Optimal Energy Management of Electrified Powertrain

Lars Nielsen
Linköping University

Swedish Hybrid Vehicle Centre
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Summary

Vehicle powertrain electrification, i.e. combining the internal combustion engine (ICE) with an electric motor (EM), is a potential way of meeting the increased demands for efficient and low emission transportation, at a price of increased powertrain complexity since more degrees of freedom (DoF) have been introduced. Optimal control is used in a series of studies of how to best exploit the additional DoFs. The size of the additional energy storage, e.g. battery, influences the optimal control solution characteristics and which level of detail that needs to be modeled.

For off-highway vehicles the power source is typically a diesel engine. There are however gains to be made in electrifying even heavy duty powertrains. One such example is the diesel-electric powertrain in which the diesel engine, whose rotational speed is a DoF, is used together with a generator to produce electric power. The architecture is thus the same as a series hybrid, however with the added requirement of good transient control. How to optimally control the engine-generator (GenSet) in a series hybrid is an unanswered question, especially for turbocharged engines. Using optimal control and a developed model, the turbocharger dynamics are shown to have a strong impact on how to control the GenSet and neglecting these can lead to erroneous estimates both in the response of the GenSet as well as how it should be controlled. Also the objective, whether time or fuel is to be minimized, influences the engine speed-torque path to be used, even though it is shown that the time optimal solution is almost fuel optimal. To increase the freedom of the powertrain, a small energy storage can be added to assist in the transients, making it a hybrid. This is shown to be especially useful to decrease the response time of the powertrain in a transient manner, but the manner it is used, depends on the duration of the transient.

In hybrid electric vehicles (HEV) the size of the energy storage reduces the impact of poor transient control, since the battery can compensate for the slower dynamics of the ICE. For HEVs the problem instead is how and when to use the battery to ensure good fuel economy. In a plug-in HEV (PHEV) the battery is even larger, enabling all-electric drive, making it desirable to use the energy in the battery during the driving mission. A controller is designed and implemented for a PHEV Benchmark and is shown to perform well even for unknown driving cycles, requiring a minimum of future knowledge, relying only on information that could be easily retrieved from a GPS. An extension to also include topography information is also suggested. The project was conducted during 2014 and first half of 2015 at Linköping University

Background

Combining a~~n~~ combustion engine (ICE) and an electric motor (EM) seems to be a good compromise both ensuring range and increasing efficiency at the price of increased cost of the vehicle. There are several ways, both with and without electrical energy storage, in which the two can be combined. If the vehicle has more than one source of energy, e.g. battery and fuel, it is denoted a hybrid. Several different hybrid architectures exist but the main delimitation is if the ICE is mechanically connected to the wheels, together with an EM this is called parallel hybrid, or if it is only used together with a generator to produce electrical power, i.e. series hybrid. There also exist combinations of the two denoted series-parallel or power split hybrids.

In a diesel-electric powertrain the architecture is that of a series hybrid, but without an energy storage. This means that a generator is mounted on the output shaft of the diesel engine and that the ICE-generator combination (GenSet) produces electrical power to the motors that propel the vehicle.

These complex powertrains all have in common that they have at least one extra Degree of Freedom (DoF) compared to the conventional powertrain, EM torque in a parallel hybrid, generator power and engine speed for series hybrid and engine speed for the diesel-electric powertrain. In order to realize the full potential of the powertrain this DoF needs to be exploited, which requires a sophisticated control system optimizing the energy flow. The size of the battery also has a strong impact on the energy management of the vehicle and required details of the model and control.

General project description

The main objective is to study optimal energy management of electrified powertrains. The level of hybridization has a strong impact on the nature of the models and methods suitable to solve the problem. In the project modeling for optimal control as well as optimal control studies are~~is a~~ central parts.

Achieved results

A controller is designed and implemented for a suggested PHEV Benchmark [4, 5] and is seen to perform well even for unknown driving cycles, requiring a minimum of future knowledge. The suggested controller was the winner of the benchmark [4] but is also further extended to include topography information. This PHEV problem was solved using optimal control methods based on Pontryagins maximum principle also called ECMS. A different approach is used to cope with all degrees of freedom in diesel-electric systems where the energy management is solved with methods and software tools from numerical optimal. Optimal control trajectories for engine, electric machine, and battery are computed for transients where both minimum time and minimum fuel usage are considered [2, 3]. An open model for a diesel-electric GenSet has been developed and validated. The GenSet data was collected together with BAE Systems in Örnsköldsvik, and it is provided for Free Download [6]. Based on the model an optimal control benchmark problem has also been developed and proposed, the benchmark is provided together with two solutions from two different tools for solving numerical optimal control problems [7].

Contribution to hybrid vehicle technology

Several contributions to hybrid vehicle technology have been made. For industry producing off-highway and heavy duty machinery, the main source of power, even in the presence of electrification/hybridization is the diesel engine. How to control the diesel engine in electrified powertrains, with and without energy storage, has received very little attention. In this project both a methodology for how to approach the problems have been developed, and results have been presented showing how to exploit the DoFs. Further a model has been made freely available for the academia and industry to conduct their own studies, and an optimal control benchmark has been suggested, aimed at assisting in the development of new optimal control tools.

For passenger cars, and especially plug-in hybrid electric vehicles, the main contribution is a control methodology showing how close to optimal performance can be achieved using only information available in a GPS.

Uniqueness and news value

The project has shown the benefits of electrification and hybridization also for the off-highway industry, both developing a methodology for how to solve the problems, and showing what the benefits are of different levels of electrification. These topics have received very little attention from the research community. A further novelty is showing ~~but~~ both academia and industry that complex optimal control problems of the size seen in the project, can be solved using numerical optimal control, advancing the use of these methods.

The energy management controller suggested for a plug-in hybrid electric vehicle is shown to be the best performing controller in the IFP PHEV benchmark, showing a methodology to implement close to optimal energy management using a minimum of future knowledge.

Timing and finance

PhD thesis defended 5th of June 2015

The total project budget is SEK 0.675 million, 0.675 of which is funded by SHC.

Executors and collaboration

The main project executor is PhD student Martin Sivertsson, with support by main supervisor Lars Eriksson and project leader Lars Nielsen. There is also a Chalmers sister project lead by Bo Egardt. A paper [5] is published together with several of the leading universities in the field of energy management for hybrid electric vehicles. The measurements for the model in [6] was conducted in collaboration with BAE Systems in Örnsköldsvik.

Dissemination of Results

In order to spread the results of the project, how to bridge the gap between numerical optimal control and real-time energy management of hybrid electric vehicles, a new mandatory task has been included in the master's course TSFS03 Vehicle Propulsion Systems at Linköping University. In the task the students are required to design an energy management controller for a quasistatic model of a parallel hybrid vehicle using equivalent consumption minimization strategy. Focus is on real-time implementation and also how the achieved solution relates to the global optimum that can be computed offline, highlighting the effectiveness and simplicity of the real-time method suggested in the project.

Further the results have been spread to master's students at Linköping University, through seminars showing how real-time control based on optimal control theory can be implemented in practice for hybrid electric vehicles.

Papers and publications

[1] Optimal Control of Electrified Powertrains
Martin Sivertsson
PhD Thesis, defended on 5th of June 2015

[2] Optimal Transient Control Trajectories in Diesel-Electric Systems Part 1: Modeling, Problem Formulation and Engine Properties
Martin Sivertsson and Lars Eriksson
Journal of Engineering for Gas Turbines and Power 137(2), 2015

[3] Optimal Transient Control Trajectories in Diesel-Electric Systems Part 2: Generator and Energy Storage Effects
Martin Sivertsson and Lars Eriksson
Journal of Engineering for Gas Turbines and Power 137(2), 2015

[4] Design and Evaluation of Energy Management using Map-Based ECMS
Martin Sivertsson and Lars Eriksson
Oil & Gas Science and Technology – Rev. IFP, 2014

[5] A Control Benchmark on the Energy Management of a Plug-In Hybrid Electric Vehicle
A. Sciarretta, L. Serrao, P. C. Dewangan, P. Tona, E. N. D. Bergshoeff, C. Bordons, L. Charmpa, Ph. Elbert, L. Eriksson, T. Hofman, M. Hubacher, P. Isenegger, F. Lacandia, A. Laveau, H. Li, D. Marcos, T. Nüesch, S. Onori, P. Pisu, J. Rios, E. Silvas, M. Sivertsson, L. Tribioli, A.-J. van der Hoeven, and M. Wu
Control Engineering Practice 29, 2014

[6] Modeling for Optimal Control: A Validated Diesel-Electric Powertrain Model
Martin Sivertsson and Lars Eriksson
SIMS 2014 - 55th International Conference on Simulation and Modelling. Aalborg, Denmark.

[7] An Optimal Control Benchmark: Transient Optimization of a Diesel-Electric Powertrain
Martin Sivertsson and Lars Eriksson
SIMS 2014 - 55th International Conference on Simulation and Modelling. Aalborg, Denmark.

Swedish Electric & Hybrid Vehicle Centre
Chalmers University of Technology
Hörsalsvägen 11, level 5
SE-412 96 Göteborg

Phone: +46 (0) 31 772 10 00
www.hybridfordonscentrum.se