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Aspects of Thermal Management of Lithium Batteries in PHEVs Using Supercapacitors

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Summary

In this paper, the use of supercapacitors in the electric driveline of plug-in hybrid vehicles (PHEVs) is analyzed from the design, performance, and economic points-of-view. The supercapacitors are envisioned to be part of the motor and electronics package and thus the same electric drive package can be combined with batteries of different energy storage capacity (kWh) as needed to meet the specific all-electric range the vehicle. In all cases the PHEVs in the all-electric mode had the performance of an EV having attractive acceleration characteristics. A 120kW electric motor is used in all the PHEVs studied. The use of the supercapacitors to load-level the storage battery permits the use of an energy battery rather than a power battery in PHEVs. Energy batteries have higher energy density, longer cycle life, and lower cost than power batteries of the same energy storage capacity (kWh). The weight, volume, and cost of the supercapacitors plus the energy battery are close to that of a power battery for all-electric ranges of 20 miles and are less than that of the power battery for longer all-electric ranges. Simulations of PHEVs indicate that even using the supercapacitors the energy consumption (Wh/mi) of the PHEVs is slightly lower using the power battery than with the energy battery. However, the use of the supercapacitors improves the system efficiencies with the energy battery and most importantly reduces by about a factor of two the peak and average current experienced by the energy battery. In addition, the dynamic character of the battery current/power with the supercapacitors is considerably smoother than with the energy battery alone. Detailed simulation results are presented in the paper to show these effects quantitatively for both the FUDS and US06 driving cycles and for vehicles with all-electric ranges up to 45 miles.

Keywords: thermal management, lithium battery, PHEV, supercapacitor

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1 Introduction

The batteries in PHEVs store less than half the energy (kWh) stored in an electric vehicle, but the power (kW) of the motor is nearly the same. Hence the smaller battery in the PHEV operates at a much higher power density (W/kg) and lower efficiency, which results in higher heat generation and the tendency for the battery temperature to increase more rapidly than in an EV. One solution to this problem is to combine supercapacitors with the lithium battery pack and utilize the supercapacitor to load level the battery. In this way, the peak currents experienced by the battery are significantly reduced and thus the heat generation is also reduced. The resistance of the supercapacitor is much lower than the battery and as a result, the heat generation and temperature rise of the supercapacitor are more manageable.

Combining supercapacitors with the lithium battery will permit the use of EV batteries in PHEVs. The EV batteries have high energy density, long cycle life, and low cost due to their lower power requirements (W/kg) and high volume of production. Hence this approach can result in a large reduction in the cost of the storage batteries for the PHEV which can more than off-set the cost of the supercapacitors and associated electronics.

To investigate the use of batteries and supercapacitors in PHEVs, a series of **Advisor** simulations were performed to calculate the energy losses and temperature rise in the lithium battery and supercapacitor for various driving cycles and battery/supercapacitor power control strategies. The key issue concerning the control strategy is relating the maximum battery power to the state-of-charge (voltage) of the supercapacitor. The power demand of the electric motor is time-averaged during the driving cycle and when the state-of-charge of the supercapacitor is relatively high, the battery power is set to meet the average power demand of the motor. At low states-of-charge of the supercapacitor, the battery power must be increased to recharge the supercapacitor and meet the powertrain power demand. In general, proper sizing of the supercapacitors permits a large reduction in battery power/current and thus heat generation resulting in a reduced temperature rise in the battery even without cooling.

2 Characteristics of Batteries and Supercapacitors

2.1 Batteries

The differences in the energy density and power capability of EV and PHEV batteries are well recognized [1-4]. These differences are summarized in Table 1. It seems clear from the data in the table that the differences between high energy density and high power batteries are significant and that taking advantage of these differences using supercapacitors has a potential for reducing the total cost of the energy storage system in PHEVs.

Table 1: Summary of the characteristics of high energy density and high power lithium batteries

Source	Wh/kg	Cost $/kWh	Power capability	Cell Ah
M. Anderman [1, 2]				
EV	160-200	140-180		
PHEV	130-170	190-240		
NREL [3]				
40 mi PHEV	161	234	50 kW	36
10 mi PHEV	100	377	50 kW	12
UC Davis tests [4]				
Enerdel high power (Gr/NiMnO2)	120		Resistance 1.4 mOhm $(950\ W/kg)_{95\%}$	15
EiG high energy (Gr/NiCoMnO2)	165		Resistance 3.1 mOhm $(490\ W/kg)_{95\%}$	20

2.2 Supercapacitors

The energy density and power capability of selected supercapacitor cells tested [5,6] at UC Davis are shown in Table 2. Except for the devices listed for DAE-China, the devices are commercially available in high volume. The energy density and the power capability of the supercapacitors vary significantly. The best devices for this application are those with low resistance and thus high $(W/kg)_{95\%}$. High energy density is advantageous because it reduces the weight and volume of the supercapacitor unit and makes it feasible to store more energy (Wh). The cost of the supercapacitors has decreased markedly in recent years. In high volume sales, the present price of carbon/carbon cells is .5 to 1.0 cents per Farad. In very high volume sales in the future, it is likely the price will be .25 cents per Farad or even lower. When development of the high energy density supercapacitors like the DAE-future is completed, the price of supercapacitors in large volume will be even lower.

Table 2: Characteristics of selected supercapacitors tested at UC Davis

Device manufacturer	Rated Voltage	Capacitance F	Resistance (R_{ss}) mOhm	Wh/kg, 60 sec Discharges	$(W/kg)_{95\%}$
NessCap	2.7	3640	.3	4.2	930
Skeleton Tech.	3.4	3200	.47	9.1	1730
Yunasko	2.7	1270	.10	4.5	8790
Ioxus	2.85	3060	.3	5.0	1360
JSR Micro	3.8	1100	1.15	9.9	2450
DAE-China					
Carbon/carbon	2.7	1660	.6	6.1	1730
Hybrid (Gr/Li/C)	3.8	850	4.6	11.3	995
Hybrid future)	4.0	1000	1.5	22	4000

3 PHEV Electric Drives Using Supercapacitors

In this section, the cost of the energy storage (battery and supercapacitor) in the electric drive system for PHEVs of all-electric ranges up to 60 miles will be estimated. Comparisons will be made between the characteristics of systems using an energy battery and supercapacitors and one using a high power lithium battery alone. The characteristics of the energy storage components to be used in the calculations are given in Table 3. These values are based on the information given previously in Tables 1 and 2. The cost of the supercapacitors is based on a cost of .25 cents per Farad for the Skeleton device.

Table 3: Design parameters for the energy storage components in the electric driveline system

Component	Wh/kg	kg/L	$/kWh	$/Wh
Power battery	120	2.2	225	
Energy battery	165	2.2	150	
supercapacitor	9	1.4		2.5

PHEVs with electric ranges of 20, 40, and 60 miles will be analyzed. The parameters for the design and operation of vehicles with the various all-electric ranges are given in Table 4. The energy consumption Wh/mi was taken as the average between that for operation on the FUDS and US06 driving cycles. The power demands on the US06 cycle are much higher putting much higher stress (higher currents) on both the battery and supercapacitors. Detailed simulations of PHEVs on both driving cycles are discussed in the next section of the paper.

Table 4: Vehicle design and operation parameters

PHEV range (1)	Wh/mi (2)	Storage battery kWh (3)	Supercapacitor Wh (4)
20 mile	282	7	220
40 mile	282	15	220
60 mile	282	23	220

(1) All-electric range and maximum power 120kW
(2) Wh/mi is the average of the value 225 Wh/mi of the FUDS and 340 Wh/mi on the US06
(3) 75% of the energy stored in the battery is used
(4) Energy available from the supercapacitor to ½ rated voltage

As discussed in Section 1, the approach used in designing the powertrains for the PHEVs is to combine the same supercapacitor and DC/DC converter with a lithium battery sized (kWh) to meet a specified all-electric range. In this study, the power requirement of the powertrain is fixed at 120 kW for the vehicle. A high energy density, energy battery is used in all cases. The baseline PHEV design with which the supercapacitor, energy battery design is compared is a PHEV with the same all-electric range and maximum powertrain power using a power battery. As indicated in Table 5, the weight, volume and cost of the energy storage units in the two vehicles have been compared for all-electric ranges of 20, 40, 60 miles. The characteristics of the Skeleton Technology supercapacitor have been used to make the comparisons. The weights and volumes given are for the cells in all cases, but it is reasonable to assume the additional weight and volume due to packaging of the battery and supercapacitor cells into modules will be about the same in both cases.

The results in Table 5 indicate that as the all-electric range is increased, the characteristics of the supercapacitor/ battery units become increasingly favorable compared to the power battery units. The costs used in the analysis for the batteries and the supercapacitors assume high volume production for both of those components. The weight, volume, and cost of the DC/DC converter were not included in the characteristics of the supercapacitor/battery powertrain because they will be included in the electric drive package for the vehicle. All the results in Table 5 are highly dependent on the assumptions made concerning the characteristics of the components and can change significantly as their performance is improved and their costs are reduced. Nonetheless, the results in Table 5 indicate that the use of supercapacitors and energy batteries in PHEVs can make sense and should be considered for future design of PHEVs.

Table 5: Comparisons of the weight, volume, and costs of the energy storage systems with/without supercapacitors

PHEV range	Power battery kWh	Energy battery kWh	Capacitor Wh	weight. kg Vol. L of the battery plus capac.	weight. kg Vol. L of the power battery	Cost ($) of the battery plus the capac. (1)	Cost ($) of the power battery (2)
20 mile	7	7	220	66 kg 33 L	58 kg 27 L	$1600	$1575
40 mile	15	15	220	115 kg 55 L	125 kg 57 L	$2800	$3375
60 mile	23	23	220	163 kg 77 L	192 Kg 87 L	$4000	$5175

(1) The supercapacitor cost was taken as .25 cents per Farad which is $2.5/Wh

(2) The battery costs were $150/kWh for the energy battery and $225/kWh for the power battery

4 Simulations of PHEVs with Supercapacitors

The simulations of the vehicles using supercapacitors have been performed using the UC Davis version of **Advisor** originally developed by NREL. Vehicles utilizing powertrain configurations having two energy storage units such as a battery and supercapacitor have been simulated at UC Davis [7, 8]. A key element of the simulations is the control strategy used to split the power demand between the two energy storage units. In the present simulations, the power demand from the battery is related to the power demand of the vehicle averaged over 45 seconds. At each time step, the power provided by the supercapacitor is equal to the vehicle power demand minus the average power provided by the batteries. When the voltage of supercapacitors approaches the minimum (usually ½ V_{rated}) permitted, the battery provides a higher and higher fraction of vehicle power demand and recharges the supercapacitors. The detailed control strategy becomes more critical for driving cycles like the US06 that demand high power to operate the vehicle. The control strategy is less critical for lower power driving cycles like the FUDS.

4.1 Vehicle and Powertrain Characteristics

All the simulations were performed using the following vehicle inputs:

Test weight=1700kg, C_D =.27, A_f=2.5 m^2, f_r=.007, Access.=400W, electric motor 120kW, 320V

The battery size (kg and kWh) was varied to meet specified all-electric ranges of 20-60 miles. The electric drive used in the simulations is shown in Figure 1. Simulations were made for both energy and power batteries with the characteristics shown in Table 1. The simulations were made with the energy battery combined with supercapacitors of three technologies – Skeleton (activated carbon with graphene), Yunasko (carbon/carbon with very low resistance), and JSR Micro and DAE-China (hybrid Li-graphite/ carbon). The characteristics of these supercapacitor devices are given in Table 2. Each of the supercapacitors was sized (kg) to store about 220Wh.

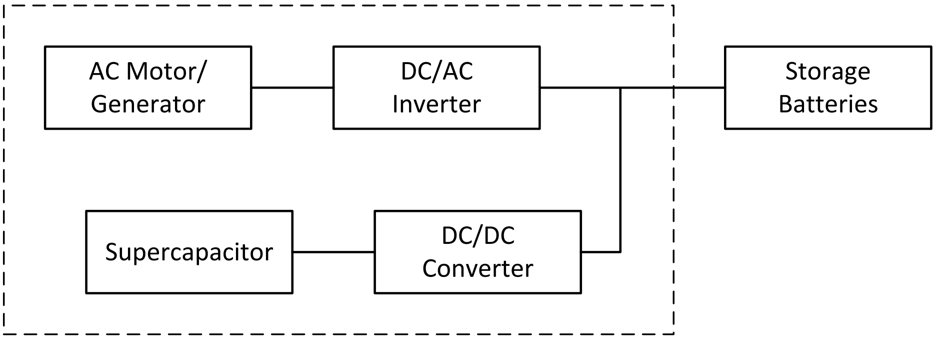


Figure 1: PHEV electric drive with supercapacitors

4.2 Driving Cycles

Simulations were performed for two driving cycles- FUDS and US06. The power demand for the vehicle on the US06 was much higher than on the FUDS. Hence as a result, it was more difficult to load-level the battery with the supercapacitor on the US06 providing a more difficult test for the control strategy and supercapacitors.

4.3 Simulation Results Using Supercapacitors

The initial simulations performed were for the PHEV operating on the energy battery and the power battery alone to get a baseline to evaluate the results using the supercapacitors. Next runs were made with both batteries for each of the supercapacitor technologies. Runs were made for both the FUDS and US06 driving cycles. The results of the simulations are given in Tables 6. For each run, values are shown for the vehicle range and Wh/mi in the all-electric mode, the battery losses (kJ) and efficiency, the capacitor losses (kJ) and efficiency, and the final battery temperature with minimal cooling. As noted previously, the control strategy for setting the battery power was to average the motor power demand over 45 sec and decrease the power from the capacitors when their voltage dropped below about ¾ rated voltage.

The results in Table 6 show that the use of supercapacitors with the batteries reduces the losses (heat generated) by a factor of two for both the energy and power battery. Even with the capacitors, the losses in the energy battery are somewhat higher than with the power battery alone without the capacitors. This is not surprising as the losses are proportional to the resistance of the battery which is about a factor of two higher for the energy battery. The losses for the US06 cycle are a factor of 2-3 higher than on the FUDS cycle with and without the capacitors. This is apparent also from the calculated temperature rises in the battery for both the energy and power batteries. The temperature rises in the smaller batteries (40 kg and 55 kg) are much larger than in the larger (80 kg and 110 kg) batteries. Even using capacitors, thermal management in a PHEV with an all-electric range of 20 miles or less will be challenging.

The lowest energy usage (Wh/mi) was calculated using the power battery alone on both the FUDS and US06 cycles. In all cases, the use of supercapacitors reduced the energy use of the vehicles with the energy battery. However, in general, the use of the supercapacitors had only a small effect on Wh/mi.

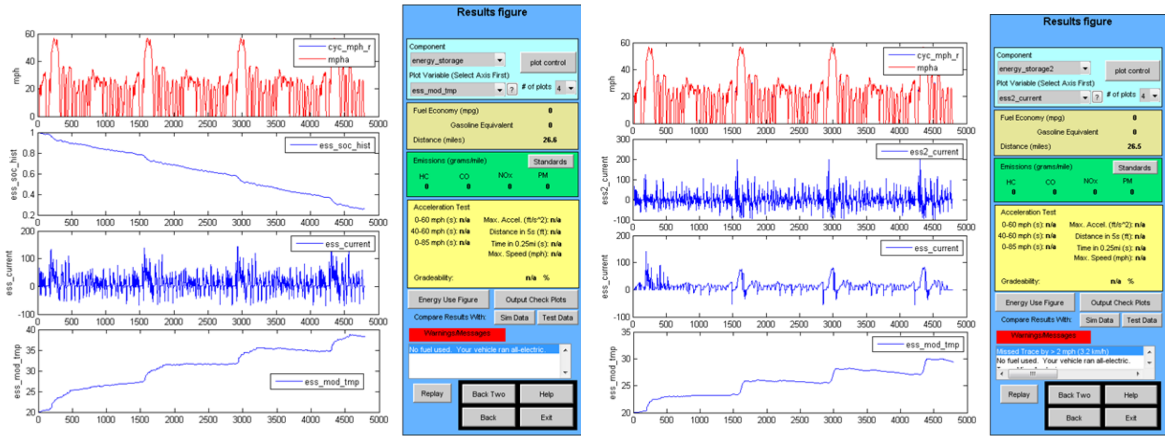
The currents required from the energy battery are shown in Figures 2-3 and 4-5 for the FUDS and US06 driving cycles, respectively. In each figure, the current profiles are shown for the energy battery alone and with the Skeleton supercapacitors. It is clear from the figures that the dynamic character of the current profiles is very different using the supercapacitors and that the magnitude of the currents experienced by the battery is significantly reduced. The battery currents with supercapacitors on the FUDS cycle are particularly low. The battery currents experienced on the US06 cycle are higher, but reduced by about a factor of two compared to those for the battery alone. The strong effect of the supercapacitors on the battery currents and associated losses are the major advantage of using supercapacitors with an energy battery in a PHEV. This is expected to increase cycle life and reduce the cooling needed for the battery.

Table 6: Summary of battery/capacitor Advisor simulation results

Bat/kg	Drive cycle	Elec. Range mi.	Wh/mi	Battery losses kJ	Battery effic. %	Capac. Losses kJ	Capac. Effic. %	Final temp. C*
Power/ 55 kg alone	FUDS	26.6	202	455	97			26
	US06	15.4	337	835	94			43
Energy/ 40kg alone	FUDS	26.6	209	1080	94			39
	US06	14.9	336	2526	85			80
Energy/ 40kg with Caps.								
24 kg Skeleton	FUDS	26.5	226	553	95	412	97	30
	US06	15.4	343	1438	89	518	94	60
24kg JSR Micro	FUDS	26.5	226	554	95	282	97	30
	US06	15.4	339	1332	89	307	96	60
28 kg Yunasko	FUDS	26.5	226	650	95	161	99	32
	US06	15.4	335	1438	89	121	98	60
20 kg future hybrid	FUDS	26.5	226	542	95	203	98	30
	US06	15.4	337	1328	89	179	98	60
Power/ 55kg with Caps.								
24 kg Skeleton	FUDS	26.5	216	207	97	422	97	23.7
	US06	15.4	326	494	97	501	94	34
24kg JSR Micro	FUDS	26.5	216	203	97	287	98	23.7
	US06	15.4	324	466	95	307	96	33
Energy/ 80kg alone	FUDS	44.7	201	886	96			
	US06	32	337	2441	91			
Energy/ 80kg with Caps.								
24 kg Skeleton	FUDS	44.7	229	544	97	507	98	27
	US06	32	330	1464	94	821	95	55
24kg JSR Micro	FUDS	44.7	226	423	97	465	98	25.5
	US06	32	331	1252	94	744	96	50
28 kg Yunasko	FUDS	44.7	226	650	95	161	99	32
	US06	32	335	1438	89	121	98	60
20 kg future hybrid	FUDS	44.7	226	542	95	203	98	30
	US06	32	337	1328	89	179	98	60

Power/ 110kg alone	FUDS	44.7	198	422	98			
	FUDS	32	323	931	97			
Power/ 110kg with Caps.								
24 kg Skeleton	FUDS	44.7	226	178	98	671	97	22.1
	US06	32	327	514	97	1222	93	32
24kg JSR Micro	FUDS	44.7	225	175	98	470	98	22
	US06	32	324	474	97	447	96	31

* the initial battery temperature was 20 deg C



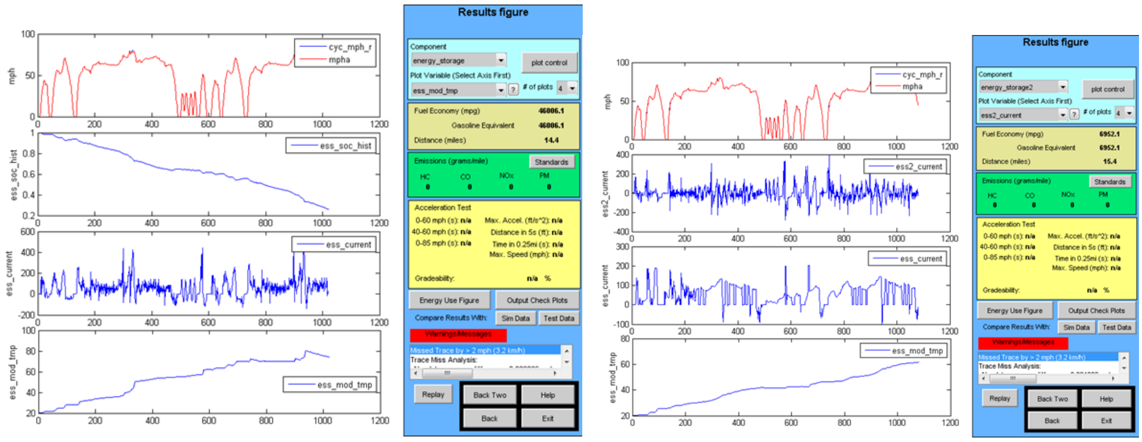
Component: energy_storage
Plot Variable (Select Axis First): ess_mod_tmp
\# of plots: 4
Fuel Economy (mpg): 0
Gasoline Equivalent: 0
Distance (miles): 26.6
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Compare Results With:
No fuel used. Your vehicle ran all-electric.

Component: energy_storage2
Plot Variable (Select Axis First): ess2_current
\# of plots: 4
Fuel Economy (mpg): 0
Gasoline Equivalent: 0
Distance (miles): 26.5
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Compare Results With:
Missed Trace by > 2 mph (3.2 km/h)
No fuel used. Your vehicle ran all-electric.

Energy battery alone

Energy battery with 24 kg Skeleton caps

Fig. 2: 40 kg Energy battery with and without caps, 3.5 FUDS cycles



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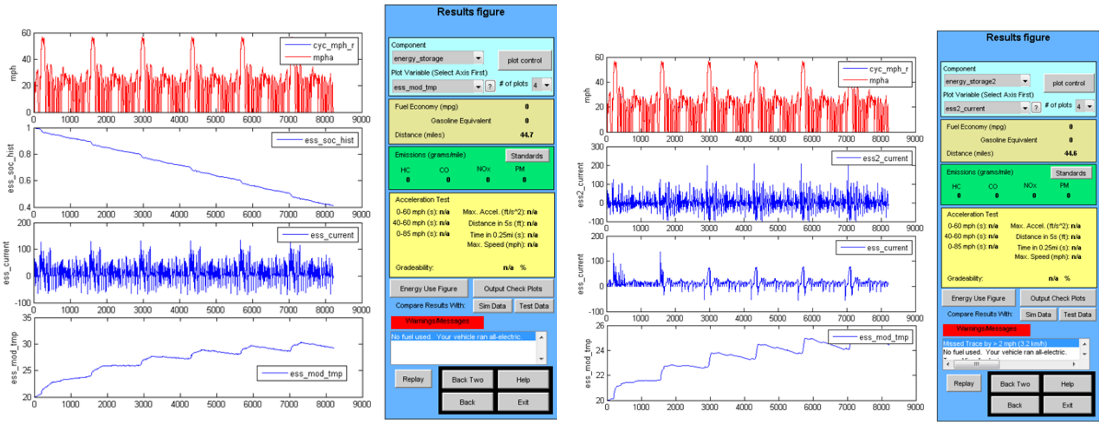
Fuel Economy (mpg): 46006.1
Gasoline Equivalent: 46006.1
Distance (miles): 14.4
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Compare Results With:
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Component: energy_storage2
Plot Variable (Select Axis First): ess2_current
\# of plots: 4
Fuel Economy (mpg): 6952.1
Gasoline Equivalent: 6952.1
Distance (miles): 15.4
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Compare Results With:
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Battery alone

Battery with 24 kg Skeleton caps

Fig. 3: 40 kg Energy battery with and without capacitors on 1.8 US06 cycles



Component: energy_storage
Plot Variable (Select Axis First): ess_mod_tmp
\# of plots: 4
Fuel Economy (mpg) 0
Gasoline Equivalent 0
Distance (miles) 44.7
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
No fuel used. Your vehicle ran all-electric.

Component: energy_storage2
Plot Variable (Select Axis First): ess2_current
\# of plots: 4
Fuel Economy (mpg) 0
Gasoline Equivalent 0
Distance (miles) 44.6
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
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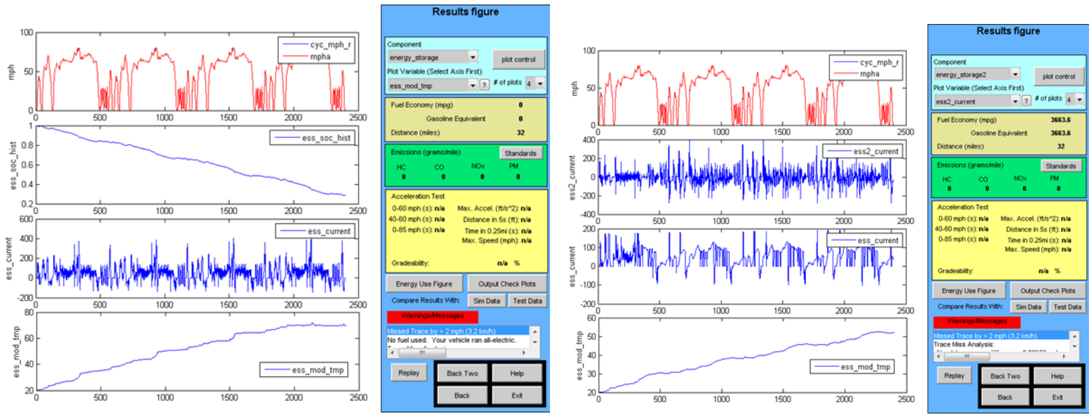
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Missed Trace by > 2 mph (3.2 km/h)
No fuel used. Your vehicle ran all-electric.

Battery alone

Battery with 24 kg Skeleton caps

Fig. 4: 80 kg Energy battery with and without capacitors on 6 FUDS cycles



Component: energy_storage
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\# of plots: 4
Fuel Economy (mpg) 0
Gasoline Equivalent 0
Distance (miles) 32
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Missed Trace by > 2 mph (3.2 km/h)
No fuel used. Your vehicle ran all-electric.

Component: energy_storage2
Plot Variable (Select Axis First): ess2_current
\# of plots: 4
Fuel Economy (mpg) 3663.6
Gasoline Equivalent 3663.6
Distance (miles) 32
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Battery alone

battery with 24 kg Skeleton caps

Fig. 5: 80 kg Energy battery with and without capacitors on 4 US06 cycles

5 Summary and conclusions

In this paper, the use of supercapacitors in the electric driveline of plug-in hybrid vehicles (PHEVs) is analyzed from the design, performance, and economic points-of-view. The supercapacitors are envisioned to be part of the motor and electronics package and thus the same electric drive package can be combined with batteries of different energy storage capacity (kWh) as needed to meet the specific all-electric range the vehicle. In all cases the PHEVs in the all-electric mode had the performance of an EV having attractive acceleration characteristics. A 120kW electric motor is used in all the PHEVs studied. The use of the supercapacitors to load-level the storage battery permits the use of an energy battery rather than a power battery in PHEVs. Energy batteries have higher energy density, longer cycle life, and lower cost than power batteries of the same energy storage capacity (kWh). The weight, volume, and cost of the supercapacitors plus the energy battery are close to that of a power battery for all-electric ranges of 20 miles and are less than that of the power battery for longer all-electric ranges. Simulations of PHEVs indicate that even using the supercapacitors the energy consumption (Wh/mi) of the PHEVs is slightly lower using the power battery than with the energy battery. However, the use of the supercapacitors improves the system efficiencies with the energy battery and most importantly reduces by about a factor of two the peak and average current experienced by the energy battery. In addition, the dynamic character of the battery current/power with the supercapacitors is considerably smoother than with the energy battery alone.

PHEV simulations were performed for vehicles operating on the FUDS and US06 driving cycles. Satisfactory operation on both cycles requires energy storage in the supercapacitors of at least 220 Wh. This is significantly higher than the 100 Wh or less required for a hybrid-electric vehicle (HEV), which utilizes the engine when the charge in the supercapacitors is depleted. In the case of the PHEV, when the charge on the supercapacitor is depleted, the storage battery experiences high current/powers. The control strategy for splitting the power demand between the supercapacitors and the battery is intended to avoid this situation. Simulations were performed using supercapacitors with energy densities from 9-22 Wh/kg with power capabilities of 1000-8000 $(W/kg)_{95\%}$. All the supercapacitors used in the simulations worked well, but those with higher energy density required less weight for the cells and those with higher power capability resulted in lower losses. The losses in the supercapacitors were less than those due to the 97% efficient DC/DC converter used in the system. Commercially available supercapacitors can be used in PHEVs.

The present study indicated that the primary reasons for using supercapacitors in PHEVs having EV like performance is to reduce the high current/power transients experienced by the battery and to permit the use of energy battery rather than power battery technologies for the energy storage battery. This approach separates the energy and power requirements and permits the same electric drive unit to be used for vehicles having a wide range of all-electric range. The use of the supercapacitors does not reduce the energy consumption (Wh/mi) of the PHEV, but the increase is only a few percent.

Reference

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