

Multi-Physics Optimization Strategies for Electric Motors

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Who is LCM

- ▶ R&D service provider
- ▶ Transfer of research results into industrial application
- ▶ Integration of technologies
- ▶ Entire innovation journey

4 Business Areas

Drives



Mechanics & Control



Sensors & Communication



Emerging Technologies



Facts

2001
FOUNDING YEAR

120
EMPLOYEES

300
CUSTOMER

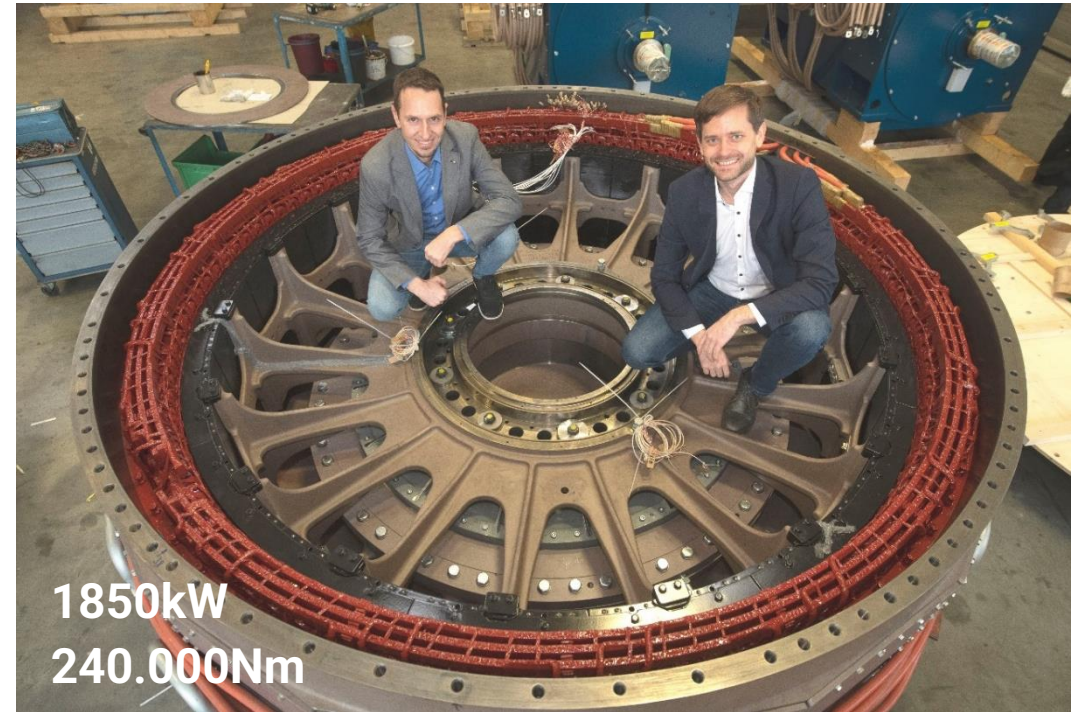
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BUSINESS AREAS

SCIENCE BECOMES REALITY

Science becomes reality

Design of electric machines

Optimized drives: From a few watts to mega watts



Introduction

Permanent magnet motor for ship propulsion

- Vessel with battery and hybrid technology.
 - At least 30% reduction of greenhouse gases.
 - Prepared for future installation of zero emission hydrogen technology.
 - Fuel savings: **400.000** liter diesel per vessel and year.
-
- Power: **1850 kW**
 - Torque: **240.000 Nm**



Introduction

Permanent magnet generator



- Enables the cost-effective modernization of small hydroelectric power plants.
- Optimized for each individual hydroelectric power plant.
- No expensive inverters required.
- Permanent magnet generator directly connected to the grid.
- Lot size one (first design must fit).

Introduction

Example of a motor for racing karts

- Acceleration 0-100 km/h within <3.5 sec
- Maximum speed 145 km/h
- Peak power 27 kW



Introduction

High-performance compressor

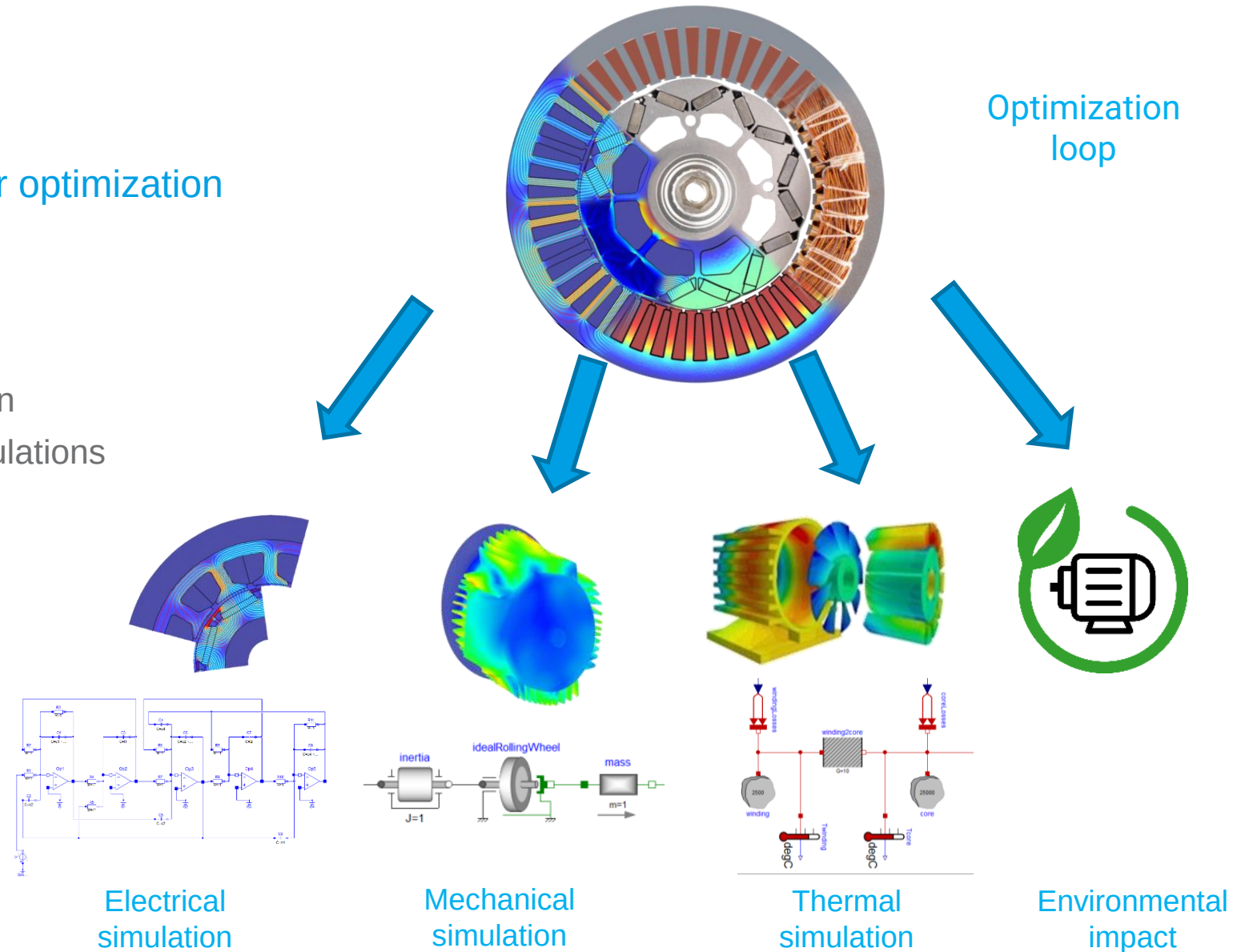
- For electric fuel cells
- Power: 22 kW
- Speed: 150.000 rpm
- Pressure rise: 2 bar



Electrical Drive Design

Efficient multi-physics simulations for optimization

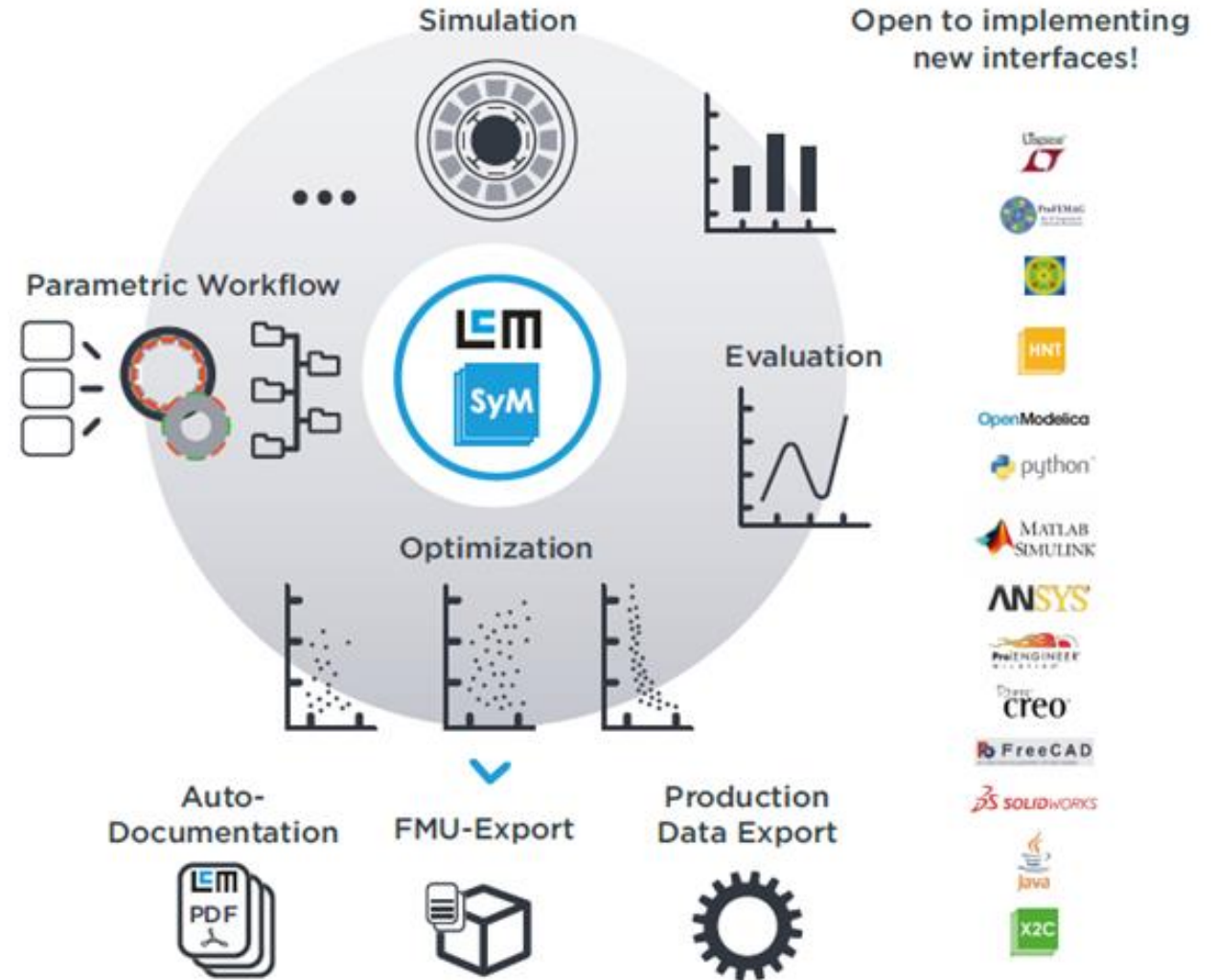
- Different tools are required
 - CAD-tool for 3D-model
 - FE-solver for electromagnetic solution
 - Time-stepping solver for system simulations
 - Optimization tool
- Frequent situation
 - Different design tools
 - Different data types
 - Different interfaces



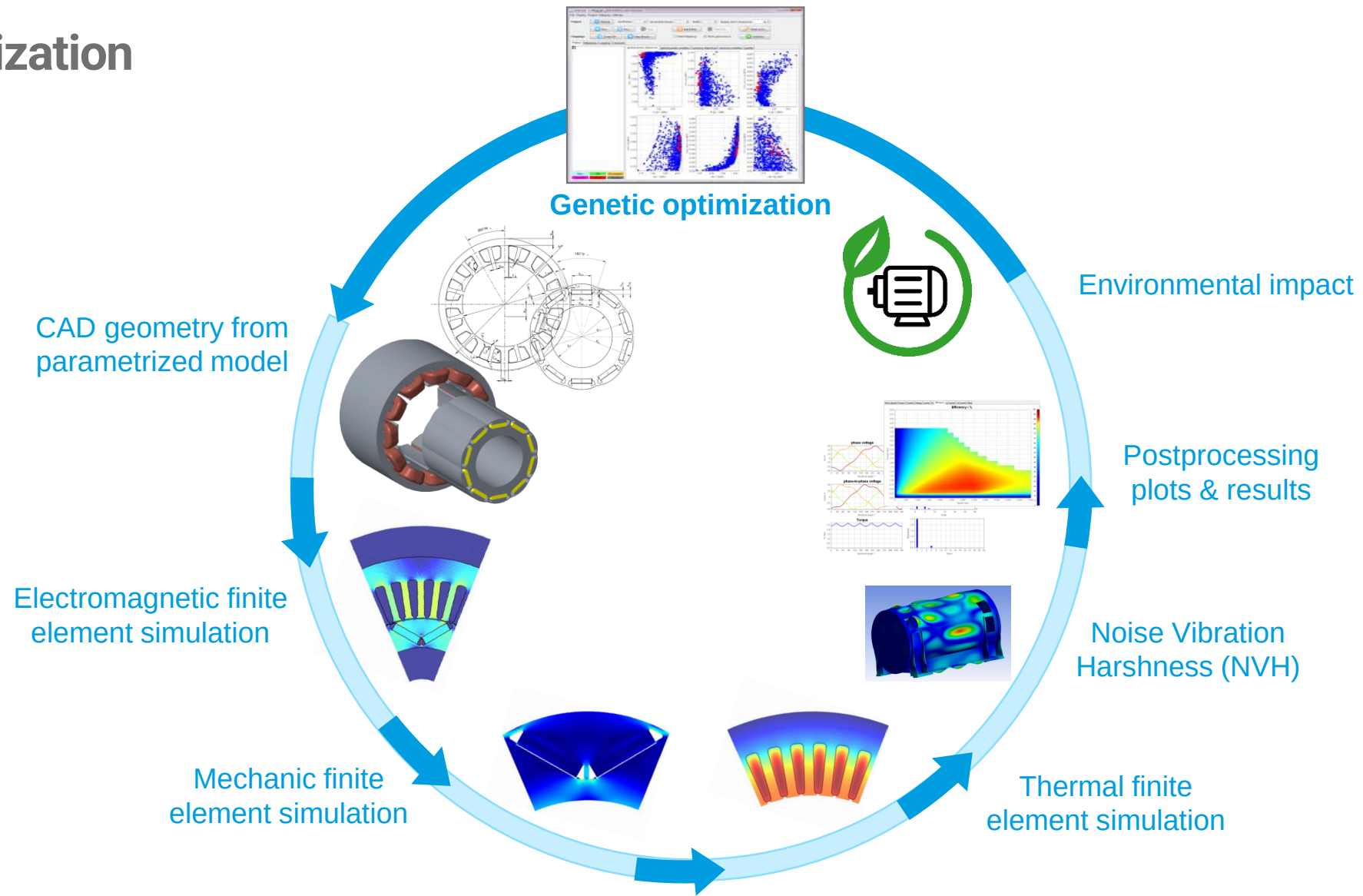
SyMSpace Model Setup

Setup of simulation workflow

- Create complex workflows from Components
- Execute & optimize workflows
- Automated documentation
- Model and data export



Optimization

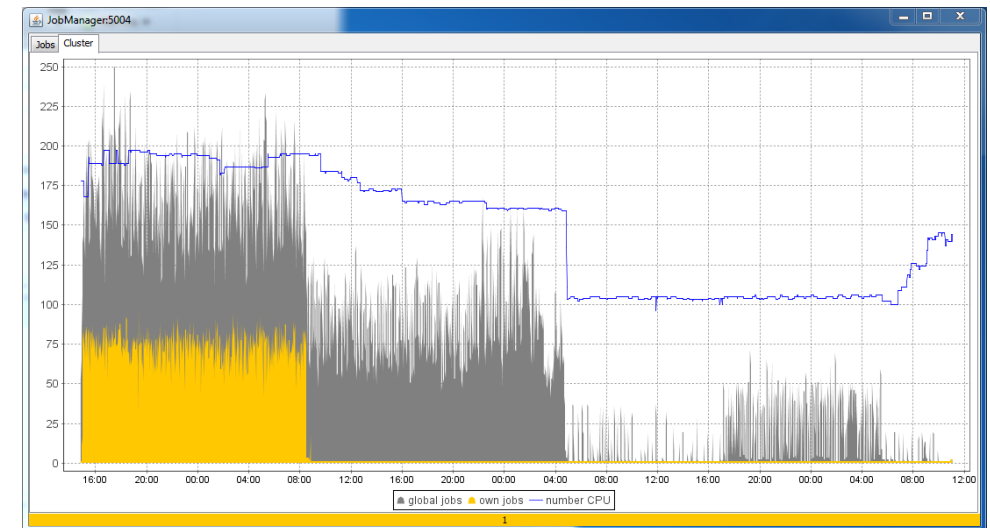


Cluster Computing with HTCCondor



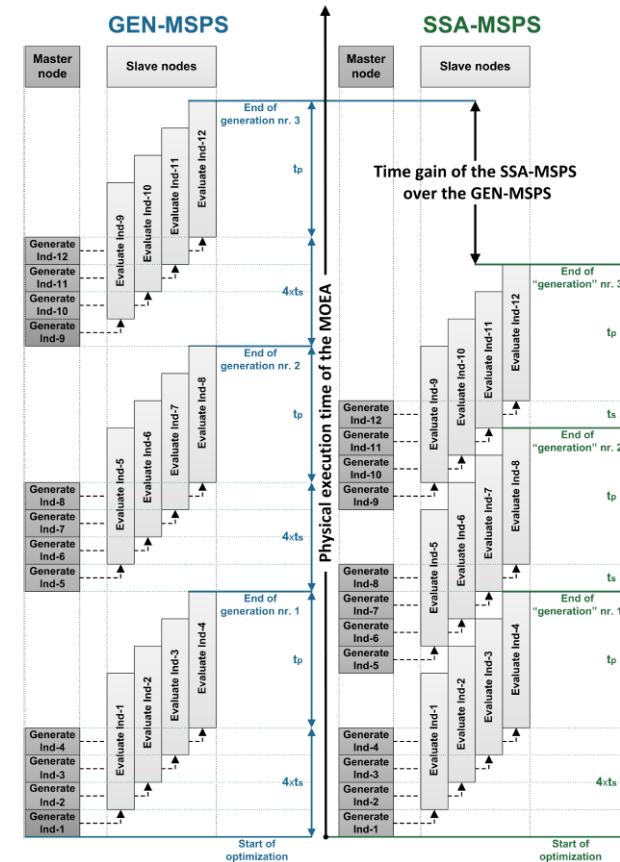
High throughput computing

- What is HTCCondor?
 - High-throughput computing software framework
 - Developed by the University of Wisconsin-Madison
- Features of HTCCondor
 - Job queuing and scheduling
 - Priority/preemption for high-priority users
 - Fault-tolerant
- Benefits of HTCCondor in Cluster Computing
 - Allows for effective use of idle computing resources
 - Provides robust job management and monitoring
 - Supports heterogeneous collection of computing resources



Optimization Algorithm

- **Grid**
Calculates any possible parameter combination.
Requires huge amount of calculation power
- **Generational NSGA-II**
(Non-dominated Sorting Genetic Algorithm II)
Steady State **Async NSGA-II**
- **Generational SPEA2**
(Strength Pareto Evolutionary Algorithm 2)
Steady State **Async SPEA2**
- **DECMO**
(Differential Evolution-based, Coevolutionary
Multi-objective Optimization algorithm)



Generation based vs. steady state algorithm

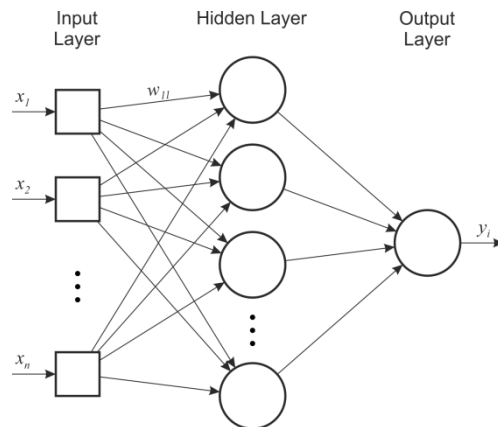
Optimization Algorithm

Hybrid Optimization Method

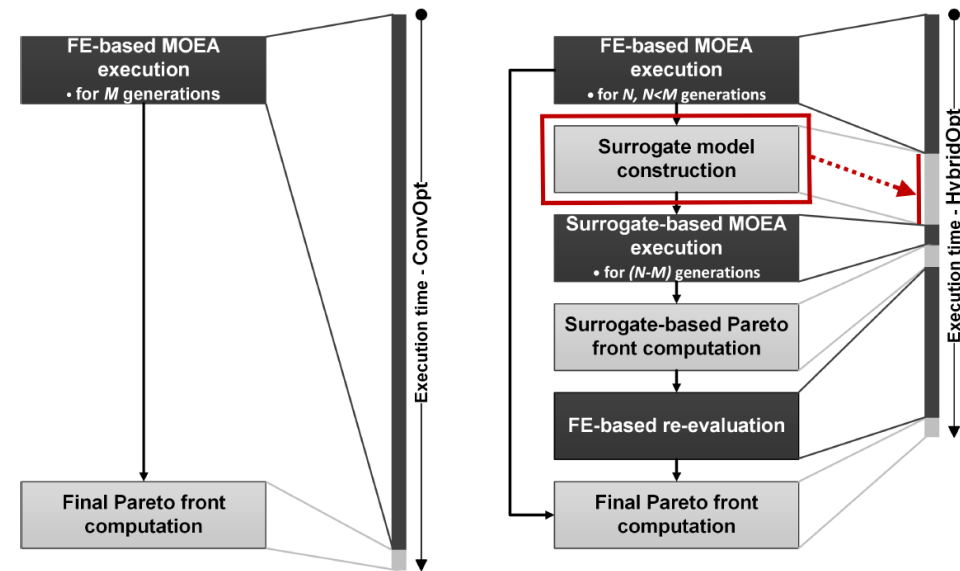
For complex simulations, a surrogate model based on artificial neural networks (ANNs) is created.

This surrogate model is created during the optimization fully automatic on-the-fly.

Optimization speed can significantly be improved.



Surrogate model

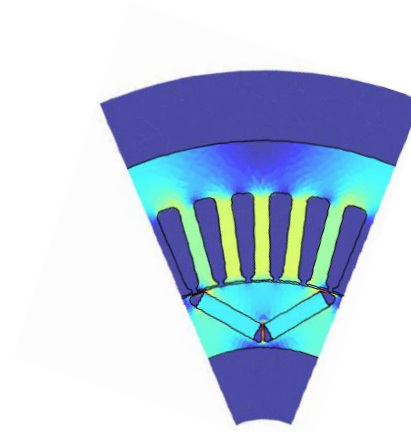


Optimization based on surrogate model

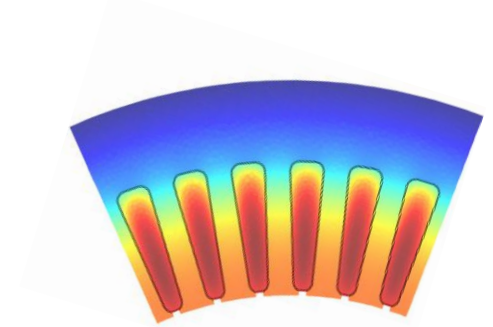
Multi-Physics Simulation

Efficient simulation models for optimization

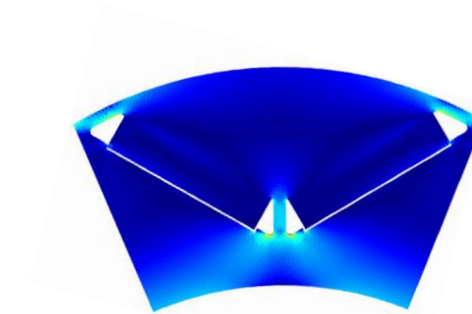
- Efficient simulation models are required for optimization
 - Simulation time should be a few minutes only.
- Simulation models for motor optimization
 - Magnetic simulation including additional losses due to PWM harmonics
 - Transient voltage effects
 - Thermal simulation:
 - 2D heat conduction problem solved with finite element method (FEA)
 - Lumped parameter models
 - Rotor strength simulation with linear and elastoplastic material.
 - Noise vibration harshness (NVH) simulation.



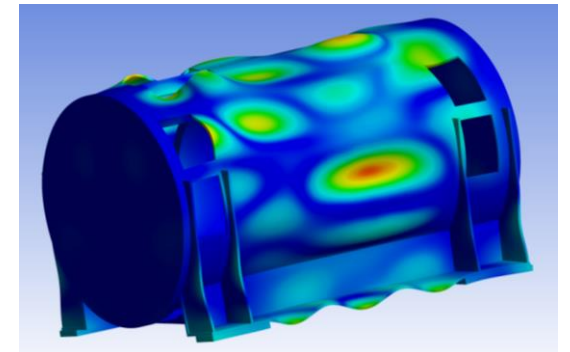
Magnetic simulation



Thermal simulation



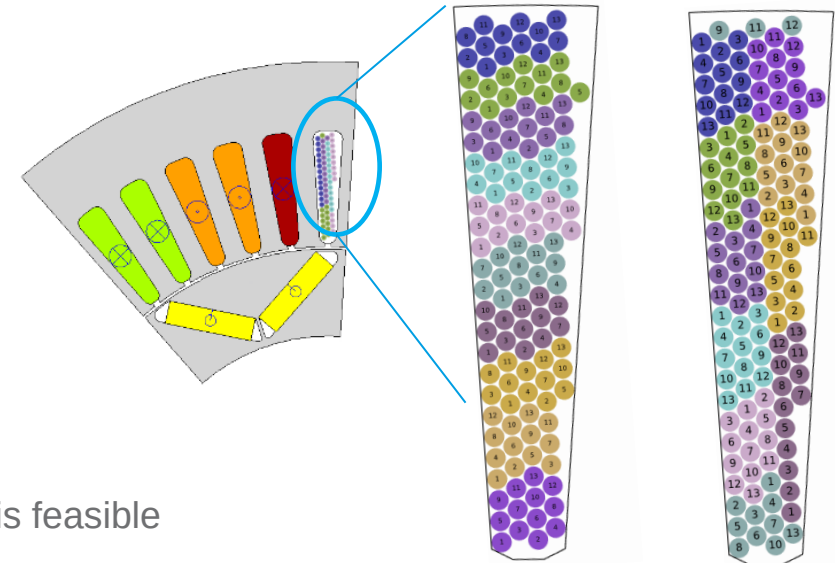
Strength simulation



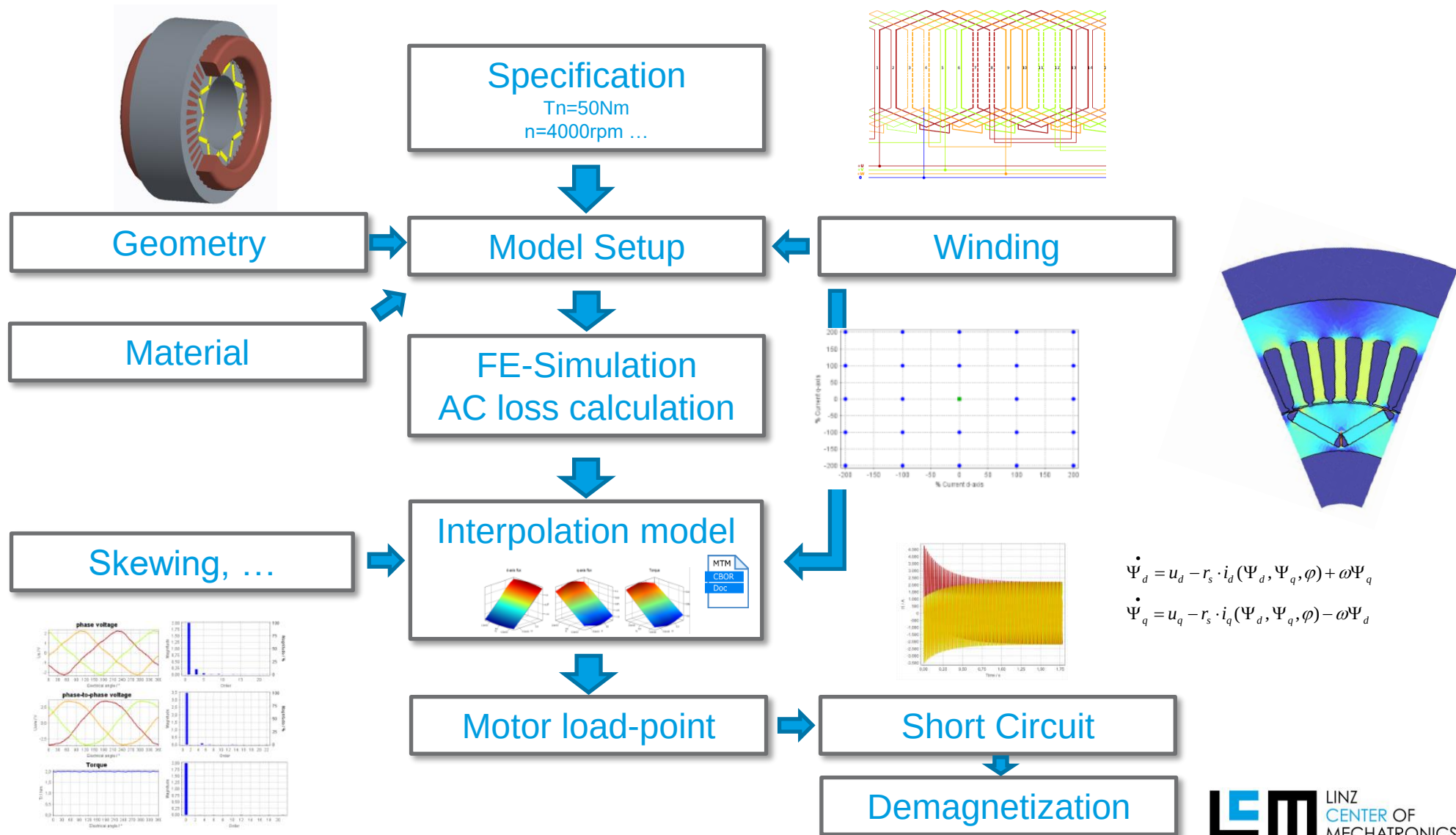
NVH simulation

Magnetic Simulation

- Generic geometry model including
 - Wire arrangement in the slot.
 - Parametric models for round wire and hair pin wires are available.
- Magnetostatic FEA for different dq-currents
 - Rotor is rotated in discrete steps.
- Time harmonic FEA for different frequencies
 - Linearized model with frozen permeability.
- Flux interpolation model based on radial base functions
 - Fast post-processing calculation of load points and torque-speed maps is feasible without FEA.
- Analytical calculation of PWM losses based on time harmonic results



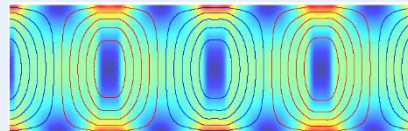
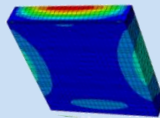
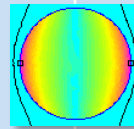
Simulation Workflow for Permanent Magnet Machines



Overview of Additional Losses

Efficient simulation method

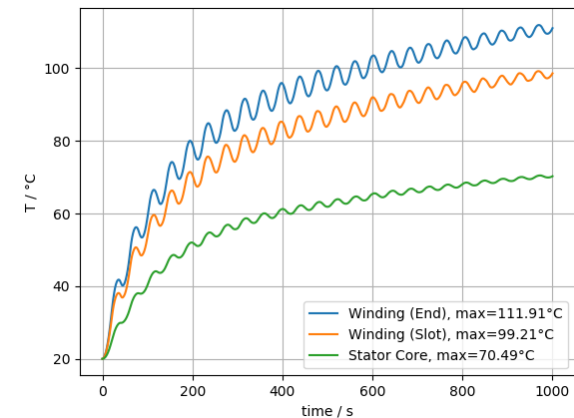
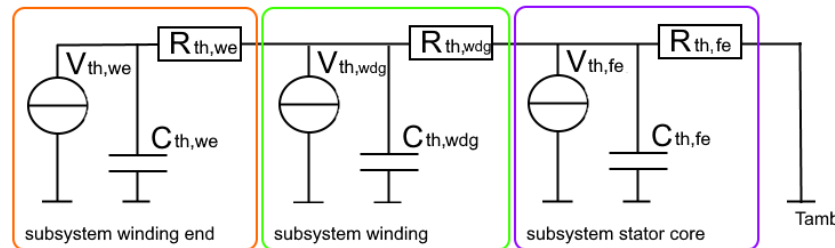
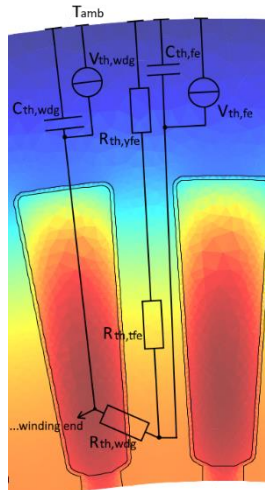
Based on magnetostatic FEM $f \leq f_{el} \frac{n_{Steps}}{2}$	Based on time harmonic FEA with frozen permeability
Proximity and skin losses	Proximity and skin losses
Losses in parallel wires	
Magnet losses (slot harmonics, current distortion)	Magnetic losses due to PWM
Losses in rotating and stationary thin-walled sleeves	
	Losses in solid materials



Thermal Simulation

Steady-state and transient simulation

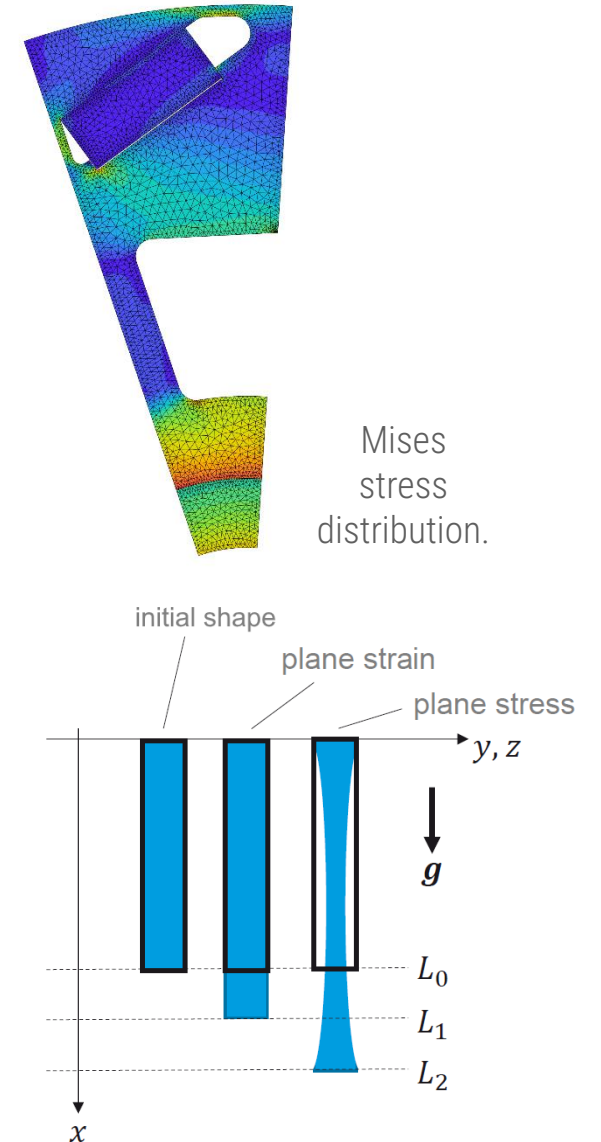
- Heat conduction problem is solved in 2D with finite element method (FEA)
→ steady-state temperature distribution.
- Parameters for equivalent thermal circuit are calculated from FEA solution.
- Thermal elements to consider 3D effects (end winding, ...) are added.
- Transient thermal simulation is based on equivalent thermal circuit.



Mechanical Strength Analysis

Rotor stress under centrifugal load

- Simulates a rotor under centrifugal load in 2D.
- Evaluation stress, strain, plastic deformation and transmittable torque.
- Linear and elastoplastic materials can be used.
- Various forms of mechanical contact:
 - Force / interference fit,
 - Contact with friction, ...
- Plane **stress** (e.g., for laminated steel stacks) or plane **strain** model can be used.
- Analyses of
 - Mises stress in the rotor.
 - Equivalent plastic strain.
 - Maximum transmittable torque for each given force fit boundary condition.



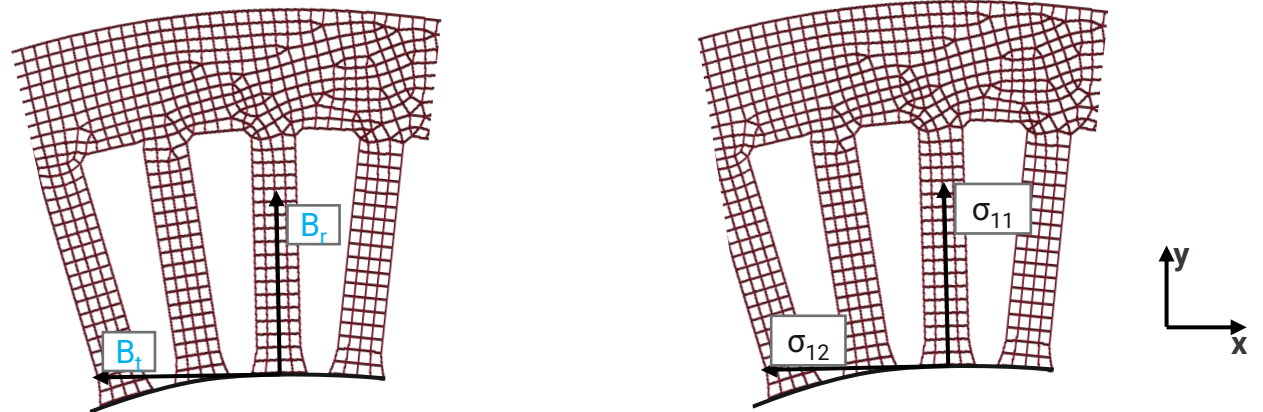
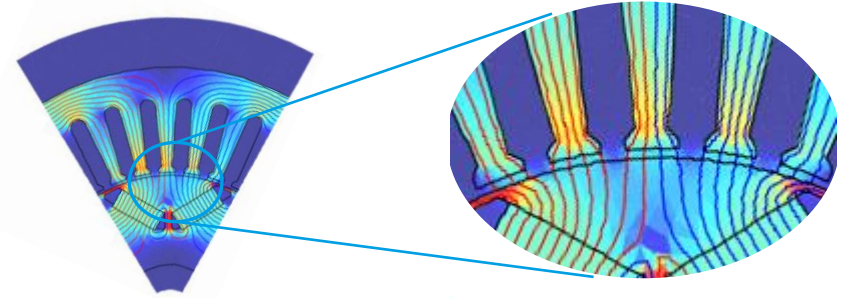
Noise Vibration Harshness (NVH) Simulation

Coupling of Electromagnetics and Mechanics

- Simulation of magnetic forces acting on the stator surface
 - Calculation of magnetic flux density in the air gap of the electrical machine
 - Surface stress is computed by Maxwell stress tensor

$$\bar{S} = \frac{1}{\mu_0} \begin{bmatrix} B_x^2 - B^2/2 & B_x B_y & B_x B_z \\ B_x B_y & B_y^2 - B^2/2 & B_y B_z \\ B_x B_z & B_y B_z & B_z^2 - B^2/2 \end{bmatrix} \quad B^2 = B_x^2 + B_y^2 + B_z^2$$

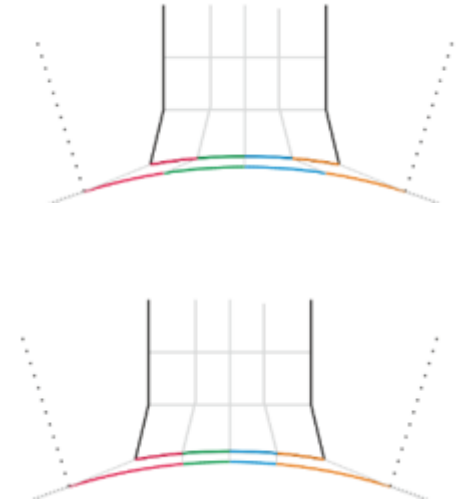
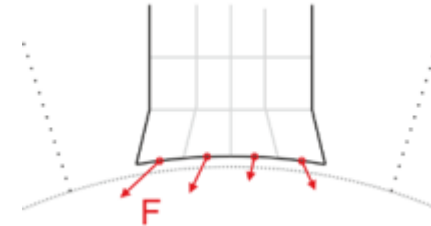
- Normal and tangential components of flux densities produce stress in normal and tangential directions on the rotor surface.



NVH Simulation

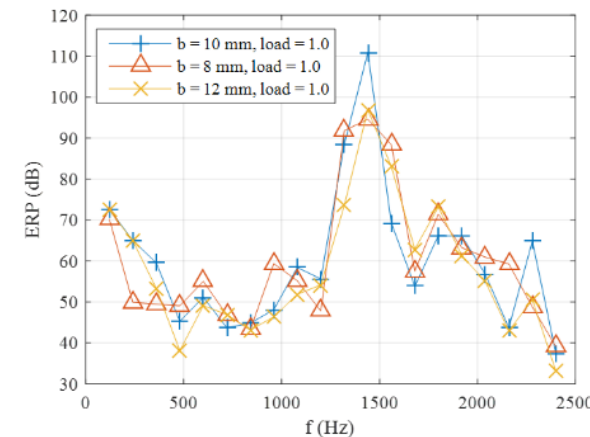
Mapping of magnetic forces onto stator teeth

- Methods of mapping magnetic forces onto stator teeth
 - One single force and torque per tooth.
 - Forces in radial and tangential directions per mechanical mesh element on stator surface.
 - The magnetic stress in the area of the slot opening must be considered.

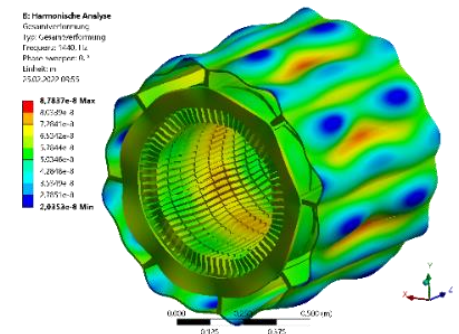


Integration methods

- Prediction of Noise Vibration Harshness (NVH)
 - Harmonic mechanical simulation for each excitation frequency.
 - Assessment of Equivalent Radiated Power (ERP) on the housing surface.

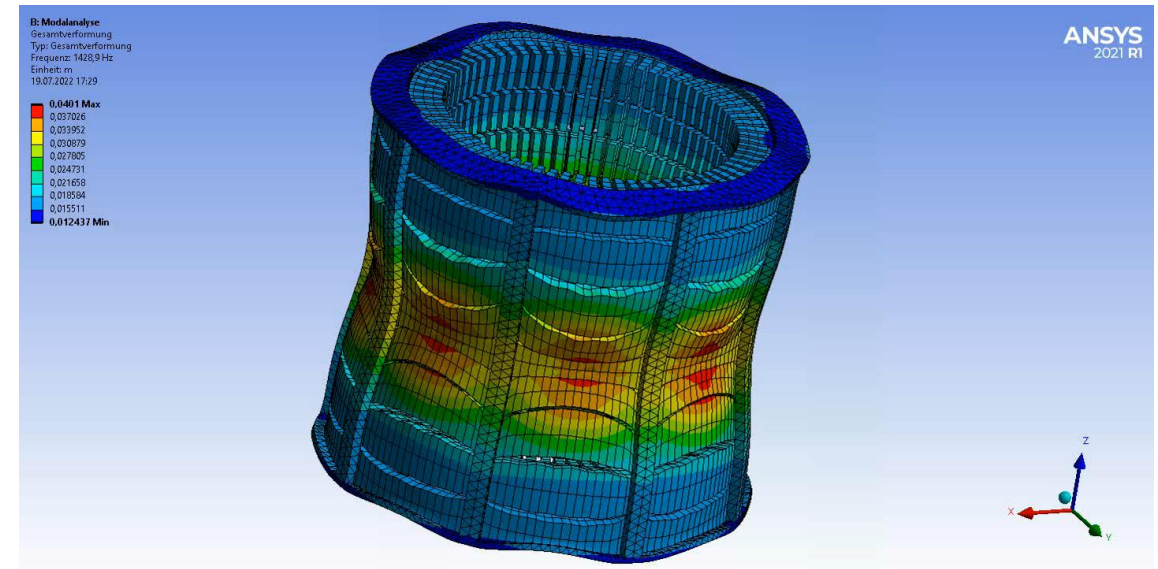
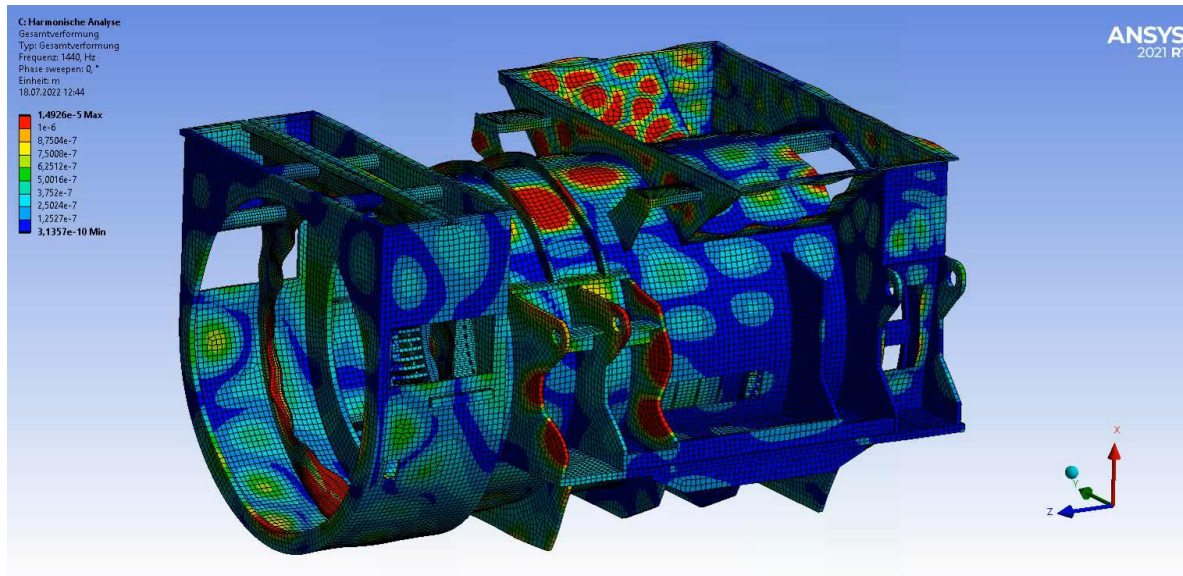


ERP as a function of excitation frequency.



NVH Simulation

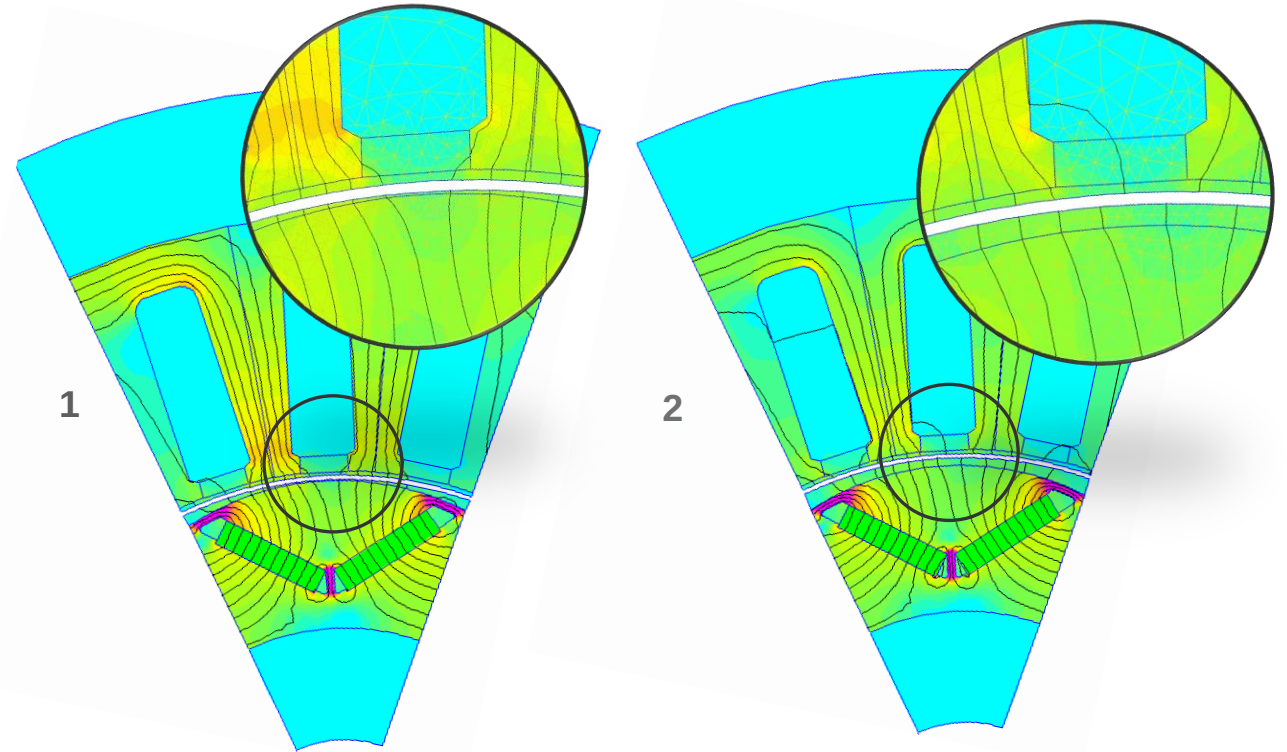
Examples



Force Calculation for Rotor / Stator Displacement

Simplified simulation method

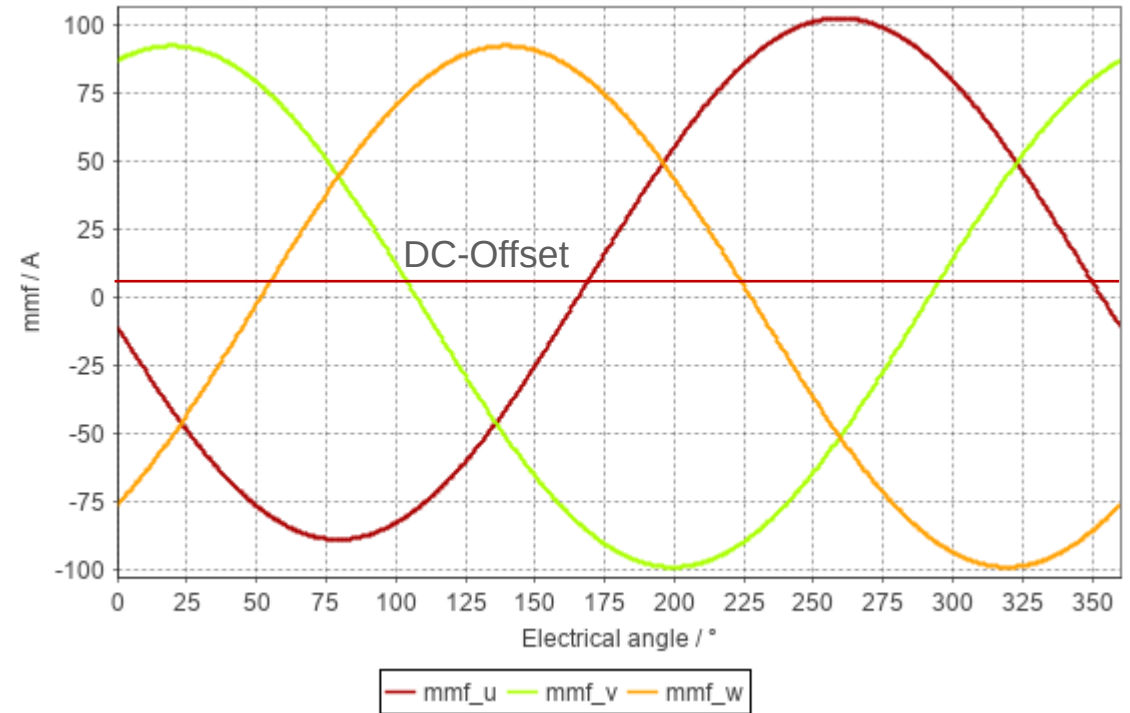
- Two additional FEMM simulations are performed for the sector:
 1. The rotor is shifted upward by the eccentricity to reduce the air gap.
 2. The rotor is moved downward by the eccentricity to increase the air gap.
- For a stator or rotor displacement, the flux density as a function of rotor position is interpolated between the increased air gap, the nominal air gap, and the decreased air gap.



Force Calculation with DC Current Component

Simulation Method

- A DC offset in the current, introduced by the inverter, leads to additional harmonics in the force spectrum.
- These include not only even-order harmonics but also odd-order harmonics, such as the 1st and 3rd.

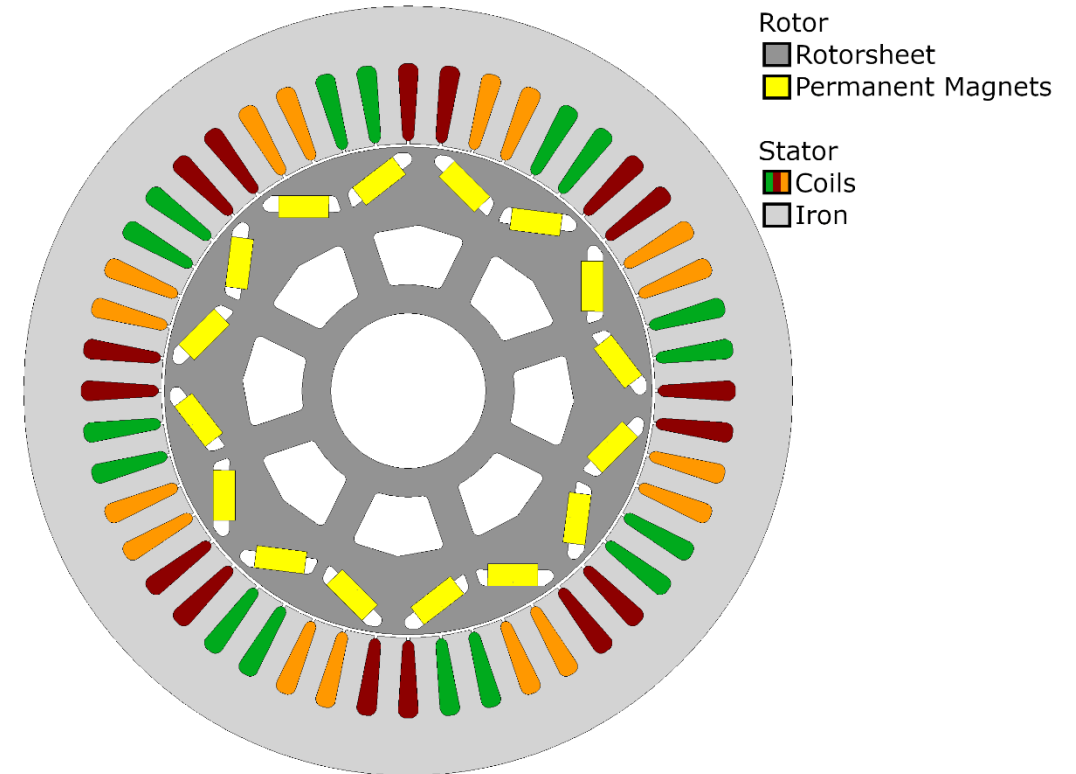


Example of MMF with additional DC

Optimization Example

Enhancing motor efficiency by consideration of mechanical sheet material [1]

- Motor design similar to Toyota Prius 2010 [2]
 - V-shape embedded magnets
- Motor specification
 - Nominal torque: 70 Nm at 2770 rpm
 - Peak torque: 200 Nm at 2770 rpm
 - Maximum speed: 14 550 rpm
 - Non-operational speed: 17 460 rpm
 - Minimum DC link voltage: 650 V

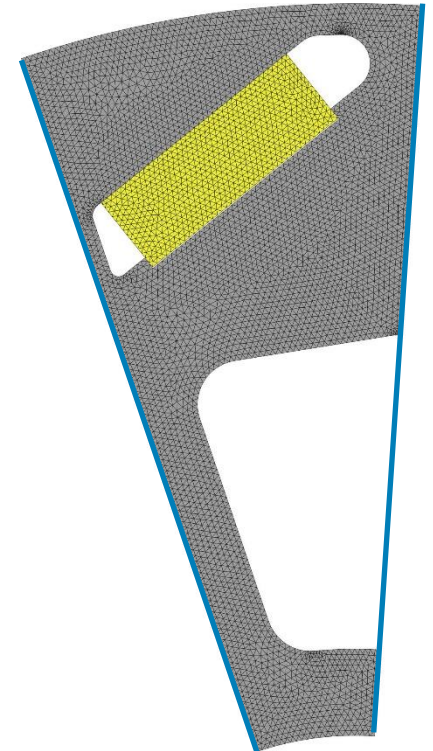


- [1] Enhancing Electrical Drive Efficiency through full consideration of mechanical sheet material properties in the design phase. B. Hartl, S. Weitzhofer, J. Passenbrunner, L. Wagner, T. Gross, International Electric Steel Sheet Summit, 2024
- [2] Burrell; Campbell; Coomer; Ayers; Wereszczak; Cunningham; Marlino; Seiber; Lin; Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System. United States. 2011. <https://doi.org/10.2172/1007833>

Optimization Example

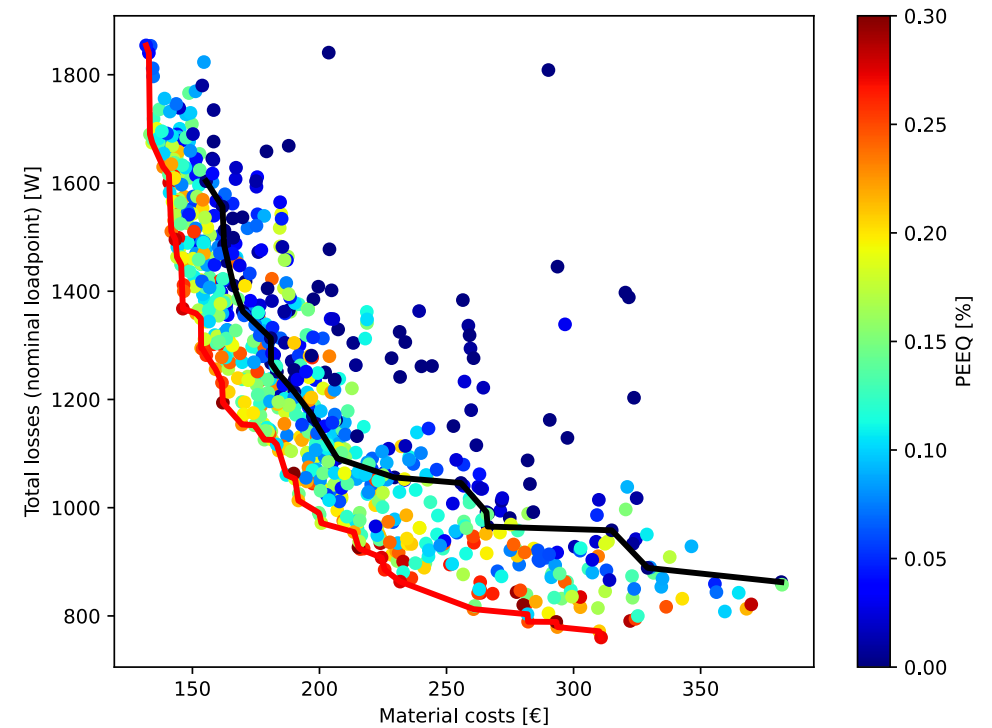
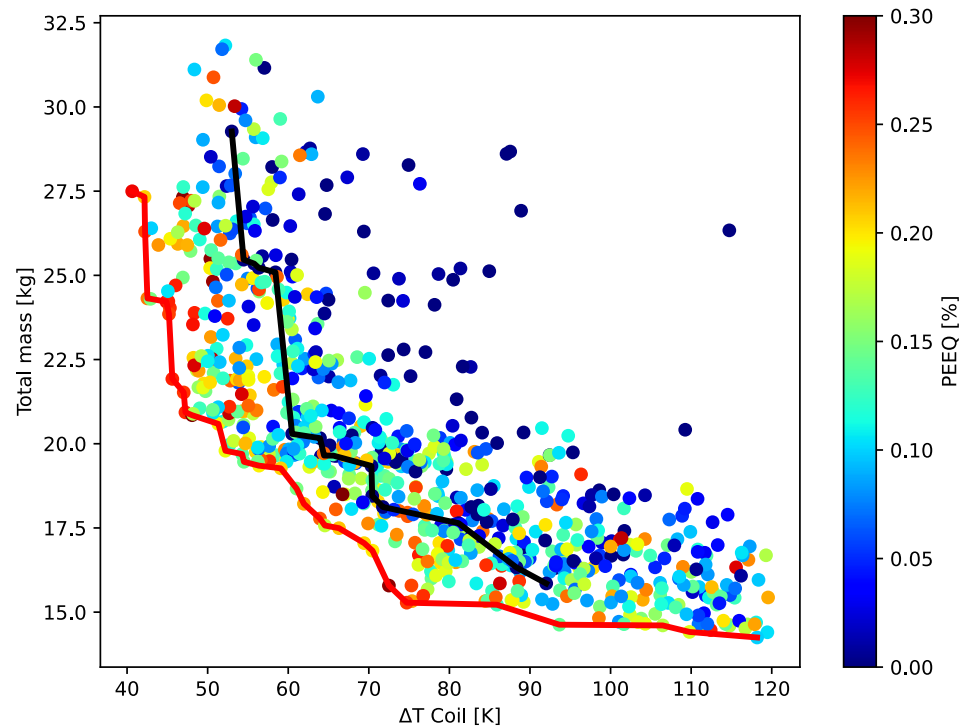
Problem definition

- Is it possible to improve the efficiency by better utilizing the rotor material?
 - Improve efficiency by allowing minimal plastic deformation.
- Objectives (Minimization)
 - RMS value of current
 - Mass of motor
 - Material costs
 - Torque ripple (cogging torque)
 - Total losses
 - Peak temperature within winding
 - Plastic strain
- Constraints
 - Maximum equivalent plastic strain (PEEQ) at non-operational speed is constrained to a maximum of 0.3%
 - Temperature within winding must not exceed 120K above stator surface temperature.



Optimization Example

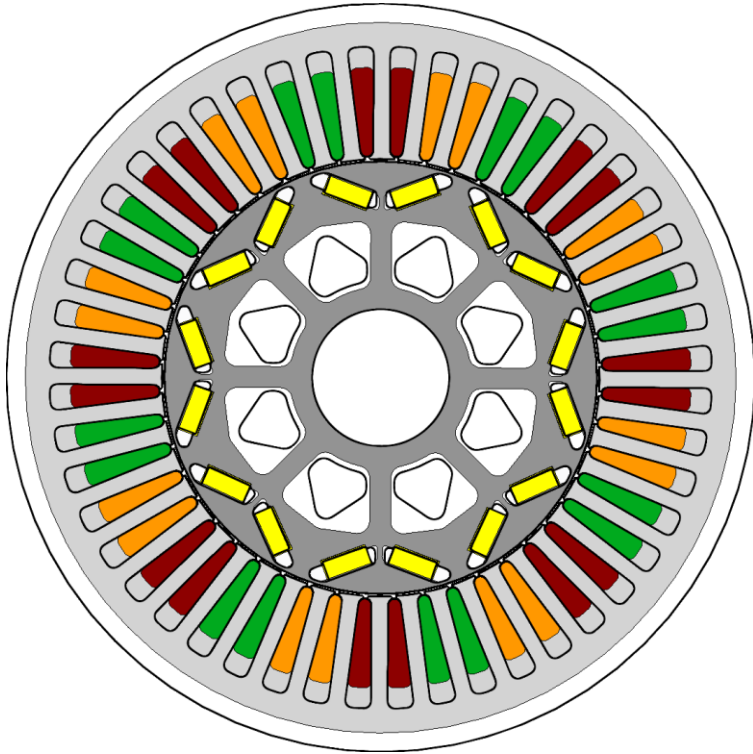
Improvements after optimization



Black line: without plastic deformation
Red line: with $<0.3\%$ equivalent plastic strain

Optimization Example

Comparison of optimized motor designs



Comparison of the motor design with plastic strain (colored)
and the motor design with elastic limits (contour)

The motor design that allows plasticity has

- 16% lower current
- 18% less weight
- 16% material cost reduction
- 18% less torque ripple
- 3% lower losses
- 5% smaller diameter

compared to the motor design with elastic simulation.

Customization
Prototyping
Development
Research
Science

