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Ultracapacitors in hybrid vehicle applications: Testing of new high power devices and prospects for increased energy density

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Abstract

This paper is concerned with testing several of the new ultracapacitors being developed –both carbon/carbon and hybrid devices – and the application of those devices in micro- and charge sustaining hybrid vehicles. The carbon/carbon devices had energy densities up to 6.9 Wh/kg, 10 Wh/L and power capabilities up to 8.8 kW/kg for a 95% efficient pulse. This performance is significantly better than that of commercially available carbon/carbon devices.

Two new hybrid ultracapacitors were tested – a 1100F device from JM energy and a 5000F device from Yunasko. The 1100F device, packaged in a laminated pouch, had energy densities of 10 Wh/kg and 19 Wh/L and a power density of 2.4 kW/kg. The 5000F hybrid device utilized carbon and a metal oxide in both electrodes. 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 and a power density of 3.4 kW/kg, 6.1 kW/L for 95% efficient pulses.

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. The results for the micro-hybrids indicated that a 10-25% 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 70% on the FUDS to 22% on the US06 driving cycles. In both micro- and mild-HEVs, the differences in the fuel economies projected using the various ultracapacitor technologies were very small.

Keywords: ultracapacitor, hybrid electric vehicle, simulation

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. This paper is concerned with testing several of the new ultracapacitors being developed –both carbon/carbon and hybrid devices – and the application of those devices in micro- and charge sustaining hybrid vehicles.

Progress is being made to significantly increase the energy density of hybrid ultracapacitors that combine carbon electrodes with electrodes that utilization Faradaic processes. Data are presented in the paper from the testing of cells 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.

2 Test results for advanced ultracapacitors

A number of new ultracapacitor devices have been tested in the laboratory at the University of California-Davis. These devices include carbon/carbon devices from Estonia (Skeleton Technologies) and Ukraine (Yunasko) and hybrid devices from Ukraine (Yunasko) and Japan (JM Energy). As indicated in Tables 1 and 2, the carbon/carbon devices have very high power capability with no sacrifice in energy density. In fact, the Skeleton Technology device has the highest energy density of any carbon/carbon device tested at UC Davis. This is primarily due to the increase in the rated voltage from 2.7V to 3.4V resulting from the use of an improved organic electrolyte. The power capability of the Yunasko device is higher than any device previously tested by a wide margin. This is due to the very low resistance of the device which also results in a RC time constant of 0.14 seconds.

The JM Energy devices (Figure 1) 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 JM Energy devices (1100F and 2300F) are given in Tables 3 and 4. 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 2) 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 5. 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.

Table 1: Skeleton Technologies 860F device

Device characteristics: Packaged weight 145.2 gm; Packaged volume 97cm3

Constant current discharge data

Current A	Time sec	Capacitance F	Steady-state resistance mOhm*	RC sec
20	72.3	861	---	
40	36	869	---	
80	17.7	858	---	
120	11.5	863	.9	.78
200	6.6	846	.9	.76
300	4	828	.8	.66

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	Time sec	Wh	Wh/kg/Wh/L	W/kg/W/L
46	78.6	1.004	6.9/10.4	317/474
81	44.5	1.001	6.9/10.3	558/835
123	27.9	.99	6.8/10.2	847/1268
184	19.3	.99	6.8/10.2	1267/1897
245	14.3	.97	6.7/10.0	1687/2526
305	10.9	.92	6.3/9.5	2101/3144
405	7.9	.89	6.1/9.2	2789/4175

Discharge 3.4V to 1.7V

Pulse power calculation at 95% efficiency

$P = 9/16 \times (1\text{- eff})\ V_0{}^2/R = 9/16 \times (.05)\ (3.4)^2/.0008 =$ 406W

$(W/kg)_{packaged}$ = 2796, (W/L)= 4185

Table 2: Yunasko 1200F device

Constant current discharge data 2.75 – 1.35V

Current A	Time sec	Capacitance F	Resistance mOhm*
30	57.3	1273	--
60	29.1	1293	---
100	17.8	1290	---
150	12.0	1281	.10
250	7.15	1276	.08
300	5.8	1261	.10
350	5.0	1268	.11

* Steady-state resistance

Constant power discharges data 2.75 – 1.35V

Power W	W/kg *	Time sec	Wh	Wh/kg
44	200	79.8	.975	4.43
72	327	51.0	1.02	4.64
102	464	35.6	1.01	4.59
152	690	24.0	1.01	4.59
200	909	18.1	1.01	4.59
250	1136	14.5	1.01	4.59
300	1364	12.0	1.00	4.55
350	1591	10.3	1.00	4.55
400	1818	9.0	1.00	4.55

* weight of device - .220 kg as tested

Pulse power calculation at 95% efficiency based on the steady-state resistance

$P = 9/16 \times (1\text{- eff})\ V_0{}^2/R = 9/16 \times (.05)\ (2.75)^2/.00011 =$ 1934W

$(W/kg)_{packaged}$ =1934/.22 = 8791

Device: Yunasko

V rated	Capacitance (F)	R mOhm	RC sec	Wh/kg
2.75	1275	0.11	0.14	4.55
W/kg (95%)	W/kg Match. Imped.	Wgt (kg)	Vol. (L)	---
8791	78125	.22	.163	---

Figure 1: Photographs of the JM Energy 1100F and 2300F devices

Table 3: Characteristics of the JM Energy 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 4: Characteristics of the JM Energy 2300F ultracap cell

Constant Current discharge 3.8V – 2.2V

Current (A)	Time (sec)	C (F)	Resistance (mOhm) **
50	71.3	2285	
100	34.3	2257	
150	22.2	2242	.77
200	16.3	2241	.725
250	12.5	2220	.77
300	10	2174	.733

** 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 *
105	260	100.8	2.94	7.6	13.7
203	526	51	2.88	7.4	13.5
301	778	32.8	2.74	7.1	12.8
400	1036	23.9	2.66	6.9	12.4
500	1295	18.6	2.58	6.7	12.1
600	1553	15.1	2.52	6.5	11.8

* based on the measured weight and volume of the cell as tested

Packaged cell weight 387 gm, 214 cm3, 1.81 g/cm^3

Peak pulse power at 95% efficiency R=1.15 mOhm

$P = 9/16*.05*(3.8)^2/.00077$ = 527 W, 1366 W/kg

Figure 2: Yunasko Hybrid ultracapacitor 5000F device

Table 5: 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

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

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

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

Table 6: 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.	2.85	350	1.2	.42	4.0	2714	24200	.07	.037
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
JME Energy (graphitic carbon/AC) *	3.8	1100 2300 (plast.case)	1.15 .77	1.211.6	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 7: 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	25-35	300K-500K	Shallow 5-10%
Micro-hybrid	45	30-50 Wh ultracapacitors	5-10	300K-500K	Shallow 5-10%

A summary of the characteristics of the various ultracapacitors tested at UC Davis [1-3] are given in Table 6. 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.

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 7 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 7, 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 7, 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.

When ultracapacitors are used alone as the energy storage unit in a charge sustaining hybrid (HEV), the objective of the control strategy is to permit the engine to operate near its maximum efficiency. As shown in [4-6], 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 selected along 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 over 2000 W/kg (see Table 6). This control strategy is referred to as the “sawtooth” strategy because a plot of the ultracapacitor state-of-charge (SOC) has the form of a saw blade.

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 [7-9]. 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 120 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 used alone; they provided all the electrical energy to the motor and accepted the regenerative braking energy.

The simulation results are summarized in Table 8 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.

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. It is possible to store more energy using the hybrid ultracapacitors , but the fuel savings appear be unaffected. The primary advantage of the hybrid 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 (10-25%) in fuel economy can be achieved using a small electric motor (4 kW) and small ultracapacitor units (5-10 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. The ultracapacitors were used to improve fuel economy with only a minimal change in vehicle acceleration performance.

Table 8: 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	10 5	300 Wh 150 Wh	45.1 43.6	48.0 46.2	34.3 33.2
JM Energy hybrid	10	100 Wh	43.6	46.2	33.0
Yunasko C/C	21	100 Wh	45.4	47.7	34.4
Maxwell C/C	25	100Wh	44.3	47.1	33.6
ICE Ford Focus engine 120 kW			25.5	36.8	26.8
Fuel economy improvement			72%	25%	22%
Micro start stop HEV	Ultracap. with a lead- acid battery	4 kW electric motor			
Yunasko hybrid	5 kg 3 kg	150 Wh 75 Wh	32.4 32.1	41.4 41.2	28.9 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
Fuel economy improvement			26%	12%	7%

The fuel economy simulation results for charge sustaining hybrids are also shown in Table 8 using carbon/carbon and hybrid ultracapacitors. The fuel economy improvements range from 70% on the FUDS to 22% on the US06 driving cycles. The prime advantage of the high power electric driveline and the larger energy storage possible with the 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.

5 Summary and conclusions

This paper is concerned with testing several of the new ultracapacitors being developed –both carbon/carbon and hybrid devices – and the application of those devices in micro- and charge sustaining hybrid vehicles. The carbon/carbon devices have very high power capability with no sacrifice in energy density. In fact, the Skeleton Technology device has the highest energy density (6.9 Wh/kg) of any carbon/carbon device tested at UC Davis. This is primarily due to the increase in the rated voltage from 2.7V to 3.4V resulting from the use of an improved organic electrolyte. The power capability of the carbon/carbon Yunasko device is higher than any device previously tested by a wide margin (8.8 kW/kg for a 95% efficient pulse). This is due to the very low resistance of the device which also resulted in a RC time constant of 0.14 seconds.

Two new hybrid ultracapacitors were tested – a 1100F device from JM Energy and a 5000F device from Yunasko. The 1100F device, packaged in a laminated pouch, had energy densities of 10 Wh/kg and 19 Wh/L and a power density of 2.4 kW/kg. The 5000F hybrid device utilized carbon and a metal oxide in both electrodes. 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 and a power density of 3.4 kW/kg, 6.1 kW/L for 95% efficient pulses.

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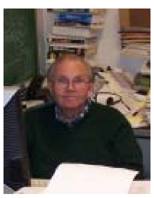

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Ph.D., 1967, Princeton University. Since 1974, Dr. Burke's research has involved many aspects of electric and hybrid vehicle design, analysis, and testing. He was a key contributor on the US Department of Energy Hybrid Test Vehicles (HTV) project while working at the General Electric Research and Development Center. He continued his work on electric vehicle technology, while Professor of Mechanical Engineering at Union College and later as a research manager with the Idaho National Engineering Laboratory (INEL). Dr. Burke joined the research faculty of the ITS-Davis in 1994. He directs the EV Power Systems Laboratory and performs research and teaches graduate courses on advanced electric driveline technologies, specializing in batteries, ultracapacitors, fuel cells and hybrid vehicle design. Dr. Burke has authored over 80 publications on electric and hybrid vehicle technology and applications of batteries and ultracapacitors for electric vehicles.

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