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Design and testing of a supercapacitor storage system for the flash recharge of electric buses

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Abstract: This paper proposes a hybrid storage for urban transport systems in order to reduce recharge time and increase its life and reliability. Proposed system is applied to a pre-existing electric vehicle, introducing through proposed revamping procedure a methodology for a fast integration of proposed systems on different vehicles. Finally, the system is calibrated and tested showing how the proposed control layout really simplifies the vehicle commissioning.

Keywords: hybrid storage systems; electrification; fast recharge; super capacitors; mechatronics; traction systems; electric powertrain.

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1 Introduction

Reliability and durability of electric storage systems are important factors for development of electric transport systems. Prices of lithium storage systems are smoothly decreasing (Naumann et al., 2015) however relative impact of storage system on the cost of electrical vehicle remains quite high, due to a corresponding increase of their size in terms of stored energy and required power specifications (Hannan et al., 2017). The need for fast recharge times and high reliability plays a key role in this sense: in order to reduce recharge times the storage is subjected to high recharge currents, which should produce an accelerated ageing of cells if they are not properly sized as stated by consolidated ageing models proposed in literature (Fernández et al., 2013; Ecker et al., 2012). Consequences in terms of systems are generally the following ones:

- high power cells with lower energy density are preferred to high energy/autonomy ones
- battery storage is a bit bigger with respect to its optimal size in terms of autonomy in order to compensate the adoption of fast partial recharge that is performed to reduce battery ageing

- a minimum performance of aged storage system has to be assured so the battery is designed to be a bit oversized in order to compensate a capacity fading of about 20%.

Supercapacitors offer superior performances in terms of specific power and are relatively immune to cycle ageing that affects electrochemical batteries (Musolino et al., 2010); however with current available technologies their specific energy ratio and their self-discharge losses are quite inferior with respect not only to lithium energy but also to lead ones.

It should be concluded that supercapacitors and batteries have currently complementary properties that should be exploited by the so-called hybrid storage systems such as the one proposed by Yu et al. (2016) or by Veneri et al. (2018) in which supercapacitors are adopted to provide high currents during transients while lithium (Yu et al., 2016) or zebra (Vener et al., 2018) batteries assure the autonomy of the vehicle thanks to their high specific energy ratio.

Respect to overcited literature authors focused their attention public transport systems in high populated urban areas.

Typical mission profiles (Barbieri et al., 2016) of urban transport systems are associated to relatively small distances (few hundred metres) between bus stops; so it should be interesting to exploit the limited time available at each bus stop, no more than 100–150 s to perform a rapid flash recharge of the bus to arrive at least at the next bus stop. Considering high currents involved and the number of resulting charge and discharge cycles, supercapacitors are the ideal solution for this kind of mission profile. However considering the limited amount of energy that can be stored in supercapacitors they have to be helped by a backup battery that assures the necessary resiliency of the system respect to variable mission profiles in which distance or time between bus stops should be variable or perturbed by external traffic conditions. Life and reliability of batteries should be acceptable even adopting a modest highly optimised size since required power profile corresponds to relatively modest currents of small duration.

In this sense proposed application is quite original and innovative with respect to current literature since high power response of the supercapacitor is exploited only during high voltage recharge phase, while during a normal mission profile the battery is designed to substantially supply the main supercapacitor storage with respect to energy limits of supercapacitors and power limits of adopted DC-DC converters.

Hybridisation of supercapacitor storage with a battery is also exploited to drastically simplify the way in which the system is controlled producing a simple and robust control loop that can be implemented and calibrated with limited computational resources.

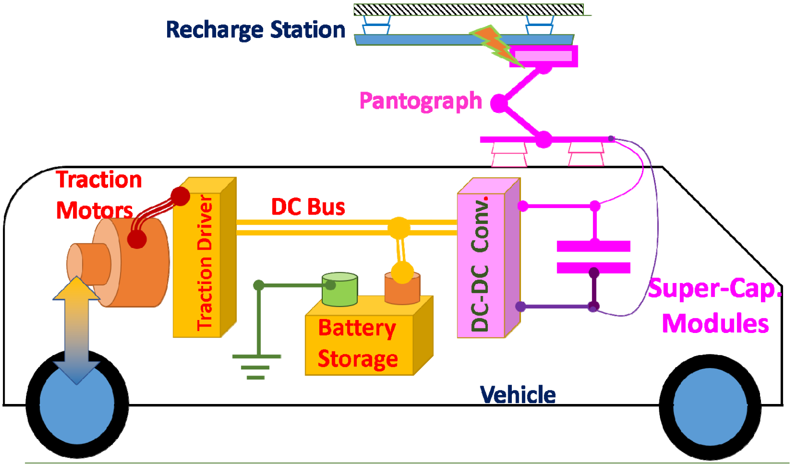
This is not the only original contribution of the research because a passive system for the recharge station based on supercapacitors is also proposed.

Finally, in order demonstrate feasibility of proposed solution we produce a low-cost prototype by revamping a pre-existing electric bus. This was also the occasion to demonstrate that proposed system, thanks to its robustness and simplicity, can be easily customised and calibrated for different vehicles.

2 General design and conception of the proposed system

As visible in the scheme of Figure 1, the system is composed by a set of supercapacitors that are directly connected to the recharge station which is supposed to be installed at the bus stop. Since a high amount of power has to be transferred in few seconds, supercapacitor modules are assembled in order to be charged at a voltage which is much higher with respect to the one of the DC bus in order to reduce the amount of current that is collected from pantograph head and more generally conducting sections.

Figure 1 Simplified scheme of proposed hybrid storage system (see online version for colours)



Also a higher operating voltage simplifies the layout of the chopper used to interface supercapacitors which is fundamentally a two quadrant power converter which should be further simplified to a single quadrant one considering that the the proposed converter has to work mainly as simple buck, step down chopper.

DC bus of the traction system is also stabilised by a battery which is fundamentally a downsized version of the storage system that should be installed on a standard electric vehicle in which the flash recharge system is not installed.

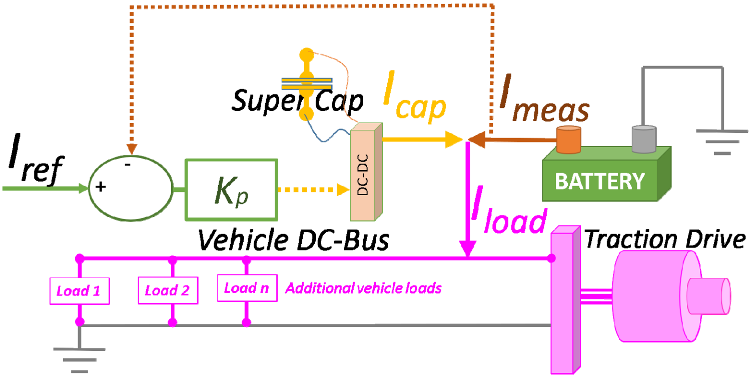
Since specific energy of the battery is much higher than the one the battery assures a reserve of power which should be used if the limited amount of energy available on supercapacitors is depleted, assuring a significant resiliency and residual autonomy of the vehicle. Also, battery is useful to optimise the sizing of DC-DC converters that are interfacing super-capacitor to DC bus since peak currents that cannot be managed by the chopper are also sustained by the battery.

Considering that most of the energy during a normal mission is provided by supercapacitors, during a standard mission the battery is subjected to very limited currents and discharge rates, so a relatively long life of the energy storage system is feasible.

For the system control loop, a very simple, self-compensating strategy is chosen.

As visible in Figure 2, a fixed desired battery current I_{ref} is chosen; the current which is effectively supplied by the battery I_{meas} is measured using a redundant sensor system (only for a purpose of safety and system reliability).

Figure 2 Proposed control loop (see online version for colours)



A closed loop current controller is used to assure that the battery current I_{meas} is close as possible to desired value I_{meas} by imposing to DC-DC choppers a compensating current I_{cap} which is drawn from supercapacitors.

In this way, the current required by connected loads I_{load} is automatically compensated as a rejected disturbance without the need of any complex prediction or measurement of applied loads.

As example by considering a simple proportional controller with gain K_p balance has to be verified and the steady state ratio between load current and the corresponding contributions of battery and supercapacitors can be easily evaluated.

Gain K_p and value of I_{ref} can be scheduled with respect to other system states such as example battery state of charge, capacitor state of energy, error between reference current I_{ref} and measured one I_{meas}.

This servo-control scheme is very robust with respect to bandwidth limits which are compensated by the battery; implementation and tuning are quite easy(for a proportional controller only one gain scheduling should be inserted as an additional feature); the proposed solution can be easily adapted to different vehicle and traction systems since the proposed power management algorithm works only on internal measurements requiring a very limited interfacing with the traction system of the vehicle since only DC bus is shared.

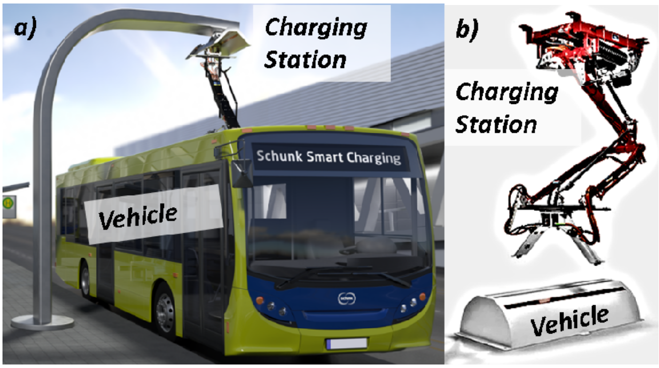
2.1 Pantograph on vehicle vs. pantograph on recharge station

Electrical contact between recharge stations and vehicles must be performed using a pantograph system that is specifically designed to assure a correct electro-mechanical contact compensating unavoidable tolerances in relative positioning between vehicle and recharge station.

In literature two possible solutions are proposed as visible in the schemes of Figure 3(a) and (b):

- *Vehicle pantograph* (*Becker and Dämmig, 2016*): An extendible pantograph is installed on the vehicle, while a fixed contact strip is placed on the recharge station: pantograph is the more expensive components and also the most sensitive in terms of maintenance and failure occurrence. Also weight added to vehicle is much higher respect to a fixed contact strip. On the other hand, maintenance can be easily performed on a single vehicle which can be retired from service but it's relatively more complex to be performed on a public infrastructure as the recharge station without interrupting its service.
- Pantograph on recharge station (https://www.schunk-carbontechnology.com/en/smart-charging, https://www.dazetechnology.com/dazeplug/): for what concern vehicle on board systems this solution is much simpler. However as previously said, an increased complication in the management of unmanned recharge stations should be carefully evaluated.

Figure 3 Pantograph on vehicle (a) and pantograph on charging station (b) (see online version for colours)



Source: https://www.schunk-carbontechnology.com/en/smart-charging

Proposed hybrid storage can be applied in both cases, however in this work authors have mainly focused their attention on the first solution, pantograph on vehicle.

2.2 Passive recharge stations with supercapacitors

Currents involved during a flash recharge should be very high, since as stated by equation (1) a faster recharge (duration of the charge is T_{charge}) respect to duration of performed mission $T_{mission}$ involves a higher mean recharge current I_{charge}:

$$\eta_{mean} T_{charge} V_{charge} I_{charge} = W_{mean} T_{mission} \Rightarrow$$
$$\Rightarrow I_{charge} = \frac{W_{mean}}{\eta_{mean} V_{charge}} \frac{T_{mission}}{T_{charge}} \tag{1}$$

Equation (1) also justifies the adoption of high recharge voltages V_{charge} respect values that really needed to feed the DC bus of the traction system. Mean efficiency η_{mean} is a constant coefficient that should be introduced to take count of the losses introduced by the energy management chain between recharge station and mean electrical power W_{mean} used by vehicle loads.

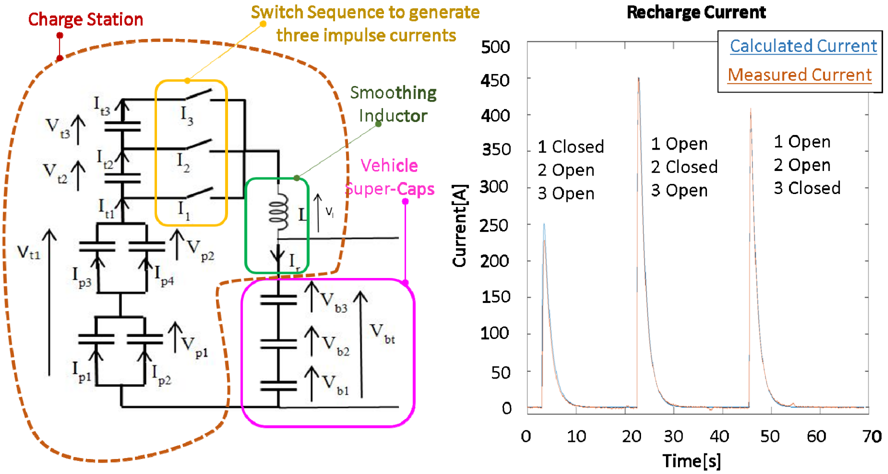
According to equation (1), considering maximum current and voltage limits of pantographs, also the distance between two contiguous recharge stations is also constrained by the limited available time for recharge operations.

Also, the electrical interfacing of recharge stations to grid should involve undesirable peaks of power and also involve the management of heavy impulsive currents.

For this reason, in this project it was proposed a passive system originally proposed by ENEA that is described in a dedicated research work which have been recently published (Ortenzi et al., 2019).

The recharge station is composed by an array of series connected supercapacitor modules that can be smoothly charged reducing peak loads on the grid. As the bus approaches the recharge stations these charged supercapacitor modules are gradually connected in series with vehicle ones producing a series of impulsive recharge currents that are smoothed with passive elements such as inductances as visible in the simplified scheme of Figure 4: considering the size of vehicle supercapacitors which should be better described in Section 3 of this work, foreseen duration of recharge system is less than 60–70 s and collected currents are quite tolerable for pantograph system.

Figure 4 Proposed passive recharge station (see online version for colours)



Source: Ortenzi et al. (2019)

3 Design for a demonstrator vehicle

In order to verify the feasibility of proposed solutions authors decide to test it on a demonstrator vehicle: a pre-existing electric bus TECNOBUS Gulliver ESP 520, visible in Figure 5, was chosen to be revamped and adapted for installation and testing of the proposed system. This vehicle was chosen as benchmark platform for the following reasons:

- cheap and affordable platform, not only vehicle but also components for maintenance are readily available on the market
- mature but well known product; wide databases of recorded mission profiles performed in different Italian cities are available and some of these tests, performed on the route visible in Figure 6, have been performed by some of the authors (Barbieri, et al., 2016).

Vehicle was originally designed for battery swapping of a large lead-acid accumulator; so there was the availability of a large volume, a redundant load capacity, and a modular battery frame that was designed to be easily accessed and moved.

Figure 5 Proposed benchmark vehicle, TECNOBUS Gulliver ESP 520

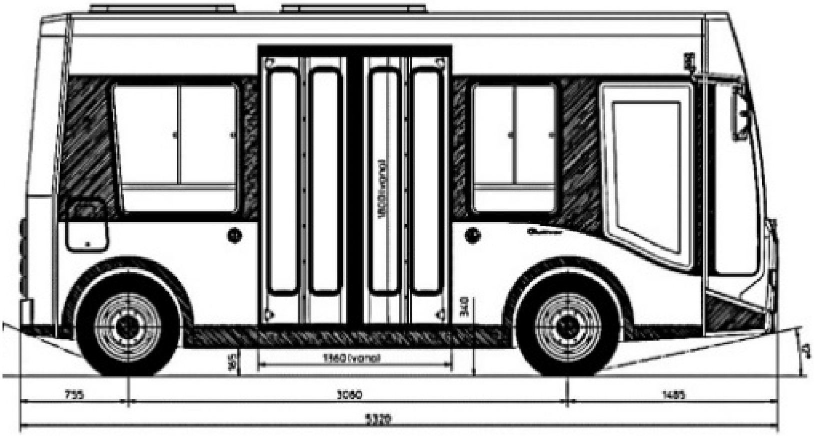


Figure 6 Example of recorded mission profile in Florence (see online version for colours)

Source: Barbieri et al. (2016)

Volume once occupied by the original battery frame was substituted as visible in Figure 7 with a modular power unit in which proposed hybrid storage system was installed.

As a part of performed vehicle integration activities, authors also installed on the roof a Schunk pantograph specifically developed for fast static recharge of vehicles at bus stops (https://www.schunk-carbontechnology.com/en/smart-charging). Composite structure of vehicle roof was not originally designed to support the additional mass of the pantograph, so authors designed an internal birdcage structure made with steel pipes which was disguised as an internal handrail for passengers as visible both in Figures 7 and 8.

Figure 7 Performed mechanical integration of the proposed hybrid energy storage system (see online version for colours)

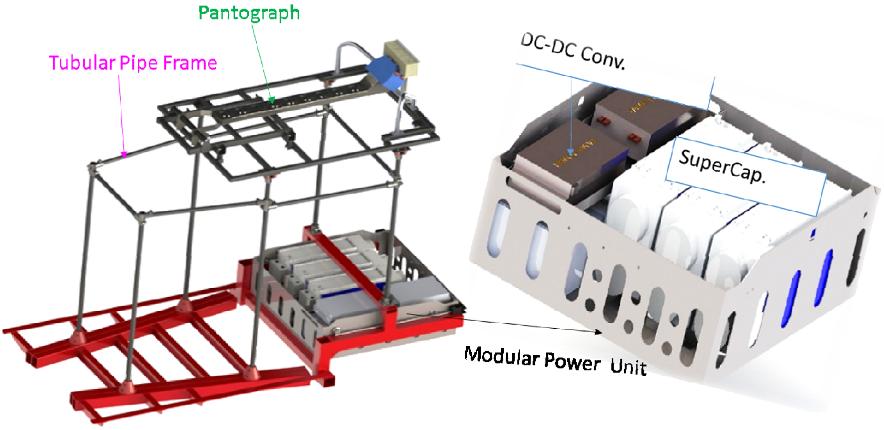
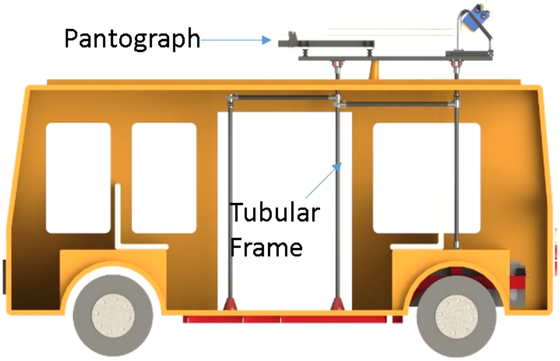


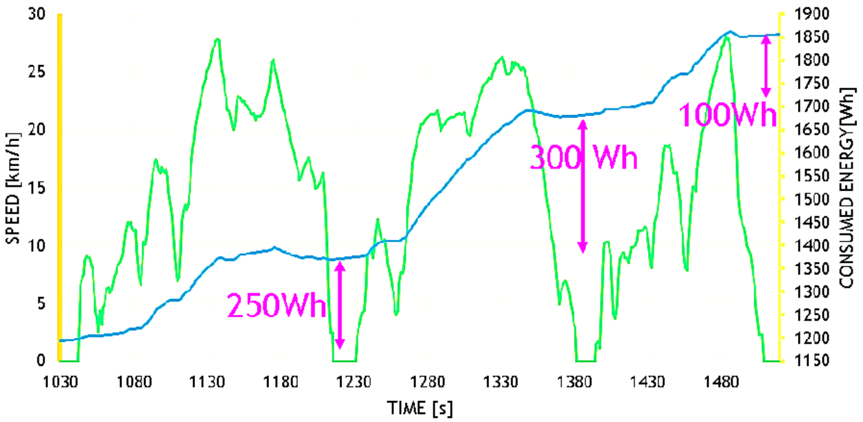
Figure 8 Vehicle-pantograph structural integration (see online version for colours)



3.1 *Sizing of hybrid storage system*

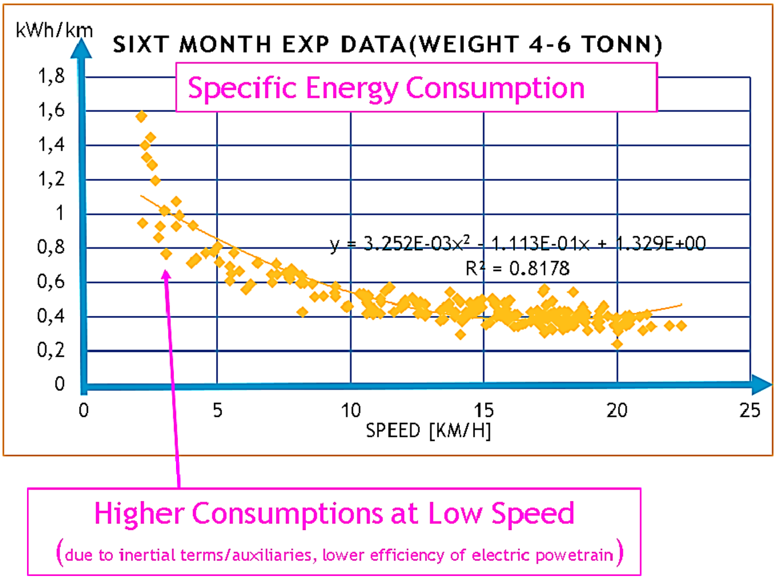
From experimental data regarding real mission profiles performed by the revamped electrical bus it was possible to understand that energy required to perform the distance between two consecutive bus-stops was variable but confined in a range of values of 200–300 Wh as visible in the examples of Figure 9. For tests in which only vehicle speed profiles were available, corresponding power profiles have been measured by testing the vehicle at ENEA of roller rig in the laboratories of Roma Casaccia in Italy: for this reason in the test sequence of Figure 9 duration of bus stops is reduced to 10 s, to accelerate the execution of long mission patterns on the rig.

Figure 9 Speed and energy consumptions (see online version for colours)



This evaluation was also confirmed by a statistical analysis of the energy needed by the bus to cover one kilometre at various speed as visible in Figure 10. This analysis was also performed in order to verify that to perform a mission of about 500 m. Probably a stored energy between 200 Wh and 300 Wh should be enough since specific consumptions of more than 600 Wh/km are recorded only for very small vehicle speeds: in this condition consumption of auxiliary systems and inefficient traction transients (braking without regeneration or high accelerations) substantially justifies this behaviour.

Figure 10 Mean specific energy consumptions of vehicle (see online version for colours)



These data were enough to perform the sizing of supercapacitor modules: authors have chosen three Maxwell modules BMOD0063 P125: since each module has a nominal capacity of 63 F and a nominal voltage of about 125 V, with three modules a total energy of more than 400 Wh can be stored. Chosen capacitor modules were connected in series resulting in a 400 V system. Series connection was chosen to reduce as much as possible the value of recharge currents as stated by equation (1). In this sense the most important limitation is represented by conducting sections of both pantograph and recharge station which should be easier and cheaper to be designed with higher voltages.

The amount of stored energy by the traction system is greatly affected by some features of the DC-DC converter that is adopted to interface supercapacitors with vehicle DC bus.

Concerning the sizing of this chopper, authors considered a modular system that can be easily sized by putting in parallel a certain number of modules (https://www.tame-power.com/en/dc-dc-converters/dcdc-non-isolated-converters) with a fixed power of about 5–8 kW. In particular, energy E_{bus} that should be transferred from supercapacitor modules to DC bus is described by equation (2):

$$E_{bus} = \frac{1}{2}\left(\max V_{cap}^2 - \min V_{cap}^2\right)\eta_{conv} \tag{2}$$

In particular, looking to equation (2), it's clearly noticeable that transferred energy E_{bus} is not limited only by converter efficiency η_{conv}, assumed for simplicity constant, but also by the value minimum value of capacitor voltage V_{cap} that can be managed by the DC-DC converter. For chosen TAME DC-DC modules these features are briefly described in Table 1.

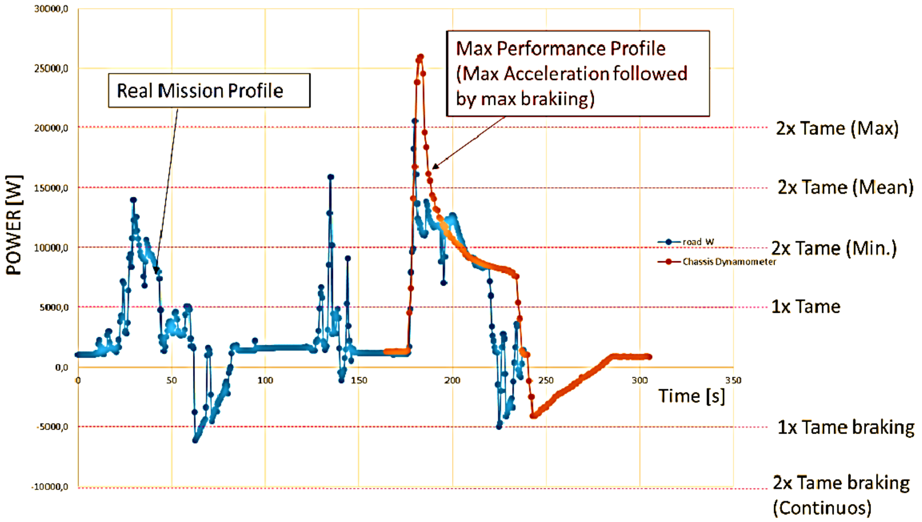
Table 1 Specifications of DC-DC converter modules (https://www.tame-power.com/en/dc-dc-converters/dcdc-non-isolated-converters) (multiple modules are adopted)

Component parameter	*Value*
DC-DC Converter	COMET Series by TAME™
Weight (one module)	About 11[kg]
Power (min/mean/max)	5/6.5/8[kW] dep. on voltage level
Efficiency	About 92% (mean nom. power)
Input voltage ratio (Max V_{cap}/Min V_{cap})	About 2 (min V_{cap} = 200 V)
Control Mode	Current Controlled (buck/boost)

Starting from a maximum stored energy of about 400 Wh adopted DC-DC modules assure the extraction on the DC bus of an energy E_{bus} of about 270–280 Wh.

In order to choose the number of DC-DC modules and consequently size the whole power converter authors considered some examples of power profiles visible in Figure 11 that have been measured with ENEA roller rig tests: the first one is an example of typical mission profile from recorded speed profiles, the second one is a test in which maximum vehicle performances both in terms of traction and regenerative braking power are fully exploited.

Figure 11 Sizing of DC-DC modules respect to simulated mission profiles (see online version for colours)



Since supercapacitors are assisted also by batteries there is no-need to size the system for peak power; authors preferred to use a solution of two DC-DC modules in order to assure a power capability between 10 kW and 20 kW. This variability of power converter performances is due to variability of input voltage provided by super-capacitors, when they are fully loaded (V_{cap} = 400 V) power performance is the maximum one, when they are almost discharged (V_{cap} = 200 V) minimum performances are assured.

This is a normal, feasible behaviour since performance is limited by maximum allowable currents.

This smaller size of the power converter is preferred in order to reduce costs and encumbrances but also to improve system efficiency since higher losses should be foreseen for a converter which is too much oversized when working with partial loads.

Concerning the installed battery the original vehicle was equipped with a 595Ah/72V lead acid battery with a total weight of 1500 kg. Thanks to the continuous support of the flash recharge system, the size of the battery was reduced to a 120Ah/72V lead acid battery. This choice was justified by the need in the first prototype of reducing cost minimising unnecessary modifications of the system: in particular the new battery assures a weight reduction of about 1200 kg that allows the installation of the new system on the bus including pantograph and corresponding structural reinforcements without increasing vehicle weight or reducing its load capability.

At the end of the design process main parameters regarding vehicle, supercapacitors, power converters and recharge stations have been summarised in Tables 2–5. In particular capacitors of recharge station described in Figure 4 and in Table 5 have been designed considering the size of vehicle supercapacitors, and the need of limiting the peak values of charging currents.

Table 2 Vehicle parameters

Vehicle parameters	
Weight (Tare/Maximum)	4270/6045[kg]
Batteries (kind/capacity/weight)	Lead Acid/595[Ah] @72[V]/1500[kg] downsized to 120 [Ah] 270 kg
Inst. traction system (nom. peak power)	21[kW]/25[kW]
Lights and on board instr. (power)	200 [W]
Air conditioning system	2[kW]

Table 3 Vehicle super capacitors

Installed super capacitors on vehicle	
Model	Three Maxwell BMOD0063 P125 series connected
Weight (one module)	About 60[kg]
Capacity (one module) and resistance	63[F] (63–76[F]) –18[mΩ]
Test current for capacitance and ESRDC	100[A]
Rated//maximum voltage (one module)	125[V]//136[V]
Max series voltage	1500[V]
Maximum current (Peak Value)	1900 [A]

Table 4 Vehicle DC-DC power converters

Bi-directional DC-DC converters to interface SuperCapacitors	
DC-DC Converter	COMET Series by TAME™
Weight (one module)	About 22[kg] (11kg)
Power (min/mean/max)	5/6.5/8[kW] dep. on voltage level
Efficiency	About 92% (mean nom. power)
Control Mode	Current Controlled (buck/boost)

Table 5 Supercapacitor and smoothing inductance (as sized for current prototype)

Recharge station	
Capacitors	Six modules Maxwell BMOD0063 P125 (same data as vehicle one)
Smothing Inductor	4[H]

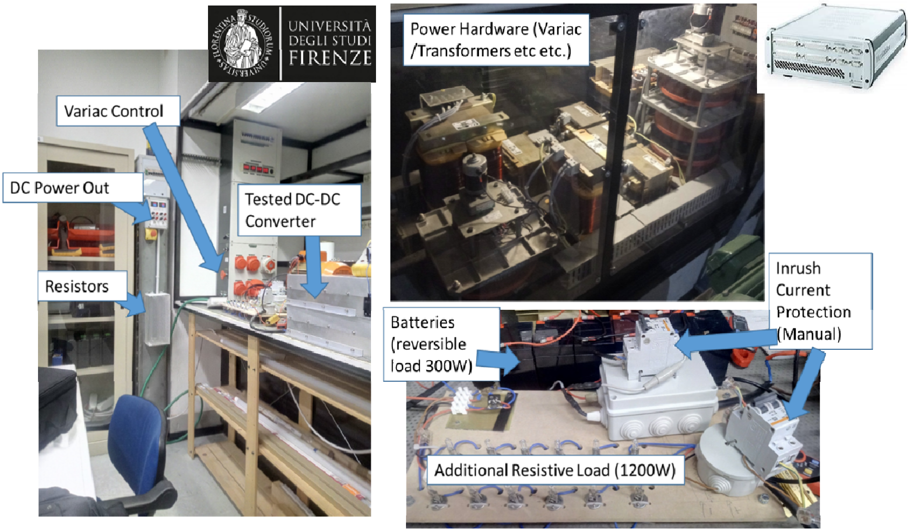
4 Preliminary testing activities on assembled demonstrator

4.1 *Fast prototyping of system control logic*

As visible in Figure 12, proposed storage system was preliminary tested in UNIFI laboratories applying a limited load (about one kW) to each power converter in order preliminary verify the control of DC-DC converters. For these preliminary tests, vehicle control logic was prototyped in Matlab-Simulink™ initially using a DSPACE

Microlabbox™ board that was also useful to perform preliminary HIL (Hardware In the Loop) and SIL (Software In the Loop) tests.

Figure 12 Preliminary testing activities at Florence University (see online version for colours)



After this preliminary testing activities, the system was assembled according the simplified scheme of Figure 13: vehicle control logic prototyped in Matlab-Simulink™ was deployed on two Arduino microcontrollers (A); during the flash charge phase microcontrollers are used to activate safety contactors (B), relays (C) and manipulator (D) that controls pantograph run. While vehicle is running, same microcontrollers are used to implement the current loop described in Figure 2: DC-DC converters (E) provide power from supercapacitors to traction systems by measuring battery current with a redundant system of Hall sensors (H). Assembled plant is completed by safety devices such as protection fuses (F) and emergency buttons (I). Additional isolated power supplies (G, J) assure the limited low voltage power needed to supply microcontrollers and auxiliary system.

4.2 Testing activities in ENEA Casaccia Research Center

A brief photographic description of the assembled prototype is visible in Figures 14–16. Vehicle prototype was preliminary tested in an internal circuit that was arranged inside the Research Center of ENEA Casaccia in Rome. Vehicle was also instrumented with GPS-GNSS sensors so as visible in Figure 17, it was possible to track vehicle trajectory: vehicle starts its route from the recharge station prototype, performing a mixed route of about 1150 m which is far higher than the expected vehicle autonomy with supercapacitors; in this way it's possible to verify not only maximum vehicle autonomy, but also to investigate and compare system behaviour system behaviour in nominal conditions (capacitors fully charged) with performances in degraded conditions when capacitors are fully discharged and backup batteries have to fully supply the vehicle in order to assure mission survival.

Figure 13 Simplified scheme of the implemented plant (see online version for colours)

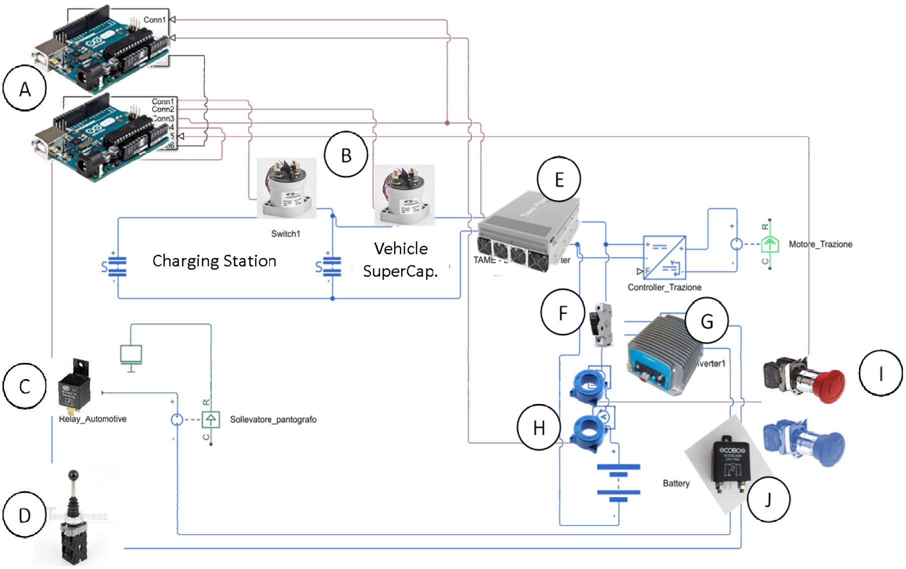
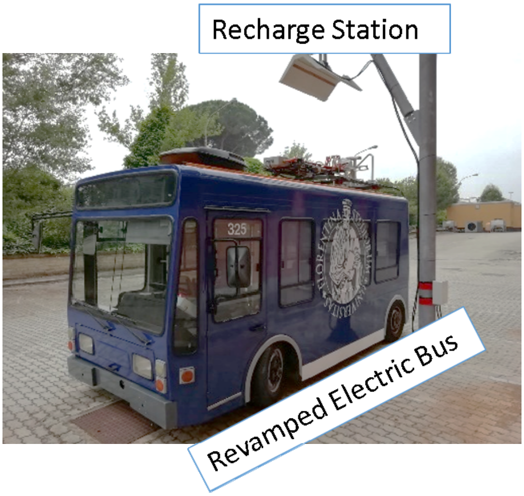


Figure 14 Assembled prototype under the recharge station at ENEA Casaccia Research Center (Italy) (see online version for colours)



In Figure 18, it’s shown a typical speed profile recorded during a mission: vehicle is deliberately accelerated and braked in order to simulate an urban traffic condition stressing the tested system with complex state transition sequences.

Figure 15 Modular power pack during assembly and installation on the bus (see online version for colours)

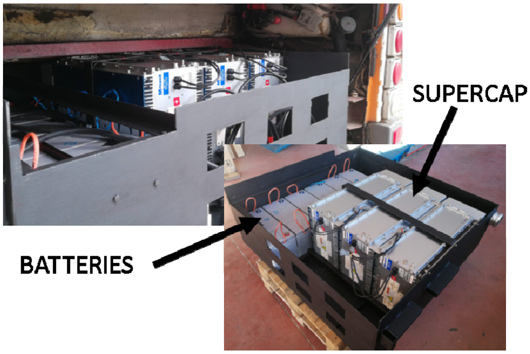


Figure 16 Installed Schunk pantograph on the vehicle (see online version for colours)

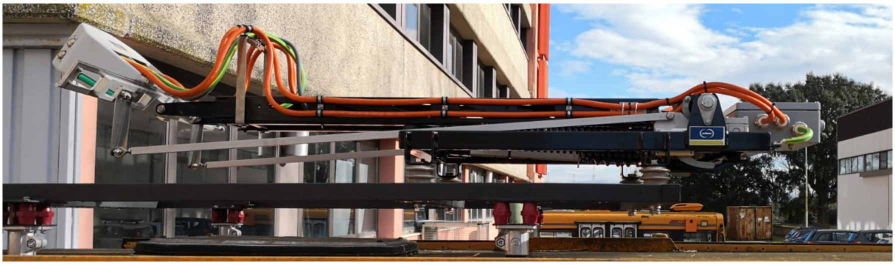
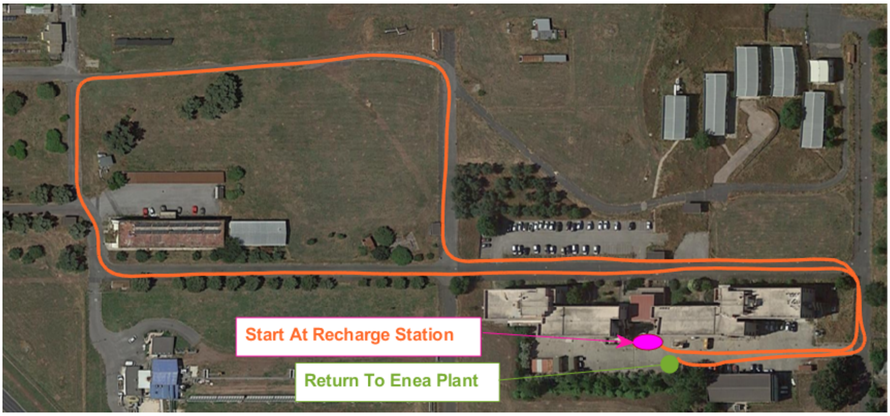


Figure 17 Typical mission profile arranged inside ENEA CASACCIA research centre (see online version for colours)



As visible in Figure 19 multiple tests with variable sequences of traction and braking manoeuvres are repeated in order to produce a statistically significant population of different events that are quite useful to test the overall stability of implemented functionalities.

Figure 18 Example of vehicle speed profile during a mission (see online version for colours)

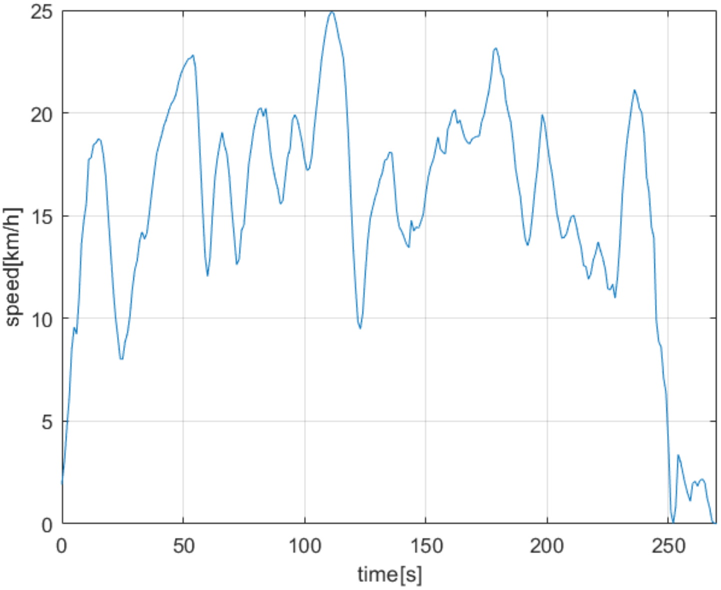
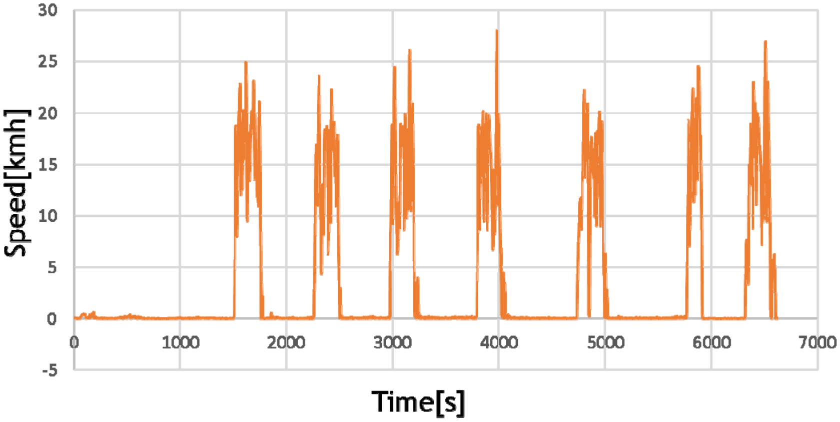


Figure 19 Repeated mission profiles (see online version for colours)

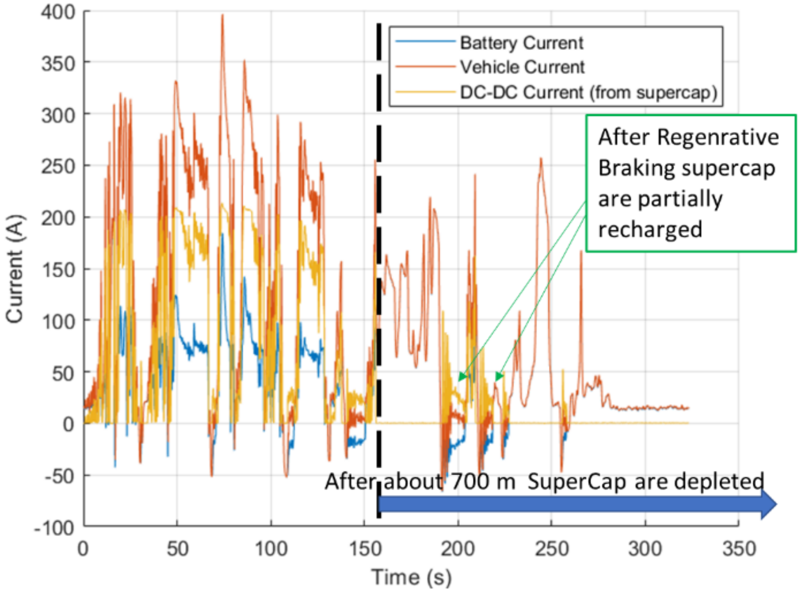


Concerning the power exchanged between vehicle, batteries and supercapacitors during a cycle, some results in terms of exchanged current on vehicle DC bus are shown in Figure 20: it's clearly noticeable that even for the cautious drive style imposed to vehicle during the mission, supercapacitors are able to assist batteries for at least 700 m, which is quite enough respect to previously described specifications.

When supercapacitors are working, they can supply about 60–70% (corresponding to an equivalent loop gain K_p of about 2.5) of the power vehicle demand contributing to drastically reduced loads to which the batteries are subjected.

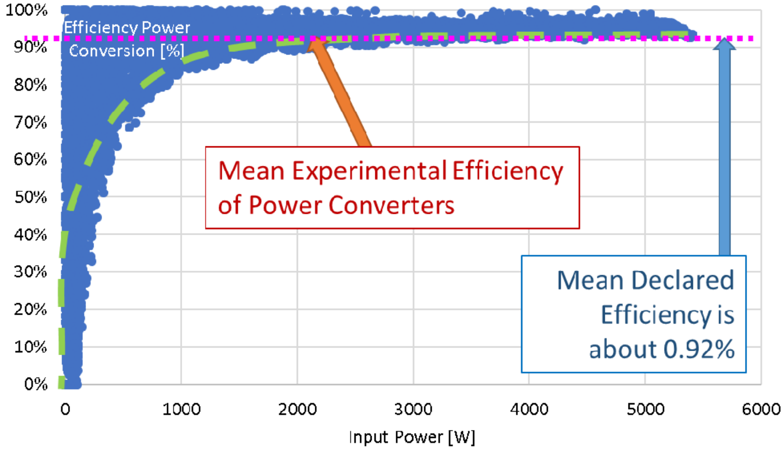
Looking to results of Figure 20 it's also clear how the good dynamic response of the chosen DC-DC converter contributes to avoid dangerous peak current and more generally assures a quite stable behaviour.

Figure 20 Example of recorded experimental mission profile (see online version for colours)



If the mission is longer or more energetically demanding than the expected mean autonomy of 700 m, stored energy in supercapacitors is depleted: supercapacitors can be partially recharged through regenerative braking, also contributing to peak shaving of the battery. However, at the end of the mission capacitors are statistically empty so their capacity can be completely exploited to store energy for the trip to the next bus stop. Concerning the measured efficiency in terms of power transfer between supercapacitors and batteries performed by adopted DC-DC converters, authors executed some measurements of efficiency which are shown in Figure 21: it's interesting to notice that globally recorded efficiency is quite similar to the value declared by the manufacturer even considering noise on measurement and multi-quadrant operation since the converter mainly works as a step down one to feed motor and less frequently as step up to recharge supercap during regenerative braking. Very low level of efficiency is recorded only when transferred power is relatively small respect to the nominal one. In this case efficiency is not only lower but also very variable, probably for the higher influence of measurement noise and of external parameters related to operating conditions (converter mode, supercap voltage etc.). Finally for a georeferenced mission profile, it's possible to know the distance between two consecutive recharge points so it's possible to schedule the gain K_p of the current loop in order to better exploit energy stored in capacitors respect to travelled distance. In particular for distances longer than 600-700m it should be convenient to reduce the gain while for shorter distances a higher value of gain K_p should be useful to further exploit energy stored in super-capacitors.

Figure 21 Measured efficiency of DC-DC converters respect to expected value (see online version for colours)



5 Improved autonomy, reliability and efficiency of batteries

It's interesting to evaluate the contribution of the system in order to improve battery life and reliability thanks to performed power shaving. This is a quite important feature especially when installed battery is relatively aged resulting in a higher storage impedance. In current prototype, lead batteries are still installed more for a matter of cost of the experimental activity, but in a short term scenario they should be substituted with lithium batteries, in particular in order to have a relatively inexpensive and reliable system, a good candidate in this sense is Li[NiCoMn]O_2 batteries, briefly called NMC batteries. Also, for these batteries are available in literature (Ceraolo et al., 2018) reliable ageing models also complete calibration data respect to existing and widely used cells. For this reason authors focused their attention considering the possible benefit of applying the proposed system to the same revamped bus in which the existing battery storage is revamped with lithium cells. In particular, the following scenarios are considered:

A Installed lithium battery pack has the same volume as the existing lead acid ones: for considered cells, the new battery pack has about three times more stored energy, 360 Ah vs. the original 120 Ah.

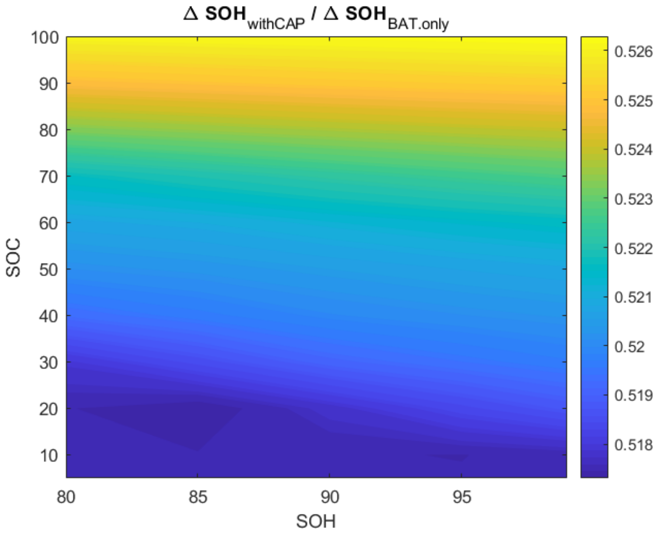
B Installed lithium battery pack has the same weight as the existing one: the new battery pack has about 4.87 times more stored energy, 585 Ah vs. the original 120 Ah. This value is also more feasible with respect to the original pack of lead acid that was originally placed on the vehicle (595 Ah). Additional volume needed is compatible with current bus layout also considering that thanks to the structural modifications described in Figure 3, the roof of the bus that currently contains only the pantograph can sustain the installation of a large part of on-board subsystems.

Considering these possible scenarios, the same experimental load cycle that is visible in Figure 20 is applied on a Simulink simulation model that reproduces the corresponding behaviour of the two battery packs (360/585 Ah) subjected to the same loading cycle. In particular it's considered the application of the cycle at different values of state of charge and of state of health: behaviour of proposed hybrid storage respect to a scenario in which the battery is installed without any help from super-capacitor.

In particular the more interesting scenario is probably the second one (B) since it corresponds to a battery which has almost the same size as the one originally designed for the vehicle.

Looking at results of Figures 22–24 proposed system can approximately double both life and autonomy of installed batteries. Concerning the storage efficiency, application of supercapacitors increases the conversion efficiency of the battery by about 5%. Energy losses due to conversions on supercapacitors are equivalent to about the 8% but only a half of the total power delivered during the cycle is provided by supercapacitors. Consequently, it should be concluded that the total efficiency of proposed system is higher (1–2%) or at least equal to a system with only batteries since the improved efficiency of the battery compensates losses on supercapacitors and converters especially for low values of battery SOC and SOH.

Figure 22 Ratio between battery health losses (B size of 585Ah) for a single loading cycle calculated with proposed hybrid storage and with proposed hybrid storage and with only batteries (see online version for colours)



For scenario A the shape of the response in terms of life, reliability and efficiency is quite similar to the ones of Figures 22–24, however the level of the improvement is much higher as expected: in Table 6 mean simulated improvements in terms of expected life, autonomy and efficiency for scenarios A and B are compared; in particular results are referred to a case with a starting SOC of about 50% and a SOH of 90% (about half of the foreseen life): for a smaller battery (Case A) relative improvement is obviously higher.

Figure 23 Ratio between battery state of charge (B size of 585 Ah) for a single loading cycle calculated with proposed hybrid storage and with proposed hybrid storage and with only batteries (see online version for colours)

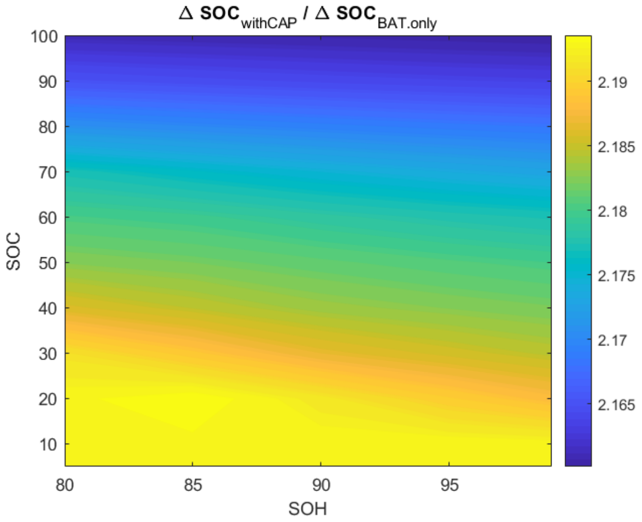


Figure 24 Percentage of efficiency improvement (B size of 585 Ah) for a single loading cycle calculated with proposed hybrid storage and with proposed hybrid storage and with only batteries (see online version for colours)

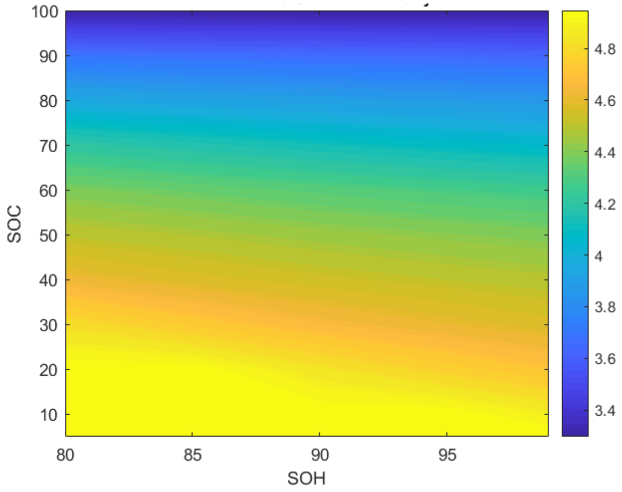


Table 6 Mean estimated improvements in terms of efficiency and reliability

Parameter	*Value for Storage A (360[Ah])*	*Value for Storage B (585[Ah])*
%of Efficiency improvement	9.92%	4.98%
Relative improvement in terms of ΔSOH/cycle	0.4789	0.5174
Relative improvement in terms of ΔSOC/cycle	2.335	2.194

6 Conclusions and future developments

This paper presented the complete development of an innovative flash charge system for urban transport systems. Activities performed on demonstrator vehicle clearly indicate that proposed approach is not only feasible but also easily customisable and optimisable: system can be easily installed also on vehicles which were not originally designed for this purpose. Currently authors are working to the following prosecutions of the proposed works:

- system upgrade to different battery technologies
- integration of the proposed system in a localisation system to perform a mission oriented optimisation of the control logic of the proposed energy management system.

Finally authors are considering the extension of proposed technology to tramways and railway systems exploiting their previous experiences in this field (Pugi et al., 2014, 2018).

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