



Article Design of LCC-P Constant Current Topology Parameters for AUV Wireless Power Transfer

Kangheng Qiao 💿, Enguo Rong 💿, Pan Sun *, Xiaochen Zhang and Jun Sun

School of Electrical Engineering, Naval University of Engineering, Wuhan 430000, China; qiaokangheng@163.com (K.Q.); rongenguo@163.com (E.R.); vin_zxc@163.com (X.Z.); sunjundd@163.com (J.S.) * Correspondence: chinasunpan@163.com; Tel.: +86-159-7222-6502

Abstract: The wireless power transmission (WPT) of an autonomous underwater vehicle (AUV) tends to have non-negligible eddy current loss with increasing frequency or coil current due to the conductivity of seawater. In this paper, the inductor-capacitor-capacitor and parallel (LCC-P) topology and the magnetic coupler with an H-shaped receiver structure are chosen to achieve a compact system on the receiving side. The conditions for constant current output of the LCC-P topology are analyzed based on the cascaded circuit analysis method. The traditional parameter design method does not consider the influence of eddy current loss on the system circuit model, by introducing the equivalent eddy current loss resistance at both the transmitting side and receiving side, a modified circuit model of the WPT system in the seawater condition was obtained. Afterward, a nonlinear programming model with the optimal efficiency of the constant current mode as the objective function is established, and the genetic algorithm is used to obtain the optimal system parameters. An underwater AUV-WPT prototype was built and the finite element simulation and experimental results verified the theoretical analysis.

Keywords: inductor-capacitor-capacitor (LCC-P) topology; constant current (CC); parameter design; eddy current loss; genetic algorithm

1. Introduction

Wireless power transfer (WPT) does not require a physical connection to achieve energy transmission [1]. Compared with wired charging technology, it has the advantages of safety, concealment, and strong environmental adaptability [2,3]. It has been widely used in electronic devices [4], electric vehicles [5], and autonomous underwater vehicles (AUVs) [6–9]. The energy supply problem of AUVs greatly restricts the endurance and working range of AUV. The use of WPT technology for AUV charging can effectively expand the endurance range of AUV and improve the concealment of charging.

The space inside the AUV is very limited, which puts forward high requirements on the weight and volume of the receiver of the system, that is, the receiver should be as compact as possible, including the optimization of the magnetic coupler [7–9], compensation topology select [10–16], etc. The magnetic coupler selects the arc shaped transmitter and the H-shaped structure receiver proposed by [17], which not only occupies a small volume but also has the characteristics of light weight. The function of the compensation topology is to adjust the reactive power in the system by adding inductive or capacitive elements, thereby improving the transmission efficiency. The topology with a simple structure on the receiving side is more suitable for the actual application requirements of AUV.

The series-series (S-S) topology is widely used due to its simple structure, and the resonant frequency is decoupled with the coupling coefficient and the load [13], which is beneficial for wireless charging systems. However, in AUV-WPT systems that is prone to misalignment, the output power will increase with the occurrence of the misalignment, which will lead to overcurrent and is not conducive to the safety of the system.



Citation: Qiao, K.; Rong, E.; Sun, P.; Zhang, X.; Sun, J. Design of LCC-P Constant Current Topology Parameters for AUV Wireless Power Transfer. *Energies* **2022**, *15*, 5249. https://doi.org/10.3390/ en15145249

Academic Editors: Ka Wai Eric Cheng and Yun Yang

Received: 24 June 2022 Accepted: 19 July 2022 Published: 20 July 2022

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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). Hou et al. [14] added a parallel resonant capacitor on the basis of SS topology to form the series-series parallel (S-SP) topology, combining the advantages that the value of the SS topology output voltage gain intersection value is fixed and does not vary with the coupling coefficient, and the input phase angle at the series-parallel (SP) topology gain intersection point is zero. It makes the S-SP topology insensitive to the change in the coupling coefficient of the magnetic coupler, so it has better adaptability to variable parameters. However, the resonance condition is related to the mutual inductance, so it is difficult to maintain the resonance state under variable coupling conditions. Thrimawithana et al. [15] proposed a double-side inductor-capacitor-inductor (LCL) topology to keep the transmitting coil current constant when the receiver is unloaded. However, the self-inductance value of the transmitting coil needs to be the same as the resonant inductance, which greatly limits the flexibility of the parameter design. Li et al. [16] proposed a double-side LCC topology, which has been widely used in electric vehicle wireless charging systems. The double-side inductor-capacitor-capacitor (LCC) topology has the advantage of the high degree of freedom in parameter design; the resonant frequency is decoupled with coupling coefficient and load. However, the number of compensation components used in the circuit is large, leading to a high cost and large size, which is unfavorable for AUV with compact interior space.

In this paper, the WPT system including an inductor-capacitor-capacitor (LCC-P) topology combined with an H-shaped magnetic coupler is studied, which can make the receiver more compact and save space. LCC-P topology can reduce the voltage/current stress on switching devices and achieves similar performance as the double-side LCC topology with fewer compensation components at the receiver. By introducing the equivalent resistance at both the transmitter and receiver, a modified circuit model of an underwater WPT system was obtained. Based on the model, the genetic algorithm is used to complete the optimal design of the parameters of the system with the objective of constant current output and optimum efficiency.

This paper is organized as follows: the circuit analysis of the LCC-P topology in Section 2, the influence of the eddy current loss in the seawater condition on the system parameters is analyzed and based on the genetic algorithm, and the resonance parameters of the system are optimized with the goal of the highest efficiency in Section 3. An experimental prototype is established to verify the results of theoretical analysis in Section 4. The conclusions are drawn in Section 5.

2. Circuit Analysis

The WPT system using LCC-P topology is shown in Figure 1, which can be divided into four parts: inverter, compensation topology, magnetic coupler, rectifier and filter circuit. S₁–S₄ are four power MOSFETs of the inverter and D₁–D₄ are the rectifier diodes, V_{dc1} and V_{in} represent the DC input voltage and inverter output voltage, L_f , C_f , are the compensation inductance and capacitance, L_p , L_s , are the self-inductances of the transmitter and the receiver of the magnetic coupler, M is the mutual inductance, C_p and C_s are the compensation capacitance on the transmitting side and the receiving side, respectively. V_{dc2} represents the DC output voltage on the load.



Figure 1. The circuit topology with LCC-P compensation.

Based on the cascade analysis method of [18], the equivalent circuit of LCC-P topology in constant current (CC) mode is shown in Figure 2. The circuit can be equivalent to the cascade of a reverse-L circuit, a series circuit and a π circuit. The voltage-fed reverse-L circuit has the output characteristic of a current source, the series circuit driven by a current source can achieve CC output, and the π circuit driven by a current source can achieve CC output. As aforementioned, the output characteristics of the circuits at all levels change as follows: voltage source \rightarrow current source \rightarrow current source, so as to achieve CC output for LCC-P topology.



Figure 2. Equivalent circuit of LCC-P topology in CC mode.

Assuming that the resonant frequency of the system working in the CC mode is ω_{CC} , the reverse-L circuit and the π circuit should satisfy:

$$\frac{1}{j\omega_{\rm CC}C_{\rm f}} + j\omega_{\rm CC}L_{\rm f} = 0 \tag{1}$$

$$\frac{1}{j\omega_{\rm CC}C_{\rm S}} + j\omega_{\rm CC}L_{\rm S} = 0 \tag{2}$$

Under the CC mode, the total input impedance of the system can be obtained as:

$$Z_{\text{inCC}} = \frac{\frac{1}{j\omega_{\text{CC}}C_{\text{f}}} \left(j\omega_{\text{CC}}L_{\text{p}} + \frac{1}{j\omega_{\text{CC}}C_{\text{p}}} + Z_{\text{ref}} \right)}{\frac{1}{j\omega_{\text{CC}}C_{\text{f}}} + j\omega_{\text{CC}}L_{\text{p}} + \frac{1}{j\omega_{\text{CC}}C_{\text{p}}} + Z_{\text{ref}}} + j\omega_{\text{CC}}L_{\text{f}}$$
(3)

where, Z_{ref} is the reflected impedance at the receiving side, which can be expressed as:

$$Z_{\rm ref} = \left(R_{\rm eq} + \frac{1}{j\omega_{\rm CC}C_{\rm S}}\right) \left(\omega_{\rm CC}^2 C_{\rm S}M\right)^2 \tag{4}$$

Substituting (1), (2) into (3), the total input impedance of the system can be obtained:

$$Z_{inCC} = \frac{\frac{L_f}{C_f}}{\frac{1}{j\omega_{CC}C_f} + j\omega_{CC}L_P + \frac{1}{j\omega_{CC}C_p} + \left(R_{eq} + \frac{1}{j\omega_{CC}C_S}\right)\left(\omega_{CC}^2 C_S M\right)^2}$$
(5)

In order to meet the zero phase angle (ZPA) of the system, it is necessary to satisfy Im $(Z_{inCC}) = 0$, which can be calculated as

$$\frac{1}{j\omega_{\rm CC}C_{\rm f}} + j\omega_{\rm CC}L_{\rm p} + \frac{1}{j\omega_{\rm CC}C_{\rm p}} + \frac{1}{j\omega_{\rm CC}C_{\rm S}}\left(\omega_{\rm CC}^2C_{\rm S}M\right)^2 = 0$$
(6)

Through the above analysis, when the system parameters of the LCC-P topology satisfy (1) and (2), the CC output can be realized at the frequency ω_{CC} . Due to the water flow and low positioning accuracy of the underwater WPT system, the transmitter and the receiver of the magnetic coupler are vulnerable to misalignment, resulting in large fluctuations in mutual inductance [19]. It can be found from (1) and (2) that the CC output characteristics of the system are decoupled with the mutual inductance, i.e., the CC output

characteristics are not affected by the misalignment of the AUV in the seawater condition, which is conducive to the stable power supply of the AUV wireless charging system.

3. Parameter Optimization

3.1. Eddy Current Loss Analysis

The basic electrical characteristics and characterization parameters of different transmission media are quite different. The transmission media included in common application scenarios of WPT systems include air, freshwater, and seawater. The parameters of different transmission media are compared in Table 1 [3].

Table 1. Parameters Compassion of Three Media.

Media	Relative Permittivity	Conductivity (S/m)	Relative Permeability		
air	1.0006	0	1.000004		
freshwater	81	0.01	0.999991		
seawater	81	4	0.999991		

The conductivity in air and fresh water is almost 0, which can be approximated as non-conductive. Therefore, when the transmission medium of the WPT system is air or fresh water, eddy current loss does not need to be considered. The conductivity in seawater is higher than the former, and the alternating magnetic field will generate eddy currents in the seawater medium, resulting in eddy current losses, which will reduce the transmission efficiency of the WPT system in seawater. AUV wireless charging systems usually work in seawater conditions, so eddy current loss calculation formula. However, this method is only applicable to the system where the transmitter and the receiver of the magnetic coupler are symmetrical, and the influence of ferrite on the magnetic field in practical application scenarios is not considered. Therefore, the finite element analysis was performed using Ansoft Maxwell software to obtain the eddy current loss in seawater when the alternating current passed through the coil.

The coil resistance can be neglected because Litz wire is generally used for winding the coils [21], so the relationship between the currents of the transmitting and receiving coils can be expressed as [12]:

$$I_{\rm S} = \frac{j\omega_0 M I_{\rm p}}{j\omega_0 L_{\rm S} + \left(R_{\rm eq}//\frac{1}{j\omega_0 C_{\rm S}}\right)} \tag{7}$$

From (7), it can be found that the current phase difference is influenced by the topology parameters on the receiving side and vary from 0 to 45 degrees. This paper takes the current phase difference of 45° as an example to analyze the influence of frequency and coil current on eddy current loss.

To analyze the influence of frequency on the eddy current loss, eddy current loss under 50 kHz to 150 kHz is captured. The current in the transmitting coil and the receiving coil is given as 1 A, and the total eddy current loss result is shown in Figure 3.

The blue line represents the eddy current loss at each frequency, the red line represents the ratio of eddy current loss at each frequency to that at 50 kHz. It can be seen from Figure 3 that the eddy current loss increases sharply with the increasing frequency, therefore, eddy current loss is a non-negligible factor for underwater WPT system. In order to make a direct equivalent to the influence of the eddy current loss in the circuit, the eddy current loss P_{eddy} can be divided into the sum of the eddy current loss P_{eddy_P} generated by the transmitting coil and the eddy current loss P_{eddy_S} generated by the receiving coil.



Figure 3. The eddy current loss variation with frequency.

When the unilateral coil is excited by the current, the eddy current loss in the seawater divided by the square of the current is a fixed value. The equivalent eddy current resistances on the transmitting coil and receiving coil can be expressed as:

$$\begin{cases} P_{eddy_p} = I_p^2 R_{eddy_p} \\ P_{eddy_s} = I_s^2 R_{eddy_s} \end{cases}$$
(8)

The eddy current loss of the transmitting coil and the receiving coil as well as the corresponding equivalent eddy current resistance simulation results are shown in Figure 4. It can be seen from Figure 4 that the eddy current loss increases significantly with the increase in the coil current, so it is necessary to consider the influence of the eddy current loss on the system in the seawater condition. The ratio of the eddy current loss generated by the unilateral coil to the square of the coil current is a fixed value, the transmitting coil is 30 m Ω , and the receiving coil is 8 m Ω . Accordingly, the influence of eddy current loss can be considered into the system, and when the operating frequency is determined, the equivalent eddy current resistance is a fixed value, which is an inherent parameter decoupled from the operating state of the system.



Figure 4. Simulated the eddy current loss caused by different excitation currents. (**a**) Generated the eddy current loss in seawater by the transmitting coil; (**b**) Generated the eddy current loss in seawater by the receiving coil.

3.2. Objective Function Construction

The equivalent circuit model of an LCC-P WPT system in seawater condition is shown in Figure 5. Considering the internal resistance and equivalent eddy current resistance of each coil, the genetic algorithm is used to optimize the parameters of the system to achieve the optimal system efficiency.



Figure 5. Equivalent circuit of the WPT system in seawater condition.

According to the mesh current method, I_{in} , I_p , I_s , I_{eq} are the currents of the corresponding meshes, and the non-source components in the circuit are expressed in impedance form as $Z_{Li} = j\omega L_i$ (i = f, p, s); $Z_{Ci} = 1/j\omega C_i$ (i = f, p, s), and define $Z_M = j\omega M$, the resonant operating frequency of the system $\omega_0 = \omega_{CC}$. Based on Kirchhoff's law, the equations of the equivalent circuit can be obtained:

$$\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} \mathbf{I}_{\text{in}} \\ \mathbf{I}_{\text{p}} \\ \mathbf{I}_{\text{S}} \\ \mathbf{I}_{\text{eq}} \end{bmatrix} = \begin{bmatrix} \mathbf{V}_{\text{in}} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$
(9)

In (9), the impedance matrix is a sparse matrix, and all non-zero elements can be obtained as:

$$\begin{cases}
Z_{11} = R_{\rm f} + Z_{\rm Lf} + Z_{\rm Cf} \\
Z_{22} = (R_{\rm p} + R_{\rm eddy_p}) + Z_{\rm Lp} + Z_{\rm Cp} + Z_{\rm Cf} \\
Z_{33} = (R_{\rm S} + R_{\rm eddy_S}) + Z_{\rm LS} + Z_{\rm CS} \\
Z_{44} = R_{\rm eq} + Z_{\rm CS} \\
Z_{12} = Z_{21} = - Z_{\rm Cf} \\
Z_{23} = Z_{32} = - Z_{\rm M} \\
Z_{34} = Z_{43} = - Z_{\rm CS}
\end{cases}$$
(10)

(9) can be simplified as ZI = V, which the current vector I can be solved, and then the transmission efficiency can be expressed as:

$$\eta(\omega) = \frac{|I_{\rm eq}|^2 R_{\rm eq}}{\operatorname{real}(V_{\rm in} I_{\rm in}^*)} \tag{11}$$

when wirelessly charging the AUV battery, in the CC mode, the charging current remains unchanged, while the charging voltage will continue to increase, so that the equivalent resistance of the load will slowly increase, causing the system to deviate from the designed operating state. Assuming that the change interval of the equivalent load R_{eq} in the CC mode is (R_{min} , R_{max}), in order to ensure that the system has excellent charging efficiency in the CC mode, an objective function with the optimal efficiency is established to measure the level of charging efficiency throughout the charging phase.

$$F(\omega, L_f) = \frac{1}{R_{\text{max}} - R_{\text{min}}} \int_{R_{\text{min}}}^{R_{\text{max}}} \eta_{\text{sea}}(\omega, R_{\text{eq}}) dR_{\text{eq}}$$
(12)

Integrate the η_{sea} of the efficiency corresponding to the R_{eq} in the load interval (R_{min} , R_{max}), and establish the nonlinear programming model with the optimal efficiency as follows:

$$\begin{cases} \max F(\omega, L_{f}) \\ s.t \begin{cases} \omega_{1} \leq \omega \leq \omega_{2} \\ L_{f1} \leq L_{f} \leq L_{f2} \end{cases}$$
(13)

where, (ω_1, ω_2) is the frequency sweep range, (L_{f1}, L_{f2}) is the compensation inductance sweep range. In order to ensure that the output current meets the requirements, the constant current system also needs to constrain the transconductance G_V of the system. Set the lower limit of the transconductance to meet the output requirements is G_{Vmin} , and integrate the inequality conditions into the objective function is:

$$\begin{cases} \max F(\omega, L_{f}) \\ s.t \begin{cases} C_{f} > \frac{1}{\omega_{0}^{2}L_{p}} \\ |G_{V}| > |G_{Vmin}| \end{cases}$$
(14)

3.3. Function Solving

The function (13) established based on the efficiency optimization is a nonlinear function and has many constraints, and the traditional nonlinear model solving algorithm is easy to fall into the local optimal solution. As an adaptive global optimization search algorithm, the genetic algorithm was first proposed by Professor Holland of the University of Michigan [22]. It is a new method for complex system optimization.

The genetic algorithm also has its shortcomings, such as poor local search ability, immature convergence and random walk phenomena, resulting in poor convergence performance and long convergence time of the algorithm. In order to quickly obtain the convergent global optimal solution, the fitness function F_W of the genetic algorithm is to be established and consider the constraints to establish a penalty function W as:

$$N = \sum_{i=1}^{2} \gamma_i \mathbf{w}_i \tag{15}$$

where, γ_i is the weight coefficient of each constraint, and w_i is the penalty factor, as shown below:

I

$$\mathbf{w}_{i} = \begin{cases} \frac{\max(0, \frac{1}{\omega_{0}^{2}L_{p}} - C_{f})}{\frac{1}{\omega_{0}^{2}L_{p}} - C_{f}} & i = 1\\ \frac{\max(0, |G_{V\min}| - |G_{V}|)}{|G_{V\min}| - |G_{V}|} & i = 2 \end{cases}$$
(16)

According to the penalty factor, the fitness function of the algorithm can be defined as

$$F_{W} = \frac{F}{\max(1, W)}$$
(17)

From (15) to (16), when the parameter satisfies the inequality constraint, the penalty term W = 0, the penalty function does not penalize the fitness function, at this time $F_W = F$; when an inequality constraint cannot be satisfied, the corresponding penalty amount W>0 will be generated, and the larger the out-of-bounds amount, the greater the value of the penalty amount, at this time, $F_W = F/W$. The fitness of the individual will be reduced, so that the probability of being selected as the parent for breeding the next generation in the iterative process of the genetic algorithm will be extremely low, which means that the parameters of the non-optimal solution of efficiency will be discarded until the efficiency is optimal. The optimal solution can be obtained by using the rand function of MATLAB to generate the initial population { $(\omega_i, L_{fi}) I = 1, 2 \dots 200$ } and the fmincon function for nonlinear optimization. The process of the genetic algorithm is shown in Figure 6.

3.4. Algorithm Validation

In this paper, an AUV-WPT system with a rated power of 700 W is designed. The parameters L_p , L_s and M of the H-shaped magnetic coupler proposed in [17] are fixed. Therefore, it is only necessary to add the coil inductance constraints to the genetic algorithm, which will not affect the correctness of the parameter optimization proposed in this paper.

Based on the genetic algorithm in Section 3.3, a set of optimized effective solutions for the resonant frequency f_0 and compensation inductance L_f of the WPT system obtained are 96.15 kHz and 9 μ H, respectively. By substituting the optimized results into the CC output conditions of the LCC-P topology, the other parameters of the system can be calculated and values are shown in Table 2.



Figure 6. Flow chart of genetic algorithm.

Table 2. Parameters Optimization of Genetic Algorithm.

Parameter	Symbol	Value
Transconductance	G _V	0.067
Resistance range	$R_{ m L}$	10–20 Ω
Resonant frequency	f_0	96.15 kHz
Transmitter inductance	L_{p}	49.84 µH
Transmitter-side series compensation capacitance	C_{p}	88.23 nF
Receiver inductance	$\hat{L_{S}}$	26.28 μH
Receiver-side parallel compensation capacitance	$C_{\rm S}$	104.18 nF
Compensation inductance	L_{f}	9 μH
Transmitter-side parallel compensation capacitance	C_{f}	304.44 nF

When the system compensation network parameters are fixed, and the operating frequency and load of the system are changed, the output characteristics of the WPT system based on the LCC-P topology are shown in Figure 7.





It can be seen from Figure 7a that at the designed CC operating point with the best efficiency, the WPT system realizes the ZPA and has the conditions to achieve soft switching; Figure 7b shows that at the designed CC output frequency point, the system can realize the CC output characteristic independent of the load.

4. Experiments

An experimental prototype was built to verify the above theoretical analysis and optimization results, which is shown in Figure 8. The system specifications and the circuit parameters are listed in Table 3. The rated power is set to 700 W, and the conductivity is increased to 4 S/m by adding sea salt to the freshwater to simulate the real seawater condition.



Figure 8. Experimental prototype.

Table 3. System Parameters.

Note	Symbol	Value (Air)	Value (Seawater)
Resonant frequency	f_0	96.15 kHz	96.15 kHz
DC input voltage	$V_{\rm dc1}$	100 V	100 V
Transmitter inductance	L_{p}	49.84 µH	49.26 μH
Transmitter resistance	$\hat{R_p}$	90 mΩ	$120 \text{ m}\Omega$
Transmitter-side series compensation capacitance	C _p	88.23 nF	88.23 nF
Receiver inductance	L_{S}	26.28 μH	26.39µH
Receiver resistance	$R_{\rm S}$	35 mΩ	43 mΩ
Receiver-side parallel compensation capacitance	$C_{\rm S}$	104.18 nF	104.18 nF
Compensation inductance	L_{f}	9 μH	9μH
Transmitter-side parallel compensation capacitance	C_{f}	304.44 nF	304.44 nF
Coupling coefficient	k	0.438	0.443
Resistance range	$R_{\rm L}$	10–20 Ω	10–20 Ω

The SCT3040KL silicon carbide power MOSFET is selected to form the full-bridge inverter, and the control module adopts the TMS320F28335 chip. In order to reduce the coil loss, the coil is wound with 0.1×400 strands of Litz wire. The receiving side adopts a bridge uncontrolled rectifier. Input voltage/current, output voltage/current, transmission power and transmission efficiency are measured by the power analyzer ZLG PA5000H.

4.1. Seawater Effects

The input and output power and efficiency tests of the system in air and seawater conditions are shown in Figure 9. Where, U_{dc1} , I_{dc1} and P_1 represent the system input voltage, current, power, respectively, U_{dc2} , I_{dc2} and P_2 represent the system output voltage, current, power, respectively, η_1 and η_2 represent the DC-DC efficiency in air condition and seawater condition, respectively.

DC input		DC output		DC input		DC output		
Udc1	99.88 v	Udc2	113.66 ∨	Udc1	99.91	v	Udc2	114.53 v
ldc1	8.597 ^	ldc2	6.933 🔺	ldc1	8.813	A	ldc2	7.005 A
P1	0.8587 w	P2	0.7880 ww	P1	0.8805	ĸW	P2	0.8023 kw
η1	91.77 %	DC-	DC efficiency	η1	91.12	%	D	C-DC efficiency
(a)			(b)					

Figure 9. Power and efficiency test. (a) Air condition; (b) Seawater condition.

The results show that this AUV-WPT system is capable of transferring power efficiently. In addition, the transmission power in the seawater condition is slightly greater than that in air, while the transmission efficiency is slightly lower than that in air. Combining Table 3 and Figure 9, it can be found that the eddy current in seawater enhances the magnetic field between the magnetic coupler and increases the coupling coefficient, thereby increasing the output power in the seawater condition. However, due to the additional eddy current loss caused by seawater, the transmission efficiency is ultimately reduced compared to air.

In the case of air and seawater as two transmission media, if the coil currents on the transmitting coil and receiving coil of the magnetic coupler are kept the same, the eddy current loss will be the difference between the total losses in the two cases, and the eddy current loss in the experiment can be calculated as [23]:

$$P_{\rm eddy} = P_{\rm loss_seawater} - P_{\rm loss_air}$$
(18)

The eddy current loss varying with the input voltage and the load resistance are shown in Figure 10. It can be seen that eddy current loss increase sharply with increasing input voltage for a fixed load of 16 Ω , and more gently with load resistance for a fixed input voltage of 100 V. In general, the experimental results are consistent with the simulated results, the reason for the small discrepancy in the values is that in order to ensure the safety and operability of the experiment, the seawater under the experimental condition only submerges the transmitting coil and the seawater region is smaller than the simulated condition, so the experimental results of the eddy current loss will be slightly smaller than the simulated results. However, the consistency of the curve proves the feasibility and effectiveness of the method of equivalent eddy current loss as two resistances of the coil.



Figure 10. Eddy current loss variation in seawater condition. (a) With V_{dc1} ; (b) With load resistance R_L .

4.2. Analysis of System Output Characteristics

To verify that the parameters design can achieve a CC output for the LCC-P topology. By adjusting the load resistance, the relationship between output voltage and current with load is shown in Figure 11. The results show that as the load changes, the output current decreases slightly, but basically remains at an output level of about 7A, while the output voltage increases linearly with the addition of the load. At the rated load of 16 Ω , the output current is about 7A and the output voltage is about 115 V, which can meet the charging demand of AUV.



Figure 11. Output voltage/current variation with load resistance.

Setting the input voltage to 100 V and changing the load resistance, the DC-DC efficiency and output power vary with the resistance, as shown in Figure 12. The input voltage was fixed at 100 V by a programmable DC power supply, and the resistance of the load was changed with an adjustable load box. It can be seen from Figure 12 that as the load resistance increases, the efficiency of the load gradually increases, and the maximum efficiency in seawater condition is 91.85%. The output power is proportional to the load resistance, which also indicates that the output current is independent of the load. Therefore, the system can easily control the charging to the AUV. The validity of the parameter design is verified by the experimental results.



Figure 12. Output power/efficiency variation with load resistance.

5. Conclusions

In this paper, the underwater WPT system with an LCC-P topology has been modeled and analyzed, and the effect of eddy current loss generated by seawater on the system is considered. Finite element simulations and experimental results show that when the magnetic coupler and transmission medium are determined, the eddy current loss of the system is only related to coil current and frequency. By introducing the equivalent eddy current loss resistance at both the transmitting side and receiving side, an improved circuit model of the underwater WPT system is developed and the genetic algorithm is used to obtain the optimal system parameters. A prototype of the AUV-WPT system was built and the experimental results verified the theoretical analysis. The results show that the system can transmit 802.3 W of power in seawater with a transmission efficiency of 91.12 %. **Author Contributions:** Conceptualization, K.Q. and P.S.; Methodology, X.Z.; Software, K.Q. and X.Z.; Validation, K.Q., E.R. and J.S.; Formal analysis, E.R.; Writing—Original Draft Preparation, K.Q.; Writing—Review and Editing, K.Q., E.R. and P.S.; Funding acquisition, P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Hubei Provincial (Grant No. 2018CFA008 and No. 2019CFB608) and the National Natural Science Foundation of China Youth Project (Grant No. 52007195).

Acknowledgments: The authors would like to acknowledge the financial support from the Natural Science Foundation of Hubei Provincial and the National Natural Science Foundation of China Youth Project.

Conflicts of Interest: The authors declare no conflict of interest.

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