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PHEV Development Platform

DOE Merit Review
28 February, 2008

Theodore Bohn
Argonne National Laboratory
Sponsored by Lee Slezak

U.S. Department of Energy

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*Dan Bocci- low level controls software development
Dominik Karbowski- PSAT/High level controls software

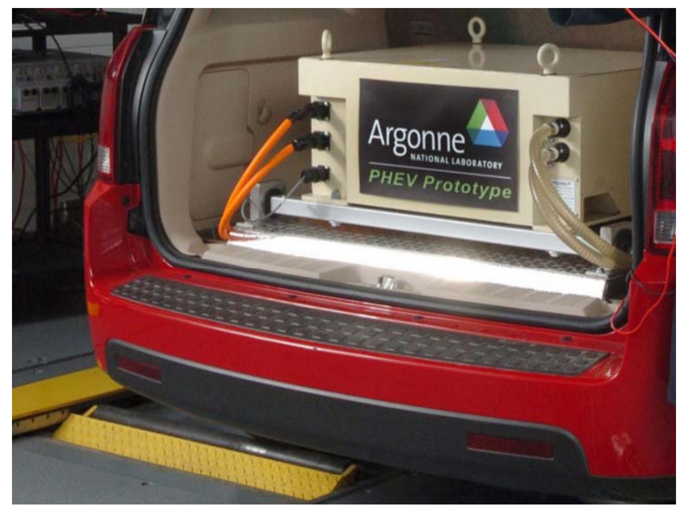
Objective: *Create an all-electric mode capable PHEV vehicle development platform with open controller as research tool.*

FY08 Budget: $700k, Spent $120k to date

• There currently exists no 'available' PHEV, conversion or other, that is able to complete a UDDS cycle without starting engine. (due to power-split limitations) By creating an in-house PHEV development platform with open control system a wide variety of high level vehicle control strategies, such as blended mode vs all electric mode, can be evaluated.

PHEV development platform:

- Can be used for evaluation of battery sizing methods and battery technologies, along with PHEV test procedures.



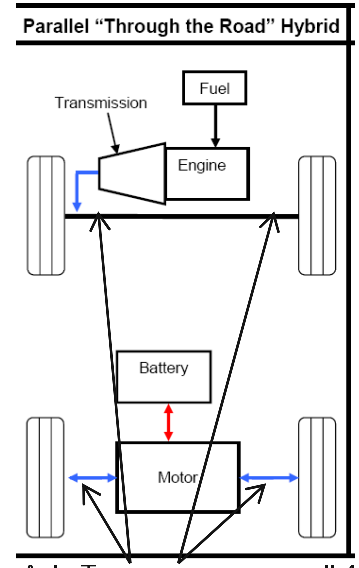
- Through-the-road parallel hybrid electric vehicle, based on a stock Saturn Vue Greenline mild hybrid platform with 75kW rear drive system and 10kWhr li-ion battery.

• Rear electric drive system is modular such that other comparable drive motors can be evaluated in an apples-apples comparison.

Description of Experiment: Through-the-Road parallel hybrid(TTR)

- Through-the-road parallel hybrid electric vehicle with axle torque sensors front and rear to measure power ‘through-the-road’.

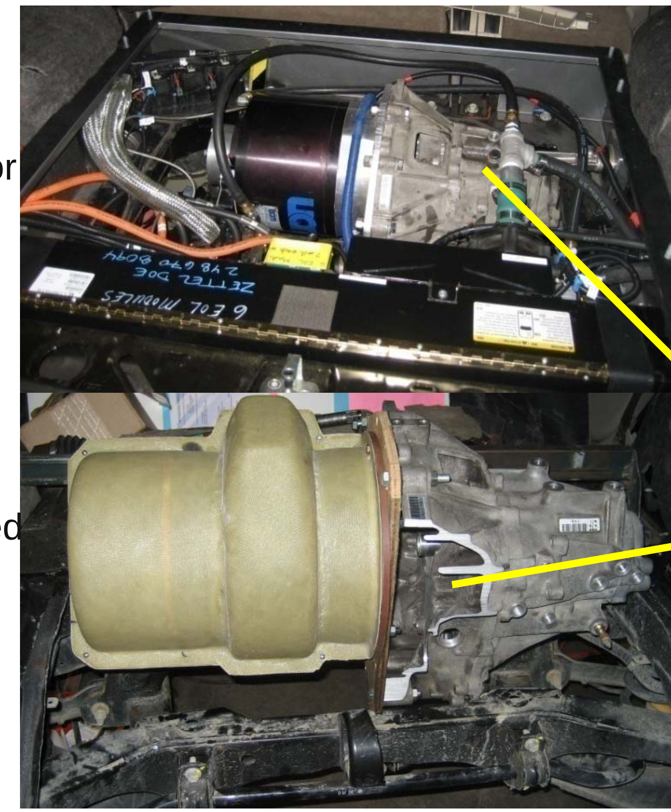
- Additional electric drive powertrain in the rear of the vehicle; interchangeable 120kW air cooled AC induction machine, or 75 kW liquid cooled permanent magnet motor; ~8:1 fixed gear ratio.



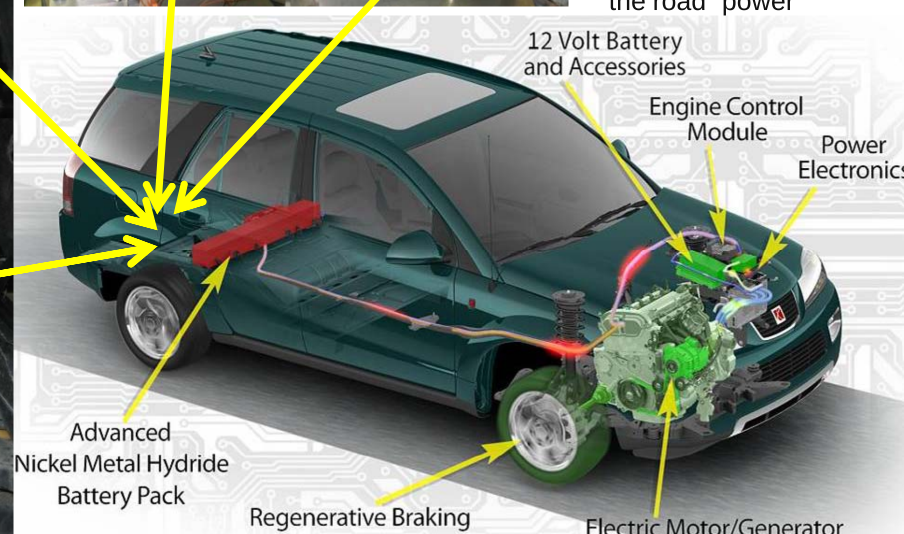
Axle Torque sensors on all 4 ½-shafts to measure “through the road” power

75 kW liquid cooled PM motor

120kW air cooled AC induction machine



55kW Prototype, OEM motors

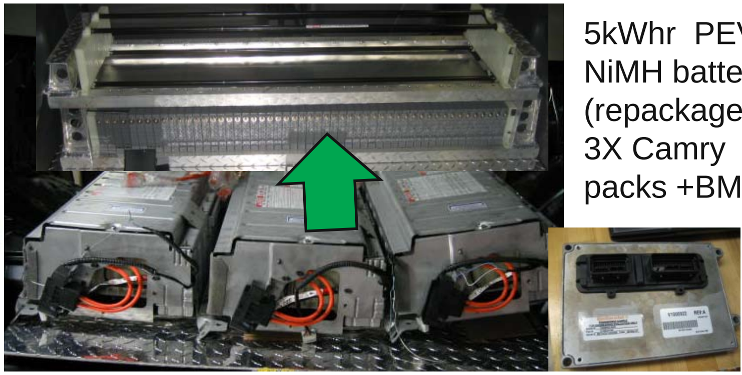


Future Tool for Vehicle-to-Grid and Smart Charging Experiments

- TTR PHEV Platform uses CAN communication for all components, including stock Saturn Vue powertrain
- CAN communication, along with intelligent chargers allows for Vehicle-to-Grid bi-directional charging experiments, as well as uni-directional 'Smart-grid' charging, controlled by utilities.
- Comparison of various chargers and batteries are planned experiments for this platform.

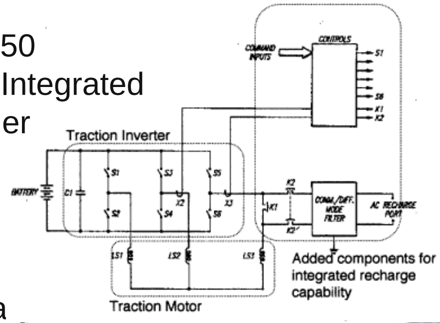
10kWhr JCS Li-ion battery

8kWhr A123 Li-ion battery



5kWhr PEV NiMH battery (repackaged 3X Camry packs +BMS)

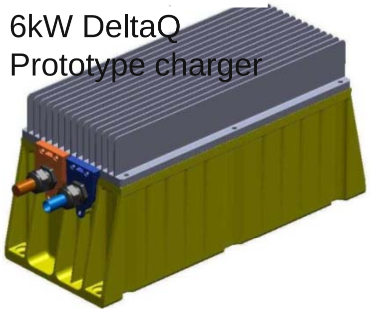
20kW AC150 'reductive' Integrated V2G charger



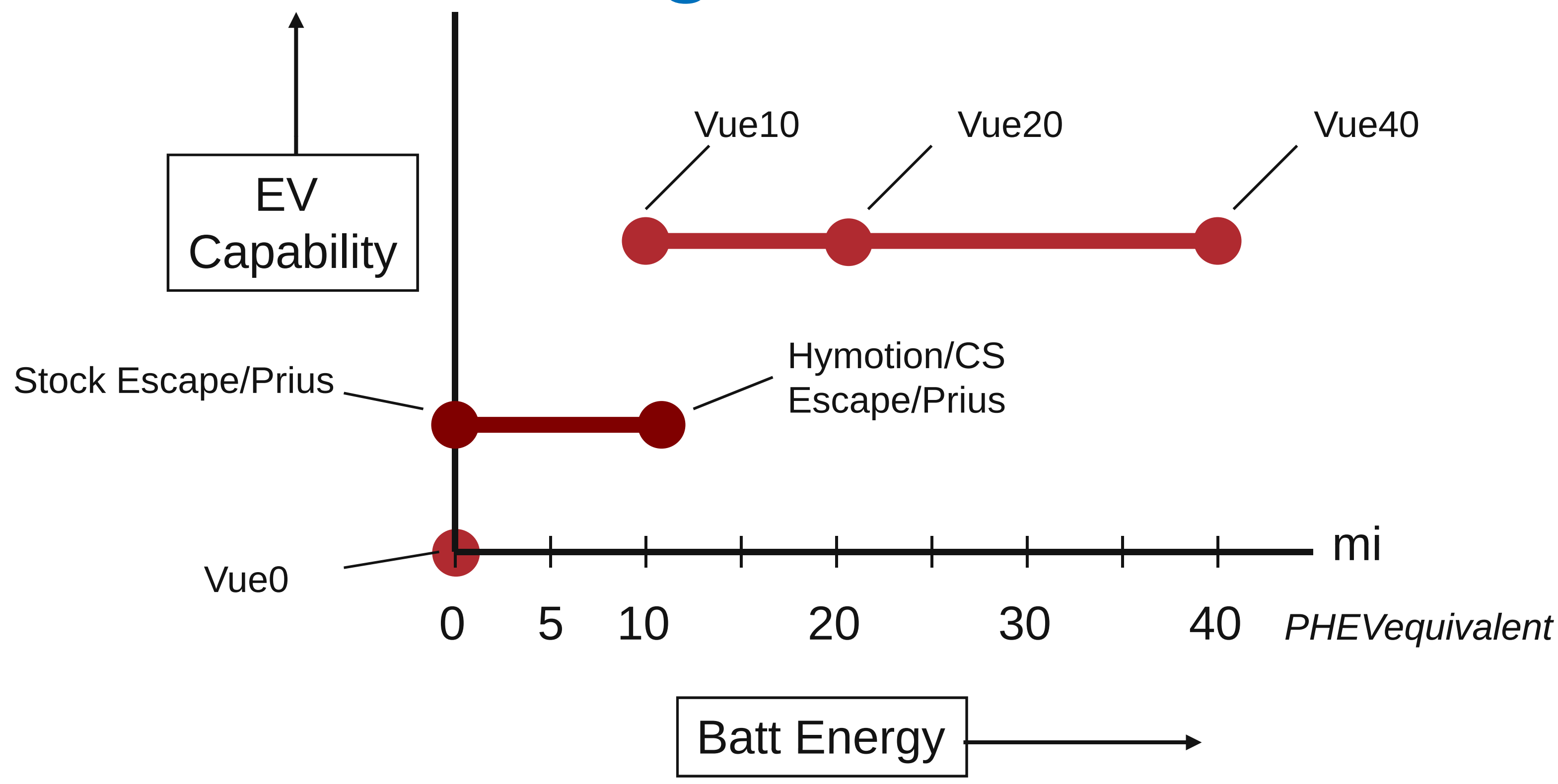
1.6kW Brusa 120/240VAC charger

1.2kW Delta 120/240VAC charger

6kW DeltaQ Prototype charger



AER PHEV Platform: EV Capability and Range Estimates



PHEVequivalent = 55/45 City/Hwy, Based upon "petroleum displacement factor'" method
SOC: 90% down to 20% total capacity

Accomplishments to Date:

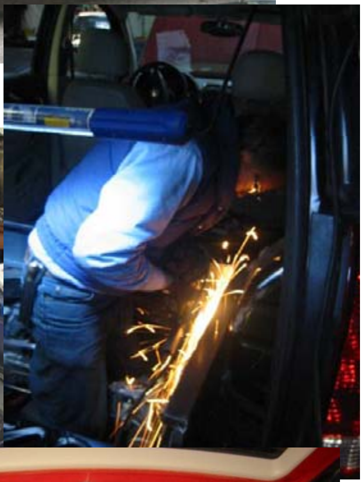
- Project initiated July 2006- vehicle donation solicitation to GM (pre-production mule), delivered autumn 2006.

- 2006-2007 Components procured: multiple electric drive systems, gear boxes, HV batteries, custom drive shafts with torque sensors, fuel flow measurement hardware, control system hardware

- 2006-2007 Vehicle modification/construction including batteries and rear drive system by custom fabricator.

- Jan 2007- Low level control system code completed

- Vehicle on display at HybridFest, July 2007



FY08 Work Plan, Accomplishments to Date:

FY08 WorkPlan:

- Complete low voltage control system wiring
- Commission low level control system
- Debug/overcome incompatibility obstacles with Saturn Vue powertrain fault detection system.
- Develop high level control software based on PSAT models
- Debug interface software between high level and low level controls
- Test vehicle on 4WD Chassis dynamometer as well as on-road
- Perform requested studies for J1711 procedures refinement
- Implement 'shift-by-wire' actuator to overcome Vue powertrain drag in EV mode.

FY08 Accomplishments to Date:

- Low voltage control wiring completed and commissioned low level control system
- Major progress on debug of complications due to Saturn Vue powertrain fault detection system- implemented several work around solutions (i.e. spoofing the Vue vehicle controls into allowing engine shut down at highway speed, restart, etc)
- High level control software based on PSAT models nearly complete, untested.
- Debug interface software between high level and low level controls
- Tested vehicle on 4WD Chassis dynamometer during controls debug.
- Ran briefly in EV only mode; triggered fault in JCS battery protection system.

Accomplishments for Remainder of FY08:

Lessons Learned/Obstacles:

• Discovered Unique Mobility no longer supports CAN software upgrades for their motors built in 2006; replaced with UQM drive, built in 2007 with current version of processor.

• During debug of control system found that Vue powertrain controller identified external engine shut-down as a fault…..and restarted engine (not convenient during EV only mode).

• Found sensitivity in JCS BMS control system. Learned that battery controller produced in 2006 is no longer supported. This Battery was not intended for vehicle.

Accomplishments/Plans for Remainder of FY08

• Install 'shift-by-wire' actuator on Vue automatic transmission to reduce drag.

• Complete high level control software based on PSAT models, debug in vehicle.

• Debug interface software between high level and low level controls.

• When vehicle fully commissioned, run planned experiments. (J1711 blended mode, AER validation; intelligent charging experiments, compare/contrast various battery size/chemistry, as well as compare performance of various drive systems.)

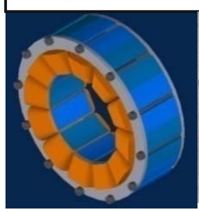
• Prepare for publicity events involving DOE PHEV technology/research.

Support of Other DOE Programs

Energy Storage Tech Team

-Validation of battery sizing
-Vehicle to grid operation impact on batteries

EE Tech Team



-In-vehicle validation of electric motor performance
-Vehicle to grid benchmark/embedded controls

Battery HIL + Ultracap Studies

-Cold weather/battery limitations
-Cost reduction challenges
-Charge-efficiency assumptions/studies

PHEV Development Platform

J1711

- various control strategies
- different chemistries

MATT in APRF

- EV operation issues

PSAT at ANL

- Control system development and validation

Future Plans:

The TTR PHEV Development Platform project is a multi-year program with new initiatives related to incorporating new component technologies.

-Battery technologies; Larger format A123 li-ion batteries, Enerdel lithium titanate cells, Altain Nanotechnologies Lithium-titanate batteries; ultracapacitor-battery combinations

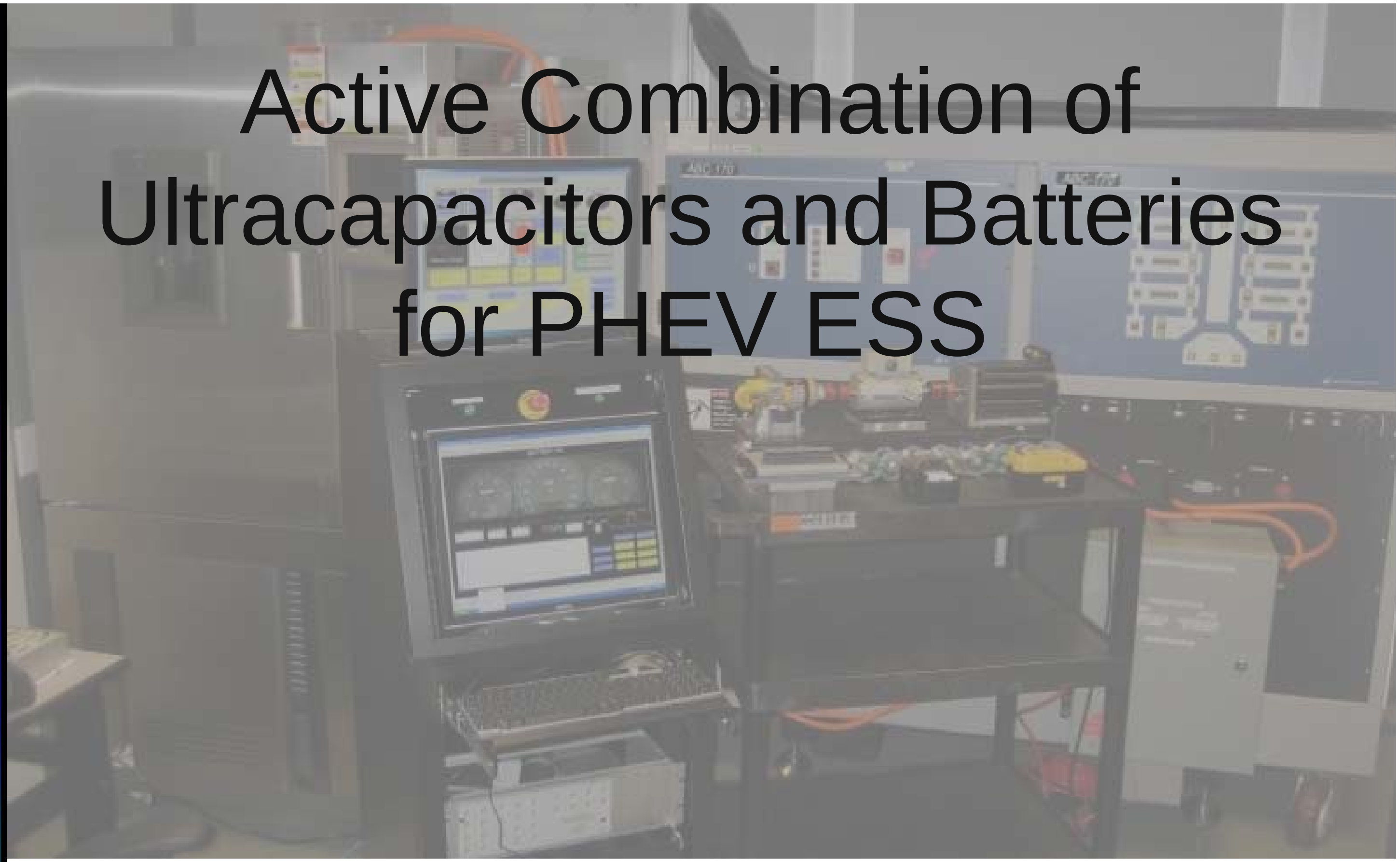
- Control algorithms including in-depth investigations on optimizing petroleum displacement via blended mode vs adaptively dispatched electric only operation.

- Exploration of small engine technology deployment in series PHEVs.

- This research builds upon previous modeling studies on ESS sizing, peak power/energy requirements of PHEVs. Some studies will be revisited with new insights from this PHEV Development Platform.

- Explore new ways to blend electrical energy with petroleum energy as a tool for SAE J1711 validation methods.

Active Combination of Ultracapacitors and Batteries for PHEV ESS



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Maxwell TECHNOLOGIES
John Miller
(Hardware Collaborator)

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*Dan Bocci- Ultracap simulations/controls software
Neeraj Shidore- Battery HIL collaboration

This presentation does not contain any proprietary or confidential material

Objective: *Investigate Benefits of Active Combination of Ultracapacitors and Advanced Chemistry Batteries*

- Battery manufacturers generally agree that warranty claims on a PHEV sized battery pack is a major concern. Any technology that can prolong/ensure longer battery life may have more value in that capacity than the cost of that hardware/technology.

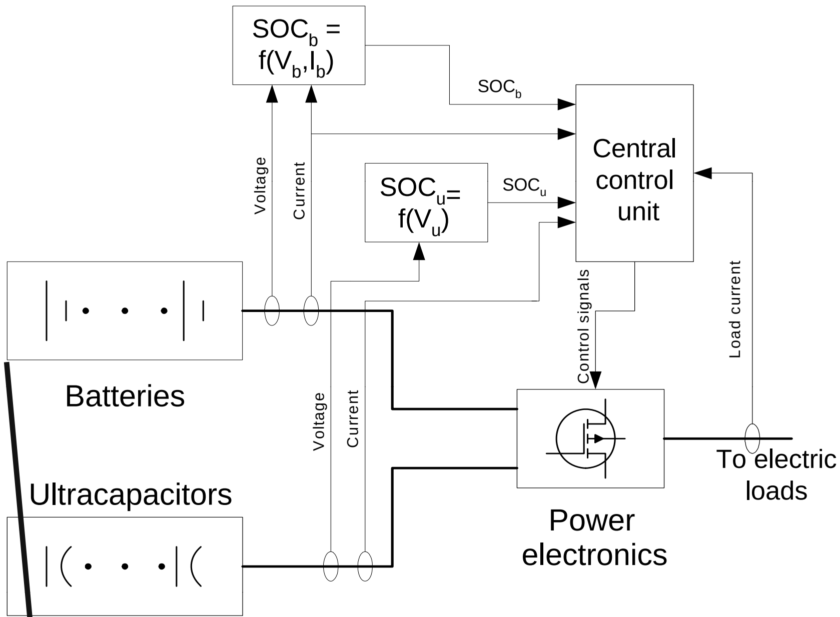
- Component cost and reliability are major concerns of most HEV/PHEV designers. This experiment will investigate the required additional costs of ultracapacitors and electronics as well as the differential benefits of this approach (i.e. apples-to-apples comparison of EES with/without ultracapacitors).

- New SOC control strategies for the ultracapacitor bank need to be developed.

- By limiting peak power delivered by the li-ion battery, especially in cold weather operation where the li-ion battery may be damaged at high loads, the ESS requires less over-sizing, thus saving battery costs.

- The ultracapacitor bank will be sized to absorb/source one regen braking/accel event.

Active Combination of Ultracapacitors With Li-ion Batteries (Phase I Experiment Hardware)



Thermal Chamber

ABC-170 (170kW CAN controlled power supply {power electronics})

Ultracapacitor/Battery Experiment Hardware

Virtual Vehicle

dSpace Autobox Central Control Unit

Maxwell 650F (8 x 2.7v ea.)

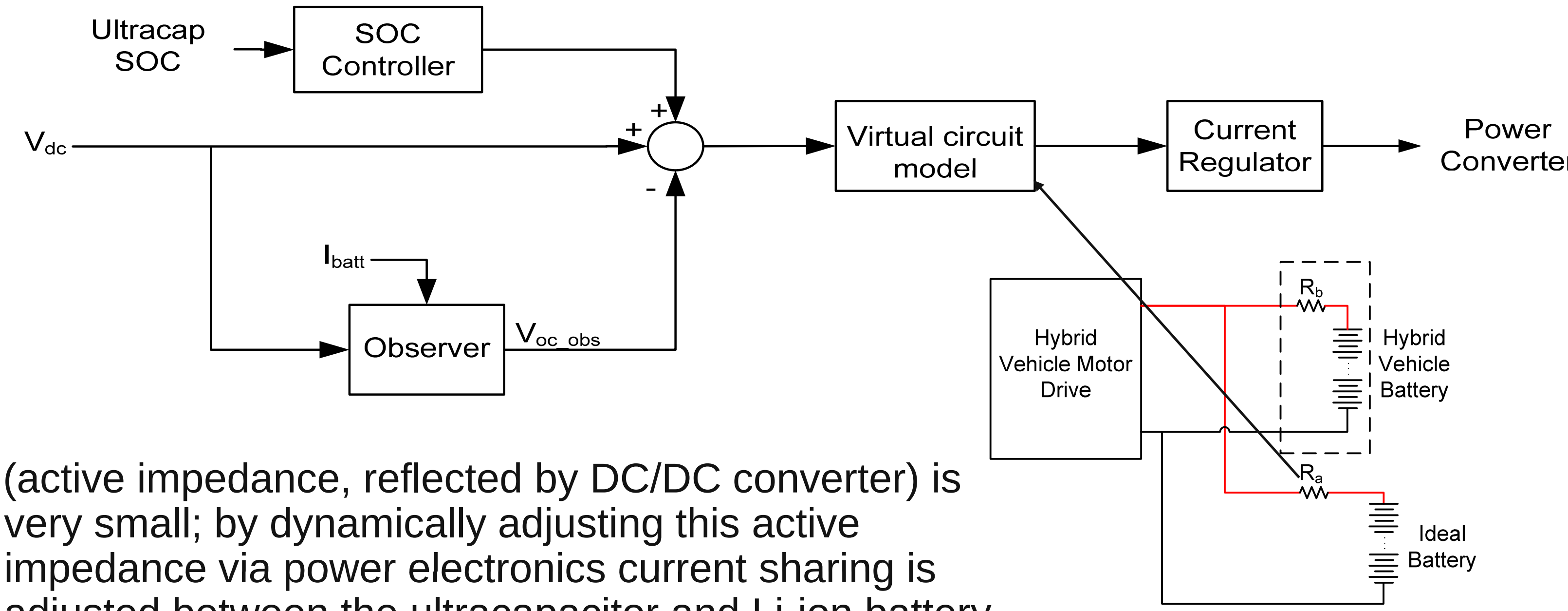
Dewalt/A123 Li-ion Battery Pack, 36v, 2.6ahr

Accomplishments to Date

FY08 Budget: \$200k Spend \$20k to date

- Discussions with Maxwell Technologies about collaboration started in Spring 2007.
- Feasibility studies and preliminary component/circuit level simulation performed in June 2007.
- Capacitor hardware donated to ANL July 2007. Small capacitor bank assembled.
- Dewalt 36v cordless tool pack purchased. Battery and charger/BMS characterized.

Key Technology Improvement:
Current Regulator Virtual Electrical Model Topology



R_a (active impedance, reflected by DC/DC converter) is very small; by dynamically adjusting this active impedance via power electronics current sharing is adjusted between the ultracapacitor and Li-ion battery

FY08 Work Plan

• Gather information on cost of power electronics in high volume for DC/DC converters. Study cost of magnetics components in particular.

Exposed Prius Inductor

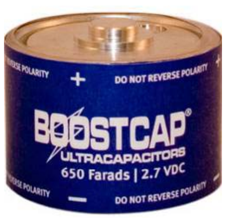
• Complete experiment controls software, refine current regulator.

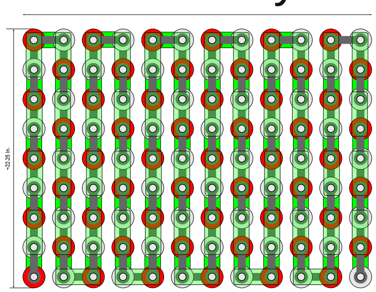
• Complete assembly of full sized ultracapacitor bank (~112 cells), ~24” x 24” x 3”

• Study leakage inductance issues with long series string of capacitors, especially control response (inductance slows rate of change of current). Implement revised buswork to minimize leakage inductance

• Test actively coupled ultracapacitor bank with VL41M Li-ion battery on HIL stand.

• Attach ultracapacitor experiment hardware to VL41M battery in ANL PHEV Prototype vehicle. Run on chassis dynamometer.

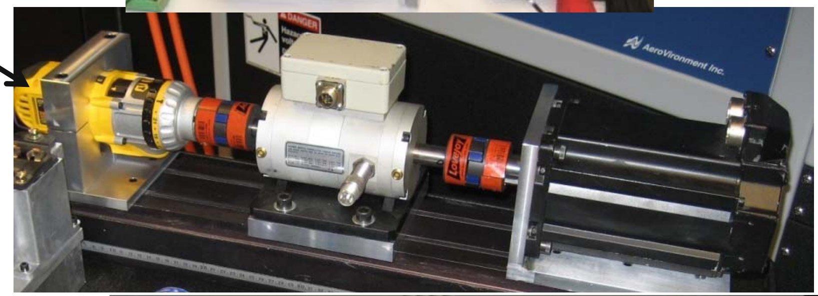


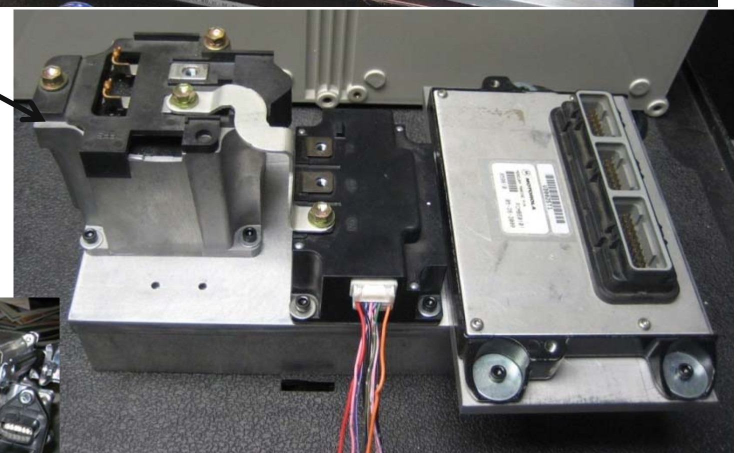


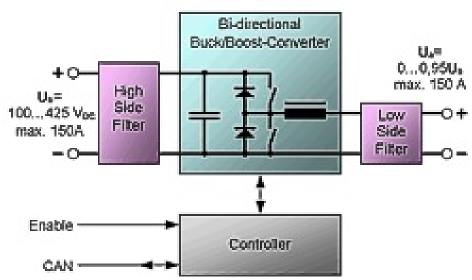
108 x 650F Ultracap, Camry 30kW DC/DC converter

FY08 Work Plan- Progressively Higher Power Experiments

1. 1kW power level, emulated load/power electronics, using Prius current profile UDDS{<100A}, voltage scaled; 1/6th
2. 1kW power level, physical motor loads- 1kW Dewalt motor, battery, torque sensor, servo load motor
3. 36v boost converter, based on Prius electronics (21kW max)
4. Camry boost converter based (30kW)
5. Fully capable, commercially available, CAN based 60kW DC/DC converter







FY08 Accomplishments to Date: ESS Model Assumptions, Results

- Ultracap Model: Maxwell equivalent circuit model, 100 series 650F modules
- Battery Model: Johnson Controls-SAFT VL41M li-ion model
- Power Converter: (ideal) Power in = Power out
- Battery Current Profile : ANL Prius data, US06 drive cycle, stock NiMH battery, 20C

Results:

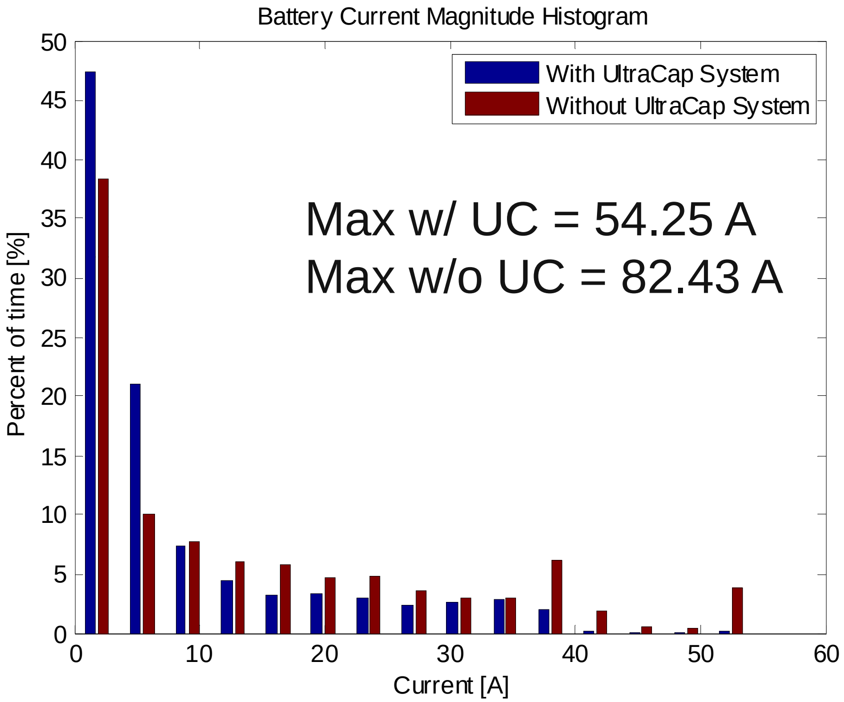
Ahrs
- Batt = -0.6732
- Cap = 0.5741
- Cycle = -0.0991

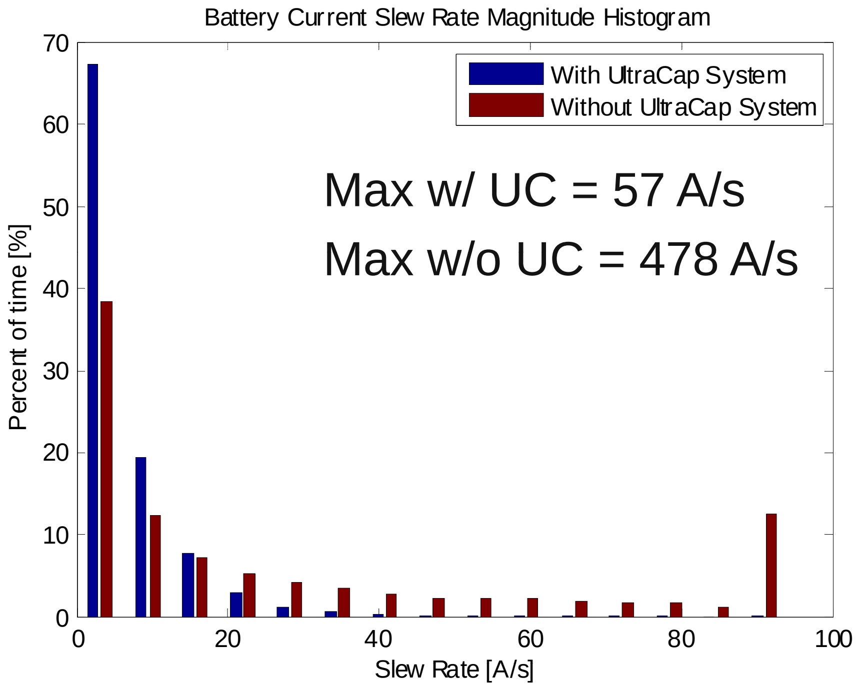
Watt Hours
- Batt = -194.368
- Cap = 161.677
- Cycle = 32.69

Ultracap SOC
- Min = 26.1 %
- Max = 74.4 %

Ultracap Current
- Min = -104 A (into caps)
- Max = 97.4 A (out of caps)

Ultracap Power
- Min = -22.2 kW (into caps)
- Max = 19.5 kW (out of caps)





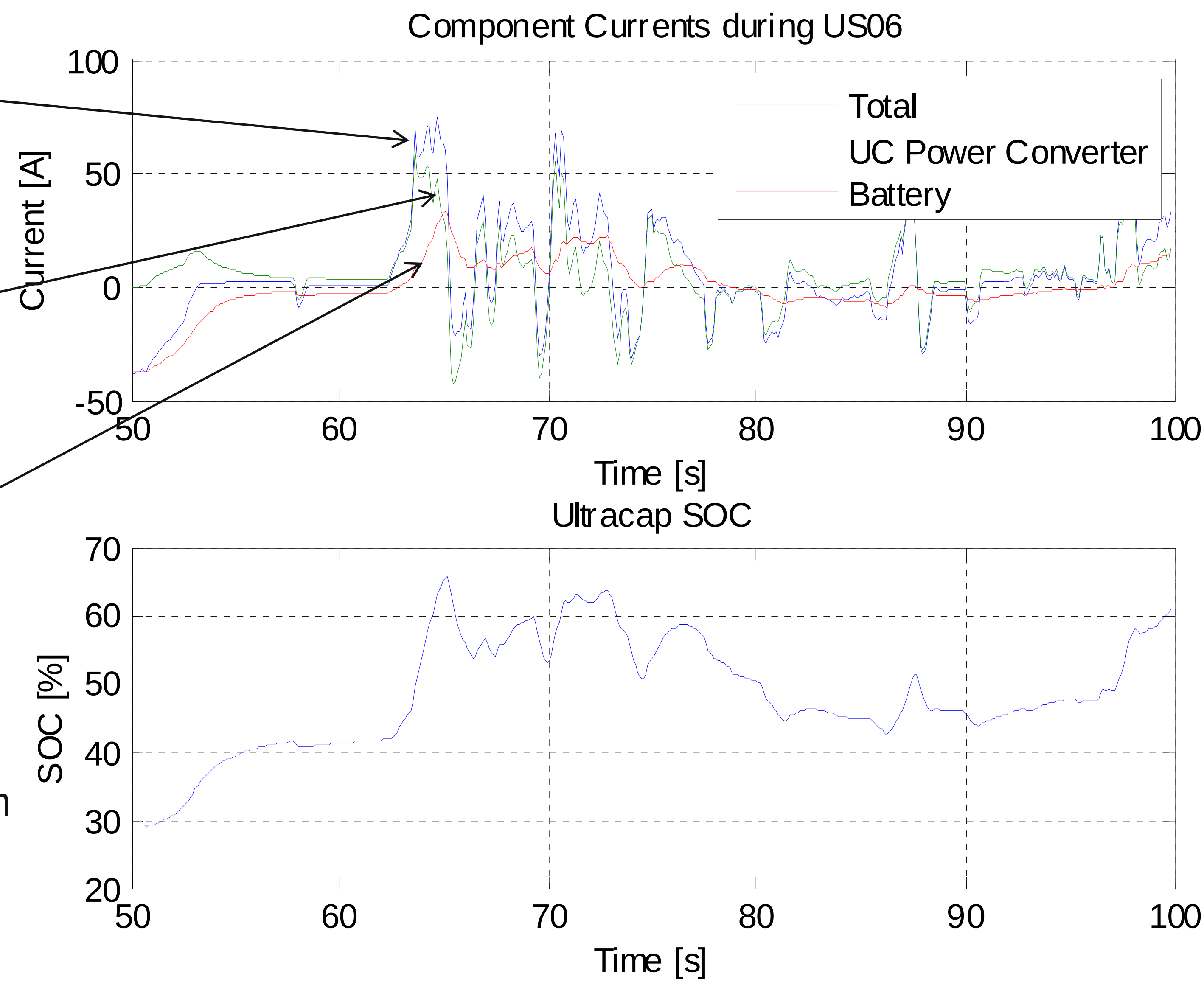
Currents vs Time, Net Change in Battery Current

Blue line is road load (battery current w/o ultracaps)

Green line is U-cap current (dynamic)

Red line is new battery current- more averaged.

SOC is maintained over this 'real world' Prius current trace, on US06 segment



Support of Other DOE Programs

Energy Storage Tech Team

-Battery performance/reliability improvement study
-Explore other batteries best matched with U-Caps

EE Tech Team

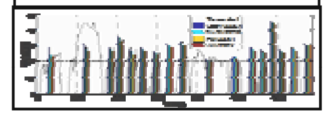
-Power electronics component costs
-Control bandwidth algorithms for SOC/tracking
-Cost of embedded controls/processors

PHEV Development Platform

Ultracap Studies

-Cold weather/battery limitations
-Cost reduction challenges
-Charge-efficiency assumptions/studies

Battery HIL



PSAT at ANL

- Vehicle level simulations and component validation/sizing

Future Work:

- Active combination of ultracapacitors with batteries for PHEV applications is a multi-year program.

- Studies and experiments for power electronics components size and cost reduction as well as lower-cost controller hardware are planned for the future.

- This work will leverage interest from OEM's, DOE EE-Tech Team & ES-Tech Team.

Papers / Presentations:

- Advanced Capacitor World Summit; July 2007 *"Battery HIL and Decoupling Battery Load Transients With Ultracapacitor Storage"*
- *SAE Hybrid Symposium, San Diego, CA Feb 14, 2008; "Ultracapacitor Energy Storage Methods for PHEVs"*
- SAE Paper 2008-01-1003, "*Dc-dc Converter Buffered Ultracapacitor in Active Parallel Combination with Lithium Battery for Plug-in Hybrid Electric Vehicle Energy Storage*"
- *IEEE Vehicle Propulsion and Powertrain Conference, Harbin China, Sept 2008,* "Dc-dc Converter Actively Cou pled Ultracapacitor-Lithium Battery for Plug-in Hybrid Electric Vehicle Energy Storage"