

Impedance Spectroscopy for Determination of Total Dissolved Solids in Aqueous Solutions of Sodium Chloride and Magnesium Sulphate

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Abstract—Impedance spectroscopy was performed on Sodium Chloride and Magnesium Sulphate solutions to accurately determine Total Dissolved Solids (TDS) in solution. This was done despite the electrical conductivity measurement (the standard technique for determining TDS) of the two types of aqueous solutions being different at similar TDS levels. A novel method for using impedance spectroscopy to differentiate between the two salts in aqueous solution is described. It was found that impedance values from only two frequencies was enough to discriminate between the Sodium Chloride and Magnesium Sulphate solutions, which means that TDS can accurately be determined from the impedance data as the solute is known. Work is in progress to develop a low-cost version of the system to provide point-of-care water quality monitoring solution to those in need.

I. INTRODUCTION

Impedance spectroscopy is an electrochemical analysis technique that describes any measurement where the electrical impedance of a sample or interface is determined across a range of frequencies [1]. Impedance spectroscopy has been shown to be useful for measurements on various aqueous solutions [2]–[5]. The impedance spectroscopy measurement is useful because it can cover a broad range of variables as different phenomena affect the impedance of a water solution at different frequencies [6]. In this case, however, the use of impedance spectroscopy for one specific application is examined.

More specifically, the use of impedance spectroscopy is being considered for water quality monitoring. Impedance spectroscopy has been used for water quality measurements in the past [7]–[9], but it has never been used to optimise the determination of Total Dissolved Solids (TDS). To this end, a low-cost impedance spectroscopy device is being developed.

Total Dissolved Solids is a common water quality metric that is often determined by using a conversion factor from an Electrical Conductivity (EC) measurement. This method is fundamentally flawed as the relationship between TDS and EC is only linear for very specific cases [10]. A solution to this problem is presented: impedance spectroscopy generates more data, which can be used to determine TDS in different

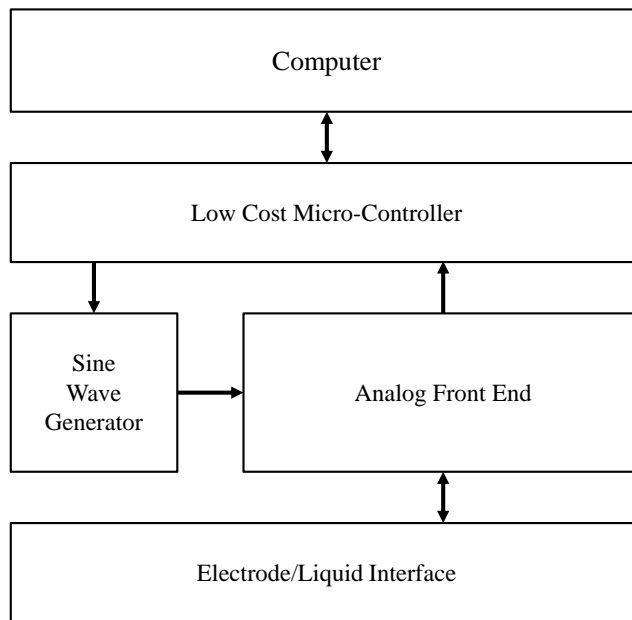


Fig. 1. Block diagram of the proposed low-cost impedance spectroscopy system.

aqueous solutions with a greater accuracy than the typical EC method.

A proof of concept is presented by comparing impedance measurements for two different salts dissolved in water, namely Sodium Chloride (NaCl) and Magnesium Sulphate (MgSO_4). The measurements were performed using the LCR-8000G Series LCR meter from GW Instek. This device was used for the preliminary results as the low-cost impedance system is still under development [11].

II. CIRCUIT DESIGN

A simplified block diagram of the impedance spectroscopy system is shown in fig. 1. The system is largely controlled by a computer program through a USB interface: The computer program commands the micro-controller, which is responsible for the actual measurements.

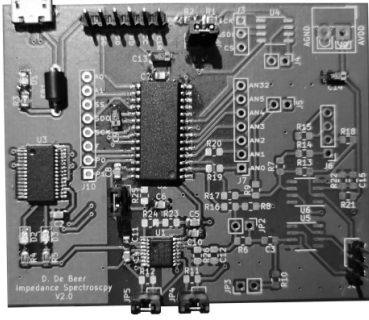


Fig. 2. Image of the low-cost impedance spectroscopy PCB under development.

The micro-controller adjusts the frequency of the wave generator and measures the outputs of the analog front end. The analog front end contains two amplifiers: a voltage buffer amplifier and a transimpedance amplifier. The former buffers the signal from the wave generator to the electrode while the latter converts the resultant current to a voltage that is measurable by the micro-controller.

The design of the analog front end is crucial due to the sensitive nature of the impedance spectroscopy measurement. In short: the system allows a variable frequency voltage to be applied across an electrode and the resultant current is measured to determine impedance. A prototype of the system has been manufactured, but the performance of the system has not yet been characterised.

The Printed Circuit Board (PCB) of the system is completely designed and can be seen in fig. 2. The analog front end portion (right side) of the PCB still needs to be assembled and tested. The digital side (left) including the digital wave generator is complete and has been successfully tested.

III. TEST SETUP

For preliminary testing, an LCR was used with electrodes to measure the impedance spectrum for various concentrations of NaCl and MgSO₄ solutions. The data from these measurements was analysed in order to prove the validity of the impedance spectroscopy measurement as a way to determine TDS accurately.

The solutions for the various NaCl concentrations were prepared by dissolving 5 g of NaCl in a litre of distilled water, resulting in a solution with a TDS of 5000 ppm. Another solution is created by taking some of the initial solution and diluting it by a factor of 10. This process is repeated 3 more times so that the concentrations spans 5 orders of magnitude. The MgSO₄ solutions were prepared by following the same procedure.

Common off-the-shelf header pins with 2.54 mm spacing were used as electrodes for the impedance measurement. An impedance sweep was then performed using the LCR meter and the data is logged to a PC for detailed analysis.

IV. PRELIMINARY RESULTS

Fig. 3 shows how the magnitude of impedance varies with salt concentration for NaCl and MgSO₄ at frequencies of 1 kHz and 1 MHz. Only these frequencies are shown as they contain enough information to derive the TDS. At 1 MHz the impedance of the water samples is almost entirely real. The reciprocal of the 1 MHz is therefore very close to the EC of the sample. At 1 kHz the double layer capacitance plays a key role and the impedance is largely reactive. Down to a concentration of approximately 5 ppm, the 1 MHz impedance changes almost linearly with concentration (on the log-log scales of the graph).

This negative linear relationship is seen due to the fact that conductivity changes roughly linearly with TDS. The linear relationship between EC and TDS is given by

$$EC \approx kTDS, \quad (1)$$

where k is a positive constant. The magnitude of impedance ($|Z|$) is therefore approximately given by

$$|Z| \approx \frac{1}{kTDS}, \quad (2)$$

which on the log-log scale is

$$\log |Z| \approx -\log kTDS. \quad (3)$$

This does not, however, solve the problem of converting from EC to TDS for any salt as the different salts would need different scale values, k , to convert between EC and TDS. Therefore, the salt needs to be identified for the TDS to be calculated.

Fig. 4 shows the ratio between the 1 MHz and 1 kHz impedance values for NaCl and MgSO₄. This ratio is almost identical for the two salts even though the magnitude of their impedance responses (Fig. 3) differ by almost a factor of 4. One can therefore identify which of the two salts are being measured by comparing the value of the ratio (which is the same for both salts) to the magnitude of the impedance response (which is different).

V. DISCUSSION

Using the relationship described in (3), one can approximately determine the TDS in the solution if the value for k is known. In this case, two possible values for k exists: one for NaCl and another for MgSO₄. The exact value for k is largely dependent on experimental parameters and is somewhat arbitrary for the proof of concept. The use of k as a linear operator between EC and TDS is already an approximation.

The results do show, however, that one can determine whether a solution contains NaCl or MgSO₄. This is done by comparing the characteristic curve from fig. 4 to the impedance magnitudes from fig. 3. It is important to note that this method will not work for the full concentration range as ambiguity can arise at the low concentrations: this is due to the curve from fig. 4 not being monotonic.

Due to the ability to discriminate between NaCl and MgSO₄, a scaling factor (k) or a more sophisticated function,

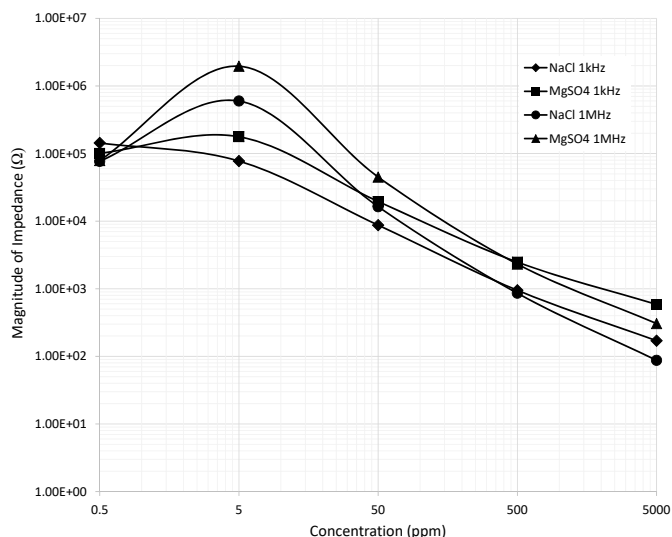


Fig. 3. Impedance magnitude, $|Z|$, as a function of concentration with aqueous solutions of NaCl and $MgSO_4$.

can be used to convert the impedance data to a TDS value based on the salt that is present. This means that TDS can accurately be determined in the 5000 ppm to 5 ppm range with this experimental setup. One can, as mentioned, use more complex algorithms (instead of a linear approximation) to accurately determine TDS over a wider range of concentrations, but more data will be required to verify that the algorithms work.

This method of determining TDS is efficient as only two frequencies are required for this specific measurement. As mentioned in the previous section, the salts are identified by comparing the impedance values at 1 kHz and 1 MHz. This is because this ratio is based on the dissolved solids in the solution and not the conductivity. Therefore, the ratio can be used to predict what the magnitude of the impedance at that concentration should be for the two different salts. Since the two data points used for the ratio are sufficient to determine the salt present and the TDS in that solutions the method is very efficient.

This method combines two very well-established measurements in the form of Impedance Spectroscopy and Electrical Conductivity (for determination of TDS) in a novel way in order to improve the results of the latter. This method includes scope for more diverse measurements that might allow a wider range of salts to be identified and consequently a wider variety of solutions where TDS can be determined with accuracy.

VI. CONCLUSION

The preliminary results are promising for this specific application of impedance spectroscopy. It was shown that impedance spectroscopy can be used to solve one of the fundamental problems with determining Total Dissolved Solids using Electrical Conductivity.

These results need to be repeated with the low-cost impedance spectroscopy system being developed to verify the

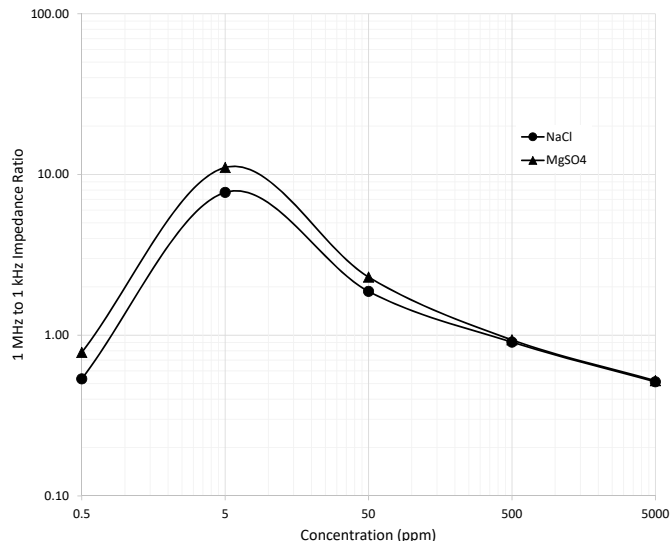


Fig. 4. Ratio between impedance values at 1 MHz and 1 kHz.

performance of the device. Once the operation of the system is verified, the scope of the solutions being measured can be increased. This would entail a wider range of salts, across a wider range of concentrations and eventually a mix of many different solids in a solution.

It is important to note that these results have various limitations. There is no guarantee that the same technique will work for all salts or mixtures of salts in water (mixtures of salts is what would be found in almost any practical water sample). Furthermore, if any salt exists that exhibit very similar impedance characteristics to another salt then the measurement would become fundamentally ambiguous, which could be problematic for some applications.

Impedance spectroscopy, however, is a versatile measurement technique, and the frequency range can be extended to get more information out of the system. Certain high frequency polarisation effects could hold the key to accurately characterising a wide range of solutes in water. The future of this project is to develop the impedance spectroscopy system into an all-purpose water quality measurement system that should be able to derive various quality parameters if the system is accurate enough with a sufficiently wide frequency range.

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