SHC PROJECT SUMMARY REPORT

Over actuated fault-tolerant HEVs

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Summary

This project started in 2009 and ended 2015 and was made in collaboration with Volvo Cars, AB Volvo and BAE Systems Hägglunds (during the first phase). The challenges of the trends in chassis and driveline electrification in combination with the continuing growth of individual road transport have led to the research objectives of this project. The goals of this research are to characterize the influence of different failure modes on the dynamic behaviour of vehicles and the associated driver-vehicle interaction as well as developing fault-tolerant control strategies for compensation of these failure modes.

The central research question is formulated as follows: *To what extent influence different failure modes the dynamic behaviour of vehicles and driver reactions, and how can severe failure modes be prevented by exploiting over-actuation through fault-tolerant control strategies?*

Since particular focus is on HEV concepts where propulsion power is obtained from in-wheel motors at each wheel an important initial task was to present an electromagnetic design of a light in-wheel motor to fulfil the required specifications. As a result from the motor design procedure, various transient models have been obtained which accurately predicts the behaviour of the motor during various types of electrical faults and control methods. These transient models, and simplified versions of them, have been used in various vehicle simulations to predict vehicle behaviour for different vehicle control strategies during failure modes. A method to assess possible risks of failures has been proposed and evaluated. Possible consequences on the dynamic behaviour of the vehicle caused by the identified faults have been analysed, and solutions on to how to compensate for the occurring faults have been developed. As an example, if the propulsion power suddenly vanishes from one wheel of a vehicle, the remaining vehicle, can, if properly controlled, maintain vehicle stability and thereby guaranteeing passenger safety. Also the effect of including drivers in the loop has been studied.

Background

Today, it is apparent that the hybridization of vehicle drivelines provides a mean for lowering the fuel consumption, thereby reducing the environmental impact of the vehicle. Several electric and hybrid-electric driveline configurations also offer other advantages including an improved maneuverability and an increased passenger safety. However, the introduction of drivelines containing power electronics and electric machines also raises important questions concerning reliability and behavior during electrical faults which, indirectly, affects passenger safety. The overall goal of this project is to analyze the impact of failure modes (caused by electrical and other faults) and the degree of in-built fault-tolerance for different vehicle control strategies in electric and hybrid-electric drivelines. Particular focus is on HEV concepts where propulsion power is obtained from in-wheel motors at each wheel. The solutions will be depending on which forces that do occur and which sensors and actuators that are available. The vehicle control strategy will also be depending on actual type of failure mode. Finally, verifying measurements of the level of fault-tolerance for various vehicle control algorithms on a vehicle prototype are made.

General project description

This project has focused on the three themes fault, driver and control, resulting in the following aspects:

• Classification of faults in electric vehicles

– Which faults are relevant for vehicle stability?

– How severe is each fault and what is its influence on the dynamic behaviour of electric vehicles?

– What method can be used for classifying faults according to controllability?

• Control strategies for fault handling

– How can the vehicle stability under a failure condition be improved?

– How do over-actuation and fault-tolerant control approaches come into play?

– How does a suitable fault-tolerant control strategy influence the driver behaviour?

• Driver-vehicle behaviour during a failure condition

– How do drivers react to a critical failure mode?

– Can driver behaviour be generalised based on di↲erent failure conditions?

– How can the driver behaviour during a failure condition be modelled?

– How does the driver react to a failure when fault-tolerant control is implemented?

Achieved results

- A broad failure mode and effect analysis for an electric vehicle with wheel hub motors is presented. The focus is on the electric driveline with a newly designed permanent magnet synchronous machine purposely developed for automotive wheel hub applications.
- Fault models applicable for vehicle dynamic simulations have been derived for various faults to be able to analyse their effects on the vehicle stability.
- A fault classification method is developed to determine the influence of a fault on the vehicle, compromising traffic safety. Three indices are developed to cover and detect all possible vehicle responses for longitudinal, lateral and yaw motion, namely vehicle stability index, lane keeping index and collision avoidance index. The controllability of all three indices is classified according to ISO 26262 and merged in a final fault influence index.
- Three control strategies are proposed in order to compensate for faults. These fault handling strategies, which are based on the control allocation method, are implemented, analysed and compared in a simulation environment for a specific electric vehicle and its faults. Two manoeuvres were tested, where one of the reaches the actuator limitations. The optimal control allocation algorithm can handle the fault for both manoeuvres

without deteriorating vehicle stability. The two simplified control allocation approaches perform well as long as the actuator limits are not reached. Under real-time conditions, only the simplified methods are fast enough to produce applicable results.

- The fault handling capability of one of the simplified control allocation strategies is verified with an experimental vehicle. This pseudo-inverse control allocation method reduces the effect of a fault on the vehicle directional stability and supports the vehicle in following its intended path. Considerable improvements are made despite restrictive actuator limitations.
- Driver-vehicle interactions during a wheel hub motor failure are analysed for two experimental studies in a moving-base driving simulator and an electric vehicle on a test track. The wheel hub motor failure is initiated at motorway speed in the driving simulator study and at urban speed for the field study. The fault classification method reaches high controllability classes for the manoeuvres at motorway speed, while the urban speed is not as critical.
- A method for deriving driver reaction times to a fault is presented and applied to measurement data of two experimental studies. The average steering wheel reaction time is found to be at 0,55 s for the motorway manoeuvres, while it reaches XX s for the urban manoeuvres.
- A failure sensitive driver model is developed based on the experimental study in the driving simulator. The behaviour of this driver model imitates the measured driver responses and can be applied for failures during straight line driving and cornering manoeuvres.
- The driver-vehicle interaction in combination with the pseudo-inverse control allocation strategy improved vehicle directional stability and path holding considerably. The fault handling strategy supports the driver by reducing the necessary steering effort and yaw compensation if a fault occurs.

Contribution to hybrid vehicle technology

The work presented in this work is aimed to improve the vehicle safety of electric and hybrid electric vehicles. The implementation of new electric driveline systems can lead to unforeseen failures, resulting in unpredictable vehicle behaviour and threaten passengers and other traffic participants. These potential failures have been analysed and classified in a systematic approach regarding their consequences on the dynamic behaviour of the vehicle. Strategies to compensate for the failures are developed, enabling the vehicle to come to a safe stop. Driver behaviour during different failure conditions has been studied and a failure sensitive driver model is developed based on this driver behaviour.

The project has contributed to SHC deliverables with 1 PhD, 1 Lic. Tech, 4 international journal paper publications and 9 refereed conference articles. Among them international collaborations are shown by 1 co-authored journal paper and 3 refereed conference papers. Two co-authored journal papers and 1 conference proceeding confirm the industrial relevance. The multi-disciplinary collaborations are shown in 3 co-authored journal papers and 6 conference proceedings with researchers from other disciplines (Psychology and Electrical engineering and power electronics). And also 3 papers is co-authored with a researcher from another Swedish research provider (VTI).

The project also has contributed to the aims of Theme 1 within SHC since it has:

- Developed, adapted and evaluated methods that supports virtual development of hybrid systems, based on mathematical models of components and systems.
- Developed, adapted and evaluated methods and algorithms for modeling, control and optimization of hybrid systems.

Uniqueness and news value

See *Achieved results* above.

Timing and finance

Project timing: 2009-08 – 2015-06

Funding was provided by the Swedish Hybrid Vehicle Centre (SHC), and the European Commission and VINNOVA through the research program EVERSAFE (ERA-NET Electromobility+). Total cash budget from SHC: 4500 kkr

Executors and collaboration

This research has been carried out at KTH Vehicle Dynamics at the Department of Aeronautical and Vehicle Engineering, School of Engineering Sciences, Kungliga Tekniska Högskolan (KTH) in Sweden. The research by the PhD student Daniel Wanner has been funded in this project. Project leader and main academic supervisor was Professor Annika Stensson Trigell. Also the academic advisors Associate Professor Lars Drugge at KTH and Dr. Mats Jonasson at Volvo Cars have contributed to the project results. Also the collaboration with Associate Professor Oskar Wallmark at KTH Electrical Energy Conversion has been very valuable. Also, the work of various Master students at our division is gratefully acknowledged and has undoubtedly enriched this work.

This project has had the same steering group as the sister project “Generic vehicle motion modelling and control for enhanced driving dynamics and energy management” with PhD student Johannes Edrén. Members of this steering group have contributed to the results (Oskar Wallmark and Mats Leksell from Electrical machines and power electronics at KTH, Leo Laine at AB Volvo, Olof Noreus at BEA Systems Hägglunds (during the first phase), Gunnar Olsson and Mattjis Klomp from Saab Automobile and Mats Jonasson at Volvo Cars). Jonasson has contributed a lot to the project, especially regarding detailed vehicle models, experimental data, approaches to control allocation, many ideas for control strategies and interpretation of industrial relevance of the findings.

The collaboration within the project EVERSAFE has also been very valuable. Especially the precious lessons on traffic psychology and the great hospitality during the visit in Chemnitz given by Isabel Neumann, Maria Kreußlein and Peter Cocron is appreciated. Also the precious technical discussions and valuable inputs from Maxim Bierbach and Patrick Seiniger at the Federal Traffic Research Institute (Bast) and from Bruno Augusto and Fredrik Bruzelius at the Swedish National Road and Transport Research Institute (VTI) have been very valuable to the results.

During the final experimental studies at KTH, Petter Tomner at the Integrated Transport Research Lab (ITRL) assured that the prototype vehicle was prepared in time. Together with Mikael Nybacka, they were valuable assets supporting the coordination and setting up the experimental vehicle. The assistance of Danilo Prelevic during the design of the additional brake system certainly improved the quality of the experiments.

Papers and publications

Journal publications:

“Fault classification method for the driving safety of electrified vehicles”. Wanner, D., Drugge, L. and Stensson Trigell, A. Vehicle System Dynamics, Vol. 52, No. 5, pp. 704–432, 2014.

“Control allocation strategies for an electric vehicle with a wheel hub motor failure”. Wanner, D., Jonasson, M., Wallmark, O., Drugge, L. and Stensson Trigell, A. International Journal of Vehicle System Modelling and Testing, 2015 (in press).

“Analysis and evaluation of force allocation strategies in an electric vehicle with in-wheel motors”. Wanner D., Edrén J., Wallmark O., Jonasson M., Drugge L. and Stensson Trigell A. Submitted for publication, 2013.

“Single wheel hub motor failures and their impact on vehicle and driver behaviour”. Wanner, D., Kreusslein, M., Augusto, B., Drugge, L. and Stensson Trigell, A.: Submitted for publication, 2015.

Publications in conference proceedings:

“Survey on fault- tolerant vehicle design”. Wanner, D., Stensson Trigell, A., Drugge, L. and Jerrelind, J. Proceedings of the 26th Electric Vehicle Symposium (EVS26), Los Angeles, USA, May 6–9, 2012.

“Fault-tolerant control of electric vehicles with in-wheel motors through tyre-force allocation”. Wanner, D., Edrén, J., Jonasson, M., Wallmark, O., Drugge, L. and Stensson Trigell, A., Proceedings of the 11th International Symposium on Advanced Vehicle Control (AVEC 12), Seoul, Korea, September 9–12, 2012.

“Influence of vehicle parameters on directional stability during electric powertrain faults in passenger cars”. Wanner, D., Drugge, L. and Stensson Trigell, A. Proceedings of the FISITA World Automotive Congress, Maastricht, The Netherlands, June 2–6, 2014.

“Wheel hub motor failures and their impact on the driver”. Kreusslein, M., Cocron, P., Neumann, I., Pereira, M., Augusto, B., Wanner, D. and Krems, J.F. Proceedings of the European Conference on Human Centred Design for Intelligent Transport Systems (HUMANIST), Vienna, Austria, June 5–6, 2014.

“Experimental study on single wheel hub motor failures and their impact on driver-vehicle behaviour”. Wanner, D., Neumann, I., Drugge, L., Cocron, P., Bierbach, M. and Stensson Trigell, A. Accepted for publication in the Proceedings of the 17th International Conference on Advanced Vehicle Technologies (AVT), Boston, USA, August 2–5, 2015.

“Design and experimental evaluation of a fault-tolerant control strategy with and without driver in the loop”. Wanner, D., Drugge, L. and Stensson Trigell, A. Accepted for publication in the Proceedings of FASTzero2015, Gothenburg, Sweden, 2015.

“Fault handling strategy in an electric vehicle with four wheel hub motors”. Wanner, D., Nybacka, M., Wallmark, O., Drugge, L. and Stensson Trigell, A. Accepted for publication in the proceedings of the 24th International Symposium on Dynamics of Vehicles on Road and Tracks, Graz, Austria, August, 17–21, 2015.

“Single wheel hub motor failures and their impact on vehicle and driver behavior”. Wanner, D., Kreusslein, M., Augusto, B., Drugge, L. and Stensson Trigell, A.: Submitted for publication 2014.

“Regenerative braking failure in an electric vehicle”. Wanner, D., Drugge, L., Stensson Trigell, A., and Bierbach, M. To be submitted, 2015.

Licentiate Thesis:

“Faults and their influence on the dynamic behaviour of electric vehicles”. D. Wanner, Licentiate thesis TRITA-AVE 2013:48, Oct. 2013.

Doctorate Thesis:

“Controlling over-actuated road vehicles during failure conditions”. D. Wanner. Doctoral thesis TRITA-AVE 2015:23, June 5, 2015.

Other Publications:

“Driver and vehicle behaviour to power train failures in electric vehicles – experimental results of field and simulator studies”. M Cocron, P., Neumann, I., Kreusslein, M., Pereira, M., Wanner, D., Drugge, L., Bierbach, M. and Augusto, B. Deliverable of ERA-Net Elecromobility+ project EVERSAFE – Everyday Safety for Electric Vehicles, August, 2014.

“What happens if electrified vehicles fail?”. D. Wanner. Smarta Fordon Conference, Stockholm, Sweden, Jan. 2013.

“Fault tolerant generic vehicle control”. D. Wanner and J. Edrén. Vehicle Dynamics Challenges – SAFER & SVEA Seminar, Gothenburg, Sweden, May 2013.