Design and fabrication of axial flux ferrite magnet brushless DC motor for electric two-wheelers

Fasil, Muhammed; Mijatovic, Nenad; Holbøll, Joachim; Jensen, Bogi Bech; Almunia, J.; Seoane, A.; Altimira, R.

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Design and fabrication of axial flux ferrite magnet brushless DC motor for electric two-wheelers

M. Fasil\textsuperscript{a}, N. Mijatovic\textsuperscript{a}, J. Holbøll\textsuperscript{a}, B.B. Jensen\textsuperscript{b}, J. Almunia\textsuperscript{c}, A. Seoane\textsuperscript{c}, and R. Altimira\textsuperscript{c}

\textsuperscript{a}Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby, 2800, Denmark. Tel: (+45) 45 25 35 00;
\textsuperscript{b}Department of Science and Technology, University of the Faroe Islands, Torshavn, FO-100, Faroe Islands. Tel: +298 292560
\textsuperscript{c}IMA S.L., Avda. Rafael Casanova 114, 08100 Mollet del Vallés, Barcelona, Spain. Tel: +34 935795415

Presented by
Muhammed Fasil
Ph.D. Student

DTU Electrical Engineering
Department of Electrical Engineering
Background - Importance of improved ferrite magnets to the growth of electric vehicle

- There is a demand for electric vehicle (EV) propelled by environmental causes and fuel price fluctuations

- At present, performance/price factor compared to IC engine vehicles are holding back the growth of EVs
Background - Importance of improved ferrite magnets to the growth of electric vehicle

- There is a demand for electric vehicle (EV) propelled by environmental causes and fuel price fluctuations

- At present, performance/price factor compared to IC engine vehicle are holding back the growth of EV

- The cost of batteries used in electric vehicles (EVs) has been falling fast and is almost certainly well below the estimates made by many analysts in the past decade¹.

- A low cost powertrain could lead to affordable, efficient and performing EVs in market earlier than expected!

- Introduction of improved energy density ferrite magnet based PM motors is a possible solution to low-cost powertrain

Outline

- Background
- Specification of electric motor powertrain for two-wheeler
- Challenges in substituting rare earth magnet with ferrite in electrical machines
- Design details of ferrite magnet motor
- Mechanical assembly of motor
- Fabrication of the motor
- Conclusion
Specification of electric motor powertrain for two-wheeler

Emmo electric scooter

[Existing motor: Sintered rare earth permanent magnet motor]

### Specification of vehicle drive

<table>
<thead>
<tr>
<th>S.N</th>
<th>Name</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Maximum vehicle mass including load</td>
<td>kg</td>
<td>130</td>
</tr>
<tr>
<td>2</td>
<td>Maximum (Rated) vehicle speed</td>
<td>kmph</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>Time to reach rated speed of vehicle</td>
<td>s</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>Rated speed of motor</td>
<td>rpm</td>
<td>330</td>
</tr>
<tr>
<td>5</td>
<td>Rated power of motor</td>
<td>W</td>
<td>700</td>
</tr>
<tr>
<td>6</td>
<td>Rated torque</td>
<td>Nm</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>Rated voltage</td>
<td>V</td>
<td>48</td>
</tr>
</tbody>
</table>
Challenges in substituting rare earth magnet with ferrite in electrical machines

![Graph showing residual flux density vs. intrinsic coercivity force for different magnet types.

- Ferrite
- Bonded NdFeB (RE)
- Sintered SmCo (RE)
- Sintered NdFeB(RE)

Residual flux density (Tesla) (Indicates amount of flux generated)

Intrinsic coercivity force (kA/m) (Indicates resistance to demagnetization)
Challenges in substituting rare earth magnet with ferrite in electrical machines

- What others are doing
  - Motor without any magnets
    - Switched reluctance motors
    - Synchronous reluctance motors
  - Motor with magnets
    - New topologies to that allows putting more magnet in an efficient way such as axial flux machines, dual rotor machines

- Nanopyme motor topology and configuration offers
  - Low cost position sensing and simple controller
  - Easy to wound and easy to repair modular concentrated winding
  - Direct drive with no gears offers lesser components and improved reliability
Design details

<table>
<thead>
<tr>
<th>Design constraints</th>
<th>Optimised designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of stator slots</td>
<td>Design</td>
</tr>
<tr>
<td>Number of rotor poles</td>
<td>$L_m$ (mm)</td>
</tr>
<tr>
<td>Length of airgap</td>
<td>$h$ (%)</td>
</tr>
<tr>
<td>Outer diameter of stator</td>
<td>$\lambda_d$ (%)</td>
</tr>
<tr>
<td>Gross slot fill factor</td>
<td>$L_{yr}$ (mm)</td>
</tr>
<tr>
<td>Width of slot opening</td>
<td>$W_t$ (mm)</td>
</tr>
<tr>
<td>Depth of slot lip</td>
<td>$N_c$</td>
</tr>
<tr>
<td>Depth of slot mouth</td>
<td>$D_{ct}$ (mm)</td>
</tr>
<tr>
<td>Current density of coil</td>
<td>$L_t$ (mm)</td>
</tr>
<tr>
<td>Ratio of pole arc to pole pitch</td>
<td>$L_{as}$ (mm)</td>
</tr>
<tr>
<td></td>
<td>$R_{ph}$ (m$\Omega$)</td>
</tr>
<tr>
<td></td>
<td>$I_{ph}$ (A)</td>
</tr>
<tr>
<td></td>
<td>$P_{Cu}$ (W)</td>
</tr>
</tbody>
</table>

Design details:
- Design constraints:
  - Number of stator slots: 18
  - Number of rotor poles: 16
  - Length of airgap: 0.4 mm
  - Outer diameter of stator: 260 mm
  - Gross slot fill factor: 50%
  - Width of slot opening: 1 mm
  - Depth of slot lip: 2 mm
  - Depth of slot mouth: 2 mm
  - Current density of coil: 4.5 A mm$^{-2}$
  - Ratio of pole arc to pole pitch: 1

Optimised designs:
- Design:
  - 63
  - 88
  - 124
  - 143
  - 158
  - 270

Design details table:
- $L_m$ (mm)
- $h$ (%)
- $\lambda_d$ (%)
- $L_{yr}$ (mm)
- $W_t$ (mm)
- $N_c$
- $D_{ct}$ (mm)
- $L_t$ (mm)
- $L_{as}$ (mm)
- $R_{ph}$ (m$\Omega$)
- $I_{ph}$ (A)
- $P_{Cu}$ (W)
Mechanical assembly of the motor

- Coils
- Stator
- Magnets
- Wheel
- End Plate
- Rotor yoke
- Tooth
- Magnets
Fabrication of motor - stator tooth

Material: M400-50A
Fabrication of motor - stator coils
Fabrication of motor – tooth mounting assembly

Tooth holder

Tooth holder

Shaft
Fabrication of motor – tooth mounting assembly
Fabrication of motor – Completed stator and rotor position sensor mounting
Fabrication of motor – Rotor yoke and magnet assembly
Completed motor on vehicle
Conclusion

- Introduction of improved energy density ferrite magnet based PM motors could improve the adoption rate of electric vehicles by offering low-cost powertrain.

- DTU along with Nanopyme partners has fabricated and successfully completed first trial assembly of axial flux ferrite magnet motor for electric two-wheeler application.

- In coming weeks DTU will fine-tune the motor assembly and integrate the motor to wheels of vehicle.

- The on-board vehicle test of powertrain according to ISO 13064 standard is scheduled for October 2015. This will be followed by test bench evaluation of motor.
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