SUPERCAPACITOR TESTING FOR HYBRID COMMERCIAL VAN APPLICATIONS IN THE EUROPEAN PROJECT HCV

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Abstract

The hybrid electric vehicle (HEV) is an excellent option for simultaneous reduction of fuel consumption and exhaust emissions in urban areas. However, substantial research efforts and industrial development are necessary to reduce cost and further improve high-efficient hybrid systems including key components such as the energy storage system, the electric machine, power electronics and electric auxiliaries. A large European Project, named HCV (Hybrid Commercial Vehicles), started in January 2010 with the participation of 18 European organizations and with the scope to develop and demonstrate the current Heavy Duty (HD) HEVs in preparation of the next generation of hybrid commercial vehicles. A dedicated "Energy Storage Systems" Subproject was planned to verify technical performances and reliability of the storage systems (Lithium-ion and supercapacitors) in relation to the specific HEV architectures and drivetrains. In ENEA Laboratories, electric and safety abuse testing has been carried out on cells and even modules of commercial supercapacitors (or electrochemical capacitors, SC), together with the definition of common testing procedures.

This testing activity was aimed at: 1) identifying basic selection parameters for cells and modules; and 2) evaluating the behavior of the same samples in HCV-specific driving profiles and safety/abuse tests to optimize design and assembly and confirm the capacity to fulfill the projected performances during the service life.

This paper summarizes major achievements and experimental results of SC testing in ENEA laboratories, by describing the tailored procedures for verifying the suitability of the selected SCs to power a hybrid commercial van by using exclusively an SC storage system. The electrical and abuse testing (vibration on modules) confirmed basic performances and also the correctness of the system design with some indications about thermal management and cell controls, as well as about the robustness of different case materials in the module assembly.

I. INTRODUCTION

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.

A dedicated *Energy Storage Systems* SubProject, coordinated by ENEA (Italian National Agency for New Technologies, Energy and Economic Sustainable Development), 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 in order to assist component and vehicle manufacturers. These activities have been aimed at analyzing 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 (EES); 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 optimization (estimation of State of Health and State of Life).

One of the HEV developed in the project has been an IVECO commercial van, which was designed with SC as the only energy storage system in support to the main thermal engine. The challenging choice had to be experimentally verified and validated by matching the estimated technical performances under defined operating conditions. A procedure of electrical and abuse/safety testing has thus been developed and applied to various cells and modules. ENEA in its dedicated SC testing Laboratory has carried out electrical testing on SC cells and modules and mechanical (vibration) tests on some modules. These activities and the main achieved results are summarized in this paper, by also describing the tailored testing procedures, which are based on the specific HEV commercial van configuration and targeted performances.

Initially, the basic characteristics of the SC samples under tests are presented, followed by the description of the dedicated test procedure that was adapted to the duty cycle required by the HEV manufacturer. Finally, the experimental campaign is reported with the key results and conclusions.

II. THE REFERENCE HYBRID VEHICLE AND SC SAMPLES

The HCV project allowed adapting an IVECO reference HEV (a parallel hybrid commercial van) with well-defined basic technical specifications and designed with an ESS using SC. Altra-IVECO has modified a Daily 5-ton delivery van, equipped with an ESS able to supply a maximum power (in charge and discharge) of 45 kW, a maximum voltage and current of about 300 V and 200 A and a delivered energy up to the end-of-life (EOL) of the ESS of 800 Wh. Fig. 1 shows the Daily Hybrid van developed in HCV.

Fig. 1. IVECO Daily Hybrid van developed in the HCV project.

Samples of commercial SC cells and purpose-designed modules were made available for safety/abuse and electrical testing. The SC cells were based on a conventional commercial EDLC (Electric Double Layer Capacitor) with both electrodes made in activated carbon. DimacRed, another participant to the project, supplied more 60 SC cells as single units or assembled in modules of six cells each. At the end of the project, DimacRed prepared and supplied three different assemblies of the modules with and without containment case, but with the same internal configuration and technical performances, with the only difference in physical characteristics of weight and volume. Table 1 summarizes basic characteristics of SC cells and modules, while Fig. 2 presents the assembled module with included some control electronics (temperature sensors and wiring for cell voltage measurements).

TABLE I. SC CELL AND MODULE TECHNICAL SPECIFICATIONS

Properties	**Cell**	**Module**
Model	BCAP3000	Xboost500
Capacitance (F)	3000	500
Nominal voltage (V)	2.7	16.4
Max voltage (V)	2.85	17.1
Max continuous current ΔT 15°C (A)	130	50
Max peak current (A) for 1 s	2200	2100
Mass (kg)	0.510	4.4
Energy (Wh)	3.04	
Specific energy (Wh/kg)	6.0	5.96
Usable specific power (W/kg)	5900	5900
Operative Temperature Range	-40 +65	-40 +65
Cycle life	1,000,000	>45,000

Fig. 2. 2nd generation of SC module (named Xboost500) for HCV.

III. THE TESTING PROCEDURE

The electrical test procedure of SC cells and modules have been organized, after a survey of existing standard and procedures, in five different test sequences aimed at different testing scopes [1-4]:

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

To achieve a proper adaptation of testing procedures to the samples' characteristics, the technical specifications of the complete HEV storage systems have been scaled down and adapted to the sample sizes (cells and modules) by using a *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. In the case of the Daily designed storage system composed of a total of 144 cells, the BSF has been roughly rounded in 144. For example, if the Battery Size Factor is (6x8x3=) 144 cells for this particular system design, the 45-kW Peak Discharge Power to be used in life cycling test would then be scaled down at a pulse power level of 45000/144 = 312.5 W for such cells and multiplied by six for the pulse power level to be used in module testing. These BSF are constant for all the tests.

IV. ELECTRICAL TESTING ON SC CELLS

A dedicated ENEA SC Test Facility has been used to perform electrical and thermal testing on single cells and small modules. During the cell testing, the external temperature of the SC cell is measured with a dedicated sensor. Fig. 3 displays an example of the test control screen with control data and results elaboration with a continuous vision of the sample under test.

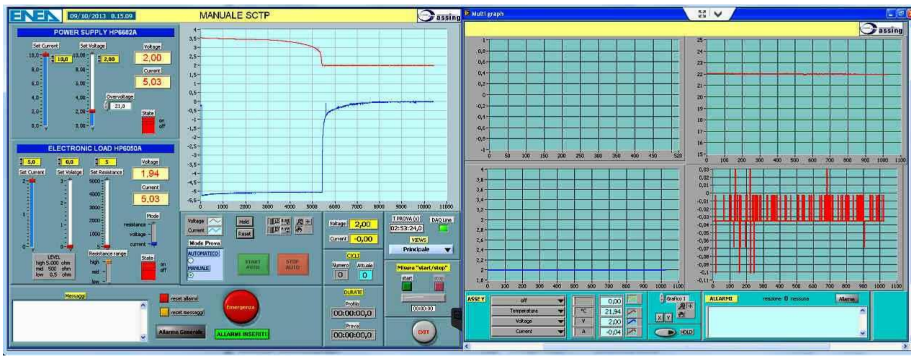

Fig. 3. User interface of the Labview SW during manual SC testing.

The SC test plan included the following electrical tests:

- Basic characterization
  - Capacitance determination
  - Internal resistance (ESR = Equivalent Series Resistance)
  - Peak power
  - Fast charge and discharge
  - Self-discharge
- Accelerated life cycling tests at various temperatures with the specific ALTRA-IVECO driving cycle
- Intermediate parameter check ups

A. Basic characterization of SC cells

After initial formation cycles (a few complete standard cycles, charge/discharge, repeated to verify nominal working voltage), the capacitance has been measured at room temperature (RT) and at 40 °C. The calculated value at RT of 3020 F confirmed the nominal value of 3000 F. The internal resistance (ESR = Equivalent Series Resistance) was also calculated with a specific test during charge and discharge, giving the following values at RT: ESR_{ch} = 0.426 mΩ with a current step of 80 A; ESR_{disch} = 0.416 mΩ with a current step of 60A (the nominal value, indicated by the manufacturer, of ESR_{disch} is 0.29 mΩ with a current step of 100A).

The fast charge tests were aimed at defining the capability in energy storing of the SC in selected current and time ranges. The nominal measured energy content of the cell was 3.04 Wh. Fig. 4 gives the adapted profile used for the fast charge test. The fast discharge tests have been also performed.

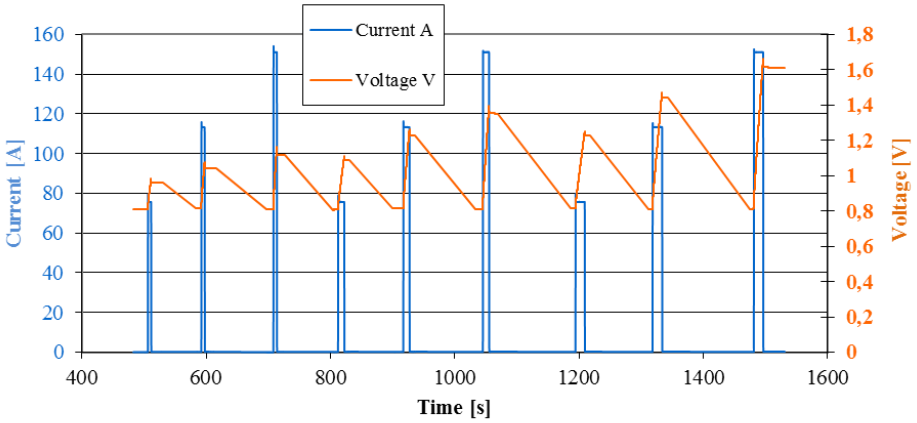

Fig. 4. Fast charge test profile for BCAP3000 cell.

These fast charge/discharge tests confirmed the lack of problems of the SC cells in any testing conditions and the high charge/discharge energy efficiency at high current rates. The peak power test was carried out to verify one of the most important features of SC: the high power density. The current and voltage profiles for peak power tests are shown in Fig. 5.

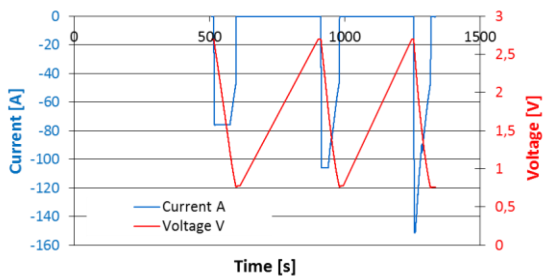

Fig. 5. Current and voltage profiles for peak power test.

The maximum (specific) peak power reached (for 5s) at a maximum peak current of about 150 A is about 750 W/kg (corresponding to a cell peak power for a continuous period of 5s of 370 W).

Finally, the self-discharge behavior of the SC sample was analyzed, by measuring the voltage for 72 hours at OCV (open circuit voltage), starting from a fully charged cell, as shown in Fig. 6. The open circuit voltage (OCV) declined as expected without any deviation.

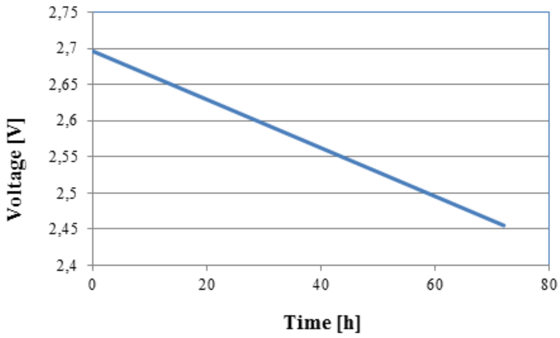

Fig. 6. OCV decline during self-discharge test.

B. Life cycle testing of SC cells

The life cycle tests on the SC cell had the purpose to estimate potential cycle life in HCV application by applying the simplified ALTRA-IVECO driving pattern, referred to the complete vehicle battery power requirement and scaled down from the complete vehicle storage system to the cell level. The micro-cycle proposed by the vehicle manufacturer (ALTRA-IVECO) was lasting 167 s, which corresponded a travelled distance of 1 km. The micro-cycle must be repeated 18 times per hour (including 10 min of stop), 180 per day and 45,000 times per year (with daily service 10 h long). Seasonally, the yearly cycle was further divided in three parts, with three different temperatures of 20 °C, 30 °C and 40 °C. In addition, in order to accelerate technical performance degradation and better assist modelling definition and validation, the cell has been tested not only at RT but also at the temperature of 40 °C. Fig. 7 describes the simplified driving profile (only current) scaled down at cell level.

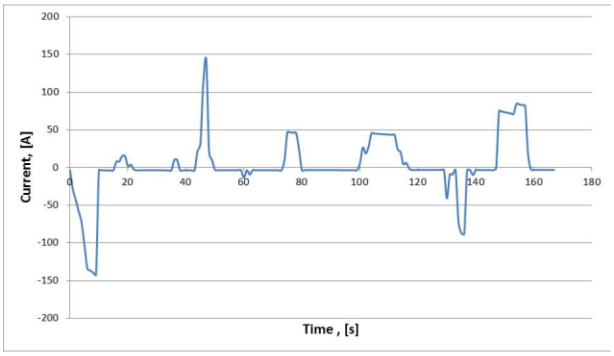

Fig. 7. ALTRA-IVECO current profile (micro-cycle) scaled down at cell level.

In total 21,200 micro-cycles were performed at RT, which corresponds to 118 working days and 21,200 km of travelled distance. In summary, the cycle life test has simulated about half a year of working time.

The degradation of basic performances, such as capacitance and ESR (during charge, ESR_{ch}, and during discharge, ESR_{dch}), during life cycle testing at RT was very limited and well below the standard end-of-life criteria (loss of 20% of nominal capacitance and doubling, or increase of 100%, of ESR). This conclusion is directly derived from the test results summarised in Fig. 8.

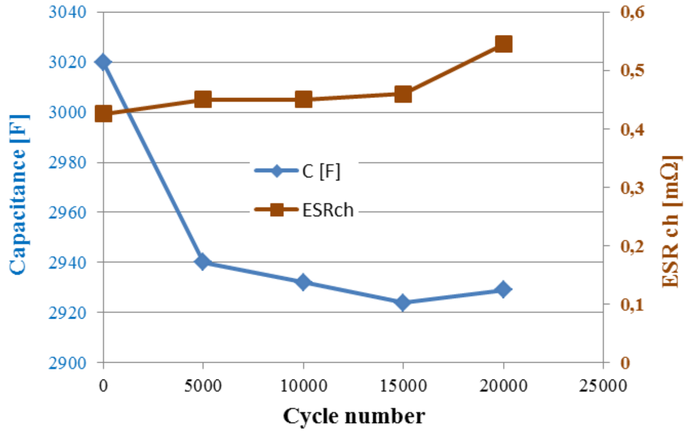

Fig. 8. Capacitance and ESR_{ch} trends during cycle life testing.

The SC technical performances resulted not affected by the more severe micro-cycle derived from HCV application in ALTRA hybrid commercial van, demonstrating a high stability, consistent with the declared cycle life of 1,000,000 of complete charge/discharge cycles.

The ALTRA-IVECO cycle life testing has been repeated at a higher temperature (40 °C), by trying to accelerate performance degardation. In total, more than 8,000 micro-cycles were completed, which correspond to an additional working period of about 45 days and about 8,045 km. In total, the SC cell accumulated a total service life of 164 working days (with respect to a planned year operation of 250 days) with two different temperatures corresponding to the minimum and maximum values required by the Altra-IVECO procedure. Periodically, the capacitance has been measured at RT and also at 40 °C to verify degradation. For accumulating as many cycles as possible, it was decided to limit the performance control to capacitance measurements, because the other tests during parameter check-ups required longer time.

At the end of life testing, a limited degradation of the capacitance as a combined effect of the life cycling and the higher temperature effectively occurred. After a working period of 164 days at two different temperatures, the SC capacitance was reduced of 4.7% (the initial value was 3020 F and the final 2878 F). During all the tests, the SC sample was instrumented with a temperature sensor on the external case to follow all the variations in temperature, confirming the limited thermal stress (and temperature variation) of the cell case in any testing condition.

V. ELECTRICAL TESTING ON SC MODULES

ENEA repeated a similar testing process on 2nd Generation SC modules, by carrying out basic characterization and life cycle testing. The electric formation and initial characterization have been carried out on all the modules by measuring the capacity at various discharge rates. The measured capacitance corresponded to the nominal one of 500 F.

The life cycle testing was carried out on the selected SC module by using the ALTRA-IVECO charge/discharge micro-cycle, with a scaling factor different from that used for cells, reported in Fig. 9.

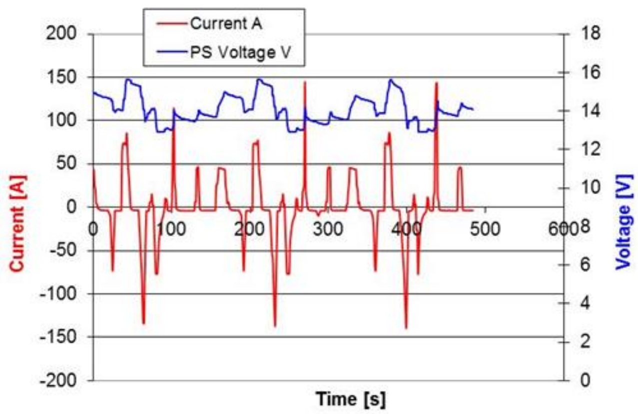

Fig. 9. Scaled-down Altra-IVECO micro-cycle at module size.

This test was originally designed to verify voltage dispersion with a limited number of full charge and discharge cycles, due to the absence of a BMS (Battery Management System), able to manage and equalize cell voltage during cycling. However, it was subsequently decided to stress module behavior by increasing the temperature and continuing life cycling with intermediate quick capacitance controls to try to accelerate degradation and assist the estimation of SOC. In total the life testing lasted 2145 micro-cycles, corresponding to 2,145 km (120 working hours). The tests were limited by the increase of the temperature, which required special attention to avoid exceeding the maximum recommended value. Every three hours of testing there was an interruption for limiting the temperature increase, as shown in Fig. 10.

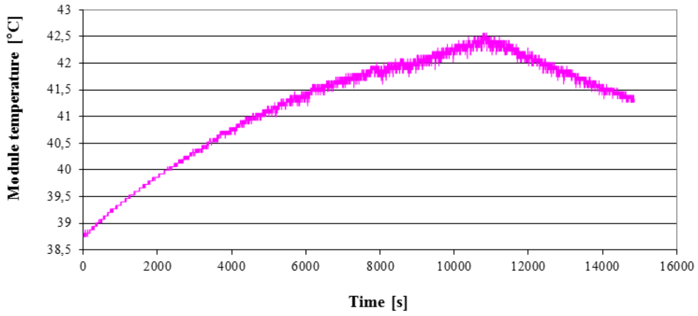

Fig. 10. Temperature variation during module testing with a test interruption after three hours.

The final module capacitance decreased of about 4% at the end of the high temperature cycling.

Finally, thermal analysis with infrared camera was also performed on the SC module at RT with limited increase of temperature, which reached a maximum of 29.1 °C. Fig. 11 gives an example of one of the thermograms recorded during life testing.

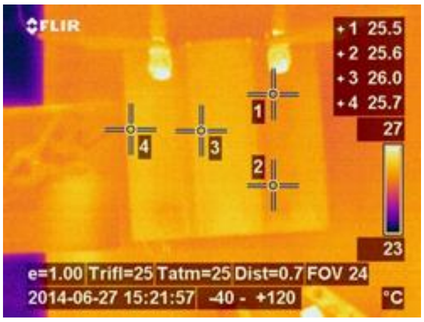

Fig. 11. Thermogram with an infrared camera of theSC module during life testing.

The reached temperature value even during testing at 40 °C has always been well below the maximum recommended value of 65 °C, giving clear indications about the limited need of thermal management in real operations.

VI. Abuse Testing on SC Modules

ENEA abuse testing was concentrated on the definition and execution of mechanical (vibration) testing on Gen 2 SC modules, together with a Gen 3 SC module, used for comparison. These tests, which have been carried out with an electro-dynamic shaker in the ENEA Vibration Hall, illustrated in Fig. 12.

Fig. 11. The SC module on the electrodynamic shaker.

The complete test was performed as follows:

- the state-of-charge of the module was put at 80% (HEV application);
- the power spectrum density (PSD) vs. frequency was set as shown in Table 2;
- test duration was of 8 hours for each of the three planes of the module under test.

TABLE II. VALUES OF PSD AT VARIOUS FREQUENCIES FOR VIBRATION TEST

Frequency, Hz	PSD, $(m/s^2)^2/Hz$
10	20
55	6.5
180	0.25
300	0.25
360	0.14
1000	0.14
2000	0.14

Two configurations of SC modules were tested, differing only for the case material: one in ABS (Acrylonitrile-butadiene-styrene) and the other one, only for comparison, in polypropylene (PP). The ABS module showed a response up to hazard level 1 [3]. This means that there was no venting, fire, or explosion, but there were physical damages to the module case with undefined small leakages. The visual control after each vibration tests allowed for the verification of the small physical damages of the case. However, electrical tests after vibration tests, supported by thermal analysis, confirmed that internally there was no damage able to modify or reduce the electrical performances and the thermal behavior of the module, as reported in Table 3.

TABLE III. FINAL CHARACTERIZATION CYCLING OF THE SC MODULE AFTER VIBRATION TESTS

Cycle number	Step description	Starting voltage [V]	Final voltage [V]	Current [A]	Capacity [Ah]	Capacitance [F]
1	Discharge	14.2	3.4	3	1.5	500
	Charge CC/CV	4.1	16.3	25	1.8	531
2	Discharge	16.2	3.5	3	1.8	510
	Charge CC/CV	3.7	16.3	25	1.8	514
3	Discharge	14.3	3.5	3	1.5	500
	Charge CC/CV	4	16.3	25	1.8	526
4	Discharge	14.4	3.5	3	1.5	495
	Charge CC/CV	3.8	16.3	25	1.8	518
5	Discharge	16.2	3.5	3	1.7	482
	Charge CC/CV	3.8	16.3	25	1.8	518

However, no significant reduction of capacitance was registered due to the execution of the vibration test, demonstrating that no specific effects on the electrical performances occurred in Gen 2 SC module after vibration test.

VII. CONCLUSIONS

The experimental characterization of SC cells and modules was able to achieve the complete determination of the technical performances and their suitability to the specific application to the HEV van developed in the HCV project. The experimental results substantially have confirmed the general good behavior of the selected cells and the assembled modules:

- The characterizations have verified the nominal characteristics of the samples with a negligible spread of values: a confirmation of the maturity of the production level.
- The cycle life with standard cycles, accelerated cycles and the HCV-tailored cycle resulted excellent with negligible deterioration of performances for SC cells and modules.
- The thermal behavior of SC cells and modules was usually inside the recommended limits with only some precaution during cycling of modules, for which thermal management was carefully evaluated and recommended.

- All the attempts (with different cycles and higher temperatures) to accelerate performance decline of SC cells and module performances were ineffective in giving clear indications on how to model their behavior and allow for an estimation of SOH (State Of Health).

In conclusions, the complete experimental analysis at ENEA showed that the SC cells and modules presented a limited degradation of the capacitance as a combined effect of the life cycling and of the use of higher working temperature, while minor mechanical damages of the module case during vibration tests had no impact on the electrical performances of the tested module.

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