Study on Underwater Wireless Power Transfer via Electric Coupling with a submerged electrode

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Abstract— **Wireless power transfer (WPT) is studied for battery charging in the IoT world. WPT via electric coupling is studied for apparatuses in water using the effect of large dielectric constant of water. One electrode is isolated from water and another electrode is exposed in water for underwater WPT. The power transfer efficiency is over 75%.**

Keywords-component; underwater; wireless; power; transfer; capacitor; resonance; dielectric constant

I. INTRODUCTION

Wireless power transfer (WPT) technology attracts many attentions [1][2]. The WPT has many advantages of safety and stability, since the electrodes need not to be exposed on a surface of apparatuses. When underwater WPT is available, the underwater apparatus will have large flexibility of the operation.

The underwater WPT via electric coupling were reported with two capacitors [3]. The two capacitors had the same configuration and consisted of two copper plates with a gap of 5 mm between which water was placed. In this work, one pair of electrode is exposed in water and another capacitors is isolated from water. The tolerances and frequency characters are examined comparing with two capacitors type.

II. EXPERIMENTS

The underwater WPT via electric coupling usually uses two capacitors, as shown in Fig. 1. Both capacitors have same construction and inductance of L_1 and L_2 are placed both sides. The resonance frequency is decided by the half capacitance and the inductance of L_1+L_2 because of series connection. Relative dielectric constant ε_w of water is about 80 and the resonant frequency in water is 0.11 times compared to that in air.

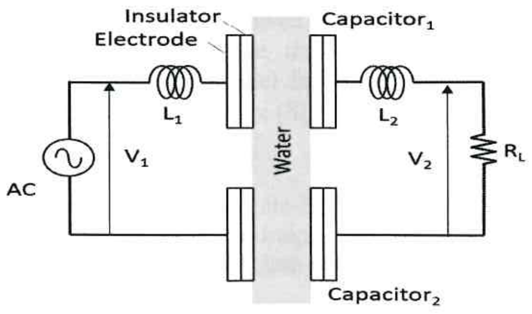


Figure 1. Construction for under water WPT with two capacitors

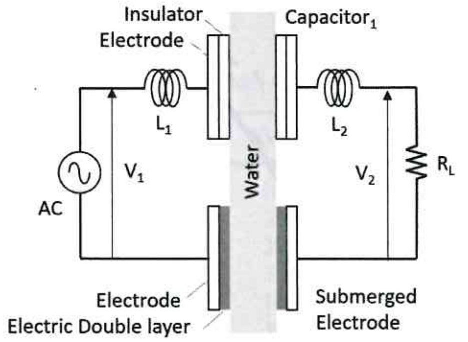
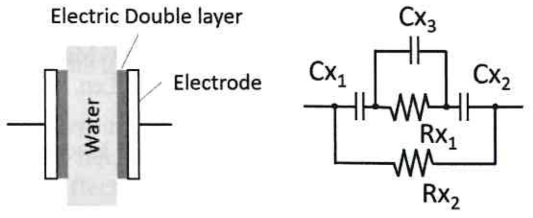


Figure 2. Construction for underwater WPT with single capasitor

Underwater WTP is possible when one side electrode is not insulated from water, since tap water, for example, has electrical conductivity. When none-pure water acts as resistance, the resonant frequency is decided by the single capacitance and total inductance of L_1+L_2.

A. Impedance of water

The electrode is considered as shown in Fig.3. In this work, the area *S* of electrode is 170mm x 50mm and gap *d* is 5mm. The electric double layer is made on the electrode surface and the thickness of double layer is about 1nm that is size of few water molecules [4]. The capacitance of Cx_1 and Cx_2 in Fig. 3 becomes so large and do not depend on the gap *d*. The parameters are listed in Table 1. Cx_1, Cx_2 and Cx_3 are calculated with $\varepsilon_0\varepsilon_w S/d$, and Rx_2 is a measured value by low voltage DC.



(a) Submerged electrode (b) Equivalent model

Figure 3. Eelctrode model in water

TABLE I. WATER IMPEDANCE PARAMETERS

Cx_1	Cx_2	Cx_3	Rx_2
6000uF	6000uF	1.2nF	1100Ω

170mm x 50mm electrode and 5mm gap in water

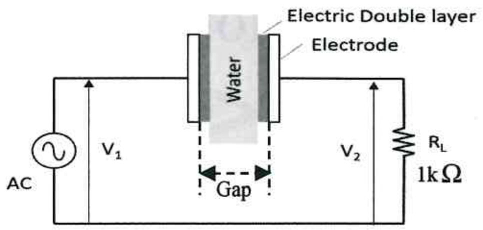


Figure 4. Mesurement of water impedance

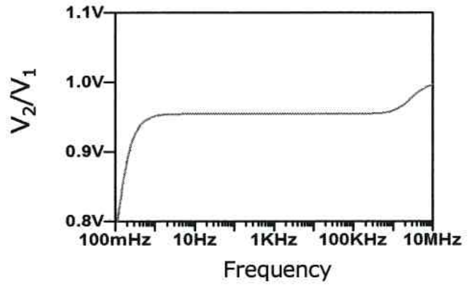


Figure 5. Calculated frequency dependence of water impedance

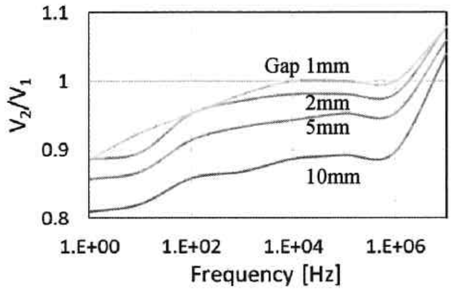


Figure 6. Measured frequency dependence of water impedance

Fig. 4 shows the measurement circuit of water impedance in the frequency range from 1Hz to 10MHz. The voltage ratio of input V_1 and output V_2 was 0.95 at 100 kHz and the Rx_1 is calculated to be 45Ω. The calculated value in other frequency are shown in Fig. 5. The measured values are shown in Fig. 6 and the tendency is similar.

At low frequency, the results are different. When the level is adjusted at 1Hz, Cx_1 and Cx_2 should be 650uF. When the level is adjusted at 10Hz, Cx_1 and Cx_2 should be 75uF. However each values do not satisfy in the low frequency range. If the low frequency about 10Hz is used, other model is needed. Also, at high frequency range over 1MHz, the influence of inductance of ever parts becomes large, and the model have to take into account of inductance.

The pair of electrodes in water will work as a RC circuit shown in Fig. 3(b). If the frequency is between 100 kHz and 1 MHz and the load resistance is over 1 kΩ, the circuit acts as a resistor.

B. Single capacitor WPT

Test composition is shown as Fig. 2. The inductance of L_1 and L_2 is 340uH. R_L is 3kΩ. The electrode size of C_1 is 182mm x 150mm, insulators thickness is 2mm and the gap between insulators is 5mm of water. Size of submerged electrode is 170mm x 50mm and a gap is 5mm. First experiment is the frequency dependence of input and output voltage to find a peak which is suitable for transmitting power with sine wave input. Resonant frequency is 700 kHz at this experiment shown in Fig 7.

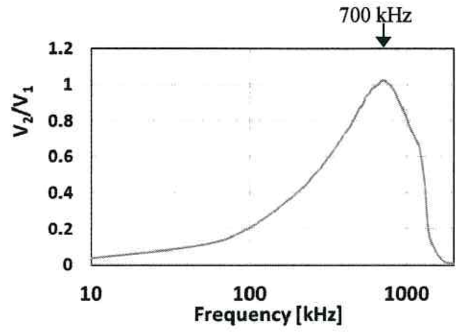


Figure 7. Frequency dependence of V_1/V_2 with the single capacitor

Next, efficiency is measured in both sine wave and square wave are applied at 700 kHz shown in Table 2. In this experiment, input power P_{in} is estimated from voltage V_1 and input current I_i measured by the current probe. Output power P_o is estimated from V_2 and R_L' value.

TABLE II. TRANSMISSION EFFICIENCY IN SINEWAVE AND SQUAREWAVE INPUT

Waveform	P_{in} [mW]	P_{out} [mW]	Efficiency [%]
Sine	25.8	19.8	76.7
Square	51.8	32.3	62.4

The reason why the efficiency becomes lower when square wave is applied as an input, is that a harmonic components of the square wave is missing because of the circuit is resonant circuit. The C_1 is estimated to be about 0.1nF from the resonant frequency. If the thin insulator is used, the C_1 is more than 1nF and the frequency tendency becomes broader.

III. DISCUSSION

Single capacitor type doesn't require severe positioning comparing with the two capacitors type, however, the performance depends on ion concentration in water. The single capacitor type will work as two capacitors type in pure water and work as a single capacitor in the sea or usual water. In addition, single capacitor WPT system which the electrode is exposed to water, the performance will be affected by the electrode surface condition.

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