Permanent magnet machines and actuators

Geraint Jewell

The University of Sheffield

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Key PM Properties for Electro-Mechanical Devices

- High remanence  ⇒  High airgap flux density
- High coercivity  ⇒  Demagnetisation withstand
- High temperature capability  ⇒  Demagnetisation withstand
  Environmental capability
- Corrosion resistance
- High mechanical strength  ⇒  High speed operation
- Low electrical conductivity  ⇒  Rotor loss
- Formability  ⇒  Ease of manufacture
  Scope for product integration
- Ease of magnetisation  ⇒  Ease of manufacture
- COST
Brushless PM machines

- Also called electronically commutated
- So-called brushless DC or AC operation
- Always used in conjunction with a power electronic converter
- Electronically commutated as a function of rotor position
- Can operate as motors and generator – switch between two modes very rapidly
- Arguably more competitive as motors than generators in most ‘standard’ speed applications

Radial field

Axial field
Key features of performance

- High efficiency – can be >95% even at modest powers
- High power density compared to competing technologies
- Capable of high speed operation
- Reasonably good short-term overload capability
- Well suited to very high pole numbers
  - Important feature for high torque / low-speed applications
Efficiency in Electrical Machines

Can be traded off against machine volume up to a point where machine becomes thermally limited.

Higher airgap flux densities generally give higher efficiencies – particularly in low to medium speed applications.

Highly influenced by size (larger machines tend to be more efficient).

Tends to vary over operating range of the machine.

Can be >98% in some cases.
High Performance PM Traction Drive

10,000 rpm maximum speed
35kW continuous rating (70 kW peak)
0.7kW / Kg continuous (2kW/kg peak)
Total weight of motor 42kg (incl 3.5kg of NdFeB)
Power density of electrical machines

![Graph showing the relationship between power density (kW/Kg) and output shaft base speed (rpm). The graph contains several data points marked with numbers from 2 to 18.](image_url)
1MW range PM machines

• Several impressive demonstrator machines with ratings in the 0.5-1.0 MW range
• Many aimed at military vehicles
• Very competitive power and torque densities

DRS PA44-5W
Canopy Technologies LLC HA57-100
DRS 370kW CR32-50
OSSA Powerlite 597kW
Key performance indicators and design parameters of a series of intermediate speed PM machines

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Rated power (MW)</td>
<td>0.97</td>
<td>0.34</td>
<td>0.74</td>
<td>0.37</td>
<td>0.60</td>
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<tr>
<td>Rated torque (Nm)*</td>
<td>1287</td>
<td>1120</td>
<td>2712</td>
<td>1761</td>
<td>5179</td>
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<tr>
<td>Maximum speed (rpm)</td>
<td>6000</td>
<td>3600</td>
<td>4000</td>
<td>3600</td>
<td>1100</td>
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<tr>
<td>Topology</td>
<td>Axial-field</td>
<td>Axial-field</td>
<td>Axial-field</td>
<td>Radial-field</td>
<td>Radial-field</td>
</tr>
<tr>
<td>Number of poles</td>
<td>Not known</td>
<td>28</td>
<td>36</td>
<td>20</td>
<td>Not known</td>
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<tr>
<td>Total weight (kg)</td>
<td>160</td>
<td>195</td>
<td>354</td>
<td>227</td>
<td>791 (incl. converter)</td>
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<tr>
<td>Machine diameter (m)</td>
<td>0.61</td>
<td>0.65</td>
<td>0.78</td>
<td>0.48</td>
<td>0.55</td>
</tr>
<tr>
<td>Axial length (m)</td>
<td>0.16</td>
<td>0.22</td>
<td>0.26</td>
<td>0.44</td>
<td>0.60</td>
</tr>
<tr>
<td>Torque density (Nm/kg)</td>
<td>8.0</td>
<td>5.7</td>
<td>7.5</td>
<td>7.7</td>
<td>6.5</td>
</tr>
<tr>
<td>Torque density (kNm/m³)</td>
<td>27.5</td>
<td>15.1</td>
<td>19.0</td>
<td>22.1</td>
<td>35.5 (excl. converter)</td>
</tr>
<tr>
<td>Power density (kW/kg)</td>
<td>6.1</td>
<td>1.74</td>
<td>2.10</td>
<td>1.62</td>
<td>0.75</td>
</tr>
<tr>
<td>Power density (MW/m³)</td>
<td>20.7</td>
<td>4.55</td>
<td>7.9</td>
<td>4.64</td>
<td>4.1</td>
</tr>
<tr>
<td>Peak efficiency</td>
<td>96%</td>
<td>95%</td>
<td>95%</td>
<td>95%</td>
<td>98.9%</td>
</tr>
</tbody>
</table>

* rated torque is not necessarily at maximum speed
Active Vehicle Suspension

Project partners:
Loughborough University
Jaguar Land Rover Research UK Ltd

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Peak force capability</td>
<td>5kN</td>
</tr>
<tr>
<td>Rms force capability</td>
<td>2kN</td>
</tr>
<tr>
<td>Nominal stroke</td>
<td>+/- 50mm</td>
</tr>
<tr>
<td>Maximum stroke</td>
<td>+/-100mm</td>
</tr>
<tr>
<td>Average output power</td>
<td>50W</td>
</tr>
<tr>
<td>Peak/Rms velocity</td>
<td>1.5/1.0m/s</td>
</tr>
</tbody>
</table>
Toyota Prius

Introduced in 1997
Sales to 2006 (all models): 552,657

Most detailed information available for 2004 model
Two excellent and comprehensive public-domain reports from: Oak Ridge National Laboratory
‘Report on Toyota / Prius Motor Design and Manufacturing’ (ORNL/TM-2004/137)
Electric Motor

Permanent magnet brushless AC synchronous motor (NdFeB magnets)

Liquid cooled (ethelyne/glycol)
Total active mass = 36.3kg
Power density = 1.37kW/kg
Torque density = 11Nm/kg

Source: Oak Ridge National Laboratory
Drive machine rotor

8-pole sintered NdFeB magnets (~1.8kg)

Source: Oak Ridge National Laboratory
Rotor construction

- so-called ‘inset magnet rotor’

Usually requires high tolerances

Source: Oak Ridge National Laboratory
Magnet segments

Over-mould sintered NdFeB in a polymer carrier

- tolerance on width and lock-in

is achieved by polymer

Source: Oak Ridge National Laboratory
LP shaft generator

- Output power - 250kW over speed range 1050rpm - 3100rpm
- Output voltage - 350V DC
- High efficiency - >95%
- Located within tail-cone

Air-cooled
Direct drive
Finalised design

- Stator core: 90kg
- Stator winding: 52kg
- Rotor magnets: 22kg
- Rotor core: 19kg

TOTAL (active weight) 183kg

Power to weight ~ 1.36kW / kg of active mass
High temperature application of PM materials
Ultra high temperature actuator

Operates in 800°C ambient
Pure reluctance actuator
24% Cobalt Iron stator and armature cores
Mica insulated wire (not viable long-term)
High temperature wires

- VonRoll Isola - SK 650
  - Mica tape wound nickel-plated copper wire (500°C)

- CGP - Cerafil 500
  - nickel-plated copper alloy wire with ceramic insulation (450°C)

- Fujikura - Fujithermo A
  - nickel-plated copper wire with convertible ceramic insulation and protective layer (400°C)
Typical turbine tip clearance actuation system

200-250°C

>500°C

Actuator

Spring

Outer casing

Push rod

Segment

HPT turbine blades

Clearance
Clearance Variation - Symmetrical

Clearance Variation - Asymmetrical

Features of application

- High temperature environment – high temperature wire and modest current densities
- Modest strokes (up to a few mm) – normal force actuators may be preferred
- Relatively slow response required (100s of ms) – solid cores
- Very precise positional control required – hysteresis could be difficult to accommodate
- High forces (several kN) – highly dependant on degree of pressure balancing employed
- Predictable and benign failure mode – fail outwards in turbine
- Nominal force specification of 1kN at 2mm (part of a general study comparing different actuator technology specifications)
Permanent magnet polarised reluctance actuators

• High holding force with zero current
• Fail to closed position with zero current
• Permanent magnet is located in stator
Basic operating principle

Current can aid or oppose PM flux

Electromagnetic design involves many trade-offs
Magnetic materials

49% Cobalt Iron stator core and armature $\text{Sm}_2\text{Co}_{17}$ magnets
Electromagnetic and thermal design optimisation

2.84kg – 350N/kg
Fujithermo A – high temperature wire

Ceramic coated wire
Continuous maximum temperature rating of 420°C
Experimental measurements

• Characterised on an Instron load-frame with 300 °C heater stage
• Eliminates the need for bearings in prototype
Experimental measurements at 225\textdegree C ambient

Zero current

225\textdegree C
Experimental measurements at 225°C ambient