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Optimal control strategy of ultra-capacitors in hybrid energy storage system for electric vehicles

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Abstract

This paper describes a novel Energy Management Strategy (EMS) for hybrid energy storage systems, when used to supply urban electric vehicles. A preliminary off-line procedure, based on nonlinear programming, is performed in order to optimize the battery current profile for fixed working cycles. Hence, a suitable control strategy, which is based on a constrained minimization problem, is tailored for real-time applications. This control strategy exploits the off-line solution of a proper isoperimetric problem and aims to dynamically optimize the battery durability by reducing peak charging/discharging current values. The main advantage of the analysed EMS consists in the easy on-board implementation through the use of one single parameter, which can be quickly identified through a simple off-line numerical procedure. The proposed strategy is evaluated in simulation environment, through the use of a Matlab-Simulink model, for the case study of an urban electric vehicle running on a ECE 15 driving cycles. Simulation results have confirmed the good performance of the above strategy in reducing the battery peak charging/discharging current through the proper management of the hybrid energy storage system.

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Keywords: Hybrid Energy Storge Systems; Electric Vehicles; Isoperimetric Optimization; Electric Double Layer Capacitors; Zebra Batteries

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1. Introduction

Nowadays, increasing environmental concerns and the expected depletion of oil resources are drawing the interest of researchers and manufacturers of the automotive sector towards new technical challenges, supporting clean and sustainable transportation systems [1]. In this regard, the use of electric propulsion systems appears to be a promising solution for near-term future, especially for the urban mobility context. In fact, vehicles equipped with these kinds of propulsion systems can benefit of various advantages, such as the possibility to operate in urban areas without tailpipe emissions and high values of well-to-wheel conversion efficiency [2]. In addition, recent development in battery technologies allows reaching high values of energy density, with consequent positive effects on the expected vehicle autonomy. Unfortunately, the mission of road electric vehicles is generally characterized by variable load demand and high power peaks, which are due to frequent acceleration and braking phases. These power peaks, as widely recognized in the scientific literature [3] [4], involve adverse effects for the on board battery packs, in terms of charging/discharging efficiency and durability.

A feasible solution for the above issues is represented by the use of hybrid energy storage systems (HESSs), which are based on a combination of batteries with high power density storage devices, such as supercapacitors. In this case, it is clear that the vehicle steady state operations can be performed by using the energy coming from the battery pack, whereas the peak charging/discharging power demands can be managed through the proper use of supercapacitors. With this aim, various papers reported in the scientific literatures have focused the attention on hybrid energy storage systems, mainly in terms of component sizing and optimal energy management strategies on the basis of the expected vehicle mission [5][6]. In this context, for the specific case study of an urban vehicle, this paper firstly introduces an optimal off-line energy management strategy (EMS), which is aimed to minimize the battery current variance through nonlinear programming. Then an on-line strategy, based on the calculus of variations theory, is proposed and compared with the off-line EMS through the use of simulation environment. This comparison is performed in terms of effectiveness in reducing the effect of high charging/discharging current peaks on battery durability.

2. Case Study and Optimization Problem

An electric version of the Renault Master is considered in this paper as case study of electric vehicle supplied by a hybrid energy storage system. The same version of this vehicle, supplied only by the battery pack, has been already considered by the authors in a previous paper, which reports the main vehicle characteristics and operative conditions [7]. The architecture chosen for this kind of vehicle is based on the well known SC/battery configuration, which is described and proposed in [8]. This configuration allows the management of power fluxes between the battery pack and supercapacitors by means of the proper control of a bidirectional DC/DC converter. The block scheme and electric parameters of the considered power-train, supplied by the hybrid energy storage system, is reported in Fig. 1.

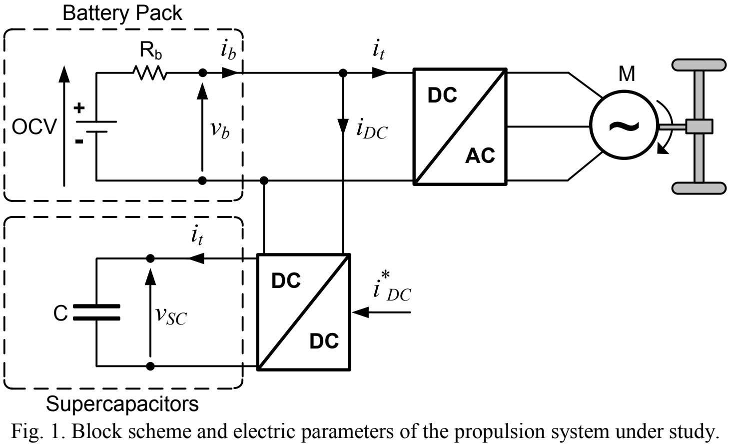

Fig. 1. Block scheme and electric parameters of the propulsion system under study.

The above described hybrid energy storage systems is based on 2 x 38 Ah - 550 V ZEBRA batteries, which are connected in electrical parallel, and a 63 F – 125 V module of supercapacitors. The DC/DC bidirectional power converter, realizing the integration between the two storage systems, can be control through the reference value of supercapacitors current reported on the DC-Link side I_{DC}^*.

A preliminary constrained optimization problem is stated for identifying an optimal off-line strategy able to operate for fixed driving cycles and also evaluating the goodness of real-time control strategy. In other words, the optimal battery current profiles derived by this off-line procedure can be considered as a benchmark to evaluate the performance of real-time control strategies [9]. This procedure gives as output the optimal reference values of battery current, $i_b^*(t)$, and the optimal initial value of supercapacitors voltage, v_{SC}^0, on the basis of the analyzed driving cycle. The proposed formulation is based on the following simplified hypothesis:

- The battery, as generally suggested in the scientific literature and reported in [10], is modelled by using a simplified internal resistance model. For this reason, the battery voltage, v_b, can be expressed as $v_b = OCV - R_b i_b$;
- The DC-DC converter is supposed to be ideal (i.e. $v_b i_{DC} = v_{SC} i_{SC}$)
- The supercapacitors charging/discharging efficiency is not taken into account.

This off-line control strategy is based on the minimization of an objective function which is defined by the following equation (1):

$$\Psi = \int_0^T (i_b - E[i_b])^2 dt \tag{1}$$

The above equation represents the battery current variance, where *E[i_b]* is the expected value of i_b.

The first constraint can be defined by taking into account that the contribution of super-capacitors, in terms of energy, can be neglected in comparison with the amount of energy stored in the battery pack. For this reason, supercapacitors are only used for supplying peak power demand and during regenerative operations. As a consequence, for a considered driving cycle, the integral of the supercapacitors instantaneous power should be equal to zero, as reported in the equation (2):

$$\int_0^T (OCV - R_b i_b)(i_b - i_t) dt = 0 \tag{2}$$

The above isoperimetric constraint also allows the reduction of the effect of supercapacitors initial State of Charge on the performance evaluation of a specific control strategy. Two additional technical constraints are required, in order to avoid undesired operative conditions for the supercapacitors. These constraints are also referred to as inequality constraints and are expressed in the following relations (3).

$$\begin{cases} v_{SC,min} \le v_{SC} \le v_{SC,max} \\ i_{SC,min} \le i_{SC} \le i_{SC,max} \end{cases} \tag{3}$$

The last constraint is represented by a dynamic inner constraint, which takes into account the electrical behaviour of supercapacitors and the voltage ration of the considered DC/DC converter. This constraint is expressed through the equation (4).

$$\frac{dv_{SC}}{dt} = \frac{v_b}{C v_{SC}} (i_b - i_t) \tag{4}$$

The inequality constraint of equation (3) related to i_{SC} can be reported in terms of i_b and v_{sc}:

$$i_{SC,min} \le \frac{v_b (i_b - i_t)}{v_{SC}} \le i_{SC,max} \tag{5}$$

On the bass of the considered simplified hypothesis and equation (2), the expected values of the supercapacitors current reported on the DC Link, $E[i_{DC}]$, can be considered equals to zero. As a consequence, the expected value of battery current $E[i_b]$ is equal to the expected value of the traction current, $E[i_t]$, which only depends on the requirements of the considered driving cycle, for the vehicle under study. For this reason the minimization of Ψ is equivalent to the minimization of, Φ , as reported in the equation (6):

$$\Phi = \int_0^T i_b^2 dt = 0 \tag{6}$$

The proposed minimization of the objective function, Φ, with its constraints can be handled with *nonlinear programming (NLP)* [11], as some of the analysed constraints are non-linear. The solution of the above optimization procedure, which can be performed in Matlab environment, gives as output the optimal reference values of battery current, i_b^*, and the optimal initial supercapacitors voltage v_{SC}^0. As mentioned at the beginning of this section, this reference values can be used for off-line optimization of battery current profile on fixed working cycles.

A second optimization procedure for the minimization of the equation (6) can be based on the λ-control strategy, which is proposed in [12]. In this case, the off-line optimization of one single parameter allows the implementation of a real-time control strategy, which optimizes the battery current profile. For this procedure, only the isoperimetric constraint, reported in equation (2), is considered, without taking into account inner and inequality constraints. According to the theory of calculus of variations [11] the optimal reference values of battery current, $i_b^*(t)$, can be evaluated by solving the system of equations reported in (7), which is function of λ and i_b.

$$\begin{cases} \frac{\partial}{\partial i_b}[i_b^2 + \lambda(OCV - R_b i_b)(i_b - i_t)] = 0 \\ \int_0^T (OCV - R_b i_b)(i_b - i_t)dt = 0 \end{cases} \tag{7}$$

From the first equation of (7) the battery current i_b can be written as a function of λ as it follows:

$$i_b = \frac{\lambda(OCV + R_b i_t)}{2(\lambda R_b - 1)} \tag{8}$$

Hence, thorough the substitution of (8) in the second equation of (7) it is possible to obtain:

$$G(\lambda) = \int_0^T \left(OCV - R_b \frac{\lambda(OCV + R_b i_t)}{2(\lambda R_b - 1)}\right)\left(\frac{\lambda(OCV + R_b i_t)}{2(\lambda R_b - 1)} - i_t\right) dt = 0 \tag{9}$$

This last relation allows the determination of the constant parameter λ* which provides the optimal battery current reference, i_b^*. Obviously, the proposed optimization requires in advance the knowledge of future values of i_t, required for λ* evaluation, and the whole system would be clearly non-causal. With the aim of solving this problem and for properly taking into account the inequality constraints, the λ* value is updated according to the block scheme reported in Fig. 2.

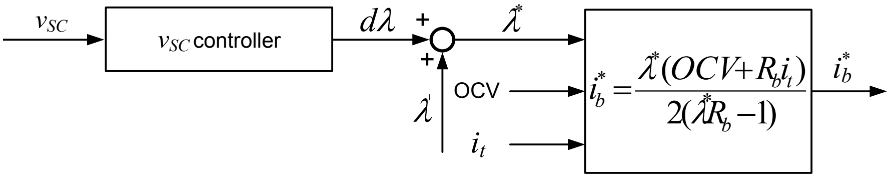

Fig. 2. Block Scheme of the λ on-line control strategy.

The v_{SC} controller allows to satisfy the lower and upper limits of supercapacitors voltage values. The reference value i_{DC}^* for the power converter control can be obtained through the difference between the battery reference current value i_b^* and the traction current i_t.

3. Simulation results and Discussion

Preliminary information on the performance of the above proposed off-line and on-line EMS can be obtained through a numerical vehicle model. This model has been built in Matlab-Simulink environment and is realized by extending the model described in [7] with supercapacitors and DC/DC converter simulation blocks. In particular, supercapacitors are simulated through the classical equivalent circuit described in [13], where only the capacitance and equivalent series resistance are considered. The DC/DC converter is simulated as an ideal device, where $v_{SC} i_{SC} = v_{DC} i_{DC}$, and can be controlled through the reference value of the supercapacitors current reported on the DC-Link side, i_{DC}^* [14]. A maximum charging/discharging current of 100 A has been considered for the supercapacitors, in order to take into account the electric power limitation of the DC/DC converter.

The first evaluations are carried out for the vehicle under sturdy running on an ECE 15 driving cycle, with the off-line EMS. The main results of this simulation are reported in Fig. 3.

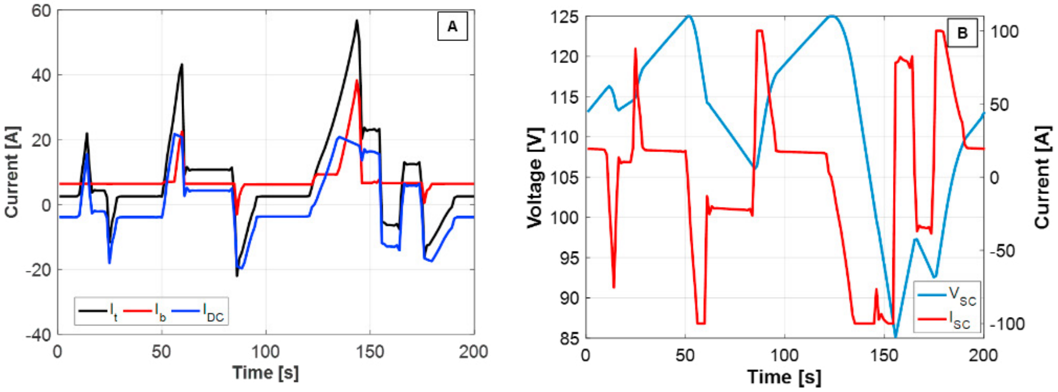

Fig. 3. Simulation Results for the vehicle running on ECE 15 driving cycle with off-line EMS: traction, battery, DC-link Current (A) supercapacitors voltage and current (B) versus time.

As shown from the simulation results, a maximum traction current I_t of about 60 A is required during the last phase of the driving cycle (A). In this case, the off-line EMS limits the battery current to a maximum value of 38 A through the use of supercapacitors, which are discharged with the maximum allowed current of 100 A and reach the minimum voltage value of 85 V (B). In addition, during the deceleration phases, the regenerative current values are almost completely used to charge the supercapacitors, avoiding peak charging current for the battery pack. It is clear that with this EMS, the use of supercapacitors allows a reduction of the maximum battery discharging current up to 33%.

Further evaluations have been carried out in simulation environment in order to analyze the performance of the on-line EMS for the vehicle under sturdy running on an ECE 15 driving cycle. The main results of this simulation are reported in Fig. 4.

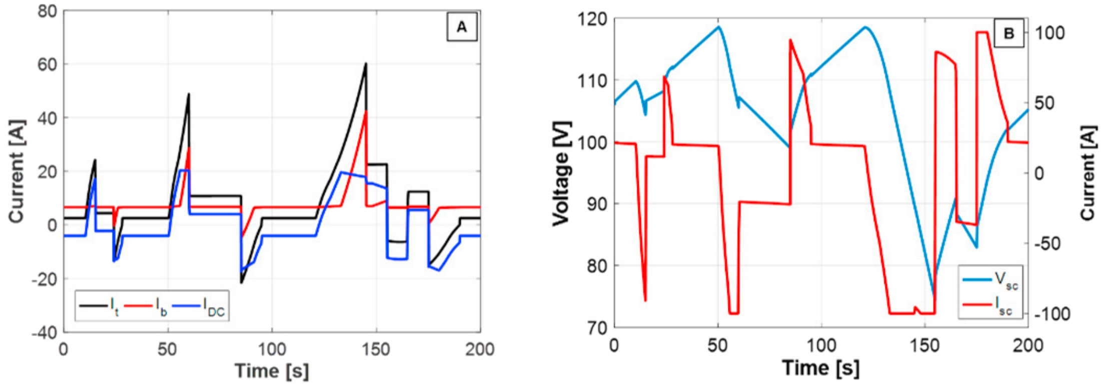

Fig. 4. Simulation Results for the vehicle running on ECE 15 driving cycle with on-line EMS: traction, battery, DC-link Current (A) supercapacitors voltage and current (B) versus time

In this case the on-line EMS limits the battery current to a maximum value of 42 A through the use of supercapacitors, which are discharged with the maximum allowed current of 100 A and reach the minimum voltage value of 72 V (B). Also for this test, regenerative current values are almost completely used to charge the supercapacitors. A reduction of the maximum battery discharging current up to 30 % is obtained with this EMS.

On the basis of the equation (6), the performance of the above proposed EMSs can be evaluated through the equation (10), which defines the *efficacy* of the analyzed EMS.

$$Eff = \frac{\int_0^T i_t^2 dt - \int_0^T i_b^2 dt}{\int_t^T i_t^2 dt} \cdot 100 \tag{10}$$

In particular, efficacy values of 66% and 64.5 % have been respectively evaluated for the off-line and on-line EMS on the considered driving cycle. This result confirms the good performance of the on-line EMS, in comparison with the benchmark represented by the off-line EMS for the vehicle running on the ECE 15 driving cycle. For this reason, the λ-control strategy represents a promising real-time strategy to be further investigated with future simulations and experimental activities.

4. Conclusions

In this paper, the performance of a hybrid energy storage system, which integrates a Zebra battery pack and a supercapacitor module, have been analyzed. This analysis has been carried out for the specific case study of an urban electric vehicle. In particular, two different energy management strategies have been proposed and compared with the aim of reducing the battery charging/discharging peak current values. Preliminary simulation results have shown the good performance of both off-line and on-line EMS in supplying the considered vehicle on an ECE 15 driving cycle. Future works will be related to further simulation analysis and experimental performance evaluations of the above EMSs, through the use of a 1:1 scale laboratory test bench.

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Authors 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.