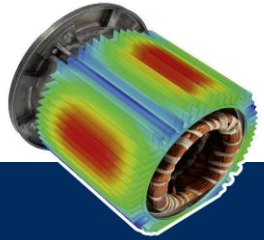
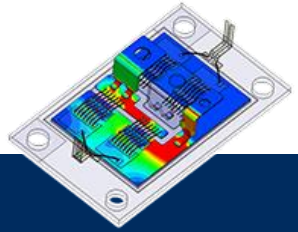
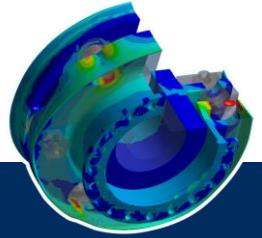
CADFEM®

Simulation ist mehr als Software®







Die FEM-Simulation als integraler Bestandteil während der Musterphase in der Motorenberechnung

Philipp Siehr

Speaker – Philipp Siehr

- 2009 – 2016 **Mathematics** (Ruprecht-Karls University Heidelberg)

- 2016 – 2018: **Simulation Engineer** (AMK Automotive GmbH & Co.KG)
  - Electric Drives for industry and automotive
  - Development of a tool using Ansys Maxwell to simulate a set of >10000 motor designs.
    It is possible to find configurations for specific customer requests within seconds.

- Since 2018: **Business Development Manager** (CADFEM GmbH)
  - Focus on computation of electric drives:
    - Early design phase
    - Detailed analysis in all physical domains
    - System level integration

CADFEM – Simulation is more than Software

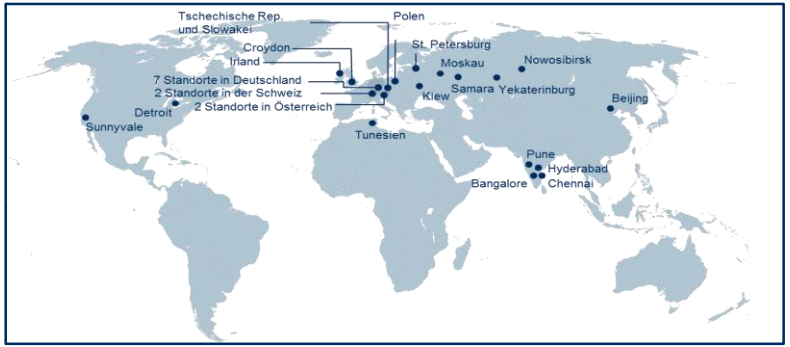
PRODUCTS
Software und IT Solutions

SERVICES
Advice, Support, Engineering

KNOW-HOW
Transfer of knowledge

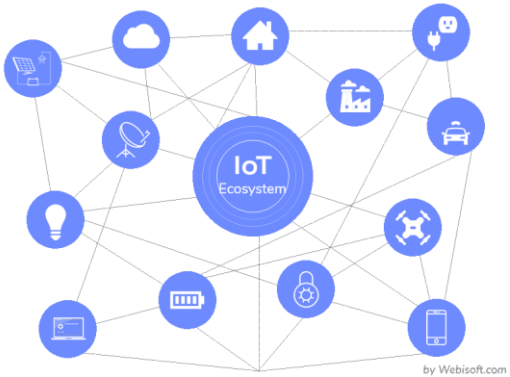
CADFEM in D, A, CH
- 1985 founded
- 2,300 customers
- 10 locations
- 220 employees (worldwide > 350)
- ANSYS Elite Channel Partner

LS-DYNA
ROCKY
optiSLang
Motor Design Limited



Big Industry Trends

Internet of Things



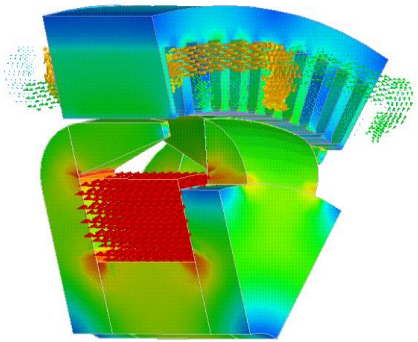
Webisoft.com

2018: 11bn connected things
2020: 20bn connected things
Quelle: Statista.com

5G

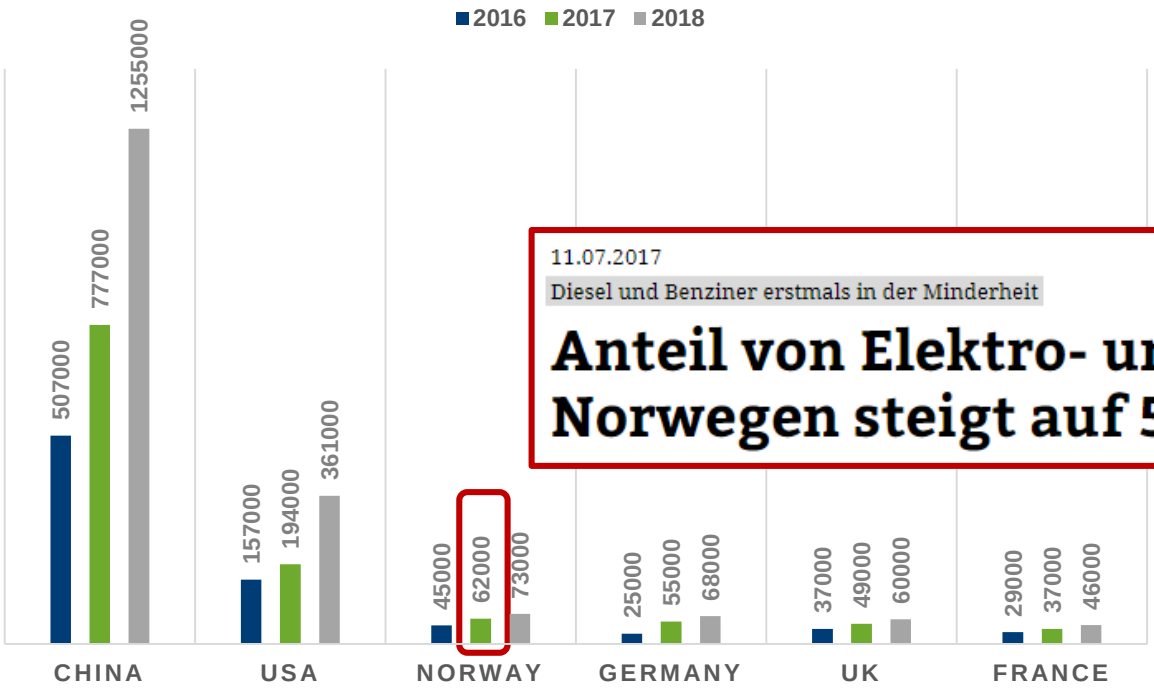
2013: „Neuland“
2018: „Noch nicht durchschrittenes Terrain“
Angela Merkel

Electrification



Next slide

Sales of Electric Cars and Hybrids



11.07.2017

Diesel und Benziner erstmals in der Minderheit

Anteil von Elektro- und Hybridautos in Norwegen steigt auf 53 Prozent

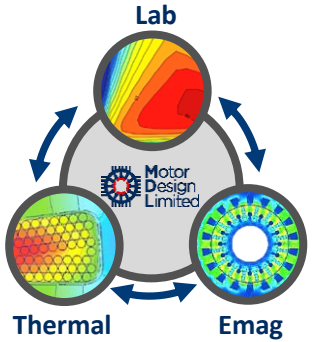
http://www.manager-magazin.de/unternehmen/autoindustrie/norwegen-elektroauto-anteil-steigt-auf-53-prozent-a-1157126.html

Quelle: CAM

From the Idea to the Operation

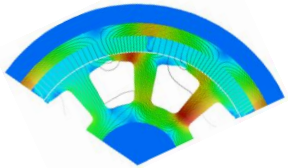
Design > Analysis > Operation

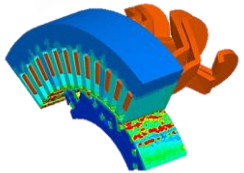
Design
Efficient Motor Design Toolkit



Motor-CAD
Motor Design Limited

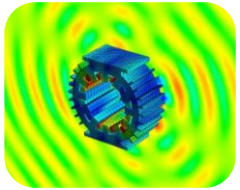
2D & 3D Analysis
Advanced Magnetics Modelling





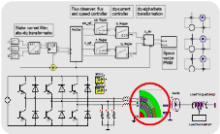
Maxwell 2D & 3D
ANSYS

Coupled Analysis
NVH, Cooling, ...



Mechanical &CFD
ANSYS

System Validation
Control logic, software



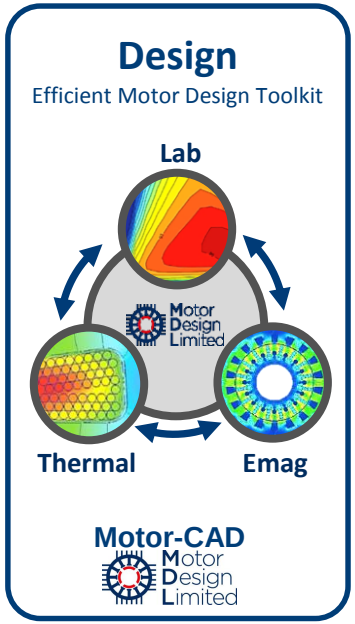
Motor Design Limited — Concept Design

System Validation

3D Physical Validation

Twin Builder
ANSYS

Design Phase



Objectives

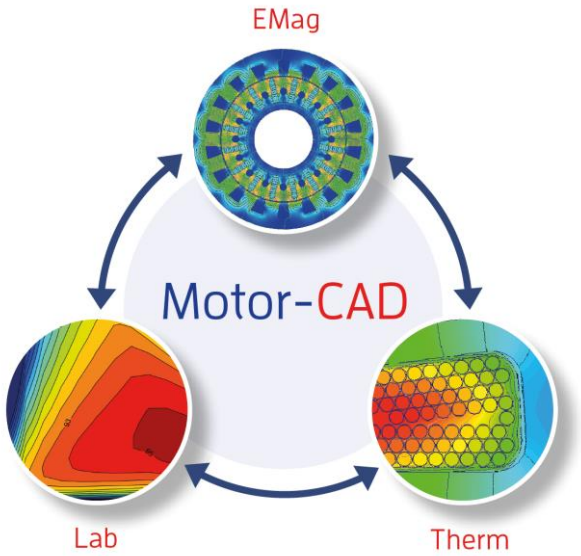
- Investigation of the possibilities
- **Fast** evaluation of different designs
- Coupled preliminary electromagnetic and thermal analysis
- **Fast** evaluation of performance maps and duty cycles

Requirements

- Software to evaluate fast and accurate electromagnetic and thermal behaviour
- Automated workflows for data exchange
- Capability for preliminary optimization and sensitivity analysis

Motor-CAD Software

- Motor-CAD modules are developed to enable fast and accurate analysis in one integrated software
  - **EMag** - Combined 2D FEA and analytical algorithms for fast calculation of electromagnetic performance.
  - **Therm** - Heat transfer and flow network circuits automatically set up to provide steady-state and transient thermal predictions.
  - **Lab** - Efficiency mapping and drive cycle analysis within minutes.
  - **Mech** - 2D FEA based solution in Motor-CAD to analyse stress and displacement in rotors during operation.



- Written by motor design experts in the language of the motor designers so very easy to use.

Example Specicifation Sheet

Parameter	Value	Unit
DC supply voltage	450	V
Max AC line current	900	A (peak)
Peak output power	235	kW
Peak torque	300	Nm
Base speed	6000	rpm
Max speed	15000	rpm
Continuous power at base speed	80	kW
Continuous torque at base speed	100	Nm
Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

Geek vs. Nerd

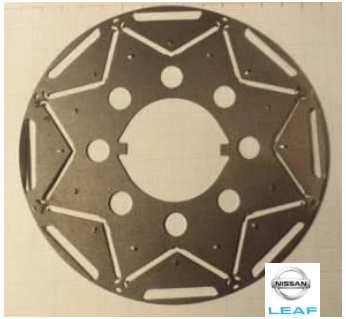
Geek ⟷ **Nerd**

- Highly Theoretical
- Pen&Paper-Solution
- Analytical Formulas

- Theory based idea
- Verify with FEM
- Optimize

- Pure FEM
- HPC-Cluster
- Parameter studies
- Optimization

Design Phase – Motor Type



	IM	BPM
Density Torque	+/-	++
Efficiency	+/-	++
Weight	+	++
Inverter	+	+/-
Cost Motor	+/-	-
Cost System	+/-	+/-
Sound	+	++

Quelle: Seminar Prof. Dr. phil. Dr.-Ing. habil. Harald Neudorfer

- Brushless Permanent Magnet Motors are most common as traction motors
- Tesla is one of the few companies using Induction Motors.
  Tesla Model 3 uses „AC induction front & switched reluctance, partial permanent magnet rear.“
  (Twitter, @elonmusk, 19. Mai 2018)
- The 2018 Audi e-tron also uses an IM Motor

Design Phase – Estimate Dimension

Parameter	Value	Unit
DC supply voltage	450	V
Max AC line current	900	A (peak)
Peak output power	235	kW
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Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

- For a rotational movement the electromagnetic torque is given by:

$$T = \frac{\pi^2}{4\sqrt{2}} \cdot k_{w_1} A B D^2 L_{fe}$$

- k_{w1} fundamental winding factor
- L_{fe} the axial active length
- $A = \frac{Total\ Amp{-}Cond.}{Airgap{-}circ.} = \frac{2mN_{ph}I_{RMS}}{\pi D}$, electric loading
- $B = \frac{avg.\ flux\ dens}{surface} = \frac{2\mathrm{p}\phi}{\pi D L_{fe}}$, magnetic loading

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  - $B = \frac{avg.\ flux\ dens}{surface} = \frac{2p\phi}{\pi D L_{fe}}$, magnetic loading

- With $V_{rotor} = \frac{\pi}{4} D^2 L_{fe}$ it follows:

$$TRV := \frac{T}{V_{rotor}} = \frac{\pi}{\sqrt{2}} k_{w_1} A B$$

Design Phase – Estimate Dimension

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Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

$$TRV = \frac{T}{V_{rotor}} = \frac{\pi}{\sqrt{2}} k_{w_1} AB$$

- Values from experience or literature

Motor Type	TRV [kN/m³]
Enclosed Motor - ferrite	5-15
Enclosed Motor - NdFeB, SmCo sintered	15-40
Enclosed Motor - NdFeB, SmCo bonded	10-20
Servomotors	15-50
Aerospace Machines	30-75
Liquid cooled machines	75-250

- Small remark: Since A~I and B~ϕ we can directly see T~Iϕ.

Design Phase – Estimate Dimension

Parameter	Value	Unit
DC supply voltage	450	V
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Servomotors	15-50
Aerospace Machines	30-75
Liquid cooled machines	75-250

$$TRV = \frac{T}{V_{rotor}} = \frac{\pi}{\sqrt{2}} k_{w_1} AB$$

We assume:

- stator/rotor ratio: 0.55
- Active length: max. 0.8*L
- Active Diameter: 10mm for cooling

- $TRV_{peak} = \frac{300*2^2}{\pi(0.55*0.26)^2*0.115*0.8} * 0.001 = 203 \frac{kN}{m^3}$
- $TRV_{cont} = \frac{100*2^2}{\pi(0.55*0.26)^2*0.115*0.8} * 0.001 = 68 \frac{kN}{m^3}$

⇒ Rare-Earth, liquid cooled.
⇒ Rotor diam 145mm, Stator diam 260mm, $L_{Fe} = 90mm$

Design Phase – Number of Poles

Parameter	Value	Unit
DC supply voltage	450	V
Max AC line current	900	A (peak)
Peak output power	235	kW
Peak torque	300	Nm
Base speed	6000	rpm
Max speed	15000	rpm
Continuous power at base speed	80	kW
Continuous torque at base speed	100	Nm
Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

- The fundamental frequency is given by

$$f = \frac{np}{60}$$

with n in rpm, p pole pairs.

Pole pairs (p)	Fundamental frequency (f) [Hz]
1	250
2	500
3	750
4	1000
5	1250
6	1500

- Inverter has to be able to modulate.

Design Phase – Number of Poles

Parameter	Value	Unit
DC supply voltage	450	V
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Base speed	6000	rpm
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Continuous torque at base speed	100	Nm
Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

- Advantages of higher pole number:
  - Higher TRV, due to reduced leakage
  - Lower dimension of stator back iron
  - Reduced end-winding dimensions
    → reduced copper loss
- Disadvantages of higher pole number:
  - Higher inverter losses
  - Higher magnet losses
  - Requires short pole pitch → concentrated windings.
  - Lower reluctance torque
- Manufacturability

⇒ Let‘s choose 4 pole pairs (p=4).

Design Phase – Number of Slots

Parameter	Value	Unit
DC supply voltage	450	V
Max AC line current	900	A (peak)
Peak output power	235	kW
Peak torque	300	Nm
Base speed	6000	rpm
Max speed	15000	rpm
Continuous power at base speed	80	kW
Continuous torque at base speed	100	Nm
Cooling System	Liquid	
Volume (L/W/H)	115 / 270 / 270	mm

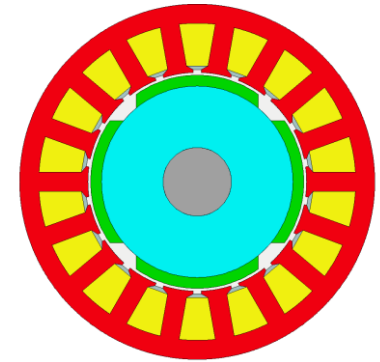
- The possible number of slots [s] can be chosen with respect to:
  - $s > p$
  - $\frac{s}{m * parallel\_paths} \in \mathbb{N}, m = phases$
  - $\frac{p}{parallel\_paths} = 2k,\ k \in \mathbb{N}$
  - $\frac{s}{m * \gcd(s,p)} \in \mathbb{N}$

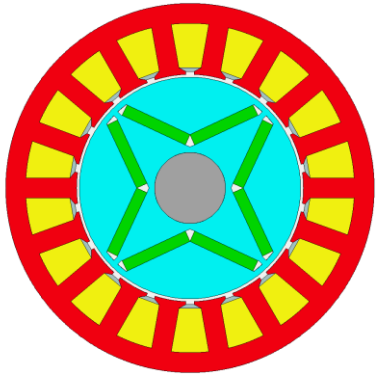
- With p=4, we can choose:

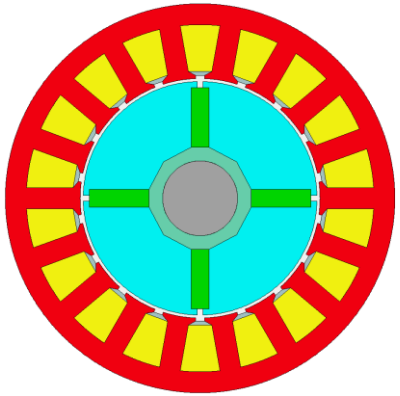
$$s \in \{12,24,36,48,72,84 \dots\}$$

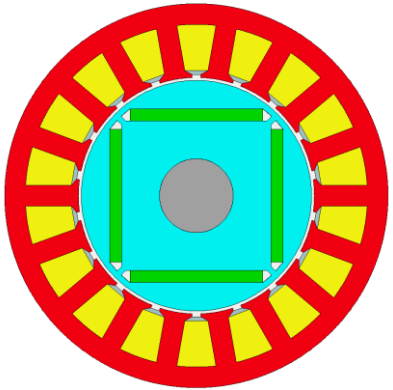
⇒ We choose s=48, based on the circumference at the airgap (~450mm), and cooling properties.

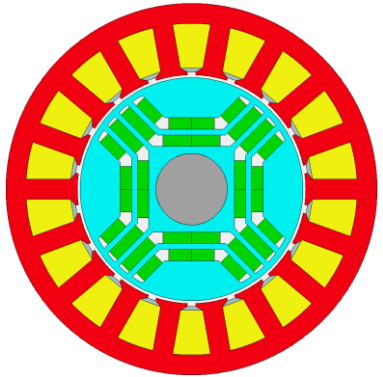
Design Phase – Rotor









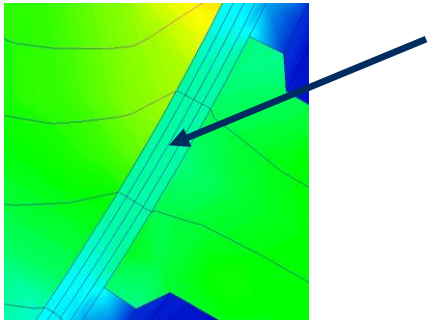


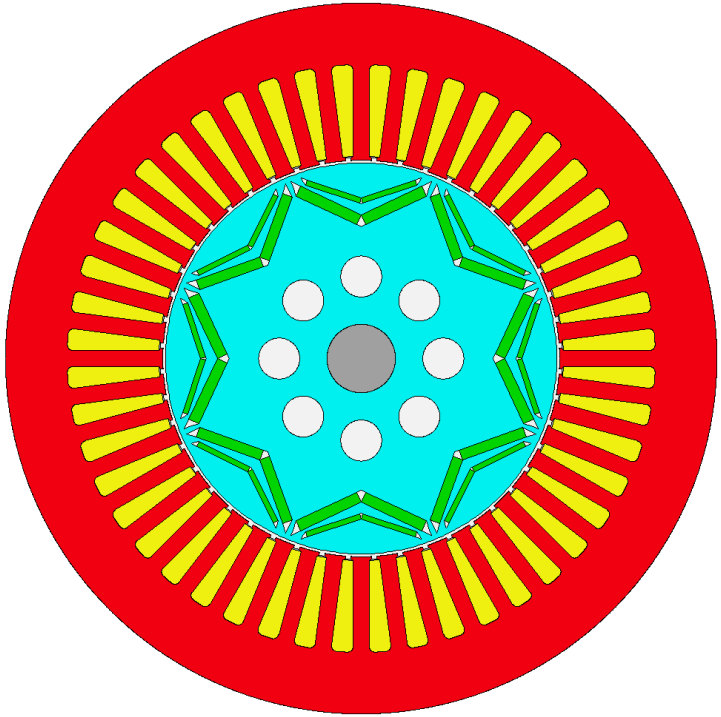
- Surface Mounted
- Interior / Tangential
- V-Shape
- U-Shape
- Spoke / Radial

Design Phase – Initial Design

Parameter	Value	Unit
Rotor Diam	145	mm
Stator Diam	260	mm
L_{Fe}	216	mm
Pole pairs	4	
Slots	48	
Rotor Topology	V-shape, 2layer	

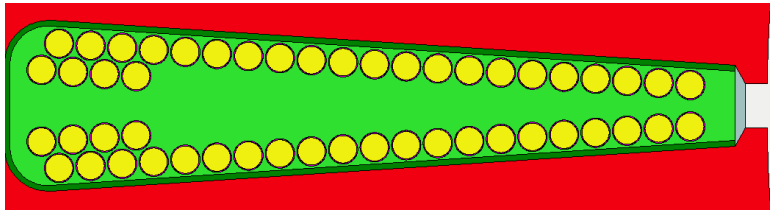
Choice of Magnet Volume: Based on FEA computation I=0A and airgap flux density of B=0.7-0.9T.

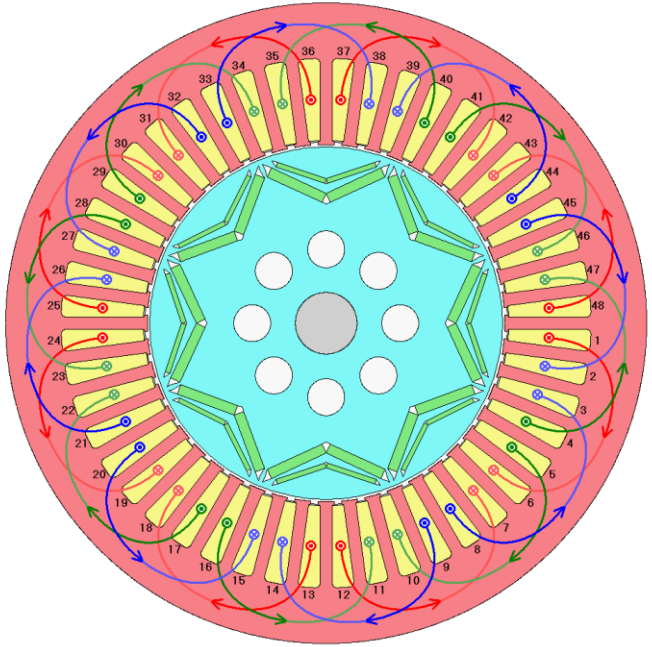




Design Phase – Initial Design

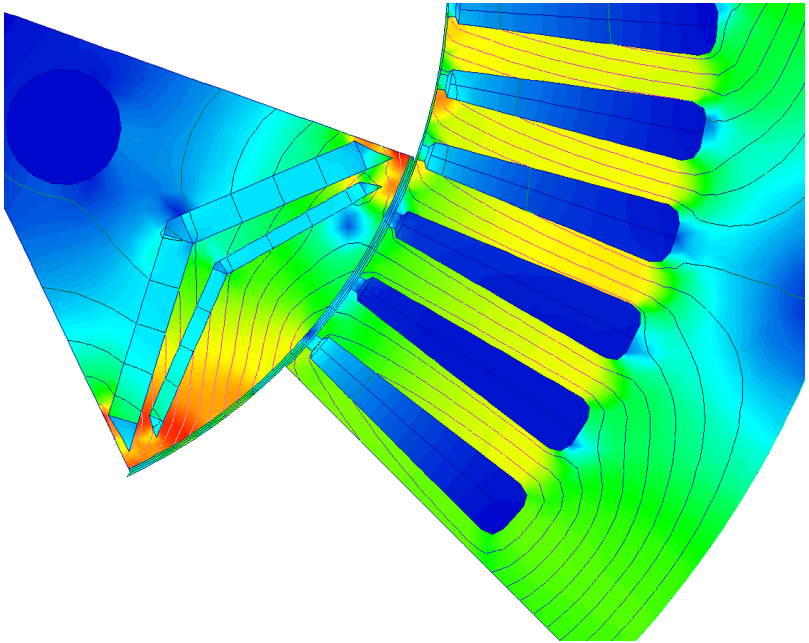
Parameter	Value
Phases	3
Connection Type	Star
Winding Pitch	5
Copper Slot Fill	0.4
Conductors/Strands[1]	5*10=50
Winding Diameter (insulation/copper)	1.35mm / 1.25mm

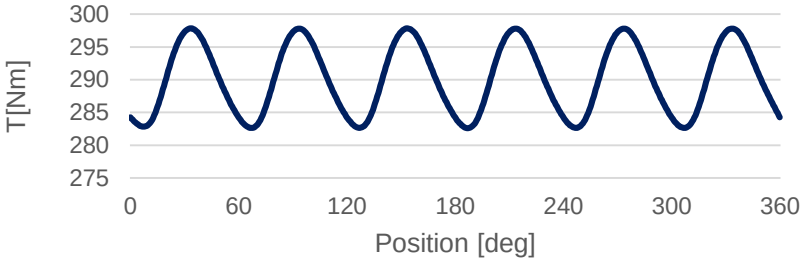




[1]Reason: manufacturability

Design Phase – Single Point n=6000rpm, I=900A





- Goal was 300Nm
  → Not too bad.
- Possible solution:
  - Axial length
  - Steeper V-shape
  - More Magnet Volume (1 Layer, thicker)
  - Ratio diameter Stator / Rotor

Design Phase – ECE Model

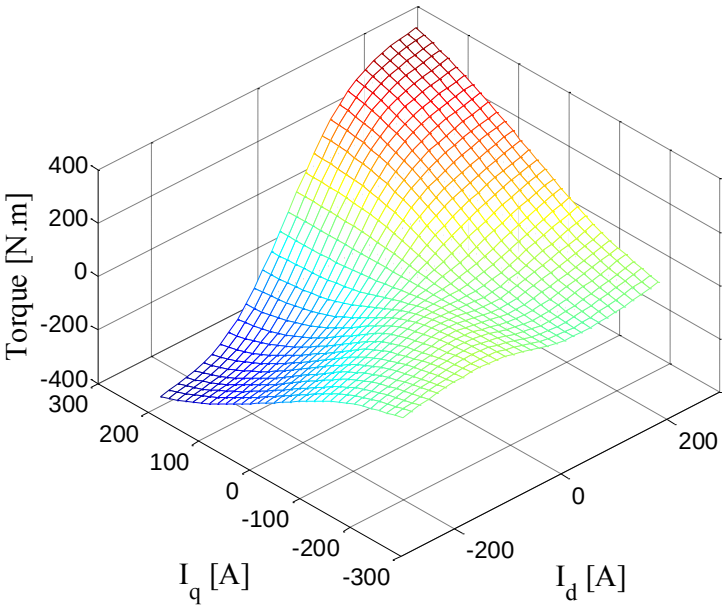
- Step 1: Model Order Reduction
  → ECE-model (equiv. circuit extraction)
  - Lookup-table for Torque, Flux Linkage, Voltage …
    T = T(id,iq)
  - Includes saturation (nonlinear)
  - Does not include transient effects, e.g. eddy current loss.

- Step 2: Control Strategy
  → Maximum Torque per Ampere (MTPA)

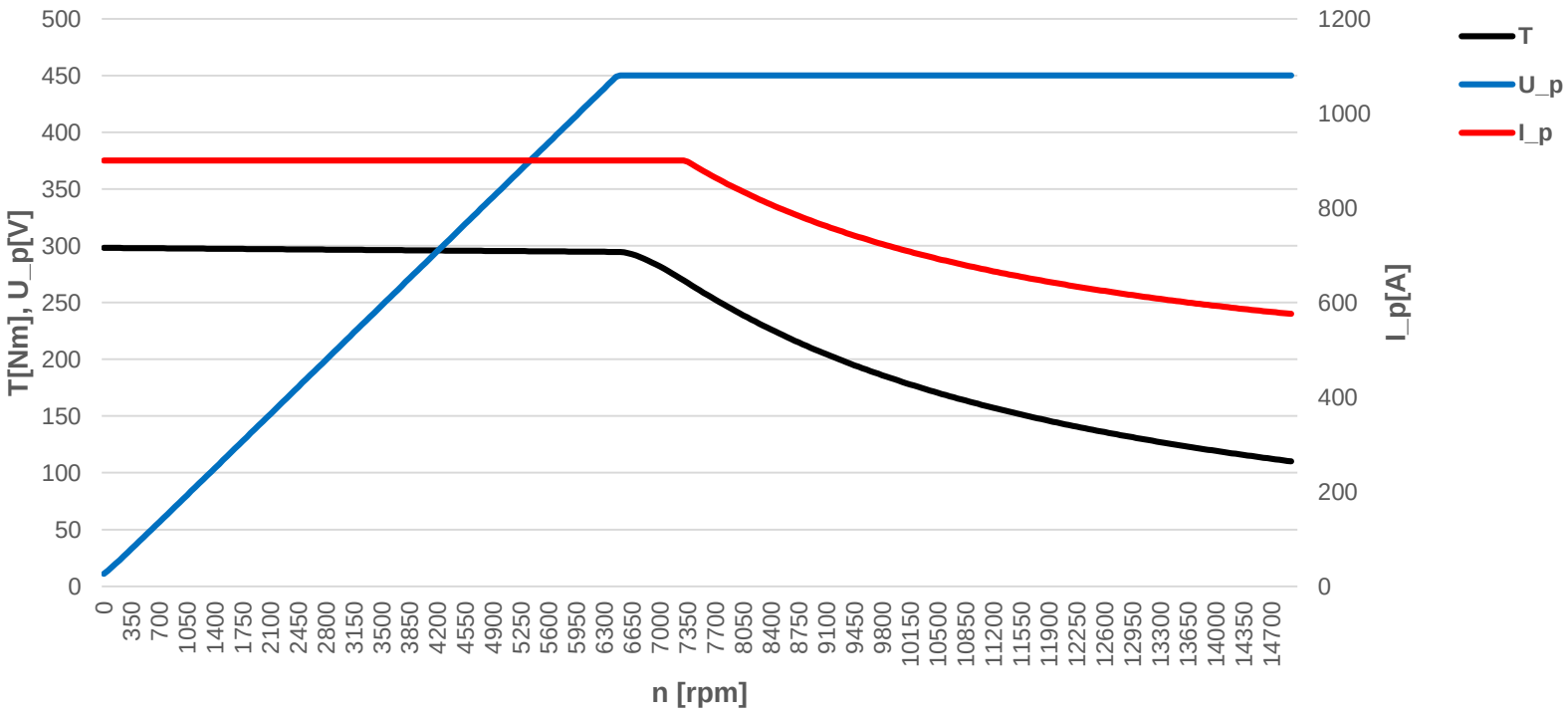
$$\min I_s = \sqrt{i_d^2 + i_q^2},$$

$$T_{shaft} - T_{demand} = 0$$

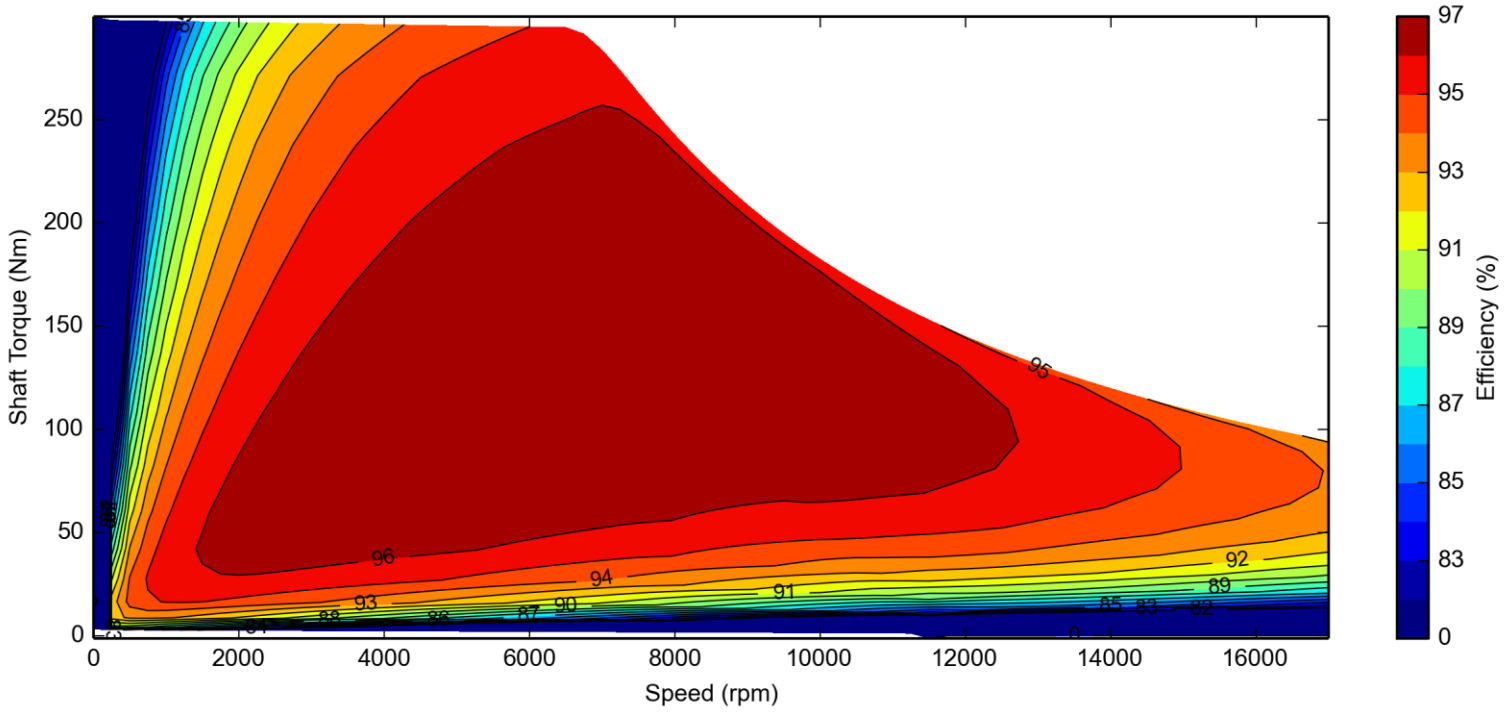
$$\sqrt{u_d^2 + u_q^2} \leq V_{lim}$$



Design Phase – Torque Curve



Design Phase – Efficiency Map

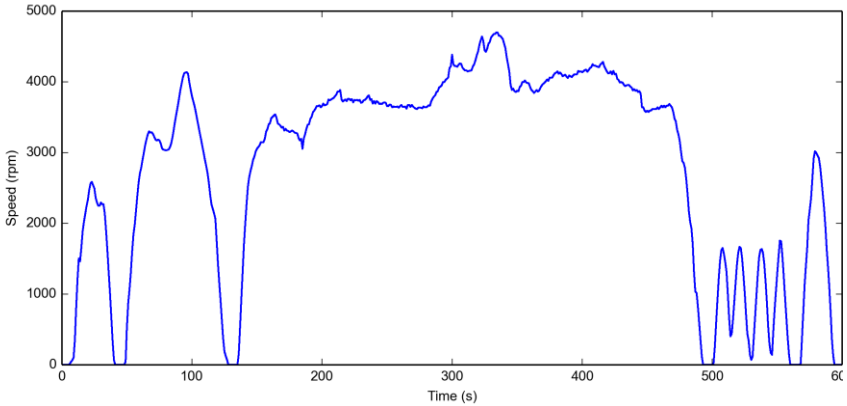


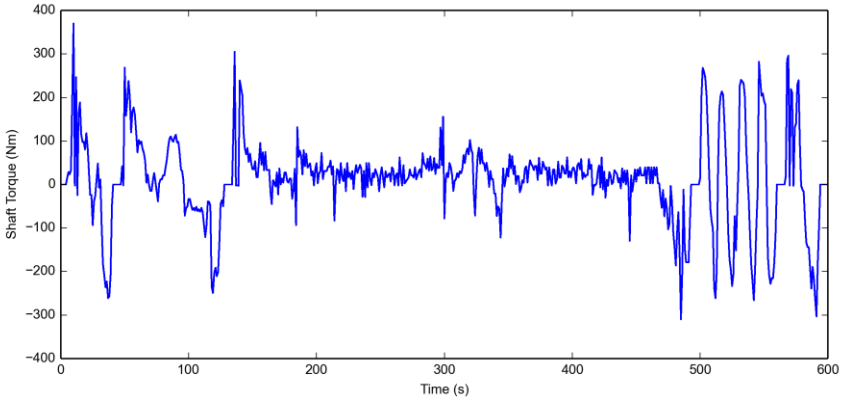
Design Phase – Drive Cycle

- US06 Cycle
  - 6 minutes with 600 Time/Speed Points
  - Torque due to load
- Full FEA ~1 day computation time
- ECE-Model → 10sec

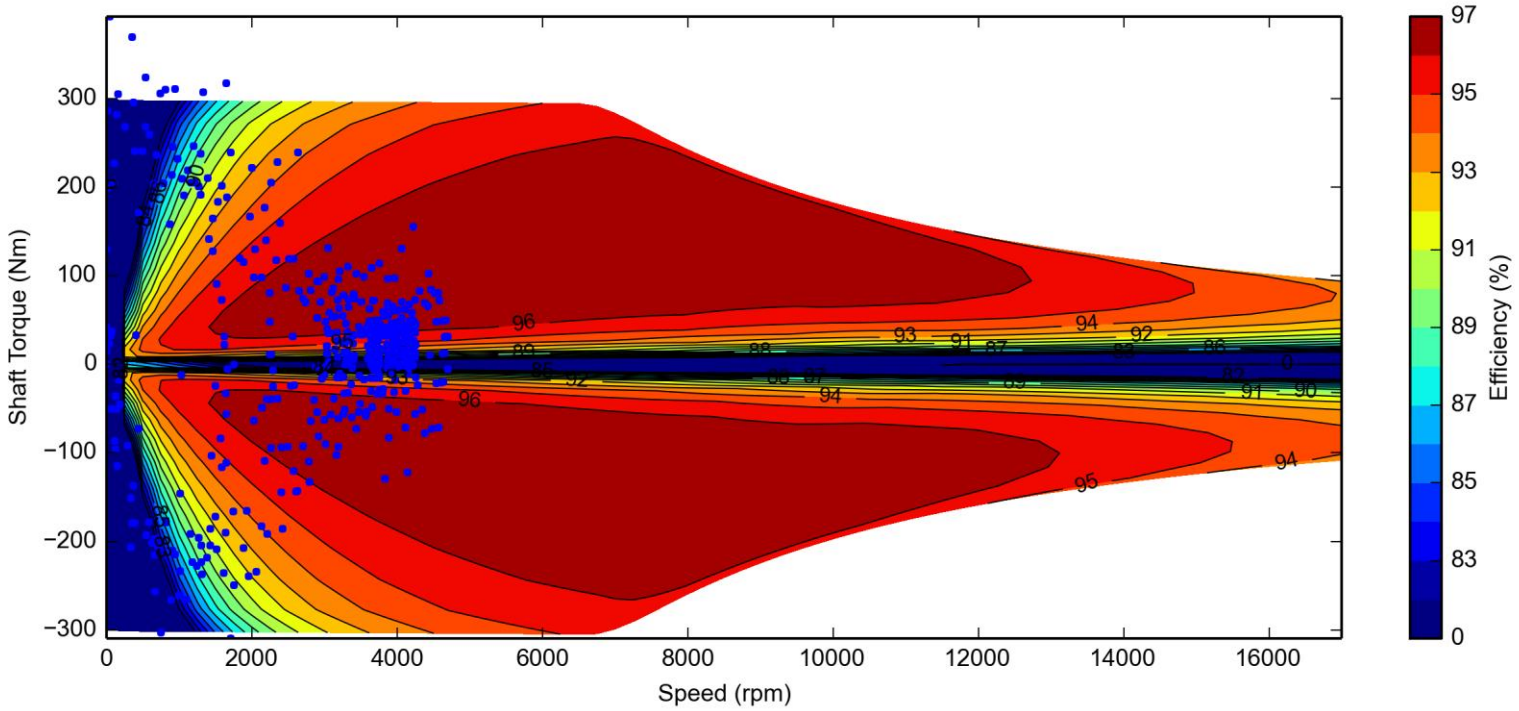
Vehicle Model:

Mass:	1360	Frontal Area (m²):	1.746	Wheel Radius (m):	0.3
Rolling Resistance Coefficient:	0.0054	Drag Coefficient:	0.26	Mass Correction Factor:	1.04
Air Density:	1.225	Final Drive Ratio:	4.113	Motoring Torque Ratio:	1
Generating Torque Ratio:	1	Max. Torque:	500	Max. Speed:	2E4





Design Phase – Efficiency Map and Cycle



Design Phase – Predefined Lumped Circuit

- Heat transfer modelled by resistance:
  - Conduction

$$R_{th} = \frac{L}{kA}$$

    - A: path area
    - L: length from geometry
    - k: thermal conductivity of material
  - Convection

$$R_{th} = \frac{1}{hA}$$

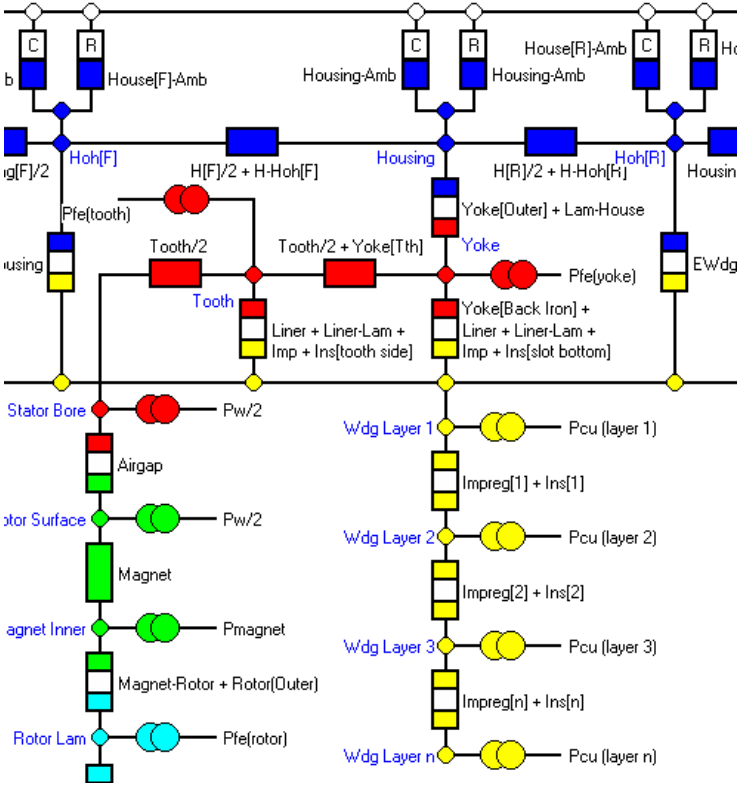
    - h: heat transfer coefficient. [Test data or CFD analysis]
  - Radiation

$$R_{th} = \frac{1}{hA} = \frac{(T_1 - T_0)}{\sigma \varepsilon F \left(T_1^4 - T_0^4\right) A}$$

    - ε: emissivity, F view factor
- Thermal capacity

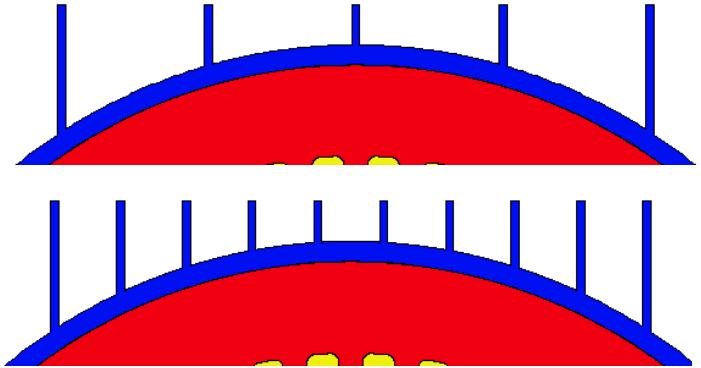
$$C = c_m m$$

- Flow models

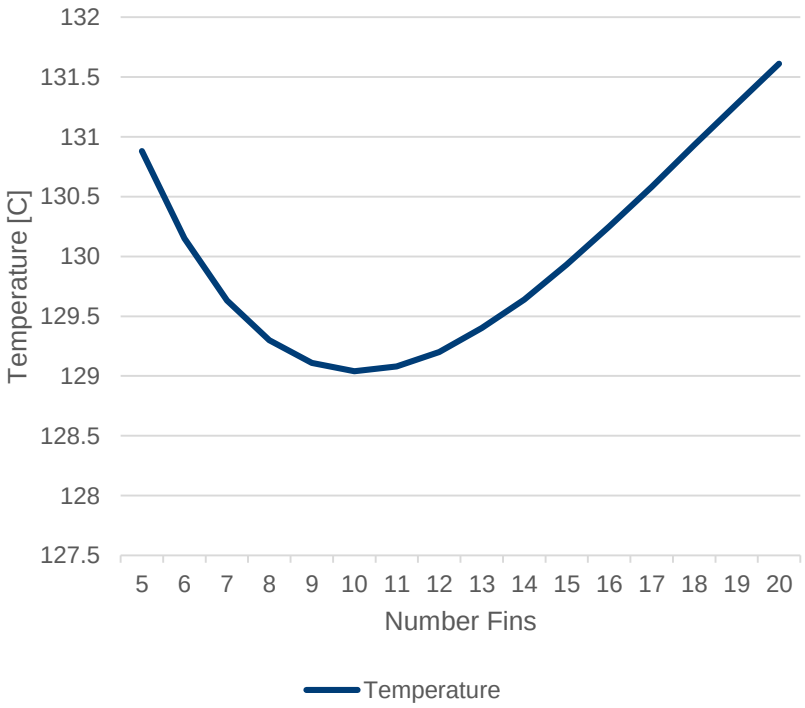


Design Phase – Example

- What is the optimal amount of fins, to minimize the average temperature of the winding?

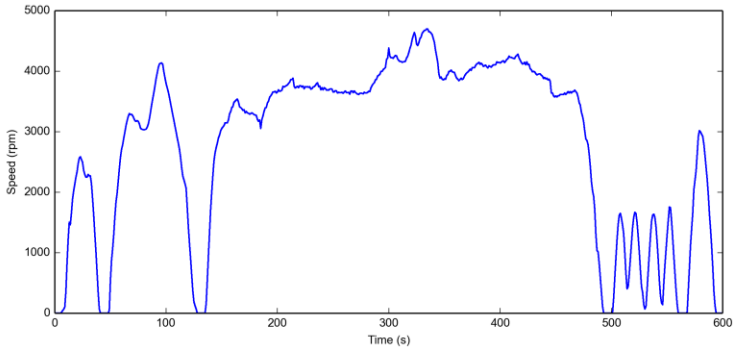


  - For this example: $P_{Cu} = 500W$, fixed width
- Lumped Circuit: <2s for each design → <1min computation time

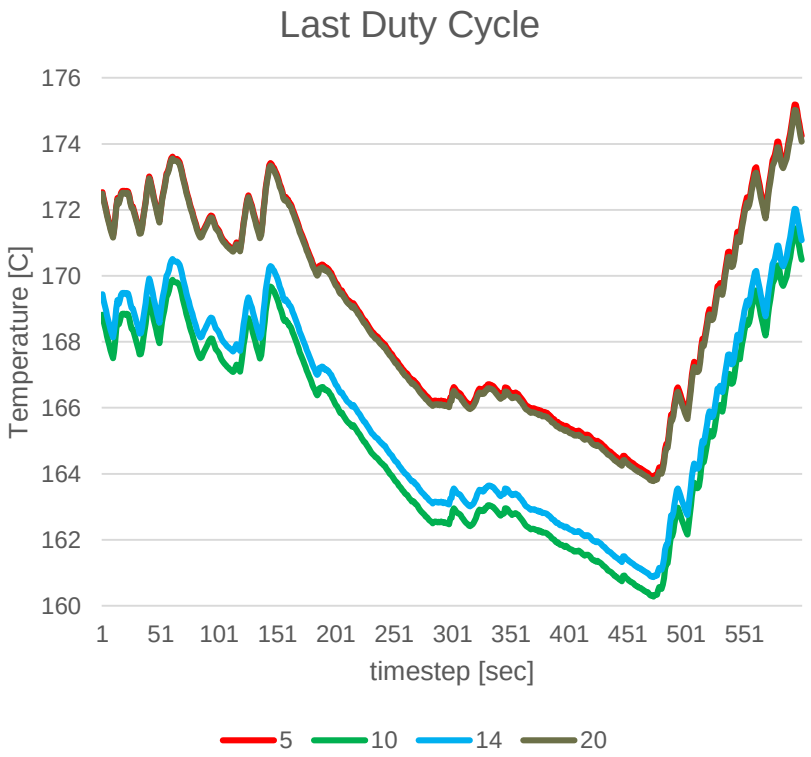


Design Phase – Example transient

- What is the optimal amount of fins, to minimize the average temperature of the winding – after 3 cycles US06?
  - 3 cycle = 30 min real time



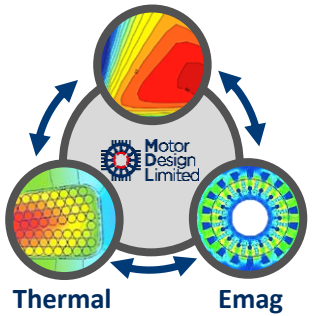
- Lumped Circuit: ~75s for each design→ <20min computation time



Analysis

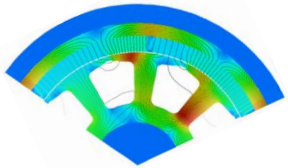
Design > Analysis > Operation

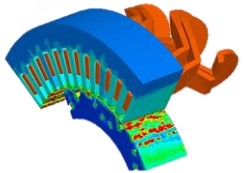
Design
Efficient Motor Design Toolkit



Motor-CAD
Motor Design Limited

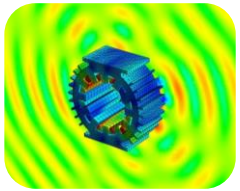
2D & 3D Analysis
Advanced Magnetics Modelling





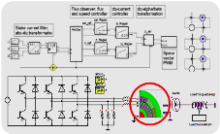
Maxwell 2D & 3D
ANSYS

Coupled Analysis
NVH, Cooling, ...



Mechanical &CFD
ANSYS

System Validation
Control logic, software



Motor Design Limited — Concept Design

System Validation

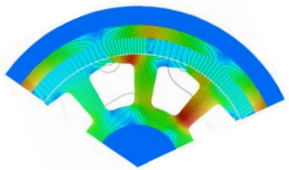
3D Physical Validation

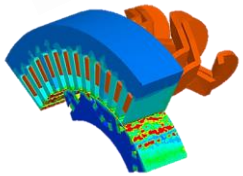
Twin Builder
ANSYS

Analysis

2D & 3D Analysis

Advanced Magnetics Modelling



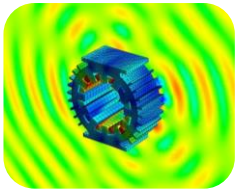


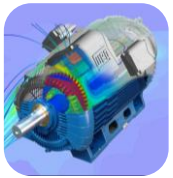
Maxwell 2D & 3D

ANSYS

Coupled Analysis

NVH, Cooling, ...





Mechanical &CFD

ANSYS

Objectives

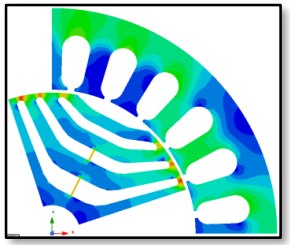
- 3D Electromagnetic Effects
- Coupled Analysis:
  - Thermal
  - Structural
  - CFD
  - Power Electronics and System
  - Acoustics / NVH
- Generate deeper physical understanding

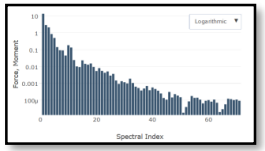
Requirements

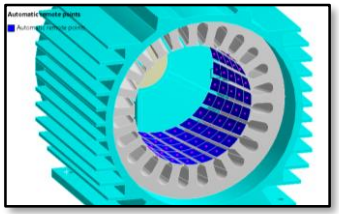
- Very versatile and high-end simulation tools
- Easy coupling of all physical domains
- Sensitivity and robustness analysis over different tools and many parameters
- Workflow automation and file data handling

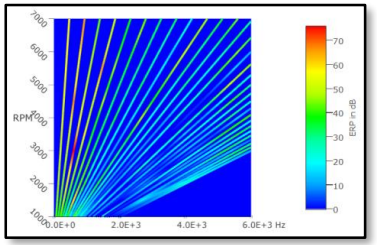
CADFEM ANSYS Extension - Electric Drive Acoustics inside ANSYS

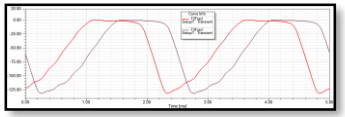
Electro-magnetic Analysis → **Excitation Loads (FFT)** → **Harmonic Vibration Analysis** → **Oscillation, ERP, Waterfall Plot**









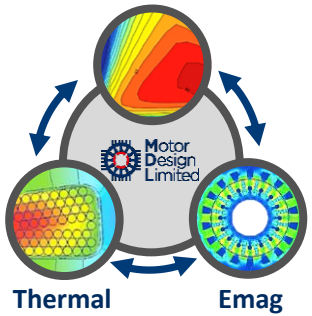


ANSYS GUI Enhancement

System

Design > Analysis > Operation

Design
Efficient Motor Design Toolkit



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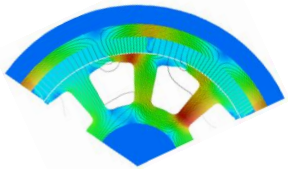
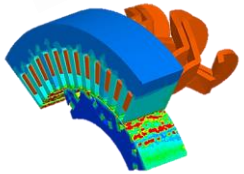
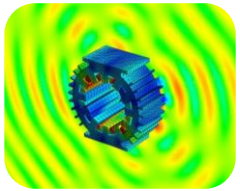
2D & 3D Analysis
Advanced Magnetics Modelling





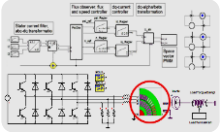
Maxwell 2D & 3D
ANSYS

Coupled Analysis
NVH, Cooling, ...



Mechanical &CFD
ANSYS

System Validation
Control logic, software



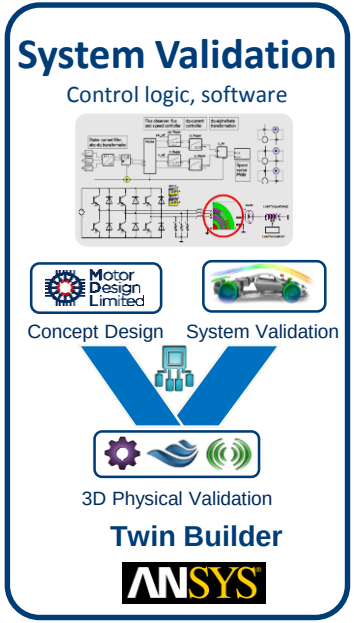
Motor Design Limited — Concept Design

System Validation

3D Physical Validation

Twin Builder
ANSYS

System



Objectives

- Analysis and optimization of a system without extensive coupled FEM simulation
- Implementation of third party behavior models
- Fast evaluation of performance maps and duty circles on a system level

Requirements

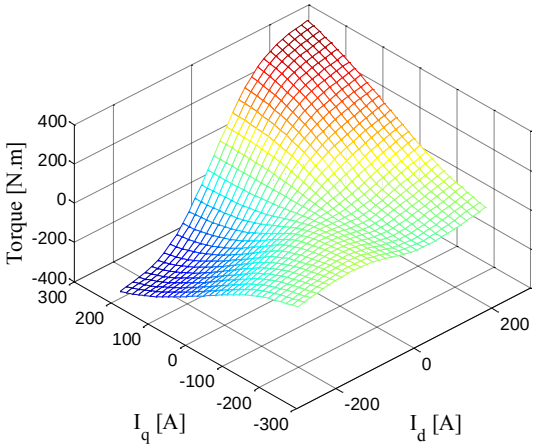
- Behavior Models generated by previously used tools
- Platform / System simulator

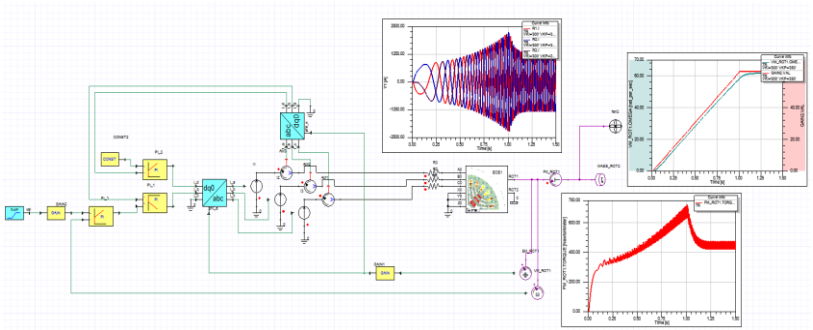
System Model

- Model Order Reduction
  → ECE-model (equiv. circuit extraction)
  - Lookup-table for Torque, Flux Linkage, Voltage …
    T = T(id,iq)
  - Includes saturation (nonlinear)
  - Does not include transient effects, e.g. eddy current loss.

- Combination of ECE Motormodel with:
  - Inverter
  - Load, Car Model
  - Thermal Behavior Model
  - Acoustic Model

- Standardized Interface: FMI / FMU





Summary / Outlook

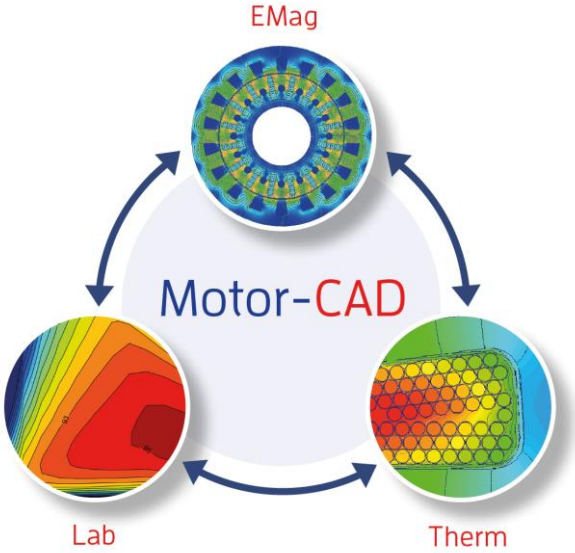
Several ideas on simulation based motor design have been presented.

First we derived an initial design based on analytical formulas, then electromagnetic FEM computations improved the model.

Thermal behavior can be simulated very fast using a lumped circuit simulation.

With the ECE Model and the lumped circuit model efficiency maps and duty cycles can be computed very quickly.

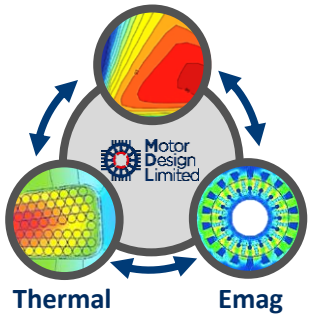
- Additional strategies are based on optimizers including:
  - Efficiency Map
  - Electromagnetic Duty Cycle
  - Continuous Torque Map
  - Thermal Duty Cycle
  - Cogging Torque
  - Torque Ripple



From the Idea to the Operation

Design > Analysis > Operation

Design
Efficient Motor Design Toolkit



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2D & 3D Analysis
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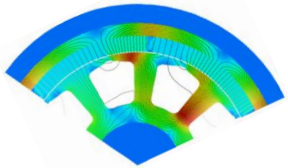

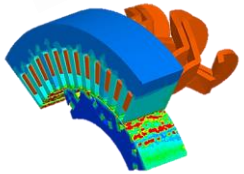

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ANSYS

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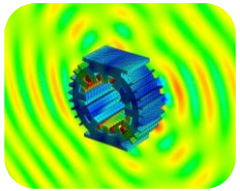
NVH, Cooling, ...



Mechanical &CFD
ANSYS

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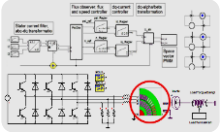

Motor Design Limited — Concept Design

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3D Physical Validation

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