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# Deliverable 3200.8

# Algorithm for SC

## Summary

This deliverable presents a mathematical technique and a related practical algorithm, able to on-line evaluate the SC (supercapacitor) cell's state-of-charge (SOC), based on a cell's mathematical model (detailed in D3200.6 [1]) and on a Luenberger-style estimation.

This work is part of WP3200 "Basic storage system testing and modelling", in Task 3230 "Modelling", with the scope to develop and experimentally validate, dedicated mathematical models for Li and SC cells. As planned, the algorithm and the mathematical model analysed in this report are the practical exemplifications of dynamic models derived from testing activities to support the implementation of BMU (battery management unit) for SC modules and systems.

This report shows the results of the proposed technique that are satisfying for the practical needs of a hybrid commercial vehicle.

# Table of contents



# List of figures

## List of tables

## Nomenclature

1. Acronyms

MST Multiple-Step test

OCV Open-Circuit Voltage

SC Supercapacitor

$SOC_Q$ Charge-based State-of-Charge

$SOC_E$ Energy-based State-of-Charge

SOC When SOC acronym is used without subscripts it must be taken as $SOC_Q$

2. Other common quantities

$C_n$ nominal supercapacitor capacitance (e.g. in F)

$\varepsilon_i$ max error on current measurement $I$ *p.u. of* $I_{maxs}$

$\varepsilon_s$ max allowed error on SOC estimate

$\varepsilon_Q$ max allowed error charge exiting the cell (Ah)

$I_t$ Main-branch supercapacitor current

$I_{maxs}$ maximum current the sensor can measure

$k_{fb}$ SOC estimator feedback constant

$R_0$ Algebraic supercapacitor internal resistance

$R_\mathrm{i}$ ($i$=0, 1, …) i-block supercapacitor internal resistance

$C_\mathrm{i}$ ($i$ =0, 1, …) i-block supercapacitor internal capacitance

$\theta$ inner supercapacitor temperature

$\theta_a$ ambient temperature

$V_\mathrm{n}$ rated capacitor voltage (=maximum under normal operation)

$V_\mathrm{est}$ estimated capacitor voltage

$V_\mathrm{oc}$ Open-circuit voltage (equal to OCV)

# Introduction

In deliverable D3200.6 [1], a detailed mathematical model of the supercapacitor of the HCV project was illustrated.

The issues concerning an adequate choice on the detail level of the model, as well as an automated evaluation of numerical values of the parameters defining the equivalent circuit at different SOC levels were discussed.

This deliverable presents how this model can be successfully used to on-line evaluate the SC's State of Charge (SOC).

# Technical progress

## *The supercapacitor*

The basic characteristics of this supercapacitor, as supplied by the manufacturer, are shown in Table 1.

**Table 1. Basic characteristics of the SC cell.**

| | |
|---|---|
| Manufacturer | Maxwell |
| Model | BCAP3000 |
| Capacitance (F) | 3000 |
| Nominal voltage (V) | 2.7 |
| Max voltage (V) | 2.85 |
| Max continuous current ΔT 15°C (A) | 130 |
| Max continuous current ΔT 40°C (A) | 210 |
| Max peak current (A) | 2200 |
| Mass (kg) | 0.510 |
| Energy (Wh) | 3.04 |
| Specific energy (Wh/kg) | 6.0 |
| Usable specific power (W/kg) | 5900 |
| Impedance match specific power (W/kg) | 12000 |
| Cycle life | $10^6$ |

These are nominal values, based on pre-defined operating measuring conditions, and supplied by the SC manufacturer.

## *A basic technique: the OCV-SOC correlation*

A very easy technique to estimate the supercapacitor SOC is called OCV-SOC correlation (this is the same name that has been used for lithium cells in deliverable D3200.7, [2]).

This technique basically consists of the combination of what is usually called "ampere-hour counting" with voltage-based measurements, which are very important to avoid that the accumulation over time of measuring and computing errors causes large errors on the calculated SOC.

Ampere-hour (Ah) counting implies continuously measuring the cell current (for instance current $i_{ch}(t)$, considered positive when charging), and taking the integral of it. In case the measuring process would be unaffected by errors, the supercapacitor SOC would be (cf. the $SOC_Q$ definition in deliverable D3200.6):

$$SOC_Q = Q / Q_{\max} = \frac{\int i_{ch(}t)dt}{C_n V_n}$$

It is rather apparent that pure Ampere-hour counting cannot give an $SOC_Q$ measure that is valid over time, since in real life the current measure is affected by measuring errors that contribute to $SOC_Q$ in a way that grows with time.

The situation can be clarified using the SC model introduced in deliverable D3200.6, and shown for the reader's convenience also in Figure 1.

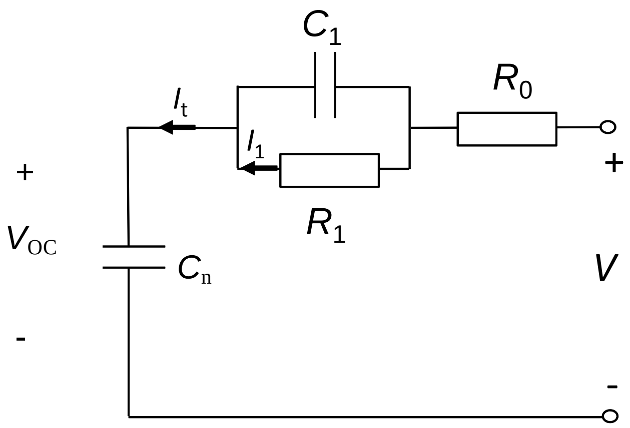


**Figure 1. The SC model chosen in deliverable D3200.6.**

Considering this figure, compensation of the accumulated errors can be made when the cell current stays equal to zero for a suitable time, and therefore the voltage can be assumed to be equal to the $V_{OC}$.

When current becomes zero, cell's voltage $V$, after a transient in which the capacitor $C_1$ gets discharged, reaches voltage $V_{0C}$ i.e. what is commonly called Open Circuit Voltage (OCV).

This transient after current zeroing has been discussed in deliverable D3200.7 [2], whose Figure 4 is reproduced in Figure 2 of this report for reader's convenience.

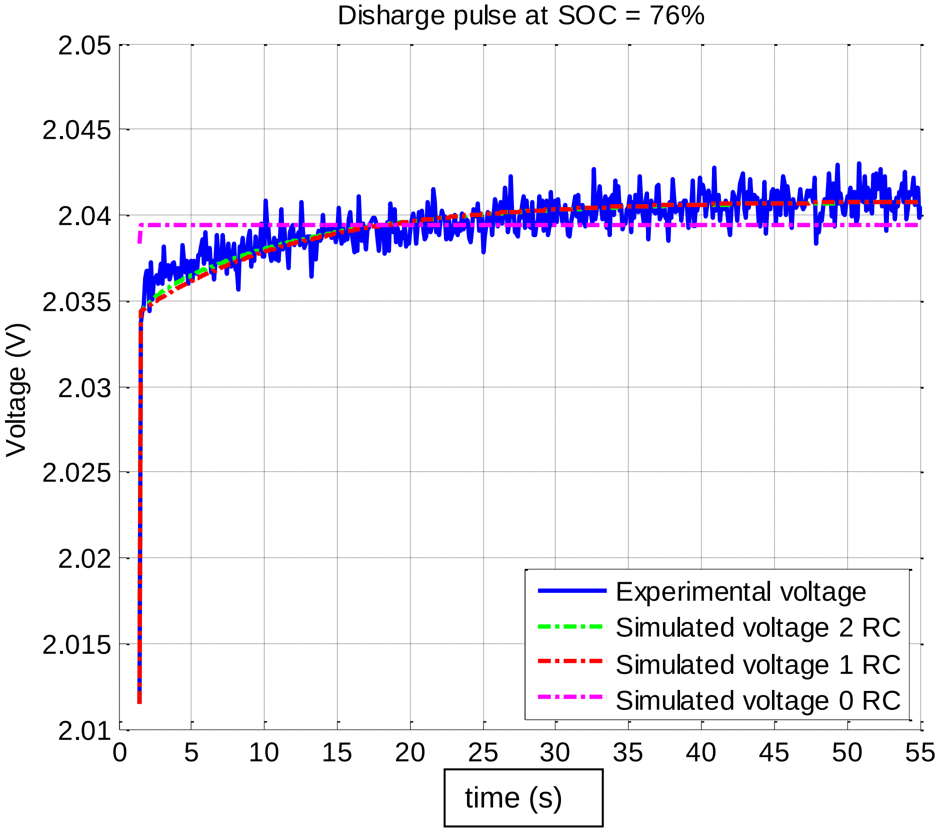


**Figure 2. The voltage transient after a discharge (duplication of figure 4 of D3200.6).**

The transient shows that the measured voltage stabilises after current zeroing in a few tens of seconds, a time after which the cell's voltage is equal to $V_{OC}$=OCV (cf. again Figure 1)

It is also of interest to estimate the maximum time interval between which two OCV measures are to be taken, to avoid excessive errors on $SOC_Q$ produced by the ampere-counting technique.

The reasoning is similar to what already been presented in deliverable D3200.7 for lithium cells, but it is repeated here because there are significant differences.

The HCV supercapacitor can be exploited up to very high currents. In case the peak current is exploited, a sensor capable of as much as 2000 A must be provided.

However, since the maximum continuous current is much lower, it can be supposed to have a sensor with a maximum current of 2000 A.

To perform this analysis, let us define some symbols (Table 2; the symbols are a subset of those used in deliverable D3200.7).

**Table 2. Symbols to evaluate accumulated error on SOC and relative description.**

| Symbol | meaning | Description | Example value |
|---|---|---|---|
| $I_{maxs}$ | | Maximum current the sensor can measure | |
| $\varepsilon_I$ | max current error | the maximum error the current sensor can make, as a ratio to $I_{maxs}$ | 0.01 |
| $\varepsilon_Q$ | max charge error | maximum error on the charge exiting the cell, as obtained by numerical integration of the measured current | - |
| $\varepsilon_S$ | max SOC error | maximum allowed error on SOC estimate, before an OCV-SOC correction is needed | 0.10 |

To evaluate the error induced on $\varepsilon_Q$ by the errors on current measure and subsequent numerical integration, it can be assumed that:

- time is measured with a precision that is much higher than that of current, and therefore errors on the measure of time can be neglected;
- errors in evaluation of the integral of current as a consequence of the numerical integration formulas are negligible as well.

Both assumptions are reasonable, because time is actually measured very well with cheap instrumentation, and numerical integration can be very precise at a very low cost using the computation power of modern microcontrollers with floating-point units.

Under these assumptions it can be written that:

$$\varepsilon_Q = \varepsilon_i \times I_{maxs} \times \Delta t \qquad (1)$$

and

$$\varepsilon_s = \frac{\varepsilon_Q}{Q_n} = \frac{\varepsilon_Q}{V_n C_n} = \varepsilon_i \times \frac{I_{maxs}}{V_n C_n} \times \Delta t \qquad (2)$$

Note that equation (1), i.e. the assumption that time can be measured with unlimited precision, allows to eliminate $\varepsilon_Q$ from equation (2).

Equation (2) can be used to evaluate the maximum time interval between two consecutive measures to guarantee a given $\varepsilon_S$ error, taking as known the instrumentation maximum error $\varepsilon_I$.

Considering the numerical values shown as example in Table 2, and taking $I_{maxs}$=2000 A, Vn=2.7 V, $C_n$=3000 F, from equation (1) we obtain:

$\Delta t$=40s

This is a very short time, since imposing to have zero current for a time of 1-2 seconds (for waiting the voltage to be stabilised) each 40 s or less, is a demanding requisite.

It would be much better if a different technique, allowing SOC to be correctly evaluated without the need of having some time intervals in which the supercapacitor current is continuously zero. This is what is done in the following section.

### *The proposed algorithm: Luenberger-style estimation*

The principle of Luenberger-style SOC evaluation was already introduced in deliverable D3100.5 [3], (Figure 6 in that deliverable).

Its principle can be applied to a supercapacitor, giving rise to the scheme shown in Figure 3.

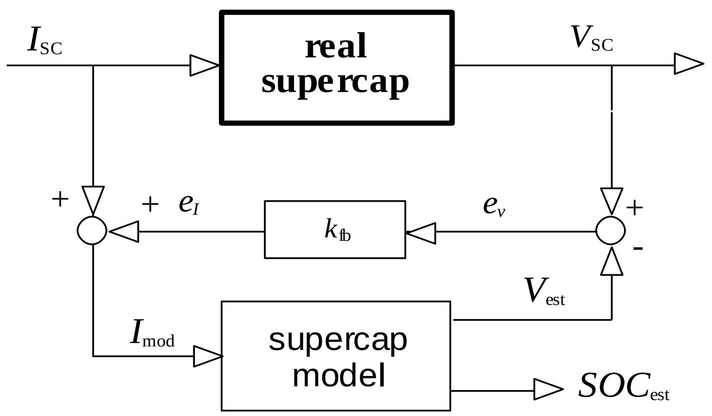


**Figure 3. The Luemberger SOC estimation technique applied to a supercapacitor cell.**

The block “supercap model” contains the model shown in figure 1. Therefore it receives the current $I_{mod}$ (that corresponds to $I_t$ in figure 1) and computes $V$ and SOC, the latter as an algebraic function of $V_{oc}$..

The estimation mechanism is as follows.. Consider an initial condition in which the estimated voltage $V_{est}$ is equal to the actual supercapacitor voltage $V_{sc}$. In this condition the voltage error $e_U$ and the current error $e_I$ are zero.

The supercapacitor model receives as input the model current $I_{mod}$=$I_{SC}$.

Naturally, as a consequence of measuring errors, model uncertainites and numercial computation errors, some difference betweeen $V_{est}$ and $V_{SC}$ appears.

This gives rise to a voltage error, then a current error.

In this case the model current will be:

$$I_{mod} = I_{SC} + k_{fb}e_v = I_{SC} + k_{fb}(V - V_{est})$$

The presence of the signal $e_I$ tends to correct the errors on $V_{est}$ and to keep well aligned $V_{est}$ with $V_{sc}$. When this happens, the model is reproducing well the actual SC behaviour, and therefore the model estimation of $SOC_{est}$ is a good approximation of the supercapacitor SOC.

It is important to fine-tune the feedbak constant $k_{fb}$: higher values give higher corrections. The best operation is when the supercapacitor model well reproduces the real supercapacitor behaviour and the measuring errors are small. In this case small values of the feedback constant are acceptable.

Typically $k_{fb}$ is in the order of 1÷10 A/V.

# Results and Discussion

## *Reference Cycle definition*

The quality of the SOC estimation applied to the cell was tested on the following main reference cycle. The cycle, corresponding to the real usage of the SC module on-board HCV hybrid vehicles is shown in Figure 4 and as provided by ALTRA.

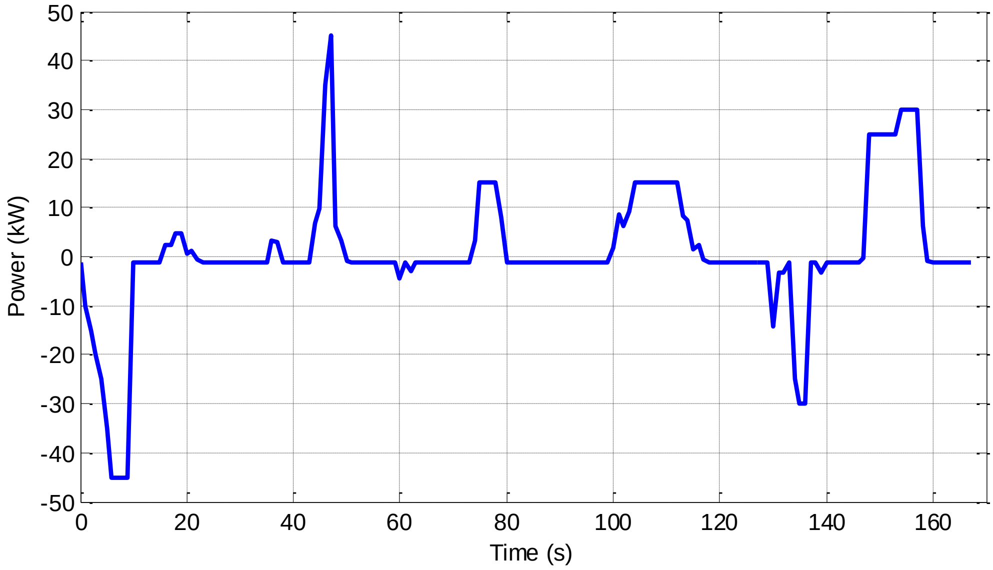


**Figure 4. Reference cycle (power vs time) for the SC module.**

Power is negative when the SC is delivering power, positive otherwise.

Before using it in tests, some modifications of this cycle were made:

- ❑ the shape of the power-vs-time cycle has been retained also as a current-vs-time. This is due to the University of Pisa's hardware that requires defining programmatically the current over time. However, for the sole purpose of SOC evaluation algorithm this is acceptable, since only the general trend of the current must be reproduced. There is no need to have a more closely-matching power profile;

- the scaling factor (constant between all the power values in Figure 4 and the current values used in tests, shown in Figure 5) was chosen to have a current that is sufficiently meaningful for the actual cell operation. The peak current was set to 50A.
- finally, a slight constant current was added, to the profile to render it charge-balanced (Ah-neutral micro-cycle). This allows longer tests to be performed without having to stop as a consequence of capacitor emptying or depletion.

The final cycle obtained after all these modifications is shown in Figure 5.

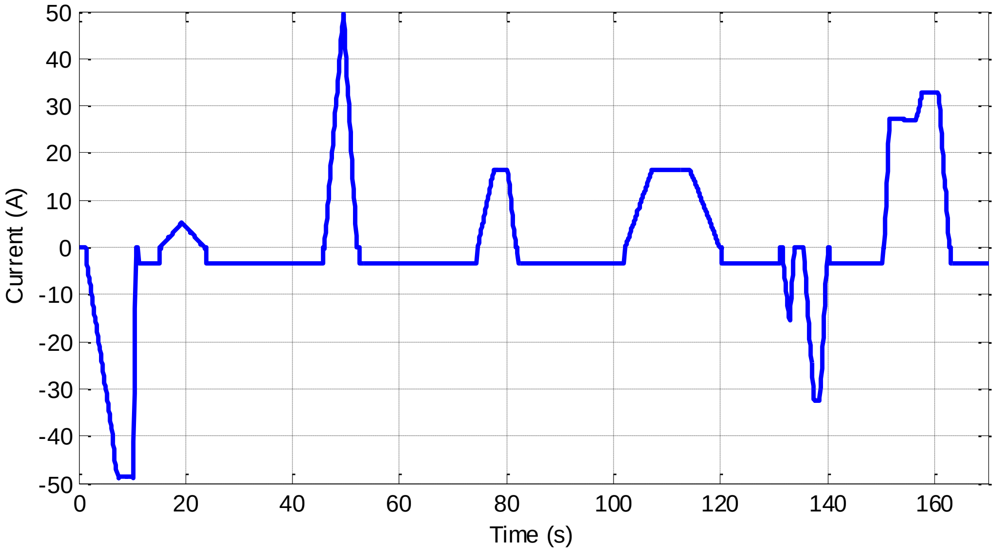


**Figure 5. Reference cycle (current vs time) for the SC under test.**

This cycle is repeated continuously during the tests.

### *Laboratory Test Results*

A first lab test consists in subjecting the cell to 48 repetitions of the reference cycle shown in Figure 5, and measuring voltage and current. This is called *Test 1*. Test1 was performed starting from an average supercapacitor SOC.

Figure 6 shows *test1* current, both globally and with a detailed view.

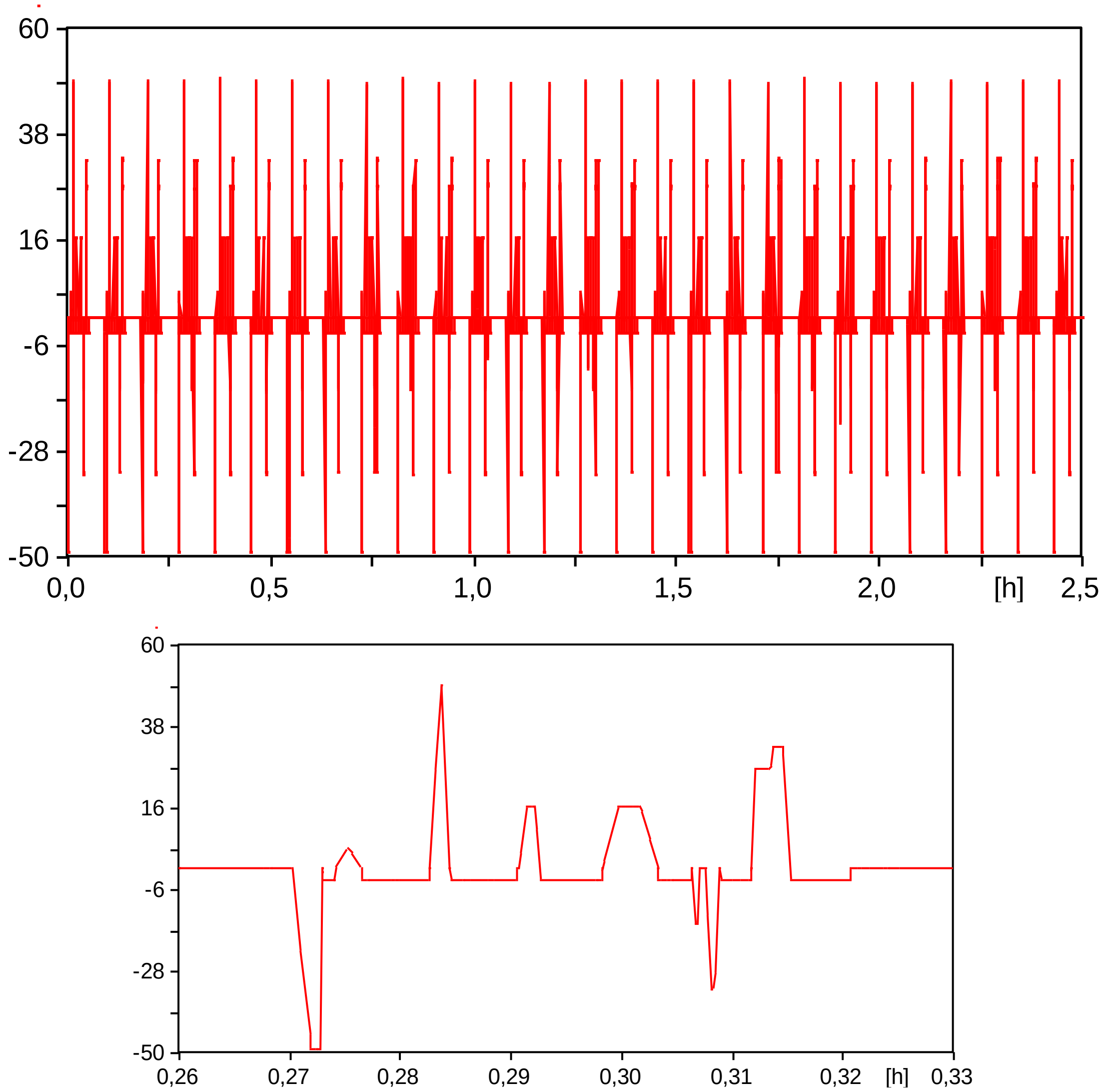


**Figure 6. Cell current (A) during <u>test 1</u> (bottom: expansion of part of top figure).**

Figure 7 shows the measured cell voltage corresponding to the current illustrated in Figure 6.

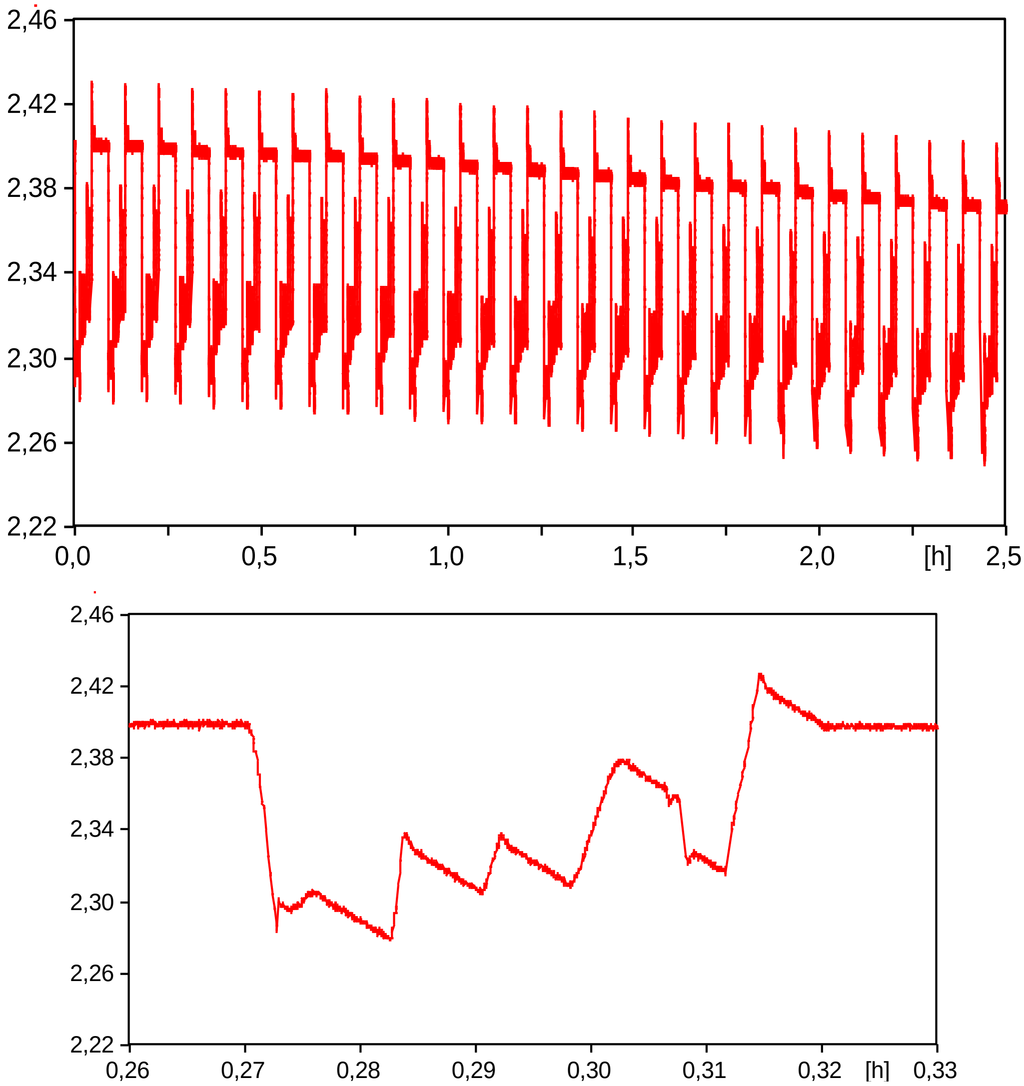


**Figure 7. Cell voltage (V) during test 1 (bottom: expansion of part of top figure).**

Finally, Figure 8 shows the integral of the imposed cell current to indicate that the cycle is well balanced (does not charge nor discharge the supercapacitor).

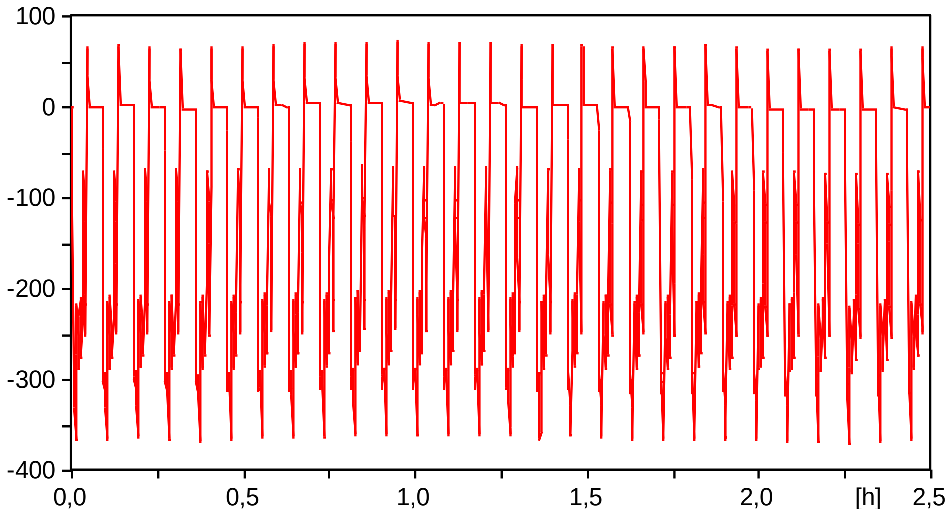


**Figure 8. Integral of current of Figure 6 (J).**

A second test consists of a long rest phase to evaluate supercapacitor self-discharge.

To make the test more realistic, the rest phase was performed after a first group of cycles of the type of Figure 5, and at the end of it an additional group of cycles is performed.

This test is called *test2*.

Figure 9 shows *test2* current, while figures 10 and 11 show the corresponding cell voltage and charge (=integral of current) respectively.

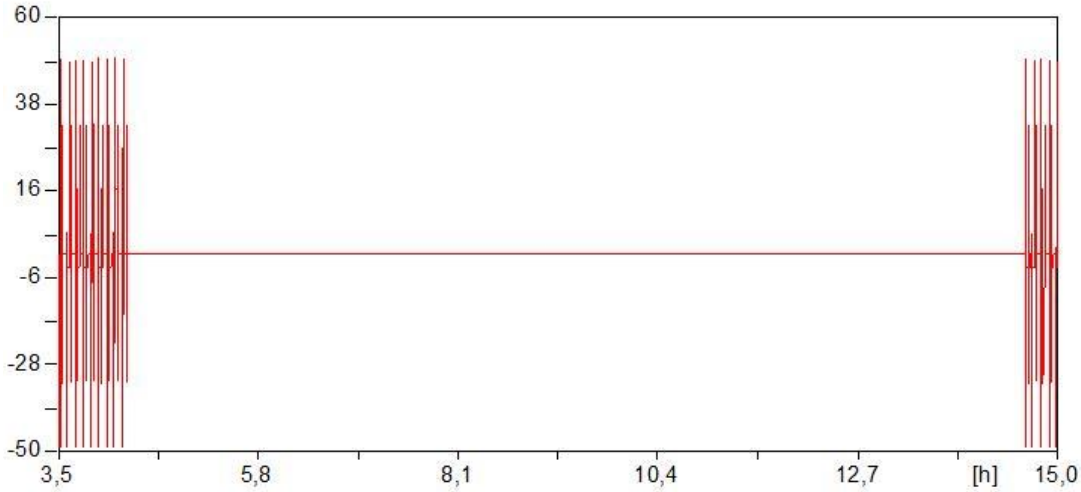


**Figure 9. Cell current during test2.**

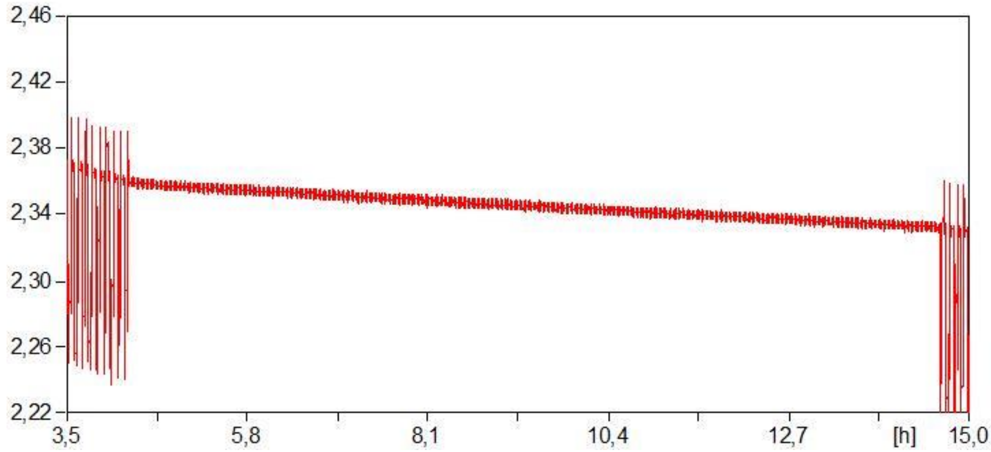


**Figure 10. Cell voltage during test2.**

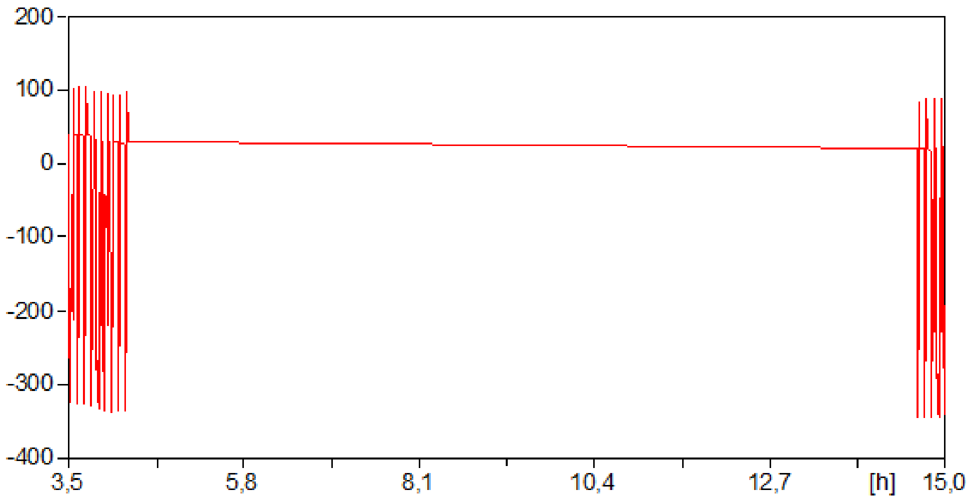


**Figure 11. Cell charge during test2.**

It is well visible that during the rest phase the SC voltage reduces significantly, indicating that some self-discharge is occurring.

## *SOC estimation*

SOC Estimation will be performed according to the technique pictorially described in Figure 3.

Verification of the quality of the SOC estimation procedure proposed is made in three steps:

- step 1: the quality of the SC model obtained in previous studies, whose results are reported in deliverable D3200.6 is verified by subjecting the model to the actual cell current and verifying the matching of estimated and actual SC voltage
- step 2: the technique depicted in Figure 3 is implemented and verified

- step 3: long term effects, in which the effects of long periods of inactivity (e.g. during nights) are verified and checked.

Naturally, in both steps the used supercapacitor model is the one shown in Figure 1, which was the one discussed and chosen in deliverable D3200.6. The corresponding numerical parameters are those found in that deliverable, in particular in the plots shown in Figures 10 to 13 of that deliverable.

Although in that deliverable linear interpolation curves were used, the experimental values were by far constant over SOC. Therefore, it has been decided to make the first tests on SOC estimation using constant values for these parameters. These tests showed that SOC estimation can be effectively made neglecting the parameter dependence on SOC, and constant values can be assumed without loss of precision. For simplicity sake, then, an on-line algorithm can use fixed values for the electrical parameters. The assumed fixed values can be those shown in Table 3.

**Table 3. Numerical model parameters used for SOC algorithm evaluation.**

| Parameter | Value | Unit |
|---|---|---|
| $C_n$ | 3330 | F |
| $R_1$ | 0.1 | mΩ |
| $C_1$ | 100e3 | F |
| $R_0$ | 0.495 | mΩ |

**Step 1.**

The quality of the obtained model under is first checked by submitting the test current to the model and comparing model's and experimental voltage.

The result is displayed in Figures 12 and 13 in two timespans. From the detail of Figure 13 it is apparent that the quality of model is very good; however, the global trend of Figure 12 indicates, as expected, that some voltage drift occurs over time.

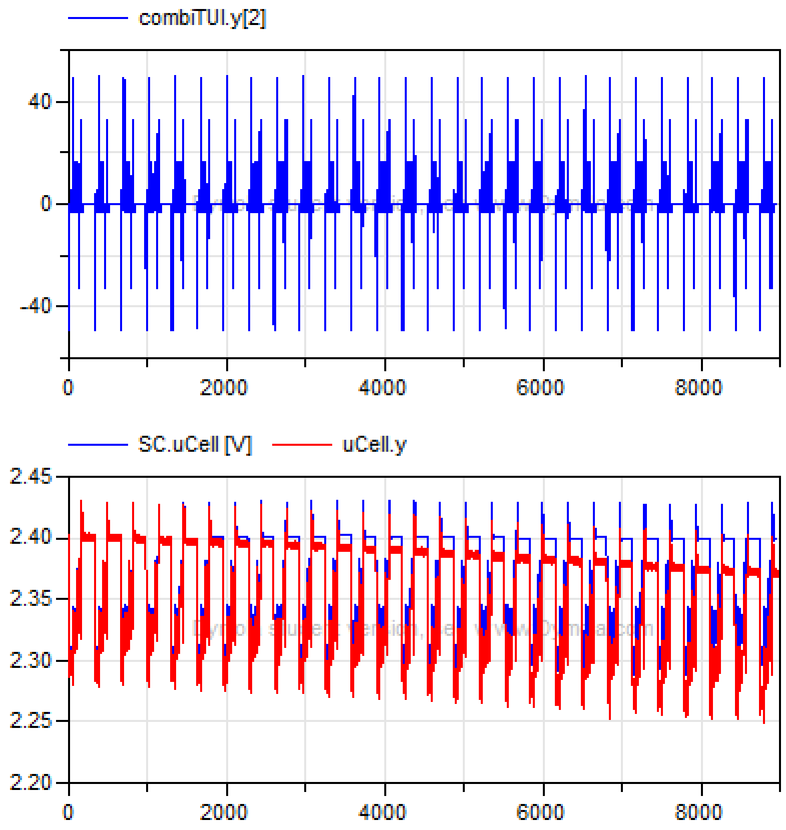


**Figure 12. Comparison of model and experimental cell behavior along *test 1*. Top: cell current; Bottom: model (SC.uCell) and actual (uCell.y) voltage.**

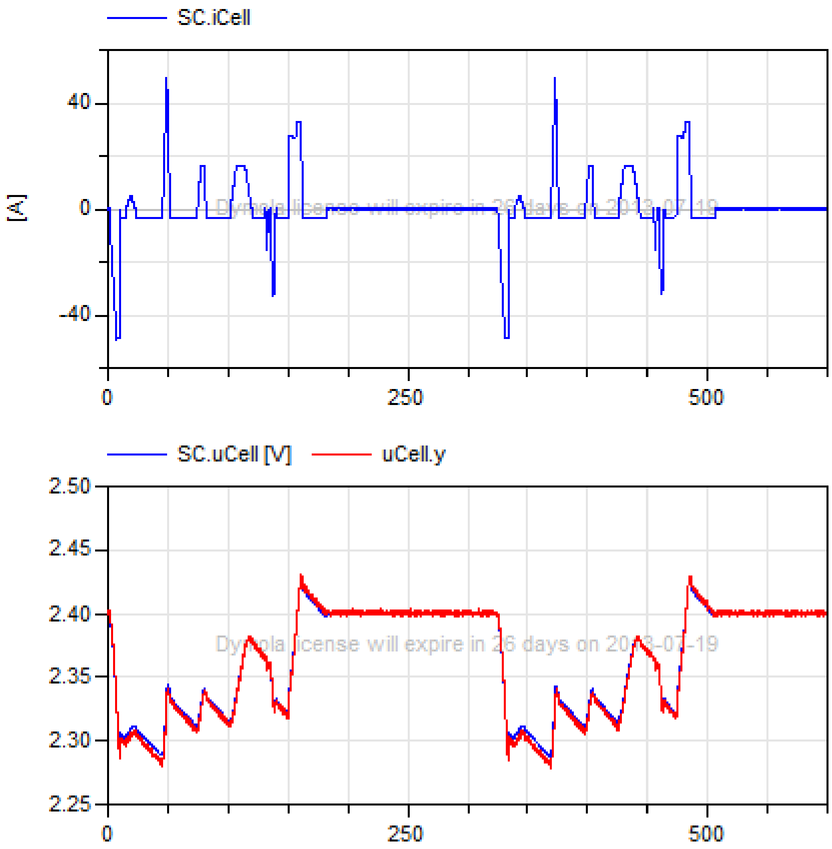


**Figure 13. Expansion of the first part of Figure 12.**

## Step 2

The voltage drift displayed in Figure 12 is expected to be corrected by the feedback algorithm that we proposed in Figure 3.

The algorithm is run using two different values for the feedback constant: $k_{fb}$ = 1A/V and $k_{fb}$=10A/V.

The corresponding voltages are shown in Figures 14 and 15.

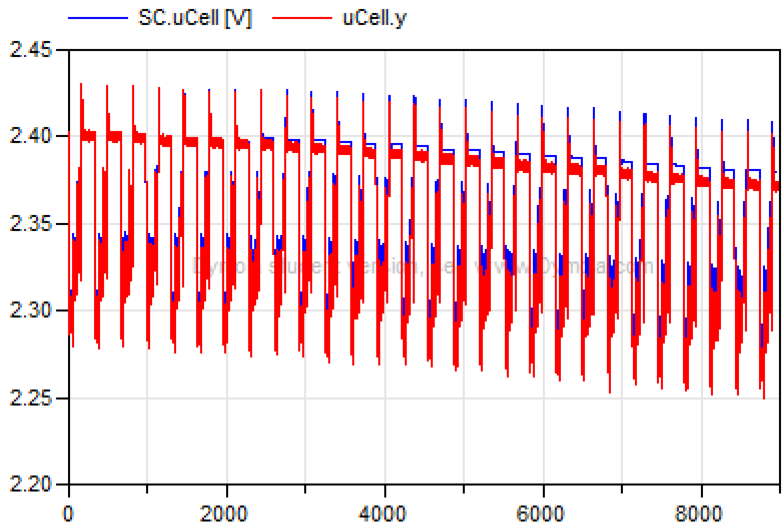


**Figure 14. Comparison of model (SC.uCell) and measured (uCell) voltages when $k_{fb}$=1 A/V.**

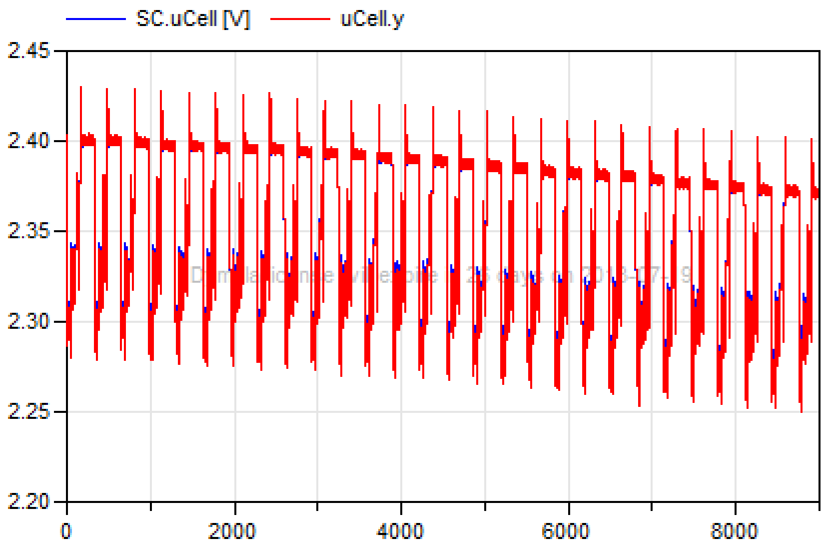


**Figure 15. Comparison of model (SC.uCell) and measured (uCell.y) voltages when $k_{fb}$=10 A/V**

It is evident that while using k=1A/V the voltage error is reduced but still visible, using 10 A/V, the error is in practice totally offset.

Naturally, some slight differences are still visible, but only using an expanded representation of quantities. This is done in Figure 16 in which the last 200 seconds of the transient are shown.

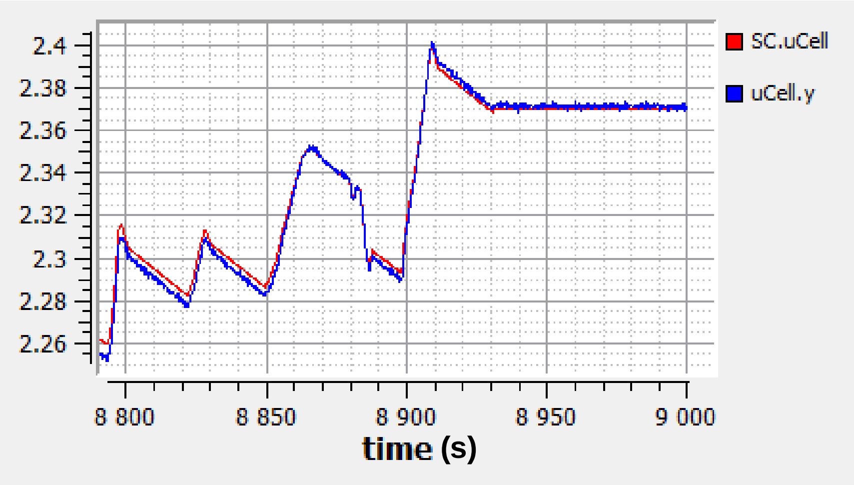


**Figure 16. Expansion of the last 200 seconds of Figure 15.**

## Algorithm sensitivity to errors

The proposed algorithm is robust in terms of errors on the measured current, since it corrects itself based on voltage feedback.

Errors on voltage measurements are more critical. Consider for instance the drawing of Figure 17.

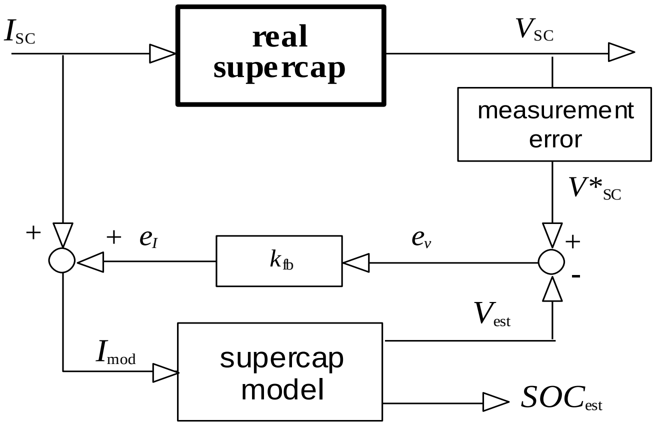


**Figure 17. The Luemberger SOC estimation in presence of measurement errors on voltage.**

The algorithm is designed so that the voltage and current errors are as small as possible.

When it succeeds it can be assumed that:

$V_{est} \cong V^*_{SC}$

Consider for simplicity a steady-state situation, e.g. the current is steadily null (zero). Under this condition, it is (Figure 1):

$V_{est} = V_{OC}$=OCV

And finally:

$$SOC_{est} = \frac{V_{OC}}{V_n} = \frac{V_{est}}{V_n} \cong \frac{V_{SC}^*}{V_n}$$

Therefore any percentage measuring error on $V_{SC}$ implies an equal percentage error on estimated SOC ($SOC_{est}$ is the SOC estimation).

This is acceptable since sensors with precision around 1% are cheap enough, and a 1% error on SOC is acceptable.

**Long term stability**

Similarly to the case of lithium cells, we define “long term stability” the quality of the proposed SOC estimation algorithm to remain close to the actual value over long periods of time.

Indeed in the case of supercapacitors this is much smaller issue, because of the higher simplicity of the device behaviour and the corresponding simplicity of the proposed algorithm.

In the previous section named “laboratory test results”, it was seen that during rest phases lasting several hours the supercapacitor shows a non-negligible self-discharge.

No special problems are expected to occur with the proposed SOC estimation algorithm, since during rest phases OCV is equal to the measured voltage, and therefore actual OCV is a direct consequence of the measured voltage according to do the $SOC_Q$ definition itself (introduced in page 5 of deliverable D3200.6) i.e.:

$$SOC_Q = Q / Q_{\max} = \frac{V_{OC}}{V_n}$$

Therefore at the end of the rest period a valid $SOC_Q$ estimation is immediately available as the ratio of $V_{OC}$ and $V_n$.

If the SOC estimator is left in operation during bust rests, it stays in touch with the SC’s SOC, and nothing must be done.

In case the SOC estimator is stopped during rest phases, for instance to avoid drawing the energy during nights, it is advisable to start the algorithm before the SC starts drawing or absorbing current, so that to measure $V_{OC}$ and, based on it, update $SOC_Q$.

Even though this initial SOC update based only on $V$=$V_{OC}$ is not done, the algorithm’s feedback operation rapidly updates the SOC value. This is shown in Figure 18 that explains how the algorithm is able to recover an initial SOC error using only the $k_{fb}$-based feedback.

In the simulation the transient of test 1 is simulated, but considering an initial 1% initial SOC error, roughly equivalent to the error that would have to be induced by the rest phase of test 2, that, as clearly visible in figure 10, shows a total voltage reduction of 27 mV, equivalent to 1% of the nominal voltage $V_n$=2.7V. Figure 18 is produced using to $k_{fb}$=10 A/V.

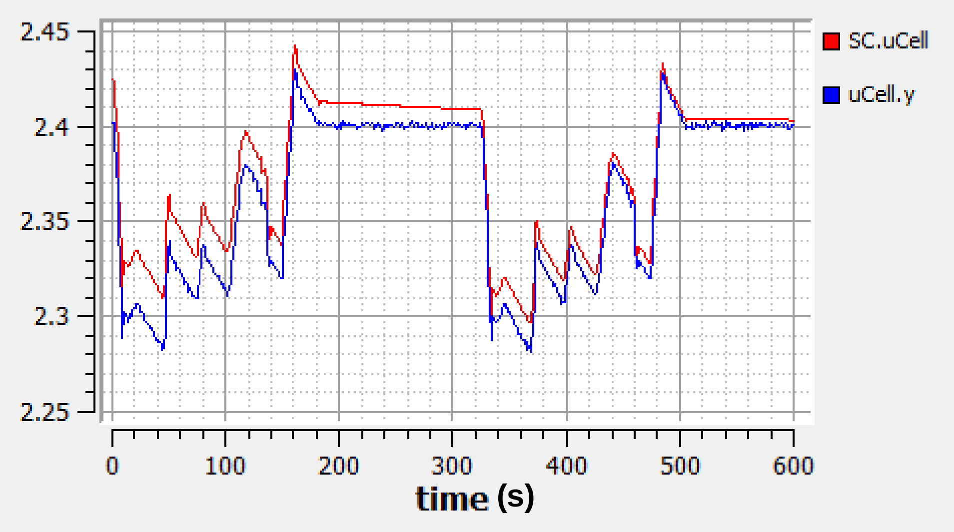


**Figure 18. Recovery of an initial SOC error,
such as the one due to the 16-hour rest phase of test 2.**

Figure 18 clearly shows that the one per-cent error is rapidly recovered. It is to be repeated that this is shown just to evidence the algorithm's robustness. It is again stressed that it is advisable to reset the inner model SOC counting at the end of rest phases, based on the cell's voltage measure, which in that condition is equal to $V_{oc}$, i.e. algebraically linked to $SOC_Q$.

## Conclusions

This document has shown the results of the research carried out in order to produce a SOC estimator for the HCV's supercapacitors.

A Luenberger-style estimator has been proposed, described and validated. It is very simple, effective and robust. It completely avoids drifts on the measured SOC (that in pure Ah-counting techniques would occur due to measuring errors), and allows fast recovery of initial SOC errors. The proposed algorithm is based on both the current and voltage measurements.

When the cell is at rest it automatically gives priority to the voltage measure, while when the current is rapidly changing, the integral of current has the highest effect.

## References

1. Hybrid Commercial Vehicle (HCV) FP7-Project, "Preliminary model definition for SC cell, D3200.6," University of Pisa, 2013.
2. Hybrid Commercial Vehicle (HCV) FP7-Project, "Algorithm for Li cells, D3100.7," University of Pisa, 2012.
3. Hybrid Commercial Vehicle (HCV) FP7-Project, "Preliminary model definition for Li cells, D3100.5," University of Pisa, 2012.