Advanced Electric Motor Technologies

2D- and 3D-FEM-Analysis of Axial Field Permanent Magnet Synchronous Motors
– a Comparison (FEMAG-2D vs. FLUX-3D)

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FEMAG-Anwender-Treffen, Hannover 2014
Target

- Short overview of the axial field PM synchronous machine technology highlighting the relevant aspects for modeling and analysis
  - diversity of configurations

- Comparison of modeling and analysis using a 2D- and a 3D-FEM approach
Main features

- D/L-ratio (short machines with large diameter, ideal for some applications)
- High inertia (flywheel)
- Modularity due to multi-stacking
- For larger diameter the number of poles can be easily implemented

Drawbacks

- strong axial magnetic stator-rotor attraction force
- mechanical design and manufacturing technology difficulties
  - bearing and imbalance
  - stator stack stamping and assembling
- power limitation of AxF-PMSM
  - for higher torque (i.e. larger outer diameter) the mechanical stress of the rotor-shaft interface becomes prohibitive
    > multi-stack machines
Introduction / AxF- vs. RF-PMSM

Figure 1.11. Performance comparison of RFPM and AFPM machines [214].

Sipati, IEEE
Introduction / Applications

- Power generation
- Automotive
  - Traction for EV and HEV
  - Auxiliary drives (pumps, actuators, ...)
- Ship and submarine propulsion
- Electromagnetic aircraft launch systems
- Drill rigs, elevators
- Penny-motor
- Rotary actuators
- Vibration motors
- Hard disc drives
- Pumps in medical devices
- ...
Introduction / Types of AxF-PMSM

<table>
<thead>
<tr>
<th>Structure</th>
<th>Single Stator Single Rotor (Single sided)</th>
<th>Double Stator Single Rotor (Kaman type)</th>
<th>Single Stator Double Rotor (Torus type)</th>
<th>Multi-stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>Iron core</td>
<td>Iron core</td>
<td>Ironless core</td>
<td>Iron core</td>
</tr>
<tr>
<td>Slotting</td>
<td>Slotted</td>
<td>Slotted</td>
<td>Slotless</td>
<td>Slotless</td>
</tr>
<tr>
<td>Winding</td>
<td>Drum winding (tooth-wound)</td>
<td>Drum winding (tooth-wound)</td>
<td>Drum winding</td>
<td>Drum winding (tooth-wound)</td>
</tr>
<tr>
<td>PMs</td>
<td>NS</td>
<td>NN</td>
<td>NS</td>
<td>NN</td>
</tr>
</tbody>
</table>
Introduction / Types of AxF-PMSM / Examples of configurations

3-D view of a four-pole-pair/12-slot SSSR AFPM machine

3-D view of a four-pole-pair/12-slot DSSR AFPM machine

Fig. 4. Flux paths in 2-D plane for DSSR structure of the AFPM machine. (a) Surface-mounted PM structure. (b) Buried PM structure. (c) Interior PM structure without steel disc.
Introduction / Types of AxF-PMSM / Examples of configurations

3-D view of a four-pole-pair/12-slot SSDR AFPM machine

Fig. 6. Flux paths in 2-D plane for SSDR AFPM machine. (a) NN PM structure. (b) NS PM structure.
Introduction / Types of AxF-PMSM / Examples of configurations

Fig. 8. 3-D view of a four-pole-pair/12-slot multistage AFPM machine ($N = 2$ stator; $N + 1 = 3$ rotors).

AFPM topologies: (a) Torus slotted NN and (b) Torus slotted NS

AFPM topologies: Torus slotted NS multi-stack [1].
Introduction / Windings for AxF-PMSM

Figure 2.8. Single-layer winding of an AFPM machine with $m_1 = 3$, $2p = 6$, $s_1 = 36$, $y_1 = Q_1 = 6$ and $q_1 = 2$.

Fig. 2. AFPM winding types: (a) drum (tooth-wound) and (b) ring (core-wound) [46].

Fig. 1. Axial flux micro-motor: schematic (above) and stator picture.
Introduction / Materials used for the core of AxF-PMSM

3D-Design

Figure 3.4. Powder salient pole stators for small single-sided AFPM motors. Technologies, LLC, West Lebanon, NH, U.S.A.

Figure 3.5. SMC powder salient pole for small single-sided AFPM motors: (a) single SMC pole; (b) double-sided AFPM motor. Courtesy of Höganäs, Höganäs, Sweden.
Analysis approaches for AxF-PMSM

- Analytical (mainly for slotless configurations)
- NMEC (non-linear magnetic equivalent circuits, see literature)
- 2D-FE
- 3D-FE
- their multiple combinations (see literature)
Topological transformation of the AxF-PMSM

- Use of homeomorphic (equivalent) topological transformation (without a change of the structure)

- **AxF-PMSM > Linear-PMSM (one or more slices)**

- **AxF-PMSM > Inner-/Outer-Rotor-PMSM (one or more slices)**
MATLAB-scripted Pre- and Postprocessor for FEMAG and FLUX
Case studies

- **AxF-PMSM without radial overhang** in stator and/or rotor
  - Case study #1: AxF-PMSM / teeth *without tooth-tip*
    - M400-50A stator and sintered NdFeB-PM
  - Case study #2: AxF-PMSM / teeth *with tooth-tip*
    - M400-50A stator and sintered NdFeB-PM

- **AxF-PMSM with radial overhang** in stator and/or rotor
  - Case study #3: AxF-PMSM
    - SMC-stator and rotor flux concentration using hard ferrite PM
Case study #1: AxF-PMSM / teeth without tooth-tip

- \( n_s = 6 \)
- \( n_p = 4 \)
- \( D_{so} = 50 \text{ mm} \)
- \( D_{si} = 25 \text{ mm} \)
- \( h_{yr} = 3 \text{ mm} \)
- \( h_{PM} = 1.5 \text{ mm} \)
- \( h_{ts} = 7 \text{ mm} \)
- \( h_{ys} = 3 \text{ mm} \)
- \( \text{gap} = 1 \text{ mm} \)

- \( S/R: \text{M}400-50A \)
- \( \text{PM: Br20} = 1.2 \text{ T} \)
- \( n_{tc} = 10 \)
- \( S_{\text{fill}} = 40 \% \)
- \( n = 3000 \)
- \( I_{\text{ph\_rms}} = 7.0711 \text{ (sinusoidal current controlled)} \)
Case study #2: AxF-PMSM / teeth with tooth-tip

ns = 6
np = 4
Dso = 50 mm
Dsi = 25 mm
hyr = 3 mm
hPM = 1.5 mm
hts = 6 mm
htt = 1 mm
hys = 3 mm
gap = 1 mm

S/R: M400-50A
PM: Br20 = 1.2 T
ntc = 10
Sfill = 40 %
n = 3000
I_ph_rms = 7.0711 (sinusoidal current controlled)
Case study #3: AxF-PMSM with radial overhang in stator

- ns = 6
- np = 4
- Dso = 50 mm
- Dsi = 25 mm
- hyr = 3 mm
- hPM = 3.0 mm
- hts = 6 mm
- htt = 1 mm
- hys = 3 mm
- gap = 1 mm

S/R: SMC-Somaloy 500
PM: Br20= 0.4 T

- ntc = 10
- Sfill = 40 %

- n = 3000
- I_ph_rms = 7.0711 (sinusoidal current controlled)
Case study #1: 2D-FE linear machine approach

Modeling and analysis

CS1 1-slice (L_slice = 12.5 mm)

L = 117.8 mm

Graphs showing bemf ph, bemf ll, cogging, and load shifts.
Case study #1: 2D-FE linear machine approach

Modeling and analysis

CS1 3-slices (L_slice = 4.167 mm)

L = 91.6 mm

L = 117.8 mm

L = 144.0 mm
Case study #1: 2D-FE linear machine approach

Modeling and analysis
Case study #1: 2D-FE IR (1 slice) approach

Modeling and analysis

Dso = 57.5 mm
Dsi = 37.5 mm
Lstk = 12.5 mm
hyr = 3 mm
hPM = 1.5 mm
hts = 7 mm
hys = 3 mm
gap = 1 mm
Case study **#1**: 3D-FE approach

Modeling and analysis

Mesh: 181059 volume elements
Computation time: about 100 min.
Case study #2: 2D-FE linear machine approach

Modeling and analysis – similar approach

CS2 1-slice \((L_{\text{slice}} = 12.5 \text{ mm})\)

\(L = 117.8 \text{ mm}\)

CS2 5-slices \((L_{\text{slice}} = 2.5 \text{ mm})\)

\(L = 86.5 \text{ mm}\)

CS2 3-slices \((L_{\text{slice}} = 4.167 \text{ mm})\)

\(L = 91.6 \text{ mm}\)

CS2 5-slices \((L_{\text{slice}} = 2.5 \text{ mm})\)

\(L = 102.1 \text{ mm}\)

CS2 5-slices \((L_{\text{slice}} = 2.5 \text{ mm})\)

\(L = 133.5 \text{ mm}\)

CS2 5-slices \((L_{\text{slice}} = 2.5 \text{ mm})\)

\(L = 149.2 \text{ mm}\)

CS2 5-slices \((L_{\text{slice}} = 2.5 \text{ mm})\)

\(L = 144.0 \text{ mm}\)
Case study #2: 2D-FE IR (1 slice) and 3D-FE approach

Modeling and analysis – similar approach

Mesh: 181059 volume elements (same FEM-Model used)
Computation time: about 100 min.
Case study #3: SMC stator core and hard ferrite PM

3D-FE-approach – mandatory

Mesh: 193808 volume elements  
Computation time: about 100 min.
Case study #1: Overview of the computational results

<table>
<thead>
<tr>
<th>Approach</th>
<th>2D-FE-linear</th>
<th></th>
<th>2D-FE-IR</th>
<th>1-slice</th>
<th>3D-FE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-slice</td>
<td>3-slices</td>
<td>5-slices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Psi_PM* [%]</td>
<td>2.5</td>
<td>-1.6</td>
<td>-1.6</td>
<td>8.3</td>
<td>0.0</td>
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<tr>
<td>T_shaft* [%]</td>
<td>2.7</td>
<td>-1.7</td>
<td>-1.7</td>
<td>5.0</td>
<td>0.0</td>
</tr>
<tr>
<td>eta_motor* [%]</td>
<td>0.4</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-1.6</td>
<td>0.0</td>
</tr>
<tr>
<td>T_cogg_pk-pk* [%]</td>
<td>58.4</td>
<td>10.9</td>
<td>5.6</td>
<td>13.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

* - relative deviation, 3D-FE = 100 %
Case study #2: Overview of the computational results

<table>
<thead>
<tr>
<th>Approach</th>
<th>CS 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2D-FE-linear</td>
</tr>
<tr>
<td></td>
<td>1-slice</td>
</tr>
<tr>
<td>( \Psi_{PM} )  [%]</td>
<td>-2.0</td>
</tr>
<tr>
<td>( T_{shaft} ) [%]</td>
<td>-2.3</td>
</tr>
<tr>
<td>( \eta_{motor} ) [%]</td>
<td>-0.4</td>
</tr>
<tr>
<td>( T_{cog} ) [pk-pk*] [%]</td>
<td>42.6</td>
</tr>
</tbody>
</table>

* - relative deviation, 3D-FE = 100 %

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Conclusion and further work

- **AxF-PMSM without radial overhang** in stator and/or rotor
  - 2D-FE linear machine approach
    - accuracy:
      - 3-slices: good
      - 5-slices: very good
  - 2D-FE-IR approach
    - Accuracy:
      - coarse fast estimation (no special tools requirement)
  - **3D-FE approach** is necessary for a higher accuracy

- **AxF-PMSM with radial overhang** in stator and/or rotor
  - **3D-FE approach** is mandatory
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