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Experimental characterization of hybrid power systems under pulse current loads

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Abstract

Lithium-ion batteries, ultracapacitors, and parallel combinations of these devices were characterized with respect to their ability to meet the power demands of pulsed loads. Data are presented in the form of Ragone plots that relate the impact of current amplitude and pulse duty to the specific power and energy storage capacities. Adding a 50 F ultracapacitor in parallel with the battery exhibited up to a 20.3% increase in energy capacity as compared to a continuous discharge of the battery alone. The peak current capacity of the hybrid system was limited to 10 A, to prevent exceeding the maximum safe current of 2.4 A for the battery alone. The hybrid systems also suffered less voltage droop during the pulse 'on' time when compared to the battery alone. However, when considered on a per mass basis, the energy and power densities were lower for the hybrids than for the battery alone.

Keywords: Hybrid power sources; Current pulsing; Battery/capacitor hybrids; Pulsed systems; Specific energy; Specific power; Energy density; Power density

1. Introduction

Lithium-ion batteries provide 2–3 times higher specific energy per unit weight (~100 Wh/kg) than conventional battery technologies (lead–acid, nickel/cadmium), but do not provide comparable benefits with respect to specific power. The objective of the work reported here was to determine whether the specific power capacity could be increased, with minimal degradation of specific energy capacity, by adding an ultracapacitor in parallel with the battery. Ultracapacitors can provide extremely high power per unit weight (~500–700 W/kg). Such hybrid energy storage devices might be better able to supply the total power demands of a system that experiences considerable variations in load (e.g. cellular phone, portable computers, electric vehicles). Such hybrids have been discussed previously [1,2], but no quantitative study has characterized their energy and power densities under pulsed load conditions. Here we show a series of Ragone plots (i.e. specific power versus specific energy) for a lithium-ion battery connected in parallel with either a 5 or 50 F capacitor as the duty of the pulsed load was varied. The performances of the battery alone, capacitor alone, and battery/capacitor hybrids are compared and contrasted.

2. Theory

Ragone plots typically relate the total energy available from a storage device to the rate at which that energy is extracted (power), on a per mass basis. Here, we extend that concept to pulsed conditions and present our results in the form of graphs that relate the pulsed power level to the total energy supplied, as a function of the pulse duty. The total specific energy supplied by the energy storage device during a string of pulses is

$$E_{ST} = \frac{1}{m}\int_0^{\tau} v(t)\cdot i(t)\,dt \quad (1)$$

where E_{ST} is the total specific energy, $v(t)$ the time varying voltage, $i(t)$ the current, τ the total time and m the mass of the energy storage device(s). In our experiments, the current during the 'off' period was not quite zero; hence our measurement of the total specific energy includes some amount of energy supplied while the pulse was nominally off. This leakage current during the off time was measured at 19.8 mA, and typically accounted for a greater percentage of the total energy supplied as the duty decreased.

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The specific energy supplied during the active pulse period, which we term the pulsed specific energy, E_{SP}, is given by

$$E_{SP} = \frac{1}{m}\int_0^{\tau} v(t) \cdot i(t) \cdot g(t)\,dt \quad (2)$$

where $g(t)$ is a gate function equal to 1 when the pulse is active and zero when the pulse was nominally 'off'. Note, during constant current discharges E_{SP} was equal to E_{ST}.

The specific power varied during the course of a battery discharge as the battery voltage decreased. We characterize the performance of the battery in terms of the average specific power, P_{SP}, which we define as

$$P_{SP} = \frac{E_{SP}}{\tau D} \quad (3)$$

where D is the fraction of time the current pulse is active. Only the pulsed specific energy is considered for the calculation of the average specific power.

3. Experimental

3.1. System

The layout of the experimental system is presented in Fig. 1. A small 1.2 Ah. prismatic lithium-ion battery, model PSC340848-1200, was obtained from the Polystor Corporation but not used as delivered. The electronic protection pack was removed so that its unknown characteristics would not interfere with measurement of the inherent battery characteristics. Ultracapacitors were Maxwell PowerCache, models PC-10 and -100 and were used as delivered. Since the nominal voltage rating of each capacitor was approximately one half that of the battery, two ultracapacitors were connected in series to match the operating voltage of the lithium-ion battery (up to 4.2 V). Currents were measured by Hall effect sensors, model CS-25-NPA, manufactured by the Amploc Corporation and configured for the applicable current range. The 10 A magnetic latching relays, KUL series, were obtained from the Tyco Electronics Corporation and were used as delivered. All physical dimensions and pertinent information for both the battery and ultracapacitors were measured and are given in Table 1.

An Agilent Technologies electronic load, Model 6060B, was used to draw pulsed current from the battery, capacitor and hybrid systems. The electronic load was rated to operate over the range of 3–60 VDC and 0–60 A. Operations <3 VDC were possible, but at lower peak currents that were still within our operational requirements. Rated current slew rate was 50 A/μs. The internal transient generator was capable of generating current pulses at rates from 0.25 Hz to 100 kHz at the maximum slew rate. The pulse duty of the electronic load was controllable from 0.03 to 0.97. When the pulse was "off", the electronic load drew a residual current of 19.8 mA.

The battery/capacitor system was recharged before each test by a Hewlett Packard Model 6625A dual output dc power supply. The power supply's output channel was rated at 0–16 VDC at a maximum current output of 2 A. A

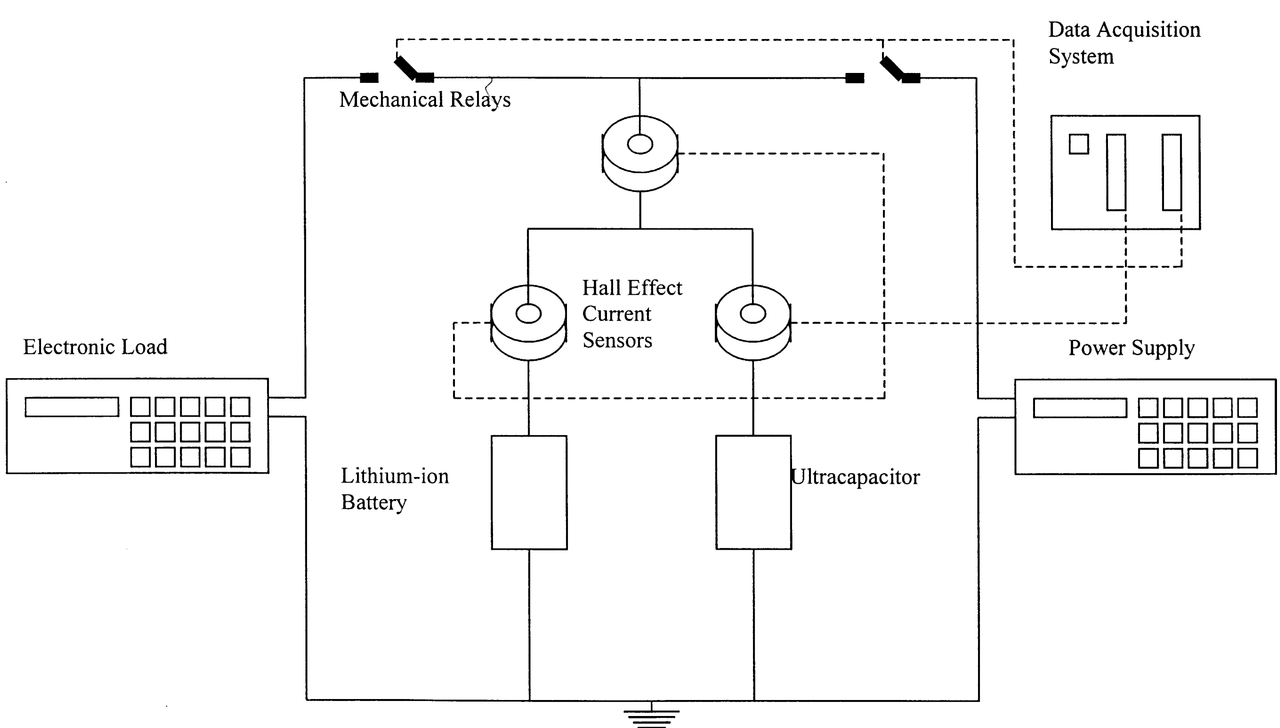

Fig. 1. Experimental layout of the battery/capacitor hybrid system.

Table 1
Component specifications used for calculations

Component	Weight (kg)	Volume (l)	ESR (mΩ)
Lithium-ion battery	0.041456	0.0139545	150
Capacitor (5 F)	0.016120	0.006093	300
Capacitor (50 F)	0.074620	0.056205	30

National Instruments general-purpose interface bus card PCI-GPIB was used to remotely control both the electronic load and dc power supply.

Data acquisition, control and analysis were accomplished using ®LabVIEW software manufactured by the National Instruments Corporation. Data acquisition hardware components include a PCI-MIO-16E-4 multifunction interface card, SCXI-1000 chassis, SCXI-1300 32 channel analog input module with SCXI-1303 connector block, and an SCXI-1161 eight channel switching relay.

3.2. Data acquisition

Since the time required to discharge a battery could be quite long, it was necessary to limit the data acquired so as to yield manageable file sizes. A multi-resolutional data sampling approach was adopted, as shown in Fig. 2. In this experiment (3 A at 0.25 duty, 1 Hz), data were acquired at 1 kilosample/s for only 1 out of every 10 periods. This yielded a file size of approximately 56 kb for each pulse acquired. The file was then read into a subroutine that calculated the specific pulsed energy, E_{SP}, and total specific energy,E_{SP}, for this single pulse. These calculations are then multiplied by the total number of pulses (10) that occur before the software program loops for another acquisition. The program is written such that it is flexible enough to account for higher sampling rates, faster pulse frequencies, number of pulses sampled before data loop reacquisition and current level during the active pulse. Data acquisition terminates at the first instant when the battery voltage drops <2.8 V.

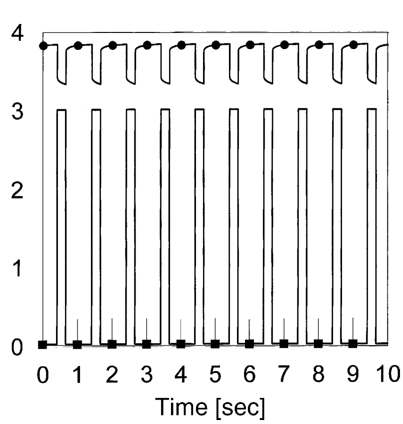

Fig. 2. A typical data set acquired during a single data acquisition loop: current (■), voltage (●).

3.3. Charging and discharging regime

The protection pack attached to the lithium-ion battery by the manufacturer was designed to protect the battery from over voltage, over current, and under voltage conditions. The protection pack was removed before testing, but the testing routine was written so as to ensure that the manufacturer's limits were not exceeded. After each test, the power supply recharged the battery at a constant current of 1 A until the rated voltage of 4.2 VDC was reached. Once the rated voltage was achieved, the power supply shifted into a constant voltage mode until the current dropped below 50 mA. The pulse discharge protocol was designed so as to prevent the battery current from exceeding 2.4 A at any time. All testing was terminated when system voltage decreased <2.8 V.

3.4. Pre-testing

Before starting the testing, the lithium-ion battery was cycled between 4.2 and 2.8 VDC approximately 100 times. This was done because data from the manufacturer showed a steep decline in full state of charge during the first 50–75 cycles. The actual testing was started after approximately 100 complete charge/discharge cycles of the lithium-ion battery, which ensured that the tests were done when the lithium-ion battery was well into the plateau region of the manufacturer's capacity curve. After all pulse current discharge testing was completed, several constant current discharges of the lithium-ion battery were conducted at a C/5 rate. These tests indicated a capacity of 1.1314 Ah, which was 5.7% below the manufacturer's full rated capacity of 1.2 Ah. This correlated with the manufacturer's reported capacity fade at this discharging rate.

4. Results and discussion

4.1. Prismatic lithium-ion battery

Fig. 3 shows the specific power and energy supplied by the lithium-ion battery under pulse conditions at various pulse duties. The data points are labeled with the value of current corresponding to the specific power. At high currents, the available energy increased with decreasing duty. At low currents, the available energy was essentially independent of pulse duty. This data is consistent with our understanding of the electrochemical processes—at high power and low duty, lithium gradients inside the battery relax between pulses, thereby, yielding a higher net capacity than under constant current discharge (where the lithium density at the electrode surface becomes depleted, dropping the battery voltage before all of the energy is extracted). At low currents, the effect of duty cycle was diminished because the relaxation rate of the lithium density gradients was faster than the depletion rate. The lithium-ion battery yielded more specific

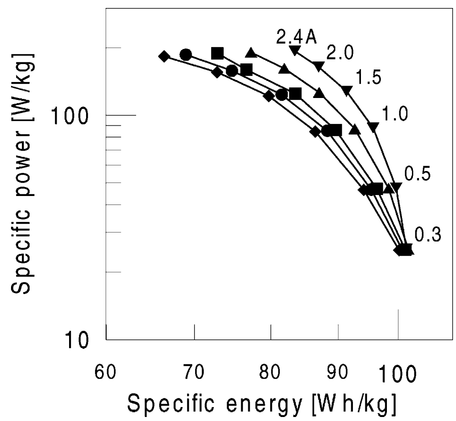

Fig. 3. Ragone plots show that specific power and energy for lithium-ion battery are a function of pulse duty. Numbers indicate current amplitude at data points: 0.10 (▼), 0.25 (▲), 0.50 (■), 0.75 (●), 0.95 (◆).

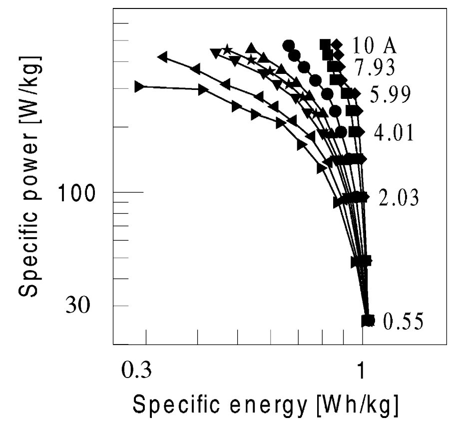

Fig. 5. Ragone plots for 50 F capacitor at various pulse duties: 0.03 (◆), 0.05 (■), 0.10 (●), 0.15 (▲), 0.20 (★), 0.25 (▼), 0.50 (◀), 0.75 (▶).

energy under pulsed conditions than under steady discharge conditions.

4.2. Ultracapacitors

Figs. 4 and 5 show the results of similar pulse discharge measurements on 5 and 50 F ultracapacitors alone, respectively. This data is consistent with pulse discharging the lithium-ion battery.

Fig. 6 shows Ragone plots for the two capacitors at duty = 1.0, but for discharging through two different limited voltage increments. In one case, the capacitors were almost discharged (5.4–0.75 VDC) through their full operating voltage range; in the other case, only the voltage range of the lithium-ion battery from full charge to effectively depleted (4.2–2.8 VDC) was considered. Obviously, the total energy removed from the capacitors was larger in the case of the larger differential voltage. Also obviously, the 50 F capacitor held more energy and could sustain higher discharge currents. The 5 F capacitor could be discharged up to its maximum rated current of 3 A, but the 50 F capacitor could be tested only to 10 A (out of its maximum rated current of 24 A) due to the maximum current rating of the mechanical relays. In all cases, the ultracapacitors held relatively little energy as compared to the lithium-ion battery.

4.3. Hybrid systems

In a hybrid system, the battery and capacitor each provided a share of the power to the load during the active pulse and then the battery recharged the capacitor during the pulse 'off' time. Fig. 7 shows the individual current profiles for the lithium-ion battery, 50 F ultracapacitor, and load in a hybrid system. The 4 A load pulse had an on time of 1 s, and off time of 3 s, yielding a 0.25 pulse duty and a 4 s period (this was different than the 1 s period typical of our tests, but is shown here to demonstrate clearly the recharging of the ultracapacitor by the battery during the pulse off period). When the load current was essentially zero, the battery

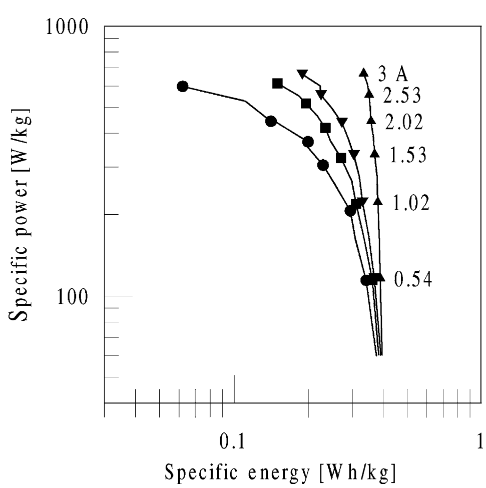

Fig. 4. Ragone plots for 5 F capacitor at various pulse duties: 0.03 (▲), 0.10 (▼), 0.15 (■), 0.25 (●).

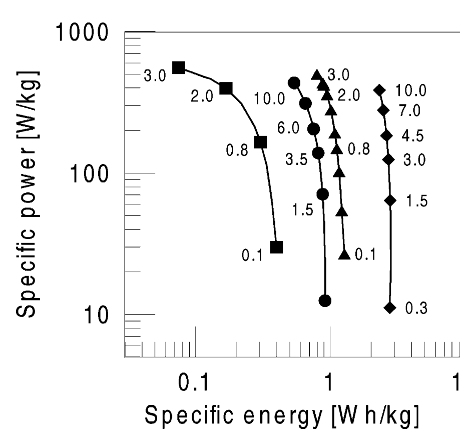

Fig. 6. Ragone plots for discharging of capacitors between different voltage limits: 5.4–0.1 VDC, 5 F (▲), 50 F (◆), 4.3–2.8 VDC, 5 F (■), 50 F (●).

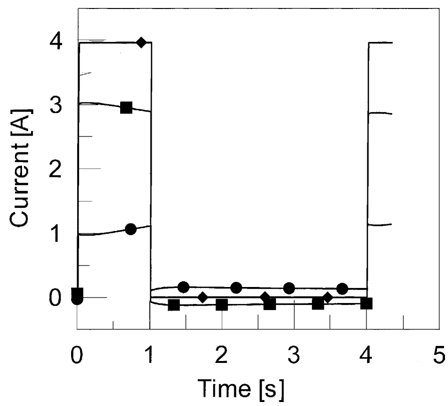

Fig. 7. Battery (●), capacitor (■) and load (◆) currents when operating at 4 A, 0.25 duty, 0.25 Hz. Note that battery recharges capacitor during 'off' period.

current was positive indicating discharging and the capacitor current was negative indicating charging.

Table 1 shows the manufacturer's rated equivalent series resistance (ESR) of each component. Generally, current is shared between components according to the relative ESR values (but note that ESR is actually a simplification of the actual electrochemical processes and cannot be used to entirely predict the current sharing under all circumstances). Since the 50 F capacitor had a smaller ESR than the lithium-ion battery, it assumed a greater percentage of the load current. This condition was reversed for the 5 F capacitor, which had a higher ESR than the battery and supplied a smaller portion of the load current.

Ragone plots for the two hybrid systems (with 5 and 50 F capacitors) and for the battery alone are shown in Fig. 8. This shows that, at a given load current, the specific energy and power decreased as the ultracapacitor size increased, even while the maximum achievable current increased. The total weight of the hybrid system lowered the values of the specific energy and power as compared to the single lithium-ion battery. On a specific (mass) basis alone, there

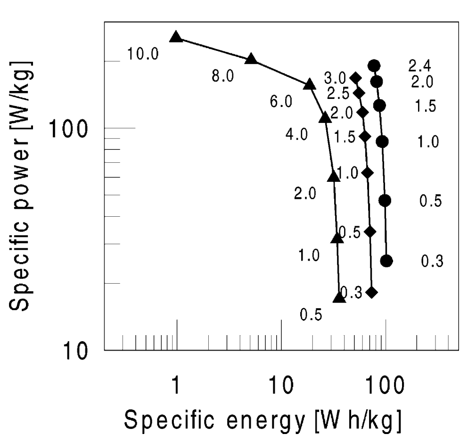

Fig. 8. Ragone plots at 0.25 duty for lithium-ion battery alone (●), battery and 5 F capacitor (◆), battery and 50 F capacitor (▲). Numeric annotations correspond to current at each measurement point.

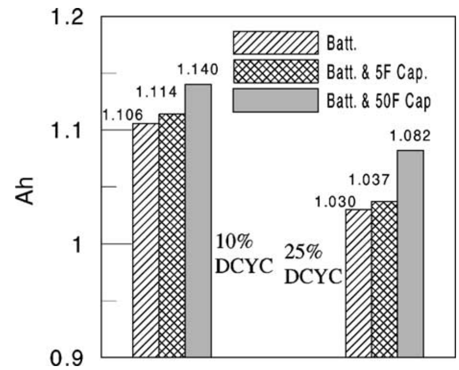

Fig. 9. Increase in capacity for various configurations compared to constant current discharge of the lithium-ion battery at 2.024 A.

is little or nothing to gain by pairing capacitors with lithium batteries. On a cost basis, the hybrid might achieve higher powers at lower cost, and of course the hybrid does allow delivering larger currents without paying for more batteries. The addition of the 50 F capacitor allowed the hybrid system to achieve 10 A and the 5 F hybrid to 3 A, without exceeding the battery discharge current limit of 2.4 A allowed by the manufacturer.

A comparison of the capacities of the battery and hybrids on an Ah basis are shown in Fig. 9 and the percentage increase in these quantities are shown in Fig. 10. These plots show that the Ah capacities increased as the duty decreased and the Ah capacity was largest when the largest ultracapacitor was used. The Ah capacity of the hybrid with 50 F capacitor, at 0.10 duty, was 1.140 Ah, a full 20.3% larger than the capacity of the battery alone while discharging at a constant 2.024 A.

That fact alone was not responsible for the 20% increase in capacity of the hybrid system, since the energy stored in the capacitor at the beginning of the test was <1% of that stored in the battery. The increase in capacity came because the capacitor supported the load voltage, allowing smaller droop during the pulse event. Fig. 11 shows clearly that the voltage drop during a 2A, 0.25 duty pulse time is considerably less for the hybrid than for the battery alone. This

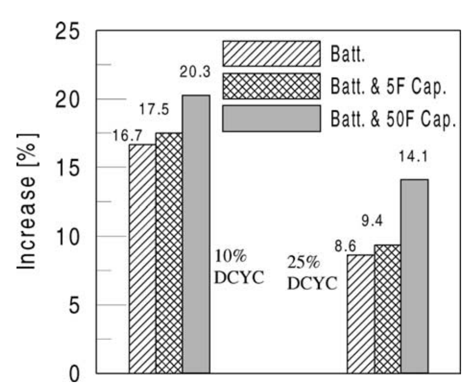

Fig. 10. Percentage increase in capacity for various configurations compared to constant current discharge of the lithium-ion battery at 2.024 A.

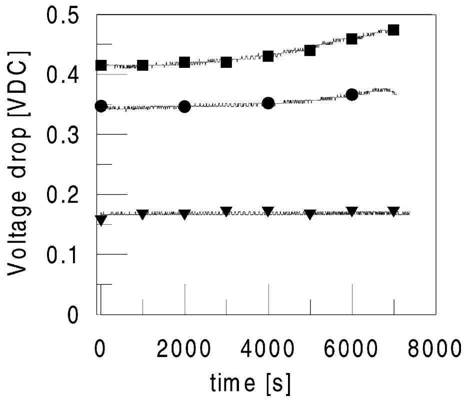

Fig. 11. Voltage drop during a 2 A 25% duty current pulse compared to open circuit voltage: lithium-ion battery alone (■), battery and 5 F capacitor (●), battery and 50 F capacitor (▼).

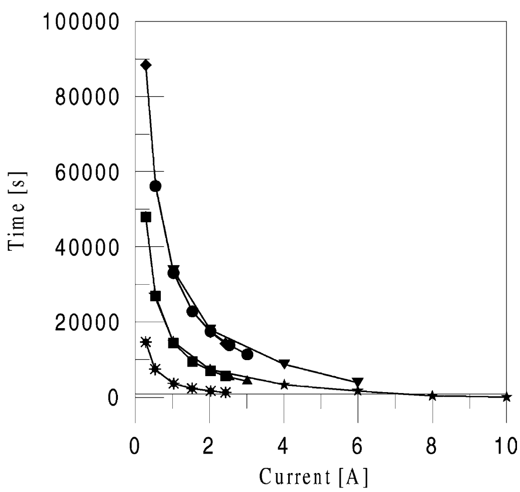

Fig. 12. Battery run down time for various systems and duties: lithium-ion battery 0.10 (◆), 0.25 (■), 1.00 (✱), battery and 5 F capacitor 0.10 (●), 0.25 (▲), battery and 50 F capacitor 0.10 (▼), 0.25 (★).

allowed the system to run longer, and deliver more energy, before the voltage first fell below the test cut-off voltage of 2.8 V. Generally, the larger the capacitor, the lower its ESR and, hence, the less voltage drop during the active pulse. The voltage drops for the hybrid systems using 5 and 50 F capacitors were approximately 0.35 and 0.17 VDC over the range of currents discharged. Also, the larger the capacitor, the more linear the voltage droop tended to become as the system was discharging.

Fig. 12 graphs the total system runtime for the battery alone and for the two hybrid systems as a function of the pulse current amplitude at several pulse duties. The hybrid systems operated for dramatically longer times before reaching the 2.8 V cut-off voltage. System runtime increased with capacitance and with lowering of the pulse duty.

5. Conclusions

Under a pulsed current discharge regime, the energy available from a lithium-ion battery increased as the pulse duty decreased. The increase in available capacity, compared to the capacity measured at constant discharge current, amounted to 15.56% at 0.10 duty and 4.24% at 0.50 duty.

Pairing an ultracapacitor with a lithium-ion battery yielded only a marginal increase in available capacity and an increase in available current. But evaluating the hybrid systems on a mass basis showed no benefit because the battery/capacitor hybrid yielded only one third of the available specific energy and power compared to the battery alone.

The hybrid systems studied here might be improved by adding power electronics that would use a greater fraction of the energy stored in the capacitor on each pulse. Also, discharging the capacitors through a greater voltage range would increase the available power, which would allow for significant reduction in the size and mass of the capacitor needed for a given project. This is the subject of a future investigation.

Acknowledgements

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References

[1] W.G. Pell, B.E. Conway, J. Power Sources 63 (1996) 255–266.
[2] J.R. Miller, in: Proceedings of the Fifth International Seminar on Double Layer Capacitors and Similar Energy Storage Devices, Boca Raton, FL, 4–6 December 1995.