

Chapter 4

Simulation

Presented in this chapter is the implementation of the natural voltage response method and the current switching method in simulation. A simulation model is designed to represent the practical system and utilised to generate simulation data. The simulation data is analysed to obtain the parameters of the equivalent electric circuits. Lastly, the NVR method and the CS method is verified and validated.

4.1 Introduction

The NVR and CS method is tested in simulation before it is practically implemented. The simulation model is developed to represent the practical system as closely as possible. The software must be able to simulate the EECs and other electrical components.

Verification and validation are processes which are implemented to ensure the accuracy of the simulation model. During the verification process the simulation model is reviewed, inspected, tested and checked to indicate whether the model

conforms to the requirements. Validation is the process whereby multiple model results are produced and compared to indicate the accuracy of the model.

The NVR method will be verified with a simulation model of the Randles cell and the CS method will be verified with a simulation model of the Randles-Warburg cell. The parameter values of the Randles cell is varied and multiple simulation data is generated in order to validate the NVR method. The simulation data is analysed and the results are compared. If the error between the simulated and calculated parameter values of the Randles cell parameters are small, the NVR method is considered to be validated. The same approach is followed to validate the CS method.

4.2 Natural voltage response method

4.2.1 Simulation model

A simulation model is developed for the NVR method. A Simulation Program with Integrated Circuit Emphasis (SPICE) software package is needed to generate the simulation data for the NVR method. LTspice[®] is used to generate the SPICE data. Since the SPICE simulations are performed under ideal conditions the following assumptions are made:

- Ideal switching.
- Ideal power sources with noise-free output.
- Ideal conductors with no parasitic effects.
- Ideal PEM electrolyzers containing only resistive and capacitive effects.

A depiction of the simulation model in LTspice[®] is presented in Figure 4.1. It consists of the source voltage, the Randles cell, the standard thermodynamic voltage, the switch and the switching signal source.

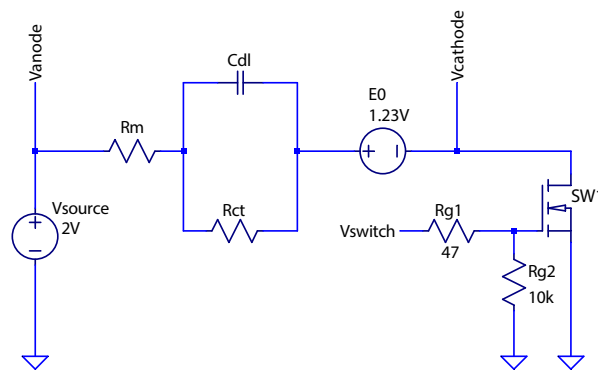


Figure 4.1: LTspice[®] schematic: Simulation model for NVR method

A flow diagram which illustrates the simulation procedure for the NVR is depicted in Figure 4.2. The first step is to develop the Randles cell simulation model in LTspice[®]. Simulation values for the Randles cell parameters are selected and applied. To perform the simulation, specific LTspice[®] command settings are applied.

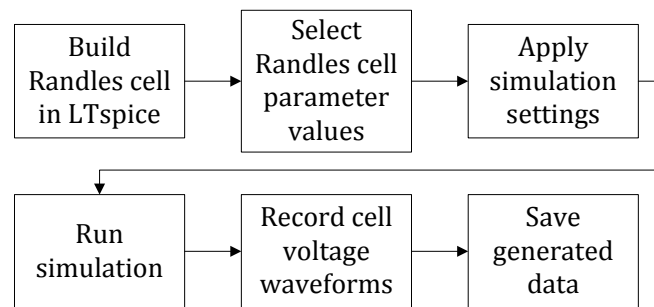


Figure 4.2: Flow diagram: NVR simulation process

The simulation command settings consists of the stop time, the time to start saving data and the maximum time step. Other important simulation settings are the SPICE settings and the data compression settings, which are given in appendix A.3.

In order to obtain accurate results of the membrane resistance, the voltage drop after current interruption should be sampled at a high frequency. The time to measure the voltage drop after current interruption should be in the order of 0.5 to 10 ns [28]. The LTspice[®] command settings that were used to obtain the fast voltage drop is given in Table 4.1.

Table 4.1: The LTspice[®] command settings for NVR method (Fast acquisition to obtain R_m)

LTspice [®] command setting	Value
Stop time	50 μ s
Time to start saving data	0 s
Maximum timestep	10 ns

The LTspice[®] command settings that were used to obtain the voltage drop due to the discharging of C_{dl} through R_{ct} is given in Table 4.2. The current and voltage waveforms are given in Figure 4.5.

Table 4.2: The LTspice[®] command settings for NVR method (Slower acquisition)

LTspice [®] command setting	Value
Stop time	1 s
Time to start saving data	0 s
Maximum timestep	10 μ s

4.2.2 Simulation analysis

A flow diagram of the simulation analysis is depicted in Figure 4.3. The current and voltage waveform is read into the analysis program. The parameter I_0 is read from the current waveform, where the parameters t_0 , V_0 , and V_1 are read from the voltage waveform. From these results R_m and R_{ct} can be calculated. The parameters t_1 and $v(t_1)$ are read from the voltage graph to calculate τ_{rc} . From the parameters R_{ct} and τ_{rc} the double layer capacitance C_{dl} can be calculated.

LabVIEW[™] is used for the mathematical analysis of the NVR method. The simulated data from the simulation model is read into LabVIEW[™]. The data is analysed and the parameters of the Randles cell are calculated as described in Section 3.2.

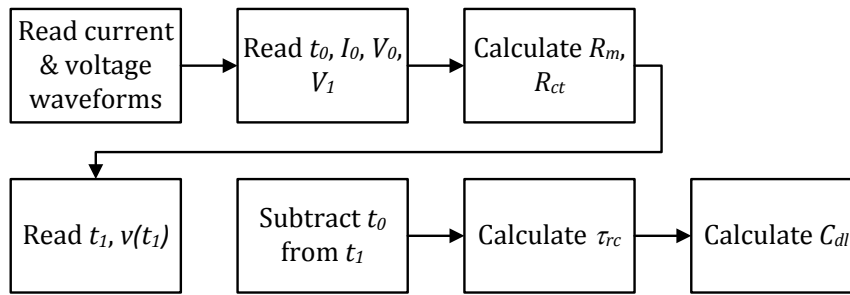


Figure 4.3: Flow diagram: NVR simulation analysis

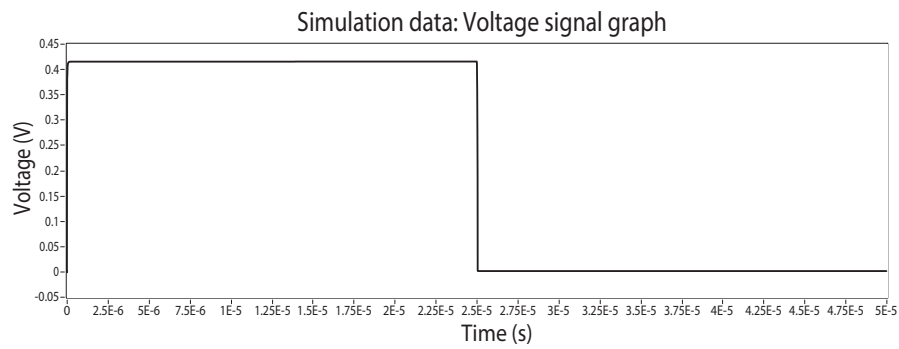
4.2.3 Simulation verification

The NVR method must be verified and validated before it can be practically implemented. Applicable simulation values are selected for the Randles cell. The current and voltage waveforms are generated for the selected simulation parameter values. The generated waveforms are used to obtain the parameters of the Randles cell through the theory of the NVR method. The calculated parameter values are then compared with the original simulation values. If the calculated Randles cell parameter values correlate with the simulated values, the NVR method is considered verified.

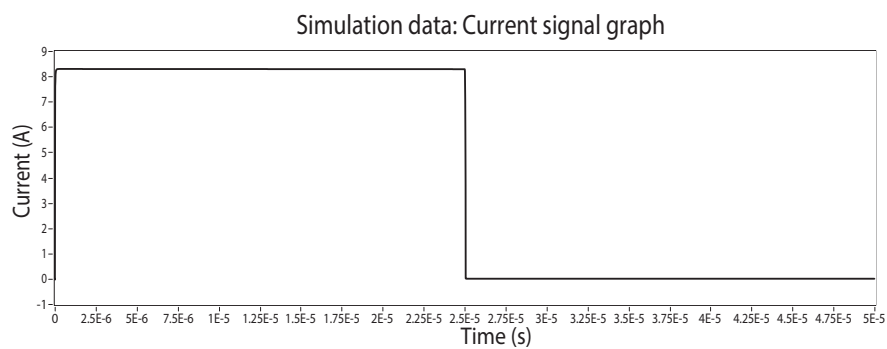
The current and voltage waveforms given in Figure 4.4 are used to calculate the parameter R_m . The current and voltage waveforms depicted in Figure 4.5 are used to calculate the parameters R_{ct} and C_{dl} .

The parameters I_0 , t_0 , t_1 , V_0 , V_1 are read from the current and voltage waveforms, depicted in Figure 4.4 and Figure 4.5. These values, presented in Table 4.3, are used to calculate the parameters of the Randles cell.

The calculated parameters of the Randles cell are presented in Table 4.4. It is possible to generate simulation data for specific Randles cell parameter values, in the form of current and voltage waveforms, and calculate the Randles cell parameters from the simulation data. From the results it is seen that a negligible error is introduced in the calculation of the Randles cell parameters from simulation data. Thus, the NVR method is verified.



(a) Cell voltage



(b) Cell current

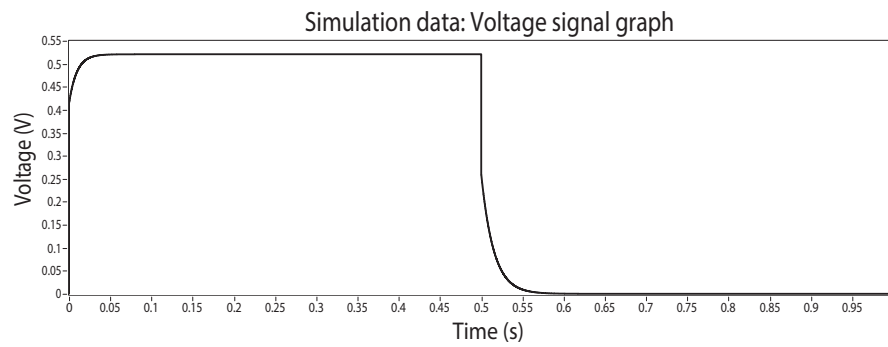
Figure 4.4: Simulation data: NVR waveforms - fast acquisition

Table 4.3: Simulation results: NVR parameter values

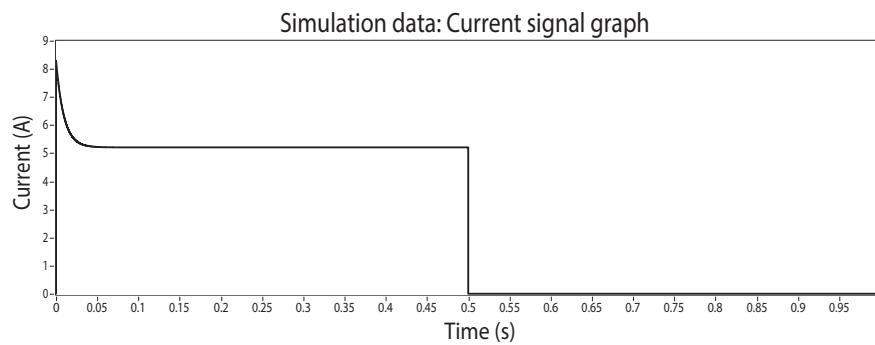
NVR parameter	Value
I_0	5.207 A
t_0	500 ms
t_1	15 ms
V_0	521 mV
V_1	260 mV
V_{t1}	95.7 mV
τ_{rc}	15 ms

4.2.4 Simulation validation

To ensure the quality and accuracy of the simulation model the NVR method should be validated. Multiple simulations are run for different Randles cell parameter values. The Randles cell parameters are calculated from the simulation data and the errors are considered. The NVR method is considered validated if the error, between the



(a) Cell voltage



(b) Cell current

Figure 4.5: Simulation data: NVR waveforms - slower acquisition

Table 4.4: Simulation results: Randles cell component values

Equivalent circuit parameter	Simulated value	Calculated value	Error (%)
R_m	50 m Ω	50.04 m Ω	0.07
R_{ct}	50 m Ω	49.96 m Ω	0.07
C_{dl}	300 mF	300.21 mF	0.0698

calculated and simulated Randles cell parameter values, is small.

Table 4.5: Simulation results: NVR parameters

NVR parameter	Simulation 1		Simulation 2		Simulation 3		Simulation 4	
	Value	Unit	Value	Unit	Value	Unit	Value	Unit
I_0	5.207	A	5.15	A	5.13	A	5.2	A
t_0	500	ms	0.5	ms	500	s	0.5	s
t_1	13.51	ms	14.36	ms	15.75	ms	16.17	ms
V_0	520.7	mV	522.6	mV	523.3	mV	520.7	mV
V_1	468.3	mV	434.1	mV	420.5	mV	395.5	mV
V_{t1}	169.5	mV	159.6	mV	150.9	mV	141.7	mV
τ_{rc}	13.29	ms	14.24	ms	15.37	ms	15.76	ms
	Simulation 5		Simulation 6		Simulation 7		Simulation 8	
	Value	Unit	Value	Unit	Value	Unit	Value	Unit
I_0	5.281	A	5.408	A	5.207	A	5.286	A
t_0	500	ms	500	ms	500	ms	500	ms
t_1	17.01	ms	16.51	ms	17.41	ms	15.61	ms
V_0	517.9	mV	513.8	mV	520.7	mV	517.9	mV
V_1	359.2	mV	324.3	mV	301.9	mV	253.6	mV
V_{t1}	132.1	mV	119.3	mV	110.9	mV	93.23	mV
τ_{rc}	16.98	ms	16.49	ms	17.37	ms	15.62	ms

The calculated Randles cell parameter values, of simulations 1 to 8, are represented in Table 4.6. From the results it is seen that the calculation error is small for all the calculated Randles cell parameter values. It is concluded that the NVR method is repeatable for different Randles cell parameter values and that the calculation error is negligible. Therefore the NVR method is validated.

Table 4.6: Simulation results: Randles cell parameters

Equivalent circuit parameter	Simulation 1			Simulation 2		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	10 m Ω	10.06 m Ω	0.633	16.5 m Ω	16.56 m Ω	0.348
R_{ct}	90 m Ω	89.94 m Ω	0.070	85.1 m Ω	84.94 m Ω	0.679
C_{dl}	150 mF	147.9 mF	1.453	170 mF	167.7 mF	1.391
	Simulation 3			Simulation 4		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	20 m Ω	20.05 m Ω	0.226	24 m Ω	24.05 m Ω	0.1993
R_{ct}	82 m Ω	81.95 m Ω	0.055	76m Ω	75.95 m Ω	0.0631
C_{dl}	190 mF	187.6 mF	1.274	210 mF	207.46 mF	1.226
	Simulation 5			Simulation 6		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	30 m Ω	30.03 m Ω	0.1138	35 m Ω	35.04 m Ω	0.1108
R_{ct}	68 m Ω	67.97 m Ω	0.05036	60 m Ω	59.96 m Ω	0.0646
C_{dl}	250 mF	250.15 mF	0.061	275 mF	275.18 mF	0.06417
	Simulation 7			Simulation 8		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	42 m Ω	42.03 m Ω	0.0722	50 m Ω	50.03 m Ω	0.0722
R_{ct}	58 m Ω	57.97 m Ω	0.0525	48 m Ω	47.97 m Ω	0.0565
C_{dl}	300 mF	300.18 mF	0.05893	325 mF	325.21 mF	0.06546

4.3 Current switching method

4.3.1 Simulation model

A flow diagram of the simulation procedure for the CS method is depicted in Figure 4.6. The first step is to generate a SPICE model of the Randles-Warburg cell. The Randles-Warburg parameters are selected and applied as well as the Warburg coefficients. The LFSR PRBS generators are developed and the applicable PRBS settings are applied. The simulation settings are applied and the simulation is performed. The waveforms are recorded and the generated simulation data is saved.

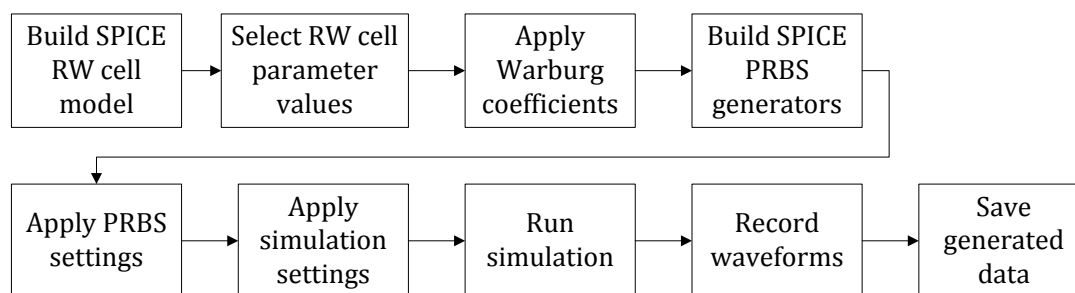


Figure 4.6: Flow diagram: CS method simulation process

The LTspice[®] simulation command settings for the CS method are presented in Table 4.7. An applicable value must be selected for the maximum time step. The time step of LTspice[®] solver can still change, since it is sometimes necessary for the solver to use a smaller time step. The simulation maximum time step is selected as $10 \mu\text{s}$, since accurate results are obtained from the simulation data. Selecting the maximum time step higher than $10 \mu\text{s}$ produces inaccurate results.

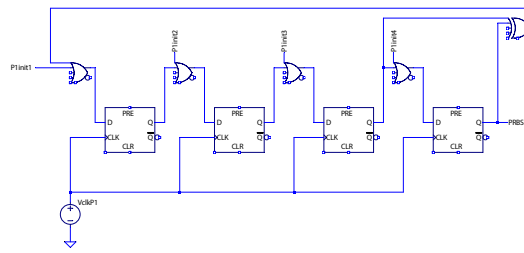
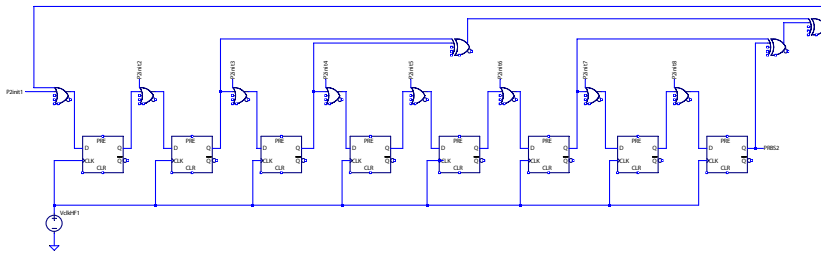
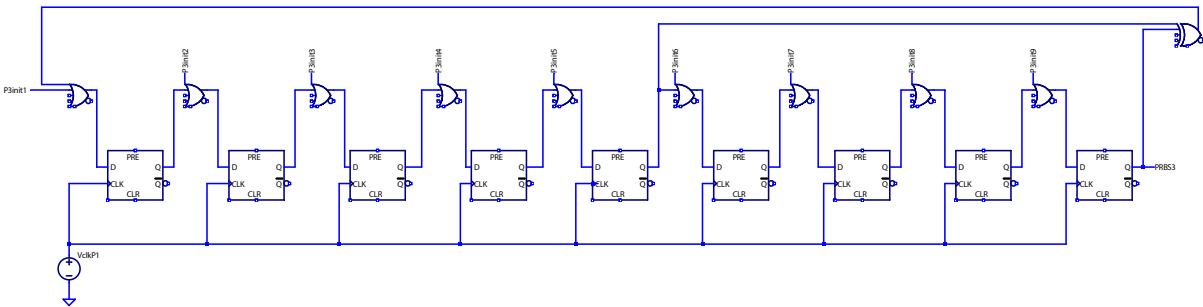
By selecting the maximum time step smaller than $10 \mu\text{s}$, makes little difference in the results obtained from the simulation data. Also, the simulation data should not be compressed since inaccurate results are obtained when the simulation data is analysed. The stop time of the simulation is the combined period lengths of the three PRBS signals. The same SPICE and data compression settings were used for the CS method as described in Section 4.2.1.

Table 4.7: The LTspice[®] command settings for CS method

LTspice [®] command setting	Value
Stop time	5.1272 s
Time to start saving data	0 s
Maximum timestep	$10 \mu\text{s}$

A depiction of the 4-bit LFSR simulated in LTspice[®] is given in Figure 4.7. The 8-bit and 9-bit LFSRs are depicted in Figure 4.8 and Figure 4.9, respectively.

The Randles-Warburg cell LTspice[®] simulation model is depicted in Figure 4.10. The Randles-Warburg cell is simulated in LTspice[®] under the same assumptions as

Figure 4.7: LTspice[®] schematic: 4-bit LFSR PRBS generatorFigure 4.8: LTspice[®] schematic: 8-bit LFSR PRBS generatorFigure 4.9: LTspice[®] schematic: 9-bit LFSR PRBS generator

discussed in Section 4.2.1. The simulation model consists of the source voltage, the Randles-Warburg cell, the standard thermodynamic voltage, the switch and the PRBS switching signal source. The PRBS LFSRs are used to generate the PRBS signal. The PRBS signal is applied to the switch and the resulting current and voltage waveforms are generated.

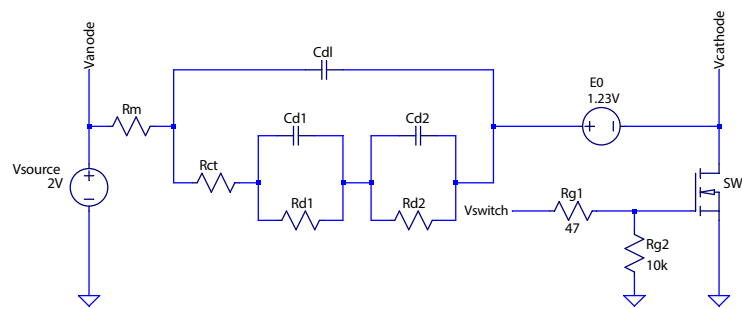


Figure 4.10: LTSpice[®] schematic: Simulation model for CS method

4.3.2 Simulation analysis

A flow diagram of the analysis procedure is depicted in Figure 4.11. The simulated current and voltage waveform data are read into the analysis program. The simulation data was generated with a varying time step, since the solver in LTSpice[®] does not use a fixed time step to generate data. The simulation data is resampled, with a linear interpolation technique, to the same value as the LTSpice[®] maximum time step of 10 μs .

The simulation data is filtered with a 10th order Butterworth lowpass filter and a cut-off frequency of 2 kHz. The data is down-sampled to the same sampling time as the clock period of the third PRBS signal. This is done to ensure that all the necessary data is retained and accurate results are produced. The sampling time of the down-sampled signal is $T_s = 200 \mu\text{s}$. (Down-sampling the data increases the computation time of the SI solver.)

The parameter R_m is calculated with the NVR method and the coefficients of the Randles-Warburg impedance transfer function are calculated with SI. The remaining parameters (R_{ct} , C_{dl} , R_d and τ_d) are calculated with a non-linear simultaneous equation solver. Once the parameters of the Randles-Warburg are calculated, it is validated as discussed in Section 4.3.4.

LabVIEW[™] and MATLAB[®] are used for the mathematical analysis of the data. The LabVIEW[™] SI toolbox is used to compute a transfer function from the simulated

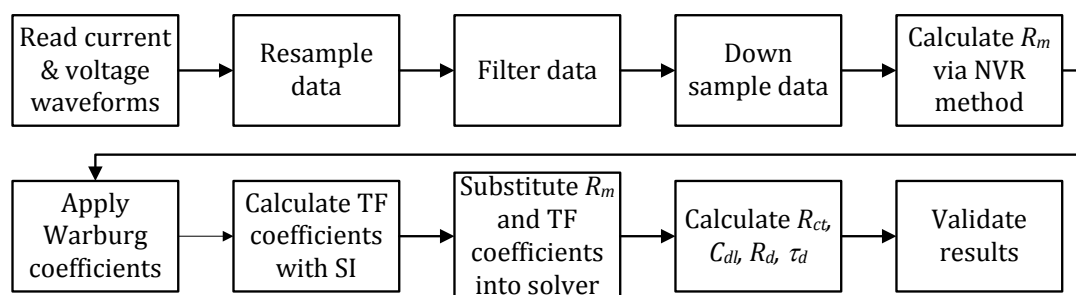


Figure 4.11: Flow diagram: CS method analysis

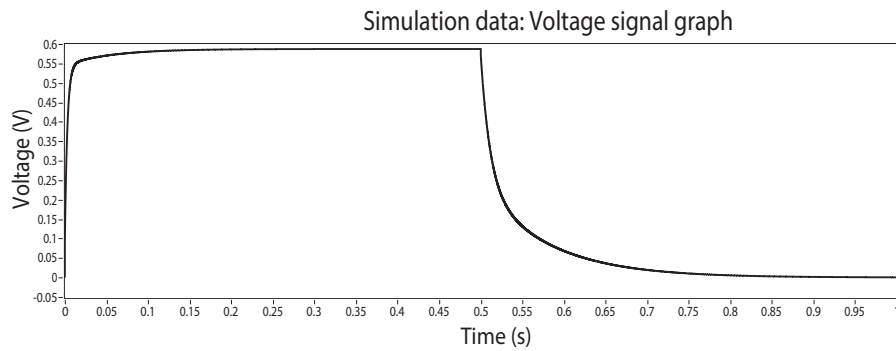
stimulus and response signals. From the computed transfer function, real values are developed for the coefficients b , c , d , f and g . The EEC parameters of the Randles-Warburg cell are calculated by solving the five non-linear simultaneous equations to obtain R_{ct} , C_{dl} , R_d and τ_d .

The non-linear simultaneous equations are solved using a non-linear solver in MATLAB[®]. A .NET object of the MATLAB[®] non-linear solver is generated using the deployment tool in MATLAB[®]. The generated .Net object is used in LabVIEW[™] to solve the system of simultaneous equations. The front panels of the LabVIEW[™] program is presented in appendix A.1.1. The MATLAB code is given in appendix A.2.

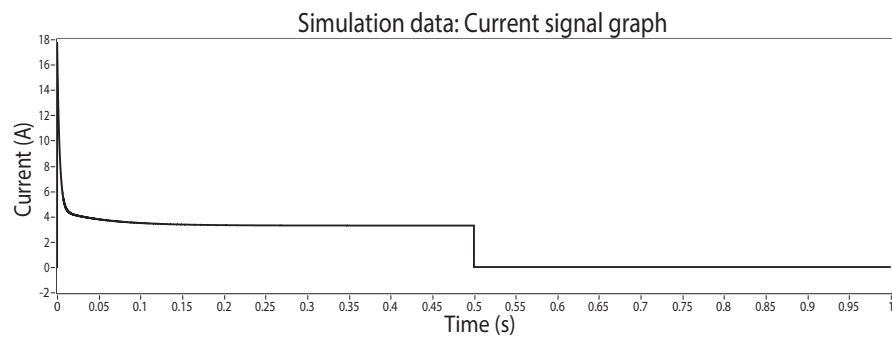
4.3.3 Simulation verification

The CS method must be verified and validated before it can be practically implemented. The same approach that was used to verify the NVR method is used to verify the CS method. For the simulation model applicable Randles-Warburg cell parameter values are selected. Current and voltage waveforms are generated for the selected simulation parameter values. The generated waveforms are analysed to obtain the parameters of the Randles-Warburg cell through the theory of the CS method. The calculated parameter values are compared with the initial simulation parameter values. The CS method is considered verified if the calculated Randles-Warburg cell parameter values correlate with the simulated value.

The waveforms generated from simulation are depicted in Figure 4.12, Figure 4.13 and Figure 4.14. The NVR curve, consisting of the voltage and current waveform, is depicted in Figure 4.12.



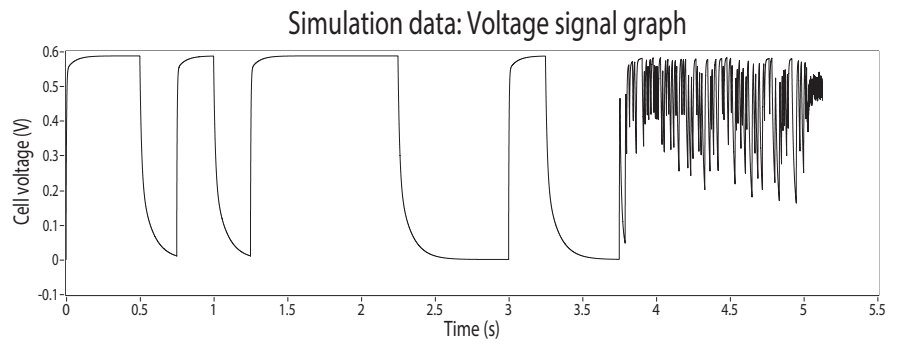
(a) Cell voltage



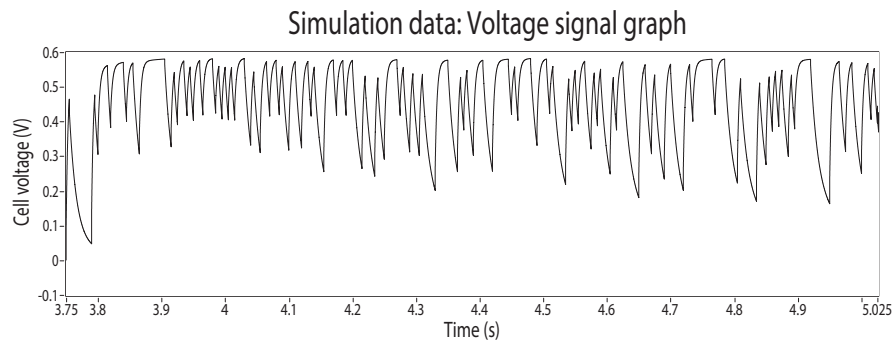
(b) Cell current

Figure 4.12: CS method simulation results: NVR curve for calculating R_m

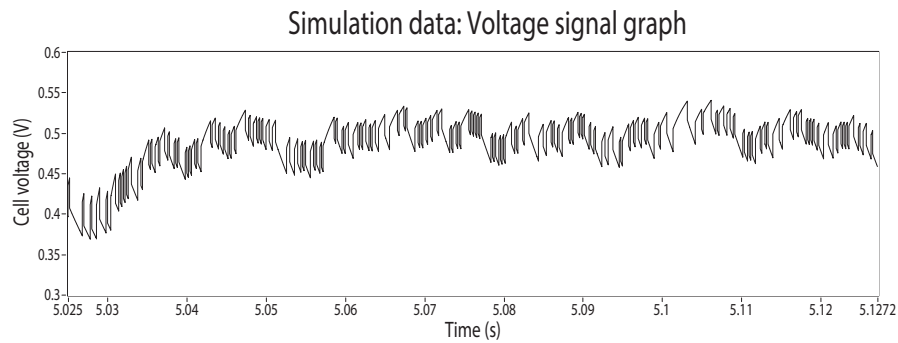
The voltage signal, before it is filtered and resampled, is depicted in Figure 4.13. In Figure 4.13 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 4.13 (b) and (c) are depictions of the voltage waveforms for the duration of the second and third PRBS signals, 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 4.13: CS method simulation results: Cell voltage for the duration of PRBS signals

The current signal, before it is filtered and resampled, is depicted in Figure 4.14. In Figure 4.14 (a) is a depiction of the complete signal for the duration of the three PRBS signals. In Figure 4.14 (b) and (c) are depictions of the current waveforms for the duration of the second and third PRBS signals, respectively.

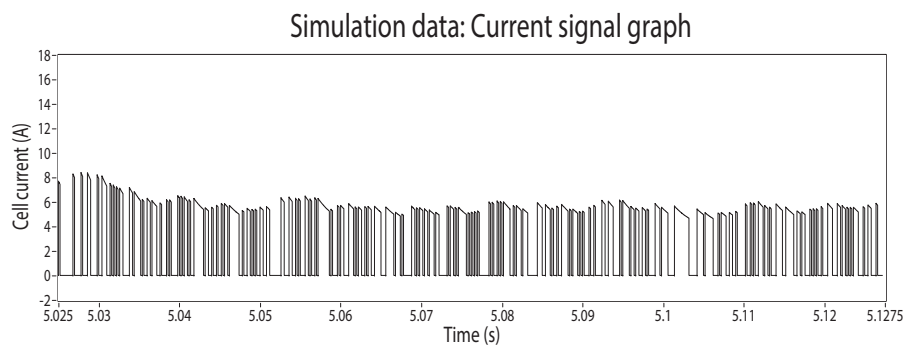
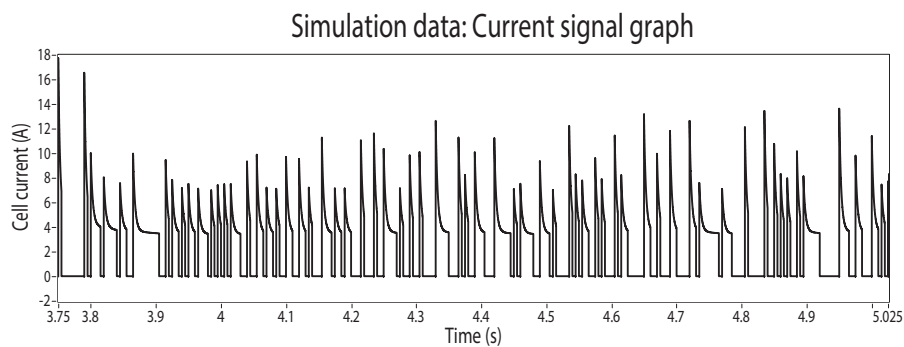
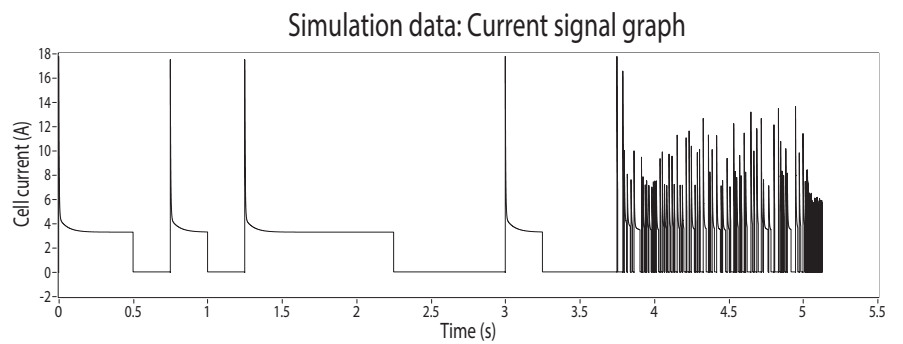
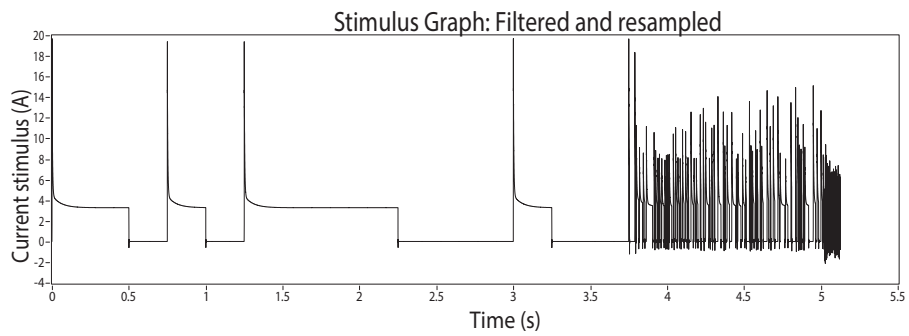
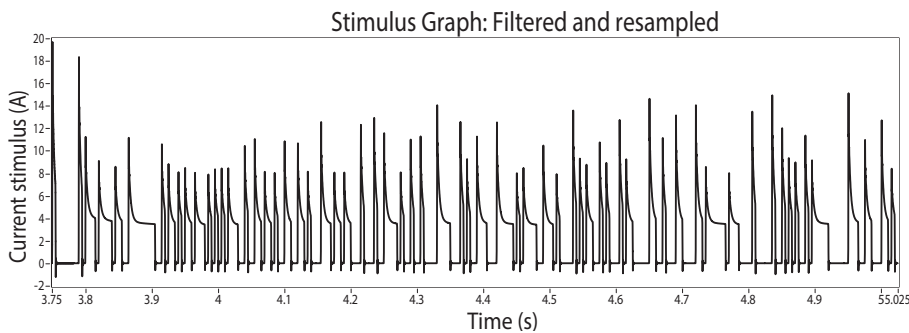


Figure 4.14: CS method simulation results: Cell current during applied PRBS signals

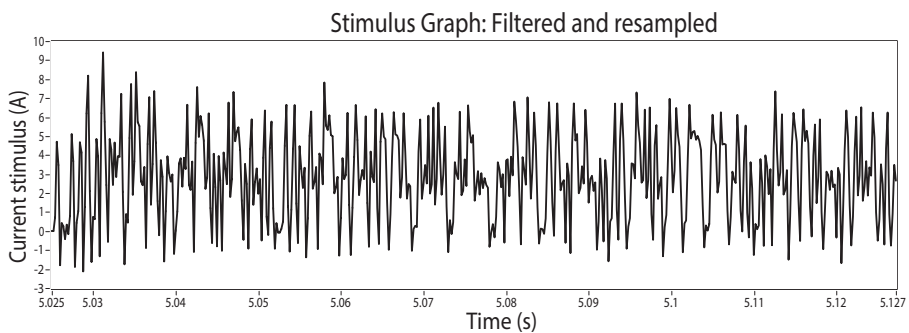
The filtered and resampled stimulus signal, for the duration of the three PRBS signals, is depicted in Figure 4.15. In Figure 4.15 (a) is a depiction of the complete signal. In Figure 4.15 (b) and (c) are depictions of the current waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell stimulus - Complete signal



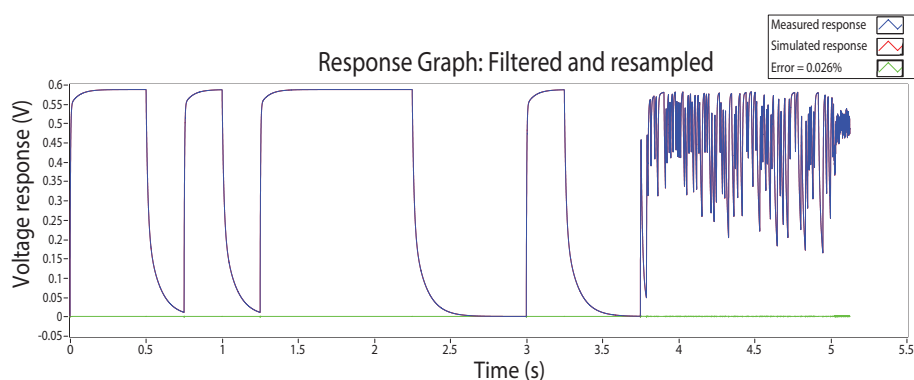
(b) Cell stimulus - Portion during PRBS 2 signal



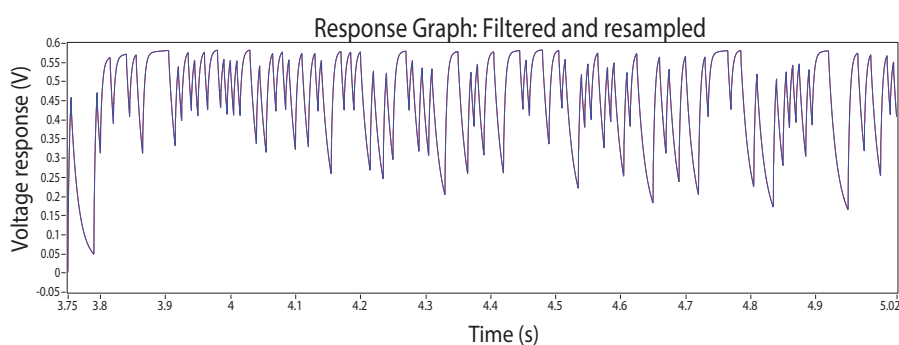
(c) Cell stimulus - Portion during PRBS 3 signal

Figure 4.15: CS method simulation results: Cell stimulus during applied PRBS signals

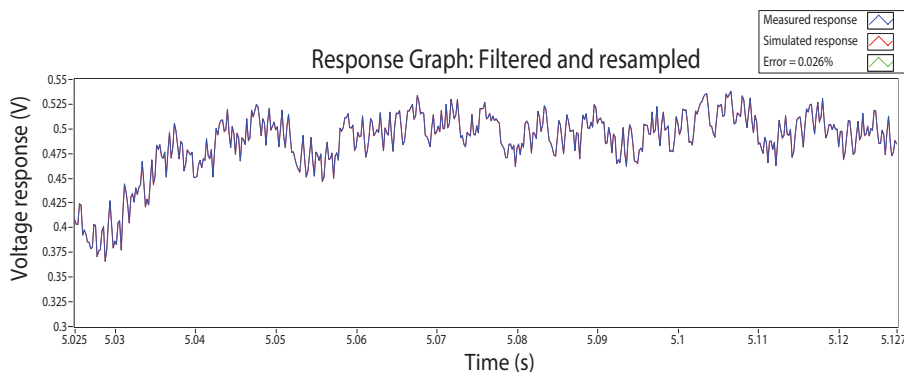
The filtered and resampled response signal, for the duration of the three PRBS signals, are depicted in Figure 4.15. In Figure 4.15 (a) is a depiction of the complete signal. In Figure 4.15 (b) and (c) are depictions of the voltage waveforms for the duration of the second and third PRBS signals, respectively.



(a) Cell response - Complete signal



(b) Cell response - Portion during PRBS 2 signal



(c) Cell response - Portion during PRBS 3 signal

Figure 4.16: CS method simulation results: Cell response during applied PRBS signals

The SI toolbox is used to generate the Randles-Warburg cell transfer function coefficients. A model simulation toolbox, within the SI toolbox, is used to simulate the response of a signal to an input (stimulus) signal. The simulation model of the Randles-Warburg cell is validated if the measured response signal correlates with the simulated response signal. From Figure 4.16 it is seen that the error between the measured

response and the simulated response waveform is negligible. Further validation of the simulation model is discussed in the following section.

The Randles-Warburg cell transfer function coefficients were generated with SI and is presented in Table 4.8.

Table 4.8: CS method simulation results: Randles-Warburg transfer function coefficients

Transfer function coefficient	Simulated value	Calculated value	Error (%)
b	0.000010	0.0000054	46.21
c	0.009446	0.009363	0.879
d	0.179100	0.179129	0.016
f	0.000945	0.000890	5.775
g	0.091561	0.090990	0.624

The calculated parameters of the Randles-Warburg cell is given in Table 4.9. It is possible to generate simulation data for specific Randles-Warburg cell parameter values, in the form of current and voltage waveforms, and calculate the Randles-Warburg cell parameters from the simulation data. From the results it is seen that a negligible error is introduced in the calculation of the Randles-Warburg cell parameters from simulation data. Thus, the CS method is verified.

Table 4.9: CS method simulation results: Randles-Warburg cell parameter values

Equivalent circuit parameter	Simulated value	Calculated value	Error (%)
R_m	5 m Ω	5.3 m Ω	6.00
R_{ct}	115 m Ω	112 m Ω	2.58
C_{dl}	100 mF	95.7 mF	4.26
R_d	60 m Ω	62 m Ω	3.34
τ_d	230 ms	230.8 ms	0.36

4.3.4 Simulation validation

The CS method should be validated to ensure the quality and accuracy of the simulation model. Simulation data is generated for various parameter values of the Randles-Warburg cell. The data from the multiple simulations are analysed and the results are compared. The CS method is considered validated if the error, between the calculated and simulated Randles-Warburg parameter values, is small.

The coefficients of the Randles-Warburg transfer function are presented in Table 4.10. From the results it is seen that the errors introduced between the simulated and the calculated coefficient values are small. The error introduced in the value of coefficient b is high and can be ascribed to the order of the coefficient value. The lower the order of the coefficient value, the higher the probability for a calculation error.

Table 4.10: CS method simulation results: Randles-Warburg transfer function parameters

Transfer function coefficient	Simulation 1			Simulation 2		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
<i>b</i>	0.000010	0.0000054	46.21	0.000016	0.000012	30.75
<i>c</i>	0.009446	0.009363	0.879	0.009332	0.009244	0.943
<i>d</i>	0.179100	0.179129	0.016	0.164175	0.164186	0.007
<i>f</i>	0.000945	0.000890	5.775	0.001096	0.001034	5.662
<i>g</i>	0.091561	0.090990	0.624	0.098259	0.097624	0.646
	Simulation 3			Simulation 4		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
<i>b</i>	0.000025	0.000019	23.57	0.000041	0.000032	21.52
<i>c</i>	0.009904	0.009813	0.922	0.011542	0.011431	0.960
<i>d</i>	0.154250	0.154260	0.007	0.142355	0.142359	0.003
<i>f</i>	0.001306	0.001231	5.725	0.001667	0.001558	6.525
<i>g</i>	0.107934	0.107247	0.637	0.127803	0.126932	0.681
	Simulation 5			Simulation 6		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
<i>b</i>	0.000072	0.000056	21.79	0.000117	0.000091	22.28
<i>c</i>	0.015119	0.014980	0.919	0.019373	0.019193	0.932
<i>d</i>	0.136445	0.136445	0	0.133520	0.133522	0.002
<i>f</i>	0.002376	0.002197	7.521	0.003268	0.002980	8.730
<i>g</i>	0.162531	0.161437	0.161	0.200610	0.199173	0.716
	Simulation 7			Simulation 8		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
<i>b</i>	0.000196	0.000154	21.50	0.000281	0.000220	21.64
<i>c</i>	0.024993	0.024764	0.917	0.030001	0.029730	0.904
<i>d</i>	0.132625	0.132627	0.001	0.129700	0.129701	0.0005
<i>f</i>	0.004236	0.003812	10.01	0.004958	0.004373	11.81
<i>g</i>	0.240774	0.238968	0.751	0.279834	0.277674	0.772

The error introduced between the measured response and the simulated response waveforms, for simulations 1 to 8, is presented in Table 4.11. The error values are used to validate that the calculated response signal correlates with the original stimulus signal.

Table 4.11: CS method simulation results: System identification - Simulated response errors

Simulation nr	Error (%)
1	0.026
2	0.017
3	0.014
4	0.010
5	0.012
6	0.007
7	0.005
8	0.005

The calculated Randles-Warburg parameters, for simulations 1 to 8, are presented in Table 4.12. From the results it is seen that the calculation error is small for all the calculated Randles-Warburg cell parameter values. It is concluded that the CS method is repeatable for different Randles-Warburg cell parameter values and that the calculation error is negligible. Therefore the CS method is validated.

Table 4.12: CS method simulation results: Randles-Warburg parameters

Equivalent circuit parameter	Simulation 1			Simulation 2		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	5 m Ω	5.3 m Ω	6.00	10m Ω	10.21 m Ω	2.1
R_{ct}	115 m Ω	112 m Ω	2.58	100 m Ω	97.5 m Ω	2.5
C_{dl}	100 mF	95.7 mF	4.26	125mF	119.8 mF	4.15
R_d	60 m Ω	62 m Ω	3.34	55m Ω	56.8m Ω	3.24
τ_d	230 ms	230.8 ms	0.36	245 ms	245.8 ms	0.33
	Simulation 3			Simulation 4		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	15 m Ω	15.7 m Ω	4.64	20 m Ω	20.6 m Ω	2.97
R_{ct}	90 m Ω	87.7 m Ω	2.53	80 m Ω	78 m Ω	2.5
C_{dl}	150 mF	143.6 mF	4.26	175 mF	165.9 mF	5.18
R_d	50 m Ω	51.6 m Ω	3.23	43 m Ω	44.4 m Ω	3.32
τ_d	270 ms	270.9 ms	0.35	330 ms	331 ms	0.32
	Simulation 5			Simulation 6		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	25 m Ω	25.5 m Ω	1.9	30 m Ω	30.4 m Ω	1.47
R_{ct}	75 m Ω	73.3 m Ω	2.3	72 m Ω	70.44 m Ω	2.24
C_{dl}	200 mF	186.4 mF	6.55	225 mF	207 mF	8.01
R_d	37 m Ω	38.3 m Ω	3.43	32 m Ω	33.2m Ω	3.72
τ_d	435 ms	436.4 ms	0.32	550 ms	551.6 ms	0.29
	Simulation 7			Simulation 8		
	Simulated value	Calculated value	Error (%)	Simulated value	Calculated value	Error (%)
R_m	40 m Ω	40.4 m Ω	1.02	50 m Ω	50.4 m Ω	0.7
R_{ct}	68 m Ω	66.7 m Ω	2.12	60 m Ω	58.8 m Ω	2.05
C_{dl}	250 mF	226.1 mF	9.61	275 mF	255.65 mF	7.036
R_d	25 m Ω	26.1 m Ω	4.2	20 m Ω	20.9 m Ω	4.48
τ_d	675 ms	676.6 ms	0.24	800 ms	801.7 ms	0.21

4.4 Conclusion

Simulation models are developed for the NVR method and the CS method. The current interrupt method is verified by calculating the Randles cell and Randles-Warburg cell parameters from simulation data. The error introduced in the calculated parameter values of the two EECs should be small.

It is seen from the results of the NVR method, that the parameters of the Randles cell can be calculated from simulation data. The NVR method is validated by repeating the simulation for different Randles cell parameter values and showing that the calculation error remains small. It is therefore concluded that the NVR method is validated.

It is seen from the results of the CS method, that the parameters of the Randles-Warburg cell can be calculated from simulation data. Multiple simulation data were analysed and the calculation error of the Randles-Warburg cell parameter values remain small. The error between the measured response signal and the simulated response signal also remains small. Therefore, it is concluded that the CS method is validated. Since the NVR method and the CS method are verified and validated in simulation, it can be practically implemented.