Electrification: Need for innovative solutions in electrical machines for automotive traction units

Mircea Popescu, Motor Design Ltd, UK

26 June 2020, CADFEM Technology Day
Topics

• About MDL
• Electrified Systems
• Electrical Machines Innovation (Materials)
• Electrical Machines Innovation (Designs)
About Motor Design Ltd

- **Software developers: Ansys Motor-CAD**
  - Developers of Ansys Motor-CAD – world-leading tool for the design and analysis of electric motors.
  - High level of customer support and engineering know-how.
  - Developed with expert electric machine designers.

- **Consultancy**
  - Design, analysis & training.
  - Led by motor design experts with significant industry and academic experience.

- **Research**
  - Involved in collaborative government/EU-funded research projects.
  - Collaborate with Universities worldwide to develop electric machine modelling techniques and create validation data.
About Motor Design Ltd

Customers across 6 industry sectors:
Automotive, aerospace, rail, renewables, industrial & appliances.

43% of the team are design engineers
30% of the team are software developers
47% of the team have a PhD

MDL Headquarters
Wrexham, UK

MDL Asia
Shanghai, China

MDL USA
Ohio, USA

Developing Motor-CAD software since 1998
MDL has OEM software partnership with Ansys

www.motor-design.com

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Worldwide Customers
Customers in 33 countries and over 470 companies worldwide.
E-Machines: The need for rapid design

Enables:
- Comprehensive design space exploration
- Better design and topology decisions
- More optimised designs
- Complete multiphysics evaluation of design candidates against the full specification
- Reduced risk of costly problems in the later development stages.

Rapid multiphysics design tool providing analysis across the full torque/speed operating range
E-Machines: The need for design, analysis validation

Electric Machine Design Tool

Specialist physics-based numerical tools for multiphysics analysis

- Detailed physics based numerical simulation
- Coupled specialist tools for multiphysics analysis

Rapid multiphysics design tool providing analysis across the full torque/speed operating range

www.motor-design.com
Ansys Motor-CAD: Motor design types and templates

• Covers all typical types of radial flux rotating electric machines.

• Motor Types:
  – Brushless permanent magnet (inner & outer rotor)
  – Induction
  – Synchronous reluctance
  – Switched reluctance
  – Synchronous wound field
  – Permanent magnet DC
  – Single phase induction.

• Extensive range of parametrised templates & geometries.
Challenges of Designing Electrified Systems

• **Development Costs** – prototyping & physical testing are expensive

• **Complexity** – multiple physical domains, HW/SW integration, multiple scales

• **Energy Efficiency** – a 1% improvement in energy usage is significant

• **Reliability** – how does the system respond in the event of faults?

• **Certification** – for Safety & Electromagnetic Compatibility (EMC)

SIMULATION IS ESSENTIAL

Courtesy of Ansys © 2020
Technology Drivers for Aerospace Electrification

Electric Machines
- Motors
- Generators

Power Conversion
- AC/DC Converters (TRUs, ATRUs)
- DC/DC Converters
- Chargers

Energy Storage
- Batteries
- Fuel-Cells

Courtesy of Ansys © 2020
Elements of an Electrified System

Power Source
- Generator
- Battery
- Fuel Cell
- Solar Panel
- Utility Grid
- …

Power Isolation & Protection
- Switchgear
- Circuit Breakers
- Fusing
- …

Power Conversion & Control
- Inverters
- Rectifiers
- DC-DC Converters
- Frequency Converters
- Electronic Control

Power Distribution
- Cables
- Bus Bars
- …

Electrical Loads
- Electronics
- Lighting
- …

Electro-Mechanical Loads
- Motors
- Solenoids
- …

Courtesy of Ansys © 2020
Technical Challenges for Electrical Machines Design

System Requirements in Aerospace Applications

Technical challenges associated with propulsion in aerospace are significant including safety, mass and performance.

Particular safety challenges include:

High availability for motoring or generating functions.

Bi-directional power for ‘always on’ permanent magnet machines. $1 \times 10^{-9}$ for fire.

Typical requirements:

- Power between 20 kW to 2MW
- Voltages from 600V to 1000V, 3kV ongoing
- Motoring and generating
- Air cooling

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Electrical Machines Innovation

Fault Redundancy

- Multiplex system, comprising multiple nominal balanced three-phase motor drive units
- Motor units share a common housing and a common output shaft
- Motor units are electromagnetically independent
- Minimal thermal interaction between motor units
Electric Steel - > Cobalt iron

- Higher magnetic permeability
- Benefit in achieving higher peak torque (~ 20 - 25%) in the same volume and power supply
- Designs to be done with limited field weakening region, i.e. base speed/max speed ratio < 1
- Requires careful processing (annealing)
- Carpenter
- VAC

Source: Carpenter Specialty Alloys.
Electrical Machines Innovation

- **Electrical Steel - > Silicon iron** more silicon and thinner laminations to reduce iron losses
- Due to lower losses, become preferred solution in high power density traction motors (Ampere, Canoo, Bolt)
- Arnon 4, 5 and 7
- Cogent Hi-Lite: NO10 to NO35
- JFE Steel 10JNEX

Source: Arnold Magnetics
Electrical Machines Innovation

- Square symbol denotes CoFe steel type
- Diamond symbol denotes SiFe steel type.
- M270-35A and M235-35A are common 0.35-mm thickness SiFe grades with a typical yield strength of around 350MPa and 450MPa, respectively.
- SiFe thinner grades than 0.35mm, such as NO30 and NO20, which have 0.30mm and 0.20mm respectively thickness.

Electrical Machines Innovation

New materials – copper bars coated with nano-carbon

<table>
<thead>
<tr>
<th></th>
<th>INCREASED AMPACITY</th>
<th>ELECTRICAL CONDUCTIVITY</th>
<th>THERMAL CONDUCTIVITY</th>
<th>CORROSION PROTECTION</th>
<th>ADHESION STRENGTH</th>
<th>FLEXIBLE</th>
<th>EASINESS OF APPLICATION</th>
<th>FLAME RESISTANCE</th>
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<td><strong>THERMAL</strong></td>
<td>5</td>
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<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
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<tr>
<td><strong>PLUS</strong></td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
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<tr>
<td><strong>PROTECT</strong></td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td><strong>FLEX</strong></td>
<td>4</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

**BEST PERFORMANCE**

- **5**
- **4**
- **3**
- **2**
- **1**
- **0**

POOR PERFORMANCE OR LACK OF PROPERTY
Coated bus bars

Conductor size 22 x 0.7mm

AMPACITY Cu @ 200°C

<table>
<thead>
<tr>
<th>TEMPERATURE, °C</th>
<th>CURRENT, A</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>40</td>
<td>100</td>
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<tr>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>80</td>
<td>140</td>
</tr>
<tr>
<td>100</td>
<td>160</td>
</tr>
<tr>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>140</td>
<td>200</td>
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<tr>
<td>160</td>
<td>220</td>
</tr>
<tr>
<td>180</td>
<td>240</td>
</tr>
<tr>
<td>200</td>
<td>260</td>
</tr>
<tr>
<td>220</td>
<td>280</td>
</tr>
</tbody>
</table>

41% increase
Electrical Machines Innovation

Hairpin Winding

Additive Manufactured Coils

Tecnomatic

AM CuCrZr, insulated,

AM AISiMg, uninsulated,

AM CuCrZr shaped profile electrical machine winding
AM processing of magnetic materials (eg NdFeB)
Internally cooled magnets and rotor
Topology optimised low-inertia rotor
Integrated cooled power electronics
Cooled stator and housing
Integrated oil/water heat exchanger

APM 200 - Equipmake
Electrical Machines Innovation

Flux density plots for APM 200

Core loss density for APM 200
Laminated Magnets

- Increases efficiency through further reduction of eddy currents
- Thinnest available insulating layers <20 microns for maximum energy density
- Performance at temperatures up to 200°C
- Magnet layers from ½ mm and up in custom shapes/sizes to suit your design
- Developed to solve a customer need
- Can use SmCo or GBD Neo

Arnold Magnetics
Electrical Machines Innovation

Laminated Magnets

Magnet loss density with monolithic magnets (1 segment/pole)

Magnet loss density with laminated magnets (3 segments/pole)
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Carbon Fibre Sleeving

**Wraptite Carbon Fibre Sleeving**
- Wound in place or pressed on sleeve
- Inconel or stainless steel also available

**Dynamically balanced**

**Precision fit end ring to lock in magnets**

**Precision SmCo and Neo Magnets**
- Precision fabricated
- OD ground
- Magnetically stabilized
- From grade 26 to 55

Arnold Magnetics

www.motor-design.com
Electrical Machines Innovation

Carbon Fibre Sleeving

Flux density plots for high-speed generator (120krpm)

Magnetic Loss density plots for high-speed generator (120krpm)
Electrical Machines Innovation

Air-gap winding composite development

- Glass fiber reinforcement (x, y directions)
- Aluminium conductors (z direction)
- Kevlar weave

- Composite matrix of
  - 1.7 mm dia. aluminium wires
  - 0.7 mm reinforcing glass fiber rods
  - 1.25 mm Kevlar thread weave
- Structure vacuum impregnated with a high temperature grade of epoxy and cured
- First sample achieved a 27% conductor fill
• a stator sleeve is introduced in the airgap to isolate the stator from the rotor.
• Stator is flooded with oil, passing through the cooling ducts at slot opening and stator back iron
• intensive direct cooling to the machine but at the same time could prevent any liquid from entering the airgap.
Oil spray cooling

- Housing water jacket is a common cooling solution.
- Copper loss at end winding can be substantial.
- Heat flow path of end winding is relatively longer when compared to active winding.
- Hot spot is usually located at the end winding.
- Improvement solution, the end winding can be cooled by oil spray.
- Direct cooling method.
- An active cooling that gives very high convective heat transfer coefficient (HTC).

For example, HTC can reach up to about 10,000 W/m²/K at Jet Impingement Velocity of 10 m/s by using automatic transmission fluid (ATF), Bennion and Moreno [2015]
Oil spray cooling

For oil spray cooling, oil is gone through two processes:
1) Oil is atomised and breaks into small droplets;
2) Oil drops are directed onto a target surface.

Oil spray nozzles:
- Oil spray – spray angle > 0°
- Oil jet – concentrated jet with spray angle of 0°
- Oil mist
- Oil droplets
Oil spray cooling

• To remove the undesired heat from electrical machines, the cooling mechanism relies ultimately on the convective cooling.

• provide the highest convective heat transfer coefficient.

• up to about 10,000 W/m²/K at nozzle hole flow velocity of 10 m/s by using automatic transmission fluid (ATF)

• direct oil cooling as it cools heat generating components directly (stator/rotor end winding, rotor end ring, magnet)


www.motor-design.com
Oil spray cooling

- ATF is supplied from oil pump to cool the stator and coil end winding through the inner pipe.
- The oil passed through rotor core to cool the magnet actively.
- Thus, the motor is cooled efficiently and increased the current density up to 58% compared to Toyota Prius 2009 motor.

Impact of the thermal conductivity of different potting materials

High-performance liquid-cooled electric machines

\( k \) varies from 0.25 to 3.2 W/mK

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**TABLE I**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Varnish</th>
<th>Epoxide</th>
<th>SbTCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/mK)</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.85 )</td>
<td>3.20</td>
</tr>
<tr>
<td>Dielectric strength (kV/mm)</td>
<td>( \approx 80 )</td>
<td>( \approx 20 )</td>
<td>( \approx 10 )</td>
</tr>
<tr>
<td>Volume resistivity at 25(^\circ)C (( \Omega \cdot \text{cm} ))</td>
<td>( &gt; 10^{15} )</td>
<td>( &gt; 10^{14} )</td>
<td>( &gt; 10^{14} )</td>
</tr>
<tr>
<td>Viscosity (Pa-s)</td>
<td>-</td>
<td>3.5</td>
<td>25</td>
</tr>
<tr>
<td>Price (Pu)</td>
<td>1.0</td>
<td>( \approx 2.0 )</td>
<td>( \approx 4.0 )</td>
</tr>
</tbody>
</table>

Cooling pipes system

**TABLE I**

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma$ [MS/m]</th>
<th>$\delta_{\text{low}}$ [°C]</th>
<th>$k_{\text{pipe}}$ [W/K/m]</th>
<th>$E_{\text{pipe}}$ [GPa]</th>
<th>$t_{\text{pipe}}$ [mm]</th>
<th>$\rho_f$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>0.19</td>
<td>0.19</td>
<td>2.4-4.1</td>
<td>2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>ABS</td>
<td>0.17</td>
<td>0.2</td>
<td>2-2.6</td>
<td>2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>PTFE</td>
<td>0.25</td>
<td>0.4-1.8</td>
<td>2</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicone Rubber</td>
<td>200</td>
<td>1.22</td>
<td>2-4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>70</td>
<td>0.05</td>
<td>2-4</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper (square)</td>
<td>58.5</td>
<td>&gt;500</td>
<td>385</td>
<td>117</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Copper (round)</td>
<td>58.5</td>
<td>&gt;500</td>
<td>385</td>
<td>117</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>1.35</td>
<td>&gt;500</td>
<td>12-45</td>
<td>190-203</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>36.9</td>
<td>&gt;500</td>
<td>204</td>
<td>69</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>5-15</td>
<td>&gt;500</td>
<td>5-15</td>
<td>360</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>1.05</td>
<td>&gt;500</td>
<td>50-90</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Fibre</td>
<td>0.75</td>
<td>100</td>
<td>5-7</td>
<td>150</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

MADONNA et al.: IMPROVED THERMAL MANAGEMENT AND ANALYSIS FOR STATOR END-WINDINGS OF ELECTRICAL MACHINES, Trans. On Ind Electronics, 2018

www.motor-design.com
Through slot/conductors liquid cooling

HEAT EXTRACTION THROUGH CONVECTION

Power traction EV – liquid and forced air cooled motor

Porsche ©

In-wheel BPM motor

Protean Electric ©
Electrical Machines Innovation

Power traction: BPM liquid cooled stator package and rotor shaft (Fraunhofer)
### FY17 Accomplishments - Prius Machine Design Trends

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>Stack</th>
<th>Power</th>
<th>Voltage</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Prius</td>
<td>3.5”</td>
<td>33 kW</td>
<td>274VDC</td>
<td>6000</td>
</tr>
<tr>
<td>2004</td>
<td>Prius</td>
<td>3.3”</td>
<td>50 kW</td>
<td>500VDC</td>
<td>6000</td>
</tr>
<tr>
<td>2010</td>
<td>Prius</td>
<td>2”</td>
<td>60 kW</td>
<td>650VDC</td>
<td>13000</td>
</tr>
<tr>
<td>2017</td>
<td>Prius</td>
<td>2.4”</td>
<td>53 kW</td>
<td>600VDC</td>
<td>17000</td>
</tr>
</tbody>
</table>

- ‘02, ‘04, and ‘10 stator laminations have very similar OD/ID with 48 slots.
- Increase of voltage, speed, and design quality yielded significant power density (kW/L) and specific power (kW/kg) improvements.

Note: speed reducer required for ‘10 speed level.
Electrical Machines Innovation

- Prius 2017 - Dimensions can be approximated
- Assumed magnet (N42UH) and electrical steel grades (M250-35A)
Brushless Permanent Magnet Machines

Dual stator
Axial-flux

- Axial separation with 4 electro-magnetically independent stages
- Limited axial thermal interaction between stages
- Four separate rotors on a common shaft

Internal rotor
Radial-flux

- Circumferential separation with minimal winding mutual coupling
- Thermal interactions via back iron and casing
- Design uses a single shared rotor

CleanSky,
www.eletad.eu
Electrical Machines Design

Axial-flux machine prototype

Pre-formed Stator winding

Rotor magnets and carrier

CleanSky, www.eletad.eu

www.motor-design.com
Radial-flux machine prototype

Wound stator
(prior to varnishing)

Rotor assembly

CleanSky, www.eletad.eu
Phase coils individually terminated (and instrumented with thermocouples)

Neighbouring coils grouped into four star connected 3-phase motor units

CleanSky, www.eletad.eu
Radial-flux machine prototype

Phase coils individually terminated (and instrumented with thermocouples)

Neighbouring coils grouped into four star connected 3-phase motor units
Electrical Machines Design

Radial-flux machine model

Flux density plots

Magnetic loss density plots

CleanSky, www.eletad.eu
Electrical Machines Design

Brushless Permanent Magnet Machines

- Circumferential separation with minimal winding mutual coupling
- Thermal interactions via laminated steel and axle
- Design uses propeller hub as rotor casing

Housing

Rotor Back Iron

Magnet

Laminated Stator

Stator coils

Outer Rotor

- 6-phase
- 24 slots
- 20 poles

Outer Rotor

- 9-phase
- 18-slots
- 16-poles

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Electrical Machines Design

Induction Machines

- Design couples via gearbox shaft to propeller axle

Laminated Stator

Rotor Back Iron

Inner Rotor
- 6-phase
- 36 slots
- 50 bars
- 4 poles

Outer Rotor
- 6-phase
- 36 slots
- 50 bars
- 6 poles

- Hairpin winding
- Thermal interactions via laminated steel and casing / axle

- Design uses propeller hub as rotor casing

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www.refreedrive.eu
Electrical Machines Design

Switched Reluctance Machine

Laminated Stator

Rotor Back Iron

Stator coils

Inner Rotor
4-phase
8 teeth
6 poles

Inner Rotor
5-phase
10 teeth
8 poles

• Circumferential separation with minimal winding mutual coupling
• Thermal interactions via laminated steel and casing
• Design uses shaft coupled via gearbox to propeller axle
Summary

- Electrical motors for high-performance applications have to comply with:
  - High safety factor (fault tolerant operation)
  - High power density (low mass)

- Key to potential solutions:
  - Advanced materials: CoFe, NGO steel, special additive coils, coatings
  - Multiplex systems
  - Liquid cooling systems

- Various topologies can be used depending on operating range and supply
  - Brushless PM or Reluctance PM assisted machines
    - Radial and Axial flux
    - Inner and Outer rotor
  - Induction machines
    - Inner and Outer rotor
  - Switched reluctance machines
    - Inner and Outer rotor
Thank You for Your Attention!
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