SHC PROJECT SUMMARY REPORT

Energy Management of HEVs – fuel optimal control

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Summary

Hybrid and plug-in hybrid vehicles are equipped with a powertrain that provides at least two power sources for propulsion. This gives additional freedom in operation of the powertrain, and the task to exploit this extra degree-of-freedom to improve overall energy efficiency is termed *energy management*. This project investigates the energy management problem for plug-in-hybrid vehicles, for which an additional challenge is to plan the use of the (large) battery, in particular for driving missions extending beyond the all-electric-range.

Based on the observation that information about the future driving is essential for an optimal energy management strategy, the project focuses on recurrent driving patterns, as exposed by commuters, and the availability of GPS data. A conceptual framework is described, where optimal control strategies are computed for recurrent missions, based on statistical driving data and using computing resources either on-board the vehicle or in the "cloud".

Based on the conceptual framework for optimizing the energy management for plug-in hybrid vehicles, the project has successfully demonstrated that the approach is technically and industrially feasible with the following highlights:

- Computations based on dynamic programming can be organized efficiently, so that memory and CPU requirements allow an optimal energy management strategy to be calculated within a second using moderate computing resources (e.g. a desktop).
- Fuel savings up to 10% has been demonstrated on a high fidelity simulation platform. Savings depend on the character of the route.
- An ingredient of the project has been cooperation with Volvo Cars, in which an implementation of the real-time control functions has been accomplished in the ECU of the V60 production plug-in hybrid vehicle.
- The main project has been conducted as a PhD project and resulted in a PhD degree by Viktor Larsson, based on several scientific journal and conference papers (listed in the report).

Background

Electrified powertrains have the potential to reduce both fuel consumption and CO_2 emissions within the transportation sector. However, due to the high cost of battery capacity, hybrid electric vehicles (HEVs) and Plug-in HEVs (PHEVs), rather than battery electric vehicles, are expected to be the viable electrified option during the foreseeable future; at least for vehicles that frequently travel longer distances.

The HEV powertrain has at least two complementary power sources, i.e. a combustion engine and one or several electrical motors. Consequently, there is at least one additional degree of freedom in how to meet the driver's traction request. The task of the energy management system is to decide operating points of the engine and the motor(s) so that the overall fuel economy is maximized. The fundamental problem is that the optimal operating strategy can be found only if the future driving conditions are known a priori.

During the last decade significant attention has been given to the topic of optimal energy management of conventional charge sustaining HEVs, and many different energy management strategies have been developed; both for situations where the future driving conditions are known and unknown. The research has indicated that it often is possible to obtain near optimal fuel economy even if the future driving conditions are unknown.

General project description

For a PHEV there is also a degree of freedom in how to discharge the battery, at least if the length of a trip exceeds the electric range. The trivial discharge strategy is to operate as an electric vehicle until the battery is depleted and then proceed in charge sustaining operation as a conventional HEV; a so-called charge-depleting charge-sustaining (CDCS) strategy. However, it is possible to improve fuel economy if the battery is discharged gradually throughout the trip. A gradual discharge lowers the average discharge current, thereby lowering the resistive losses that are quadratic in current. Consequently, for a PHEV to obtain a near optimal fuel economy, it is crucial to have a priori information regarding the future trip.

The project has therefore considered PHEVs and trips that exceed the electric range. More specifically, the work has focused on two different aspects:

1) How to obtain a priori information by processing of logged historical driving data.
2) How to apply efficient computational methods, both in terms of pre-computing an optimal energy management strategy and controlling the PHEV in real-time.

The project has primarily been devoted to investigations using computer software for optimization and dynamic simulation, but in cooperation with Volvo Cars an implementation of some of the algorithms has been done in the V60 plug-in hybrid vehicle, and some initial experimental results were obtained at the end of the project.

Achieved results

The main results of the project can be described as a system for route optimized energy management of PHEVs. The basic idea is to identify frequently travelled routes from logged historical driving data. Given the driving conditions along a route, it is then possible to pre-compute an optimal energy management strategy, e.g. on a server or in a smartphone. The pre-computed solution can then be transmitted to the vehicle and be used as a sort of feedforward information for the control system that is implemented in the vehicle.

The proposed system has been evaluated in simulations and the results indicate that the fuel consumption of a PHEV can be reduced with up to 10% on some routes. High figures are likely if the route starts with highway driving and the length is about 1.5-2 times longer than the electric range of the PHEV.

The project has resulted in a number of scientific publications (3 journal papers and 7 conference papers) and a PhD thesis. The main contributions from a scientific viewpoint are:

- A conceptual framework covering both identification of frequently travelled routes and optimization of the energy management. The routes are identified from logged historical driving data using hierarchical agglomerative clustering and the optimal energy management strategy is computed offline with Dynamic Programming (DP).
- A methodology to approximate the DP cost-to-go with a spline function, meaning that the memory storage requirements can be reduced significantly.
- A DP algorithm where the sub-problems are solved analytically based on a local approximation of the cost-to-go. Thereby it is not necessary to grid the torque split and evaluate the cost-to-go with interpolation. The method is thus very efficient in terms of computational demand.
- A closed-form minimization of the Hamiltonian for a powertrain configuration with two degrees of freedom. The solution is implemented as an Equivalent Consumption Minimization Strategy (ECMS) strategy with very low computational demand. The strategy is validated in a test drive with a production PHEV.

Contribution to hybrid vehicle technology

The main contribution from an academic perspective is in terms of efficient computational methods. Much of the focus has been to reduce both computation time and memory requirements. The project has demonstrated that it is possible to solve the energy management problem with Dynamic Programming in a few seconds (or less) using a desktop computer without compromising solution accuracy or numerical stability.

Furthermore, the project has also demonstrated that model-based optimal control methods are possible to implement in a production vehicle. A novel energy management strategy for the Volvo V60 PHEV was implemented both in Volvo's simulation platform and then later tested in a production vehicle. The vehicle implementation required only a few kB of memory in the Electronic Control Unit.

A consequence of the demonstrated implementation is that the benefits of reduced fuel consumption for an important group of drivers – commuters – are within reach within a near future. The project has therefore contributed to the SHC mission in a concrete way.

Uniqueness and news value

The novelty of the work is mainly that analytic solutions and spline functions are utilized when solving the energy management problem. Furthermore, the project has also presented a study that both identifies commuter routes from historical driving data and optimizes the PHEV energy management system. There have not been any detailed studies published on that topic before.

The press release that summarized the main results of the thesis generated over 30 articles in international blogs and newspapers.

Timing and finance

The project has been running during the period 2009-03-01—2014-06-30, concurrent with Viktor Larsson’s time as a PhD student. The nominal PhD period of 5 years was extended by 4 months in order to include the final implementation of the algorithms in the V60 PHEV.

The project has evolved over the years in a fairly normal fashion. During the initial period, until Viktor’s licentiate degree, there was more focus on literature study and PhD courses, and the research explored several ideas concerning treatment of uncertainty in energy management. After the lic degree, the PHEV focus was central, and the research was directed towards the system concept as well as computational issues, and then finally the experimental implementation.

The total project budget is SEK 4.85 million, 4.5 of which is funded by SHC.

Executors and collaboration

The main contributor to the project results is Viktor Larsson, who has been working as a PhD student all along the project. Bo Egardt has served as advisor and Lars Johannesson as co-advisor. The academic environment has included several other related projects on optimization and control of hybrid powertrains; this is an important factor also when there is not a very tight cooperation between projects. Contributing to the total environment is also the cooperation with Victoria Swedish ICT (Lars Johannesson) and the SHC partners.

The project clearly benefited from the close connections with Volvo Cars (Anders Lasson), and thanks to a concurrent FFI project with VCC, there was an opportunity to go all the way to a practical implementation. During the first years of the project an industrial reference group with members from Volvo Cars (Bengt Norén, Anders Lasson), AB Volvo (Jonas Hellgren, Jerker Lennevi), and Saab (Lars G Johansson) provided useful input.

Papers and publications

Ph.D. thesis

V. Larsson, “Route Optimized Energy Management of Plug-in Hybrid Electric Vehicles”, 2014

Licentiate thesis

V. Larsson, “On Discharge Strategies for Plug-in Hybrid Electric Vehicles”, 2011

Journal papers

V. Larsson, L. Johannesson, B. Egardt, S. Karlsson, *"Route Optimized Energy Management of Hybrid Electric Vehicles"* IEEE Transactions on Intelligent Transportation Systems, vol 15, no. 3, 2014

V. Larsson, L. Johannesson, B. Egardt, *"Analytic Solutions to the Dynamic Programming sub-problem in Hybrid Electric Vehicle Energy Management Problems",* Accepted for publication in IEEE Transactions on Vehicular Technology, 2014

V. Larsson, A. Karlsson, L. Johannesson, A. Lasson, B. Egardt, *"Real-Time Energy Management of a Plug-in Hybrid Electric Vehicle based on a closed-form minimization of the Hamiltonian",* Submitted to Control Engineering Practice, 2014

Conference papers

A. Furberg, **V. Larsson**, B. Egardt, *"Optimal Selection of Driving Modes along a Commuter Route for a Plug-in Hybrid Electric Vehicle",* Accepted to the 19th IFAC World Congress, 2014

V. Larsson, L. Johannesson, B. Egardt, *"Cubic Spline Approximations of the Dynamic Programming Value Function in HEV Energy Management Problems",* Proceedings of the European Control Conference, 2014

V. Larsson, L. Johannesson, B. Egardt, *"Comparing Two Approaches to Precompute Discharge Strategies for Plug-in Hybrid Electric Vehicles",* Proceedings of the 7th IFAC Advances in Automotive Control, 2013

V. Larsson, L. Johannesson, B. Egardt, *"Benefit of Route Recognition in Energy Management of Plug-in Hybrid Electric Vehicles",* Proceedings of the American Control Conference, 2012

M. Pourabdollah, **V. Larsson**, B. Egardt, *"PHEV Energy Management: A Comparison of Two Levels of Trip Information",* Proceedings of the SAE World Congress, 2012

V. Larsson, L. Johannesson, B. Egardt, *"Influence of State of Charge Estimation Uncertainty on Energy Management Strategies for Hybrid Electric Vehicles",* Proceedings of the 18th IFAC World Congress, 2011

V. Larsson, L. Johannesson, B. Egardt, *"Impact of Trip Length Uncertainty on Optimal Discharging Strategies for PHEVs",* Proceedings of the 6th IFAC Advances in Automotive Control, 2010