xEVCO

Final report English, public part

    

Project within Energy and Environment

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FFI

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: *Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.*

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Executive summary

The xEVCO project was conceived in 2010 to increase the knowledge base on hybrid electric vehicles in the Western Sweden automotive engineering cluster. This cluster contains government agencies, Universities, Research Institutes, contracting companies as well as system and component suppliers to Volvo Car Corporation. The project was run by Volvo Car Corporation with SP and Chalmers participating as active, contributing partners to the project.

Ultimately the objective for the project is to secure Volvo and Sweden's competitiveness as a competent and efficient (P) HEV provider. It is necessary to have this technology in your product portfolio for several reasons if you wish to remain a competitive alternative in the global automotive market.

The core task of xEVCO has been to develop models for virtual validation and verification of all the major components, their properties, functions and attributes to make up a complete PHEV drivetrain including the battery. Models are used for concept development and concept choice and further along for validation and verification of properties and attributes. By using virtual techniques such as modeling and simulation, the ever shorter vehicle program lead times can be met and costs can be reduced significantly. The models are used in various simulation environments such as Model-In-the-Loop, Software-In-the-Loop and Hardware-In-the-Loop. xEVCO has brought these techniques forward significantly and they are now considered state-of-the-art working practice at Volvo Cars.

The engineering development modeling and simulation methods for PHEV vehicles derived from xEVCO have now been put into context with the traditional vehicle development methods. This project has contributed vastly to secure concept development in phase with the base programs meeting the necessary extremely short lead times in this very competitive industry. It is now almost possible to develop a HEV in the same time frame as a conventional ICE powered vehicle.

The use of modern modeling and simulation techniques developed in xEVCO support the Green, Safe and Connected functionality that today's customers require.

Although a lot of significant progress has been made in the project there is still a number of remaining issues that require further research. Examples can be found within understanding thermal management and DC ripple phenomena especially. There are also aspects of the developed models that need validation testing to understand the scope that results can be scaled in.

Background

Today, vehicle electronics accounts for about 20-30% of a vehicle's production cost. The plug-in HEVs adds another 10%. High cost PHEVs require a balanced top-down design involving "Green, Safe & Connected" functionality. xEVCO responsible for part of the method development required to meet the challenge.

Objective

To raise the level of knowledge and to broaden the recruitment base of hybrid technology personell in the western Swedish competence cluster in view of second-generation hybrid system for launch in 2017.
Enable skilled interfaces between 'traditional mechanical vehicle development "and" future electric vehicle development. "
Develop deep knowledge in:
o Vehicle control with focus on Functional-logical view, energy balance, transient states.
o Electric drive & battery systems with a focus on models and characteristic parameters during vehicle operation.

Dedication

This report is compiled from a number of individual reports written by the team members from Volvo Cars, Chalmers and SP who participated in the xEVCO project. I wish to thank them all for all their good work and effort to make this a successful and happy project. It has been a true pleasure to work with you all. I also want to thank Vinnova/ FFI for giving us the opportunity to carry out the project. It is my sincere belief that the results from the project will benefit us all for years to come.

Malcolm Resare

Project realization

WP1 Model factory

Introduction

The following chapter aims at conclude the work performed in work package 1 at Volvo Car Corporation as a part of the xEVCO project. Focus has been on models in the second domain and an important part has been to develop processes and guidelines to ensure the quality on the models.

Process

To use simulation and simulation models as a tool in a large and complex more than mere models are needed. A process for documentation, maintenance and specification and last but not the least a *validation* process is necessary to control quality and confidence of the models.

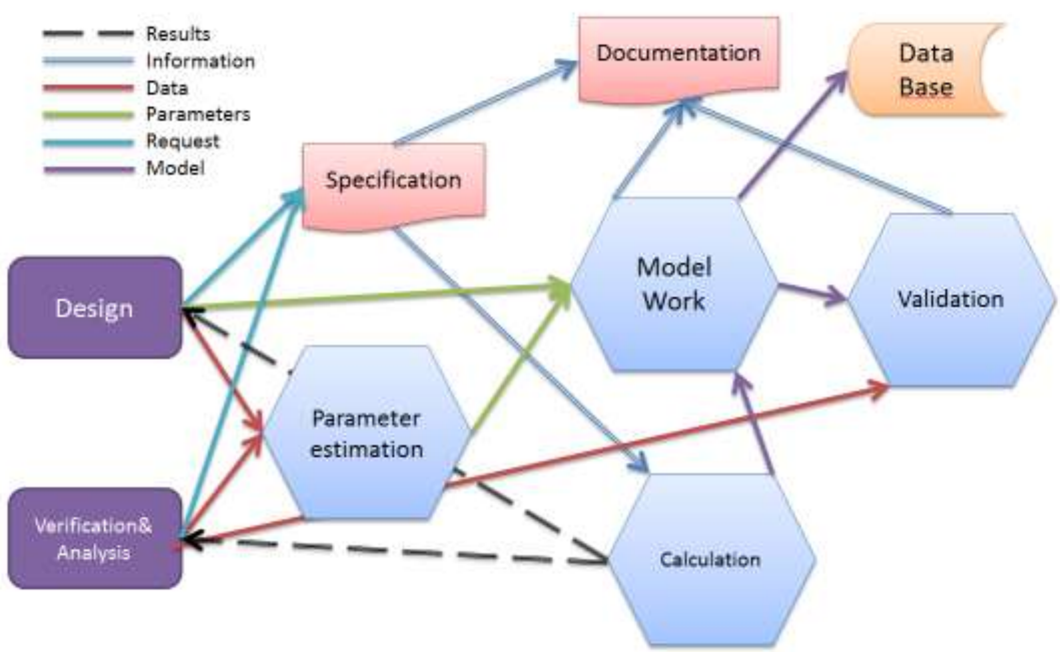

FIGURE 1, EXAMPLE ON WORK FLOW WITHIN AN ORGANIZATION WHICH EMPLOYS SIMULATION AND SIMULATION MODELS IN TECHNICAL DESIGN WORK

In the project templates for documentation and specification have been produced and a tool for model validation been developed. The need for simulation models within the organization and a data base for documentation of the modelling work have been established, see Figure 1 an example of a work flow.

Plant models

A plant model is a model of a physical component or sub system of physical components.

Examples on plant models developed within the xEVCO project

The battery is a complex component and several models are needed for different aspects. Examples on model needs are; estimation of driving range and fuel consumption in a hybrid vehicle which only require a very simple model, test of software will often require a more dynamic model and estimations of long term behavior of the battery which require measurements on long term. Models can also be used to evaluate limitations in use of the battery which might be necessary for the long term life of the battery but will degrade the performance of the total system, to estimate the temperature of the model in different ambient temperatures and models can be used to evaluate battery sizes, concepts and different types of battery cells.

As for the battery different simulation needs will result in models of different complexity also for the electric machines. Examples on simulation needs are; fuel consumption simulations, dimensioning issues and estimation of component used on different drive cycles, test of software and the result of different limitations in the machine. More complex models may be used to evaluate not only concepts on a vehicle level but also more detailed evaluations of the machine construction, e.g. the positioning of magnets, different cooling concepts and materials.

FIGURE 2, DRIVE PACK WITH ELECTRIC MACHINE, CONVERTER AND CLUTCH

Fewer model needs has, at the moment, been identified for the charger than for batteries and electric machines. There are indication on that the need for models will increase in the future, since the whole energy chain from grid to road needs to be certified.

For the dcdc-converter the modelling need is similar to that of the charger. A simple temperature model has been developed and the efficiency is important for estimation of fuel consumption.

To test electric control units before actual use in a vehicle a hardware-in-the-loop (HiL) rig is used. During the years the xEVCO project has been running several HiL rigs have been developed and the project has delivered models of electric machines, batteries and of the dc-link and the communication between the components. The models have been integrated in the environment and are in daily use in the test and verification activities.

Tool evaluation

The work package has also evaluated two commercial computer tools; Ansys Maxwell for electro-magnetic simulations and Mathworks Simscape with is a tool for multidomain simulations. Both tools are under development and we have had he possibility to give feedback and comments to improve usability and functionality.

Conclusions

The xEVCO project has delivered a large and important contribution to the knowledge about simulation models within electrification, a new area, to Volvo Car Corporation. Not the least in the areas of understanding which models we need and which levels of complexity are available and necessary.

Future Work

Several areas has been identified as interesting for future work

- The processes could be improved further especially regarding validation of models
    - More measurements
    - Which kind of measurement are needed to do a good validation
- Parameter studies and sensitivity analyses of models and systems
- Battery models for high frequency behavior, an important feature for studies of current ripple
- Battery models for cold conditions, below -5 centigrade
- Further develop the possibility to run models and hardware together in rigs, which enables early tests and to optimize software on an earlier stage
- The charge procedure which demands for a new view of the system since most of simulations made up to date is aimed at a vehicle in motion

xEVCO WP2:1 Transient electrical events and the micro second domain

Background

The focus on the work package is on modeling the drive system with transient models (micro-seconds) and suggesting fault-tolerant solutions that are also cost effective, environmentally friendly and comparable in performance to other same-size drive systems for plug-in hybrid electric vehicles.

The transverse flux machine (TFM) has only recently been considered for vehicle applications. It is known to be able to give high torque density and has a possibility of being fault tolerant (and may be favourable regarding recycling aspects).

Regarding cost, the comparison is difficult and is often based on material and manufacturing cost in general terms.

Objectives and Project Realization

Two motor types, the synchronous machine with internal permanent magnets (IPM motor) and the transverse flux machine (TFM), are modelled and compared with the intention to investigate several aspects like fault tolerance, efficiency, and torque density. The IPM motor is the 2004 Prius IPM motor which is chosen as a reference motor that allows validation of the models. In the models it is a possibility to investigate the effect of different pole numbers, skewing of the stator, open-circuit and short-circuit faults, losses (including permanent magnet loss) and thermal effects. The models include both 2D and 3D effects.

Results and deliverables

The results of finite element simulations of the electromagnetic properties (previously validated against measurements) show that in comparison with a commercial motor (the IPM motor), the TFM has similar performance, a higher core and magnet weight and a lower copper weight. It also has an expected advantage regarding manufacturing cost and cost of recycling and it has lower copper loss.

Publications

1. S. Lundmark, Alatalo, M., Mellander, B.E., Thiringer, T., Grunditz, E. (2013) “Chapter 3 in the e-book: Systems perspectives on Electromobility” Book Chapter.
2. Sonja Tidblad Lundmark and Mikael Alatalo (2013) “A segmented claw-pole motor for Traction Applications Considering Recycling Aspect”, EVER Conference on Electrical Vehicles and Renewable energies, Monte Carlo, Monaco, paper *EVER13-73*, 27-29 March 2013.
3. Palmberg, Eva; Lundmark, Sonja; Thiringer, Torbjörn; Alatalo, Mikael; Karlsson, Robert, (2013) “Wireless charging-some key elements”, Research report, Chalmers University of Technology, Department of Energy and Environment, Division of Electric Power Engineering, Göteborg, 69 pages.

4. Sonja Tidblad Lundmark, Ali Rabiei, Tarik Abdulahovic, Stefan Lundberg, Torbjörn Thiringer, Mikael Alatalo, Emma Arfa Grunditz and Christian Du-Bar (2012) "Experiences from a Distance Course in Electric Drives including on-line Labs and Tutorials", the International Conference on Electrical Machines, ICEM, Marseille Sep 2012.

Presentation:

Docent lecture *"Electric Motor Drives for Traction Applications Considering Recycling Aspects"* June 4, Department of Energy and Environment, Chalmers University of Technology

Conclusions and Future work Suggestions

Models for permanent magnet machines are constructed, including 2D and 3D effects, and thermal estimations, allowing possibilities for motor design improvements and comparisons regarding fault tolerance and other motor performance and cost aspects. One such investigation shows the pro and cons of a transverse flux machine, and an internal permanent magnet motor.

Future work may include:

- Include optimization methods to reduce for instance iron core and magnet weight
- Field weakening and drive cycle performance for both type of motors
- Improved thermal modeling and cooling, including CFD for both motor types and comparison with measurements from the PhD project. Also usage of the results from Ansys Mechanical as input to Maxwell, will allow a better model of effects such as demagnetization of magnets due to higher temperature and a better estimation of coil resistance.
- Continued fault modeling comparison with the TFM, the IPM motor and results from the PhD project.
- Coupling to mechanical models would allow estimation of strength of barriers (in the rotor), or other mechanically weak parts of the machine (such as claws in the TFM).
- Calculations of end winding reactance, as it influences fault tolerance and demagnetization aspects.

xEVCO WP2:2 Harmonic analysis of a tracthe DC bus in a drive system.

The purpose of the work-package that covers transient electrical events is to investigate how current and voltage ripple is formed on the high voltage bus that connects the battery pack to the inverters. The main focus lies in how to create a sufficiently accurate simulation model of the entire drive system in a modern hybrid vehicle that includes a high-voltage battery, interconnecting cables, inverters and electric machines. The development of the model was done in close cooperation with Volvocars and adapted for a modern hybrid vehicle. Several measurements were performed on a real system in order to verify the validity of the simulation model over a large operating range. Once the model had been tuned to match the measurements, it was found that the conformity between the simulation model and the measurements were sufficiently good over the desired operating range. Based on this, the model was used to investigate both sensitivity to parameter variations and the effect of a transient event. As a common connection between the different work packages within the xEVCO-project, the input from a fictive active safety system was used as an input to investigate its effect on the DC-bus during a sudden evasive maneuver.

The Electric System within a Hybrid Vehicle and the purpose of Systemization

The electric system in a modern hybrid vehicle is a complex design that consists of many different components that must be able to coexist within a small volume. Factors that complicate the design are that that many of the components are newly developed (e.g. the battery and the inverter - the manufacturers have little experience in long term design), the harsh environment within a vehicle (temperature, vibrations), safety of the electric systems (no failure is allowed) and the low cost, high volume market that forms the automotive market today. These factors make the system aspect extra important; if the system can be optimized so that the lifetime of a component can be increased or a redundant component can be removed, a great profit can be made. A typical system of a drive system is depicted in Figure 1; a high voltage battery feeds an inverter that controls an electric machine. The inverter is typically fed via a long cable which will affect the system performance. A high current ripple on the DC-bus may give unwanted effects (e.g. heating) in the battery which in turn may shorten its lifetime. Hence is it crucial that the voltage and current ripple on the DC-bus can both be predicted with sufficient accuracy and minimized in order to lower the losses.

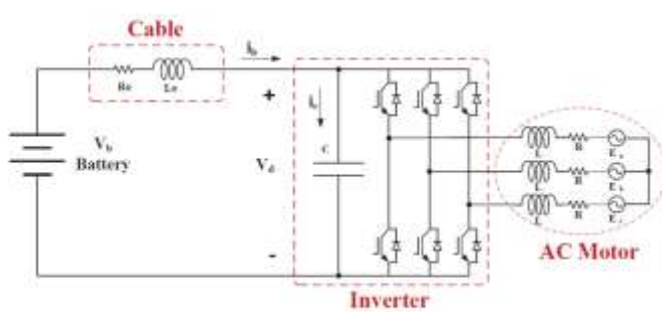

FIGURE 3: SCHEMATIC OF A TYPICAL DRIVE SYSTEM IN A MODERN HYBRID VEHICLE.

Validity of the simulation model

The simulation model that was developed in this project was compared to measurements on a real hybrid vehicle and the results were shown to be sufficiently satisfactory. The AC-quantities (i.e. the output from the inverter) were simulated with very good accuracy; this means that the implemented model of the electrical machine was shown to work well for a harmonic analysis on the AC-side quantities. On the DC-side, the battery current was simulated with good accuracy within the investigated operating range, see Figure 2, left graph. The resulting battery voltage was found to be more difficult to measure; a majority of the oscillations in the measurement are most likely due to measurement interference, but a part of it still needs to be accounted for. The proposed simulation model does not account for smaller parasitic elements which make the simulation model slightly to ideal; more quantified elements and a more detailed model is most likely needed in order to capture the higher frequency oscillations.

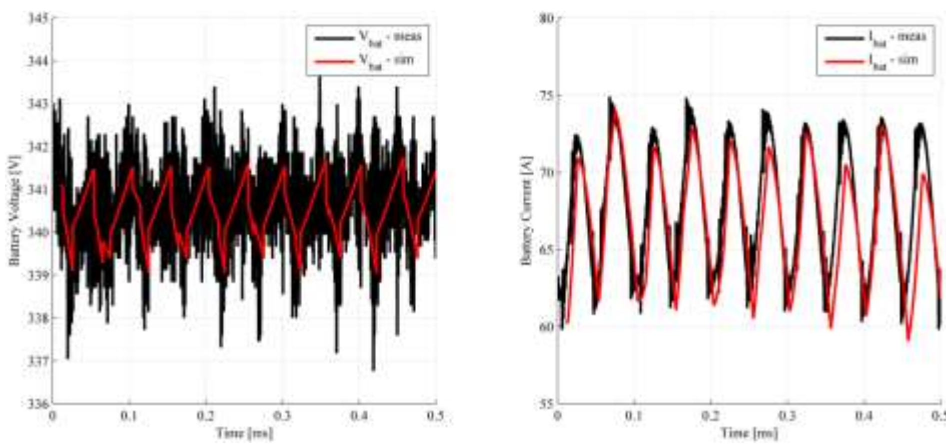

FIGURE 4: LEFT: SIMULATED AND MEASURED VOLTAGE RIPPLE ON THE DC-BUS.
RIGHT: SIMULATED AND MEASURED CURRENT RIPPLE IN THE DC-BUS

What can be analyzed with the model?

Since the proposed model was found to be sufficiently accurate, it was used to investigate two properties; parameter sensitivity and transient events, see Figure 3. The parameter analysis showed that it is the DC-link capacitor in combination with the DC-cable inductance that determines the current ripple on the DC-link. The other system parameters (e.g. cable resistance and battery inductance) were found to have minor effects. Since the model consist of not only a full motor model, but also a full implementation of a full inverter controller where you can change both the controller parameters and the switching strategy, the model can be used to investigate transient events. This means that the behavior on the DC-bus can be analyzed if a sudden torque step is applied on the wheels. An example of this can be an active safety system that controls the electric machine on the rear wheels. The system can e.g. demand a sudden torque increase in order to compensate for a fast evasive maneuver; the effect on the DC-bus can thus be analyzed with the proposed model of the drive system.

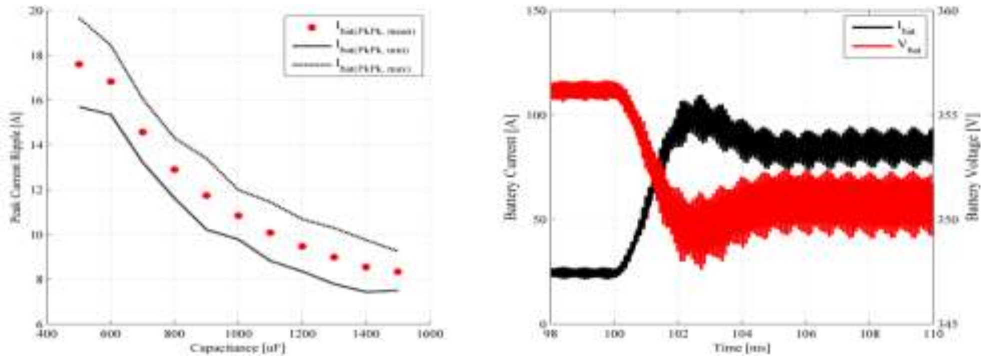

FIGURE 5: LEFT: PEAK RIPPLE ON THE BATTERY CURRENT AS A FUNCTION OF THE DC-LINK CAPACITANCE. RIGHT: BATTERY CURRENT AND VOLTAGE DURING A TRANSIENT EVENT, I.E. A TORQUE STEP ON THE ELECTRIC TRACTION MOTOR.

Future Work

- Investigate different motor types, e.g. switched reluctance machines or different types of IPM machines.
- Investigate the battery impedance further. By performing a more thorough frequency sweep, preferably on multiple cells or an entire battery pack, the impedance as a function of frequency can be determined for both higher and lower frequencies.
- Re-evaluate and measure the voltages in the system. By measuring both the battery and the inverter voltage, the effect of the DC-link cable can be evaluated.
- Build a measurement system with battery, inverter and cables. By rebuilding an own measurement system, the system parameter can be varied individually.
- Investigate the losses in the system. How does the current and voltage ripple affect the efficiency of the system? How does different system configurations (eg switching patterns, cable lengths) affect the overall efficiency.
- Increase the accuracy of the simulation by implementation of more advanced simulation models that in involve FEM co-simulation of the electric circuit and the machine/cable.

System simulations of a larger system. If several machines are connected to the same DC-bus, how will the system performance be affected? Can harmful resonances occur if the system parameters are selected in an unfavorable way?

xEVCO WP3 Hybrid Active Safety and the ms time domain.

Introduction

The xEVCO project has focused on supplying models connected to the concept “Green, safe and connected” from a complete car point of view. The project also focused on describing possible ways to do relevant evaluations in simulated environments.

To show that it is possible to analyze and evaluate the models of electric drive systems into a complete vehicle scenario has a problem been formulated where it is assumed that a customer of a hybrid vehicle either buy the product with the intention that the electric powertrain shall be a complement to a smaller traditional drive line based on a combustion engine and still utilize same power or to minimize fuel consumption. Regardless of the reason there is an interest from a customer point of view regarding hybrid technologies. The customer value will for most be conceptually evaluated in active safety perspective. The goal is a modular simulation environment that will offer the possibility to evaluate active safety functionalities for complete vehicles with hybrid architecture.

In figure 1 a principal view of the complexity in this part of the project. Starting with the development of a mathematical model for a specific physical reality to the implementation into a software model/simulation.

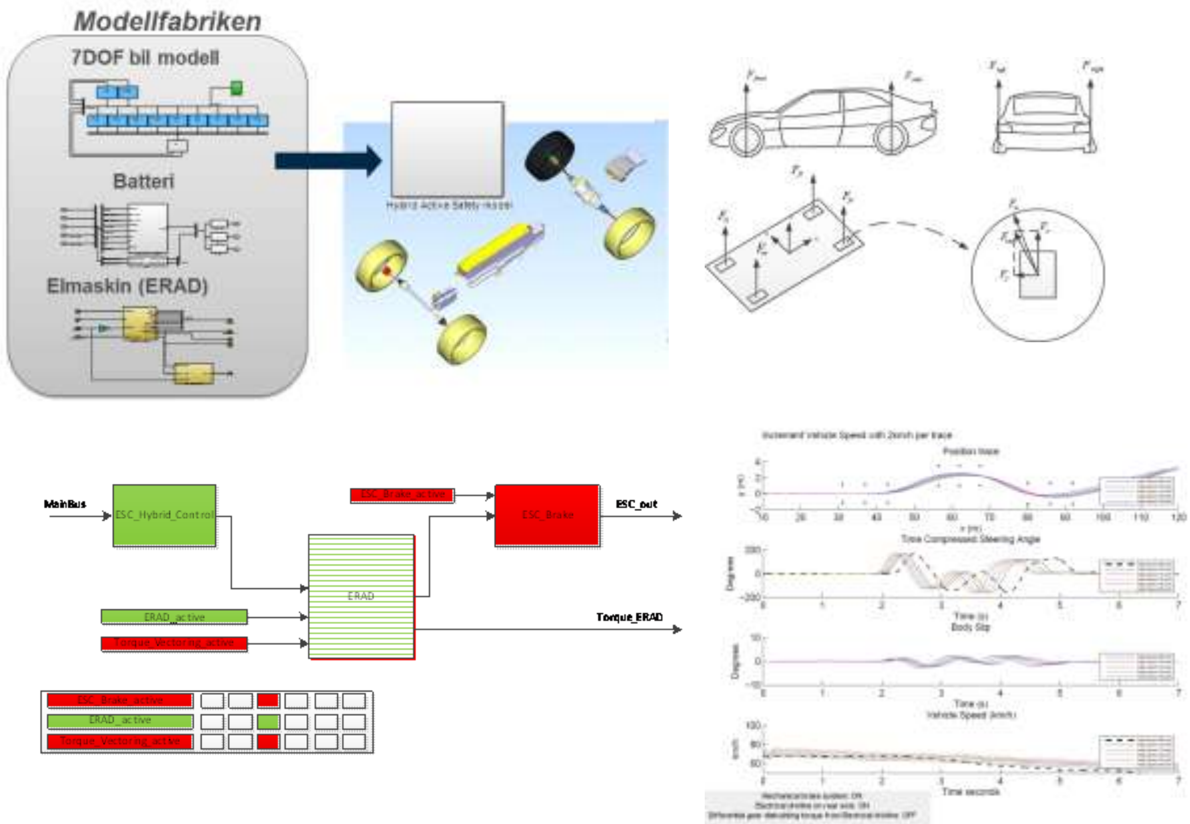

Figure 1. The scope for work package 3.

Simulation environment and vehicle model

In the project another work package has focused on designing a platform for a generically simulation environment named “model factory”. The work there has focused on the crossover competence between vehicle electronics and power electrics. The intention is to show that this platform can be developed further to show a sustainable concept for virtual evaluation and verification.

In work package 3 a conceptual model for hybrid ESC architecture has been developed. The first part describes the mathematics behind the ESC algorithm. The mathematic model is then implemented into a larger vehicle model.

Conceptual evaluation of active safety performance

As a part of the work with evaluating the hybrid ESC architecture a validation against real data has been conducted. In figure 2 an example of simulation result with hybrid ESC and no ESC is shown. With the hybrid ESC active an increase in performance with 5.7 % can be achieved.

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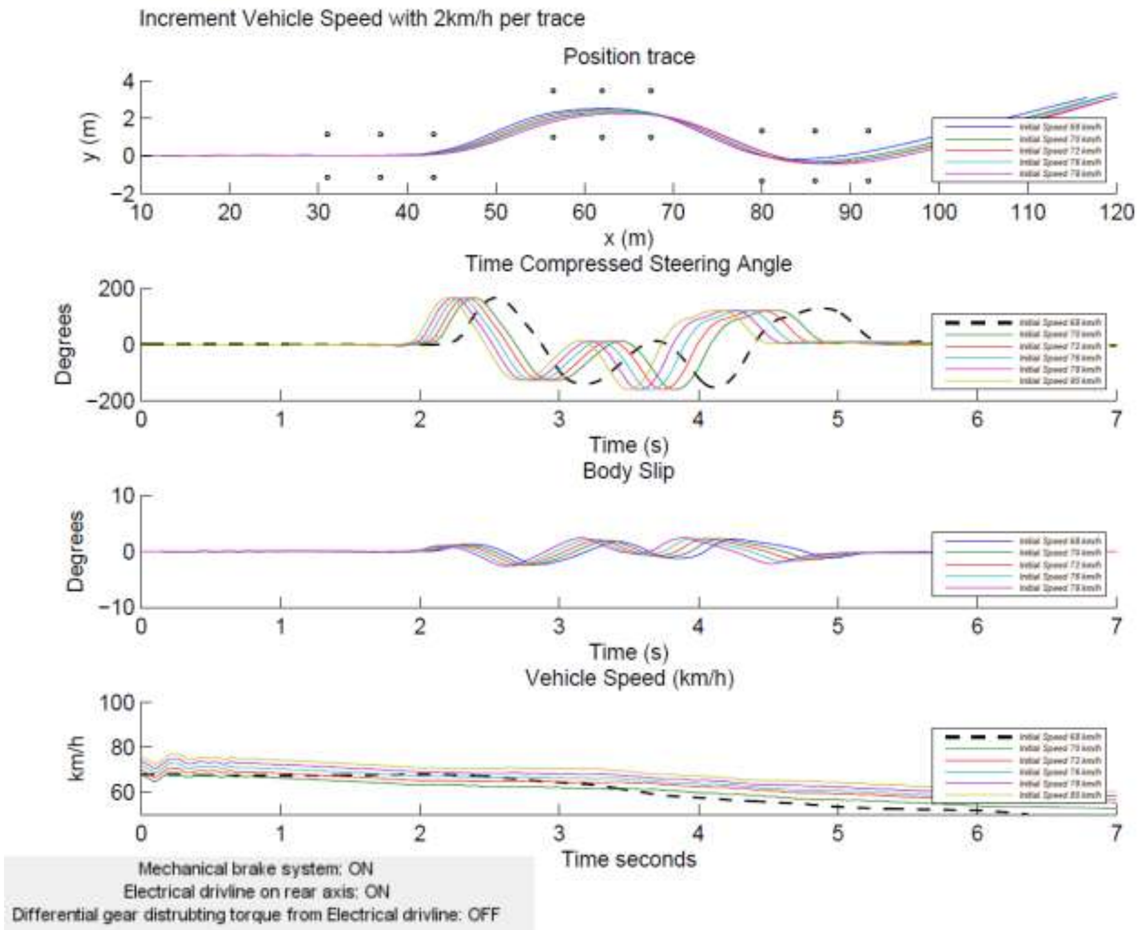

Figure 2. A simulation with hybrid ESC and no ESC.

Conclusions and future work

By introducing advanced models early in the development process in combination with advanced vehicle-scenario simulations the development time can be reduced and the use of prototypes can be minimized or avoided.

The xEVCO project has in its result with success shown that a combination of validated vehicle models and architectural simulations can be used to a large extent to evaluate and proof a design suitable for implementing in a real vehicle.

Future work should focus on increasing the use of advanced models into the structure presented as the model factory. By using advanced models in an early stage in development it is believed that the time for development will decrease. Furthermore should there be a focus on the structures for using models in e.g. simulation and verification tool chain. By optimizing the infrastructure it is also believed to improve the development process.

xEVCO; WP4 Drive cycle based models, the second time domain

Introduction

The following chapter will conclude Work Package 4. Focus has been on deepening some of the models from WP1.

Thermo Models

In an electrified vehicle many components both emit heat and are sensitive to exposure for high temperatures, examples are batteries, electric machines and converter, and therefor needs cooling. To understand the components thermal behavior and how an effective cooling system should be constructed is of high importance to make the vehicle energy and cost effective.

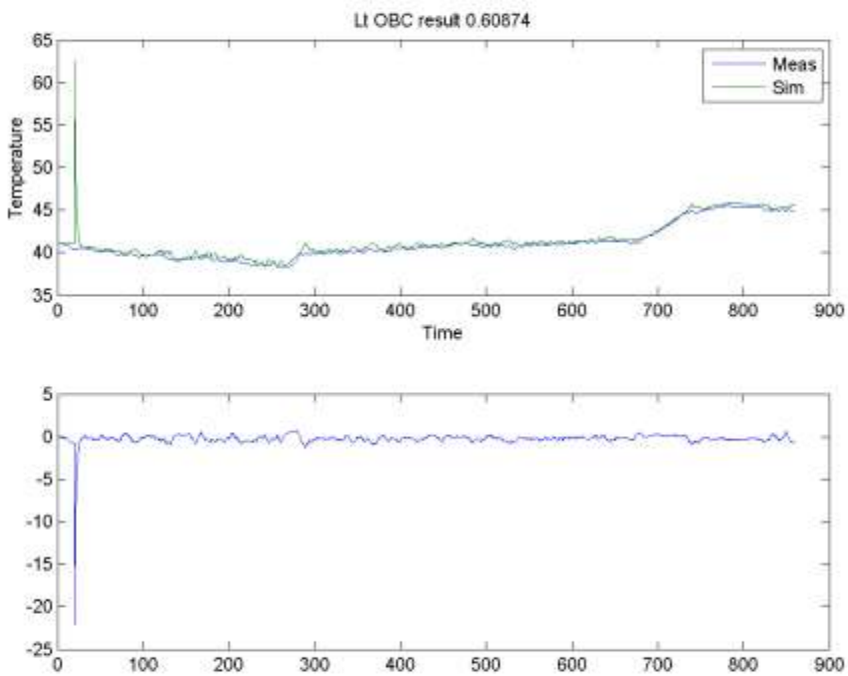

FIGURE 6, RESULT FROM THE THERMO MODEL, ESTIMATION OF THE TEMPERATURE OF THE COOLING FLUID AFTER THE CHARGER, THE AVERAGE MEAN SQUARED ERROR IS APPROXIMATELY 0.6 CENTIGRADE

Figure 6 shows a good correlation between the estimation of the cooling temperature after the charger.

Parameter estimation

In the section **Process** it was discussed that it in some cases is possible to parameterize models from measured data. Different model structures have been compared and a simple dynamic model with one time constant is a robust solution for most cases.

Conclusion

Thermal models are an important area and we have made progress, especially with simpler models for a system view. For parameter estimation a method for parameterize battery cells is now up and running.

Future work

Thermal models

- More measurement is needed to gather information about the system and to validate models
  - Measurements in a controlled environment on the individual components
  - Investigation of the impact of other heat transport mechanism than through the cooling system
- CFD (Computational fluid dynamics) calculations to validate the heat transfer numbers further

Parameter estimation

- Which kinds of measurements are needed?
- More components than the battery
- Estimate parameters for aged or cold batteries

xEVCO WP5 Fault tolerant electrical drives, the PhD student part of the project

Summary

The PhD student part of the project takes place mainly at Chalmers University of Technology. The overall goal of the PhD project is to gain knowledge about electric drive systems for hybrid electric vehicles at various faults, including transient modeling.

Four shorter reports have been delivered from the PhD project to the major xEVCO project. A master thesis regarding thermal modeling of radial flux machines was also carried out as a part of the PhD project in collaboration with Volvo Cars. Further, hardware and a machine prototype where developed within the project, for thermal verification later on in the PhD project.

The PhD project will continue even after the end of the major xEVCO project with more deepened analysis regarding the modeling of the electrical machines and drive systems. A Licentiate thesis is planned during the spring of 2014 and PhD thesis in August 2016.

Faults in the electrical drive system

The different faults that are presented in the literature are often divided into machine and converter related faults, some of these faults are listed in Table 1.

TABLE 1: MACHINE AND CONVERTER RELATED FAULTS THAT ARE MENTIONED IN THE LITERATURE.

Machine related faults	**Converter related faults**
• Windings – Open circuit – Short circuit (complete) – Short circuit (turn-turn) – Short circuit (phase-phase) – Short circuit (phase-frame) • Mechanical	• Power device – Open circuit – Short circuit • DC-link capacitor

The study in the PhD project has been focusing on the electrical faults, both machine and converter related, where it is likely to be able to operate when a fault occur. The post fault performance in case of a more fault tolerant machine design is investigated, when a phase-short circuit or a phase-open circuit occurs

Machine design

In the literature, several design methods to improve the fault tolerance of electric machines are presented. One strategy is to increase the insulation (electric, magnetic and thermal) between different parts in the machine to avoid fault propagation. Another strategy is to limit the short circuit current by a 1 per unit inductance of the phases. Redundancy is often used to make sure that the machine is able to deliver a minimum level of torque or power even after a fault occurs. The aim of the machine design within the PhD project is to investigate/quantify how different methods for increased fault tolerance impact the on the performance of the drive system.

Operation during a phase open circuit fault

One option to run the machine during a phase open circuit is presented in the technical report. The torque production from each phase together with the total torque production is shown in Figure 7. The figure shows the torque production during three different time interval. The first interval represents the normal, balanced three phase operation. In the last interval, the open circuit fault is introduced and the controller acts to maintain a constant but reduced torque production. It can be seen that this particular machine, using the strategy and constraints presented in the report, is able to maintain an average torque production of approximately 57% when it is operated during a phase open circuit fault.

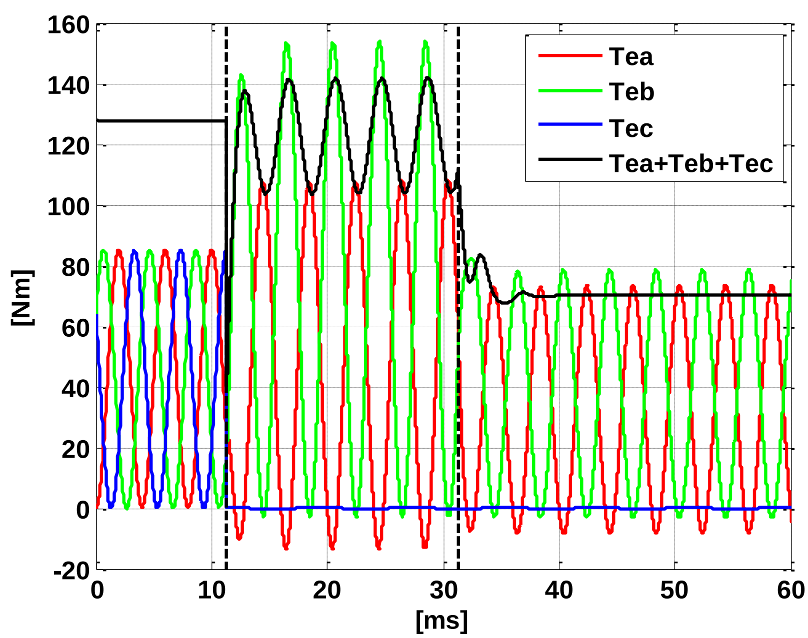

FIGURE 7: TORQUE PRODUCTION BEFORE AND DURING A PHASE OPEN CIRCUIT FAULT.

Conclusion and future work/continuation of the PhD project

No final conclusions are presented from the PhD part of the project as it is only half way through. As mentioned previously, it will continue even after the end of the major xEVCO project with more deepened analysis regarding the modeling of the electrical machines and drive systems. A Licentiate thesis is planned during the spring of 2014 and PhD thesis in August 2016.

The subject has been and is still very interesting. A study of the thermal aspects, both during normal operation and operation during faults, has been pointed out as interesting topic to be continued in the future. Another interesting point is the control of the unbalanced machine when operating during various faults. It is also important to include and evaluate the capability of the other components in the electric drive system, such as the converter and the DC-link components.

Results and deliverables

Delivery to FFI-goals

xEVCO project can be said to support the following general objectives stated by the ICFTU and Vinnova.

- the industry is capable of competitively the knowledge-based production in Sweden.
- contribute to a continued competitive automotive industry in Sweden
- lead to industrial technology and skills
- contribute to security of employment, growth and strengthen R & D activities
- support research and innovation environments
- work to ensure that new knowledge is generated and implemented, and that the existing knowledge is implemented in industrial applications
- strengthen the collaboration between the automotive industry and government agencies, universities and research institutes
- ensuring that the national skills supply and regulating the R & D to compete globally established

Knowledge and results dissemination

Project results have been disseminated through four seminars have been arranged. These have been estimated by the approximately 35 people at a time who visited and participated in them.

Furthermore, an informal network of researchers and others interested in the simulation of electrified vehicles the so-called Maxwell Society formed. They have had several meetings where issues within the project area have been discussed.

On a few occasions has further presentations of results presented including eg include Volvo Cars internal annual technology exhibition.

Publications

A list of publications can be found after each WP.

Conclusions and future research

Recomenedations for future work can be found after each WP.

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