Integration and Testing of a DC/DC Controlled Supercapacitor into an Electric Vehicle

Gregory Wight, Harold Garabedian, Beat Arnet, Jean-Francois Morneau

Abstract

The primary goal of this project was to demonstrate improved performance and equipment reliability in a Solectria Force electric vehicle associated with the installation of a Maxwell PowerCache ultracapacitor module and a Solectria prototype integrated controller. A supercapacitor provides a high efficiency energy storage unit that can provide short bursts of power and rapidly capture braking regenerative energy. These characteristics are consistent with the energy use associated with acceleration/deceleration in electric vehicles[2]. The test program included summer and winter testing on a suburban test course, acceleration testing on a flat roadway and dynamometer, an urban driving course, cold and warm temperature dynamometer testing on the FUDDS cycle, and dynamometer testing on the US EPA IM240 cycle. The supercapacitor efficiently responded to high power demands and effectively recovered regenerative energy, modulating peak battery current. The capacitor system allowed more total energy to be drawn from the batteries. Due to the inefficiency of energy transfer into and out of the capacitor through the DC/DC controller, range and performance improvements as compared to the control vehicle depended strongly on the driving cycle.

Keywords: Supercapcitor, ultracapacitor, energy storage, vehicle performance, EV

1 Introduction:

The primary goal of this project was to demonstrate improved performance and equipment reliability in a Solectria Force associated with the installation of a Maxwell PowerCache ultracapacitor module and integrated controller. This goal was accomplished by a team effort involving DARPA and the Notheast Advanced Vehicle Consortium, Solectria, Inc., Maxwell Technologies, HydroQuebec and EVermont. All testing was conducted under the direction of EVermont, and the test objectives were set to evaluate the performance of the drive system under cold weather conditions as well as optimum temperatures. The vehicles were tested in a broad variety of roadway and dynamometer situations.

2 The Vehicles:

Two Solectria Force electric vehicles were utilized in this project. Each was outfitted with thirteen new 12-volt Sonnenschein Lead-Acid batteries for a pack voltage of 156 v. The Maxwell PowerCache ultracapacitors (PC7223) were packaged in two blocks of 28 each, with an overall voltage rating of 120 v. The Solectria DC400 DC/DC Controller is a buck-boost converter programmed to optimize the applications of the capacitors[1]. The capacitor modules, DC/DC converter and cooling fans were mounted in the rear of the vehicle, above the rear battery box. This substantial additional weight brought the test vehicle to a curb weight of 2820 lb (stock Force weight = 2500 lb) and a rather ungainly 42% front/58% rear weight distribution. The control vehicle was brought to similar specifications with sand bags.

The data acquisition system utilized a Campbell CR10X DAS in each car with voltage, temperature, current and rpm sensors to record the following parameters:

- Vehicle speed
- Battery volts
- Capacitor volts
- DC/DC current
- Battery current
- Capacitor current
- Accessory current
- Cabin heat current
- Front battery box temperature
- Rear battery box temperature
- Ambient temperature
- Capacitor temperature

3 Test Program

Vehicle testing included acquiring data as the capacitor-equipped car and the control car operated on a number of roadway and dynamometer situations:

- Summer Road Tests
  - Driving on a 20 mile suburban/highway test course
  - Urban driving in congested downtown area
  - Acceleration testing on a closed airport runway
- Winter Road Tests
  - Driving on a 20 mile suburban/highway test course
  - Urban driving in congested downtown area
  - Acceleration testing on a closed airport runway
- Cold and Warm Dynamometer Tests utilizing the FUDDS Cycle
- Dynamometer Tests of the capacitor equipped vehicle only with capacitor engaged and disabled, utilizing the IM240 cycle
- Dynamometer Tests of the capacitor equipped vehicle only with capacitor engaged and disabled, repeated maximum acceleration events

3.1 Suburban Road Course

The 20.4 mile test course consists of seven miles of rolling rural secondary two-lane road where speed averages 35 mph, followed by two miles of urban driving and several traffic lights, a long steep hill, and several miles of Interstate highway driving. The course has proven to be valuable for base lining performance of a number of different electric and hybrid vehicles.

3.2 Urban Driving Test Course

The urban course was set up in Burlington, VT, a medium sized metropolitan area with fairly typical traffic congestion. Both vehicles were brought to full charge before the testing began. A seven-mile course through the heart of the city center was driven in mid-day traffic continuously until the vehicles were depleted of energy. Substantial stop and go driving was experienced as the two vehicles followed one another.

3.3 Airport Acceleration Test Course

A 4022-foot long runway at a small airport was closed and the ¼ mile test course set up. Vehicles were transported to the airport and charged overnight. Side-by-side, the two vehicles executed maximum acceleration events until depleted of energy, while all test parameters were recorded.

3.4 Cold and Warm FUDDS Tests

EVermont partner laboratory LTEE of HydroQuebec conducted dynamometer tests of the two vehicles to eliminate roadway variables and to allow comparison of data to other standardized test results. The Federal Urban Dynamometer Driving (FUDDS) test was utilized. At a temperature of 20°C, both vehicles were charged then driven on the FUDDS cycle repeatedly until depleted of energy. This test was repeated a second time. Next the vehicles were allowed to come to equilibrium in a cold chamber at -20°C and again tested two times each on the FUDDS cycle.

3.5 Dynamometer Tests on the IM240 cycle

To eliminate potential differences between the two vehicles and/or the drivers the capacitor equipped car was tested on a dynamometer programmed for the EPA IM240 driving cycle. Six tests were run, each starting with a fully charged battery and capacitor and proceeding to repeat the 240 second cycle with minimal stops until battery depletion. The six tests alternated having the capacitors and DC/DC converter engaged and disabled – three in each mode, all with an operator experienced with the IM240 cycle.

3.6 Acceleration Tests on the Dynamometer

Again to eliminate potential differences between the two program vehicles or drivers, full acceleration events were executed on the dynamometer with the same driver. Again, the vehicle was tested with capacitors on and off, on successive days, executing maximum acceleration events until battery energy was exhausted.

4 Results

Over the course of two years of testing, large quantities of data have been acquired. Not all have been completely analyzed yet. Results for each of the vehicle driving tests are discussed in this section.

4.1 Urban Driving

In the first round of urban driving, the capacitor-equipped car traveled around the course more times than the control car and was, in fact, able to drive 30% farther. However, when the same test was repeated on a cold day, both vehicles traveled the same distance, while the control car used 17% less energy to do so. Figure 1. is a plot of a portion of one city driving test. It shows how dramatically the supercpacitor reduces the peak battery current.

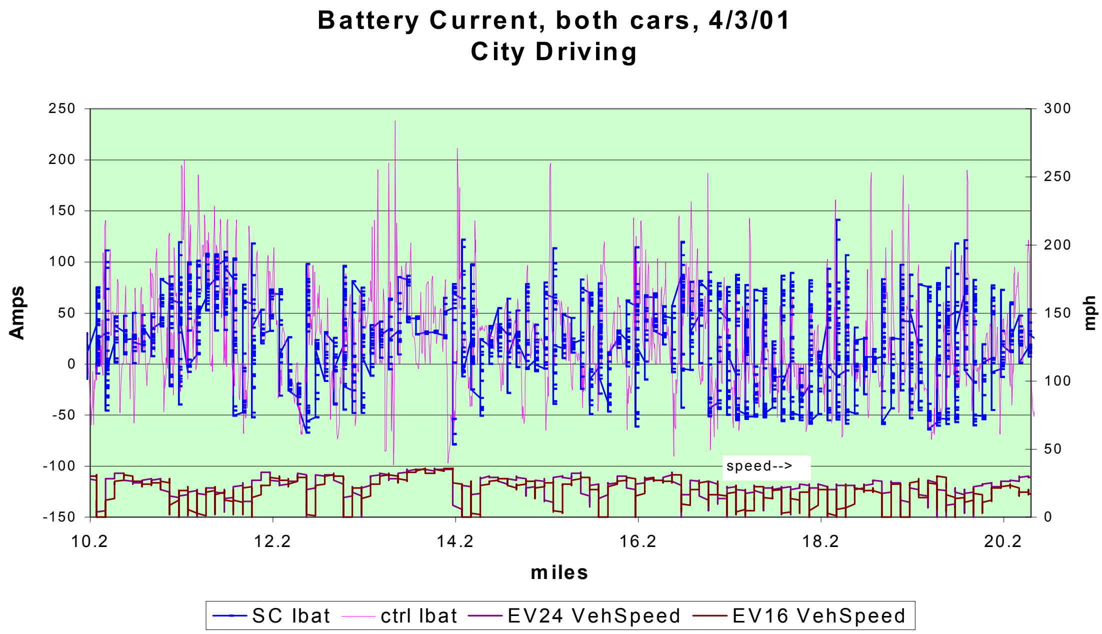

Figure 1.

The urban drive test was repeated a third time, but with only the single car driven, first with the capacitors engaged, and the next day with them unplugged. In both modes the vehicle was able to travel approximately the same distance. This time the capacitor-equipped mode had 7% less range and 20% higher energy consumption (KW-hr/mi). There were, however, sections of the test course over which the capacitor-equipped vehicle had lower KW-hr/mi data than when in non-capacitor mode, indicating that driving cycle greatly affects the operation of the drive train. On one two mile section of the course, the capacitor vehicle was 100% more efficient than the control mode.

4.2 Airport Acceleration Testing

Acceleration testing on the airport runway demonstrated the advantage of the capacitor system on battery stress. The capacitor-equipped vehicle was able to complete 117 ¼ mile acceleration/deceleration events, while the control car, operating side-by-side, completed only 87. Thus, this test indicated a range enhancement, on this severe operating cycle, of 34%. Figure 2. shows a typical acceleration event. The battery current peaks are substantially lower with the capacitor in the system.

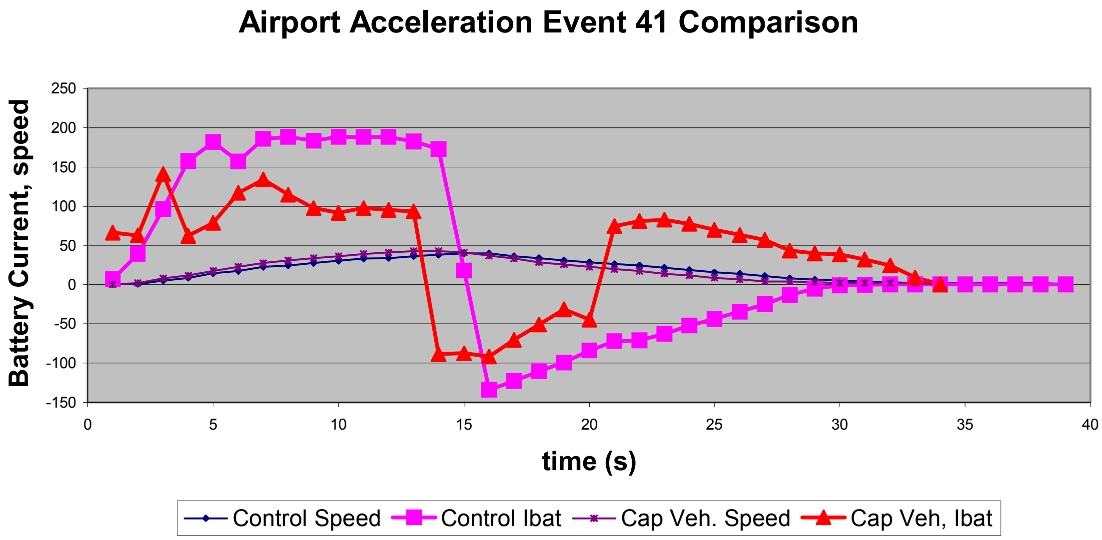

Figure 2.

4.3 Dynamometer Acceleration Testing

Dynamometer acceleration testing (using the single test car in two modes) was undertaken to confirm the airport results. However, the results were mixed. There were indications that the capacitor sometimes helped the performance under hard acceleration, but energy consumption was greater per mile or per acceleration event, for the capacitor mode. The capacitor allowed the extraction of nearly 25% more energy from the batteries, due to the Peukert Effect, before the battery voltage fell to unacceptable levels. Because of the inefficiencies of the DC/DC controller's transfer of energy, however, the extra energy did not result in greater range (See Figure 3.) In each mode, the vehicle completed 55 acceleration events before performance fell off.

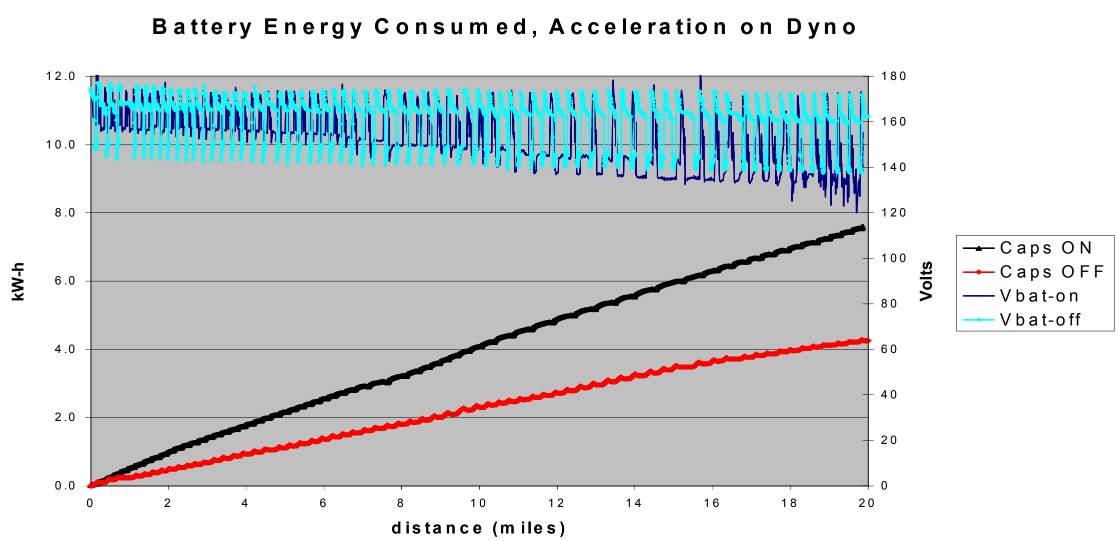

Figure 3.

A kilowatt-hour meter on the charger recorded the amount of energy needed to fully recharge after each round of acceleration testing. The Capacitor-on acceleration testing required 13.3 AC KW-hr to recharge the batteries and capacitors (capacity of the supercapacitors is only .082 KW-hr) after the test, while the non-capacitor testing required only 11.3 AC KW-hr for complete recharge, providing another indicator of enhancement of battery capacity resulting from the supercapacitor and DC/DC controller..

4.4 IM240 Dynamometer Testing

For tests on the IM240 dynamometer cycle, only the capacitor-equipped car was used, and tests were run with capacitors switched on and off. The IM240 test is a 240 second varying speed cycle that models in a short trip the salient features of the Federal Urban Dynamometer Driving (FUDDS) cycle. See Figure 4. for the speed trace.

Driving on the dynamometer eliminated variables of wind, traffic, and driver characteristics (an operator familiar with the IM240 driving cycle performed all dynamometer tests). On successive days, the vehicle was driven with the capacitor engaged, then disengaged, a total of three times each. The batteries and capacitor were charged overnight, and AC charger energy recorded. Table 1. shows a summary of the data.

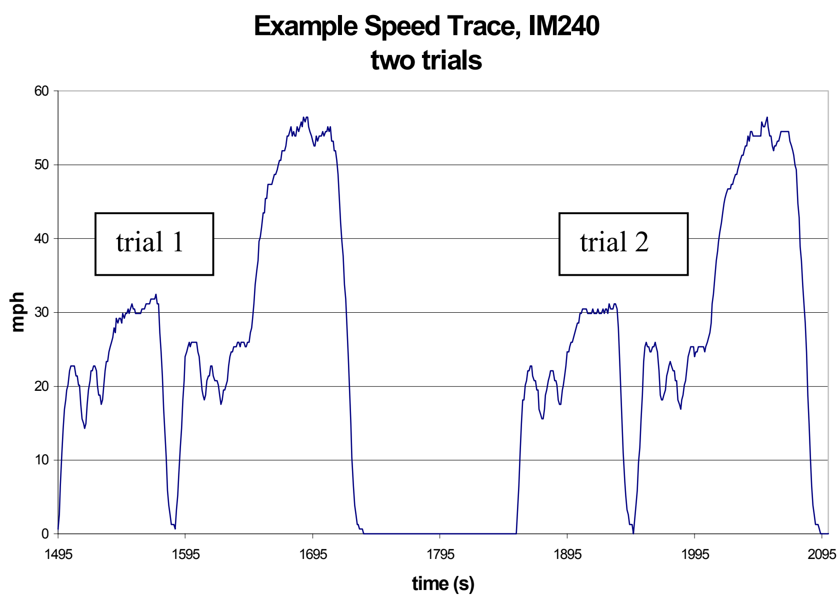

Figure 4. IM240 Speed Trace

RUN #	NUMBER IM240 CYCLES	CAPA-CITOR STATUS	MILES	A-H	AC KW-HR	AC KW-HR/MI	DC KW-HR	DC KW-HR/MI
1	16	ON	31.2	47.2	12.8	0.41	6.94	0.22
3	18	ON	35.2	51.5	12.9	0.37	7.59	0.22
5	18	ON	35.2	51.2	13.0	0.37	7.61	0.22
2	19	OFF	37.2	49.9	12.4	0.33	7.39	0.20
4	19	OFF	35.2	48.4	12.4	0.35	6.88	0.20
6	16	OFF	31.2	42.1	10.5	0.34	6.26	0.20

Table 1. Dynamometer Tests, IM240

The IM240 is a very demanding driving cycle which ought to demonstrate the advantages of the capacitor well. Whereas in side-by-side on road city driving, the capacitor car demonstrated a 20% poorer efficiency compared to the unmodified car, in the IM240 dynamometer testing, the capacitor disadvantage in terms of DC KW-hr/mi (battery energy) was consistently only 9%. In terms of AC KW-hr/mi (charger energy) the capacitor mode had 12.7% poorer efficiency.

Table 1. also shows that the capacitor allowed the batteries to provide substantially more energy.

Successive trials of the IM240 cycle were executed with just a few seconds between runs until the vehicle was no longer able to follow the prescribed speed trace. The criterion for ending the test was two successive runs with excursions beyond the allowed ± 2 mph deviation from the IM240 specifications. A comparison of the last valid cycle on each of the six IM240 tests in Figures 5. and 6. shows dramatically how the capacitor affects the battery current demanded by this driving cycle.

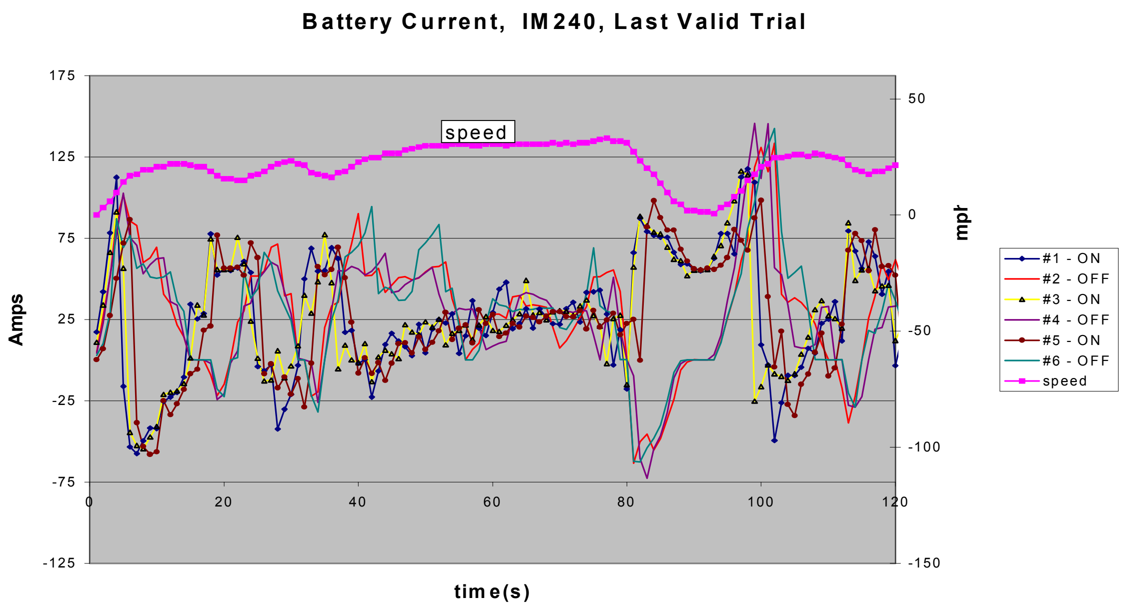

Figure 5. First half of cycle, dramatic differences are seen between the battery currents of the non-capacitor car and the capacitor version.

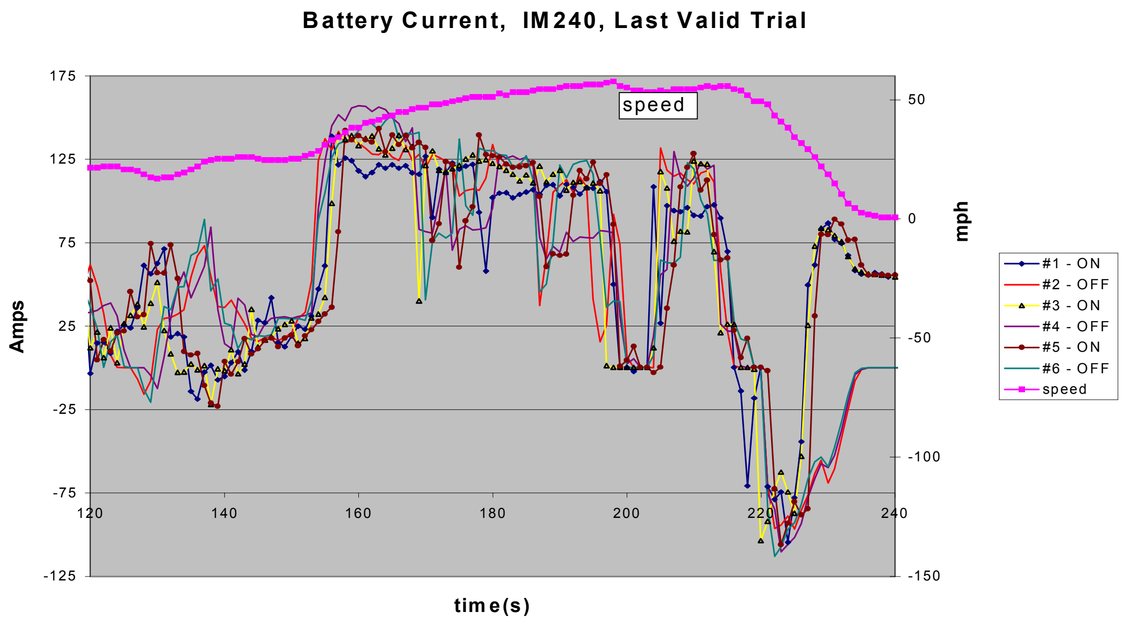

Figure 6. Last half of cycle, capacitor is depleted of energy; little difference thereafter

4.5 FUDDS Dynamometer Testing

The Capacitor car and the control car both underwent +20°C and -20°C cycles on the FUDDS cycle. As Figure 7. shows the current demands were dramatically different for the two cars. For all the FUDDS tests the standard deviation of battery current for the capacitor-equipped vehicle was 37 amps, while for the control car the standard deviation was 44 amps. The reduced variability and peak heights mean less stress on the batteries. The overall efficiencies for the two vehicles on the warm test were 4.18 mi/KW-hr for the capacitor vehicle and 4.73 mi/KW-hr for the control vehicle. For the -20°C tests, the efficiencies were lower; 3.60 mi/KW-hr for the capacitor, 4.13 for the non-capacitor.

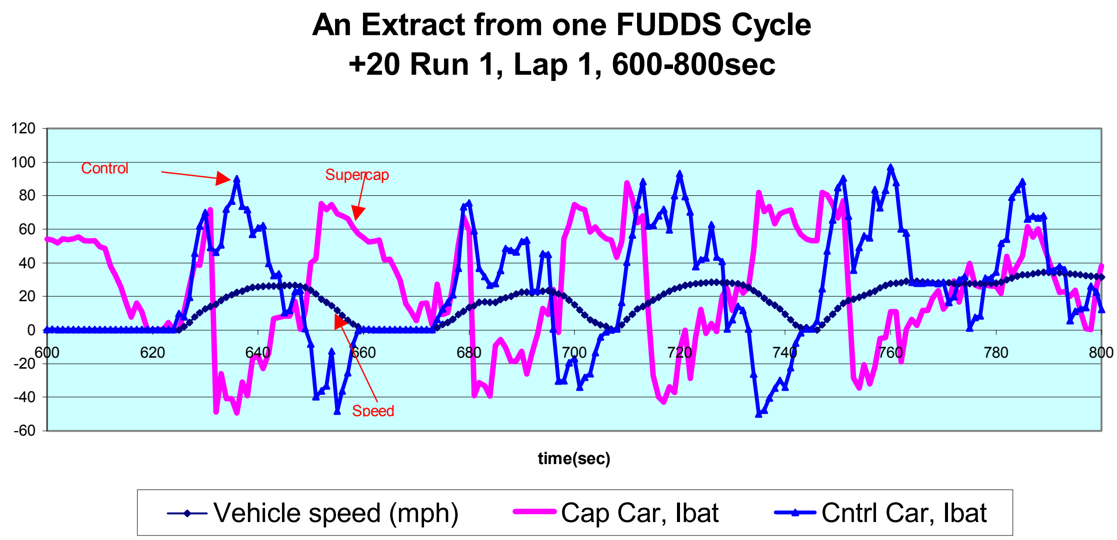

Figure 7. FUDDS comparison

5 Conclusion

Extensive testing of supercapacitors integrated into an EV has been conducted. The results point to a number of conclusions about the feasibility of such a system. The most significant conclusion at this point is that incorporating a DC/DC controlled supercapacitor into the EV drive train effectively modulated the peak battery current and reduced the strain on the batteries. This modulation was demonstrated in every test conducted. A second significant conclusion is that the supercapacitor allowed greater energy extraction from the batteries, that is, the capacity of the batteries was enhanced through lower average current draw and/or lower current peaks.

These two effects will allow greater vehicle range per charge and longer battery life.

Inclusion of the capacitor, with its ability to rapidly absorb regenerative braking energy, makes the vehicle more energy efficient. However, the inefficiency of the DC/DC converter in transferring energy from the capacitor to the battery or battery to capacitor reduces the gains due to recapture. The efficiency and/or range benefit of the capacitor and controller system is greatly drive-cycle dependant. For the various tests performed, Table 2. lists the "fuel efficiency" comparisons.

Test	Non-cap mi/KW-hr	Cap mi/KW-hr	% Improvement over non-cap
City drive 7/12/00	5.37	5.59	+4%
City drive 4/3/01	5.36	4.62	-14%
City drive 4/17/01	5.64	4.52	-20%
City drive 4/17/01 best 2 mi	2.57	5.14	+100%
Airport acceleration	3.59	2.78	-23%
Dynamometer acceleration	4.70	2.61	-44%
Dynamometer IM240	5.00	4.55	-9%
Dynamometer FUDDS warm	4.73	4.18	-11%
Dynamometer FUDDS cold	4.13	3.60	-13%

Table 2. Energy Efficiency Comparisons

Clearly, the drive cycle strongly affects the efficiency gains the capacitor provides. The Maxwell Powercache Ultracapacitors used in this study have a capacity of only 82 W-hr. Constant acceleration of the 2820 pound vehicle from 0 to 50 miles per hour requires the addition of 89 W-hr of kinetic energy, if friction and aerodynamic drag are neglected. The DC/DC converter efficiency is expected to be only in the 50 to 70% range [3], so it is clear that these particular capacitors are not optimized for accelerations from zero to fifty mph. Optimization of the controller programming for these and other drive cycles needs investigation[1]. Additionally, the controller efficiency could perhaps be improved. For stop and go driving, the capacitor ought to show best results, particularly if sized to provide all the energy needed for accelerations. A city bus application seems ideal.

Still to be answered in this study is the effect of the Supercapacitor on battery life. This will be studied through a parallel trial of complete battery strings challenged with the battery current cycle derived from the FUDDS tests.

6 References

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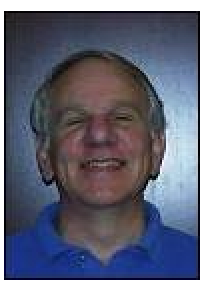
7 Authors



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This project was funded by grants from the US Defense Advanced Research Projects Agency (DARPA) and the Northeast Advanced Vehicle Consortium (NAVC).

1 Page Summary

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The primary goal of this project is to demonstrate improved performance and equipment reliability in a Solectria Force associated with the installation of a Maxwell PowerCache ultracapacitor module and integrated controller.

A supercapacitor provides a high efficiency, temporary energy storage container that can be used as an energy reservoir to provide short bursts of power. These characteristics lend themselves to the rapid energy recovery associated with regenerative braking and the rapid energy consumption associated with acceleration in electric vehicles. Supercapacitors used in this capacity reduce strain on and number of cycles imposed on batteries by diverting high power demands away from the batteries. Supercapacitors can also reduce the Peukert Effect; by extracting energy at a slower average rate, the system with the supercapacitor will allow more energy to be drawn and extend the vehicle range.

Two Solectria Force electric vehicles were modified; one had the supercapacitor and controller integrated, the other was unchanged except for adjustments to match the weight distribution of the test car. The test program included summer and winter testing on a defined suburban test course, acceleration testing on a runway and dynamometer, an urban driving course, Dynamometer testing on the FUDDS cycle, and dynamometer testing on the US EPA IM240 cycle. Still in progress is life cycle bench testing of battery strings.

As expected, the supercapacitor efficiently responded to power demands and effectively recovered regenerative energy, modulating peak battery current. The capacitor system also allowed more total energy to be drawn from the batteries. While the capacitor more efficiently recovered regenerative energy, the inefficiency of energy transfer into and out of the capacitor through the DC/DC controller caused the overall vehicle's overall energy efficiency to decline on some driving cycles.

The advantage of the supercapacitor and controller system appears to be strongly dependant on the driving cycle. The capacitor can improve vehicle performance and efficiency on some driving cycles by allowing normal acceleration (using capacitor energy) when the battery charge is too far depleted to provide acceleration energy. In addition, inclusion of the capacitor in the system reduces stress on the batteries significantly and will increase battery life.

Much additional study is required into capacitors with higher energy density and into design and programming of the DC/DC controller for greater efficiency and to take advantage of the capacitor's characteristics.