Impedance Spectroscopy

Fortgeschrittenen Praktikum I / II

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August 14, 2014

Abstract

This experiment examines the impedance of a single RC-circuit and two RC-circuits in series. Different types of RC circuits will lead to different impedances at different frequencies. The goal of this experiment is to examine the behaviour of the impedance with different circuits and frequency ranges. Furthermore the data should be analyzed and fitted. At the end the impedance spectra of a solar cell should be measured.

Contents

1 Introduction

When we apply a DC voltage on a resistor, the magnitude of the voltage will change. But if we apply an AC voltage on the resistor, not only the magnitude but also the phase will change. This resistance is called impedance Z. By measuring the impedance of an RC-circuit, i.e. the magnitude and phase, we can determine its resistance. This is used in actual solar cell research to determine the recombination resistance and the chemical capacitance of solar cells.

2 Theory

2.1 Impedance

The impedance can be described with an amplitude and a phase. This leads to the idea to represent the impedance as a complex number $Ae^{i\vartheta}$, with A Amplitude and ϑ phase. If we apply a voltage $U = U_0 e^{i\omega t}$ with a current $I = I_0 e^{i\omega t}$ to a resistor, we will measure an amplitude and a phaseshift, which leads to the voltage $U' = U_1 e^{i(\omega t+\vartheta)}$ and current $I' = I_1 e^{i(\omega t+\varphi)}$. With Ohm's law $U = RI$ we receive

$$Z = \frac{U'}{I'} = \frac{U_1 e^{i(\omega t+\vartheta)}}{I_1 e^{i(\omega t+\varphi)}} = \frac{U_1}{I_1} e^{i(\vartheta-\varphi)} \tag{1}$$

This is the general impedance of any AC-circuit.

2.2 RC-circuit

The following picture shows a parallel RC-circuit:

parallel RC-circuit

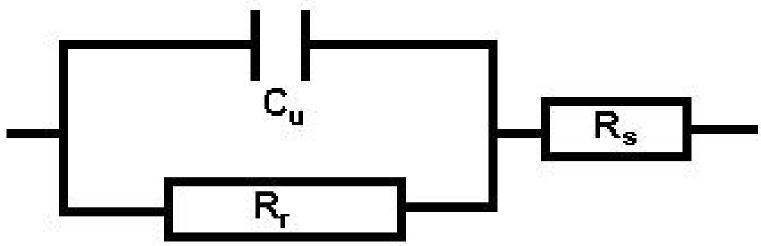

Figure 1: Parallel RC-circuit with a resistor R_s in series. R_s represents the losses in cables and devices.

The impedance of C_u and R_r parallel is given by

$$\frac{1}{Z_p} = \frac{1}{R_r} + i\omega C_u \tag{2}$$

and therefore impedance Z of the whole circuit is

$$Z = R_s + \frac{1}{\frac{1}{R_r} + i\omega C_u} = \frac{R_r}{1+\omega^2 C_u^2 R_r^2} + R_s - i\frac{\omega C_u R_r^2}{1+\omega^2 C_u^2 R_r^2} \tag{3}$$

If we sweep the frequency and plot the real and imaginary part of Z with ReZ on the x-axis and ImZ on the y-axis, the generated graph is called a Nyquist plot.

Nyquist plot of a RC-circuit

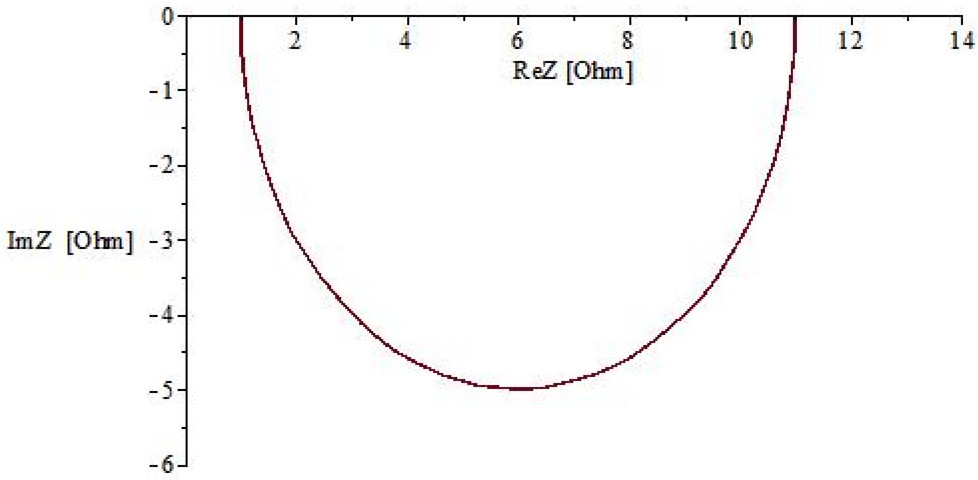

Figure 2: Nyquist plot of the impedance of a RC-circuit with $R_s = 1\,\text{Ohm}$, $R_r = 10$ Ohm and $C_u = 2\mu F$.

2.3 Fitting an Impedance

It is in general not possible to fit vector functions (at least with Mathematica and Igor) like $\mathbb{R} \rightarrow \mathbb{R}^2, f(x) \mapsto (Re[f(x)], Im[f(x)])$ as we have it in our case. But it is possible to write this function as a skalar like $\mathbb{R}^2 \rightarrow \mathbb{R}$ but with an additional parameter $f(x,s) \mapsto (Re[f(x)], Im[f(x)]) \cdot (1-s, s)$. This is a function we can fit. In general we receive the form

$$f(\omega, s) = Re[Z](1-s) + Im[Z]s \tag{4}$$

and if we put in our impedance from the RC-circuit we receive

$$Z(\omega, s) = \left(\frac{R_r}{1+\omega^2 C_u^2 R_r^2} + R_s\right)(1-s) - \frac{\omega C_u R_r^2}{1+\omega^2 C_u^2 R_r^2} s \tag{5}$$

Another point is, that we have now the double amount of points as with the two dimensional function. Our new parameter s determines if the value is a real or imaginary part of Z so s can take values of 0 (real) or 1 (imaginary).
For further information see [NLSF page].

3 Experimental Setup

Experimental Setup

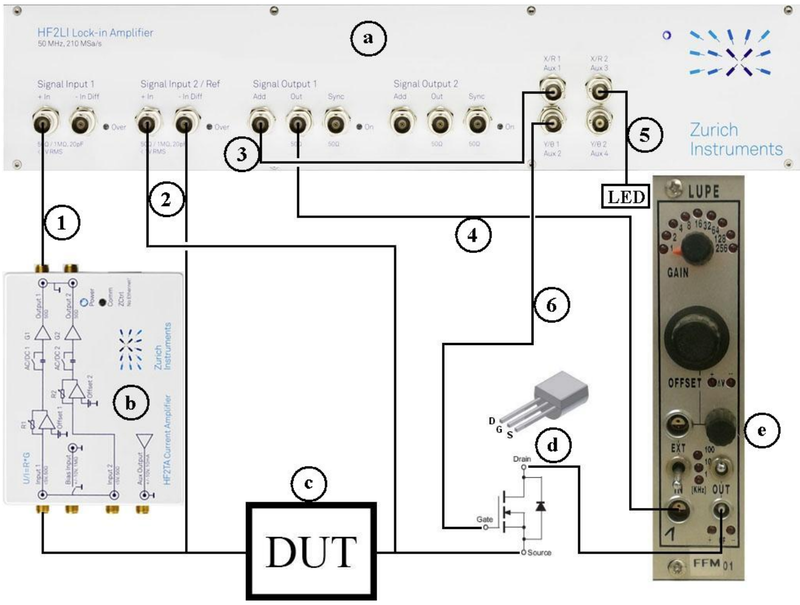

Figure 3: Our experimental setup with an HF2LI Lock-in Amplifier, HF2TA Current Amplifier and a magnitude stabilisator.

(a) **HF2LI Lock-in Amplifier** from Zurich Instruments which provides our AC signal and measures the current and voltage.

(b) **HF2TA Current Amplifier** from Zurich Instruments to amplify our current in order to be able to measure the current.

(c) The RC-circuit or the cell

(d) MOSFET to open or close the current circuit. With this we can measure the voltage with a closed circuit setup without modifying anything.

(e) This device stabilizates the magnitude of our signal.

1. Cable to the HF2LI to measure the current.

2. With these two cables the current of the cell/circuit is being measured by the HF2LI.

3. This adds a bias offset to the output AC signal. This is used for solar cell measurements. The cell itself has a voltage and to negate this we add the same voltage but with opposite sign to our output AC signal. There should be no DC voltage at the cell, because the measurement depends on the bias voltage (you can test this if you want). This mechanism ensures that at the cell is only the AC voltage.

4. The AC output signal from the HF2LI.
5. This DC signal is to power the LED.
6. This signal powers the gate of the MOSFET to open or close the circuit.

4 Measuring the Impedance

Follow these steps to measure the impedance:

1. Check if everything is set up as shown in figure 3.
2. Make sure your **HF2LI Lock-in Amplifier** and the **Regler Rack 10** is turned **on**
3. Start the the **ISMeasurement.exe** program located in L:\fp\Experimente\FP49_Impedanzspektroskopie
4. In the settings tab, **load the settings**. The right path should already be choosen (L:\fp\Messdaten\EIS\Zhinst\ZurichInstrumentsSettings.zicfg)
5. The first table with **Cell V**, **LED V** and **% Illumination** as column captions are only needed if you measure a solar cell. Make sure that there is no entry and that the **Calculate Voltage** button is on false. If you measure a solar cell, you need to fill this table to measure with different illuminations. If a solar cell is illuminated, it creates a voltage (you can easily check this with a multimeter). As described in the experimental setup section, this voltage has to be added to the AC signal. In general, a desired **Cell V** (cell voltage) is given and the voltage of the LED has to be calculated, so that the LED emits exact the intensity the cell needs to produce **Cell V**. This program automatically calculates this **LED V**. All you need to do is to fill in the **Cell V** (usually between 0.45 and 0.6) and the **% Illumination** (any number). You can choose as many different cell voltages as you want. Just make sure that the **% Illumination** is different in every data entry.
6. In the next table, you can choose the **frequency** you want to sweep and the **amount of points** it should measure. The **bandwidth** determines the precision of the measurement. The lower the bandwidth, the higher the accuracy, but the measurement will take longer. If **Log Sweep** is 0, then the points are distributed linearly on the sweep range. Otherwise they will be distributed logarithmically. You can split up your measurement in different sweep ranges with different bandwidths and amount of points to optimize your measurement.
7. Choose a **non-existing folder** to save the data. The program will automatically save a plot and the data into this folder after the measurement (even if you abort the measurement). Make sure you have write permissions.

8. Do not touch the **Advanced Settings** tab. To obtain the default settings, first restart the program and the HF2LI Lock-in Amplifier and then load the settings again.

9. Go to the **Measurements** tab and start you measurement. You can see the current measurement point and frequency. The progress and a time estimation is also available. If the error light is on, then is probably something in the settings tab at the 2nd table wrong. Choose other parameters for the frequency range, amount of points and/or the bandwidth.

10. Wait until the measurement has finished.

11. Grab your data in the folder you have choosen. The file "1.txt" contains the data that is needed for the automatic plot and "3.txt" has the columns [Frequency, ReZ, ImZ]. **Note:** The imaginary part in every file has been multiplied by -1, so we have a positive semi circle. Bear this in mind when you implement the fitting function.

12. If you measured a single RC-circle, you can copy both the Igor Experiment and Procedure file from L:\fp\Experimente\FP49_Impedanzspektroskopie\IgorFitting\1RC to your measured data and just run the igor procedure. If you measured two RC-circuits in series then you need to copy the files in the 2RC folder and you need to create a Coef.txt file in the **Data Analysis** tab of the program.

13. The last tab, the **Data Analysis** is to calculate your starting coefficients for the fit. Load the file 3.txt created by your measurement. Then drag the cursor to the first root or the closest point to it of the graph. Then click on **Add** to add the values to the table. Now drag the cursor to the first maximum and press **Add**, and then the same with the second maximum. Click on **Save** to create the coef.txt file you need for the fit. Now you can run the Igor procedure for two RC-circuits in series.

5 Excercises

5.1 Measurements

- Build a RC-circuit and measure the impedance. Find a good frequency sweep range which covers the whole semi circle.

- Measure two RC-circuits in series. How do you need to choose the resistances and capacities to get two separated semi circles? Make a measurement of two separated semi circles, otherwise you will not be able to fit it. Create a coef.txt file after the measurement.

- Measure a solar cell.

5.2 Data Analyzation

- Fit the Nyquist plot of a single RC-circuit and with two in series with the Igor procedure given or do the fit with another tool of your choice.

- Determine the resistances of your circuit. How big are the resistances? Does it fit with a simple multimeter measurement? If not, why not? How big is the capacity?

References

[NLSF page] http://mathworld.wolfram.com/NonlinearLeastSquaresFitting.html