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Ultracapacitors in the Place of Batteries in Hybrid Vehicles

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Abstract

This paper is concerned with the use of ultracapacitors in hybrid vehicles in place of batteries. In the case of the mild, charge sustaining hybrid, the ultracapacitors would replace a lithium or nickel metal hydride battery: for a stop-start micro-hybrid, the capacitors would be used in combination with a lead-acid battery with the capacitors starting the engine, accepting energy during regenerative braking, and providing accessory loads during relatively short stop periods. Test data are shown for the performance of advanced carbon/carbon and hybrid lithium ultracapacitors indicating higher energy density (more than 2X) than that of commercially available carbon/carbon cells from Maxwell and NessCap. The advanced devices showed no sacrifice in high power capability in order to achieve the higher energy density.

Simulations of mid-size passenger cars using the advanced ultracapacitors in micro-hybrid and charge sustaining hybrid powertrains were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis. The influence of the ultracap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. Significant improvements in fuel usage were predicted for all the hybrid powertrains using ultracapacitors for energy storage. The results for the micro-hybrids indicated that a 7-25% improvement in fuel economy can be achieved using a small electric motor (4 kW) and small ultracapacitor units (5-10 kg of cells). The fuel economy improvements for the mild-HEV ranged from over 70% on the FUDS to 20% on the US06 driving cycle. In both micro- and mild-HEVs, the differences in the fuel economies projected using the advanced ultracapacitor technologies were very small. It is possible to store more energy using the advanced ultracapacitors, but the fuel savings appear be unaffected. The primary advantage of the advanced ultracapacitors is that the energy storage unit is smaller, lighter, and lower cost and there is more reserve energy storage to accommodate a wider range of vehicle operating conditions. In the mild hybrids, the fuel economy improvement was greater using ultracapacitors than with a lithium battery primarily because of the higher round-trip efficiency of the ultracapacitors.

Keywords: ultracapacitor, hybrid electric vehicle, micro-hybrid, mild-hybrid, fuel economy

1 Introduction

The development of ultracapacitors (electrochemical capacitors) suitable for hybrid vehicle applications has continued in various countries around the world even though the auto companies have been slow to adopt the technology for the hybrid-electric vehicles HEVs). In the first generation HEVs, the auto companies used nickel metal hydride batteries very successfully and more recently the companies are using lithium-ion batteries. In both cases, the batteries are sized by the power and battery cycle life requirements. The resultant batteries for the HEVs stores 1-1.5 kWh and uses on a regular basis only 5-10% of the total energy stored even though larger amounts of energy are clearly available if needed for special driving situations. In this paper, the potential for replacing the lithium-ion batteries with ultracapacitors and the advantages of this replacement are considered for several hybrid vehicle designs.

Progress is being made to significantly increase the energy density of ultracapacitors both for carbon/carbon devices and hybrid ultracapacitors that combine carbon electrodes with electrodes that utilization Faradaic processes. Data are presented in the paper from the testing of the advanced devices using graphitic carbons and metal oxides in various combinations with activated carbon. Energy densities up to 30 Wh/kg have been measured without a sacrifice of power capability. The test results indicate that the prospects for achieving high energy density in commercial devices are improving significantly and it can be expected that new products suitable for vehicle applications are likely within five years. Vehicle designs and simulations using the advanced ultracaps are presented and control strategies using ultracapacitors to their best advantage are highlighted.

2 Test results for advanced ultracapacitors

A number of new ultracapacitor devices have been tested in the laboratory at the University of California-Davis (1-3). These devices include carbon/carbon devices from Estonia (Skeleton Technologies) and Ukraine (Yunasko) and hybrid devices from Ukraine (Yunasko) and Japan (JSR Micro). As indicated in Tables 1, the carbon/carbon device from skeleton Technology (Figure 1) has high power capability with no sacrifice in energy density. In fact, the Skeleton Technology device has the highest energy density (9Wh/kg) of any carbon/carbon device tested at UC Davis. This is due to improved carbon (higher specific capacitance) and an increase in the rated voltage from 2.7V to 3.4V resulting from the use of an improved organic electrolyte.

The JSR Microdevices (Figure 2) utilize a graphitic carbon in the negative and an activated carbon in the positive. Such devices are often referred to as lithium capacitors (LiC). Lithium ions are intercalated into the negative and stored in the double-layer at the positive electrode. The voltage of the LiC varies between 3.8V and 2.2V. The characteristics of the JSR Micro devices (1100F and 2300F) are given in Tables 2 and 3. When packaged in a laminated pouch, the energy densities of the devices are about 10 Wh/kg and 19 Wh/L. When packaged in rigid, plastic case as shown in Figure 1 for the 2300F device, the energy densities are 7.5 Wh/kg and 13 Wh/L. The laminated pouch power densities are 2400 Wh/kg and 4500 W/L for 95% efficient pulses. Both values are high values, especially for hybrid ultracapacitors.

The Yunasko 5000F hybrid device (Figure 3) utilizes carbon and a metal oxide in both electrodes. Different metal oxides are used in the two electrodes and the percentages of the metal oxides are relatively small. Test results for the device are given in Table 3. The voltage range of the device is quite narrow being between 2.7 and 2.0V. The energy density is 30 Wh/kg for constant power discharges up to 2kW/kg. The device has a low resistance and consequently a very high power capability of 3.4 kW/kg, 6.1 kW/L for 95% efficient pulses.

Figure 1: Photograph of the 3200F Skeleton Technologies device

Table 1: Test data for the Skeleton Technologies 3200F device

Device characteristics: Packaged weight 400 gm, packaged volume 284cm3

Constant current discharge data

Current A	Time sec	Capacitance F	Resistance mOhm Steady-state R	RC sec
50	107.7	3205		
100	52.7	3175		
200	25.5	3178	.475	1.51
300	16.5	3173	.467	1.48
350	14	3202	.485	1.55
400	12	3168	.468	1.48

Discharge 3.4V to 1.7V
Resistance calculated from extrapolation of the voltage to t=0
Capacitance calculated from C= I*t disch/ delta from Vt=0

Constant power discharge data

Power W	W/kg	Time sec	Wh	Wh/kg	Wh/L
106	265	123.1	3.62	9.05	12.8
201	503	64.9	3.62	9.05	12.8
301	753	42.4	3.55	8.88	12.5
400	1000	31.1	3.46	8.65	12.2
500	1250	24.3	3.38	8.45	11.9
600	1500	19.8	3.3	8.25	11.6

Pulse power at 95% efficiency: $P = 9/16\ (1\text{- eff})\ V_R^2/R_{ss}$, $(W/kg)_{95\%} = 1730$, $(W/L)_{95\%} = 2436$
Matched impedance power: $P= V_R^2 / 4\ R_{ss}$, (W/kg) = 15, 400

Table 2: Characteristics of the JSR Micro 1100F ultracap cell

Constant Current discharge 3.8V – 2.2V

Current (A)	Time (sec)	C(F)	Resistance (mOhm) **
20	86.4	1096	
40	41.9	1078	
60	27.2	1067	
75	21.4	1063	1.2
100	15.7	1057	1.15
150	10.1	1056	1.1

** Resistance is steady-state value from linear V vs. time discharge curve

Constant Power discharges 3.8V – 2.2V

Power (W)	W/kg	Time(sec)	Wh	Wh/kg *	Wh/L *
50	347	106.7	1.47	10.2	19.1
83	576	61.9	1.43	9.9	18.6
122	847	40.1	1.36	9.4	17.7
180	1250	26.2	1.31	9.1	17.0
240	1667	19.1	1.27	8.8	16.5

* Based on the measured weight and volume of the cell as tested
Laminated pouch cell weight 144 gm, 77 cm3, 1.87 g/cm^3
Peak pulse power at 95% efficiency R=1.15 mOhm
$P= 9/16*.05* (3.8)^2 /.00115 = 353$ W, 2452 W/kg

Table 3: Characteristics of the 5000F Yunasko hybrid ultracapacitor

Constant current 2.7-2.0V

Current A	Time sec	Capacitance F	Resistance short time mOhm	Resistance long time mOhm	RC sec
25	134.4	5333	--	--	
50	65.4	5274	1.25	--	
75	41.3	5163	1.1	1.6	8.3
100	30.3	5602	1.36	1.75	9.8
125	21.5	5363	1.4	1.56	8.4
150	15.0	4592	1.28	1.53	7.0

Constant power 2.7-2.0V

Power W	W/kg	Time sec	Wh	Wh/kg	W/L
55	809	134	2.05	30.1	1447
109	1612	69.6	2.11	31.0	2868
152	2248	48.4	2.04	30.0	4000
201	2973	34.9	1.95	28.7	5289
260	3846	24.6	1.78	26.2	6842
310	4586	17.3	1.49	21.9	8157

Weight 68g, volume 38 cm3 pouch packaged

Pulse resistance tests at V=2.50V

Resistance mOhm

Pulse test	75A	150A
Discharge pulse	1.25	1.6
Bounce back I=0	1.5	1.6

Efficiency 95% $P= .95x.05\ V^2/R = .95x.05x\ (2.7)^2/.0015 =231$

$(W/kg)_{95\%} = 3395$, $(W/L)_{95\%} = 6078$

Figure 2: Photographs of the JSR Micro 1100F and 2300F devices

Figure 3: Photograph of the 5000F Yunasko Hybrid ultracapacitor 5000F device

A summary of the characteristics results of the various ultracapacitors tested at UC Davis are given in Table 4. Except for the devices from Skeleton Technologies and Yunasko, all the devices listed in the table are commercially available. Most of the commercial carbon/carbon devices have an energy density of 4-5 Wh/kg and a power capability of 1000 W/kg for 95% efficient pulses. The high power capability of the hybrid devices indicates that their increased energy density can be fully exploited in applications such as hybrid vehicles in which the device would be sized by the energy storage requirement.

Table 4: Summary of ultracapacitor device characteristics

Device	V rate	C (F)	R (mOhm) (3)	RC sec	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell	2.7	2885	.375	1.1	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
Vinatech	2.7	336	3.5	1.2	4.5	1085	9656	.054	.057
Vinatech	3.0	342	6.6	2.25	5.6	710	6321	.054	.057
Ioxus	2.7	3000	.45	1.4	4.0	828	7364	.55	.49
Ioxus	2.7	2000	.54	1.1	4.0	923	8210	.37	.346
Skeleton Technol.	3.4	3200	.47	1.5	9.0	1730	15400	.40	.284
Skeleton Technol.	3.4	850	.8	.68	6.9	2796	24879	.145	.097
Yunasko*	2.7	510	.9	.46	5.0	2919	25962	.078	.055
Yunasko*	2.75	480	.25	.12	4.45	10241	91115	.060	.044
Yunasko*	2.75	1275	.11	.13	4.55	8791	78125	.22	.15
Yunasko*	2.7	7200	1.4	10	26	1230	10947	.119	.065
Yunasko*	2.7	5200	1.5	7.8	30	3395	30200	.068	.038
Ness	2.7	1800	.55	1.0	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.1	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.3	4.4	982	8728	.522	.379
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18225	.50	.572
JSR Micro (graphitic carbon/ AC) *	3.8	1100 2300 (plast. case)	1.15 .77	1.21 1.6	10 7.6	2450 1366	21880 12200	..144 .387	.077 .214

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated
(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge
(3) Steady-state resistance including pore resistance
* All devices except those with * are packaged in metal/plastic containers:
Those with * are laminated pouched packaged

Table 5: Energy storage unit requirements for various types of electric drive mid- size passenger cars

Type of electric driveline	System voltage V	Useable energy storage	Maximum pulse power at 90-95% efficiency kW	Cycle life (number of cycles)	Useable depth-of-discharge
Electric	300-400	15-30 kWh	70-150	2000-3000	deep 70-80%
Plug-in hybrid	300-400	6-12 kWh battery 100-150 Wh ultracapacitors	50-70	2500-3500	deep 60-80%
Charge sustaining hybrid	150-200	100-150 Wh ultracapacitors	25-30	300K-500K	Shallow 5-10%
Micro-hybrid	45	30-50 Wh ultracapacitors	5-10	300K-500K	Shallow 5-10%

3 Vehicle design considerations

The energy storage requirements for hybrid-electric vehicles vary a great deal depending on the type and size of the vehicle being designed and the characteristics of the electric powertrain in which they are to be used. Energy storage requirements for various vehicle designs and operating modes are shown in Table 5 for a mid-size passenger car. Requirements are given for electric vehicles and both charge sustaining and plug-in hybrids. These requirements can be utilized to size the energy storage unit in the vehicles when the characteristics of the energy storage cells are known. In some of the vehicle designs considered in Table 5, ultracapacitors are used to provide the peak power rather than batteries.

In the vehicles using only ultracapacitors, the key issue is the minimum energy (Wh) required to operate the vehicle in real world driving because the energy density characteristics of ultracapacitors are such that the power and cycle life requirements will be met if the unit is large enough to met the energy storage requirement. As shown in Table 5, for passenger car applications, the energy storage in the ultracapacitor can be 150 Wh or less even if the ultracapacitor is used alone for energy storage.

Ultracapacitors can be used alone in place of batteries in both micro and mild charge sustaining hybrid vehicles. As shown in [1-3], this can be done by operating the hybrid vehicle on the electric drive only when the power demand is less than the power capability of the electric motor; when the vehicle power demand exceeds that of the electric motor, the engine is operated to meet the vehicle power demand plus to provide the power to recharge the ultracapacitor unit. In this mode, the electric machine is used as a generator and the engine operating point is near its maximum efficiency line (torque vs. RPM). The recharging power is limited by the power of the electric machine because ultracapacitors have a pulse power efficiency greater than 95% for W/kg values of 1-1.5 kW/kg (see Table 4). This control strategy is intended to keep the engine from operating in the low efficiency part of the T, RPM map. As indicated in Figure 4, the size (kW) of the electric motor can be relatively small even for large passenger cars using V-8 engines.

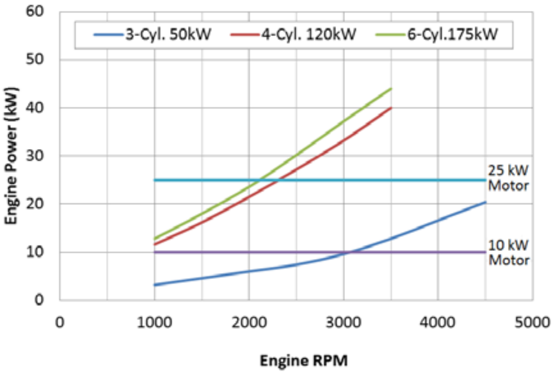

Figure 4: Minimum engine power for efficiency operation for various size engines

4 Vehicle simulation results using ultracapacitors

Simulations of mid-size passenger cars using ultracapacitors in micro-hybrid and charge sustaining hybrid powertrains were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis [4-10]. All the powertrains were in the same vehicle having the following characteristics: Test weight 1660 kg, C_d =.3, A_F =2.25 m^2, f_r =.009. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The engine rated power was 125 kW for both the conventional ICE vehicle and the hybrids. Special attention in the simulations was on the use of the advanced ultracapacitors whose characteristics were discussed in Section 2. All the hybrids use the single-shaft arrangement similar to the Honda Civic hybrid. The same permanent-magnetic AC electric motor map (Honda Civic) was used in all the hybrid vehicle designs. In the micro-hybrid powertrain, the ultracapacitors were combined with a lead-acid battery which was maintained in a high state-of-charge. In the mild-hybrid, the ultracapacitors were alone; they provided all the electrical energy to the motor and accepted the regenerative braking energy.

The simulation results are summarized in Table 6 for a conventional ICE vehicle and each of the hybrid designs. The influence of the ultracap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. Significant improvements in fuel usage are predicted for all the hybrid powertrains using ultracapacitors for energy storage.

Table 6: Mild-HEV and Micro-HEV Advisor simulation results using carbon/carbon and hybrid ultracapacitors
Mid-size passenger car: weight 1660 kg, C_d .3, A_f 2.2 m2, fr .009

Energy storage system	Weight of the ultracaps (kg)*	Energy stored	mpg FUDS	mpg FEDHW	mpg US06
Mild HEV	20 kW electric motor				
Yunasko hybrid	12	300 Wh	47.4	46.5	32.2
	6	150 Wh	45.3	46.0	31.6
JM Energy hybrid	11	100 Wh	47.8	47.2	31.9
Yunasko C/C	22	100 Wh	46.0	46.4	31.6
Maxwell C/C	28	100Wh	47.2	47.5	32.2
Skeleton 2014 C/C 3200F	13	115	47.8	47.0	31.9
High power LiTiO battery	14	1120	40.6	40.3	30.5
ICE Ford Focus engine 120 kW			25.5	36.8	26.8
Fuel economy improvement			80%	27%	19%
Micro start stop HEV	Ultracap. with a lead- acid battery, 4 kW electric motor				
Yunasko hybrid	5 kg	150 Wh	32.4	41.4	28.9
	3 kg	75 Wh	32.1	41.2	28.5
Yunasko C/C	11 kg	50Wh	32.2	41.2	28.6
Maxwell C/C	12 kg	50 Wh	32.3	41.3	28.3
Skeleton C/C 3200F	5	50Wh	33.1	40.2	28.0
Fuel economy improvement			26%	12%	7%

*weight of cells only without packaging in a pack

The fuel savings for the mild- HEV designs were much larger than for the micro-hybrids. This was expected because electric motor was much higher power and the energy storage (Wh) was much larger in the case of the mild- HEVs. In both cases, the differences in the fuel economies projected using the various ultracapacitor technologies were very small. More energy can be stored using the advanced ultracapacitors having a higher energy density, but the fuel savings appear be unaffected. The primary advantage of the advanced ultracapacitors is that the energy storage unit is smaller and lighter and there is more reserve energy storage to accommodate a wide range of vehicle operating conditions. In addition, storing more energy should make it easier to achieve good driveability.

The results for the micro-hybrids indicate that significant improvements (7-25%) in fuel economy can be achieved using a small electric motor (4 kW) and small ultracapacitor units (5-12) kg of cells). In the micro-hybrid designs, the rated engine power used was the same as that in the conventional ICE vehicle in order that the performance of the hybrid vehicle when the energy storage in the ultracapacitors is depleted would be the same as the conventional vehicle. Laboratory studies of ultracapacitors with a 12V lead-acid battery (x) indicates that the ultracapacitors can provide the accessory load when the vehicle is stopped unless the stop time is long (> 60 sec).

The fuel economy simulation results for charge sustaining hybrids are also shown in Table 6 using carbon/carbon and advanced ultracapacitors. The fuel economy improvements range from over 70% on the FUDS to about 20% on the US06 driving cycle. The prime advantage of the high power electric driveline and the larger energy storage possible with the advanced hybrid ultracapacitors is that the larger fuel economy improvements can be sustained over a wide range of driving conditions. All the advanced ultracapacitors have high power capability and thus can be used with the high power electric motor used in charge sustaining hybrid drivelines. Thus the hybrid ultracapacitor technologies give the vehicle designer more latitude in powertrain design and in the selection of the control strategies for on/off operation of the engine. Also shown in Table 6 are simulation results for a mild hybrid using a high power lithium titanate oxide battery. The fuel economies for the vehicle using the battery are all lower than those using the ultracapacitors primarily because the round-trip efficiency with the capacitors was higher than with the batteries. For example, for the FUDS cycle the efficiency was 98% with the capacitors and 91% with the lithium battery.

A second advantage of the ultracapacitors is longer life in the vehicle. This is particularly true of the carbon/carbon devices which are expected to last the life of the vehicle. The cycle life of the advanced ultracapacitors is expected to be shorter than the carbon/carbon devices, but testing (11) of the JSR Micro lithium capacitor has shown a cycle life of about one million cycles at room temperature. At the present time (2014), the cost of commercially available carbon/carbon capacitors (ex. Maxwell) is much higher than the lithium batteries on a $/Wh basis. However, as indicated in Table 6, only about 1/10 as much energy (Wh) is stored in the capacitors as in the battery in order to provide the needed power at high efficiency and to meet the cycle life requirement for shallow cycles. In high volume, it seems likely that the cost of the ultracapacitor pack will be less than that of the battery pack for the hybrid vehicle. In addition, since the unit cost ($/Wh) of the capacitor will decrease proportional to its energy density, the cost of higher energy density carbon/carbon devices similar to the Skeleton Technology device should be even lower than present devices.

5 Summary and conclusions

This paper is concerned with the use of ultracapacitors in hybrid vehicles in place of batteries. In the case of the mild, charge sustaining hybrid, the ultracapacitors would replace a lithium or nickel metal hydride battery: for a stop-start micro-hybrid, the capacitors would be used in combination with a lead-acid battery with the capacitors starting the engine, accepting energy during regenerative braking, and providing accessory loads during relatively short stop periods. In the micro-hybrid case, the ultracapacitors also provide energy to power the relatively small electric motor during vehicle accelerations.

Test data are shown for the performance of advanced carbon/carbon and hybrid lithium ultracapacitors indicating higher energy density (more than 2X) than that of commercially available carbon/carbon cells from Maxwell and NessCap. The advanced devices show no sacrifice in high power capability in order to achieve the higher energy density. The higher energy densities should result in a lower cost for the capacitor pack compared to a battery pack providing the same functionality in the vehicle.

Simulations of mid-size passenger cars using the advanced ultracapacitors in micro-hybrid and charge sustaining hybrid powertrains were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis. The influence of the ultracap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. Significant improvements in fuel usage were predicted for all the hybrid powertrains using ultracapacitors for energy storage. The results for the micro-hybrids indicated that a 7-25% improvement in fuel economy can be achieved using a small electric motor (4 kW) and small ultracapacitor units (5-10 kg of cells). The fuel economy improvements for the mild-HEV ranged from over 70% on the FUDS to 20% on the US06 driving cycle. In both micro- and mild-HEVs, the differences in the fuel economies projected using the advanced ultracapacitor technologies were very small. It is possible to store more energy using the advanced ultracapacitors, but the fuel savings appear be unaffected. The primary advantage of the advanced ultracapacitors is that the energy storage unit is smaller and lighter and there is more reserve energy storage to accommodate a wide range of vehicle operating conditions.

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