Master's Thesis

Coil Array Inductive Power Transfer System for Autonomous Underwater Vehicle

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Abstract

For a long time, providing a stable, safe, and efficient power supply for underwater electromechanical equipment has always been a concern in deep-sea exploration. Compared with the complicated docking mechanism, potential safety hazards, and expensive price of traditional wet-mate connectors, wireless power transmission (WPT) technology can transmit energy without any electrical contact between the power supply and the electrical equipment, which provides an effective solution to the aforementioned drawbacks of wired charging. There are many uncontrollable factors in the seawater working environment. Therefore, this topic takes the equivalent circuit and magnetic field distribution as the theoretical basis to study the energy transmission characteristics of underwater WPT and proposes corresponding improvements and solutions to the current problems and deficiencies. Especially for the unstable output voltage of the receiver and excessive magnetic flux density at the internal of AUV.

Keywords:

Autonomous underwater vehicle, inductive power transfer, underwater wireless power transfer, undersea

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1 Introduction

1.1 Background and research purpose

In the foreseeable future, the electrification of ocean systems, renewable ocean power sources, and ocean energy networks will be necessary, which will help accelerate the growth and deployment of ocean renewable energy and ways to explore and understand the ocean [1]. To achieve electrification in the ocean, it is necessary to deploy corresponding sensor networks underwater and process the data received by underwater sensors in a timely manner (Figure 1.1). At the same time, underwater sensors are also an essential tool for studying the marine environment. They can easily and flexibly explore underwater terrain and ecological environment, which provides convenience for the deployment of underwater sensor networks. An excellent underwater AUV needs to have good equipment waterproofness, long-distance underwater controllability, and power durability. For the water-resistance of the equipment, we can use high-performance waterproof and pressure-resistant materials. The remote controllability needs to solve the problems of long-distance underwater wireless communication. The durability of electrical equipment requires low energy consumption AUV and high-energy batteries or a continuous power supply. Sufficient power supply can keep underwater sensors and AUVs in an efficient and stable working state for a long time. Indirectly, reducing human interference when electrical equipment is working underwater can also improve work efficiency and reduce deployment costs. Therefore, the energy supply for underwater electrical equipment has become a novel research direction. Such methods can solve the energy supply problem of underwater equipment economically and ensure the system to perform long-term and stable work [3].

In traditional marine engineering, power is supplied to underwater equipment

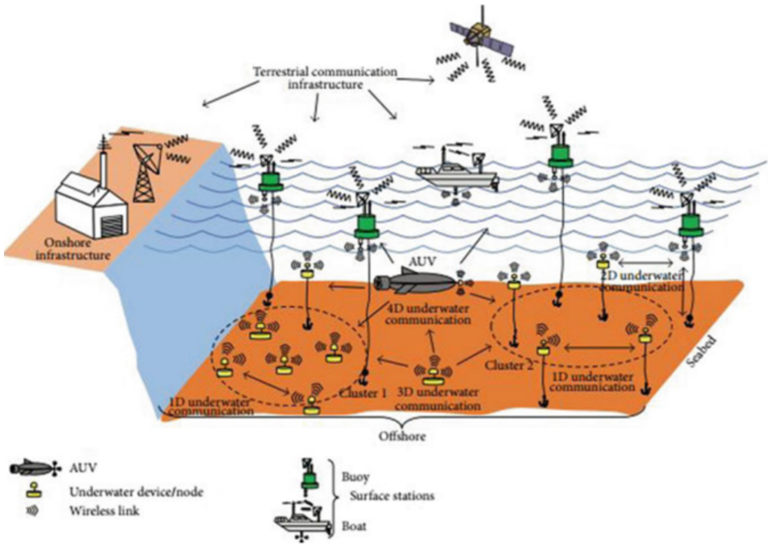


Figure 1.1: Underwater sensor networks architecture [2].

through wet-mate subsea connectors [4]. For the traditional wet plug interface technology, its high cost, complex docking method, poor safety performance, and easy to be corroded by seawater, make its disadvantages in marine engineering increasingly obvious. Wireless Power Transfer (WPT) simplifies the connection between underwater equipment and power supply, reduces the continuous operating cost of underwater equipment, saves a lot of resources, and gradually gains the favor of scholars.

The ocean itself and its surroundings contain a lot of energy, such as tidal energy, wave energy, ocean current energy, sea temperature difference energy, and sea salt difference energy. Ocean energy is rich, widely distributed, clean, and pollution-free, but low energy density and strong regionality. These advantages make it attractive as grid-connected energy, and may also make it an isolated and remote ocean energy source, thereby providing a valuable source of ocean space. Continuous development provides power solutions that are attractive. The rapid development of distributed ocean energy applications (such as underwater sensor networks, ocean sensors and monitoring technologies, ocean automatic network buoys, and deep-sea and tsunami buoys) is beneficial. In particular, it can power an autonomous underwater vehicle (AUV) whose service life is limited by its battery power.

1.2 Wireless power transfer technologies

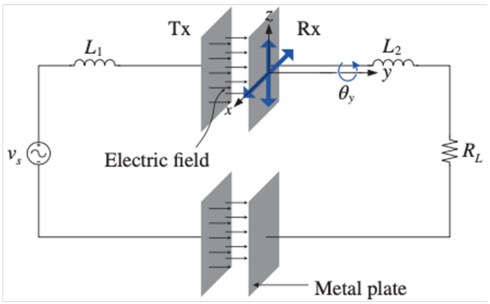
Broadly speaking, power transfer without direct electrical contact between the primary and secondary is wireless power transfer. Wireless power technology can be divided into two main categories, near-field (nonradiative region) power transfer and far-field (radiative region) power transfer. Near-field means the area within about 1 wavelength (λ) of the antenna. The range of near-field devices is conventionally divided into two categories [ref] (Suppose the distance between two antennas is represented by D_{range}, and the diameter of two antenna coils is represented by D_{ant}.):

- Short range, the distance between two antennas is less than the diameter of antenna: $D_{range} \leq D_{ant}$. In this range, power is usually transferred through non-resonant capacitive or inductive coupling.
- Mid-range, the distance between two antennas is less than 10 times the diameter of antenna: $D_{range} \leq 10D_{ant}$. In this range, energy is usually transferred through resonant capacitive or inductive coupling.

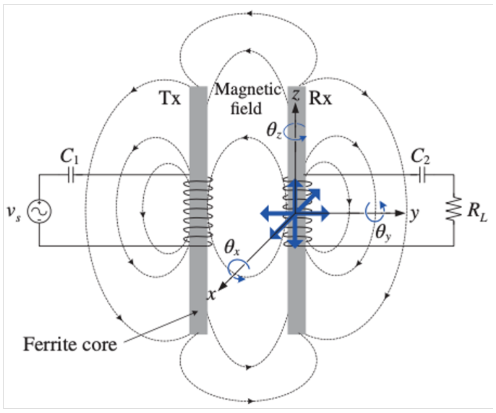
Table 1.1: The different wireless power transmission technologies.

Technology	**Range**	**Frequency**	**Antenna devices**	**Applications**
Microwaves	hm – km	GHz	Parabolic dishes, phased arrays, rectennas	Satellite, drone aircraft
Optical	dam – km	≥THz	Lasers, photocells, lenses	Drone aircraft, space elevator
Capacitive	cm – m	kHz – MHz	Metal plate electrodes	Smartcards, biomedical implant
Inductive	mm – m	Hz – GHz	Tuned wire coils, lumped element resonators	Electric toothbrush, smartphone, electric vehicle

Far-field or radiative region, power is transmitted by means of electromagnetic waves, like radio waves, microwaves, or light waves. When the operating frequency (f) is relatively low, wavelength $\lambda = c/f$, at this time the diameter of the antenna is much smaller than the wavelength, $D_{ant} << \lambda$, and the radiated power will be very small. When the diameter of antenna is about wavelength, $D_{ant} \approx \lambda$, radiate power will be efficient. When the diameter of antenna is much great than wavelength, $D_{ant} >> \lambda$, we can using high-gain antennas to concentrate electromagnetic waves on a narrow beam and directly aim at the receiver to improve transmission efficiency.



(a) Capacitive power transfer [3].



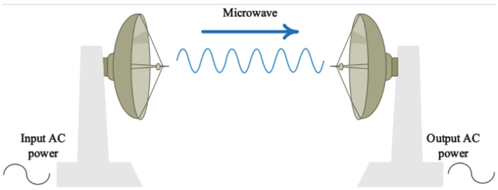
(b) Inductive power transfer [3].

Figure 1.2: Near-field wireless power transfer.

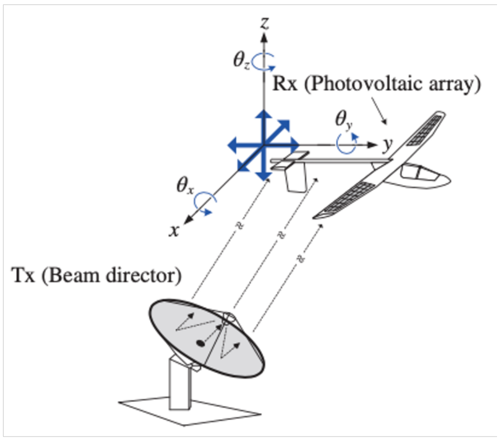
Therefore, near-field wireless power transfer systems mainly include inductive coupling power transfer and capacitive coupling power transfer (Figure 1.2). Far-field wireless power transfer systems mainly include microwave, optical, and acoustic power transfer (Figure 1.3). The respective characteristics are shown in the table 1.1.

1.3 Underwater wireless power transfer

WPT technology has unique advantages in special environments, and along with the continuous development of landing application research and the emergence of a large number of results, it has attracted the attention of underwater technology



(a) Microwave power transfer [1].



(b) Laser power transfer [3].

Figure 1.3: Far-field wireless power transfer.

researchers.

Underwater Seawater has a blocking effect on high-frequency electromagnetic waves. The distance of electromagnetic waves propagating underwater is inversely proportional to the frequency, making it difficult to achieve long-distance power transmission.

Conductivity Due to the electrical conductivity of seawater, traditional wireless power transmission analysis methods are no longer applicable. At present, the system modeling and related theoretical analysis of underwater wireless power transfer technology need to be improved.

Undercurrent The submarine landform is complex and there is undercurrent. The coupler core is liable to drift under water, and there are problems such as difficulty in docking, which results in low transmission efficiency.

Other Impact: Microbial enrichment, temperature, salinity

1.4 The main research content of this thesis

This paper mainly studies the underwater wireless power transfer system, and analyzes the difference between the underwater environment and the land environment WPT system. Considering the durability and high reliability of underwater

AUV, this paper proposes a novel coil array power transfer system. It provides reference materials for the subsequent research on the wpt system of multiple coil groups.

1.5 Roadmap

The first chapter analyzes the background of this research and its research purpose and significance, analyzes the characteristics and advantages and disadvantages of mainstream WPT technology, and provides a basis for using IPT technology as an underwater wireless energy transmission system in the following text. A detailed summary and analysis of the current research status of related technologies at home and abroad, including underwater wired energy transmission technology, WPT technology in underwater and air media, and an explanation of the research focus of this article.

The second chapter focuses on the analysis of the basic theory of wireless energy transmission. First, the basic IPT model is explained, and its working principle is analyzed. Then explained the related technology of compensation network. Finally, analyze the underwater IPT system model.

2 Basic principles of IPT

This chapter will first introduce the principle of IPT technology from the physical level, and then introduce the principle of IPT technology from the circuit level, analyze the relationship between different equivalent models, and derive system energy transmission indicators that can represent system performance. And analyze the influence of relevant design parameters on system transmission performance. Analyze the influence of the medium on the system performance in the WPT process, and propose an equivalent model in the underwater working environment. Perform simulation analysis on the derivation to ensure that complete theoretical support is provided for more detailed theoretical research and research on new IPT technology.

2.1 Inductive coupling model

Figure 2.1 depicts the circuit model of IPT systems, where the transmitting coil L1 and the receiving coil L2 are directly connected to the power source and the load, respectively. Denote M as the mutual inductance, r_1 and r_2 as the equivalent AC resistance of coils.

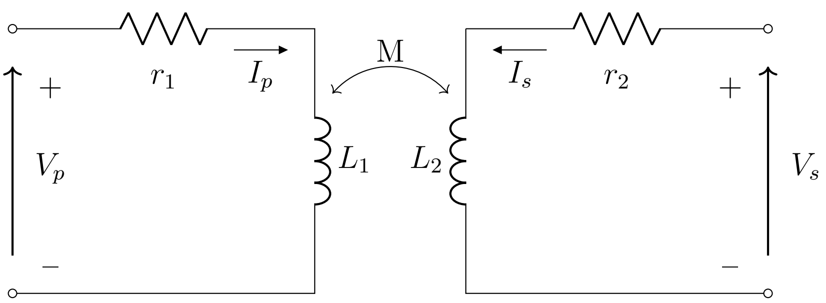


Figure 2.1: Inductive coupling model.

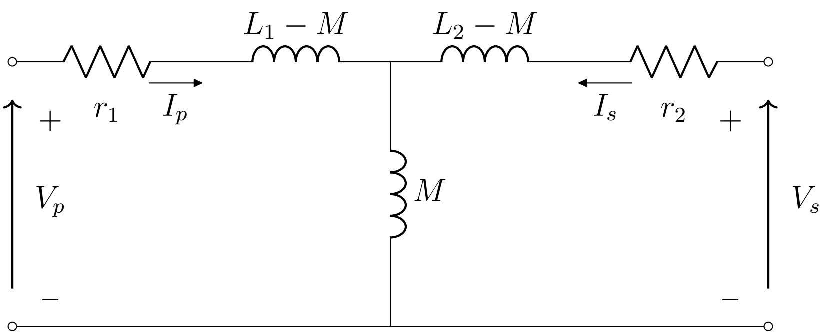


Figure 2.2: Equivalent circuit of inductive coupling model.

Therefore, the equivalent circuit can be expressed as figure 2.2. According to the Kirchhoff's circuit laws. The following formulas can be easily found.

$$V_p = I_p[r_1 + j\omega(L_1 - M)] + (I_p + I_s)j\omega M \tag{2.1}$$
$$= r_1 I_p + j\omega L_1 I_p - j\omega M I_p + j\omega M I_p + j\omega M I_s \tag{2.2}$$
$$= (r_1 + j\omega L_1)I_p + j\omega M I_s \tag{2.3}$$
$$V_s = j\omega M I_p + (r_2 + j\omega L_2)I_s \tag{2.4}$$

The above equations can be expressed as the following matrix equation.

$$\begin{bmatrix} V_p \\ V_s \end{bmatrix} = \begin{bmatrix} r_1 + j\omega L_1 & j\omega M \\ j\omega M & r_2 + j\omega L_2 \end{bmatrix} \begin{bmatrix} I_p \\ I_s \end{bmatrix} \tag{2.5}$$

2.2 Compensation network technology

A compensation network is a network that makes some adjustments to compensate for system electrical defects. If capacitor compensation is used only on the primary or secondary side, it is called single-sided compensation topology; when capacitor compensation is used on both the primary and secondary sides at the same time, it is called double-sided compensation topology. The calculation of the capacitance value of single-sided compensation is relatively simple, but the actual effect is not as good as the double-sided compensation method. Therefore, this article only discusses bilateral compensation. As shown in the figure 2.3, according to the different connection modes of the capacitors on both sides,

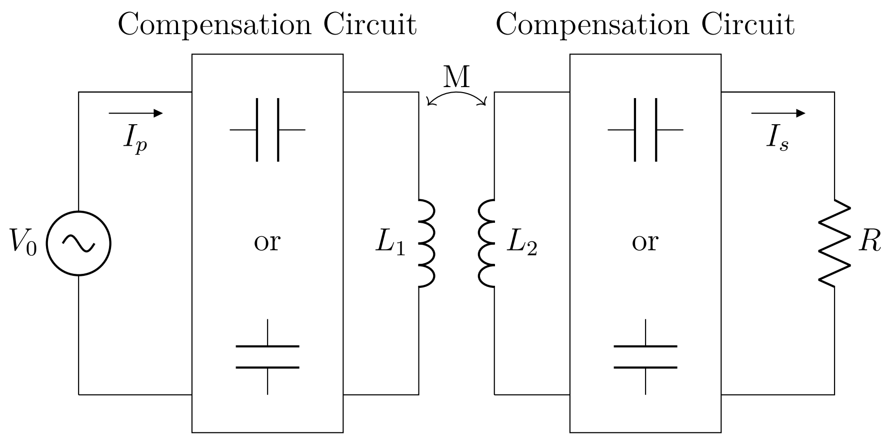


Figure 2.3: Compensation networks.

resonance compensation can be divided into four structures: S-S (series), S-P (parallel), P-S, P-P.

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

2.3 Underwater WPT system model

In the seawater environment, the electrical parameters of seawater as the transmission medium are quite different from those in the air, as shown in the table. Therefore, the conventional mutual inductance model of Eq. and Eq. cannot reflect the influence of seawater media on transmission, and cannot completely and accurately describe the transmission behavior under seawater.

Table 2.1: The dielectric constant & conductivity of some materials at 25°C under 1kHz.

Material	**Relative permittivity**	**Conductivity**
Vacuum	1	0 S/m
Air	1.0006	0 S/m
Ultra pure water	81	5.5×10^{-6} S/m
Drinking water	81	0.005 – 0.05 S/m
Seawater	81	5 S/m

3 Coil array WPT

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3.1 Simulation evaluation

3.1.1 Simulation evaluation

3.2 Coil array WPT in the air

3.3 Coil array WPT under seawater

4 Conclusion

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4.1 Future works

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