Responsible (Name, Organisation) Massimo Ceraolo – Università Pisa	**DELIVERABLE REPORT**		Page 1(27)
Issuer (Name, Organisation) Massimo Ceraolo – Università Pisa	Date 30/03/2015	WP No 3400	Report No D.3400.11 rev2
Subject Model validation for SC modules			Dissem. Level **PU**

Deliverable 3400.11

Model validation for SC modules

Table of contents

List of figures

List of tables

Summary

This Deliverable describes and reports about activities carried out in the framework of the EU Project “HCV”, as part of the SP 3000 “Energy Storage System”. The activities described hereafter are required to achieve results planned in WP3400 “Module assembly and testing”, in the Task 3450 “SC module model validation”, aimed at experimentally validate the dynamic models developed in WP3200 “Basic storage systems testing and modelling” and in WP3400, by means of life and ageing testing.

In particular, this deliverable describes the experimental activities, carried out at the University of Pisa (UPisa) and also at the supporting testing laboratories (AIT and ENEA), and discusses the details of the mathematical model developed for the HCV project’s supercapacitors (SC) module, based on the experimental results.
The structure of the model and all the numerical values of the parameters are found from experimental results obtained at UPisa laboratories (with inputs from AIT and ENEA) and discussed, taking as reference the procedure already detailed in D3200.6 for the supercapacitor cell.
The deliverable presents also a mathematical technique able to on-line evaluate the SC module’s state-of-charge (SOC) based on a Luenberger-style estimation, already employed for the supercapacitor cell and detailed in D3200.8.

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

2. Other quantities

C_i	(*i*>0) i-block supercapacitor internal capacitance
C_n	nominal supercapacitor capacitance (e.g. in F)
I_t	Main-branch supercapacitor current
R_i	(*i*>0) i-block supercapacitor internal resistance
R_0	Algebraic supercapacitor internal resistance
θ	inner supercapacitor temperature
θ_a	ambient temperature
V_n	rated capacitor voltage (=maximum under normal operation)
V_{oc}	Open-circuit voltage *(similar to OCV)*

Introduction

In the deliverable D3100.5 [1], discussion of mathematical models available for supercapacitors was presented. A general model was defined: Figure 1 shows the general structure, with slight modification of symbols respect to the version used in D3100.5. This is a family of models that allowed different degrees of precision, depending on the number of *R-C* blocks: the higher this value, the higher the model's precision, but also the models complexity.

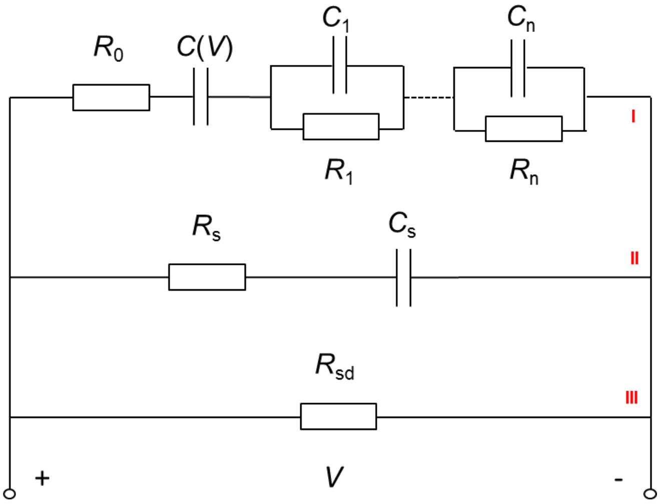

Figure 1. Generic structure of electric model of supercapacitor (1st form).

This model can be used as a graphical-mathematical model of the SC behaviour. Its usage is not limited to off-line studies of the SC behaviour, but it can be also very important in facilitating the determination SC SOC, using Luenberger-style techniques, as described later.

Therefore, if detailed experimental evaluations of the considered SC must be made, the parameters of the chosen model have to be determined, and verification of the model quality evaluated.

The full definition of the SC module behaviour needs to be performed according to the following steps:

1. verification of the applicability of the general model, whose circuital description is shown in Figure 1, to the SC module chosen for HCV demonstrators.
2. detailed definition of the SC mathematical model. It relates to the need of choosing a unique structure from the family of circuits shown in Figure 1, i.e. to neglect some features or to determine the number *n* of R-C blocks.
3. detailed definition of model numerical parameters (values of E, R's, C's at different values of SOC).
4. detailed definition of the algorithm to estimate the SC module SOC.
5. verification of model and SOC estimation algorithm quality.

The next section of the deliverable in principle follows this order.

Technical progress

Measures of supercapacitor state in terms of charge and energy

SC voltage variation during charge and discharge is much higher than the corresponding voltage of lithium batteries.

This high voltage variability must be taken into account when considering the energy entering or exiting the device.

The maximum safe, repetitive voltage that can be stored in an SC cell is normally called rated capacitor voltage V_n, and this term was used in deliverable D3100.5 [1]. Therefore the maximum energy that can be stored in practice in a supercapacitor is:

$$E_{\max} = \frac{1}{2} C_n V_n^2$$

Correspondingly the maximum charge that can be stored in the device is:

$$Q_{\max} = C_n V_n$$

If we want to represent the *energy* stored in a supercapacitor as a ratio of the corresponding maximum energy, the following quantity may be used:

$$SOC_E = E / E_{\max} = \frac{(1/2) C_n V}{(1/2) C_n V_n^2} = \frac{V^2}{V_n^2}$$

If, however, we want to represent the *charge* stored in a supercapacitor as a ratio of the corresponding maximum charge, the following quantity may be used:

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

In deliverable D3100.5 [1], SOC_E was introduced. However, to ease comparison with the battery, in this document SOC_Q is used. Supercapacitors are normally cycled in use between $V_n/2$ and V_n. As a consequence, SOC_Q varies between 0,5 and 1.

The model that is obtained is largely independent on SOC choice between the two definitions above described, and therefore the results are not influenced by this choice.

The SC module

While deliverable D3100.5 [1] dealt with cell modelling in general, this document refers to the SC module chosen for the HCV project. The basic characteristics of this device, as declared by the manufacturer, are reported in Table 1.

Table 1. Basic characteristics of the SC module

Manufacturer	DIMAC RED SRL	
Model	X-BOOST 500	
Capacitance (F)	500	
Nominal voltage (V)	16.2	
Max voltage (V)	17.1	
Max continuous current (A)	147	
Max peak current (A)	2170	
Short circuit current (A)	9300	
Mass (kg)	4.1	
Cycle life	10^6	

Definition of the detailed model architecture

In the Deliverable D3100.5 a survey of literature about SC mathematical models was performed, that has shown a general uniformity of the models that all can be with minor differences reproduced using the equivalent circuit shown in Figure 1. As visible it consists of three branches. Further details are reported in D3200.6 [2].
In case of no interest in considering the slow dynamic of the device, the second and the third branches of the model can be neglected, by considering, consequently, only the first branch. The model without the second and the third branch, and with a generic number of blocks *n*, is reported in Figure 2.

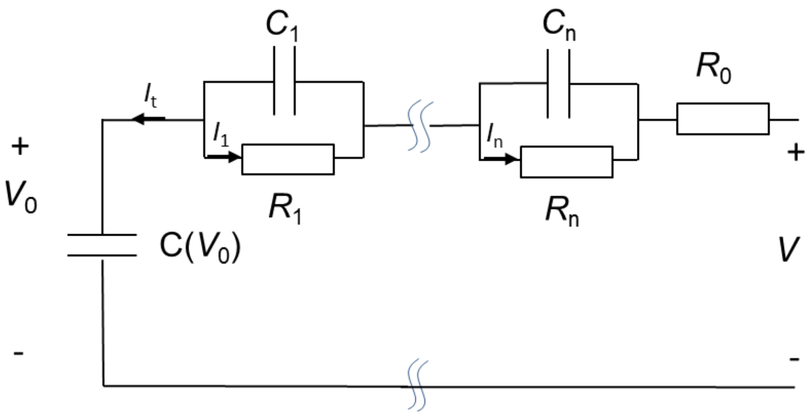

Figure 2. Model of Figure 1 without the second and the third branch.

The transients simulated by the *R-C* blocks have time constants $R_k C_k$ around one second or tens of seconds respectively. Therefore they can be neglected, whenever only the very first parts of the SC dynamic response is of interest.
If slow transients (except the main charge/discharge process) can be disregarded, the first branch can be simplified with the electric circuit of Figure 3.

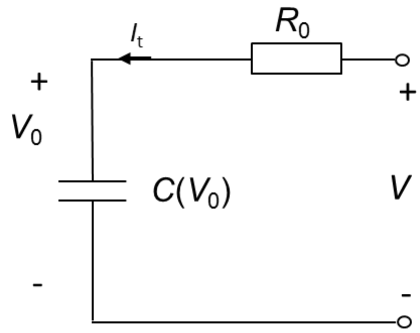

Figure 3. First branch model adequate when slow transients (except the main charge/discharge process) can be disregarded.

The mathematical model of Figure 2 has a generic number of *R*-*C* blocks, and the best value for *n* had to be chosen: to avoid excessive complexity of the model, and therefore of the procedure to evaluate the numerical values of parameters, the basic decision of considering two options was chosen: *n*=1 and *n*=2.

On the other hand, the model reported in Figure 3 is representative of the situation without any *R*-*C* block, in which *n* is equal to zero. Naturally, with *n*=0 the precision is expected to be low, but also the procedure to draw parameters from experimental tests is simplified.

The procedure to evaluate all values of R_k's and C_k's is the same as for the SC cell, detailed in the deliverable D3200.6 [2], and can be applied to the result of the MST (Multiple-Step-Test), at different values of SOC, and therefore values of R_k's and C_k's at different values of SOC are determined. To understand the process, some results are discussed here.

Figure 4 shows a comparison between experimental and simulated voltage at the end of a discharge pulse, at SOC = 65%. The voltage response to the same current of the considered battery model depends on the number *n* of *R*-*C* blocks, and the numerical values of all R_k's, C_k's, V_{oc}.
A procedure to identify all these values is used that minimises the error between actual and simulated voltage profile. The error function chosen is:

$$\varepsilon = \min\left\{\sum_{k=1}^{K}\sqrt{(v_{k,\mathrm{actual}} - v_{k,\mathrm{model}})^2}\right\} \quad (1)$$

Where *k*=1, 2, …*K* are the individual values at equidistant times t_1, t_2, t_K.

The numerical values obtained after this process are reported in Table 2.

Table 2. Numerical values of model parameters as identified for SOC=65%.

n	V_{oc} (V)	R_0 (mΩ)	R_1 (mΩ)	R_1C_1 (s)	R_2 (mΩ)	R_2C_2 (s)
0	10.69	3.49	---	--	--	--
1	10.69	2.81	1.05	23.6	--	---
2	10.69	2.82	0.21	2.7	1.20	53.8

Figure 4 shows the actual and simulated voltages, considering all the analysed cases.

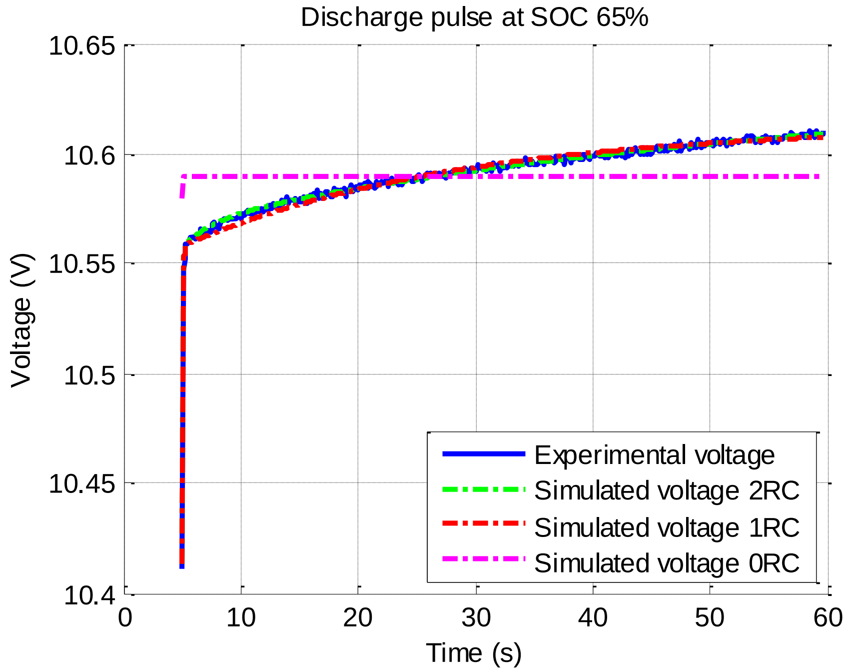

Figure 4. Voltage behaviour at the end of a discharge process, while SOC=0.65. Comparison between experiment and model for 0 RC, 1 RC and 2 RC blocks (R's, C's, V_{oc} determined by error minimisation).

The comparison demonstrates that configuration with 1 RC block or 2 RC blocks shows rather acceptable results, while the 0 block one has a distinct disadvantage.

Moreover, results with n=1 and n=2 are nearly equivalent. It was therefore concluded that the complication due to the use of two R-C blocks can be avoided. Therefore the following has been adopted:

Decision. The adopted model was decided to have one *R-C* block.

If instead we consider the charge-based MST, the result when SOC=65% is that shown in Figure 5.

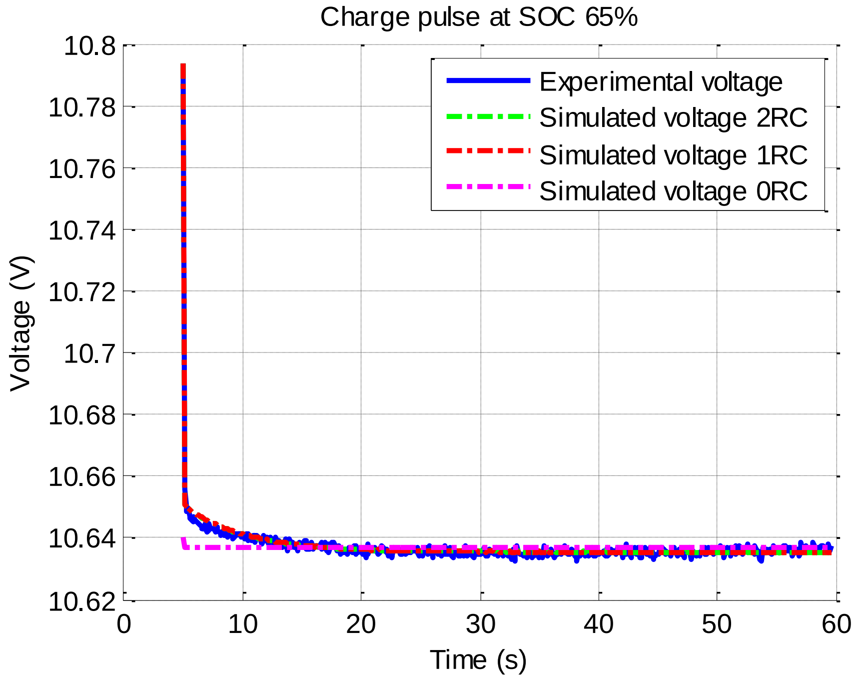

Figure 5. Voltage behaviour at the end of a charge process, while SOC=0.65. Comparison between experiment and model (R's, C's, V_{oc} determined by error minimisation).

The corresponding numerical parameters are presented, at a predefined SOC, both for charge and discharge transients, in Table 3.

Table 3. Model numerical parameters at SOC=65%, after charge and discharge processes.

Transient	V_{oc} (V)	R_0 (mΩ)	R_1 (mΩ)	R_1C_1 (s)
After charge	10.69	2.81	1.05	23.6
After discharge	10.69	2.85	0.26	4.5

If the procedure to identify all parameters is taken literally, all parameters have values during charge and discharge.
This duality, however, is a potential source of big difficulties, arising when the SC is under continuously varying currents. Indeed, if the model parameters suddenly switch from charge to discharge values, whenever the current at SC terminals changes its sign, it is not difficult to foresee large mismatches between simulated and actual values.

The basic idea, which is the same already presented in deliverable D3200.6 [2] for the SC cell, is therefore that of adopting a unique value for V_{oc}, both during charge and discharge, due to the fact that hysteresis is absent, and using intermediate values for the other parameters:

Decision.
- The adopted model V_{oc}, *R*'s and *C*'s parameters do not depend on history except for their dependence on temperature and SOC.

The choice of resistance and capacitance values for the model at different SOC must somehow take into account what happens during charge and during discharge.

Figure 6 to Figure 8 show the comparison of two techniques:

- Technique 1, in which the numerical values are the arithmetic means between those obtainable during end-of-charge and end-of-discharge identification process. This technique is the simplest to implement.
- Technique 2, in which the numerical values are determined by minimising the error considering both end-of-charge and end-of-discharge transients.

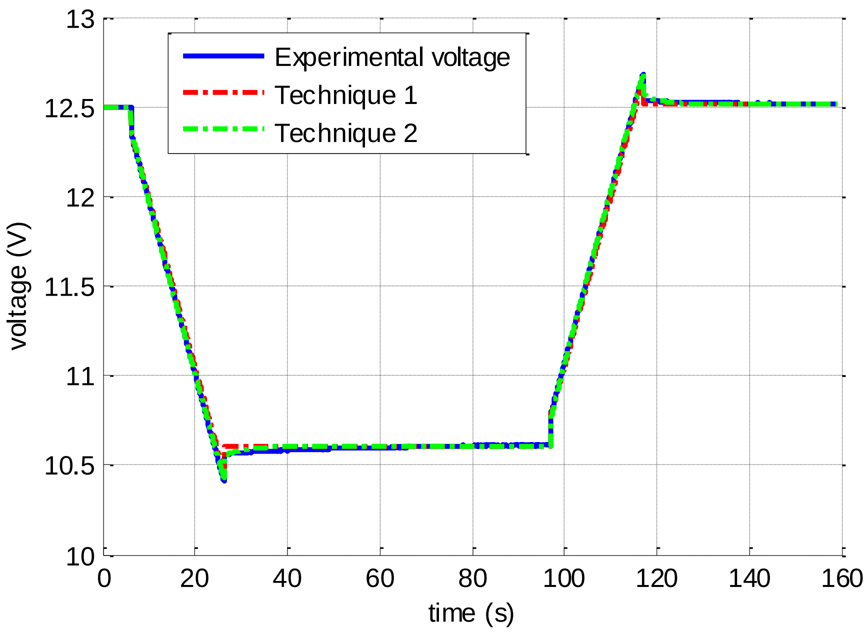

Figure 6. Comparison of voltage behaviour of models whose R-C parameters are evaluated with mean value charge/discharge (Tech. 1) or global optimisation (Tech. 2).

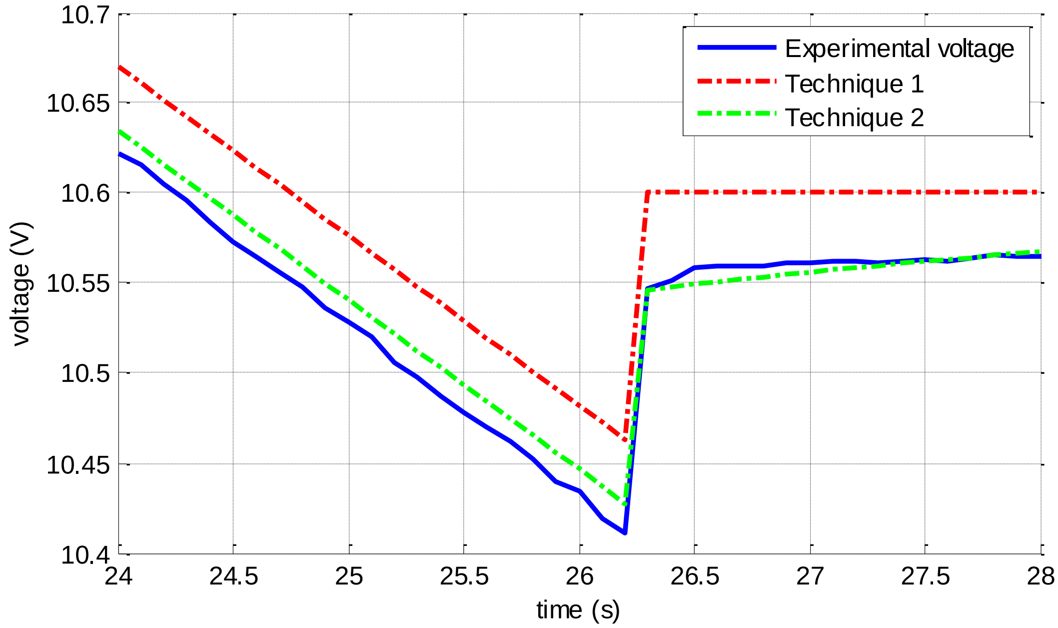

Figure 7. Expansion of left part of Figure 6.

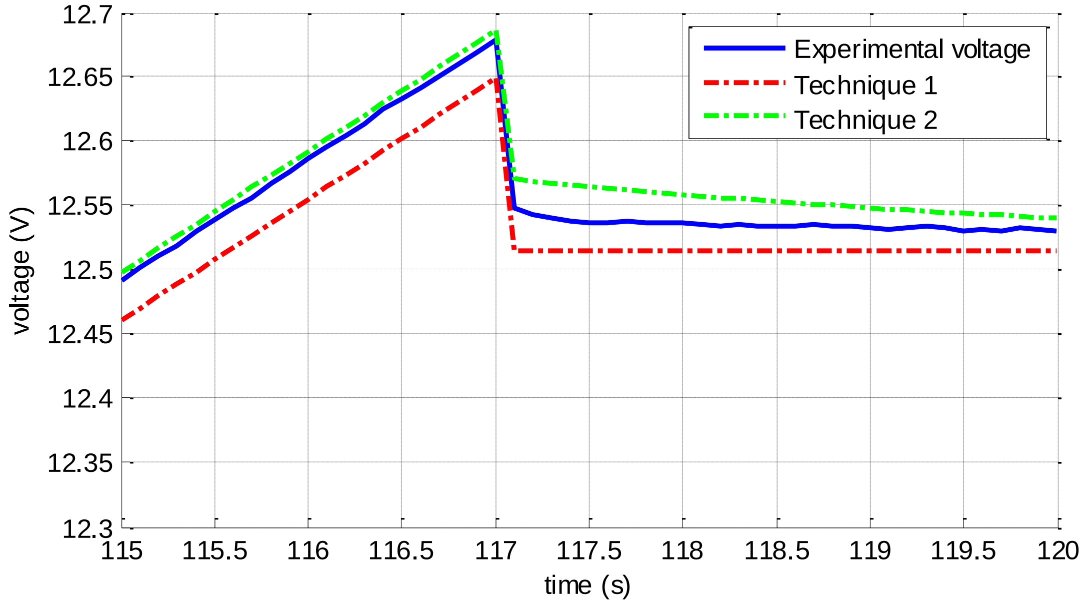

Figure 8. Expansion of right part of Figure 6.

It is apparent that the two techniques are rather equivalent. The actual implementation of evaluation of numerical parameters of the model can therefore be done in either way.
The choice could be made considering practical issues related to the automatic determination of the numerical values from experimental tests. In fact, since it is expected that a periodical update of these values will become necessary to follow the SC ageing during the vehicle usual life, it is advisable to produce techniques to identify the numerical values of the model parameters that are easy to automate.

Conclusions

This section analysis allows to draw the following conclusions:

1) an equivalent circuit of the type shown in Figure 2 is adequate for simulation purposes, assuming *n*=1 (one R-C block)
2) the numerical values for the circuit parameters (C, R_0, R_1, C_1) can be obtained as the arithmetic mean of those obtained in charge and discharge phases.

Determination of model parameters as a function of SOC

In the previous section several alternatives for the supercapacitor model architecture have been analysed and compared to each-other.
Two main conclusions were drawn regarding the circuit architecture and the parameter evaluation procedure.

This section documents the results obtained by evaluation of the circuit's parameter at different values of the SC SOC.

To draw these parameters, a simplified MST (Multiple Step Test) was carried out that allows determination at different values of SOC. The supercapacitor went through cycle tests with the current shown in the upper part of Figure 9 and the corresponding measured voltage is shown in the lower part of the same figure.

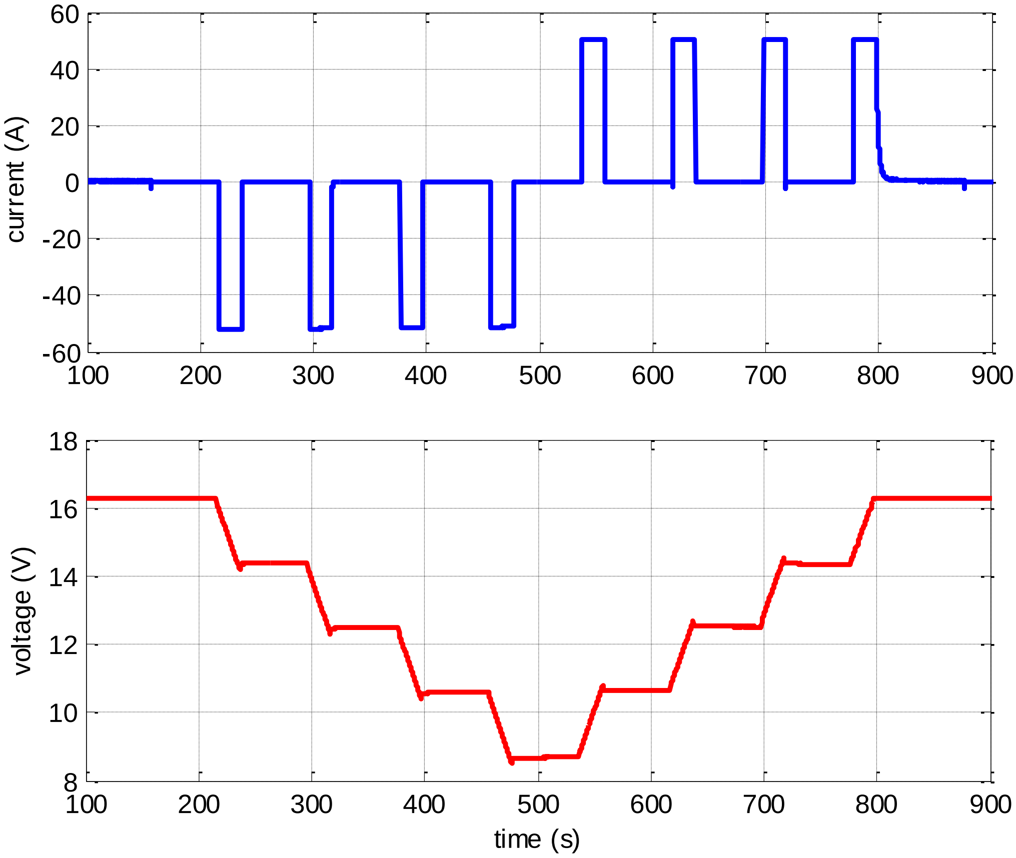

Figure 9. Current and voltage profiles as measured during MST.

In line with the deliverable D3400.10 [3], also for the SC module the general uniformity of cells was checked. In accordance with DIMAC RED guidelines and recommendations, the module was opened to directly measure partial voltages: because of its inner structure, it was possible to access to three pairs of cells connected in series, whose voltages are shown in Figure 10. The maximum difference of around 0.1 V tends to remain constant during the test.

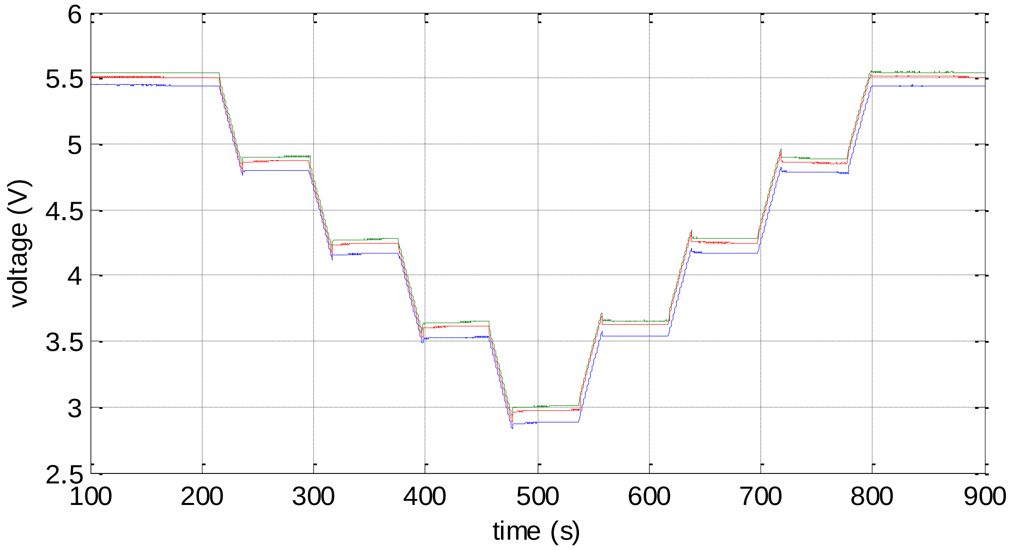

Figure 10. Partial voltages as measured during MST.

Determination of the five parameters R_0, R_1, R_1C_1 has been performed this way at various values of SOC, by using the technique presented in the previous section, in which the numerical values are the arithmetic mean between those obtainable during end-of-charge and end-of-discharge identification process. The results obtained are displayed from Figure 11 to Figure 13.

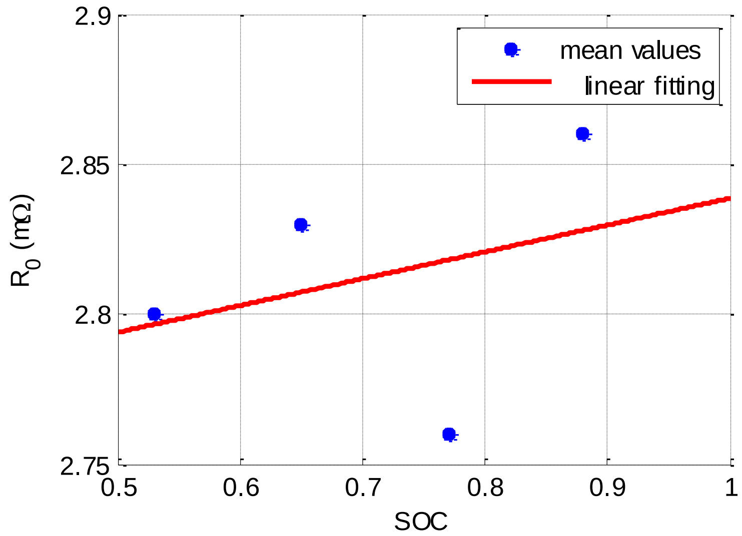

Figure 11. Experimental data on R_0 and linear interpolation.

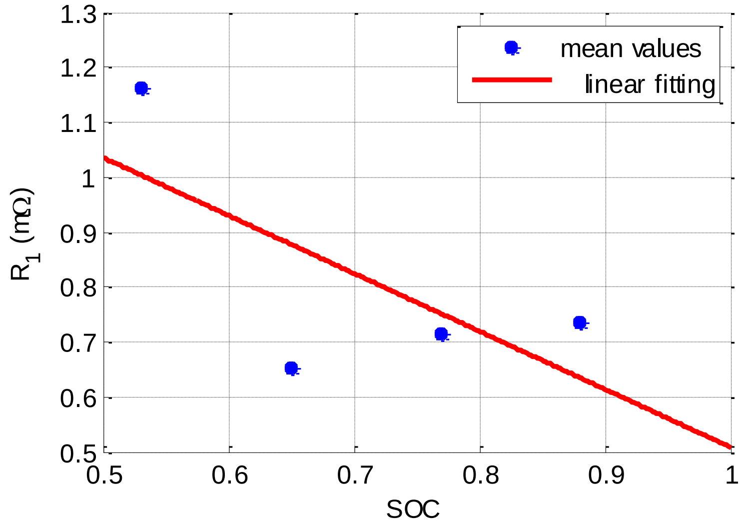

Figure 12. Experimental data on R_1 and linear interpolation.

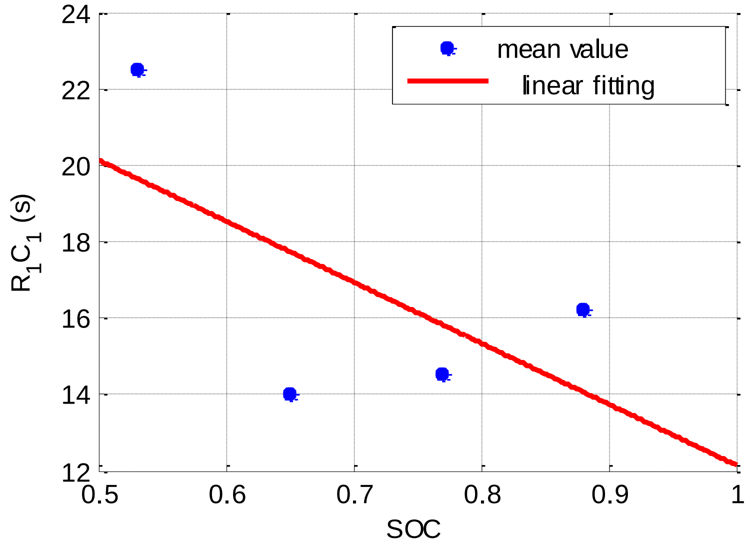

Figure 13. Experimental data on time constant R_1C_1 and linear interpolation.

Figures 11 to 13 show that parameters R_0 R_1, R_1C_1 are by large constant over SOC. Fluctuations seem more related to measuring errors (and the chosen sampling time) than to actual variation over SOC. Therefore it appears reasonable to assume for these parameters constant values. Just for completeness, however, also linear interpolation straight lines (minimising squared differences) are shown.
It is not advisable to use more complicated interpolation curves, since changes in measuring technique, while not changing significantly the absolute values of these parameters, impact substantially on their trend over SOC.

Finally, Figure 14 shows the V_{oc} values. Thanks to the absence of hysteresis, there is no difference between the values obtained during the discharge-based MST, and those obtained during the charge-based MST.

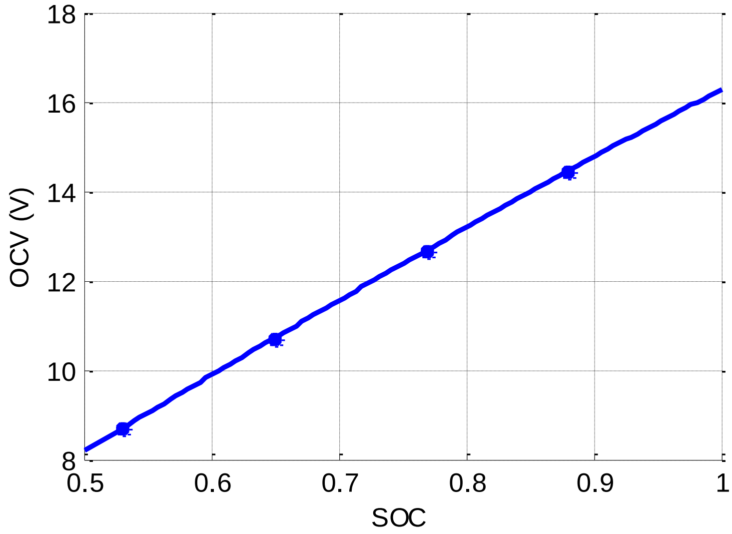

Figure 14. Experimental data on voltage V_{oc}, after discharge steps and after charge steps.

The results shown from Figure 11 to Figure 14 indicate modest variation of parameters over SOC. Therefore two ways are possible:

- The SOC dependence is totally disregarded, and R_0, R_1, C_1 and C are all taken as constant over SOC.
- A linear dependence is supposed.

The electrical circuit of Figure 2 in the form of one RC-block has been modelled, and the parameters evaluated with Technique 1 were introduced, considering or not the SOC dependence. Giving as input to the model the MST current profile, the voltage output was compared to the measured experimental voltage. Results are substantially equivalent, as it is possible to infer by the following two figures (Figure 15 and 16).

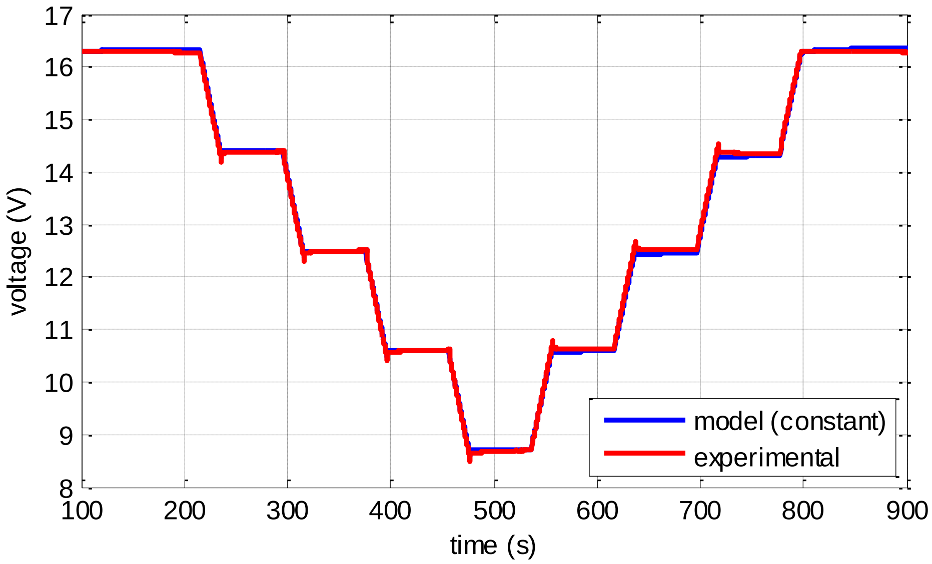

Figure 15. Experimental and simulated voltage during MST, constant parameters.

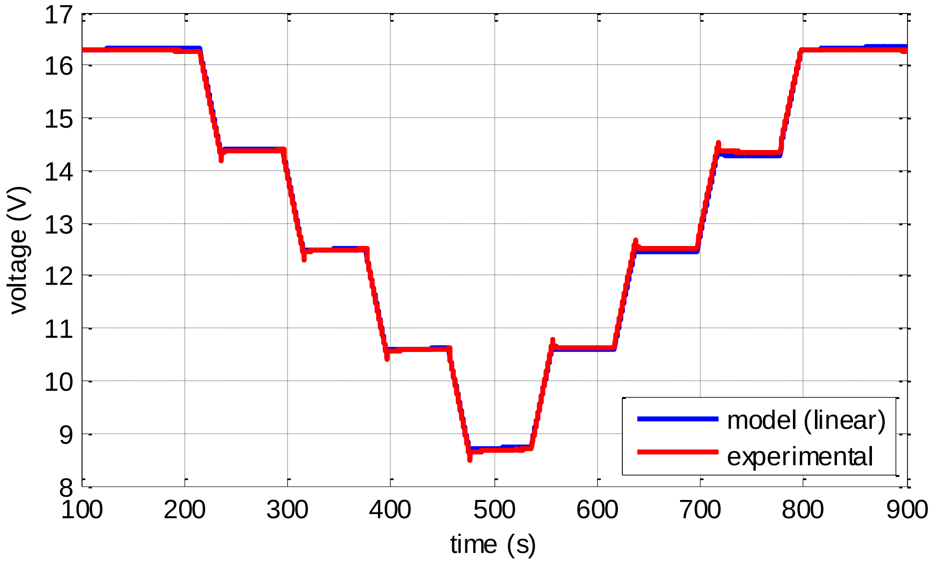

Figure 16. Experimental and simulated voltage during MST, linear dependence of parameters over SOC.

Conclusion
Considering the modest variation of the parameters both with simulation results, R_0, R_1, C_1 and C, can be taken as constant over SOC.

SC SOC evaluation: the OCV-SOC correlation technique

A possible very easy technique to estimate the SC SOC is called OCV-SOC correlation. This technique basically consists of what is usually called "ampere-hour counting". Ampere-hour 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 SC SOC would be as already detailed in the previous section:

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

It is rather apparent that pure Ampere-hour counting cannot give an SOC_Q measurement that is valid over time, since in real live the current measurement is affected by measuring errors, contributing to SOC_Q in a way that grows with time. To this error, it is necessary to add the accumulated errors due to the numerical integration and other numerical operations.

Compensation of the accumulated errors can be made at times in which the cell current is null for a suitable time, and therefore, the cell terminals voltage can be assumed to be equal to the OCV, as detailed in the deliverable D3200.8 [4].

Also for the module it is 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 analysis, equivalent to what already presented for the SC cell, is here repeated for clarity, with the Table 4 containing the used symbols.

Table 4. Symbols to evaluate accumulated error on SOC and relative description

Symbol	meaning	Description	Example value
I_{maxs}		Maximum current the sensor can measure	
ε_I	max current error	the maximum error the current sensor can make, as a ratio to I_{maxs}	0.01
ε_Q	max charge error	maximum error on the charge exiting the module, as obtained by numerical integration of the measured current	-
ε_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 ε_Q by the errors on current measurement 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:

$$\varepsilon_Q = \varepsilon_i \times I_{maxs} \times \Delta t$$

and

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

This very clearly shows that at equal ε_I and ε_s, the maximum time Δt for which the Ampere-counting can proceed before OCV-SOC correction depends on f_i.

As a consequence, considering I_{maxs}=2000 A, Vn=16.2 V, C_n=500 F we obtain:
Δt=40 s, that is a very short time. Therefore imposing to have zero current for a time of 1-2 s at least each 40 s is a demanding requisite.

It would be much better to have a different technique, allowing SOC to be correctly evaluated without having to ask for times during which high current is zero. This is what is done in the following section.

Luenberger-style algorithm to estimate the SC module's SOC

The principle of Luenberger-style SOC evaluation was already introduced in deliverable D3100.5 [1] and already applied to the SC cell in D3200.8 [4]. The scheme is repeated in Figure 17.

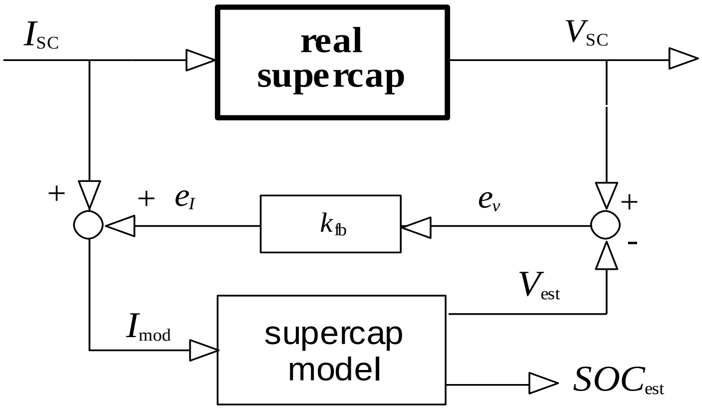

Figure 17. The Luemberger SOC estimation technique applied to the supercapacitor module.

The estimation mechanism is very simply explained. Consider an initial condition in which the estimated voltage U_{est} is equal to the actual supercap voltage V_{sc}. So the voltage error e_U and the current error e_I are zero. So 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} appers. 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 current error 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 is a good evaluation 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 SC module 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 18. The cycle was provided by ALTRA.

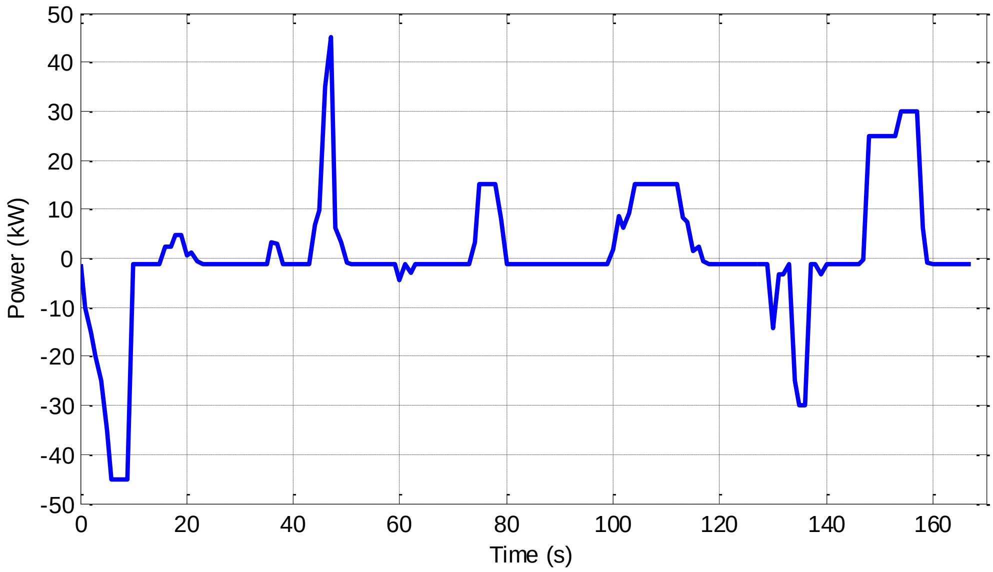

Figure 18. Reference cycle (power vs time) for the SC module.

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 Pisa University's hardware that requires to define 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. No need exists to have closely-matching power profile.
- the scaling factor (constant between all the power values in Figure 18 and the current values used during the tests) was chosen to have a current that is sufficiently meaning for actual module operation. The peak current was set to 50 A.
- finally, a slight constant current was added, to make the cycle charge balanced. This allows longer tests to be performed without having to stop as a consequence of capacitor emptying or depletion.

Lab results

The lab test consists in subjecting the cell to 48 repetitions of the reference cycle shown in Figure 19 (bottom), and measuring voltage and current. The test was performed starting from an average supercapacitor SOC. Figure 19 shows the measured test current, both during a portion and with a detail.

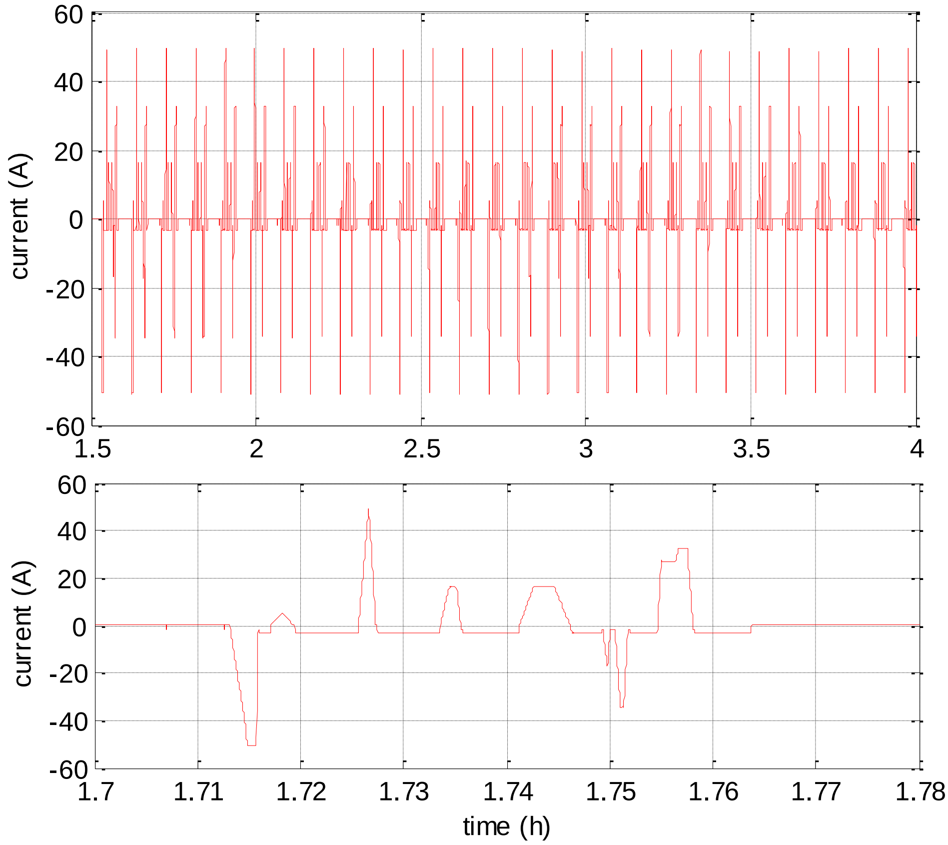

Figure 19. Cell current during a portion of the test (top), expansion of part of top figure (bottom).

Figure 20 shows the measured module voltage corresponding to the current illustrated in Figure 19.

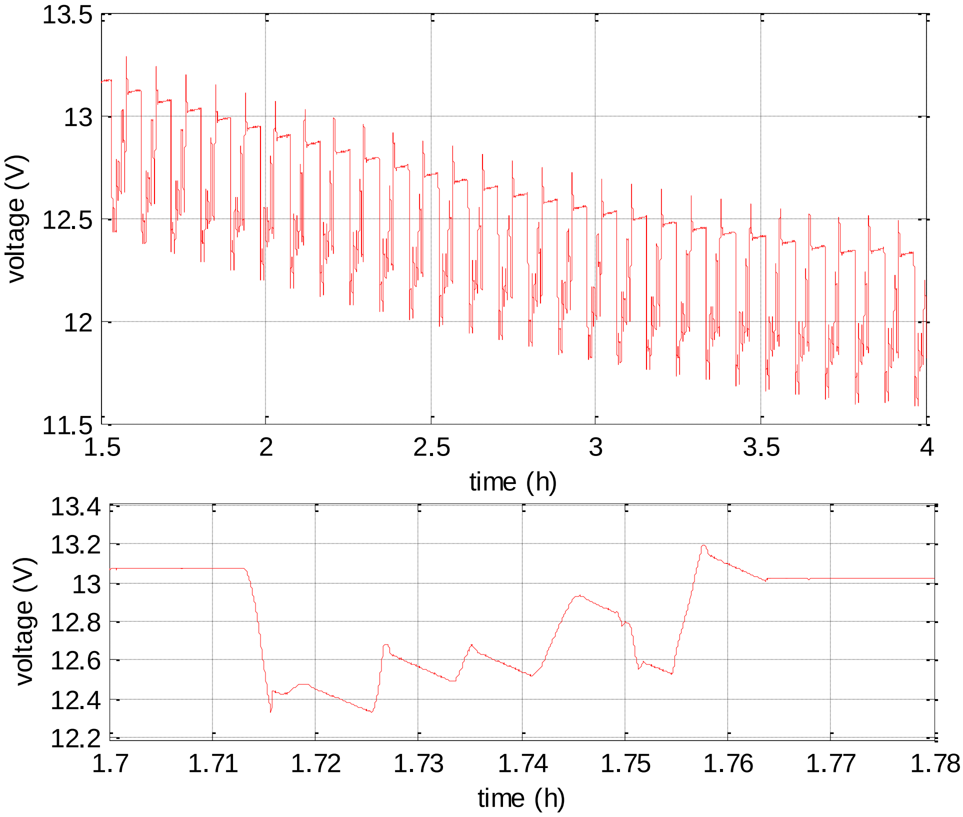

Figure 20. Module voltage during a portion of the test (top), expansion of part of top figure (bottom).

SOC estimation

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

- Step 1: the quality of the SC model obtained, whose results are reported in previous section, is verified by subjecting the model to the actual cell current and verifying the matching of estimated and actual module SC voltage.
- Step 2, the technique depicted in Figure 17 is implemented and verified.
- Step 3: long term effects, in which the effects of long periods of inactivity (e.g. during nights) have been verified and checked.

Naturally, in both steps the used supercapacitor model is the one already discussed in deliverables D3200.6 and D3200.8. The corresponding numerical parameters are found using criteria explained in the previous section, and summarised in Table 5.

Table 5. Numerical model parameters used for SOC algorithm evaluation

Parameter	Value	Unit
C_n	500	F
R_0	2.82	mΩ
R_1	0.65	mΩ
C_1	19967	F

Step 1
The quality of the model was firstly checked by submitting the test current and comparing model's and experimental voltage. Exactly as obtained for the SC cell (D3200.8), the model shows a good quality, but the global trend indicates that some voltage drift occurs over time.

Step 2
The voltage drift is expected to be corrected by the feedback algorithm, which is proposed in Figure 17. The algorithm runs using two different values for the feedback constant: k_{fb} = 1A/V and k_{fb}=10A/V. The corresponding voltages are shown in Figure 21 and Figure 22.

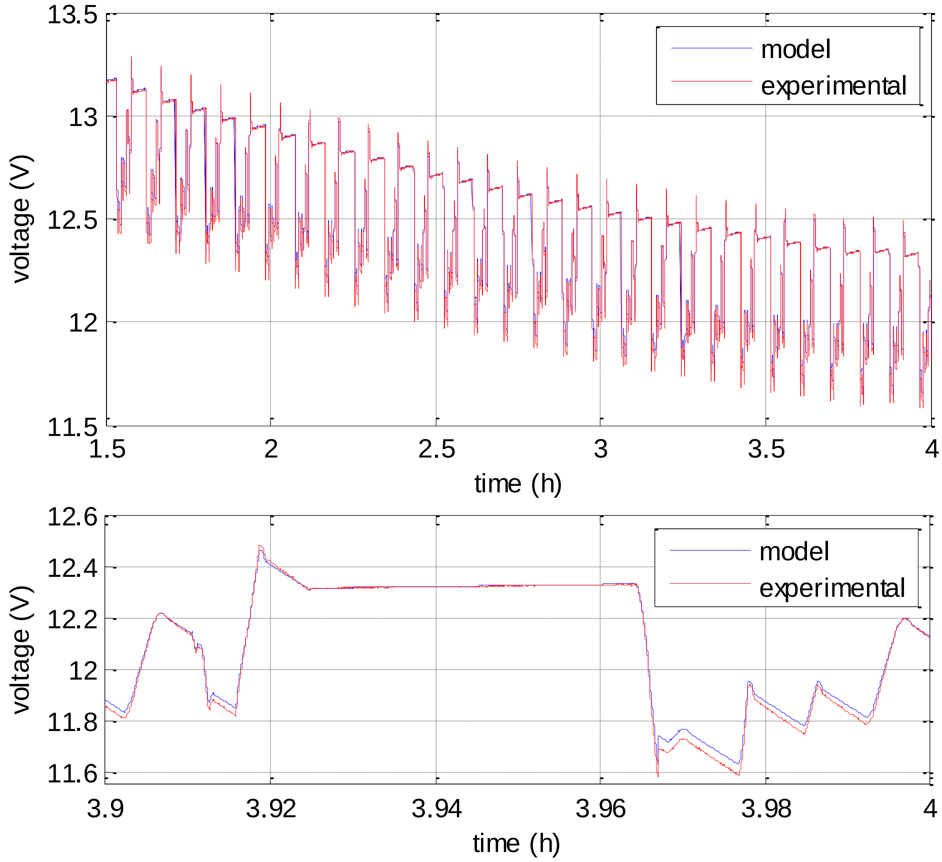

Figure 21. Comparison of model and measured voltages when k_{fb}=1 A/V (top), expansion of part of top figure (bottom).

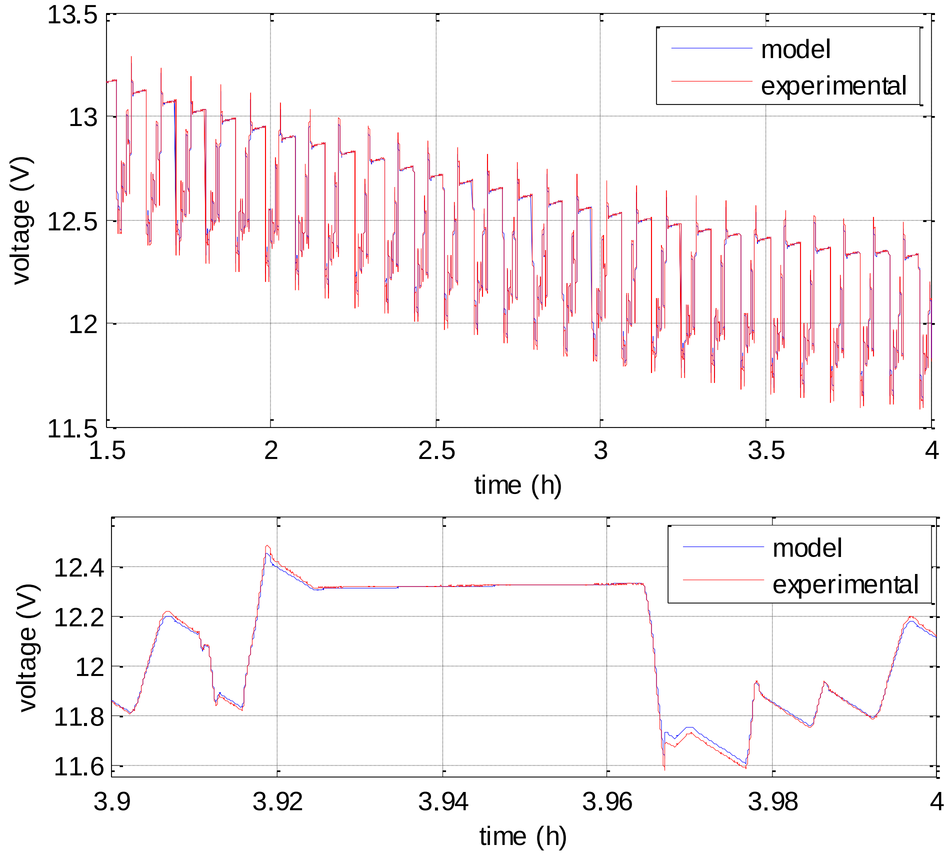

Figure 22. Comparison of model and measured voltages when k_{fb}=10 A/V (top), expansion of part of top figure (bottom).

It is evident that both using k=1A/V and k=10 A/V the voltage error is in practice totally offset. Naturally, some differences are still visible, but only using an expanded representation of quantities. This is done in Figure 21 (bottom) and Figure 22 (bottom), in which the last 360 seconds of the transient are shown.
The proposed algorithm is robust in terms of errors on the measured current, since it corrects itself based on voltage. Errors on voltage measurement are more critical, since any percentage measuring error on SC module voltage implies an equal percentage error on estimated SOC, as detailed in D3200.8.

<u>Step 3</u>
Similarly to the case of lithium batteries, the "long term stability" indicates 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 a smaller issue, because of the higher simplicity of the device behaviour and the corresponding simplicity of the proposed algorithm.

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 the SOC_Q definition itself here recalled:

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

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 bus 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 23 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 the test is simulated, but considering an initial 1% SOC error. Figure 23 is produced using k_{fb}=10 A/V.

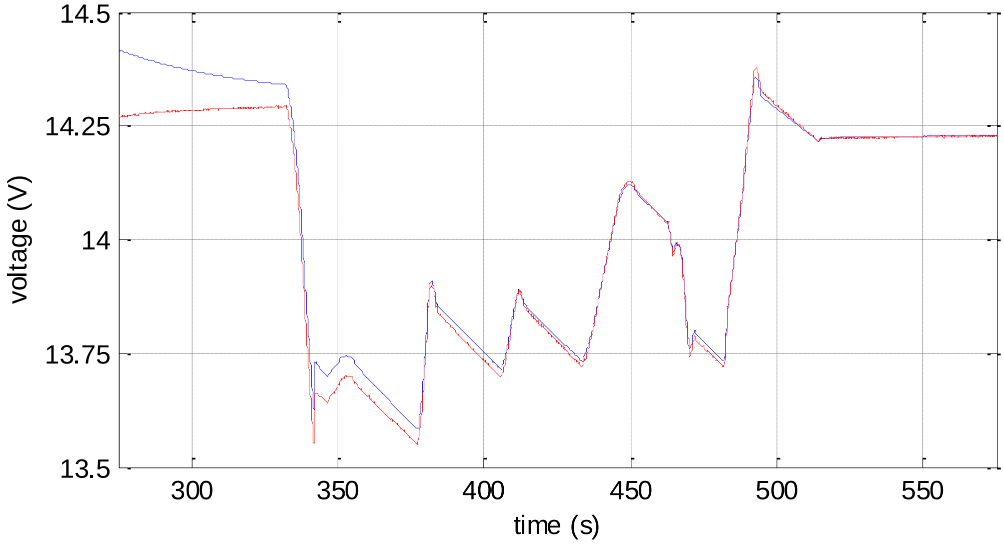

Figure 23. Recovery of an initial SOC error,
(recovery can be immediate if SC model cell V_{OC} is updated at the end of rest period).

The figure shows that the one per-cent error is rapidly recovered. It is to be repeated that this is shown just to evidence the algorithm 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 module voltage measurement, which in that condition is equal to V_{oc}, i.e. algebraically linked to SOC_Q.

Conclusions

- This deliverable has dealt with all the practical issues encountered when implementing in practice for the HCV SC module a suitable mathematical model.
- Test results were produced at the University of Pisa's laboratories (with additional data from AIT and ENEA), analysed and discussed.
- The application of parameter identification procedure to the experimental results of the MST on the HCV has allowed a correct evaluation of numerical values for all the model parameters.
- These results were aimed to produce an SOC estimator for the HCV SC module. A Luenberger-style estimator was proposed and described, that is very simple, effective and robust.
- The activity presented has shown that modelling and SOC evaluation procedures, already defined for the SC cell and presented in D3200.6 and D3200.8, are perfectly adjustable also for the SC module, giving the same quality of results.

References

[1]. Hybrid Commercial Vehicle (HCV) FP7-Project, “Modelling Test Matrices for Li batteries and SC, D3100.5,” University of Pisa, 2012.
[2]. Hybrid Commercial Vehicle (HCV) FP7-Project, “Preliminary model definition for SC cell, D3200.6,” University of Pisa, 2013.
[3]. Hybrid Commercial Vehicle (HCV) FP7-Project, “Model validation for Li modules, D3400.10,” University of Pisa, 2013.
[4]. Hybrid Commercial Vehicle (HCV) FP7-Project, “Algorithm for SC, D3200.8,” University of Pisa, 2013.