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Energy storage tailored-test programme for HD hybrid vehicles in a European Project

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Abstract

The development and large diffusion of advanced heavy duty (HD) commercial hybrid vehicles are significantly affected by current economic and technical limitations, which can be improved by advanced highly-efficient and less expensive components, such as alternative storage systems configurations, and drivetrain integration and assembly. In the European Project HCV (Hybrid Commercial Vehicles), different types (urban buses and commercial vans) and generations of HD hybrid vehicles (HEV) have been developed by using various types of storage systems in order to optimize performance and reduce costs in combination with the improvement of other components and assembly processes. In this project, performance and reliability of the storage systems have been carefully characterized in relation to the selected HEV architectures, together with mathematical models of two storage technologies: lithium-ion batteries (Li) and electrochemical capacitors (also named supercapacitors). The adopted approach was to adapt, whenever possible, existing testing procedures (and standards) to the performance characteristics and operating conditions of the storage systems in the project HEVs. In this way, electrical behaviour and abuse situations have been verified in controlled environment in the testing laboratories and design and control recommendations, verified with specifically developed mathematical models, have been transferred to the energy storage suppliers and vehicle manufacturers. All these activities have been carried out in a dedicated Subproject "Energy Storage Systems", having the participation of energy storage system assemblers (Magna and DimacRed), vehicle manufacturers (Altra-IVECO and Volvo) and testing laboratories (AIT, ENEA, University of Pisa and Volvo). This paper initially describes the electrical and safety test programme tailored to HCV storage systems and specific HD HEVs technical specifications. The second part is dedicated to the reporting and analysis of the key experimental results and developed models for Li and supercapacitor cells and modules.

Keywords: heavy duty hybrid vehicles, energy storage, lithium-ion battery, supercapacitors, testing

1 Introduction

The evolving emission legislation and the increasing fuel prices accompanied by a global CO_2 emission reduction discussion represent an extremely challenging demand for research and development. Known improvement measures of pollutant emissions usually come along with deterioration of engine efficiency and vice versa, e.g. the NO_x/fuel economy trade-off is well known for diesel engines.

With this background, the hybrid electric vehicle is an excellent option for simultaneous reduction of fuel consumption and exhaust emissions. Research efforts are needed to develop high-efficient hybrid systems including hybrid components such as the energy storage system, the electric machine, power electronics and electric auxiliaries. Cost is today considered as a major obstacle for market introduction of hybrid technologies in commercial vehicles.

The development of advanced heavy duty (HD) hybrid vehicles (buses, trucks and commercial vans) then requires significant improvements in the drivetrain technologies with the possibilities to use alternative or complementary storage systems to perform key functions (traction assistance to conventional internal combustion engine, regenerative braking and, eventually, pure electric traction mode for a limited range). A 4-year European Project, named HCV (Hybrid Commercial Vehicles), started in January 2010 with the participation of 18 European organizations (vehicle manufacturers, components integrators and suppliers, research organizations) and with the scope to develop and demonstrate the current hybrids in preparation for the next generation of hybrid commercial vehicles by using various types of storage systems: the final practical objectives were to reduce powertrain cost of about 40% and fuel consumption of 30% in a city bus cycle, compared with current hybrid bus technologies. To better assist suppliers/assemblers and vehicles manufacturers in designing and installing the various storage systems and optimize their use in different hybrid vehicle applications, a dedicated "Energy Storage Systems" SubProject has been planned and dedicated to the experimental evaluation of the performance and reliability of the storage components (cells and modules) in relation to the specific HEV architectures and drivetrains, developed in the HCV project. These activities have been aimed at analysing electrical and safety performances and developing mathematical models of two energy storage technologies, which may play a fundamental role for the success of market introduction of hybrid vehicles: lithium-ion (Li) batteries and supercapacitors (SC). The main objectives of the activities on energy storage systems have been: 1) to improve the reliability/safety and reduce the costs of the Electric Energy Storage; 2) to carry out basic characterization for evaluation & bench test of technologies/suppliers (including, for the power buffer type, supercapacitors) allowable for short-medium term industrial applicability; 3) to carry out ageing, safety and life testing, and modelling implementation for control optimisation (estimation of State of Health and State of Life).

These activities have been jointly carried out by 7 organizations (AIT-Austrian Institute of Technology, DimacRed, ENEA, IVECO-Altra, Magna, University of Pisa and Volvo) and is summarised in this paper, by describing the tailored- testing procedures, based on the specific HEV configurations and targeted performances, and the main experimental results so far achieved in various test activities and in different laboratories, with some reference to the developed mathematical models.

2 HD HEV Energy storage systems: a tailored testing programme

The key component of the hybrid vehicles investigated in the HCV project is the energy storage system, for which a specific sub-project has been dedicated for carefully testing and experimentally verifying the behavior of cells and modules. These activities were mostly aimed at optimizing the use and understanding the behavior of the energy storage systems in the HCV applications. The testing activities have been concentrated on electrical and abuse testing on the selected storage technologies selected: lithium-ion batteries and supercapacitors (SC). The samples to be tested were single cells or complete modules (basic assembled unit of the final storage system to be used on the different HEVs) of Li-ion and SCs.

The dedicated test procedures have been developed by adapting existing procedures and standards to the HCV-specific Li or SC cells and modules and on restricted types of applications: the used approach can be easily extrapolated or extended to other vehicle types, whenever operating conditions and duty cycles for the battery systems are made available. Furthermore, the set has also a secondary ambition to test and validate specific tests (as ageing or cycle life), which can be eventually utilized, as pre-normative research and international collaborations, in standard definitions, even if some confidentiality aspects of the tested technology must be maintained. For the abuse testing, a cost-effective test matrix was also prepared to combine more valuable test sequence with the available number of samples.

2.1 HCV-tailored test procedures

The approach used in specializing already available test procedures (and even standards) to the experimental energy storage test needs in HCV project is very simple and follows a 4-step route:

1. EUCAR and FreedomCar [1-7] testing procedures and also various specific standards [8-10] have been carefully revised and adapted.
2. The test sequences mostly containing operating conditions and general duty cycles in existing procedures have been changed by introducing the operating conditions and performance characteristics identified for the HCV commercial HEVs [11]. These modifications have been made possible by the definition of the technical specifications of the HEVs and of the storage systems by the two vehicle manufacturers at the beginning of the project.
3. Application-oriented duty cycles as identified by the vehicle manufacturers have been used for the execution of life and ageing tests that are still underway.
4. Definition and use of additional tests for the development of mathematical models of the HCV storage technologies and for the identification of performance characteristics or module design and control needs.

2.2 ESS technical specifications

There are two 2nd generation HEV under development in the HCV project that have been used as reference HEVs (both parallel hybrid vehicles) for the definition of the basic technical specifications to be used for the design and test of the energy storage system (ESS). Altra-IVECO has been improving a Daily 3.5 ton delivery van with a powertrain requiring from the ESS a maximum power (in charge and discharge) of 45 kW, a maximum voltage and current of about 300 V and 200 A and an available energy up to the end-of-life (EOL) of 800 Wh: these specifications have been defined for two alternative ESS, one based on Li-ion technology and the other one on SC; instead, Volvo has been developing a 12-m city bus (a second generation parallel hybrid) only using an Li-ion ESS with the following specifications: ra peak power of 90 kW over the life (120 kW at BOL), a rated voltage of 633 V, a peak current of 150 A, and an available energy also at EOL of 1200 Wh.

These technical characteristics have been scaled down and adapted to the sample sizes (cells and modules) by using the concept of *Battery Size Factor (BSF)*, intended as an integer number, which is the minimum number of cells expected to be required to meet all the performance and life targets. For example, in the case of the Altra HEV Li-ion ESS, the BSF has been roughly rounded to 192 [12], while if the ESS is based on SC the BSF is 144 [13].

These BSF remain constant scaling factors for all subsequent performance and cycle life tests. Any test profile is then scaled by dividing the nominal profile power levels by the BSF. For example, by applying this BSF to the Altra ESS design, the 45-kW Peak Discharge Power for HCV to be used in life cycling test would then be reduced at a pulse power level of $45000/192 \approx 230$ W for Li-ion cells, while for SC cells a pulse power level 312.5 W must be used. In case of module testing, the achieved pulse power must be multiplied by the number of cells in the module.

2.3 Application-oriented duty cycles

To better assist the design and optimization of ESS, both manufacturers have defined (or measured) power duty cycles for the reference HEVs. For example, Altra-IVECO has proposed a power micro-cycle for the mild hybrid version of its Daily van.

The reference micro cycle for this configuration is described in Figure 1. The overall duration is of 167 sec, which corresponds to a travelled distance of 1 km and an ESS variation of SOC (State-Of-Charge) of 5 %.

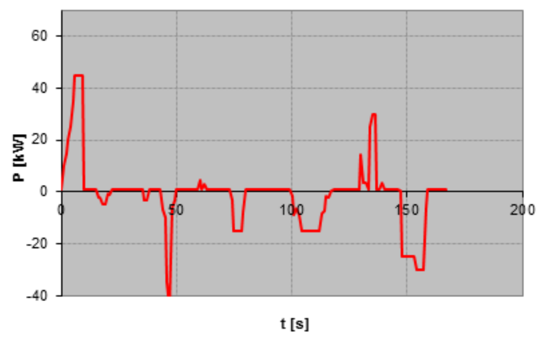

Figure 1: Selected power micro-cycle for Altra HEV Daily van.

For life testing analysis, this micro-cycle must be repeated 180 time in a day (with an idle time of 10 min every 18 micro-cycles) and in total 45,000 times in a year. To take into account also temperature effects and variations, three different temperatures have been selected (20, 30 and 40 °C) for carrying out yearly cycles. Analogously, Volvo has supplied more detailed and experimental duty cycles (power and cell voltage and current) for a typical city urban route.

2.4 Additional specific test sequences

A specific test matrix for modelling purposes has been defined and verified.

The test shown in Figure 2 is able to give a lot of information on the battery, much more than only the OCV-Correlation curve. For its importance it is given in this document a name of its own: it will be called **Multiple-Step Test (MST)**. This test can be performed exactly as reported in Figure 2, starting from a fully–discharged battery or a fully-charged battery and by using charging current steps or discharging current steps. Therefore, the MST can be charge-based and discharge–based.

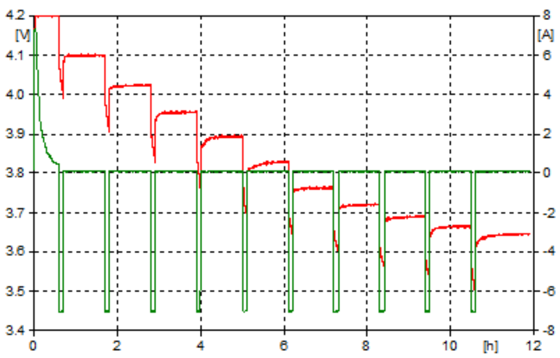

Figure 2: The discharge-based Multiple-Step Test. Green: current; red: voltage.

Each MST will be performed, both in charge and discharge at different temperatures. Moreover, they will be basically performed on single cells, to evaluate actual cell performance, independently on the effects of the Battery Management System (BMS).

The related test matrix is shown in Table 1: Test matrix at different temperatures.

Table 1: Test matrix at different temperatures.

temperature/°C test type		15	0	20	40
charge-based MST		x	x	x	x
discharge-based MST-		x	x	x	x

The tests reported in Table 1 have been performed in these cases:

- for 3 different new cells to evaluate not only the cell performance, but also its statistical spread;
- for some (1-3) cells having had faults or failures inside, such as ion-loss or electrode active-material loss;
- for 3 different old cells to evaluate cell performance and statistical spread for old batteries.

Normally, MST will be performed at a unique current, the best candidate being 4.4 A, i.e. the one-hour discharge for the project cell.

Other dedicated tests have been proposed and carried out, and are mainly aimed at analysing the behaviour of the HCV modules with and without electronic board. The purpose of these tests is to various design and performance characteristics at module level.

This test sequence is divided in:

1. Short cycling life (50 continuous charge/discharge cycles of Altra and Volvo type, without module management system) to verify cell voltage dispersion;
2. Thermal behaviour, aimed at determining temperature distribution (with temperature sensor mapping or thermography) in the module during short cycling to investigate thermal management needs;
3. Determination of polarization curves at module level (proposed by Magna), aimed at the characterization of the power capability of energy storage modules.
4. Life time performance at different energy windows (proposed by Magna), complementary to life cycle testing with HCV duty cycles. This test specification deals with the evaluation of life performance of energy storage modules, which in this case are lithium-ion modules (Li-Ion).

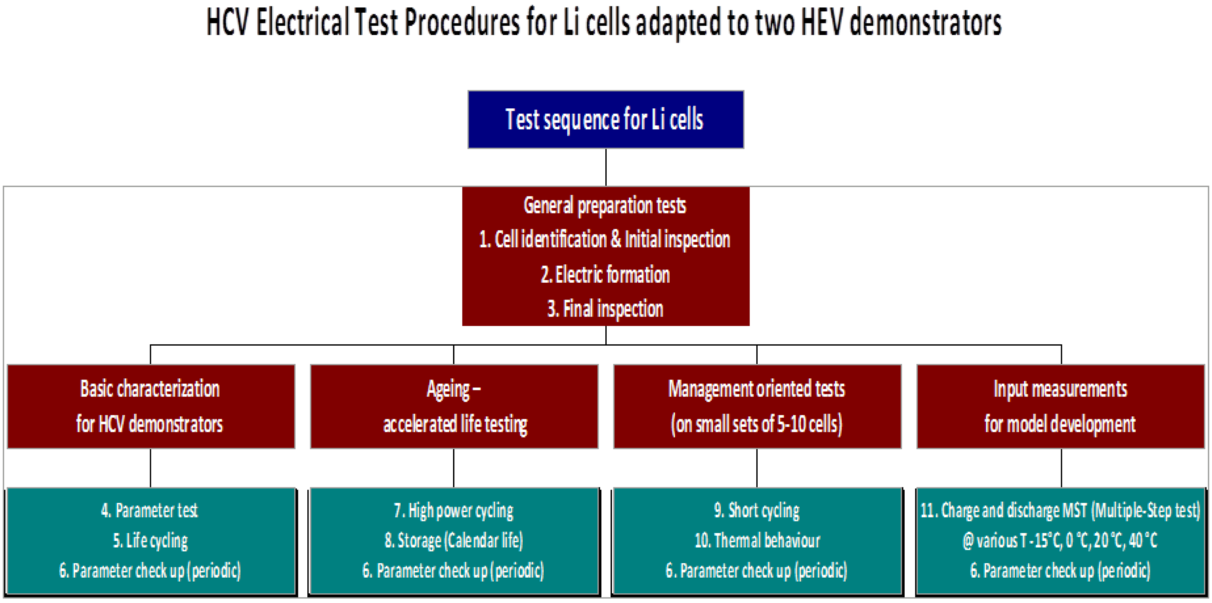

Figure 3: Overview of HCV Li cell test procedures.

Finally, aging and safety/abuse testing have been defined and performed.

2.5 Electrical test procedures for Li and SC

In summary, the electrical test procedures of Li and SC cells and modules have been structured in five different test sequences aimed at different testing scopes:

1. General preparation tests.
2. Basic characterizations for the designed operating conditions of the HCV demonstrators.
3. Ageing – accelerated life testing to estimate cell life under with degradation accelerating factors to give quick feedback to system design and road demonstrations phases.
4. Management-oriented tests on a small set of series-connected cells (or module with balancing electronic board) to study management needs in terms of voltage dispersion and thermal control.
5. Input measurements for modelling to collect operating data for the definition and validation of mathematical models.

Figure 3 presents the flowchart of the electrical test procedures for Li-ion cells and modules [12], while for SC samples a similar test sequence has been defined, with minor tests and only one ESS configuration, referred to Altra hybrid Daily [13]. Test matrices have been also prepared to optimize the use of available number of samples (initially limited by budget restrictions) among the various tests (including safety) and laboratories.

2.6 Safety test procedures for Li and SC

Abuse testing is aimed at characterizing energy storage systems Li and SC cells and modules during off- normal or in severe operating conditions/environments. The test program of abuse testing has the main objective to identify through controlled simulation testing all the possible risks conditions. These conditions has been then analysed to clearly define mitigation measures to be used in design, control and usage of such storage systems. Failure pathways have been also investigated by means of the abuse testing results (and not on post-mortem analysis), so as to eventually propose novel parameters [14].
After the verification of compatibility of testing condition in existing safety test procedures and standards with HCV ESS specifications, the abuse testing and safety procedure has been concentrating on:

1. Mechanical (vibration)
2. Thermal
3. Electrical
4. Mixed (for example mechanical and electrical together)

A safety testing matrix, reported in Table 2, based on key influencing parameters, has clearly identified the needed cells (3 at least used for each test for acceptable statistics).

Table 2: Definition of samples to be used in each safety test.

Test	# Li Cells	# Li Modules	# SC Cells	# SC Modules
Overcharge/Overvoltage	3	1	3	1
Short Circuit	3	1	0	0
Overdischarge / Voltage reversal	3	1	3	1
Thermal Stability	3	0	3	0
Elevated Temperature Storage	9	0	9	0
Rapid Charge	0	1	0	1
Controlled Crush	6	0	6	0
Penetration	3	1	3	1
Immersion	0	1	0	1
Total	*30*	*6*	*27*	*5*

2.7 Samples under test

Basically, the lithium-ion cell technology used in the project is based on iron phosphate cathode, while the SC cells were based on a commercial carbon/carbon technology. A set of 200 Li cells (an advanced generation of 4.4 Ah and 3.6 V each) have been made available together with more than 60 SC cells (3000F and 2.7V). In addition, various Li and SC modules have been assembled for dedicated testing (abuse and electrical, see Figures 4 and 5).

Figure 4: SC module (16.2V, 500F, 5.9 kW/kg) supplied by DimacRed

Figure 5: Li-ion module (8,5 Ah, 59,4 V, 505 Wh, 11,25 kW, about 10 kg) with cover prepared by Magna e-car

3 Some experimental results

In the last two years electrical and safety testing on Li and SC cells and modules have been carried out and partially completed, even if most of life cycling testing is still underway and most work on module testing must be performed. Some key results and examples of the experimental testing work are reported hereafter.

3.1 Safety testing

Safety testing on cells has confirmed the general reliability in most common stresses and shocks: mechanical, thermal and electrical [15, 16].

Before Overcharge/Overvoltage test, the cells were formed with three cycles and charged to SOC = 100%. The test was conducted at room temperature. 4-wire sensing system was used for the electrical measurements. The thermal measurements were conducted with two temperature sensors on the surface of the battery and with one temperature sensor close to the safety valve (Figure 6). Li cells were overcharged to a total SOC = 150%. Figure 7 shows the measured parameters of one Li-ion cell. Further test was also conducted up to a final SOC of 200%. Again no catastrophic event or a voltage breakdown could be observed. Only liquid electrolyte was lost and the plastic casing melted at the anode side of the battery (Figure 8).

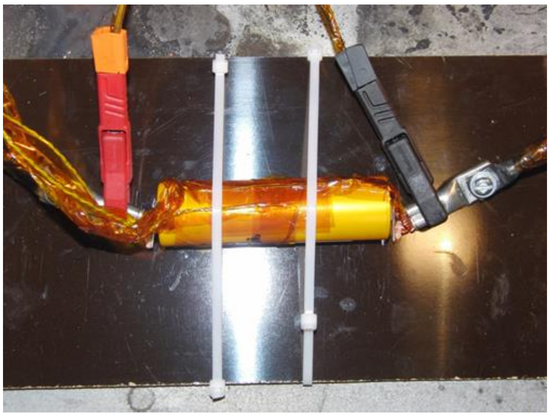

Figure 6: Setup for overcharge test. 4 wire sensing, 3 thermal sensors (2 surface, 1 valve).

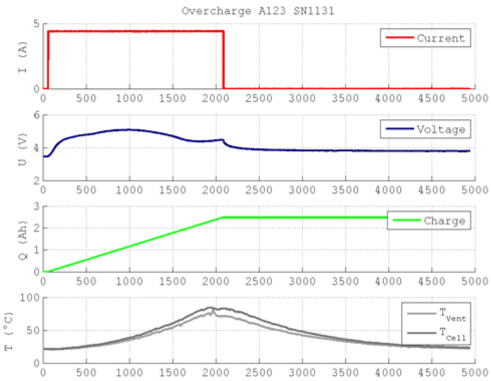

Figure 7: Measured values of an Li-ion cell during overcharge to SOC=150%.

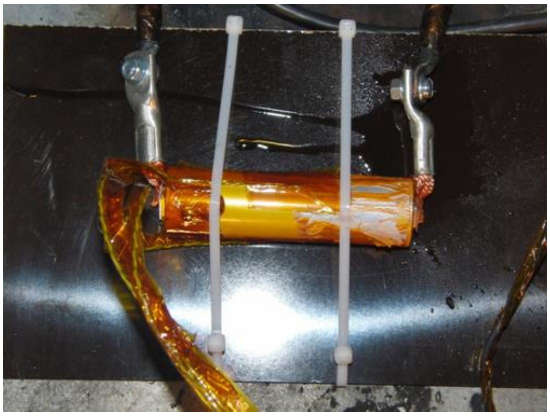

Figure 8: Cell after overcharge test. Electrolyte released over vent.

Similar safety tests have been carried out on SC cells.

Figure 9 shows an SC during crush test: deformation of the sample is clearly visible in Figure 10.

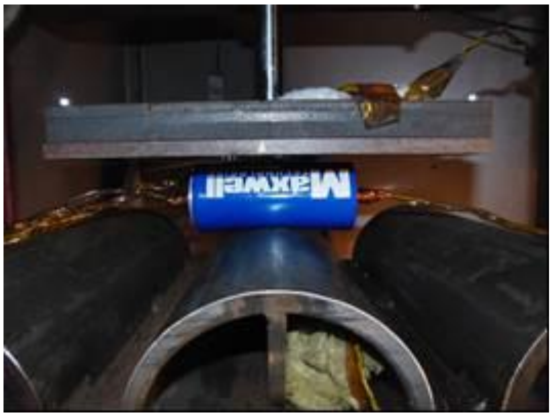

Figure 9: Maxwell SC in hydraulic press for Controlled Crush Test

Figure 10: SC cell deformation after crush test

The deformation was the only effect resulting in this test.

Figure 11 reports about the results of the thermal stability tests on SC cells. Before the test, the cells were formed with 30 cycles and charged to SOC = 100%. The cell was placed in a heating chamber. The thermal measurements were conducted with two temperature sensors on the surface of the cell and with one temperature sensor close to the safety valve. Four sensors for ambient temperatures were spaced in the chamber.

After temperature stabilization at 100°C, the temperature was constantly increased in steps of 5 °C. At 190 °C the cell was damaged as shown in Figure 12.

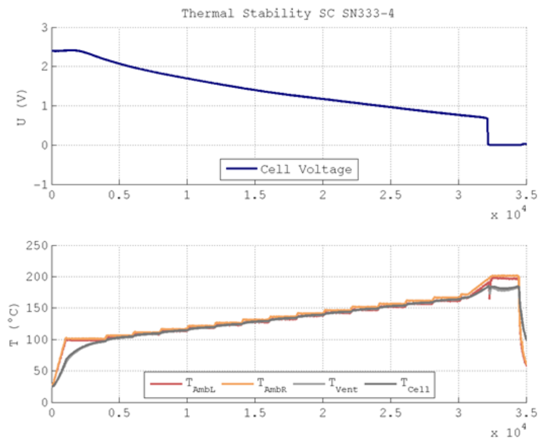

Figure 11: SC cell measurements during thermal stability tests

Figure 12: Cell after thermal stability test. Release of electrolyte through hole in casing

In general, it can be stated that no one of the cells of both Li-ion and SC technology showed uncritical behaviour during safety testing, being consistent with EUCAR safety level of acceptance. In no one of the tests, fire, rupture or explosion could be observed, even using gas emission measurements. The safety testing on modules was postponed after electrical testing due to the limitation of available samples.

3.2 Electrical testing

Examples of electrical testing illustrate the different scope and uses and are briefly reported hereafter.

3.2.1 Basic characterization electrical testing

Initial characterization tests have been carried on all the cells and modules delivered at participating laboratories.

Figure 13 clearly shows that the behaviour of the Li cells is sufficiently uniform as expected, considering the level of industrialization of the supplied cells, while Figure 14 gives an example of capacity test on one Li cell.

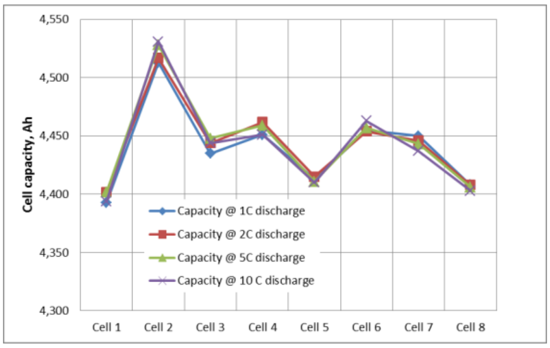

Figure 13: Capacity of cells at various discharge current rates

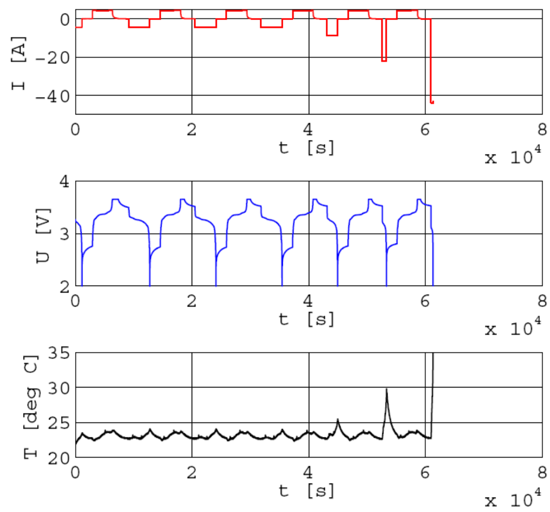

Figure 14: Measured parameters and related curves during capacity test of Li-ion cell

Figure 15 presents some results about life test of two Li-ion modules.

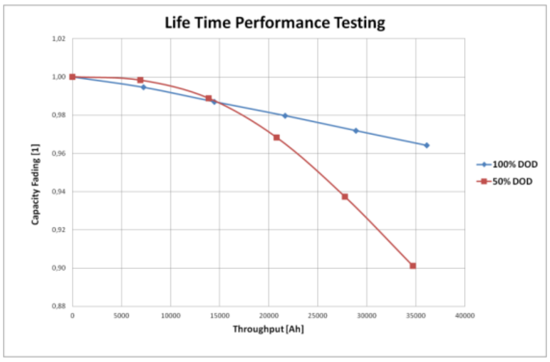

Figure 15: Comparison of module capacity decline of two Li modules during life testing

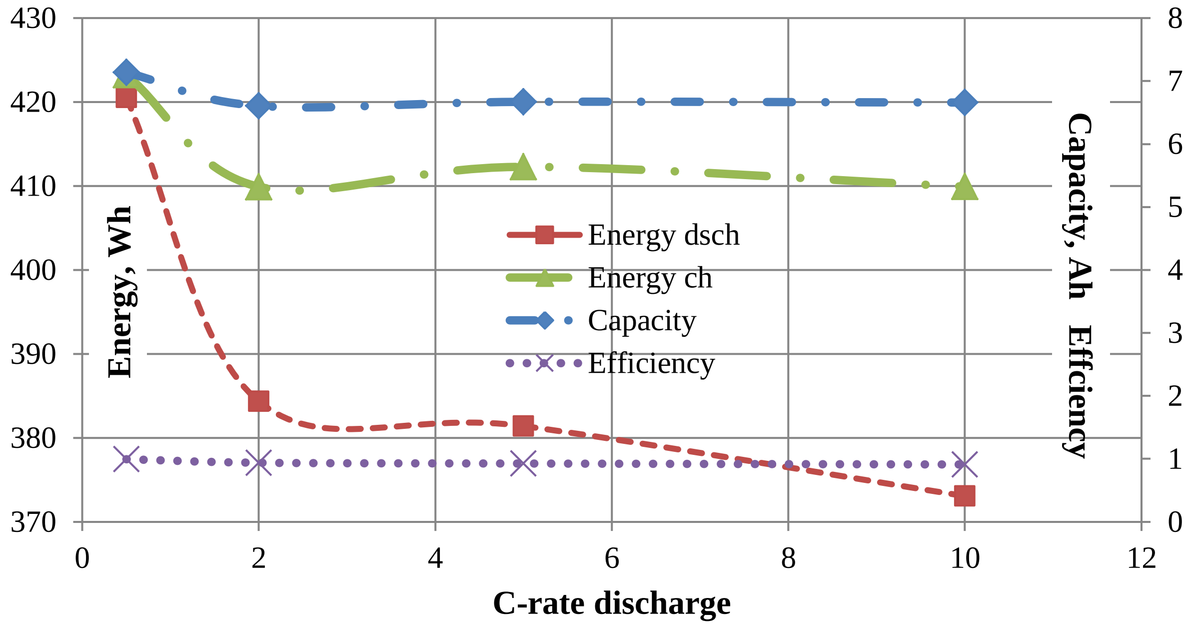

Figure 16: Summary of Li modules testing results

3.2.2 Management-oriented tests

After the performance determination tests of modules, already illustrated in Figure 15 and also in Figure 16, some tests were devoted to verify module design and other aspects (polarization curves and cycle life at various energy windows). Figure 17 and 18 show the temperature distribution at beginning and at the end of a complete charge/discharge cycle, achieved by means of thermography.

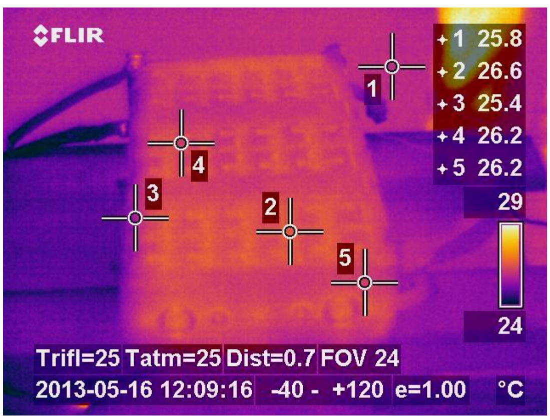

Figure 174: Module thermograph almost at the beginning of test

Thermal behaviour during cycling has been investigated by means of infrared camera, which is able to give interesting feedback for the module assembly and thermal management need.

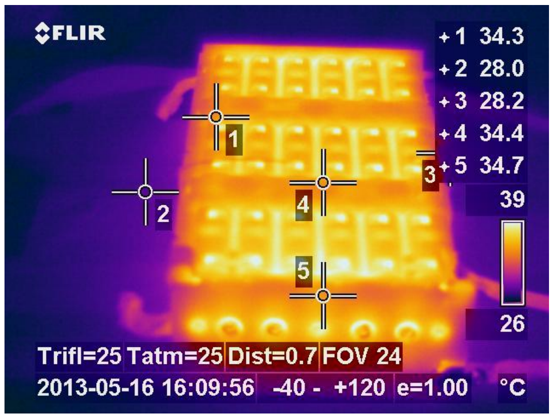

Figure 18: Module thermograph at the end of test

The module thermographs clearly show up a gradual increase of temperature during testing (without cooling system or thermal management), but the reached temperatures are still considered in an acceptable window for LFP technology and for the working conditions recommended by the battery and vehicle manufacturers.

The thermal behaviour of SC modules was equally investigated by taking into account the cooling needs proposed by the HCV manufacturers. Figure 19 presents the heating of the SC module after one hour of life cycling. The overheating is limited to 8.55 °C.

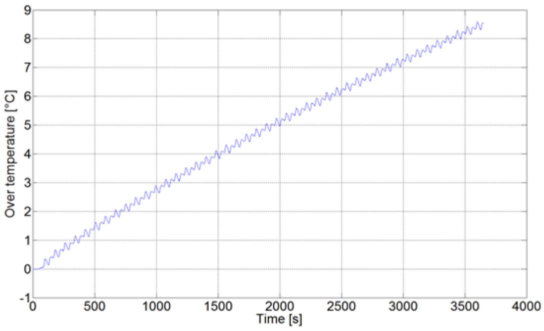

Figure 19: Overheating of an SC module after one hour of life cycling test

After 5000 cycles the temperature increase was much more significant by reaching a maximum temperature of about 63 °C, as shown in Figure 20.

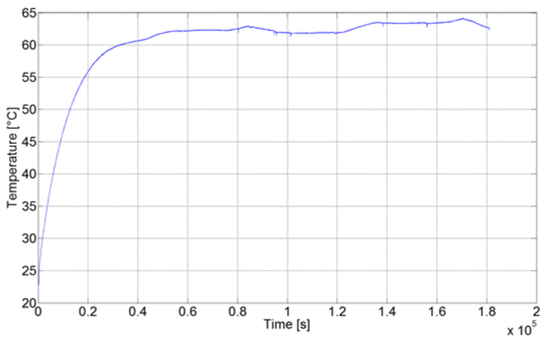

Figure 20: Temperature increase of an SC module after 5000 cycles

Finally, some accelerated life tests were also performed to extrapolate the expected life of SC module in relation to the defined targets: preliminary calculations give a rough lifetime estimation of 12.2 years, well beyond the target end of life requirement of 6-8 years.

3.2.3 Measurements for model development

Finally, experimental activities have been carried out for modelling purposes. In particular, selected model parameters and the EKF algorithm (for estimating in a simplified manner the ESS SOC) were validated [17-20] for Li-ion technology by using various duty cycles and, analogously, a model was developed and validated for SCs.

Figure 21 shows the block diagram for the developed hybrid estimator (for Li cell) of the ESS SOC based on EKF.

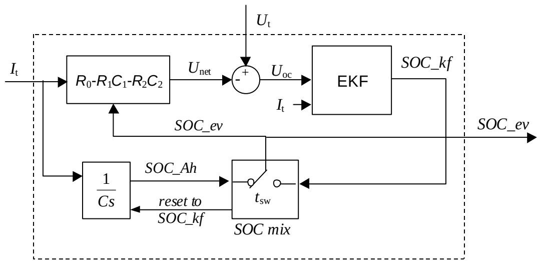

Figure 21: Hybrid SOC evaluator, actual implementation [17, 19, 20]

The validation of the models and the related algorithms for both storage technologies has been done by experimental tests, of which an example is given in Figure 22, by applying the Altra cycle. The estimated *SOC* (red curve) matched the *SOC* obtained by the numerical integration of the measured current (blue curve) recovering the initial error. This result is representative of the high level of stability and reliability of the proposed algorithm, able to work properly also without redefinition of the initial parameters.

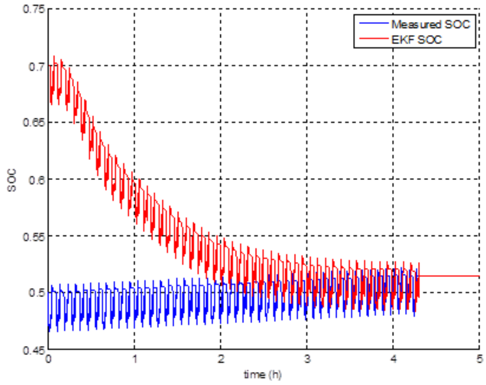

Figure 22: Experimental evaluation of battery SOC estimation using the EKF-based model, applied to an aged cell, for ALTRA road cycle

In the same way, an algorithm, based on a Luenberger estimator, has been developed for the SC cells: it has been defined and validated in order to be robust in terms of error corrections on the measured current and voltage [18].

Figure 23 presents the block diagram for estimating the SC SOC.

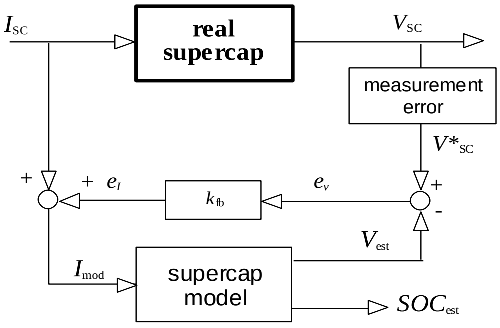

Figure 23: The Luenberger SOC estimation in presence of measurement errors on voltage

The algorithm is designed so that the voltage and current errors are as small as possible. Figure 24 experimentally confirms the validity of the selected model and the related algorithm.

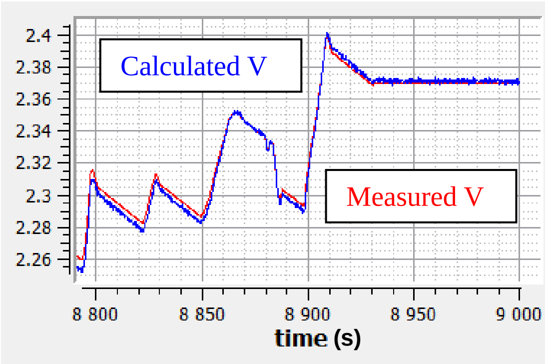

Figure 24: SOC estimation for an SC cell during transient

4 Conclusions

The application of dedicated testing procedures for ESS experimental characterization during the development phase of advanced electrically-propelled vehicles results highly functional and effective in improving and optimizing design and use of energy storage systems, by adequately tailoring (and customizing) existing procedures and established standards to the specific needs of the component and vehicle manufacturers and the targeted service duties. Combining conventional safety and electrical tests with more dedicated tests in this paper we have showed that it is possible to optimize not only the design but also the integration and use of the ESS in the developed HEVs. The addition of dedicated tests can also assist practical control and thermal management by means of the development of dedicated mathematical models fitted to the ESS technology (Li-ion LFP and SC) and the selected operating conditions and technical specifications.

Nomenclature

AIT	Austrian Institute of Technology
BOL	Beginning of Life
BSF	Battery scaling factor
EC	European Commission
EKF	Extended Kalman Filter
EOL	End Of Life
ESS	Energy Storage System
HCV	Hybrid Commercial Vehicle Project
HD	Heavy duty
HEV	Hybrid Electric Vehicle
IEA	International Energy Agency
LFP	Lithium Iron Phosphate
MST	Multiple Step Test
SC	Supercapacitors (or electrochemical capacitors)
SOC	State-Of-Charge
SP	SubProject

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