**ARC FINAL REPORT**

**Project Title:** Energy-conscious Warm-up of Li-ion Cells from Sub-zero Temperatures

**PART I: PROJECT REPORT**

**Project Start Date:** 1 January 2014 (2017 was a 4th year non-cost extension request)

**Quad Members:**

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<th>Contact</th>
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</table>

**Motivation, Background and Objectives:**

Lithium-ion (Li-ion) battery packs are replacing other battery chemistries in commercial and military vehicles for hybrid propulsion, silent watch, and even more basic needs such as cold engine cranking. It is well documented, however, that at low temperatures, the discharge capability of Li-ion cells can be less than 70% of that at room temperature [1]. The recent winter driving data from many plug-in and all-electric vehicles raised several concerns on warm-up strategies because efficiency plummets due to the cold-start phase [2]. In addition, the current military vehicle fleet suffers from cold cranking problems. A recent task assigned by Dr. Rogers to a TARDEC working team in assessing the winterization kit to support Alaska Command in finding ways to ensure operation of equipment in extreme cold temperatures has indicated the urgency to attack the technical barrier of battery warm-up.

Battery warm-up techniques can be broadly classified as: (a) jacket, resistive, external heating, and (b) internal heating using high-frequency currents [3–5]. The electro-thermal dynamics of Li-ion cells have been shown to exhibit self-heating [6] and the use of this phenomenon to increase temperature has been discussed in literature [7]. A full order electrochemical model was developed in [8] to discuss different heating strategies of Li-ion cells but the accuracy and real-time computation of the model for such a critical task was never demonstrated [9].

Given the current status regarding battery warm-up, the three important questions that this work addressed are:

Q1: “Can a reduced order model be used to optimally warm-up cells and improve their cold performance?”

Q2: “If so, then how would one parameterize these models in realtime with on-board measurements?”

Q3: “Can we automatically optimize the current that achieves fast warm-up but judiciously trades-off the wasted energy?

This work developed a model predictive control technique that exploits the battery internal resistance for fast warm-up thus indirectly improving the cell performance (power capability and coulombic efficiency).
First, in year 1 we extended the modeling work which was conducted in previous UM/TARDEC collaborations to capture the sub-zero cell electrical and thermal behavior so that it can be used to accurately predict limitations and optimize the magnitude and frequency of the bidirectional currents. Even the complex electrochemical model in [10] could not capture the cell response during high bi-directional C-rates. The advantage of our approach relies on estimating a few key model parameters in real time using adaptive techniques.

In year 2, the proposed automated and optimal algorithm for the warm-up relied on drawing bi-directional current from the cell and hence required the presence of other battery cells or external energy storage elements such as ultra-capacitors similarly to [11-13]. The tradeoff between minimum-time to warm-up and energy wasted during warm-up was analyzed along with considerations regarding optimal sizing of the system components (capacitor, power electronics for current switching, etc.) as a function of the power requirements. Originally the proposed methodology would also assess strategies where one battery cell charges a nearby cell. Detailed analysis during the first two years of the project showed that charging nearby cells severely constraints the warm-up phase due to the limitations in the safe charge rate at sub-zero conditions.

In year 3 (beginning Jan. 2016) we designed the optimal discharge that utilizing the battery self-heating and an external resistive heater. Finally, various termination conditions (power instead of temperature) are developed and assessed.

In the 4th year (non-cost extension) the optimal policy is compared for minimum time (fastest warm-up) and minimum energy (submitted to IEEE CST and CDC 2017). Additionally, the sensitivity of the minimum warm-up energy to parametric uncertainty was investigated numerically.

**Approach:**
Most techniques discussed in literature strive to warm the cell until a certain pre-specified cell temperature is reached. Since in most applications, the cell serves as a source of power, we use the cell’s pulse power capability, instead of the temperature, as a condition to terminate the warm-up operation. Moreover, we investigated the feasibility of increasing the power capability in an energy efficient manner.

Important to the design of the control strategies is an adequate model. In our work, we employed equivalent circuit models. Adopting techniques from statistical and nonlinear system analysis, the feasibility of estimating model parameters has been examined. Results of feasibility studies were then used to guide the real-time parameterization scheme.

In the first year (Jan.-Dec. 2014) of this study we developed a verified a low order equivalent circuit model for the electrothermal cell behavior during cold conditions leveraging previous work by Monroe’s team [L5-L7] and an ARPA-E funded project [14]. In addition, we developed a battery warm-up technique that utilized an external ultra-capacitor to shuttle energy to-and-from a battery, thereby increasing the cells’ temperature by internal heat generation.

In the second year (Jan.-Dec. 2015), we developed an online state/parameter estimator based on the notion of relative significance, which is being integrated with the warm-up technique developed in the first year.

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1 References that have a letter such as [L5] and [J2] are references produced by this group in work under the scope of this funding. References cited as [2] are from literature and can be found at the end of this document.
The warm-up technique developed thus far is able to adapt the simplified models of the battery's temperature and voltage dynamics and increase its temperature until the desired power can be delivered; however, as indicated earlier, the method relies on the presence of an external ultracapacitor, and the time to complete the warm-up phase depended on the penalty one imposed on the energy discharge.

In the third year (Jan.-Dec. 2016) of the project, we optimized the current drawn from the battery based on the battery constraints and especially diffusion limitations that cause overpotentials limiting the current drawn and thus increasing the warm-up energy and period. We found surprisingly that if the overpotential is significant and insulation is available, rest period can contribute to internal heat generation without current drawn.

**Previous Year(s) Accomplishments:**

**2014**

**2014 Q1 Tasks**: Develop a fast battery model through model order reduction of Electro-Thermal-Chemical model

**2014 Q1 Accomplished**: Performed in 2015 instead; Highlights below; Documented in C1

**2014 Q2 Tasks**: Sensitivity analysis and Fisher Information observability

**2014 Q2 Actual**: Model Validation: Fast forward from Q4 and performed a validation for the fixed-parameter model due to the availability of the instrumented cell and the data acquisition

**2014 Q3 Tasks**: On line parameter estimation

**2014 Q3 Actual**: Optimization of the bidirectional current sequence for energy conscious & fast warm-up

**2014 Q4 Tasks**: Model Validation

**2014 Q4 Accomplished**: (from Q2). Documented the optimal energy conscious algorithm with a invention disclosure and a provisional patent application.

**2015**

**2015 Q1 Tasks**: Offline models of the electrical dynamics are influenced by highly nonlinear internal processes and are influenced by a variety of factors; additionally, the initial conditions of the model are seldom known a priori. Using the Fisher Information Matrix (FIM) as a means to assess state/parameter observability, we developed a methodology that can rank the states and parameters based on relative estimability.

**2015 Q2 Tasks**: We analyzed the feasibility of estimating states and parameters of the electrical and thermal model simultaneously.

**2015 Q3 Tasks**: We investigated the feasibility of using the ranking methodology developed in 2015 Q1 to sequentially update the estimates of states and parameters of the results of the task in 2015 Q2.

**2015 Q4 Tasks**: Coupled with the fast warm-up optimization method developed in YR1 with the methodology developed in 2015 Q3

**2015 Q1-3 Accomplishments**: Highlights are listed below and are document in C3 and J4.

**2016 Q1 Task**: Model heating system including airflow and solve the optimum current draw problem

**2016 Q1 Actual:**
A model of a system that contains a battery and a battery-powered external heater was developed. An optimization problem that aimed to find the energy optimal warm-up strategy with the battery powered external heater was formulated and solved. The terminal constraint for this problem was stipulated in terms of cell temperature.

**2016 Q2 Task:** Define the optimization problem for optimally sizing heaters to efficiently warm-up cells

**2016 Q2 Actual:**
The optimal policy to the problem in 2016Q1 was approximated as a sequence of constant voltage, constant current and rest phases. It was shown that the solution to the problem in 2016Q1 can be used to size external battery-powered heater banks.

**2016 Q3 Task:** Investigate the influence of model uncertainty on the optimal solution to the problem in Q2 (Monte Carlo and alternate methods)

**2016 Q3 Actual:**
To draw a parallel between the solution to the problem in 2016Q2 and 2014Q3, the optimal control problem was solved with as power as terminal constraint. One factor-at-a-time perturbation based sensitivities of the policies in 2016Q2 and 2016Q3 was studied.

**2016 Q4 Task:** Experimentally verify the solutions by constructing a test-bed

**2016 Q4 Actual:**
A 6T pack was instrumented with sensors but there was very large cell-to-cell variability in the capacity and resistance of the cells making the low temperature experiments dangerous and probably not very useful.

Instead, we sought to solve for an implementable approximation of the optimal policy for battery warm-up. To address this problem, a relation between the optimal solution and the reachable set was established. Subsequently, new tools to approximate the backwards reachable set were developed, and it was shown that the generated approximation of the optimal solution was adequate with less than 0.02% of overestimation of the battery minimum energy needed for a cold-start at -10 degrees Celsius.

To increase our confidence on the results since the experiments were not performed, a comparison of optimality metric and its robustness to various battery parameters was initiated with a 2017 non-cost extension request.

**2016 Deliverables:**

<table>
<thead>
<tr>
<th>Research tasks and deliverables</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
</tr>
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<tbody>
<tr>
<td>Model heating system including airflow and solve the optimum current draw problem (CDC 2016)</td>
<td>100% accomplished</td>
<td>Define the optimization problem for optimally sizing heaters to efficiently warm-up cells (TCST (in prep) )</td>
<td>100% accomplished</td>
<td>Assessment of feasibility of warm-up and approximating the optimal solution as an real-time implementable feedback law. 100% accomplished</td>
</tr>
<tr>
<td>Investigate the influence of model uncertainty on the optimal solution to the problem in Q2</td>
<td>100% accomplished</td>
<td></td>
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<tr>
<td>(Monte Carlo and alternate methods)</td>
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2017 Deliverables (non-cost extension):

<table>
<thead>
<tr>
<th>Research tasks and deliverables</th>
</tr>
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<tbody>
<tr>
<td>Q1</td>
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</table>

Major Milestones and Deliverables since Project Start:

Highlights in Cold Battery Model:

1) Results from prior independent work in references [1,19] and [7,20] and the Quad members in J1-2 and C1-2 showed that battery electro-thermal dynamics can be approximated well with equivalent circuit models over an important frequency range. The frequency range is dictated by the frequency of the hardware associated with the bi-directional current necessary during battery warm-up by electrochemical limitations. The fast battery model was parameterized over the 05-95 % SOC range with ambient temperatures between -20C to 5C. The model is validated using a sequence of bidirectional pulses as such profiles are of interest in this specific application. Validation of the electrical and thermal dynamics when a 1Hz pulse (charge peak current: 5A, discharge peak current: 10A) is applied to the cell shows the following errors.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rms. error</th>
</tr>
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<tbody>
<tr>
<td>Voltage</td>
<td>70mV</td>
</tr>
<tr>
<td>Core Temperature</td>
<td>0.3C</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>0.6C</td>
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</tbody>
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Table 1 Open-loop prediction errors tabulates the rms. errors in estimating voltage and temperatures for the said current profile.

No other low order battery model achieves this level of accuracy for battery cold-start behavior with results documented in C1 and J3.

2) A method to increase the battery’s temperature---while penalizing energy discharge---such as to increase the cell’s power capability to meet requirements has been developed. The proposed method utilizes bi-directional currents and shuttles energy between the battery and an ultra-capacitor; the magnitude of the current to be drawn at any instant is computed to keep the battery’s terminal voltage in a safe range. Using this methodology, the effective energy utilized while warming the battery can be reduced by over 10%; however, at the expense of the total time it takes to reach the objective. Details of this methodology have been document in J3 and an initiative to protect this IP is also underway (P1).

3) A novel method to estimate the states and parameters of the electrical and thermal models of a Lithium-ion battery, in real-time, has been developed. The developed technique uses information about the relative significance of the various states and parameters to simplify the tuning process and has been shown to be effective in estimating parameters and states of a battery that is warmed from -5C to 10C. The performance of the proposed estimator structure in the context estimating the power capability of Li-ion cells has been documented in J4.
<table>
<thead>
<tr>
<th>Year/Month</th>
<th>Highlights</th>
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<tbody>
<tr>
<td>2014/ Q1-2</td>
<td>A low-order electro-thermal model for sub-zero operation was developed</td>
</tr>
<tr>
<td>2014/ Q3-4</td>
<td>A method to energy consciously warm batteries using pulsed current has been proposed.</td>
</tr>
<tr>
<td>2015/ Q1-2</td>
<td>A novel online state/parameter estimation strategy that is easy to tune and is empirically verified to be provide ‘accurate’ estimates has been designed</td>
</tr>
<tr>
<td>2016/Q1-3</td>
<td>It was shown that the energy-optimal warm-up strategy for Li-ion batteries using an external convection heater is similar to a conventionally applied technique. Novel techniques to solve for feasibility of warm-up were developed.</td>
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**ARC/TARDEC/Industry Benefits:**

*Project needs to have demonstrated added value in at least one of the following areas:*

1) **Interactions with and benefits to other ongoing ARC research**

This work creates synergies among the following projects:

- Vahidi’s supercapacitor models could be used as the auxiliary energy storage for enabling the bi-directional current drawn from the battery cells.[Project 1.10]
- Thompson’s new supercapacitor chemistries could be also integrated in a novel ultra-efficient warm-up scheme. Our approach is agnostic to the supercapacitor chemistry and can account for limitations arising from commercial supercapacitors. [Project 4.20]
- Lin Ma’s work on the heat transfer of the cooling system could be utilized to develop the dynamic model of coolant flow and temperatures of the various elements inside the battery compartment. This model will be utilized in the research undertaking in year three to optimally size the heating element required to warm the battery from sub-zero temperatures. [Project 4.13]
- Monroe’s project is investigating the planar electro-thermal battery coupling in an effort to model instabilities and planar patterns under various boundary conditions (spot heating and cooling or manufacturing imperfections). This model could be used in an ongoing effort to develop more accurate models of the Li-ion battery as it warms-up and can be used to relax some of the conservative assumptions made in this project. [Project 4.15]
- Filipi’s and Wagner’s work on Battery management accounting for battery degradation could benefit from degradation model induced under cold conditions (plating etc.) [Projects 4.4, 4.9]

2) **Interactions with and benefits to ongoing TARDEC work**

Engineers at TARDEC have a lot of interest in the battery modeling and warm-up studies. Dr. Ding and others in the TARDEC energy storage team have developed warm-up strategies and so this work will provide to him the model and analytical basis for improving and automating his techniques.

One quote from globenewswire.com

The standard battery for the United States and many NATO ground combat vehicles is the "6T" battery. For example, a HUMVEE vehicle has two 6T batteries under the passenger’s seat; an Abrams tank can have from six to twelve 6T batteries. The installed base of 6T batteries in United States military vehicles alone is over one million batteries.

Our approach of adaptively parameterizing multi-physics models is very relevant for vehicle applications and is not currently pursued by any DOE-funded research program such as the BATT or the CAEBATT or the BES.
3) Interactions with and benefits to ongoing work at Industry partner

Ford: Our interaction with the Ford “Battery Controls” group via Dyche Anderson will provide insight in commercial strategies and could transition to enable higher winter efficiency.

GE: Dr. Aaron Knoblock from GE provided surface sensors integrated in a board for distributed sensing of the cell temperature (skin temperature near the active electrodes, instead of the typical location on an NTC temperature sensor on the top of the cell). This work is contributing and leveraged by our ARPA-E contract.

4) ARC Seminar

(2014) ARC seminar ‘Energy conscious warm-up of Li-ion cells from sub-zero temperatures’

Leveraged Funding:

This research plan is not funded by any other source but it leverages the sensors, testing equipment, and data from the ARPAe/GE funding (AMPED 2012-2015) our portion ~$180k/year till Dec 2015 out of $1.5M to the UM/ARC team (Chuck Monroe and Bogdan Epureanu) and $4.5M to the whole GE&Ford team.

Publications, Presentations, Copyrights, Patents or other Tech Transfer:

Papers

Journal Articles


J5. S. Mohan and A.G. Stefanopoulou, Jason Siegel, Ram Vasudevan “An Energy-Optimal Warm-Up of Li-ion Batteries from Sub-Zero Temperatures and its Approximations”, IEEE TCST (submitted)

Conference papers (6+ pages, peer reviewed)

C1. S. Mohan, Y Kim, A. Stefanopoulou, Y Ding, “On the Warm-Up of Li-ion Cells from Sub-zero Temperatures,” American Control Conference (ACC), Portland, Oregon, June 2014


Related papers in 2013 that build the foundation for this work (leveraged by Ford funding)


Related paper in 2014 that helps this work (funded by ARPA-E to GE/Ford/UM)

L4. N. Samad, Y. Kim, J. Siegel, A. Stefanopoulou, “Influence of Battery Downsizing and SOC Operating Window on Battery Pack Performance in a Hybrid Electric Vehicle”, VPPC 2015, Accepted

Related paper of a different ARC project team in 2014 this project-quad helped with


Presentations

Jason Siegel; Battery safety, Knowledge Foundation Symposium 2016
Anna Stefanopoulou: Stretching the Utilization 48V Battery Management Systems, SAE Workshop 2016
A. Stefanopoulou, TARDEC Innovation talk, April 2015
A. Stefanopoulou, Ford Battery Controls review, April 2014
A. Stefanopoulou, Material Research Society Annual meeting (MRS 2014), Symposium Q: Materials, Technologies and Sensor Concepts for Advanced Battery Management Systems

Patents


Others

Honors, Awards, Keynote/Plenary and Named Lectures, Special Memberships:

Jason Siegel and Anna Stefanopoulou received the 2016 Control System Technology award for their Battery models and management.
A. G. Stefanopoulou “Operating at the limit of powertrain efficiency” (Semi-Plenary American Control Conference, Portland Oregon, June 2014)

References