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Sliding Mode Control Based on PSO Adaptive Frequency-Decoupling for Hybrid Energy Storage System with Battery State of Charge estimation

***Abstract**. This work investigates the frequency decoupling approach based energy management strategy for the storage system of electric vehicles composed from lithium-ion batteries and super-capacitors. The aim is to realize the high energy density output of the battery and high power density output of the super-capacitors. For that, a frequency decoupling is used to separate the low frequency content of power demand and distribute it to battery and rout its high frequencies into the super-capacitors. The cut-off frequency is adapted with PSO metaheuristic optimization algorithm. A first order sliding mode (FOSM) control of the DC bus voltage is presented. The simulation tests are effectuated to validate the effeteness of the proposed method. In final, an estimating of the state of charge SOC is introduced to determine the battery discharging capacity.*

***Streszczenie**. W pracy tej zbadano strategię zarządzania energią opartą na podejściu odsprzęgania częstotliwości w systemie magazynowania pojazdów elektrycznych składającym się z akumulatorów litowo-jonowych i superkondensatorów. Celem jest uzyskanie dużej gęstości energii wyjściowej akumulatora i dużej gęstości mocy superkondensatorów. W tym celu stosuje się oddzielenie częstotliwości w celu oddzielenia części zapotrzebowania na energię o niskiej częstotliwości i rozdzielenia jej do akumulatora oraz skierowania wysokich częstotliwości do superkondensatorów. Częstotliwość odcięcia jest dostosowywana za pomocą metaheurystycznego algorytmu optymalizacji PSO. Przedstawiono sterowanie napięciem szyny DC w trybie ślizgowym pierwszego rzędu (FOSM). Przeprowadza się badania symulacyjne w celu sprawdzenia skuteczności zaproponowanej metody. Na koniec wprowadza się ocenę stanu naładowania SOC w celu określenia zdolności rozładowania akumulatora. (**Sterowanie trybem ślizgowym w oparciu o adaptacyjne odsprzęganie częstotliwości PSO dla hybrydowego systemu magazynowania energii z oceną stanu naładowania akumulatora**)*

Keywords: Hybrid storage system energy management, frequency decoupling, sliding mode control, electric vehicle
Słowa kluczowe: Hybrydowy system magazynowania energii, odsprzęganie częstotliwości, sterowanie trybem przesuwnym,

Introduction

Hybrid power systems, which combines power sources using advanced power electronics systems becomes a strategic solution for the electric vehicles (EV) energy system. The use of the battery with the super-capacitor is proving to be one alternative available approach. With the advantages of super-capacitor (high power density, fast charging and high life cycle), a hybridization can offer higher performance and increase both sources' lifetime [1], [2].

Due to different characteristics of the two components, a suitable energy management strategy must be provided considering different constraints. Various energy management strategies (EMSs) have been proposed. Generally, they are grouped in three principal methods: optimization-based methods, rule-based methods, and learning based methods [3], [4]. Frequency decoupling is one of deterministic rules that belong to rule-based methods.

Thıs approach is applied to the energy management control. In this method, the power demand form load is separated into the high frequency component provided by the SC side and the low frequency component from the battery side [5], [6]. The output power of Both of SC and Battery is changed dependıng on different driving conditions.

Frequency decoupling can offer a better degree of smoothing of the current on the battery, limit the power demand in order to protect the battery and release the load stress of the battery. Therefore, the battery lifespan can be prolonged naturally.

In order to improve the power separation, an optimum value of the cut-off frequency should be calculated and adopted [2].

State of charge (SOC) is an important indicator for multiple battery control strategies. İt characterize the state of the storage elements, estimate vehicle mileage and prolong battery life. However, SOC of battery cannot be measured directly [7]. Therefore, it must be approximated using the measuring of some other related physical quantities such as voltage, current,…etc.

Several methods of battery SOC estimation are proposed such as current integration method, open-circuit voltage method, Kalman filter algorithm, machine-learning algorithm, and so on [8]. SOC can also estımated with Sliding Mode Observer method. Based on the Lyapunov stability theory, this nonlinear state observer can provide high accuracy and fast convergence [9].

This paper investigates the sliding mode control strategy scheme based on PSO adaptive frequency sharing to control the flow power of the energy system in electric vehicles and presents a sliding mode observer synthesis for battery SOC estimation.

At last, simulation results are shown to prove the advantages of using of the frequency decoupling energy management strategy in term of distribution of energies and powers respecting the performance of the energy sources involved.

1. Hybrid storage system (hss) modeling

1.1. Battery cell model

A simple battery cell model based on first-order RC equivalent circuit model (one RC model), is adopted (Fig. 1)[10], [11].

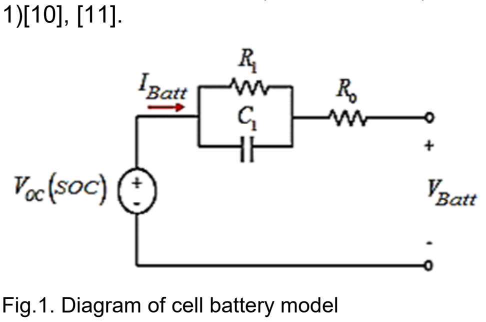


Fig.1. Diagram of cell battery model

The electrical behavior of the selected model can be can be expressed as follows:

(1) $$\begin{cases} \dot{V}_1 = -\frac{1}{C_1 R_1} V_1 + \frac{1}{C_1} I_{Batt} \\ S\dot{O}C = -\frac{1}{C_n} I_{Batt} \\ V_{Batt} = V_{OC}(SOC) - R_0 I_{Batt} - V_1 \end{cases}$$

Where V_{Batt} is the terminal voltage of the battery cell, V_1 is the voltage of the (R_1C_1) pair, V_{OC} is the open circuit voltage function of state of charge(SOC), I_{Batt} is the load current, R_0 is the equivalent internal resistance, R_1 and C_1 are polarization resistance and capacitance, C_n is the nominal battery capacity.

The open circuit voltage can be described by the following sixth-order polynomial in following equation [12], [13]:

(2) $$V_{OC}(SOC) = 14.7958 \times SOC^6 - 36.6148 \times SOC^5 + 29.2355 \times SOC^4 - 6.2817 \times SOC^3 - 1.6476 \times SOC^2 + 1.2866 \times SOC + 3.4049$$

The state of the battery cell can be summarized as follows:

(3) $$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{C_1 R_1} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ -\frac{1}{C_n} \end{bmatrix} u \\ y = f(x_2) - x_1 - R_0 u \end{cases}$$

With:
$x = [V_1 \quad SOC]^T, u = I_{Batt}, y = V_{Batt}, f(x_2) = V_{OC}(SOC)$

The battery is composed of cells, which connected in series and/or parallel configurations to provide the required energy (battery Pack). Total voltage and current of the battery are expressed as follows [3]:

(4) $$\begin{cases} V_{Bat\_tot} = N_{SB}.V_{Batt} \\ I_{Batt\_tot} = N_{PB}.I_{Batt} \end{cases}$$

Where V_{Bat_tot}, I_{Batt_tot} are the voltages and currents of the battery pack, N_{SB} is the number of cell battery with modules connected in series and N_{PB} the number of cell battery modules connected in parallel.

1.2. Super capacitor cell model

The super-capacitor is modeled as an ideal capacitor C placed in series with an equivalent resistance R_{SC} (Fig. 2) [14].

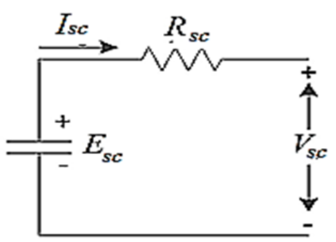


Fig.2. Diagram of cell super capacitor model

The super-capacitor terminal voltage can be expressed as follow [15]:

(5) $$V_{SC} = E_{SC} - R_{SC} I_{SC}$$

E_{SC} is cell nominal voltage.

The total voltage and current of the surper capacitor pack are defined as [3]:

(6) $$\begin{cases} V_{sc\_tot} = N_{SC}.V_{sc} \\ I_{sc\_tot} = N_{PC}.I_{Batt} \end{cases}$$

Where V_{sc_tot}, I_{sc_tot} are the voltages and currents of the super-capacitor pack, N_{SC} and N_{PC} are the number of cell super-capacitor modules connected in series and in parallel, respectively.

The state of charge (SOC) of the super capacitor is defined as [16]], [24]:

(7) $$SOC_{sc} = \frac{V_{sc\_tot} - V_{sc\_min}}{V_{sc\_max} - V_{sc\_min}}$$

Where V_{sc_min} and V_{sc_max} are respectively the minimum and the maximum surper capacitor SC voltages.
Where J_T is the total rotating parts inertia (Kg.m^2), f is the friction coefficient and T_t is the total wind turbine torque [18] [31].

1.3. Topogical structure

A fully active topological structure is implemented to distribute and manage the energy between battery and super capacitor. Thıs topology use two bidirectional *DC/DC* converters [16], (Fig. 3). Therefore, the hybrid power system is decoupled and each components can be controlled independently.

The propulsion system of the electric vehicle is considered as a source of current that ensures the two operating phases of the electric vehicle (traction phase and braking energy recovery phase) [17], [19].

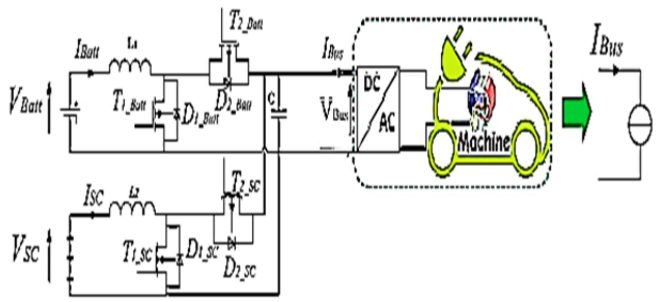


Fig.3. Fully active topological structure of HSS [17]

This parallel topological structure model can be expressed as follows [15], [18]:

(8) $$\begin{cases} \frac{C.dV_{bus}}{dt} = (1-\alpha_B) I_{batt} + (1-\alpha_c) I_{sc} - I_{Bus} \\ \frac{L_1.dI_{batt}}{dt} = V_{batt} - (1-\alpha_B) V_{bus} \\ \frac{L_2.dI_{sc}}{dt} = V_{sc} - (1-\alpha_c) V_{bus} \end{cases}$$

Where V_{bus} is the *DC* bus voltage output, it must be controlled and regulated, I_{Bus} is the load current, α_B and α_c are respectively the duty cycles of the power converters for battery and super capacitor (control inputs).
L_1, L_2 are respectively the battery and super-capacitor smoothing inductances, C is the filter capacitor.

The parameters of the hybrid storage system (HSS) are summarized in Table 1(see Appendix).

2. Energy managment strategy

The managing of the power flow of the HSS is achieved using the frequency decoupling method. This technique divides the required power into two parts: low-frequency power use principally the batteries and high-frequency power provided by the super-capacitor.

The batteries provide the average power, however, the high variability contents of the power request can be supported by the super-capacitor. A high pass filter is used to achieve the power separation. Therefore, the load current supported by super capacitors can be expressed as [17], [19]:

(9) $$I_{Bus-HF}(s) = I_{Bus}\frac{\tau_{HF}.s}{\tau_{HF}.s+1}$$

Where τ_{HF} is the filtering time constant.

2.1. Adaptation of the frequency of separation

The filtering time constant must be determined and adapted to minimize the battery current fluctuations and then the cell's degradation. An optimization algorithm like can be used to satisfy this request offering a good value of the filtering time constant.

PSO algorithm is an efficient chaotic optimization algorithm emulating the flight behavior of groups of birds discovering nourishment source [20].

It consisits to generate a swarm (group) of particle (which represent candidate solutions). The particles move around a *D*-dimensional space towards its prior personal best position p_{id} and the global best position in the swarm p_gd [20], [21].

When better position are found, the entire swarm will move to that position. The process is repeated until to achieve an optimal solution (the best position) or reach the termination condition.

For PSO algorithm, a particle's velocity coordinate and position coordinate of individual bird are updated as follows: [22], [23]:

(10) $$v_{id}^{n+1} = w.v_{id}^{n} + c_1.\varphi.(p_{id}^{n}\text{-}x_{id}^{n}) + c_2.\varphi.(p_{gd}^{n}\text{-}x_{id}^{n})$$

(11) $$x_{id}^{n+1} = x_{id}^{n} + v_{id}^{n+1}$$

Where $X_i = [x_{i1}, x_{i2 .....} x_{id}]^T$ which represents the present position of i^{th} particle.

$V_i = [v_{i1}, v_{i2 .....} v_{id}]^T$ represents the velocity of the i^{th} particle.

c_1, c_2 are positive constants used to represent the cognitive and the social learning. φ is a random vector within $[0,1]^D$, w is the inertia weight, which balance between global exploration and local exploration, *n* represents the iteration number.

To analyze whether swarm has reached the best solution, a specific function is used to call fitness function.

Since the objective of our study is to reduce the battery current demand (to extend its lifetime), its ***RMS*** value is a relevant performance index.

Therfore, the fitness fuction is defined as [17], [25]:

(12) $$\min(I_{Batt\_rms}) = min\left\{\sqrt{\frac{1}{T}\int_0^T {I_{Batt}}^2(t)dt}\right\}$$

T is the time corresponding to the itinerary portion in which optimisation is applied.

The selected parameters for PSO algorithm are presented in Table 2 (see Appendix).

2.2. Dc voltage layer control

The direct voltage control diagram shown in Fig. 4 describes the principle of energy management based on the frequency decoupling method. The purpose of this local control is to use the battery to provide steady state power and the super capacitors to provide transient power demands. For that, we opted for a control scheme that brings together current and voltage control loops integrated with the power electronics layer.

On the battery side, a cascading voltage regulation loop is designed in order to control the voltage level of the direct voltage bus V_{bus} (Fig. 4). An external voltage adjustment by a PI regulator gives the battery current reference ($I_{batt-ref}$), and the internal by first sliding mode (FOSM) for the control of the battery current.

A regulation loop (by FOSM) is implemented on the super-capacitor side to control the power sharing. This loop uses the value I_{Bus-HF} as a reference to solicit the super capacitors for high current variation. I_{Bus-HF} is adapted to a super capacitor current reference I_{SC_ref} by application of gain (V_{bus}/V_{sc}) based on the power balance on the converter.

The PI regulator gains were determined by the trial-error method.

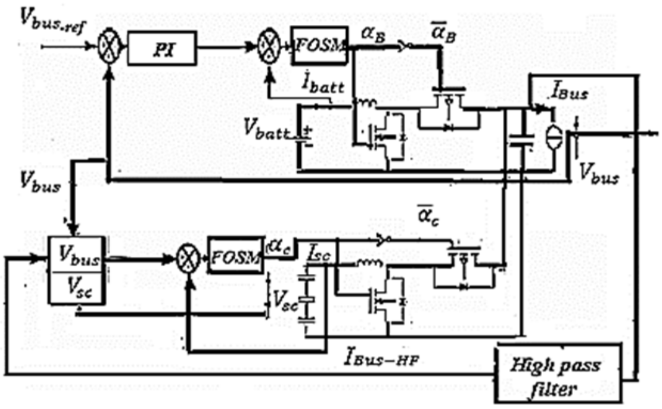


Fig. 4. Diagram of direct voltage control

2.3. First order sliding mode control for battery and sc current control shynthesis

In our study, each of the battery and the SC currents are controlled using first order sliding mode control.

The main idea behind the sliding mode controller (SMC) consist in bringing the state trajectories of the system towards a surface which the system can slide to its desired final value, then using of a suitable logic commutation around the sliding surface toward the origin point [26], [27], (Fig. 5).

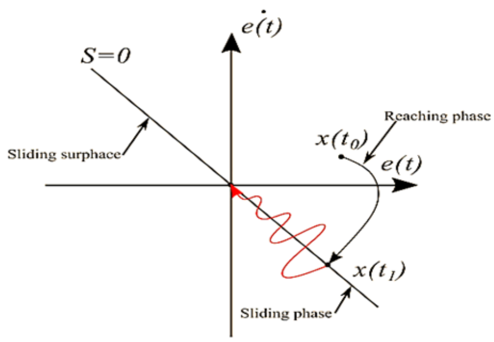


Fig.5. Principle of sliding mode control [28]

a) Battery FOSM current control

This regulation loop imposes a battery current reference I_{batt_ref} and generates a duty cycle control α_B.

The sliding surface is defined as a function of the tracking error of the battery current as:

(13) $$S_{batt} = I_{batt} - I_{batt\_ref}$$

Differentiate this surface with respect to time:

(14) $$\dot{S}_{batt} = \dot{I}_{batt} - \dot{I}_{batt\_ref}$$

From (8), we have:

(15) $$\dot{I}_{batt} = \frac{1}{L_1}[V_{batt} - (1-\alpha_B)V_{bus}]$$

Substitute (15) in (14):

(16) $$\dot{S}_{batt} = \frac{1}{L_1}[(V_{batt} - (1-\alpha_B)V_{bus}] - \dot{I}_{batt\_ref}$$

During sliding mode: $\dot{S}_{batt} = 0$
Therefore,

(17) $$\alpha_{B(equi)} = \frac{-V_{batt}}{V_{bus}} + 1 + \dot{I}_{batt\_ref}\frac{L_1}{V_{bus}}$$

To ensure the convergence mode, we add the discontinuous law function:

(18) $$\alpha_{B(n)} = -K_B\, sign(S_{batt})$$

Where :K_B is positif gain

Finlay, the total control law is expressed as:

$$\alpha_B = \alpha_{B(equi)} + \alpha_{B(n)}$$
(19) $$= \frac{-V_{batt}}{V_{bus}} + 1 + \dot{I}_{batt\_ref}\frac{L_1}{V_{bus}} - K_B.sign(S_{batt})$$

b) Super capacitor FOSM current control

This control loop requires a SC current reference I_{SC_ref} and generates a duty cycle control α_C.

(20) $$S_{SC} = I_{SC} - I_{SC\_ref}$$

After derivation:

(21) $$\dot{S}_{SC} = \dot{I}_{SC} - \dot{I}_{SC\_ref}$$

From (8), we get:

(22) $$\dot{I}_{SC} = \frac{1}{L_2}[V_{SC} - (1-\alpha_C)V_{bus}]$$

Substitute (22) in (21)

(23) $$\dot{S}_{SC} = \frac{1}{L_2}[(V_{SC} - (1-\alpha_{SC})V_{bus}] - \dot{I}_{SC\_ref}$$

During sliding mode: $\dot{S}_{SC} = 0$
So,

(24) $$\alpha_{C(equi)} = \frac{-V_B}{V_{BUS}} + 1 + \dot{I}_{SC\_ref}\frac{L_2}{V_{bus}}$$

During convergence mode:

(25) $$\alpha_{C(n)} = -K_{SC}\, sign(S_{SC})$$

Where :K_{SC} is positif gain.

The total SC current control law determined by:

(26) $$\alpha_C = \frac{-V_B}{V_{BUS}} + 1 + \dot{I}_{SC\_ref}\frac{L_2}{V_{bus}} - K_{SC}.sign(S_{SC})$$

3. SOC battery estimation based on sliding mode observer

This section presents a sliding mode observer synthesis for SOC estimation of the battery. In this approach, the gain calculated in Luenberger observer to reduce the difference between the outputs of the system and the observer is replaced by a discontinuous function of the difference [29], [30]:

(27) $$\begin{cases} \dot{\hat{x}} = f(\hat{x},u) - \rho.sign(y-\hat{y}) \\ y = h(\hat{x}) \end{cases}$$

With:
ρ is a gain matrix.

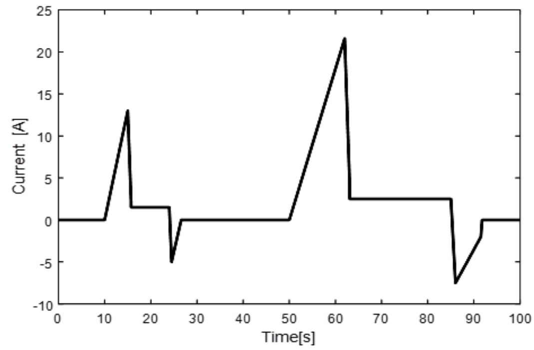
For our case, the structure of the designed SOC Sliding Mode Observer is shown in the following equation:

(28) $$\begin{cases} \dot{\hat{x}}_1 = -\frac{1}{C_1R_1}\hat{x}_1 + \frac{1}{C_1}u + \rho_1 sign(y-\hat{y}) \\ \dot{\hat{x}}_2 = -\frac{1}{C_n}u + \rho_2 sign(y-\hat{y}) \\ \hat{y} = f(\hat{x}_2) - \hat{x}_1 - R_0 u \end{cases}$$

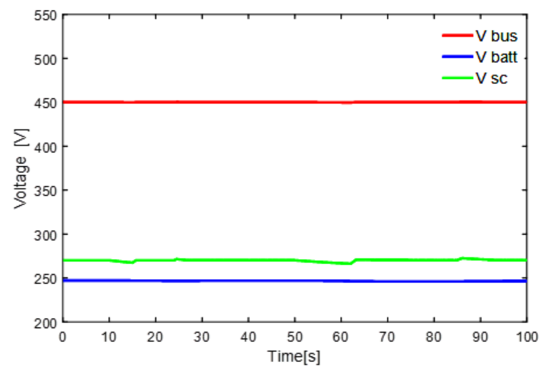
ρ_1 , ρ_2 : are sliding-mode observer gains (can be determined with trial and error method).

4. Results and discussion

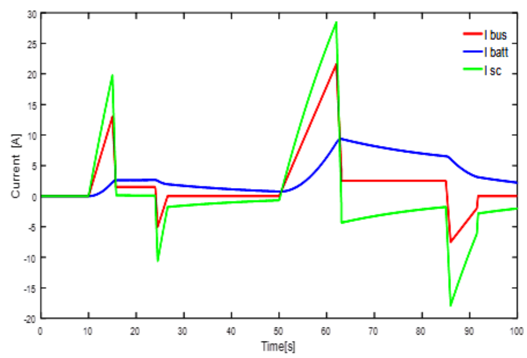
a)



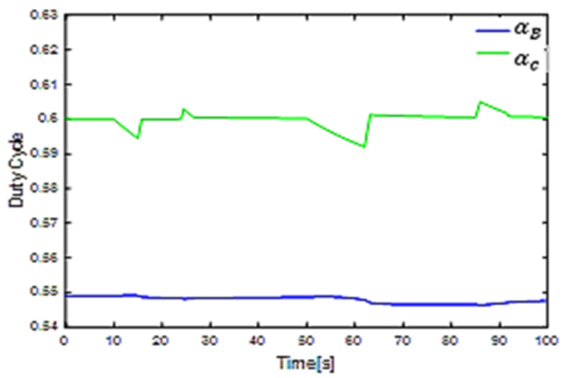
b)



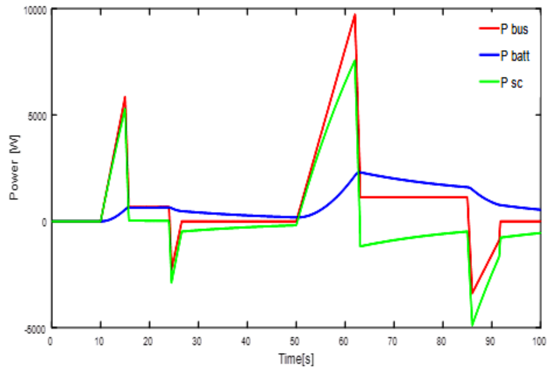
c)



d)



e)



f)

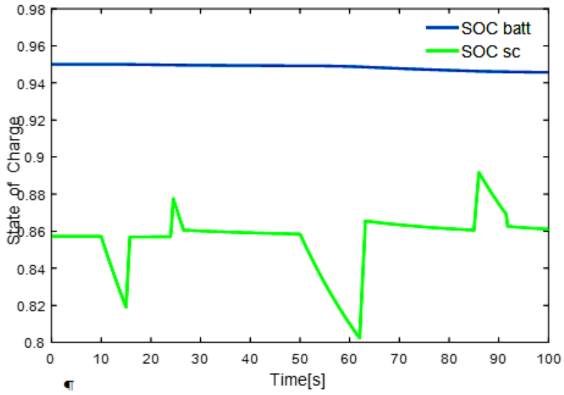


Fig 6. Hybrid storage system responses; (a)Vehicle current source; (b) Voltage responses ; (c) Evolution of system currents ; (d) Duties cycles responses; (e) Powers system responses ; (f) State of charge responses

The main objective of this simulation study is to validate the theoretical concept of power frequency decoupling discussed during the design of the local control. For that, we consider a load current profile corresponding to a part of the new European cycle NEDC Conduct (Fig. 6 (a)). This is integrated into the simulation thanks to the representation of the demand of a bidirectional vehicle current source. Simulation tests are effectuated under MATLAB / Simulink environment. With PSO algorithm, the cutoff-frequency is chosen equal to the value 0.04 Hz.

The responses of battery source voltage (V_{batt}), super-capacitor source (V_{SC}) and direct current (DC) bus voltage (V_{bus}) are shown in Fig. 6 (b). We have noticed that during the considered cycle, the *DC* bus voltage remains constant at the desired value which means a quite regulation of the DC bus voltage. The battery voltage decreases slightly with increasing energy demand. Also, the voltage of the supercapacitor has large variations in response to the current drawn/injected into the super-capacitor(sometimes charge and sometimes discharge).

The current waveform shown in Fig. 6 (c) confirms that the battery provides almost constant current and the super-capacitor supports power transients (at sudden increased of the load current) whenever they are available.

Simulation results showed that the battery current demand can be reduced according to user preferences (mainly between 50s and 60s), which provides better battery protection and improved service time.

We can see from Fig. (e), that the ouput power is shared betwen the battery source and SC source thanks to the frequency separation strategy.When the vehicle accelerate, SC source react immediately by suppling the peak power which reduces the impact of load surge on battery. The battery is used just to supply the steady state power demand. During the vehicle deceleration, a regenerative break can be recover all the power to the SC bank.

As can be seen from Fig. 6(b), the values of the voltages of the battery and the super-capacitor are different. Thus, the two duty cycles for the two power converters have different values (Fig. 6(d)).

We can note that the duty cycle of the super-capacitor has an important variation (compared to that of the battery) corresponding to the variation of the super-capacitor voltage, when the bus voltage (V_{bus}) is almost constant.

Fig. 6(f) show the state of charge of the two integrated power sources. A fast variations response of SC can be observed. The SC supply the transitory power (in case of acceleration) wich diminuate its state of charge and recovres energy(in case of braking process) wich increase its availability. As a result, the battery state of charge decreases slightly (consume 0.005% of its initial charge) which means a reduction of stress at the battery and an extended battery lifespan.

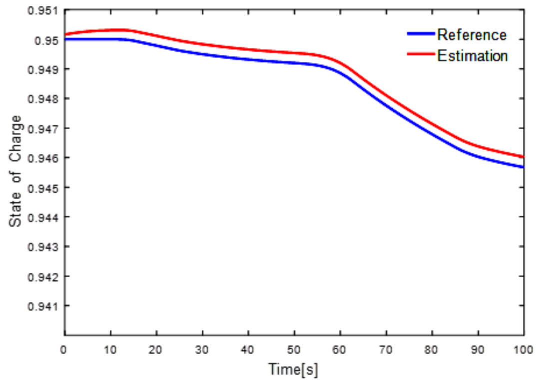


Fig. 7. State of charge battery estimation

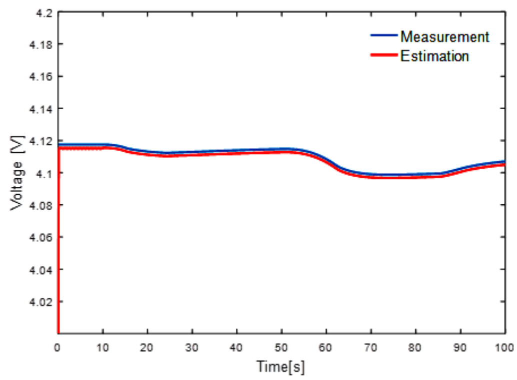


Fig.8. Cell battery voltage estimation

Both of the SOC and the cell voltage estimation of battery are shown respectively in Fig. 7 and Fig. 8. Since in practice, initial SOC value may not be accurate due to various factors (self-discharge), different initial SOC values were set to verify the performances of sliding mode observer. We can note that the synthetized observer provides a good voltage and SOC battery estimation accuracy with small error estimation.

Conclusion

This paper investigated the energy management in hybrid storage system, which combines battery and super-capacitor power sources.

The flow power of the energy system was shared using a decoupling frequency strategy. An optimization of the cut-off

frequency with PSO algorithm improves the power separation and provides a better degree of smoothing of the current on the battery.
In addition, the FOSM controller allows to a good regulation of the DC bus voltage despite the variations of the charge bus current.

An estimation of the SOC of the battery with a sliding mode observer is introduced to characterize the state of the battery and contribute therefore to perfect the energy distribution.

Simulation results prove the energy efficiency of the entire system in terms of power management and extending the life of storage systems.
Thus, future work will be focused on combinations between energy management strategies and the robustness tests against various factors as the parameter uncertainty, the age effect, and ambient temperature.

Acknowledgement
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Appendix

Table1. Initialization Parameter PSO

Parameters	Values
Cognitive learning c_1	2
Social learning c_2	2
Inertia weight w	0.7
Swarm size N	50
Problem dimensionality D	1
Maximum number of iterations n	100

Table 2. Hybrid Storage System Parameters

Component	Parameters	Values
Battery	Polarization resistance $R_1(\Omega)$	0.0097
	Polarization capacitance $C_1(\mu F)$	570.86
	Equivalent internal resistance $R_0(\Omega)$	0.0027
	Nominal capacity C_n(Ah)	3.6
	Number of series cell N_{SB}	60
	Number of parallel cell N_{PB}	6
	Equivalent series resistance $R_{SC}(\Omega)$	0.0030
	Cell nominal voltage E_{SC} (V)	2.7
Super-capacitor	Number of series cell N_{SC}	100
	Number of parallel cell N_{PC}	2
	Minimum voltage V_{sc_min}(V)	210
	Maximum voltage V_{sc_max}(V)	270
Converter (*DC/DC*)	Battery smoothing inductance L_1(mH)	0.00058
	SC smoothing inductance L_2(mH)	0.00058
	Filter capacitor $C(\mu F)$	2200

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