

# Data Analysis and Modelling of a Sodium Salt Matrix with Low-Cost Impedance Spectroscopy <sup>†</sup>

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## Abstract

This study investigates the use of impedance spectroscopy for fingerprinting aqueous salt solutions. By analysing solutions containing Sodium Nitrate ( $\text{NaNO}_3$ ), Sodium Sulphate ( $\text{Na}_2\text{SO}_4$ ), and their mixtures, we explore how impedance data can potentially be used to distinguish between different salt compositions and concentrations. Our findings demonstrate the potential of this method for precise solution characterisation as well as highlighting the benefits of access to low-cost impedance analysers such as the one used for this investigation. More research and data is required to fully realise the potential of this approach.

**Keywords:** impedance spectroscopy; EIS; electrochemistry; low-cost; fingerprinting; data modelling

## 1. Introduction

Electrochemical Impedance Spectroscopy (EIS) is a powerful technique for electrochemical analysis. As the cost of using EIS continues to decrease, it is becoming suited to new applications that were previously not feasible [1–3]. One such application is the on-site, low-cost analysis of aqueous solutions [4]. EIS can provide insight into the movement of ions at or near the electrode surface, potentially enabling the identification and analysis of salts in solution [5]. By correctly “fingerprinting” the effect of a salt on the impedance spectrum, it theoretically becomes possible to identify the contents of a solution based on impedance data alone. This paper details the method for analysing impedance data to facilitate this fingerprinting process. With a larger dataset, this method could enable the identification of solution contents based solely on their impedance.

## 2. Experimental Setup

For the measurements, we utilised a custom low-cost impedance spectroscopy device, as depicted in Figure 1 [6]. The experiment involved a matrix of aqueous salt samples, which contained either Sodium Nitrate ( $\text{NaNO}_3$ ), Sodium Sulphate ( $\text{Na}_2\text{SO}_4$ ), or a mixture of both. The proportions of the different salts in the sample sets were systematically varied, as shown in Table 1. For each sample set, a total of five samples were prepared by diluting the original samples, with the resulting concentrations detailed in Table 2.

A round interdigitated electrode from DropSens was employed for the measurements, as illustrated in Figure 2. The impedance measurements were conducted over a frequency range of 40 Hz to 8 MHz, with an applied voltage of 100 mV and a DC offset of 0 V.



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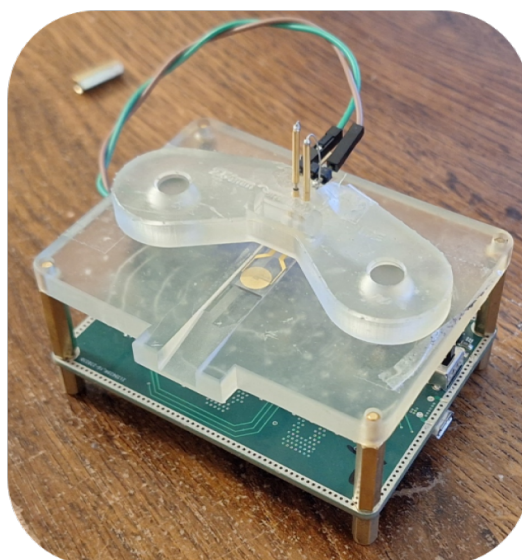
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**Table 1.** Table showing the proportion of Sodium Nitrate ( $\text{NaNO}_3$ ) and Sodium Sulphate ( $\text{Na}_2\text{SO}_4$ ) in each of the five sample sets.

| Sample Set | % $\text{NaNO}_3$ | % $\text{Na}_2\text{SO}_4$ |
|------------|-------------------|----------------------------|
| A          | 0                 | 100                        |
| B          | 25                | 75                         |
| C          | 50                | 50                         |
| D          | 75                | 25                         |
| E          | 100               | 0                          |



**Figure 1.** Image of the low-cost impedance device. Pictured is the device with a 3D-printed electrode holder attached above the circuit board.

**Table 2.** Table showing the total salt concentration of each sample in a sample set.

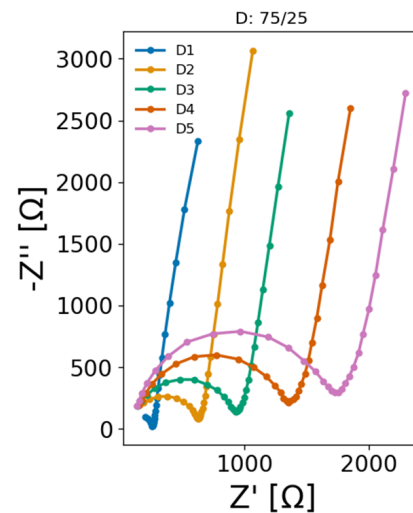
| Sample                            | 1    | 2    | 3    | 4    | 5    |
|-----------------------------------|------|------|------|------|------|
| Total Salt Concentration (mmol/L) | 0.64 | 0.16 | 0.04 | 0.02 | 0.01 |



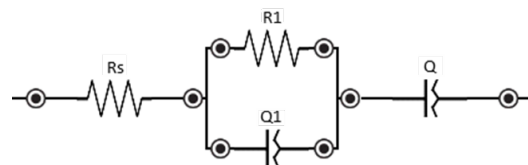
**Figure 2.** DropSens Gold Interdigitated Electrode (round).

### 3. Data Modelling

Based on the Nyquist plots, one of which is shown in Figure 3, we selected a model for fitting the data. The model was fitted using a modified version of the Python package PyEIS (ver. 1.03; Christian K. Knudsen, Trondheim, Norway) [7,8]. The chosen model, depicted in Figure 4, is the R-RQ-Q model [9]. This notation for an impedance model has parallel elements next to each other, with series elements separated by a dash. This model includes several components: a resistor,  $R_s$ , which represents the series resistance of the cable; a resistor,  $R_1$ , which denotes the resistance of the conductive electrolyte RQ circuit; a constant phase element,  $Q_1$ , which models the capacitance in the RQ circuit; and another constant phase element  $Q$ , which represents the interfacial (double-layer) capacitance. Constant phase elements behave almost like capacitors, but have an exponent in addition to a magnitude.



**Figure 3.** Nyquist plots of the impedance measurements for sample set D. This set had a composition of 75% Sodium Nitrate ( $\text{NaNO}_3$ ) and 25% Sodium Sulphate ( $\text{Na}_2\text{SO}_4$ ).



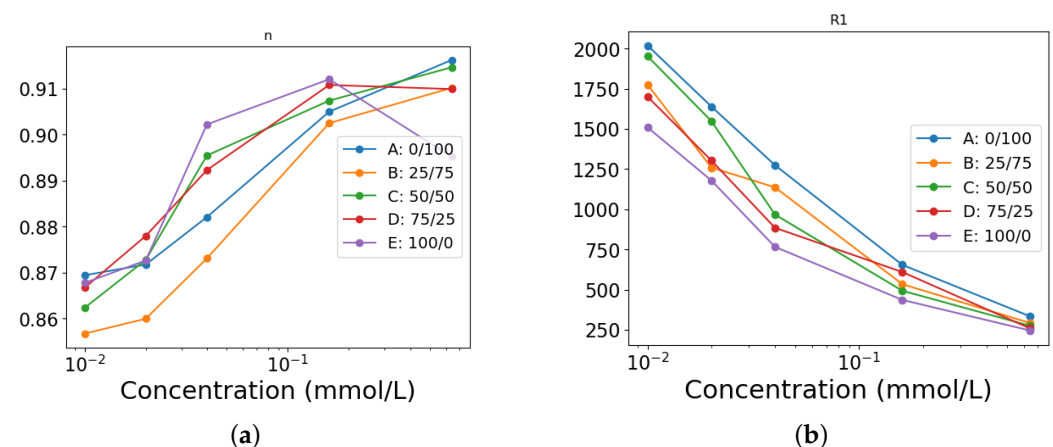
**Figure 4.** Schematic of the R-RQ-Q impedance model.

## 4. Results

From the extracted parameters derived from the modelling process described in the previous section, we can plot these parameters against the total salt concentration of the solutions. These two parameters were selected because their behaviours are most starkly opposed.

Figure 5a illustrates the exponent of the interfacial capacitance as a function of concentration. It is observed that the exponent increases at higher concentrations and is also sensitive to the proportions of the salts present in the samples.

Figure 5b presents the bulk solution resistance of the various samples as a function of salt concentration. The data indicates that the resistance decreases approximately linearly with increasing concentration and varies with different salt concentrations.



**Figure 5.** Two of the extracted impedance parameters plotted against total salt concentration. The composition of the various samples sets can be seen in Table 1. (a) Exponent of the constant phase element model of the interfacial capacitance,  $Q$ . (b) Resistance of  $R_1$ , the resistance in the RQ circuit.

## 5. Discussion

The two extracted parameters in Figure 5a and 5b show that the different impedance parameters are not being affected by the salt concentrations or the salt proportions in a similar manner. The resistance of the solution is changing roughly linearly with the increasing salt concentration and is additionally decreasing as the proportion of Sodium Sulphate is increasing.

This would suggest that the total ionic mobility of Sodium Sulphate is higher than that of Sodium Nitrate, which is supported by the literature. The trends in the exponent of the interfacial capacitance is much less clear. The closer the exponent is to 1, the closer the behaviour of the CPE is to a normal capacitor. The complex behaviour in this parameter along with the other parameters could be used to “fingerprint” the specific salt concentration with its corresponding salt proportions.

## 6. Conclusions

This initial data, along with the procedure to generate it, clearly demonstrates the ease with which low-cost impedance spectroscopy can be used to measure aqueous solutions. Given the ease and low cost of the measurement, in conjunction with the modelling and analysis workflow, one can easily start to accumulate a larger dataset of impedances for different aqueous solutions.

Future work includes significantly expanding the dataset for these salt matrices. For the “fingerprinting” to be effective, a much larger dataset will be required. Different electrodes and impedance spectroscopy parameters will also be investigated.

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