Investigation of Wireless Power Transfer Under Water Via Capacitive Coupling Technique

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To cite this article:
Anwar A Saleh Mohamed. Investigation of Wireless Power Transfer Under Water Via Capacitive Coupling Technique. Communications. Vol. 6, No. 3, 2018, pp. 45-49. doi: 10.11648/j.com.20180603.11

Received: December 19, 2018; Accepted: January 10, 2019; Published: February 20, 2019

Abstract: The aim of this study is to analyze and evaluate the efficiency of wireless power transfer under different types of water, in this work, a preliminary investigation about the behavior of a parallel plate capacitor immersed in the seawater is presented. The reference structure consists of two square copper parallel plates with a side of 18 cm. Four media have been considered (air, de-ionized water, seawater and tap water); the distance between the plates has been varied from 0.5 cm to 50 cm per each medium, and the transmission coefficient of the capacitive coupling model is recorded for each case. The measurements are performed in the frequency range 30KHz - 50 MHz. By analyzing the results, the tendency of the coupling is more capacitive in the case of deionized water and tap water while it is more resistive in the case of seawater because of the significant connectivity of the salt water. The maximum efficiency noted to be at the frequency around 2.5MHz. An equivalent circuit model has been carried out and some considerations about the power transfer mechanism in capacitor-based (capacitive coupling) structure in the seawater have been deduced.

Keywords: Capacitive Wireless Power Transfer (CPT), Undersea Wireless Power Transfer (U-WPT), Resistive Coupling, Capacitive Coupling Wireless Power Transfer

1. Introduction

Ordinary wireless power transfer (inductive type) invaded many daily applications within few years like mobile phones [1], laptop [2], televisions [3], electrical bicycle [4] and electric cars [5].

Recently Undersea Wireless Power Transfer (U-WPT) is becoming important the use of underwater charging system platform to recharge AUV [6], which are often energy-limited by their battery for several applications ranging from oil platform maintenance to oceanographic investigations to cite a few [7]. So far, many studies have been carried out to extend the wide body of knowledge produced for terrestrial applications [9-11] to the undersea ones. Along this path, some peculiar differences have emerged, in particular: the seawater has a significant conductivity, thus WPT via inductive coupling lacks of efficiency because of the relevant Eddy currents [11]. Capacitive coupling can be envisaged as a valuable alternative; however the few studies carried out so far have still evidenced limitations due to the conductivity of the water [12-13]. It is clear that a deep investigation to exploit all the opportunities to increase the efficiency of U-WPT is needed, both to minimize the cited detrimental factors and to take advantages of the peculiarities of seawater.

According to this motivation, the present work focuses on the analysis of the performance of a single parallel plate capacitor immersed in the seawater charging AUV [15], so as to obtain an accurate circuit model to be utilized in future WPT applications. The results of this preliminary investigation highlight the differences with air as well as with pure water applications, and open the door to new hypothesis for modeling U-WPT.

2. Experimental Analysis

The parallel plate capacitor is investigated by measuring its transmission coefficient versus frequency (from 30 kHz to 50 MHz) when the capacitor is immersed in four different media: air, deionized water, seawater and tap water.

The experimental setup is sketched in Figure 1. The transmission coefficient ($S_{21}$) is measured by using a
vector network analyzer (VNA) (model Fieldfox N9918A). The two internal pins of the SMA connectors are connected to the two plates of the capacitor via two wires. It is worth noticing that unlike a purely inductive coupling made up of coils that are purely magnetically coupled without any ohmic connection, neither for the signal, nor for the ground, the latter experiment cannot be considered a truly example of WPT, because the ground references on both sides of the Device Under Test (DUT) are in common via the VNA ground. Consequently, a return ground path for the current is provided outside the water tank; however, this experiment is useful to focus on the performance and behavior of the single capacitor when different media are considered.

The two metal plates of the capacitor, two square copper plates with a side of 18 cm, are placed inside two thin plastic bags (thickness of the plastic film around 0.1 mm) to prevent direct contact of any part of the DUT with the liquid. Such isolated plates are finally placed inside a container (volume 56x36x30 cm$^3$), which has been filled with the liquid under test.

Before starting with the measurement of the capacitor, the transmission coefficient of the standalone wires is evaluated (see Figure 2) by connecting the two wires together. As a whole, the wires can be approximated as a series inductor on the order of 2 µH (1 µH for each wire), thus introducing by themselves a low-pass behavior (the cut-off frequency lies around 10 MHz) to the interconnection. Such a behavior must be taken into account when considering the capacitor performance in the subsequent analysis.

2.1. Measurements in Air

Firstly, the DUT (a series of a connecting wire, the capacitor and a wire again) is measured in air and the measurement results are reported in Figure 3. The relationship between the geometry of the parallel plate capacitor and its equivalent capacitance $C$ is described by the following well-known equation:

$$C = \varepsilon_0 \varepsilon_r \frac{d}{A}$$  \hspace{1cm} (1)

Where $\varepsilon_0$ is the permittivity of the vacuum, $\varepsilon_r$ is the relative permittivity of the medium, $A$ is the area of the square plate and $d$ is the distance between the plates.

In the present case, $\varepsilon_r$ is almost equal to 1, since the impact of the plastic films can be considered negligible. Consequently, by varying the distance of the parallel copper plates of the capacitor in air, its equivalent capacitance changes accordingly.

This is testified by the fact that the frequency associated with the maximum value of $S_{21}$ increases as the distance $d$ between...
the plates increases. As a whole, the setup under test can be approximated as a series resonant circuit, with a capacitance that varies as a function of distance \( d \) (see Figure 4).

**Figure 4.** Circuit model for the measured capacitor both in air and in deionized water.

### 2.2. Measurements in Deionized Water

The same measurements are then performed in deionized water. The results are illustrated in Figure 5. Again, the resonant frequency of the circuit varies with \( d \), so the circuit can be still modeled as in Figure 4, with the only difference that the equivalent capacitance is higher in the deionized water than in the air, as expected, due to the higher permittivity of the water (\( \varepsilon_r \) around 80 in the latter case [14]). As a consequence, the main resonant frequency of the circuit is lower than in the previous analysis.

**Figure 5.** Transmission coefficient of the capacitor under deionized water for different distances of the copper plates. The results are reported in a subset of the total frequency range, i.e., 1-50 MHz.

### 2.3. Measurements in Seawater

Finally, the circuit is immersed in the seawater. The latter is prepared by adding 35g of salt for each liter of tap water, according to [13].

By adding salt, the water becomes moderately conductive (in particular, a conductivity \( \sigma \) around 4 S/m is achieved [14]). As a consequence, the behavior of this medium is closer to a lossy conductor than a dielectric.

This is evidenced by Figure 6, where it is shown that the measured transmission coefficient of the circuit under test is fairly independent of the distance between the copper plates of the capacitor.

Moreover, the total capacitance is higher than the one measured in the deionized water. As a consequence, the previous circuit model cannot be applied in the present case.

### 3. Equivalent Model for a Capacitor Under Seawater

In order to derive an extended model that accounts for the new situation stated by the conductive dielectric, it is worth underlining two aspects:

- the seawater acts also as a conductor. The value of the equivalent resistance depends on the conductivity of the water, and in a first guess approximation, also on the area of the copper plates \( A \), and on the distance \( d \) between the plates according to the second Ohm law:

\[
R = \frac{d}{\delta A}
\]

**Figure 6.** Transmission coefficient of the capacitor under sea water for different distances of the copper plates.

Due to the large area of the copper plates adopted in the experiment, \( R \) varies between 0.4 to 4 \( \Omega \) as \( d \) varies between 0.5 to 50 cm, and this is a conservative estimation performed by assuming that only the water strictly between the two plates participates to the ion transport. Such a resistance, in parallel with \( C \), almost short-circuits the latter capacitance, which has a negligible effect in such a scenario.

A direct consequence to that the seawater in the proximity of the covering film of the plates is seen by the copper plate as a bad metallic surface with a thin plastic dielectric layer in between that is actually another capacitive structure. Eventually, due to the presence of the seawater, instead of having a structure, the line up of which can be considered: Metal-Insulator-Metal (M-I-M) (where the “I” layer was represented by air or deionized water in the previous experiments) here we are in front of a more complex line-up where the seawater behaves as a bad metal medium from the capacitive point of view and as a low resistor from the conductance point of view. Assuming for the sake of brevity that this medium can be considered as a Non Ideal Metal (NIM), the resulting line-up can be considered of the kind of: M-I-NIM-I-M where “I” this time is just the plastic film isolating the plates from water.

In order to account for this new situation, the equivalent circuit is proposed in Figure 7. Besides the inductors, which are associated with the external connecting wires and do not change with respect to the previous situation, two fixed capacitors \( C_f \) are introduced to account for the presence of the two M-I-NIM structures, actually implemented by inserting the isolated plates into the seawater. It is worth noticing that the plastic film is much thinner than the distance between the plates considered so...
far (about two order of magnitude), the two fixed capacitances are thus expected to be higher than the capacitance measured in the deionized water case.

**Figure 7.** Circuit model for the measured capacitor seawater.

In order to have a first guess estimation of the value of these capacitances an a-posteriori fitting of the experimental results has been performed and the reasonable value of 7 nF has been found. Equation (1), in fact, provides 7 nF when a dielectric permittivity of about 2.5 is assumed for the plastic film and the thickness of dielectric film is set to 0.1 mm.

**Figure 8.** Comparison of the measured transmission coefficient of the capacitor under sea water with the circuit model, note that by varying the R in the range 0.4-4 ohm no appreciable effect on the behavior is detectable.

In this case R varies significantly with distance, yielding a corresponding decrease of the transfer efficiency, but still no significant variation in frequency shape, i.e, in the reactances that are experienced, as testified by Figure 9.

**Figure 9.** Transmission coefficient of the capacitor under tap water for different distances of the copper plates.

To assess the model and also to extend its validity, a case where the variation of R is larger than in the seawater is carried out. It consists of the adoption of tap water as a medium. Tap water, in fact, exhibits a lower conductance than the seawater, but still high enough to be considered a NIM from the point of view of the equivalent circuit model.

4. Conclusion

This paper describes some experiments to investigate the actual nature of the non-inductive coupling in seawater. This experimental campaign is carried out by starting from the simplest non inductive coupling structure that can be conceived: a single series capacitor consisting of a couple of parallel plates and a medium in between (air, deionized water, sea water and finally tap water). The results have been used to provide equivalent circuit models, the parameter of which have been evaluated by fitting the experimental data to the schematic simulations. From this activity some consideration can be deduced that can be of a certain interest for the development of contactless Power Transfer undersea. In particular, the activity pointed out how the conductivity of the water, that is usually considered detrimental for the inductive coupling as well as for the capacitive one, is actually the main mechanism of ion transfer in the seawater and it can be in principle exploited by using a capacitor-like structure where the two plates of the capacitor are kept isolated from the water, so that the nature of the contact still non ohmic.

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