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Short communication

Effect of ultracapacitor-modified PHEV protocol on performance degradation in lithium-ion cells

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HIGHLIGHTS

► An ultracapacitor in parallel with a battery was modeled and tested experimentally.
► The ultracapacitor lowered the energy throughput of the battery.
► Batteries coupled with an ultracapacitor showed less capacity loss.
► Batteries coupled with an ultracapacitor showed less resistance growth.

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ABSTRACT

The cycle life of lithium-ion batteries was investigated using a modified USABC electric vehicle testing protocol designed to simulate the effect of a hybrid energy-storage system (ultracapacitor and battery) in a plug-in hybrid electric vehicle. A side-by-side comparison of battery capacity and impedance changes with and without the effect of the ultracapacitor was performed. Calendar-life degradation effects were corrected for using control cells. The battery's rate of cycle-related capacity degradation decreased by a factor of 2 and rate of cycle-related impedance degradation, by a factor of 5.9 when exposed to the ultracapacitor-modified profile. The modified profile avoids exposure to regeneration energy and reduces maximum voltage of the battery.

1. Introduction

With their very attractive combination of high specific- and volumetric-power and energy densities, lithium-ion batteries are being considered for use in many types of electric vehicles, such as hybrid, plug-in hybrid, and fully electric vehicles (HEVs, PHEVs, and EVs, respectively). Each vehicle application has a unique set of requirements for the battery, but a common thread among them is long cycle life [1–3]. EV and PHEV applications stress the battery more than the HEV application does because they use a large fraction of the available energy (~80% for an EV, ~50–60% for a PHEV, but ~10% for an HEV). Many ideas have been proposed to lessen the stress on the battery, thereby increasing its life. One such is to use an ultracapacitor in parallel with a battery to ease the power demands on the battery [4–6]. Here, the ultracapacitor would absorb energy from regenerative braking and assist the battery during discharge. Using an ultracapacitor would be expected to affect the cycle life of a PHEV or EV battery by lessening its energy throughput and peak discharge power. Quantification of this hypothesized effect is the primary goal of this work.

In this study, the effect of an ultracapacitor in parallel with a lithium-ion battery on cycle life was investigated for the PHEV application. Because matching the operating voltage ranges and impedances of a battery and an ultracapacitor is difficult, the ultracapacitor is assumed to be actively connected to the battery with a bi-directional dc/dc converter. The effect of the ultracapacitor on battery voltage and energy throughput was modeled at the Rochester Institute of Technology. The results from the model were used to modify the charge-depleting, dynamic stress test (DST)

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profile that is used by the U.S. Advanced Battery Consortium (USABC) to test PHEV batteries for cycle life. Side-by-side testing was performed using the DST profiles [2] with and without modification to experimentally determine the difference in degradation rates.

2. Experimental approach

2.1. Modeling

The model battery–ultracapacitor system was designed to reduce the peak discharge power on the battery and to completely absorb the regenerative braking power. In this way, the battery was not exposed to high voltage during regenerative braking events. The system consisted of a series string of battery–ultracapacitor units. Each unit consisted of an ultracapacitor connected in parallel with the battery through a bidirectional dc/dc converter. The capacitance of the ultracapacitor was 195 F at 3.8 V. The total energy of the ultracapacitor system that could be used was 80 W·h (minimum to peak) and its peak power was ∼30 kW for both charge and discharge. The round trip efficiency of the ultracapacitor unit was fixed at 87%.

The state-of-charge (SOC) of the ultracapacitor was managed by a set of threshold rules:

- If the vehicle power was all from regenerative braking, the ultracapacitor should absorb it all.
- If the vehicle power was discharge and greater than 22 kW, the battery power was the vehicle discharge power minus 22 kW from the ultracapacitor.
- At the same time, if the SOC of the ultracapacitor was greater than 50%, the ultracapacitor was discharged at the 3-kW rate whenever the vehicle discharge power demand was greater than 3 kW. This was to prevent charge transfer to the battery.
- If the SOC of the ultracapacitor was more than 10 W·h below 50%, charging took place at the 2-kW rate.

This model was implemented in Microsoft® Excel®.

2.2. Testing

Six commercially available, 5-A·h lithium-ion cells were used for this work. The cell chemistry was based on $LiMn_2O_4$ and graphite. The tests consisted of characterization and calendar- and cycle-life testing using procedures based on those in the USABC Battery Test Manual for Plug-in Hybrid Electric Vehicles [2]. Briefly, the batteries were characterized in terms of their capacities at the C/1 and 10-kW rates at 40 °C. The batteries were also characterized using the hybrid pulse-power characterization test (HPPC) to determine how battery resistance (and power) changes with SOC. The data from the HPPC test were used to calculate a battery size factor (BSF); from the initial HPPC results, the BSF was found to be 316.

After characterization, two batteries were cycled using the baseline DST profile and two, with modifications suggested by the model. Each discharge cycle started from a fully charged battery. Ten percent of the rated capacity was removed at the C/1 rate, and the cell was allowed to rest for 1 h. The discharge continued by repeated application of the respective DST profile. From the test manual, each discharge cycle removed 3.4 kWh of energy, which was scaled by the BSF [2]. In this case, the fixed amount of energy was 3400 W·h/316, or 10.76 W·h. The batteries were recharged according to the manufacturer's recommendations.[1]

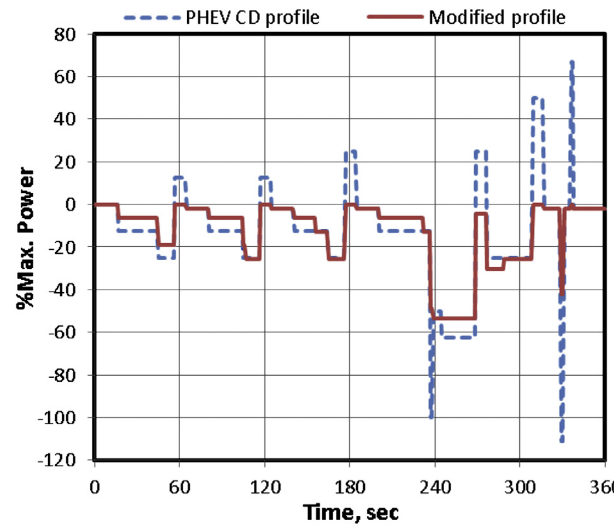

Fig. 1. PHEV profiles used in this work. Discharge is denoted as negative power in the figure.

The remaining two batteries were tested for calendar life so that the net effect of the two cycle-life protocols could be ascertained free of calendar-life effects. These batteries were tested at 60% SOC (∼3.92 V) and at 40 °C. Sixty-percent SOC was chosen because it represented an approximate average of the SOCs between which the battery would be cycled.

Every 2 weeks (100 cycles),[2] testing was stopped and the batteries were characterized by using a reference performance test (RPT). The reference performance test consisted of a capacity measurement at the 10-kW rate and the HPPC test. Testing was then resumed for a total of 5 RPTs, after which the cells could not be cycled due to high cell resistance.

The data from the RPT measurements were collected, normalized to $t = 0$, and averaged. The $t = 0$ points were omitted from all plots and subsequent analyses. For the sake of simplicity, changes in cell performance were gauged in terms of 10-kW-rate capacity and HPPC resistance at 50% SOC (∼3.89 V). Plots of these data were then analyzed for trends, using the LINEST function in Microsoft® Excel®.

3. Results

3.1. Modeling

On the basis of results from the model, the PHEV DST profile was modified as shown in Fig. 1. When compared with the baseline profile, also shown in Fig. 1, it can be seen that the modified profile limited the discharge and regeneration power. The large discharge power peaks were lessened and all regeneration ("regen") power peaks were removed. Here, the stored energy in the ultracapacitor assisted the battery during discharge.

3.2. Testing

The profiles shown in Fig. 1 were repeated during cell discharge. Typically, six repetitions were used to remove 10.76 W·h. Figs. 2 and 3 show the voltage response of the cells to the discharge profiles shown in Fig. 1. From Figs. 2 and 3, the two voltage

[1] Charge at the 5-A rate to 4.2 V; for constant-voltage charge at 4.2 V, the current is less than 1.5 A.

[2] 1 cycle = discharge 10.76 W·h of energy plus recharge. Accumulating 100 cycles took 2 weeks.