SLUTRAPPORT

2013-10-08

Projekt	
Ref. nr 10-161 ”Svänghjul som effekthanteringssystem och energilager”	
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Svensk sammanfattning

P.g.a. det internationella forskningssammanhang där vi verkar är denna slutrapport skriven på engelska. Nedan följer en svensk sammanfattning av delmål som sattes upp. I praktiken fortsätter projektet med konstruktion och utvärdering av effektomvandlingssystemet (PCS) för både låg och hög spänning, hur upp- och urladdningen av batterierna hanteras, optimering av den elektriska maskinen och analyser av undersystem.

Sju vetenskapliga publikationer bifogas som appendix 1-7 enl. referenslistan.

1. Summary

For reasons of the international research context in which we operate the final report is written in English. Below is a Swedish summary of the milestones from the application. In practice, the project continues with design and evaluation of the power conversion system (PCS) for both low and high voltage, the charging and discharging of the batteries is handled, optimization of the electrical machine and analysis of the system.

The project has achieved the stated main objectives and all milestones
Scientific publications related to this project are listed at the end.

2. Mål

Project goals listed in the application are:

Huvudmål:
Huvudmål: utveckla forskningen vid avdelningen för ellära kring svänghjul för fordon som kan hantera erforderlig effekt samt erbjuda tillräckligt höga energiöverföringsmöjligheter både till drivmotor/er och till batterierna. Detta innebär att generatorn inte ska överhettas samt kunna överföra el på både hög- och lågspännings nivå.

Delmål:
Detta projekt kommer att bestå av två delar:

1) Experimentell uppbyggnad av skalenlig elektrisk drivlina i labmiljö, baserad på svänghjul.. **Mål:** demonstrera drivlina i lab som körs mot batteri och simulerade hjulmotor. En vetenskaplig publikation.

   This goal is presented under "Experimental set up"

2) Vidarutveckling av metoder simuleringsmetoder för full drivlina i fordonsapplikation som inkluderar luftgapslindade synkronmaskiner och kraftelektronik för matning av denna. **Mål:** Simulering som modellerar drivlinans funktion baserad på faktiskt geometri, krets och kalibrerad mot experiment. En vetenskaplig publikation.

   This goal is presented under "Simulations"

3. Experimental set-up

An axial flux coreless flywheel machine was designed and built before 2010, when this project continuation was grandet. The novel characteristic is that it has two isolated sets of windings. This flywheel machine geometry is presented in Figure 1.

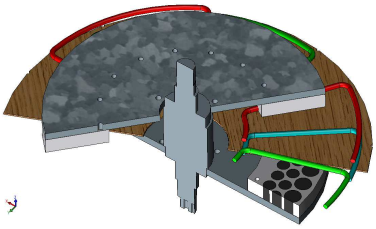


Figure 1 - Cut away representation of the second prototype.

The experimental set up has been used to investigate drag losses. Series of spin down test have been performed at different air pressures and the losses have been calculated. Some of the results are shown in Figure 2, showing that drag losses become significant at higher speed operation. The operation of electric machines at low pressure reduces the losses but compromises the heat transfer. The performed tests help in the selection of the working pressure and may be useful also for other applications. A thorough description of the losses is presented in [5].

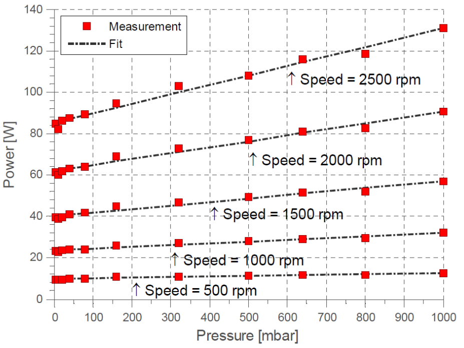


Figure 2 – We studied the air friction loss at different rotational speed and air pressure. Results have been published in [5].

System demonstration

All the components required to run an electric vehicle, from power source to traction motor, has been constructed and is operational at Uppsala University. Also the "road" has been implemented in the tests. The power flows through the wheels in an electric car. We made all the tests in the lab, so we had to simulate the "road". We connected the traction motor to a motor/generator that produced the same friction as a real road.

The driveline is able to source relatively constant DC power, while delivering high power transients to the traction motor, as shown in Figure 3.

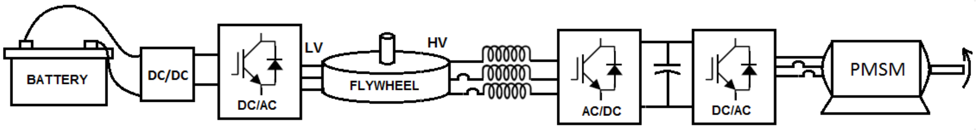


Figure 3 – Schematics of the flywheel based all-electric driveline.

Results have shown that a smoother output power can be obtained from the battery supply when using the flywheel as a power buffer, as shown in Figure 4. The reduction of the power fluctuation on the battery side eliminates the stress related to power density, potentially increasing the battery life time.

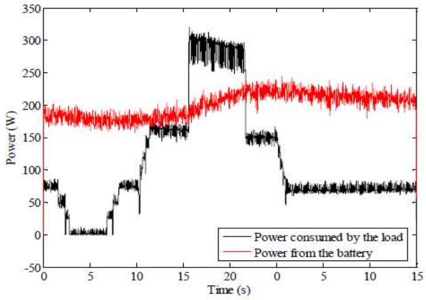


Figure 4 – Power consumed by the load and the battery from the battery during an experimental test.

The "road" is implemented with a generator connected to the motor shaft and that controls the torque and speed of the traction motor. This way, it is be possible to create an environment closer to the real situations and simulate controlled loads, including standard drive cycles. An illustration of the experimental set-up which interconnects the shafts of two permanent magnet synchronous machines is shown in Figure 5. The two machines are identical, being the first machine used as a traction motor (speed controlled) and the second machine used as load, to simulate different torque situations. A picture of the same system is shown in Figure 6.

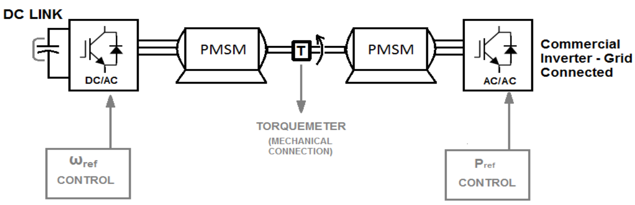


Figure 5 - Shaft Interconnection Schematics

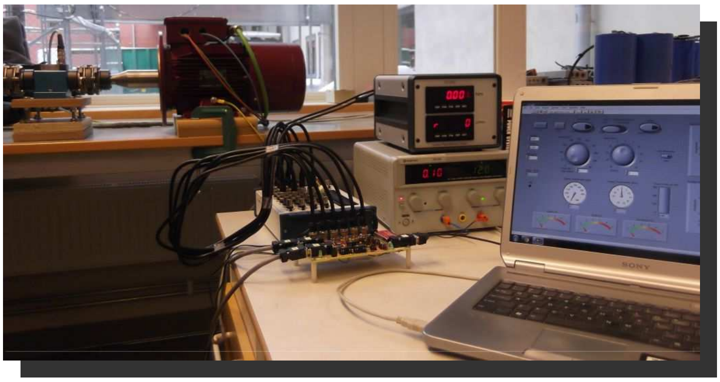


Figure 6 – Picture of the shaft Interconnection in the driveline.

The drive cycles, which were simulated and investigated previously, were scaled down in order to fit with the experimental set-up. In this work, tests with the American standard drive cycle (Federal Test Procedure - FTP72) and the New European Drive Cycle (NEDC) have been performed.

Unpublished results for the New European Drive Cycle (NEDC) are shown in Figures 7 and 8. Both show the power in the consumed by the electric motor during the experimental test, however, the power shown in Figure 7 is a theoretical result obtained from the simulations. The power shown in Figure 8 is the electrical power measured at the input terminals of the traction electric motor. The difference between the two values can be attributed to the losses in the traction electric motor, which has an efficiency of around 90%.

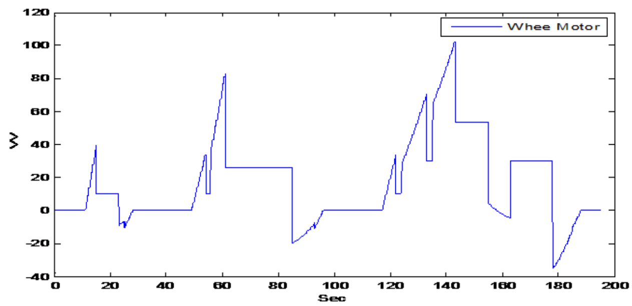


Figure 7 - Theoretical power obtained from the simulations.

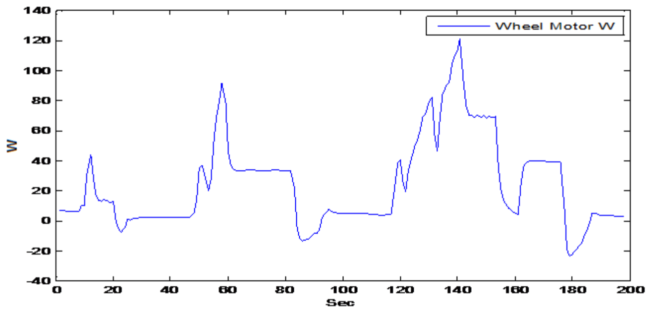


Figure 8 – Measured electric power in the input terminals of the traction motor.

Kommentar [j1]: I will plot better results as soon as I manage to treat the data I have…

Further development

The driveline has proven functionality. The next step is to improve the performance of each component to show the fully potential and improvements over traditional driveliens. We are currently making developments in the flywheel machine, magnetic bearings and power electronics. New practical experience will be gained when a radial instead of an axial topology will be build. A schematic representation of the doubly wounded flywheel is presented in Figure 8. The flywheel machine consists of a rotor with outer magnets and an inner ferromagnetic rotating part. The stator is placed in between of the two parts of the rotor and it is represented in orange in the figure. The bearings are represented in green, while there is an active magnetic bearing in the lower part. A carbon fibre shell has been designed and constructed for the new machine.

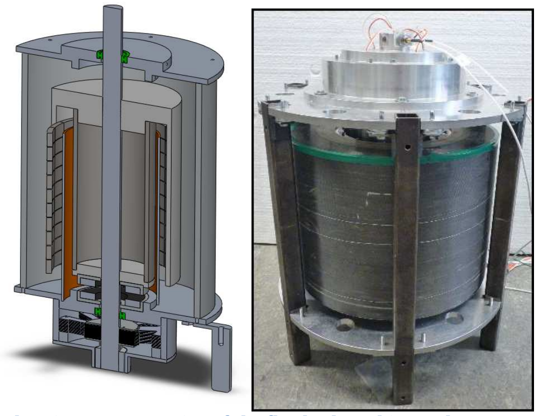
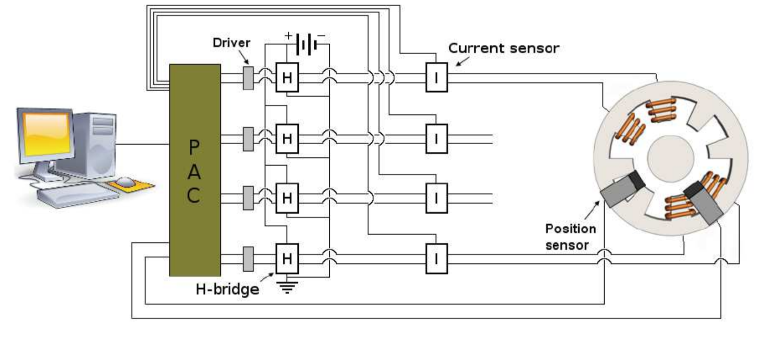


Figure 8 - Cut away drawing representation of the flywheel machine and current construction status.

A control system for magnetic bearing has been constructed using power electronics and a PAC (Process Automation Controller) from National Instruments. Eddy current sensors measure the position of the rotor with high bandwidth (25 kHz) and accuracy (<5 um). PAC system controls the current through the coils with a bandwidth of 4 kHz, which controls the electromagnets force to stabilize to the rotor shaft. The system is presented in Figure 9.



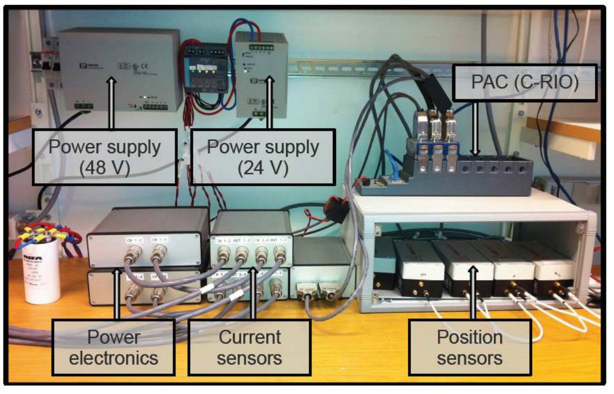


Figure 9 – Schematics of the magnetic bearing control and the lay out in the lab.

Currents in the magnetic bearing coils create a radial force that was measured. The comparison of the measurements and simulated values are presented in Figure 10. Other parameters have been measured, such as the stiffness. The stiffness is how quickly the force change given a change in current strength, and it is an important in the design of magnetic bearings. This quantity indicates how fast the force change given a change in control flow. The optimized geometry resulted in an increase in the power rigidity by 300% at the chosen operating point.

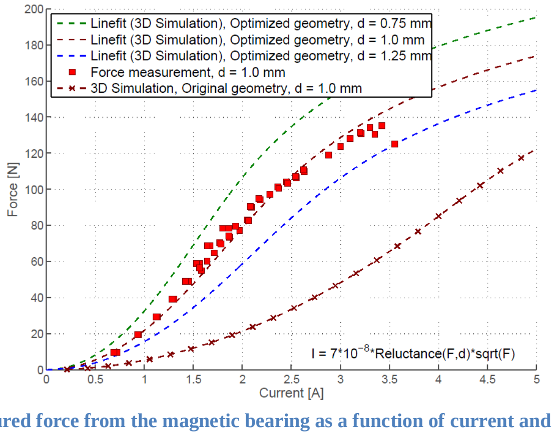


Figure 10 – Measured force from the magnetic bearing as a function of current and comparison with simulations. Nominal value of the air gap, d, is 1.0 mm.

4. Simulations

Simulations are used to develop individual components in the driveline and to present the advantages of the driveline in complex systems. An example of simulations of individual components is the investigation in magnetic bearing topologies conducted. The driveline as a system has been simulated for electric vehicles and for the integration of renewable energies.

Magnetic bearings are the optimal technology to stabilize the rotor with minimal losses because the flywheel high rotational speed and the vacuum containment. Active magnetic bearings (AMB) have proven to be the most promising implementation of this technology due to their high load capacity and good cushioning. Active control system provides controllable dynamics which can be used to minimize vibration at oscillation frequencies or allow the rotation axis to coincide with a principal axis. Active control of the rotor position also makes it possible to identify mechanical defects of the rotor before these leads to the flywheel fails.

An optimization of the electromagnets shape was conducted to minimize the losses occurring in the magnetic bearings. The optimization was conducted by running simultaneously the commercial software products Solidworks, Comsol and Matlab. An automated optimization loop was running in Matlab. Matlab sends the geometry parameters to SolidWorks, that draws the electromagnet geometry and export it to Comsol. Comsol makes all the simulations and sends the results to Matlab, in particular, the resultant force between the electromagnet and rotor. Figure 11 shows the original geometry, the final geometry and the parameters included in the optimization.

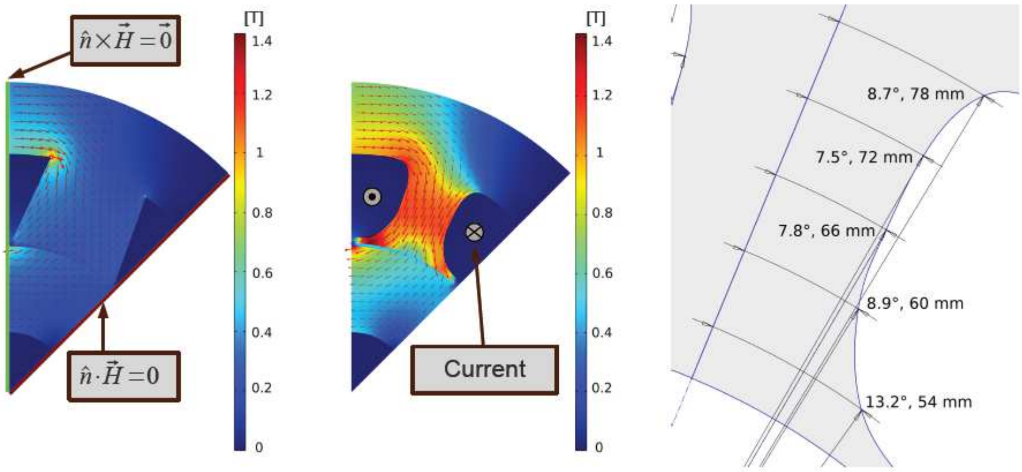


Figure 11 – From left to right; the original geometry based on a constant average area of the magnetic flux. The optimized geometry and a sketch of the geometry with the optimization variables.

The PhD student Johan Lundin focuses his research in the system analysis. He presented simulations of the driveline performance under standard drive cycles for electric vehicles. Figure 12 shows the speed profile of a standard FTP 75 drive cycle. It is clear that the peak power required when we drive is much higher than the average power. All the components should be dimensioned almost ten times higher than the average utilization. An intermediate energy storage would reduce the demand for many components.

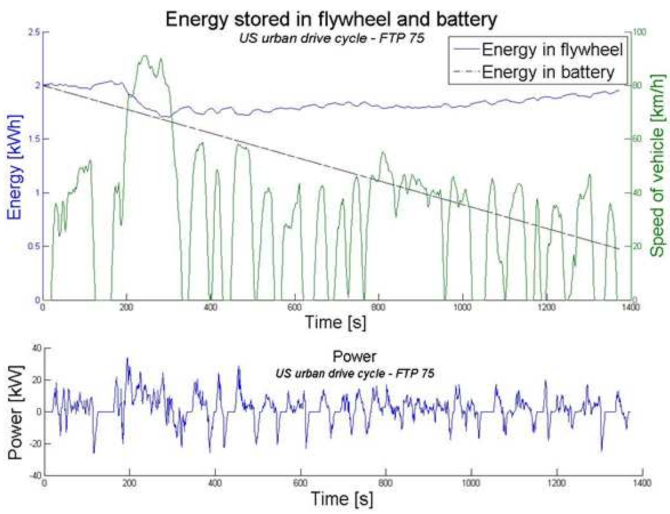


Figure 11 – Drive cycle for passenger car (FTP 75), showing a steady supply of energy from the battery can be complemented by a flywheel that handle power peaks. The average power is only 4 kW, while the peak power is up to 36 kW.

Renewable energies such as wind, solar and wave power has similar power profiles. A wave power station has been simulated. Reference from the conference [4] shows that a flywheel with the same lay out as the driveline for electric vehicles enhances the power quality of the power station. Figure 12 shows the circuit diagram of the proposed system. Figure 13 shows the power delivered by a wave power plant from measurements and how a flywheel would deliver this power.

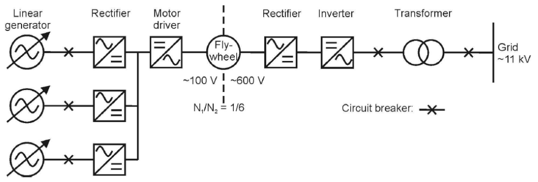


Figure 12 – Circuit diagram of the proposed system applied on linear wave energy converters

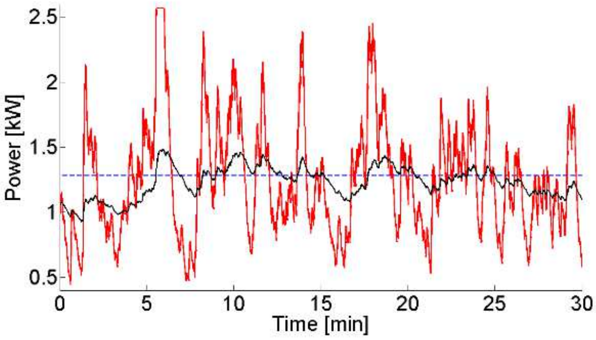


Figure 13 – power out from the flywheel with flywheel energy storage capacities of 50 kJ (red) and 500 kJ (black) respectively.

5. Project impact and continuation

The project has shown impressive results, and more important, it has a brilliant future. The project has been awarded with a grant "Fullskalig Energieffektiv drivlina för Elfordon" Stem 36396-1. The project got funding to build an electric vehicle to test the concept onboard.
Vetenskapsrådet has granted the project with a collaboration with two universities in Brazil with the Avtals-ID C0624201, “Studie av Svänghjul som Energilager I Smarta Elnät med inslag av Distribuerad Generation”.
The project has call the attention of other interested actors. The project has been presented to Trafikverkets Färjerederiet and Lightcraft Design Group AB and we are in negotiations to create a consortium to further develop electric drive lines for ferries.

References and appendixes

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Conferences

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Disertations

Janaína Gonçalves de Oliveira, "Power Control Systems in a Flywheel based All-Electric Driveline", Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, ISSN 1651-6214; 844

Juan de Santiago Ochoa, "FEM analysis applied to electric machines for electric vehicles", Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, ISSN 1651-6214; 845

Licentiate thesis

Johan Abrahamsson, "Kinetic Energy Storage and Magnetic Bearings, for vehicular applications", UURIE 327-11L, Uppsala 2011

Johan Lundin, "Flywheel in an all-electric propulsion system", UURIE 328-11L, Uppsala 2011