A New Battery/UltraCapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles

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***Abstract*—In this paper, a new battery/ultracapacitor hybrid energy storage system (HESS) is proposed for electric drive vehicles including electric, hybrid electric, and plug-in hybrid electric vehicles. Compared to the conventional HESS design, which uses a larger dc/dc converter to interface between the ultracapacitor and the battery/dc link to satisfy the real-time peak power demands, the proposed design uses a much smaller dc/dc converter working as a controlled energy pump to maintain the voltage of the ultracapacitor at a value higher than the battery voltage for the most city driving conditions. The battery will only provide power directly when the ultracapacitor voltage drops below the battery voltage. Therefore, a relatively constant load profile is created for the battery. In addition, the battery is not used to directly harvest energy from the regenerative braking; thus, the battery is isolated from frequent charges, which will increase the life of the battery. Simulation and experimental results are presented to verify the proposed system.**

***Index Terms*—Battery, control, dc/dc converters, electric vehicles, energy storage, hybrid electric vehicles (HEVs), plug-in vehicles, power electronics, propulsion systems, ultracapacitor (UC).**

I. INTRODUCTION

ENERGY storage systems (ESSs) are of critical importance in electric, hybrid electric, and plug-in hybrid electric vehicles (EVs, HEVs, and PHEVs) [1]–[9]. Of all the energy storage devices, batteries are one of the most widely used. However, a battery-based ESS has several challenges providing the impetus to look for additional solutions [1]–[5]. In battery-based ESSs, power density of the battery needs to be high enough to meet the peak power demand. Although batteries with higher power densities are available, they are typically priced much higher than their lower power density counterparts. A typical solution to this problem is to increase the size of the battery. However, this also causes an increase in cost. In addition, thermal management is a challenge for batteries to safely work in high power-load conditions not only to cool down the battery, but also to warm up the battery in cold temperatures in order to reach the desired power limits. In addition, an issue concerning the life of the battery is the balancing of the cells in a battery system. Without the balancing system, the individual cell voltages tend to drift apart over time. The capacity of the total pack then decreases rapidly during operation, which might result in the failure of the total battery system. This condition is especially severe when the battery is used to do high-rate charge and discharge [6], [7]. In addition to these issues, applications that require instantaneous power input and output typically find batteries suffering from frequent charge and discharge operations, which have an adverse effect on battery life [6], [7]. For such systems, it is crucial to have an additional ESS or a buffer that is much more robust in handling surge current.

In order to solve the problems listed previously, hybrid energy storage systems (HESS) have been proposed [3]–[5], [10]–[16]. The basic idea of an HESS is to combine ultracapacitors (UCs) and batteries to achieve a better overall performance. This is because, compared to batteries, UCs have a high power density, but a lower energy density. This combination inherently offers better performance in comparison to the use of either of them alone. Several configurations for HESS designs have been proposed, which range from simple to complex circuits. Based on the use of power electronic converters in the configurations, HESS can be classified into two types: passive or active. Conventional active methods use one or multiple full size dc/dc converters to interface the energy storage device to the dc link. In this case, full size refers to the fact that the dc/dc converter forms the sole path for the flow of energy in the device.

In the most widely used conventional HESS designs, the battery pack is directly connected to the dc link while a half-bridge converter is placed between the UC bank and the dc link. However, in order to utilize the power density advantage of the UC, the half-bridge converter must match the power level of the UC. In most cases, the half-bridge converter is a significant portion of the cost. Although this design solves the problem of the peak power demands, the battery still suffers from frequent charge and discharge operations. To solve all these aforementioned problems, a new HESS is proposed in this paper.

The proposed HESS will be presented and verified in detail in this paper. This paper is organized as follows. Section II is a general introduction to HESS. Section III presents design considerations for different HESS configurations. Section IV discusses the topology and operating modes of the

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TABLE I
TYPICAL CHARACTERISTIC OF BATTERY CELLS

Chemistry	Nominal Cell Voltage (Volt)	Energy Density (Wh/Kg)	Power Density (kW/kg)	Cycle life (Times)
Lead Acid	2	30-40	0.18	Up to 800
Ni-Mh	1.2	55-80	0.4-1.2	Up to 1,000
Li-Ion	3.6	80-170	0.8-2	Up to1,200
Li-Polymer	3.7	130/200	1-2.8	Up to 1,000
Li-Iron Phosphate	3.2/3.3	80-115	1.3-3.5	Up to 2,000

TABLE II
TYPICAL CHARACTERISTIC OF ULTRACAPACITOR CELLS

Chemistry	Nominal Cell Voltage (Volt)	Energy Density (Wh/Kg)	Power Density (kW/kg)	Cycle life (Times)
UC	2.5/2.7	2-30	4-10	Over 1,000,000

proposed HESS. Section V focuses on the case study and Powertrain System Analysis Toolkit (PSAT) simulation results. A comparative analysis is presented in Section VI. Experimental verification is presented in Section VII followed by the conclusion, which is given in Section VIII.

II. HYBRID ESSs

Both batteries and UCs fall under the category of electrochemical devices. However, operating principles of both these devices are different which make their characteristics highly different [3], [4]. Table I lists some of the key characteristics for different battery types while Table II shows the same for UCs. As the tables show, batteries have a relatively high energy density of 30–200 Wh/kg, which vary with chemistry and power density. On the other hand, UC has a much lower energy density and significantly higher power density. At the same time, the life of the UC is over one million cycles, which is much higher than that of batteries. Also, UCs have superior low-temperature performance compared to batteries. These characteristics allow for an optimal combination in order to achieve an improved overall performance.

The topologies of HESS have been studied over the past few years. Here, a review of the most widely used HESS topologies is given.

A. Basic Passive Parallel

Passive paralleling as discussed in [4] and [10] is the simplest method of combining battery and UC bank together because the two energy sources are hybridized without any power electronic converters/inverters. Fig. 1 shows the basic topology of the passive parallel method. In this method, since the two sources are always paralleled, $V_{\mathrm{Batt}} = V_{\mathrm{UC}} = V_{\mathrm{DC}}$. The UC essentially acts as a low-pass filter.

Advantages of this method include ease of implementation and no requirements for control or expensive power electronic converters. The major problem with this topology is that it cannot effectively utilize the UC stored energy. This will be further discussed in Section III.

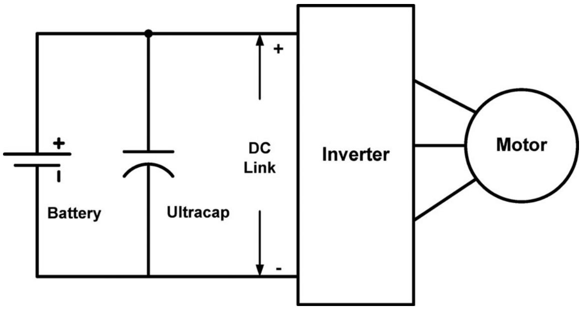

Fig. 1. Basic passive parallel hybrid configuration.

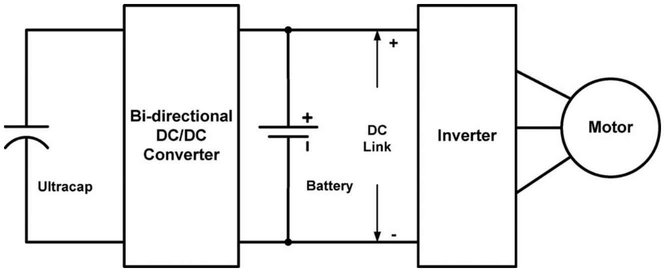

Fig. 2. UC/battery configuration.

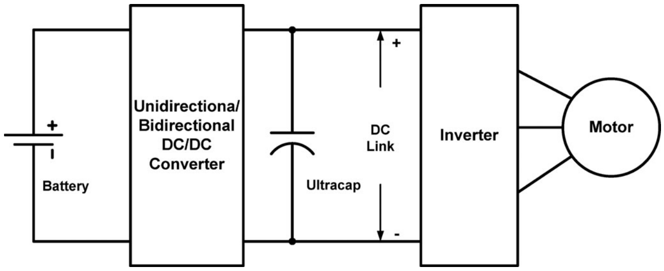

Fig. 3. Battery/UC configuration.

B. UC/Battery Configuration

The UC/battery configuration [12] is the most studied and researched HESS. Fig. 2 shows the diagram of the HESS configuration. By using a bidirectional dc/dc converter to interface the UC, the voltage of UC can be used in a wide range. However, the bidirectional converter needs to be of a larger size in order to handle the power of the UC. In addition, the nominal voltage of the UC bank can be lower. The battery is connected directly to the dc link; as a result, the dc-link voltage cannot be varied.

C. Battery/UC Configuration

By swapping the positions of the battery and UC in the UC/battery configuration, we get the battery/UC configuration [10], [13] as shown in Fig. 3. In this configuration, the voltage of the battery can be maintained lower or higher than the UC voltage. The UC is connected to the dc link directly working as a low-pass filter. The control strategy applied to this topology allows the dc-link voltage to vary within a range so that the UC energy can be more effectively used.

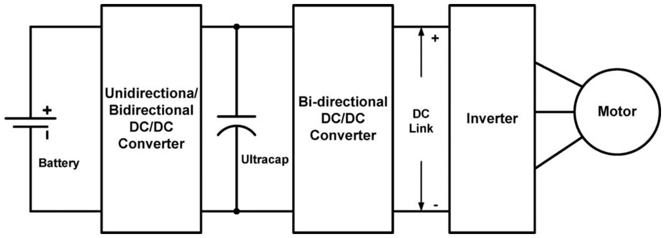

Fig. 4. Cascaded configuration.

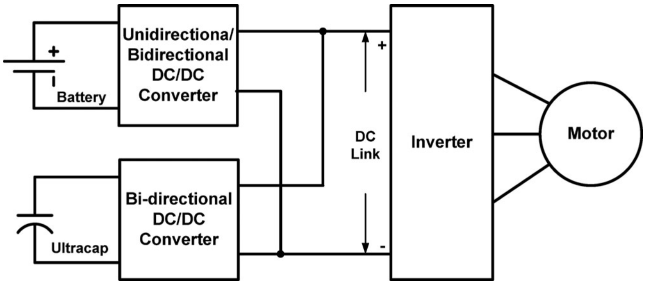

Fig. 5. Multiple converter configuration.

D. Cascaded Configuration

To make a better working range of the UC of the battery/UC configuration, another bidirectional dc/dc converter was added between the UC bank and the dc link. This forms a cascaded converter topology as can be seen in Fig. 4.

E. Multiple Converter Configuration

Instead of cascaded connection of the two converters, the multiple converter method [15] parallels the output of the two converters. Fig. 5 shows the diagram of the multiple converter topology. The outputs of the two converters are the same as the dc-link voltage. Voltages of both the battery and the UC can be maintained lower than the dc-link voltage, less balancing problem so as incurred. The voltage of the UC can vary in a wide range so the capacitor is fully used. The disadvantage of this method is that two full-size converters are necessary.

F. Multiple Input Converter Configuration

As we discussed in Section II-E, the cost of multiple converter configuration is expensive because it requires two full-size bidirectional converters to interface both battery and UC. Multiple input converter topologies [15], [16] are proposed in order to reduce the cost of the overall system. The system diagram of the multiple input converters method is shown in Fig. 6.

III. HESS DESIGN CONSIDERATIONS

While many design considerations have been addressed by researchers, most discussions focus on the specific topology used, with not much detail from the system perspective. This section discusses the basic design considerations that should be considered in the development of battery/UC HESS topologies.

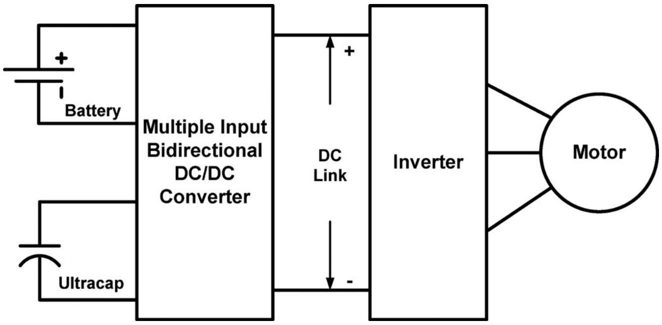

Fig. 6. Multiple input converter configuration.

A. Voltage Strategy of the Two Energy Sources

In designing a battery/UC HESS, the selection of the voltage strategy is strongly related to the characteristics of the battery and UCs used [4], [8]. Higher voltage capacity for the energy storage device presents a higher demand for the cell balancing circuit. This is because cell imbalances grow exponentially with the number of cells in series [6]. One approach to reduce balancing needs is to use cells with lower performance variations (capacity, internal resistance, and self-discharge rate). However, a matched performance is essentially reached by cycling a big batch of cells and finding similar cells that can be grouped together. A better matched performance typically indicates the need for a bigger batch of cells to select from. This will result in an added cost to the total battery pack. Therefore, depending on the characteristics of the battery and UC cells, a voltage tradeoff between the storage elements needs to be made. It must be noted that in most cases, UCs are easier to balance with lower additional cost.

Topology of an HESS depends significantly on the voltage strategy selected [4], [8]. In the following discussion, V_{UC}, V_{Batt}, and V_{DC} are referring to the voltage of the UC bank, voltage of the battery pack, and voltage of the dc link, respectively. If ($V_{\mathrm{UC}} < V_{\mathrm{Batt}} = V_{\mathrm{DC}}$), it indicates that a battery pack is connected directly to the dc link and a UC connected to the dc link through a bidirectional dc/dc converter. In this case, the power rating of the dc/dc converter needs to be matched to that of UC in order to fully utilize the higher power capability of the UC. The advantage of this voltage strategy is the ability to use the entire range of the UC where a lower voltage UC bank is needed. If ($V_{\mathrm{Batt}} < V_{\mathrm{UC}} = V_{\mathrm{DC}}$), it refers to a switch in positions between the battery and the UC with reference to the previous method. The UC bank is now connected to the dc link directly, while the battery is connected to the dc link through a dc/dc converter. With this topology, the voltage of the battery can be maintained at a lower magnitude so that less balancing issues need to be addressed. If $V_{\mathrm{Batt}} = V_{\mathrm{UC}} = V_{\mathrm{DC}}$, it means that the battery and the UC are directly paralleled and connected to the dc link. The most significant advantage of this topology is that no dc/dc converter is needed. However, the working range of the UC is very small. If $V_{\mathrm{Batt}} \neq V_{\mathrm{UC}} \neq V_{\mathrm{DC}}$ (not necessarily unequal), then both the battery and UC are connected to the dc link through power electronic converters or other mechanisms.

B. Effective Utilization of UC Stored Energy

While energy delivery in a battery is not a function of voltage, energy storage in an UC obeys the law of storage in a standard capacitor as shown in

$$E_{\text{Cap}} = \frac{1}{2}CV^2. \tag{1}$$

Voltage of the UC needs to be discharged to half of the initial voltage in order to deliver 75% of the energy stored. The ability to use the UC energy storage effectively is a major criterion in evaluating HESS configurations. If the UC is connected to the dc bus via a dc/dc converter ($V_{\text{UC}} < V_{\text{Batt}} = V_{\text{DC}}$), 100% of the energy can be delivered theoretically. However, a safety margin is allowed in order to prevent a reverse charge of unbalanced cells. When a voltage variation of 66% is permitted, 90% of the UC energy can be delivered. If the battery and UC are paralleled passively, the voltage of the UC cannot change a lot. Even in an aggressive discharge (within the battery power limits), the voltage of the battery pack can drop only up to 20% of the nominal voltage. Assuming that the UC is designed to cover the nominal voltage, $V_{\text{Max}} = V_{\text{Nom}}$, the total energy that can be delivered by the UC is

$$\begin{aligned}\text{Eff}_{\text{Cap}} &= \frac{E_{\text{Utilized}}}{E_{\text{Total}}} = \frac{(1/2)C \cdot V_{\text{Nom}}^2 - (1/2)C \cdot V_{\text{Min}}^2}{(1/2)C \cdot V_{\text{Nom}}^2} \\ &= \frac{V_{\text{Nom}}^2 - V_{\text{Min}}^2}{V_{\text{Nom}}^2} = 36\%. \end{aligned} \tag{2}$$

The actual energy available is less than 36% because a margin needs to be allowed for the UC to cover higher voltage of the battery pack during charging or regenerative braking.

C. Protection of the Battery From Overcurrent

An important design concern of a battery/UC HESS is to fully utilize the significantly higher power limits of the UC to support acceleration and fully recover energy through regenerative braking. Unlike applications such as laptops that draw a relatively constant and predictable current from the battery, ESSs in automotive propulsion applications undergo frequent charge and discharge cycles. These frequent charges are typically current surges caused by unpredictable regenerative braking. If this surge is injected directly into a battery without regulating, the battery could die very quickly. This is especially true for lithium-ion batteries [3], [6], [7]. The common engineering solution for this problem in a battery ESS is to provide charging and discharging power limits to the controller (usually a lookup table with state of charge (SOC) and battery temperature as inputs). This allows the hybrid system optimizer to follow power limits in order to protect the battery. The discharging power limit ensures that no additional power is drawn from the battery during aggressive acceleration while the charging power limits force the hybrid controller to activate mechanical brake early in order to absorb the portion of extra energy that cannot be taken by the battery. This process is a tradeoff where energy is expended for the security of the battery pack. In a battery/UC HESS system design, it is important to utilize much higher power limit of the UC to not only protect the battery but also increase the overall performance of the electric drive system.

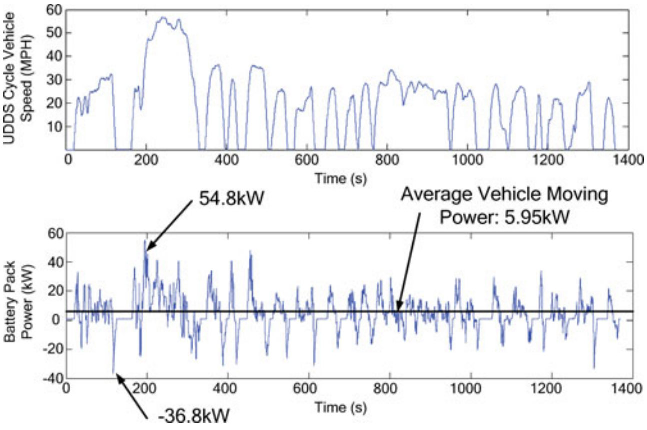

Fig. 7. UDDS simulation results for a mid-size EV (2003 Honda Accord EV) with battery only ESS.

D. HESS Total Cost

Compared to a conventional battery ESS, two major components are added to a battery/UC HESS: UC and the dc/dc converter (if employed). UC technology has made great strides in increasing energy density. However, UC cost is still a major component of the overall HESS system cost.

Power handling capacity of the converter is another important factor that influences cost of the HESS. If a higher power dc/dc converter is needed, a practical issue is the additional cost. Special thermal management is also required [9] that adds complexity and increases overall cost of the system. However, a tradeoff still exists between energy stored in the UC bank and cost associated with an effective HESS solution.

IV. PROPOSED HESS

A. Averaging Concept

Conventional HESS connects the UC via a dc/dc converter to satisfy the real-time peak power demands of the powertrain controller. This will require the dc/dc converter to have the same power capability as the UC bank or at least higher than the maximum possible demand value. The proposed HESS achieves this in a different way, which can be considered an application of the averaging concept. The averaging concept is introduced as follows.

Fig. 7 shows the battery pack power of a mid-size electric vehicle simulated in PSAT with the United States Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule (UDDS). The UDDS is a driving cycle standard that is designed to simulate city driving in the U.S. The cycle simulates an urban route of 12.07 km (7.5 mi) with frequent stops. The maximum speed is 91.2 km/h (56.7 mi/h) and the average speed is 31.5 km/h (19.6 mi/h). The duration of the cycle is 1369.00 s.

As can be seen from Fig. 7, the start stop nature of city driving will result in frequent charges and discharges of the battery at

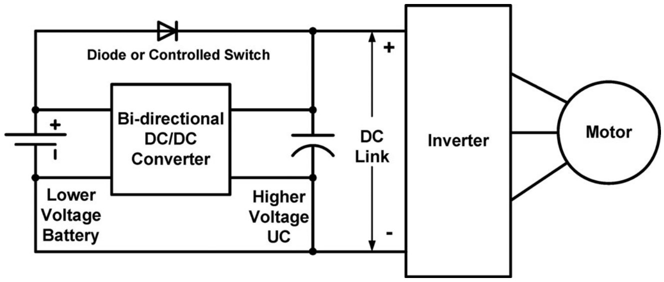

Fig. 8. Proposed HESS configuration.

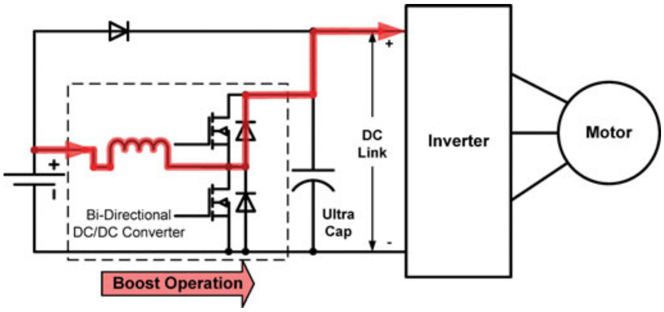

Fig. 9. Low constant speed operation energy flow.

high power, which ranges from -36.8 to 54.8 kW according to the simulation data. However, based on calculations, the average moving power of the battery pack is only 5.95 kW, which is about 1/10 of the peak power.

The significant difference between the peak and average power suggests the following: ideally, if an energy storage device that is good at handling power is employed to work as a buffer, we only need a dc/dc converter to feed 5.95 kW constant power to charge the buffer energy storage device (BESD). In this case, the dc/dc converter size is minimized with the cost of an increased BESD size. However, for a specific vehicle application, the averaging nature allows the dc/dc converter and the BESD size to be optimized in order to achieve the same result.

Based on the averaging concept, the new battery/UC HESS configuration is proposed and the diagram is illustrated in Fig. 8. In this configuration, different from the conventional HESS designs, the high-voltage dc link is allowed to vary in a predefined ratio. The motor drive is designed to be able to handle the current at the lower voltage. A higher voltage UC bank is always directly connected to the dc link so as to provide peak power demands whereas a lower voltage battery is connected to the dc link via a power diode (or a controlled switch). A reduced size bidirectional dc/dc converter is connected between the battery and the UC to convey energy to charge the UC. The dc/dc converter is always controlled to try to maintain the voltage of the UC higher than that of the battery. Therefore, in most cases, the diode is reverse biased.

Typically, the high-voltage dc link is allowed to vary in a 2:1 ratio. This results in 50% of voltage discharge ratio of the UC. The voltage discharge ratio of the UC is defined as the final voltage over the initial voltage. There is no strict rule when determining the UC discharge ratio. Typically, a 50% ratio results in 75% of the stored energy being utilized. The reason to select a 50% discharge ratio is that in a constant power application, the decrease of V_{UC} is in an exponential manner. On the other hand, the load is demanding a constant power which is the product of the voltage and current; therefore, the UC current will increase exponentially which will result in inefficiency.

In order to explain the operation of the HESS, an all-electric vehicle is used as an example. In an electric vehicle application, the operation of the HESS can be separated into four modes. They are vehicle low and high constant speed operating modes, acceleration mode, and deceleration (regenerative braking) mode. The practical operation of the HESS is complex, but it is a combination of the aforementioned four modes. The four operating modes will be discussed next in detail.

B. Mode I: Vehicle Low Constant Speed Operation

The constant speed operation of the vehicle was separated into two depending on if the power of the dc/dc converter P_{conv} can cover the power demand P_{dmd}. If P_{dmd} is equal to or smaller than P_{conv}, we call this operating condition the low constant speed mode. If the vehicle is running at a higher speed in which P_{dmd} is higher than P_{conv}, we call it the high constant speed mode. Both the low and high constant speed operating modes are ideal modes, since in practical vehicle driving the power demand is always changing. They are defined here in order to explain the operation of the proposed HESS.

Fig. 9 shows the energy flow of the low constant speed operation of the HESS. In a low-speed operating mode, since $P_{\mathrm{conv}} > P_{\mathrm{dmd}}$, the voltage of the UC V_{UC} can be maintained higher than the voltage of the battery V_{Batt}; the dc-link voltage V_{DC} can also be maintained at any value higher than the battery voltage. In the constant speed mode, the UC is neither absorbing nor providing power to the electric motor. Since the UC voltage is higher than that of the battery, the main power diode is reversely biased. There is no energy flow through the diode. The battery is not providing any energy directly to the motor inverter.

C. Mode II: Vehicle High Constant Speed Operation

In the high constant speed operating mode, $P_{\mathrm{dmd}} > P_{\mathrm{conv}}$, V_{UC} can no longer be maintained higher than V_{Batt}. Therefore, the main power diode is forward biased. The battery is providing energy directly to the motor inverter. In this mode, the dc/dc converter will be turned OFF. Fig. 10 shows the energy flow of the high constant speed operating mode.

D. Mode III: Acceleration

At the beginning of the acceleration mode, assume $V_{\mathrm{UC}} > V_{\mathrm{Batt}}$. Since $P_{\mathrm{conv}} < P_{\mathrm{dmd}}$, V_{UC} will keep decreasing. Energies from the UC and the dc/dc converter are both supporting the vehicle acceleration. Fig. 11 illustrates the energy flow of the acceleration mode phase I.

With the decreasing ofV_{UC}, V_{UC} will drop to the same level asV_{Batt}. When $V_{\mathrm{UC}} = V_{\mathrm{Batt}}$, the battery and UC become

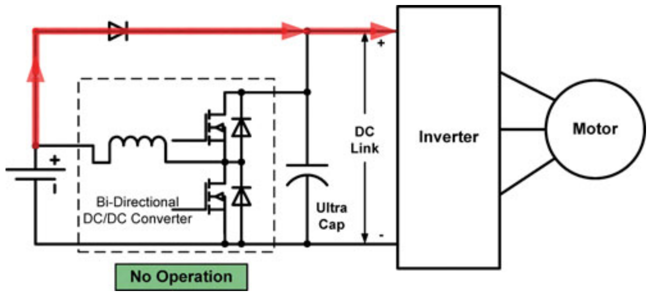

Fig. 10. High constant speed operation energy flow.

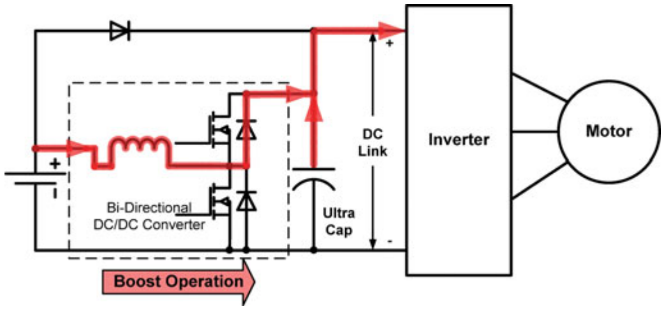

Fig. 11. Acceleration mode phase I energy flow.

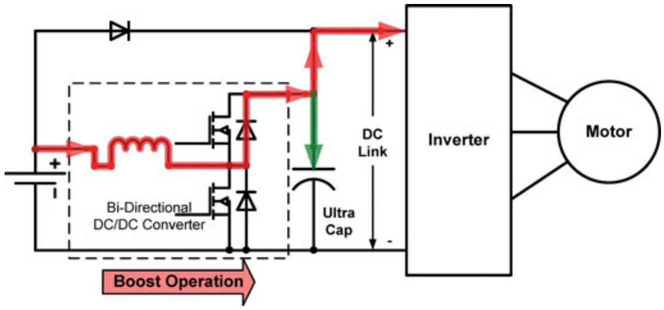

Fig. 12. Acceleration mode phase II energy flow.

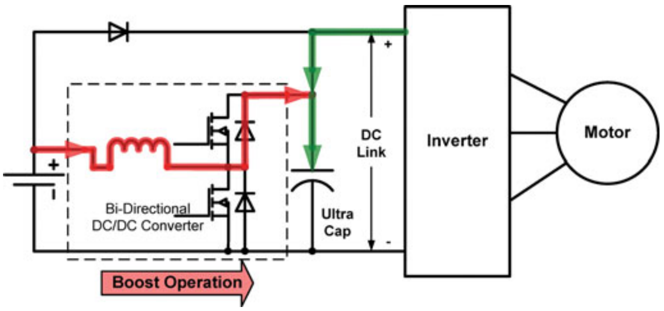

Fig. 13. Regenerative braking phase I energy flow when $V_{\mathrm{UC}} < V_{\mathrm{UC\_tgt}}$.

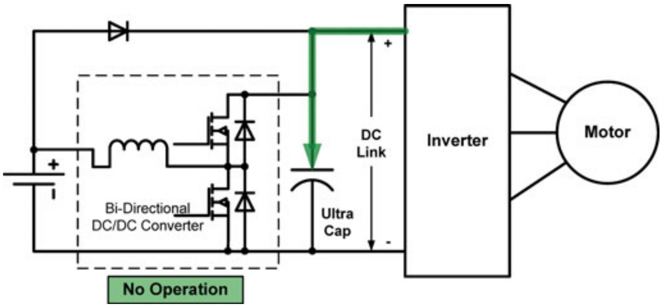

Fig. 14. Regenerative braking phase I energy flow when $V_{\mathrm{UC}} \geq V_{\mathrm{UC\_tgt}}$.

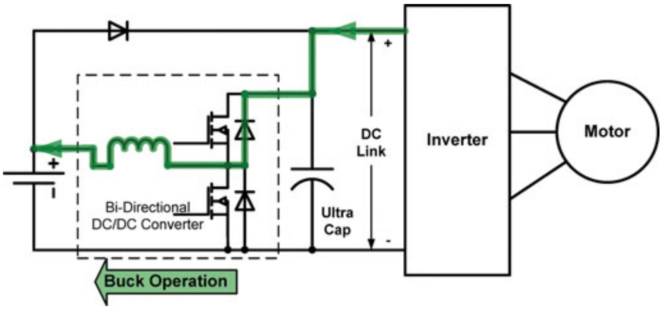

Fig. 15. Regenerative braking phase II energy flow.

directly paralleled through the diode. The system enters the high constant speed operating mode. In the high constant speed operating mode, if P_{dmd} becomes less than P_{conv}, the power difference between P_{conv} and P_{dmd} will be used to charge the UC. The energy flow is illustrated in Fig. 12.

E. Mode IV: Deceleration (Regenerative Braking)

In the deceleration mode, there are two phases. In phase I, the regenerative power will be injected into the UC only. In phase I, the dc/dc converter might be in boost operation or no operation depending on whether V_{UC} is less than the target UC voltage $V_{\mathrm{UC\_tgt}}$ or greater than or equal to the target UC voltage $V_{\mathrm{UC\_tgt}}$. The energy flow diagrams for the two conditions are shown in Figs. 13 and 14, respectively.

Fig. 15 shows the energy flow of the regenerative braking phase II. Phase II describes the working conditions of the continuous regenerative braking. If continuous regenerative braking is needed, in order to make sure V_{UC} is within the safe operating range, the dc/dc converter will work in buck mode to convey the energy from the UC to the battery. When designing the proposed HESS, the ESS components can be properly sized such that regenerative braking phase II can be used as less as possible. This will extend the life of the battery as well as increase the accuracy of battery SOC estimation.

V. CASE STUDY AND SIMULATION RESULTS

A case study of the proposed HESS design has been carried out and the designed system is simulated using the PSAT software in order to prove the concept of the HESS.

A. Simulation Setup

An all-electric vehicle PSAT model based on a 2003 Honda Accord was built. Fig. 16 shows the drivetrain configuration of the vehicle.

The design goal is to use the UC to cover the city driving power demands of the vehicle with the energy feeding from

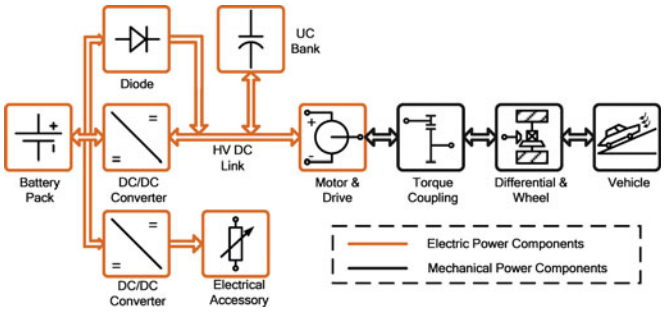

Fig. 16. Simulated drivetrain configuration in PSAT.

TABLE III
SPECIFICATIONS OF THE SIMULATED VEHICLE AND DRIVETRAIN COMPONENTS

Chassis	2003 Honda Accord
Vehicle Weight	1737.80 kg (With the 2 energy storage systems)
Drivetrain Configuration	2 wheel drive electric with single reduction ratio of 16
Electric Motor	UQM PowerPhase 75
Motor Power	36kW continuous, 75kW peak
UC Bank	375V max 16.67F
UC Bank Configuration	150 Maxwell PC2500, 2.5V 2500F in series
Battery Pack	172.8V 180Ah Ni-MH
Battery Pack Configuration	144 1.2V 90Ah cells in series and 2 in parallel
DC/DC Converter	Constant efficiency, 12kW peak
Accessory Power	500W

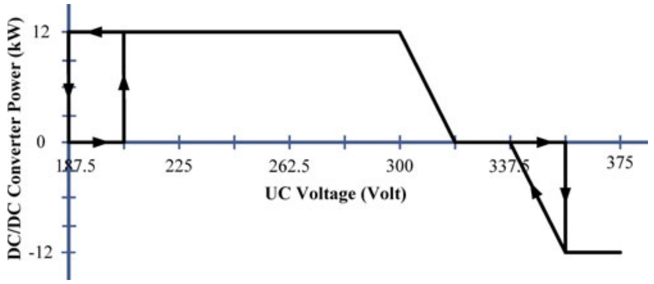

Fig. 17. Hysteresis control of the UC voltage.

the dc/dc converter. Based on the existing 2003 Honda Accord EV Model in PSAT software, a new powertrain controller is designed in order to replace the battery only ESS with the proposed HESS. The battery of the HESS is sized in order to deliver the same range as with the EV ESS; the UC is sized in order to satisfy the design goal which is to use the UC to cover the city driving power demands of the vehicle with the energy feeding from the dc/dc converter. Several dc/dc converter and UC rating combinations are simulated and Table III shows the final list of the components of the modeled vehicle.

Hysteresis control schemes were applied to control V_{UC} by managing the power of the dc/dc converter. The implemented dc/dc converter power strategy based on the UC open-circuit voltage is shown in Fig. 17. Modeling of the hysteresis V_{UC} regulation was accomplished in MATLAB/Stateflow.

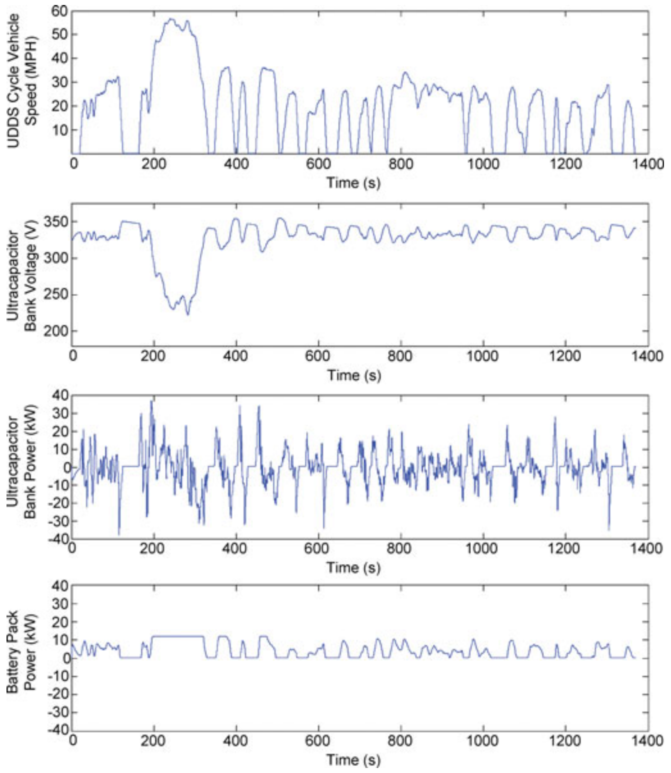

Fig. 18. PSAT simulation results with the dc/dc converter power limited to 12 kW.

B. Simulation Results

The configured vehicle was simulated in PSAT with the U.S. EPA UDDS. Fig. 18 shows the vehicle speed, UC voltage, UC power, and battery pack power of the configured vehicle with the dc/dc converter power limited to 12 kW.

The simulation results indicate that the designed HESS is working as expected. During the overall drive cycle, the UC bank can cover the power needs with the 12 kW dc/dc converter pumping energy to recover the power consumption. As can be seen in Fig. 18, the peak power of the UC bank ranges from −38 kW to 37.3 kW. On the other hand, the peak power of the battery pack is limited to 12 kW as shown in the figure.

In order to evaluate the impact of the dc/dc converter power on the performance of the HESS, the dc/dc converter power is derated to 9 kW. Fig. 19 shows the simulation results. As can be seen, with the decreased power, in the acceleration, V_{UC} will drop to the same level as V_{Batt} which result in a direct parallel of the two energy storage devices. The battery power will increase in order to cover the power demand from the controller.

VI. COMPARATIVE ANALYSIS

A. Compared to Battery Only ESS

The same Honda Accord vehicle configured with a battery only ESS is simulated with the UDDS drive cycle. Fig. 20 shows

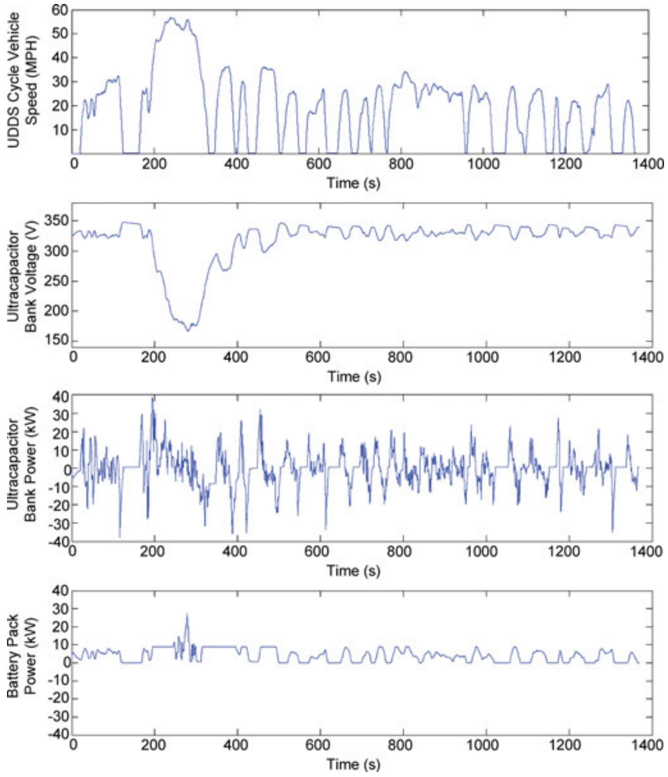

Fig. 19. PSAT simulation results with the dc/dc converter power limited to 9 kW.

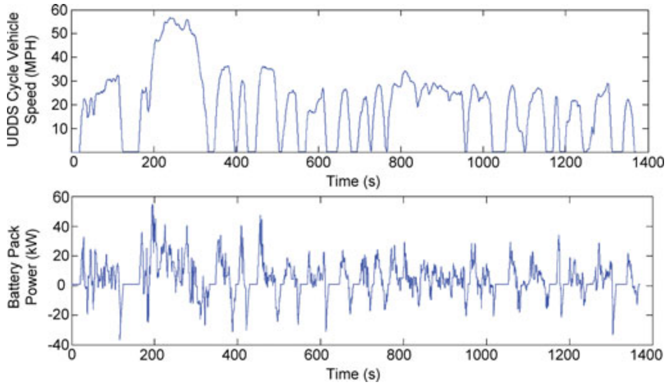

Fig. 20. Simulation results with the battery only ESS.

the simulation results. As can be seen in the figure, without the peak power assist from the UC bank, the battery needs to provide peak power up to 60 kW, compared to the proposed HESS where the battery power was limited to 12 kW. The decreased power demand from the battery is very important for the drivability of the vehicle when the battery temperature is too low to provide sufficient power.

B. Compared to Conventional UC/Battery HESS

In order to compare to the conventional UC/battery HESS, following two assumptions are made prior to the comparison.

1) Both of the UC voltage discharge ratios in the conventional HESS and the proposed HESS are limited to 50%.

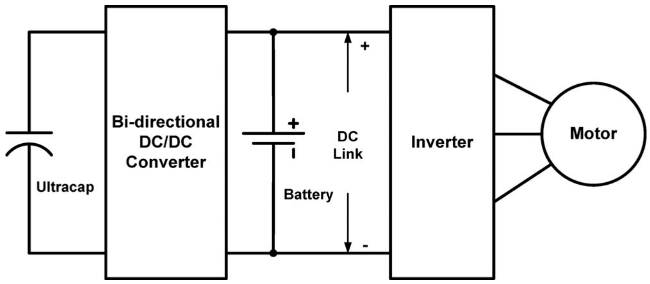

Fig. 21. Conventional UC/battery HESS configuration.

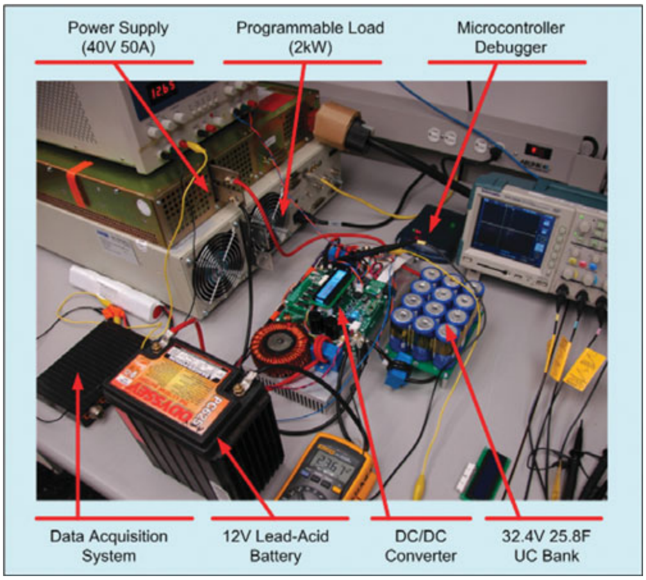

Fig. 22. Experimental test setup.

2) The same storage-size UC banks are applied to the two configurations.

The same storage size here is defined as, when a 50% V_{UC} discharge ratio is allowed, the two UC banks will discharge the same amount of energy although they may have different voltage and capacitance ratings.

As can be seen from the conventional HESS topology in Fig. 21, the UC bank and the dc/dc converter are in series. In other words, the smaller capacity component will be the bottleneck of the overall system. In order to fully utilize the power capacity of the UC, a matched capacity dc/dc converter is desired. In the proposed HESS, the dc/dc converter and the UC are in parallel to provide power; in this configuration, the UC will allow up to 75% of the energy use naturally and the full power capability of the UC is utilized. Control wise, in the proposed topology, the UC will naturally absorb the peak power from regenerative braking without stressing the battery pack while for the conventional HESS, precise control of the dc/dc converter is required in order for the UC to follow the negative power demands.

Even though the proposed HESS has lots of advantages as discussed earlier, several problems need to be addressed. Apparently, a wider operating voltage range is needed for the motor

TABLE IV
LIST OF MAJOR COMPONENTS OF THE EXPERIMENTAL SETUP

Power Supply	40V 50A DC Switching type, 3phase input
Electronic Load	NHR 4750-2 (2kW, 100A Max)
DC/DC Converter	450V 40A Half-bridge, bi-directional, non-isolated
Data Acquisition System	Race Technology DL2 (0-12V 100Hz 16bit)
Battery	Odyssey PC625 12V 18Ah
Ultra-Capacitor Bank	32.4V 25.8F (12 Maxwell 2.7V 310F cells in series)
Bypass Switch	Tyco Electronics EV200AAANA Contactor

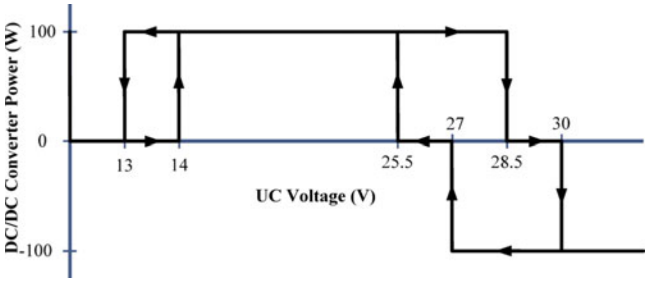

Fig. 23. Implemented hysteresis control of the UC voltage.

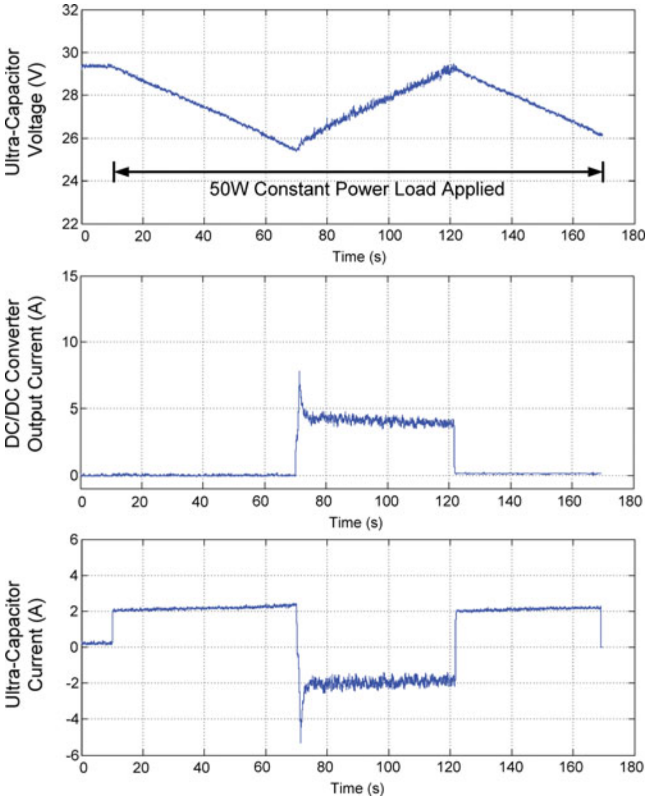

Fig. 24. HESS experiment at 50 W constant power load with the hysteresis control.

drive which may require the increment of the voltage rating of the insulated gate bipolar transistor devices used. However, in higher voltage operation, with the same amount of power delivered, the current can be reduced. It is possible to boost the overall efficiency if the system is properly sized and controlled, which leaves room for future research.

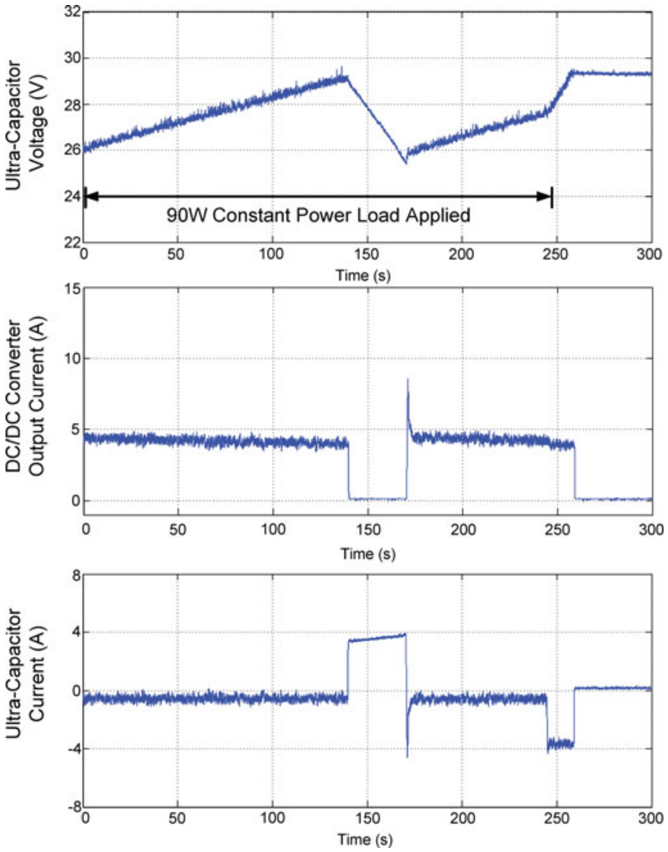

Fig. 25. HESS experiment at 90 W constant power load with the hysteresis control.

VII. EXPERIMENTAL VERIFICATION

A scaled-down HESS experimental setup was constructed in order to further validate the electrical viability of the proposed topology as well as the applicability of the hysteresis $V_{\rm UC}$ control. The finished experimental setup is illustrated in Fig. 22. Major components used in this experimental setup are listed in Table IV. Among these components, the dc/dc converter and the UC bank are designed and built (packaged) in-house.

The maximum voltage of the UC bank used in this experiment is 32.4 V with a surge max voltage of 34.2 V. In order to ensure the safe operation of the UC, the max voltage is limited to 30 V. During the testing, the dc/dc converter is programed to work in a constant power mode with a power limit of 100 W. Hysteresis $V_{\rm UC}$ control is applied and the control scheme is illustrated in Fig. 23. This control scheme will allow the UC voltage to vary between 25.5 V and 30 V when less than 100 W of load is applied.

The variable load available is programed to provide negative power only. It cannot be programed to supply power. In this experimental verification, a discharge test is done and the experiment results are presented as follows.

Fig. 24 illustrates the results when 50 W constant power load is applied to the HESS. The dc/dc converter is turned ON once

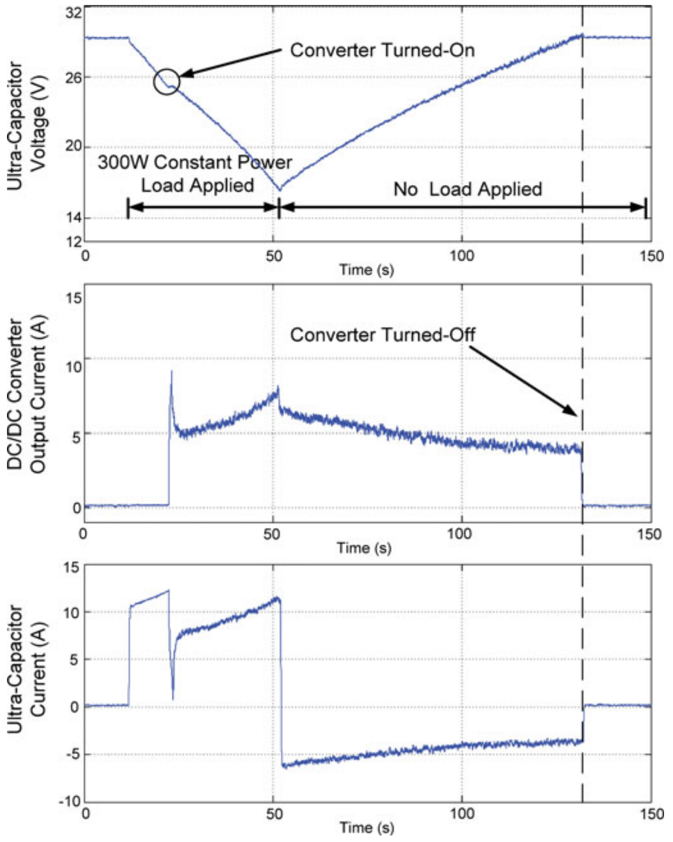

Fig. 26. HESS experiment at 300 W constant power load with the hysteresis control.

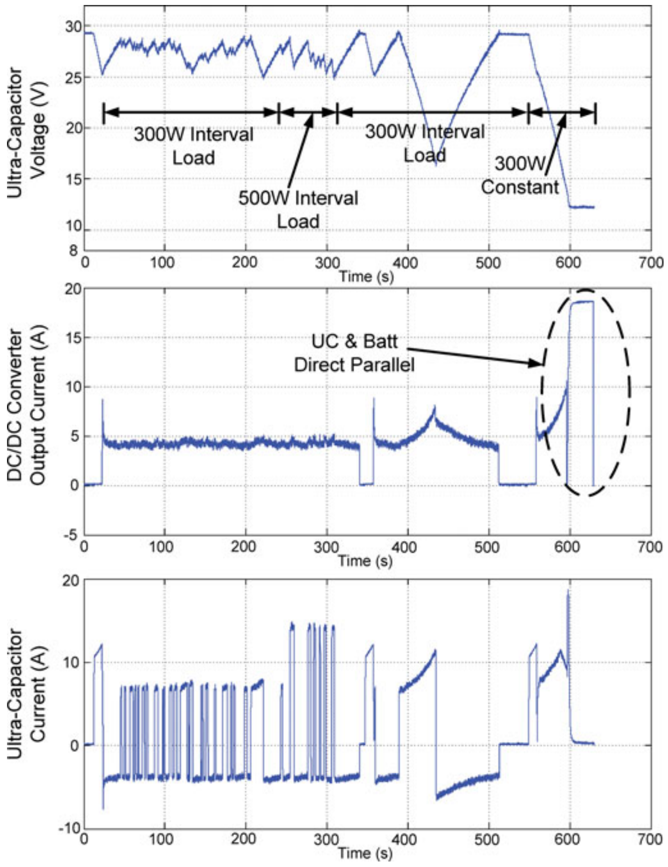

Fig. 27. HESS experiment with the interval load.

V_{UC} drops to 25.5 V and turned OFF when 28.5 V of UC voltage is reached. It can be seen from the figure that, when the power demand is less than the dc/dc converter power, V_{UC} can be maintained with the proposed hysteresis V_{UC} control. Fig. 25 shows that when 90 W of constant load is applied, V_{UC} can be maintained still. However, the charging time is much longer compared to the condition when 50 W load is applied.

Fig. 26 illustrates the results when 300 W constant power load is applied to the HESS. The dc/dc converter is turned ON when 25.5 V of V_{UC} is reached. Since the 300 W power demand is higher than the limited power of the dc/dc converter, V_{UC} continues to decrease until the load is disconnected. After the load is removed, the UC bank is charged with the 100 W power and the dc/dc converter is turned OFF when 28.5 V of V_{UC} is reached.

An interval load test is applied as well and the results are shown in Fig. 27. When 300 W constant load is applied, V_{UC} keeps decreasing. As soon as $V_{\mathrm{UC}} = V_{\mathrm{Batt}}$, the UC and the battery pack become directly paralleled. This verifies that the bypass switch is electrically viable.

The experimental results have shown that the proposed HESS is electrically viable, as well as the hysteresis V_{UC} control is verified to be applicable to the topology.

VIII. CONCLUSION

In this paper, a new HESS design has been proposed. Compared to the conventional HESS, the new design is able to fully utilize the power capability of the UCs without requiring a matching power dc/dc converter. At the same time, a much smoother load profile is created for the battery pack. As a result, power requirement of the battery pack can be reduced. Drivability of the vehicle at low temperatures can be improved as well. The operating fundamentals of the proposed HESS were explained in detail in four operating modes. A case study and simulations were carried out in order to prove the concept of the new HESS. Simulation results show that the new HESS can operate in all modes of operation described in this paper. A comparative analysis was given in order to address the advantages and challenges of the proposed HESS.

The comparative analysis shows that the proposed HESS requires a smaller size dc/dc converter to convey energy to charge the UC bank, while still utilizing up to 75% of the UC energy. In addition, a relatively constant load profile is created for the battery by using the topology, which is good for the life of the battery. It is also possible to boost the overall efficiency if the system is properly sized and controlled. Therefore, future work related to this paper will focus on the analysis of the system efficiency in the high-voltage conditions. On the other hand, sizing of the dc/dc converter versus the selection of the UC needs to be addressed in order to minimize the cost of the overall system while still maintaining the benefits of the proposed system. .

A scaled-down experimental setup was built in order to verify the electrical viability of the proposed HESS. Finally, the experimental results show that the topology is electrically viable and the hysteresis control is a simple but effective control strategy for the proposed HESS.

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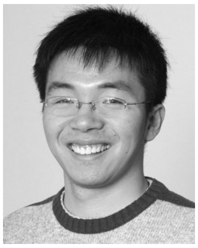

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