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Investigation and Design of Wireless Power Transfer System for Autonomous Underwater Vehicle

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Abstract—With the development of wireless power transfer (WPT) technology, it is possible to transfer power to the batteries without plug-in cables and human interaction for autonomous underwater vehicles (AUVs), taking advantage of high safety, high reliability and unattended capability. However, when implementing the WPT system under the seawater environment, the electrical properties of seawater including the permittivity and the conductivity cause a significant changing in the parasitics of winding coils underwater. The seawater, which owns higher permittivity and conductivity compared to the air, not only causes extra parasitic capacitance to coils but also conducts extra eddy current loss, and thus reduces the system efficiency. In this paper, the characteristics of winding coils underwater are investigated and an optimized design methodology for underwater WPT system with series-series (SS) compensation is proposed. A 200-W underwater WPT prototype is built and experimentally verifies the analysis for the coils and the optimized design approach. The experimental demonstration also shows the system efficiency comparison between the air, the water, and the seawater environments.

Index Terms—Underwater wireless power transfer, inductive power transfer, Series-Series compensation, optimized design, autonomous underwater vehicles

I. INTRODUCTION

For autonomous underwater vehicles (AUVs), the capacity of batteries is the critical factor which determines their mission lifetime. Nevertheless, it is of great difficulty to replace the batteries or use plug-in battery chargers for the AUVs to prolong the operation time, unlike terrestrial vehicles because of operating costs as well as human safety issues. Currently, the emergence of wireless power transfer (WPT) offers a better choice for transmitting power to the AUVs [1, 2, 3, 4]. With the WPT technology for the underwater conditions, several benefits can be achieved including lower operating costs due to corrosion and short circuit, improving operational safety and considerably reducing manual risks. Nowadays, the WPT has already been applied in many applications to realize over-air wireless power transmission. In the small-power field, the WPT systems based on microwave technology or inductive power transfer (IPT) are capable of transmitting power between centimeter-sized distance and has been extensively applied in consumer electronics especially smart phones [5][6]. Besides, recent research for inductive power transfer has verified the feasibility in the higher power applications such as electrical vehicles [7, 8, 9].

However, unlike the terrestrial applications, the WPT underwater is facing significant challenges caused by the electrical properties of water environments. The freshwater and the seawater have the relative permittivity of 80 and 85 respectively (which of the air is 1), and this attribute would significantly influence the modeling of winding coils underwater. The parasitic capacitances over the winding coils under the air conditions are usually neglected for its lower value and insignificant contribution for coils impedance. Whereas for underwater coils the parasitic capacitance would move the resonance frequencies of coil impedance to lower frequencies, and therefore affect the compensator network and the system operation frequency. Moreover, the seawater is remarkably more conductive than the air and the freshwater. Thus, the magnetic field produced by the transmitter and receiver coils would create appreciable eddy current within the water, which leads to the extra power loss during power transmission.

In this paper, the underwater wireless power transfer system is investigated and especially the characteristics of winding coils underwater environment are analyzed. Based on the investigation, the design considerations for the WPT system underwater are presented and an optimized design methodology is proposed to achieve the maximum system efficiency. A 200-W underwater WPT prototype is built, which is demonstrated in the air, the fresh-water and the sea-water respectively. The optimized design approach is verified by experimental results and its peak efficiency can achieve at 94.3% in the seawater environment.

II. CIRCUIT OPERATION AND UNDERWATER COIL CHARACTERS

1) Operation principle and Series-series compensation for IPT: The basic structure for inductive power transfer consists of an AC source, two coupled coils named transmitter coil (Tx) and receiver coil (Rx), and the load, as illustrated in Fig. 1. As the AC source giving a current excitation to the coil Tx, the magnetic flux ψ_{12} and ψ_{11} are generated by the Tx and part of the flux (ψ_{12}) would be coupled with the Rx coil. If a close-loop electrical path is build by the load connected to the Rx, for example a resistor, an induced current would be generated in the load, which means the power from the AC source is transferred to the load. It is noticed that with the induced current goes through the Rx coil, the

magnetic flux ψ_{21} and ψ_{22} would be generated and coupled with magnetic flux ψ_{12} . Therefore, the Tx coil and the Rx coil are magnetically coupled and accordingly create the electrical interaction.

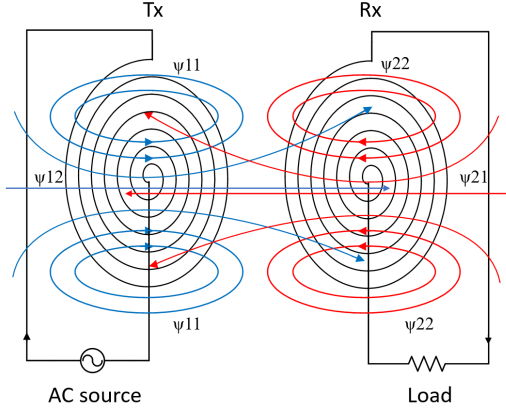


Fig. 1. Fundamental operation with two-coil WPT system

In the over-air environment, the two coupled coils can be electrically modelled in three types: transformer model, coupled inductor model and T-model, as shown in Fig. 2. The coupled coils in the WPT system can be regarded as a loose-coupled transformer, whose leakage inductance is in the same order of its magnetizing inductance. However, the energy from the AC source cannot be entirely transferred from the Tx coil to the Rx coil because a large amount of energy would be stored in the primary leakage inductance. Thus, adding capacitors to form a resonant compensation network with the leakage inductance is a must to enhance the power transfer capability for the WPT system [10].

Series-Series compensation is the most widely used topology in IPT system, which has load-independent current output characteristic and high reliability with coil misalignment [11, 12, 13, 14]. A typical WPT system with S-S compensation, consisting of the DC source, the inverter, the primary compensation capacitor, the Tx and Rx coils, the secondary compensation capacitor, the rectifier and the load, is illustrated in Fig. 3(a) and its equivalent circuit with the T-model is shown in Fig. 3(b).

The fundamental operation of the S-S compensation topology can be described as [15, 16, 17],

$$\begin{bmatrix} \dot{U}_1 \\ \dot{U}_2 \end{bmatrix} = \begin{bmatrix} j\omega L_1 + \frac{1}{j\omega C_p} + R_1 & j\omega L_m \\ L_m & j\omega L_2 + \frac{1}{j\omega C_s} + R_2 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad (1)$$

where L_1 equals $L_p + L_m$ while L_2 equals $L_s + L_m$, and L_p , L_s are leakage inductance of primary and secondary coils respectively while L_m is the mutual inductance between two coupled coils; ω is the angular frequency; C_p and C_s are the value of compensation capacitance; R_l is the equivalent load resistance, which can be calculate by fundamental harmonic approximation (FHA) with different configuration of rectifier; and R_1 and R_2 are the equivalent series resistance of the

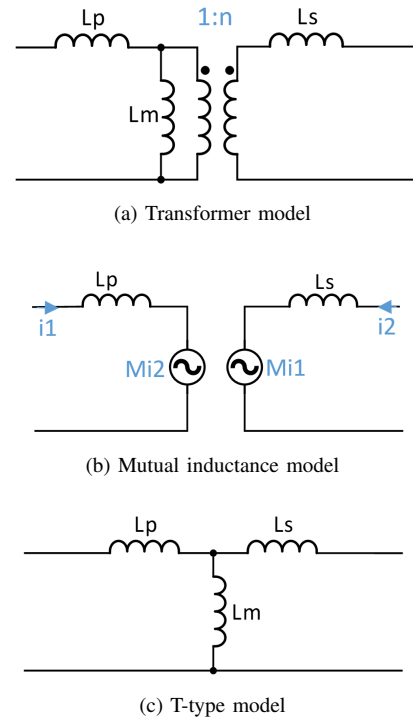
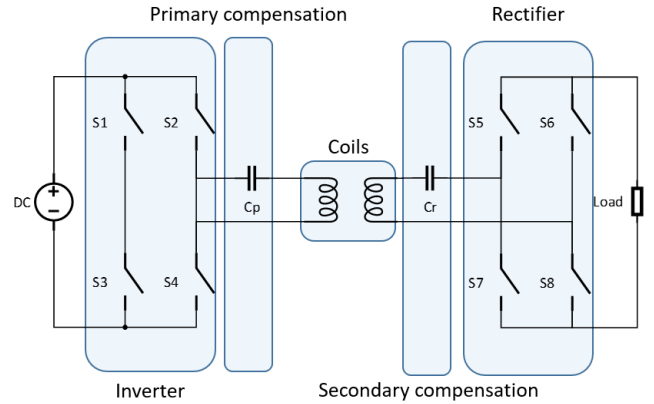
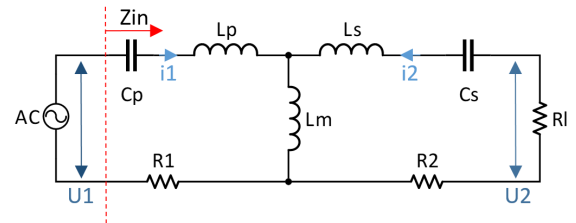


Fig. 2. Equivalent electrical model for a pair of coupled coil



(a) Structure diagram of WPT system with S-S compensation



(b) Equivalent circuit of S-S compensation WPT system with T-type model

Fig. 3. Structure of WPT system with S-S compensation

primary and secondary coils. To ensure that both primary side and secondary side working at the same resonant frequency and realize achieve the maximum power transfer capability

for the system, the series compensation capacitors C_p and C_s are designed to compensate with $(L_p + L_m)$ and $(L_s + L_m)$ correspondingly. Thus, the relationship between switching frequency and parameters of resonant tank can be described as

$$f = \frac{1}{2\pi\sqrt{(L_p + L_m)C_p}} = \frac{1}{2\pi\sqrt{(L_s + L_m)C_s}} \quad (2)$$

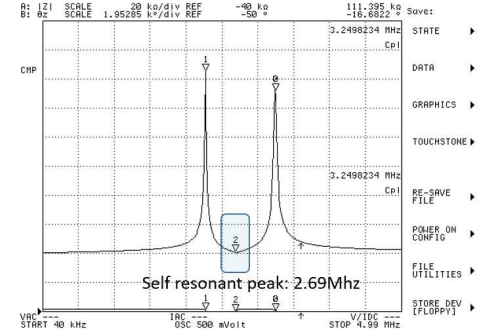
In practical design, the minimum equivalent series resistance (ESR) of coils is preferred to reduce the power loss. Thus, in order to simplify the analysis, the ESRs are neglected and the input impedance, current and voltage in the system can be described as:

$$\begin{cases} Z_{in} = \frac{\omega^2 L_m^2}{R_l} \\ \dot{i}_1 = \frac{\dot{U}_1 R_l}{\omega^2 L_m^2} = \frac{\dot{U}_2}{j\omega L_m} \\ \dot{i}_2 = \frac{\dot{U}_1}{j\omega L_m} \\ \dot{U}_2 = -\frac{\dot{U}_1 R_l}{j\omega L_m} \end{cases} \quad (3)$$

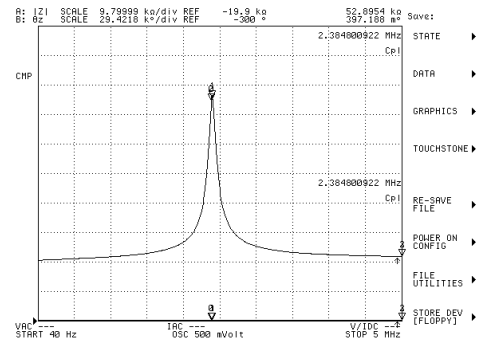
where Z_{in} is the input impedance of the system, as illustrate in Fig. 3; \dot{U}_1 is the output voltage of the inverter; \dot{U}_2 is the voltage of the load; \dot{i}_1 and \dot{i}_2 are the current in the Tx and Rx. It can be found equation (3) that when operating at resonant frequency, WPT system with S-S compensation can be regarded as a voltage-controlled current source; and combined with equation (2), the system's resonant frequency is depended on the parameters of coils and compensation capacitors. Besides, the input impedance without the imaginary part means that no harmonic current is needed to build and maintain magnetic flux between two coils and thus a high transmission efficiency could be realized. For a specified transfer distance, one coil configuration has its corresponding self inductance and coupling factor. With a specified voltage gain and load condition, the efficiency of entire system can be optimized by choosing switching frequency and its corresponding compensation capacitance. Thus, in order to optimize the design for high efficiency and high reliability for components, a trade-off between coil configuration and voltage stress on compensation capacitors must be considered.

2) *Underwater Coils Character*: Though the S-S topology utilizes coupled magnetic field to achieve power transfer from the transmission coil to the receiver coil, whose operation is hardly influenced directly by the seawater environment, the characters of underwater coils would shift compared with over-air coils because of the higher permittivity and high conductivity of the seawater. The permittivity of fresh water and seawater is between 80 and 85, while the permittivity of air is 1. Thus, extra parasitic capacitance between wires and wires for two coils would occur and produce a low-impedance path for high-frequency current. In order to investigate the influence from the extra parasitic capacitance, the impedance of a series of underwater coils are measured by the impedance analyzer to observe the shift of its self-resonance. An high-frequency excitation is added on the coils and swept from 40 kHz to 5 MHz. And a comparison of impedance measurement

results from the coil build by 29 turns/ 60*0.1 mm diameter litz wire are shown in Fig. 4. It can be found that the self-resonant frequency of the over-air coils is 2.69 MHz as shown in Fig. 4(a). As shown in Fig.4 (b), the impedance of the underwater coils shows a totally different characters. The self-resonance frequency and a high-impedance peak disappear because extra parasitic capacitance between the Tx coil and Rx coil causes a low impedance path for AC current.



(a) Air condition



(b) Seawater condition

Fig. 4. Impedance measurement results of coils

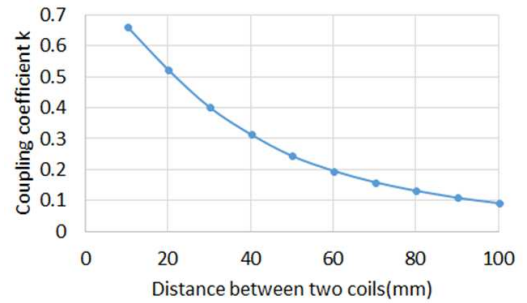


Fig. 5. Coupling coefficient of underwater coil with various distance 29 turns with inner 50mm/ 60*0.1mm litz wire

Comparing to the air whose conductivity is approximately zero, fresh water has a conductivity of 0.1 S/m while sea water has an even higher conductivity of around 4 S/m. Thus, extra eddy current loss in the seawater would reduce the system efficiency [18]. Though with excellent heat conduction capa-

bility, the temperature rise will not destroy the components or the coils, a high efficiency is hard to achieve especially with a large transmission distance.

In addition, the coupling coefficient of coils are measured by the impedance analyzer in the seawater condition. The results in Fig. 5 illustrate that with a constant number of turns the coupling coefficient decreases with increasing of the transmission distance, which shows similar with the over-air condition. The coupling coefficient is able to get 0.4 at 30 mm transmission distance for the coil which consists of 29 turns with inner diameter of 50 mm and build by 60*0.1 mm litz wire, as shown in Fig. 7.

Take these issues into consideration, when designing an underwater WPT system, the characters of coils must be evaluated firstly as the reference for switching frequency selection. And the extra power loss from the eddy current in the water must be considered and compensated.

III. OPTIMAL PARAMETER DESIGN FOR 200W UNDERWATER WPT SYSTEM

Optimization design for efficiency of an underwater WPT system necessitates many trade-offs and iterations with the configuration of coils and power loss estimation. Once the design specifications of the system is determined the choice of compensation of series capacitors and resonant frequency are constrained in the optimization to achieve higher efficiency. The flow chat of proposed optimization method is shown in Fig. 6. The fundamental reference of the design is the character of underwater coils from impedance measurement. The energy losses of MOSFETs from inverter, diodes from rectifier, winding loss from coils and ESR loss from compensation capacitors are considered and calculated as the function of switching frequency and worked as the final reference of design. The proposed optimization routine is described in the following steps:

Step 1 Measure inductance and resistance of coil

The coils inductance and resistance are measured by impedance analyzer with sweeping number of turns and frequency. In the design the initial inner diameter of coils is selected as 50 mm and the number of turns is swept from 27 to 37 turns. The transmission distance is set as 30 mm in the seawater environment.

Step 2 Calculate corresponding resonant frequency

The voltage gain for the system at resonant frequency is given by

$$\left| \frac{\dot{U}_2}{\dot{U}_1} \right| = \frac{R_l}{\omega L_m} \quad (4)$$

And according to (4), the switching frequency corresponding to different number of turns from the step 1 can be calculated. The switching frequency must be lower than one tenth of the self-resonant frequency otherwise lower number of turn must be adopted.

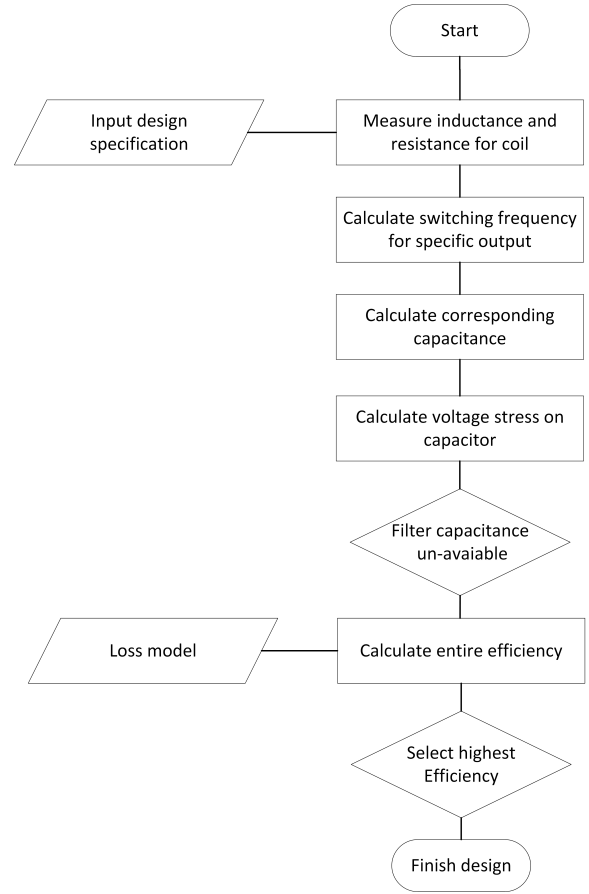


Fig. 6. Flow chat of the proposed efficiency optimization approach

Step 3 Calculate corresponding compensation capacitance
With the switching frequency kept the same as the resonance frequency the corresponding compensation capacitance can be calculated by equation (2). After this step the parameters of resonant tank with its winding configuration can be decided.

Step 4 Calculate voltage stress on capacitors

The voltage stress on capacitors is another limitation for higher efficiency and high reliability of the system. Since in every duty cycle, the power stored in coils is equal to the power that compensated by capacitors. The voltage stress on capacitors can calculated by

$$|V_c| = \frac{R_l}{\omega L_m} \left| \frac{\dot{U}_1}{k^2} \right| \quad (5)$$

Step 5 Calculate estimated power loss and select optimized point

Total power loss on coils, compensation capacitors and switches is calculated with sweeping switching frequency and the design with lower power loss can be selected as the optimized point for the system. In this design the calculated power loss is shown in Table.I. and the number of turns of 29 is selected for the design with lowest power loss. A power

TABLE I
PARAMETER SWEEPING RESULTS FOR OPTIMIZED DESIGN

Number of turns	Resonant frequency (kHz)	Compensation capacitance (nF)	Voltage stress on cap. (V)	Mutual inductance (uH)	Couple coefficient	Power loss (W)
37	58.82	28.81	293.8	108.23	0.425	9.535
36	63.15	26.30	300	100.80	0.416	9.46
35	67.04	24.55	302.3	94.96	0.413	9.75
34	72.35	22.63	305.1	87.99	0.410	8.73
33	77.79	20.70	309.8	81.83	0.404	8.37
32	83.67	18.89	315.8	76.09	0.396	8.32
31	89.78	17.37	319.7	70.90	0.390	8.28
30	97.86	15.80	322.3	65.04	0.388	7.811
29	105.68	14.38	327.7	60.24	0.382	7.64
28	115.01	12.92	334.6	55.35	0.373	7.72
27	125.14	11.65	341.5	50.87	0.366	7.89

loss model used in power loss calculation is presented in the appendix.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Following the optimized design presented in section III, the a couple of coils is built by litz wires with plastic supporter and screws, as shown in Fig. 7 and a 200 W underwater WPT prototype is set up, as shown in Fig. 8. A water tank with customized supporter could provided distance adjustment as well as water proofing for the coils. The detailed parameters of the prototype is given in Table II. The compensation capacitance is selected as 15 uF to match the commercially available ceramic capacitors and correspondingly the switching frequency is adjusted to be 103.5 kHz.

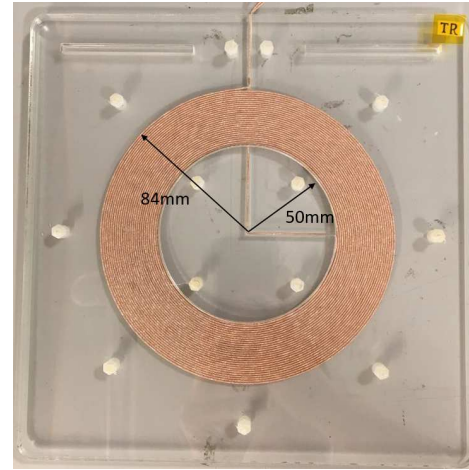


Fig. 7. Underwater coil built by litz wire

TABLE II
PARAMETERS OF 200W UNDERWATER WPT PROTOTYPE

	Value
Inverter	IRFH5215/Full bridge
Rectifier	FSV10150V/Full bridge
Gate Driver	Si8273
Primary coil	29 turns / 60*0.1mm Litz wire 156.7uH
Secondary coil	29turns / 60*0.1mm Litz wire 157.4uH
Primary compensation	C2012NP02W332J 3.3nF/450V * 4 CGA4F4NP02W 1.8nF/450V * 1 TDK
Secondary compensation	C2012NP02W332J 3.3nF/450V * 4 CGA4F4NP02W 1.8nF/450V * 1 TDK
Switching frequency	103.5 kHz

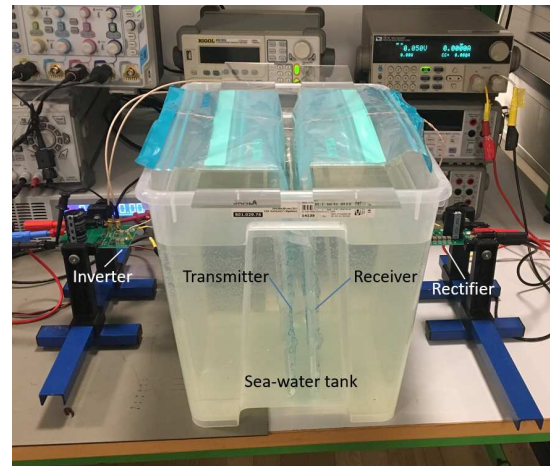
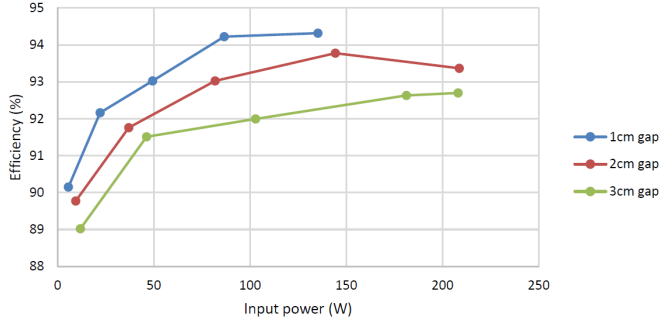


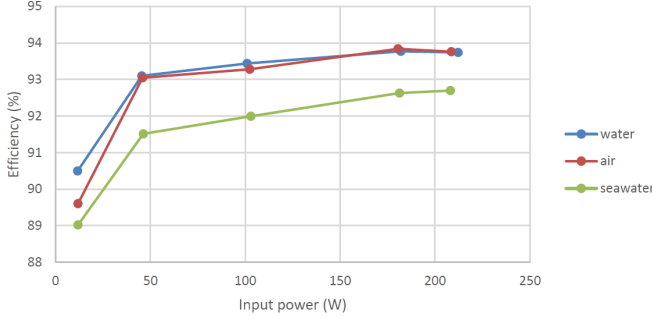
Fig. 8. 200W Underwater wireless power transfer system setup

The open-loop test is carried out for the prototype to verify the power transmission capability and a comparison among over-air condition, under-water condition and under-seawater is made to investigate the influence brought by seawater environment. The input and output voltage are both set as 100

V and the efficiency against transmission distance is given in Fig. 9(a). For an optimize-design underwater system, the efficiency is kept within a flat region from 100 W to 200 W at difference transmission distance and the peak efficiency



(a) Underwater system efficiency with difference transmission distance



(b) Efficiency comparison with 30mm transmission distance

Fig. 9. Efficiency measurement results of prototype

achieved 94.5%. The efficiency achieves 92.3% with 30 mm transmission distance in the seawater condition. Generally the power efficiency drop with increasing of transmission distance and drop rapidly as it approach 25% of rated power.

The efficiency comparison is also conducted in different transmission environment. Fig. 9(b) shows the efficiency of system in over-air condition, under-water condition and under-seawater condition at 30 mm transmission distance. At different transmission power, the efficiency of over-air condition and under-water condition is identical but both higher than that of under-seawater condition. At the operating point 200 W output power and 100 V output voltage, the total system loss in under-seawater condition was found to be approximately 1% lower than other two condition, which is brought by the large conductivity and eddy current loss of seawater.

V. CONCLUSION

This paper presents the investigation and design of underwater WPT system for AUV charging application. The characters of underwater coils are investigated with impedance measurement and the influence caused by extra parasitic capacitors and conductive seawater environment are discussed. With the measurement results of underwater coils, an optimized design approach for underwater S-S compensation topology is proposed and utilized to design a 200 W IPT system. A 103.5 kHz underwater WPT system is built and tested in under-seawater condition and its power transfer capability of 200 W is achieved. The experimental results verify the proposed optimized design approach and an efficiency comparison among

over-air condition, under-water condition and under-seawater condition is conducted.

ACKNOWLEDGMENT

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APPENDIX: POWER LOSS MODEL OF THE SYSTEM

The appendix provides the loss model which is used to estimate the power loss and select the optimized point for the system in section III.

The conduction loss from each MOSFET in inverter can be calculated by:

$$P_{conduction} = I_{RMS}^2 R_{DS(on)} \quad (6)$$

where I_{RMS} is the RMS value of the current on a MOSFET; $R_{DS(on)}$ is the drain-source conduction resistance of the MOSFET. The turn-on loss of the switches can be calculated by:

$$P_{turn-on} = \frac{1}{2} C_{oss} V_{ds(on)} f_s \quad (7)$$

where $V_{ds(on)}$ is the drain-to-source voltage of the MOSFET before it is turned on; C_{oss} is the output capacitance of the MOSFET and f_s is the switching frequency. The The turn-off loss of the switches can be calculated by [19]:

$$P_{turn-off} = \frac{i_{off}^2 t_{off}^2}{48 C_{oss}} f_s \quad (8)$$

where i_{off} is the current on the MOSFET when it is turned off and t_{off} is the fall time of the current. Since at resonance frequency the current on coils is sinusoidal thus the winding loss on coils can be calculated by

$$P_{coil} = i_l^2 R_{ac,f} \quad (9)$$

where i_l is the RMS value of current on a coil and $R_{ac,f}$ is the AC resistance at specific frequency, which can be measured by the impedance analyzer. The power loss on a diode from the rectifier is given by

$$P_D = V_F i_{ave} \quad (10)$$

where V_F is the forward voltage of the diode when it conducts and i_{ave} is the average value of current on the diode. Finally, the power loss on compensation capacitors can be calculated by

$$P_{cap} = I_{cap}^2 R_{esr} \quad (11)$$

where I_{cap} is the RMS value of current on capacitors and R_{esr} is the equivalent series resistance of the capacitors. In practical if the compensation capacitor consist of several capacitors in parallel, the ESR should be calculated as several resistors in parallel.

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