Traction motor optimisation considering system influences using Ansys Motor-CAD and optiSLang

Jonathan Godbehere

18th May 2021
Content

• Company Introduction

• Electric Drive Unit (EDU) design: trends and challenges

• IPM traction motor optimization within an EDU system

• Next steps in the design process

• Summary
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.
Ansys Motor-CAD software
Integrated multiphysics design tool

• Ansys Motor-CAD is the market leading tool dedicated to the design and analysis of electric motors.

• Combines analytical and FE methods for fast and accurate performance prediction.

• Enables rapid and accurate Multiphysics design of electric machines across the full operating envelope.

Quickly and iteratively evaluate motor topologies and concepts to produce designs that are optimized for size, performance and efficiency.
Content

• Company Introduction

• Electric Drive Unit (EDU) design: trends and challenges

• IPM traction motor optimization within and EDU system

• Next steps in the design process

• Summary
Electric Drive Unit (EDU) design: trends and challenges

Need for a system led design process

- Higher efficiency
- Increased torque and power density levels
- Reduced costs
- Increasing volumes and mass production
- Increased integration
- Shorter development cycles
Problem Statement

• In EDU development we are aiming for the highest drive cycle efficiency, lowest cost and smallest volume for a given performance

• To achieve this we need to make design decisions with regards to motor, inverter and gearbox that consider the whole EDU performance

• The optimal individual components ≠ optimal overall system

• Can the E-machine be optimized in such a way, where these interactions are accounted for?

Data-driven exploration of the design space utilizing multiphysics simulation

Yes! With Motor-CAD and optiSLang
Content

• Company Introduction

• Electric Drive Unit (EDU) design: trends and challenges

• IPM traction motor optimisation within an EDU system

• Next steps in the design process

• Summary
EDU Specifications

• **EDU output:**
  - Max. speed = 100 MPH
  - Max. axle torque = 3000 Nm
  - Max. EDU power = 150 kW
  - Peak power @ peak torque ≈ 120 kW
  - Peak power @ max. speed = 100 kW

• **Transmission:**
  - 2-stage, single speed transmission
  - Gear ratio 8 – 12

• **Inverter:**
  - SiC technology: 720 V\_dc
  - Maximum current = 200 – 300 A\_rms

• **E-machine requirements:**
  - Maximum stator outer diameter = 210 mm
  - Maximum active length = 165 mm
  - Continuous (thermal steady-state) power requirements, alongside the peak
IPM traction motor optimization scenario

**Multi-objective:**
- Min energy consumption over WLTP-3
- Min active mass
- Min material cost

**Multi-constraints:**
- Peak Power @ 3 operating points:
  - Peak torque, peak power & max. speed
- Continuous Power @ 3 operating points
  - Peak torque, peak power & max. speed
- Rotor stress @ 20% overspeed
  - Average and maximum values

- V-IPM motor
- 48 slots, 8 poles
- Hairpin winding
- Water jacket cooling
### EDU traction motor design space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>lb</th>
<th>ub</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Active length</td>
<td>95</td>
<td>165</td>
<td>mm</td>
</tr>
<tr>
<td>2 Gear ratio</td>
<td>8</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>3 Bridge thickness</td>
<td>0.7</td>
<td>2.0</td>
<td>mm</td>
</tr>
<tr>
<td>4 Magnet post thickness</td>
<td>1.5</td>
<td>4.0</td>
<td>mm</td>
</tr>
<tr>
<td>5 Magnet thickness</td>
<td>2.5</td>
<td>6.0</td>
<td>mm</td>
</tr>
<tr>
<td>6 V pole angle</td>
<td>90</td>
<td>160</td>
<td>°</td>
</tr>
<tr>
<td>7 Pole arc ratio*</td>
<td>0.4</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>8 Web thickness ratio*</td>
<td>0.05</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>9 Slot depth ratio*</td>
<td>0.40</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>10 Slot opening ratio*</td>
<td>0.30</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>11 Slot width ratio*</td>
<td>0.45</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>12 Stator bore ratio*</td>
<td>0.66</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>13 Max. inverter current</td>
<td>200</td>
<td>300</td>
<td>A_{rms}</td>
</tr>
<tr>
<td>14 Stator outer diameter</td>
<td>160</td>
<td>210</td>
<td>mm</td>
</tr>
</tbody>
</table>

* Ansys Motor-CAD v14 - V-IPM (web) template

- Ratio based parameterization (V14) enables easy scaling over a broad design space
- Full motor parametric study is undertaken: 600 cases, 15-20 min per case so a total of ~2 days (parallelisation possible to reduce simulation time)
- Key EDU design parameters are added inputs to the design space:
  - Traction motor space envelope
  - Gear Ratio
  - Inverter Current
A Meta-model of Optimal Prognosis (MOP) of the E-machine is built through a sensitivity analysis, using Motor-CAD.

The MOP model is then used in optimisation stage to create pareto fronts of ‘best designs’.

‘Best designs’ are validated in Motor-CAD.
Motor-CAD V-IPM Script Simulation Workflow

- A multi-physics simulation strategy is utilised:
  - Coupled Electromagnetic-thermal simulations
  - Mechanical stress

- Max. current is an input:
  - Max. current is used to assess peak torque & power
  - Sets a limit when max. current not required

- Gear ratio as an input:
  - Scales speed within the Motor-CAD simulation
  - Dictates the maximum working speed and overspeed of the E-machine
  - Output power is sampled at key operating points: 3 for peak and 3 for continuous

- WLTP class-3 automotive drive cycle generated using vehicle model.
  - Gear ratio changes the E-machine torque and speed in the automotive drive cycles

---

**Key**

- E-mag. module
- Therm. module
- Lab module
- Mech. module

**Start**

- E-machine geometry setup

**34.3 s, 3.1%**

- E-machine geometry

**25.3 s, 2.3%**

- Drive cycle analysis, WLTP-3

**Continuous power, 3 speeds**

**935.9 s, 84.9%**

- Lab Sat & Loss model build

**Total simulation time = 1102.5 s = 18 mins, 22.5 s**

**15.8 s, 1.4%**

- Torque ripple

**3.0 s, 0.3%**

- Maximum torque vs. speed

**85.4 s, 7.7%**

- Coupled thermal steady-state

**2.8 s, 0.3%**

- Rotor overspeed

**Peak torque @ low speed OP**

**1161.6 s**

- Coupled thermal transient
Meta-model of Optimal Prognosis (MOP)

- Matrix that shows the Coefficient of Prognosis (CoP) of all output parameters with respect to input parameters:
  - Input parameters to the sensitivity analysis are shown horizontally
  - Output parameters, i.e. constraints and objectives are shown vertically
  - Last column shows overall quality of the Metamodel – good quality achieved

- EDU system input parameters: space envelope, gear ratio and inverter current all have measurable impacts on numerous constraints and objectives
Optimisation Results: Motor Packaging vs Performance

• The motor space envelope is often constraint within the overall EDU packaging

• Pareto fronts show impact of increasing motor volume on motor cost and energy consumption
  - Increasing stator Outer Diameter (OD) with constant motor length increases the motor space envelope
  - A higher motor space envelope reduces motor energy consumption

• Compromise between motor volume, cost and energy efficiency can easily be quantified

➢ Trade-off between motor volume and competing component packaging requirements can be communicated to system engineering team
Optimisation results: Impact of gear ratio on motor performance

- The transmission gear ratio determines the maximum motor speed and peak torque
- Pareto fronts show impact of increasing gear ratio on motor cost and energy consumption
  - A higher gear ratio/motor speed reduces motor cost and energy consumption
  - Also increases motor bearing loss
- A higher gear ratio often increases transmission cost

➢ Using the graphs shown design trade-offs between motor and transmission can easily be quantified and communicated between different component teams
Optimisation results: Impact of inverter current on motor performance

• The maximum inverter current determines the peak torque and power the motor can deliver

• Pareto front shows the impact of increasing the inverter current on motor cost and energy consumption
  – A higher inverter current reduces motor cost and increases motor efficiency
  – A motor thermal limit is eventually encountered, when increasing the inverter current

• A higher inverter current does increase inverter VA rating and inverter loss

➢ Using the graphs shown design trade-offs between motor and inverter can easily be quantified and communicated between different component teams
Optimisation results: impact of peak torque requirement

- The peak torque requirement has a significant impact on many aspects of the E-machine: size, magnet volume
- Advantage of the meta-model approach:
  - E-machine requirements are set on the optimisation side, which runs fast
  - Easy to alter specific requirements and observe their effect in isolation
- A higher peak torque demand reduces efficiency and increases cost

➢ Using the graphs shown, design trade-offs between motor and specification can easily be quantified and communicated between different component teams
System EDU Optimisation Results and Design Trade-offs

- Motor energy consumption and cost varying with motor OD, inverter current and gear ratio
- Extremely powerful tool to quantify system design trade-offs
- Results enable ease of communication between motor designer, system engineers and component designers
- Easily presentable enabling management to make quantifiable system design trade-offs:
  - % reduction in motor energy consumption requires % increase in space/current/gear ratio
- Optimisation of 18,000+ cases based on Meta Model approach took ~30 min, compared to ~80 days if done manually
Content

• Company Introduction

• Electric Drive Unit (EDU) design: trends and challenges

• IPM traction motor optimisation within an EDU system

• Next steps in the design process

• Summary
Next steps: repeat with different E-machine topologies

- **Meta-model simulation time:**
  - \(\approx 20\) mins per iteration
  - 400 to 600 samples
  - 8 Motor-CAD blackbox in parallel
  - \(\approx 16.7\) to 25 hours

- **One meta-model gives an extremely wide design space to explore.**

- **Meta-model simulation time is short enough that more motor topologies can easily be investigated, for example:**
  - Different pole and slot numbers
  - Different winding topologies
  - Different rotor topologies
  - Different active materials
Next steps: EDU System Simulation

- **Ansys Motor-CAD Function Mockup Interface (FMI):**
  - Runs Motor-CAD files live within a system simulation.
  - The Lab module saturation and loss mapping techniques, keep electromagnetic simulations fast.
  - Easily load in different Motor-CAD designs, from the previous optimisation procedure.

- **Combined with transmission and inverter models,**
  we compute the WLTP-3 drive cycle consumption per component:
  - Transmission = 7.14 Wh/km
  - E-machine = 6.90 Wh/km
  - Inverter = 4.30 Wh/km

- **The various EDU configurations can be benchmarked in full,** allowing an optimised system solution.

*Model developed by University of L'Aquila*
Summary

• System design and optimisation drives faster, lower cost development processes as well as better overall performance of the Electric Drive Unit system.

• A combined optimization workflow with Ansys Motor-CAD and Ansys OptiSLang provides a unique, unparalleled solution for full design exploration of E-machines including EDU system influences.

• The workflow presented provides insight in key design trade-offs between e-machine, inverter and transmission performance against system design objectives, such as mass, cost and energy consumption.

• These results enable ease of communication between the component designers for the e-machine, inverter and transmission, as well as the system design teams responsible for the key attributes and requirement cascading.