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Integration between super-capacitors and ZEBRA batteries as high performance hybrid storage system for electric vehicles

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Abstract

This paper presents experimental evaluations on the performance of a hybrid energy storage system to supply urban electric vehicles. The paper starts with a description of nickel chloride batteries and electric double layer capacitors with details on their related advantages. Then, a laboratory test bench is presented to experimentally evaluate the performance of the realized hybrid storage system, obtained through a controlled DC/DC bidirectional power converter, supplying an electric power-train in real operative conditions on standard driving cycles. The main results of this study shows the importance of using that power converter to take advantage of the power characteristics of the super-capacitor and to easily implement on board energy management strategies to increase the whole vehicle performance.

Electric Vehicles; Hybrid Energy Storage Systems; Power Converter; Energy Management.

1. Introduction

The wide diffusion of electric and hybrid vehicles in the automotive market has been limited in recent years by the performance of on-board electric energy storage systems. In fact, in order to match the main needs of the great part of vehicle users, the energy storage systems are imposed to satisfy a high number of requirements. In particular, energy storage systems for automotive applications should be characterized by high power and energy density, long cycle-life, high reliability, wide operative temperature range, low environmental impact [1]. Unfortunately, existing storage technologies are not able to simultaneously satisfy all these requirements. An example is represented by lithium based storage systems, which have shown good performance in supplying electric vehicles, with high travel range and good dynamic response

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to driving cycle power requirements [2]. On the other hand, the performance and lifetime of these batteries are strongly affected by their working temperature and operative conditions [3]. In addition, the cost of lithium batteries is still very high and environmental issues related to lithium metal disposal need to be taken into account [4]. Sodium - nickel chloride batteries could be considered an interesting alternative to lithium technologies. In fact, they combine reduced cost, high safety and durability with energy density values, which are comparable with the most common lithium technologies. Sodium - nickel chloride batteries, also known with the acronym ZEBRA (Zeolite Battery Research Africa) [5], are characterized by a temperature working range of 520-560 K. The high working temperature have actually affected the development of ZEBRA batteries for automotive applications, since they present self-discharging issues, related to the need of maintaining high operative temperature even when the battery pack is not supplying the electric drive. On the other hand, this kind of battery has been successfully used in urban public transportation means, when the vehicle mission, during working hours, is quite predictable and the batteries can be easily charged during resting times. A significant drawback of ZEBRA storage technologies is the low power density values in comparison with the most recent lithium technologies, with consequent low performance in terms of vehicle acceleration and charging times.

In this context, the use and management of on-board hybrid energy storage systems, which combine different storage technologies, is becoming a key point of interest for the scientific literature related to automotive applications. In this context, Electrochemical Double Layer Capacitors (EDLCs) are considered particularly suitable for realizing hybrid energy storage systems in combination with ZEBRA battery packs [6], [7]. In fact, EDLCs are able to store a higher amount of electric energy, in comparison with traditional electrostatic and electrolytic capacitor technologies, and are able to supply/receive higher values of electric power, in comparison with traditional battery technologies. In addition, they also present high durability in terms of charging/discharging cycle. The chemical composition of EDLCs is quite similar to the case of traditional capacitors. The main differences are in 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. Moreover, each electrode presents a porous structure, which allows obtaining very high values of energy density realizing equivalent active areas up to 2000 m^2/cm^3. The rated cell voltage for an EDLC is of about 2.6 V [8].

On the base of the above considerations, this paper starts from a description of a laboratory dynamic test bench, which has been set up for experimental performance evaluations of a hybrid storage system based on ZEBRA batteries and EDLCs. The integration of the two storage system is performed by means of an interleaved DC/DC bidirectional converter, which allows the control of on-board energy fluxes. Simulation results for preliminary evaluations related to on/board energy management strategies are reported.

2. Experimental Set-up

A dynamic test bench has been set up in the laboratories of the Istituto Motori in order to carry out experimental analysis on hybrid storage systems, when supplying an electric drive running on standard driving cycle in real operative conditions. Part of this test bench has been already used and described in another paper, published by the same authors, which is focused on the performance evaluation of the ZEBRA battery pack in dynamic conditions [9]. The main scheme of the laboratory test bench is reported in Fig. 1.

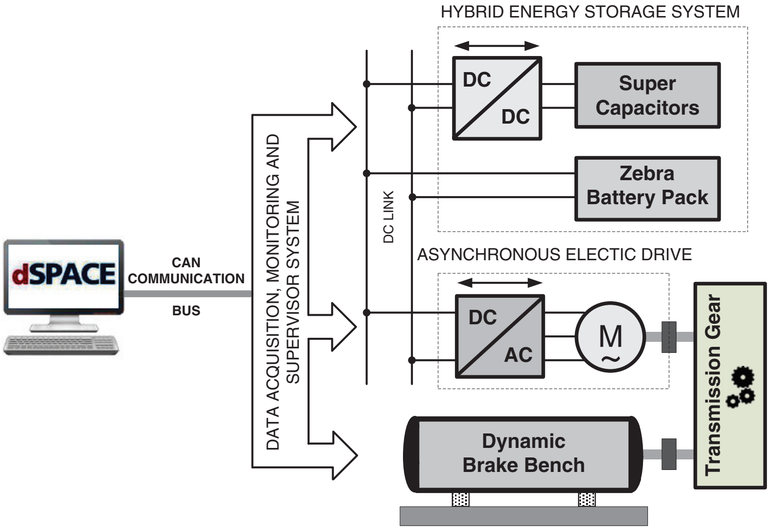

Fig. 1. Block Scheme of the laboratory test bench.

As shown in the above scheme, the electric drive is coupled with the dynamic brake through a fixed ratio transmission gear. This configuration allows the simulation of road and aerodynamic resistant forces directly applied to the wheel shaft. The electric drive is based on a 65 kW asynchronous machine, which is controlled through a bidirectional AC/DC converter and supports regenerative braking operations. The dynamic brake is supplied by the main grid through a bidirectional power conversion system, which allows the brake to work either as a generator or as a motor on the base of the required operation. This means that the brake is also able to simulate negative road slopes and vehicle inertia, using the energy coming from the main grid. The battery pack is realized with two 38 Ah – 550 V ZEBRA batteries, which are both provided with their Battery Monitoring Interface (BMI). The two batteries are connected in parallel and are controlled by an external intelligent device called Multiple Battery System (MBS). More details on the ZEBRA battery pack, electric drive and brake characteristics are reported in [9]. The integration of the super-capacitor bank with the Zebra battery pack is performed through a bidirectional DC/DC power converter, based on IGBT technology. This converter has been designed and realized to allow the implementation of different on-board energy management strategies. For this reason, its embedded control board is able to support the following control modes [10]:

- Super-capacitors current, I_{SC}, control mode
- DC-Link voltage, $V_{DC\text{-}Link}$, control mode
- DC-Link current, $I_{DC\text{-}Link}$, control mode

In particular, the I_{SC} control mode is obtained through a feedback loop control scheme, which modifies the PWM modulation of the converter, in order to track the reference super-capacitors current value, I^*_{SC}. The $V_{DC\text{-}Link}$ control mode is performed through an external PI control loop, which sets the super-capacitors reference current value I^*_{SC}, on the base of the difference between the reference, $V^*_{DC\text{-}Link}$, and actual, $V_{DC\text{-}Link}$, DC-Link voltage values. The $I_{DC\text{-}Link}$ control mode is performed by assuming the simplifying hypothesis that no power losses are related with the DC/DC power converter operations. For this reason, this control is carried out by setting the super-capacitors reference current value, I^*_{SC}, on the base of the following equation (1).

$$I_{SC}^{*} = \frac{V_{DC-Link} I_{DC-Link}^{*}}{V_{SC}} \tag{1}$$

The voltage and current reference values, for the above described control modes, can be set by an external supervisor, which interacts with the DC/DC converter through CAN communication bus or analogue voltage signal.

3. Simulation and Results

A simulation model has been built in Matlab-Simulink environment in order to perform preliminary evaluations related to on-board energy fluxes, before running experimental analysis with the test bench presented above. The simulation model is based on the evaluations and blocks, which have been already described in [9]. In this work, the model has been extended with the integration of super-capacitors bank and DC/DC converter. In particular, the super-capacitor bank has been simulated following the 'classical' equivalent circuit reported in [8]. In this case, the suggested model includes a capacitance C, an equivalent series resistance (ESR) and an Equivalent Parallel Resistance (EPR). On the base of the considerations reported in [11], this last term can be neglected in case of road vehicle applications, where short charging/discharging cycles are generally performed. For this reason, in this paper only the capacitance C and the ESR are taken into account. The DC/DC power converter is modelled as an ideal device on the base of the input/output power balance, which is realized taking into account the measured values of battery and super-capacitors voltage. The model of the DC/DC converter also gives the possibility of using, in simulation environment, the control modes described in the previous section. In fact, a controlled current source is used for the simulation of the I_{SC} control mode, whereas the other two control modes are performed with external control loops. This allows preliminary evaluations of on-board energy management strategies to be performed in simulation environment . The block scheme of the super-capacitors model with the related control modes is reported in Fig. 2.

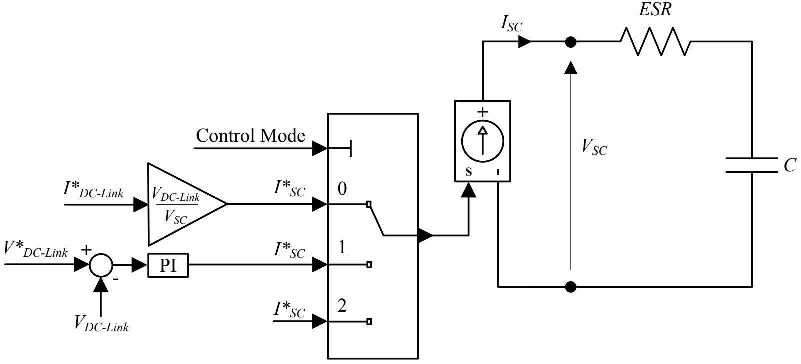

Fig.2. Block scheme of super-capacitor model with $I^*_{DC\text{-}Link}$ (0), $V^*_{DC\text{-}Link}$ (1) and I^*_{SC} (2) control modes.

An example of simple on-board energy management strategy is considered in this paper, by setting a constant super-capacitors discharging power of 1 kW. This strategy is performed taking advantage of the I_{SC} control mode, which is allowed by the DC/DC power converter. In fact, the super-capacitor discharging current reference, I^*_{SC}, can be evaluated as the ratio between the reference super-capacitors electric power, P^*_{SC}, and the super-capacitors voltage, V_{SC}. For the evaluation reported in this section an electric version of Renault Master, whose main characteristics are reported in [9], has been considered as case study. In particular, Fig.3 shows the main simulation results for that vehicle, running on the urban part of the NEDC standard driving cycle.

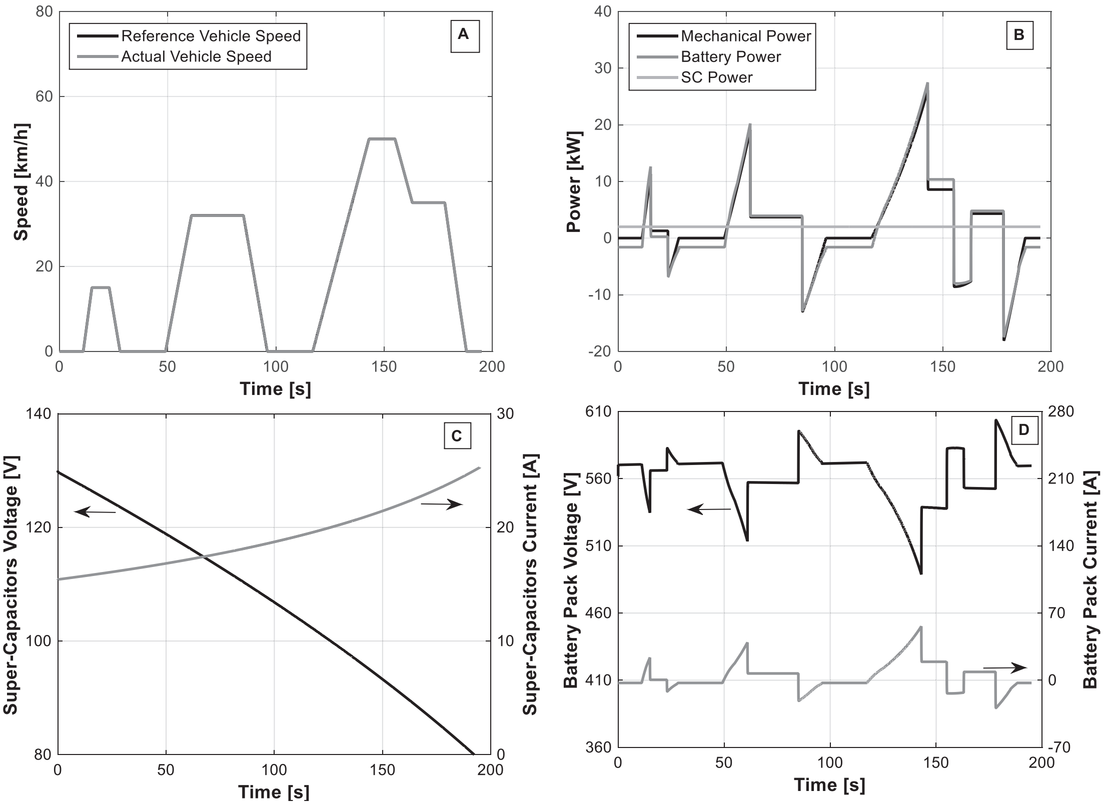

Fig. 3. Simulation results for an electric version of Renault Master running on the urban part of the NEDC driving cycle: Reference and Actual Speed (A), Battery, SC and Vehicle Power (B), SC Voltage and Current (C), Battery Voltage and Current (D) vs Time.

As reported in the above Figure, the considered vehicle, in the proposed configuration, is able to follow the dynamic requirement of the urban driving cycle (A). The super-capacitor constant power supports the electric power coming from the battery pack, during the acceleration and steady state phases, whereas the batteries are charged by the super-capacitors during the resting phases (B). On the whole driving cycle, the super-capacitors voltage drops from its initial value of about 130 V up to the value of 80 V, whereas the super-capacitors current increases its value of about 10 A (C). The battery pack current reaches a maximum value of about 65 A during the most demanding step of the driving cycle, whereas the maximum recharging current of about 25 A, with a corresponding battery pack voltage of about 605 V, is evaluated during the regenerative braking operations.

4. Conclusions

In this paper, preliminary evaluations on the performance of a hybrid energy storage system, supplying an electric vehicle on urban driving cycles, are presented. With this purpose, a laboratory experimental set-up has been proposed, in order to perform the integration of the hybrid energy storage system with the propulsion system of an electric vehicle. In particular, this integration has been realized through a DC/DC bidirectional power converter, which supports different embedded control modes for on-board energy fluxes management. Preliminary evaluations have been carried out by means of a Matlab-Simulink simulation model, by using a simplified energy management strategy. Simulation results have shown the good behavior of the whole power train, in following the dynamic requirements of the urban part of NEDC driving cycle. The simulation model and the test bench described in this paper allow theoretical and experimental evaluations of optimized energy management strategies, which will be object of future publications by the same authors.

5. Copyright

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6. Biography

Ottorino Veneri graduated and awarded his PhD in Electrical Engineering by the University of Naples Federico II. Since 2002 he works as a researcher with the Istituto Motori of the National Research Council of Italy. His main fields of interest are the electric drives for transportation systems, electric energy converters, electric energy storage systems and power sources with hydrogen fuel cells.