

# Power-Balance and Wavelet-Transform Based Power Management of Battery-Supercapacitor Hybrid System for Electric Vehicles

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## ABSTRACT

Power management of a hybrid energy storage system (HESS) with battery and supercapacitor(SC) is of critical importance for electric vehicles to achieve good driving performance, long traveling range and high energy efficiency. Due to the great differences in dynamic characteristics between battery and supercapacitor, and the complexity of a HESS, proper power management strategy between battery and supercapacitor remains to be challenging. The proposed research in this paper is to develop a power-balance and wavelet-transform based strategy for power distribution in a way such that each device can be utilized optimally. The transient dynamics is first decoupled via wavelet-transform algorithm while the power-balance algorithm is employed to improve system robustness based on the desired velocity-SOC relationship and a fuzzy logical controller. Finally some simulations have been conducted with results shown that the proposed strategy is valid and effective.

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## INTRODUCTION

Hybrid energy storage system with battery and supercapacitor has recently emerged as one of the most effective power sources for improved driving performance, traveling range and energy recovery to various electric vehicles, such as pure, hybrid and plug-in hybrid electric vehicles. While battery alone has faced several challenges, including low power density, short cycling life, challenges in thermal management in high power-load conditions, supercapacitor, however, has much higher power density and has emerged as an attractive pairing for batteries. As a result of the hybridization, a downsized battery with reduced weight becomes possible that can operate without large current spike for extended life [1, 2, 3, 4, 5].

Mounting research effort has been devoted to improving the performance of HESS from various topological structures [6,7,8], such as passive or active structures with or without DC/DC converters respectively. While the passive structure has relatively simple topology and is easy to realize, the power flow cannot be actively controlled. In fact, the power flow is purely determined by the voltage level caused by the internal resistance of each device since both battery and supercapacitor are directly connected in parallel under the same voltage. Although actively structured HESS with bidirectional DC/DC converters are widely considered to be effective solutions in addressing the limitations and drawbacks of the passively structured HESS [9], proper management strategy of power flow between these two energy storage devices becomes crucial in achieving optimal performance. This however, remains to be challenging due to the great differences of their dynamic characteristics and the complexity of the HESS [10].

Baisden and Emadi [11] presented a look-up table strategy to determine the proportion of power flow in and out of each individual energy storage device. Reference [12] presents an optimization frame for computing the sub-optimal current flow of the HESS in electric vehicle to ensure that the supercapacitor is well charged for the possible upcoming acceleration when traveling at slower speed. They all required deterministic power demand with known driving patterns and scenarios [13]; While they are easy to implement and computationally efficient, comprehensive understanding of the physical system and driving environment is typically hard, if not impossible, to obtain. Other similar research can be found from papers listed in [14, 15, 16].

Reference [17] adopted the idea of neural networks and developed an efficient energy-management system for the HESS in hybrid electric vehicles with closed form approaches. Reference [18] defined a new quantity called the battery working state (BWS) by utilizing fuzzy logic controller to make a decision on the power split between the battery and the engine. Reference [19-20] introduced a wavelet-transform-based power management strategy. While they were non-deterministic nature and typically did not need any prior information about the driving conditions, the performance may vary depending on the particular driving patterns and historical data used in training, which can hardly guarantee optimality. Other similar research can be found in the following papers [21, 22, 23].

On the other hand, the power management strategies presented in prior research were mainly developed for the improvement of system efficiency, life expectancy of the HESS, or system

robustness individually. Little research was found from the literature on power management strategies that considered all these three objectives collectively.

This paper proposes an integrated power management strategy with power-balance and wavelet-transform based approaches, by taking full advantage of each individual energy storage subsystem, by considering the disturbances caused by uncertain and/or unknown driving environment, and by considering all three objectives for improved system efficiency, life expectancy and robustness.

To properly handle the transient dynamics between low and high frequency decomposition of power demand, a Haar-wavelet-transform based algorithm is employed with smallest loss of important edge information compared to conventional filtering techniques. Further, to cope with system disturbances caused by inaccurate and/or uncertain power demand in order to improve system robustness, a desired velocity-SOC relationship is established and a fuzzy logical controller is employed. To verify the proposed research, the HESS models are built and the proposed wavelet-transform algorithm and the power-balance algorithm of power management strategy are implemented and simulated under MATLAB/Simulink and tested with urban dynamometer driving schedule (UDDS).

The remainder of this paper is organized as follows: [Section II](#) mainly discusses models of a HESS with battery and supercapacitor. A power-balance and wavelet-transform based power management algorithm and strategy are presented in [Section III](#) with simulation results depicted in [Section IV](#). Finally conclusions are made in [Section V](#).

## MODELING OF BATTERY AND SUPERCAPACITOR

In order to present and verify the proposed power management strategy, each model of battery and supercapacitor is established in this section.

### Dynamic Model of the Battery

Lithium-ion batteries have higher energy density than any other type batteries, roughly twice as much energy density as NiMH batteries do. Therefore it is the ideal candidate for the application in EVs. In the research, a lithium-ion battery is considered as the main energy storage unit capable of coping with the base load and the low-dynamic variation driving and regenerative energy.

Compared with other battery models, the Partnership for a New Generation of Vehicles (PNGV) model has more high voltage accuracy and is more suitable for modeling lithium-ion battery [24], and its equivalent electrical schematic is shown in [Figure 1](#).

The model consists of one RC pair that describes the double layer effect, which is a fast dynamic process with a time constant ranging from hundreds of milliseconds to several seconds. Where  $U_{oc}$  represents an ideal voltage source, which describes the battery open-voltage;  $R_0$  is ohm resistance;  $C_b$  describes the open-voltage

fluctuation results from the time accumulation of load current; Polarization resistance  $R_p$  and polarization capacitance  $C_p$  describe the battery's over-voltage  $U_p$ , used to describe the dynamic characteristics of the battery;  $I_L$  and  $U_L$  are the load current and load voltage of the battery respectively.

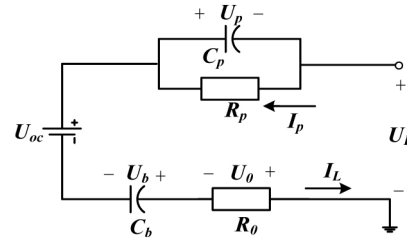


Figure 1. PNGV battery equivalent electrical schematic

State Of Charge (SOC) is traditionally used to indicate the residual electricity of the battery. Its definition is usually expressed by [Eq. \(1\)](#):

$$SOC = SOC_0 - k_{ch} \cdot k_{dis} \frac{\int \varepsilon \cdot I_{bat} dt}{C_{bat}} \quad (1)$$

where  $SOC_0$  represents the initial value of SOC;  $k_{ch}$  and  $k_{dis}$  describes the influence coefficients on the current integration from charging current ( $I_L < 0$ ) and discharging current ( $I_L > 0$ ) respectively, if the battery is charging,  $k_{dis} = 1$ , if the battery is discharging,  $k_{ch} = 0.9$ .  $C_{bat}$  represents the nominal capacity of battery;  $\varepsilon$  is the coulomb efficiency (including charging efficiency  $\varepsilon_{ch}$  and discharging efficiency  $\varepsilon_{dis}$ ).

The main state equations for the PNGV battery model are given by [Eqs. \(2\), \(3\) and \(4\)](#).

$$\begin{bmatrix} \dot{U}_b \\ \dot{U}_p \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C_p R_p} \end{bmatrix} \cdot \begin{bmatrix} U_b \\ U_p \end{bmatrix} + \begin{bmatrix} \frac{1}{C_b} \\ \frac{1}{C_p} \end{bmatrix} \cdot I_L \quad (2)$$

$$U_L = [-1 \quad -1] \cdot \begin{bmatrix} U_b \\ U_p \end{bmatrix} - R_0 \cdot I_L + U_{oc} \quad (3)$$

$$I_L = \frac{\left\{ U_{oc} - U_b - U_p - \left[ (U_{oc} - U_b - U_p)^2 - 4 R_0 P_L \right]^{\frac{1}{2}} \right\}}{2 R_0} \quad (4)$$

where the terminal voltage of capacitor  $C_b$  can be calculated by load current integration:

$$U_b = \int I_L \cdot dt \quad (5)$$

The polarization voltage and current can be written as follows respectively

$$U_p = R_p \cdot I_p$$

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and

$$I_{p,k} = \left(1 - \frac{1 - \exp(-T)}{T}\right) \cdot I_{L,k} + \left(\frac{1 - \exp(-T)}{T} - \exp(-T)\right) \cdot I_{L,k-1} + \exp(-T) \cdot I_{p,k-1} \quad (7)$$

where  $T = \frac{\Delta t}{\tau}$ , and  $\Delta t$  represents the sample time,  $\tau$  represents the battery time constant.

Then the available load power can be calculated using the multiplication of load current and load voltage:

$$P_L = U_L \cdot I_L \quad (8)$$

The model of a PNGV battery is developed in the Simulink environment of MATLAB using the relations in Eqs. (1), (2), (3), (4), (5), (6), (7), (8), which is shown in Figure 2.

### Dynamic Model of the Supercapacitor

Supercapacitor has wider working range, higher working efficiency and longer cycle life than that of the battery. On the other hand, as the power-assisted energy storage system, it has the characteristics of high-power density and relatively low internal resistance compared with battery. So it is available for providing high power bursts to meet the power demand of electric vehicles.

In this subsection, the mathematical modeling of the supercapacitor system used in the simulation is presented. Figure 3 shows one branch RC equivalent circuit of the supercapacitor. The model consists of a capacitance  $C$  and an equivalent parallel resistance  $R_{ep}$  representing the self-discharging losses, an equivalent series resistance  $R_{esr}$  representing the charging and discharging resistance. The  $R_{ep}$  models the leakage effects and only impacts the long term energy storage performance of the supercapacitor system [25].

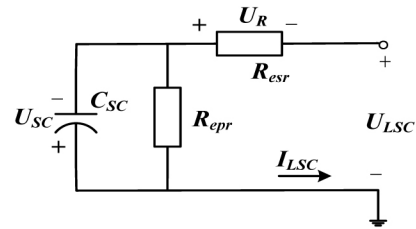


Figure 3. Supercapacitor equivalent electrical schematic

Based on Figure 3, the load voltage of supercapacitor can be written by Eqs.(9) and (10).

$$\dot{U}_{SC} = -\frac{U_{SC}}{C_{SC} \cdot R_{ep}} + \frac{I_{LSC}}{C_{SC}} \quad (9)$$

and

$$U_{LSC} = U_{SC} - R_{esr} \cdot I_{LSC} \quad (11)$$

In order to indicate the residual electricity of the supercapacitor, The State Of Voltage of the supercapacitor is used to describe as a percentage of the rated energy capacity, which depends on the terminal output voltage and is defined as in Eq. (11):

$$SOV = \frac{U_{LSC} - U_{min}}{U_{max} - U_{min}} \quad (12)$$

where  $U_{max}$ ,  $U_{min}$  are the maximum and minimum terminal voltage of the supercapacitor respectively.

## POWER-BALANCE AND WAVELET BASED POWER MANAGEMENT

### Wavelet Transform Algorithm

Since battery cycle life is typically less than two thousand times, frequent and deep charge-discharge processes will result in a sharp attenuation in battery cycle life. In order to solve this problem and cope with load power demand effectively while avoiding the rapid-variation and large-differential power demand for battery, the use of a frequency decoupled algorithm that extract the high-low frequency components from the total power demand based on the different dynamic characteristics of battery and supercapacitor is quite essential for power management of the HESS. For the development frequency decoupled algorithms, the wavelet transform is a relatively new and powerful tool in the analysis of the power transformer transient phenomenon because of its ability to extract information from the transient signals simultaneously in both the time and frequency domain by employing the long windows at low frequencies and short windows at high frequencies, rather than conventional Fourier Transform which can only give the information in the frequency domain [26]. Moreover, wavelet transform can narrows the correlation in different features tremendously and

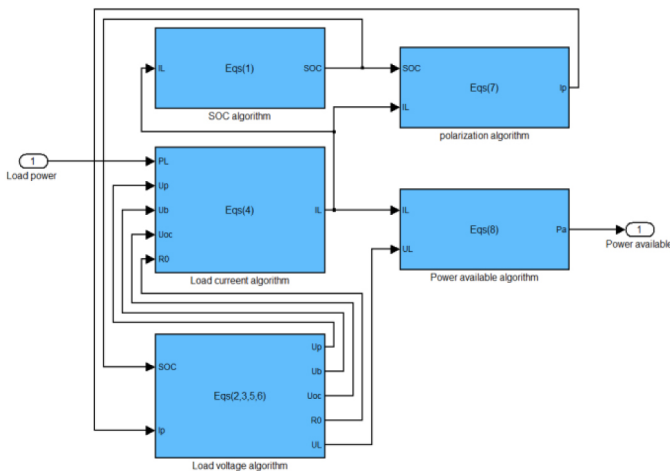


Figure 2. PNGV battery dynamic model