Modelling the RESS: Describing Electrical Parameters of Batteries and Electric Double-Layer Capacitors through Measurements

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Abstract

Being able to predict the behaviour of Rechargeable Energy Storage Systems (RESS) such as batteries and Electric Double-Layer Capacitors (EDLC) relies on the models used to represent them. Research on the development and enhancement of these models is performed on two tracks: on one hand by defining the model topology, where a trade-off is sought between the reduction of components in the model equivalent scheme and the ability of the model to describe all potential system behaviour and, on the other hand by improving the method of calculating the magnitudes of the different components in the model. The storage devices examined in this paper are divided in two groups, electrochemical devices and electrical double layer capacitors. The first group consists of lead-acid, lithium, Ni-Cd and Ni-MH batteries. The second group comprises of Electric Double-Layer Capacitors (EDLC). For every model used to describe a battery or EDLC, different techniques are implemented to calculate the magnitude of the components. The work presented in this paper will elaborate to the calculating method used in NREL's FreedomCAR test-manual adapted to fit different battery- and EDLC models. This method consists of an iterative approach to the equations of the model using data gathered from performing tests on the battery or supercapacitor. Validation of the models obtained through this calculating method will be done by performance tests on the storage devices. As the models of batteries and supercapacitors are a key aspect in the simulation software for hybrid-vehicles more accurate models result in more accurate simulations. These simulation programs depend upon the underlying component models, the data generated by which determines the accuracy of the program's data-output. The availability of reliable storage RESS models will thus be a key element in to allow overall vehicle modelling.

Keywords: Battery Model, EDLC, Simulation

1 Introduction

Modelling of batteries and EDLC's (Electrochemical Double Layer Capacitors) is carried out by acquiring data from tests performed on these energy storage devices. The data are acquired using the RESS test-facility called Digatron. Figure 1 shows the test-facility.

Figure 1: Front view of the Digatron test-facility

The test-facility comprises of two test-circuits, giving the opportunity to test different energy storage devices at the same time. All essential data is logged onto the hard-drive of a connected computer, witch also runs the software for controlling the Digatron. Tests-sequences for storage devices are inputted in the program (BTS-600), compiled and loaded in the memory of the Digatron.

2 Reference test and calculation method

2.1 NREL test method

The test method described in the FreedomCAR Battery Test Manual (appendix D) [1] consists of a test cycle (Hybrid Pulse Power Characterisation test, HPPC-test), a battery model for pulse load conditions and a calculation method for defining the magnitudes of the model's components. This calculation method is used as a reference method for other models within the paper and future work. The test cycle, model and the calculation method are described in 2.2, 2.3 and 2.4 respectively.

2.2 Test cycle (HPPC-test)

The HPPC-test cycle (Figure 2) is performed to derive the battery's dynamic power capabilities during a 10sec discharge and 10sec regenerative load. By performing this test on different levels of discharge (every 10%), the characteristic of the internal resistance and polarization resistance lead to a function of the State of Charge (SoC). Figure 3 shows the initial start phase of the HPPC-test, whereas Figure 4 shows the complete HPPC-test.
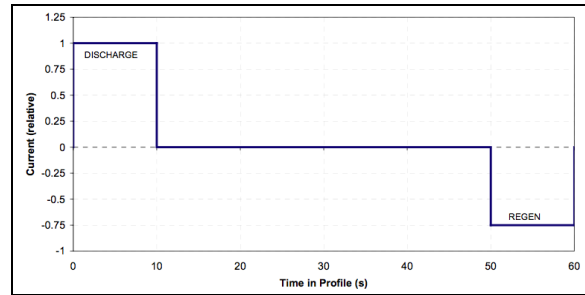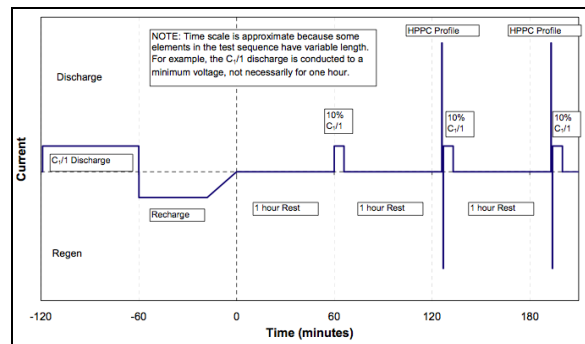

Figure 2: HPPC-test profile (source: [1])

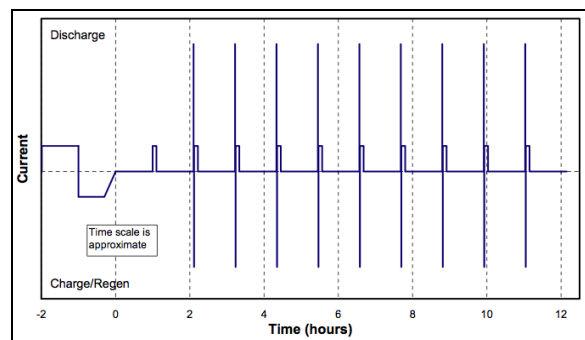Figure 3: HPPC-test initial phase (source: [1])

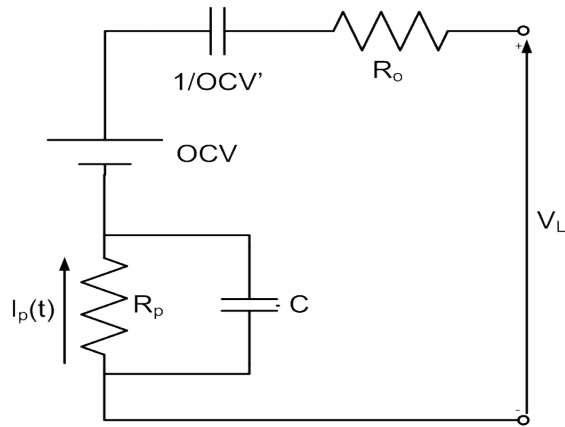Figure 4: HPPC-test complete (source: [1])

2.3 Scheme

Figure 5: The FreedomCAR battery model

Describing every complex non-linear parameter over the life-span of the battery using available test data is difficult, therefore NREL linearized the battery model. Figure 5 represents the scheme used in the FreedomCAR test-manual [1]; this model is commonly referred to "The FreedomCAR Model". Five components, each representing a different aspect of the battery, are needed to make up the model. An overview of these different aspects is given by Table 1. Table 1 also includes the used abbreviations for current and voltage within the model.

Table1: Parameters of the model (source: [1])

OCV	An ideal voltage source that represents "open circuit" battery voltage	[V]
R_o	Battery internal "ohmic" resistance	[Ω]
R_p	Battery internal "polarization" resistance (e.g., due to concentration gradients)	[Ω]
C	Shunt capacitance around R_P	[F]
τ	Polarization time constant, τ = R_p*C	[sec]
I_L	Battery load current	[A]
I_P	Current through polarization resistance	[A]
V_L	Battery terminal voltage	[V]
1/OCV'	A capacitance that accounts for the variation in open circuit voltage with the time integral of load current I_L. OCV' is not usually equal to the slope of V_L measured open circuit vs. battery state of charge	[V/A sec]

2.4 Calculation method

The Kirchhoff Voltage Law (KVL) describing the FreedomCAR model – or PNGV[1] model – is given by equation 1. This equation forms the basis upon which the "battery parameter estimator spreadsheet" by NREL is constructed. In this spreadsheet the load-current (I_L) and the time-vector - as recorded in the test-cycle - are used as input-variables to calculate the battery's terminal voltage ($V_{L,i(est)}$). Since these recordings are made at discrete points in time, the load-current I_L, polarization-current I_P and terminal voltage V_L are accommodated with an i in subscript. Equation 5 is the discrete form of equation 1. In order to calculate I_P the differential equation 2 is used. A solution of this differential equation in discrete form is given by equation 3; this equation is implemented in the battery parameter spreadsheet to calculate I_P in the discrete recording points i.

$$V_L = OCV - OCV'(\int I_L \cdot dt) - R_0 \cdot I_L - R_P \cdot I_P \quad (1)$$

$$dI_P/dt = (I_L - I_P)/\tau \quad (2)$$

$$I_{P,i} = \left(1 - \frac{1 - e^{-\frac{\Delta t}{\tau}}}{\frac{\Delta t}{\tau}}\right) \times I_{L,i}$$
$$+ \left(\frac{1 - e^{-\frac{\Delta t}{\tau}}}{\frac{\Delta t}{\tau}} - e^{-\frac{\Delta t}{\tau}}\right) \times I_{L,i-1}$$
$$+ e^{-\frac{\Delta t}{\tau}} \times I_{P,i-1} \quad (3)$$

$$(\Sigma I_L \Delta t)_i = (\Sigma I_L \Delta t)_{i-1} + (I_{L,i} + I_{L,i-1}) \cdot (t_i - t_{i-1})/2 \quad (4)$$

$$V_{L,i(est)} = OCV_0 + OCV' \cdot (\Sigma I_L \Delta t)_i - I_{L,i} \cdot R_0 - I_{P,i} \cdot R_P \quad (5)$$

V_L is the terminal voltage and is therefore measurable. The recorded data of V_L can be used to calculate the difference between measured and estimated terminal voltage. ΔV_i is the difference between the measured voltage $V_{L,i}$ and the calculated (estimated) voltage $V_{L,i(est)}$. This difference is used as an indicator for the accuracy of the estimated terminal voltage (equation 6 shows the difference in voltage in a discrete manner). In the "battery parameter estimator spreadsheet" the difference between these two voltages is plotted.

$$\Delta V_i = V_{L,i(est)} - V_{L,i} \quad (6)$$

The spreadsheet uses an estimate for τ to calculate

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$V_{L,i(est)}$. After calculating $V_{L,i(est)}$ for all points during the test-cycle, the estimated terminal voltage curve is compared to the measured terminal voltage curve using the correlation-factor r^2. τ is then manually adjusted to maximise $r^2 (>0.995)$. In the battery parameter estimator spreadsheet OCV_0, OCV', R_0 and R_P are calculated with the Excel® function LINEST. LINEST is a multiple linear regression formula using the I_P, I_L, $(\Sigma I_L \Delta t)$ vectors.

The work presented in the next section expands this calculation method with the ability to automatically adjust the value of τ according to the sum of the squared errors ΔV_i. This new procedure is written in the Matlab® environment allowing the procedure to be modified to suit different schemes.

3 Adjusted calculation method

3.1 Scheme

The preliminary scheme used to accommodate these updates to the NREL calculation method is the same as the scheme shown in Figure 5.

3.2 Calculation method in Matlab

The calculation method implemented in Matlab will now be outlined.

The accuracy (value of the sum of the squared terminal-voltage errors) and τ are set at a desired starting value.

Acquired data from the Digatron is imported in the Matlab procedure, this data consists of the time vector T, load-current vector I_L and the terminal-voltage vector V_L. This data is used to calculate the polarization-current vector I_P with the help of the Runga Kutta II method [2]. Using this calculated data and the imported data from the Digatron, the procedure is able to calculate OCV_0, OCV', R_P and R_0 with the multiple linear regression formula of Matlab. All imported and calculated data is used to produce the terminal-voltage vector $V_{L,(est.)}$. $V_{L,(est.)}$ is subtracted from V_L to calculate the terminal-voltage error vector ΔV.

In the final step of the procedure I_P, I_L, $V_{L,(est.)}$, V_L and ΔV are plotted and presented to the user together with various statistical information and the values for τ, OCV_0, OCV', R_P, R_0. An example of these outputs is presented in section 4

(Test results) of the paper.

Once the first iteration cycle has been completed, the value of the accuracy is adjusted to further refine the value of τ and to maximise r^2.

4 Test results

4.1 Test results with FreedomCAR calculation spreadsheet

As an example for the FreedomCAR calculation spreadsheet, the test-data of a lithium battery are represented. The data were recorded during a test-cycle[2] where the lithium-battery (producer's data sheet for the battery shown in table 2) was submitted to a discharge-current of 40A and a charge-current of 15A, with a rest-period in between. Input-data for the spreadsheet were imported from the recorded data. The Input-data consisted of the time-vector, the load-current vector and the terminal-voltage vector.

Table 2: Data-sheet for the tested battery

Battery voltage	3.2V (2.1 ... 3.65V)
Capacity	10Ah
Constant discharge current	120A cont.
Maximum discharge current	140A 18s
Maximum charge current	30A
Internal resistance	6mΩ (>1000 cycles)
Mass	400g
Dimensions	138-40-40mm

Table 3 presents the calculated results from the FreedomCAR spreadsheet. The table is automatically generated by the LINEST Function used in the spreadsheet. τ has in this case a chosen value of 11,42sec. The calculated values for OCV_0, OCV', R_P and R_0 (as seen in row 5 of table 3) are 3,34V, 3,2Asec/V, 1,88mΩ and 4,64 mΩ respectively. r^2 is for the chosen value of τ equal to 0,995. Row 6 in table 3 represents the standard-deviation on the respective values in row 5 of table 3.

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2   The test-cycle values for current and rest-period where in accordance with the FreedomCAR requirements

Table 3: Test-results from the FreedomCAR spreadsheet

τ	11,42		
r^2	0,995		
Regression analysis			
OCV'	**R_p**	**R_o**	**OCV_0**
3,20E-05	1,88E-03	4,64E-03	3,34E+00
2,45E-06	3,56E-05	3,10E-05	1,48E-03

Table 4: Test-results from the adjusted calculation method

τ	11,420		
r^2	0,9956		
Regression analysis			
OCV'	**R_p**	**R_o**	**OCV_0**
3,99E-05	1,80E-03	4,73E-03	3,35E+00
2,26E-06	3,25E-05	2,84E-05	1,37E-03

The graph in figure 6 shows the measured terminal-voltage V_L versus the estimated terminal-voltage curve $V_{L,(est.)}$.
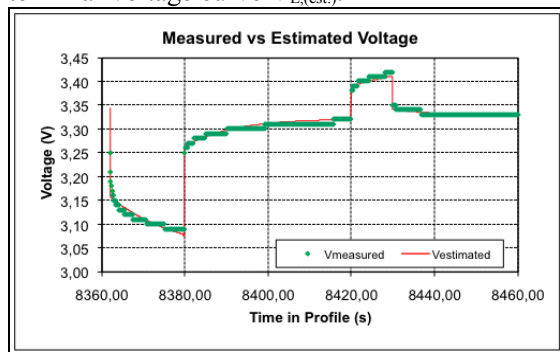
Figure 6: V_L versus $V_{L,(est.)}$

Figure 7 shows ΔV_L (Error in estimated terminal-voltage) in function of time.
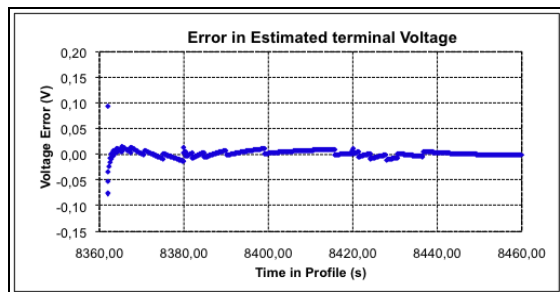
Figure 7: Error in Estimated terminal Voltage

4.2 Test results with adjusted calculation method

The same imported data as for the FreedomCAR calculation spreadsheet were used in this adjusted calculation method. For τ a start-value of 5sec was chosen and for the accuracy 0,04. Output data from the Matlab procedure where as follows.

First part: regression data

Second part: graphical output

The graphical output presents various calculated and imported parameters of the adjusted calculation method in function of time.
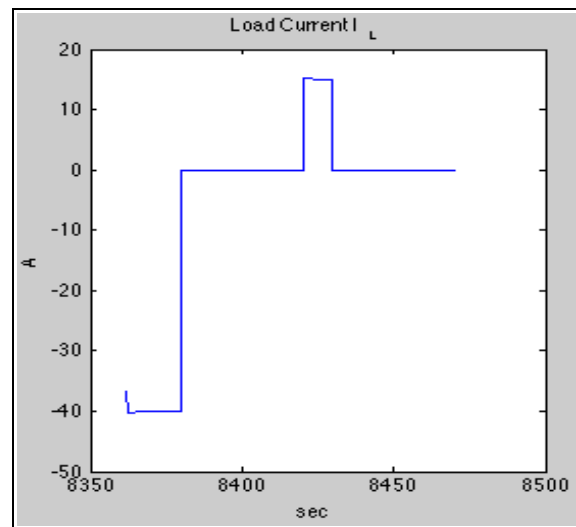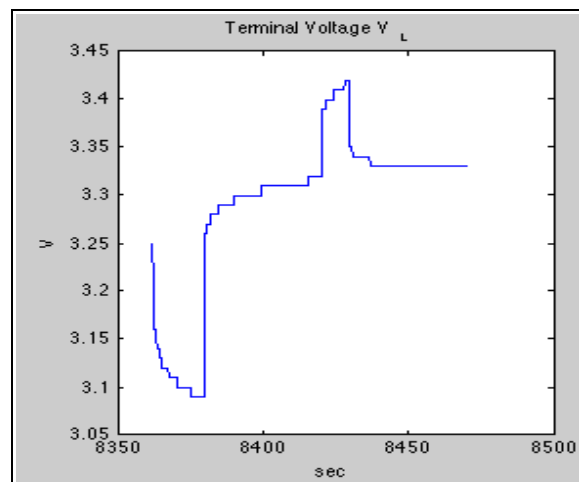

Figure 8: Measured load-current I_L
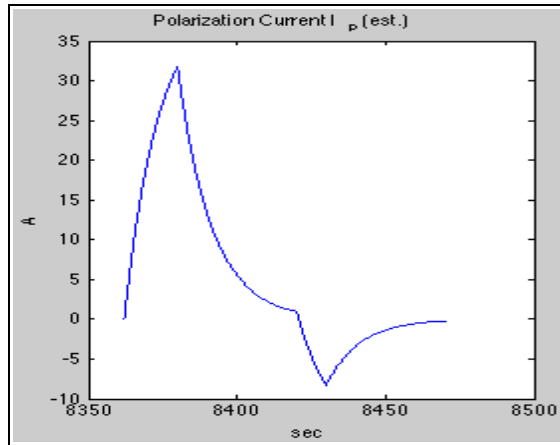

Figure 9: Measured terminal-voltage V_L

Figure 10: Calculated polarization-current I_P using Runga Kutta II method
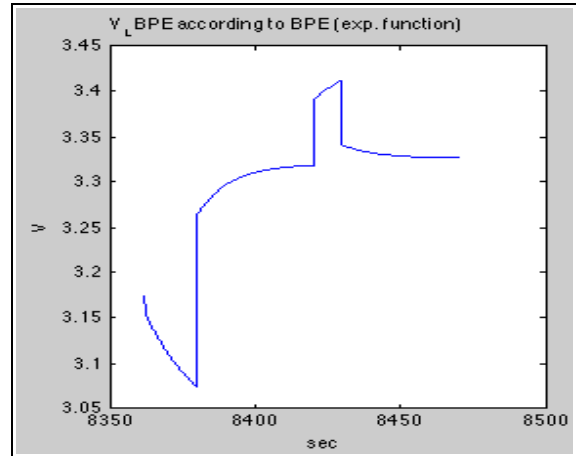

Figure 13: Calculated terminal-voltage $V_{L,(est.)BPE}$ using polarization-current I_P calculated with equation 3
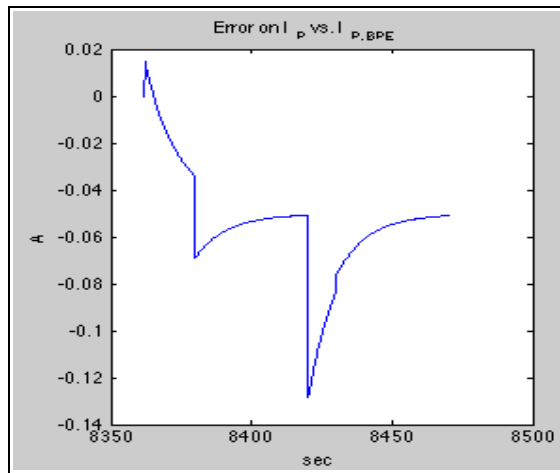

Figure 11: Error on I_P calculated with the Runga Kutta II method vs. $I_{P, BPE}$ calculated using equation 3
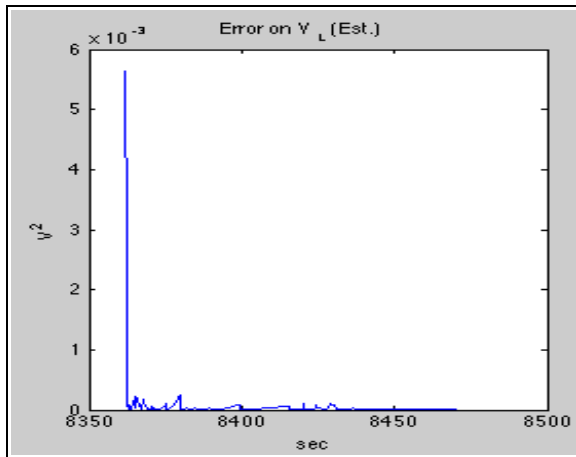

Figure 14: Error on estimated terminal-voltage $V_{L,(est.)}$. Error on $V_{L,(est.)} = V_L - V_{L,(est.)}$
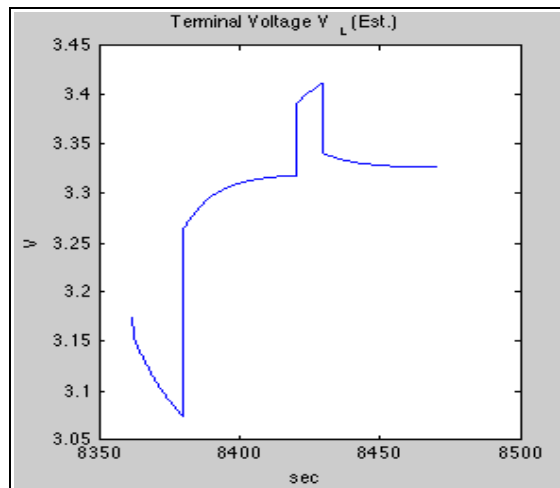

Figure 12: Calculated terminal-voltage $V_{L,(est.)}$ using polarization-current I_P calculated with the Runga Kutta II method
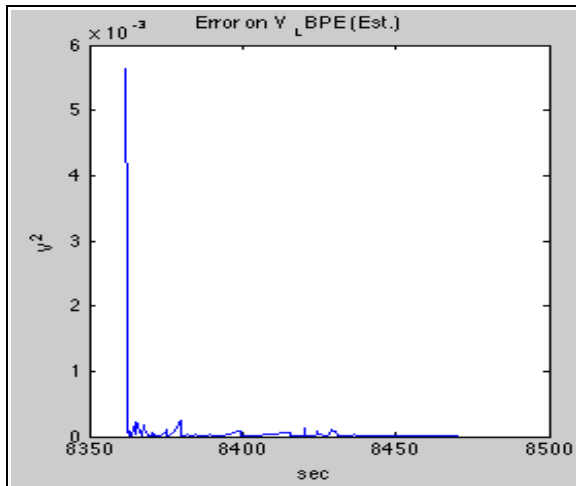

Figure 15: Error on estimated terminal-voltage $V_{L,(est.)BPE}$. Error on $V_{L,(est.)BPE} = V_L - V_{L,(est.)BPE}$

4.3 Comparison of the test methods

4.3.1 Comparison of the regression data

Table 5 displays the regression data for the FreedomCAR calculation method and the adjusted calculation method.

Table 5: Comparison of the regression data

Regression analysis for FreedomCAR method			
OCV'	R_p	R_o	OCV_0
3,20E-05	1,88E-03	4,64E-03	3,34E+00
2,45E-06	3,56E-05	3,10E-05	1,48E-03
Regression analysis for Adjusted method			
OCV'	R_p	R_o	OCV_0
3,99E-05	1,80E-03	4,73E-03	3,35E+00
2,26E-06	3,25E-05	2,84E-05	1,37E-03

OCV', R_P, R_0, OCV_0 calculated with the FreedomCAR calculation method and the adjusted calculation method all correspond in magnitude and standard-deviation. The difference between both calculations is presented in table 6. ΔOCV' is the largest difference of all calculated parameters, by taking the standard-deviations on OCV' in to account ΔOCV' can be reduce to -2,85E-06 or 9% difference.

Comparing the regression data from the adjusted calculation method with the FreedomCAR calculation method revealed a strong correlation. With this in mind, the Matlab procedure can be adapted for other RESS-models.

Table 6: Difference between calculation methods

	OCV'	R_p	R_o	OCV_0
Δ	-0,79E-05	0,08E-03	-0,09E-03	-0,01E-03
in %	24	4	2	0,3

4.3.2 Comparison of the calculated terminal-voltage $V_{L,(est.)}$ versus V_L

Figure 9 represents the measured terminal-voltage V_L in function of time. Comparing this curve with the graph shown in figure 12 reveals a similar plot. This means that the adjusted calculation method can simulate the response of the battery's terminal-voltage V_L in a satisfying way. Supporting this fact is the magnitude of the error on $V_{L,(est.)}$ (compared to V_L), represented in figure 14. In figure 14 a steep decline of the error is noted after the initial part of the test. Even in the initial part the error on the terminal-voltage is small in comparison with the terminal voltage $V_{L,(est.)}$ (peaking at 5,7E-03V).

Since equation 3 was already implemented in the Matlab procedure to compare the polarization-current I_P (figure 11) with the polarization-current calculated with the Runga Kutta II method (figure 10), $V_{L,BPE}$ was calculated and plotted (see figure 13). The curve plotted in figure 13 correlates to the curves of figure 12 and figure 9, meaning that the FreedomCAR calculation method can simulate the response of the battery's terminal-voltage V_L in the same accurate way as the adjusted calculation method. The error on the terminal-voltage $V_{L,BPE}$ compared to the terminal-voltage V_L is presented in figure 15. Remarks on this graph are the same as the remarks made on figure 14 (stated in 4.3.2 paragraph 1).

4.3.3 Adjusted calculation model applied on Thevenin battery model

As an example for the adjusted calculation method, the parameters for the Thevenin battery model are calculated using the data from the previous test. The Thevenin battery model is shown in figure 16.
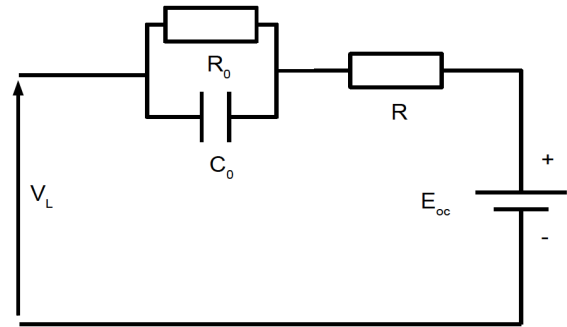

Figure 16: Thevenin battery scheme

The regression data calculated by the Matlab procedure for the Thevenin model are given in table 7.

Table 7: Regression data for Thevenin model

τ	14,13	
r^2	0,9950	
Regression analysis		
R [Ω]	R_o [Ω]	E_{oc} [Ω]
4,41E-03	2,32E-03	3,33E+00
1,41E-05	2,46E-05	2,19E-04

Calculation of the terminal-voltage V_L is

represented in figure 17 where V_L is plotted in function of time. The equation 7 was used to calculate V_L. In equation 7 is I_0 the current passing through R_0 and I_L the current through the battery's terminal connectors.

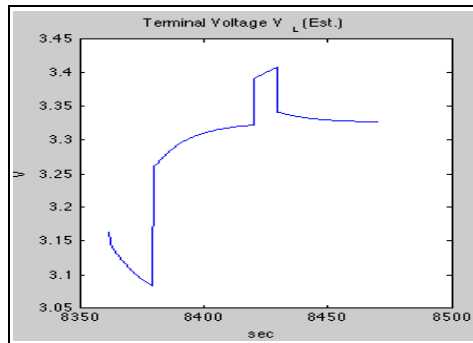$$V_{L,i(est)} = E_{oc} - I_{L,i} \cdot R - I_{0,i} \cdot R_0 \qquad (7)$$

Figure 17: Calculated terminal-voltage V_L using equation 7

5   Conclusions

Adjusting the FreedomCAR calculation method and writing the calculation procedure in the Matlab environment, enabled the creation of a more flexible and accurate way of calculating the magnitudes of the RESS model's components. Adapting the procedure to fit other models (schemes) can now be done with the adjusted calculation method as a reference procedure, giving the opportunity to expand the procedure to many more models. Expanding the procedure to fit more models is part of the future research as is the adaptation of the models to suit different load-conditions.

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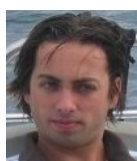
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