Battery-Supercapacitor Hybrid System for High-Rate Pulsed Load Applications

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***Abstract*—Modern batteries (e.g., Li-ion batteries) provide high discharge efficiency, but the rate capacity effect in these batteries drastically decreases the discharge efficiency as the load current increases. Electric double layer capacitors, or simply supercapacitors, have extremely low internal resistance, and a battery-supercapacitor hybrid may mitigate the rate capacity effect for high pulsed discharging current. However, a hybrid architecture comprising a simple parallel connection does not perform well when the supercapacitor capacity is small, which is a typical situation because of the low energy density and high cost of supercapacitors.**

This paper presents a new battery-supercapacitor hybrid system that employs a constant-current charger. The constant-current charger isolates the battery from supercapacitor to improve the end-to-end efficiency for energy from the battery to the load while accounting for the rate capacity effect of Li-ion batteries and the conversion efficiencies of the converters.

I. INTRODUCTION

Rate capacity effect in batteries significantly degrades their discharge efficiency under high load currents. Electronic systems commonly exhibit large fluctuation in load current, which defy the maximum discharge capacity of batteries. Typical electronic systems determine the battery size based on their expected average power consumption, and thus a large pulsed discharging current with peak greatly exceeding the average value can significantly shorten the battery service life in a charge-discharge cycle.

We need to reduce the peak current draw in battery powered electronics with the highly fluctuated load. Electric double layer capacitors, more commonly known as supercapacitors, are widely exploited to mitigate such load current fluctuations in the batteries. They have a superior cycle efficiency, which is defined as the ratio of the energy output to energy input, which reaches almost 100%, and so they are suitable for energy storage with frequent charge-discharge cycles.

Generally, the larger the supercapacitor is, the higher the energy efficiency will be. However, supercapacitors have a significant disadvantage in terms of their volumetric energy density and cost per unit of stored energy compared to the batteries. For portable applications where the size is a constraint and cost is a factor, size of the supercapacitor should be minimized while achieving a reasonable energy efficiency.

Another concern is the terminal voltage variation coming from the characteristics of a capacitor in the sense that the terminal voltage is linearly proportional to the state of charge of the supercapacitor. The terminal voltage increases or decreases dynamically as the supercapacitor is charged or discharged. The variation of the supercapacitor terminal voltage is much higher than that of ordinary batteries. As a result, the efficiency of power converters, which are connected to a supercapacitor varies significantly by the difference in their input and output voltage levels.

We must simultaneously consider the energy efficiency and energy density to optimize the battery-supercapacitor hybrid for portable applications. More precisely, we propose a new battery-supercapacitor hybrid energy storage system that employs a constant-current charger isolating the battery from supercapacitor to maximize the deliverable energy density i.e., the end-to-end energy delivery per unit of volume of energy storage elements, while accounting for the rate capacity effect of Li-ion batteries and the conversion efficiencies of the charger and the regulator.

II. RELATED WORK

Supercapacitors are widely used for energy storage in various applications. Specifically, supercapacitors are gaining more attention as energy storage elements for renewable energy sources which tend to have a high charge-discharge cycle frequency, and demand high cycle efficiency and good depth-of-discharge (DOD) properties [1]. There are several related battery-supercapacitor hybrid architectures in the literature on hybrid electric vehicles (HEVs). A bidirectional converter-based approach is introduced for the regenerative brake-equipped HEVs [2]. A DC bus-based architecture for the battery-supercapacitor hybrid system is described in [3]. However, it is difficult to directly apply these architectures to portable applications because they are designed for the HEV which involves high-power operation. In contrast, one must address many other factors such as size, weight, cost, and circuit complexity in portable battery-powered systems.

A supercapacitor in parallel with a Li-ion battery forms a hybrid energy storage that supports a higher rate of discharg-

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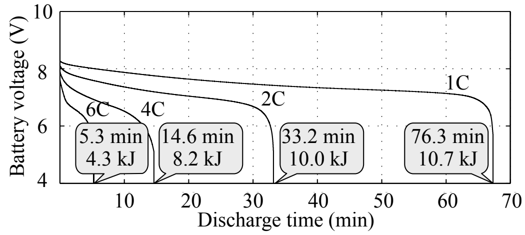
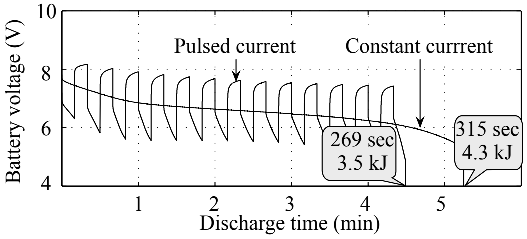


(a) Discharging at a constant current of 1C, 2C, 4C, and 6C.



(b) Discharging at a 6C constant current and 12C pulsed current of a 20 s period and a 50% duty cycle.

Fig. 1. Discharging a 350 mAh 2-cell Li-ion battery with (a) different constant current and (b) pulsed and constant currents.

ing current thanks to the high power density of the supercapacitor [4], and thus reduces the impact of the rate capacity effect. Under pulsed load conditions, the supercapacitor acts as a filter that relieves peak stresses on the battery. This type of parallel battery-supercapacitor connection storage has been characterized and evaluated with pulsed load current and compared to the battery-alone systems in [5]. A simplified model, which helps theoretical analysis in terms of performance enhancement is provided in [6]. Duty ratio, capacitor configuration and pulse frequency play important roles in performance optimization of such a hybrid storage [7].

III. BATTERY-SUPERCAPACITOR HYBRID SYSTEM

A. *Rate Capacity Effect*

Fig. 1(a) shows the voltage drop and total amount of delivered energy from the battery with a constant discharging current of 1C, 2C, 4C, and 6C, when using 2-cell series Li-ion GP1051L35 cells [8]. The discharge efficiency (defined as the ratio of energy delivered from the battery to the load to the nominal energy storage in that battery) at 6C load current is merely 40.2% of the 1C discharge efficiency. In practice, intermittent large amount of discharging current is often applied to batteries due to significant load current fluctuation of a typical battery-powered electronics circuit or systems. Furthermore, as presented in Fig. 1(b), drawing a pulsed current of 12C with a 50% duty cycle, which is 6C on average, results in only 81.3% delivered energy and a shorter service life compared to drawing a constant current of 6C. In this paper, we target the high-rate pulsed load applications which seriously reduce the battery service life due to the rate capacity effect.

B. *Parallel Connection Architecture*

A battery-supercapacitor hybrid shown in Fig. 2 is a simple way of reducing the effect of load fluctuation on the supplied voltage level. The supercapacitor connected in parallel acts as a low pass filter that prunes out rapid voltage changes. The battery-supercapacitor hybrid is thus effective in reducing voltage variation. The supercapacitor shaves the short duration, high amplitude load spikes and makes a wider duration but lower amplitude which would result in better energy efficiency due to lower rate capacity effect in the batteries.

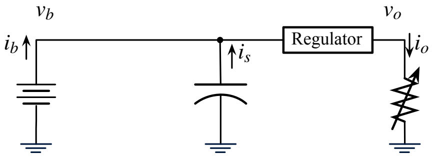


Fig. 2. Parallel connection battery-supercapacitor hybrid systems.

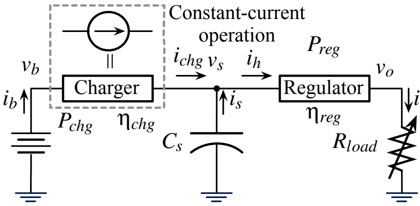


Fig. 3. Battery-supercapacitor hybrid system using a constant-current charger.

The filtering effect of the supercapacitor is largely dependent on its capacitance un the parallel connection architecture. A larger capacitance results in better filtering effect. As a result, the parallel connection has a limited ability to reduce the rate capacity effect in the Li-ion battery when the capacitance value of the supercapacitor is not sufficiently large. Unfortunately, due to the volumetric energy density and cost constraints in its practical deployment, the supercapacitor capacitance is generally rather small.

C. *Constant-Current Architecture*

We introduce a new hybrid architecture using a constant-current charger to overcome the disadvantage of the conventional parallel connection hybrid architecture as shown in Fig. 3. The constant current charger separates the battery and the supercapacitor. It maintains a desired amount of the charging current regardless of the state of charge of the supercapacitor whereas, in the conventional parallel connection architecture, the charging current is not controllable and varies greatly as a function of the state of charge of the supercapacitor. Consequently, the proposed hybrid architecture can reduces variation in the battery discharging current even with a small supercapacitor.

There are several problems that must be addressed in order to develop a constant-current architecture. In the next sections, we will find a practical way to use a constant-current charger for the battery-supercapacitor hybrid and then optimize the operating conditions of the proposed system.

IV. CONSTANT-CURRENT ARCHITECTURE DESIGN

The amount of delivered power from the battery to the load will depend on the terminal voltage of the supercapacitor with fixed supercapacitor charging current. Therefore, we need to charge the supercapacitor up to certain voltage at the initial state to deliver enough power to the supercapacitor. The supercapacitor will be precharged up to a certain voltage level before supplying power to the load as illustrated in interval ⓐ of

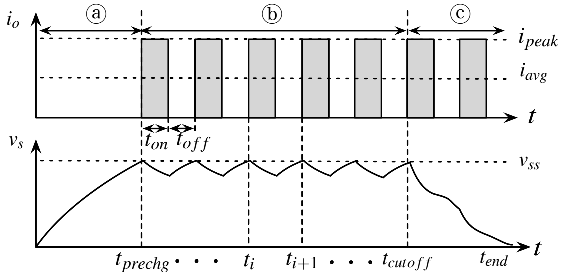


Fig. 4. Precharge and steady-state operation of supercapacitor.

Fig. 4. We use part of the pre-charged energy in the supercapacitor after the battery cut-off time, t_{cutoff} (which denotes the time after which the battery's remaining capacity fall below 20%). However during intervals ⓐ and ⓒ in Fig. 4, the variation in input and output voltage difference affect converter efficiency. We consider this amount of energy to calculate the end-to-end energy efficiency. The amount of reusable energy which is available for the load from the pre-charged energy in the supercapacitor is given by

$$E_{reusable} = \int_{t_{cutoff}}^{t_{end}} i_o v_o dt. \tag{1}$$

where i_o, v_o, and t_{end}, denote the load current, load voltage, and service life of the hybrid system, respectively.

Next, we carefully control the charging current and the terminal voltage of the supercapacitor to achieve efficient and stable operation. The supercapacitor terminal voltage must be maintained within a proper range in order to meet the load power demand. If supercapacitor terminal voltage is too high, excessive power will be transferred from the battery to the supercapacitor. Therefore, the terminal voltage continuously rises until some other circuit element pinches off the voltage rise at that terminal. On the other hand, the load demand may not be met when supercapacitor terminal voltage is too low.

We should have steady-state operation during interval ⓑ in Fig. 4 with periodic pulsed load and constant charging current. We need to make the supercapacitor voltage at the start time of the high current time period equal to the voltage at the end time of the low current time period ($v_{ss} = v_s(t_i) = v_s(t_{i+1})$). Different charging currents cause the proposed hybrid architecture to operate at different steady states for the same pulsed load. We determine not only the capacitance but also the charging current since the charging current and the supercapacitor terminal voltage affect the efficiency of the switching converters.

The amount of energy delivered to the load is given by

$$E_{ss} = \int_{t_{prechg}}^{t_{cutoff}} i_o v_o dt = \int_{t_{prechg}}^{t_{cutoff}} \eta_{reg} i_h v_s dt, \tag{2}$$

where η_{reg}, i_h and v_s are the power conversion efficiency of the voltage regulator in the system, input current of the output regulator, and input voltage of the output regulator, respectively. Finally, energy delivered to the load, $E_{deliver} = E_{resuable} + E_{ss}$. As a result, the overall energy efficiency from the battery to the load in the hybrid system is given by

$$\eta_{system} = \frac{E_{deliver}}{E_{stored}} = \frac{1}{E_{stored}} \int_0^{t_{end}} i_o v_o dt, \tag{3}$$

where E_{stored}, and $E_{deliver}$ denote the stored energy in the battery, delivered energy to the load, respectively.

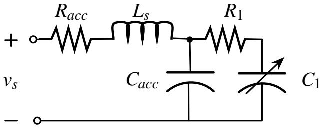


Fig. 5. Simplified supercapacitor equivalent circuit model.

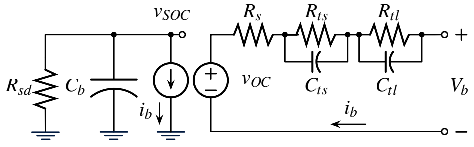


Fig. 6. Li-ion battery equivalent circuit model.

The energy density of the system may be calculated as

$$\rho_{hybrid} = \frac{E_b + E_s}{H_b + H_s}, \tag{4}$$

where E_b, E_s, H_b and H_s are the amount of stored energy in the battery, amount of stored energy in the supercapacitor, volume of the battery and supercapacitor, respectively. Finally, we get the deliverable energy density which is given by

$$\rho_{deliver} = \eta_{system} \cdot \rho_{hybrid}. \tag{5}$$

Based on definition of the system efficiency, delivered energy, volumetric energy density, and deliverable energy density, We design the constant-current hybrid system to enhance the deliverable energy density while achieving stable operation of the system. Key parameters of the supercapacitors in the proposed system are the voltage rating and capacitance. These parameter are directly related to the energy transfer efficiency and energy density of the proposed system. Capacitance value of the supercapacitor affects the efficiency due to its filtering effect on the pulsed load. Moreover, the volume of the supercapacitor is determined by its capacitance value and voltage rating. The value of charging current results in different requirement for the voltage rating for the supercapacitor because different amount of charging current results in a different steady state. These two design parameters, i. e., the supercapacitor capacitance and charging current, also strongly influence the efficiency of the charger and regulator. The maximum ratings of the switching converters, battery and supercapacitor should be considered as constraints.

V. DESIGN SPACE EXPLORATION BY SIMULATION

A. Simulation Models

We model the supercapacitor by connection of circuit elements. The equivalent circuit model incorporates a transmission line behavior, a parasitic inductor model, a charge redistribution element, and a self-discharging current model [9]. We have simplified the model of [9] to the circuit model shown in Fig. 5 for fast simulation while preserving accuracy under the actual operating condition of the hybrid system.

TABLE I
EXTRACTED SIMULATION PARAMETERS.

Battery	b_{11}	-0.67	b_{12}	-16.21	b_{13}	-0.03
	b_{14}	1.28	b_{15}	-0.40	b_{16}	7.55
	b_{21}	0.10	b_{22}	-4.32	b_{23}	0.34
	b_{31}	0.15	b_{32}	-19.60	b_{33}	0.19
	b_{41}	-72.39	b_{42}	-40.83	b_{43}	102.80
	b_{51}	2.07	b_{52}	-190.41	b_{53}	0.20
	b_{61}	-695.30	b_{62}	-110.63	b_{63}	611.50
Super-capacitor	L_s	0.93 uH	R_{acc}	34 mΩ	C_{acc}	0.8 F
	R_1	68 mΩ	C_1	$(7.2 + 0.616 \cdot v_s)$ F		
Converter	R_{sw1}	25 mΩ	R_{sw2}	25 mΩ	R_L	39 mΩ
	R_C	100 mΩ	I_{ctrl}	4 mA	Q_{sw1}	60 nF
	Q_{sw2}	60 nF	f_s	500 kHz		

We import an equivalent circuit model of the Li-ion battery from [10] as illustrated in Fig. 6. We can describe the behavior of a Li-ion battery with the equivalent circuit and the following non-linear equations:

$$\begin{aligned} v_{OC} &= b_{11}e^{b_{12}v_{SOC}} + b_{13}v_{SOC}^3 + b_{14}v_{SOC}^2 + b_{15}v_{SOC} + b_{16}, \\ R_s &= b_{21}e^{b_{22}v_{SOC}} + b_{23}, R_{ts} = b_{31}e^{b_{32}v_{SOC}} + b_{33}, \\ C_{ts} &= b_{41}e^{b_{42}v_{SOC}} + b_{43}, R_{tl} = b_{51}e^{b_{52}v_{SOC}} + b_{53}, \\ C_{tl} &= b_{61}e^{b_{62}v_{SOC}} + b_{63}, C_b = 3600 \cdot C_{init}, \end{aligned} \tag{6}$$

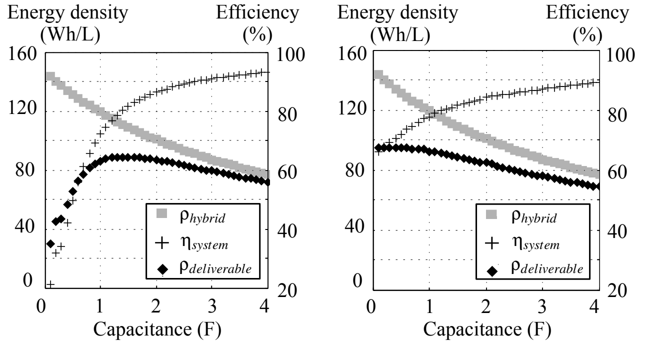
where b_{ij} are empirically-extracted regression coefficients, while C_{init} denotes the nominal energy capacity of the battery. All circuit model component values, such as value of R_s, R_{ts}, etc., are calculated from these equations.

Switching converters are used to transfer power between two different voltage levels. Batteries and supercapacitors, which have variable terminal voltages that are set according to their state of charge, are commonly paired with switching converters to supply a regulated current or a regulated voltage level to the load. The switching converter efficiency is determined by the converter loss, which comprises the conduction loss, gate-drive loss, and controller power dissipation. We import a power model of the switching converter from [11].

We obtain the discharge characteristics of Li-ion battery by measuring and extracting the regression coefficients for (6). The parameters for the supercapacitor and switching converters are measured or obtained from the datasheets. Table I shows the parameters for the GP1051L35 Li-ion cell 2-cell series battery pack of 350 mAh capacity, NessCap supercapacitor ESHSR0010C0-002R7 of 10 F capacitance [12], and Linear Technology LTM4607 converter.

B. Simulation Results

We obtain the energy efficiency and deliverable energy density by simulation using the extracted parameters. We use 10 s period, 10C discharge rate, and a pulse current with 10% duty cycle as a pulsed load. The energy efficiency, η_{system}, increases when the capacitance of the supercapacitor increases as depicted in Fig. 7(a). However, the overall volumetric energy density of the system decreases as the capacitance increasing due to the fact that the energy density of the supercapacitor is much lower than that of the battery. As shown in Figs. 7(a) and 7(b), the constant-current hybrid architecture achieves higher deliverable energy density with small capacitance because the conversion efficiency is less affected by the capacitance.



(a) Parallel connection (b) Constant-current architecture

Fig. 7. System efficiency, energy density, and deliverable energy density of the parallel connection and the constant-current architecture with pulsed load.

VI. CONCLUSIONS

The battery-supercapacitor hybrid can reduce the loss due to the rate capacity effect for the modern portable electronics which have a highly fluctuating load profile. Conventional parallel connection battery-supercapacitor hybrid needs a large supercapacitor so as to reduce the battery's peak discharging current enough to relieve the rate capacity effect on the battery. However, the large supercapacitor drastically degrades the overall available energy density which is one of the most critical constraints for the power source of portable electronics. By isolating the battery from supercapacitor, proposed constant-current architecture effectively relieves the rate capacity effect with smaller supercapacitor than the parallel connection.

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