-Electrically Coupled Undersea Wireless Power Transfer System with Shielded Electrodes

-

Ikuo Awai [1)] Kazuya Yamaguchi [2)] Dai Futagami

1) Fuji waves Co. LTD., 2-20-9 Ohe, Otsu, Shiga Pref. 520-2141 Japan
E-mail: i.awai@fujiwaves.co.jp
2) Fuji waves Co. LTD.2- 20-9 Ohe, Otsu, Shiga Pref. 520-2141 Japan
E-mail: k.yamaguchi@fujiwaves.co.jp

ABSTRACT: The power transfer underwater requires the coverage of electrodes unconditionally to avoid the corrosion induced by the electrochemical effect. The shielding and high permittivity of water collaborate to induce special effects to the wireless power transfer undersea, such as unexpected low transmission loss. The high density of NaCl in the seawater sometimes help reduce the propagation loss, contrary to the expectation. The present paper starts from the general expression of the WPT system based on the admittance matrix, moves to the real 4 electrode model, and then to the effect of electrode shielding. But the discovery of the insufficiency in the study platform of WPT system undersea, and strong resolution for its reconstruction are the conclusion.

KEY WORDS: wireless power transfer, seawater, electric coupling, electrode shield, seabed, admittance matrix, equivalent circuit expression. 4-electrode system

1. INTRODUCTION

Electrically coupled WPT (wireless power transfer) system has a quite complex structure compared with magnetic counterpart. It is often described by 4-electrode system that has 10 composing capacitances(1). The additional complexity is the necessity of disconnected ground line between the input and output terminals, which demands use of 4 port network analyzers to know the circuit response compared with the simplicity of 2 port for magnetic WPTs.

In spite of those difficulties, the inspiring points exist as follows. The extraordinarily big permittivity should give a strong coupling between the power transferring and receiving ports. Secondly, since a lot of electric lines of force made by the transferring electrodes (typically wires) end up at the surface of electrodes on the bottom wall of a sailing ship, the electric coupling is rather indifferent to the sliding movement of the ship.

Knowing the strong and weak points stated above, we started the study by describing the system on the basis of admittance matrix, but we have noticed that the real system made of 4 shielded electrodes, for instance, behaves strange enough. Spending long time to elucidate the reason, we have known that the platform for the study of WPT system under sea has not built yet(2). And hence, we will show the important points to build the platform for the study of WPT systems under water and undersea.

2. GENERAL DESCRIPTION OF SYSTEM

WPT systems are composed by 3 parts. input circuit, coupling circuit and output circuit as shown in Fig.1 Since electrically coupled circuit does not allow the connection of the ground line between the input and output circuits, coupling circuit is given by 4 port circuit shown in Fig.2 and Eq.(1) first, and converted to 2 port as shown in Fig.1.

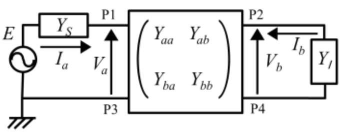


Fig.1 Electrically coupled 2 port system with separated GND

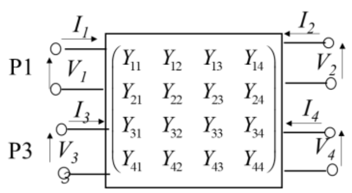


Fig.2 Original 4-port electrically coupled circuit

We take Port 1 and 3 as the input port and Port 2and 4 as the output. Then, the relations for the voltage and current becomes

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{1}$$

In the circuit conversion stated above, the following relations are used

$$
\begin{aligned}
&I_1 = -I_2 = I_a,\ \ I_2 = -I_4 = I_b \\
&V_1 - V_3 = V_a,\ \ V_2 - V_4 = V_b
\end{aligned}
\tag{2}
$$

Putting them into Eq.(1), we obtain

$$
\begin{aligned}
I_a &= Y_{11}(V_a+V_3)+Y_{12}(V_b+V_4)+Y_{13}V_3+Y_{14}V_4 \\
I_b &= Y_{21}(V_a+V_3)+Y_{22}(V_b+V_4)+Y_{23}V_3+Y_{24}V_4 \\
-I_a &= Y_{31}(V_a+V_3)+Y_{32}(V_b+V_4)+Y_{33}V_3+Y_{34}V_4 \\
-I_b &= Y_{41}(V_a+V_3)+Y_{42}(V_b+V_4)+Y_{43}V_3+Y_{44}V_4
\end{aligned}
\tag{3}
$$

Eliminating I_a from (3.a) and (3.c), and I_b from (3.b) and (3.d), one can express V_3 and V_4 with V_a and V_b. Substituting them back into Eq. (3.a) and (3.b), we should obtain the relations between I_a, I_b and V_a, V_b . Before that, the relations V_3 and V_4 with V_a and V_b.are

$$
\begin{aligned}
V_3 &= (1/D)\begin{bmatrix}\{(Y_{12}+Y_{14})C-(Y_{11}+Y_{13})B\}V_a + \\ \{(Y_{22}+Y_{24})C-(Y_{12}+Y_{23})B\}V_b\end{bmatrix} = v_{3a}V_a + v_{3b}V_b \\
V_4 &= (1/D)\begin{bmatrix}\{(Y_{11}+Y_{13})C-(Y_{12}+Y_{14})A\}V_a + \\ \{(Y_{12}+Y_{23})C-(Y_{22}+Y_{24})A\}V_b\end{bmatrix} = v_{4a}V_a + v_{4b}V_b
\end{aligned}
\tag{4}
$$

,where

$$
\begin{aligned}
&A = Y_{11}+2Y_{13}+Y_{33},\ \ B = Y_{22}+2Y_{24}+Y_{44}, \\
&C = Y_{12}+Y_{14}+Y_{23}+Y_{34},\ \ D = AB - C^2
\end{aligned}
\tag{5}
$$

Nextly, we substitute Eq.(4) into (3.a) and (3.b),

$$
\begin{aligned}
I_a &= \{Y_{11}+(Y_{11}+Y_{13})v_{3a}+(Y_{12}+Y_{14})v_{4a}\}V_a \\
&+\{Y_{12}+(Y_{11}+Y_{13})v_{3b}+(Y_{12}+Y_{14})v_{4b}\}V_b \\
I_b &= \{Y_{12}+(Y_{12}+Y_{14})v_{3a}+(Y_{22}+Y_{24})v_{4a}\}V_a \\
&+\{Y_{22}+(Y_{12}+Y_{14})v_{3b}+(Y_{22}+Y_{24})v_{4b}\}V_b
\end{aligned}
\tag{6}
$$

is obtained, and then substitution of Eq.(4) gives

$$
\begin{aligned}
I_a &= Y_{aa}V_a + Y_{ab}V_b \\
I_b &= Y_{ba}V_a + Y_{bb}V_b
\end{aligned}
\tag{7}
$$

,where

$$
\begin{aligned}
Y_{aa} &= Y_{11} + \frac{(Y_{11}+Y_{13})}{D}\{(Y_{12}+Y_{14})C-(Y_{11}+Y_{13})B\} \\
&+\frac{(Y_{12}+Y_{14})}{D}\{(Y_{11}+Y_{13})C-(Y_{12}+Y_{14})A\} \\
&= Y_{11} + (1/D)\begin{bmatrix}\{(Y_{11}+Y_{13})(Y_{12}+Y_{14})+(Y_{12}+Y_{14})(Y_{11}+Y_{13})\}C \\ -(Y_{11}+Y_{13})^2B-(Y_{12}+Y_{14})^2A\end{bmatrix} \\
&= Y_{11} + (1/D)\left[2(Y_{11}+Y_{13})(Y_{12}+Y_{14})C-(Y_{11}+Y_{13})^2B-(Y_{12}+Y_{14})^2A\right] \\
Y_{ab} &= Y_{ba} = Y_{12} + \frac{(Y_{11}+Y_{13})}{D}\{(Y_{22}+Y_{24})C-(Y_{12}+Y_{23})B\} \\
&+\frac{(Y_{12}+Y_{14})}{D}\{(Y_{12}+Y_{23})C-(Y_{22}+Y_{24})A\} \\
&= Y_{12} + (1/D)\begin{bmatrix}\{(Y_{11}+Y_{13})(Y_{22}+Y_{24})+(Y_{12}+Y_{14})(Y_{12}+Y_{23})\}C \\ -(Y_{11}+Y_{13})(Y_{12}+Y_{23})B-(Y_{12}+Y_{14})(Y_{22}+Y_{24})A\end{bmatrix} \\
Y_{bb} &= Y_{22} + \frac{(Y_{12}+Y_{23})}{D}\{(Y_{22}+Y_{24})C-(Y_{12}+Y_{23})B\} \\
&+\frac{(Y_{22}+Y_{24})}{D}\{(Y_{12}+Y_{23})C-(Y_{22}+Y_{24})A\} \\
&= Y_{22} + (1/D)\left\{2(Y_{12}+Y_{23})(Y_{22}+Y_{24})C-(Y_{12}+Y_{23})^2B-(Y_{22}+Y_{24})^2A\right\}
\end{aligned}
\tag{8}
$$

The result above is not only quite general, but also symmetric and reciprocal, resulting in a physically reasonable expression. The kQ-product theory(3) is directly applicable to these results.

3. USEFUL STRUCTURES WITH HIGH SYMMETRY

We are going to derive the response of the 2 symmetric electrically-coupled systems using the result in the last section, a normal mode system that is closed itself with no use of ground current and a common mode system that utilizes it as much as possible.

3.1. Normal mode

The present structure shown in Fig 3 prepares the hot and ground electrodes P1 and P3 for power transfer facing symmetrically to the receiving electrodes P2 and P4 respectively on the side walls of a ship. We have to be careful to the possibility that the ground admittances Y_{11},Y_{22},Y_{33} and Y_{44} which are essentially not needed for the system operation may sometimes deteriorate the response severely

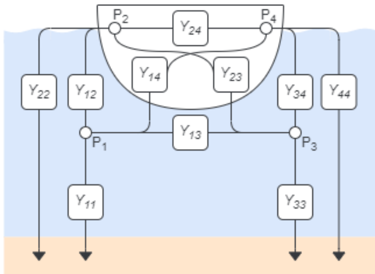


Fig.3 Admittance parameter element for 4 port system of sailing ship

Referring to Fig. 3, one knows the parameters in Eq.(3) relate

$$
Y_{11} = Y_{33},\ \ Y_{22} = Y_{44},\ \ Y_{12} = Y_{34},\ \ Y_{14} = Y_{23}
\tag{9}
$$

Thus, the quantities defined in Eq.() are calculated to be

$$
\begin{aligned}
&A = 2(Y_{11}+Y_{13}),\ B = 2(Y_{22}+Y_{24}), \\
&C = 2(Y_{12}+Y_{14}),\ D = AB - C^2
\end{aligned}
\tag{10}
$$

Substituting those relations into Eq.(8), one obtains the system responses

$$
\begin{aligned}
Y_{aa} &= Y_{11} + \frac{1}{D}\left(2\frac{A}{2}\frac{C}{2}C - \frac{A^2}{4}B - \frac{C^2}{4}A\right) \\
&= Y_{11} + \frac{A}{4D}(C^2 - AB) = Y_{11} - \frac{1}{2}(Y_{11}+Y_{13}) = \frac{Y_{11}}{2} - \frac{Y_{13}}{2}
\end{aligned}
$$

$$
Y_{ab} = Y_{ba} = Y_{12} + \frac{1}{D}\left\{\begin{aligned}&\left(\frac{A}{2}\frac{B}{2}+\frac{C^2}{4}\right)C - \frac{A}{2}\frac{C}{2}B \\ &-\frac{C}{2}\frac{B}{2}A\end{aligned}\right\} = \frac{Y_{12}}{2} - \frac{Y_{14}}{2}
$$

$$Y_{bb} = \frac{Y_{22}}{2} - \frac{Y_{24}}{2} \tag{11}$$

Now we can derive the response for the practical 4 electrode system using the relations

$$\begin{aligned}
Y_{11} &= y_{11} + y_{12} + y_{13} + y_{14} \\
Y_{22} &= y_{12} + y_{22} + y_{23} + y_{24} \\
Y_{33} &= y_{13} + y_{23} + y_{33} + y_{34} \\
Y_{44} &= y_{14} + y_{24} + y_{34} + y_{44} \\
Y_{12} &= -y_{12},\ \ Y_{13} = -y_{13},\ \ Y_{14} = -y_{14}, \\
Y_{23} &= -y_{23},\ \ Y_{24} = -y_{24}\ \ Y_{34} = -y_{34},
\end{aligned} \tag{12}$$

The lower case letters indicate the admittance between 2 electrodes in a 4-electrode system shown in Fig.4. ,where P_1 and P_3 indicate wire electrodes for power transfer, and P_2 and P_4 are plate electrodes for power receive.

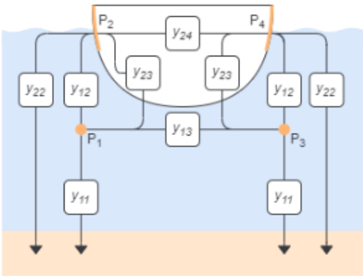


Fig.4 4-electrode equivalent circuit

Now we substitute Eq. (12) into (10)

$$\begin{aligned}
A &= Y_{11} + 2Y_{13} + Y_{33} = 2(y_{11} + y_{12} + y_{14}), \\
B &= Y_{22} + 2Y_{24} + Y_{44} = 2(y_{22} + y_{12} + y_{14}), \\
C &= Y_{12} + Y_{14} + Y_{23} + Y_{34} = -(y_{12} + y_{14}) \\
D &= AB - C^2 = 4\{(y_{12} + y_{14})(y_{11} + y_{22}) + y_{11}y_{22}\}
\end{aligned} \tag{13}$$

is obtained. Then using the following relations induced by the symmetry,

$$y_{11} = y_{33},\ \ y_{22} = y_{44},\ \ y_{12} = y_{34},\ \ y_{14} = y_{23} \tag{14}$$

In addition to it, Eqs. (12) and(13) are substituted in (11), the final simple relation is derived

$$\begin{aligned}
Y_{aa} &= y_{13} + \frac{y_{11} + y_{12} + y_{14}}{2} \\
Y_{ab} &= Y_{ba} = \frac{y_{14} - y_{12}}{2} \\
Y_{aa} &= y_{24} + \frac{y_{22} + y_{12} + y_{14}}{2}
\end{aligned} \tag{15}$$

3.2. Common mode

Its structure is shown in Fig. 5 which substitutes the power transferring ground line by the real ground, and thus P3 disappears. In this case Eq.() is calculated as

$$\begin{aligned}
&Y_{33} = \infty,\ \ A = \infty,\ \ \frac{B}{D} = 0,\ \ \frac{C}{D} = 0, \\
&\frac{A}{D} = \frac{1}{B},\ \ B = Y_{22} + 2Y_{24} + Y_{44}
\end{aligned} \tag{16}$$

and, hence, we know Eq.() is calculated as

$$\begin{aligned}
Y_{aa} &= Y_{11} - \frac{(Y_{12} + Y_{14})^2}{Y_{22} + 2Y_{24} + Y_{44}} \\
Y_{ab} &= Y_{ba} = Y_{12} - \frac{(Y_{12} + Y_{14})(Y_{22} + Y_{24})}{Y_{22} + 2Y_{24} + Y_{44}} \\
Y_{bb} &= Y_{22} - \frac{(Y_{22} + Y_{24})^2}{Y_{22} + 2Y_{24} + Y_{44}}
\end{aligned} \tag{17}$$

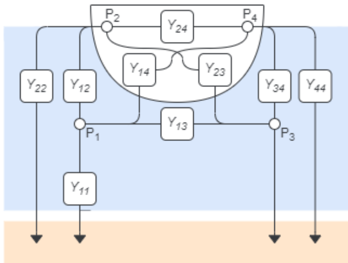


Fig.5 Admittance parameter element for common mode

Now we move onto the 4-electrode system again, and obtain the structure shown in Fig.6, where the electrodes connected to Port 3 are grounded, the following unifications are executed,

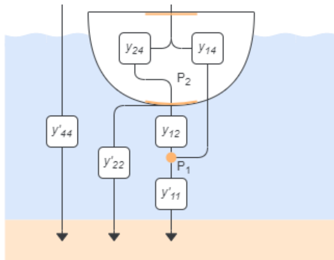


Fig.6 3-electrode equivalent circuit

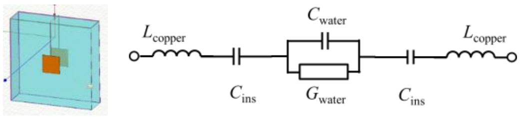
$$y_{11} + y_{13} = y'_{11},\ \ y_{22} + y_{23} = y'_{22},\ \ y_{44} + y_{34} = y'_{44} \tag{18}$$

As a result, we have obtained system response,

$$\begin{aligned}
Y_{aa} &= y'_{11} + \frac{(y_{12} + y_{14})(y'_{22} + y'_{44})}{y_{12} + y'_{22} + y_{14} + y'_{44}}, \\
Y_{ab} &= Y_{ba} = -\frac{y_{12}y'_{44} - y_{14}y'_{22}}{y_{12} + y'_{22} + y_{14} + y'_{44}}, \\
Y_{bb} &= y_{24} + \frac{(y_{12} + y'_{22})(y_{14} + y'_{44})}{y_{12} + y'_{22} + y_{14} + y'_{44}}
\end{aligned} \tag{19}$$

4. ELECTRODE SHIELDING

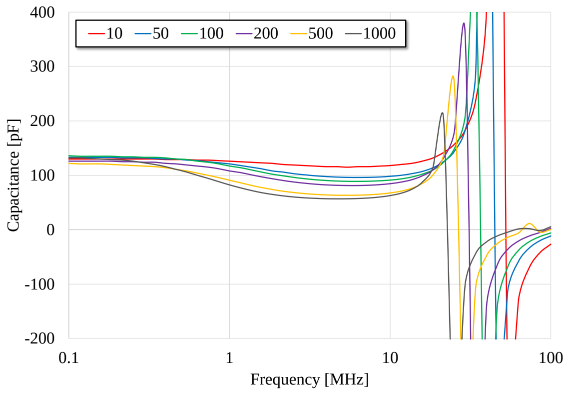
Water is a good solvent that solves many kinds of substances to make a solution. Electrodes react with the Na and Cl ions typically in the sea, resulting in the 4 electrochemical reactions, which are named charge transfer, substance transfer, electric double layer, and hydration. The shielding of each electrode at least obstructs the worst one out of 4 reactions, that is charge transfer, or chemical reaction in other words, on the electrode's surface, prohibiting the energy transfer from the WPT system we are studying. It also protects the electrodes from corrosion as a result.



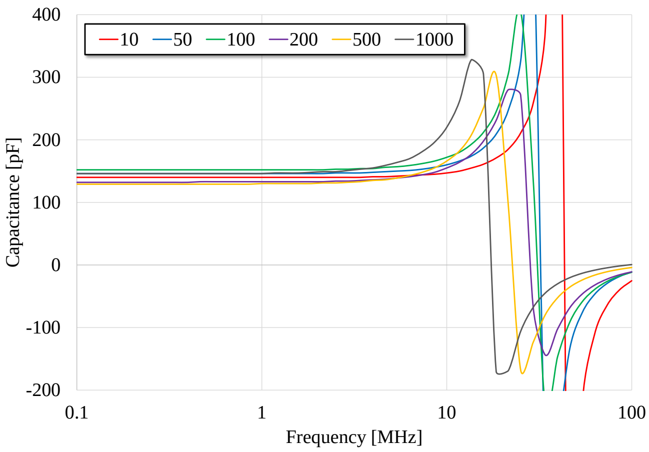
ε_{ins}=3.0,ε_w=81, σ_w=0.014,or 4.0[S/m], L_{copper}=100[nH]

Fig.7 Measurement and simulation setup for water sandwiched by shielded electrodes

We have started the EM simulation study on the shield effect using the structure shown in Fig. 7. whose parameters are listed in [illegible]



(a) Fresh water



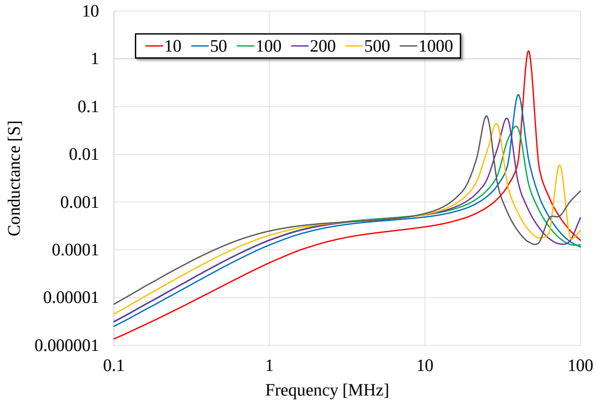
(b) Sea water

Fig.8 Capacitance of the structures in Fig.7(Distance in mm)

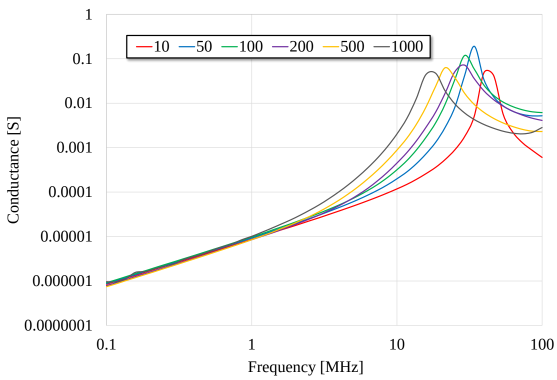
The interesting result is the constant capacitance irrespective of the electrodes distance especially for the seawater. It may be due to the high conduction current in the sea even for the longer distance, because the electric lines of force expands transversely. resulting in the strong connection of 2 electrode capacitances at the ends. In the fresh water, the connection is not so significant.

The conductivity shown in Fig.9 increases according to the frequency. It could be the side effect of the increase of the susceptance of 2 electrode capacitances at the ends.

The dielectric material for the electrode shield can be chosen according to the necessity. We can prepare artificial dielectrics with relative permittivity more than 100(4). It will be used to shield the electrodes, in order to realize the water-equivalent surround for those.



(a



(b)Sea water

Fig.9 Conductance of the structures in Fig.7(Distance in mm)

5. PLATFORM FOR STUDY OF WPT SYSTEM

We have met 4 serious problems in the course of study of WPT system underwater. First, it is too big to build with the real size. As a result, we have to study with a smaller model in the first stage at least. But we do not know the scaling law to connect the real and the smaller models.

Secondly, we do not know how the real system could be constructed, electromagnetic property of bottom of water specifically. It is usually made of soils with water penetrated gradually, but how is the penetration and what kind of soils?

Third problem is that we do not have any good EM (Electro-magnetic) simulator that has perfectly matched boundary for the bottom of water, though that for air has been prepared since long ago.

Fourth one is extraordinarily high conductivity of the seawater. The conductivity proportional to the salt density and constant irrespective of frequency is accepted generally(5). But it is quite strange, being compared to the frequency dependent permittivity of the ionosphere. The Na and Cl ions in the seawater are too heavy compared with the electrons in the ionosphere(6).

We will begin with the third problem.

5.1. Water as a malicious resonator

Figure 9 shows an experimental power transfer comparison for the normal and common modes in the hand-made system for a sailing ship model in the canal(7). You can find the normal mode shows far smoother response than common mode. It is because the latter couples with many resonant modes of the water resonance which the canal makes, while the former does not couple to the water resonance because it makes its own path as shown in Fig.4. The water resonances have the frequency close to the WPT system due to their rather big size and the high permittivity of water inside.

The remedy for that should be to expel the resonance. It could be possible by very big models or EM absorbers, in other words, by frequency shift to the region low enough, or suppression of the water resonance itself.

In the case of ordinary EM systems, they are always assumed to be placed in the air with neither reflection nor coupling with other system, and thus, WPT systems under water should enjoy the same treatment to avoid the useless difficulty.

Since the present coupling problem in Fig. show just the unnecessary coupling with the other system, it should be suppressed either in the experiment or EM simulation. The composite PML (Perfectly Matched Layers) is one of the candidates for EM simulation.

5,2 Real system's behavior

Since we have not experienced real systems with dimension of several meters, we are going to build those in a lake. If we find some new effect that we have not encountered in the laboratory, it would be useful to find the new adaptation.

One of the most important things for us is that the data for WPT in the lake is rare compared with in the sea. We expect quite higher power transfer efficiency, which could be applicable to the water transport in the river or lake very soon. The data in the lake may also be the starting point for the study in the sea and the reference for the EM simulation.

5.3 Scaling law

As far as we have studied the scaling law for the electromagnetic field, it has some restrictions which cannot be satisfied for the WPT systems, e.g. number of materials used in the system, or the frequency characteristic of the material constant. After some trials, we have found it should be difficult to cope with the restrictions.But, if a good absorbing boundary for the bottom of water is constructed for an EM simulator successfully, we do not have to construct a real-sized model. Instead, we can construct it in a computer and calculate the response comparing with the theoretical result.

5.4 Conductivity of seawater

As long as we have looked for EM simulators, we could not find any one that deals with the seawater differently in terms of conductivity from the solid dielectric materials. Why do they neglect the hydration effect of the ions in the water?

Why do they assume it is proportional to the density of salt irrespective of frequency ? Why do they assume conductivity is constant irrespective of the frequency?

CONCLUSION

. Considering the complexity of the electrically coupled WPT system under seawater, we have introduced a general immittance matrix concept for the analysis of sailing ships on the sea. Though it is a versatile method compared with conventional 4 electrode equivalent model, it turned out that there remains more serious problems in the present topic. Thus, we have moved in the next to sort out of the remaining important problems in the WPT system undersea.

ACKNOWLEDGMENT

The authors wish to acknowledge the assistance and support by Acquisition, Technology & Logistics Agency of the Ministry of Defense, Japan.

REFERENCES

(1) H. Zhang, F. Lu, H. Hoffmann, W. Liu and C. C. Mi, "A Four-Plate Compact Capacitive Coupler Design and LC-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Application", IEEE Trans. Power Elec., Vol. 31, No. 12, pp. 8541-8551, Dec. 2016.
(2) R. Somaraju, J. Trumpf, "Frequency, Temperature and Salinity Variation of the Permittivity of Seawater", IEEE Trans. Antennas Propagation, Nov. 2006, pp.1441-1448. *al Convention, IEICE*, BI-90-1, Mar. 2018
(3) T. Ohira, "Power Transfer Theory on Linear Passive Two-Port Systems", *IEICE Trans. Electron.* Vol E101C, No.10, pp719-726, Oct. 2018.
(4) Y. Zhang, A. Inoue and I Awai, "Design a Fabrication of an Artificial Dielectric Flat Lens Antenna," *IEICE Trans B.* Vol. J95-B, No. 12, pp.1634-1641, Dec. 2012.
(5) N. S. Midi K. Sasaki, R. Ohyama, N. Shinyashiki, "Broadband Complex Dielectric Constants of Water and Sodium Chloride Aqueous Solutions with Different DC Conductivities", IEEJ Trans.2014, Sept. pp.S8-S12T.
(6) H. Yoshida, *JAMSTEC*, Private Communication
(7). Tsujimura, Y. Zhang and I. Awai, "Capacitively Coupled Wireless Power Transfer to Sailings Ships", *Proc. APMC*, Nov. 2022.