Continuous monitoring of conductivity using a uniform magnetic field

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Abstract. A spherical coil was used to measure a broad range of conductivities of solutions of NaCl in water. The method proposed in this paper relates the conductivity of the sample with the frequency at the minimum value of an imaginary admittance spectrum when the coil is immersed in the solution. There is a high correlation between the experimental results and the fit equation ($r = 0.95$). Since the proposed method is an inductive one, the drawbacks of electrode methods are avoided, e.g. the interface polarization impedance. The method presented is fast, does not require an estimate for the $Q$ factor and the measurements do not depend on the sample volume when the coil is completely immersed. This system is capable of continuous monitoring of biological and inorganic samples.

1. Introduction

Conductivity of liquid is usually measured with instruments which have electrode arrays [1-8] and these electrodes apply variable electric potential on the sample and the current through it is measured. Nonetheless, a double layer and a polarization impedance are yielded in the electrode-electrolyte interface and both of these have an influence on the measurements because of the charge transfer, chemical reactions, accumulation of ions etc. [2-12]. In order to correct the effects produced by double layer polarization, different electrode configurations with different spacings in between are used [4-5, 7, 13-14].

Some researchers have used electromagnetic induction techniques, which enable the conductivity of aqueous electrolyte solutions to be measured without using electrodes [15], thus avoiding the effects of double layer polarization [2, 10]. Additionally, these methods enable the conductivity of aggressive liquids or chemically unstable samples containing metals to be measured [16-17].

Some researchers have used induction techniques to obtain the conductivity by the transient response decay of a magnetic field which is generated by Eddy currents induced in the sample [8, 18]. Others obtained the conductivity by changing the resonance frequency [19], the circuit quality factor ($Q$ factor) [3, 20] or the impedance change of an inductive system [1, 12]. In order to determine the biological tissular conductivity, Li and Kruger have measured the $Q$ factor change which is produced by the magnetic power dissipation of a sample within a time variable magnetic field [21]. However, this setup prevents the continuous monitoring of biological suspensions, because the coil can not be
immersed in the liquid and the sample size needs to be less than the coil. Additionally, the sample must be prepared in the form of a dish and be located in the central axis in the middle of the coil. Other researchers use the method of the two transformers [21-24]. These are in counterphase and tuned with a series circuit in order to get a null output of the system in a point of the space. When a sample is later placed there, an unbalance in the magnetic field is produced [9], then a phase shift occurs in the secondary, which is proportional to the sample conductivity. Nevertheless, this technique is very sensitive to small changes in frequency, therefore high accuracy crystal oscillators must be used. In addition, the initial heating of the transformers must be taken into consideration because of the dissipation of power and, in accordance with this, it is necessary to wait until the electrical configuration becomes thermally stable in order to begin taking the measurements [25]. Others have used bridge circuits to measure the unbalance of the field produced by the sample [8] and this technique also requires a system calibration with a sample of known conductivity [26]. Variations of the technique of the two transformers have different pairs of inductive elements such as: two wound inductances or two toroids. The main concept is that one of the toroids or inductances is a transmitter and the other is a pickup of the field generated by the induced currents in the sample [27]. Both the electric potential and its unbalance are produced by the induced field and measured on the pickup element [12] and these quantities are proportional to sample conductivity. A special case of pickup element is presented in [28]. In this study, gradiometers are adequately distributed to look into the possibility of magnetic induction tomography in order to generate an image of conductive regions of samples but, in order to achieve this, a 30 A peak to peak current must go through the transmitter coil. Additionally, there is a great requirement for stability and to reduce noise and sophisticated algorithms are also required for data analysis, calibration and data averages. Despite all of the above, the system still produces fuzzy images with artifacts. Foxboro® commercial inductive systems for industry are also used. These systems are comprised of two toroids but these are voluminous and require a large quantity of sample liquid. It is also necessary to consider its cell constant for the measuring process.

In general terms, open geometry systems exhibit field nonlinearities and boundary effects, like in: Hartwig et al [3], Ishida et al [8], Minott et al [9], Crowley and Rabson [12], R. A. Williams [17], Limin Li and Kruger [21], Bianchetti et al [24], Meyers et al [25] and Arnold and Meeten [26]. The above phenomena occur because the field lines are not confined to an open geometry system, so distribution of the field lines depends on the electric properties of the sample [16].

Design, fabrication and testing of a spherical coil are presented in [23] and this kind of inductance generates a uniform field inside [23, 29] so that nonlinearities and boundary effects are suppressed inside the coil. The application of a spherical coil to measure biomass without the use of electrodes is presented in [29]. The sample conductivity is obtained from a coil conductance change, when the coil is out of and then immersed in the sample. This method enables measurements to be taken with only one inductive element.

The method presented can be carried out quickly and results can also be obtained rapidly; here a sinusoidal 150 mV voltage was applied on a spherical coil in a range of frequency between 1 MHz and 10 MHz. The conductivity value is obtained from the frequency at the notch tip of the susceptance curve. The system does not require an estimate for the Q factor. Since the proposed method is an inductive one, the drawbacks of electrode methods are avoided. Unlike other methods and systems, a spherical coil allows continuous monitoring of liquid samples, for example biological suspensions, and, also depending on the coil coating, it is possible to run continuous monitoring of aggressive or chemically reactive liquids.

2. Materials and methods

2.1. Measuring cell

The measuring cell is a spherical coil (Figure 1) which is made out of wound wire, isolated with dielectric varnish and fixed with acrylic over a hollow plastic sphere. The hollow sphere has two opposed orifices in its axis. The outer diameter of the coil is 3.95 cm, the inner diameter of the orifices
is 7.99 mm and the wire gauge is 1mm in diameter. The orifices enable the coil to be completely filled with liquid samples.

Figure 1. Spherical coil.

2.2. Sample
Saline solutions (NaCl in water) were prepared in 250 mL and 1000 mL standard beakers; the sample conductivity from 234 µS/cm to 76.7 mS/cm was measured with a Handylab LF 12 (GmbH) conductivity meter. The sample temperature was held to ambient temperature (T=25 °C).

2.3. Measuring system
The coil was immersed in a liquid sample and connected to an impedance analyzer (Solartron 1260). The setup was controlled by the SMaRT 3.2.1© computer software (Figure 2).

Figure 2. Measuring system.

2.4. Measuring protocol
In order to minimize experimental errors, the coil was immersed in the saline solutions from lowest to highest conductivity. A sinusoidal RMS voltage of 150 mV in the frequency range from 1 MHz to 10 MHz was applied by the impedance analyzer. For the purpose of avoiding artifacts and transient effects, every measurement was repeated 5 times and averaged. The current through the system was measured on the same electric nodes of the applied voltage, i.e. the connection is bipolar. The imaginary part of complex admittance was measured for every frequency sweep.
3. Results
The measurements are independent of liquid volume if the coil is completely immersed. Coil susceptibility spectrum has a well defined notch for every frequency sweep. Susceptance is in the magnitude order of $10^{-4}$ $\mu$S/cm but it diminishes by two magnitude orders until $10^{-6}$ $\mu$S/cm in the notch, specifically at the imaginary admittance minimum and this behavior is shown in Figure 3, where 3 spectra of 3 saline solutions of different conductivity between 3 MHz and 4 MHz are shown.

![Image](image3.png)

Figure 3. Susceptance vs. frequency for 3 samples of different conductivity.

Figure 4 shows dispersion of frequency at notch tip of the susceptance versus sample conductivity. The frequency goes from 5.3 MHz to 2.5 MHz while the conductivity increases from 234 $\mu$S/cm to 76700 $\mu$S/cm. The continuous line is the trend.

![Image](image4.png)

Figure 4. Frequency at notch tip of the susceptance versus sample conductivity.
The relationship between the frequency at notch tip of the susceptance and the sample conductivity is given by equation (1):

\[ f = -0.48 \ln \sigma + 7.77 \]  

(1)

Where \( f \) = frequency in MHz and \( \sigma \) = Conductivity in µS/cm.

The negative sign in equation (1) indicates that the frequency at notch tip of the susceptance decreases as the sample conductivity increases and the latter is shown in Figure 4. This behavior can also be seen in Figure 3.

The coefficient of determination for this fit was \( R^2 = 0.90 \) and therefore the changes in the conductivity of the sample explain 90% of the changes in the frequency at notch tip. The residual sum of squares (RSS) between equation (1) and experimental data is 0.92.

4. Discussion

The method presented in this paper relates the conductivity of every liquid sample with the frequency that coincides to the imaginary admittance minimum of a spherical coil immersed in the solution (equation (1)).

Besides the inductance of the spherical coil, it is also necessary to consider an inter-turn capacity and the conductive medium (solution). All these elements comprise of a leaky tank circuit (a circuit LC of an inductance L and a capacitance C in parallel connection) which resonates and the complex admittance is measured on this. The resonance frequency of any tank circuit occurs when inductive reactance equals capacitive reactance and this, in turn, produces an admittance minimum (impedance maximum).

It is worth mentioning that the inter-turn capacity has a magnitude that remains constant in all measurements independent of the medium change (see figure 5). This capacity is reproducible and depends on spherical coil geometry. In Figure 5, the measured resonances for different concentrations have been overlapped. It can be noticed that changes do not occur on the right of the notch, showing that the model capacitance does not depend on the medium. From this fact, it follows that the change in resonance notch is not due to dielectric loss of inter-turn capacity.

![Figure 5](image.png)

Figure 5. Susceptance spectra overlapping. The notches were matched at the resonance frequency \((f_r)\) to show that the model capacitance (on the right of the notch) does not depend on the concentration of the solution used.
A plausible hypothesis is that the position changes of resonance notches are caused by inductance changes, the latter being generated by changes in the conductive properties of the medium inside the coil. It is known from Maxwell’s laws that the conductive, capacitive and magnetic properties of a system are imbricated, then a change in conductivity of the medium alters the induced field and this is reflected in the inductance.

In our work, a frequency sweep of an electric current through a spherical coil is carried out and in this way, a uniform magnetic field is generated; this field goes through the sample inside the coil. Next, the susceptance spectrum of every conductivity solution is registered. The results are fitted to a logarithmic model, which relates the frequency at susceptance notch tip and sample conductivity. It is possible to directly measure sample conductivity with this system and the fit equation; we can say measurements are absolute rather than relative. In 1976 Crowley work [12], direct measurements are also done but, after the values of a known resistivity (conductivity) have been found by computer simulation. Unlike the Li and Kruger method, ours allows continuous monitoring.

In Hugo Sanabria and John H. Miller’s study, the ion concentration of conductive solutions was incremented and, as a result of this, the relaxation frequency (modeled by a harmonic oscillator) of the sample diminished [13]. In the study presented here, the sample conductivity was increased and, as a result of this, the frequency at notch tip of imaginary admittance spectrum decreased. Following the mechanical-electrical analogies, there is a relationship between potential and kinetic energy of a mechanical system and electromagnetic energy of an electrical system, so the behavior of a spring-mass system (harmonic oscillator) is analogous to that of a resonance circuit (LC tank circuit) and its change of impedance (admittance). The Hugo Sanabria and John H. Miller’s study and that presented here agree regarding the behavior of the measured variables due to conductivity changes. Despite using an electrode technique in the first study and inductive method in the second the similarities between the two are remarkable.

In general, the measurement method presented is quite fast and enables the measurement of relatively low conductivities (from 234 µS/cm to 76.7 mS/cm) and the measurements were calibrated by finding a fit between sample conductivity and the susceptance spectrum. Depending on the coil coating, the system has the potential to measure the conductivity of corrosive or chemically reactive liquids in a variety of operating temperatures. The method does not have the drawbacks of electrode methods that cause measurement interference. This method also allows the measurement of conductivity of biological suspensions, since electric fields (which can cause dielectric relaxation phenomena) are not applied.

Finally, the technique presented in this paper could be viewed as precise, supported by the fact that the coefficient of determination obtained from the fit has a value of $R^2 = 0.9$, in other words, the conductivity of the sample explains 90% of the variations in frequency at notch tip of the susceptance spectrum.

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