Power Electronics Architecture R&D

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2013 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

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Project ID: APE056

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Overview

Timeline

- Start – FY13
- Finish – FY15
- 22% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY13: $ 375K

Barriers

- Boost ratio/range and efficiency that can drive dc-dc converter architectural choices,
- Potential cost addition due to choice of dc-dc converter and hybrid energy storage systems

Targets Addressed

- Traction Drive Power Electronics DOE 2020 targets
  - Power density: >13.4 kW/l
  - Specific power: >14.1 kW/kg
  - Service life: >15 years or 13000 hours

Partners

- ORNL - Burak Ozpineci, Bradley Brown, Jianlin Li, Lixin Tang, Tim Burress, Madhu Chinthavali, Cliff White, Larry Seiber, Steven Campbell

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Project Objective

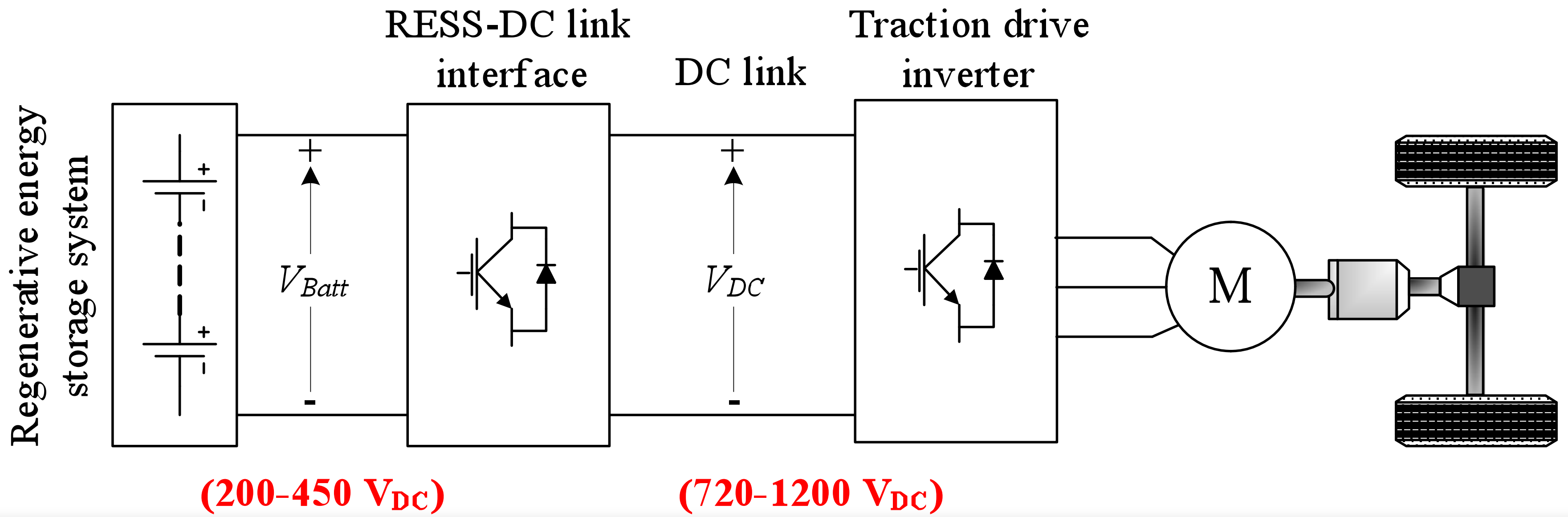
- **Overall Objective**
  - Develop a bi-directional buck/boost dc-dc converter between the regenerative energy storage systems (RESS) and the dc link (traction drive inverter),
    - Active energy management, inverter efficiency improvement, better RESS utilization.
  - Design a hybrid battery/ultra-capacitor energy storage system architecture,
    - Improved regenerative braking performance, improved overall fuel economy (all-electric range), improved power density, peak power capability, and improved battery lifetime.
  - Design a modular reconfigurable battery and dc-dc converter architecture,
    - Lower overall power electronics kVA rating and cost reduction on dc-dc converter.
- **FY13 Objective**
  - Model, simulate, and analyze a modular reconfigurable dc-dc converter architecture.

Milestones

Date	Milestones and Go/No-Go Decisions	Status
April 2013	Milestone: Model and simulate the modular reconfigurable dc-dc converter structures that are best utilized to meet the vehicle power demand.	On track
August 2013	Milestone: Model and simulate various hybrid RESS architectures.	On track
August 2013	Go/No-Go decision: *CHANGE if simulation results show that hybrid RESS approach outperforms the reconfigurable and modular RESS battery approach.*	
September 2013	Milestone: Prepare a summary report that documents the results, findings, performance comparisons, and recommendations to be incorporated into the annual VTO report.	On track

Approach/Strategy

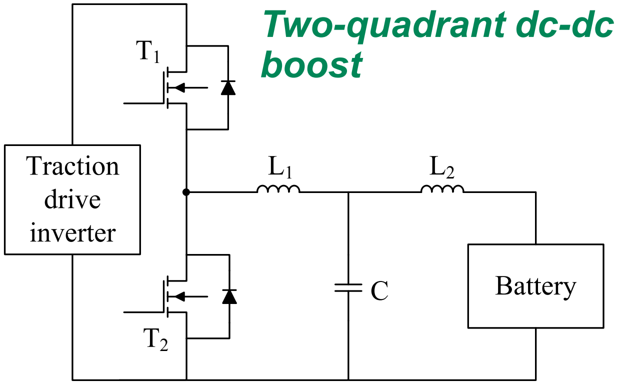
- Current State-of-the-art Traction Drive System
  - Single battery pack utilized regardless of the power demand,
  - Single energy storage system (batteries) → Coupled power and energy requirement,
  - Regenerative Energy Storage System (RESS) - Motor drive inverter interface converter High inverter current → Lower efficiency
- Future traction drive system layout



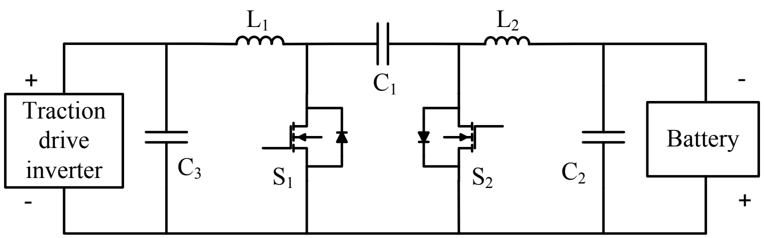
Approach/Strategy

- **Develop bidirectional dc-dc converter architectures:**
  - Dual active bridge dc-dc converter,
  - Two-quadrant dc-dc buck-boost converter,
  - Resonant/improved dual active bridge converter,
  - Single stage dual active half-bridge dc-dc converter,
  - Current boosted active clamp forward dc-dc converter,
  - Bi-directional four switch buck-boost dc-dc converter,
  - Bi-directional dc-dc CUK converter,
  - Integrated buck/boost converter,
  - Multi-phase interleaved ZVS dc-dc converter.

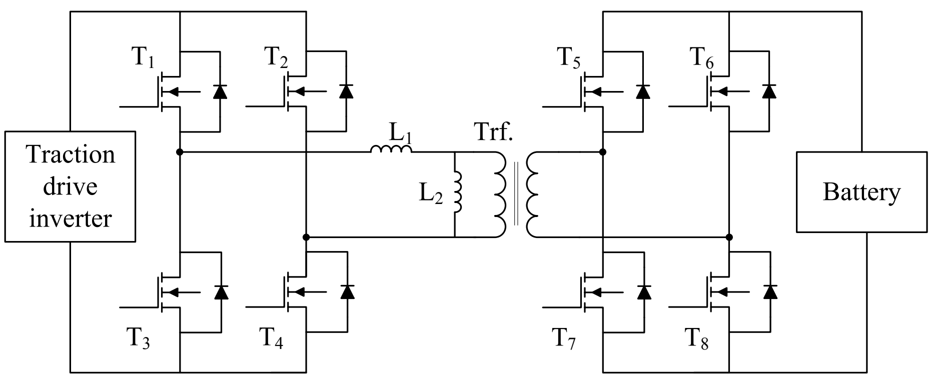
Two-quadrant dc-dc buck-boost

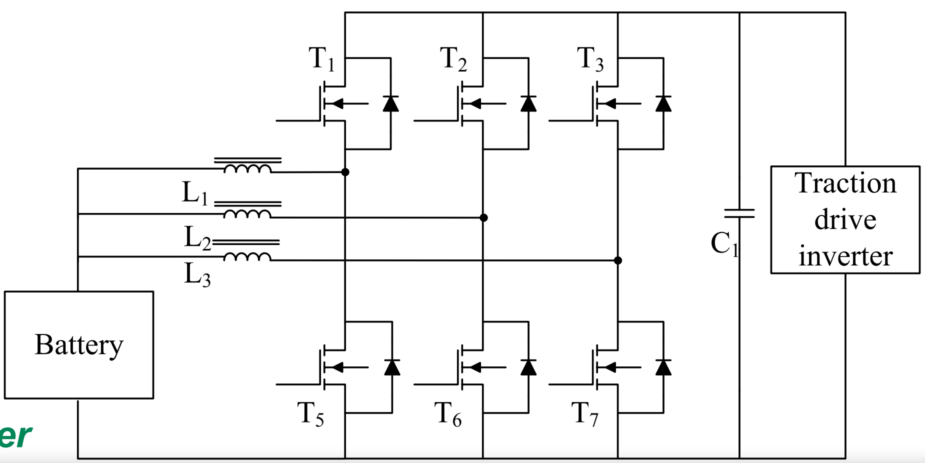


Bi-directional CUK



Dual active-bridge dc-dc converter



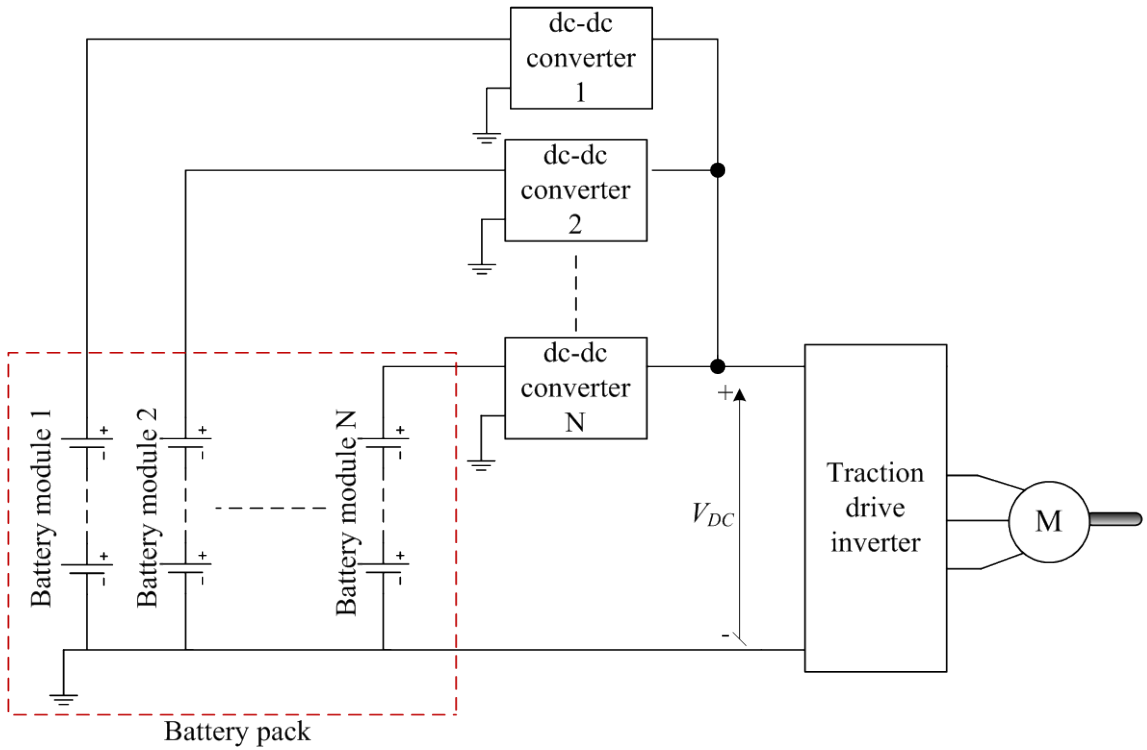


Interleaved 3-phase dc-dc converter

Approach/Strategy (Cont'd)

- **Develop control systems for active energy management that have potential for cost reduction and efficiency improvement.**

- **The RESS and modular dc-dc converters will be best utilized to meet the vehicle power demand.**
- **Utilize wide bandgap devices,**
- **Design for lower overall kVA rating and cost,**
- **Improved service life,**
- **Reduce the thermal management burden.**



Modular reconfigurable RESS and dc-dc converters

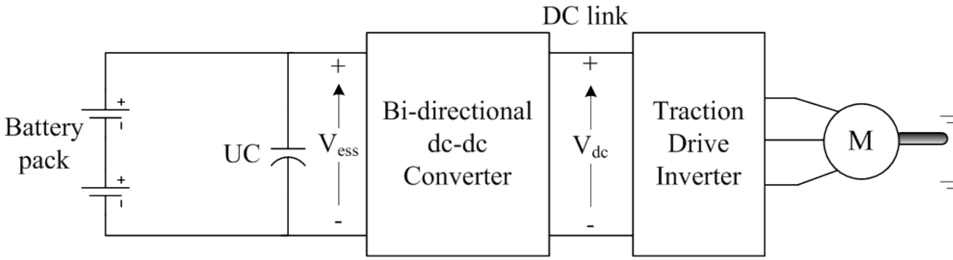
Technical Accomplishments and Progress – Overall

- Reviewed and modeled bi-directional dc-dc converter architectures that interface the RESS to the traction drive inverter and created a summary report discussing on the operation principles, controls, advantages and drawbacks.
- Reviewed and modeled hybrid RESS architectures and created a summary report based on the advantages, drawbacks, control systems, performance, number of parts, etc.
- Selected and modeled four battery/UC hybridization strategies.
  - Built simulation models of the battery and UC.
  - Modeled hybridization architectures.
  - Due to simulation time constraints, a portion of the UDDS drive cycle, t=[690, 760] that includes acceleration, braking, and idling simulated for these hybridization architectures.
  - Collected and compared simulation results.
  - Created a comparison results table for these RESS hybridization architectures.

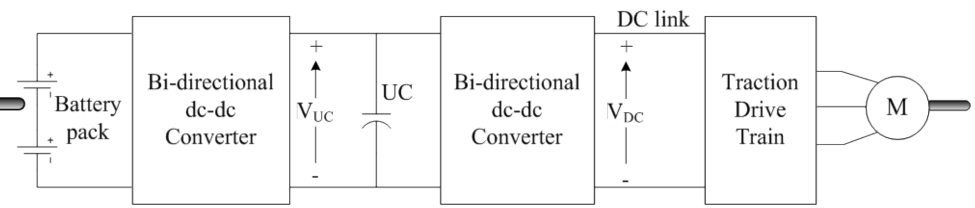
Technical Accomplishments and Progress

- **Developed power electronic interfaces for hybrid RESS:**
  - **Decoupled energy and power: battery/ultra-capacitor (UC)**
  - **Active power and energy management based on the drive train power demand**

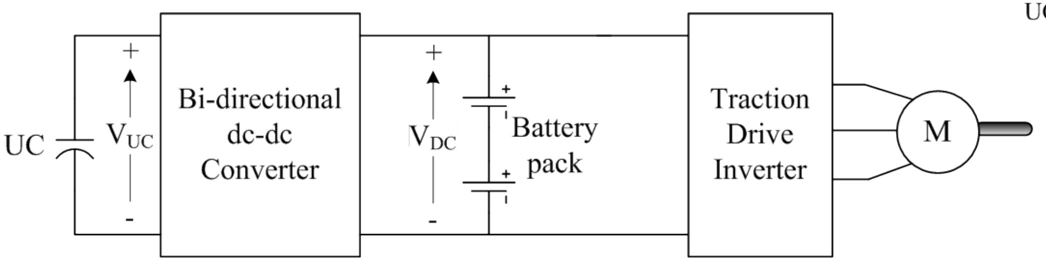
Passive Parallel Architecture (PPA)



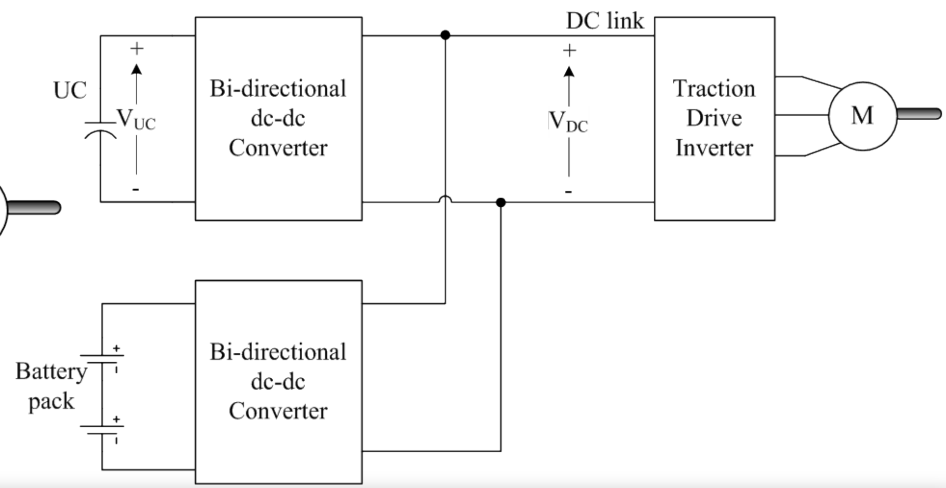
Cascaded Converters Architecture (CCA)



UC – dc-dc Converter – Battery Architecture (UCDCBA)

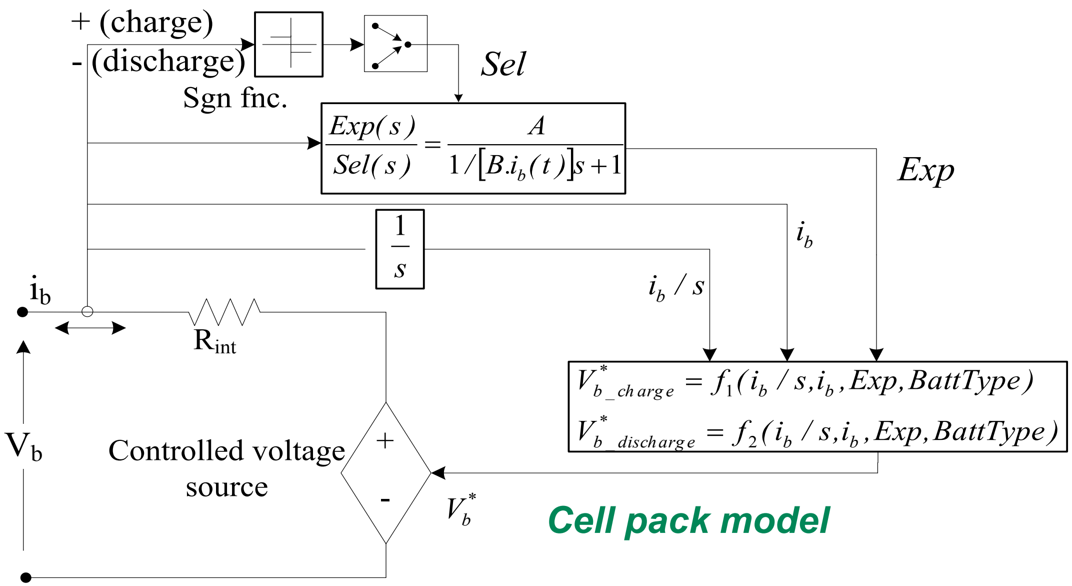


Parallel with Multi-Converters Architecture (PMCA)

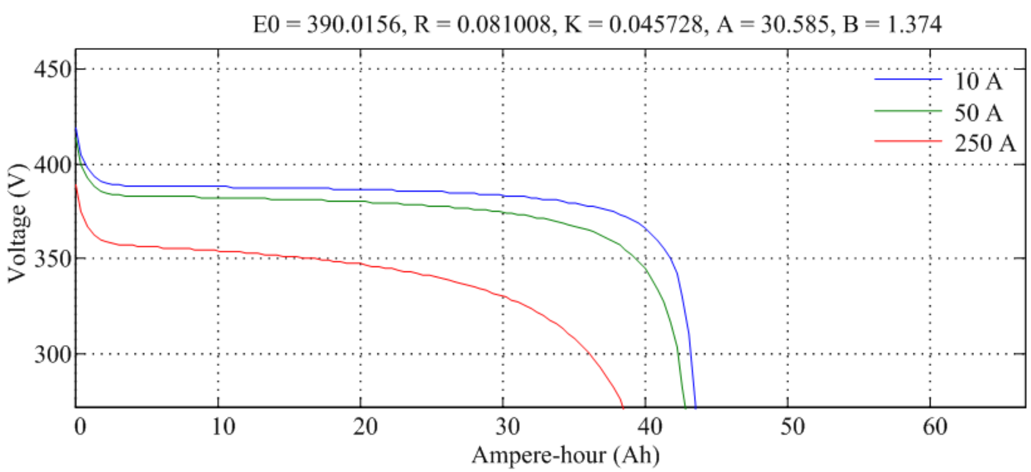


Technical Accomplishments and Progress

- **Implemented a cell pack model needed in dynamic system simulations**



Cell pack model

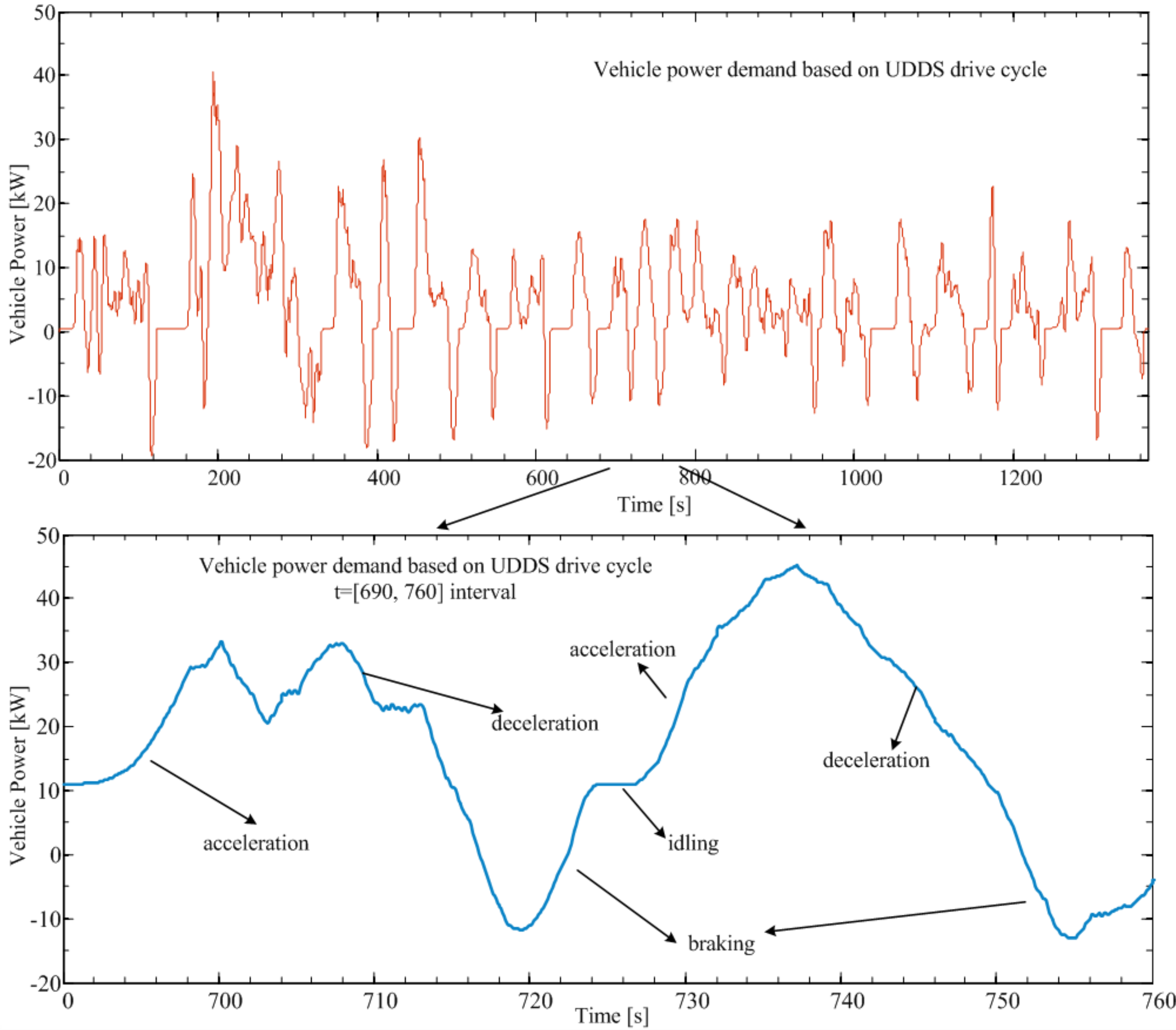


Example discharge curves

- **Utilized the governing charge and discharge equations of the model**
- **A controlled voltage source was used (current controlled voltage source to represent V=f(I) cell characteristics)**
- **Voltage was calculated with a non-linear equation based on the state-of-charge (SOC) of the cell; V=f(I,SOC)**
- Reference: O. Tremblay and L. –A. Dessaint, “Experimental Validation of a Battery Dynamic Model for EV Applications,” *World Electric Vehicle Journal*, vol. 3, May 13 - 16, 2009.

Technical Accomplishments and Progress

- **Completed simulations for the passive parallel, cascaded, modified cascaded, and the multiple parallel converters architectures under same conditions.**
- **Due to simulation time constraints, a portion of the UDDS drive cycle, t=[690, 760] that includes acceleration, braking, and idling simulated for these hybridization architectures.**

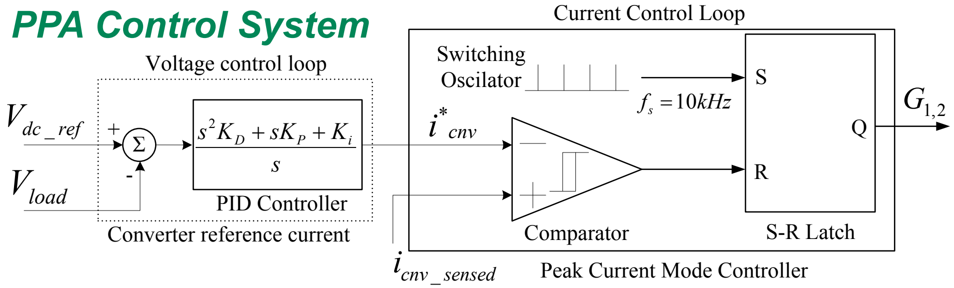


UDDS drive cycle power demand

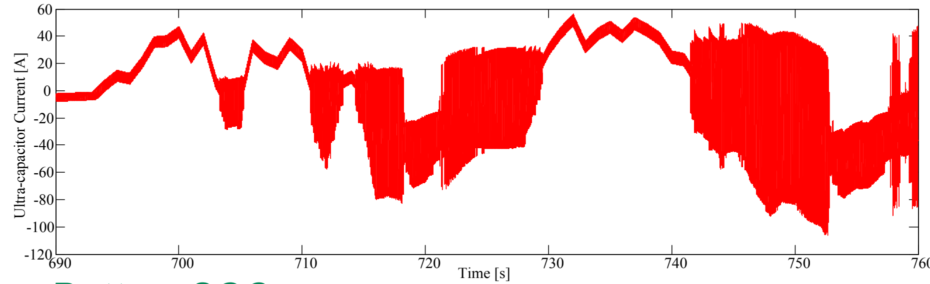
Technical Accomplishments and Progress

- **Completed PPA (Passive Parallel Architecture) Simulations**

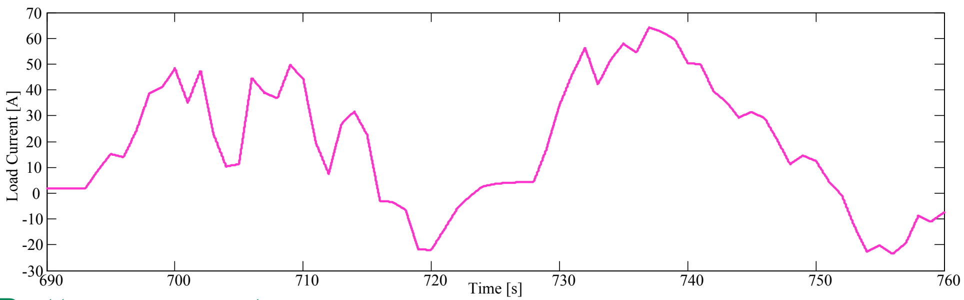
PPA Control System



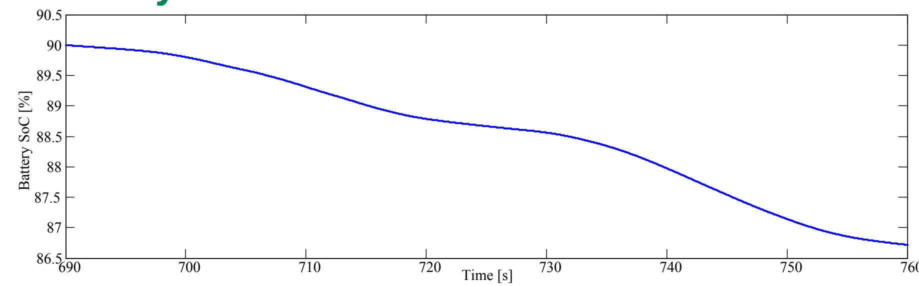
UC current



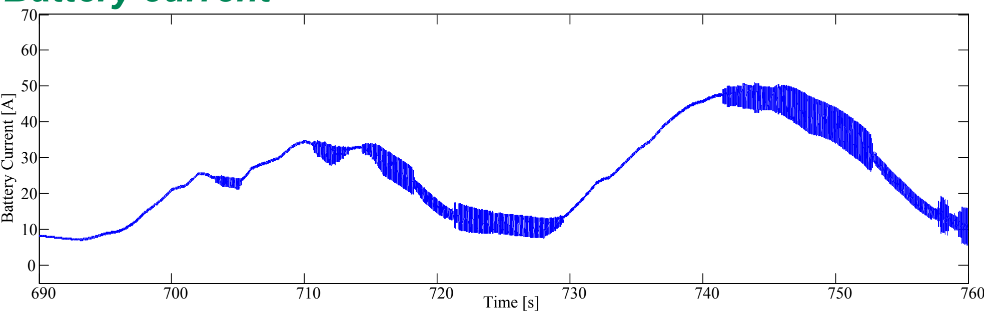
Load current



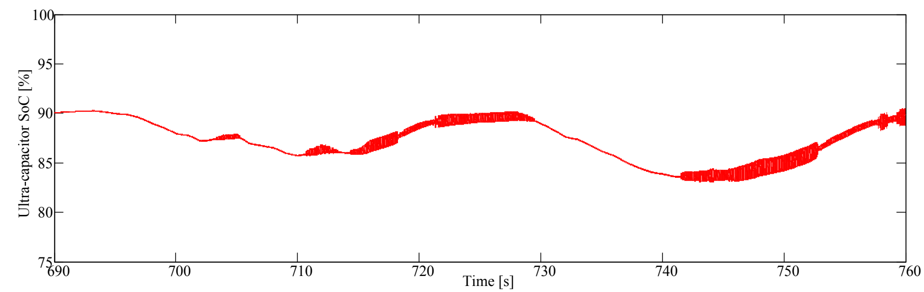
Battery SOC

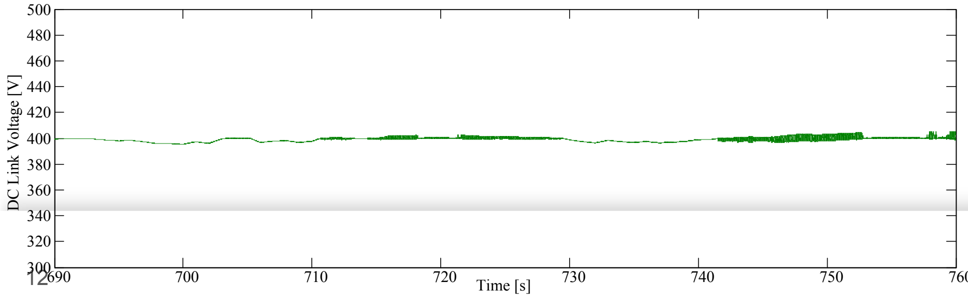


Battery current



UC SOC



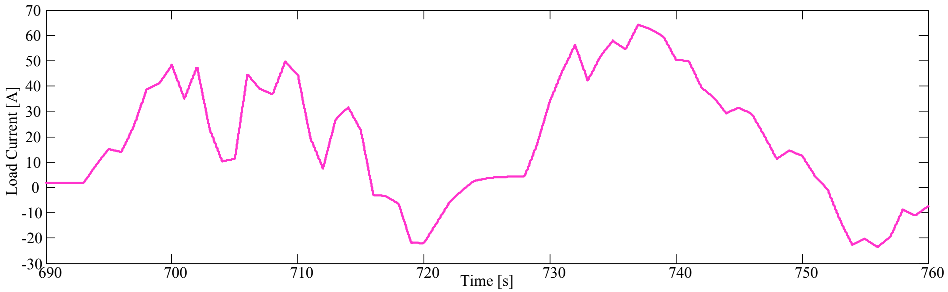


DC link voltage

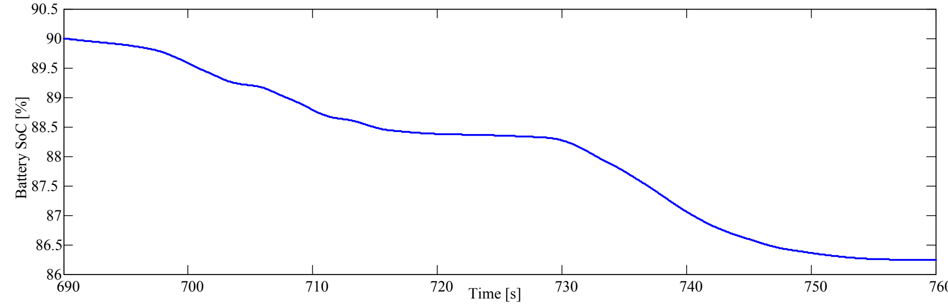
Technical Accomplishments and Progress

- **Completed CCA (Cascaded Converters Architecture) Simulations**

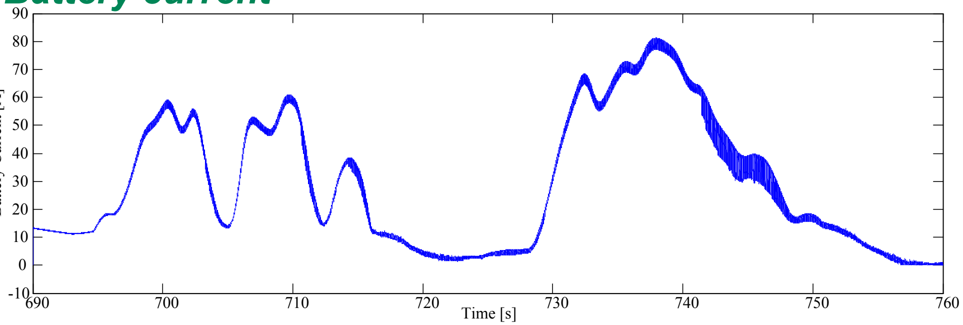
Load current



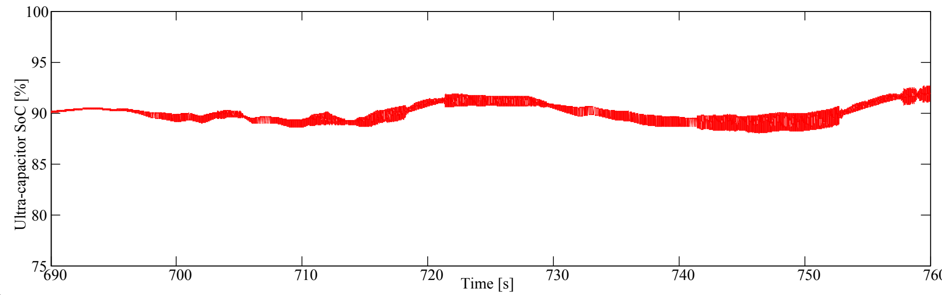
Battery SOC



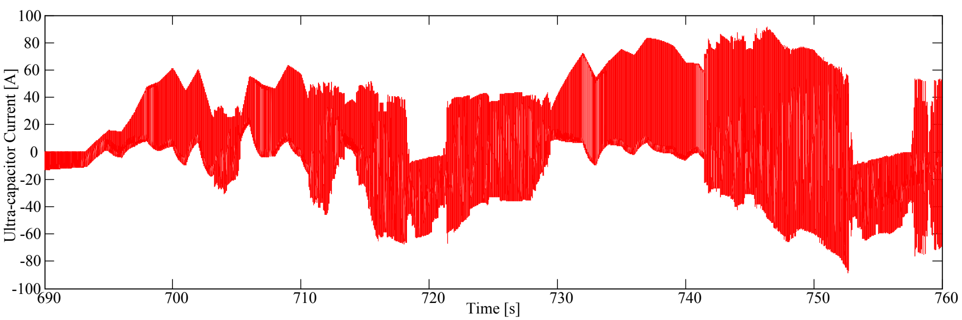
Battery current



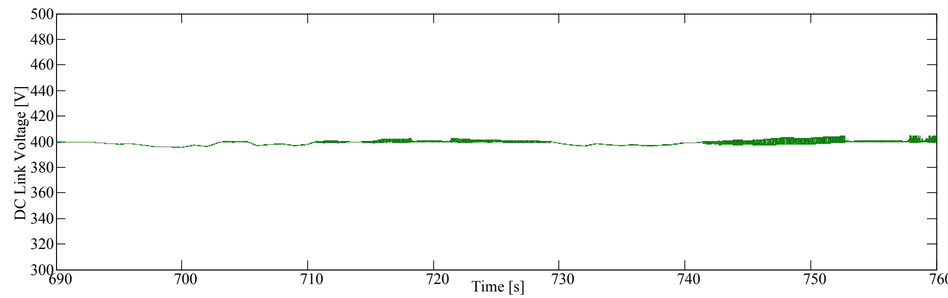
UC SOC



UC current



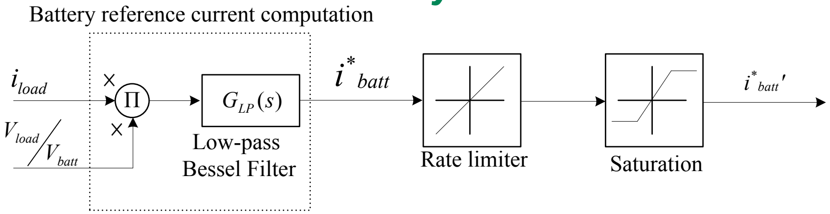
DC link voltage



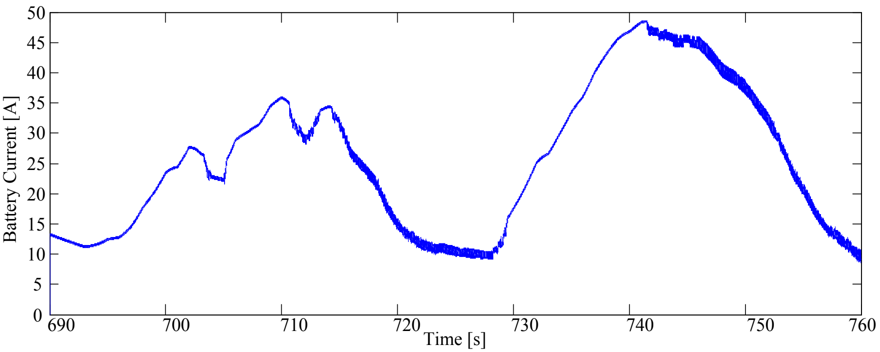
Technical Accomplishments and Progress

- **Completed CCA (Cascaded Converters Architecture) Simulations with modified controls**

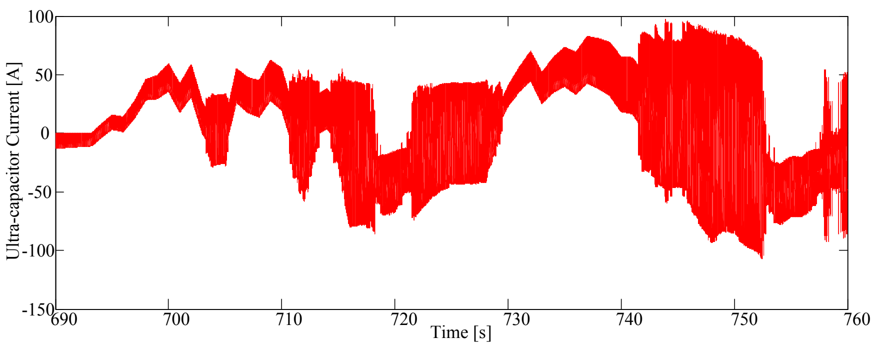
CCA Modified Control System



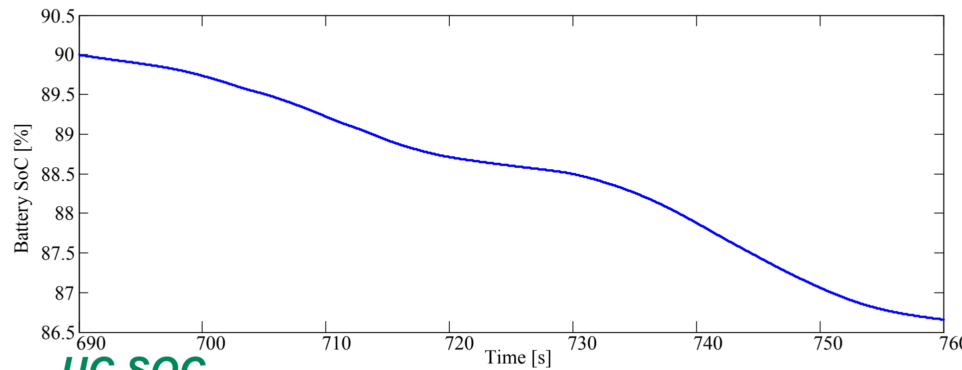
Battery current



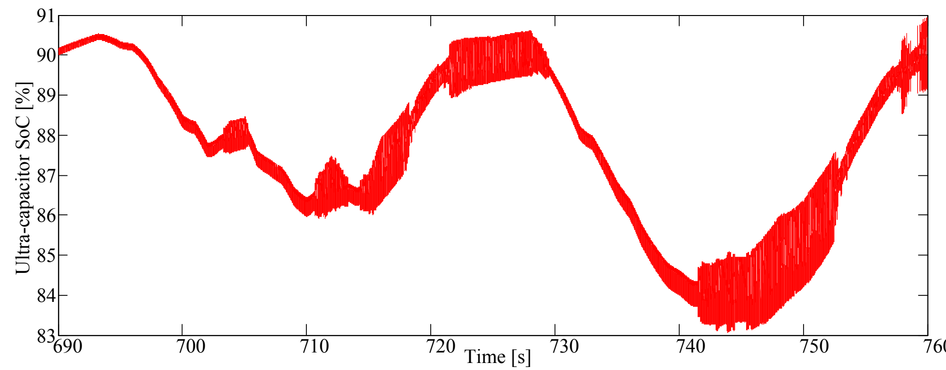
UC current



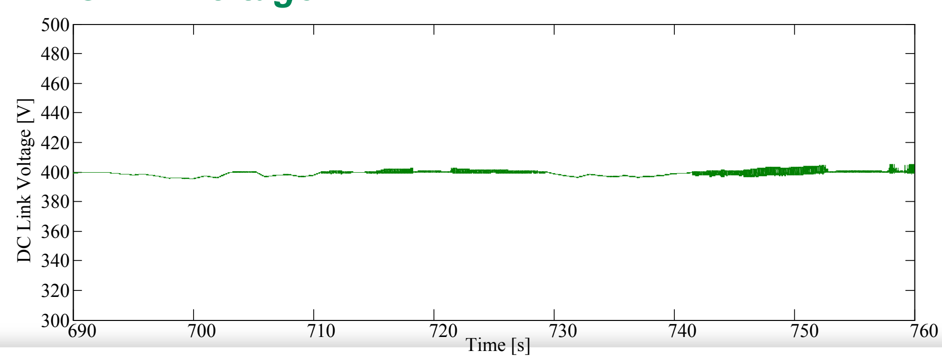
Battery SOC



UC SOC



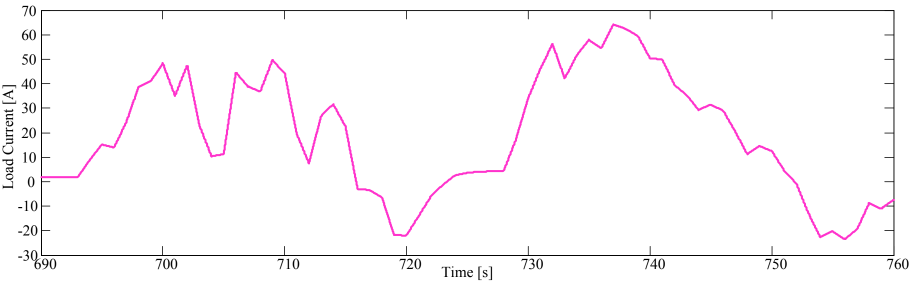
DC link voltage



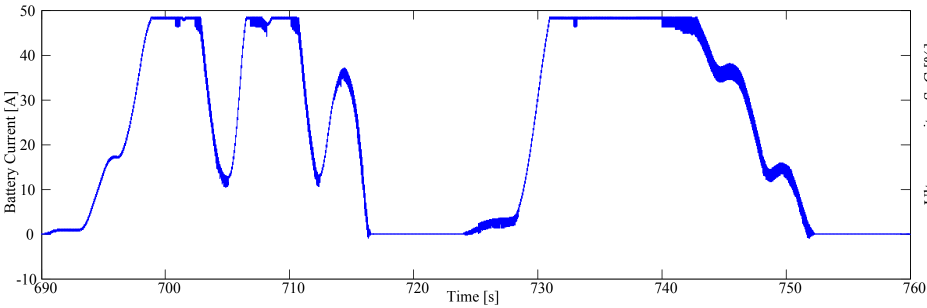
Technical Accomplishments and Progress

- **Completed MPCA (Multiple Parallel Converters Architecture) Simulations**

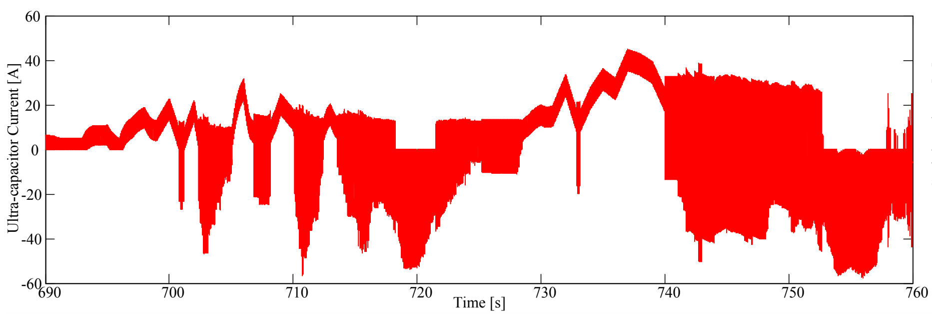
Load current



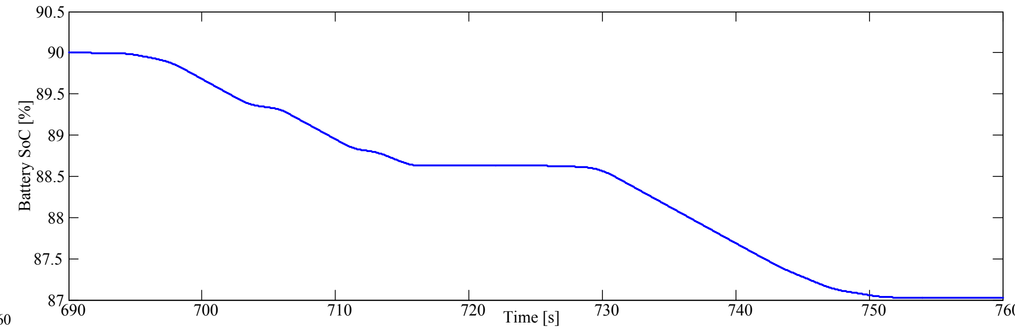
Battery current



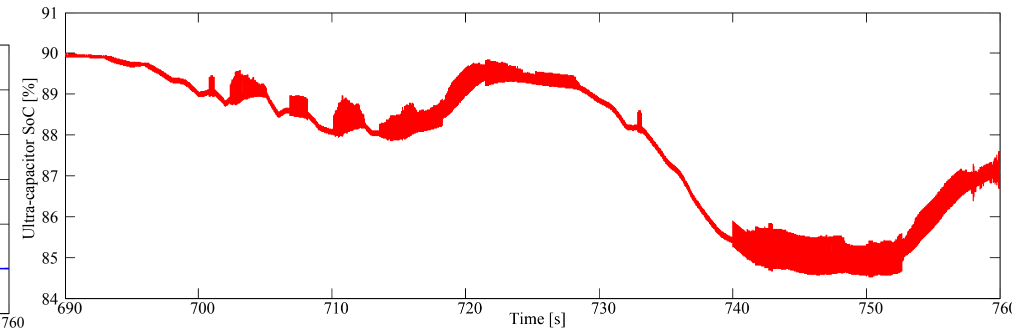
UC current



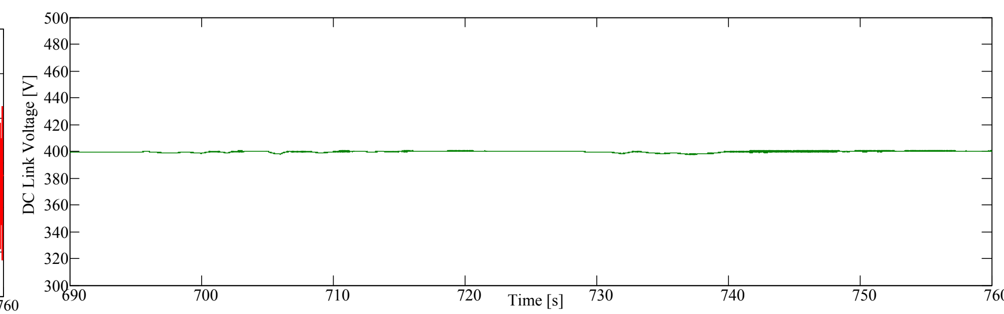
Battery SOC



UC SOC



DC link voltage



Technical Accomplishments and Progress (Cont'd)

- **Created Results Table**

Criteria	Passive Parallel (PPA)	Cascaded Converters (CCA)	Cascaded (manipulated controls) (CCA)	Parallel Converters (MPCA)
Control simplicity	1	2	3	3
Structure complexity	1	2	2	2
Number of converters	1	2	2	2
Number of inductors	1	2	2	2
Total inductor mass	2	3	3	2
Number of transducers	5	6	6	6
Cycle-end battery SoC	86.7194%	86.2462%	86.6598%	87.0305%
Cycle-end ultra-capacitor SoC	89.8995%	91.9084%	90.4502%	87.1022%
Maximum battery current ripple	~7 [A]	~9 [A]	~1.7 [A]	~1.8 [A]
Cycle based energy efficiency (RESS and dc-dc converters combined)	95.25%	90.34%	90.72%	95.25%
Maximum DC link voltage variation percentage	2.52%	2.42%	2.51%	0.77%

Conclusions

- According to the simulation results, PPA has the simplest structure and the least number of parts and components.
- The high efficiency of PPA is mainly due to the simple configuration and to the fact that there is no additional dc-dc converters used for hybrid RESS.
- Although PPA has high efficiency, it does not provide control flexibility and the battery current ripple and DC link voltage ripple values are not as good as MPC architecture.
- MPCA provides the highest efficiency (as high as the PPA) and the best DC link voltage and battery current ripples.
- Improving the controls with an additional current rate limiter for the CCA improved the efficiency and the overall performance.
- Efficiency is computed as the cycle based energy efficiency; i.e., the input and output power of the system is integrated over the time period of simulation.

Collaboration and Coordination

Organization	Type of Collaboration/Coordination
Maxwell, IOXUS	Fast response electrochemical capacitor development
Chrysler	Power electronics dc-dc interface trends for RESS
ORNL Energy Storage Program	Design guidelines and research on modular battery pack configuration
ORNL Battery Manufacturing Facility	Manufacturing research on modular battery development

Proposed Future Work

- **Remainder of FY13**
  - Modeling, simulations, and analysis of modular reconfigurable dc-dc converter architectures. Share results with APEEM team members.
- **FY14**
  - Fabricate and test a candidate 10 kW reconfigurable dc-dc converter architecture for experimental validation of models and simulations. Share results with APEEM team members.
- **FY15**
  - Fabricate and test a full rated (55 kW) reconfigurable dc-dc converter architecture. Share results with APEEM team members.

Summary

- **Relevance:** This project is targeted toward active energy management and reduced size and cost of the power electronic converters that interface RESS and traction drive inverter.
- **Approach:**
  - Develop a bi-directional buck/boost dc-dc converter between the regenerative energy storage systems (RESS) and the dc link (traction drive inverter),
  - Design a hybrid battery/ultra-capacitor energy storage system architecture,
  - Design a modular reconfigurable dc-dc converter architecture,
- **Collaborations:** Collaborations with Chrysler, Maxwell, IOXUS, and ORNL's Energy Storage Programs and Battery Manufacturing Facility are being used to maximize the impact of this work.
- **Technical Accomplishments:**
  - Reviewed and modeled bi-directional dc-dc converters.
  - Reviewed and modeled hybrid RESS architectures and created a summary report based on the advantages, drawbacks, control systems, performance, number of parts, etc.
  - Selected and modeled four battery/UC hybridization strategies. Run the simulations and compared the performance results.