Electromagnetic and Thermal Analysis of Motor & Drive Systems with Complex Duty Cycles – Case Studies in Power Traction
[Challenges and Practical Solutions for the Electric Machine Drive Systems]

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Outline

1. Introduction

2. Coupled electromagnetic and thermal optimal design
   - The need and the means
   - Complex drive cycles
   - Electromagnetic FEA and equivalent lumped thermal networks
   - Large scale optimization

3. Case studies – innovative technologies
   - Computational benchmarks - Toyota Prius and Nissan Leaf
   - European developments - Evoque (Al windings and spoke ferrite)
   - Formula E – Equipmake (record high specific torque spoke IPM)

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Motor Design Ltd (MDL)

- MDL founded in 1998
- Based in England near border with Wales
- Strategic partner of ANSYS
- Develop Motor-CAD & Motor-LAB software
- Carry out consultancy projects
- High tech projects funded by industry, UK and European Union, e.g.:
  - Evoque_e – electric drive trains with JLR
  - HVEMS – improved manufacturing techniques with *Make Like Production* prototyping facility
  - VENUS – axial flux reluctance motors for traction
  - ADEPT – to create training material for traction systems and train PhD students.
SPARK and PEIK at University of Kentucky

- UK enjoys a longstanding tradition in electric machines and drives
  - Early developments on linear and PM motors, and vector control
  - Many learned machines using the many Nasar and Boldea classic books
- PEIK - Power and Energy Institute of Kentucky, launched on the basis of a large DOE grant in 2010
- Core faculty in electric power engineering and many others in related fields
- Endowment established and inaugural L. Stanley Pigman Chair started in 2015
- On-going research on electric machines and drives, power electronics and systems, renewable and alternative energy technologies
- SPARK and other laboratories
- MDL and ANSYS strategic partnerships.
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Coupled Electromagnetic and Thermal Analysis

PM machine specific characteristics

- Variation of PM characteristics with temperature
  - Torque per amp (torque constant) changes
  - Risk of demagnetization, especially in PM hot spots
- Variation of winding conductor characteristics with temperature.

Initialization
- Phase current: I
- Estimated (initial) temperatures: winding $T'_w$ and permanent magnet $T'_m$
- Iteration: $k=1$

Update
- $T'_w$, $T'_m$
- $k=k+1$

Electromagnetic field analysis
Calculations to include
- Copper losses $W'_e$
- Core losses $W'_f$

Thermal analysis
Calculations to include
- Copper winding temperature $T''_w$
- Magnet temperature $T''_m$

$\frac{|(T'_w - T''_w)/T'_w|}{|T'_m - T''_m|/T'_m|} \leq \varepsilon_w$

No

Yes

Model
Losses
Temperature
Variable Speed Motor Drives

- Constant torque
- Fan or pump load curve
- Duty / driving cycle, incl. transients
- **Analysis of each design requires analysis for multiple operating conditions.**

![Efficiency Map](image)

- Shaft torque, pu
- Speed, pu
- Normalized torque
- Normalized speed
- Efficiency map
- 2 Hp
- 4 Hp
- 6 Hp
- 8 Hp
- 10 Hp
- Fan load
- Cyclic representative points
- Urban Dynamometer Driving Schedule
Coupled Analysis – Motor-CAD

Electromagnetics
• Ultra-fast 2D FEA in the abc reference frame
• Seconds on a state of the art PC workstation
• Analytical calculations for end effects

Thermal and air-flow
• Equivalent 3D networks
• Calculation time one order of magnitude shorter than for electromagnetics

Coupling methods
• “Serial”, typ. 6 iterations for each of Emag and thermal
• “Weak”, typ. only 2 iterations for Emag and 6-10 for thermal

“Cutting edge”
• Design for complex duty cycles
• Large-scale optimization studies.
Fast Duty Cycle Analysis

Motor-LAB

Maxwell

Motor-CAD Therm

Motors and Drives Systems Conference, Jacksonville, FL, Jan 2016
Torque, Speed and Calculated Loss vs Time

- Torque vs time
- Speed vs time
- Total Loss
- Copper Loss
- Core Loss
Multi-objective Optimization

- Minimize cost and minimize losses (i.e. maximize efficiency)
- Thousands of design “candidates” (variations) may have to be analyzed
- Collection of “best compromise” designs
- Definition of a Pareto front
  - improvement in one objective can only be achieved through a deterioration in another objective, e.g. cost vs. efficiency tradeoffs
- Quantify the effects on other performance indices
  - impose constraints.
Systematic Optimal Design Comparison

- Ensuring a fair basis for comparison
- In practice, many times, the differentiation between topologies may be much smaller
- Additional performance indices further complicate the process.
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Toyota Prius

• Very popular car, but limited EV range
• Multiple models over the years, e.g. 2004, 2010
• Nickel-Metal Hydride battery
• 60kW Nd-Fe-B IPM motor
• Performance and design data published by Oak Ridge National Lab
• Simulation models available in MDL and ANSYS software.

Source:
https://www.ornl.gov/content/technical-reports
Nissan LEAF

- All electric BEV
- 124 mile range
- 80kW IPM Motor
- Performance and design data published by Oak Ridge National Lab
- Simulation models available in the MDL and ANSYS software together with a step by step 92 page tutorial.

Source: https://www.ornl.gov/content/technical-reports
Evoque_e / Concept_e

MHEV (Range Rover Evoque):
- JLR – Jaguar Land Rover
- Mild Hybrid with 48V lithium ion battery pack
- 15 kW crank integrated motor with disconnect clutch
- Sandwiched between the prototype diesel engine (90 PS) and 9 speed transmission

PHEV (Range Rover Sport):
- Plug-In Hybrid with prototype petrol engine (300 PS) and 8 speed transmission
- Longitudinally mounted within a Range Rover Sport
- 150kW electric motor
- 320-volt lithium ion battery packaged in the boot

BEV (Range Rover Evoque):
- Bespoke research demonstrator based on JLR aluminium vehicle architecture
- Modified underbody to mount the 70 kWh HV lithium ion traction battery and electric axle drive (EAD) units
- Front drive unit with single speed transmission coupled with an 85 kW electric motor
- Rear drive unit features a twin speed transmission coupled with a 145 kW electric motor.

Source: newsroom.jaguarlandrover.com/en-in/jlr-corp/news/2015/09/jlr_low_and_zero_emissions_powertrain_090915/?&locus=1
Evoque_e / Concept_e

Stator technologies and design
- Aluminium winding
- Special stator lamination.

Evoque_e / Concept_e

Rotor technologies and design
- Ferrite magnets
- High speed spoke.

AIM Motor Introduction

- FIA Formula E started in 2014
- 1 and 5. Identical cars: Spark-Renault SRT_01E
- 2: Powertrain and electronics: McLaren Electronics
- 3: Gearbox: Hewland
- 4: Battery 200kW: Williams Advanced Engineering
- 6: Tyres: Michelin.

Typical racing car driving cycle for one lap - LeMans
# Comparative Performance

<table>
<thead>
<tr>
<th>Motor</th>
<th>Type</th>
<th>Torque (Nm)</th>
<th>Mass (kg)</th>
<th>TRW (Nm/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius (2004)</td>
<td>Interior PM</td>
<td>400</td>
<td>51</td>
<td>7.8</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>Interior PM</td>
<td>300</td>
<td>46</td>
<td>6.5</td>
</tr>
<tr>
<td>Tesla S</td>
<td>Induction</td>
<td>430</td>
<td>90</td>
<td>4.8</td>
</tr>
<tr>
<td>YASA 400</td>
<td>Axial PM</td>
<td>360</td>
<td>24</td>
<td>15.0</td>
</tr>
<tr>
<td>AIM</td>
<td>Spoke PM</td>
<td>110</td>
<td>9</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Values listed are for peak torque and active material mass.
AIM Motor Factsheet

• E-motor for racing applications
• Peak torque = 110Nm
• Cont. torque = 70Nm
• Max speed = 12,000rpm
• Power = 73/60 kW
• Max. current = 325Arms
• Field oriented control
• Rare-earth magnets
• Non-oriented thin gage silicon steel
• Liquid and air cooled
• Active materials mass = 9.5kg

• Manufactured by Equipmake
• Electromagnetic & Thermal design by Motor Design Ltd.
AIM Motor Stator and Rotor

Non-magnetic bolts

Magnet

Rotor hub
AIM Motor Modeling
Magnetic Field and Copper Losses

Flux-lines and flux-density distribution on (peak) load

AC losses in the stator winding
Core Losses

- Most core losses located in the stator
- Rotor surface can also have high loss density
- Highest loss concentration occurs in stator teeth and winding.

Core losses on (peak) load
Magnet Losses - Sources

- PMs may be electrically conductive
- Conductivity increases 6%-10% for 100C temperature rise
- Higher PM losses in surface SPM than interior IPM
- Surface BPM may require a retainer sleeve with additional losses
- Retainers of glass fibre or carbon fibre
- Eddy-current induced by:
  - Space MMF harmonics
  - Permeance variation
  - Time current harmonics
- Induced eddy-currents create PM losses
- Magnet losses mitigation methods:
  - Integer or fractional slots/pole
  - Segmentation.

### Resistivity (ohm*m)

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1.7 x 10^{-8}</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.8 x 10^{-8}</td>
</tr>
<tr>
<td>Steel</td>
<td>10 x 10^{-8}</td>
</tr>
<tr>
<td>SmCo 1-5 Alloys</td>
<td>50 x 10^{-8}</td>
</tr>
<tr>
<td>SmCo 2-17 Alloys</td>
<td>90 x 10^{-8}</td>
</tr>
<tr>
<td>NdFeB – sintered</td>
<td>160 x 10^{-8}</td>
</tr>
<tr>
<td>NdFeB – bonded</td>
<td>14,000 x 10^{-8}</td>
</tr>
<tr>
<td>Ferrite</td>
<td>10^5</td>
</tr>
</tbody>
</table>
Magnet Losses - Mitigation

Distribution of specific on-load PM losses; losses are averaged for a full mechanical cycle

\[ \frac{P_{\text{segmented}}}{P_{\text{monolithic}}} = \frac{L + \tau}{mL + n\tau} \]

- m = transversal segments
- n = axial segments

Effect of segmentation on the magnet losses
Efficiency maps (MTPA)

\[ I_{\text{max}} = 325 \text{Arms}, \ T_{\text{wdg}} = 160^\circ \text{C}, \ T_{\text{mag}} = 120^\circ \text{C} \]
Duty Cycle

Loss model of the typical racing car driving cycle for one lap
Transient Thermal Analysis

Results for 20 laps drive cycle
Experimental Data

Measured and calculated torque (q-axis current excitation, PMs at 40\(^\circ\)C)

Measured total loss vs. current and speed at 40\(^\circ\)C
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Conclusion

- Motor performance under duty / driving cycles is simulated using advanced ultra-fast multi-physics analysis techniques
- Combination of electromagnetic, thermal, and mechanical stress
- The software tools serve for design optimization with thousands of candidate designs
- Ultra-high torque density (12Nm/kg) AIM motor developed for Formula E traction application
- Example innovative technologies
  - Spoke rotors for high speed operation
  - Concentrated windings with very high slot fill factor (Cu or Al)
  - Combined fluid and air-cooling
  - Etc.
- The AIM motor is currently scaled up for a 450Nm / 200kW rating and 25Nm/kg !!!
The SEMPEED Consortium was recently established to further the art of electric machine design. Two academic sites at University of Kentucky and Marquette University and one partner software company, Motor Design Ltd (MDL). Four inaugural members: Grundfos, Kollmorgen, MTS, and Regal Beloit. Inspired by the legacy of the SPEED Consortium. The continued support of ANSYS for our academic research is gratefully acknowledged.
References


Thank you for your attention!

www.motor-design.com