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ORIGINAL ARTICLE

Development of new improved energy management strategies for electric vehicle battery/supercapacitor hybrid energy storage system

Nassim Rizoug · Tedjani Mesbahi · Redha Sadoun · Patrick Bartholomeüs · Philippe Le Moigne

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Abstract Hybrid energy storage systems (HESS) are used to optimize the performances of the embedded storage system in electric vehicles. The hybridization of the storage system separates energy and power sources, for example, battery and supercapacitor, in order to use their characteristics at their best. This paper deals with the improvement of the size, efficiency, or cost of the embedded source using new management strategies for HESS. In addition, one of the most important advantages of this novel strategies is the improvement of battery lifetime. As a result of this development, significant reductions in the cost and optimizing the performance of electric vehicles can be achieved. Simulation results show that the RMS (root mean square) power of battery is effectively reduced, and the quantity of charge can be considered as main factor in the concepts of embedded energy management. Experimental validation is achieved with a low power test bench, where the battery and supercapacitor are emulated by power electronic devise with electrical models of the storage system implemented in software environment. The experimental results verify the proposed energy management strategies through demonstrating the decreasing of the power constraint applied to the battery.

Keywords Electric vehicle · Battery · Energy management strategy · Hybrid energy storage system · Battery lifetime · HESS sizing

N. Rizoug (✉)
S2ET-ESTACA Ecole Supérieure des Techniques Aéronautiques et de Construction Automobile, Rue Georges Charpak, BP53061, 53061 Laval Cedex 9, France
e-mail: nassim.rizoug@estaca.fr

T. Mesbahi · P. Bartholomeüs · P. Le Moigne
Ecole Centrale de Lille, EA 2697 - L2EP - Laboratoire d'Electrotechnique et d'Electronique de puissance, Ecole Centrale de Lille, F-59000 Lille, France

R. Sadoun
Assystem SA, 23 place de Wicklow, 78180 Montigny le Bretonneux, France

Introduction

Reducing the flow of the greenhouse gases which are the causes of global warming could prevent up to 3 million premature deaths annually by the year 2100, as it is suggested in new study (Prasad and Rahn 2013). In recent years, the transport of goods and people is responsible for a large and growing share of global emissions affecting climate. Furthermore, many efforts are pointed out to mitigate the pollution in urban areas (Emori et al. 2008). Under these circumstances, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs) can contribute to a greener and cleaner environment by substantially reducing the dependence on non-renewable fossil fuels such as gasoline and diesel (Prasad and Rahn 2013; Emori et al. 2008).

Nevertheless, this contribution of EVs in the reduction of greenhouse gases will be realized only if the costs and the performances of the conventional cars will be comparable with those based on electric population

(Galdi et al. 2006; Amjadi and Williamson 2010). The main problem of the actual EVs is due to the size and cost of the embedded storage system. Many kinds of batteries are widely used in automotive application. In particular, the Li-ion battery has attracted the interest of several car manufacturer groups, due to their high energy density, light mass, and good lifetime (Paul et al. 2013; Alahmad and Hess 2008). Despite improvement of the battery characteristics using Li-ion technologies, the performances of the electric storage system remain still far from conventional vehicle (Fig. 1).

One way to improve the Li-ion battery lifetime and reduce its weight is to use supercapacitors as a secondary power source. The performances of supercapacitors are perfectly complementary to those of batteries. Indeed, these devices have very high power density, low serial resistance, a very high cyclability (several millions cycles) and reliability (Alahmad and Hess 2008). However, the use of HESS in EV application increases the complexity of the embedded power supply architecture but also gives opportunities to improve it (Choi et al. 2012; Ortuzar et al. 2007).

R. Sadoun (Sadoun 2013) has proposed a comparison between the size of high-power Li-ion battery and hybrid energy storage system HESS (High energy Li-ion + Supercapacitors). The result of this study proves the interest of the hybrid solution for high values of range. Hybridization allows also the improvement of the source lifetime, by the reduction of the stresses applied to the battery.

Several literatures have presented different management strategies for hybrid storage system composed with battery and supercapacitors (Uno and Tanaka 2013; Njoya Motapon et al. 2014). These works try to reduce the battery RMS power to improve the lifetime of this last one. All the literature studies do not include the change of hybrid storage system size if they change the management strategy. In this paper, we propose the development of new power management strategies for hybrid energy storage system (HESS) taking into account the improvement of the source size and the lifetime of this last one (Fig. 2).

The main objective is to take advantage of this new power supply architecture to increase the global performances (Hu et al. 2016).

This paper proposed a novel approach of energy management in electric vehicle application based on the reducing of the power stresses applied to the Li-ion battery with the best size of the HESS. One of the main advantages of this proposition is the introduction of a rule able to improve the lifetime of battery/supercapacitor hybrid energy storage systems. This paper is organized as follows. The specifications of the electrical vehicle characteristics and model which is used for this study is detailed in the "HESS characteristics and configuration" section. In the "Modeling of electric vehicle" section, characteristics and configuration of HESS are presented. Then, the battery/supercapacitor HESS sizing is described in the "Battery/supercapacitor HESS sizing" section. In the "Power management strategies presented in the literature" section, a comparison of several classical energy management strategies is made with different criterions (weight and battery power constraint). Next, new proposed methods are presented and compared with previous classical methods. The simulation and experimental results of the proposed solution are shown and analyzed in the "Approach based on dynamic limitation of the battery power according to the supercapacitor state of charge" section. Finally, conclusions and final comments are given in the last section.

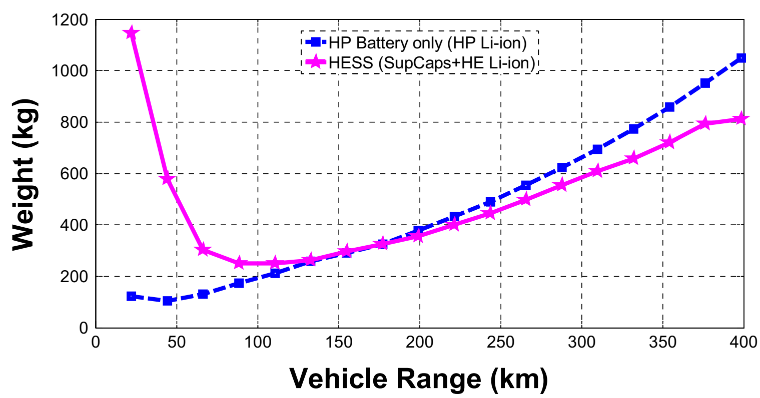


Fig. 1 Weight of storage systems according to the vehicle range (Sadoun 2013)

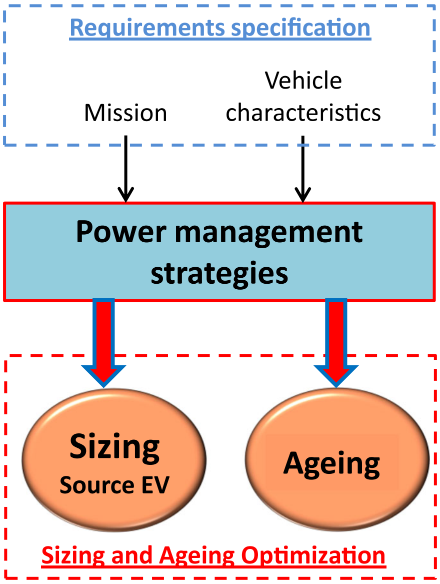


Fig. 2 Power management strategies to improve size and aging of the HESS

HESS characteristics and configuration

The battery/supercapacitor HESS has more advantages in comparison with original traction battery because the use of supercapacitors allows ensuring the high accelerating and recovering power during braking mode (Mousavi et al. 2011). However, the following issues are the motivation for the hybridization of the embedded energy storage system:

- Limited power density of the Li-ion cell
- Need for maximize energy recovery during braking
- Size reduction of embedded energy storage system
- Improve the Li-ion battery lifetime
- Reduce the overall cost of embedded source

In this context, the HESS solution can be useful and reliable in electric population application. In addition, to achieve a long durability, the Li-ion battery must ensure the average power of electric vehicle.

Li-ion battery characteristics

Li-ion batteries seem to be a competitive solution to supply electric vehicles because of their unique abilities such as high voltage, high energy density, low self-discharge, fast charging, and durability (Banaei and Fahimi 2010; Rahimi-Eichi et al. 2014). However, there are many different types of Li-ion batteries that can be used for automotive power applications (Mousavi et al. 2011; Affanni et al. 2005).

The KOKAM cells (40HED) are chosen in our case to compose the battery pack (Table 1).

Supercapacitor characteristics

Supercapacitors do not store as much energy as a Li-ion battery, but have the ability to release and accumulate this energy very quickly (high power density) (Juergen et al. 2006). For that, these devices are suitable for high-power vehicle applications, which provide the power required to accelerate the vehicle or recover the available energy during braking phase (Burke 2007).

In this study, the Maxwell technology 350/2.7 is chosen. The characteristics of these cells are indicated in Table 2.

Battery/supercapacitor HESS configuration

To associate a high energy storage system, such as a Li-ion battery, with an auxiliary energy storage system, such as supercapacitors in the same dc-bus, several configurations are proposed in literature (Kohler et al. 2009; Camara et al. 2012).

One of these configurations is selected in our case, where the chosen architecture is based on connection of the battery to the dc-bus directly without a converter, as illustrated in Fig. 3.

On the other hand, the supercapacitor pack is connected to dc-bus via a bidirectional dc/dc converter (Camara et al. 2012; Dusmez and Khaligh 2014).

Table 1 Characteristics of Li-ion battery KOKAM 40HED (Hammani et al. 2012)

Battery	Value
Nominal voltage (V)	3.7
Capacity (Ah)	40
Specific energy (Wh/kg)	133.8
Max current charge/discharge (A)	40/40
Weight (kg)	0.935
Volume (l)	0.42

Table 2 Characteristics of Maxwell technology 350/2.7 supercapacitor (Sadoun et al. 2011)

Scp	Value
Nominal voltage (V)	2.7
Capacity (F)	350
Power density (W/kg)	4300
Energy (Wh)	5.062
Weight (kg)	0.063
Volume (l)	0.053

Modeling of electric vehicle

Dynamic vehicle model

To determine the size of embedded energy storage system, a dynamic model for the car motion is necessary. This allows us to calculate the power and energy needed for electric propulsion, allowing us to estimate the theoretical electric vehicle demands for any trip (Mesbahi et al. 2013). Therefore, both power and energy profiles are obtained by the simulation of the electric vehicle model, where the input is the set-point driving cycle (speed of a vehicle according to time) (Sadoun 2013).

However, the driving cycles (UDC, NEDC, ARTEMIS) are produced by different countries and organizations to assess the performance of vehicles in various ways, as for example fuel consumption and polluting missions (Brundell-Freij and Ericsson 2005; Ericsson 2001).

In our study, the Artemis cycle with an average slope of 2.5% is used to size the HESS. Figure 4 shows the urban and road ARTEMIS cycles (Sadoun 2013).

The used model takes into account several forces, as well as the road and velocity profiles, which, the development of these forces are detailed in Mesbahi et al. (2013), Sadoun et al. (2012), and Sadoun et al. (2011). The load force F_{res} is the sum of whole forces apply to the vehicle, where it is expressed by

$$F_{\text{res}} = F_{aero} + F_{roll} + F_{\text{gx}} + F_{\text{acc}} \quad (1)$$

$$\begin{cases} F_{aero} = 0.5.\rho.s.C_x.V_{\text{VEH}}{}^2 \\ F_{roll} = (M_{\text{EV}} + M_{\text{ESS}}).g.\left(C_0 + C_1.V_{\text{VEH}}{}^2\right) \\ F_{\text{gx}} = (M_{\text{EV}} + M_{\text{ESS}}).g.\sin(\propto) \\ F_{\text{acc}} = (M_{\text{EV}} + M_{\text{ESS}}).\dfrac{dV_{\text{VEH}}}{dt} \end{cases} \quad (2)$$

where F_{aero} is aerodynamic drag force, F_{roll} is the rolling resistance force, F_{gx} is gravitational force, and F_{acc} is acceleration force.

These forces are expressed according to the EV and ESS weight (M_{EV} and M_{SSE}). As a result, the EV required power can be described as follows:

$$P_V = \left((M_{\text{EV}} + M_{\text{ESS}}).\frac{dV_{\text{VEH}}}{dt} + F_{aero} + F_{roll} + F_{\text{gx}}\right).V_{\text{VEH}} \quad (3)$$

The driving resistances are as follows: the aerodynamic drag force (F_{aero}), the rolling resistance force (F_{roll}), the gravitational force F_{gx} and F_{acc} is the acceleration force (Sadoun 2013).

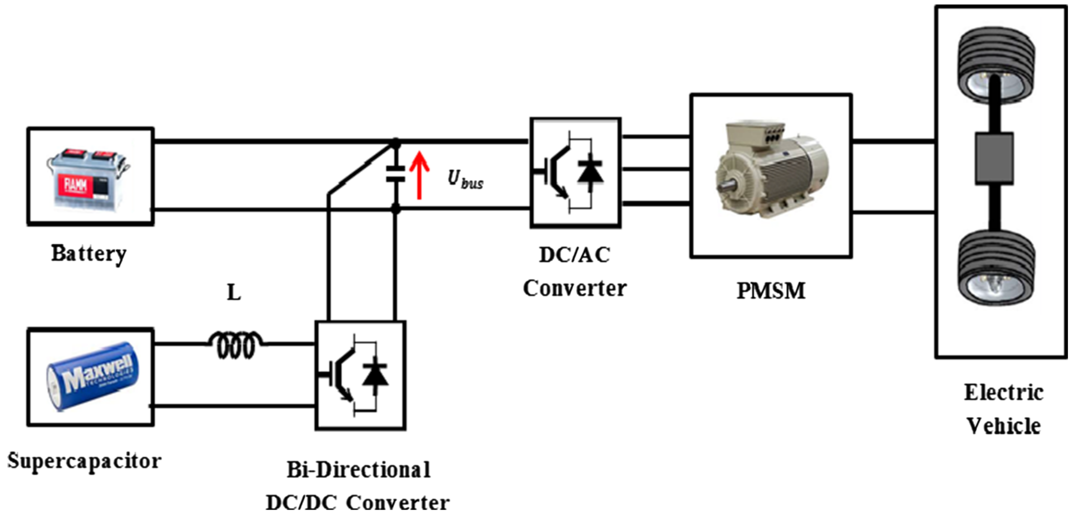


Fig. 3 Architecture of the HESS

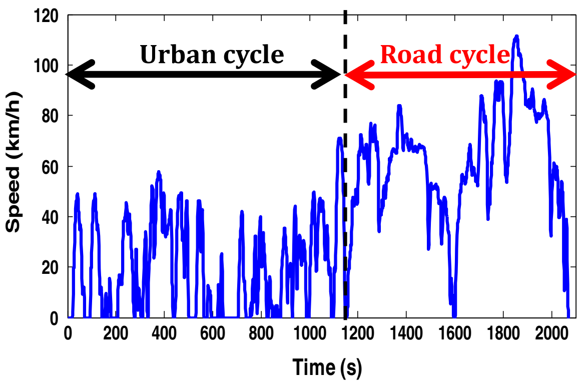


Fig. 4 ARTEMIS speed profile

The characteristics of electric vehicle used in our application are showed in the Table 3.

In this study, the range of electric vehicle is set at 150 km, where to achieve this distance the ARTEMIS driving cycle must be repeated seven times. Figure 5 shows the typical required power and energy according to driving cycle.

The propulsion power of electric vehicle is defined by positive part in Fig. 5, where the recovery power during braking phase is presented via negative values. However, the energy demand is calculated by integrating the electric vehicle power over the time. With the following equation, we can estimate the energy necessary for our mission.

$$E_{V\_cons} = \int_0^t P_V(t).dt \tag{4}$$

E_{V_cons} is the maximum energy provided by the battery to ensure 150 km of EV range shown in Fig. 5.

P_{V_cons} and P_{V_rec} are the maximum consumed and recovered power of EV, respectively.

Table 3 Parameters of the simulated EV (Hammani et al. 2012)

Parameters	Value
Vehicle mass (kg)	860
Frontal area (m^2)	2.75
Air density (kg/m^3)	1.2
Penetration air coefficient	0.3
Rolling resistance coefficient Cx	0.008

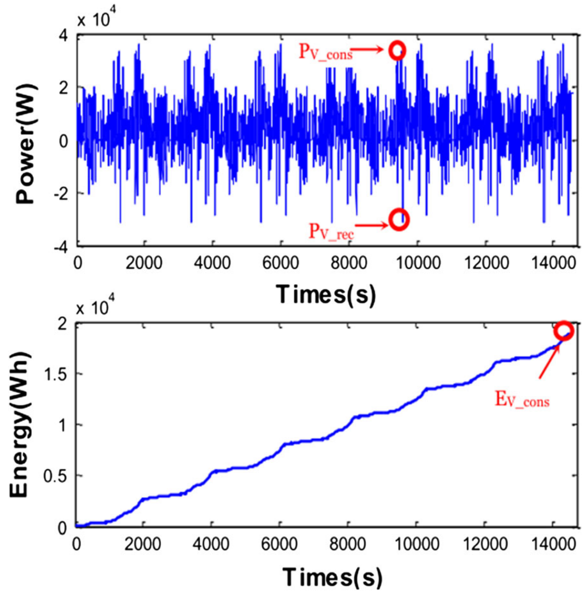


Fig. 5 The typical power and energy required on the ARTEMIS driving cycle

Battery/supercapacitor HESS model

Modeling of Li-ion battery cell

The lithium-ion battery is known as the most promising green battery and favored by most new-energy vehicles due to its tremendous advantages. However, the battery is a nonlinear system; the models usually used by most R&D groups can be classified into two typical kinds: the electrochemical model and the equivalent circuit model (ECM) (Xiong et al. 2011).

In this context, an equivalent circuit model is the most common and straightforward way of representing the dynamic behavior of a Li-ion battery cell (Thanagasundram et al. 2012; Gholizadeh and Salmasi 2014).

Using this approach of modeling, a Li-ion battery cell can be presented by open-circuit voltage (OCV) (Waag et al. 2013), with a series connection of two RC circuits, which signify the charge transfer and diffusion processes, as well as the double layer capacitance phenomenon, and series resistance R_0 represent internal resistance (Aziz and Ramli 2012). Nevertheless, in our application, the value of OCV(soc) is dependent on SOC and current direction, as well as series resistance R_0.

The battery terminal voltage obtained from the proposed model can be described by the following equation:

$$\hat{V}_{bat} = V_{OCV} + V_{R_\Omega} + V_{RC} \quad (5)$$

In our case, the impact of temperature on OCV has been neglected and the voltage evolution according to SOC is approached by the following nonlinear equation:

$$\begin{aligned} OCV(SOC) = {} & x_1 + x_2.e^{(x_3.(1-soc))} + x_4.e^{(x_5.soc)} \\ & + x_6.e^{\left(x_7.(1-soc)^2\right)} + x_8.e^{\left(x_9.(\ soc)^2\right)} \\ & + x_{10}.e^{\left(x_{11}.(1-soc)^3\right)} + x_{12}.e^{\left(x_{13}.(soc)^3\right)} \end{aligned} \quad (6)$$

where $x_{1\ldots13}$ are optimal parameters chosen to make the battery model fits the experimental data very well (Hu et al. 2015).

The SOC of battery cell is obtained by integrating the cell current overtime (Brand et al. 2014):

$$SOC = 100.\left(SOC_{int} - \frac{1}{Q_n}\int \eta\ I_b\ dt\right) \quad (7)$$

where SOC_{int} is the initial SOC value, I_b is the battery current, η is the Coulombic efficiency, and Q_n the nominal capacity of the tested cell (Q_n = 40 Ah).

The voltage drops across battery internal resistor related to the SOC and current sign is expressed by

$$V_{R_\Omega} = I_b.\frac{x_{14}}{\sqrt{soc + x_{15}.soc.sign\ (I_b)}} \quad (8)$$

where x_{14} and x_{15} are optimal parameters of equivalent series resistance R_Ω.

The voltage corresponds to the $R_{dll}C_{dll}$ and $R_{dif}C_{dif}$ circuits is given by

$$\begin{cases} V_{RC} = V_{dll} + V_{dif} \\ V_{dll}(s) = I_2(s).R_{dll} = \dfrac{1}{1 + sR_{dll}C_{dll}}.\dfrac{I_b.R_{dll}}{s} \\ V_{dif}(s) = I_4(s).R_{dif} = \dfrac{1}{1 + sR_{dif}C_{dif}}.\dfrac{I_b.R_{dif}}{s} \\ I_1 + I_2 = I_3 + I_4 = I_b \end{cases} \quad (9)$$

where the time constants for $R_{dll}C_{dll}$ and $R_{dif}C_{dif}$ circuits are $\tau_{dll} = R_{dll}C_{dll}$ and $\tau_{dif} = R_{dif}C_{dif}$, respectively (Hu et al. 2015; Mesbahi et al. 2016) (Fig. 6).

Modeling of supercapacitor cell

Since several years, supercapacitors are a promising technology in order to improve energy storage in automotive applications (Riu et al. 2004; Kuperman et al. 2013). In order to model the supercapacitor cell, various model kinds are proposed in literature such as electrochemical models and equivalent circuit models. However, the equivalent circuit models of supercapacitors are very useful and reliable in electrical power application (Buller et al. 2002; Torregrossa et al. 2014).

In this way, the supercapacitor model presented in Fig. 7 has been preferred to the others, because it is much more representative of physical phenomenon appearing inside the component (ion mobility into porous electrode with different accessibility) (Rizoug et al. 2010). However, the element r_s corresponds to the series resistance caused by the metallic conductors and the electrolyte. Thus, an infinite ladder network of infinitesimal resistors and capacitors presents the pore impedance of supercapacitor (Rizoug et al. 2012; Kreczanik et al. 2014).

The parameters of the supercapacitor model can be identified using a hybrid approach based on frequency and temporal characterization:

$$\begin{cases} R = 3(R_{BF} - R_{HF}) \\ r_s = R_{HF} \\ C = a\ V_{sc}^2 + b\ V_{sc}^2 + c \end{cases} \quad (10)$$

where R_{BF} and R_{HF} correspond to the parameters of the transmission line mainly identified by the frequency characterization. The parameters a, b, and c represent fit parameters of the capacitance variation according to the operating voltage. These parameters are identified by using the temporal characterization with a discharge/charge test of supercapacitor cell (Rizoug et al. 2010).

Battery/supercapacitor HESS sizing

In the present paper, the electric vehicles is propelled by the electric motor drive, using a Li-ion battery, and supercapacitor packs as embedded energy storage

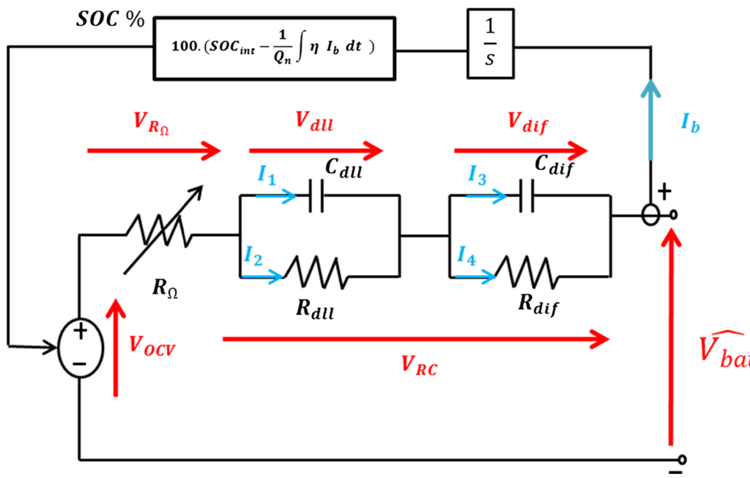


Fig. 6 Equivalent circuit model of battery

system. For that, the HESS must be sized so as to ensure that the autonomy and capacities defined by the requirements are upheld. However, in our case, the range of electric vehicle is set at 150 km.

Sizing of battery pack

The battery pack will be sized to ensure the energy of ARTEMIS driving cycle with 150 km of EV range, where this energy consumed E_{V_cons} presents a maximum of energy generated by battery pack (Carignano et al. 2014; Schaltz et al. 2009).

In order to achieve a full size of battery pack, the determination of the battery cell number $N_{bat\_cells} = N_{bat\_p}$. N_{bat_p} is a necessary step (Hu et al. 2014). For this reason, we need to know many parameters such as the speed profile, the rate of power recovery during braking phases, and the depth of discharge DOD (Rahimi-Eichi et al. 2014). In this way, the battery pack energy can be estimated by

$$E_{bat} = N_{bat\_cells}.C_{cel\_bat}.U_{cel\_bat}.\mathrm{DOD} \tag{11}$$

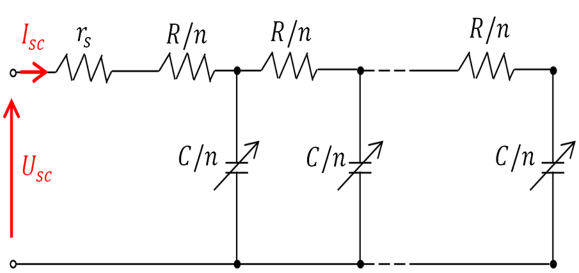


Fig. 7 Model and parameters defined with the hybrid approach

where C_{cel_bat} is the nominal capacity of a battery cells.

The DOD of batteries in automotive power application is taken around 80% (Sadoun et al. 2012). By using whole these parameters, we can calculate the branches number N_{bat_p} by

$$N_{bat\_cells} = \frac{E_{V\_cons}}{(E_{cel\_bat} - \alpha_{bat\_cons}\, w_{cel\_bat} 1.4)} \tag{12}$$

with w_{cel_bat} and E_{cel_bat} are the weight and the energy of the battery cell, respectively. α_{bat_cons} represents the variation of consumed energy E_{V_cons} according to the HESS weight.

The weight and volume of the packaging system (BMS, box…) is taken into account using two ration ε_{bat} and γ_{bat}. So, the both weight and volume of the battery pack are expressed by Mesbahi et al. (2013) and Sadoun et al. (2011):

$$\begin{cases} W_{bat} = (1+\varepsilon_{bat}).N_{bat\_cells}.w_{cel\_bat} \\ V_{bat} = (1+\gamma_{bat}).N_{bat\_cells}.V_{cel\_bat} \end{cases} \tag{13}$$

with $\varepsilon_{bat} = \gamma_{bat} = 0.4$ and V_{cel_bat} is volume of the battery cell.

Sizing of supercapacitor pack

The supercapacitors can give the best option in terms of power density to deliver the peak power necessities during a driving cycle of an electric vehicle (Perez-Pinal et al. 2007; Hammar et al. 2010).

In order to ensure, the maximum powers P_{bat_cons} and P_{bat_rec}, the supercapacitor is sized just according to the needed energy ΔE_{sc} (Sadoun et al. 2011; Camara et al. 2012; Schaltz et al. 2009). The series number of supercapacitor cells is given by

$$N_{sc\_s} = \frac{U_{bus}}{U_{cel-sc}} \quad (14)$$

where U_{cel-sc} is nominal supercapacitor cell voltage.

As well as the supercapacitor branch number N_{sc_p} can be estimated according to the maximum voltage of supercapacitor pack ($U_{sc\ max}$) and the nominal capacity of the supercapacitor cell C_{cel_sc} by the following equation:

$$N_{sc\_p} = \frac{8.\Delta E_{sc}}{3.U^2_{sc\_max}} \cdot \frac{N_{sc\_s}}{C_{cel\_sc}} \quad (15)$$

Therefore, the weights and volumes of the supercapacitor pack are given by (Sadoun et al. 2011):

$$\begin{cases} W_{sc} = (1+\varepsilon_{sc}).N_{sc\_s}.N_{sc\_p}.w_{cel\_sc} \\ V_{sc} = (1+\gamma_{sc}).N_{sc\_s}.N_{sc\_p}.V_{cel\_sc} \end{cases} \quad (16)$$

with $\varepsilon_{sc} = \gamma_{sc} = 40\%$ are the ratio of the packaging weight and volume, and W_{cel_sc}, V_{cel_sc} are the weight and volume of the supercapacitor cell, respectively (Hammani et al. 2012).

Power management strategies presented in the literature

In the case of the hybrid storage system, the energy management strategy allows dividing the mission power between the two storage technologies (battery and supercapacitors) (Camara et al. 2010; Hu et al. 2017). The power mission is computed using the speed mission. Figure 8 presents the principle of the power management in the case of hybrid storage system composed with battery and supercapacitors (Azib et al. 2010).

Recently, several management strategies of hybrid energy storage system have been developed. These ones can be classified into rule-based methods and optimization-based control strategies (Fig. 9).

The rule-based methods can be obtained by different ways, for example, by the load power filtering, the limitation of battery power, (Salmasi 2007; Romaus et al. 2009). As all of these conventional strategies follow static rules or offer only adaptation by static rules, they do not meet the formerly defined specifications concerning flexibility and adaptation of the importance of the objectives to the surroundings (Gholizadeh and Salmasi 2014; Riu et al. 2004).

Different optimization-based control strategies have been reported in literature. Indeed, several objective functions can be optimized in HESS such as, efficient power splitting, loss minimization, optimal sizing, and battery lifetime criterion (Perez-Pinal et al. 2007; Thounthong et al. 2007). Nevertheless, due to the complexity and variety of driving cycle, the precise mathematical model for energy management system is difficult to establish (Wang et al. 2010). That is why the classic energy management methods are used until now in automotive power application.

In this way, a causal energy management strategy is necessary for the operation of the vehicle in urban traffic, which can manage in real time the stochastic influences on the driving cycle and hence the EV power demand (Romaus et al. 2010).

Proceeding from a conventional strategy of the battery power limitation, we develop a novel approach of energy management based on the decreasing of power stresses applied to the Li-ion battery in hybrid energy storage system for use in electric vehicle applications.

This optimal approach is based on the variable limitation of battery power according to the supercapacitor stat of charge SOC to ensure the distribution of power in HESS. Therefore, the main goal of our proposition is to reduce the RMS battery power and operate the HESS at its highest efficiency point. Consequently, the volume and the mass of battery/supercapacitor HESS can be reduced, and their lifetime may increase.

Several power management strategies are developed and presented in the literature. The main objective of these methods is the reduction of the battery RMS power. To validate the developed methods, four literature methods will be taken as a reference. To ensure the repeatability and reproducibility of the solution, just deterministic methods are chosen like reference methods (Wirasingha and Emadi 2011).

The first method named EMS1 is the filtering strategy which take into account the frequency characteristics of the two systems (battery and supercapacitors). The filtering of the load power gives us the power insured by

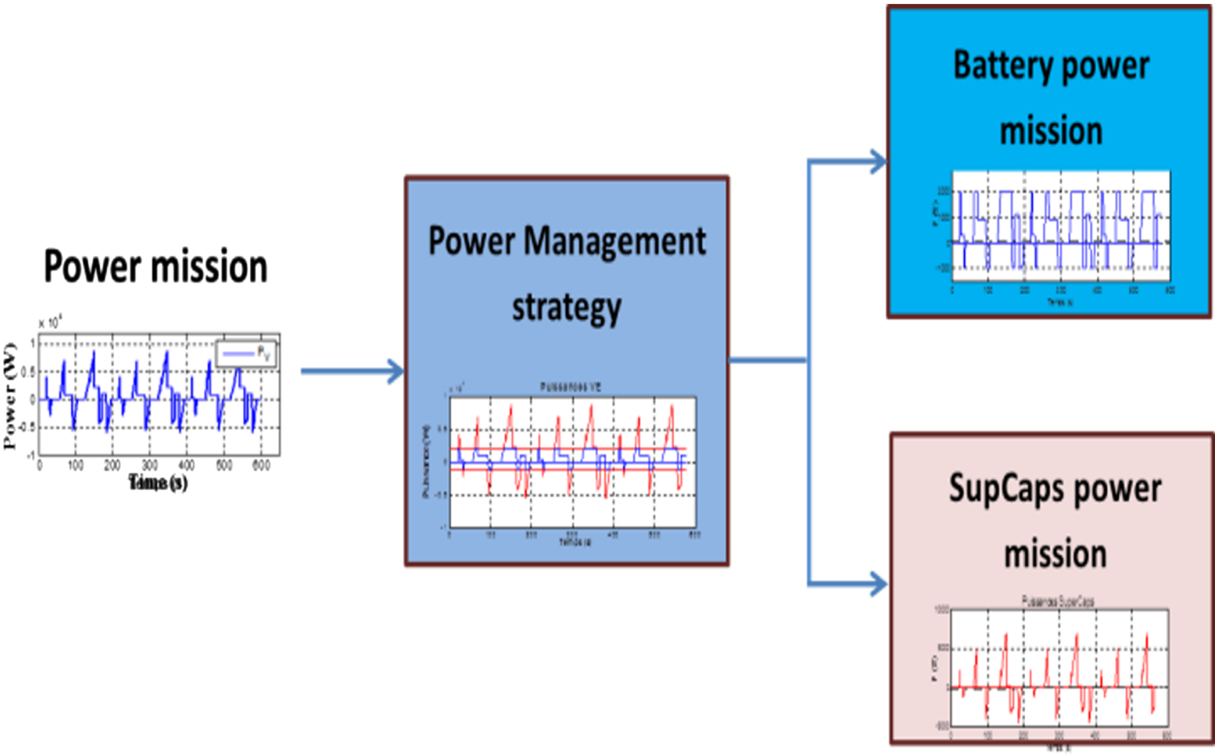
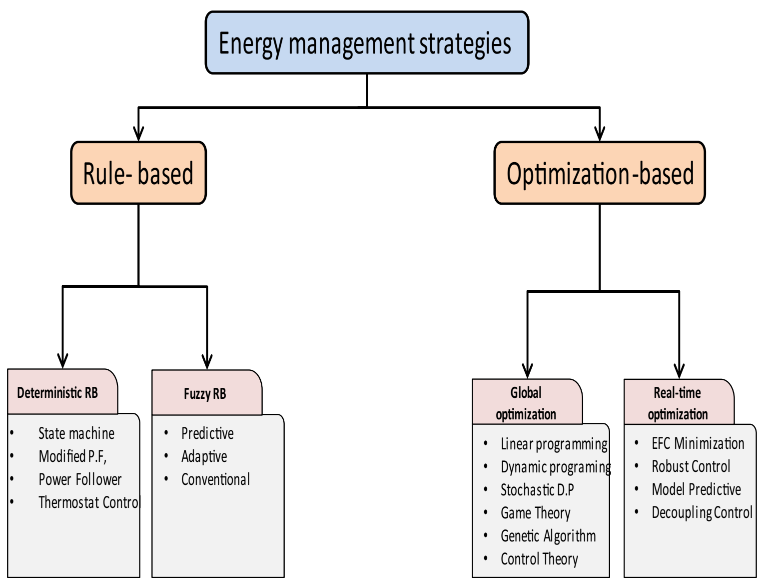


Fig. 8 Power management strategy for hybrid storage system

the battery, and the supercapacitor pack produces in this case the high frequency power. So, the supercapacitor operates in high power low energy phases and battery insures the low power high energy phases (Njoya Motapon et al. 2014).

The second method named EMS2 is based on the limitation of the battery power. In this case, the power of the battery is limited according to the maximum rates of charging and discharging power cells (Rahimi-Eichi et al. 2014).

Fig. 9 Classification of the power management strategies



The third and fourth methods named EMS3 and EMS4 are respectively the EMS1 and EMS2 methods with regulation of the supercapacitor state of charge. In this case, the battery stabilizes the supercapacitor voltage around defined level.

This method allows reducing the supercapacitor weight (Mesbahi et al. 2014). Figure 10 presents the additional regulation step with the two first methods.

Figure 11 presents the battery RMS power of the four literature methods (EMS1, EMS2, EMS3, and EMS4). The RMS power represents the stress applied to the battery, the value of this power can influence the lifetime of this last one.

The results presented in Fig. 11 prove that the method EMS1 reduces the RMS power of the battery cells and the method 4 gives us the maximum constraint applied to the battery cells. According to these results, we can conclude that the method EMS1 give the best solution. So, we must size the storage system with the four power management strategies, in order to get a clearer idea about the influence of the strategies on the weight of the HESS. Figure 12 presents the improved method which allows us to size of the storage system according to the power mission of the two components (battery and supercapacitors). The additional weight due to the embedded storage system is added with the vehicle weight to compute the power mission.

Figure 13 presents the weight of the storage system with the four power strategies. This figure shows that the method EMS1 gives us the highest weight with 379 kg and the best weight is given by the EMS4 strategy with 285 kg.

So, the improvement of the RMS power influences also the weight of the storage system. For that, we must include the weight of the storage system like parameter with the RMS power optimization.

In our case, the weight of the storage system is kept at the best value, which is 285 kg (238 kg for the battery and 47 kg for the supercapacitor). In the next section, we present the new developed strategy. Our objective is the reduction of the battery stress (RMS power) with the best storage system weight (285 kg).

Approach based on dynamic limitation of the battery power according to the supercapacitor state of charge

Energy management strategies are used to control the power dividing between the two storage components

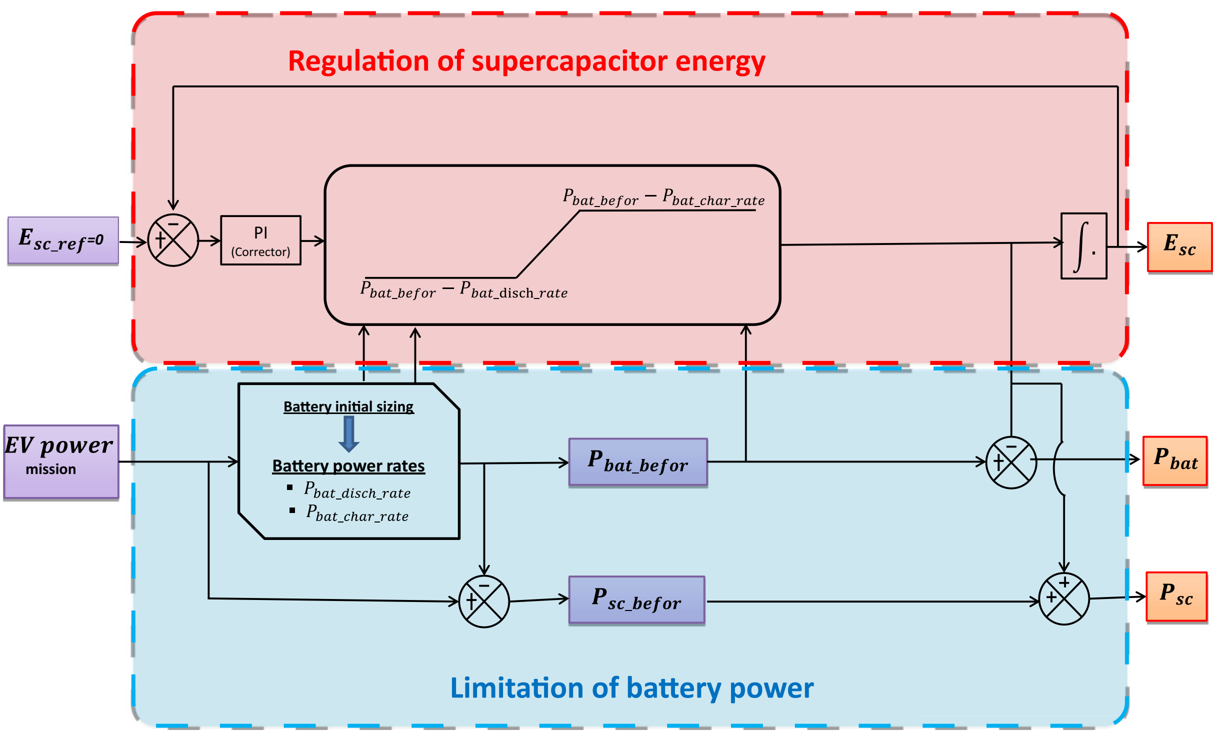
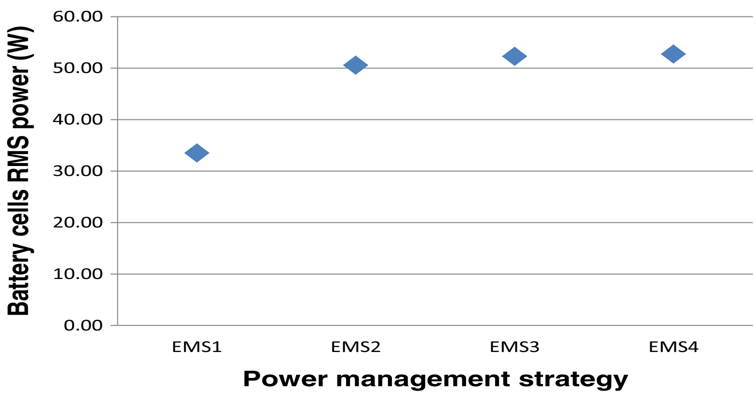


Fig. 10 Regulation of the supercapacitor state of charge

Fig. 11 Battery RMS power with the four literature strategies



which represent the embedded storage system. This last one must ensure the load power. The power management strategy takes into account the storage component behaviors (Melero-Perez and Fernandez-Lozano 2009; Guidi et al. 2009).

In this context, increasing the global efficiency allows improving the car range, with the consumption reduction and increasing of the storage component lifetimes (Caux et al. 2010; Garcia et al. 2010).

In this section, four improved energy management strategies for battery/supercapacitor HESS are suggested and investigated to control the power flow, as well as to reduce the RMS battery power. All these strategies are based on the dynamic limitation of the battery power, and the variation of this last one according to the supercapacitor SOC. These strategies allow the reduction of the battery RMS power, with the compliance of the storage component (battery and supercapacitors) sizes. At the same time, battery ensures the regulation of the supercapacitor voltage around defined level.

For our study, the performance of the EMS4 strategy is taken like reference, and all the developed methods must keep the same size (285 kg) and improve the battery RMS power.

Dynamic limitation of the battery discharge power according to the supercapacitor SOC and restriction of battery energy recovery (ESM4/S1)

In this section, we present the basic approach of the energy management strategy developed in our laboratory. This approach is based on the variable limitation of battery power according to the supercapacitor state of charge. However, the optimal sizing of HESS and long lifetime of the battery are the main goals of our strategy. For these reasons, this proposed strategy use the energy state of supercapacitor like main factor to change the power split between the two storage components (Fig. 14).

To keep the instantaneous supercapacitor energy E_{sc} lower than the sizing energy value, the limit of the battery discharge power is switched to higher value when the supercapacitor state of charge exceeds the

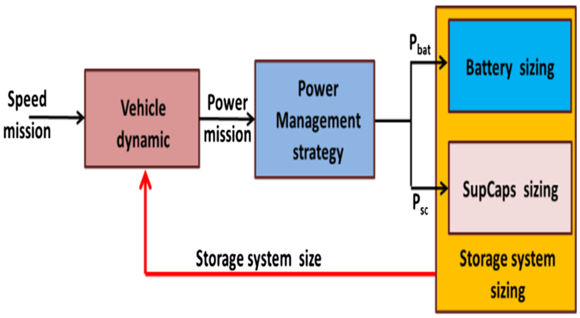


Fig. 12 Sizing of the storage system according to the power mission of battery and supercapacitor

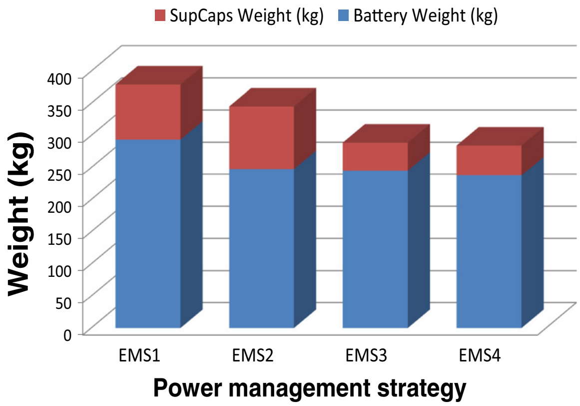


Fig. 13 Size of the storage system with the four literature strategies

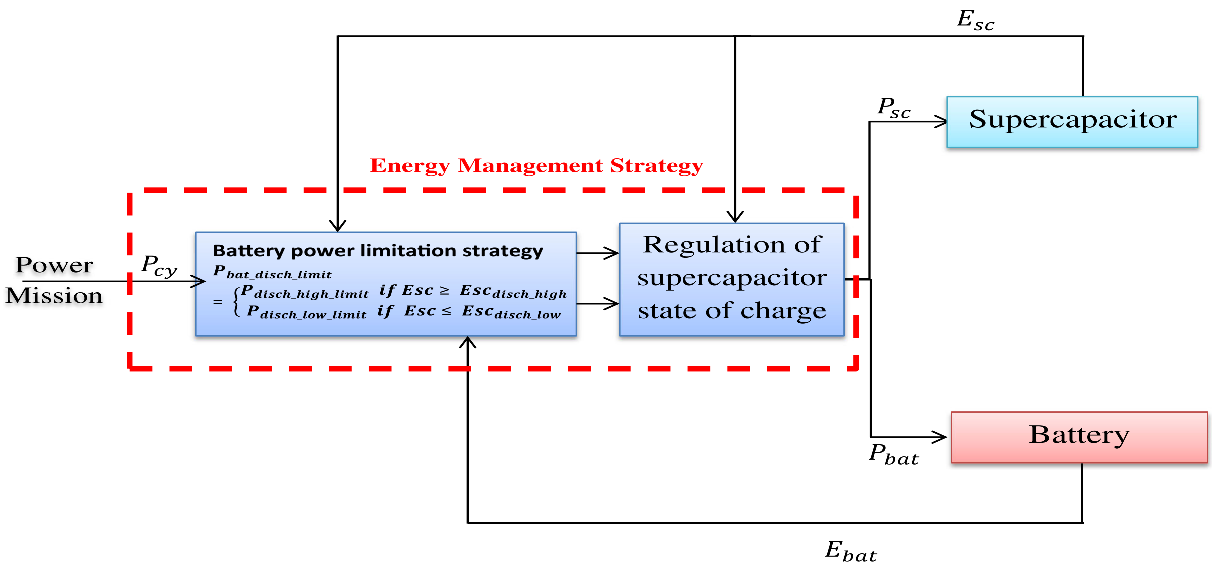


Fig. 14 Strategy based on the limitation of the battery power according to the supercapacitor SOC

higher limit (Esc_{disch_high}), and this limit is switched to lower value when the supercapacitor state of charge decreases less than the lower limit (Esc_{disch_low}):

$$P_{bat\_disch\_limit} = \begin{cases} P_{disch\_high\_limit} & if\ Esc \geq Esc_{disch\_high} \\ P_{disch\_low\_limit} & if\ Esc \leq Esc_{disch\_low} \end{cases} \quad (17)$$

$P_{disch\_high\_limit}$, is the maximum continuous power supported by the battery pack, and the $P_{disch\_low\_limit}$ is the average value of the battery mission power. Esc_{disch_high} and Esc_{disch_low} are computed according to the vehicle mission.

The limit of the battery charge power is kept at constant value $P_{rec\_33\%}$. This value allows us to recover 33% of the energy during the braking phases (Sadoun et al. 2011).

$$P_{bat\_char\_limit} = P_{rec\_33\_\%} \quad (18)$$

This improved strategy reduces the global power stress applied to the battery and respect the storage component (battery and supercapacitors) sizes.

Variation of the battery charge and discharge power limitation between two levels (P_{lim_high} and P_{lim_low}) according to the supercapacitor state of charge (ESM4/S2)

This strategy uses the idea of dynamic limitation of the battery power according to the supercapacitor SOC with the two battery power limits: charge and discharge. The evolution of these power limits according to the supercapacitor SOC is given by the Formula 12 and 13:

$$P_{bat\_disch\_limit} = \begin{cases} P_{disch\_high\_limit} & if\ Esc \geq Esc_{disch\_high} \\ P_{disch\_low\_limit} & if\ Esc \leq Esc_{disch\_low} \end{cases} \quad (19)$$

The charge power is negative, which gives

$$P_{bat\_char\_limit} = \begin{cases} P_{char\_high\_limit} & if\ Esc \leq Esc_{char\_high} \\ P_{char\_low\_limit} & if\ Esc \geq Esc_{char\_low} \end{cases} \quad (20)$$

This strategy allows the reduction of the battery RMS power and forbids the overcharging of the supercapacitors.

Dynamic limitation of the battery power according to the supercapacitor SOC with continuous variation of the battery power limit $P_{lim} = f(SOC_{sc})$ (ESM4/S3)

Using the same approach of dynamic limitation of the battery power according to the supercapacitor SOC with a regulation of the supercapacitor voltage around a well-defined value, the battery power limits are changed with a fast continuous variation according to the supercapacitor SOC. A mathematical function is developed in order to ensure the fast changing of battery power limits, which is defined and optimized after a lot of simulation tests:

$$P_{\text{bat\_}disch\text{\_}limit} = \begin{cases} K_{\text{sc}}.\text{Esc} \;\; if \;\; \text{Esc}\geq 0 \\ 0 \;\; if \;\; \text{Esc}\leq 0 \end{cases} \quad (21)$$

$$P_{\text{bat\_char\_}limit} = \begin{cases} 0 \;\; if \;\; \text{Esc}\geq 0 \\ K_{\text{sc}}.\text{Esc} \;\; if \;\; \text{Esc}\leq 0 \end{cases} \quad (22)$$

where K_{sc} is the coefficient of continuous function.

Figure 15 presents the management approach using these functions according to supercapacitor SOC.

Dynamic limitation of the battery power according to the supercapacitor SOC with continuous variation of the battery power limit and increasing the operation voltage of supercapacitors

Using the last power management strategy (ESM4/S3) allows reducing the battery power stress. On the other hand, the supercapacitors' RMS power is very low compared to the maximum power of this component. So, to improve the battery power, we must increase the RMS power of the supercapacitors more and more. For that, we can overcharge the supercapacitors by the decreasing of the battery power limits. For this reason, the operation voltage of supercapacitors is increased to ensure the load demand. This method ensures the increasing of the supercapacitor stresses and the decreasing of the battery stresses, to obtain finally the equalization of the stresses between the two components (battery and supercapacitors).

Results and discussion

Simulation results

In order to evaluate the performance and feasibility of the proposed energy management strategies for battery and supercapacitor HESS, a simulation work has been done using MATLAB/Simulink software.

Figure 16 shows the comparison between the sizing results of the battery/supercapacitor HESS, which the literature energy management strategies are compared with the development strategies.

It clearly appeared from Fig. 16 that the battery/supercapacitor HESS weight decreased up to the optimal value given by EMS4. In order to study the power constraints of Li-ion battery in electric vehicle applications, the optimal weight of HESS must be keep constant. Indeed, it is evident that the proposed energy management strategies have the ability to maintain the optimal weight of HESS.

Two main factors are defined for energy management strategies comparison: RMS battery power and battery quantity of charge.

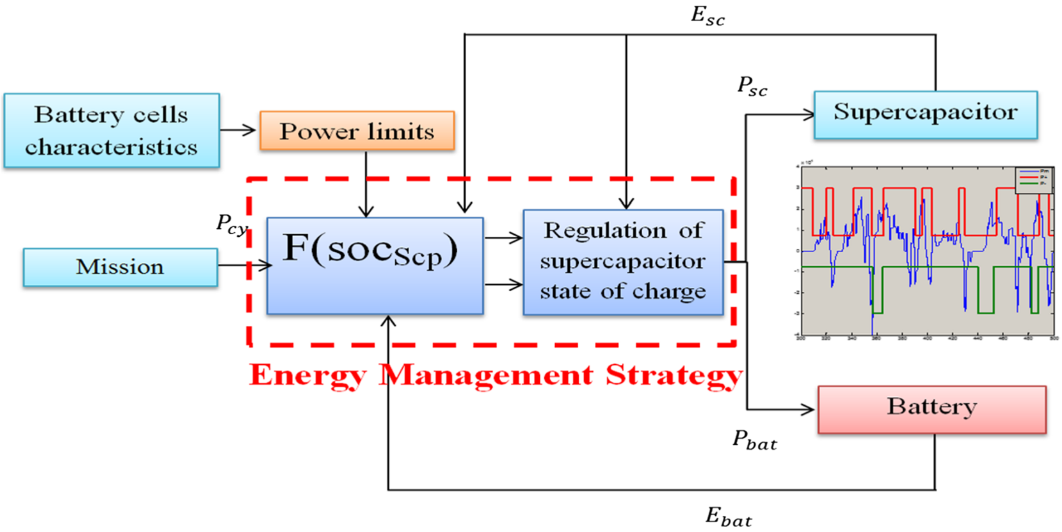


Fig. 15 Using of linear functions between the limit of the battery power and the supercapacitor state of charge

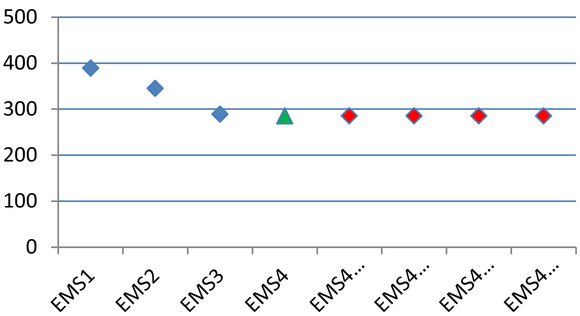


Fig. 16 The weight of HESS for different energy management strategies

RMS battery power

This factor corresponds to a reduction of the global constraints of the battery and it is heating during HESS operation.

The RMS value of the battery power P_{rms} is calculated as the following equation (Kreczanik et al., 2014):

$$P_{rms} = \sqrt{\frac{1}{T}\int_0^T P_{Bat}^2 \, dt} \quad (23)$$

where P_{Bat} is the battery power.

Battery quantity of charge

The battery quantity of charge is introduced to evaluate the partial charge and discharge during drive cycle, which there are many acceleration and deceleration phases. However, this parameter can be given a signification for battery aging process. This factor is defined by the following formula:

$$\mathrm{Ah} = \left(\frac{1}{V.3600}\right)\int_0^T |P_{Bat}| \, dt \quad (24)$$

Figure 17 shows the RMS battery power correspond a tested energy management strategies. This result shows a low RMS power with the developed methods compared to the literature methods. In particular, the developed energy management strategy (EMS4/S4), which gives a lowest RMS battery power compared to the other methods. As a result, the decreasing of the power stresses applied to the Li-ion battery via the energy management strategies improves the HESS lifetime and reduces its global cost.

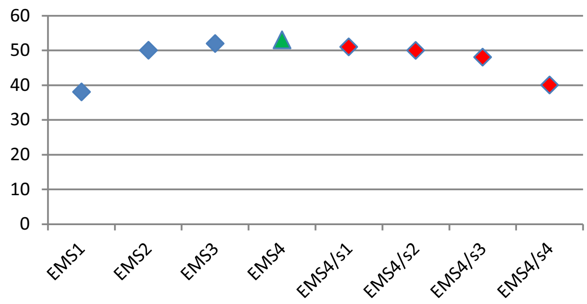


Fig. 17 RMS battery power

The last parameter which can influence the lifetime of the battery is the battery quantity of charge (Ah) in charge and discharge phases. Figure 18 shows that the developed energy management strategies give a lowest Ah in comparison with the literature methods. This result confirms the advantage of our approach, which used to develop these strategies.

Experimental results

In order to validate the proposed energy management strategies, a test bench is developed in our laboratory (Fig. 19). This last one is composed with two storage system emulator for battery and supercapacitors. The load is emulated by the return of energy to the DC power supply (Konig et al. 2014).

Figure 20 presents the principle of the battery emulator. Using this last one, we can estimate the battery state of charge, and we can also modify the parameters of this storage system.

The characteristics of the battery emulator are well detailed in (Mesbahi et al. 2013) (Fig. 21).

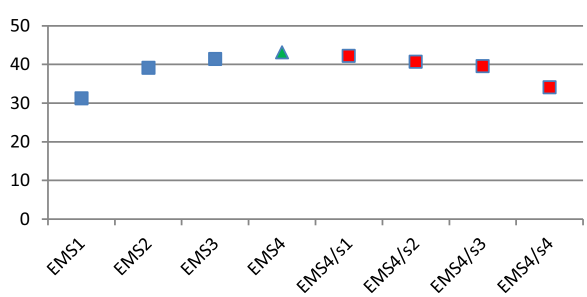


Fig. 18 Battery quantity of charge

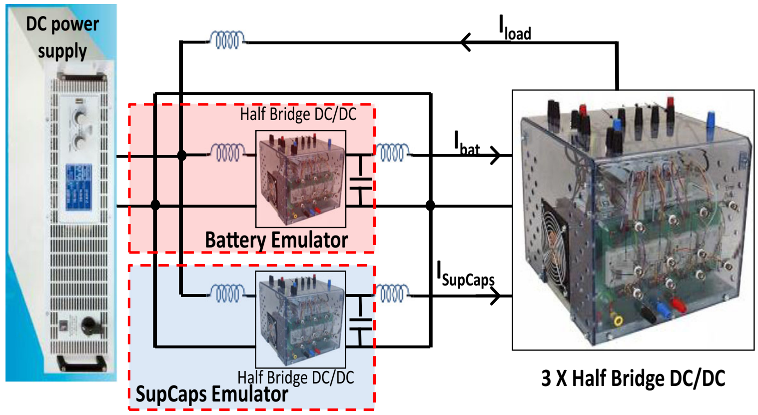


Fig. 19 Test bench developed to validate the developed strategies

The DC bus of embedded supply is regulated by the control of the battery power through a boost DC/DC converter. However, a dSPACE DS1104 controller board is used to control the whole system. So, with this developed test bench, we can validate our energy management strategies of battery/supercapacitor HESS.

This controller board enables the linking of the MATLAB/Simulink environment to real converter hardware. The currents and voltages of the storage system emulators and that of the load are acquired through sensors. Several tests were performed with a power scale ratio 1/15. Figure 22 presents the measured load current (ARTEMIS), which emulated by a DC/DC converter. In our case, we use Buck/Boost DC/DC converter commuted at 10 kHz.

Figure 23 shows the battery current with EMS4 strategy and that obtained with the developed EMS4/s4 strategy. This result shows the lowest fluctuation of the battery current in the case of the developed strategy compared to that of

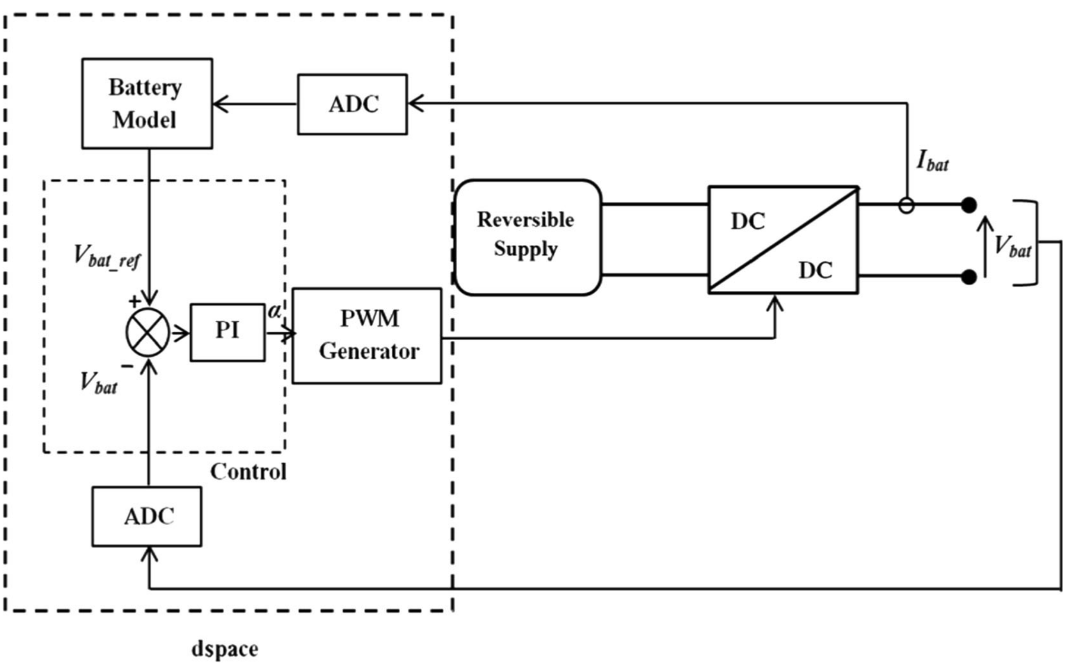


Fig. 20 Battery emulator design

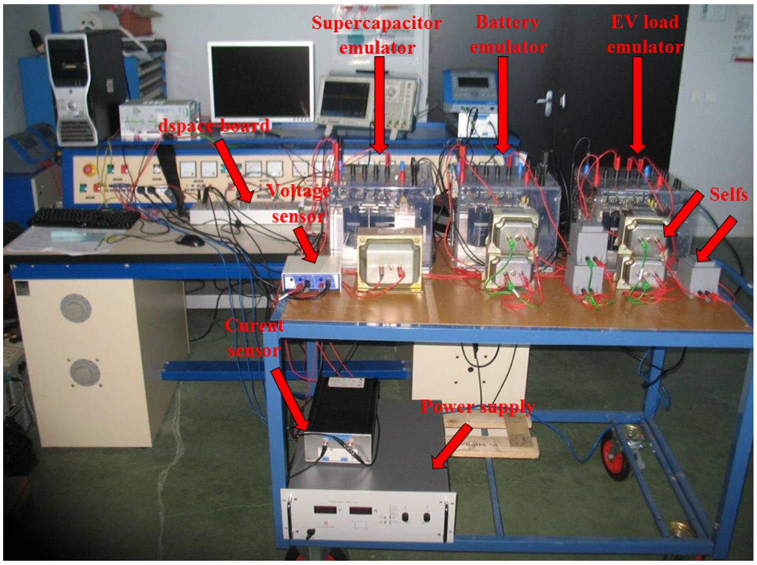


Fig. 21 Test bench

literature method that can give the lowest battery RMS power. On the other hand, the result (Fig. 24) shows the increasing of the supercapacitor power fluctuation that can increase RMS power of this component. So, our strategy balances the stresses between the two storage systems (battery and supercapacitors).

Figure 25a presents the battery SOC during the part of EV mission (one ARTEMIS cycle). This figure shows that all strategies give the same SOC at the end of the mission. If we zoom, we can find a difference between the SOC evolutions with these strategies (Fig. 26), and if we analyze the results of this last figure and that of the Fig. 27, we can show that the gap between the battery SOC of the EMS4 strategy and those of the developed strategy depends on the evolution of the supercapacitors SOC. The more use of the supercapacitor increases the battery SOC. Figure 25b presents the battery SOC during 150 km (ARTEMIS cycle repeated seven times).

Because of the ratio (1/15) between the real load power and the power level in our tests, the RMS power is compared with that of the EMS4 strategy. Figure 28 presents the battery RMS power of the developed strategies compared to that of the EMS4 strategy. This result proves the

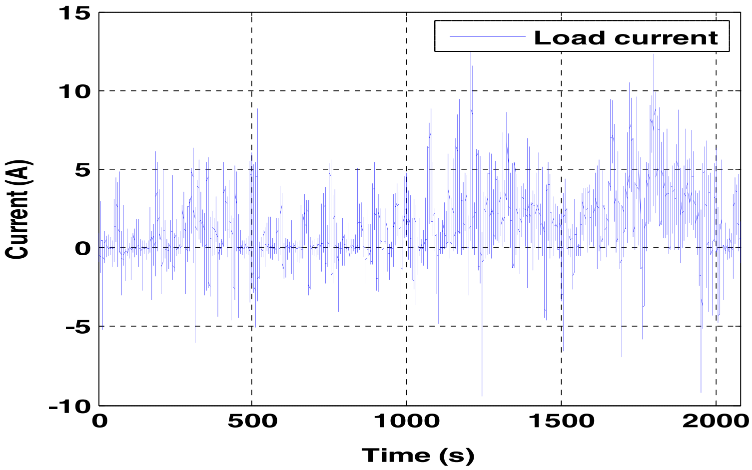


Fig. 22 EV load current (ARTEMIS) with 1/15 scale ratio

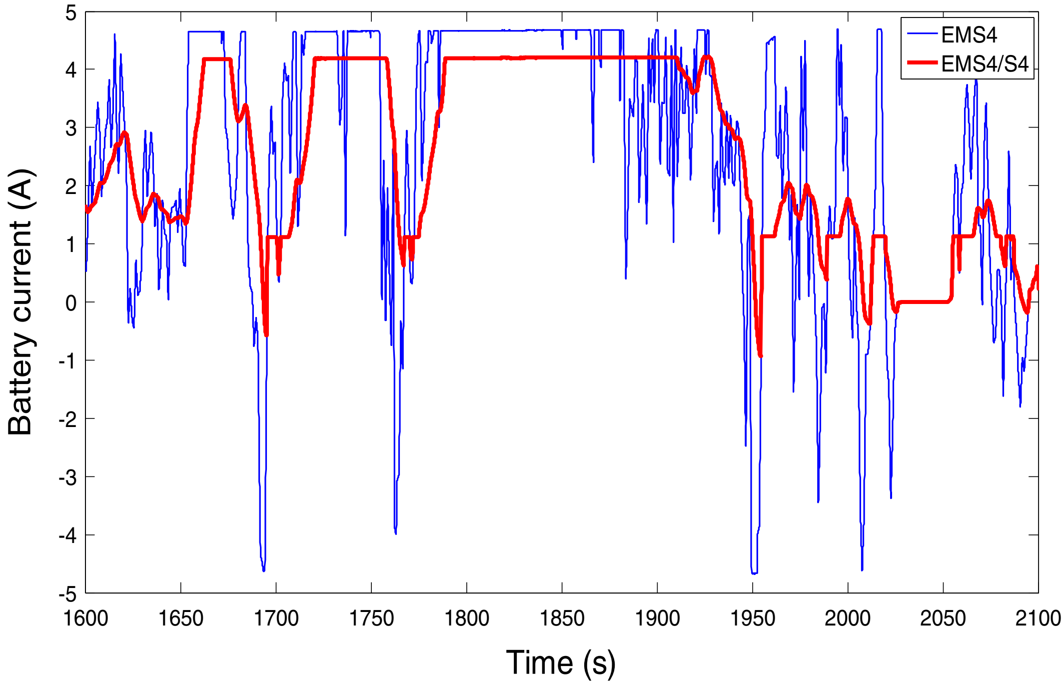


Fig. 23 Battery current with literature method (EMS4) and that developed in our laboratory (EMS4/S4)

decreasing of the RMS power with the developed strategies. The low gap between the experimental results and that of the simulations are dues to the simulation errors and the measurement noises.

On the other hand, Fig. 29 shows the increasing of the supercapacitor RMS power with the developed strategies. This results show also the low gap between the experimental and the simulation values of the

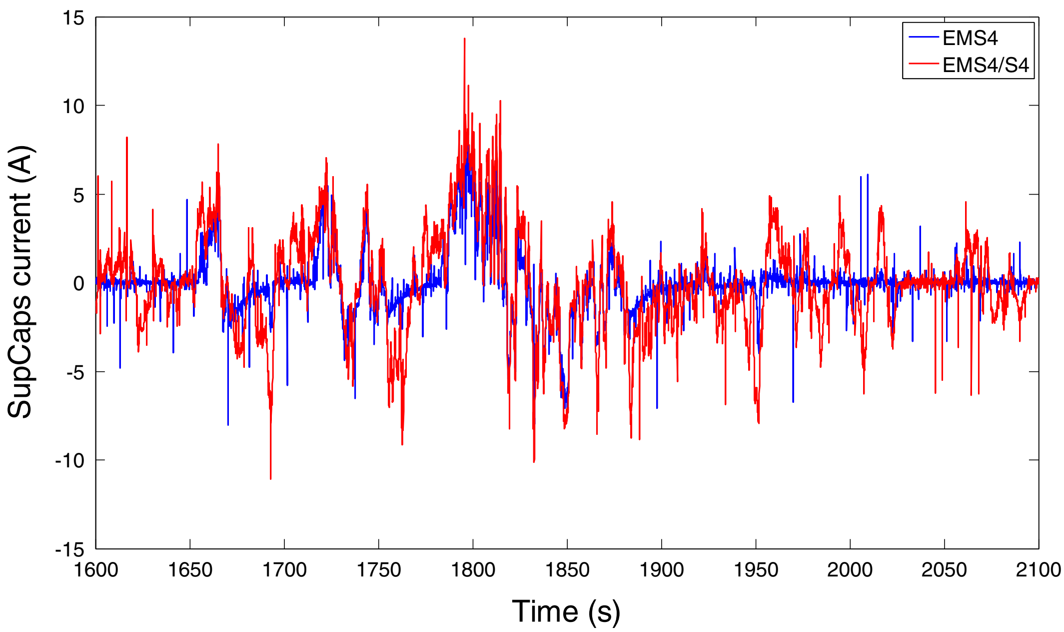


Fig. 24 Supercapacitor current with literature method (EMS4) and that developed in our laboratory (EMS4/S4)

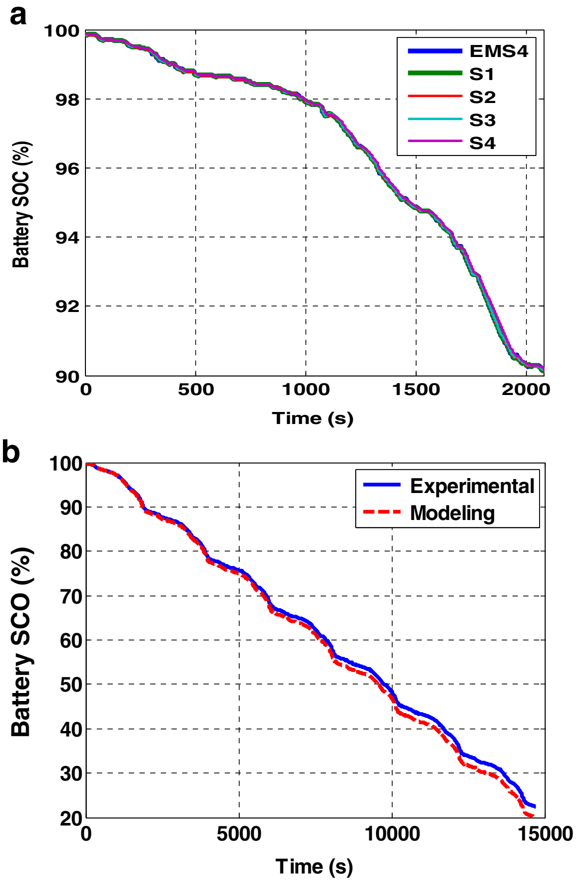


Fig. 25 **a** Battery SOC with developed strategies. **b** Battery SOC with EMS4 strategy

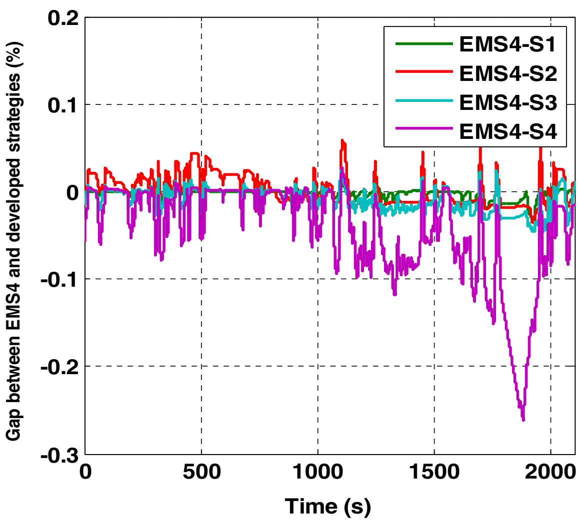


Fig. 26 Gap between EMS4 battery SOC and developed strategies

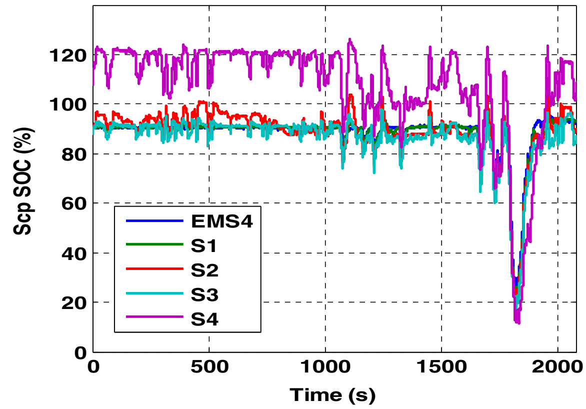


Fig. 27 EMS4 supercapacitor SOC with developed strategies

RMS power. This increasing of the power is very important compared to the EMS4 methods but very low compared to the power limits of the supercapacitor cells.

Figure 30 shows that the maximum supercapacitor cell RMS power is given by the EMS4/s4 strategy (14.4 W). This RMS power represents 5.3% compared to the power limit of this cells (270 W). For the battery, the RMS power given by the EMS4/s4 (34.1 W) represents 22.7% compared to the power limit of this battery cells (270 W).

Conclusion

In this paper, new energy management strategies for battery/supercapacitor hybrid energy storage system has been developed and tested in the case of electrical vehicle application. The main idea of

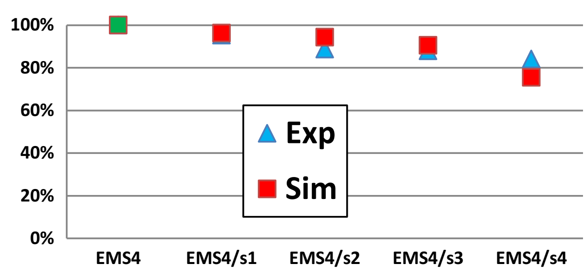


Fig. 28 RMS battery power of developed EMS's compared to that of the EMS4 strategy

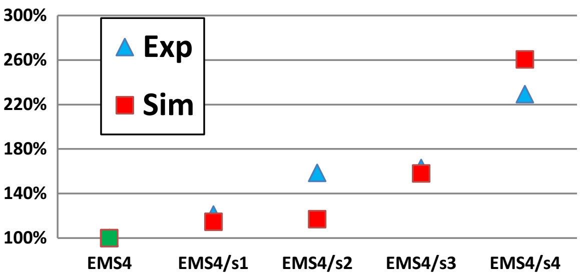


Fig. 29 RMS supercapacitor power of developed EMS's compared to that of the EMS4 strategy

all developed EMS's is based on the variable limitation of battery power according to the supercapacitor SOC to ensure the best distribution of electric vehicle power between the two storage systems of the HESS. However, our study shows that the select of the energy management strategy is a key issue to improve the source size and decreases the constraints applied to Li-ion battery.

The obtained results show, for the same driving cycle of electrical vehicle (EV range, maximum acceleration, and energy recovery), and for the same size of the hybrid storage system (optimal size), the use of developed energy management strategies allows reducing the battery power stresses.

By using one of these developed EMS's, the battery and supercapacitor power constraints can be adjusted. As a result, the state of health (SOH) of the battery may be well controlled during electrical vehicle operation. This allows us to improve the lifetime of battery and reduce the global cost of HESS.

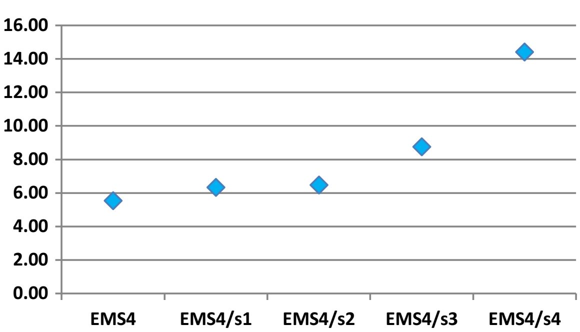


Fig. 30 RMS supercapacitor cells RMS power of developed EMS's and the EMS4 strategy

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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