Project 4.32: Tools for Optimal Selection of Energy Storage Technology in Electrified Military Vehicles
PI: Onori (Clemson)

Project started: 2017
Estimated end: 2019

Resources / Funded effort:
2017  PI 1 SM, RS 10%, 1 GSRA

key:
PI  Principal Investigator (faculty unless otherwise indicated)
co-PI  co-Principal Investigator (faculty unless otherwise indicated)
FAC  faculty quad member
RS  research scientist
PD  post-doctoral student
GSRA  graduate student research assistant
RA/temp  temporary student assistant (part time)
SM  summer month
AY  9 months basis
CY  calendar year – 12 month basis
Eqpt  equipment (> $5,000 requires executive committee approval)
ote: research supplies and travel are not listed
Project 4.32: Tools for Optimal Selection of Energy Storage Technology in Electrified Military Vehicles

**ARC NEW PROJECT PROPOSAL**

Project 4.32: Tools for Optimal Selection of Energy Storage Technology in Electrified Military Vehicles

**Quad Members:**

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**Project Duration:**

Starting date: 1/1/2017 Estimated duration: 3 years

**Motivation and Background:**

**Summary:** The principal objective of the proposed research is the development of comprehensive set of modeling and statistical tools for the optimal selection of energy storage technology that is most appropriate for the application of interest. This is yet an unexplored research field that has not been fully investigated. Application-specific tactical trucks will experience load requirements that are characterized by different duty cycles, transients, frequencies, temperature, and varying road grade.

In [1], a methodology is proposed to segregate load requirements in a hybrid electric vehicle application with main focus being the investigation of use of a dual-source battery and ultracapacitor pack “in place of the seemingly unattainable (in satisfying cost, power, energy, and reliability requirements) single-battery solution”. Segregating the load requirements allows making an informed decision on the energy storage system that would be best suited to handle the type of load [1].

As military vehicles move towards electrification, the extremely wide spectrum of available technologies (as displayed in Figure 1) shows that the approach of one-energy storage element fits all does not seem to be the optimal one, both in terms of cost, obtainable performance (especially over considerable duration of time) over different environmental conditions. To that end, the aim of this proposal is to systematically address the questions:

- what is the best energy storage technology for the application of interest?
- will a single energy storage system suffice, or is there a need for a hybrid energy storage system? And if so, what is the best solution?

The tools developed through this work will be general enough to be applied, with adequate knowledge of application-specific load profiles, to domains like, robotics, smart grid, and aerospace.

**Background:** Hybridization of military vehicles is a result of the increasing cost of fuel, and the increase in power and energy demand caused due to the advent of newer technologies and weapons in tactical trucks [3]. Hybrid electric technology allows for efficient use of the engine, improving fuel economy and also contributes in saving cost associated with the transportation of fuel to remote war locations [4]. Inclusion of adequate energy storage systems in tactical trucks offers the capability of running Silent Watch missions.
The power demanded in a Silent Watch mission setting ranges from a few kilowatts to tens of kilowatts for varying duration with minimum noise and usually in harsh temperature environment [5]. In addition, for missions being conducted in low temperature regions, the energy storage system should be able to reliably assist with cold starts. The drive cycle and the environmental conditions experienced by various military vehicles will depend on the missions they cater towards. A tactical truck used for cargo or moving heavy equipment will experience a largely different drive cycle than a tactical truck used for Silent Watch missions. In such cases, the optimal electrochemical energy storage system for the two classes of trucks would (or could) be different.

Energy storage technologies like lead acid (PbA), nickel-metal hydride, lithium ion (Li-ion), and ultracapacitors have enabled mild to full hybridization of the powertrain. The spectrum of available energy storage devices is clearly learned from the Ragone plot in Figure 2, where each device is located in the energy density versus power density plane. These energy storage systems are responsible for improving the fuel efficiency by peak shaving during high acceleration, initiating cold starts, regenerative braking, and allowing start-stop functionality, and fulfilling critical mission-related electrical demands. The typical power and energy requirements of tactical trucks, combined with the information on the strengths and weaknesses of the available energy storage systems, will help decide the optimal energy storage system that is best suited to deal with the requested load. Li-ion batteries offer high cycling capability, have high energy density and are better suited to longer duration, medium power events [7]. However, ultracapacitors have low energy density and are better suited for handling short power transients. Alternatively, a hybrid energy storage system combining Li-ion batteries and ultracapacitors will be able to cater to medium power events and short transients equally well.

**Research Objectives:**

The principal objectives of the proposed research are outlined as follows:

- Develop a tool to segregate the load requirements in application-specific drive cycles into peak, intermediate, and steady state loads, along with their respective time duration (short, medium, and long time frames). The driving cycle segregation method will be applied to driving cycles typical of hybrid tactical trucks.
- Define segregation-based coefficients to derive statistics of the peak, intermediate, and steady state loads within the drive cycle.
- Validate first principles model of Li-ion batteries and ultracapacitors (and PbA if this chemistry is of interest for TARDEC) against application-specific duty cycles. The validation will be conducted in the PI’s Battery Aging and Characterization (BAC) laboratory. Physics-based degradation dynamics will
also be included, leveraging the PI's earlier work, to capture the behavior of the battery dynamics with aging within the context of energy storage device optimization.

- Use hybrid tactical trucks vehicle simulator for energy storage systems integration and assessment.
- Based on the information from the driving cycle segregation-based analysis along with the dynamics and aging-oriented knowledge of energy storage systems, simulation of the hybrid tactical truck operating with different combination of energy storage systems (both in a standalone and in a coupled configuration) will be performed with the aim of assessing (and minimizing) energy cost and maximizing fuel economy.

**Approach:**
The approach towards achieving the aforementioned research objectives involves the following steps:

- Perform literature review on various hybrid tactical trucks and their respective application-dependent drive cycles. Seek input from TARDEC for field data, if possible. The load profile holds key to the optimal energy storage systems, as it provides information on the desired maximum acceleration, power assist need during start, presence of auxiliary loads, regenerative braking capability, gradeability and side slope performance.
- Perform load segmentation on the application-dependent drive cycles. Segmentation is carried out on the basis of the ratio of power to energy (P/E), which is related to the event’s time constant. Through segmentation, the loads are separated on the basis of magnitude and duration. Principal Component Analysis or Proper Orthogonal Decomposition (POD) methods can be used to generate the singular value decomposition (SVD) of the segregated cycle. Energy storage system dynamics will be treated along the same way, and snapshots of system response will be recorded and be processed through the same SVD method [5, 6]. Analysis of the overlapping energy system response and driving cycle principal modes will be conducted to seek the energy system that optimally matches the application. Load segmentation of drive cycles can be also performed using an anti-causal, zero-phase digital FIR averaging filter as in [1]. Comparison of the two approaches can be carried out. Segregation-based coefficients will be generated by the SVD-POD analysis to identify the frequency of the loads and the sequence in which the loads appear in the drive cycle. This will provide critical information on the energy density and power density requirement from the hybrid power source.
- During mission-dependent unforeseen scenarios like extreme temperatures, high discharge current and deep depth-of-discharge, first principles battery models can accurately predict the battery response. Physics-based electrochemical-thermal-degradation battery model for Li-ion cells with two different cathode chemistries, lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA), have been identified at the BACH lab by the PI’s team. These models can be further validated using drive cycle data representative of the operation of tactical trucks. From PI’s earlier work, equivalent circuit models for PbA and Supercapacitor, and semi empirical aging models of PbA are available. However, electrochemical based models for PbA and supercapacitor will be developed, identified and validated [10, 11]. Moreover, the methodology developed is general enough to be able to include aging and degradation dynamic considerations within the battery models and so to use capacity fade and power fade as constraints during the optimal selection of an energy storage system for tactical truck vehicle. In collaboration with TARDEC, appropriate duty cycles will be selected to carry out aging experiments for the identification and validation of aging related parameters.
- Hybrid tactical vehicle simulator will be adapted to be able to interface with the spectrum of energy storage device models developed. An extensive simulation-based study will be conducted for various P/E ratios of different combinations of energy storage systems to satisfy the drive cycle demands such that fuel economy is maximized and energy cost minimized.
- Disseminate the results obtained from this project through publications and presentations.
Proposed Timeline:

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<th>Year One Research Tasks and Deliverables</th>
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| Q1 • Literature review and analysis of application-specific duty cycles from TARDEC-provided field data;  
  • Beginning of the thermal testing activity for Li-ion and ultracapacitor. |
| Q2 • Investigation of SVD-POD methods for load segregation;  
  • Development/identification/validation of electrochemical-thermal-based Li-ion and ultracapacitor models. |
| Q3 • Perform load segregation using SVD-POD method;  
  • Development of hybrid tactical vehicle simulator. |
| Q4 • Comparison of load segregation results with the approach given in [1], and identify segregation-based coefficients;  
  • Integrate simulator with electrochemical-thermal-based models and perform simulations. |

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<th>Long-term goals</th>
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| Y2 • Extend the generalized modeling and statistical methodology to include the aging dynamics;  
  • Experimental validation and aging experiments for Li-ion batteries of different cathode chemistries |
| Y3 • Validation of the modeling and statistical methodology with the inclusion of aging constraints |

ARC/TARDEC/Industry Benefits:

1) Interactions with and benefits to other ongoing ARC research

This project aims at investigating a simulation-based methodology for optimally evaluating and selecting energy storage elements for handling the types of loads for which they are best suited. The results of this work can work as an input to Dr. Filipi and Dr. Ivanco’s work on modeling and optimization of electrified propulsion systems.

2) Interactions with and benefits to ongoing TARDEC work

The outcome of this research will provide optimal energy storage solutions for hybridization of tactical trucks that will help drive down energy costs while improving fuel efficiency. Further, this work will provide validated first principles physics-based models to predict the electrochemical response of the battery and ultracapacitor under a mission-driven scenario.

3) Interactions with and benefits to ongoing work at Industry partner

The PI will be collaborating with Boeing Research & Technology for the proposed research. The Letter of Interest from Boeing Research & Technology is attached (filename: 2017_new_Onori_LOI.pdf). We intend to extend the tools developed through this work towards the optimal selection of energy storage systems in the aerospace industry.
Leveraged Funding:
The proposed research builds upon prior experience of the PI on PbA battery characterization and modeling for military and passenger applications, recent work on modeling and estimation of Hybrid Energy Storage System (PbA in parallel with Supercapacitors), and physics-based lithium-ion battery model involving coupled electrochemical-thermal-degradation dynamics. The experimental activity conducted in this project will leverage the PI aging campaign on NMC cells conducted within a project funded by JCI using facilities available at the BACH lab. This project will not be requesting funding for experimental equipment.

Qualifications:
Simona Onori (PI) has been a faculty member at Clemson University since 2013, and prior to that she was a research scientist at The Ohio State University, since 2007. She has been conducting research in the area of energy storage system modeling, simulation, estimation and control with focus on PbA and Li-ion batteries and Supercapacitors. She has co-authored a book on Energy Management Strategies for HEVs, two-book chapters and more than 70 peer-reviewed papers in journals and conferences. She is chair of the IEEE CSS Technical Committee of Automotive Control. She is the recipient of the 2016 Energy Leadership Award in the category Emerging Leader (for the Carolinas), the 2015 Innovision Award (South Carolina), 2012 Lumley Interdisciplinary Research Award by OSU College of Engineering, and the TechColumbus 2011 Outstanding Technology Team.

Anirudh Allam is a PhD candidate in the Automotive Engineering Department who has been researching on li-ion battery electrochemical modeling with emphasis on degradation dynamics. He is the BACH lab manager and responsible for carrying out battery aging and characterization experiments, building experimental setups that account for battery modules in different configurations, hybrid energy storage systems (PbA battery in parallel with a module of Supercapacitors), and developing the power electronics for balancing circuits.

Facilities and Equipment:
Upon joining Clemson University, the PI funded the BACH laboratory which is aimed towards the physics-based model development, optimization, diagnostics, and prognostics of advanced energy storage systems for automotive applications. The BACH laboratory consists of: (1) two Multi-channel Arbin BT2000 Industrial Testing Systems capable of performing real-time battery charging and discharging experiments with accurate programming control and fast data acquisition, (2) a ESPEC BTX-475 Environmental Chamber, (3) five custom Peltier Junctions to replicate extreme environmental conditions to test the effects of temperature on the performance of lithium-ion cells and battery modules, (4) an Electrochemical Impedance Spectroscopy (EIS) machine to measure the internal impedance of electrochemical cells at varying frequencies, (5) a dSPACE Midsize Simulator for real-time Hardware-in-the-Loop testing of powertrain and battery systems, ECU functions and running integration tests, (6) a dSPACE MicroAutoBox for compact and robust rapid prototyping of estimation and control algorithms, (7) a working prototype of Hybrid Energy Storage System (HESS), built by the PI, by connecting six Double Layer Capacitors (DLCs) in parallel with a Lead Acid (PbA) battery. In addition, the PI has established the High Computing Performance Center for Advanced Powertrain that houses five powerful workstations. The center consists of: (1) Two workstations equipped with state-of-the-art Intel Xeon E5-1650 v3 @ 3.5GHz Turbo processors and 32 GB (4X 8 GB) DDR4 DRAM to run computationally expensive physics-based models, (2) Two workstations, dedicated for battery testing activities, which are compatible with the Arbin BT2000 systems and Peltier Junctions, and (3) one workstation hosting the dSPACE ControlDesk and containing an Intel Core i7 4790 @ 3.6GHz processor with 32 GB (4X 8 GB) DDR3 DRAM, dedicated for Hardware-in-the-Loop testing.
Publications from Prior Work closely related to the proposed project:

- Marelli, S. and Onori, S., “Multi-objective supervisory controller for hybrid electric vehicles” in Automotive Air Conditioning - Optimization, Control and Diagnosis, Editors: Zhang, Quansheng, Li, Shengbo, Eben, Deng, Ku, Springer 2016 (this research has been entirely conducted at CU by Onori and her student)
- Arunachalam, H., Battiat, I., Onori, S., "Provability of Macroscale Models of Lithium-ion Cells subject to Degradation from the SEI Layer Growth", Proceeding of the ASME Dynamic Systems and Control Conference, DSCC, Minneapolis, Minnesota, October 12-14, 2016
- S. Onori, A. Manenti, Y. Guezennec, “New PbA battery modeling structure and validation capturing the Peukert effect”, 8th International Conference on Lead-Acid Batteries LABAT, Budapest, 2011

References:


