State-of-health estimation of lithium-ion batteries in electric vehicles

T3:4 Battery system – Life model

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Summary

This project addresses the need for simple and cost-effective methods for estimating the state-of-health (SOH) of batteries under electric vehicle operation.

Within the scope of this project, such a method has been developed. The method can estimate the SOH indicators capacity and resistance solely based on an input of on-board available signals such as current, voltage, and temperature. The concept is based on data-driven battery models and virtual tests in correspondence to standard performance tests as established in laboratory testing. The method has been applied for battery data collected in field tests and has also been validated under controlled conditions in laboratory. The method has been shown to work for EV, HEV, and PHEV battery data i.e. a variety of different batteries, operating conditions, and usage patterns.

The demonstration of this simple SOH estimation method represents a contribution to hybrid vehicle technology. The implementation of this kind of methods in tomorrow's hybrid vehicles will be an important factor for their broad commercial success as a suitable SOH estimation method will not only ensure safe and reliable HEV operation, it even contributes to cost-effectiveness as the battery can be utilized in an optimized way and the method itself only relies on simple resources.

Apart from the PhD student (Verena Klass) and the supervisors (Mårten Behm, Göran Lindbergh) at Applied Electrochemsitry at KTH, Pontus Svens (Scania) has been involved in one of the studies within the scope of this project. The research in the project has been dependent on battery data from industry, which has been delivered by ETC Battery and FuelCells AB, Volvo Car Corporation, and Scania AB. The project started in March 2009 and was completed by the doctor defense in September 2015. The total financial support from SHC is SEK 4.5 million.

Background

When lithium-ion batteries are used as energy storage in automotive traction systems for electric or hybrid electric vehicles, it is essential to manage the energy storage in order to optimize its performance, reliability, and lifetime.

The state-of-health (SOH) of automotive batteries is an essential parameter that preferably should be monitored during the operation of traction batteries in order to enable optimized battery utilization. Accessing the battery SOH on-board is not a trivial question as conventional standard tests established in laboratory testing for determination of degrading battery properties such as capacity and resistance are not accessible during constant battery operation. A way to avoid this problem is the usage of a battery model that captures the essential battery behavior.

General project description

The introduction of electric and hybrid electric vehicles provides a situation where battery operating data from vehicle application is available. In field tests, battery data is collected but it is not obvious how the data can be used in order to improve for future battery operation. Conventional battery testing in controlled laboratory environments is still performed. The objective of this project was to make use of the available field data trying to condensate information on the battery from the raw signals and in this way rendering the data meaningful information.

In order to reach this goal, a method to access battery performance measures from the raw data had to be found. The chosen solution was the application of a statistical learning method (support vector machine, SVM) that can build data-driven models in combination with the concept of virtual tests where standard performance tests from laboratory testing were applied virtually to the derived battery model in order to access the desired battery performance measures. In the case of the applied standard test being a capacity or pulse test, the SOH indicators capacity and resistance can be estimated.

After a first proof-of-concept of this method using plug-in hybrid electric vehicle (PHEV) battery data (from ETC), the method was improved with the help of a laboratory study where electric vehicle (EV) operation of a battery cell (from Volvo cars) was emulated under controlled conditions providing the possibility of validating the estimation results. In a follow-up study based on the same laboratory data set, the method was further improved with the addition of a current history variable to the model input. Finally, the SOH estimation method was applied to another data set from emulated hybrid electric vehicle (HEV) operation of a battery cell on board a conventional heavy-duty truck. Within the scope of another SHC project (T3:12), activities on the substitution of the SVM model with a systems identification model has been initiated.

Achieved results

The main result of this project is the developed SOH estimation method.

The SVM method incorporated in this SOH estimation method is found to be a powerful tool for handling large amounts of battery operating data at a reasonable computational load.

From on-board battery data, SVM models were created that can describe the battery behavior accurately. The models were based on different model architectures in the different studies within this project. The most elaborated model architecture was a current/temperature/state-of-charge (SOC)/current history-input in order to predict the voltage output.

Applying virtual tests that correspond to standard performance tests to the derived SVM models gave access to SOH indicator estimations such as capacity and resistance. This is a very convenient tool as virtual tests can be validated with the established and familiar laboratory tests and the SOH estimations based on the virtual tests correspond to meaningful battery properties as derived from real standard tests.

The method can be implemented into the battery management system (BMS) of an electric vehicle in order to monitor the SOH of the traction battery from measured signals voltage, current, temperature and the BMS's state-of-charge (SOC) estimation (project in cooperation with KTH Integrated Transport Research Lab).

Contribution to hybrid vehicle technology

Simple SOH estimation methods are vital for the broad commercial success of hybrid electric vehicles. A suitable SOH estimation method will not only ensure safe and reliable EV operation, it even contributes to cost-effectiveness as the battery can be utilized in an optimized way and the method itself only relies on simple resources.

From an academic point of view a deeper understanding of the behavior of batteries under EV operation has been gained and it has been learned more about how EV operating conditions influence battery performance. The necessity of electrochemical knowledge for the improvement of battery models for such applications and conditions was obvious.

The industry is interested in methods for on-board state estimation. For the industry it is thus interesting to see that methods other than equivalent circuits can be used for on-board battery state estimation. In the context of strict requirements for fuel reductions and emission regulations, it is important to build competence about batteries for vehicle applications; i.e. electric and hybrid electric vehicles as a way of emission and fuel reduction in transport.

In terms of SHCs target of funding research with high industry-relevance within hybrid electric vehicles, it was contributed with the communication of results to industrial cooperation partners (ETC, Volvo Cars, Scania).

With respect to SHCs focus on the system perspective, the implementation activities of the developed method within the KTH Integrated Transport Research Lab and the cooperation with the Signals and Systems department at Chalmers (T3:12) can be mentioned.

Uniqueness and news value

A novel method for on-board battery SOH estimation has been developed. The data mining method that was chosen for the incorporated data-driven battery model, i.e. SVM, has previously only been tested for battery SOC estimation, not for voltage and subsequent SOH estimation as in this project. The concept of virtual tests where standard performance tests for capacity and resistance estimation are applied virtually to a black-box battery model in order to access battery property estimations i.e. estimations of capacity and resistance is unique as well. The SVM-based battery model itself is comparably good at estimating voltage from an input of on-board measured signals. In contrast to many other methods in the literature, this method does only rely on on-board available signals. It is not necessary to have any previous knowledge about the battery or perform laboratory tests in order to make the model work. This makes the method very versatile. Basically without changes to the model design, the method has therefore been able to be applied to EV, PHEV, and HEV battery data. Apart from the uniqueness of the general concept of the SOH estimation method, the incorporated model has been equipped with a new feature that is rarely found in data-driven battery models. A current history variable has been included in the model input in order to account for the effects of diffusion resistance on the battery voltage dynamics.

Timing and finance

- 2009: PhD project and cooperation with Think started, however terminated due to the companies financial difficulties
- 2010/2011: Received Volvo V70 PHEV prototype data from ETC (Vattenfall/Volvo cars project) and started testing SVM method
- 2012/2013: Received Volvo Electric C30 data and battery cells from Volvo Cars and built set-up and control in laboratory, performed experiments
- 2013/2014: Implementation project together with KTH Integrated Transport Research Lab
- 2014/2015: Received HEV emulation data from Scania, Verena Klass on 10-month parental leave
- 2015: PhD defense planned for September

The total project budget is SEK 5.2 million, 4.5 of which is funded by SHC.

Executors and collaboration

All modeling, experimental work on single cells in lab and data analysis has been performed at Applied Electrochemistry at KTH (Verena Klass, Mårten Behm, Göran Lindbergh).

The project has been dependent on access to real-life battery field test data from vehicle operation. ETC Battery and Fuel Cells Sweden AB provided PHEV data, Volvo Car Corporation EV data, and Scania CV AB (Pontus Svens) provided us with HEV emulation data.

Dissemination of Results

International conference participation:

- Poster (and paper in conference proceedings) *Life time performance of battery packs in electric vehicles* (#11) at Advanced Automotive Battery Conference 2010
- Presentation (and paper in conference proceedings) *Real-life performance modeling of lithium-ion battery packs in electric vehicles* (#437) at 220th ECS Meeting Boston 2011
- Poster *Lithium-ion battery packs in electric vehicles: Real-life performance evaluation* (#AF0032) at International Meeting on Lithium Batteries South Korea 2012
- Presentation *Performance estimation method for lithium-ion battery packs in electric vehicles* at Advanced Battery Power conference 2013 in Aachen, Germany

Swedish conference participation:

- Presentation *Strategies for battery pack data collection and analysis* at Battery Workshop Djurönäset 2010
- Presentation *Ny metod för prestandaövervakning av fordonsbatterier under drift* at Energimyndighetens konferens Energirelaterad fordonsforskning in Örebro in April 2013
- Poster *State-of-health estimation method for lithium-ion batteries in electric vehicles* at NordBatt1 in Uppsala in December 2013

Apart from showing results from this project at international and Swedish conferences, results were also communicated within KTH throughout the years, e.g. with posters at the yearly KTH Energy Day and KTH Chemistry School Day as well as presentations within the seminars at Applied Electrochemistry.

SHC seminars and workshops:

- Presentation *Life time performance of batteries in electric vehicles* at the SHC workshop in Göteborg in November 2011
- Result slides at the SHC evaluation meeting in October 2010
- Presentation *Evaluating Real-Life Performance of Lithium-Ion Battery Packs in Electric Vehicles* at the SHC meeting in January 2012
- Poster *Lithium-Ion Battery Packs in Electric Vehicles: Real-Life Performance Evaluation* at the SHC day in Göteborg in May 2012
- Presentation *State-of-health estimation method for lithium-ion batteries under electric vehicle operation* at SHC X-Theme meeting in Katrineholm in November 2013
- Poster *Estimating battery health in electric vehicles* at SHCs conference Roads to the future in Stockholm in March 2014
- Presentation *State-of-health estimation method for lithium-ion batteries under electric vehicle operation* at the SHC evaluation meeting in June 2014 (Mårten Behm)
- Presentation *State-of-health estimation method for lithium-ion batteries under electric vehicle operation* at SHC X-Theme meeting in Hallsberg in March 2015

Planned publications:

- Capturing lithium-ion battery dynamics with support vector machine-based battery model
  V. Klass, M. Behm, G. Lindbergh
  Manuscript submitted to the Journal of Power Sources
- State-of-health estimation of lithium-ion battery under emulated HEV operation on board heavy-duty truck
  V. Klass, P. Svens, M. Behm, G. Lindbergh
  Manuscript

Papers and publications

- Li-ion battery performance in electric vehicles
  V. Klass, M. Behm, G. Lindbergh

AABC 2010 - Advanced Automotive Battery Conference (2010) 45-48

- Evaluating real-life performance of lithium-ion battery packs in electric vehicles
  V. Klass, M. Behm, G. Lindbergh
  ECS Transactions **41** (2012) 1-11

- Evaluating real-life performance of lithium-ion battery packs in electric vehicles
  V. Klass, M. Behm, G. Lindbergh
  Journal of the Electrochemical Society **159** (2012), A1856-A1860

- A support vector machine-based state-of-health estimation method for lithium-ion batteries under electric vehicle operation
  V. Klass, M. Behm, G. Lindbergh
  Journal of Power Sources **270** (2014), 262-272

- Capturing lithium-ion battery dynamics with support vector machine-based battery model
  V. Klass, M. Behm, G. Lindbergh
  Journal of Power Sources **298** (2015), 92-101

- Battery Health Estimation in Electric Vehicles
  V. Klass
  Doctoral thesis 2015

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