GETTING THE BEST FROM A BATTERY

UPDATED: JANUARY 30, 2017

PROJECT TITLE: Control Enabling Solutions with Ultrathin Strain and Temperature Sensor System for Reduced Battery Life Cycle Cost

PROGRAM: Advanced Management and Protection of Energy Storage Devices (AMPED)

AWARD: $3,128,285

PROJECT TEAM: GE Global Research (Lead), University of Michigan, Ford Motor Company

PROJECT TERM: January 2013 – December 2016

PRINCIPAL INVESTIGATOR (PI): Dr. Aaron Knobloch

TECHNICAL CHALLENGE

The performance and cost per kilowatt hours (kWh) of batteries for electric vehicles (EV) has improved significantly in recent years, and cell-level energy density continues to increase, but we do not reap the full benefit of these advances at the vehicle level because today's battery management systems (BMS) apply conservative operating limits that do not allow the full amount of a battery's energy to be accessed. In fact, the battery packs used in today's xEVs are typically 1.25-2 times larger than would be required to power that vehicle if the full capability of the battery chemistry could be accessed. Developing new approaches to battery management that can safely and reliably access more of the stored energy contained in the cells is a key technological challenge for battery systems.

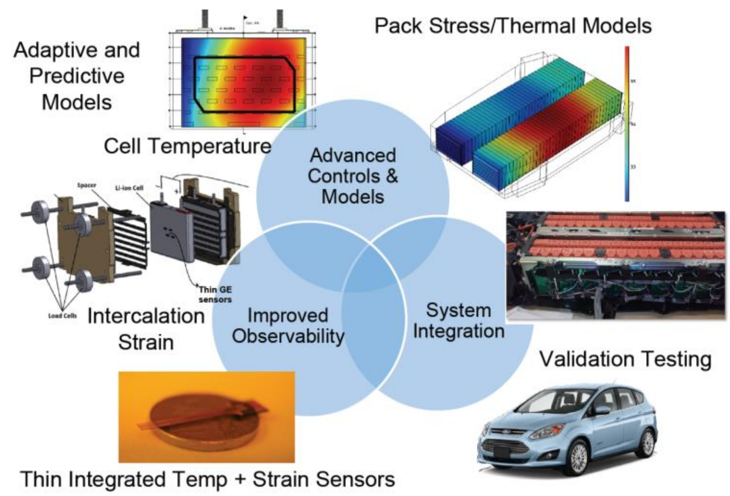
TECHNICAL OPPORTUNITY

With recent advances in industrial processes and vehicle on-board processing capability, there are two immediate opportunities for enhancing battery management and control. The first is employing sensor technologies that directly probe physical parameters, such as the distribution of temperature and strain across the battery, enabling more informed active and dynamic battery management. Low cost, low-profile sensors are now possible through flexible packaging expertise developed for state-of-the-art, high-volume manufacturing processes used in consumer electronics, integrated circuit (IC) packaging, and miniaturized electronics in healthcare imaging. The second opportunity is leveraging the growing on-board processing capabilities of vehicle control systems to run battery management schemes with control algorithms that can respond dynamically to the sensor information. When more state-relevant information can be measured and battery system developers can utilize real-time models, energy storage systems will realize sizable gains in battery performance. Such opportunities require teams, which bring together experts in sensors, multi-physics modeling and battery system integration.

INNOVATION DEMONSTRATION

The goal of the GE led research team, in partnership with University of Michigan, and the Ford Motor Company, was to develop a smart, cost effective sensing system that significantly increases the utilization of stored energy in battery packs while maintaining or improving upon system lifetime for vehicle applications. The team addressed three technical challenges – 1) an ultrathin sensor array capable of measuring cell strain and surface temperature across multiple cells within a battery pack, 2) reduced order modeling for real-time computation and observability analysis for a minimum number of sensors, and 3) sensor-pack integration and system evaluation of sensors and adaptive battery control. The elements of the team's innovative approach are illustrated in Figure 1.

Figure 1: Fusing Physics-Based Models & Sensor Data



The team evaluated different polymer substrates and different deposited metals for the sensors, with the goal of reducing thickness 20 times compared with state-of-the-art battery system sensors, which are typically 2-3 mm thick. The resulting co-located strain and temperature sensor array is under 100 μm thick, enabling the sensor array to be placed between the battery cells within the pack. The sensors achieved accuracy to <0.1 C and <0.1 mm in displacement.

The University of Michigan team developed reduced order physics-based models to utilize the information from the GE sensor array, extracting the thermal and stress features to be used in a new type of battery control algorithm. Predicting the swelling of the entire cell as it charges and discharges in an operating vehicle environment would normally be too computationally intensive for practical use. The team overcame that challenge through observability analysis and estimation techniques that span many physical scales from the electrode level phenomena (5 μm, 50 msec) to the cell level (10 cm, 1 sec), to the pack at the vehicle level (1.0 m, 5 sec). To quantify cell swelling, the team developed innovative experimental methods and specialized laboratory fixtures that measure the battery free and constrained swelling along with its thermal behavior.

The sensor data, paired with a simplified, reduced order physics-based model, are utilized in real time to optimize pack performance under operation, and make predictions on the state of health of the pack. To evaluate performance, the team instrumented a full battery pack with 76 cells from a Ford Fusion Hybrid Vehicle with their new sensors and control system for testing at Ford Motor Company. The results immediately enabled multiple innovations in real-time management. These include setting power limits, fast warm-up, and state of health estimation of capacity fading based on monitoring shifts in bulk stress. Analysis from the team's demonstration on the Ford battery pack indicated that these innovations can enable downsizing of the battery with associated increase in energy utilization by 19% per cell and a projected decrease in available battery capacity of only 0.5% after 100,000 miles of use. The initial testing on a hybrid electric vehicle (HEV) pack was a useful demonstration of this approach to improved battery systems, and the results are promising that the integration of advanced sensors with model-predictive controls can improve performance in EV battery systems, but it will require continued development and deployment on larger battery electric vehicle (BEV) packs to reap the maximum benefits and value from this technology.

PATHWAY TO ECONOMIC IMPACT

This collaboration brought together a diverse set of experts in sensor technology, materials, mechanics, automotive engineering, controls, and modeling, resulting in advances in hardware and in modeling and control software for battery systems. The IEEE Control Systems Society recognized this team's efforts in pushing the boundary in battery controls with the CSS 2016 Controls Technology Award[1] "for the development of an advanced battery management system accounting for electro-thermo-mechanical phenomena."

Amphenol Advanced Sensors was the commercialization partner for the sensors developed under this program. In December 2013, Amphenol acquired the GE Advanced Sensors business including this research program and the resulting intellectual property. Since the onset of this program, new generation temperature sensors contributed 20% growth in sales for Amphenol Advanced Sensors in EV applications. This growth was a combination of probe, chip on flex, and skin temperature designs.

Based on testing results from the Ford HEV application, the team estimated a potential 15% cost reduction from battery downsizing, and noted improved drivability from faster warm-up in cold weather. That is promising, but for relatively small HEV packs, that savings in the pack would be correspondingly small (measured in the tens of dollars per vehicle). The advanced sensor and control system would have a larger impact for larger BEV packs, where the utilization improvements that the team demonstrated would yield much bigger savings.

LONG-TERM IMPACTS

The GE team sought to improve battery utilization by 20% through the integration of an array of low-cost sensors with an advanced physics-based battery control scheme, and demonstrated 19% improved utilization in validation testing on an HEV pack. Technologies like GE and Michigan's advanced sensors and control offer an additional path to improve effective energy density in a battery pack. Taking the long-term U.S. DRIVE battery cost goal of $125 kWh-1, the value for a system-level flexibility enabled by 20% improved utilization would exceed $1,000 per vehicle for a 45 kWh BEV pack. The pack-level validation testing with Ford during this ARPA-E award demonstrated that battery systems outside of the cells themselves can significantly improve usable energy density through better capacity utilization.

[1] The Control Systems Technology Award recognizes outstanding contributions to control systems technology either in design and implementation or in project management.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of January 2017, this team's project has generated seven invention disclosures to ARPA-E, five U.S. Patent and Trademark Office (PTO) patent applications, and resulted in four patents.

Patents:

Youngki Kim, Shankar Mohan, Jason Siegel, Anna Stefanopoulou, "Bulk Force in a Battery Pack and Its Application to State of Charge Estimation," US20160064972A1.

Aaron Knobloch, Jason Karp, Yuri Plotnikov, Chris Kapusta, Yizhen Lin "Battery Cell Health Monitoring using Eddy Current Sensing" US20150340744A1.

Chris Kapusta, Aaron Knobloch, Jason Karp, "Modular Flexible Sensor Array" US20160370210A1.

Chris Kapusta, Yizhen Lin, Jason Karp, Aaron Knobloch, "Method and System for Monitoring Battery Cell Health" US20160160380317A1.

The GE team has also published the scientific underpinnings of this technology extensively in the open literature. A list of publications is provided below:

Publications:

Ki-Yong Oh, Jason B. Siegel, Lynn Secundo, Sun Ung Kim, Nassim A. Samad, Jiawei Qin, Dyche Anderson, Krishna Garikipati, Aaron Knobloch, Bogdan I. Epureanu, Charles W. Monroe, and Anna Stefanopoulou. "Rate dependence of swelling in lithium-ion cells." *Journal of Power Sources*, 267(0):197 - 202, 2014.

Shankar Mohan, Youngki Kim, Jason B. Siegel, Nassim A. Samad, and Anna G. Stefanopoulou. "A phenomenological model of bulk force in a li-ion battery pack and its application to state of charge estimation." *Journal of The Electrochemical Society*, 161(14):A2222-A2231, 2014.

K.-Y. Oh, N. Samad, Y. Kim, J. Siegel, A. Stefanopoulou, Bogdan I. Epureanu, "A Novel Phenomenological Multi-Physics Model of Li-Ion Battery Cells," Journal of Power Sources Vol. 326, pp 447-458, Sept 2016.

K. Oh, B. I. Epureanu, J. B. Siegel, A. G. Stefanopoulou, "Phenomenological Force and Swelling Models for Rechargeable Lithium-Ion Battery Cells," Journal of Power Sources, Vol. 310, pp 118-129, Apr 2016.

N. Samad, Y. Kim, J. B. Siegel, A. Stefanopoulou, "Battery Capacity Fading Estimation Using a Force-Based Incremental Capacity Analysis," Journal of The Electrochemical Society Vol. 163 Issue 8, pp. A1584-A1594, Jan 2016.

Nassim Samad, Boyun Wang, Jason B. Siegel, Anna G. Stefanopoulou, "Parameterization of Battery Electro-Thermal Models Coupled with Finite Element Flow Models for Cooling," ASME Dynamics Systems Measurements and Control, to appear 2017.