SHC PROJECT SUMMARY REPORT

T2:2 Sensorless Control of PMSynRel Machines in a Plug-in Hybrid Electric Vehicle Application

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Summary

The presented projected is an integrated part of Theme 2's main project on Electrical drives for electric and hybrid electric vehicles. The overall aim is to study possibilities for enhancing the electrification of the drive trains by making the electrical parts more feasible, especially from a cost point of view.

In this project, an integrated charger concept and sensorless control techniques are considered and investigated. Dynamic models of the integrated charger concept in consideration are developed, which not only provides valuable insights of the concept but can also be used for controller design and tuning.

To enable stable sensorless control over a wide speed and torque range, sensorless control techniques are thoroughly investigated and analysed. Challenges due to the high torque demands are highlighted and solutions are proposed. A special but very important issue is how to achieve robust rotor polarity detection for the PMSynRel machine in consideration and a method is proposed and analysed.

To experimentally evaluate sensorless control in PHEV applications, an off-vehicle test bench is implemented. Torsional oscillations and active damping schemes are studied and evaluated in the test bench. The result is used for predicting the impact of sensorless control in active damping schemes.

The project has worked closely with the other participating universities (CTH and LTH) and has been supervised by a reference group incorporating the industrial partners. The project started 2008 and ended 2013. The finance came from SHC and amounted to 1220kkr p.a.

Background

This project focuses on the cost reduction and reliability improvement of an electric drive equipped with a PMSynRel machine for a PHEV application.

The PMSynRel machine, combining the advantages of permanent-magnet synchronous machines and synchronous reluctance machines, is an attractive machine topology in PHEV applications and is considered in this project. Moreover, apart from being a traction motor, the PMSynRel machine in consideration can also be operated as a motor/generator set when charging the battery from the grid. This special use of the PMSynRel machine, known as an integrated charger, enables the elimination of a heavy and costly transformer from the charging system. In this project, modelling of the motor/generator set is conducted to obtain a better understanding of this novel concept.

When operating for traction, the inherit advantages of PMSynRel machines, such as a high torque/power density and a high efficiency, can only be achieved via proper control, which requires the knowledge of rotor position. Therefore, a mechanical position sensor is often mounted on the rotor shaft to detect the rotor position. Apart from the increased axial length and cost, the reliability of the overall system is reduced by the potential failure of the position sensor and the associated cabling. An alternative solution is to implement position estimation (sensorless control) techniques which utilize the voltage and/or the current measurements to indirectly detect the rotor position instead of using the physical position sensor. By doing so, the cost reduction and reliability improvement can be achieved.

To introduce sensorless control in PHEV applications, position estimations must be stable over the whole speed range. Therefore, sensorless control techniques are thoroughly investigated and analysed in this project. Challenges of sensorless control appearing at low-speed range due to high torque demands are highlighted and solutions are suggested. Torsional drive-train oscillations and active damping schemes are also considered in this project. Of particular interest for sensorless operation in automotive applications, the impact of slow speed estimation on the possibility of achieve good active damping control is investigated and a design approach that allows the implementation of an active damping scheme using estimated speed is suggested.

General project description

Sensorless control has been researched for a long time and can today be said to be fairly well-known for standard drive systems, however, it is not used to any larger extent in vehicle applications. In this project, emphasis is put on aspects that are important when sensorless control is implemented in a drive train , e.g. for a passenger car.

When implementing sensor less control for a hybrid vehicle, special care has to be put on the starting conditions. In a hybrid vehicle the electrical machine is often used to crank the engine. This only takes part of a second and the machine is therefore pushed to its limit when it comes to delivering starting torque. The high current will most likely make the electromagnetic circuit highly saturated and this makes the sensorless difficult to guarantee.

In the project various sensorless methods are investigated and evaluated. The two most important rely on injection of a rotating or a pulsating voltage vector. The analysis requires detailed models and intensive FEM simulations are conducted to create dynamic models of the electrical machine and also to create models that can be used to compute control parameters.

The analysis gives as a result the possibility to in graphical form show the capability of the drive system. As an example, Fig. 1 shows the feasible region for sensorless control for the integrated charger that has been used in this project.

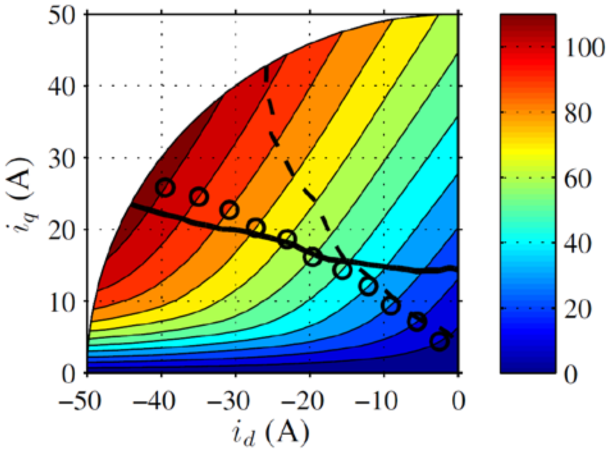

Fig. 1. Feasible operating region for the integrated charger. The i_d/i_q-combinations below the solid line can be operated sensorless. Circles shows optimal current trajectory for maximum torque per ampere (MTPA). Colour bar indicates the torque.

Another important aspect for vehicle implementation is to know the initial position of the rotor so that the control can make sure that the rotor and thereby the vehicle always moves in the desired direction when started. The detection of the initial position is done by identifying the polarity of the magnets mounted on the rotor. The normal procedure is again to inject a voltage vector, but the result must take into account the exact design of the magnetic structure of the rotor. The analysis of the integrated charger reveals an inverse behaviour of the polarity and therefore suitable measures must be taken.

All theoretical findings have been implemented and verified in a laboratory test set-up.

The last part of the project investigated oscillations in vehicle drive trains. These oscillations, which occur primarily at low speed, can severely reduce the comfort of the vehicle. The project has analysed a simplified system, see Fig. 2, and proposes mitigation methods for the un-wanted torsional oscillations.

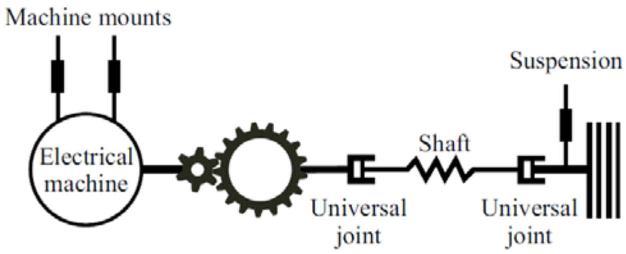

Fig. 2. Mechanical model of an electrical drive train.

Achieved results

The achieved results are reported in scientific publications and are also summarised in the doctoral thesis by Shuang Zhao. The proposed methods for sensorless control in hybrid vehicles offers a solid foundation for designers of electrical drives to be used in e.g. passenger cars. High-lights of the results can be summarised as follows:

- Two dynamic models of the integrated charger concept are developed, which can be helpful for controller design and tuning.
- An experimental mapping technique is proposed which can be implemented to find the feasible region for a stable sensorless operation.
- A particular case when detecting the rotor polarity to initiate a proper sensorless control at low-speed region is presented.

- Means to extend the maximum torque achieved for sensorless operation at low-speed are proposed. The output torque is increased from 45% to around 95% when operating sensorless.
- A test bench that can emulate torsional oscillations in a drive-train is proposed. The setup can be used to tune an active damping controller. The proposed approach can be attractive for evaluating various control schemes outside a vehicle environment.
- Aspects to implement a sensorless active damping scheme are investigated. A method for tuning the electric drive outside a vehicle environment is detailed.

Contribution to hybrid vehicle technology

The outcome of this project can be used as a guideline when implementing sensorless control in electric and hybrid electric applications. It also points out a potential failure of rotor polarity detection for some rotor designs but solutions are suggested.
Applying proposed methods, the maximum output torque of a sensorless-controlled electric drive can be significantly increased without manipulating the machine design and the hardware of control system.
The proposed test bench can be helpful when designing and tuning active damping control schemes outside a vehicle environment.
This project highlights the limitation of speed estimation in an active damping control scheme. Means to improve a sensorless-controlled active damping control are proposed.
Using the results of the project has the potential to create a proper implementation of sensorless control in hybrid vehicles and this will make the systems cheaper without jeopardizing the safety.
SHC has as a goal to facilitate introduction of electric- or semi-electric vehicles which will lead to an increased efficiency and thereby lower total energy consumption. A reduced cost of the vehicles will make a massive introduction of energy-efficient vehicles easier.

Uniqueness and news value

The uniqueness of the project lies in the highly relevant aspects that has been analysed for implementation of sensorless control in vehicles. Sensorless control will make mechanical transducers superfluous and this will not only reduce cost thanks to the reduced number of components on-board, but it will also increase the inherent safety thanks to a reduced need of cabling and mechanical mounting.

Timing and finance

The project was financed from 2008 until 2013.

Executors and collaboration

The project has been a part of the grand project of Theme 2 in SHC. It has shared reference group with the other sub-projects and has contributed to vivid collaboration between the participating universities.

Papers and publications

S. Zhao, S. Haghbin, O. Wallmark, M. Leksell, S. Lundmark, and O. Carlson, “Transient modeling of an integrated charger for a plug-in hybrid electric vehicle,” in *Proc. 14th European Conference on Power Electronics and Applications (EPE)*, 2011.
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S. Zhao, O. Wallmark and M. Leksell, “Low-speed sensorless control with reduced copper losses for saturated PMSynRel machines,” accepted for publication in *IEEE Transactions on Energy Conversion*.

S. Zhao, A. Lasson, O. Wallmark, and M. Leksell, “Off-Vehicle evaluation of active oscillation damping schemes,” in *Proc. IEEE Energy Conversion Congress and Exposition (ECCE)*, 16-20 September, 2013. The revised version included in this thesis is accepted for publication in *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

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S. Nategh, O. Wallmark, M. Leksell and **S. Zhao**, “Thermal analysis of a PMaSRM using partial FEA and lumped parameter modeling,” in *IEEE Transactions on Energy Conversion*, vol. 27, no. 2, pp. 477-488, June 2012.

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