E-machine Optimization considering Electric Drive Unit (EDU) System Requirements

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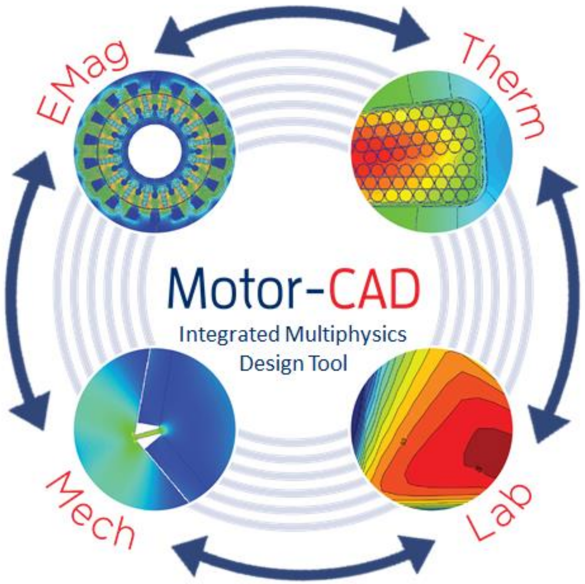
17th June 2021

Ansys

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

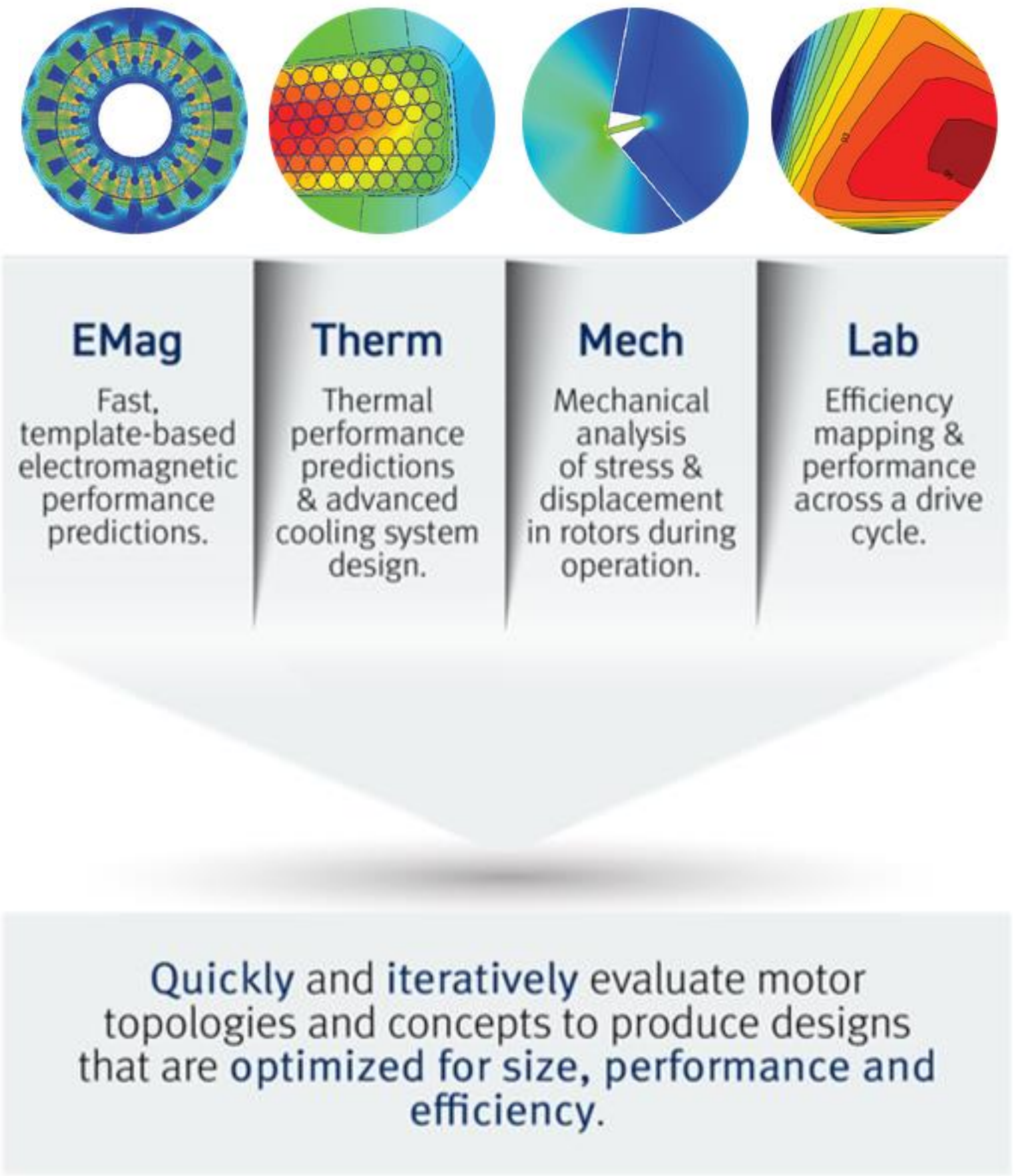
Ansys Motor-CAD & Motor Design Ltd



- **Software developers: ANSYS Motor-CAD**
  - Design, analysis and optimization of electric motors
  - High level of customer support & engineering know-how
  - Embedded engineering expertise
- **Consultancy**
  - Design, analysis and training courses
  - Led by motor design experts
- **Research**
  - Government / EU-funded research projects
  - Collaborate with universities worldwide

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.



Micro SME

LYRA ELECTRONICS
Inverter
Design, Prototype Build & Testing

SME

Motor Design Limited
eMachine
Electromagnetics & Thermal Design

iNetic – POWERING YOUR PRODUCTS
eMachine
Mechanical Design, Prototype build & Testing

BRANDAUER PRECISION PRESSINGS
eMachine
Lamination Stamping

OEM

JAGUAR / LAND ROVER
EDU
Project, Design, Procurement & EDU Integration

Compact EDU with Advanced-Technology

(CompETe)

TIER 1

TATA STEEL
Electric Steel Material Supply & Stamping Development

FUCHS – LUBRICANTS. TECHNOLOGY. PEOPLE.
Lubricant
Design, Analysis & Manufacturing

ACADEMIC

ADVANCED PROPULSION CENTRE UK

Newcastle University
Transmission
Design, Prototype Build & Testing

WMG Innovative Solutions
EDU Testing & eMachine Prototype Build

LEADING ELECTRIFICATION

ELECTRIFIED PORTFOLIO

Electrification across our product range continues with 1 Battery Electric Vehicle (BEV), 8 models now on sale with plug-in hybrids (PHEV) and 11 with mild-hybrids (MHEV).

WORLD CAR OF THE YEAR

Jaguar I-PACE won an **unprecedented treble**; 2019 World Car of the Year, World Design Car of the Year and World Green Car of the Year, alongside over 80 global industry awards.

ELECTRIFIED SALES

Achieved **6% electrified sales** in 2019, with a commitment to offer electrified options for all new models from 2020

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Electric Drive Unit (EDU) design: trends and challenges

Need for multi-criteria design process

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

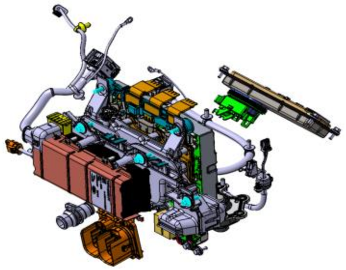
Need for Multi-Physics Analysis and Optimization to meet EDU targets

Effective multi-physics analysis allows true optimization targeting the integrated drive unit (system) requirements.

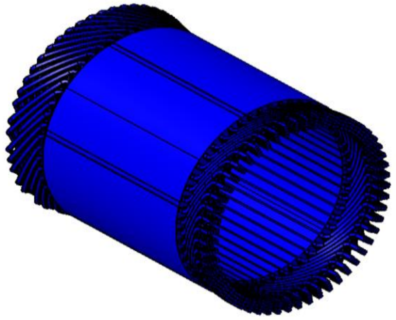
Drive unit system-level design parameters

Gear ratio
Maximum current
Modulation strategy
PWM-frequency
Pole No.
Cooling system
...

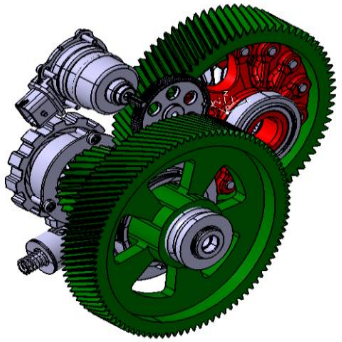
Single component design based on system optimization output



inverter

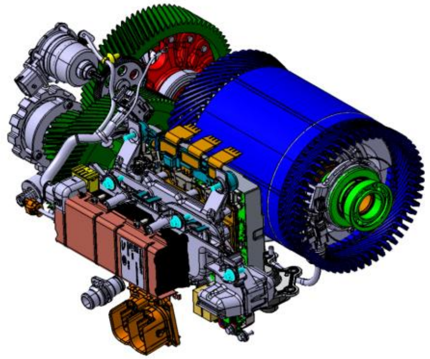


eMachine

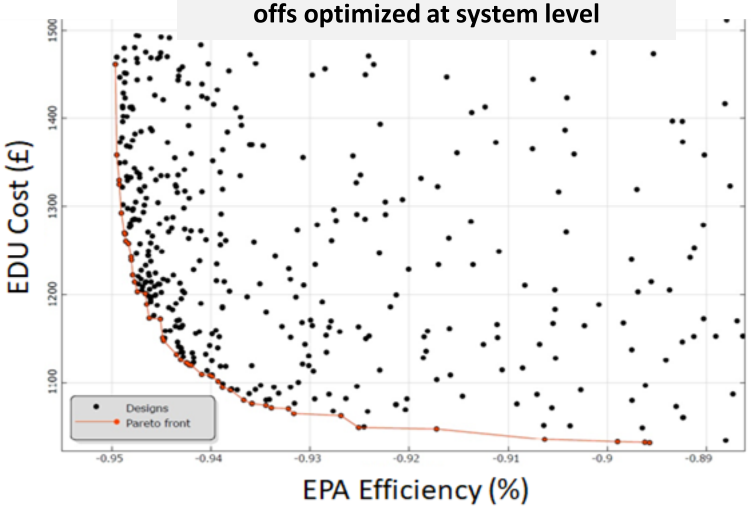


gearbox

Multi-physics, multi-domain modelling & Optimisation



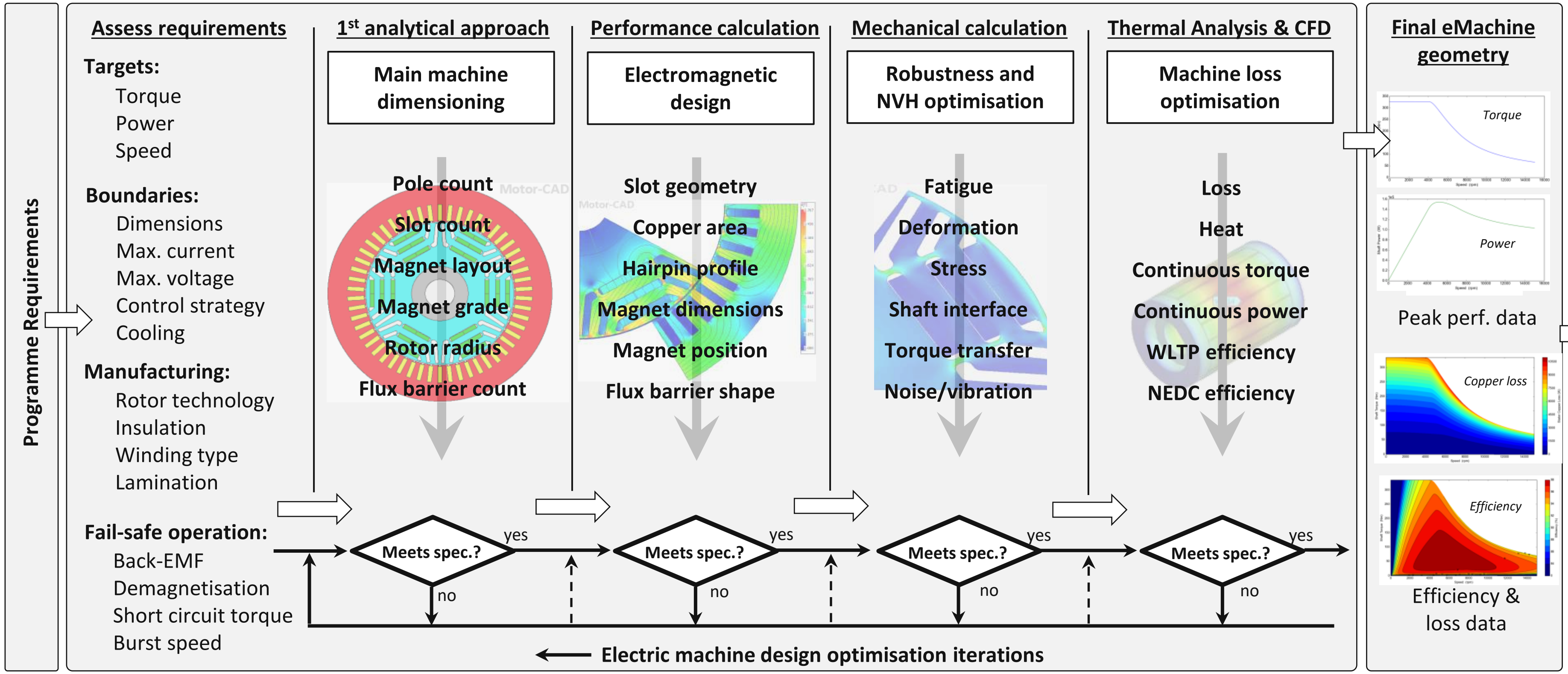
Efficiency, Power density & cost trade-offs optimized at system level



Electric Drive Unit (EDU) design: trends and challenges

Need for a system led design process

Particular example of the eMachine

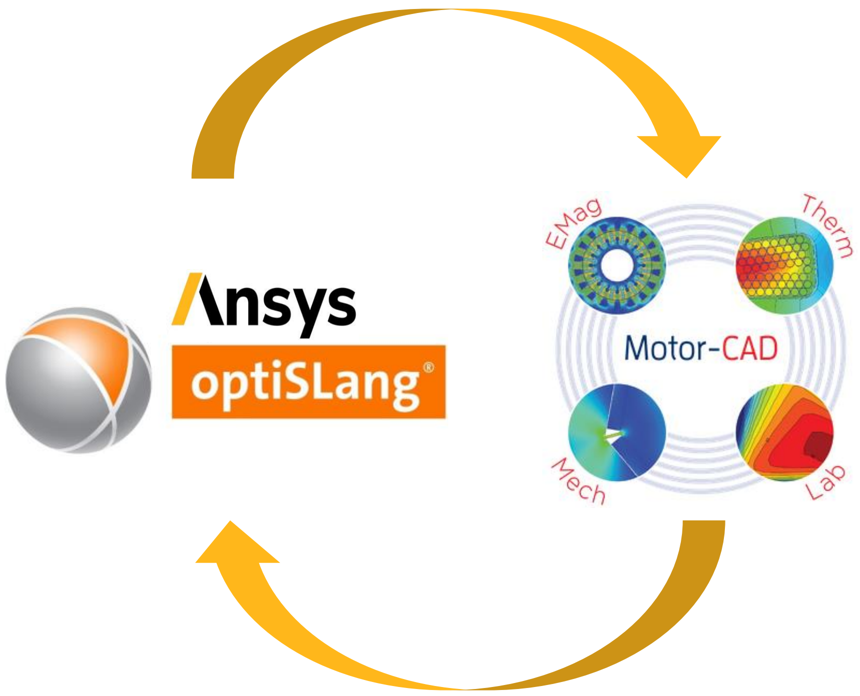


Inverter and gearbox selection add an additional system-level loop to the optimisation run with max. current, speed and dimensions of the eMachine boundaries becoming variable input parameters

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?

Yes! By combining forces between **Motor-CAD** and **optiSlang** we can create a new and unique system optimization solution



Data-driven exploration of the design space utilizing multiphysics simulation

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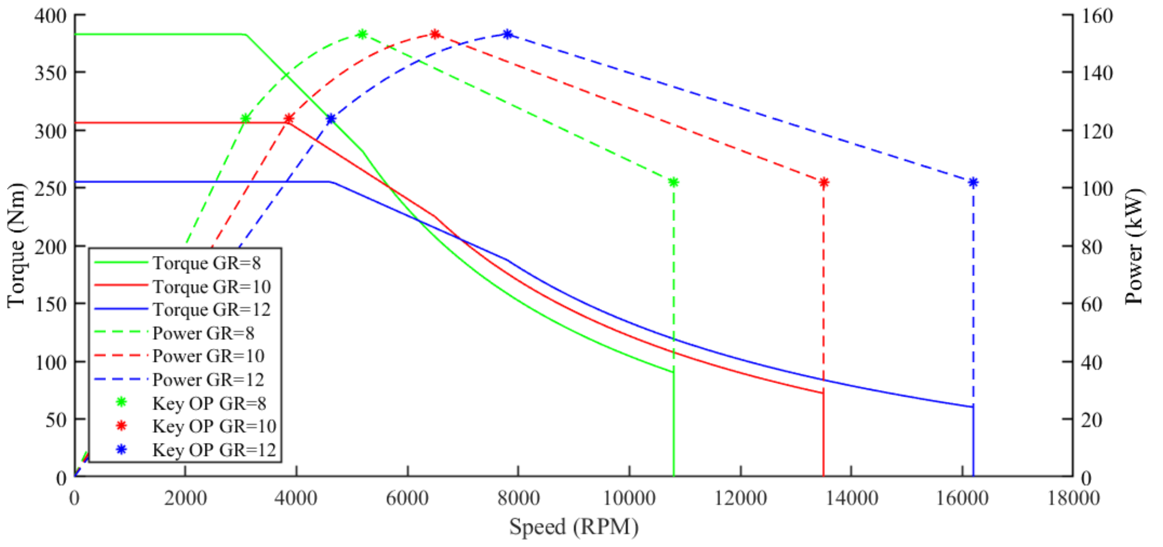
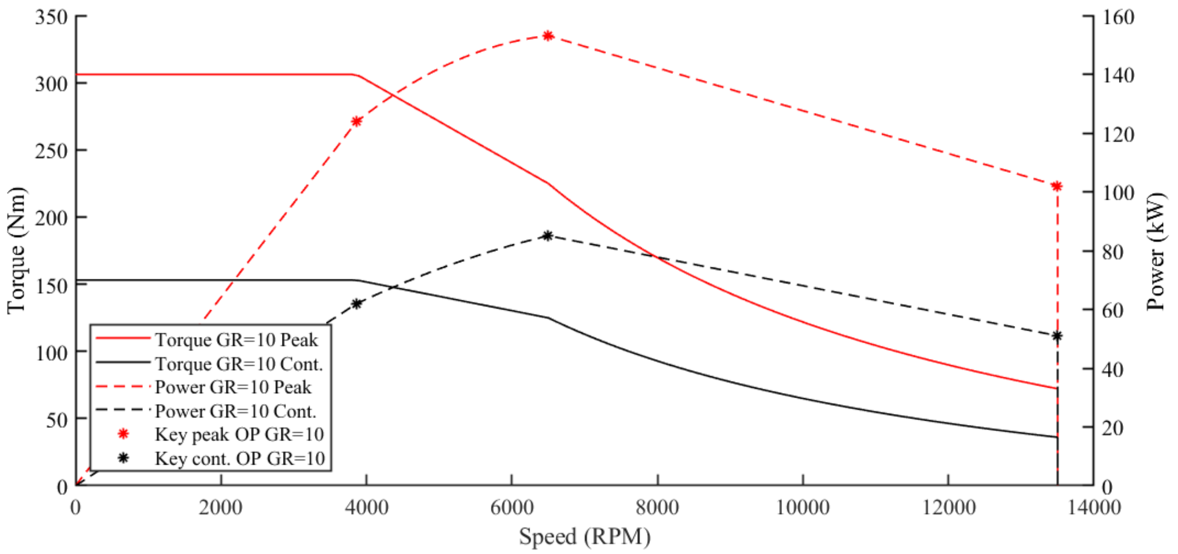
EDU Specifications

- **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

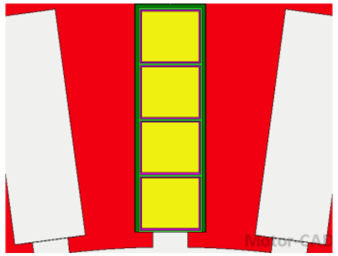


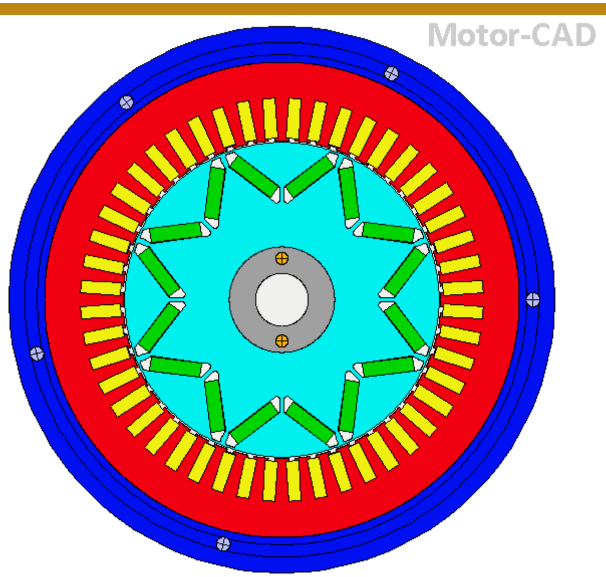


IPM traction motor optimization scenario

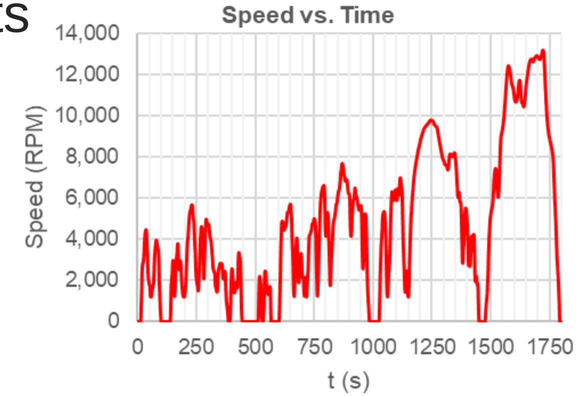
- **Multi-objective:**
  - Min energy consumption over WLTP-3
  - Min active mass
  - Min material cost
- **Multi-constraints:**
  - Peak Power @ 3 operating points:
    - Peak torque, peak power & max. speed
  - Continuous Power @ 3 operating points
    - Peak torque, peak power & max. speed
  - Rotor stress @ 20% overspeed
    - Average and maximum values

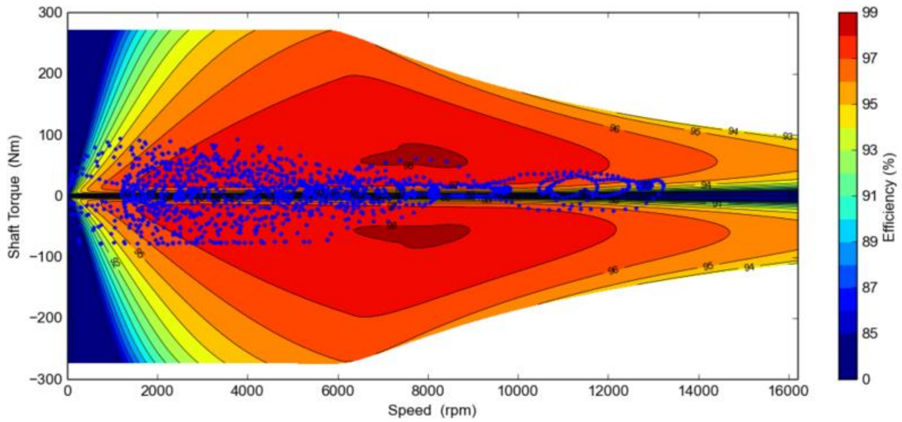
- V-IPM motor
- 48 slots, 8 poles
- Hairpin winding
- Water jacket cooling





WLTP-3 Drive Cycle

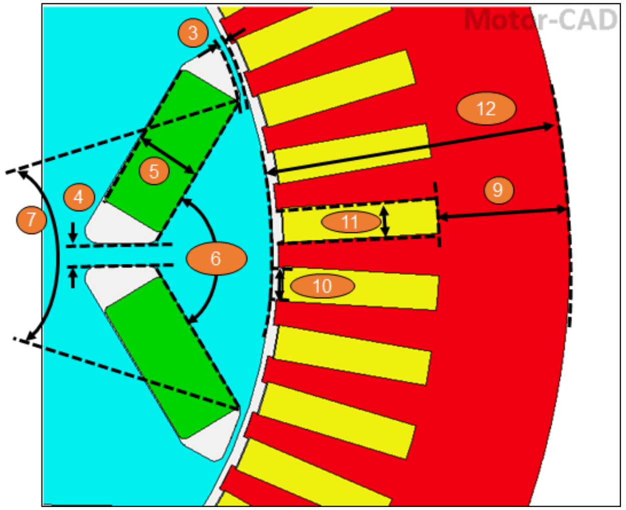




Design Space including EDU parameters

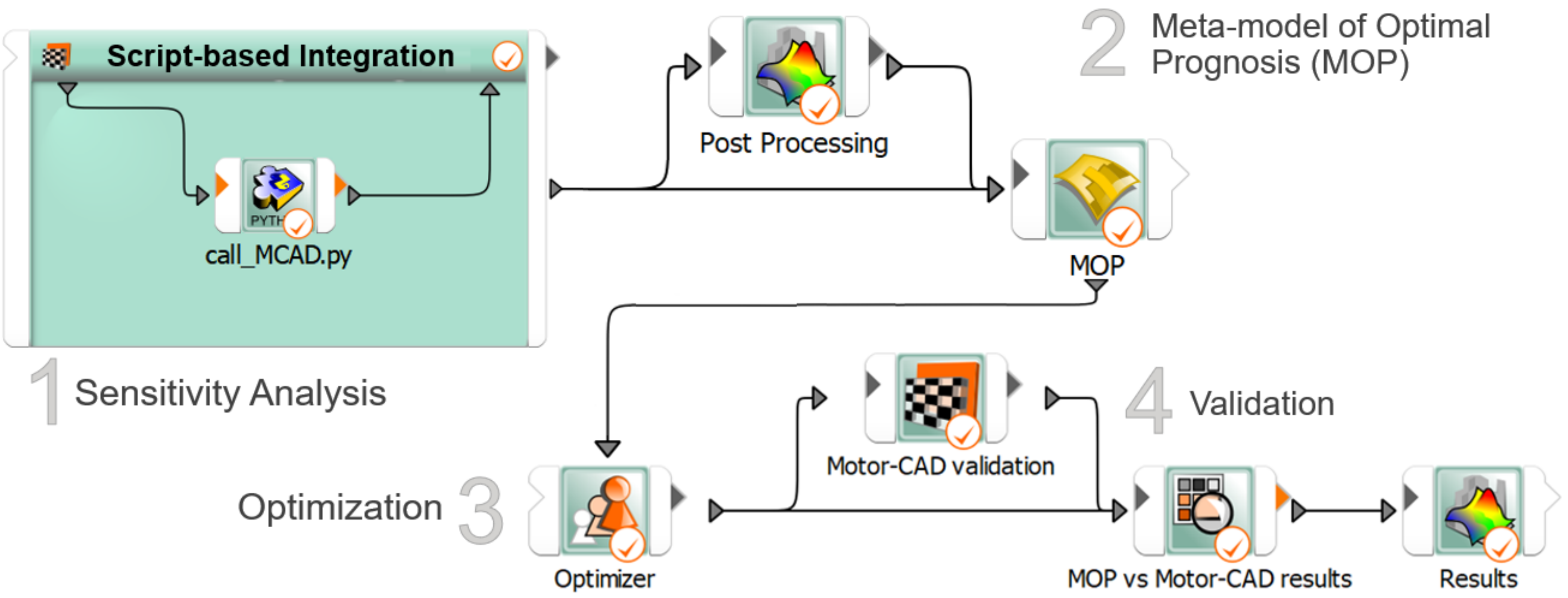
	Parameter	lb	ub	Unit
1	Active length	95	165	mm
2	Gear ratio	8	12	
3	Bridge thickness	0.7	2.0	mm
4	Magnet post thickness	1.5	4.0	mm
5	Magnet thickness	2.5	6.0	mm
6	V pole angle	90	160	°
7	Pole arc ratio*	0.4	0.8	
8	Web thickness ratio*	0.05	0.5	
9	Slot depth ratio*	0.40	0.65	
10	Slot opening ratio*	0.30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

* 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

Optimization Workflow



A Meta-model of Optimal Prognosis (MOP) of the E-machine is built through a sensitivity analysis, using Motor-CAD.

→

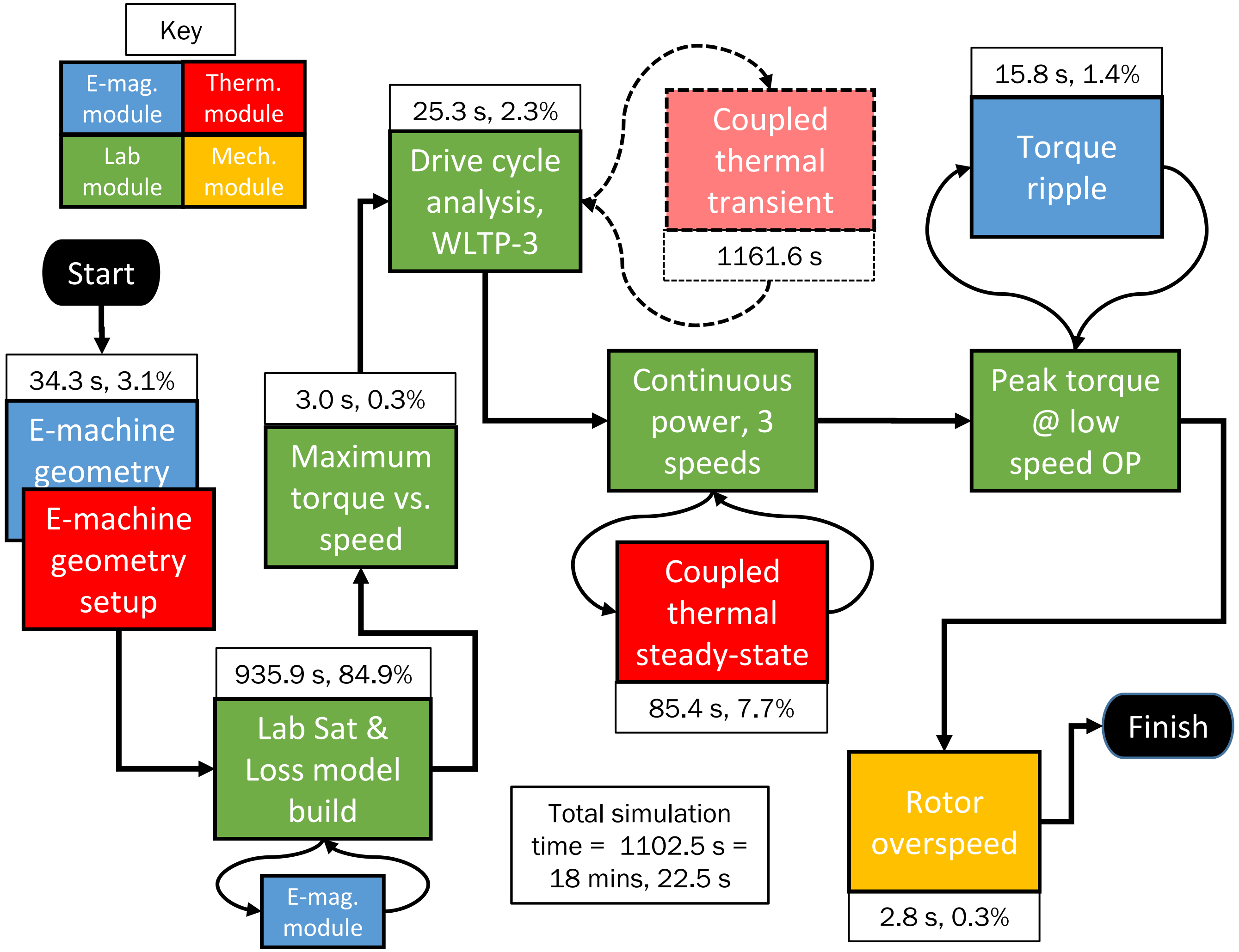
The MOP model is then used in optimization stage to create pareto fronts of 'best designs'

→

'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 over-speed 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
  - 1800 data points, sampled at 1 second intervals



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

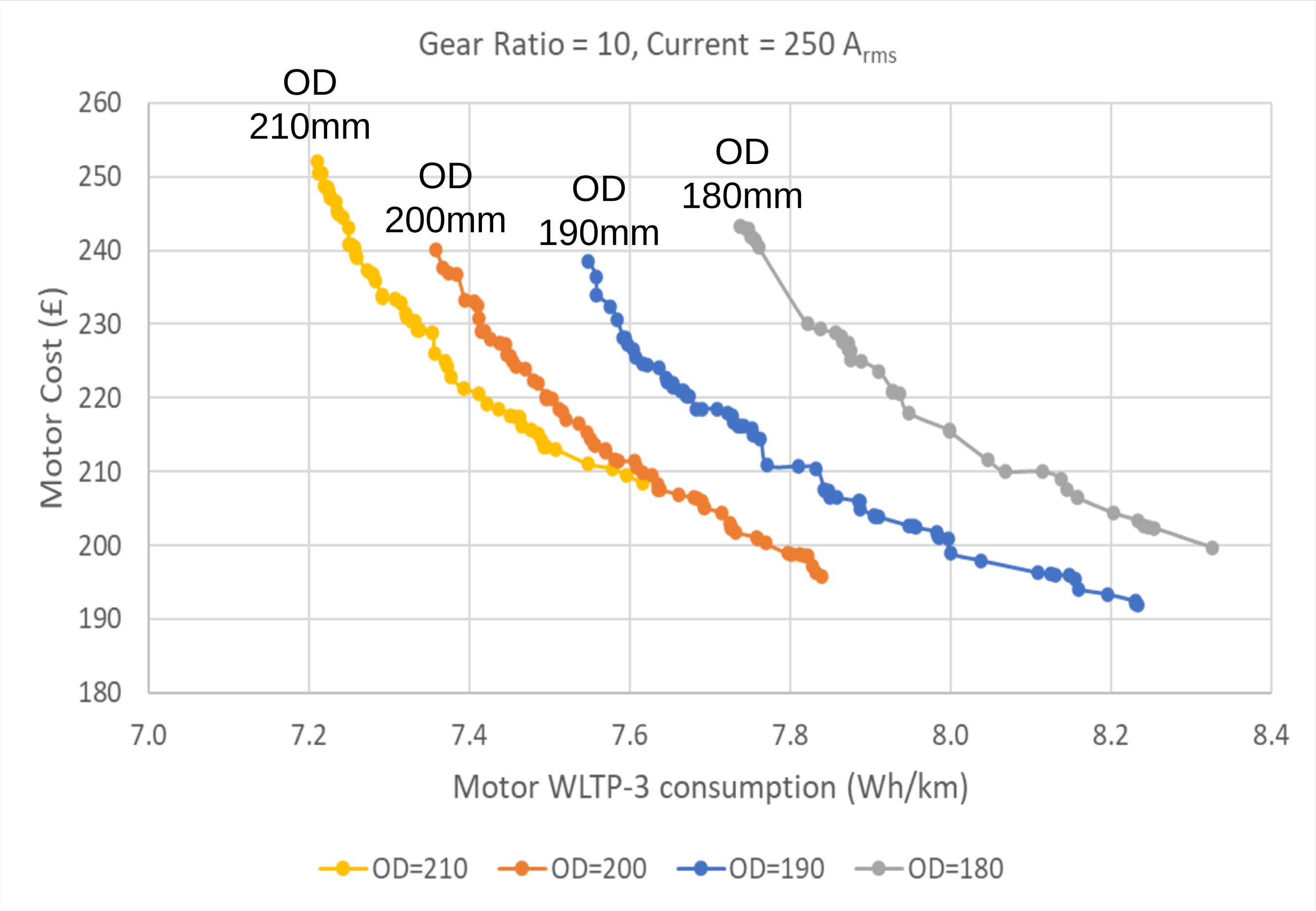
Total effects

Models	i_Active_Length	i_Gear_Ratio	i_L1_Bridge_Thickness	i_L1_Magnet_Post	i_L1_Magnet_Thickness	i_L1_Pole_Ang	i_L1_Pole_Arc_Ratio	i_L1_Web_Thickness_Ratio	i_MaxCurrent_RMS	i_Slot_Depth_Ratio	i_Slot_Op_Ratio	i_Slot_Width_Ratio	i_Split_Ratio	i_Stator_OD	Total
o_Weight_Act	43.2 %													56.8 %	99.3 %
o_WLTP_Consumption	18.5 %	16.6 %	3.3 %	9.4 %	10.1 %	19.4 %	33.2 %	2.2 %		7.7 %	3.8 %	4.2 %	4.4 %	35.1 %	95.6 %
o_Stress_Max		28.5 %		11.2 %	3.4 %	10.8 %	25.6 %						6.3 %	19.8 %	95.9 %
o_RMSCurrentDensity									12.7 %	28.5 %		20.4 %	7.3 %	35.5 %	99.5 %
o_OutputPower_PeakTorque	29.6 %	14.9 %	1.0 %	1.7 %	7.9 %	3.1 %	13.0 %	3.5 %	11.6 %	2.6 %		3.4 %	1.2 %	9.8 %	99.4 %
o_OutputPower_MaxSpeed	3.4 %	2.4 %	5.3 %	7.8 %	42.9 %	4.5 %	22.9 %			1.1 %	1.7 %	1.0 %	3.4 %	4.0 %	97.6 %
o_OutputPower_MaxPower	17.1 %	10.5 %	2.7 %	2.8 %	23.5 %	4.6 %	19.7 %	2.9 %	10.3 %	1.1 %		2.0 %	1.9 %	7.8 %	97.5 %
o_L1_Magnet_Post_Avg_Stress		19.7 %		30.9 %	1.6 %	16.2 %	18.0 %						6.1 %	17.4 %	98.8 %
o_L1_Bridge_Avg_Stress		29.8 %	9.8 %	1.9 %	6.6 %	1.7 %	41.8 %	1.1 %					3.4 %	12.3 %	98.2 %
o_Active_Vol_Cost	24.3 %				33.5 %	5.3 %	22.4 %							14.7 %	97.2 %

Parameter

Optimization Results: Motor Packaging vs Performance

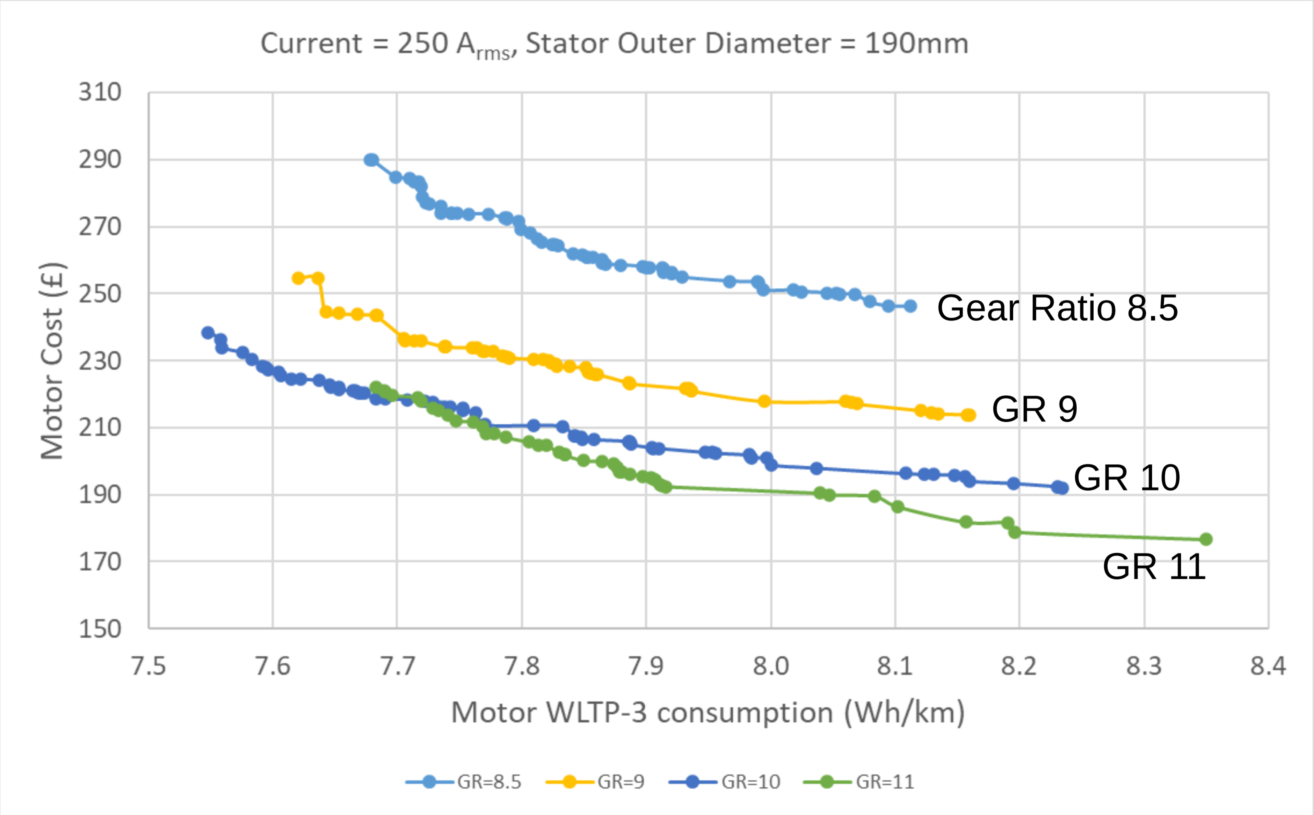
- The motor space envelope is often constraint within the overall EDU packaging
- Pareto fronts show impact of increasing motor volume on motor cost and energy consumption
  - Increasing stator Outer Diameter (OD) with constant motor length increases the motor space envelope
  - A higher motor space 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**

Optimization results: Impact of gear ratio on motor performance

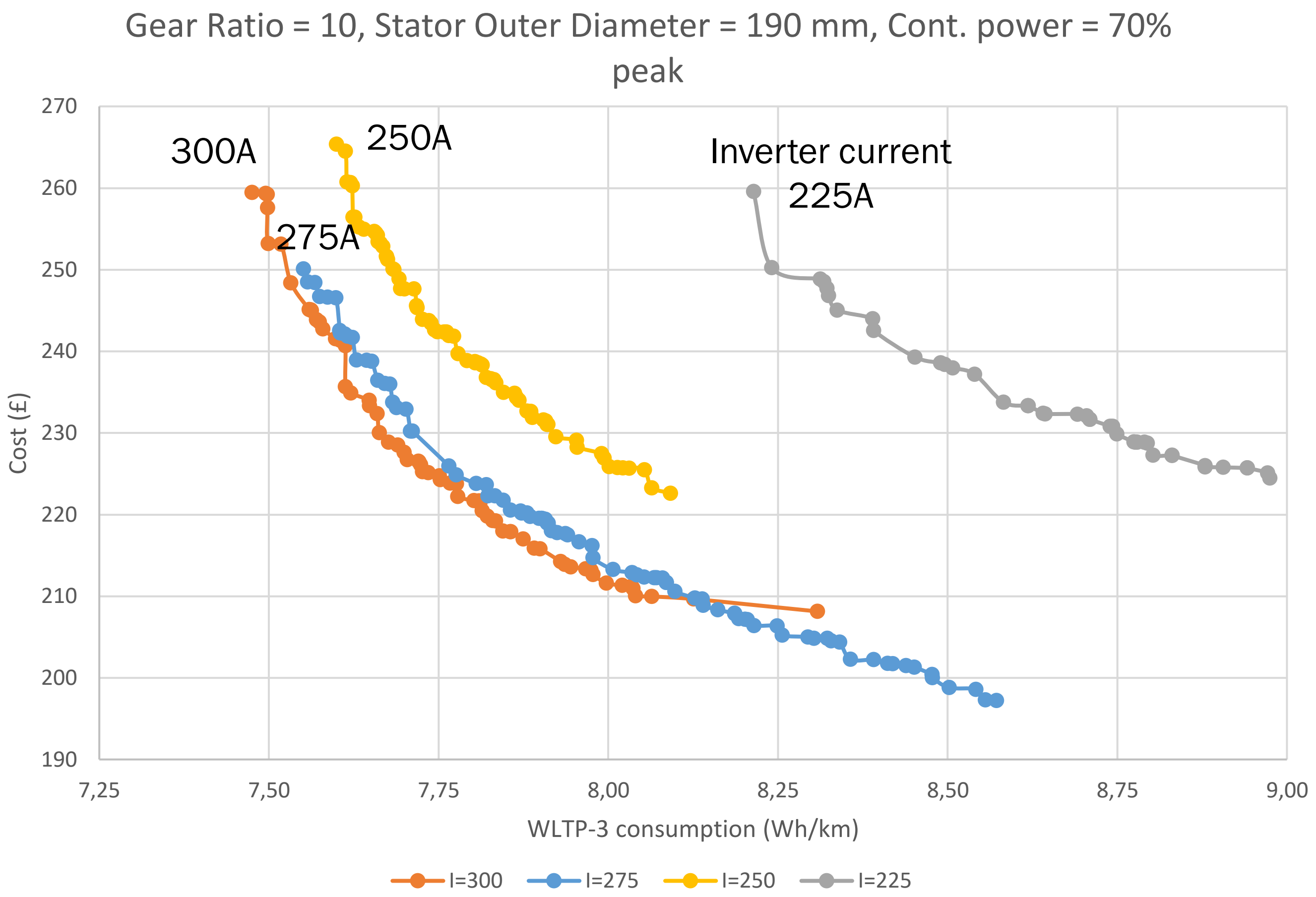
- The transmission gear ratio determines the maximum motor speed and peak torque
- Pareto fronts show impact of increasing gear ratio on motor cost and energy consumption
  - A higher gear ratio/motor speed reduces motor cost and energy consumption
  - Also increases motor bearing loss
- A higher gear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

Optimiszation results: Impact of inverter current on motor performance

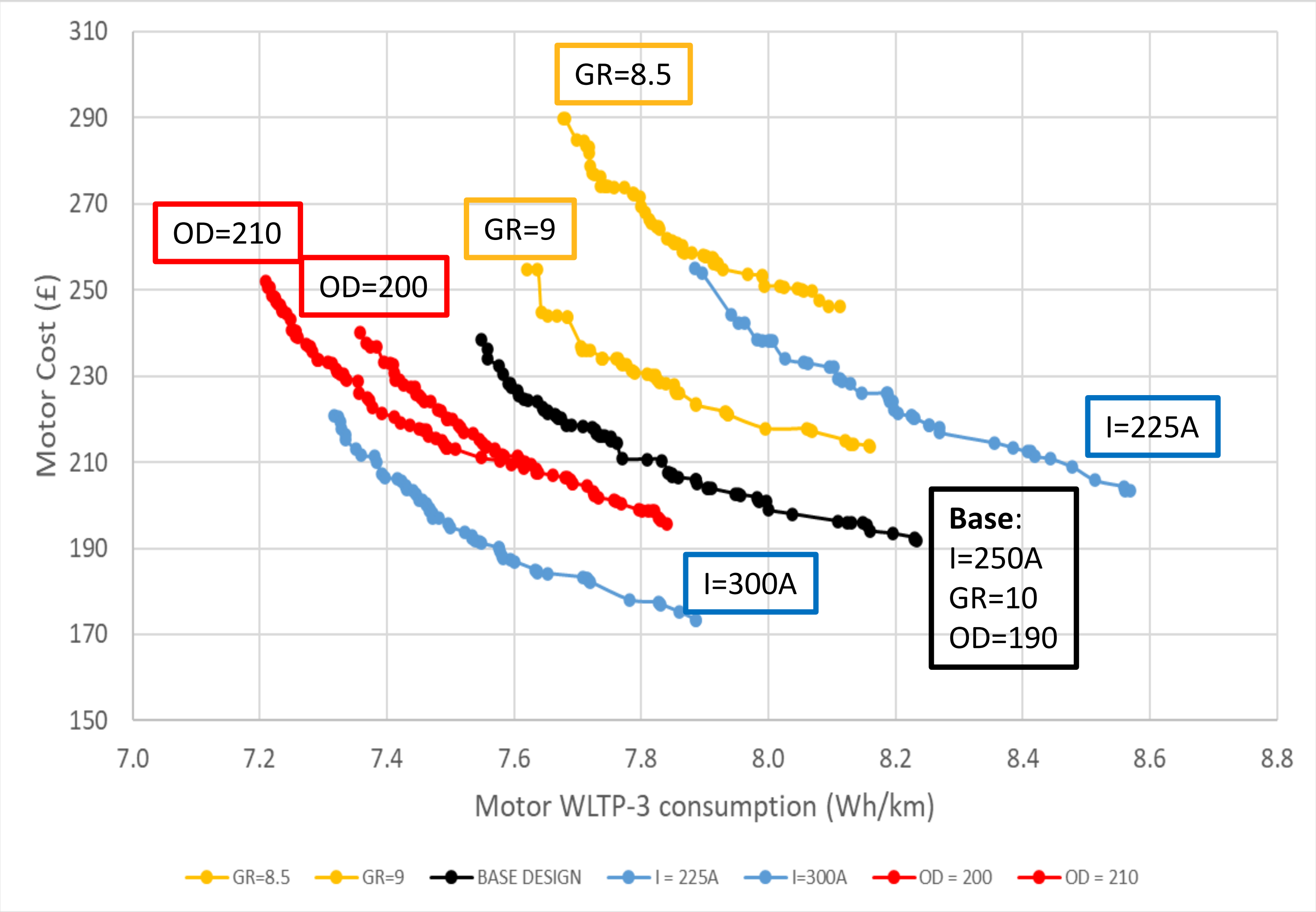
- The maximum inverter current determines the peak torque and power the motor can deliver
- Pareto front shows the impact of increasing the inverter current on motor cost and energy consumption
  - A higher inverter current reduces motor cost and increases motor efficiency
  - A motor thermal limit is 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**

System EDU Optimization 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
- Optimization of **18,000+ cases** based on Meta Model approach took **~30 min**, compared to **~80 days** if done manually



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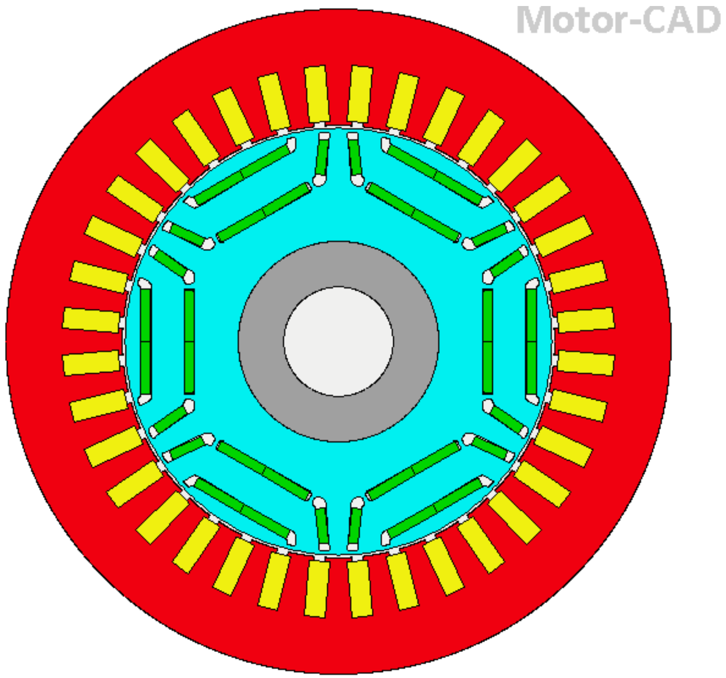
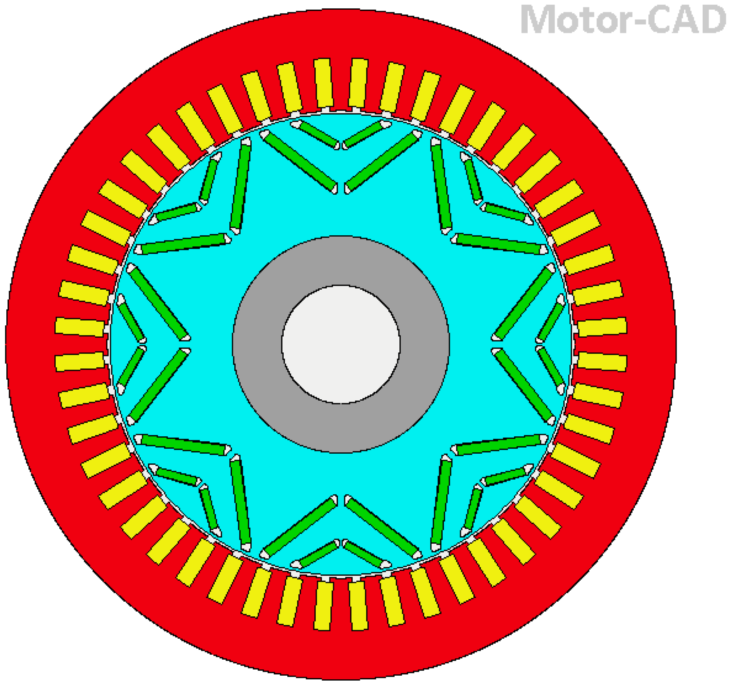
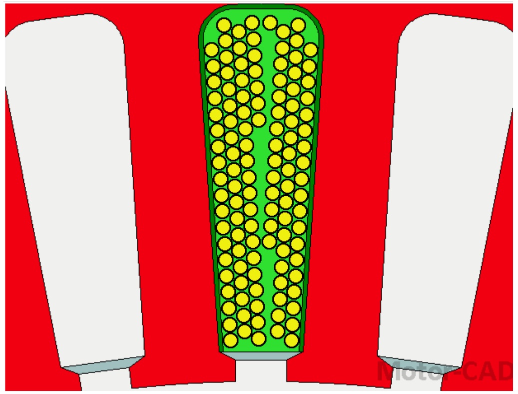
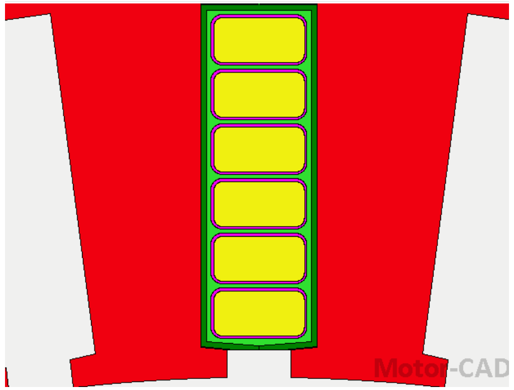
Next steps: repeat with different E-machine topologies

- **Meta-model simulation time:**
  - ≈ 20 mins per iteration
  - 400 to 600 samples
  - 8 Motor-CAD black-box in parallel
  - ≈ 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



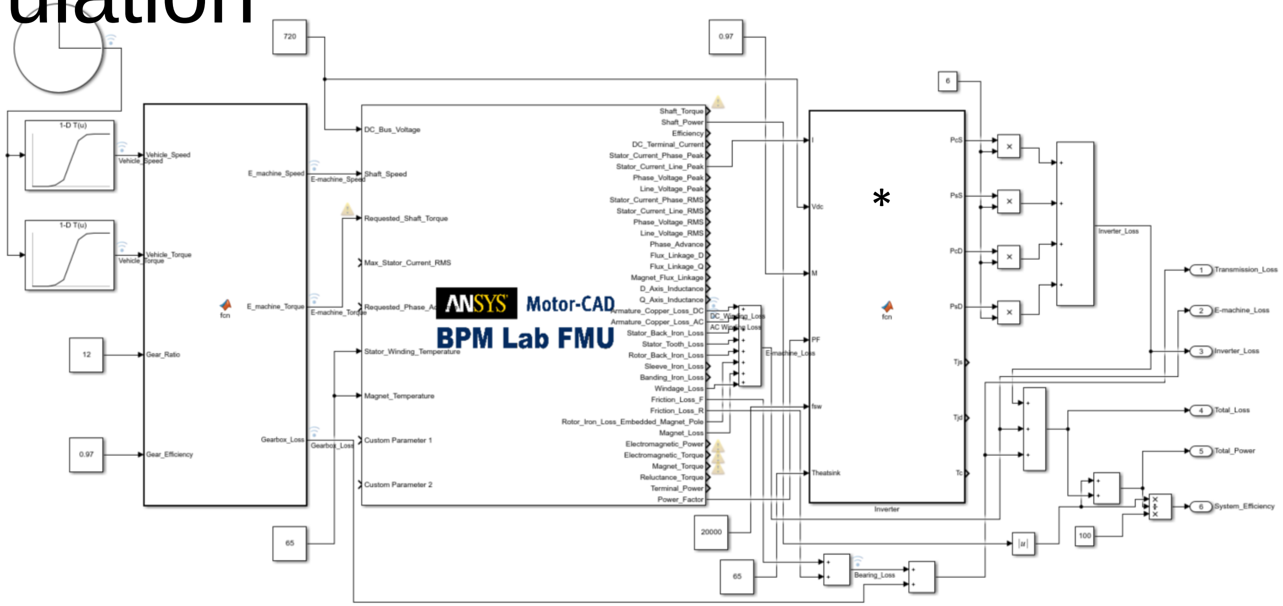






Next steps: EDU System Simulation

- **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.

Ansys