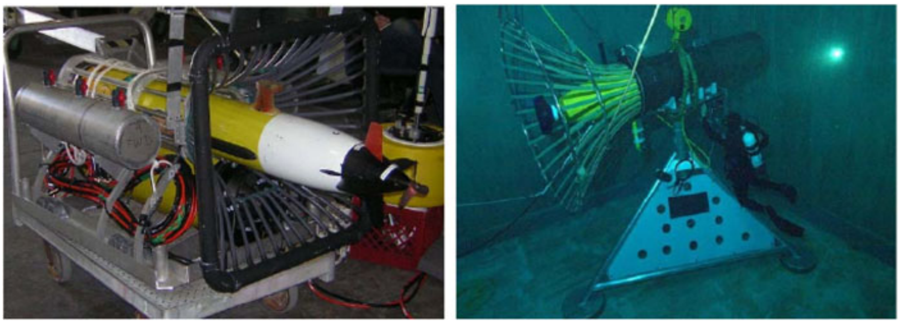

Fig. 12. Photograph of the AUV and docking station [21].

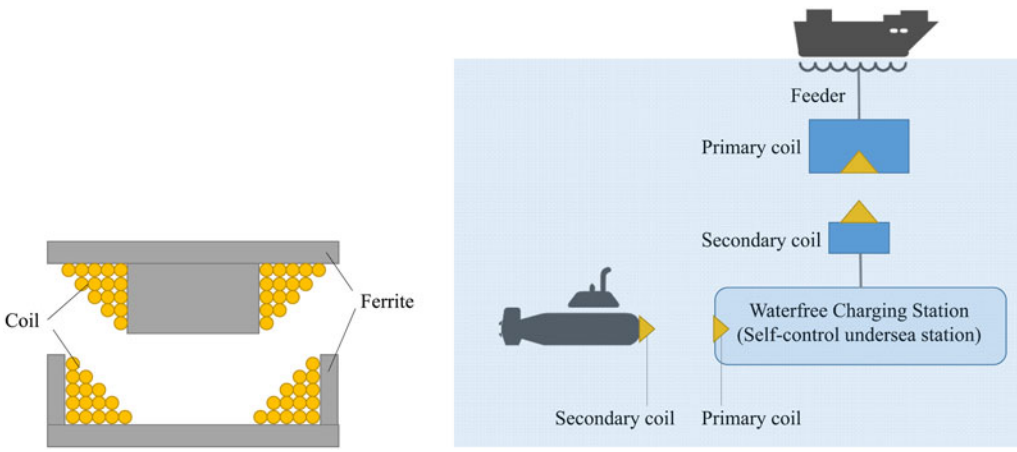

Fig. 13. Contact-less power transfer system developed by Tohuku University and NEC company.

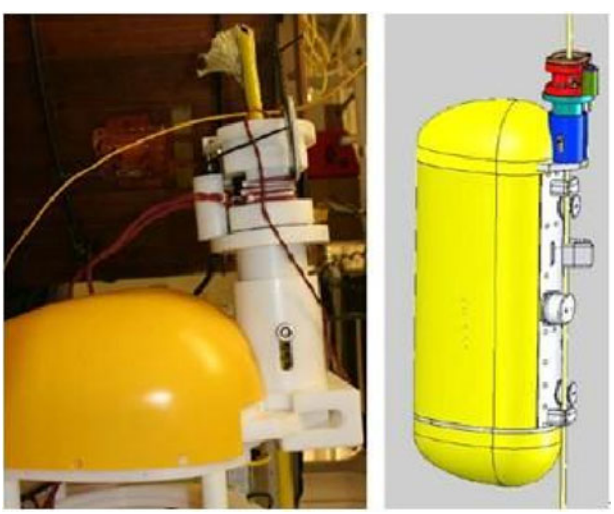

Fig. 14. Inductive charging system for the seabed observation system designed by Washington University.

Environmental disturbance

The underwater WPT system is not only affected by the conductivity of seawater, but also influenced by the pressure, temperature, salinity, ocean current velocity, and adherent microorganism. All the factors mentioned above will alter the surrounding magnetic circuit, and cause variation in system performance. Current research on WPT considering environmental factors mainly focuses on the angular and horizontal misalignment, temperature and salinity etc. Research on multiple environmental factor disturbance based on multi-field coupled analysis is to be carried out.

Sealing and housing

In deep-sea environment, the high pressure of seawater puts forward challenges on the sealing and housing design of the electromagnetic coupler. Major concerns include material selection and structural analysis. The chemical property of the housing and sealing material should remain stable and resistive to corrosion by sea-water in long-term applications. Besides, the transmitter and receiver side should be easily mated, and the mated coupling should be robust against random turbulence in a deep-sea environment. The EMI problem should also be taken into account.

Conclusion

In this paper, the submarine WPT techniques were overviewed with emphasis on technical challenges and typical applications.

The key technical issues of underwater WPT systems were summarized in terms of attenuation in seawater, evolution of coupling structure, and heat dissipation issues. Typical applications were also discussed, including AUV and oceanic monitoring and maintenance equipment.

Discussion about future development is given as follows:

Fig. 15. INPUD DON100 HE30 underwater inductive charging equipment [30].

Table 2. Comparison of underwater WPT systems

Category	Application	Developer	Power	Efficiency
Wireless charging to AUV	Odyssey II	MIT/WHOI	200 W	79%
	REMUS 100	Hydroid	N/A	N/A
	REMUS 600	Hydroid	N/A	N/A
	Bluefin 21	Bluefin Robotics		
	Marine Bird	Kawasaki	N/A	N/A
	AUV	Tohuku University and NEC company	500 W	90%
	Contact-less power transmission system	Zhejiang University	400 W	90%
Sea observation system	ALOHA-MARS seabed observation system	Washington University	250 W	70%
	INPUD CAN/DON series wireless charging products	MESA company	100 W	90%
	Buoy system	TRITON Company	180 mW	N/A
	Underwater sensors	Tianjin University	N/A	N/A

(1) Distance and misalignment

The transmission efficiency drops dramatically as the increase of distance, and this case worsens in an underwater environment, as the permittivity and permeability of seawater is hundred times larger than that in the air. The eddy loss in seawater is a particular concern in underwater WPT systems. Meanwhile, the seawater medium makes the WPT system even more vulnerable to misalignment. The structure of the magnetic coupler should be able to direct the magnetic flux flow and minimize magnetic leakage. Such design concerns should be included in corresponding parameter optimization.

(2) Security

Heat generation and magnetic leakage are two major concerns regarding security issues in underwater WPT applications. High temperature will accelerate the insulation aging of equipment, as well as causing bio-fouling effects, so researcher need to pay attention to heat dissipation design when utilizing this system. Possible electromagnetic pollution is another public concern, additional shielding methods should be taken to ensure a safe biological environment in the surrounding area.

(3) Extreme environment

In deep-sea application, such as a seafloor observation network, the wireless charging system suffers from high pressure and low temperature, which affects the behavior of ferrites and causes unexpected saturation. Extra protection must be taken to shield and support the magnetic coupler and power modules. On the other hand, the ocean currents may affect the precise positioning of stationary charging, clamping and fixing equipment are always included to maintain a stable power transmission between the transmitter and receiver.

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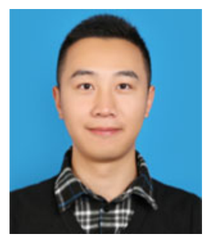

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