Chapter 5

Practical implementation

Presented in this chapter is the practical implementation of the current interrupt method. An overview of the experimental setup and procedure is discussed. Results from the natural voltage response method and current switching method are presented and discussed. The practical validation of the NVR method and the CS method are also presented and discussed.

5.1 Introduction

The purpose of the CI method is to model various characteristics of the PEM electrolyser. The characteristics include the following, Membrane Electrode Assembly (MEA) components of the electrolyser like the PEM, the catalyst layer and other electrochemical phenomena. To address this need the NVR and CS methods were verified and validated with simulation models and are practically implemented.

The experimental assembly, the equipment that was used for the duration of the experiments and the experimental conditions are discussed. The purpose of this chapter is to illustrate that the NVR method and CS method can be practically implemented.

The practical implementation of the NVR method is discussed. The experiments were performed at various temperatures and cell current values. The experimental results of the NVR method and the Randles cell parameters are discussed. The validation of the PEM resistance values are discussed.

The practical implementation of the CS method is discussed. The experiments were performed for the same temperatures and current values as the NVR method. The practical results of the CS method and the Randles-Warburg cell parameters are discussed. The system response of the Randles-Warburg cell is validated with SI.

5.2 PEM electrolyser experimental setup

A block diagram of the experimental setup is shown in Figure 5.1. The hotplate is used to heat the water and is pumped to the anode of the PEM electrolyser. Thermocouples T1 to T4 are used to measure the temperatures of the water at the inlet, the water in the cylinder, the anode and the cathode. The National Instruments (NI) Compact Reconfigurable Input Output (cRIO) controller and the oscilloscope are accessed wirelessly with the personal computer through a Wireless Access Point (WAP).

The NI cRIO controls two modules where one is used to generate the switching signal for both the NVR and SI methods, and the other module reads the thermocouple measurements. The oscilloscope is used to measure the voltage and current waveforms, via voltage and current probes, for both the NVR and SI methods. The power supply delivers the DC to the PEM electrolyser and in turn hydrogen is produced. An Negative Metal Oxide Semiconductor Field Effect Transistor (NMOSFET) is used as the switch. A detailed design and visual depiction of the switch

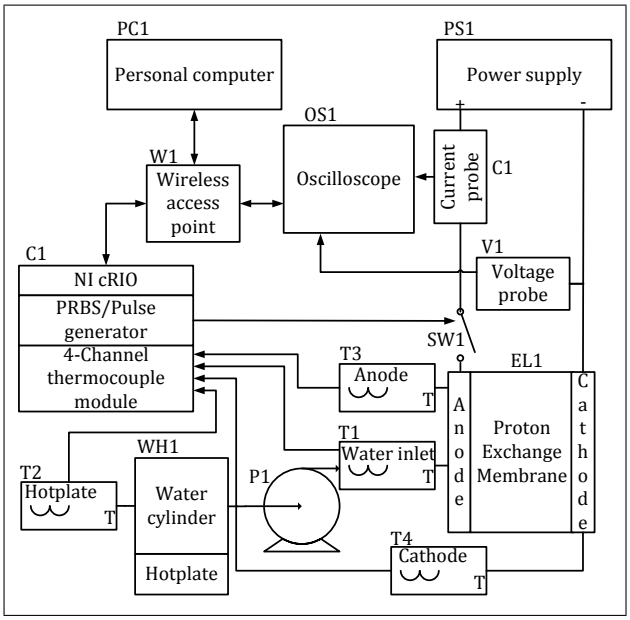


Figure 5.1: Block diagram: PEM electrolyser experimental assembly

is presented in appendix B. A visual depiction of the experimental setup is shown in Figure 5.2.

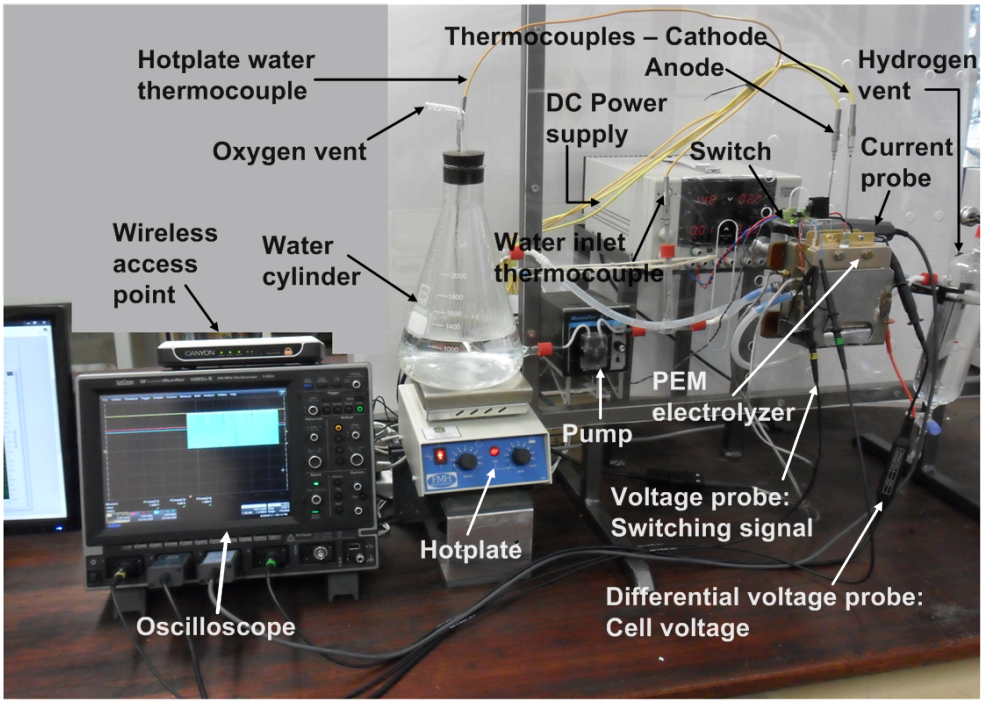


Figure 5.2: PEM electrolyser experimental assembly

5.2.1 Experimental procedure

In Figure 5.3 a flow diagram of the experimental procedure for both the NVR method and CS method is shown. Firstly, the practical system is assembled as discussed in Section 5.2. The NVR method and CS method are applied separately under the conditions that are discussed in Section 5.2.2. The current and voltage waveforms are recorded and the data is saved. The data will be analysed to obtain the EEC parameter values.

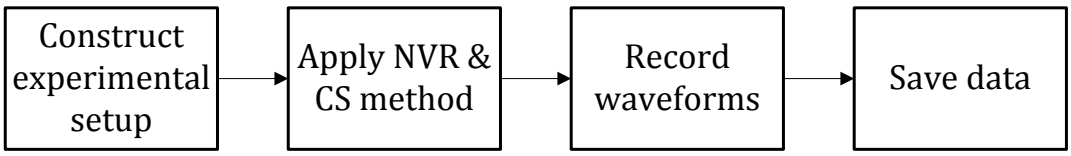


Figure 5.3: Flow diagram: Experimental procedure

The simulation model was simulated in an ideal environment. Since there exist non-ideal effects such as noise and other parasitic components within the practical system the following assumptions are made:

- Non-ideal power source.
- Non-ideal switch.
- Non-ideal conductors which exhibits resistive and inductive effects.
- Non-ideal PEM electrolyser which exhibits resistive, capcitive and inductive effects.

5.2.2 Experimental conditions

The characteristics of the PEM electrolyser and the experimental conditions are presented in Table 5.1.

Table 5.1: PEM electrolyser characteristics and experimental conditions

Characteristics and conditions	Value
Membrane area	5 cm^2
Membrane type	Nafion® 117
Catalyst loading: Anode	4.5 mg Pt/cm^2
Cathode	3.5 mg Pt/cm^2
Gas diffusion layer: Anode	Titanium mesh
Cathode	Carbon paper
RH	100%
Water flow rate	10 ml/min
Water inlet temperature	60-80 °C
Pressure	Atm

The experimental assembly and the experimental conditions were discussed. The practical implementation of the NVR method and the CS method are discussed in the succeeding sections. The results from each method are presented a conclusion.

5.3 Natural voltage response method

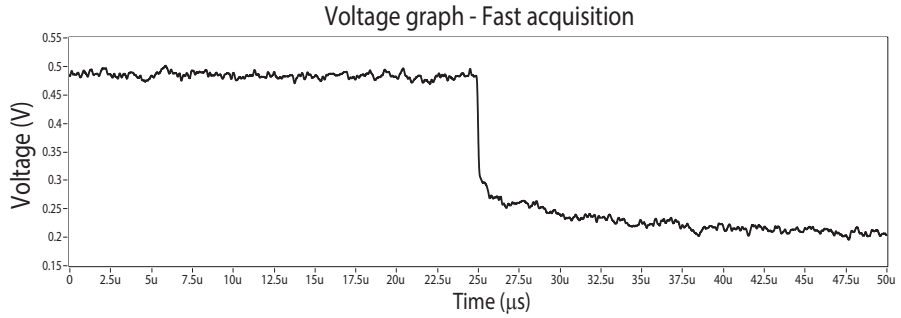
In this section the practical implementation of the NVR method is discussed. The current and voltage waveforms are shown in Figure 5.4 and Figure 5.4 . The waveforms in Figure 5.4 are used to calculate the parameter R_m. The current and voltage waveforms depicted in Figure 5.5 are used to calculate the parameters R_{ct} and C_{dl}. Nine experiments were performed and the values of the cell current and temperatures are presented in Table 5.2.

The parameters I_0, t_0, t_1, V_0, V_1 are read from the current and voltage waveforms and are depicted in Figure 4.4 and Figure 4.5. These values, presented in Table 5.3, are used to calculate the parameters of the Randles cell.

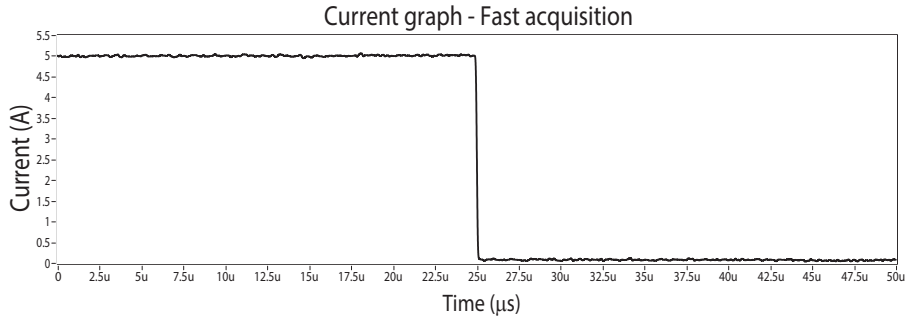
The calculated parameters of the Randles cell are presented in Table 5.4. At low current densities the activation losses are high. From the results it is noted that R_{ct} decreases

Table 5.2: Experimental conditions: Temperature and cell current values

Experiment	Temperature	Cell current
1	60 °C	1 A
2	60 °C	3 A
3	60 °C	5 A
4	70 °C	1 A
5	70 °C	3 A
6	70 °C	5 A
7	80 °C	1 A
8	80 °C	3 A
9	80 °C	5 A



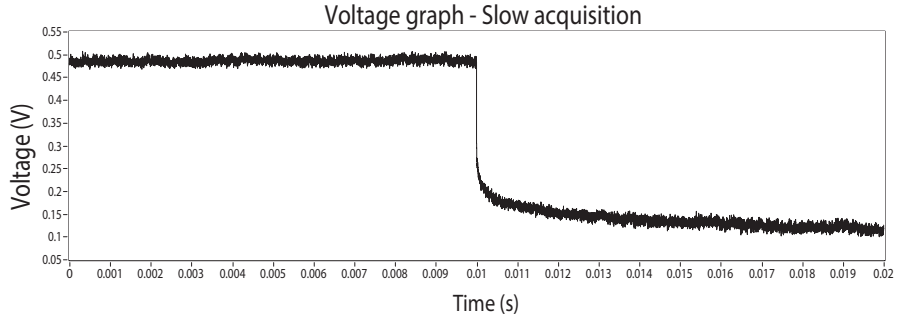
(a) Cell voltage



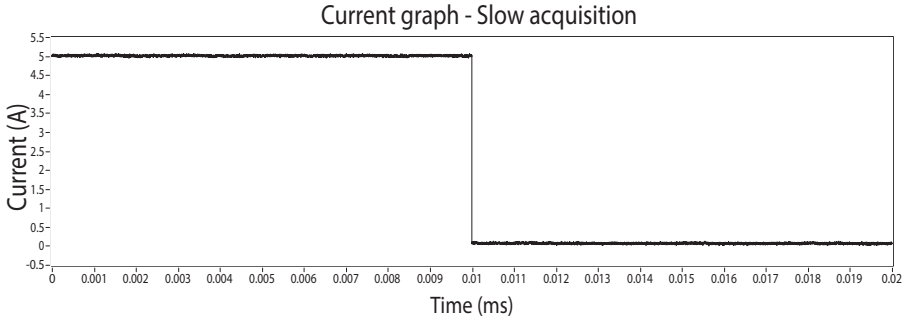
(b) Cell current

Figure 5.4: Experimental data: NVR curve (Fast acquisition)

with an increase in the cell current. This correlates with the theory of the PC, where the activation losses drop with an increase in current density.



(a) Cell voltage



(b) Cell current

Figure 5.5: Experimental data: NVR curve (Slower acquisition)

5.3.1 Practical validation

The membrane resistance values are validated with conductivity values for Nafion 117 type membranes [29]. The conductivity of the PEM can be calculated by:

$$\sigma = \frac{L}{AR_m}, \tag{5.1}$$

where σ is the PEM conductivity (S/cm), A is the area of the MEA (cm^2) and R_m is the membrane resistance (Ω).

It is noted that the conductivity values for Nafion 117 ranges from 0.07 S/cm at RH 100% (25°C) to 0.14 S/cm RH 100% (65°C) [29]. For the PEM with an active area of 5 cm^2, this correlates to a membrane resistance of 50.8 mΩ down to 25.4 mΩ. The conductivity values (σ_m) of the PEM is presented in Table 5.5. From the practical results it is seen that the calculated conductivity values correlates with the conductivity values given in [29]. It is concluded that the calculated PEM membrane values are validated.

Table 5.3: Experimental results: NVR parameters

NVR Parameter	Experiment 1 Value	Experiment 2 Value	Experiment 3 Value
I_0	1.101 A	3.010 A	4.600 A
t_0	0.100 s	0.100 s	0.100 s
t_1	0.200 s	0.200 s	0.200 ms
V_0	272.2 mV	446.6 mV	736.8 mV
V_1	237.8 mV	330.4 mV	558.9 mV
V_{t1}	142.5 mV	207.5 mV	245.1 mV
τ_{rc}	19.55 ms	14.25 ms	11.39 ms
	Experiment 4	Experiment 5	Experiment 6
I_0	1.010 A	3.050 A	5.000 A
t_0	0.100 s	0.100 s	0.100 s
t_1	0.200 s	0.200 s	0.200 ms
V_0	269.8 mV	413.3 mV	635.8 mV
V_1	228.8 mV	310.4 mV	441.4 mV
V_{t1}	182.3 mV	207.5 mV	225.1 mV
τ_{rc}	43.69 ms	24.33 ms	14.84 ms
	Experiment 7	Experiment 8	Experiment 9
V_0	280.2 mV	454.2 mV	484.3 mV
I_0	1.000 A	3.010 A	5.130 A
V_1	237.3 mV	332.3 mV	420.5 mV
V_{t1}	160.3 mV	215.1 mV	305.5 mV
t_0	0.100 s	0.100 s	0.100 s
t_1	0.200 s	0.200 ms	0.200 ms
τrc	25.37 ms	24.57 ms	11.19 ms

Table 5.4: Experimental results: Randles cell parameter values

NVR Parameter	Experiment 1 Value	Experiment 2 Value	Experiment 3 Value
R_m	35.82 mΩ	38.74 mΩ	38.67 mΩ
R_{ct}	210.2 mΩ	110.1 mΩ	121.5 mΩ
C_{dl}	93.01 mF	129.4 mF	93.74 mF
	Experiment 4	Experiment 5	Experiment 6
R_m	28.18 mΩ	39.03 mΩ	38.88 mΩ
R_{ct}	226.5 mΩ	101.8 mΩ	88.28 mΩ
C_{dl}	192.9 mF	238.9 mF	168.1 mF
	Experiment 7	Experiment 8	Experiment 9
R_m	38.82 mΩ	40.02 mΩ	35.75 mΩ
R_{ct}	237.3 mΩ	110.4 mΩ	81.97 mΩ
C_{dl}	106.9 mF	222.5 mF	135.5 mF

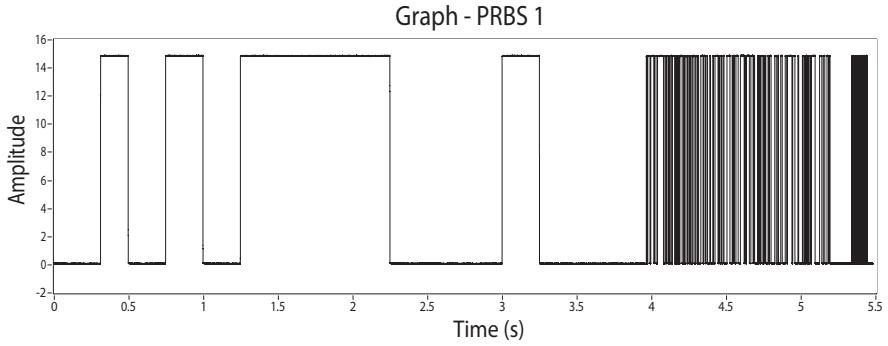
Table 5.5: Experimental results: PEM resistance and conductivity values

Experiment	σ_m
1	0.099
2	0.092
3	0.092
4	0.126
5	0.091
6	0.091
7	0.091
8	0.089
9	0.099

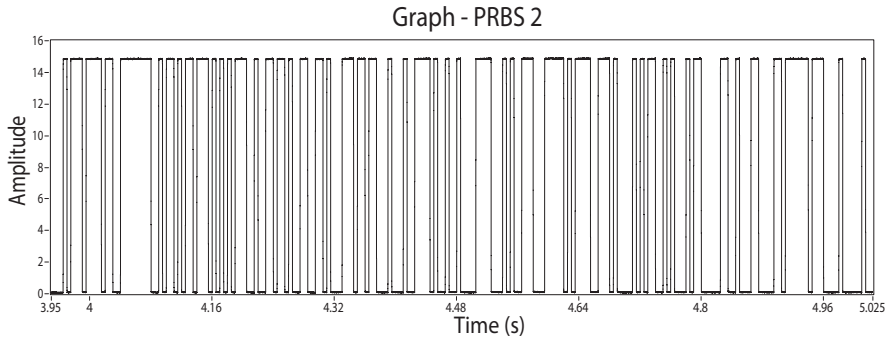
5.4 Current switching method

In this section the practical results of the CS method are presented and discussed. The parameters of the Randles-Warburg cell are calculated as described in Section 3.3. In Figure 5.6 is a depiction of the three PRBS signals that are applied to the switch.

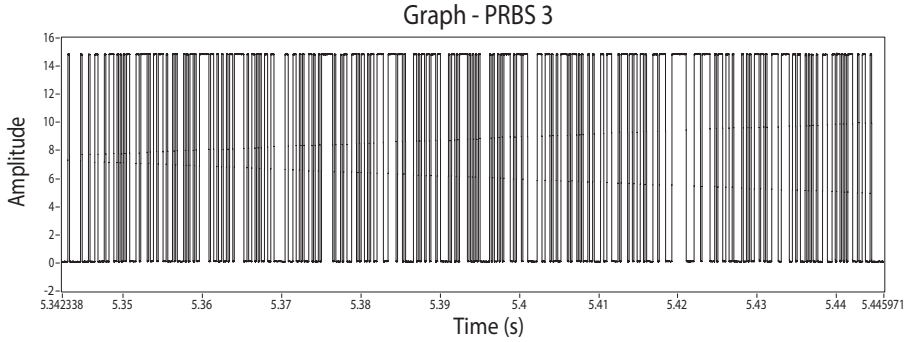
In Figure 5.6 (b) is a depiction of the second PRBS signal and in (c) is a depiction of the third PRBS signal. The cell current, cell voltage, stimulus and the response graphs were generated for experiment 9. Only the waveforms of experiment 9 are included since it would be redundant to include the graphs for every experiment. The different graphs are only used for illustration purposes.



(a) Complete PRBS signal



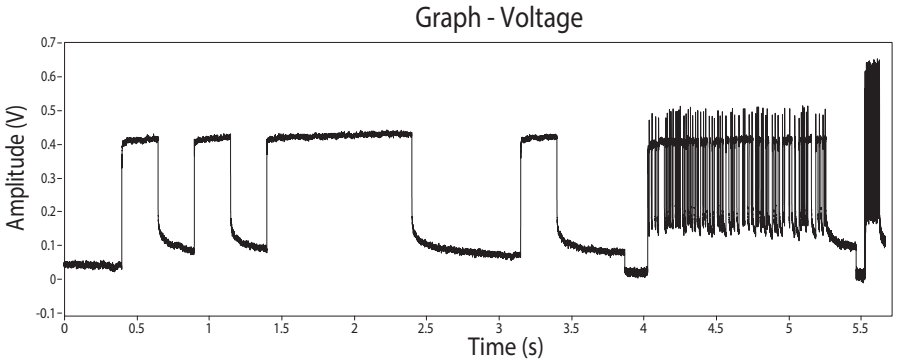
(b) PRBS 2 signal



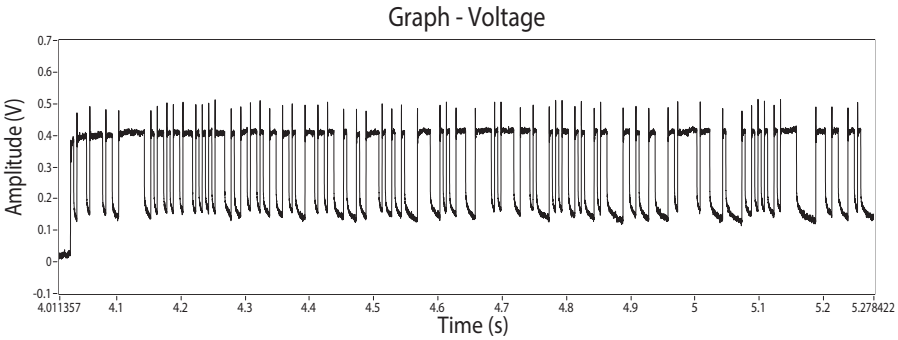
(c) PRBS 3 signal

Figure 5.6: CS method experimental data: PRBS switching signals

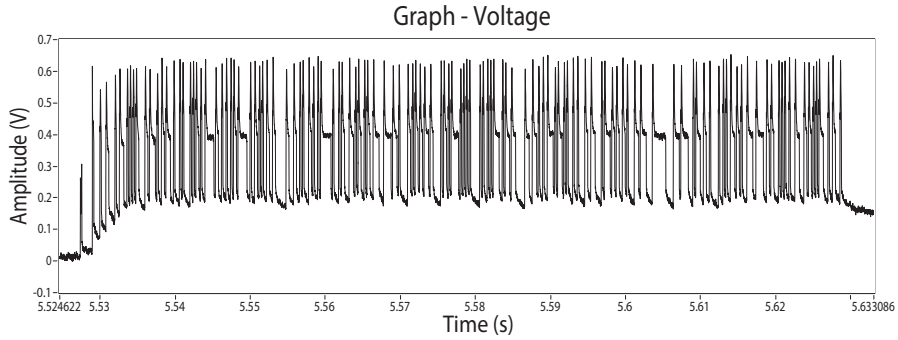
The measured voltage signal, before it is filtered and resampled, is depicted in Figure 5.7. In Figure 5.7 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 5.7 (b) and (c) are depictions of the voltage waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell voltage - Complete signal



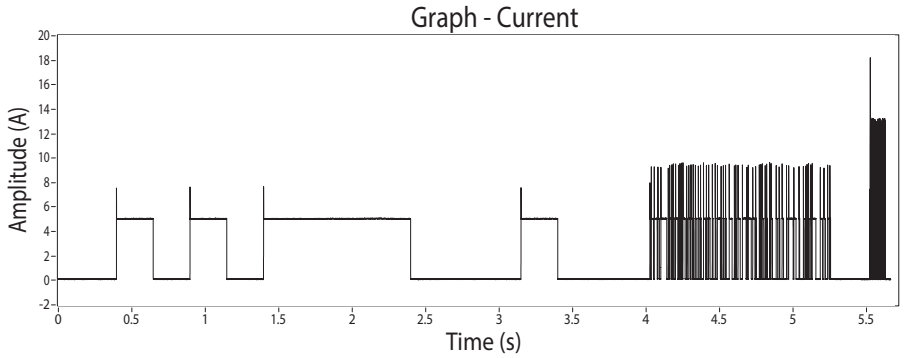
(b) Cell voltage - During application of PRBS 2 signal



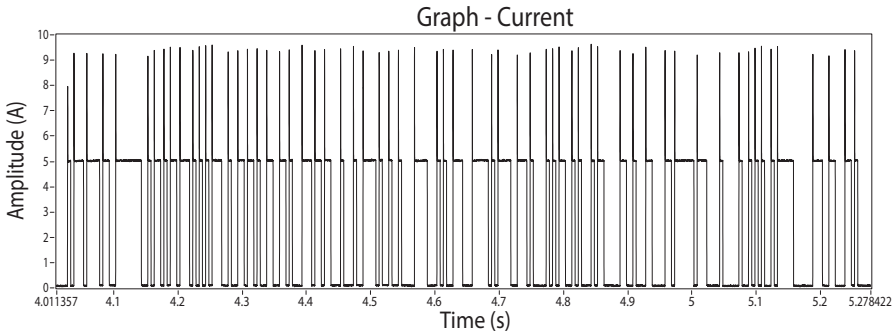
(c) Cell voltage - During application of PRBS 3 signal

Figure 5.7: CS method experimental data: Cell voltage during applied PRBS signals

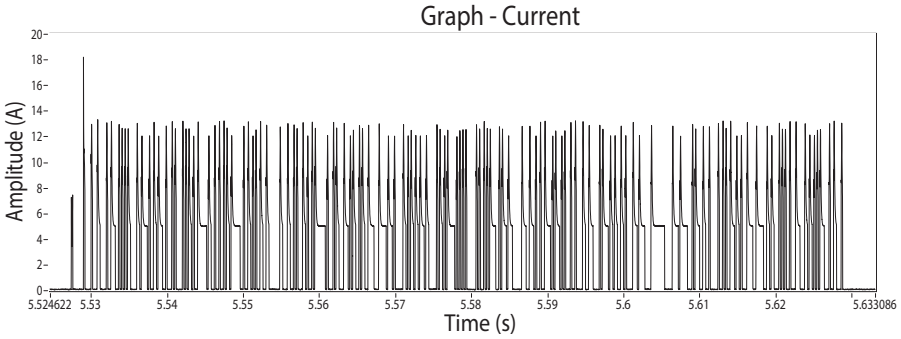
The measured current signal, before it is filtered and resampled, is depicted in Figure 5.8. In Figure 5.8 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 5.8 (b) and (c) are depictions of the current waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell current - Complete signal



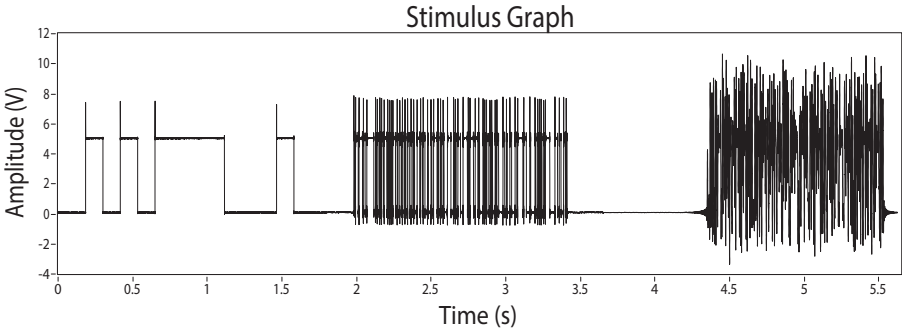
(b) Cell current - During application of PRBS 2 signal



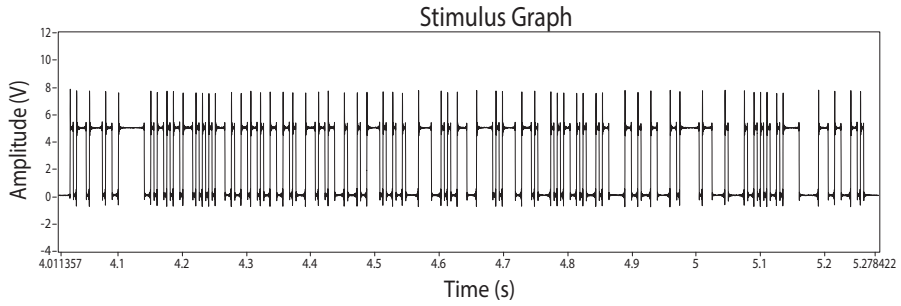
(c) Cell current - During application of PRBS 3 signal

Figure 5.8: CS method experimental data: Cell current during applied PRBS signals

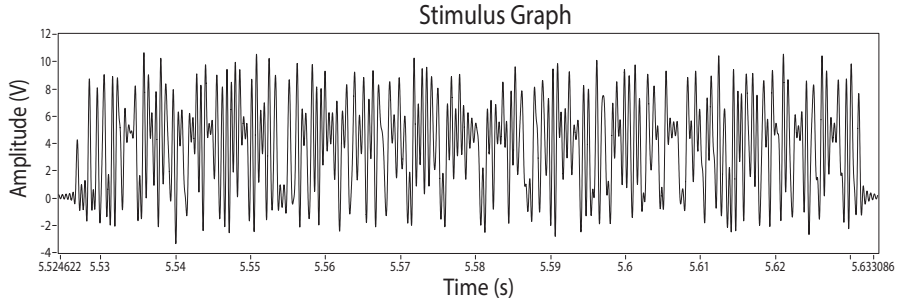
The filtered and resampled stimulus signal is depicted in Figure 5.9. In Figure 5.9 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 5.9 (b) and (c) are depictions of the stimulus waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell stimulus - Complete signal



(b) Cell stimulus - Portion during PRBS 2 signal



(c) Cell stimulus - Portion during PRBS 3 signal

Figure 5.9: CS method experimental data: Cell stimulus during applied PRBS signals

The Randles-Warburg transfer function coefficients were generated with SI. The values of the transfer function coefficients, for experiments 1 to 9, are presented in Table 5.6.

Table 5.6: CS method experimental results: Transfer function coefficients

NVR Parameter	Experiment 1	Experiment 2	Experiment 3
b	0.002512	0.002138	0.001765
c	0.230148	0.178270	0.130480
d	0.314000	0.183317	0.141817
f	0.051175	0.044085	0.036090
g	1.584900	1.871769	1.557275
	Experiment 4 Value	Experiment 5 Value	Experiment 6 Value
b	0.002188	0.001970	0.001833
c	0.230658	0.102690	0.131897
d	0.342633	0.164676	0.121535
f	0.048150	0.044168	0.042217
g	1.577000	1.801330	1.804687
	Experiment 7 Value	Experiment 8 Value	Experiment 9 Value
b	0.001926	0.001542	0.001284
c	0.191846	0.132585	0.100007
d	0.278994	0.144966	0.106949
f	0.045560	0.037797	0.031752
g	1.387679	1.544480	1.444471

The R_m values presented in Table 5.7 were calculated with the NVR method as discussed in Section 5.3. The coefficients, the R_m values and the Warburg coefficients are used in the non-linear simultaneous equation solver to obtain the parameters of the Randles-Warburg cell. The calculated Randles-Warburg parameters are presented in Table 5.7.

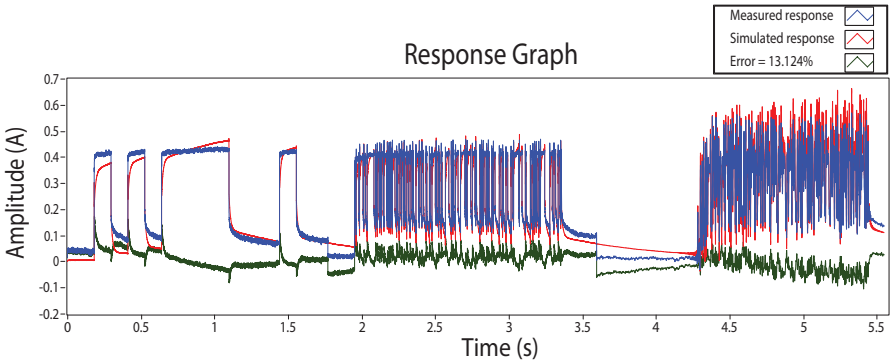
Table 5.7: CS method experimental results: Randles-Warburg parameters

NVR Parameter	Experiment 1	Experiment 2	Experiment 3
R_m	35.82 mΩ	38.74 mΩ	38.67 mΩ
R_{ct}	93.53 mΩ	46.85 mΩ	39.08 mΩ
C_{dl}	181.5 mF	146.0 mF	233.9 mF
R_d	187.6 mΩ	99.22 mΩ	65.04 mΩ
τ_d	4.760 s	5.740 s	4.755 s
	Experiment 4 Value	Experiment 5 Value	Experiment 6 Value
R_m	28.18 mΩ	39.03 mΩ	38.88 mΩ
R_{ct}	98.85 mΩ	433.3 mΩ	28.95 mΩ
C_{dl}	146.0 mF	192.2 mF	252.9 mF
R_d	218.8 mΩ	83.36 mΩ	54.53 mΩ
τ_d	4.132 s	5.513 s	5.533 s
	Experiment 7 Value	Experiment 8 Value	Experiment 9 Value
R_m	38.82 mΩ	40.02 mΩ	35.75 mΩ
R_{ct}	87.31 mΩ	39.19 mΩ	29.61 mΩ
C_{dl}	222.1 mF	265.6 mF	306.7 mF
R_d	115.2 mΩ	66.15 mΩ	42.21 mΩ
τ_d	4.138 s	4.705 s	4.413 s

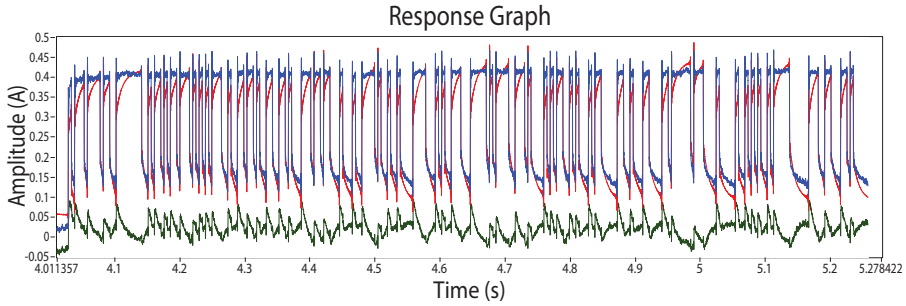
5.4.1 Practical validation

In this section the validation of the response signal is presented. The model validation toolbox is used to simulate the response of a signal to an input (stimulus) signal. The simulated response is compared with the measured response and the calculated error is reviewed.

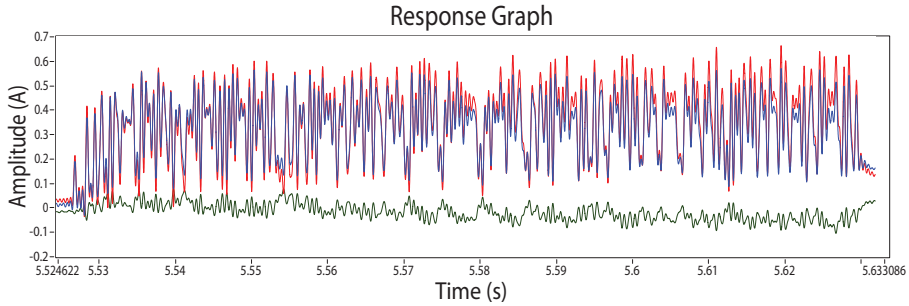
The filtered and resampled response signal is depicted in Figure 5.10. In Figure 5.10 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 5.10 (b) and (c) are depictions of the response waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell response - Complete signal



(b) Cell response - Portion during PRBS 2 signal



(c) Cell response - Portion during PRBS 3 signal

Figure 5.10: CS method experimental data: Cell response during applied PRBS signals

From Figure 5.10 it seen that error is relatively large, but the simulated response has the same trend as the measured response. The errors between the measured response and the simulated response graphs are presented in Table 5.8.

Table 5.8: CS method experimental results: Measured response versus simulated response errors

Experiment nr	Error (%)
1	17.02
2	12.91
3	12.09
4	17.55
5	13.77
6	11.46
7	19.31
8	15.45
9	13.12

5.5 Conclusion

The NVR method was practically implemented to obtain the parameters of the Randles cell. The PEM resistance values were validated with the conductivity values of Nafion® 117. The CS method was practially implemented to obtain the parameters of the Randles-Warburg cell. The measured response of the Randles-Warburg cell was compared with the simulated response. Future recommendations regarding this project are presented in the succeeding chapter.