

Analyzing Sea Environment's Effects on Inductive Power Transfer Systems: Equivalent Circuit Parameters and Performance Analysis

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Abstract— In this paper, the component-level and system-level influences of sea environments on the inductive power transfer (IPT) system are investigated. Archimedean coils are placed on the seabed and under the underwater unmanned vehicle (UUV) to recharge UUV's battery during its marine life monitoring mission and prolong its mission duration. However, seawater, characterized by its conductivity and relative permeability, acts as an external medium for the IPT system and influences its equivalent circuit parameters (e.g. self and mutual inductances and resistances). To study these influences, finite element method (FEM) studies are performed, and the impacts of the watery external medium on the magnetic flux lines distributions are investigated. Also, the process of inducing eddy currents in the watery external medium is analyzed and illustrated. Besides, an analytic method is proposed to reflect the impacts of the external watery medium on the equivalent circuit parameters of the IPT system. A preliminary analysis is also performed to study the impacts of the watery medium on system-level performances of the IPT system (e.g. output power, efficiency). The obtained results from theoretical and FEM studies are cross-verified by performing experimental studies over a prototype IPT system.

Keywords— Eddy current induction, Equivalent circuit modeling, External watery medium, Finite element studies, Inductive power transfer, Underwater unmanned vehicles, Marine life protection

I. INTRODUCTION

In recent years, Underwater Unmanned Vehicles (UUVs) have been employed for ocean explorations, environmental monitoring, and underwater infrastructure inspection [1]. Ideally, UUVs should perform long-term navigation over the seabed. However, the limited battery capacity of electric UUVs restrains the navigation duration [2]. In this context, there are proposals to use a complementary fuel-cell system [3] or install a chain of wireless charging stations on the seabed and also the UUV itself [4]. This way, a UUV can navigate along the charging stations and approach the nearest charging station to recharge itself after battery depletion while preserving its mobility [5].

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The research on the design of wireless charging systems (WCSs) for UUV application was mainly focused on coil shape/geometry design to make the WCS misalignment tolerant. A novel coil structure is proposed in [6] to make the wireless transfer efficiency and output power robust to the misalignment between the transmitter coil of the charging station and the receiver coil of the UUV. In this light, decoupled coils are embedded in the UUV and they are wound in a reverse direction to make magnetic flux lines of the receiver coil pair perpendicular and make the mutual inductance robust to misalignments. A wireless transfer efficiency of 92% is reported for an output power of 664 W. A new unipolar magnetic coil geometry folded in 360 degrees is proposed in [7] to minimize leakage flux lines and make the WCS performance robust to transmitter/receiver coil misalignments. The designed WCS was able to transmit 5 kW charging power and feature high magnetic coupling (about 0.75). According to [7], external medium (air or water) has little impact on WCS performance under high coupling factors and the system efficiency would be around 83% under various misalignment scenarios. In [8] the WCS is extended to transmit both charging power and data between UUV and the charging station as well as among a swarm of UUVs by employing tri-axis magnetic coils.

Despite the wealth of research on coil geometry design, the influences of the external watery medium (EWM) that exists between the charging station and the UUV have not been comprehensively studied in previous research work [9]. High frequency (HF) magnetic fluxes of the Inductive Power Transfer (IPT) system would traverse the EWM and would induce considerable eddy current losses in them according to the Lenz law [10]. Meanwhile, the distribution of the original magnetic flux would be altered due to the magnetic fluxes generated by the flowing eddy current through the EWM [11]. On these bases, considerable alterations are expected in the IPT system's equivalent circuit parameters (ECPs) [12]. Authors of [13] have addressed the issue of induced eddy currents on the seawater and reflected those influences on the equivalent circuit model using the two-port network theory. However, they did not provide a

sound theoretical/mathematical study to model the reflected equivalent circuit parameters. Also, the influences of the EWM over the resistances of magnetic coils, self and mutual inductances between windings, and the performance at the system level were not discussed discretely.

There is an absence of a comprehensive study to investigate and model the influences of EWM on the ECPs and induced eddy currents and system-level operation indices of the IPT system. Therefore, this research makes two main contributions:

- To examine the effects of concerned EWM on the ECPs, Finite Element Analysis (FEA) is performed using ANSYS Maxwell software. Additionally, a theoretical equivalent electrical circuit model is proposed for the IPT system and the impacts of the EWM are integrated into the original lumped ECPs and a thorough analysis of the original and modified ECPs is conducted.
- The modified ECPs are utilized to parameterize the electrical equivalent circuit, and through performing electromagnetic transient simulations in MATLAB/Simulink software, the system-level effects of EMOs (e.g. changes in output charging power and system efficiency) are identified and properly analyzed. Experimental studies are also performed to verify the precision of the foreseen effects of EWM at the component level.

II. CONFIGURATION OF THE UUV-WCS

To conduct this study we have proposed an embedded Archimedean magnetic coil, series compensating capacitor, (high-frequency) rectifier, passive filter, and a battery under the UUV. Also, we have considered a wireless charging station that incorporates an Archimedean magnetic coil, a series compensator, a water-proof container, and a high-frequency inverter, see Fig. 1. Approximate electrical conductivity (σ [S/m]) and electromagnetic permeability (μ [H/m]) of the seawater at -30 degrees Celsius and -40 degrees latitude is considered to be 4.5 and $4\pi \times 10^{-7}$ (close to that of free space), respectively [14].

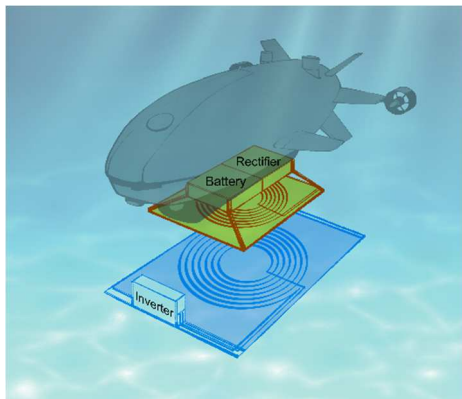


Fig. 1. The investigated system consists of an underwater unmanned vehicle and related inductive/wireless charging system.

Upon examining the μ and σ values for the seawater, it is evident that the seawater can allow eddy current induction and can influence the magnetic flux lines. Yet, the relative permeability of the seawater is close to that of vacuum air.

III. MODELING AND ANALYSIS USING AN EQUIVALENT CIRCUIT

A. UUV-IPT System Modelling

Fig. 1 illustrates the schematics and configuration of the UUV-IPT arrangement. Fig. 2 displays the equivalent circuit of the analyzed arrangement operating at the operating frequency of 85 kHz. The components corresponding to the magnetic coils in Fig. 1, namely resistance (R_i), self-inductance (L_i), and compensating capacitor (C_i), are denoted as such in Fig. 2, with i belonging to the set $\bar{S}_{Coil} = \{t, s\}$. The EWM is represented by an equivalent eddy current circuit, which is interconnected with other magnetic coils [15]. This circuit incorporates a self-inductance (L_{EWM}) and resistance (R_{EWM}). Lastly, the mutual inductance existing among the i th magnetic coil/EWM couple in Fig. 1 is illustrated as $M_{i,EWM}$ (equal to $M_{EWM,i}$) in Fig. 2, where i is part of the set $\bar{S}_{Coil}$.

The inverter's switching is controlled to generate square-wave voltage. The duty cycle for both switch pairs, namely $[S1, S2]$ and $[S3, S4]$, is set at half cycle. Consequently, the (peak and fundamental) phasor denoting the inverter voltage is $V_t = (4/\pi)V_{in} \angle 0^\circ$, with V_{in} representing the inverter's DC link voltage. Regarding the peak value of the fundamental harmonic current, it can be represented as $I_t = |I_t| \angle -\theta_{in}$ where $|I_t|$ is the magnitude of the current, and θ_{in} is the system's input impedance angle. Furthermore, the switch pairs' conducting resistance is depicted as $2r_{DS}$ in Fig. 2.

The current level and voltage level of the battery are denoted as I_{bat} and V_{bat} . The voltage waveform (V_s) at the rectifier terminal could be approximated as a square wave. At the fundamental frequency, the rectifier's voltage and current phasors (V_s and I_s) are in phase, and related values are given by $V_s = (4/\pi)(V_{bat} + 2V_D) \angle -\theta_s$ and $I_s = (\pi/2)I_{bat} \angle -\theta_s$ (where $\theta_s \geq 0$). Forwards voltage drop of the rectifier circuit is considered by $2V_D$. As a result, the load resistance seen by the rectifier's AC terminal can be determined as $R_L = V_s/I_s = (8/\pi^2)(V_{bat} + 2V_D)/I_{bat}$. Moreover, the value of each capacitor in series with the related magnetic winding can be calculated to realize a specific frequency for their natural oscillations (f_n^i), ($f_n^i = \omega_n^i/(2\pi)$), with $C_i = 1/[(2\pi f_n^i)^2 L_i]$.

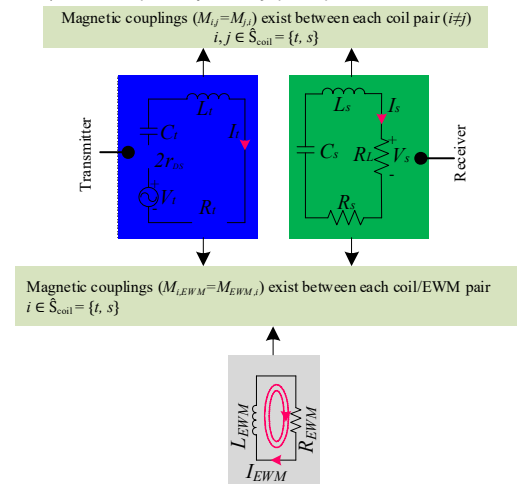


Fig. 2. Equivalent circuit at the fundamental frequency for the IPT system.

Upon obtaining the passive elements in Fig. 2 and the input inverter's voltage in fundamental frequency, the phasor currents can be specified by employing the system's matrix model calculations, represented as (1)-(8). In these equations, ω_s [rad/s] corresponds to the inverter's switching frequency, and $\bar{S}_{coil}(i)$ refers to the i th element of the $\bar{S}_{coil}$ row vector.

In (1), the phasor currents of (transmitter and receiver) windings are represented with I_t and I_s , correspondingly. Also, the phasor current of virtual eddy current winding is represented with I_{EMO} . By expanding the impedance matrix in (1) - $\mathbf{Z}$ - using the impedance values defined in (3) to (8) into (1), it becomes evident that the off-diagonal item values are purely imaginary. On the other hand, the diagonal item values comprise both real and imaginary parts and imaginary parts.

$$\begin{bmatrix} V_t \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{t,t} & Z_{t,s} & Z_{t,EWM} \\ Z_{s,t} & Z_{s,s} & Z_{s,EWM} \\ Z_{EWM,t} & Z_{EWM,s} & Z_{EWM,EWM} \end{bmatrix} \begin{bmatrix} I_t \\ I_s \\ I_{EWM} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \mathbf{I} \\ \mathbf{V} \end{bmatrix}_{3 \times 1} = \begin{bmatrix} \mathbf{Z} \end{bmatrix}_{3 \times 3}^{-1} \begin{bmatrix} \mathbf{V} \end{bmatrix}_{3 \times 1}, \quad (2)$$

$$Z_{t,t} = 2r_{DS} + R_t + \frac{1}{j\omega_s C_t} + j\omega_s L_t, \quad (3)$$

$$Z_{t,s} = Z_{s,t} = -j\omega_s M_{t,s} \quad (4)$$

$$Z_{t,EWM} = Z_{EWM,t}, Z_{t,EWM} = -j\omega_s M_{t,EWM}, \quad (5)$$

$$Z_{s,s} = R_s + R_L + j\omega_s L_s + \frac{1}{j\omega_s C_s}, \quad (6)$$

$$Z_{s,EWM} = Z_{EWM,s} = -j\omega_s M_{s,EWM}, \quad (7)$$

$$Z_{EWM,EWM} = R_{EWM} + j\omega_s L_{EWM}, \quad (8)$$

B. Analytical investigations on the effects of the EWM

The aim is to investigate and assess the influence of the EWM on the ECPs within the parameters of the equivalent circuit. In theory, this is accomplished by representing $\mathbf{I}_{EWM}$ as a combination of actual windings' currents (9), subsequently including (9) into (1). By doing so, changes in the matrix impedance (denoted as $\mathbf{Z}'$ in (10)) can be analyzed. Consequently, it becomes simple to obtain (11)-(15) representing the system parameters by (3)-(8). For instance, $Z'_{t,t}$ and $Z'_{t,s}$, which represent test diagonal and off-diagonal items of $\mathbf{Z}'$, are expressed in (14) and (15) respectively.

Upon comparing (14) and (3), as well as (15) and (4), it becomes evident that the EWM increases the R_t , diminishes L_t , introduces mutual resistance between windings s and t , and decreases the $M_{t,s}$. By referring to (14) and (15), it can be inferred that the extents of variations in the actual winding parameters depend on the virtual eddy winding parameters. These effects are present in all ECPs of the UUV-IPT system, but their levels need to be assessed through finite element studies. Fig. 3 depicts the studied system's equivalent electric circuit with modified ECPs.

$$\mathbf{I}_{EWM} = -\frac{(Z_{EWM,t}I_t + Z_{EWM,s}I_s)}{Z_{EWM,EWM}}, \quad (9)$$

$$\begin{bmatrix} V_t \\ 0 \end{bmatrix} = \begin{bmatrix} Z'_{t,t} & Z'_{t,s} \\ Z'_{s,t} & Z'_{s,s} \end{bmatrix} \begin{bmatrix} I_t \\ I_s \end{bmatrix}, \quad (10)$$

$$Z'_{t,t} = Z_{t,t} - Z_{t,EWM} \frac{Z_{EWM,t}}{Z_{EWM,EWM}}, \quad (11)$$

$$Z'_{t,s} = Z'_{s,t} = Z_{t,s} - Z_{t,EWM} \frac{Z_{EWM,s}}{Z_{EWM,EWM}}, \quad (12)$$

$$Z'_{s,s} = Z_{s,s} - Z_{s,EWM} \frac{Z_{EWM,s}}{Z_{EWM,EWM}}. \quad (13)$$

$$Z'_{t,t} = 2r_{DS} + R_t + \underbrace{\frac{R_{EWM} \omega_s^2 M_{t,EWM}^2}{R_{EWM}^2 + \omega_s^2 L_{EWM}^2}}_{\text{Added self resis tan ce}} + \frac{1}{j\omega_s C_t} + j\omega_s \left(L_t - \underbrace{\frac{L_{EWM} \omega_s^2 M_{t,EWM}^2}{R_{EWM}^2 + \omega_s^2 L_{EWM}^2}}_{\text{Subtracted self induc tan ce}} \right), \quad (14)$$

$$Z'_{t,s} = - \underbrace{\left(\frac{R_{EWM} \omega_s^2 M_{t,EWM} M_{s,EWM}}{R_{EWM}^2 + \omega_s^2 L_{EWM}^2} \right)}_{\text{Introduced mutual resis tan ce}} - j\omega_s \left(M_{t,s} - \underbrace{\frac{L_{EWM} \omega_s^2 M_{t,EWM} M_{s,EWM}}{R_{EWM}^2 + \omega_s^2 L_{EWM}^2}}_{\text{Subtracted imaginary term}} \right), \quad (15)$$

C. 3D FEA: Investigating the Effects of EWM on ECPs

A comprehensive FEA is performed on the UUV-IPT system. The investigation includes analyzing the effects of the EWM on the ECPs of UUV-IPT. Two scenarios are considered: one with the EWM present and another without the EWM. The magnetic coils are all excited simultaneously with a peak current of 5A, a frequency of 85 kHz, and a phase angle of zero degrees. The coils share the same geometry with 20 turns (N), an inner radius (r_i) of 60 mm, and 100 strands (n_{st}).

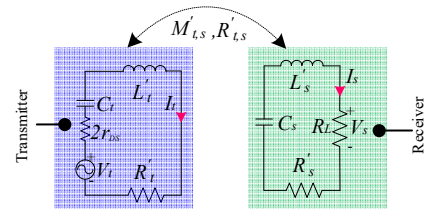


Fig. 3. Equivalent electric circuit at the fundamental frequency for the UUV-IPT system, featuring altered ECPs.

In Table I, the computed (L_t and R_t) for the transmitter winding and (L_s and R_s) for the receiver winding by the 3-D FEA are presented at the operating frequency of 85 kHz. Additionally, $M_{t,s}$ and $R_{t,s}$ are reported in Table I for both

scenarios.

TABLE I. EQUIVALENT CIRCUIT PARAMETERS CALCULATED BY 3-D FINITE ELEMENT STUDIES

	Without the EWM	With the EWM
R_t	250.24 m Ω	356.94 m Ω
R_s	250.28 m Ω	356.57 m Ω
L_t	84.69 μ H	84.56 μ H
L_s	84.69 μ H	84.54 μ H
R_{t-s}	$\cong 0$ m Ω	78.05 m Ω
M_{t-s}	24.71 μ H	24.47 μ H

Analyzing the self and mutual inductances reported in Table I, these values are found to be slightly reduced in the presence of the EWM, aligning with theoretical studies. However, reduction percentages in (L_t and L_s) and M_{t-s} are respectively 0.15% (negligible) and 0.97% (negligible). To further evaluate the primary cause of these decrements, flux lines were analyzed and visualized in

Fig. 4 in a 2-D FEA. From

Fig. 4, the distribution of magnetic coils' flux lines is almost identical when the EWM is introduced. Thus, the experienced flux lengths and reluctance level by flux lines are constant which leads to negligible variations in the concerned impedance matrix.

Based on the values presented in Table I for both studied scenarios, the presence of the EWM leads to an increase in self and mutual resistance. It is observed that self-resistance experiences significant increments (around 40.63% for both the transmitter and receiver windings). Moreover, notable mutual resistance (78.05 m Ω) emerges between transmitter and receiver coils due to the presence of the EWM, which is at the same level as the DC resistance of the winding. This is because currents flowing through the windings of the system cause eddy currents to develop in the EWM, see Fig. 5. The level of developed eddy currents in the EWM is below 0.405 A/m². Notably, the level of the developed eddy current is unevenly distributed and is most prominent and observable near the windings. The flow of eddy currents in the EWM results in conductive losses.

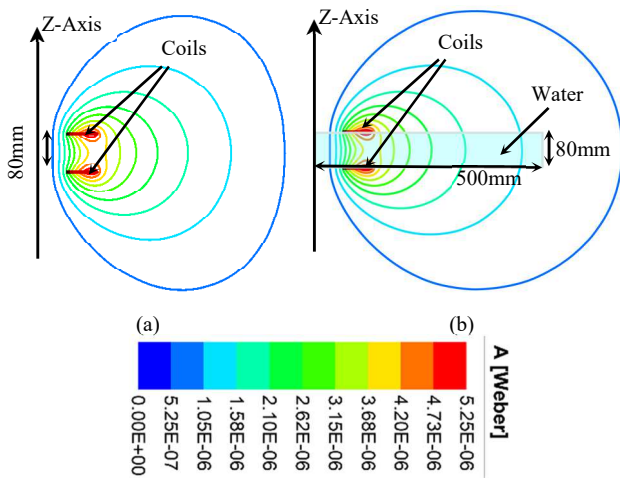


Fig. 4. The 2-D representation illustrating the distribution of the magnetic flux line in the R-IPT system: (a) Without the EWM. (b) With the EWM.

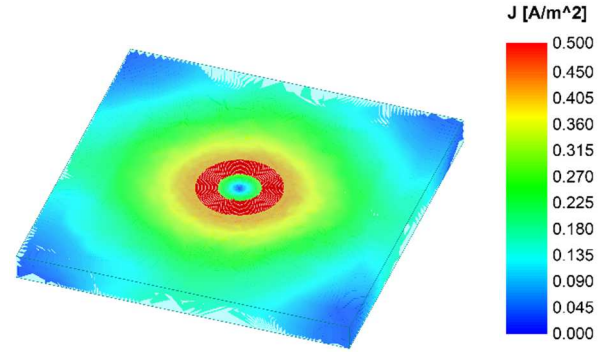


Fig. 5. The distribution of eddy current density in the EWM.

IV. SIMULATION AND EXPERIMENTAL STUDIES

A. Experimental Results

The aim is to assess the authenticity of the performed theoretical analyses and FEA regarding the influences of the EWM on the ECPs of the UUV-IPT system.

The prototype of the fabricated DR-IPT is shown in Fig. 6. Transmitter and receiver magnetic coils share an identical geometry with a turn number of 19, space turn of 1.4 mm, inner radius of 6.18 cm, strand number of 101, single strand diameter of 0.1 mm, and air gap of 7 cm. The winding parameters of the manufactured IPT system are measured using a high-frequency LCR meter at 85 kHz, and the findings are presented in Table II. ECPs are also computed using 3-D FEA.

For the first scenario (without the EWM), the maximum error between the calculated and measured values for various parameters such as L , M , R , and mutual R of the manufactured coils are reported as [1.68%, 5.73%, 8.71%, -], respectively. Similarly, for the second scenario, the corresponding maximum error is given as [1.34%, 3.17%, 5.09%, 8.00%]. These results indicate that the fabricated coils are accurately produced as the values obtained through 3-D FEA closely match the measured values. These results demonstrate that the ECPs calculated through 3-D FEA approximately match the experimental measurements, validating the accuracy of the analytical predictions and accurate fabrication of magnetic coils.

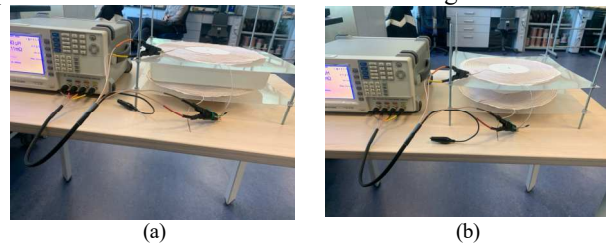


Fig. 6. (a) prototype of the IPT system with the EWM, and (b) prototype of the IPT system without the EWM.

TABLE II. MEASURED EQUIVALENT CIRCUIT PARAMETERS BY HIGH-FREQUENCY LCR METER

	Without the EWM	With the EWM
R_t	272 m Ω	375.14 m Ω
R_s	271 m Ω	374.86 m Ω
L_t	86.11 μ H	85.70 μ H
L_s	86.02 μ H	85.64 μ H
R_{t-s}	$\cong 0$ m Ω	81.91 m Ω

B. Simulation Results

The UUV-IPT system is simulated in the MATLAB/Simulink platform under both scenarios (with and without EWM). The UUV-IPT system is designed with the following specific parameters: $V_{in}=40$ V (input DC voltage of the inverter), $V_{bat}=12.6$ V (nominal battery voltage), $I_{bat}=3.04$ A (nominal charging current of the battery), $V_D=0.57$ V (forward voltage drop of diodes). Over the simulations, the airgap between magnetic coils is taken to be 8 cm.

Fig. 7 and Fig. 8 display the figures of the UUV-IPT system's voltage and current signals. Within this framework, the system's crucial performance metrics such as output power (P_{out}) and efficiency (η) are compared for both scenarios. Investigating the fundamental harmonics of the rectifier and inverter voltages, as well as the transmitter and receiver coil currents in Fig. 7 and Fig. 8, the values of P_{out} (AC terminal power of the rectifier) and η (efficiency) are observed to be [38.30 W and 83.57%] for the first scenario and [30.24 W and 79.45%] for the second scenario. When evaluating the scenarios, it becomes clear that the output power experiences a significant reduction, dropping from 38.30 W to 30.24 W in the presence of the EWM. This reduction is also visible in the waveform of the battery current in Fig. 9 from 3.04 A without presence of the EWM down to 2.40 A in presence of the EWM. This reduction can be primarily attributed to amplified losses resulting from considerably increased R_t and R_s and diminished M_{ts} which causes system detuning. Consequently, η also decreases, declining from 83.57% to 79.45%. To conclude, the parameters specified for the absence of the EWM fail to meet the required conditions when the EWM is present.

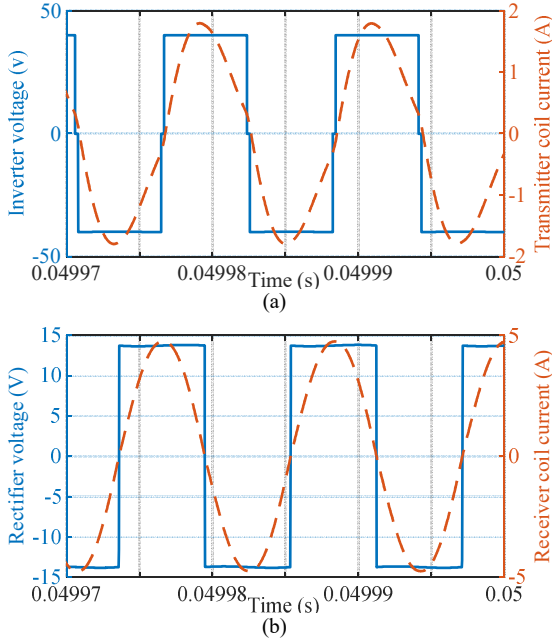


Fig. 7. Steady-state waveforms of the UUV IPT system when there is no EWM: (a) inverter terminal voltage and current and (b) rectifier terminal voltage and current.

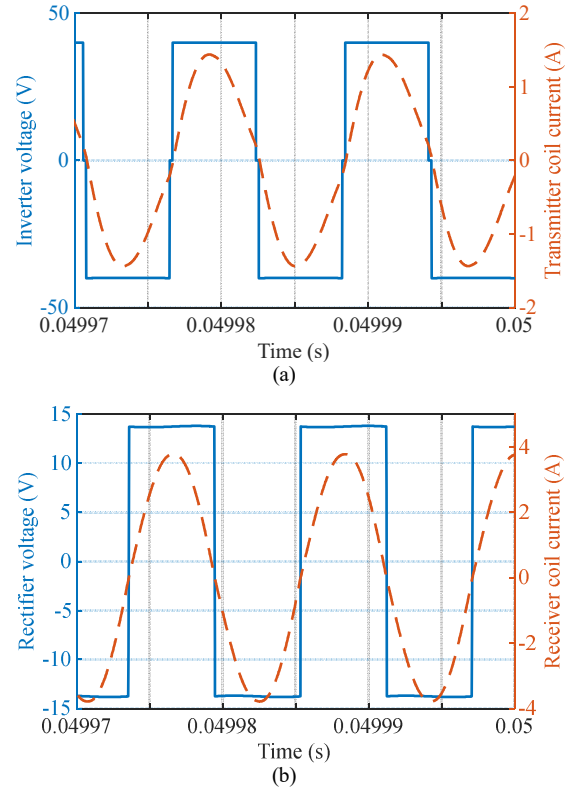


Fig. 8. Steady-state waveforms of the UUV IPT system when the EWM exist: (a) inverter terminal voltage and current and (b) rectifier terminal voltage and current.

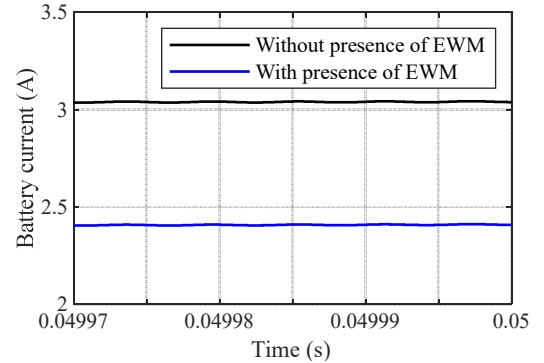


Fig. 9. Steady-state waveforms of the battery current.

V. CONCLUSIONS

This research has modeled, experimentally analyzed, and simulated the performance of a UUV-IPT system within an EWM. An approach was proposed to model the EWM as a virtual winding (eddy ring) and then to effectively distribute the influences of EWM on the actual winding parameters by employing the impedance matrix reduction method. According to performed finite element studies, the conductive EWM develops eddy currents (and hence ohmic losses) and influences the formation of electromagnetic fluxes. Therefore, the values of the magnetic windings' resistances were significantly increased and the mutual inductances between winding pairs were reduced. Also, mutual resistances were emerged between magnetic pairs, however, their self-inductances were left almost constant. Considering the system-level impacts, the UUV-IPT experienced a noticeable decline in the transfer efficiency and output power which caused a drift from original design expectations. The performed experimental

measurements confirmed the accuracy of theoretical studies regarding the influences of the EWM on the winding parameters.

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