Permanent Magnet Machine Design and Analysis Including Flux-switching PM and PM-assisted Synchronous Reluctance Machines

Part I – Overview of PM Machines, Sizing Equations and FSPM Machines

Bulent Sarlioglu, Ph.D.
University of Wisconsin-Madison, USA
sarlioglu@wisc.edu

PART I
PM Machine Design and Analysis
Machine Design Workflow

Application Requirements

Machine Requirements

Converter Requirements

Topology Selection

Converter Design

Detailed Machine Design

Modeling & Analysis

FEA Simulation

Validation

Prototyping

Performance Evaluation

Electromagnetics

Thermal

Structural

Multi-Physics

Refine Design with Optimization

Experiments

Prediction

System Optimization

Compare options

Verification

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Machine Design Requirements

Example: D.O.E. US Drive (Previous FreedomCAR program)
Goal: Develop advanced (hybrid) electric vehicles

Motor Output Specifications [1]

a. Output power and speed
- Continuous power: 30 kW
- Peak power for 18 seconds: 55 kW
- Minimum top speed: 14,000 rpm

b. Phase current
- Max phase current: 400 Arms

c. Line-to-line back-EMF
- Less than 600 V peak at 100% speed

d. Torque pulsations
- Less than 5% peak torque at any speed

e. Efficiency
- No less than 95% at 10%~100% speed for 20% rated torque

Machine Design Requirements

Inverter Output Specifications [1]

a. Operating DC link voltage
   • Nominal voltage: 325 V, and vary between 200 V to 450 Vdc

b. Power factor of load
   • No less than 0.8

c. Output current ripple
   • Percentage of peak to peak of fundamental peak value: 3%

d. Switching frequency
   • Maximum value at 20 kHz

e. Fundamental electrical frequency
   • Maximum at 1000 Hz

f. Motor input inductance
   • Minimum value: 0.5 mH

g. Efficiency
   • No less than 93% for all operating conditions

Classification of Machines by Flux Path and Winding Types

By Flux Path

- Radial Flux (Most common)
- Axial Flux
- Transverse Flux

By Winding Types

- Distributed or concentrated
- Integral slot or fractional slot

Axial flux machine, Mavilor motors

Fractional slot concentrated winding, EI-Refaie
## Evaluation of Common Machine Topologies

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| (1) Induction machine        | 1. Most widely used.  
                                 | 2. Simple and robust structure                                              | 1. Relatively low efficiency                                                 |
| (2) Surface PM Machine       | 1. High torque density  
                                 | 2. Easy control                                                            | 1. Large equivalent airgap and low motor inductance  
                                 |                                                                              | 2. Magnets retention issue                                                  |
| (3) Interior PM Machine      | 1. High torque density due to flux concentration effect  
                                 | 2. Good flux weakening capabilities                                          | 1. Not very amenable to very high-speed operation                             |
| (4) Switched Reluctance      | 1. Robust rotor good for high speed operation                              | 1. Large torque ripple  
                                 |                                                                              | 2. High acoustic noise                                                      |
| (5) Synchronous Reluctance   | 1. Salient machine without magnets  
                                 | 2. Simple control algorithm                                                 | 1. Low power factor  
                                 |                                                                              | 2. Hard to design rotor flux barriers and flux carriers                     |
## Evaluation of Common Machine Topologies

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6) Flux-Switching Machine</td>
<td>1. Robust rotor structure</td>
<td>1. Difficult to manufacture</td>
</tr>
<tr>
<td></td>
<td>2. High torque density</td>
<td>2. Requires more PM materials</td>
</tr>
<tr>
<td></td>
<td>3. PM on the stator and easy to cool</td>
<td></td>
</tr>
<tr>
<td>(7) PM-Assisted SynRM Machine</td>
<td>1. Good power density</td>
<td>1. Complicated rotor structure</td>
</tr>
<tr>
<td></td>
<td>2. Wider constant power speed ratio (CPSR)</td>
<td>2. Not amendable to very high speed operation</td>
</tr>
<tr>
<td></td>
<td>3. Safe open-circuit back-emf</td>
<td></td>
</tr>
</tbody>
</table>
Induction Motor Traction Motor

General Motors Induction Motor

Source: GM
Internal PM Traction Motor

General Motors
Permanent Magnet Electric Motor

Source: GM
Synchronous Reluctance Motor Example

Commercialized SynRM motor

Synchronous reluctance machine does not have any rotor windings or rotor PMs.
PM-Assisted SynRM Machine


PM-assisted SynRM machine shares similar properties to the IPM machine, but with inversed saliency property
Flux-Switching PM Machine


FSPM machines have been under intensive research over the past decades, and majority of the prototypes are in the lab
Common Winding Types

- **Single phase winding**: windings for single phase
  - The generated EMFs of all the phases are of equal magnitude
  - The waveforms of the phase EMFs are identical
  - The frequency of the phase EMFs are equal

- **Polyphase winding**: windings for multiple phases
  - Concentrated Windings
    - Concentrated around tooth
  - Distributed Windings
    - Lap winding
    - Wave winding
    - Concentric winding
Concentrated Winding

- All the winding turns are wound together in series to form a multi-turn coil
- All the turns in the winding have the same magnetic axis
- Examples of concentrated winding
  - DC machines
  - Field winding of salient-pole synchronous machines
  - Primary and secondary windings of transformers
  - Fractional slot concentrated winding (FSCW) machines

Source: Honda Accord 2005 hybrid electric vehicle stator
Pros and Cons for Concentrated Winding

**Pros**
- Short and compact end windings
- Compatible with fractional slot configuration
- Small cogging torque if combined with fractional slot configuration
- Possible to use segmented stator configuration
- Better manufacturability

**Cons**
- Large winding spatial harmonics compared to distributed winding
- Higher rotor iron loss compared to distributed winding

Source: Uratani Engineering
Distributed Winding

- All the winding turns are arranged in several full-pitch or short-pitch coils.
- These coils are spread in the slots around the periphery of airgap.
- Examples of distributed winding:
  - Armatures of DC or common synchronous machines.
  - Common IPM machines.

Source: Prius 2010 hybrid electric vehicle stator.
Pros and Cons for Distributed Winding

- **Pros**
  - Better utilization of the available space around the periphery of the machine
  - Less winding spatial harmonics compared to concentrated winding
  - More compatible combinations of slots and pole numbers

- **Cons**
  - Large and bulk end windings
  - Large end winding resistance and leakage inductance
  - Increase the axial length of the machine

Source: MK Pumps and motors Limited
Importance of Sizing Equation

**Sizing equation**: The basic relationship of electric machine power/torque and the key parameters, including dimensional, electric, and magnetic parameters.

**Benefits of using sizing equation**

1. Provide fast evaluation of electric machine dimensions
2. Offer preliminary calculation before detailed design is commenced
3. Enable sanity check of machine power and speed rating
Output Power - \( D_g^2 L_e \) Equation

\[
P_{out} = \frac{1}{1 + K_\phi} \frac{\pi}{2} K_e K_i K_p \eta B_g A_{tot} f \frac{D_g^2 L_e}{p} \text{ W}
\]

- \( K_\phi \): ratio of rotor side electric loading to stator side electric loading
- \( K_e \): electromotive force coefficient
- \( K_i \): Current waveform factor
- \( K_p \): Electrical power waveform factor
- \( \eta \): Machine efficiency
- \( B_g \): Amplitude of fund. airgap flux density [T]
- \( A_{tot} \): Total electrical Loading [A_{rms}/m]
- \( f \): Excitation frequency [Hz]
- \( p \): Number of pole pairs
- \( D_g \): Airgap diameter [m]
- \( L_e \): Effective stack length [m]

[T.A.Lipo 1998]

Output power is proportional to the square of the airgap diameter and effective length of the machine
Various “K” Factors

\[ K_\phi = \frac{A_r}{A_s}, \text{ ratio of rotor side electric loading to stator side electric loading} \]

\[ K_e : 2\pi K_w, \text{ electromotive force coefficient} \]
- True for sinusoidally excited machine, including induction machine, permanent magnet synchronous machines

\[ K_w : \text{ Winding factor, calculated by } K_w = K_p K_d K_{skew} \]
- \( K_p \) is the short pitch factor. It describes the penalty of having short-pitched winding instead of full-pitched windings
- \( K_d \) is the distribution factor. It describes the penalty of having distributed windings instead of concentrated windings.
- \( K_{skew} \) is the skewing factor. It describes the penalty of having skewed stator or rotor instead of non-skewed configurations.

\[ P_{out} = \frac{1}{1 + K_\phi} \frac{\pi}{2} K_e K_i K_p \eta B_g A_{tot} \frac{f}{p} D_g^2 L_e \]
Various “K” Factors

$K_i$ : Current waveform factor. It is defined by the ratio of peak value of phase current over its rms value. For balanced three phase sinusoidal excitation, the value of $K_i$ is $\sqrt{2}$.

\[
K_i = \frac{I_{pk}}{I_{rms}} = \frac{1}{\sqrt{T \int_0^T \left( \frac{i(t)}{I_{pk}} \right)^2 dt}}
\]

$K_p$ : Electrical power waveform factor. It is defined by the ratio of time-averaged instantaneous power over the peak power.

\[
K_p = \frac{1}{T} \int_0^T \frac{e(t) \times i(t)}{E_{pk} \times I_{pk}} dt
\]

\[
P_{out} = \frac{1}{1 + K_\phi} \frac{\pi}{2} K_e K_i K_p \eta B_g A_{tot} \frac{f}{p} D_g^2 L_e
\]
## Typical values of $K_i$ and $K_p$

Typical values of $K_i$ and $K_p$ and for common phase EMF and current waveforms

<table>
<thead>
<tr>
<th>Waveform</th>
<th>e(t)</th>
<th>i(t)</th>
<th>$K_i$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sinusoidal</strong></td>
<td><img src="image" alt="Sinusoidal Waveform" /></td>
<td><img src="image" alt="Sinusoidal Waveform" /></td>
<td>$\sqrt{2}$</td>
<td>$1/2\cos\phi_r$</td>
</tr>
<tr>
<td>For SPM, IPM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Rectangular</strong></td>
<td><img src="image" alt="Rectangular Waveform" /></td>
<td><img src="image" alt="Rectangular Waveform" /></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>For BLDC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\cos\phi_r$: internal power factor  
$\Phi_r$: the angle between phase EMF and stator phase current.  

[T.A.Lipo 1998]
Typical values of $K_i$ and $K_p$

<table>
<thead>
<tr>
<th>Waveform</th>
<th>e(t)</th>
<th>i(t)</th>
<th>$K_i$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triangular</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
<td>$\sqrt{3}$</td>
<td>$1/3$</td>
</tr>
<tr>
<td>Rectangular &amp; Trapezoidal</td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
<td>1.134</td>
<td>0.8</td>
</tr>
<tr>
<td>Rectangular &amp; Triangular</td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
<td>1.5</td>
<td>1/3</td>
</tr>
</tbody>
</table>
Example for Calculating $K_i$ and $K_p$

The values of $K_i$ and $K_p$ for sinusoidal current and EMF waveforms are derived:

<table>
<thead>
<tr>
<th>Waveform</th>
<th>$e(t)$</th>
<th>$i(t)$</th>
<th>$K_i$</th>
<th>$K_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinusoidal</td>
<td><img src="image" alt="Sinusoidal Waveform" /></td>
<td><img src="image" alt="Sinusoidal Waveform" /></td>
<td>√2</td>
<td>$1/2\cos\phi_r$</td>
</tr>
</tbody>
</table>

For SPM, IPM

$$K_i = \frac{I_{pk}}{I_{rms}} = \frac{1}{\sqrt{T \int_0^T \left(\frac{i(t)}{I_{pk}}\right)^2 dt}} = \frac{1}{1/\sqrt{2}} = \sqrt{2}$$

$$K_p = \frac{1}{T} \int_0^T e(t) \times i(t) \, dt = \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} \cos \phi_r = 1/2 \cos \phi_r$$
Output Torque - $D_g^2L_e$ Equation

Torque is power divided by mechanical angular speed.

\[
T_{out} = \frac{P_{out}}{2 \frac{f}{p}} = \frac{1}{1+K} \frac{1}{4} K_e K_i K_p B_g A_{tot} D_g^2 L_e
\]

Observations

• Torque equation does not contain number of pole pairs and excitation frequency (operating speed)

• Hence, electrical machine is sized by torque

Torque is proportional to magnetic loading $B_g$, electrical loading $A_{tot}$, square of airgap diameter and effective stack length.

How should magnetic loading $B_g$ and electrical loading $A_{tot}$ be selected for a machine?
Electrical Loading $A_s$

$$T_{out} = \frac{P_{out}}{2} \frac{f}{p} = \frac{1}{1+K} \frac{1}{4} K_e K_i K_p B_g A_{tot} D_g^2 L_e$$

Stator electrical loading $A_s$ is expressed as the total current divided by the circumference of the airgap

- Total current can be found multiplying number of phases with turns per phase and current in each turn

$$A_s = \frac{\text{Total RMS Ampere turns}}{\text{Circumference of Airgap}}$$

$$A_s = 2mN_t \frac{I_{rms}}{\pi D_g} \quad [\text{A}_{\text{rms}}/\text{m}]$$

$m$ : number of phases

$N_t$ : total number of turns per phase

$I_s$ : stator current [Arms]

$D_g$ : airgap diameter [m]

Electrical loading is proportional to number of turns and rms current and inversely proportional to airgap diameter
Total Electrical Loading $A_{\text{tot}}$

\[
T_{\text{out}} = \frac{P_{\text{out}}}{2 f / p} = \frac{1}{1+K} \frac{1}{4} K_e K_i K_p B_g A_{\text{tot}} D^2 L_e
\]

Assume the ratio of electrical loading on rotor and stator is $K_\phi = A_r/A_s$. Total electrical loading is calculated as

\[
K_\phi \text{ – Rotor electrical loading factor}
\]

\[
A_{\text{tot}} = A_s (1+K) \quad [\text{A}_{\text{rms}}/\text{m}]
\]

$K_\phi$ is zero if there is no electrical excitation in the rotor. For SPM, IPM, and Synchronous Reluctance machines. $K_\phi$ is zero.
What Impacts Electrical Loading?

*Electrical loading is influenced by*

1. **Maximum operating temperature** of the winding insulation
2. **Allowable efficiency** to produce desirable torque
3. **Cooling capability** to dissipate the heat produced in the winding and core
4. **Demagnetization** condition of magnets

*Larger electrical loading larger the torque production capability. Electrical loading is limited by insulation, efficiency requirement, cooling, and demagnetization concerns*
Relationship of Electrical Loading \( A_s \) with Current Density \( J_{srms} \)

\[
A_s = J_{srms} K_{cu} d_s \frac{t_s}{t_s + t_t}
\]

- \( J_{srms} \): current density [Arms/m²]
- \( K_{cu} \): slot fill factor
- \( d_s \): slot equivalent depth [m]
- \( t_s \): slot equivalent width [m]
- \( t_t \): teeth equivalent width [m]

- The widths of stator teeth and slot are assumed equal as a good starting point
- Slot fill factor for normal winding is between 0.4 to 0.6. Concentrated winding generally offer higher slot fill factor than distributed winding machines

**Electrical loading and current density are related by geometry**
### Example Current Densities $J_{\text{srms}}$ for Induction Machine

<table>
<thead>
<tr>
<th>Cooling Method [2]</th>
<th>$J_{\text{srms}}$ Current Density [Arms/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totally enclosed without external cooling</td>
<td>4.5 to 6</td>
</tr>
<tr>
<td>Forced air cooling over stator surface</td>
<td>7.5 to 9</td>
</tr>
<tr>
<td>Air cooling through stator/rotor ducts or vents</td>
<td>14 to 15</td>
</tr>
<tr>
<td>Liquid cooling in ducts or spraying on end winding</td>
<td>20 or greater</td>
</tr>
</tbody>
</table>

[T.A.Lipo, 2011]

Larger the cooling capability larger the current density used
Example Electrical Loading $A_s$ and Current Density $J_{srms}$

Representative current densities for totally enclosed, fan cooled machines for typical NEMA design

<table>
<thead>
<tr>
<th>Horse Power</th>
<th>$A_s$ [Arms/m m]</th>
<th>$J_{srms}$ [Arms/mm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P=2</td>
</tr>
<tr>
<td>1</td>
<td>11.5</td>
<td>5.4</td>
</tr>
<tr>
<td>5</td>
<td>21</td>
<td>5.1</td>
</tr>
<tr>
<td>10</td>
<td>24</td>
<td>5.0</td>
</tr>
<tr>
<td>50</td>
<td>26</td>
<td>3.1</td>
</tr>
<tr>
<td>100</td>
<td>26</td>
<td>2.3</td>
</tr>
<tr>
<td>500</td>
<td>26</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Larger the machine HP smaller the current density

[T.A.Lipo, 2011]
Magnetic Loading $B_g$ Definition

Magnetic loading is defined as the (average) flux density in the airgap. The SI unit is Tesla.

**Magnetic loading is influenced by**

1. **Material property of lamination steel and magnets**
   - For high strength magnetic material (such as Hiperco 50, Cobalt iron alloy), saturation flux density can be as high as around 2.4 T.

2. **Maximum saturation flux density in the machine**
   - For common steel, the saturation flux density in the tooth is normally between 1.5 T to 2 T while in the core is usually between 1.4 T to 1.7 T.

3. **Acceptable iron loss**
   - Operating frequency of the machine
Flux-Switching PM Machine Design and Analysis
FSPM Machine Introduction

Major Properties
• Magnets on the stator
• Concentrated windings
• Simple and robust rotor (similar to SRM without PM)
• Sinusoidal back-EMF
• Easy thermal management
• Modular stator structure
• High flux concentration

FSPM machine has been one of the most popular stator-PM machines studied in literature

Introduced by Rauch and Johnson in 1955

Single phase alternator
Principle of Operation for FSPM

Flux Linkage Properties

• PM flux linkage in the coil switches polarity when rotor tooth aligns the alternative stator tooth
• Flux linkage in the coil is almost sinusoidal
• Flux in the rotor is bi-directional

Classical d-q theory can be applied to FSPM machine due to the nature of sinusoidal flux linkage
Different Topologies of FSPM-Winding Configurations

- FSPM machine can have all poles wound (double layer winding) and alternate poles wound (single layer winding) configurations
- Double layer winding provides more compact end winding, while single layer winding provides better fault tolerant capability

Double layer winding configurations are studied more commonly

Different Topologies of FSPM - Hybrid Excitation

- Both magnets and field winding are used for excitation
- Airgap field can be easily controlled by field winding


Hybrid-excited configuration can achieve variable flux operation
Reduced Rare-Earth FSPM Machine

- Use ferrite instead of Nd for traction application
- Reduced cost while achieving comparable performance

Reduced rare-earth configurations are feasible and cost-effective

Conventional 6/4 FSPM Machine – A Good Alternative?

1. **Lowest rotor pole for 3-phase FSPM machine**

2. 6/4 topology has 60% less fundamental frequency compared to 12/10 topology

3. Switching frequency from converter is **much less demanding**

4. High frequency losses are **significantly reduced** at high-speed conditions

**6/4 FSPM machine is a good alternative for high-speed operation. However there are challenges to be overcome**
Challenges of Conventional 6/4 FSPM Machine

**Distorted Flux Linkage and Back-EMF**

- Flux linkage has large total harmonic distortion
- Conventional 6/4 FSPM machine is inferior for practical use


The even (specially 2nd) order harmonic is the main cause for distortion
Conventional 6/4 FSPM Machine

Fundamental and 2nd order Harmonics

• Total flux path at open circuit condition
• 2nd order flux linkage is caused by airgap permeance variation of stator as the rotor rotates

Proposed Novel Dual-Stator 6/4 FSPM Machine

Novel Structure Realization

• Windings directions are opposite in the two stators
• All coils are connected in series per phase
• Rotor poles are offset by 45° mechanical angle
• Magnet directions in two stators are the same

Proposed Novel Dual-Stator 6/4 FSPM Machine

Cancellation of Even Harmonics

- Fundamental component remains intact
- 2\textsuperscript{nd} order harmonic is shifted by 180° electrically
- All other even order harmonics are also shifted by 180° electrically

Flux linkage of front phase A windings

Flux linkage of rear phase A windings

Proposed Novel Dual-Stator 6/4 FSPM Machine

Resultant Flux Linkage

- Odd harmonics add up, and even harmonics are eliminated in the total flux linkage.
- Total flux linkage per phase has very small harmonic distortion.

Flux linkage of front stator coil A1 and A2

\[ \lambda_{1,2} = \sum_{h=1,3,5,...}^{\infty} A_h \cos(h\theta_e + \theta_h) + \sum_{h=2,4,6,...}^{\infty} A_h \cos(h\theta_e + \theta_h) \]

Flux linkage of rear stator coil A3 and A4

\[ \lambda_{3,4} = \sum_{h=1,3,5,...}^{\infty} A_h \cos(h\theta_e + \theta_h) - \sum_{h=2,4,6,...}^{\infty} A_h \cos(h\theta_e + \theta_h) \]

Flux linkage of total phase A winding

\[ \lambda_{\text{total}} = \sum_{h=1,3,5,...}^{\infty} 2A_h \cos(h\theta_e + \theta_h) \]


Even order harmonics are eliminated in the total flux linkage
Rotor Shifted and Magnets in Opposite Direction

- The rotor has offset poles
- Magnets in the front and rear stators have opposite orientations
- A single continuous winding wraps around both stators
- There has to be a gap between two stators to prevent magnet flux short circuiting


This topology has the advantage of simpler winding configuration
Stator Shifted without Shifting Rotor

- The rotor is not shifted, so only one type of lamination is needed
- Whole rear stator is shifted with windings
- The rear stator is shifted by 45° mechanical degree as shown
- There are multiple stator shifting angles such as 135°, 225°, and 315° to achieve the same even harmonics cancellation effect


This topology has the advantage of simpler rotor configuration
General Rule for Topology Variations

Topology variations

- The first topology can be changed to the second alternative topology.
- In fact, the rear stator and rotor can be shifted by any arbitrary angle together to achieve the even harmonics cancelation effect.


There could be infinite number of shifting angles as long as the rear stator and rear rotor maintain the relative position.
Comparison with Conventional 6/4 FSPM Machine (1/3)

Design Considerations

- Two machines are designed with same stack length and stator geometry
- Same current and electrical loading are used for both machines
- End winding resistance, inductance, and end effect are included using 3D FEA study

<table>
<thead>
<tr>
<th>Key Performance Parameters</th>
<th>Conventional 6/4</th>
<th>Dual-stator 6/4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected output power, $P_{out}$ [kW]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Rated speed, $n_r$ [rpm]</td>
<td>15,000</td>
<td>15,000</td>
</tr>
<tr>
<td>Fundamental frequency, $f_e$ [Hz]</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Electrical loading, $A_{e rms}$ [kA$_{rms}$/m]</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Stator outer diameter, $D_{o}$ [mm]</td>
<td>112.3</td>
<td>112.3</td>
</tr>
<tr>
<td>Stator inner diameter, $D_{i}$ [mm]</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>Magnet width, $d_{m}$ [mm]</td>
<td>9.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Single stator stack length, $L_{e total}$ [mm]</td>
<td>N/A</td>
<td>32.5</td>
</tr>
<tr>
<td>Total stack length, $L_{e}$ [mm]</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Gap between stators, $d_{gap}$ [mm]</td>
<td>N/A</td>
<td>20</td>
</tr>
<tr>
<td>Airgap length, $g$ [mm]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Magnet remnant flux density, $B_r$ [T]</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Turns per phase per stator, $N_t$</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Phase current, $I_x$ [A$_{rms}$]</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Current density, $J_t$ [A$_{rms}$/mm$^2$]</td>
<td>7.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Slot fill factor, $K_{slot}$</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>Resistance per phase, $R_x$ [mΩ]</td>
<td>22</td>
<td>30</td>
</tr>
</tbody>
</table>

Performance of proposed dual-stator machine is compared with conventional 6/4 FSPM machines using 3D FEA for accuracy.
It is verified that the problem of UBEMF in conventional machine has been solved by using the proposed dual-stator 6/4 FSPM machine.


- Dual-stator 6/4 FSPM machine achieves about 30% THD reduction in flux linkage, and 55% THD reduction in back-EMF compared to conventional 6/4 FSPM machine.
Dual-stator 6/4 FSPM machine achieves significantly less cogging torque and torque ripple compared to conventional 6/4 FSPM machine. In addition, torque density is about the same between proposed and conventional 6/4 FSPM machines.
Dr. Sarlioglu’s Selected Publications on FSPM Machines


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