Trends and Challenges in Components for Aircraft Electrification

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Power Electronics, Machines and Control Research Group

- Transport electrification and energy conversion
- Largest group world-wide with strong academic and industrial partnerships across the globe
- National/European leader
- >£30M active research grants with >60% of research income linked to industry

160 Researchers/Academics across the campuses
21 Academic Staff [Faculty]; 60 Contract Research Fellows; 75 PhD students
PEMC Research Group

**Electrical Machines**
Prof Chris Gerada  
Dr Michael Galea  
Dr Gaurang Vakil  
Dr Adam Walker  
Dr Tom Cox  
Dr Michele Degano

**Power Electronic Systems**
Prof Jon Clare  
Prof Pat Wheeler  
Dr Christian Klumpner  
Dr Alessandro Costabeber  
Dr Alan Watson  
Dr Giampaolo Buticchi

**Motor Drives and Electrical Systems**
Prof Mark Sumner  
Prof Serhiy Bozhko  
Prof Pericle Zanchetta  
Dr Jing Li  
Dr Tao Yang

**Power Electronic Integration**
Prof Mark Johnson  
Prof Lee Empringham  
Dr Alberto Castellazzi  
Dr Paul Evans  
Dr Neo Lophitis

**Thermal Management** : Prof Steve Pickering, Dr Carol Eastwick
The More and All Electric Aircraft

- Why is there so much interest in MEA and AEA?
- Why is Power Electronics important?
- What does the industry need?
More Electric Aircraft Technology

**Typical Civil Aircraft**

- **Jet Fuel**
- **Propulsion Thrust (≈ 40MW)**

**Electrical**
- 200kW

**Pneumatic**
- 1.2MW

**Hydraulic**
- 240kW

**Mechanical**
- 100kW

**Total “non-thrust” power ≈ 1.7MW**

- Removal of hydraulic system
  - Reduced system weight and ease maintenance
- “Bleedless” engine
  - Improved efficiency and simplified design
- Desirable characteristics of electrical systems
  - Controllability, re-configurability
  - Advanced diagnostics and prognostics

**More Electric Aircraft**

- **OVERALL GOALS**
  - Reduced operating costs
  - Reduced fuel burn
  - Reduced environmental impact

**Total Electrical System Power ≈ 1MW**

- **Engine driven generators**
- **Expanded electrical network**

**New electrical loads**
- **ELECTRICAL**
  - Cabin pressurisation
  - Air conditioning
  - Icing protection
- **ELECTRICAL**
  - Flight control actuation
  - Landing gear/Braking Doors
- **ELECTRICAL**
  - Fuel pumping
  - Engine Ancillaries

**Existing electrical loads**
- **ELECTRICAL**
  - Existing electrical loads
The main **challenge is development of new electric power systems** (EPS) capable of managing powers in the range of a few MW.
Towards All-Electric Flight

- All electric aircraft propulsion is possible
  - Series Hybrid will follow parallel hybrid technology
  - All Electric will be used when electrical energy storage becomes available with the required energy density
Potential Hybrid - electric architecture:
- gas turbines drive generators, optionally may act as direct propulsion devices
- distributed electrical machines drive propulsion devices with energy storage devices can be used to buffer energy

“Single-bus” approach

High-power machines for hybrid propulsion
- MW-class equipment
- Efficiency/losses become a critical design factor

Power distribution network cables
- Short term (5-10 years) 1 kg/km/A
- Mid Term (10 to 15 years) 0,5 kg/km/A
- Long Term (>>15 years) 0,1 kg/km/A

Targets?

Electrical Machines
- Short term (5-10 years) 7-10 kW/kg
- Mid Term (10 to 15 years) 10-20 kW/kg
- Long Term (>>15 years) 20-50 kW/kg
AIR RACE E – Demonstration Aircraft

- Electrical System Design
  - Battery System
- Mechanical System Design
  - UoN Concept Development
- Procurement
  - Battery Cells
  - Motor and PE
  - Mechanical Design Consultant
  - Aircraft Mechanical Integrator
- Airworthiness
Air Race E rules

- Maximum Continuous Power = 150kW
  - Drag $\alpha V^2$: Power = Drag x Velocity... Power $\alpha V^3$, so $V \propto \sqrt[3]{P}$
  - Best overall package will win.

- Race time ~5 minutes
  - At maximum power or according to limits.

- Manoeuvring time ~5 minutes
  - Reduced power ~40kW for circuit and landing.
Technology Bricks for Electrification

PM – low loss rotor

HV-HF windings

Modular converters

Integration
Functional-Physical

Advanced Machines

Low loss materials

Intensive Cooling

Electrical Machines
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- Drivetrain Integration
  - Mechanical
  - Power Electronics
- Materials
  - Devices, Magnetic, Electric, Thermal, Structural
- Machine-drive topologies
  - High poles/high speed/HF
- Manufacturing – additive
  - New structures
- Thermal management

4MW Propulsion Motor
Optimisation with Particle Swarm Optimisation algorithm:

- Simulates behaviour of bird flocks to find optimum of non-linear functions
- Number of particles with random initial position and velocity
- At each iteration step velocity is updated with attraction to personal best particle position
- Efficient optimisation method for electromechanical problems
- Optimisation with just 6 parameters applied for this design
- Optimisation itself is easy, it is all the scalable models which take the effort!

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower Boundary</th>
<th>Upper Boundary</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Airgap Diameter $d$</td>
<td>24</td>
<td>35</td>
<td>mm</td>
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<tr>
<td>Split Ratio $SR = d/D$</td>
<td>0.4</td>
<td>0.6</td>
<td>-</td>
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<tr>
<td>Tooth-width factor</td>
<td>0.5</td>
<td>0.7</td>
<td>-</td>
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<tr>
<td>Fin extension</td>
<td>1</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>Fin thickness</td>
<td>1</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td>Fin pitch/thickness</td>
<td>2</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

![Diagram](image)
Power Converter: Design Choices

- Multiple converter designs have been used since 2015
  - Various topology choices, linked with motor design
  - Optimisation has to be linked to optimisation of the motor
- Current design
  - 750V DC, 1000Arms, SiC MOSFETs
  - Water cooled with a dedicated radiator
  - Power Electronic Converter located under the saddle

![Diagram of 2-level Inverter, Dual-bridge Converter, and 3-level NPC Converter]
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![Diagram showing different converter designs: 2-level Inverter, Dual-bridge Converter, 3-level NPC Converter.](image-url)
Integrated Passives

- Ceramic capacitor technology is compatible with temperature range
  - COG dielectrics are low loss and up to 0.03J/cm³
  - X7R dielectrics are higher loss and up to 0.4J/cm³
  - Good CTE match to module substrate reduces cracking

- Commutation loop decoupling can be achieved by placing ceramic chips across substrate pads

- Some care is needed to avoid unwanted interaction of internal and external capacitance – more internal capacitance not always better!
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Capacitors – Performance dictated by Dielectric

• Electrolytic:
  • highest energy density,
  • low power density,
  • limited temperature range (at best -40 to 105°C),
  • high losses and poor lifetime

• Metallised polymer film:
  • low energy density (0.01~0.1 J/cm³),
  • high power density,
  • limited temperature range (typically -40 to 105°C),
  • low losses and long life

• Multi-layer ceramic:
  • low to moderate energy density (0.1~1 J/cm³),
  • high power density,
  • wide temperature range (-60 to 125°C),
  • low to moderate losses
  • long life but mechanically fragile.
Degradation of Film Capacitors

- Pulse discharge testing of film capacitors at extreme temperatures
- Self-healing leads to gradual reduction in capacitance with time
- Lower temperatures exacerbate wear-out

![Graph showing capacitance over number of discharge cycles]
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CONCLUSION

- Electrification of Transportation is happening
  - Technology development is needed
  - Power Electronics and Electrical Machines are Key technologies
  - Energy storage systems must improve

- The Jetsons’
  - Their vision is possible today 😊
  - There will still be traffic jams!
Prof Pat Wheeler received his BEng [Hons] degree in 1990 from the University of Bristol, UK. He received his PhD degree in Electrical Engineering for his work on Matrix Converters from the University of Bristol, UK in 1994. In 1993 he moved to the University of Nottingham and worked as a research assistant in the Department of Electrical and Electronic Engineering. In 1996 he became a Lecturer in the Power Electronics, Machines and Control Group at the University of Nottingham, UK. Since January 2008 he has been a Full Professor in the same research group. He was Head of the Department of Electrical and Electronic Engineering at the University of Nottingham from 2015 to 2018. He is currently the Head of the Power Electronics, Machines and Control Research Group, Global Director of the University of Nottingham’s Institute of Aerospace Technology and is the Li Dak Sum Chair Professor in Electrical and Aerospace Engineering at the University of Nottingham, China. He is a member of the IEEE PELs AdCom and was an IEEE PELs Distinguished Lecturer from 2013 to 2017. He has published 600 academic publications in leading international conferences and journals.