Rectangular conductor windings for electric motor with high performance and high production volume

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Project title: Rectangular conductor windings for electric motor with high performance and high production volume

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Sammanfattning

I samband med att framsteg görs inom elektrifiering av fordon, så när elmotor-teknik en ny period med låg kostnad och hög produktionsvolym. Lindningar med rektangulära ledare anses vara en av de mest lovande lösningarna som passar för högpresterande lågprismotorer. De förväntas att ha hög fyllfaktor, hög termisk prestanda, hög effektäthet och enkla procedurer för automatisk produktion. Målsättningen med projektet är att undersöka möjligheterna från lindningar med rektangulära ledare för att förbättra effektäthet, verkningsgrad och kostnader. En prototypespolar med rektangulära ledare för en 60 kW elmotor kommer att konstrueras, simuleras, tillverkas och experimentellt verifieras. Det viktiga syftet är att industriförbätterna i Swedish Electromobility Center samlar kunskap om denna framväxande motorteknik och utvärderar det framtida utnyttjandet i sina produkter. Projektet genomföras på Chalmers i nära samarbete med Volvo Cars och AB Volvo. Projektet genomföras under 2018.07.01-2019.06.30. Den totala kostnaden är 1,0 MSEK.

Summary

As progress of electrification of vehicles, the motor technology comes to a new era for low-cost and high-volume production. Rectangular conductor winding is considered as one of the most promising solutions suitable for high performance and low-cost motors. It is supposed to have high filling factor, high thermal performance, high power density, and easy procedures for automatic production. The objective of this project is to investigate the opportunities rectangular conductor windings provided in improvements of power density, efficiency, and costs. A 60 kW prototype motor with rectangular conductor windings is designed, simulated, prototyped and experimentally verified. The important purpose is for the industrial partners in Swedish Electromobility Centre to gather knowledge about this emerging motor technology and evaluate the future utilization in their products. Project is conducted at Chalmers with close collaboration with Volvo Cars and AB Volvo. The project is conducted under 2018.07.01-2019.06.30. Total cost is 1,0 MSEK.

Background

According to prognosis, in year 2035, total number of vehicles on the earth will reach 2 billion. Assumed half of these vehicles are electrified, we need to manufacture one billion traction motors. A promising technology which is suitable for mass and automatic production is the solid rectangular conductor windings [1].

The rectangular conductor windings are supposed to have high filling factor, high thermal performance, high power density, and easy procedures for mass production to reduce costs. The methods to manufacture such windings can be divided into 2 groups: (1) hairpin winding; and (2) continuous multi-layer winding. See Fig. 1.

The key suppliers of hairpin winding motors include Remy/BorgWarner, Hitachi, and Denso. Production line providers for hairpin windings and continuous windings locate in Japan, Italy and Germany.
Some key players in the electric vehicle markets have started to use or investigate this technology (Fig. 2). General Motors has already used high performance rectangular conductor windings in several car models (Chevrolet Bolt EV, Volt Hybrid, and Malibu Hybrid). Toyota has used rectangular conductor windings in the new generation of Prius cars.

To use rectangular conductors brings several advantages:

1. Possibility to handle the windings fully automatically;
2. High filling factor of copper in the slots;
3. High thermal conductivity in the slots;
4. Short end-winding;
5. High mechanical stiffness of conductors;
6. Fewer manufacturing steps.

These advantages enhance compactness, manufacturability, and quality and make it as the most promising winding technology for future electric motors.

However, the used rectangular conductors are much thicker than round wires used in the conventional motors. This introduces extra disadvantages like:

1. High eddy current losses in solid conductors due to high frequency of the currents in traction motors;
2. Surface insulation technology withstanding mechanical distortion;
3. Connection welding for hairpin windings;
4. Noise and vibrations – bigger issue when power density and speed are maximized because windings are not bounded and impregnated;
5. Possible EMC and parasitic capacitance;
6. Manufacturing equipment are very expensive.
Even though the rectangular conductor winding looks promising, the disadvantages and challenges still are the obstacles for wide acceptability. In Sweden, we have not evaluated the technology sufficiently. Therefore, in order to explore the opportunities provided by this technology and understand the severity of its disadvantages and limitations, a study including technology review, modeling & simulation, and prototyping & testing is motivated for academia and industry partners.

**General project description**

The project is a research project and conducted mainly at Chalmers, but with close collaboration with Volvo Cars and AB Volvo. Some synergy with other projects and expertise within SEC will be utilized.

Objective:

To study the key design issues of this winding type with the help of FEM simulations and experimental verifications. The outcomes of the project will include:

- Winding schemes and their impacts on motor performance (voltage, size, etc.).
- Slot shapes and saturation levels.
- Eddy current distribution in different conductors and AC losses depending on frequency.

A prototype stator with rectangular conductor windings for a 60 kW (peak) 400 V motor will be designed and built. The prototype motor will be tested and evaluated on a test bench at Chalmers.

**Results**

The simulation study is performed with finite element method in Ansys Maxwell. The work separates different phenomena contributions to the total copper loss by isolating different effects. The results are then compared to a simplified analytical calculation.

The following figures show the prototype stator, test setup at Chalmers, and analysis results.
Figure 3. Hairpin stator of Chalmers prototype. Left: connection side. Right: welded side.

Figure 4. Experimental set-up of 2 hairpin machines at Chalmers.
Figure 5. Magnetic fields in simulation of 4-layer hairpin winding.
Figure 6. Eddy currents induced by the proximity effect in 4-layer hairpin winding.

Figure 7: Slots with different layers of hairpin windings
Conclusions of the results

- The study shows that the major part of the losses are caused by the proximity effect between the currents in one slot. The influences from the currents in the neighboured slots are lower.

- A comparison is made by simulating the same machine design with the two different types of windings (hairpins and random-wound). The hairpin winding has lower copper losses at lower frequencies than that for random winding due to high slot filling factor. At 666 Hz, which is corresponding to the top vehicle speed, the losses from the hairpin winding exceeds the losses from the random winding. For most drive cycles of electric vehicles the hairpin winding has lower losses.

- The overload capacity of hairpin winding is better than that of random winding because of the better thermal conduction in the slots.

- The reliability of the hairpin motors is higher because of a automatic and consistent manufacturing process.

Utilization of results

- The results from the project are partly used in another project, “EU H2020 DRIVEMODE”.

- The hairpin winding concept will be used in marine propulsion project (Chalmers AoA).

Targets

To understand the influences of AC copper losses by the frequency, especially in the range of field weakening. A design guidance is proposed.
Industry contribution

Volvo Cars and Volvo AB have been actively involved in technical discussions and contributed with specifications and requirements on automotive applications.

Collaboration

We have collaboration with Volvo Cars and AB Volvo.

- Through this project, Chalmers and Volvo Cars have built a close collaboration on hairpin winding research.
- A collaboration between Chalmers and an established hairpin winding manufacturer initiated for future studies.

Dissemination of knowledge

Some results have been shared with industrial and international partners through seminar presentation together with partner visits.

Presentations:
- at Chalmers on the 11th June, 2019
- at Volvo Cars on the 19th June, 2019

Papers and publications

- One master thesis is completed in June 2019. The title is “FEA study of proximity effect in hairpin windings of a PMSM for automotive applications” by author, DAVID DEURELL, VIKTOR JOSEFSSON, Chalmers
- One academic paper is under preparation.