Outline

• Permanent Magnet (PM) Machine Fundamentals
• Motivation and Application
• Design Aspects
  - PM Material
  - PM Rotor Configurations
  - Manufacturing Processes
• Design Tools
Permanent Magnet (PM) Machine Fundamentals

- Focus on electronically controlled PM AC synchronous machines
  - Rotor magnetic field is supplied by PMs
  - Stator windings are sinusoidally distributed windings, excited by sine-wave currents
- “Brushless DC” machines can also use PMs
PM Machine Theory

- Output torque is proportional to power
- Control instantaneous torque by controlling magnitude of phase currents

\[ N = \frac{f \times 60}{p} \text{ RPM} \]

speed \( N \) in RPM
supply frequency \( f \)
number of pole pairs \( p \)

\[ T = \frac{P}{\omega_{rm}} \]

output torque \( T \)
output power \( P \)
rotor speed \( \omega_{rm} \) in rad/s
PM Machine Control

• Instantaneous torque control
  - Servo performance 0.1-10 kW
  - Fast dynamic response
  - Smooth output torque
  - Accurate rotor position sensor information needed

Single-phase equivalent circuit
PM Machine Control

- Flux-weakening control
  - Constant power drives
  - Traction, washing machines, starter/alternators
  - Require constant output power over a speed range
  - To operate above rated speed while maintaining rated terminal voltage, reduce flux by controlling magnetizing current

\[
T \propto \phi I_{arm} \\
V \propto \phi \omega
\]

torque \( T \)
magnetic flux \( \phi \)
armature current \( I_{arm} \)
terminal voltage \( V \)
magnetic flux \( \phi \)
angular speed \( \omega \) in rad/s

[1] Soong
Motivation for PM Machine

- Motivation for PM machines:
  - High efficiency (at full load)
  - High power density
  - Simple variable-frequency control
  - Rotor excited without current
    - No rotor conductor loss and heat
  - Magnet eddy current loss is lower than iron loss and rotor cage loss
PM Machine Disadvantages

• Magnet cost
• New magnet manufacturing processes
• Magnet sensitivity to temperature and demagnetization
• Little control of magnet field
  – Always have no-load spinning losses
  – Without control, over speed means over voltage – fault management issues
PM Machine Applications

• AC PM machines
  - Servo control systems
  - Precision machine tools
  - IPM – washing-machines, air conditioning compressors, hybrid vehicle traction

• DC PM machines
  - Lower cost variable-speed applications where smoothest output torque is not required
  - Computer fans, disk drives, actuators

• Industrial applications where constant speed is necessary

IPM washing-machine motors
[5] Hendershot and Miller
Design Specifications

• Electrical
• Environmental
  - Ambient temperature
  - Cooling system
  - Structure
  - Vibration
• Mechanical outputs
  - Torque
  - Speed
  - Power
• Key features of machines
  - Flux linkage
  - Saliency, inductances
  - Assembly process
  - Magnet cost
  - Number of magnets
  - Simplicity of design
  - Field weakening
  - Reluctance torque
  - Field control
  - Line start, no inverter
PM Material

- Soft magnetic material (steel) – small B-H loop
- Hard magnetic material – (PM) – large B-H loop
- Choose magnets based on high $B_r$ and $H_c$
## PM Material

<table>
<thead>
<tr>
<th>PM</th>
<th>$B_r$ (T)</th>
<th>$H_c$ (kA/m)</th>
<th>Cost</th>
<th>Resistivity ($\mu\Omega$-cm)</th>
<th>Max. Working Temp. (°C)</th>
<th>Curie Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alnico$_{5-7}$</td>
<td>1.3</td>
<td>60</td>
<td></td>
<td>47</td>
<td>&gt; 500</td>
<td></td>
</tr>
<tr>
<td>Ferrite</td>
<td>0.4</td>
<td>300</td>
<td>low</td>
<td>&gt;10,000</td>
<td>250</td>
<td>450</td>
</tr>
<tr>
<td>NdFeB (sintered)</td>
<td>1.1</td>
<td>850</td>
<td>medium</td>
<td>150</td>
<td>80-200</td>
<td>310-350</td>
</tr>
<tr>
<td>Sm$_2$Co$_7$ (sintered)</td>
<td>1.0</td>
<td>750</td>
<td>Higher than NdFeB</td>
<td>86</td>
<td>250-350</td>
<td>700-800</td>
</tr>
</tbody>
</table>

*Other important characteristics: Field to Magnetize, Thermal Stability, Mechanical Properties, Corrosion Resistance, Manufacturability, Cost.*

[3] Hendershot and Miller
PM Material

- Chinese dependency
- No shortage
  - Mountain Pass, CA
  - Idaho
  - Nd is about as common as Cu

Major Exporters to the US

Arnold Magnetic Technologies
PM Machine Rotor Configurations

- **Surface-mounted PM rotor**
  - Maximum magnet flux linkage with stator
  - Simple, robust, manufacturable
  - For low speeds, magnets are bonded to hub of soft magnetic steel
  - Higher speeds – use a retaining sleeve
  - Inset – better protection against demagnetization; wider speed range using flux-weakening; increases saliency; but also increases leakage
PM Machine Rotor Configurations

- Interior-mounted PM (IPM) rotor
- IPM Advantages
  - Extended speed range with lower loss
  - Increases saliency and reluctance torque
  - Greater field weakening capability
PM Machine Topology

• SMPM:
  - More mechanically robust
  - Magnet losses can be an issue (not shielded by rotor iron); reduce by segmenting magnets axially or radially or increasing magnet resistivity

• IPM:
  - Better demagnetization withstand

<table>
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<tr>
<th>Characteristic</th>
<th>SMPM</th>
<th>IPM</th>
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</thead>
<tbody>
<tr>
<td>Saliency</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Field Weakening</td>
<td>Some</td>
<td>Good</td>
</tr>
<tr>
<td>Controller</td>
<td>Standard</td>
<td>More Complex</td>
</tr>
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</table>
PM Manufacturing Practices

- Realistic manufacturing tolerances
  - Key parameters – stator inner diameter, rotor outer diameter, no load current, winding temperature
  - Issues with core steels – laser cutting, punched laminations, lamination thickness
  - Issues with magnets – dimensions, loss of strength due to thermal conditioning
  - High speed practice and limits – rotor diameter limits speed

Hybrid Camry PM synchronous AC motor/generator
ecee.colorado.edu
PM Machine Design Process

- Design and simulate motor and driver
  - Separately
  - Combined
- Analytical, lumped-circuit, and finite-element design tools
- Different tools are used to trade-off understanding of the design, speed, and accuracy

Finite element meshing, flux lines and B for SMPM machine

A.O. Smith
Analytical Design Tools

• Broad simplifying approximations
  – Equivalent circuit parameters
• Use for initial sizing and performance estimates
• Performance prediction
• Limitations
  – Does not initially account for local saturation
  – Requires tuning with FE results
Analytical Design Tools

• Core losses
  – Hysteresis loss
  – Eddy current loss
  – Anomalous loss – depends on material process, impurities

• Problems with core loss prediction
  – Stator iron loss: based on knowledge of stator tooth flux density waveforms
  – Usually assumes sinusoidal time-variation and one-dimensional spatial variation
  – Flux waveforms have harmonic frequency and rotational component
  – Use dB/dt method for eddy-current term, frequency spectrum method

• Torque, efficiency, inductance

Lumped-Circuit Design Tools

- Non-linear magnetic material modeling of simple geometries
- Need a good understanding of magnetic field distribution to partition
- Fast to solve, good for optimization
- Limitations
  - Requires tuning with FE results

Lovelace, Jahns, and Lang
Finite-Element Modeling and Simulation Tools

- Important aspects – model saturation
- More accurate
- Essential when saturation is significant
- Limitations
  - Meshing
  - Only as accurate as model design – 2D, 3D
  - Not currently used as a design tool due to computational intensity

Nonlinear magnetostatic FE average magnetic flux density solution for machine with solid rotor
Ideal Design Tool

- Easy to set up
- Models all significant aspects of machine that affect performance – magnetic saturation
- Efficiently simulates transient conditions and steady-state operation
References


Questions?