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Deliverable 3100.3

Report:

Electrical test plan for SC

Summary

This Deliverable describes and reports about the 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 WP3100 “Storage System specifications and Test Planning” in the Task 3110 “Preliminary application characteristics and Electric test procedure definition”. The main objectives of this Task were, as planned in the DoW (Description of Work – Annex I of the Grant Agreement):

- Definitions of key performance characteristics
    - Storage systems technical specifications for each vehicle application by Altra and Volvo
- Survey and definition of testing procedures
    - A dedicated set of electrical and abuse testing procedures for cells and modules of Li batteries and Supercapacitors (SC) will defined in relation to the specific heavy duty applications.

This Deliverable is concentrated on the definition and planning of the SC electrical test procedures and the related test plan, by using the inputs of the vehicle manufacturer (Altra), the only one using SC in the HCV project, and of the cell supplier (DimacRed).

According to the needs and plan of the HCV project, the samples will not need to be disassembled after the tests for post mortem analysis. Further organizational and control measures are the full tracing of cells with an updated locator of cell location and responsibility.

The test procedure described in this Deliverable has been developed, even by means of the experimental work of AIT, DimacRed, ENEA and Volvo. Attention was put to a careful adaptation of the existing test procedures (developed by EUCAR in previous EU Projects like ASTOR and ILHYPOS, as well as USABC and FreedomCar programs, together with existing or under development standards from IEC) to the specific technical requirements and estimated operating conditions (see also Deliverable D3100.1) of the hybrid electric vehicle (HCV) developed and demonstrated by Altra in the HCV Project.

The electrical test procedure has been developed and will be applied to increase the knowledge of the selected SC technology in order to assist EESS developer and HEV manufacturers in better using this technology with higher efficiency and reliability, with expected feedbacks on the final design and real life behaviour.

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Nomenclature/Glossary

Ambient Temperature. Temperature to which the test is performed. The temperature is set in the test tables and the tolerance is T ± 2°C.

Acclimatization. Rest of the cells/pack in the thermal chamber till to reach the set temperature. The temperature must be homogeneous in all the cells/pack volume, and the time required is considered 12 hours.

Capacitance. Ability of a capacitor to store electrical charge (in Farad).

Equalization. Procedure which is required to bring all the cells at the same electrical starting conditions. It consists in a full discharge of supercaps using a standard discharge and short circuit each cell as long as required in the test (normally 1 hour).

Nominal Capacitance (C_N). Nominal capacitance value (C_N) to be used in design and measurement condition setting (in Farad), generally, at the reference temperature.

Room Temperature (RT). 23 ± 2 °C

RWV. (Rated Working Voltage): working voltage suggested by manufacturer as maximumlevel to which the DLC can normally work in full charged state without damages. It isthe same indicated on the label of DLC.

SCH. Standard Charge

Standard Charge: The optimised charge profile, should be given by the manufacturer. Otherwise the standard charge is performed using the following profile:

- Voltage limited to RWV
- Current limited to 50 mA/Farad
- Total time 900 seconds

SDCH. Standard discharge

Standard Discharge: Slow discharge rate with the following parameters:

- Current: 5 mA/Farad
- Cut off voltage: V=0.3*RWV, or a different voltage if specified in the test plan.

Self Discharge. Discharge that takes place while the battery is in an open-circuit condition. This is a phenomenon by which a cell or battery loses energy in other ways than by discharge into an external circuit*.*

Shallow Cycling. Charge and discharge cycles, which do not allow the battery to approach its cutoff voltage.

State of Charge (SOC). The available capacity in a battery expressed as a percentage of actual capacity. This is normally referenced to a constant current discharge at the C rate. SOC = (100 – DOD), if the rated capacity is equal to the actual capacity, in %.

State-of-health (SOH). The present fraction of allowable performance deterioration remaining before EOL. (SOH = 100% at beginning of life and 0% at end of life).

Stress factors. External conditions imposed on a battery that accelerates its rate of performance deterioration.

Working Current Normalization. Each kind of EDLC is characterised by a typical level of max working current in the panorama of double layer capacitors' world, this range of current is very wide: from dozen to thousands of amps. In order to generalise the procedure to all kind and dimensions of SC available, it is necessary to set a common reference unit to define the current to perform the tests using a comparative method. In this document the current is given as a reference to the capacitance of the EDLC in testing. The unit is mA/Farad. This unit is referred to the capacitance of the single cell taking part to the pack/module: e.g. in a pack of 10 cells of 150 Farad each, connected in series, the nominal capacitance of the pack is 15 Farad. In this case, 70 mA/Farad means 10.5 A (150F x 70 / 1000).

Acronyms

A	Ampere
Ah	Ampere hours
ASTOR	EC Project “Assessment and Testing of Advanced Energy Storage Systems for Propulsion and Other Electrical Systems in Passenger Cars”
η	efficiency
BSF	SC size factor
BMS	Battery Management System
BOL	Beginning Of Life
C	Capacity, expressed in Ampere hours (Ah)
°C	Temperature degree expressed in Celsius
CAN	Communication Area Network
CVL	Charge voltage limit
DOD	Depth of discharge
DUT	Device under test
E	Energy (Wh)
EDLC	Electric double layer capacitor
EESS	Electrical Energy Storage System
EOCV	End of charge voltage
EODV	End of discharge voltage
EOL	end-of-life
ESR	Equivalent Series Resistance
EUCAR	European Council for Automotive Research
F	Farad
h	hour(s)
HCC	High Charge Current
HCV	EC Project “Hybrid commercial vehicles”
HDC	High Discharge Current
HE	High Energy
HEV	Hybrid Electric Vehicle
HP	High Power
HV	High Voltage
Hz	Hertz
I	Current
IEC	International Electrotechnical Commission
ILHYPOS	EC Project “Ionic Liquid based Hybrid Power Supercapacitor”
IR	Internal Resistance

ISO	International Organization for Standardization
J	Joule
K	Kelvin
Li	Lithium
Li-Ion	Lithium-Ion
MST	Multiple Step Test
OCV	Open Circuit Voltage
P	Power
PP	Peak Power
PPT	Peak Power Test
PHEV	plug-in hybrid electric vehicle
RT	Room Temperature (23 ± 2°C ref.)
s	seconds
SC	Standard cycle
SC	Supercapacitor
SCH	Standard charge
SDCH	Standard discharge
SI	International System
SOC	State of charge
t	Time
T	Temperature
TBD	to be defined
U	Voltage
V	Volt
W	Power
Wh	Watt hours

Introduction

This deliverable defines a series of tests to characterize aspects of the performance or life behavior of SC cells for hybrid electric vehicle (HEV) applications, selected to be designed and demonstrated in the HCV Project by one vehicle manufacturer (Altra-IVECO). Consequently, tests are defined according to the technical specifications already identified for the Altra hybrid commercial vehicle (see Deliverable D.3100.1 [6]): 1) Hybrid Daily SC storage System. The test procedures in this deliverable are directly applicable to the testing of SC cells (and also to modules), already selected and roughly presented in Appendix 1.

The results of the literature survey and in-depth analysis of existing electrical SC cells test procedures, aimed at applications in HEV (Hybrid Electric Vehicle), have been thoroughly used in the definition of the present procedure [1, 2, 3, 4, 5]. Much of the rationale for the test procedures and analytical methodologies utilized in this test procedure evolved from the EUCAR "*Specification of Test Procedures for Supercapacitors in Electric Vehicle Application*", [1], the literature survey on SC aging factors [7], and in some tests described in IEC/CENELEC standards [2].

The test procedure presented in this deliverable is intended for use on a defined SC cell and on restricted types of applications, but the used approach can be easily extrapolated or extended to other hybrid vehicle types, whenever operating conditions and duty cycles for the EESS are made available. Furthermore, the proposed testing approach 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. The HCV "tailoring" EESS testing method applied in this procedure is based on the *scaling down* at cell (and module) level the test profiles (operating conditions) and the planned environmental conditions identified by Altra [1]. These profiles are mostly based on power profiles, supplied by the Altra and adapted to the specific cell characteristics.

The electrical test procedure of SC cells has been structured in 4 different test sequences aimed at different testing scopes:

1. *Basic characterizations* for the designed operating conditions of the HCV demonstrators;
2. *Ageing – accelerated life testing* to estimate cell life under degradation accelerating factors (such as temperature and high working voltage = WV) to give quick feedback to system design and road demonstrations phases;
3. *Management-oriented tests* on a small set of series-connected cells (or final modules with and without electronic measuring system) to study management needs in terms of voltage dispersion and thermal control;
4. *Input measurements for modelling* to collect operating data for the definition and validation of mathematical models.

All in all, this procedure is based on existing test procedures (from EUCAR, previous EU projects, USABC and FreedomCar) and standards, defined at IEC level, and then adapted and "tailored" to the specific driving cycles and operating for the EESS in the Altra HEV.

Basic test conditions

Measurement parameters and accuracy

The tests have been organized in a way that a defined set of test parameters must be measured and recorded during each test for further analysis. For improving data comparability and test quality, the accuracy and tolerances of measuring equipment and methods are pre-defined. In addition the sampling frequency must be adequate for the specific test and parameter to guarantee the measurement of the relevant changes and good reproducibility of the analysed phenomena.
The basic parameters to be measured are:

1. Current
2. Voltage
3. Temperature
4. Mass
5. Volume
6. Time

The minimum equipment accuracy and tolerance for the various parameters are reported in Table 1.

Table 1. Minimum equipment accuracy and tolerance for testing.

Parameter	Accuracy	Tolerance*
Voltage	≤ 0.5 of reading	± 1 %
Current	≤ 0.5 of reading	± 1 %
Temperature	± 1 °C	± 2 °C
Mass	---	± 0.1 %
Dimensions	---	± 0.1 %
Time	± 1 %	± 1 %

* The overall accuracy of controlled or measured values, relative to the specified or actual values, shall be within the proposed tolerances. The tolerances comprise the combined accuracy of the measuring instruments, the measurement technique used, and all other sources of error in the test procedure.

Furthermore, the power must have a tolerance of ±1 % (during constant power discharge and charge), and ±2 % (during variable power discharge, ±4 % during first 2 seconds); about the energy accuracy, during dynamic cycles with variable power discharge, the value of the energy discharged in the whole cycle must be ±2 % of the theoretical value.

Temperature test and stabilisation (acclimatisation)

If not otherwise defined before each test, cell (or module) has to be stabilised at the test temperature from 2 to 6h. This period can be reduced if the thermal stabilization is reached, defined as the temperature stability is reached after one interval of 1 h during which the change of the cell temperature is lower than 1°C.
Unless otherwise stated in this procedure, cells shall be tested at RT in a climatic chamber under controlled temperature.

Samples to be tested

As previously stated, this test procedure has been developed having in mind a specific SC cell (and module) and one reference hybrid commercial vehicle already designed and made ready for demonstration by Altra/IVECO, whose technical specification and operating conditions .

Cell sample identification

The test procedure will be applied to the cylindrical (EDLC = electric double layer capacitor) double-layer type SC described in Appendix 1 (EESS design refers to Altra HEV application). The cell samples are of a well-defined chemistry and are supplied by Maxwell to DimacRed for modules and battery integration.
The cell samples will be fully identified with a code and tracing table, which will be available with clear identification for tracing each sample during its testing story from the delivery of the supplier up to the final return to the same supplier, if required.
The cell information will be also associated to the various tests and the testing laboratories in order to easily relate back to this identification system. The identification & tracing list with the definition of the cell identifier is reported in Appendix 2.

Standard cycle

Each test has to be started in the same initial cell conditions, by applying a standard cycle that must be performed before each test.

The standard cycle is normally performed at RT. Other temperatures are fixed in some special tests. The standard cycle (SC) is composed of a discharge phase (SDCH) followed by a charge phase (SCH).

Standard Discharge (SDCH)

Discharge rate: as described in Appendix 1 or in related test procedure.
Slow discharge rate with the following parameters:
- Current: 5 mA/Farad
- Cut off voltage: V=0.3*RWV, or a different voltage if specified in the test plan.

Discharge limit: the EODV is fixed at 0 V (100% DOD).
Rest after discharge: 1 hour
If the cell temperature is too high after one hour rest, the rest period must continue until the cell temperature reaches RT conditions.

Standard Charge (SCH)

Charge procedure: it will follow the conditions described in Appendix 1 or recommended in use specifications, based on a constant current (CC) phase, followed by a constant voltage (CV) phase. The optimised charge profile should be given by the manufacturer. Otherwise the standard charge is performed using the following profile:
- Voltage limited to RWV (rated working voltage)
- Current limited to 50 mA/Farad
- Total time 900 seconds.

Rest after charge: 1 hour

If, for any reason, the time interval between the end of the standard cycle and the beginning of a new test is higher than 1 hour, it is necessary to repeat the standard cycle.

Scale down of HEV references duty performances

The battery systems have been already designed for the two reference HEVs and have basic technical specifications summarized in Table 2.

Table 2. Basic technical specifications of the SC EESS for the Altra HCV demonstrator.

Properties	HCV 1- IVECO Daily
Peak Discharge Power (10 sec @ EOL, lower SOC), kW	40
Peak Charge Power (15 s @ EOL, upper SOC), kW	45
Charging Power during recovery, kW	5
Rated Voltage, V	(from 280 to) 304
Minimum EODV, (@ EOL, 45 kW x 10 s, lower SOC), V	240
Maximum braking charge voltage (@ EOL, 45 kW x 10 s, upper SOC), V	375
Max discharging current (10 s), A	190
Charging current during regenerative braking, A	190
Available energy @ EOL, Wh	≥800
Usable energy, Wh	800
Battery Size Factor (BSF)	144 (6 in series/8 parallel for each of the 3 modules series-connected)

The test procedures will start from the defined technical specifications of the complete EESS by scaling down the key testing parameters to the size of each cell. This scale down process will be roughly based on 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 the designed EESS composed of a total of 144 cells, the BSF has been roughly rounded for HEV1 in 144 For example, if the Battery Size Factor is (6x8x3=) 144 cells for this particular system design, the 45-kW Peak Discharge Power (see design Table at the end of Appendix 1) for HCV1 to be used in life cycling test would then be performed at a pulse power level of 45000/144 = 312.5 W for such cells.

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.

Overview of the test procedures

The overall characterization and testing plan for SC cells (and modules) is composed of different test procedures aimed at various purposes.

Basically, there are in total 5 test procedure types:

1. General preparation tests
2. Basic characterization tests for HCV demonstrators
3. Ageing-accelerated life testing
4. Management-oriented tests
5. Tests for input measurements for model development.

An overview of the overall procedures and their structures are reported in Figure 1.

HCV Electrical Test Procedures for SC cells adapted to ALTRA HEV

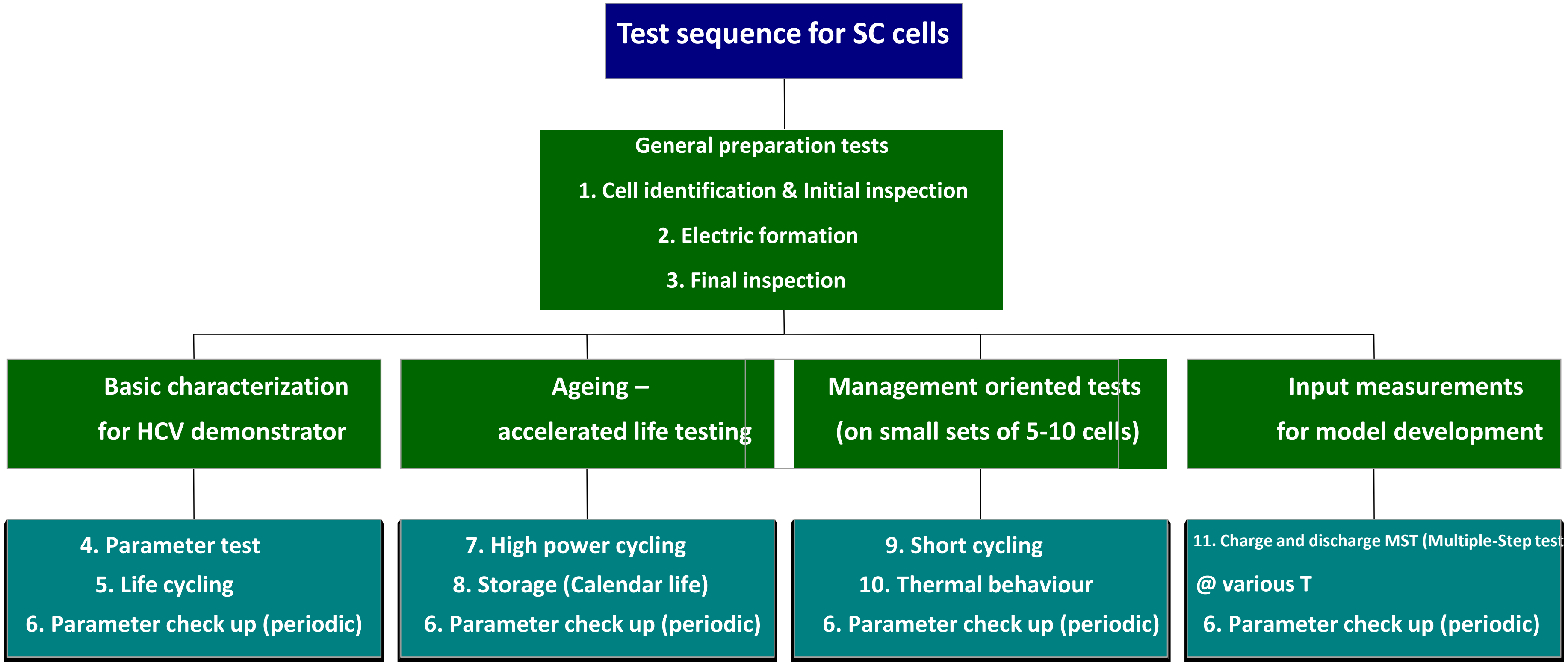


Figure 1. Overview of HCV SC cell (and module) test procedures.

General preparation tests

These tests are carried out to clearly identify the sample under test and to collect the basic physical characteristics at the beginning and at the end of each test sequence.

This procedure is composed by:

1. Cell identification/classification and initial inspection (Test 1 in Appendix 3)
2. Electric formation (Test 2 in Appendix 4)
3. Final inspection (Test 3 in Appendix 5)

The cell identification and classification has been already explained previously and will first require the verification or, eventually, the application of the cell code on the cells received by the first testing laboratory. This code and related history information must be then reported on the Code & History table on the HCV website.

Basic characterization tests for HCV demonstrators

These tests are mainly devoted to analyse the performance characteristics and the behaviour of the sample cells, when used in controlled operating conditions, similar to those foreseen on the HCV demonstrator, after defined scaling down calculation.

This test sequence is composed on dynamic tests (based on life cycling), periodically interrupted for checking basic characteristics modifications with parameter check-ups.

A parameter test is defined that determines basic performance parameters such as capacity, specific energy, specific power, fast charge capability and self-discharge in room temperature and at different environmental temperatures.

One life cycle profile is also defined that simulates the power demand for the cells in the Altra HCV demonstrator.

This procedure is composed by:

1. Capacitance (Test 4, Appendix 6)
2. ESR (Test 5, Appendix 7)
3. Fast charge/discharge (Test 6, Appendix 8)
4. Self-discharge (Test 7, Appendix 9)
5. Peak Power (Test 8, Appendix 10)
6. Cycle Life
7. Parameter check-up (periodic)

Life cycling

This sequence is a complete and integrated set of tests performed at the beginning and at the end of a complete test procedure. The objective of the parameter test is to establish the baseline performances of the cell and includes various characteristics. At the end of a complete test sequence, the same characteristics are determined and compared with the initial ones to outline degradation and significant variations in cell behaviour. The complete life cycle test sequence is reported hereafter (Test 9, Appendix 11).

Parameter check-up (periodic)

This test sequence is a periodic control at the beginning and at the end of a complete test procedure and during the execution of regular tests to verify key performances and parameters. The objective of the parameter test is to establish the baseline performances of the cell and includes various characteristics and their evolution during testing. At the end of a complete test sequence, the same characteristics are determined and compared with the initial ones to outline degradation and significant variations in cell behaviour.

The Parameter Check-up tests are described in Test 10, Appendix 12.

Ageing-accelerated life testing

It is largely recognised that major factors, able to accelerate SC degradation [7] using organic electrolytes, are the maximum working voltage (when it is close to the recommended limit) and the high temperature. The purpose of these tests is to evaluate the life of SC cells, by using accelerating factors (temperature and RWV) and compare the results with those achieved with basic life cycle testing.
Basically two different test sequences will be used:

1. Calendar life test (Test 11 in Appendix 13).
2. Life cycle tests at maximum RWV and high temperature (exactly as the life test with higher voltages and working windows).

Management-oriented tests on modules

This part of the test sequence is 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 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;

Tests for input measurements for model development

These types of tests have been mostly defined by the University of Pisa and are aimed to assist the development of mathematical models and algorithms, by measuring the required model parameters. In Appendix 12, Test 14, the test sequence is reported.

Test Matrix

A test matrix for the identification of the minimum number of SC cells has been defined for the execution of most of the tests described in this report. Table 3 reports the distribution of cells and not includes the number of modules because they have not been defined yet.

Table 3. Test matrix for SC cells (and modules).

Test	HCV1
Basic characterization	2
Ageing tests	
Calendar life	20-30
High Power Life Cycling	2
Module-like	5
Test for models	3
Total	**32-42**

Conclusions

This report contains the complete test procedures for Li cells and modules specifically tailored for HCV Li EESS and, in particular, to Altra and Volvo HEV technical specifications and operating conditions. The ambition of this test procedure has been to analyze and adapt existing test procedures and standards, also develop in other EU projects, to the specific needs of HCV Li cells and modules and to support the optimization of use of these components also by means of the identification of parameters of dedicated models.

References

1. EUCAR Traction Battery Working Group "*Specification of Test Procedures for Supercapacitors in Electric Vehicle Application*", December 1998.
2. IEC62576/Ed.1: *Electric Double-Layer Capacitors For Use In Hybrid Electric Vehicles - Test Methods For Electrical Characteristics*, 2009.
3. IEC 61982-4: Secondary batteries for the propulsion of electric road vehicles – Performance testing for lithium-ion cells and batteries.
4. J. R. Miller, A. F. Burke, E. Thomas, *Electric Vehicle Capacitor Test Procedures Manual,* DOE/ID-10491, INEL, October 1994.
5. FreedomCar, *FreedomCAR Ultracapacitor Test Manual,* INEEL, DOE/NE-ID-11173, Revision 0, September 21, 2004.
6. Hybrid Commercial Vehicle (HCV) FP7-Project, " Technical specifications for HEV, D3100.1," Altra, 2011.
7. P. Azaıs et alii, *Causes of supercapacitors ageing in organic electrolyte*, Journal of Power Sources 171 (2007) 1046–1053.

Appendices

Appendix 1

SC Cell data specifications and charge profile

Data Profile provided by SC Manufacturer/Supplier

Table 4 has been filled in and included in the test report. The supercapacitor DimacRed manufacturer/supplier has provided this information.

Table 4. SC data profile.

General data	
Manufacturer/supplier	
Company	Dimac Red S.r.l.
Address	Via Giovanni XXIII, 25 Biassono (MB), 20853
www-address	www.dimacred.it
Contact person	
Name	Vincenzo Musolino
Tel	+39 039 2494856
E-mail	v.musolino@dimacelettronica.it
Fax	+39 039 491773

System description			
Battery			
Type	Cell:	Module:	System:
Name	BCAP3000 P270	BMOD 0063	3*BMOD 0063
Date of Manufacturing			
Nominal Battery Voltage (V)	2.7	125	125
Rated Capacity (Wh)	3.03	136	136
Nominal cell voltage (V)	2.7	2.7	2.7
Number of modules	N.A.	1	3
Number of cells	1	48	144
Description of the internal connections	N.A	Heat Shrink Bus Bars	Heat Shrink Bus Bars+cables
Type of electrolyte	AN/TEATFB		
Size	Cell:	Module:	System:
Weight (kg)	0.55	59.5	180
Volume (dm^3)	0.475	85.8	258
Dimensions			

- length (mm)	138	762	755 (to better define in 5100 and 5200)
- width (mm)	14	425	680 (to better define in 5100 and 5200)
- height (mm)	60.5 (diameter)	265	310 (to better define in 5100 and 5200)

Peripherals and Instruction

BMS	Yes: **Active cell monitoring and operation** only when a single cell reaches a voltage greater than 2.73 V	No:
Thermal management	Yes: Only monitoring	No:
Safety devices	Yes	No:
Operating manual	Yes	No:

Auxiliary equipment

	BMS	Thermal Management	Connectors	Other	Tray	Total
Weight	Included in the module and negligible compared to the module dimensions.					
Volume						
Dimensions						
- length						
- width						
- height						
Power consumption	400mA per cell when active. 30 µA per cell when monitoring	Negligible. Via PT100RTD sensor				

Operating Conditions

Charging

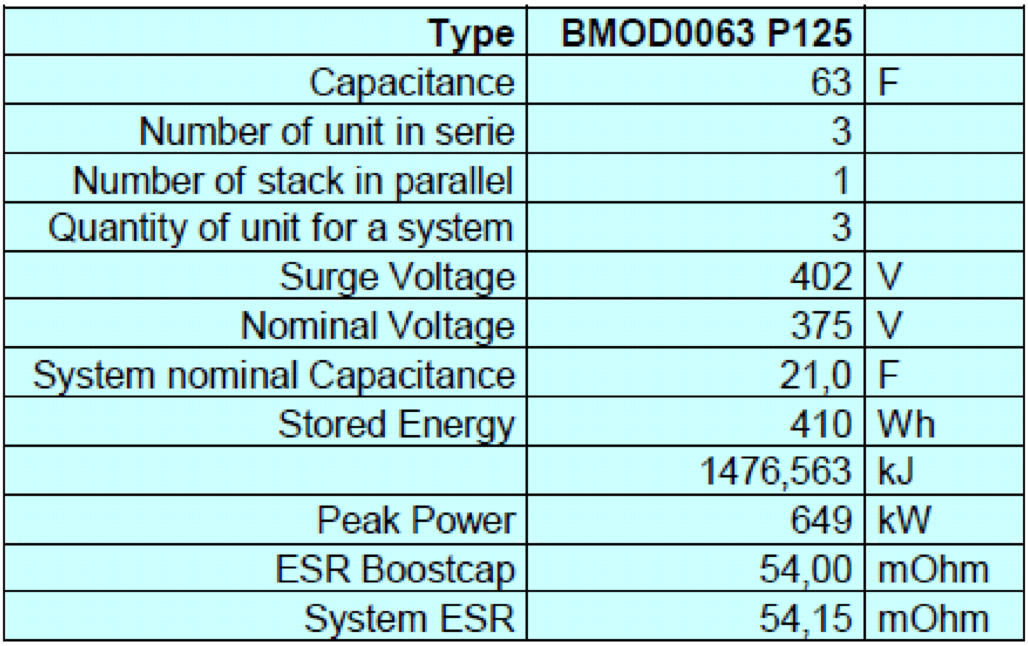
Method		According to the application	
Charging time		According to the selected current	
Temperature limits (°C)		min: -40°C	max: +65°C
Max continuous charge current (A)		150 A	
Max charge current (A)		150A continuous	
Max battery temp. at generator charge (°C)		65°C	
Max voltage at generator charge (V)		130V per module	
Charging factor		coulomb:	energy:

Full description of the charging procedure should be given in Appendix.
The description should include a charge diagram.

Discharging

Temperature limit (°C)		min:-40°C	max:65°C
Cut off voltage 100% DOD	Constant current (V)	0V	
	Constant power (V)	0V	

Max continuous discharge current (A)	150A
Max discharge current (A)	750A 1s, duty cycle 10%



Type	BMOD0063 P125	
Capacitance	63	F
Number of unit in serie	3	
Number of stack in parallel	1	
Quantity of unit for a system	3	
Surge Voltage	402	V
Nominal Voltage	375	V
System nominal Capacitance	21,0	F
Stored Energy	410	Wh
	1476,563	kJ
Peak Power	649	kW
ESR Boostcap	54,00	mOhm
System ESR	54,15	mOhm

Appendix 2

Cell identification and history table

Table 5 presents the summary history of the cell/modules under test.

Table 5. Cell identification code and history list.

Cell Identification code	Date of expedition from supplier	1st receiving laboratory	Present location and date	Present location and date (temporary transfer)	Date of final expedition to the supplier	Reception date from supplier	Note
HCVnnn_ddmmyy_name							

The identification code is structured in the following way and will be marked on each cell:
HCVnnn_ddmmyy_name

HCV = Name of the EC Project
nnn = progressive cell number starting from 001.
ddmmyy = first expedition date from supplier
name = name of the first receiving testing laboratory

The first receiving testing laboratory will also be the responsible of the history of the cell and keep trace of all the passages and work on it until the final transmission to the supplier. It will have also the responsibility to update the Cell Table on the website and inform the other participants.

Appendix 3

Test 1 – Initial inspection

The initial inspection procedure is the following:

- *Visual inspection*, consisting of checking that no damage has occurred to the test samples during delivery.
- The identification marks given by the manufacturer for each cell under test must be recorded, according to the HCV identification process. Pictures of the main components must be taken and included in the test report.
- Dimensions and weight are measured to determine whether the physical characteristics of the test samples correspond to those given by the manufacturer.

The maximum dimension of the total width, thickness or diameter, and length of a cell shall be measured using Figure 2, as derived from draft standards (IEC 61982-4).

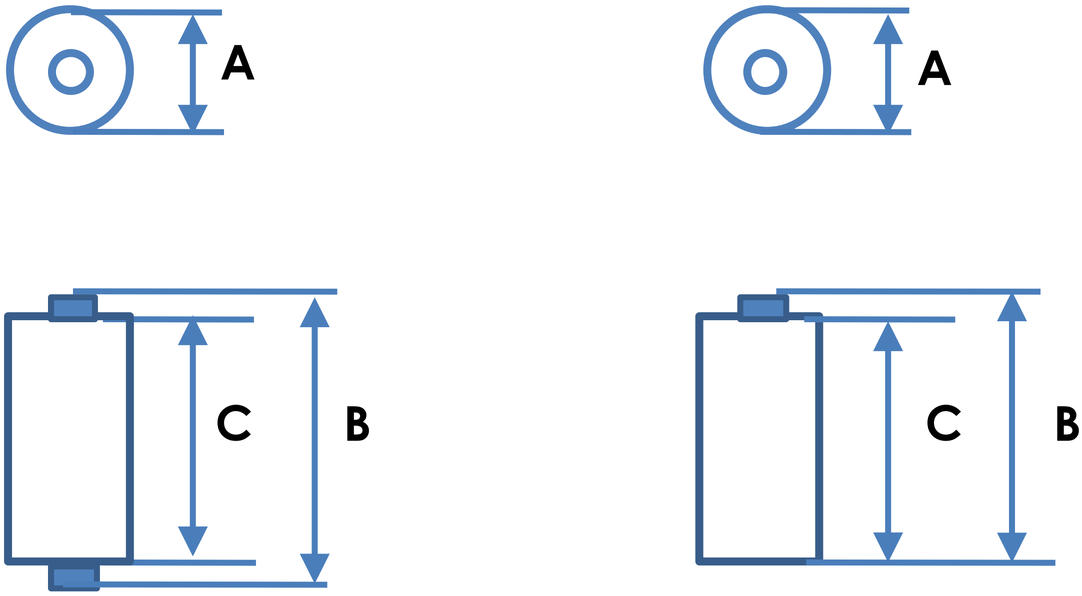


Figure 2. Methods for measuring dimensions of a cylindrical cell with or without terminals.

The examples of maximum dimension are shown in the figure, where:
A is the diameter;
B is the total length (including terminals);
C is the total length (excluding terminals).

Data report

Data to be reported in the Test Report includes visual damage, dimensions, volume and weight of the cell. In particular, the weight has to be recorded for subsequent weight controls of the cell to determine possible variations.

Appendix 4

Test 2 – Electric formation

Procedure description

The initialisation is a procedure which must be applied to the new cells only.
The purpose of this operation is to bring all the cells in the same electrical conditions before starting with the test.
Three steps are required for the initialization, as described in Table 6.

Table 6. Electric formation procedure.

Step	Phase	Voltage	Current	Time
1	Charge	Limited to RWV	Limited to 50 mA/F	2 hours
2	Discharge	≤ 100 mV (final voltage)	100 mA/F	
3	Short circuit			12 hours

The initialisation is performed at RT only.
Short circuit means that the cells (when it is possible) are connected in short circuit one by one.
When the module is sealed, the external connectors are short-circuited.

Data report

Appendix 5

Test 3 – Final inspection

Procedure description

Visual inspection, consisting of checking any visual damages that might have occurred to the test samples during the test sequence.

Shape and dimensions shall be measured to check whether deformation occurred during the test sequence. The weight has to be measured to determine whether electrolyte has been lost during testing.

Data report

Data to be reported in the Test Report is the visual damage. Also enter the weight reduction at the end of the test sequence with the information at what step of the test it was detected.

Appendix 6

Test 4 – Capacitance determination

The capacitance is the reference parameter of the state of activity of DLC. The changes of this parameter give important data on energy availability and on the ageing of the cells.
In the case of DLC packs, the capacitance of each cell in the pack should be similar, in order to avoid a non-uniform behaviour of each cell in the pack, with the consequence of a non-homogeneous distribution of the voltage in each cell and a decrease of the performances of the samples in testing.
Capacitance value is calculated using the following equations:

$$C = Q/(V_i - V_f)$$
$$Q = I * (t_2 - t_1)$$

I = Discharge current (constant) 5mA/F
V_i and V_f = Initial and final voltage considered for capacitance measurement (0.6*RWV and 0.4*RWV).
t_1 and t_2 = times (seconds) when V_i and V_f are reached.

The capacitance measurement is performed in three different levels of temperature:

-20, RT, +40°C.

The complete procedure of this test is described in Table 7.

Table 7. Capacity determination test sequence.

Step #	***Action***	***Operation***	***Temperature***
1	Equalization of cells		Test T
2	Acclimatisation		Test T
3	Standard charge		Test T
4	Discharge	Current: 5 mA/F	Test T

During the phase 4 the voltage of each cell (and/or the pack) and the current is recorded. The capacitance of the cells and the pack is calculated considering the time when the voltage passes from 0.6*RWV to 0.4*RWV.

The capacitance calculation is based on diagram in Figure 3.

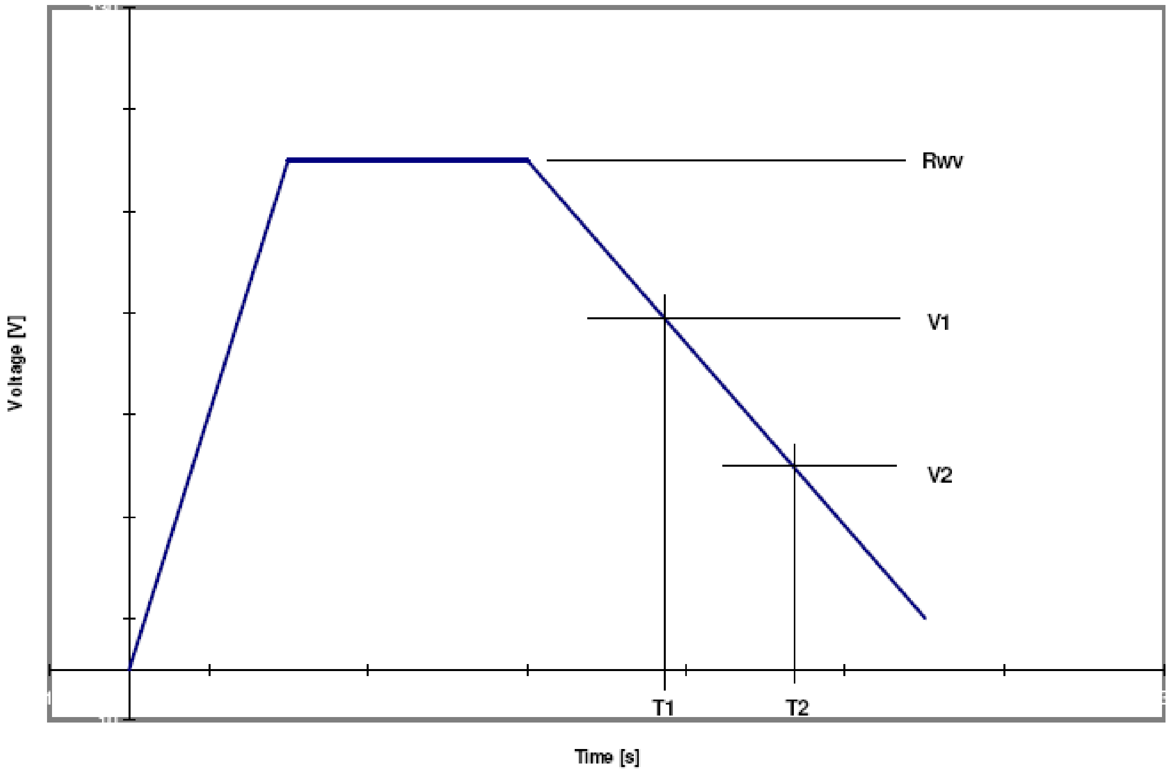


Figure 3. Capacity determination graph.

Appendix 7

Test 5 – Internal resistance (ESR = Equivalent Series Resistance)

Procedure description

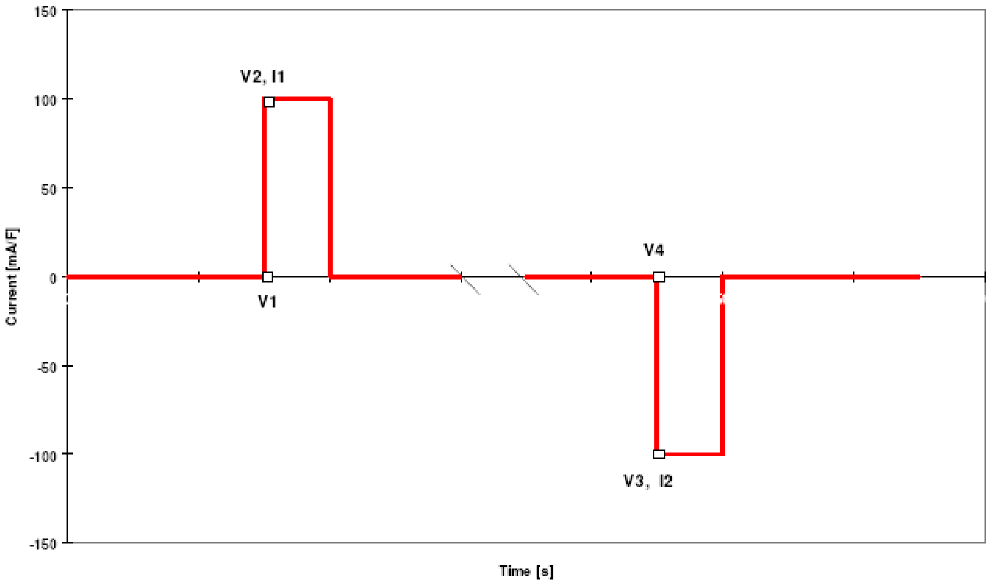
The EDLC is a high power generator for a short time. Like as all other kind of electrical generators, it is characterised by an internal resistance (basically ohmic resistance), which is the responsible of the main electrical characteristics in terms of voltage drop when high current is required.

The ESR does not depend by the voltage to which the DLC is charged and it is calculated on the drop of voltage when a constant current is supplied by the DLC.
Only the ohmic resistance is measured and two sets of measurement are required when it is possible:

1- ESR of a single cell: this measurement gives the real value of ESR of the DLC in testing and the result is not compromised by the quality of the contacts and connectors.
2- ESR on the module: in this case the total ohmic resistance is the sum of each cell's ESR and the connections that could be resistive ones. This is the real value of the ESR of the module.

Operative ESR measurement

Parameter setting:
ESR CHARGE: Voltage: limited to 1/2 RWV
Current: limited to 50 mA/F
Time: 15 minutes
ESR MEASUREMENT: measurement of the drop of voltage immediately after the closure of the circuit on the base of the ESR test cycle described in Figure 4.



$$ESR_{dch} = \frac{V1 - V2}{I1} \qquad ESR_{ch} = \frac{V3 - V4}{I2}$$

Figure 4. ESR determination graph.

The test sequence of ESR determination is described in Table 8.

Table 8. ESR test sequence.

Step #	Phase	Time, sec
1	ESR Charge	
2	Pause	15
	ESR test cycle	
3	Discharge: 100 mA/F	5
4	Pause	600
5	Charge: 100 mA/F	5
Note: Recording time = 10 ms/sample or oscilloscope		

An important parameter to be set is the acquisition time, in order to compare the drop of voltage in the same time interval. In this document the acquisition time is set in 10 ms (10 milliseconds).

If the discharge current levels are not appropriated to the EDLC in testing, other current levels can be chosen in agreement with manufacturer and mentioned in test plan. The ESR test is performed at three levels of temperature:

-20, RT, +40 °C

The SCH is performed at the test temperature. The complete test sequence is reported in Table 9.

Table 9. ESR test sequence at different T.

Step #	Phase	Temperature, °C
1	SCH	RT
2	SDCH	RT
3	Acclimatization	Test T
4	SCH	Test T
5	ESR Measurement	Test T
6	Return to Step # 3 for the test at another T.	

The test is performed from step 1 to step 5 for each temperature level.
ESR values in charge and discharge is calculated considering the ohmic drop of voltage (V) and the real current in the circuit (I).

$$ESR = \frac{(V_i - V_f)}{I}$$

Appendix 8

Test 6 – Fast charge/discharge

Procedure description

The energy recovery in EV is a very important strategy to better exploit the energy source capability for the traction.
Not all kind of batteries are able to store the energy recovered during braking with high efficiency and for the short time spent in braking.
Supercaps are able to store energy with high current rates with high coulombic efficiency and return the same capacity when the peak power of acceleration is required, with peak leveling effect on the batteries.
The test to define the capability in energy storing is planned in a view of current and time ranges referred to a normal driving profile on EV.
A matrix with two control factors (current and time) and three levels for each factor, is planned as follows:

CHARGE CURRENT	I_{max} x 0.5			I_{max} x 0.75			I_{max}		
TIME [sec]	5	10	15	5	10	15	5	10	15

If the charge current is not in line with DLC characteristics, different current ranges could be chosen in agreement with manufacturer and specified in the test plan.
The test is performed in RT only.

Discharge phase conditions: Constant current = 5 mA/F
Voltage limited to 0.3 * Rwv
Charge phase conditions: Charge current and time fixed following the matrix.
Voltage limited to Rwv

The test procedure is described in Table 10.

Table 10. Fast charge test sequence.

Step #	Phase	Conditions	Time, sec
1	Equalisation		
2	Acclimatisation		
3	SCH		
4	Discharge		
5	Pause		30
6	Charge	I_{max} x 0.5	5
7	Pause		30
8	Discharge		
9	Pause		30
10	Charge	I_{max} x 0.75	5
11	Pause		30
12	Discharge		
13	Pause		30
14	Charge	I_{max}	5
15	Pause		30
16	Discharge		
17	Pause		30
18	Charge	I_{max} x 0.5	10
19	Pause		30
20	Discharge		
21	Pause		30
22	Charge	I_{max} x 0.75	10
23	Pause		30
24	Discharge		
25	Pause		30
26	Charge	I_{max}	10
27	Pause		30
28	Discharge		
29	Pause		30
30	Charge	I_{max} x 0.5	15
31	Pause		30
32	Discharge		
33	Pause		30
34	Charge	I_{max} x 0.75	15
35	Pause		30
36	Discharge		
37	Pause		30
38	Charge	I_{max}	15
39	Pause		30
40	Discharge		

The cycle from step #3 to step #40 is performed 3 times without interruptions. The third one is considered for the data processing.

The result of the test is given as the ratio of energy supplied to the SC in fast charge and the nominal energy contents.

$$E_{nom} = \frac{1}{2} * C_{nom} * RWV^2$$

$$E_{stored} = \frac{1}{2} * C_{nom} * OCV^2$$

$$Energy\ Level\ [\%] = \frac{E_{stored}}{E_{nom}} * 100$$

In Figure 5 the cycle and the test diagram for measurements are shown.

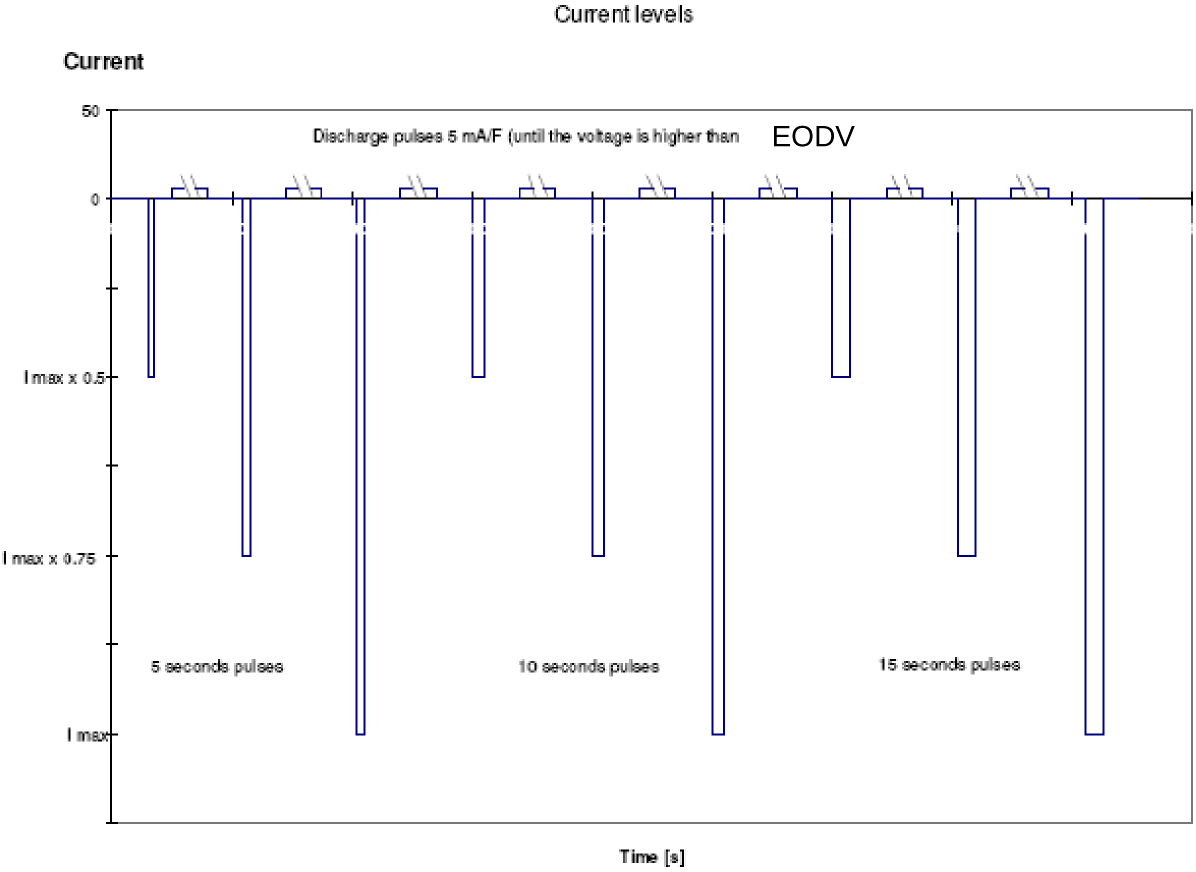


Figure 5. Fast charge profile.

The same procedure can be applied for fast discharge test, by simply exchanging charge phase with discharge phase and extending each charge phase to 600 sec.
The result of the test is given both as the final voltage (OCV) in each stage of the test and as the percentage of energy used in the discharge. The reference value is the full charged energy content (E(nom)) and the relevant parameters are the following:

$$E_{nom} = \frac{1}{2} * C_{nom} * RWV^2$$

$$E_{residual} = \frac{1}{2} * C_{nom} * OCV^2$$

$$E_{used}\ [\%] = \frac{E_{nom} - E_{residual}}{E_{nom}} * 100$$

Figure 6 shows the cycle and the diagram of the range for the measurements for the fast discharge test.

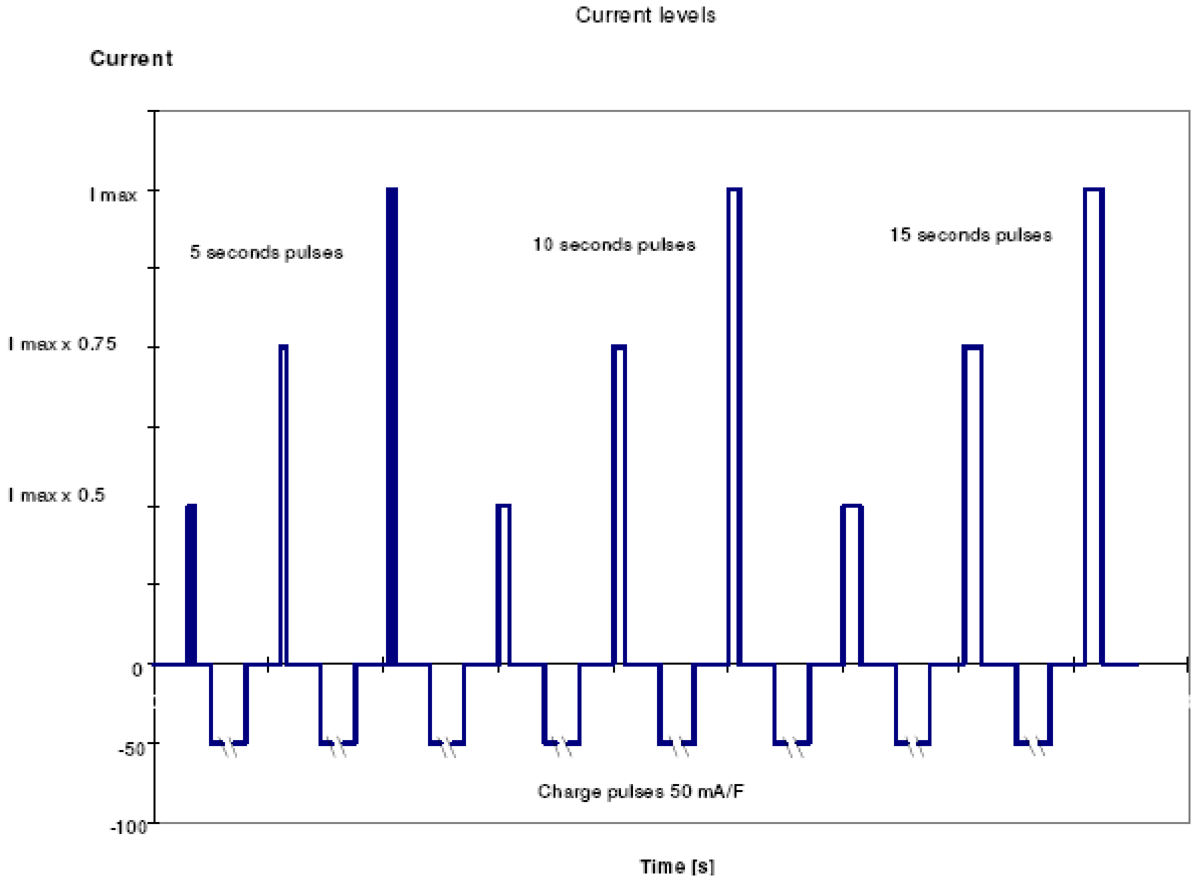


Figure 6. Fast discharge profile.

Appendix 9

Test 7 – Self discharge

Procedure description

SC undergoes a self-discharge current leakage if it not maintained in charged state. This behaviour could allow to a state of nonintervention of the SC after a more or less long time of rest of HEV.

The main factors which act on the self-discharge rate are the manufacturing technique and the ambient temperature.

The measurement of this parameter gives information on the energy available from DLC after a long rest period without any load connected.

Operative Self-Discharge measurement

Parameter setting:

1. During acclimatisation phase, the cells must be connected to the power supply in conditions of RWV.
2. The leakage of charge is monitored through the drop of voltage during the time: the test temperature is maintained constant for all the duration of the test (72 hours) and the logging of the voltage should start at least 5 minutes before disconnecting the cells from the power supply. The self-discharge curve is an exponential one and the frequency of acquisition must be relatively faster in the firsts 12 hours (e.g. sampling every 2 minutes) and longer in the final phase.
3.

The test is performed at three levels of temperature:

-20, RT, +40°C.

The self-discharge is determined according to the procedure described in Table 11.

Table 11. Self-discharge test seuqence.

Step #	Phase	Temperature, °C
1	Equalisation	RT
2	Acclimatisation	Test T
3	SCH	Test T
4	Open circuit	Test T
5	72 hours voltage recording	Test T
6	SDCH	RT

The test is performed from step 1 to step 6 for each temperature level.

Appendix 10

Test 8 – Peak power

Procedure description

The peak power is the most important parameter that distinguishes the performances of a supercaps' pack by a battery pack. In the first case we have a buffer of power with a very low energy, but it is essential to exceed some situations where very high power is required (acceleration, start-up).
The maximum power delivered by an SC is compared with the weight of the cell (specific peak power) and the time when the max power is required, referred to a minimum energy to exceed the theoretic situation on EV, is estimated in 5 seconds.
The test is carried on in constant current and the power delivered is calculated as the average power delivered in 5 seconds while the voltage is over 0.3*RWV.
The maximum current is suggested by Manufacturer as maximum load current (Ic).
The test is performed at three levels of temperature (see Table 12 for the sequence):

-20, RT, +40°C.

Table 12. Peak power test sequence.

Step #	Phase	Temperature, °C	Time, sec
1	Equalisation	RT	
2	Acclimatisation	Test T	
3	SCH	Test T	900
4	Rest (OCV)	Test T	15
5	PPT*- Current =0.5 Ic	Test T	
6	Rest (OCV)	Test T	15
7	SCH	Test T	900
8	Rest (OCV)	Test T	15
9	PPT*- Current =0.7 Ic	Test T	
10	Rest (OCV)	Test T	15
11	SCH	Test T	900
12	Rest (OCV)	Test T	15
13	PPT*- Current =0.85 Ic	Test T	
14	Rest (OCV)	Test T	15
15	SCH	Test T	900
16	Rest (OCV)	Test T	15
17	PPT*- Current=Ic	Test T	
18	Acclimatisation	RT	

*PPT = Peak Power test

The test is repeated from step #1 for each test temperature. The discharge current in peak power test should reach the maximum short circuit current (Ic) suggested by manufacturer, with the limit of 400 amperes.

The results are given using a diagram where X axis is the time to reach 0.3 * Rwv for each level of current and Y axis is the specific power (W/kg). From this diagram it is possible to extrapolate the specific power at 5 seconds discharge current.

Data deliverables:

- PP5s = Max power delivered in 5 seconds while the voltage drops from Rwv to 0.3*Rwv(Peak Power in 5 s), in different temperatures.
- Specific peak power (in 5 s), in different temperatures.
- IPP = Current to achieve 5 s peak power while the voltage ranges between Rwv and 0.3*Rwv

Appendix 11

Test 9 – Life cycle test

Procedure description

The EESS must be capable of delivering the electrical characteristics required for both HEV produced by ALTRA, as described in D3100.1 [6].

This specification is for the configuration that Iveco has foreseen on the Daily Hybrid vehicle: mild hybrid version.
The reference micro cycle for this configuration is described in Figure 7.

Vehicles: Mild hybrid vehicle

Micro cycle

- Period time: 167 s
- Cycle length: 1 km
- Delta SOC max about 5% for i.e. SC cells.

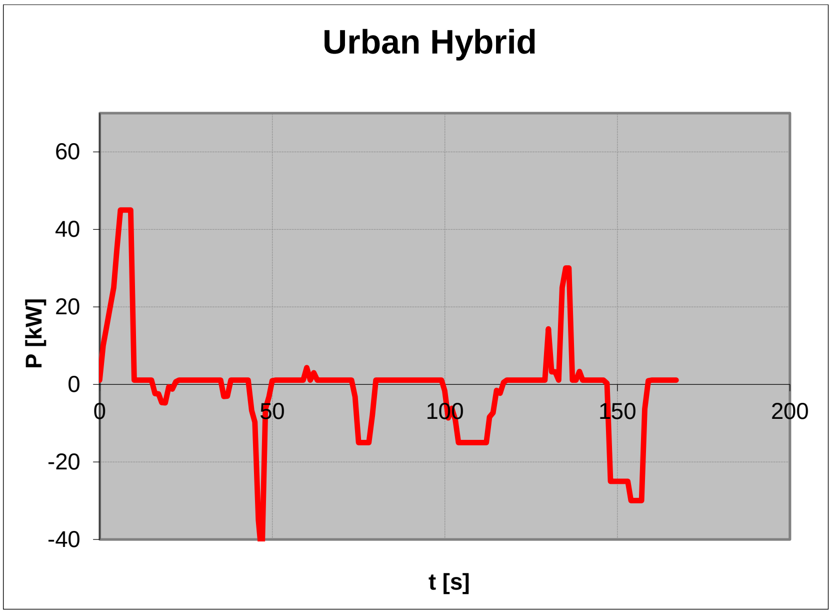


Figure 7. Selected power micro-cycle.

- ✓ *One hour cycle* = 18 micro cycles plus 10' stop

- ✓ *Daily cycle* = 10 *One hour cycle*

- ✓ *Year cycle* = 250 *Daily cycle*

Lifetime evaluation:

Year cycle in the following external temperature condition:

- ✓ 40% of 250 *Daily cycle* at 20 C°
- ✓ 40% of 250 *Daily cycle* at 30 C°
- ✓ 20% of 250 *Daily cycle* at 40 C°

The test sequence is summarized in Table 13.

Table 13. Life cycle test procedure.

Step #	Operation	Temperature
1	Parameter check-up	RT
2	Acclimatisation	Test T
3	Cycling (20,000 Altra micro-cycles)	Test T
4	Acclimatisation	RT
5	Parameter check-up	
6	Results to be compared with end of life criteria	
7	Start from Step # 2	

Appendix 12

Test 10 – Parameter check up

Procedure description

A control of the state of SC in testing is performed during any test, including life cycle testing, using the parameter check-up sequence, and comparing the test results obtained in the minimum parameter test performed before starting the life test.

During life testing, a parameter check-up is performed each 20.000th ageing cycle, ± 1000 cycles.

The fundamental parameters are tested using as a reference the values from the initial parameter test.

During aging tests, the parameter check-up is performed before the cycling or storage begins, every sixth week during cycling or storage and after the cycling or storage is completed. If the cycling is interrupted during a longer period, the six weeks are extended accordingly to the duration of the cycling break. The parameter check-up is performed on single cells is presented in Table 14.

Table 14. Parameter check-up test sequence during cycling or storage.

Step #	Test	Temperature
1	Capacitance test	RT
2	ESR test	RT
3	Peak Power test	RT
4	Self-discharge	RT

Appendix 13

Test 11 – Calendar life test

Procedure description

To be able to separate the effects of aging and the effects of cycling on the cells and modules, storage test at elevated temperatures are run in parallel with the cycling tests. Cells will be subjected to the calendar life test.

The cells have different SOC and are placed in a climatic chamber with a certain temperature. The duration of the test is normally six month. The voltage of each cell will be checked and noted at least once a week. It is not recommended to continually load the the cells by measurement instruments.

The different temperatures used in the test are 35, 45 and 60°C.

The cells will be stored at 50 and 100% SOC.

Parameter check-ups are performed every six weeks and also before the storage test starts. The parameter check-ups are performed in room temperature. The cells are cooled down to room temperature and discharged with SDCH to the end of discharging voltage, followed by a standard charge.
After the parameter check-up a standard charge is performed, followed by a SDCH to the SOC the particular cell is tested at and the cell is placed in the climatic chamber again and the calendar life test continues.

Data deliverables

Above the data deliverables included in the parameter check-up test, following data should be reported:
The voltage versus time from the weekly voltage controls.
Remaining capacity after storage period (“self-discharge”) vs. storage time

Appendix 14

Test 12 – Tests for input measurements for model development (prepared by University of Pisa)

The battery test matrices for modelling purposes are based on the Multiple-Step Test (MST). The test shown in Figure 8 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 how is reproduced in Figure 8, or starting from a fully–discharged SC and using charging current steps, instead of discharging current steps. Therefore the MST can be charge-based and discharge –based.

From the knowledge of the current drawn from the SC at each step and the measurement of the corresponding rest voltage, the correlation curve shown in Figure 8 can be derived.

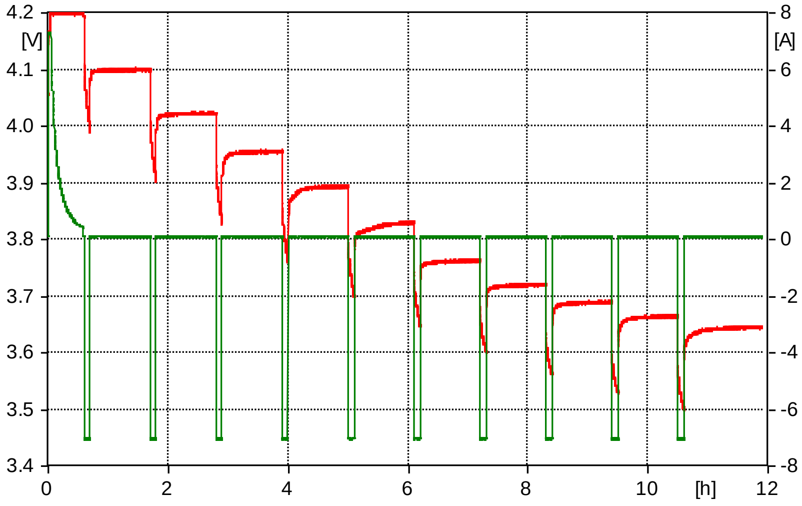


Figure 8. The discharge-based Multiple-Step Test.
Green: current; blue: voltage; horizontal scale :time (s).

Each MST will be performed, both in charge and discharge ad different temperature. 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 test matrix is therefore that shown in Table 15.

Table 15. Test matrix at different temperatures.

temperature/°C test	-40	-20	0	20	40	60
Cell parameters identification	x	x	x	x	x	x
Module parameters identification	x	x	x	x	x	x

The tests reported in Table 16 will be performed in these cases:

- for 3 different cells (BCAP3000P270 that is a 3000F cell at 2.7V) to evaluate not only the cell performance, but also its statistical spread
- for 1 module (BMOD0063 that is a 63F module at 125V).