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

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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.

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 slotted stator.

### Table 1. Machine requirements.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous torque</td>
<td>62.0</td>
<td>Nm</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>1248.3</td>
<td>rpm</td>
</tr>
<tr>
<td>Maximum outer radius</td>
<td>156.0</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum inner radius</td>
<td>90.0</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum axial length</td>
<td>64.0</td>
<td>mm</td>
</tr>
<tr>
<td>Maximum winding temperature rise</td>
<td>135.0</td>
<td>°C</td>
</tr>
</tbody>
</table>

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 backiron.
- 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%.

![Fig. 4. Charge model.](image)

(a) Axial magnetization direction.

(b) Circumferential magnetization direction.

4. Losses and Thermal Model

The main losses calculated analytically are:
1. Joule losses.
2. Stator iron losses.
3. 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.

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.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Distributed Winding</th>
<th>Toroidal Winding</th>
<th>NaN</th>
<th>NaN</th>
<th>Marand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winding temperature rise</td>
<td>134.6</td>
<td>128.0</td>
<td>135.0</td>
<td>134.8</td>
<td>134.3</td>
</tr>
<tr>
<td>Output torque</td>
<td>62.0</td>
<td>62.0</td>
<td>62.0</td>
<td>62.0</td>
<td>39.4</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95.4</td>
<td>95.6</td>
<td>95.4</td>
<td>95.5</td>
<td>94.8</td>
</tr>
<tr>
<td>PM volume</td>
<td>0.82</td>
<td>0.71</td>
<td>0.55</td>
<td>0.78</td>
<td>0.69</td>
</tr>
<tr>
<td>Power density</td>
<td>2.7</td>
<td>3.2</td>
<td>2.3</td>
<td>2.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Mass</td>
<td>13.9</td>
<td>10.9</td>
<td>15.0</td>
<td>14.7</td>
<td>10.5</td>
</tr>
<tr>
<td>Inner radius</td>
<td>90.0</td>
<td>90.0</td>
<td>90.0</td>
<td>90.0</td>
<td>113.8</td>
</tr>
<tr>
<td>Outer radius</td>
<td>156.0</td>
<td>156.0</td>
<td>156.0</td>
<td>154.0</td>
<td>156.0</td>
</tr>
<tr>
<td>Axial length</td>
<td>38.9</td>
<td>32.0</td>
<td>50.2</td>
<td>48.3</td>
<td>44.6</td>
</tr>
</tbody>
</table>