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Experimental investigation into the effectiveness of a super-capacitor based hybrid energy storage system for urban commercial vehicles

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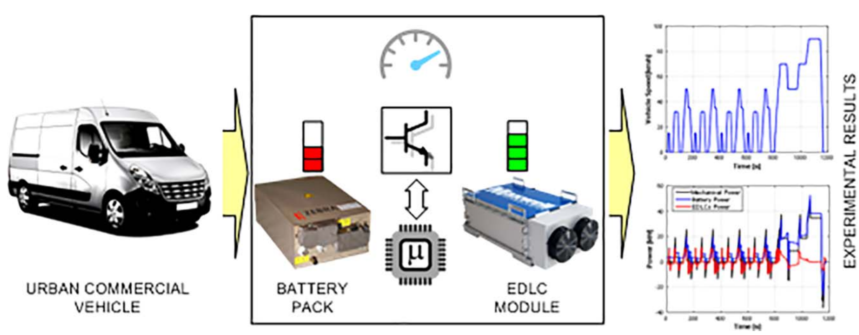
HIGHLIGHTS

- 1:1 scale laboratory test bench for electric power-trains supplied by hybrid energy storage systems.
- ZEBRA and super-capacitors based hybrid energy storage systems.
- Rule based energy management strategies.
- Laboratory experimental data on standard driving cycles.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper is aimed to experimentally analyse the effectiveness of a hybrid storage system, when powering a commercial vehicle for urban use. The hybrid energy storage system is composed by two ZEBRA batteries, combined with an electric double layer capacitor (EDLC) module. The integration of those storage systems is obtained by means of a bidirectional DC/DC converter, which balances the electric power fluxes between batteries and super-capacitors, depending on the driving operative conditions. Modeling and simulations are preliminarily conducted with reference to the specific case study of an electric version of the Renault Master, supplied by the above described hybrid storage system. That theoretical activity allows the optimization of rule based energy management strategies for the hybrid energy storage system, in terms of the effectiveness in reducing the negative effects of high charging/discharging currents on battery durability. Then, the experimentation of the real power train, connected to the mentioned hybrid storage system, is carried out through a 1:1 laboratory test bench, able to perform the analysed energy management strategies on standard driving cycles, representative of the urban mission of the commercial vehicle under study. The obtained experimental results, expressed through electrical and mechanical parameters in a wide range of road operative conditions, show that the super-capacitors can improve the expected battery lifespan, with values of maximum effectiveness up to 52%, for driving patterns without negative road slopes. The procedure followed and presented in this paper definitely demonstrates the good performance of the evaluated hybrid storage system, controlled by the DC/DC power converter, to reduce the negative consequences of the power peaks associated with the urban use of commercial vehicles.

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Nomenclature

I'_{SC}	super-capacitors current on the DC-Link side of the DC/DC power converter output current
I'^{*}_{SC}	reference value of super-capacitors current on the DC-Link side of the DC/DC power converter
V_{DC}	DC-Link Voltage
V^{*}_{DC}	DC-Link Voltage Reference
I_{SC}	super-capacitor current
I^{*}_{SC}	super-capacitor current reference
I_{Batt}	battery current
I_{DC}	DC-Link current
V_{SC}	super-capacitor voltage
V^{*}_{SC}	super-capacitor voltage reference
I_{Th}	battery current saturation threshold
v	vehicle speed

1. Introduction

In recent years, automotive industry has largely focused the research and development investments on cleaner and more efficient road mobility solutions. These new interests were mainly encouraged by an increased awareness about environmental issues and natural oil depletion [1]. In this regard, plug-in hybrid and electric vehicles (PEVs) would represent an effective near-term option. In fact, this kind of vehicles is expected to reduce fossil fuel dependency with positive effects on air quality, public health and global warming [2–3].

In addition, the development of PEVs, in their different uses for both private and corporate activities, has been further supported by recent improvements in the Energy Storage System (ESS) technology. In fact, new lithium based electrochemical batteries present good performance in terms of energy density and safety. This allows new generation of PEVs, powered by lithium battery pack, to satisfy the great part of vehicle owners' needs, especially in terms of ensuring a suitable driving range [4]. On the other hand, the mission of urban road vehicles is generally characterized by variable power demand, with peak values to be supplied or recovered by on-board ESS, during frequent acceleration and deceleration phases [5]. These are the reasons why ESS are required to be characterized by both high specific power and high energy density. Unfortunately, current battery technologies are not able to simultaneously satisfy both of these requirements. In fact, recent technologies of high specific power storage devices are still characterized by low performance in terms of energy density. In addition, high charging-discharging rates generally result in negative effect on battery efficiency, internal resistance and durability in terms of life-cycle [6–7].

The use of on-board Hybrid Energy Storage Systems (HESS), which combine the performance of electrochemical batteries with high specific power storage devices, is becoming a key point of interest for the scientific literature [8–10]. In particular, super-capacitors, also known as Electrochemical Double Layer Capacitors (EDLCs), present relevant advantages, which encourage more and more their use in automotive applications. Those advantages mainly consist in the possibility for the EDLCs to store a higher amount of electric energy, in comparison with traditional capacitor technologies, and to supply/receive higher values of electric power, in comparison with electrochemical battery technologies [11–13]. Moreover, EDLCs are characterized by long cycle life, supporting hundreds of thousands of complete charging/discharging cycles, with minimal change in their performance [14]. This is due to the fact that, although EDLCs are considered electrochemical devices, no chemical reaction is involved in their charging and discharging operations. EDLCs chemical composition is based on the presence of a conductive electrolyte salt in direct contact with the metal electrodes, whereas a separator provides insulation and allows ions transfer between the electrodes. Each electrode is realized with a porous activated carbon material, obtaining very high values of energy density with equivalent active areas up to 2000 m^2/cm^3. The rated cell voltage is 2.6 V [15].

Various solutions can be analysed for the integration of battery and EDLCs in the on-board hybrid energy storage systems. In this regard, the main power architectures, supporting the above integration are described in [16] and in [17], with specific focus on their related advantages and drawbacks in terms of cost, flexibility and efficiency. In particular, the direct parallel connection between EDLCs and battery pack represents a cheap solution to reduce fast transient in battery charging/discharging current. On the other hand, this solution makes impossible for the HESS to take advantage of the complete EDLCs voltage range. In addition, the external control of power fluxes between the two storage systems cannot be supported by this configuration. For this reason, a bidirectional DC/DC converter, interfacing EDLCs with battery pack is generally proposed in the literature as a more flexible solution. This solution, also known as UC/battery configuration, enables the evaluation of various energy management strategies, which can be performed through the proper control of the above converter. In addition, the converter can work in step up or step down mode, in order to use the whole EDLCs voltage range during their charging/discharging operations. This configuration involves higher costs, due to the high power bidirectional DC/DC converter, which is required to support the charging/discharging power of EDLCs. Cao and Emadi [17] also propose the use of new power architecture, where the integration between battery and super-capacitors is realized through the use of a bidirectional DC/DC converter which works in parallel connection with a controlled switching device.

Further studies, available in the scientific literature, are focused on energy management strategies of HESS. In particular, heuristic energy management strategies are proposed in [18–20], highlighting the effectiveness of super-capacitors in increasing the durability of the vehicle battery pack, when they are used in urban driving cycles. Ziyou et al. [21] analyse a multi-objective optimization algorithm, which is aimed to simultaneously minimize the cost of a hybrid energy-storage unit and the capacity loss of a $LiFePO_4$ battery pack, for a specific road electric vehicle running on typical urban driving cycles. A novel dynamic programming analysis method is proposed by Zhang et al. [22], in order to maximize efficiency and durability of the whole storage system. The proposed method is verified for different values of battery State of Charge (SoC) and State of Health (SoH). A novel energy management strategy in hybrid storage systems is also described in [23] by Carter et al. In this case, the authors develop a tunable strategy, which is able to achieve two separate goals. The first goal is the improvement of vehicle efficiency and autonomy, whereas the second goal is the reduction of current peak values for the battery pack, with positive consequence on the expected battery life.

The referred state of art is focused on the analysis of energy management strategies, whose goals are mainly related to increasing battery durability, vehicle autonomy and overall vehicle energy conversion efficiency. The effects of the proposed strategies are generally evaluated through modeling and simulation activities.

On the base of the above scientific literature analysis, this paper is aim to cover the lack of experimental knowledge about the positive effects of EDLC based hybrid storage systems, working in real operative conditions. For this reason, the main contribution of this paper is focused on the experimental assessment of specific energy management strategies, which maximize the effectiveness of a hybrid energy storage system, when supplying a real electric propulsion system for urban vehicles. Those strategies are preliminary evaluated and optimized through the use of simulation environment. Then the proposed activity is carried out through a 1:1 scale laboratory test-bench, able to simulate vehicle inertia and road resistant forces on standard driving cycle.