Ultracapacitor/Battery Hybrid Energy Storage System with Real-Time Power-Mix Control Validated Experimentally in a Custom Electric Vehicle

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Abstract—This paper experimentally demonstrates the benefits of integrating ultracapacitors (u-cap) into a custom electric vehicle. The new hybrid energy storage system (HESS) includes a 25 kW four-phase dc-dc converter connected in between the 33.8 kWh lithium phosphate battery pack and the u-caps. By combining the high energy-density of the battery and the high power-density and cycle-life of u-caps, the HESS delivers high power while minimizing peak battery current during acceleration and regenerative braking. Real-time power-mix control within the HESS using the dc-dc converter is the main challenge addressed in this project. In one experimental test-drive, the HESS not only improves the maximum power of the EV from 38 kW (50 hp) to 52 kW (70 hp), but also captures the majority of the regenerative braking energy, greatly reducing the stress on the battery pack.

I. INTRODUCTION

While Lithium Ion (Li-Ion) batteries for Electric Vehicles (EV) are steadily improving in power and energy density, today’s state-of-the-art cells suffer from increased capacity-fade at high charge and discharge rates [1]. The charge rate during regenerative braking (RB) is restricted to prevent the development of a Solid Electrolyte Interface (SEI) in the cells, which is a leading cause of capacity fade [2]. This project focuses on deploying a Hybrid Energy Storage System (HESS) that combines lithium phosphate batteries, ultracapacitors (u-cap) and a dc-dc converter with a simple power-mix control algorithm that is suitable for real-time implementation. U-caps have a symmetric input and output specific power of 0.5-25 kW/kg, which is at least one order of magnitude higher than typical Li-ion batteries [3]. More importantly, u-caps offer a much lower Equivalent Series Resistance (ESR) over a relatively wide temperature range, which is critical for EVs in cold climates. It is well known that the impedance of lithium ion cells increases significantly at low temperatures, as shown in Fig. 2, which is a major concern in cold climates.

The main objectives of an automotive HESS are to (1) assist the EV acceleration and (2) capture as much regenerative braking energy as possible. In both cases the u-cap State-of-Charge, $SOC_{uc}$, must be carefully managed, while limiting the battery current to reduce capacity-fade. The HESS is designed for the custom EV prototype shown in Fig. 1(a). In urban drive-cycles, this EV has a measured consumption of 180 Wh/km without RB and 133 Wh/km with RB. Following the US EPA definition that equates one gallon of gasoline to 33.7 kWh, the EV achieves 139 mpg-e without RB and 188 mpg-e with RB, respectively.

![Custom EV prototype](a)
![U-cap and liquid-cooled four-phase dc-dc converter in the trunk of EV](b)

Fig. 1. (a) Custom EV prototype. The EV has a range of over 210 km and is highway rated. (b) U-cap and liquid-cooled four-phase dc-dc converter in the trunk of EV.
As shown in Fig. 3, the 33.8 kWh HESS constructed in this work achieves better specific power with nearly the same specific energy as a Single Energy Storage System (SESS) using only a battery. To date, the HESS concept has mainly been studied using system-level EV simulations [4]–[12] or small-scale hardware emulators [13], [14]. Sophisticated power-mix algorithms have been proposed [8], [15], [16] without experimental evidence that they are practical for existing real-time embedded hardware platforms. Simulation based analyses are very useful for developing control algorithms however the results have limited accuracy. This is true even when simulating real-world drive-cycles, due to the inaccuracy in the models for the storage elements (especially the impedance) and the efficiency variations in the dc-dc converter. In [17] a 10 kW 120 V HESS system is demonstrated on an electric bus, however no drive-cycle data is provided and the power-mix control is not described. In [18] a full-scale EV with an integrated HESS is experimentally verified with a lead-acid battery pack, leading to a 28.7% improvement in driving efficiency. This project demonstrates a novel HESS in a unique lithium-battery based EV, with experimental verification of the control algorithm and high-power dc-dc converter during a real urban drive-cycle in downtown Toronto.

Fig. 2. Measured small-signal impedance (Z) of a typical 10 Ah, 3.7 V automotive lithium-ion cell for different temperatures. Note that this cell is not identical to the one used in the EV battery modules. The impedance drastically increases at low temperatures.

II. System Overview

The simplified architecture of the EV is shown in Fig. 4. The EV and HESS are controlled by several independent processing units. The Permanent Magnet Synchronous Machine (PMSM) and the three-phase inverter are controlled by the Digital Motor Controller (DMC). The DMC communicates with the Primary Computer (PC) using a dedicated Controller Area Network (CAN) to broadcast and receive critical real-time vehicle information. The torque reference for the motor is set by a potentiometer in the accelerator pedal, which is part of the user interface.

The battery management system (BMS) not only performs voltage balancing of the 24 modules, but also broadcasts the detailed battery pack status to the system CAN bus. Active cell balancing is performed separately within each module to ensure safe operation of the pack at all times. The User Interface Computer (UIC) is a linux based FreeScale server. The server relays user control signals and BMS status to the DMC through the CAN bus. The server receives and transmits real-time vehicle information through a local Ethernet router switch for data logging purposes.

A bi-directional dc-dc converter was built to regulate the power flow between the u-cap and the battery bus, \( V_{\text{batt}} \). A Compact-Rio, which is an industrial grade computer from National Instruments, is used as the real-time controller within the HESS. The Compact-Rio includes both a CPU and an FPGA. The high-level power-mix algorithm runs on the CPU, while timing-critical tasks are implemented on the FPGA. The current-mode control loop is therefore fully implemented on the FPGA to minimize the latency and react quickly to overcurrent and over/under-voltage faults.

The EV system specifications are listed in Table I. The IGBT-based dc-dc converter uses a four-phase interleaved synchronous boost topology [13], [18]. The interleaving provides reduced current ripple on the u-cap. The liquid-cooled converter is mounted directly on top of the u-caps. The 25 kW converter operates with digital average current mode control with a switching frequency of \( f_s = 20 \text{ kHz} \). The system achieves a closed-loop step response below 25 ms. The four inductors were custom designed by West Coast Magnetics with foil based windings for high power-density and low copper losses. A 144 V, 55 F, 41 kg u-cap pack was constructed by connecting three 48 V modules in series. The u-caps have a cycle-life of over one million cycles. The battery has a cycle-
life of 2800 cycles, however this estimate is specified based on a constant discharge current. The u-cap mass is slightly above 10% of the battery pack mass, representing a relatively small overhead. The u-cap pack can store enough energy to accelerate the EV from 0 to 60 km/h. A complete electromechanical model of the EV sub-systems based on [19] was developed and the parameters were tuned based on numerous measured drive-cycles.

The full model is implemented within the HESS power-mix algorithm to predict the vehicle power demand in real-time, based on user input and vehicle parameters. Unlike previous control algorithms [13], [18], this work also focuses on improving the immediate EV driving performance instead of concentrating solely on EV range and battery lifetime. For safety and logistical reasons, the HESS is modular and can be easily removed from the trunk of the EV. The car’s chromoly chassis was custom designed for the 380 kg, 33.8 kWh battery pack in the floor of the EV to achieve a low centre of mass, as shown in Fig. 5. The u-cap current is electronically limited to 200 A, while the battery current is limited to 150 A based on lifetime considerations.

III. MODEL-BASED HESS INTELLIGENT POWER-MIX CONTROL

The HESS power-mix control algorithm focuses on performance boost and RB energy capture, while also reducing battery capacity-fade due to reduced dynamic currents. The new power-mix control algorithm is designed to execute within the 250 ms loop time. The algorithm considers three main factors during operation: 1) EV speed 2) u-cap state-of-charge, \(SOC_{uc}\), 3) and driver action. The output of the algorithm is the reference current, \(I_{uc',\text{ref}}\), for u-cap current referred to the battery side, \(I_{uc'}\). The current-mode loop in the dc-dc converter senses and regulates \(I_{uc'}\) to force \(I_{uc'} = I_{uc',\text{ref}}\). For every loop iteration, the mathematical vehicle model is used to predict the current demand, \(I_{dmd}\), from the HESS. \(I_{dmd}\)
is used as the reference to calculate other current set-points, as described below. Unlike previous models that measure the load current [13], [18], predicting \(I_{dmd}\) based on the EV model has less delay, which is critical for the power-mix control to reduce peak battery currents. The control algorithm follows the programming flow chart shown in Fig. 6, which describes how \(I_{uc', ref}\) is evaluated in each of the six operating modes.

- **Mode 1**: \(I_{uc', ref} = I_{idle}\). The EV is stationary, the u-cap SOC is low and needs to be re-charged from the battery. This ensures that the u-cap pack has sufficient energy to assist with the upcoming EV acceleration.
- **Mode 2**: \(I_{uc', ref} = 0\). The EV is stationary and the u-cap SOC is above 50%; the dc-dc converter is turned off to conserve energy.
- **Mode 3**: \(I_{uc', ref} = I_{fill}\). The EV is cruising with no braking detected and \(SOC_{uc}\) is below a dynamically calculated soft limit, \(SOC_{min}\). The current \(I_{fill}\) is used to re-charge the u-cap when cruising for extended periods in the absence of significant RB energy (i.e. during highway driving). The optimal soft limit is dynamically updated based on the EV’s kinetic energy.
- **Mode 4**: \(I_{uc', ref} = I_{acc}\). The EV is cruising with no braking detected and \(SOC_{uc}\) is above \(SOC_{min}\). \(I_{acc}\) is used to assist EV during acceleration. The dc-dc converter supplies the maximum fraction of the load power from u-cap when \(SOC_{uc}\) is high, and is scaled down exponentially to zero as \(SOC_{uc}\) reaches \(SOC_{min}\).
- **Mode 5**: \(I_{uc', ref} = 0\). The EV is braking, the u-cap is fully charged and cannot capture further RB energy.
- **Mode 6**: \(I_{uc', ref} = I_{regen}\). The EV is braking and the u-cap SOC is within an acceptable range. \(I_{regen}\) is calculated to maximize the capture of RB energy. There are two kinds of RB in this prototype EV: 1) when the brake pedal is activated and 2) when the accelerator pedal is not activated, a negative braking torque proportional to speed is applied.

![Flow Chart](image)

**Fig. 6.** The HESS control algorithm flow chart.

### IV. EXPERIMENTAL RESULTS

The measured efficiency of the dc-dc converter for \(V_{batt} = 320\) V and \(V_{ucap} = 120\) V is shown in Fig. 7. A peak efficiency of 98% and 96% is achieved in buck and boost modes, respectively. High conversion efficiency is essential to ensure that the addition of the HESS does not adversely affect the driving range. Light-load efficiency is particularly important when operating in modes 1 and 3. The light-load efficiency can be further improved in the future by using well-known techniques such as phase-shedding [20] and burst-mode

<table>
<thead>
<tr>
<th>EV System</th>
<th>Value</th>
<th>Unit</th>
<th>4 Phase dc-dc Converter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Max. Motor Speed, (\omega_{max})</td>
<td>10000</td>
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<td>Input Voltage</td>
<td>0-175</td>
<td>V</td>
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<tr>
<td>Car Mass (without converter and u-cap)</td>
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<td>kg</td>
<td>Output Voltage</td>
<td>220-350</td>
<td>V</td>
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<td>Max. Power (continuous), (P_{Max})</td>
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<td>Converter Mass</td>
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<td>kg</td>
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<tr>
<td>Max. Power (30 sec), (P_{Peak})</td>
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<td>kW</td>
<td>Switching Frequency</td>
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<td>kHz</td>
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<tr>
<td>Continuous Motor Torque</td>
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<td>N</td>
<td>Inductor per Phase</td>
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<td>(\mu)H</td>
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<tr>
<td>Max. Motor Torque</td>
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<td>Nm</td>
<td>Maximum Power</td>
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<td>kW</td>
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<td>Peak Motor Efficiency</td>
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<td>Peak Efficiency</td>
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<table>
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<tr>
<th>Battery Pack</th>
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<th>4-cap Pack</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of Series modules</td>
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<td>Number of Series modules</td>
<td>Pack Mass</td>
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<tr>
<td>Pack Mass</td>
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<th>4-cap Module (BM0D0165)</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Nominal Voltage, (V_{bat, nom})</td>
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<td>V</td>
<td>Nominal Voltage, (V_{uc, nom})</td>
<td>48</td>
<td>V</td>
</tr>
<tr>
<td>Max. Current (continuous)</td>
<td>150</td>
<td>A</td>
<td>Max. Current (continuous)</td>
<td>200</td>
<td>A</td>
</tr>
<tr>
<td>Module Capacity</td>
<td>110</td>
<td>Ahr</td>
<td>Module Capacitance</td>
<td>165</td>
<td>F</td>
</tr>
<tr>
<td>Module ESR</td>
<td>6</td>
<td>mΩ</td>
<td>Module ESR</td>
<td>6.3</td>
<td>mΩ</td>
</tr>
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<td>Specific Energy</td>
<td>89.1</td>
<td>Wh/kg</td>
<td>Specific Energy</td>
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<td>Wh/kg</td>
</tr>
<tr>
<td>Specific Power</td>
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<td>kW/kg</td>
<td>Specific Power</td>
<td>7.02</td>
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<tr>
<td>Cycle Life (20% Capacity degradation)</td>
<td>2,800 Cycles</td>
<td>Cycle Life (20% Capacity degradation)</td>
<td>1,000,000 Cycles</td>
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control. The closed-loop transient response of the converter switching between 22 kW to -22 kW is shown in Fig. 8. A settling time of 25 ms is achieved in both cases. The current-mode controller is tuned to avoid overshoots. The measured data for a drive-cycle in downtown Toronto with the complete system integration is shown in Fig. 9. Several scenarios are highlighted as follows; after 420 s the controller operates in Mode 4 and the u-cap assists in acceleration. At 440 s the car decelerates and controller operates in Mode 6, where the u-cap absorbs the RB energy which causes a nearly 30% increase in $SOC_{uc}$. The fact that the battery current is nearly zero during this interval proves the accuracy of the EV real-time model used to calculate the current-command during braking. Shortly after at 500s the controller operates in Mode 2, where the dc-dc converter is turned off to converse energy while $SOC_{uc}$ is constant. Finally at 700 s the EV is idle at a traffic light and the controller caused the u-cap to draw a low-power from the battery to increase the $SOC_{uc}$ in anticipation of the upcoming acceleration. The battery current stays positive for nearly the entire drive-cycle, indicating that the majority of the RB energy is absorbed by the u-cap. During this drive-cycle, the HESS delivered 878 Wh to the inverter and received 219 Wh from RB. The battery absorbs only 39 Wh, compared to 308 Wh for the u-cap, which exceeds the regen energy as expected due to the SOC management scheme. Overall the data shows that both goals of the HESS are achieved: (1) RB energy is successfully captured in the u-cap while managing the u-cap SOC, and (2) the battery current dynamics are greatly reduced. The EV achieves a peak load power of 52 kW with the HESS, which is 36% higher than previously possible without the HESS, based on battery current limits.

Fig. 7. Measured efficiency of the dc-dc converter. Negative output power ($P_{out}$) corresponds to buck mode and positive $P_{out}$ corresponds to boost mode.

V. CONCLUSIONS

This work experimentally demonstrates the feasibility of integrating a u-cap/battery hybrid energy storage system into a modern electric vehicle. The preliminary drive-cycle testing in downtown Toronto shows that the relatively simple rule-based control algorithm successfully manages the u-cap state-of-charge and offloads the current peaks from the battery. The new algorithm is based on a real-time EV model to predict the load power and set the HESS power-mix accordingly. This HESS raises the maximum power capability of the storage by 36% while reducing RB current stress on the battery pack. This is especially valuable in cold climates to reduce capacity-fade effects. Quantifying the long-term benefits of the HESS, especially in terms of the reduction in battery capacity-fade, remains an open research topic. In order to better leverage the benefits of a u-cap based HESS in future EVs, the battery pack cost could be reduced due the relaxed thermal and ESR constraints.

ACKNOWLEDGEMENT

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Fig. 9. Measured drive-cycle test in downtown Toronto for the EV with the integrated HESS. (blue: the battery current, red: total current delivered from the HESS to the inverter load.

REFERENCES


