Different energy management strategies of Hybrid Energy Storage System (HESS) using batteries and supercapacitors for vehicular applications

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Abstract—**The energy storage is a key issue for traction applications like Electric Vehicles (EVs) or Hybrid Electric Vehicles (HEVs). Indeed, it needs a higher power and energy density, a right size, a long lifetime and a low cost. A Hybrid Energy Storage System (HESS) using batteries and supercapacitors seems to be an appropriate device to fulfill these constraints. The objective of the paper is to propose different energy management strategies of HESS using batteries and supercapacitors. Four elaborated control strategies are proposed. Different strategies are compared on different criteria: electric consumption, sizing, and the expected lifetime of the batteries.**

Keywords-hybrid energy storage system, energy management strategy, batteries, supercapacitors, ultracapacitors, electric vehicle.

I. INTRODUCTION

Since the last decade, Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have an increasing development [1]-[3]. They propose new vehicles for reduction of energy consumption and pollutant emissions. But more improvements are required to make EVs and HEVs competitive with classical vehicles [4].

One key issue of the development of EVs and HEVs is the Energy Storage System (ESS) [5]-[6]. The classical electrochemical batteries lead to the main limitations of such vehicles. First, their energy density is greatly lower than the energy density of petrol-based fuel, which affects the weight and the range of the vehicles. Moreover, the charge time is another prohibitive factor. Finally, the lifetime of batteries is not sufficient for traction applications.

New kinds of batteries have been developed to propose more efficient ESS, such as Ni-MH and Li-ion batteries. Moreover supercapacitors have been introduced in association with batteries to propose new characteristics of ESS [5]-[8]. Supercapacitors have less energy density than batteries, but they have more power density. Hybrid Energy Storage Systems (HESS) are thus proposed for power demand using supercapacitors and energy demand using batteries. In this way, the batteries can ensure only the average power and the supercapacitors can ensure the power variations. The design and the lifetime of batteries can thus be improved [9]-[12].

The objective of the paper is to propose different energy management strategies of HESS using batteries and supercapacitors. A first work has been carried out on the same topology of HESS and aimed at studying the influence and the interest of the control on the hybrid ESS [7]. The three proposed strategies were simple and only their influences on the battery current stresses have been studied. In this paper, more advanced strategies are proposed. In section II, the model and the control of the studied Electric Vehicle (EV) with HESS are presented in [14]. In section III, new strategies are detailed to manage the studied HESS. Finally in section IV, an EV with only batteries and an EV with batteries and supercapacitors are compared for the different strategies on different criteria: electric consumption, sizing, and the expected lifetime of the batteries.

II. MODEL AND CONTROL OF THE STUDIED EV WITH HESS

A. Model

The studied EV uses a HESS with batteries and supercapacitors (Figure 1). Different topologies are proposed to associate batteries and supercapacitors [13]-. The studied HESS uses an active association with two choppers in parallel [13]-[18]. The first chopper is inserted between the batteries and the DC bus and the second chopper between the supercapacitors and the DC Bus (Figure 1). This topology has the advantage to decouple the batteries and the supercapacitors. The two degrees of freedom introduced by the two choppers allows to control the power flow between the two electrical sources and to control the DC bus voltage. The traction system is composed of an inverter connected to the DC bus, an electric machine, a differential witch distributes the torque on the wheels and the environment of the vehicle.

This system is depicted using EMR (Energetic Macroscopic Representation) (upper part of Figure 2) [19]. EMR is a graphical description, which organises the system into

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interconnected basic subsystems: accumulators of energy (orange crossed rectangles), source of energy (green ovals), electrical conversion (orange squares) and distribution of energy (double squares). All elements are connected according to the interaction principle. The product of the action (example, the current *i*) and reaction (example the voltage *v*) always leads to the power exchanged by connected elements (example $p = v\ i$) [14], [19].

The equations in the REM blocks of the HESS are detailed in [7]. The equations of the traction system are developed (Figure 2).

Inverter and electric machine – They are represented by an electro-mechanical conversion element (circle) and modelled by a quasi-static model.

$$T_{em} = \frac{1}{1+\tau_{CL}} T_{em\_ref} \tag{1}$$

$$i_{tract} = \frac{P_{tract}}{u_c} \text{ with } P_{tract} = T_{em} \Omega_{gb} \tag{2}$$

with τ_{CL} is the closed loop constant time of the electric machine and P_{tract} the traction power.

Equivalent differential – This is represented by a mechanical conversion element (triangle) with a gearbox ratio k_{gb}:

$$\begin{cases} T_{gb} = k_{gb}\ T_{em} \\ \Omega_{gb} = k_{gb}\ \Omega_{wheel} \end{cases} \tag{3}$$

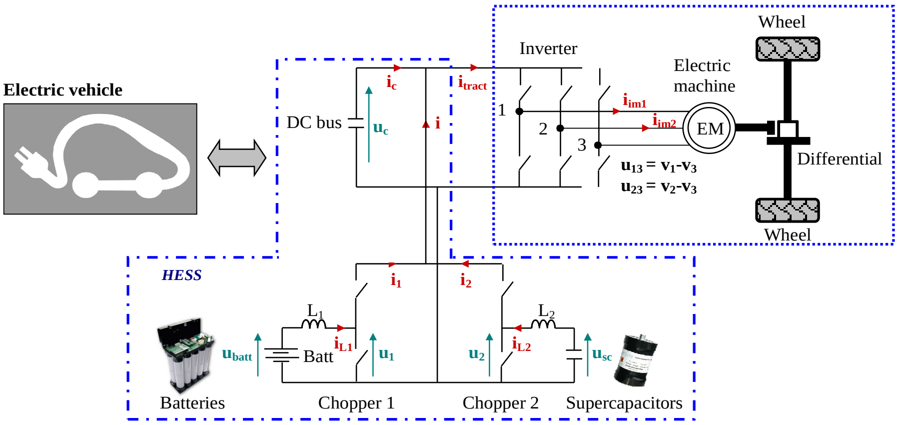

Figure 1. Studied EV with HESS

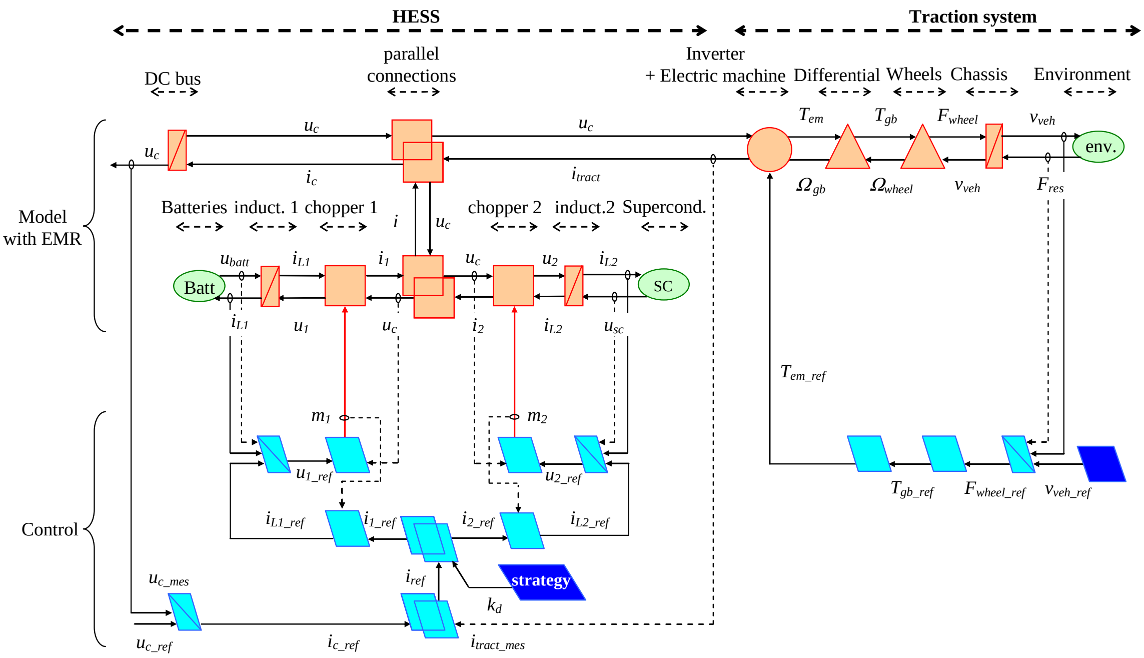

Figure 2. Model and control of the studied EV with HESS

Equivalent Wheel – This is represented by a mechanical conversion element (triangle) with radius R_{wheel}:

$$\begin{cases} F_{wheel} = \dfrac{1}{R_{wheel}} T_{gb} \\ \Omega_{wheel} = \dfrac{1}{R_{wheel}} v_{sub} \end{cases} \quad (4)$$

Chassis – This is represented by an accumulation element (crossed rectangle), with the vehicle velocity v_{sub} as the state variable:

$$F_{wheel} - F_{res} = M \frac{d}{dt} v_{sub} \quad (5)$$

with M is the mass of the chassis.

Environment – This is represented by a mechanical source (oval) which delivers the resistive force to the motion F_{res}.

$$F_{res} = F_{stat} + F_{visc} + F_{aero} + F_{down} \quad (6)$$

with F_{stat} the static friction force, F_{visc}, the viscous friction force, F_{aero}, the aerodynamic force, F_{down}, the downgrade force.

B. *Inversion-based control*

From the EMR of the system, an inversion-based control is defined using inversion rules (bottom part of figure 2) [7]. An inversion-based control of the HESS is proposed. In particular, it needs a controller to control the DC bus voltage, and two controllers to control the battery and the supercapacitor currents. A distribution coefficient k_d is introduced to distribute the power between the batteries and the supercapacitors thought the chopper currents:

$$\begin{cases} i_{1-ref} = k_d i_{ref} \\ i_{2-ref} = (1-k_d) i_{ref} \end{cases} \quad (7)$$

When $k_d = 0$ the power flow is provided by the supercapacitors, when $k_d = 1$ the power flow is provided by the batteries, when k_d has another value it defines the power sharing between both devices. A strategy block called k_d is added in order to impose the power sharing. The inversion based control of the traction part is focused on the control of the velocity of the vehicle.

III. Different Energy Management Strategies of the HESS

The aim of the energy management strategies of the HESS is that the batteries supply the average power and the supercapacitors the power fluctuations. Four elaborated strategies are studied to come up this expectation.

A. *Recharge of the supercapacitors*

For all proposed strategies, when the supercapacitors reaches their higher voltage limitation (maximal value), the batteries receive all the recovered energy and when the supercapacitors reach their lower voltage limitation (minimal value), the batteries supply all the traction energy. Generally, for a flat road, the supercapacitors reach their lower voltage limitation rather than their higher limitation because the traction power demand is more important than the recovered power. To keep the interest of the association with supercapacitors, the supercapacitors have not to reach their lower voltage limitation. The first idea is to recharge them using the batteries as soon as the vehicle is not moving. If the vehicle is at standstill long enough, the supercapacitors are recharged until a target value. The chosen target value is the maximal voltage value of the supercapacitors. Indeed, we suppose that at standstill, there will be an acceleration phase where the supercapacitors will be used and will be discharged. The second idea is to use the deceleration energy to recharge the supercapacitors .

B. *Energy management strategies*

Source resistance strategy – Generally, the internal battery resistance is more important than the internal supercapacitor resistance. Thus, for a same current, there are more losses in the batteries than in the supercapacitors. As long as $i_{tract} > 0$ (acceleration phase…), the distribution coefficient is defined from the current $i_{h\_batt\_ref}$, calculated to minimize the global losses of the HESS (8). For this calculation, we suppose that the battery and supercapacitor models are composed of a voltage source ($U_{b\ att\_0}$, U_{scp_0}) and an equivalent resistance (R_{batt}, R_{scp}). When $i_{tract} < 0$, all the recovered energy is sent to the supercapacitors.

$$i_{h\_batt\_ref} = \frac{i(R_{scp} + R_{L2})U_{batt\_0}^2}{(R_{batt} + R_{L1})U_{scp\_0}^2 + (R_{scp} + R_{L2})U_{batt\_0}^2} \quad (8)$$

with, R_{L1}, R_{L2} are the resistances of the inductances L_1 and L_2.

Vehicle acceleration strategy – The traction force F_{tract} is composed of a global resistive force F_{res} and a force function of the vehicle acceleration F_{acc} which needs the more important power demand P_{acc}. For this strategy, the supercapacitors supply and receive the power P_{acc}. The batteries supply and receive the rest of the traction power P_{tract}, i-e the power P_{res}.

$$F_{tract} = F_{acc} + F_{res} \text{ with } F_{acc} = Ma_{veh} \quad (9)$$

$$P_{tract} = P_{acc} + P_{res} \quad (10)$$
$$\text{with } P_{acc} = v_{veh} F_{acc} \text{ et } P_{res} = v_{veh} F_{res}$$

where M is the mass, v_{veh}, the velocity and a_{veh} the acceleration of the vehicle.

Filtration strategy – This strategy is based on the filtration strategy developed in [14]. As long as $i_{tract} > 0$, the batteries supply the lower frequency part of the traction current i_{tract}, while the supercapacitors supply the high frequency part. When $i_{tract} < 0$, all the recovered energy is sent to the supercapacitors.

Variable saturation current strategy – The idea of this strategy is to limit the power supplied or received by the batteries. As the DC bus is maintained constant, the current i_{h_batt} is limited. The batteries supply and receive $|i_{tract}|$ as long as it is smaller than the saturation current $i_{h\_batt\_sat}$. The supercapacitors supply the rest of the traction power. The current $i_{h\_batt\_sat}$ is the sliding mean value of the current i_{tract} on a window of 100 s.

IV. Simulation and Comparison of the Different Strategies of the HESS

An EV with only batteries and the studied EV with HESS are compared for the different strategies on different criteria and are simulated in Matlab-Simulink.

A. Assumptions

The comparison uses two assumptions. First, the batteries of the two vehicles are the same. It is not realistic for a vehicle application but necessary for a valuable comparison. Secondly, the initial and the final state of charge of the supercapacitors are equal. Thus at the end of the velocity cycle, the supercapacitors are recharged until its initial voltage value.

B. Simulation and comparaison

The two vehicles are tested on 4 ECE urban driving cycles (Figure 3, Figure 4 and Figure 5) and compared on different criteria: electric consumption (battery consumed charge in Ah), sizing (in energy and power), and lifetime (swept State of Charge (SOC), effective current) of the batteries (Figure 6).

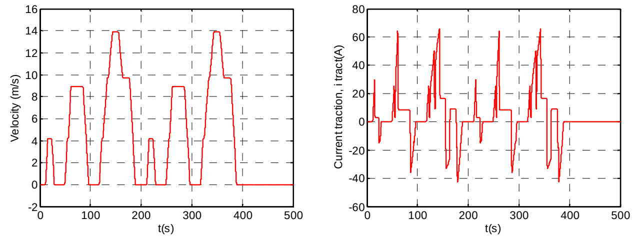

Figure 3. Velocity and traction current profile

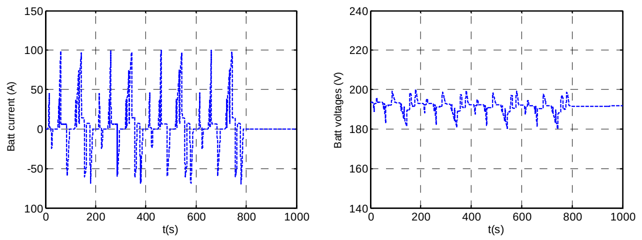

Figure 4. Battery curent and voltage for the EV

We can notice that, on this track with a specified sizing, the performances of the EV with HESS are better than those of the EV with only batteries on the studied criteria. The addition of supercapacitors would allow reducing slightly the electric consumption, reducing the sizing of the batteries and could be a possibility to increase the lifetime of the batteries.

The results are different for each strategy. In this study, the source resistance strategy and the acceleration strategy seem to be the most interesting. However, it is important to notice that the source resistance strategy is directly dependant on the sizing of the batteries and the supercapacitors and that for the vehicle acceleration strategy, the acceleration estimation can be difficult when the velocity fluctuations are frequent. Moreover, the choices of cut-off frequency for the filtration strategy (chosen here to be 6 mHz) and of the width of the window for the calculation of the sliding mean for the variable saturation current strategy (chosen her to 100s) have an influence on the performances. So, further studies are necessary to analyze and generalize these results.

V. Conclusion

An EV with HESS batteries and supercapacitors using an active association with two choppers in parallel is studied. The EMR of the system enables an inversion-based control using a distribution coefficient. Four elaborated strategies are studied to share the power demand between batteries and supercapacitors. For the different strategies, the EV with HESS is compared with an EV with only battery. It appears that the use of a HESS is interesting for the electric consumption, the size and the expected lifetime of the batteries. For different strategies, there are different results for a same sizing.

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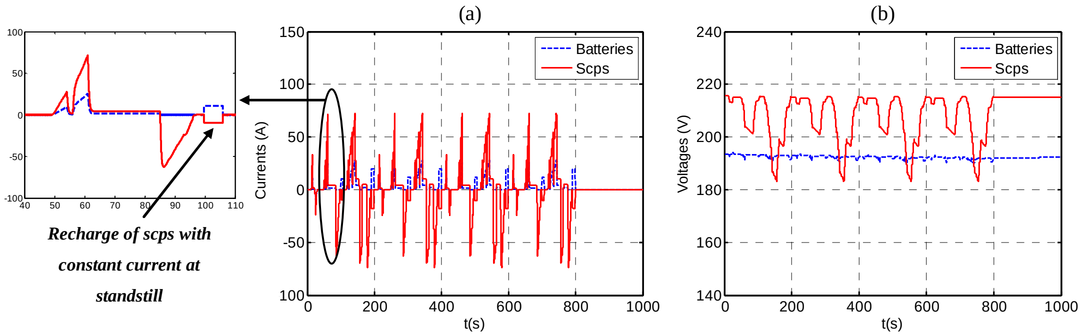
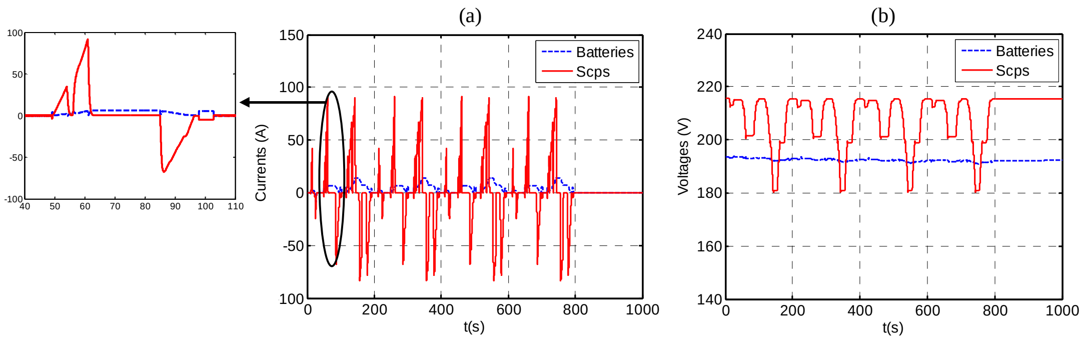
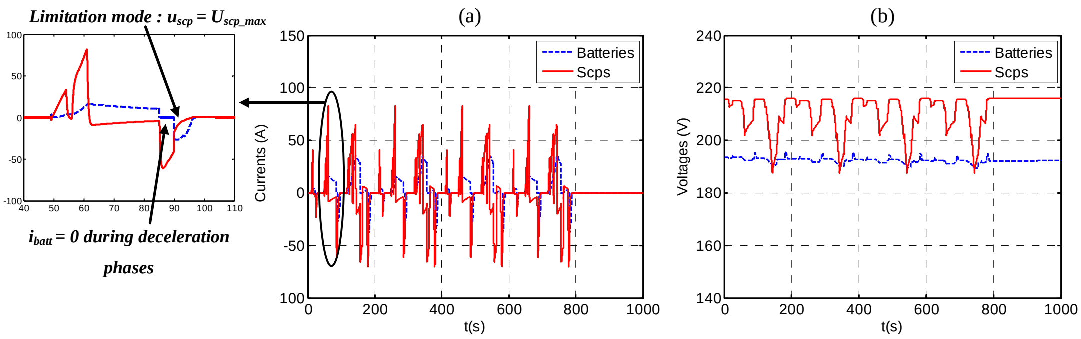


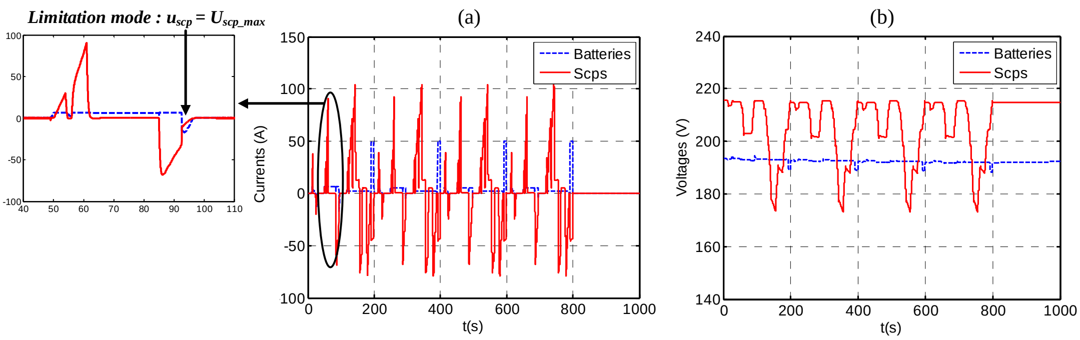
(A) Source resistance strategy



(B) Vehicle acceleration strategy



(C) Filtration strategy



(D)Variable saturation current strategy

Figure 5. Simulation results for the EV with differents strategies

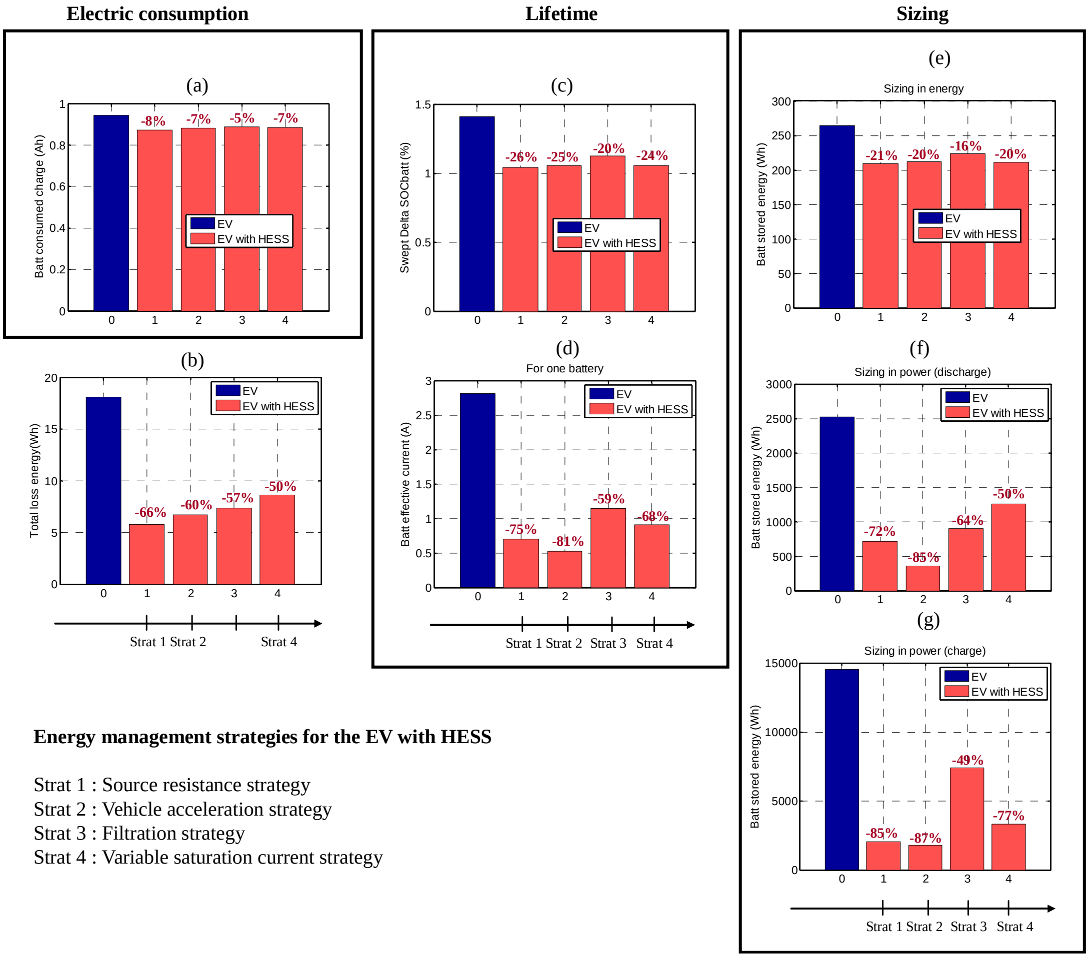
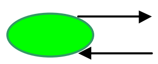
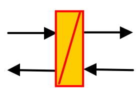
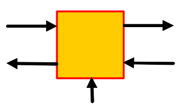
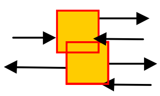
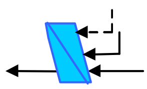
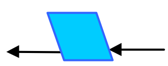


Figure 6. Comparaison of the performances of the EV and the EV with HESS

Appendix: Synoptic of Energetic Macroscopic Representation (EMR)

	Source of energy		Element with energy accumulation		Electrical converter (without energy accumulation)
	Electrical coupling device (energy distribution)		Control block With controller		Control block without controller

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