Compact rotor power transfer in wound rotor synchronous motor (WR-SM) for high performance electric vehicles

Version 1.1

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Summary

Electric and hybrid vehicles requires high performance electric motors with high peak torque, wide speed range, high efficiency, and low-cost for mass production. The commonly used permanent magnet (PM) motors and induction motors have unsatisfied performance under field weakening and are expensive in material purchase (rare earth magnets) or mass production. A wound rotor synchronous motor (WR-SM), due to its independent and controllable rotor excitation, can deliver any desired torque at any speed with high efficiency. However, the brushes and slip rings for rotor excitation need maintenance and may influence operating reliability. The purpose of the project is to develop a compact rotor excitation design and test experimentally together with a WR-SM. The results of the project show that the proposed brushless WR-SM has peak torque can be boosted up to 300%; wide area with high efficiency, flexible control; very high efficiency rotor power transfer (97%); and compact and low-cost solution for rotating transformer. The brushless WR-SM can be integrated with gearbox and share the liquid cooling system even within the motor. The controllable excitation can release the stress on converter and even batteries in term of peak current and has a great value for system optimization. The concept can be easily scaled down to mild-hybrid drivetrain (15-20kW) or scaled up to heavy-duty vehicles (200kW). The SiC based DC/AC converter developed in this project has opened a new research area - high frequency high efficiency switching technology. The project is conducted at Chalmers with the strong reference team consisting of experts from Volvo Cars, AB Volvo, and Chalmers. The project period: 2014Oct – 2015June. Project budget: 1.35MSEK, 100% funded by SHC.

Background

The trend toward electric and hybrid drives pushes the developments of optimal design of powertrain for high reliability, high efficient, high power density, and easy mass production.

Nowadays commonly used permanent magnet (PM) motors are compact and efficient, but have bad performance under field weakening and are expensive in both materials and production. Alternatively induction motors with copper cages become popular for high performance vehicles like Tesla cars. But induction motors have low efficiency in general and reduced power at higher speed. The copper rotor manufacturing is complicated process.

Theoretically the perfect motor is a wound rotor synchronous motor (WR-SM), which is used for all large power generations. Because of the independent and controllable rotor excitation, the motor can be easily controlled to deliver the any desired torque at any speed with high efficiency. Speed range can be extended to as much as to the mechanical limitation. Its high power factor makes it possible to reduce the rating of the power electronics converters. The short-term torque can be as high as 300% of the rated according to Continental/Renault. In addition, there are no expensive rare earth materials and no complicated manufacturing process.

However, the brushes and slip rings for transferring power to the rotor windings need maintenance and may influence the operating reliability. To introduce a rotating exciter like one used in large machines will significantly increase the overall size and weight of the motor. Therefore a high performance WR-SM motor with compact brushless excitation system is required.

General project description

The purpose of the project is to find a compact concept to transfer power into the rotor windings and verify the concept experimentally together with a wound rotor synchronous motor (WR-SM).

The idea the project starts with is high frequency rotating exciter. The size of exciter decreases with the increase of it frequency. The power needed in the rotor winding is not more than a few percent of the motor power. The high frequency exciter of small size can be integrated into the rotor for a compact design.

The project has been conducted in following steps:

(1) Identification of the optimal concept/design. The following parameters was studied in the project: exciter topologies, materials, voltage/current, number of poles, and frequency.
(2) The selected concept together with a WR-SM was firstly investigated with electromagnetic models and simulations.
(3) Build the prototype frequency converter and high frequency exciter.
(4) The tests on the prototype verified the feasibility of the concept.
(5) The prototype of the transformer is installed on a WR-SM and tested at different operating points to demonstrate the system feasibility.

Achieved results

The technical results of the project is a new high performance traction motor which has:

- Peak torque can be boosted up to 300%
- Wide area with high efficiency (down to 5% of peak load)
- New control possibility
- Very high efficiency rotor power transfer (5% higher than the state of art 2014)
- Compact and low-cost solution for rotating transformer (peak power 2,7kW, weight 0,4kg)

The academic results include innovative design of rotor power transfer and system testing of the brushless WR-SM. The results are planned to publish in academic papers after the project.

The results show the great potential for this motor concept to be used in high performance electric and hybrid vehicles. The study in this project is far from comprehensive due to the project resources and time. Deeper and wider study in different aspects about this concept is recommended by industry.

Contribution to hybrid vehicle technology

Electric and hybrid vehicles requires electric motors which have high peak torque, wide speed range, high efficiency, and low cost for mass production. The concept motor developed in the project has potential to satisfy these entire requirements with acceptable compactness. Some bottle necks with today's wide used vehicle electric motors such as rare earth magnets, low efficiency at partial loads, limited peak torque can be eliminated with the new concept motor.

One of the focuses in the project is to develop compact, high efficient and low-cost field power transferring system. The prototype demonstrates that the system can be used in different kinds of electric and hybrid vehicles. Because of the brushless construction the motor can be integrated with gearbox and share the liquid cooling system even within the motor.

The flexible excitation has a great value for system optimization. It can release the stress on converter and even batteries in term of peak current.

The high efficiency in particular regeneration speed and drive cycle points will improve the drive range or reduce requirements on batteries.

The machine concept can be used as motors as well as generators. For hybrid vehicles, the efficiency and controllability of the generators can be important.

The concept can be easily scaled down to mild-hybrid drivetrain (15-20kW) or up scaled to heavy-duty vehicles (200kW).

Uniqueness and news value

The compact design of rotating transformer due to innovative design with high operating frequency, Litz wire, and shaft mounted structure. Power density (6,75kW/kg, 15,2kW/liter) is the highest ever reported.

The efficiency of the brushless excitation system including converter, transformer, and rectifier reaches 97%, which is higher than the reported state of art system (92%).

By controlling the field current and stator current independently it is possible to control the motor to always operate at optimal point in both efficiency and thermal aspect. Therefore the high efficiency in very wide operating area can be realized with the promoted motor concept. The biggest improvement over PM motors is in the partial load area where most drive cycle points locate.

Timing and finance

WP1: High frequency rotating transformer (HF-RT), (2014Oct-2015April)

Design and modeling of rotating transformer

Design of DC/AC converter and controller

Construction of transformer and the frequency converter

Milestone 1: HF-RT and PE are ready built and tested stand-alone (2015April)

WP2: Wound-rotor synchronous motor (WR-SM) (2015Dec-2015May)

Investigation on test motor alternatives

Rewind/borrow/build the WR-SM

Installation with a drive motor and test with slip rings

Milestone 2: WR-SM is ready for test (2015May)

WP3: Target motor design and analysis (2015Jan-2015May)

Target motor for hybrid car applications (PHEV Volvo V60) will be specified.

Performance of 70kW motor is investigated with FE models and simulations.

Milestone 3: Efficiency & power factor map for target motor completed (2015May)

WP4: System tests of HF-RT together with the lab WR-SM (2015June)

HF-RT is installed on the lab WR-SM

Tests on HF-RT functionalities at rotating speed 1800rpm

Tests at different operating points to demonstrate the system feasibility

Tests on response time of torque and influence of field inductance

Milestone 4: Whole system tests completed (2015June)

The total project budget is SEK 1.3 million. It is funded by SHC (100%).

Executors and collaboration

Project team:

- Yujing Liu, Professor, Chalmers, project leader, responsible for idea initiation, supervision, result verification, report writing, and project management.
- Daniel Pehrman, research assistant, Chalmers, conducted rotating transformer design, prototype construction, sub-system testing and combined testing, results analysis, and design/simulation of the target motor.
- Odyssefs Lykartsis, research assistant, Chalmers, conducted DC/AC converter design, PCB design, prototyping of the converter, and sub-system testing.

Reference group of the project (both from industry and academia):

- Sören Eriksson, Volvo Cars (system requirements)
- Joachim Lindström, Volvo Cars (electrical machines)
- Pär Ingelström, AB Volvo (electrical machines)
- Martin West, AB Volvo (power electronics)
- Dan Hagstedt, AB Volvo (electrical machines)
- Anders Grauers, Chalmers (drive requirements)
- Sonja Lundmark, Chalmers (electrical machines)

Sister project:

- Master thesis project, *"High efficiency inductive charging for electric mini-cars"*, Chalmers University of Technology, January-June 2015.

Miscellaneous

The SiC based DC/AC converter developed in this project has opened a new research area - **high frequency high efficiency switching technology** in Chalmers. This technology is already used in a sister project on inductive charging for electric vehicles (master thesis). The converter will be used also for testing of a new type of inductors based on soft magnetic composite.

The further development of this technology will continue in other projects such as inductive charging and motor drives.

Papers and publications

[1] Kim Olsson and Petter Mattsson: "High efficiency inductive charging for electric mini-cars", Master thesis, Chalmers University of Technology, June 2015

[2] Yujing Liu & Daniel Pehrman: "High frequency rotating transformer used for field excitation of wound rotor synchronous motors for vehicle applications", ICEM2016, (in preparation, will submit in the beginning of 2016).