Two New Sensors Based on the Changes of the Electromagnetic Field to Measure the Water Conductivity

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***Abstract*— Water salinity and conductivity values are always required when measurements from the sea water are needed (e.g., for water pollution, in marine fish farms, feeding industry, etc.). They can be measured directly or indirectly. In order to select the best option, three main issues should be taken into account. The first one is the periodic need of calibration because of the system wear, the second one is the cost of the components of the system, which could make to deploy an expensive device, and the third one is the accuracy of the deployed system. In this paper, we propose two cheap conductivity sensors that do not need periodic calibration. The first one of them is composed by a solenoid and a commercial magnetic field sensor that detects the changes in the magnetic field when different materials are introduced in the center of solenoid. The second one is composed by two overlapped copper coils that, through one of them, are circulating energy, and induce in the other one. The different environments of the coils produce changes in the induced voltage in the second coil.**

Keywords-electrical conductivity; solenoid; copper coils; magnetic field; salinity.

I. INTRODUCTION

The conductivity is defined as the capability of a matter or medium to permit the pass of electricity through it. It is measured in Siemens/meter or microhoms/cm [1]. Electric conductivity is also defined as the natural property of each body which represents how ease the electrons can pass through it. The electrical conductivity of liquids is related with the presence of salts, which generates positive and negative ions, because they are able to carry electric energy through the solution. Those ions are called electrolytes or electrolytic conductors. The electrical conductivity depends on the temperature of the solution. Because the temperature changes, it can also change the values of the ions, solubility, and solution viscosity among other issues [2].

There are different ways to measure the electrical conductivity of the water. The traditional one is to measure the conductivity or resistance offered by the water. It can also be measured by using diamagnetic and paramagnetic proprieties of the water with different concentration of salty ions. The paramagnetic substances increase the value of the magnetic field. Moreover, the diamagnetic substances drive down the magnetic field. Generally, each material has both kinds of behaviors, but predominates one of them.

The magnetic fields are composed of electrical charges, which react with the environment. Those charges can attract or repel themselves and their behavior depends on the chemical or physical forces of the environment. Electric and magnetic charges represent different aspects of the same event. When there is no electric or magnetic charge, the electron's loads are not agitated. When an attractive force is applied, the electron's loads are agitated and begin to move in the direction of the applied force. In the case of water, its chemical composition determines the effects in the magnetic field. The interaction occurred between the electrical charges and the water molecules can cause that some atoms lose their electrons, those atoms are ionized or charged. As a result, these atoms attempt to recover the missing electrons. The combination of the ionized atoms and the magnetic fields causes the formation of an electric current in the water.

When an electromagnetic field pass through a material or medium, the measurement of the changes of the electromagnetic field can bring information about some of its proprieties. In the water medium, the measurement of electric conductivity can bring information about water quality and the quantity of dissolved salts. This is important in many areas such as water management, agriculture, aquaculture or groundwater supplies. In the case of agriculture, it is very important to know the salinity of the water used in the irrigation process; because when the soil is irrigated with water that contains high concentration of salts can produce salinization of the irrigated soils in the long term. It is estimated that 50% of cultivated fields are suffering this kind of salinization [3]. In the case of aquaculture in fresh or sea waters, changes in salinity can cause the death of the cultured species, causing huge economic losses. Moreover, saline intrusion is causing great damages in the groundwater supplies, which would lead to obtain not drinkable waters with the time. Unpolluted fresh water is becoming a limiting resource in some regions, so the saline intrusion in the aquifers of those regions must be controlled to ensure the availability of the water quality.

All these problems can be prevented and corrected using the proper control. Sensor networks, where sensor nodes are sensitive to conductivity changes, can bring an early warning signal, which allows applying the necessary measures to prevent harmful effects. In order to develop this sensor network, the first step is to develop a physical sensor able to measure the conductivity, which must be as cheap as possible, because, for example, to measure the environment of an aquaculture installation many sensors are needed. Low maintenance is also required for the sensors, so the contact between the water and the sensor should be minimized.

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If we only want to detect big changes in salinity, for example, when an object is changed from fresh water to sea water, there is no needed to have high sensibility. Moreover, in some cases, the most important issue is to reduce the maintenance of the sensor as much as possible and try to eliminate the need for periodic calibration. The goal in these cases is to place the sensor during long periods of time.

The aim of this paper is to develop two new conductivity sensors but with the purpose of having low manufacturing costs and low maintenance cost, which can be applied to different areas. We will create a magnetic field and make it pass through the water with different conductivities. It will allow us to detect if the changes in the magnetic field are correlated with the changes of the electrical conductivity. In order to measure the changes in the magnetic field we developed two different sets of assays. In the first one, we create a magnetic field with a solenoid and measure the values of that field with a commercial magnetic field sensor. In the second one, we use two copper coils, one of them has an electrical current and induces this current over the other coil, the measure of the voltage of the second coil gives information about the conductivity.

The rest of this paper is structured as follows. In Section 2, we review other articles developing conductivity sensors. In Section 3, the structure of the both sets of laboratory assays is described. Section 4, describes the assays made at laboratory to evaluate the electrical conductivity detection when there are changes in the magnetic field. Section 5 shows the obtained results. In Section 6, we make a comparison of the prices of commercial sensors and the developed sensors. Finally, Section 7 presents our conclusion and future work.

II. RELATED WORK

There are some works in the related literature where the authors developed conductivity meters. This section presents a review of those works.

In 2007, Medrano et al. [4] developed their own conductivity meter for liquids with low electrical conductivity (measuring directly the conductivity of the water). The minimum value that they were able to measure was 200pSm−1, with an error of 10%. They measure with different distances between both electrodes (0.5 to 2.5 mm) and different voltages (-10 to 10V).

Wei at al. [5] proposed in 2010 a new seawater conductivity sensor (also based on the capacity of water to transmit the electricity), which uses a bipolar pulse to avoid the effect of electrode polarization. They also propose a temperature composition with different formulas for 3 ranges of temperature 1 ºC to 10 ºC, 10 ºC to 20 ºC and 20 ºC to 30 ºC. The sensor is able to self- compensate and self-tuning.

Ramos et al. [6] created a low cost in-situ four electrode conductivity cells in 2006. It is suitable to take measurements from estuarine waters.

The other way to measure the conductivity through the alteration of the magnetic field is used only in the study of saline soils [7, 8]. In those works, two coils are used, the energy passes though one of them and a charge to the other is induced. The charge on the second coil depends on the salinity of the soil.

As far as we know, the use of the interaction in the electromagnetic field has not been used to measure the water conductivity yet (at least in the published works). Moreover, there are no papers describing the process that occurs when an electromagnetic field passes through water with different electrical conductivities. However, few commercial sensors, that use two coils to measure the induction, exist. In this paper we pretend to identify the effects of different electric water conductivities when an electromagnetic field generated by a copper solenoid passes through it.

III. STRUCTURE OF CONDUCTIVITY SENSOR

Our purpose is to detect changes of the electromagnetic field and relate it with the conductivity of the water where it is passing through. It will let us create an electrical conductivity detector. In order to measure the electrical conductivity values, we used a commercial sensor: CM 35 + [a]. By using two different methods, we developed two different inductive conductivity sensors.

For the first method, we prepared an assembly with a solenoid without core that generates the electromagnetic field. In the center of the solenoid, we introduced an assay tube, which is used as container for the water samples. Moreover, in the center of the solenoid (where the magnetic field is higher), inside the assay tube, we inserted a magnetic field sensor. The solenoid was powered by a Direct Current (DC) generator or connected to an alternative current trough a transformer from 220V to 12V, depending on the desired output measurements (in Direct Current or Alternating Current, AC); see the explained in Figure 1.

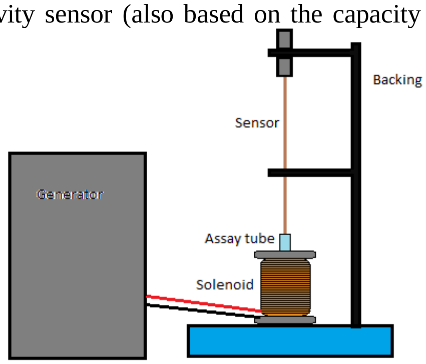

Figure 1. Structure of the first set of laboratory assay.

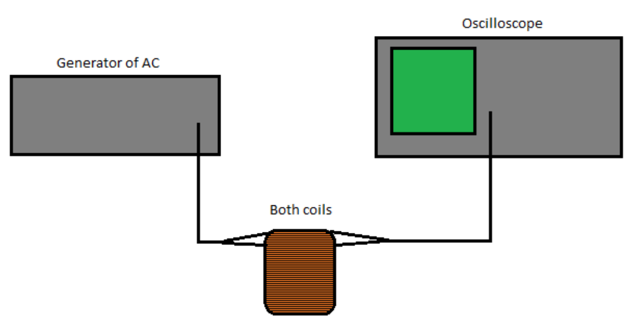

Figure 2. Structure of the second set of laboratory assay.

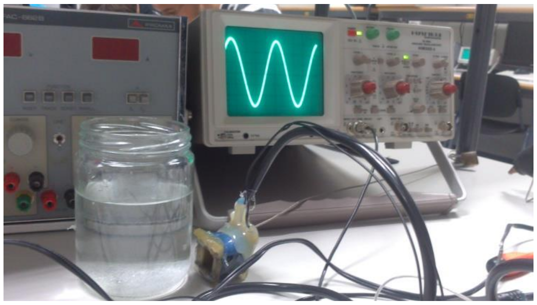

Figure 3. Laboratory set-up.

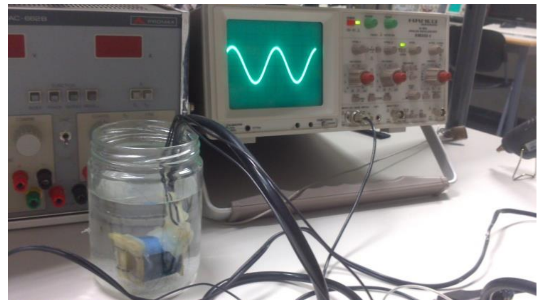

Figure 4. Laboratory set-up with the probe inside the water.

The whole structure was fixed using a laboratory support to assure that when the solenoid and the assay tube are removed (in order to change the solution), the position of the sensor respect to the solenoid is maintained. This is very important, because when the position of the sensor over the centre of the solenoid changes, vary the values of magnetic field. This backing system is useful only for the height and the vertical movement. The horizontal movement has less importance because the width of the assay tube, the centre of the solenoid and the sensor are almost the same and that precluded the horizontal movement. We built a second solenoid without the assay tube in order to avoid the potential interferences caused by the glass. In this solenoid the wire involves a plastic tube that contains the water samples. The sensor used in this set of assays was the Hall Axial Payme probe. It was connected to a Tesalameter Phaywe with a range of measurement from 0 to 2000mT.

We also developed a second experiment. We used two cooper coils. In this case, the wire has small diameter. Those coils are overlapped and do not have a core. The turn relation is 1:36.66. In one coil we introduced AC, then, we measured the induced current in the other coil. The explained structure is show in Figure 2.

Figure 3 shows the probe outside the water. The generator sends a sine signal through the coil. The coil core is air. The oscilloscope shows the obtained result. Figure 4 shows the probe inside the sea water. We can see in the oscilloscope that different results are obtained.

IV. Laboratory Assay

We have done two sets of analysis. The first one uses the solenoid and the commercial sensor. The purpose of these assays was to demonstrate that differences in the environment can produce alterations in the magnetic field. The second set of analysis was aimed to obtain more sensibility and the reduction of the cost of the sensor.

A- First set of assays: Solenoid + Commercial sensor

The initial assays were done connecting the solenoid to the DC generator. We prepared 5 solutions with different ntration of salts; consequently, they present different conductivity. The expected behaviour was to vary the magnetic field when we place probes with different water conductivity.

In order to find the best voltage to take measurements and obtain the correlation between conductivity and magnetic field values, we prepared a scanning. We measured all the samples with different voltages, those voltage and current generated in the solenoid are shown in Table I.

TABLE I. Values of voltage and current registered in the first solenoid

Voltage (V)	5	10	15
Current (A)	0.2	0.4	0.6

TABLE II. Magnetic field (mT) values when measuring different conductivities at different frequencies with 12V (AC). Solenoid 1 (with the assay tube).

Conductivity (mS)	**15Hz**	**150Hz**	**1500Hz**	**15000Hz**
Without assay tube	269	198	26	3
0,002	269	198	26	3
213	296	198	26	3

TABLE III. Magnetic field (mT) values when measuring different conductivities at different frequencies with 12V (AC). Solenoid 2 (without the assay tube.)

Conductivity (mS)	**15Hz**	**150Hz**	**1500Hz**	**15000Hz**
Without water	0.17	0.18	0.16	0.03
0,002	0.16	0.18	0.15	0.03
213	0.16	0.18	0.15	0.03

TABLE IV. Magnetic field (mT) values when measuring different conductivities at different voltages with DC

Environment	**Measured at 5V**		**Measured at 10V**		**Measured at 15 V**	
	Test A (mT)	**Test B (mT)**	**Test A (mT)**	**Test B (mT)**	**Test A (mT)**	**Test B (mT)**
Air	2,89	2,90	8,66	8,72	14,89	14,51
Water with conductivity (mS)						
0,002	2,91	2,93	8,68	8,71	14,86	14,56
0,405	2,93	2,96	8,69	8,89	14,82	14,66
191,4	2,93	2,98	8,69	8,89	14,81	14,64
285	2,97	3,01	8,70	8,90	14,82	14,59
213	2,96	3,00	8,73	8,92	14,78	14,62

Later, we measured these samples with AC at 12V. With the same purpose as before, now we change the frequency of the current in order to find the best point to perform the rest of measures and obtain the most accurate correlation. The frequencies used to take measurements were 15Hz, 150Hz, 1500Hz and 15,000Hz. In this case, we used two solenoids, the first one was the same used in the DC, the solenoid with an assay tube inside, and the second one was the solenoid with the plastic tube. The purpose was to reduce the influence of the glass tube.

In order to complete the first set of assays, we took measurements with other water samples by using the first solenoid at higher DC voltages.

B- Second set of assays: Two coils

The second set of laboratory assays was performed using the two overlapped coils. The first one was connected to AC and the second one provided an electromagnetic induction. The core of those coils was removed, allowing us to use the air or water as the coil core. Then, we took measurements in both environments, air and water (in this second case we immersed both coils in a container full of water with high salinity). The measurement of the induced voltage was taken with an oscilloscope by measuring from peak to peak the sine wave.

In a first assay, we performed several changes of the working frequency. We observed the difference of the induced voltages in the second coil when the environment changes (air or water). The second assay was also performed with different frequencies, but in this case the voltage of the second coil was fixed to 2.8V in air. Then, we introduced inside a container with salty water and compare it with the obtained voltage after this change. The aim of this assay is to find the point where the change of the voltage is higher when we change the environment. Because this point depends on each coil, we made some tests to use it in future assays.

V. RESULTS

A- First set of assays: Solenoid + Commercial sensor

First, we describe the results obtained in the first set of analysis performed with the solenoid and the commercial sensor. We are going to start showing the results obtained with AC; see Table II. We have not appreciated any correlation between the magnetic field and the conductivity of the water at 12V at any frequency. Thus this method is not useful with the used equipment (maybe with a sensor with higher sensibility we will be able to take this measure).

We repeated the same assays with the second solenoid in order to know if the problems obtained in the previous test are caused by the influence of the glass tube. The results are show in Table III. In this case we have not also appreciated any correlation between the magnetic field and the conductivity of the water at 12V; but, we have seen a difference in the magnetic field when the environment changes (air or water) only at 15Hz and at 1500Hz.

Now we present the results obtained with the assays when using DC. In this case, we only take measurements with the first solenoid because the other solenoid have less turns so the generated electromagnetic field is lower. We observed that the influence of the glass tube is not so important.

First, we took measurements with 5 samples with different concentration of salt and different voltages (shown in Table I). The conductivity of the samples has 3 intervals, 1 with the lowest conductivity, 0.002mS, other with low conductivity, 0.405 mS, and 3 samples with high conductivity 192 mS, 213 mS, and 285mS. This distribution allows us to see different issues. First of all, it is possible to distinguish between very different conductivities (low values and high values). Second, it allows us to know the different sensitivities in high conductivities or low conductivities, because the sensitivity is different at different ranges for electrical conductivity. The values of the magnetic field detected inside each sample are shown in Table IV. In this case, we did two series of measures at each voltage, to know the repeatability. Those measures are called Test A and Test B, Test A was done before and when it was finished we did the measures of Test B.

We performed two tests in order to take values for different voltages. This showed us that the sensibility increases, but, at same time, it caused some problems, because a change in the position of the sensor in the magnetic field causes variations in the lecture of the value. At high voltage values, the error committed in a single value is higher than at low voltages. It is so important when taking measurements from different ranges.

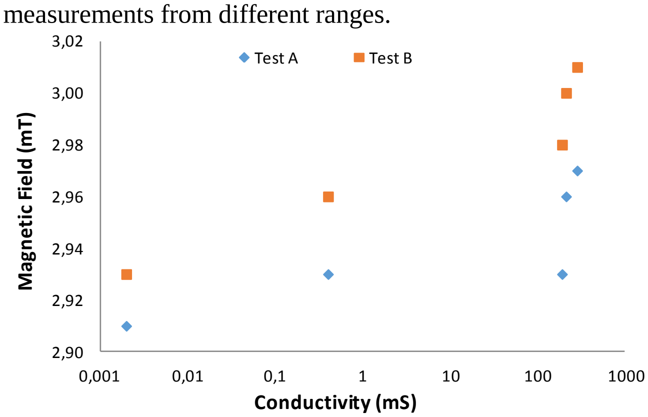

Figure 5. Representation of the data for 5V

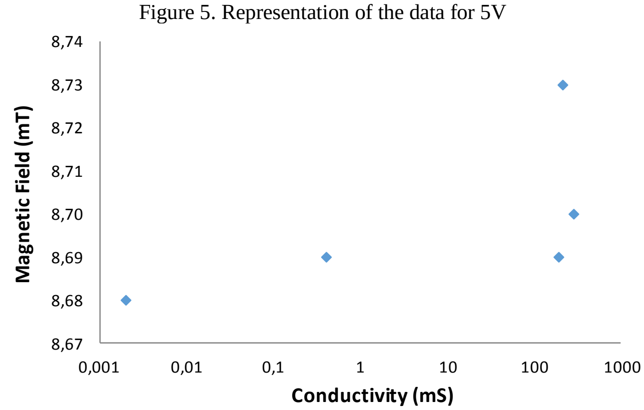

Figure 6. Representation of the data for 10 V for test A

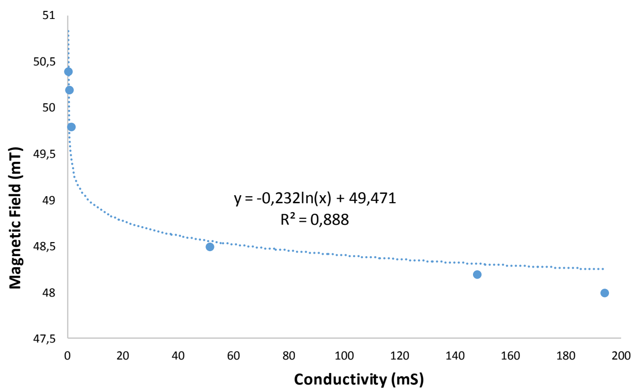

Figure 7. Representation of the data for 20V for test A

In Figure 5, we can see the measurements obtained at 5V. In this case, the results show that is possible to distinguish between different conductivities. At low conductivity, values the sensitivity is higher than at high conductivity values. Moreover, the magnetic field increases with the conductivity.

In Figure 6, the measures obtained at 10 V for test A are shown. The values are similar to the values obtained when measuring at 5V. It is possible to distinguish low values with high values, but not to distinguish between high values. At 10 V, in one case, the magnetic field value increases with the conductivity (test A) and in the other case decreases (test B).

We performed the test at 15 V two times, but both times yield confusing results, so they are not represented. We think that they may be caused by errors in the position of the sensor respect the magnetic field or because 15 V is not a good input voltage for the sensor.

We also performed measurements at 20V. The main problem was that at these voltages the coil starts to heat up, and this heat interferes with the measures. The results are show at Figure 7. In this case the values decrease when the conductivity increases and this follows (1). It defines the correlation between conductivity and the variation of the magnetic field.

Magnetic Field (*mT*) = -0,232 * ln(Conductivity (*mS*)) + 49,471 (1)

At different voltages, the changes of the magnetic field increase or decrease. We have observed that the water conductivity is different because there are differences between high and low conductivities so we introduce intermediate conductivities.

TABLE V. INDUCED COIL VOLTAGE AT DIFFERENT FREQUENCIES WHEN THE ENVIRONMENT CHANGES

Frequency (KHz)	Voltage (V) measured in	
	Air	Salty water
0,5	15	3
1	18	6,4
2	18	14
4	20	17,5
5	20	13,6
6	20	11,9
7	20	10,4
10	18	8
20	15	5
100	7,6	0,6

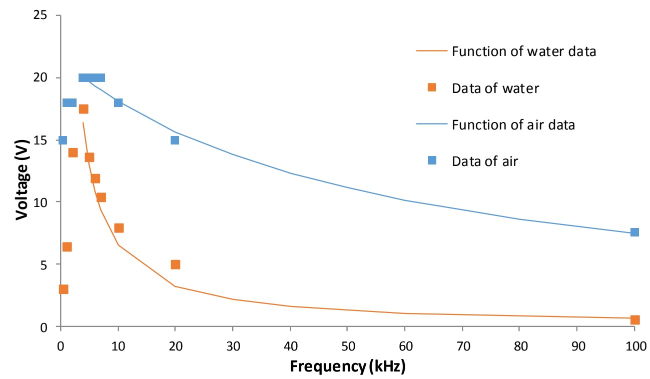

Figure 8. Representation of the data of Table V

B- Second set of assays: Two coils

In the first assay, we changed the frequency and we observed the voltage in the induced coil in both environments: water and in air. The results are show in Table V. They are represented in Figure 8. We observed that in the air, voltages increase until 4 kHz. Then, it is maintained until 7 kHz, where it starts to decrease. Otherwise, in water it increases until 4 kHz, where it starts to decrease. Both environments have the same behaviour with different peaks. These behaviours can be interpolated with the following (2) for air and (3) for water:

Voltage (*V*) =23/(-1,071-0,01984*Frequency (*kHz*)) (2)
R^2=0,86

Voltage (*V*) =653,4/Frequency (*kHz*) (3)
R^2=0,86

These results demonstrate us that it is possible to distinguish between salty water and air at any frequency, but some frequencies have higher differences.

We need to know in which frequency the difference between environments in higher, and this is what we did in the second assay. We changed the frequency, but maintaining the voltage of the induced coil in air at 2.8 V. These results are show in Table VI and represented in Figure 9.

In Figure 9, we can see that depending on the frequency, the effect of the change of environment can have different sign (positive sign or negative sign). So the voltage in the water can increase or decrease with respect to the voltages in the air. The value of the voltage in the induced coil was allways 2,8V. The point where the sign changes is at 248kHz. From 10kHz to 248 kHz the change of environment (air to water) makes to decrease the voltage. This change is higher at 10kHz and decreases until 248kHz where is null. From 248kHz the change of the environment makes to increase the voltage and the difference of voltage increases when the frequency increases. Part of this data (from 10 to 1000kHz have a logarithmic behaviour and follow (4):

$$V_{\text{of induced coil}}(\text{V}) = 0{,}5133\ln(\text{Freq. (kHz)}) + 0{,}0468 \quad (4)$$

The best point to take measurements will be the point where the values have higher differences. We can find two different points to take measurements, at high voltages

(1000kHz) and at medium voltages (10kHz). The maximum differences appear at 10kHz.

TABLE VI. INDUCED COIL VOLTAGE AT DIFFERENT FREQUENCIES WHEN THE VOLTAGE IN THE AIR IS FIXED AT 2.8V

Frequency (KHz)	Voltage (V) in Salty water
0,1	2,4
0,5	2,8
1	2,8
10	1,25
25	1,8
50,8	2
100	3,25
145	2,5
248	2,8
500	3,2
750	3,6

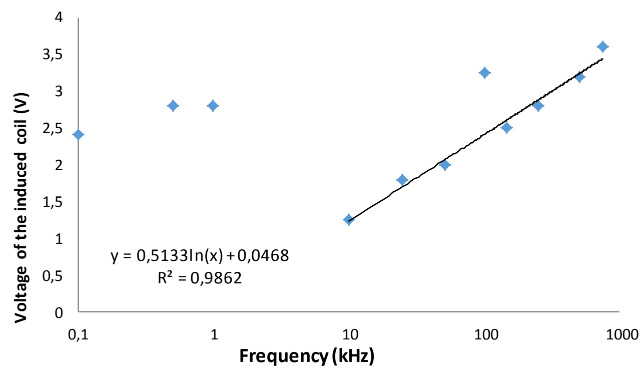

Figure 9. Representation of the data of Table VI.

TABLE VII. COMPARATIVE OF PRICES OF DIFFERENT SENSORS ON THE MARKET.

Name	Fabricant	Physical method	Range on values	Price
WQ-COND	Global Water	Condutive	0 to 200 µS/cm 200 to 2000 µS/cm 2 to 20 mS/cm 20 to 200 mS/cm 200 to 2000 mS/cm	615 €
YSI 5560	YSI	Conductive	-	292 €
PCE-CM 41	PCE Holding GmbH	Conductive	0 to 2000 µS/cm 0 to 20 mS/cm	85,00 €
HI 98309	Hanna Instruments Deutschland GmbH	Conductive	0,000 to 1,999 µS/cm	122,75 €
HI 720122-1	Hanna Instruments Deutschland GmbH	Inductive	0 to 2000 mS/cm	511 €

TABLE VIII. PRICE OF THE COMPONENETS FOR THE SENSOR 1 (SENSOR HALL + SOLENOID)

Component	Prize (€)
Sensor of Hall Effect	1.64
Voltage regulator +5V (1A output current)	14.50
Voltage regulator -5V (1A output current)	2.73
PIC 16f8775.39	5.39
Digital to Analog converter – 8 bits	8.57
Resistors and capacitors	3
Coil solenoid	7

TABLE IX. PRICE OF THE COMPONENETS FOR THE SENSOR 2 (TWO SOLENOIDS

Component	Prize (€)
Voltage regulator +5V (1A output current)	14.50
Voltage regulator -5V (1A output current)	2.73
PIC 16f8775.39	5.39
Digital to Analog converter – 8 bits	8.57
Resistors and capacitors	3
2 x Coil solenoid	14

VI. PRICES COMPARITION

In this section, we are going to make a comparative of the princes of the comertial sensors of conductivity and the developed sensors on this paper. The data of the price of comertail sensors are founded on the different websites of the fabricants, shown in Table VII. Meanwile, the price of the proposed sensors are calculated according to the necessary materials and the electronic components needed to their assembly, shown in Table VIII and Table IX.

We can see that the price can vary quite a lot from one vendor to another. The cheapest costs around 85.00 €, while the most expensive costs around 615 €.

The total price of the fisrt model (Sensor Hall + Solenoid) is 42.83€. By the other hand the total prince of the second model (Two Solenoids) is 48.19.

The new developed sensors are nearly 50% cheapest than the commercial sensors.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we demonstrated that different environments (air, fresh water and salty water) can produce different alterations in the electromagnetic field, and these alterations can be measured by different methods.

First, by using a solenoid we can measure the values of the electromagnetic field. But the sensibility of this sensor is too low and we need to increase the voltage of the solenoid in order to obtain enough sensibility in the sensor, this produces 2 problems. In the first one, the solenoid heats up and we need to turn off the solenoid between measures because this heat produces interferences (it changes the magnetic field that produces the solenoid). The second one happens because when the magnetic field increases, little changes in the position of the sensor and the solenoid produce erroneous data.

Another way to solve the problem of low sensibility was measuring the electromagnetic field through the induction of voltage in the second coil. In this case we are able to distinguish air from salty water at different frequencies. We have observed that the best frequency to measure is at 10 kHz. In some cases, we have been able to distinguish water with low conductivity from high conductivity.

The advantages of these detection methods versus the traditional ones is that we do not need to put in contact the sensors (the two copper coils or the copper coil with the magnetic field sensors) with the environment. So, there is no high degradation of the sensor along the time. This is very important because it means that the sensor can be left at any place with no maintenance. Moreover, because the sensor does not have any perishable part or is not consumed during the measurement, the lifespan of the sensor only depends on the energy source.

The main problem in the first set of assays was that there are important changes in the electromagnetic field when the position of the sensor over the solenoid changes. To prevent this in future assays, we propose to create a fixed container for liquids or to make it waterproof and introduce it inside the water. The problem in the second set of assays is that the coils have to be completely isolated. Any hole can make the coils started to drench.

We have several lines to research in future works. Although the highest sensitivity is given at high voltage, this range of measurement has problems. Moreover, the need of an energy source in the environment, where the sensor will be placed, makes us to continue with the assays at low voltages. We will also minimize the size of the coils used to take measurements. In order to achieve this purpose, we will introduce some electronic components that help us to obtain higher values and more sensitivity.

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