High Performance Electrical Machines for Electrical Propulsion

*an insight into recent and future trends for the role of electrical machines in electrical propulsion*

Chris Gerada  
Professor of Electrical Machines  
PEMC Research Group  
chris.gerada@nottingham.ac.uk
PEMC Group

- 120 strong team dedicated to research in electrical machines, drives and power electronics.
- Over £23M current grants and >2000m² laboratory space making it one of the largest groups of its kind worldwide
- Application areas:
  - Transport: automotive, marine and MEA
  - Industrial Drives
  - Renewable generation
Contents

• State of the art and recent trends in electrical machines.

• Electrical machines for future power trains.

• Enabling technologies

• Case Studies
  • Case Study 1 – high speed machine with SiC converter
  • Case Study 2 - high torque machine
  • Case Study 3 – high power density machine
E-Machines: Current Status

- Permanent magnet machines are the benchmark technology for both for direct drive and high speed motors.
- Tendency to move away from rare earth materials.
  - Copper rotor IM
  - SR and variants
- Higher frequency
- More automation and innovation in manufacturing processes
- Better understanding of losses, component degradation and life time models (and how to design for it).

Radial PM Machine
- 30kW, 1300rpm
- Hybrid Traction

High Speed Induction Machine
- 10kW, 50000rpm
- E-Turbo
Electrical Machines for Future Powertrains

- Significant increase in Torque/Power density – 30kw/litre for entire drive?
- Increased Functionality
- Increased integration (Functional and Physical)
- Increased modularity and scalability
- More standardisation of interfaces
- Enhanced efficiency
- Improved reliability, manufacturability and higher kw/(kg of rare earth)
Enabling Technologies

- Novel Machine Topologies
- Materials (soft & hard magnetic, insulation, conductors)
- Thermal management (thermal materials, cooling methodologies)
- Power electronics and control
- Manufacturing technology and processes
Advanced Materials

- Magnetic Materials
  - Lower losses
  - Higher thermal conduction
  - Cost reduction
- Thermal Materials
- Conductors and Insulators
• High frequency drives (high poles/high speed) will enable a significant improvement in drives power density.

• Drive integration (motor + PE + cooling)

• Attractive concept as allows component elimination and improves power density

• Modularity across platforms

• Advanced functionality in terms:
  • Self - awareness
  • Integrated AMB
  • Harmonic control
  • Multifunctionality
Novel Topologies

- High efficiency IM
- PM rotor + Stationary Field winding
- Field coil only used for starting (when efficiency is not an issue)
Health and Usage Monitoring

- Diagnostics and Prognostics

- Example of a fault detection when the insulation on one turn degrades.
Case Studies

• Case 1: High Speed Machine (120 krpm)

• Case 2: High Torque density machine (270kNm/m3)

• Case 3: High Power Density machine (33kW/litre)
CS1: High speed energy recovery

**Engine electrification and waste heat recovery**

- High speed an enabler for energy saving and power density
- Fuel efficiency demonstrated
- SPM machines easy option but…..

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**Combined Turbo Generator**

600Vdc, 10kW, 80krpm
Water-cooled - CUMMINS

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**High Speed IM under test**

600Vdc, 10kW, 80krpm
Water Cooled
CS1: Performance Limits

Fig. 21. Power-speed nodes and rpm√kW
• Case 1: High Speed Machine (120 krpm)

• Case 2: High Torque density machine (270kNm/m3)

• Case 3: High Power Density machine (33kW/litre)
CS2: High Torque Density Traction

• Surface PM with hallback arrays tend to give highest shear stress values as limit saturation and magnetic loading
Ways of enhancing torque density

- **Outer Rotor configuration** which has been shown to have higher torque density than the inner rotor counterpart

- **High pole number** with Single Layer concentrated winding - highest fundamental winding factor OR Double Layer concentrated winding

- **Unequal wound and unwound tooth widths** which has been shown to increase the fundamental winding factor

- **Halbach magnet arrangement** which increases the airgap flux density and consequently the torque capability.

- **High grade soft magnetic material**

- **Open slot design** (higher packing factor and lower armature induced saturation)
CS2: High Torque Density Traction

- Interleaving used to improve output torque and minimise passives
- Special thermal paths introduced to enhance heat transfer
- High saturation flux density material used to boost torque
CS2: High Torque Density Traction

- Outer rotor for effective integration and maximum torque
- Integration of electromagnetic clutch
- Advanced thermal management to minimise temperature rise.
- Peak torque of : 270kNm/m3
Case Studies

• Case 1 : High Speed Machine (120 krpm)

• Case 2 : High Torque density machine (270kNm/m3)

• Case 3 : High Power Density machine (33kW/litre)
CS3: High Power Density Machine

- Aim to achieve minimum drive-system weight through a functional integrative design considering:
  - PE/EM topology
  - Thermal Management
  - PE/EM design by utilising advanced materials
  - Advanced control
  - Advanced manufacturing

Diagram showing the machine design loop including electromechanical, mechanical, and thermal aspects, connected to power electronic converter design and control strategy.
Drive Study

- Different machine topologies considered including reluctance, PM and IM.
- A range of circuit topologies considered
- Si/SiC devices and high grade SiFe lams considered
<table>
<thead>
<tr>
<th>Description</th>
<th>IM</th>
<th>SRM</th>
<th>SPM</th>
<th>IPM</th>
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<tr>
<td>Weight</td>
<td>21.93 Kg</td>
<td>27.9 kg</td>
<td>11.1 Kg</td>
<td>11.1 kg</td>
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<tr>
<td>OD</td>
<td>183 mm</td>
<td>192 mm</td>
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<td>Axial length</td>
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<td>0.5 mm</td>
<td>0.5 mm</td>
<td>2 mm</td>
<td>2 mm</td>
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<tr>
<td>Worst-case temperature</td>
<td>229 °C</td>
<td>250 °C</td>
<td>180 °C</td>
<td>190 °C</td>
</tr>
<tr>
<td>Eff @ full speed</td>
<td>96 %</td>
<td>91.8 %</td>
<td>94.3 %</td>
<td>96.1 %</td>
</tr>
</tbody>
</table>

- PM machines have better power density than SR and IM
- Ways of managing faults possible
- NOTE: the above are for approximately similar converter kva rating
Thermal Management

- Machine fluid cooled

- Power Converter – forced air cooled and thermally integrated with other SG integration
High Power Density Machine

Additive manufacturing

Low loss specially insulated windings

Low loss laminations

• Machine capability:
  • 16 kW/Kg @ 32krpm
  • 33 MW/m^3 or 33 kW/litre

3-Level NPC drive
Conclusions

• A marked improvement in power density is expected.

• Physical and Functional integration will play a key role in the drivetrain design

• Materials a key enabling technology

• Modularity and manufacturing key enablers in cost reduction

• PM likely to play a significant role but with better utilisation