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Comparative Study of a Passive Hybrid Energy Storage System Using Lithium Ion Battery and Ultracapacitor

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Abstract

In this paper, scaled-down mathematical models, simulations, and experimental studies have been conducted to show the power sharing between battery and ultra-capacitor in a passive Hybrid Energy Storage System (HESS) using lithium ion battery and ultracapacitor. Detailed comparisons between a battery-only ESS and a passive HESS in terms of power capability, discharging time, and efficiency have been studied to investigate the advantages of passive HESS. Finally, we compare a passive HESS with an active HESS for Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) applications, and the advantages of the passive HESS over active HESS are explained.

Keywords: Passive Hybrid Energy Storage Systems (HESS), Battery, Ultra-capacitor

1 Introduction

Combining a battery pack with ultracapacitors to achieve both high power and high energy capability is considered an effective way to provide energy and power for EVs and HEVs [1], [2]. Fundamental mathematical study has already been conducted in [3] on a passive hybrid energy storage system of a battery and ultra-capacitors. Simulation study of a passive HESS showed some advantages of the system [4], [5], [6]. Experimental study of passive HESS in laboratory is in [7]. All these studies concentrate on small power scale, which is useful for portable devices and communication systems with small power demand. A HESS, capable of provide transient high power pulse for accelerating or decelerating an EV or a HEV, present potentials for better ESS design optimization, performance and life as well.

Researches in this area are mostly concentrated on simulation and experimental studies of active HESS systems using DC-DC converters [8-12]. However, as the authors noted, systematic studies on HESS systems for EV and HEV applications have been less than sufficient in publications. This paper provides studies on power performance of a scaled-down passive HESS, by means of mathematical, simulation, and experimental investigations. Consistent results from mathematical, simulation, and experimental investigations are obtained and provide a solid basis for comparing a battery only ESS and a HESS for EV and HEV applications. Advantages of HESS over a battery alone ESS are discussed followed by discussion on the advantage of passive HESS over active HESS in the last part of this paper.

2 Modelling and Simulation Studies

2.1 Components for the Passive Hybrid Energy Storage System

For the study in this part, the battery pack contains three battery modules connected in series. The battery module is a U1-12XP lithium-ion battery module from Valence Technology. The nominal voltage of each battery module is 13.35V, the capacity is 40Ah and the terminal voltage is 40V. The ultra-capacitor is an 110F, 48.6V BMOD0110 from Maxwell Technology. From the data sheets and our own measurement, the internal resistance of one battery module was found to be 0.015Ω, so the internal resistance of the battery pack is 0.045Ω, and the ultra-capacitor ESR is 0.0081Ω.

2.2 Mathematic Model

According to the exact mathematical analysis of passive HESS with battery and ultra-capacitor in [2], the current sharing between battery and ultra-capacitor for pulse load current can be described as:

$$v_o(t) = V_b + \frac{R_b}{R_b+R_c}(V_c - V_b)e^{-\beta t} - R_b I_o \sum_{k=0}^{N-1}[(1-\frac{R_b}{R_b+R_c}e^{-\beta(t-kT)})\psi(t-kT) - (1-\frac{R_b}{R_b+R_c}e^{-\beta(t-(k+D)T)})\psi(t-(k+D)T)];$$

$$i_o(t) = I_o \cdot \sum_{k=0}^{N-1}[\psi(t-kT) - \psi(t-(k+D)T];$$

$$i_b(t) = \frac{1}{R_b}[V_b - v_o(t)];$$

$$i_c(t) = i_o(t) - i_b(t). \quad (1)$$

In the above equation set, R_b and R_c are battery pack and ultra-capacitor internal resistance; C is ultra-capacitor capacitance; I_o is the magnitude of pulse load current; ψ(t) is a unit step function at t=0; V_b and V_c are battery and ultra-capacitor initial voltage; N is the total pulse number; T and D are pulse period and duty ratio, respectively; $\beta=1/(R_b+R_c)/C$; $v_o(t)$, $i_o(t)$, $i_b(t)$, and $i_c(t)$ are load voltage, pulse load current, battery current, and ultra-capacitor current, respectively. The parameters for the pulse load mathematical study of the passive HESS are:

R_b=0.045Ω, R_c=0.0081Ω, C=110F, V_b=40V, V_c=40V, I_o =30A, D=0.1, T=5s, N=10.

By putting the above current sharing relationship equations into MATLAB m-file, we can get the current sharing of passive HESS in Fig. 1 and the terminal voltage in Fig. 2.

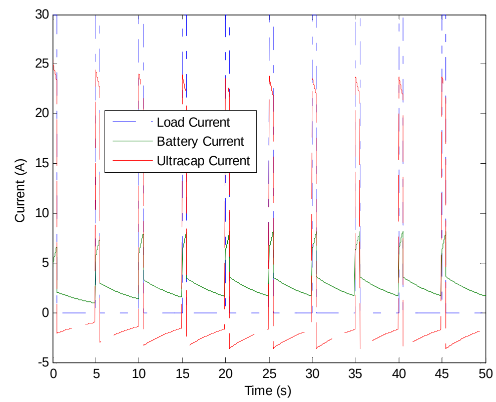

Fig. 1. Battery current and capacitor current calculated from (1)

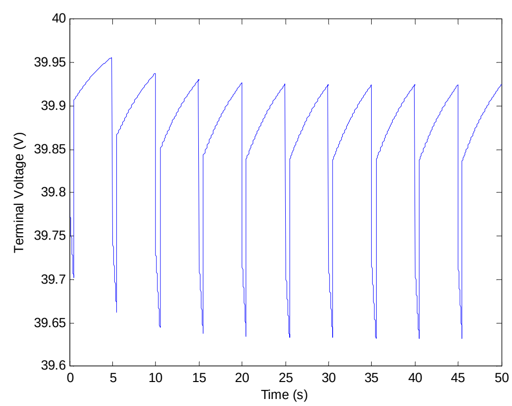

Fig. 2. HESS terminal voltage calculated from (1)

2.3 Simulation Study and Results

The simulation model of the passive HESS is established in MATLAB/Simulink, and shown in Fig. 3. Battery pack and ultra-capacitor parameters are according to the datasheets in [13] and [14]. The initial voltages of battery pack and ultra-capacitor are 40V. Simulation results are shown in Fig. 4 and Fig. 5.

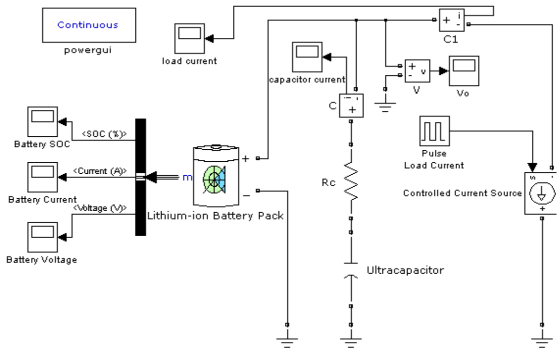

Fig. 3. Passive HESS simulation model

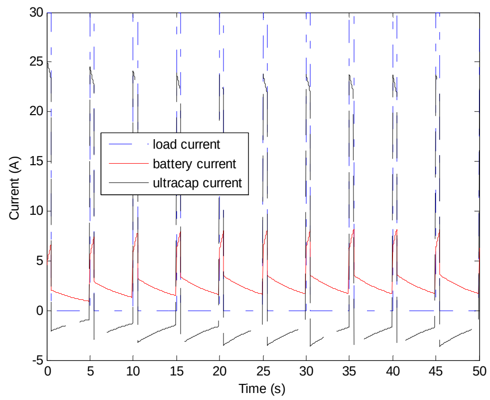

Fig. 4. Simulation result of passive HESS current sharing between battery and ultra-capacitor.

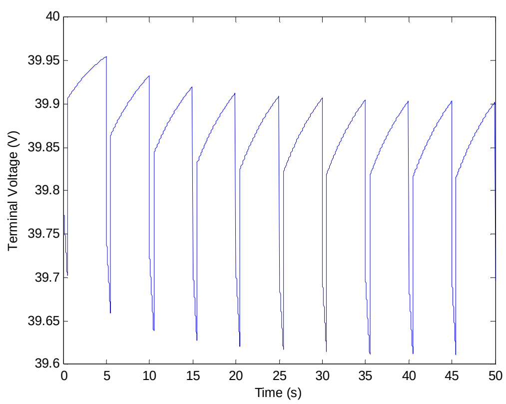

Fig. 5. Simulation result of passive HESS terminal voltage.

2.4 Results Comparison and Analysis

For mathematical result: battery current increases from 6.254A to 8.156A during pulse load, and decreases from 3.626A to 1.678A during zero load; terminal voltage decreases from 39.92V to 39.63V during pulse load, and increases from 39.84V to 39.92V during zero load. For simulation result: the battery current increases from 6.262A to 8.142A during pulse load, and decreases from 3.602A to 1.693A during zero load; terminal voltage decreases from 39.9V to 39.61V during pulse load, and increases from 39.82V to 39.9V during zero load. It can be seen that mathematical and simulation results for this passive HESS configuration are almost the same, which verifies both mathematical and simulation models.

3 Experimental Study

3.1 Experimental Setup

An experiment was constructed to measure the HESS voltage and current responses under pulsating discharge loads. The experiment equipment specifications are listed in Table I and the experiment setup is shown in Fig. 6.

TABLE I Specifications of passive HESS System

Battery Pack (Valence U1-12XP)	3 modules in series, total 19.5kg,0.0142m^3,40Ah/module,I_{max}=120A/module,$V_{nominal}$=12.8V/module,V_{cutoff}=10V
Ultra-capacitor (Maxwell BMOD0110 P048)	10.3kg,0.0114m^3,V_{max}=48.6V
Pulse Load (BK Precision 8514)	0.2Hz, 10% duty
Data Acquisition	dSPACE DS1104 PPC Controller Board

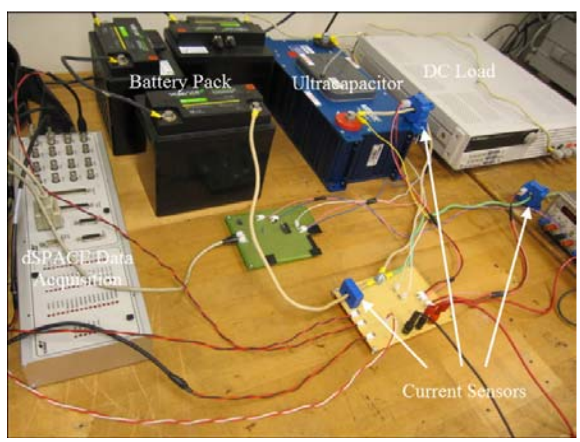

Fig. 6. Experimental setup for the passive HESS.

3.2 Results Comparison and Analysis

The experimental results are shown in Fig. 7 and Fig. 8. For experimental result: battery current increases from 8A to 10A during pulse load, and decreases from 3.634A to 1.453A during zero load; terminal voltage decreases from 39.88V to 39.49V during pulse load, and increases from 39.78V to 39.88V during zero load.

When comparing these results with mathematical and simulation results in Section 2, it can be seen that the experimental results are almost the same as mathematical and simulation results except for some minor differences. Battery shares more current in experimental result than it does in mathematical and simulation results. In addition, the terminal voltage drop during pulse load in experimental result is 0.39V, which is larger than 0.29V in mathematical and simulation result. This is mainly due to the inaccuracy of battery internal resistance. If actual battery internal resistance is less than the theoretical one, then battery needs to share more current and there will be more voltage drop on battery internal resistance [3].

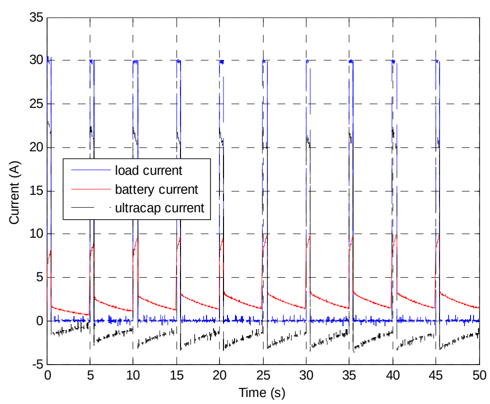

Fig. 7. Experimental result of passive HESS current sharing between battery and ultra-capacitor.

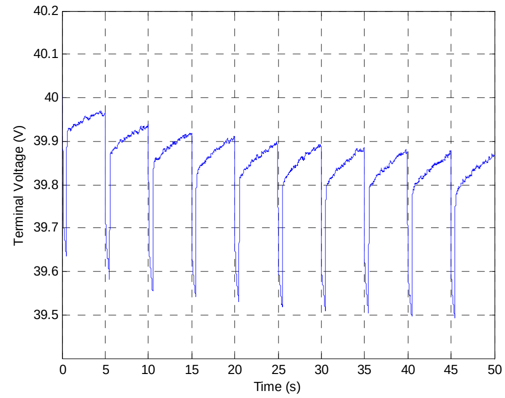

Fig. 8. Experimental result of passive HESS terminal voltage.

4 Battery Only ESS and Passive HESS

The established HESS model can adequately model the responses. Therefore the same simulation model is used for studying the system power capability. The simulation model of battery only ESS is shown in Fig. 9, and the simulation model for the passive HESS is shown in Fig. 3. The battery only ESS has three U1-12XP modules connected in series. The initial terminal voltage is 40V.

Here the same pulse load in Section II has been used for power capability comparison. The difference is that the magnitude of the pulse load has been changed. The maximum constant discharge current for the U1-12XP battery module is 80A and the maximum pulse current for 30 seconds is 120A [13]. Therefore the pulse power capability of battery only ESS is 120A×40V=4.8kW.

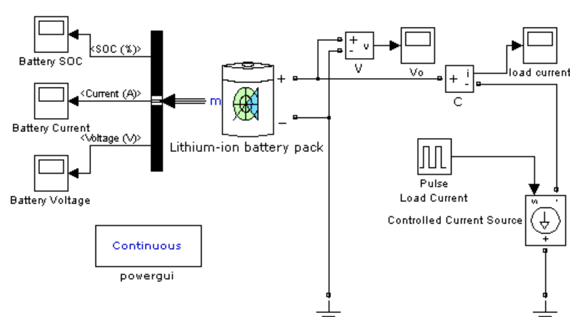

Fig. 9. Battery-only ESS simulation model.

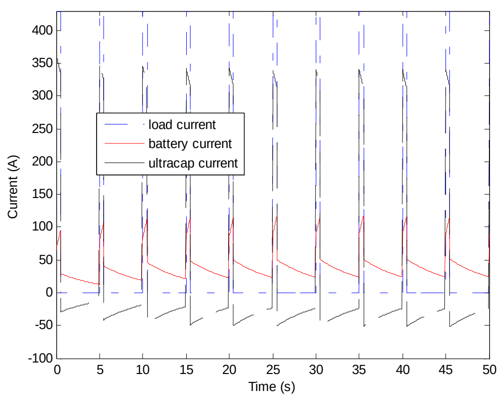

Fig. 10. Power capability of passive HESS

The power capability of passive HESS can be estimated using the simulation model in Fig. 3. To get the power capacity of the passive HESS, the battery current can be set to close to 120A, and then we get the maximum load current. The result is shown in Fig. 10, from which it can be seen that the maximum load current is 430A, when maximum pulse battery current is 117A. So the pulse capability of the passive HESS is 17.2 kW. This means that the power capability of the initial battery pack has been enhanced by 2.6 times through parallel connection with an ultra-capacitor to form a passive HESS.

4.1 Comparison of Discharging Time

To compare the discharging time between battery-only ESS and passive HESS, the load power demand should be the same. Here the power demand is pulse demand with 4.8kW magnitude, 5s period, and 10% duty ratio.

The simulation result for the discharging time of battery only ESS is shown in Fig. 11. When the battery voltage drops to cutoff voltage 30V, the simulation terminates and the discharging time is 8280s. The same simulation result for the passive HESS is shown in Fig. 12. The discharging time is 10715s. Compared with battery-only ESS, the discharging time is increased by nearly 30% for the passive HESS under this particular discharge profile

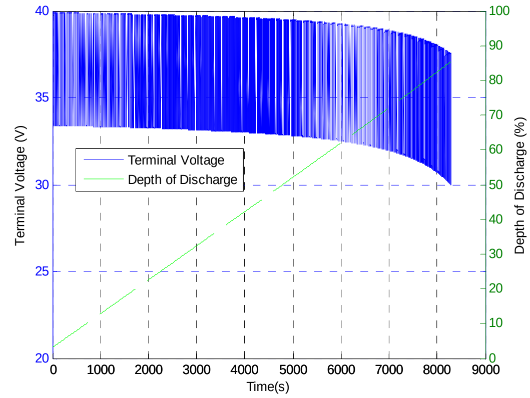

Fig. 11. Battery-only ESS discharging.

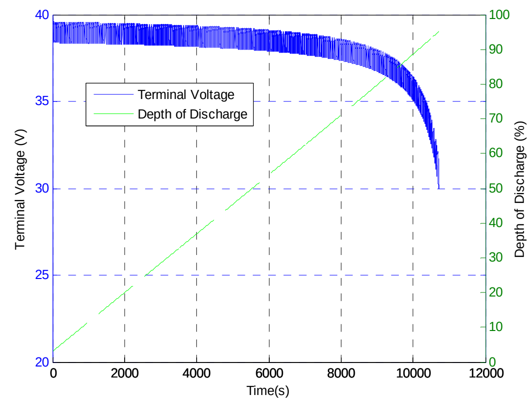

Fig. 12. Passive HESS discharging.

Also it can be seen from Fig. 11 and Fig. 12 that the voltage ripple is dramatically decreased for the passive HESS during discharge. The depth of discharge show that the battery has been fully utilized in passive HESS compared with battery-only ESS. This is because the depth of discharge increases to 95% when battery voltage drops to cutoff voltage in passive HESS while the depth of discharge only gets to 85% when battery voltage drops to cutoff voltage in battery-only ESS.

4.2 Comparison of Energy Loss

Passive HESS can have less internal energy loss because a large part of pulse load current flows through the ultra-capacitor which has a smaller internal resistance than battery [3]. This helps to reduce the heat of the battery and thus increase the life time of battery [3].

Here a UDDS drive cycle power demand is used to compare the energy loss between battery-only ESS and the passive HESS. According to the UDDS drive cycle speed file, we can get the power demand of a midsize car of 1500kg as shown in Fig. 13.

In order to satisfy the power demand of UDDS cycle, here the battery pack and ultra-capacitor have been redesigned according to the parameters of battery pack and ultra-capacitor in Section II. The new battery pack terminal voltage is 420V and capacity is 80Ah, thus the equivalent internal resistance is:

$$R_b=0.015\times420/13.35\times40/80=0.236\Omega \quad (2)$$

The ultra-capacitor pack terminal voltage is 420V, capacity is:

$$C=110\times48.6/420\times2=25.46F \quad (3)$$

The equivalent internal resistance is:

$$R_c=420/48.6\times0.0081/2=0.035\Omega \quad (4)$$

Changing the load current profile from pulse load into UDDS drive cycle load current and the parameters of battery pack and ultra-capacitor in MATLAB/Simulink models in Fig. 3 and Fig. 9, and after simulation the power sharing relationship for passive HESS can be shown in Fig. 14. For battery-only ESS, battery supplies all the power demand, so the battery power supply is equal to load power demand as shown in Fig. 14.

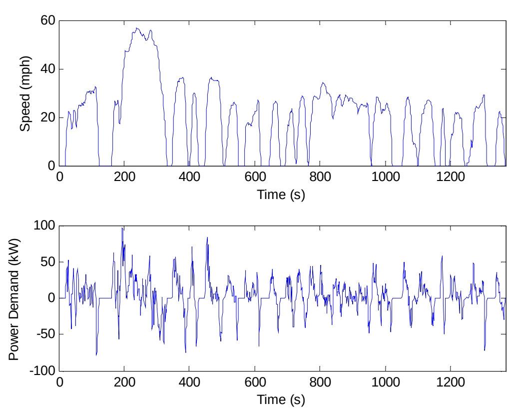

Fig. 13. UDDS drive cycle speed and power demand.

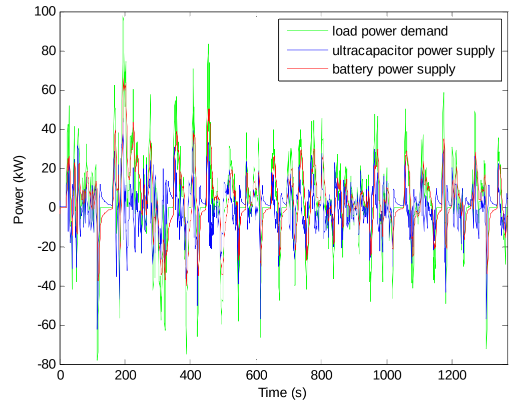

Fig. 14. Power sharing between battery and ultra-capacitor of passive HESS for scaled-down UDDS drive cycle power demand.

After doing calculation in MATLAB, we can get energy loss and total delivered energy for both battery-only ESS and the passive HESS in UDDS drive cycle. Suppose E_o, E_{bol}, E_{bhl}, E_{chl}, and E_{hl} are energy output, energy loss in battery only ESS, energy loss in battery internal resistance, energy loss in ultra-capacitor internal resistance, and total energy loss in passive HESS respectively. Then the calculated results for one UDDS cycle are:

E_o=1.37kWh, E_{bol}=0.2507kWh, E_{bhl}=0.134kWh, E_{chl}=0.01kWh, E_{hl}=0.144kWh.

So the total energy loss has decreased from 0.2507kWh to 0.144 kWh when the ESS changes from battery-only into passive HESS with battery and ultra-capacitor. The energy loss reduction is mainly due to the fact that a large amount of load current flows through the ultra-capacitor, which has a smaller internal resistance (0.035Ω) when compared with battery pack's internal resistance (0.236Ω). And the energy efficiency can be calculated using the results.

Battery only ESS energy efficiency is:

$$\eta_{bo}=E_o/(E_o+E_{bol})\times100\%=84.5\% \quad (5)$$

Passive HESS energy efficiency is:

$$\eta_h=E_o/(E_o+E_{hl})\times100\%=90.5\% \quad (6)$$

It can be seen that the energy efficiency has increased by 6% from battery only ESS to passive HESS for UDDS drive cycle.

5 Comparison of Passive and Active HESS

Active HESS uses DC-DC converters to actively control the power sharing between battery and ultra-capacitor, specifically to make battery provide low constant power for a long time and ultra-capacitor to provide high pulse power for a short time. The topology of passive and active HESS is shown in Fig. 15.

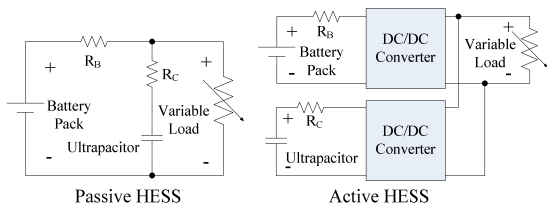

Fig. 15. Passive and active HESS topology.

Obviously active HESS has better performance over passive HESS because it can make ultra-capacitor provide most or the entire pulse load while battery provide the average and constant part of the load [3] and [4].

However, passive HESS still has advantages over active HESS with application on EVs and HEVs. Firstly, the topology of passive HESS is simple and it is relatively easy to be implemented in EVs and HEVs. Saving one or two high-power DC-DC converters will save significant cost for the EV or PHEV system. Secondly, passive HESS is more reliable compared with active HESS. The reason is that active HESS needs to change the PWM duty ratio in DC-DC converters according to the load demand but load demand of vehicle driving scenarios is always changing, so the control algorithm should be stable enough to deal with load changes. However passive HESS doesn't have this problem. Thirdly, passive HESS performance can be easily improved through choosing ultra-capacitors with larger capacitance and smaller internal resistance. With the fast development of ultra-capacitor technology in industry, optimizing battery and ultra-capacitor parameters of passive HESS is a feasible way to improve HESS performance. More importantly, simulation research has been done in [6] showing that passive HESS has a higher energy efficiency than active HESS. This is because active HESS has energy loss in DC-DC converters which are the main part of its total energy loss [6]. For the above reasons, passive HESS still has great application potential in EVs and HEVs.

6 Conclusions

A passive hybrid energy storage system is bench tested to obtain system voltage and current responses under a specific discharge load profile. The results are used to establish a Simulink model of a HESS with reasonable fidelity. The same model was used to investigate the power capability, usable energy, and the energy efficiency of the HESS during various discharge processes. The results show that the power capability, discharging time, and energy efficiency of original battery-only ESS has increased by 2.6 times, 30%, and 10%, respectively, after parallel connected with an ultra-capacitor to form a passive HESS. This is mainly due to the fact that ultra-capacitors help to provide a large amount of power during pulse power demand and it has smaller internal resistance than that of the battery pack. Dependence of HESS performances on capacitor sizing is also investigated, and results will be discussed in other papers. Finally, the advantages of the passive HESS over active HESS on EV and HEV applications were discussed.

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