Design of an Axial-Flux Permanent Magnet machine for an in-wheel direct drive application

Citation for published version (APA):

Bastiaens, K., Jansen, J. W., Jumayev, S., & Lomonova, E. A. (2017). *Design of an Axial-Flux Permanent Magnet machine for an in-wheel direct drive application*. Poster session presented at 2017 IEEE International Electric Machines & Drives Conference (IEMDC2017), 21 -24 May 2017, Miami, FL, USA, Miami, Florida, United States.

Document status and date:

Unpublished: 01/01/2017

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Design of an Axial-Flux Permanent Magnet Machine for an In-Wheel Direct Drive Application

K. Bastiaens¹, J.W. Jansen, S. Jumayev, and E.A. Lomonova

Eindhoven University of Technology

Department of Electrical Engineering

Electromechanics and Power Electronics Group

P.O. Box 513, 5600 MB

Eindhoven, The Netherlands

¹K.Bastiaens@tue.nl

1. Introduction

- An axial-flux permanent magnet (AFPM) machine is designed for the solar powered electric direct driven vehicle of Solar Team Eindhoven (STE).
- STE is competing in the Cruiser Class of the World Solar Challenge, and is the winner of the 2013 and 2015 editions.
- The currently used motor (Marand) is originally developed for the Challenger Class. Therefore, the motor has insufficient power.
- A multi-physical design approach is used.

Fig. 1. STE's solar powered electric vehicle.

Table 1.
Machine requirements.

Quantity	Value	Unit
Continuous torque	62.0	Nm
Maximum speed	1248.3	rpm
Maximum outer radius	156.0	mm
Minimum inner radius	90.0	mm
Maximum axial length	64.6	mm
Maximum winding temperature rise	135.0	°C

2. Machine Topologies

- All considered topologies are variations of the internal stator twin external rotor AFPM machine.
- Besides the conventional North-North (NN) or North-South (NS) permanent magnet (PM) arrangement, the quasi-Halbach (QH) arrangement is considered for all proposed winding topologies.
- All topologies under considerations have a slotless stator.

Fig. 2. Internal stator twin external rotor AFPM machine.

Fig. 3. 2D radial slices of the investigated winding configurations.

3. Charge Model

The design of the AFPM machine is a 3D problem, for fast optimization and avoiding having to evaluate several 2D radial slices, the 3D analytic charge model is used.

- The PMs are replaced with a distribution of magnetic surface charges.
- The method of images is used to model the disc-shaped back-iron.
- The relative permeability is taken into account through reduction of the PM remanent flux density.
- For the QH array, ideal circumferential magnetization is assumed.
- Despite the assumptions, the discrepancy between the flux density from FEM and the charge model is less than 1%.

(a) Axial magnetization direction. (b) Circumferential magnetization direction.

Fig. 4. Charge model.

Fig. 5. Flux density resulting from the surface charge model.

Fig. 6. Discrepancy between the flux density resulting from FEM and the charge model.

4. Losses and Thermal Model

The main losses calculated analytically are:

- Joule losses.
- Stator iron losses.
- Eddy current losses in the windings, including strand level proximity effect losses.

The thermal model includes the thermal dependency of the losses and the transition from the laminar to the turbulent flow regime.

Fig. 7. 2D representation of the thermal equivalent circuit model.

5. Optimization

A parametric search optimization of the geometrical parameters for maximum power density is conducted. The optimization includes an automated winding design.

- The required number of turns are estimated to match the voltage constraints of the power amplifier.
- The number of strands and strand diameter of the Litz wire and the number of parallel paths in the winding are optimized.

6. Results and Conclusion

- The distributed winding topology with a QH array achieves the highest power density, and therefore is chosen as final design.
- Compared to the Marand, the power density is more than doubled, while only increasing the PM volume and weight with 3% and 4% respectively.
- The concentrated winding topologies could not satisfy the torque requirement within the temperature and volume constraints.
- The final topology is compared with FEM, a discrepancy of 1.3% is observed.

Table 2.
Optimum designs at a mechanical speed of 1248.3 rpm.

Quantity	Distributed Winding		Toroidal Winding		Marand	Unit
	NS	QH	NN	QH		
Winding temperature rise	134.6	128.0	135.0	134.8	134.3	°C
Output torque	62.0	62.0	62.0	62.0	39.4	Nm
Efficiency	95.4	95.6	95.4	95.5	94.8	%
PM volume	0.82	0.71	0.55	0.78	0.69	dm ³
Power density	2.7	3.3	2.1	2.3	1.4	W/cm³
Mass	13.9	10.9	15.0	14.7	10.5	kg
Inner radius	90.0	90.0	90.0	90.0	113.8	mm
Outer radius	156.0	156.0	156.0	154.0	156.0	mm
Axial length	38.9	32.0	50.2	48.3	44.6	mm

Fig. 8. Torque as a function of rotor position resulting from FEM and the charge model.

Fig. 9. 2D radial slice of the final design.