Power Management of an Ultracapacitor/Battery Hybrid Energy Storage System in an HEV

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***Abstract*–To overcome the power delivery limitations of batteries and energy storage limitations of ultracapacitors, hybrid energy storage systems, which combine the two energy sources, have been proposed. A comprehensive review of the state of the art is presented. In addition, a method of optimizing the operation of a battery/ultracapacitor hybrid energy storage system (HESS) is presented. The goal is to set the state of charge of the ultracapacitor and the battery in a way which ensures that the available power and energy is sufficient to supply the drivetrain. By utilizing an algorithm where the states of charge of both systems are tightly controlled, we allow for the overall system size to reduce since more power is available from a smaller energy storage system.**

***Index Terms*–Batteries, Battery-ultracapacitor hybrids, power enhancement, optimization design.**

I. Introduction

Hybrid electric vehicles (HEV) couple the power produced by an internal combustion engine (ICE) and an electric motor to propel the vehicle more efficiently. Fuel economy improvement is obtained by using a smaller ICE (set to provide the average vehicle power demand), augmented by the electric motor (provides power demand transients). The electric motor is powered by an energy source such a battery or an ultracapacitor (UC). The energy source needs to store adequate energy to meet the averaged demand that is required from the electric motor under various driving conditions [1]. In addition to the energy requirement, the source needs to be able to deliver short high-power charge and discharge pulses. FreedomCAR sets the power pulse duration for a typical power assist hybrid at 10 seconds [2].

In principle, batteries have a relatively high energy density. They however do not posses instantaneous charge and discharge capabilities of an UC [3-5] If batteries are cycled at very high C-rates, the life of the pack is severely diminished, and may also lead to safety issues due to thermal runaway. Therefore, the battery packs in HEV's have to be oversized to ensure battery life and to avoid thermal runaway.

Due to their high specific power UC's have been considered for transient power supply and recovery in hybrid power trains [3-21]. A UC / battery hybrid energy storage system (HESS) therefore reduces the strain on the battery pack. The UC absorbs and supplies the large current pulses, and the battery provides the average power demand. This, in turn, allows for the size of the battery pack to be reduced, and sized for the energy requirement of the cycle, rather than the power requirement.

The optimal design of a HESS has been the topic of many papers. Researchers [10-11] have considered a direct parallel connection of the two sources. This setup keeps the same voltage over both sources, which in turn limits the power delivered form the UC. Other researchers have employed a bi-directional DC/DC converter placed between the batteries and the UC's [3-9]. The output of the DC/DC converter is current controlled, and controls the current output out of the battery. The UC supplies the remaining power requirement to the load. Finally, some researchers have looked at using a two input bi-directional DC/DC converter [20-21]. It will be shown that this setup gives the highest efficiency, reliability, and flexibility. A comparison of the topologies in terms of the maximum power delivery capability will be presented. The control logic and its effect on the power delivery will be investigated. The remainder of this paper is organised as follows: in Section II some general characteristics of various battery technologies and ultracapacitors will briefly be reviewed; an explanation of the topologies mentioned above is given in Section III; in Section IV the power delivery capabilities of the various topologies with different control strategies is explored; finally some conclusions are presented in section V.

II. Battery and UC Characteristics

Batteries and UC's are complex electrochemical systems, and a detailed review is beyond the scope of this paper. However, there are some electrical properties of these devices that need to be point out.

As mentioned in the introduction, batteries have a relatively high energy density (in the order of 1kW/kg; 100Wh/kg [3]), while UC's store a small amount of energy but have a very high power density (in the order of 10kW/kg; 1Wh/kg [3]). These properties allow the combination of these two sources to exhibit both high power and energy density. As seen in Table I, UC's exhibit an internal resistance an order of magnitude lower than that of batteries. This allows the UC's to supply very large currents to the load. On the other hand, due to the intrinsic properties of the UC, the voltage change as a function of the state of charge of the UC is very large. This is illustrated in Figure 1. The normalized voltage swing (Vmin/Vmax) at open circuit for batteries is higher than 0.85. while the UC voltage swing is 0.2 and is limited by the electronics which do not allow the UC depth of discharge (DoD) to go above 80%.

Additionally, due to the low energy storage capability of the UC, the state of charge (S0C) of the UC changes very

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quickly. This means that during a relatively short discharge time the UC SoC will change substantially, causing a large voltage swing.

TABLE I
ELECTRICAL PROPERTIES OF BATTERIES AND ULTRACAPACITORS

Chemistry	Nominal voltage	Min Voltage	Max Voltage	Typical internal resistance
PbA	2.1	1.6	2.75	2-30 mΩ
NiMH	1.2	1	1.5	0.1-3 mΩ
Li-ion	3.8	2	4	2-50 mΩ
UC	1.75	0.5	3	0.02-0.2 mΩ

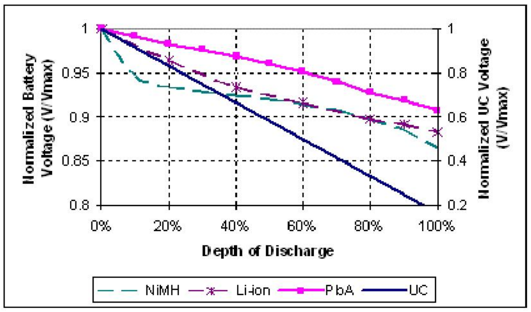

Figure 1. Normalized open circuit voltage change (Voc/Vmax) for various battery chemistries and typical UC

III. REVIEW OF HESS TOPOLOGIES

There has been a lively debate as to what is the optimal topology of a Hybrid Power Source (HPS). Available solutions vary in their flexibility and cost. In this section a review of the existing solutions and the benefits and drawbacks of each are put forward.

A. Passive Parallel Connection

The simplest method of combining two power sources is a parallel connection, shown in Figure 2. Since the two power sources are directly connected, the voltages over the two sources are equal. Buck-Boost converter 1 maintains a constant voltage on the bus by supplying the power demand of the motor from the HESS.

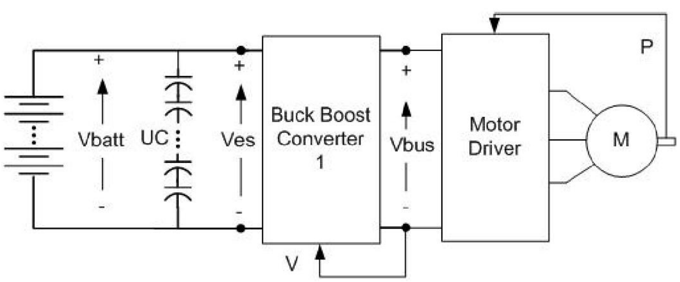

Figure 2. Topology of the passive parallel connection

B. Bi-Directional DC-DC Converter

This system has a Buck-Boost converter between the battery and the UC. This allows for the battery voltage to be different than that of the UC. It is beneficial to put the battery on the input side of buck-boost converter 1 to be able to control the current output, and therefore the stress on the battery. This makes the UC the bus voltage. Therefore the bus voltage varies with the UC SoC. Since the voltage of the UC can vary substantially, there is a large voltage swing on the input to Buck-Boost converter 2. Therefore Buck-Boost converter 2 has to be stable for a wide voltage input range. At low UC voltages the input current can be very high leading to larger IR losses and a need for high rating switches.

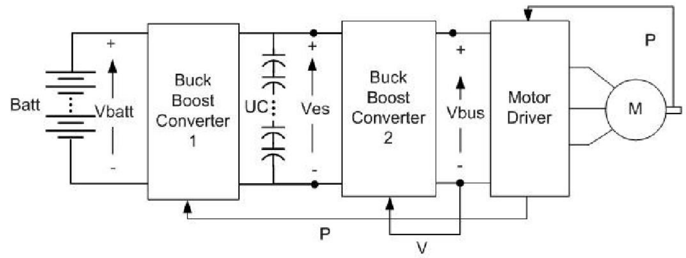

Figure 3. Topology of the Bi-Directional DC-DC Converter

C. Two-input Bi-Directional DC-DC Converter

An alternative topology uses a two input bi-directional DC-DC Converter. This topology has the same functionality as the bi-directional DC/DC converter considered in the previous section. Here the converter that controls the battery is current controlled, and the UC converter is voltage controlled. The system functions as follows: the instantaneous power requirement demand comes from the motor, and based on the state of the battery and the UC, the converter control determines the current that each source should supply.

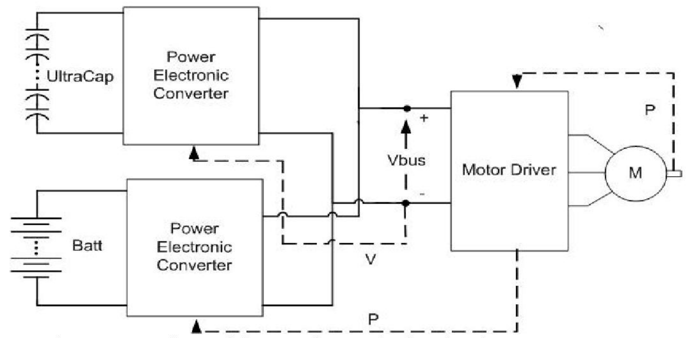

Figure 4. Topology of the Two-input Bi-Directional DC-DC Converter

As can be seen from the block diagrams of Figures 3 and 4, there is the same number of converters for both topologies. However, the two input bi-directional converter topology is superior from both stability and efficiency point of view. Assuming that the two systems are at the exact same states (meaning that the same power demand from the motor and same UC and battery SoC's). The voltages of the UC's will be the same, so the input voltages to the Buck-Boost converter 2 will be the same for both topologies. This voltage is presumably low for a large power pulse due to the properties of the UC discussed earlier. On the other hand, the current will be the sum of the UC and the battery output current in the bi directional dc-dc case as opposed to only the current of the UC in the two-input bi-directional DC-DC Converter case. The operation of converter 1 should be equivalent in both cases on the input side. The output voltage of buck-boost converter 1 will be higher for the two-input bi-directional DC-DC converter case, but the efficiency should be very close in both cases for buck-boost converter 2. Therefore the efficiency of the two-input bi-directional DC-DC converter is expected to be higher. The stability is also improved, since a failure of one source still allows the operation of the other.

IV. Case Study of the Effect of Topology and Control on Power Delivery Capability

To illustrate the effect of topology choice and control method on the power delivery capability, a case study is presented in this section. A Panasonic 6.5 Ah NiMH battery pack consisting of 20 six-cell modules is coupled with 60 Maxwell 450F UC's. The choice of 60 units is in order to match the nominal voltages of the two systems, and thus make the passive paralleling of the systems possible. For the HESS with active control it will be shown that 20 Maxwell 450F UC's can achieve the same power delivery as the passive system delivers with 60 UC's. Figures 5-7 show the ten-second pulse power capability as a function of the SoC of the NiMH battery pack, 60, and 20 UC modules respectively. The power delivery capability of the battery is calculated as follows [2,27]:

$$P_{DISCHARGE\ BATT}(SoC) = V_{MIN} \cdot \left(\frac{V_{OC}(SoC) - V_{MIN}}{R_{DISCHARGE\ BATT}(SoC)} \right) \quad (1)$$

$$P_{CHARGE\ BATT}(SoC) = V_{MAX} \cdot \left(\frac{V_{MAX} - V_{OC}(SoC)}{R_{CHARGE\ BATT}(SoC)} \right) \quad (2)$$

Where $P_{(DIS)CHARGE}(SoC)$ is the maximum power that can be (absorbed) released (by) from a source at set SoC in 10 seconds; V_{MIN} is the minimum allowed voltage on the source during discharge; V_{MAX} is the maximum allowed voltage on the source during charge; $R_{(DIS)CHARGE}(SoC)$ is the Equivalent (dis)charge resistance of the source during the ten second pulse; $V_{OC}(SoC)$ is the Open circuit voltage of the source at a set SoC; $V_{FINAL}(SoC)$ is the Voltage at the end of the ten second pulse.

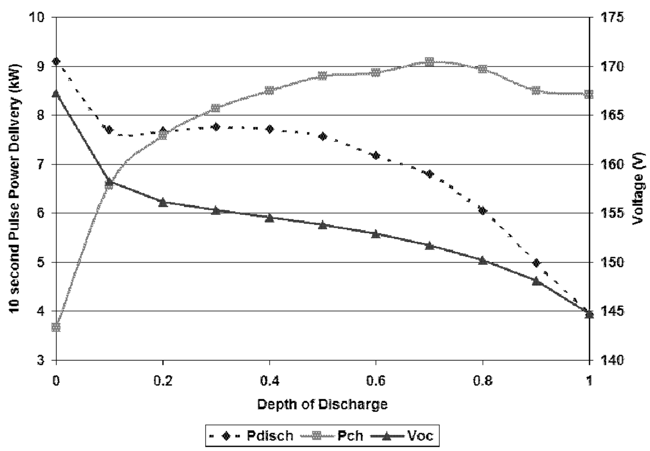

Figure 5. Ten second pulse power capability (as a function of battery SoC) of Panasonic 6.5 Ah NiMH battery pack consisting of 20 six-cell modules

The power delivery capability of the UC can be calculated similarly:

$$P_{DISCHARGE\ UC}(SoC) = V_{MIN} \cdot \left(\frac{V_{OC}(SoC) - V_{MIN}}{R_{DISCHARGE\ UC}(SoC)} \right) \quad (3)$$

where

$$R_{DISCHARGE\ UC}(SoC) = \frac{V_{OC\ INITIAL}(SoC) - V_{FINAL}(SoC)}{I_{LOAD}} \quad (4)$$

$$V_{FINAL}(SoC) = V_{OC\ FINAL}(SoC) - IR_{OHMIC} \quad (5)$$

$$Voc = \frac{Q}{C} \quad (6)$$

Equation 3 shows that the calculation of the discharge power for UC's is the same as for the battery. However, the Discharge resistance for an UC is a function of both the IR losses as well as the fact that the state of charge of the battery reduces dramatically during the discharge, as shown by the first term in Equation (5). Similarly the equations for charge power are:

$$P_{CHARGE\ UC}(SoC) = V_{MAX} \cdot \left(\frac{V_{MAX} - V_{OC}(SoC)}{R_{CHARGE\ UC}(SoC)} \right) \quad (7)$$

$$R_{CHARGE\ UC}(SoC) = \frac{V_{FINAL}(SoC) - V_{OC\ INITIAL}(SoC)}{I_{LOAD}} \quad (8)$$

$$V_{FINAL}(SoC) = V_{OC\ FINAL}(SoC) + IR_{OHMIC} \quad (9)$$

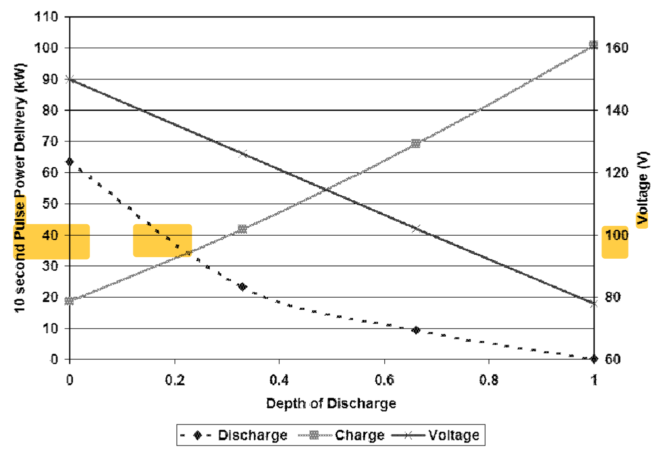

Figure 6. Ten second pulse power capability of (as a function of UC SoC) 60 Maxwell 450F UC's used for the passive parallel connection case

A. Passive parallel connection

As mentioned in the previous section, this is a direct connection between the battery and the UC which keeps the two sources at the same voltage. Therefore the voltage drop of the battery will command the rate of discharge of the UC. The power delivered by the UC can be calculated using equations (3) or (6), where V_{MIN} and V_{MAX} are the voltages at the end of charge or discharge of the battery during the ten second power pulse test at the defined state of charge.

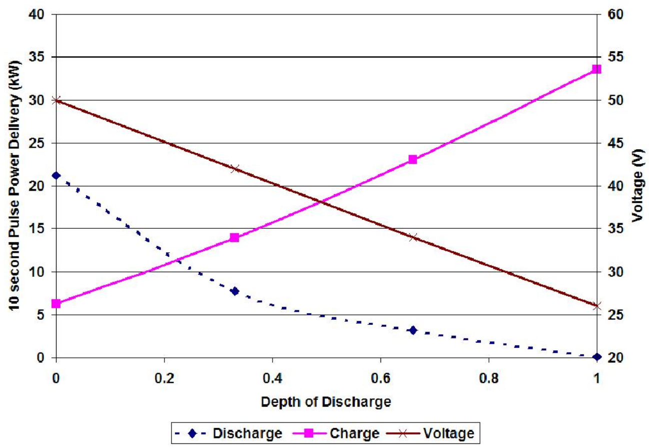

Figure 7. Ten second pulse power capability of (as a function of UC SoC) 20 Maxwell 450F UC's used for the active connection case

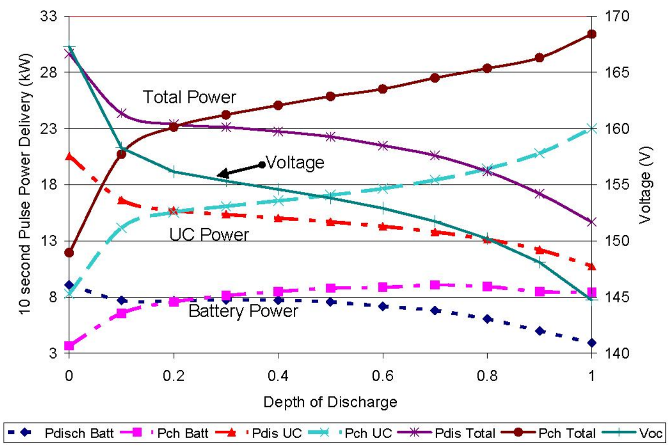

Figure 8. Ten second pulse power capability (as a function of battery SoC) of passive HESS with 60 Maxwell 450F UC's and 20 Panasonic 6.5 Ah NiMH battery modules

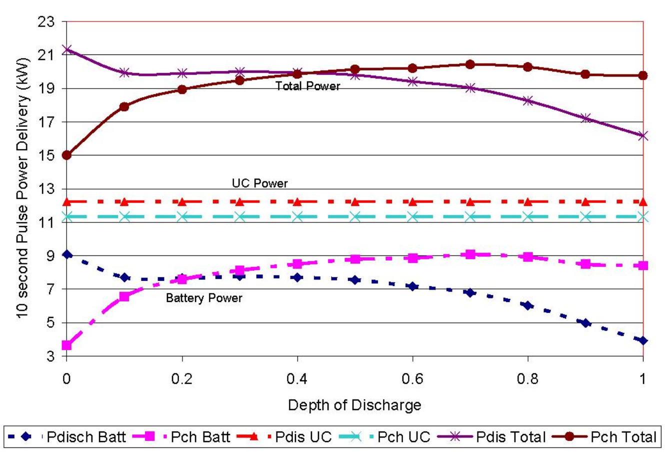

Figure 9. Ten second pulse power capability (as a function of battery SoC) of active HESS 20 Maxwell 450F UC's and 20 Panasonic 6.5 Ah NiMH battery modules with a target UC DoD at 20%

The benefit of this connection is that for short power pulses the UC is able to supply a large chunk of the power, reducing the stress on the battery. However, for longer power pulses, the ratio of the power coming from the battery increases, as the voltage of the UC drops with its SoC. Therefore this connection is most beneficial when the pulse duration is shorter than 10 seconds, and the power electronic complexity needs to be kept at a minimum.

Researchers [4] claim 2.5 times power capability improvement of the system for a 10 second pulse by utilizing this setup. The case presented here exhibits a three-fold improvement. However, the benefit is a strong function of the UC rating, and battery capabilities. The main disadvantage of the parallel method is the need to match the voltages of the two sources, which becomes prohibitive for high voltage busses. Another disadvantage is that the UC and the battery are always directly connected. Since the leakage current of the UC is substantial [26], this setup would eventually drain the battery. This can be remedied with an introduction of a switch which disconnects the two power sources at rest.

B. Control strategy to keep UC SoC Constant

Figure 7 shows that at 20% DoD the UC is able to sink and source the same amount of power. Also, the voltage of the system is close to the nominal. Therefore one simple control strategy would be to bring the SoC to the target state of charge after the high power pulse is sourced/sunk by the UC. Note that the power delivered by the introduction of active management is substantially higher. The power delivery on per-UC basis is increased three-fold.

C. Control Strategy to keep Total Power Constant

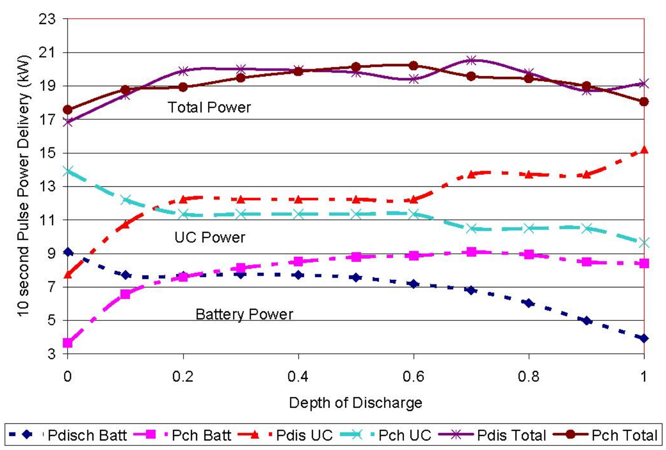

Figure 10. Ten second pulse power capability (as a function of battery SoC) of active HESS 20 Maxwell 450F UC's and 20 Panasonic 6.5 Ah NiMH battery modules with a variable target UC DoD based on constant total power goal

As mentioned earlier, there needs to be a control method for systems that utilize active control of the HPS. It is important to consider the properties of the battery and its state of charge in order to maximize the power delivery of the system. In this case, the control sets the state of charge of the UC in a way that the total power available from the battery pack is constant. The state of charge of the UC is set lower for high battery SoC in order to be able to provide more charge power and vice versa for low battery SoC. Figure 8 shows the maximum power that the system consisting of 20 Maxwell 450F UC's and 20 Panasonic 6.5 Ah NiMH battery modules can deliver as a function of battery state of charge. If this control is applied, the maximum total power capability is indeed constant, as seen in Figure 10.

D. Power capability if the power demand is predetermined

Many energy management systems assume that the driving pattern of the vehicle is known [22-24]. Some optimize the operation of the vehicle over various representative driving patterns. Researchers in [25] use GPS system data to approximate the driving schedule. Assuming that a good estimate of the driving pattern is available, the state of charge of the UC could be set so that it can provide its maximum power. For example if the exact time of a fast acceleration is know, the state of charge of the UC can be brought up to a 100% to help in the acceleration. Similarly, if the time of the fast braking is known, the UC SoC can be brought down to minimum allowed SoC to capture as much regenerative energy as possible. The battery would supply the average energy demand, while the capacitor can provide power much above the capability of the battery. Figure 9 shows the maximum power that the HESS could deliver if the power demand is predetermined, assuming that 20 450F Maxwell UC's are used in conjunction with the battery pack.

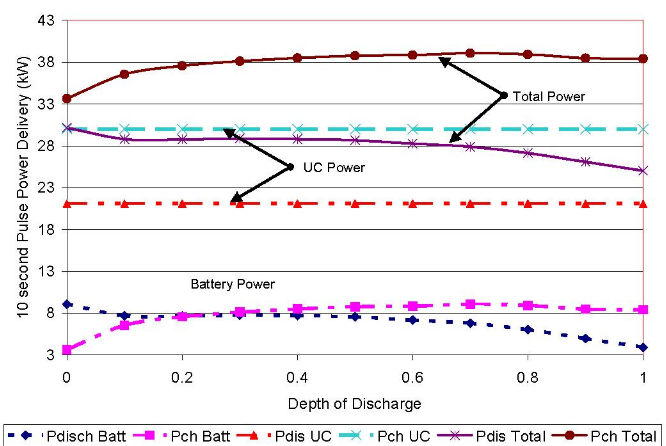

Figure 9. Ten second pulse power capability (as a function of battery SoC) of active HESS 20 Maxwell 450F UC's and 20 Panasonic 6.5 Ah NiMH battery modules assuming the knowledge of the power demand

VI. Conclusions

This paper explores the power delivery capabilities of various HESS topologies with a range of control strategies. The benefits of each topology from the efficiency and stability point of view are presented. It was shown the two input bi-directional converter is the most efficient and flexible topology.

On the control side, it was shown that understanding of the battery power delivery capability allows the HESS to deliver constant power regardless of the SoC of the battery. Also, the potential benefit of estimating the future driving pattern of the vehicle was emphasized. It was shown that the passive HESS can deliver three times the power of the battery pack alone. The same improvement is seen with an active control with only one third the number of UC's. Finally, it was shown that there is potential for five-fold the improvement over the battery alone, if the driving pattern can be predicted.

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