

Design Optimization of Electric Machines with SyMSpace

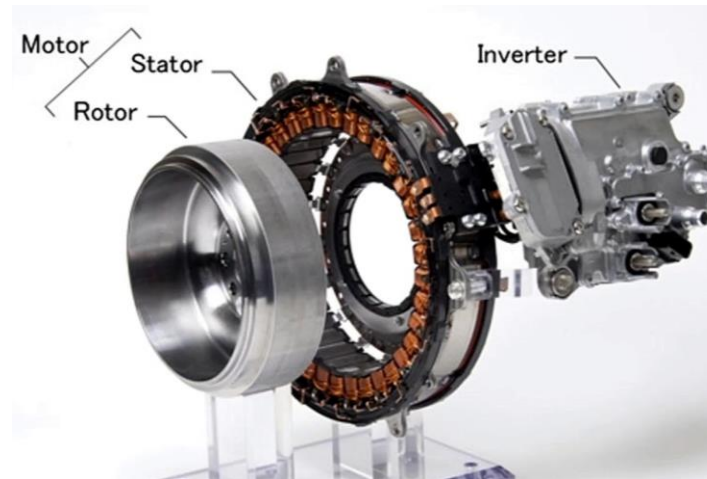
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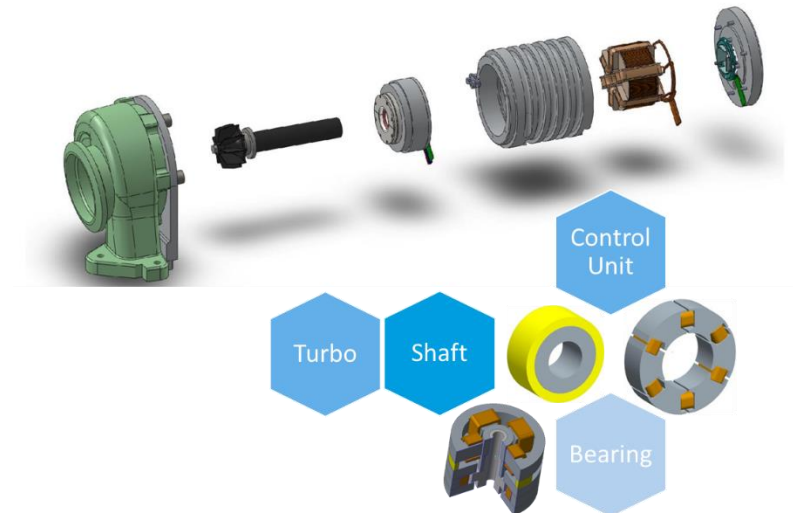
Introduction

Optimization of Electrical Drives

- Constant call for Optimal Design
 - Higher efficiency
 - Higher power density
 - Low cost
- Frequent challenges
 - Multi-physics engineering
 - Strong and unintuitive coupling
 - Large design space
 - Multiple design objectives



Physical asset

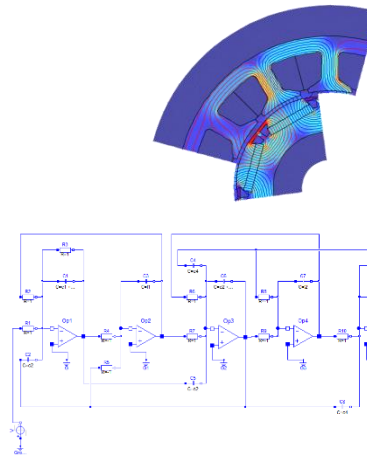
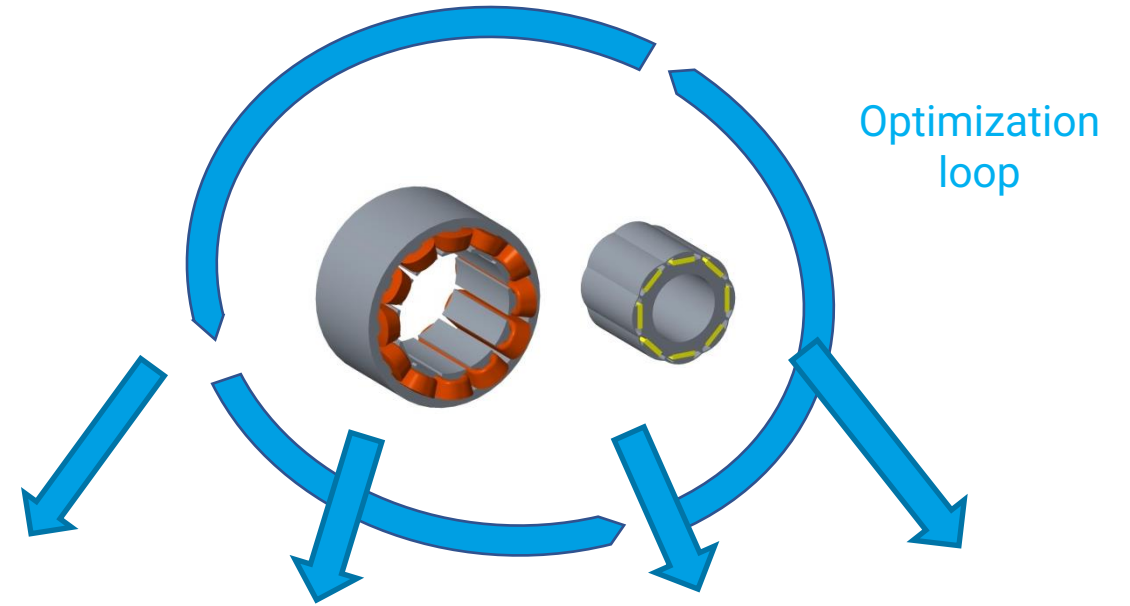


Digital representation

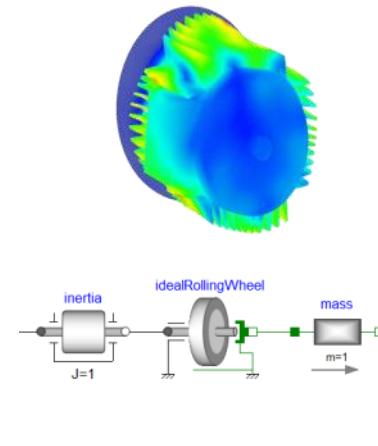
Electrical Drive Design

Efficient multi-physics simulations for optimization

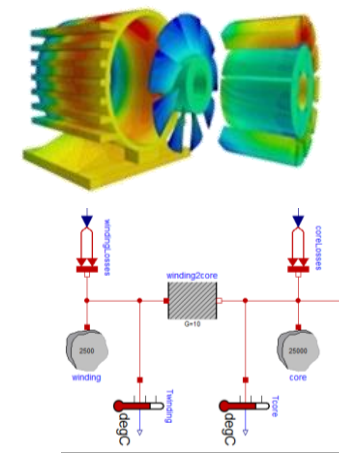
- Different tools are required
 - CAD-TOOL for 3D-model
 - FE-SOLVER for electromagnetic solution
 - Time-Stepping Solver for system simulations
 - Optimization Tool
- Frequent situation
 - Different design tools
 - Different data types
 - Different interfaces



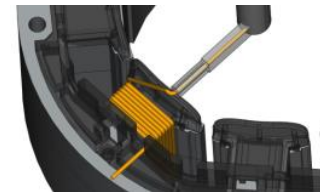
Electrical simulation



Mechanical simulation



Thermal simulation

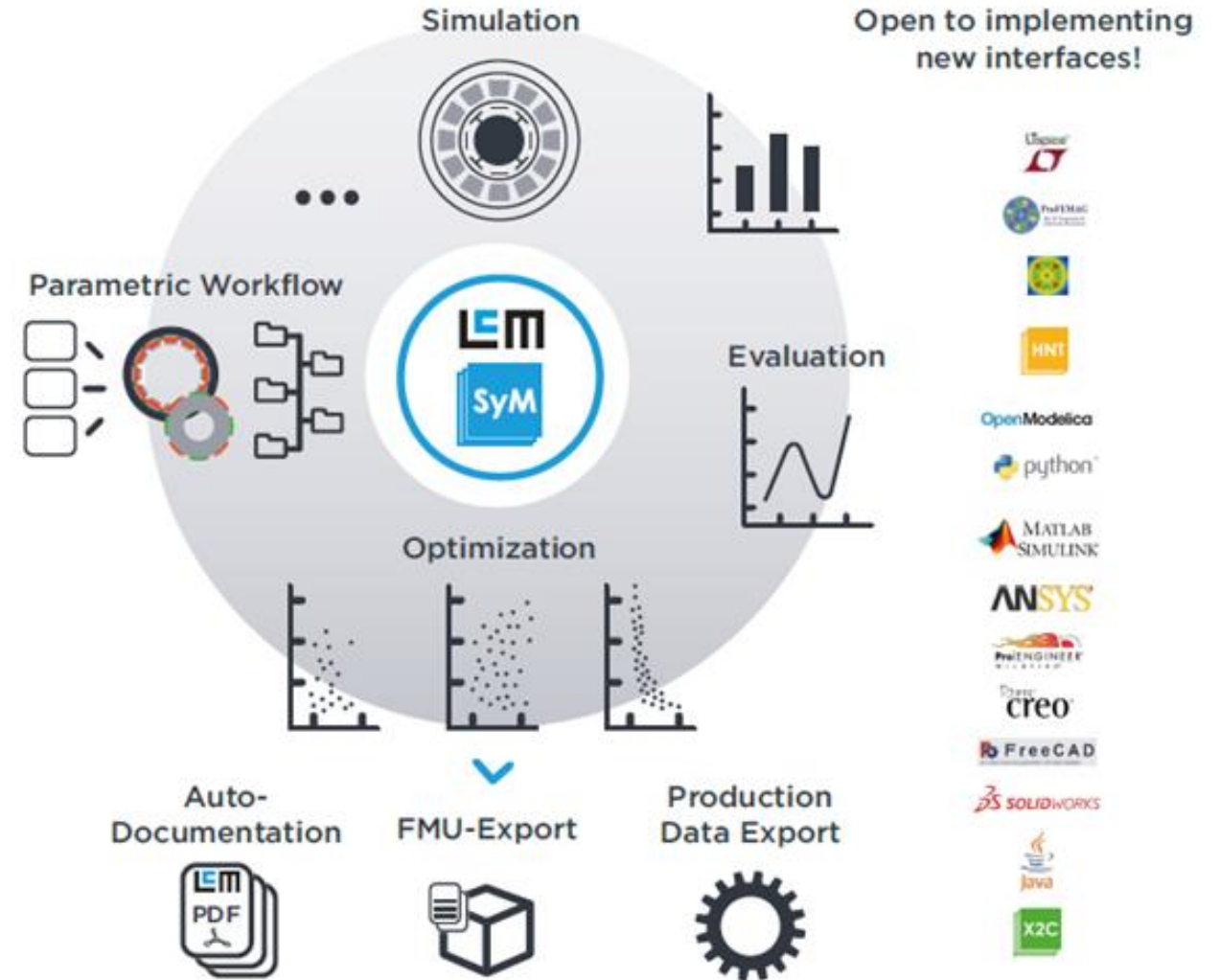


Prototyping

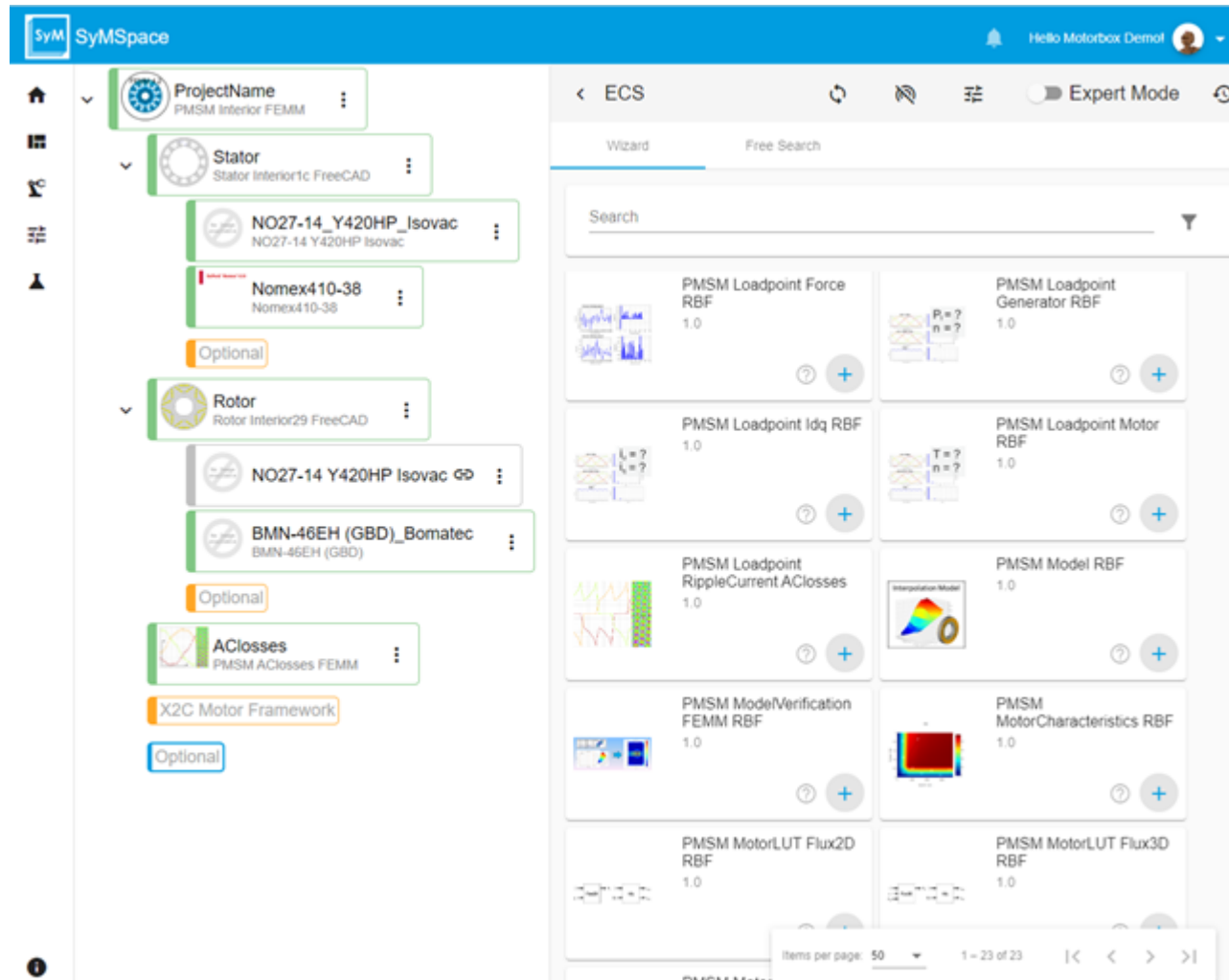
SyMSpace Model Setup

Setup of simulation workflow

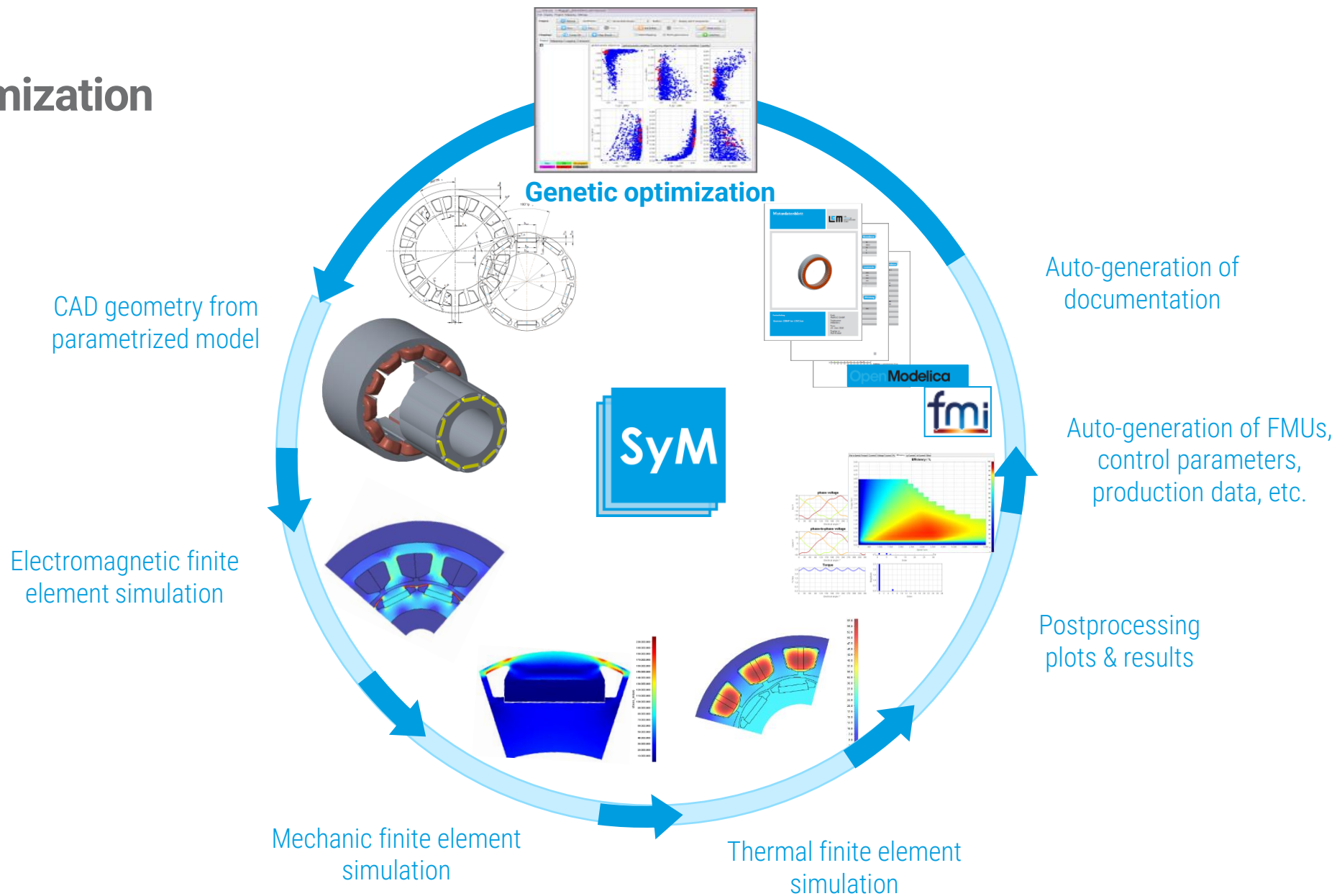
- Create complex workflows from Components
- Execute & optimize workflows
- Automated documentation
- Model and data export



Component Space Web Interface

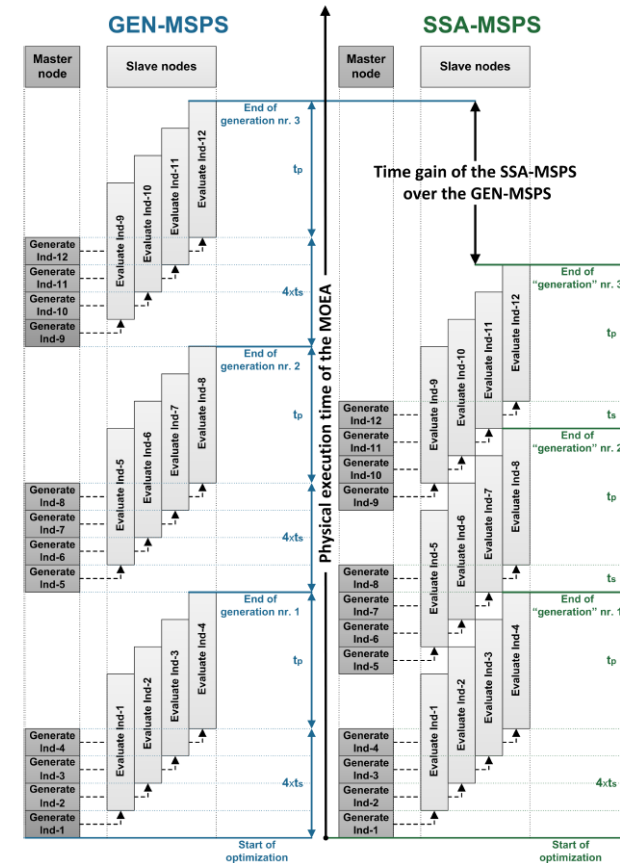


Optimization



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

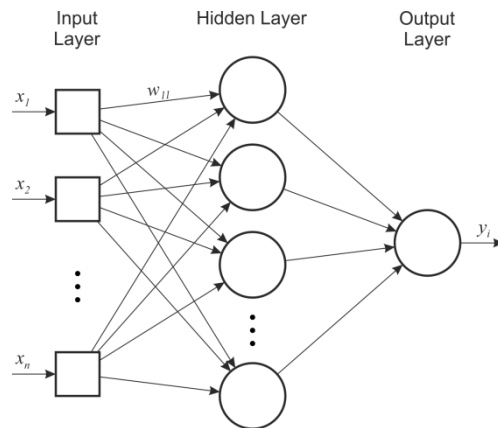
Optimization Algorithm

Hybrid Optimization Method

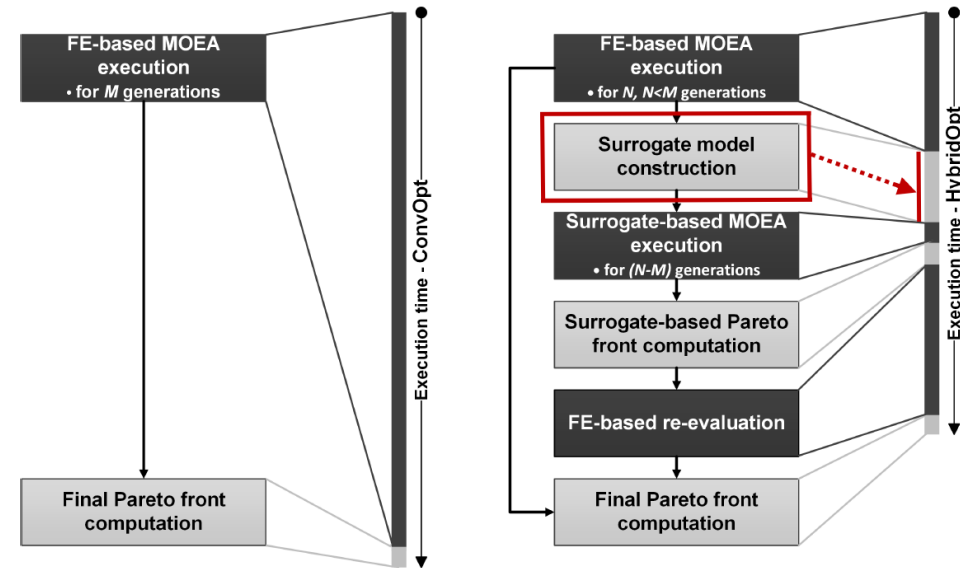
For complex simulations, a surrogate model based on artificial neural networks (ANNs) is created.

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

Optimization speed can significantly be improved.



Surrogate model

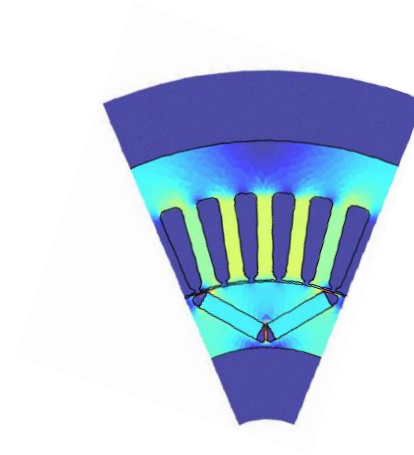


Optimization based on surrogate model

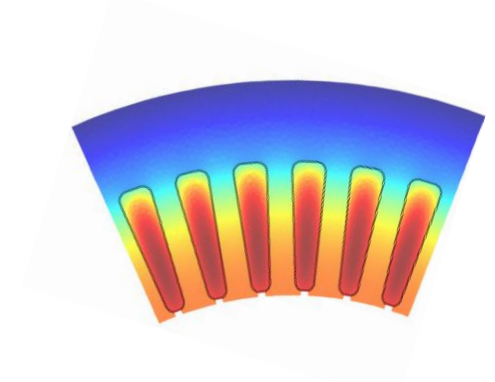
Multi-Physics Simulation

Efficient simulation models for optimization

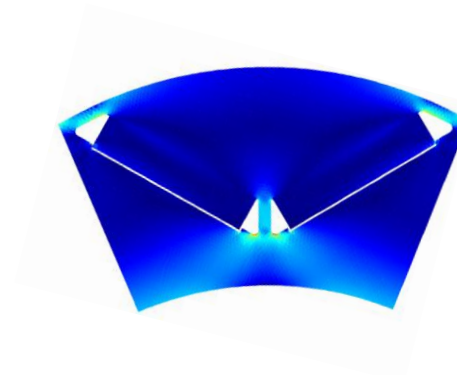
- Efficient simulation models are required for optimization
 - Simulation time should be a few minutes only.
- Simulation models for motor optimization
 - Magnetic simulation including additional losses due to PWM harmonics
 - Transient voltage effects
 - Thermal simulation:
 - 2D heat conduction problem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



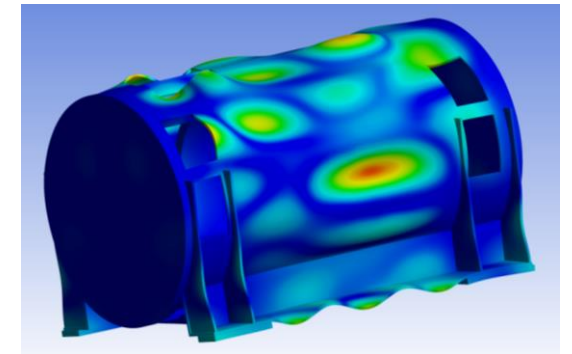
Magnetic simulation



Thermal simulation



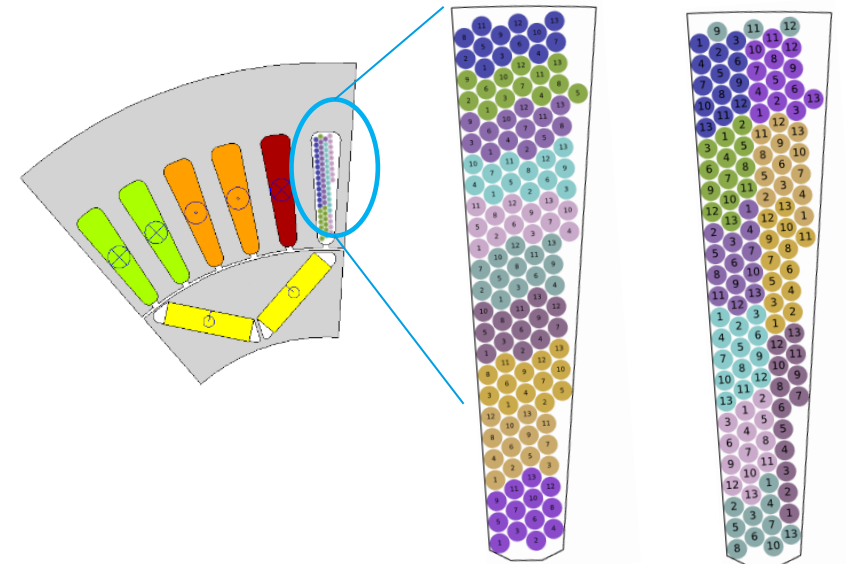
Strength simulation



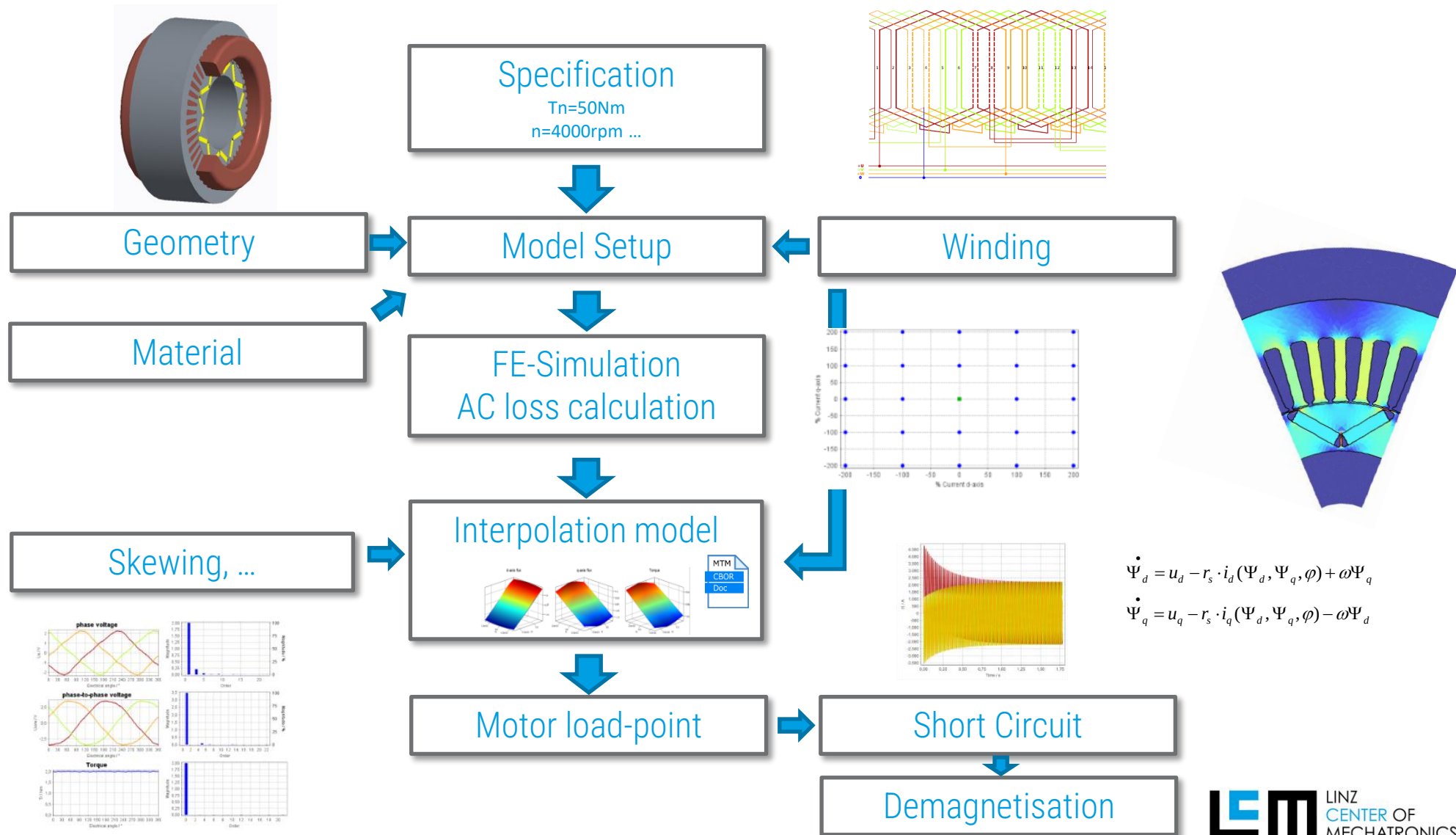
NVH simulation

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**

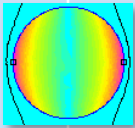
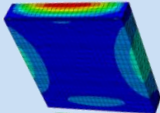
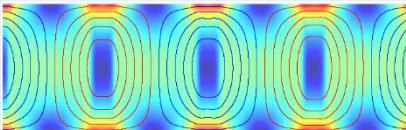


Simulation Workflow for Permanent Magnet Machines



Overview of Additional Losses

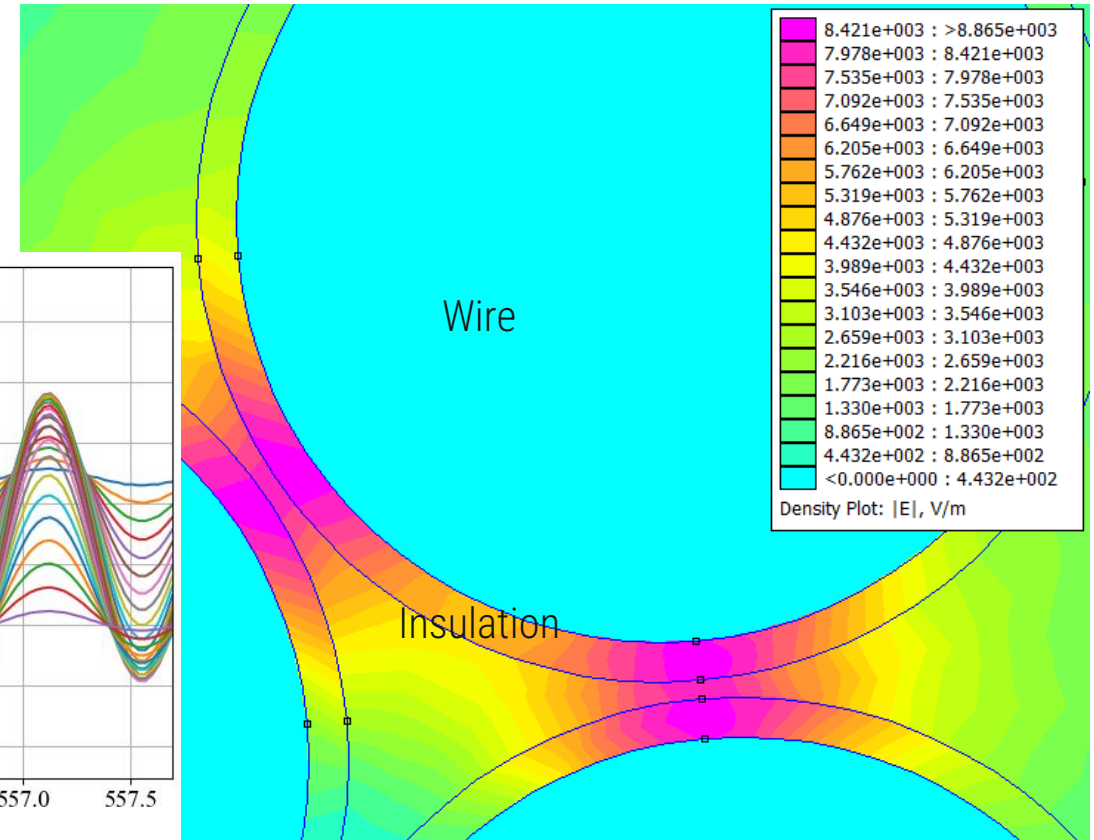
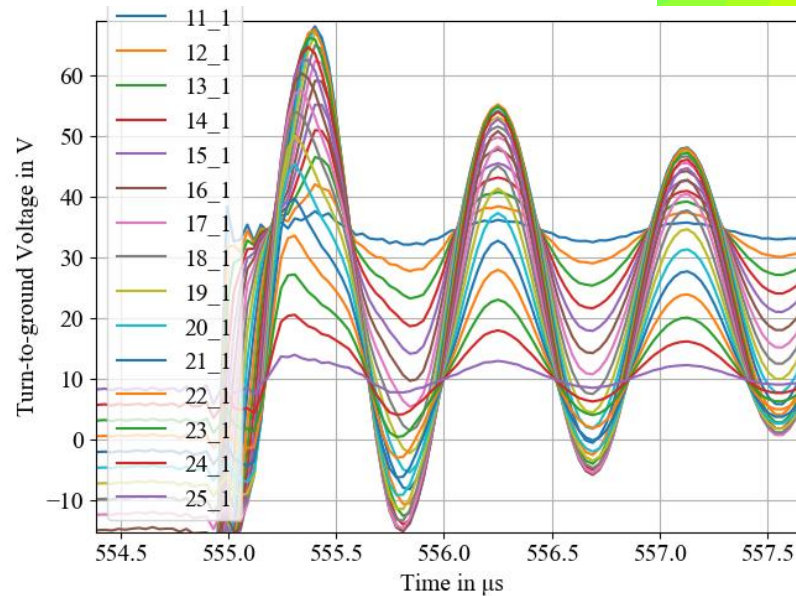
Efficient simulation method

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

Transient Voltage Effects in Electric Machines

Introduction

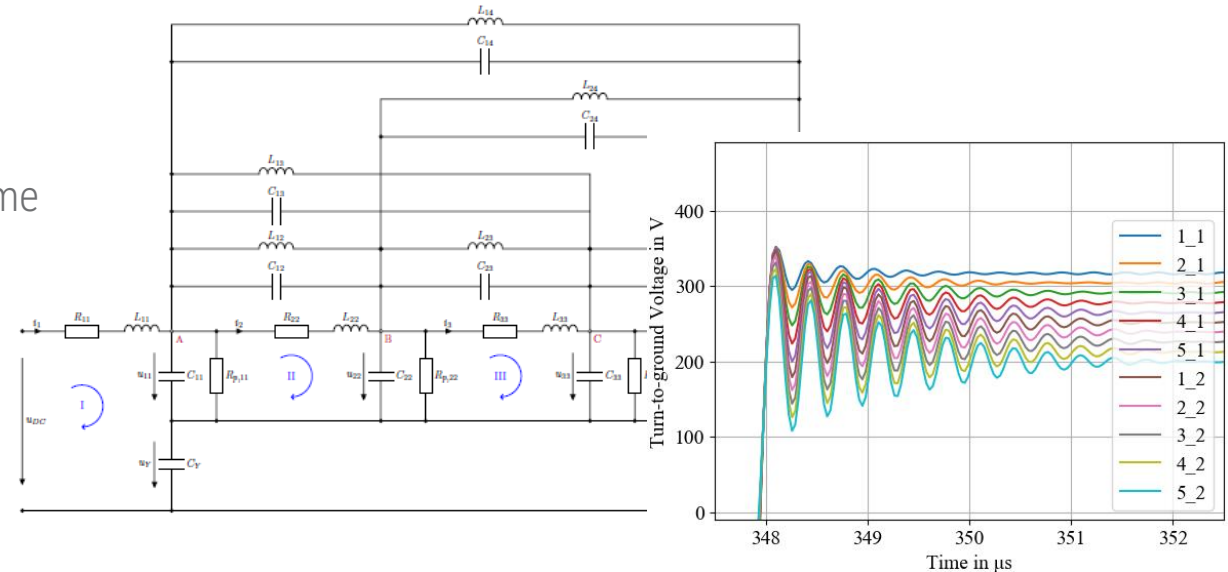
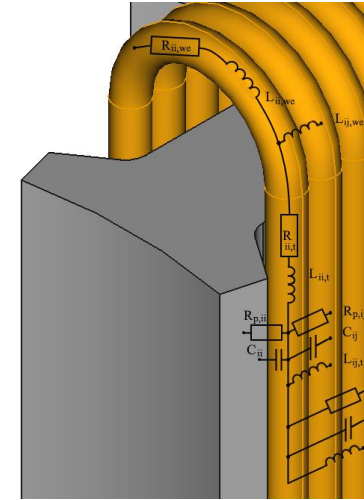
- Increasing switching frequencies and slew rates → electric stress on winding insulation in electric machines rises
- Distribution of voltage within winding is not uniform
- Transient overvoltages → damages in wire and slot insulation, partial discharge (PD)



Transient Voltage Effects in Electric Machines

Efficient simulation method

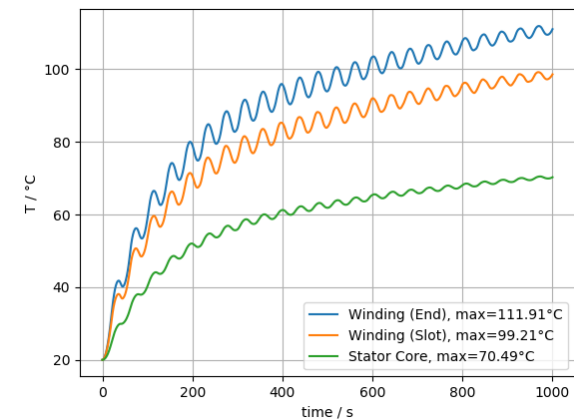
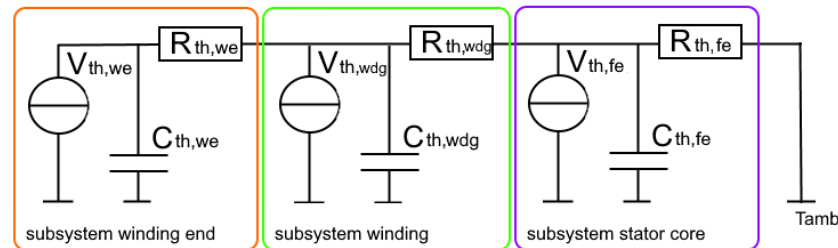
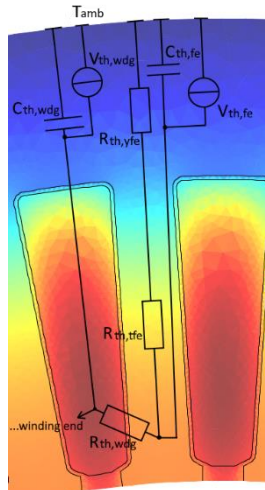
- Calculation of the resistance, inductance and capacitance matrix as function of frequency.
- Distribution of round wires and hairpin conductors is considered for worst case analysis.
- Evaluation of voltage distribution with multi-conductor transmission line network model.
- Network model is solved in frequency domain instead of time domain. In this case, time-varying elements can be easily considered.



Thermal Simulation

Steady-state and transient simulation

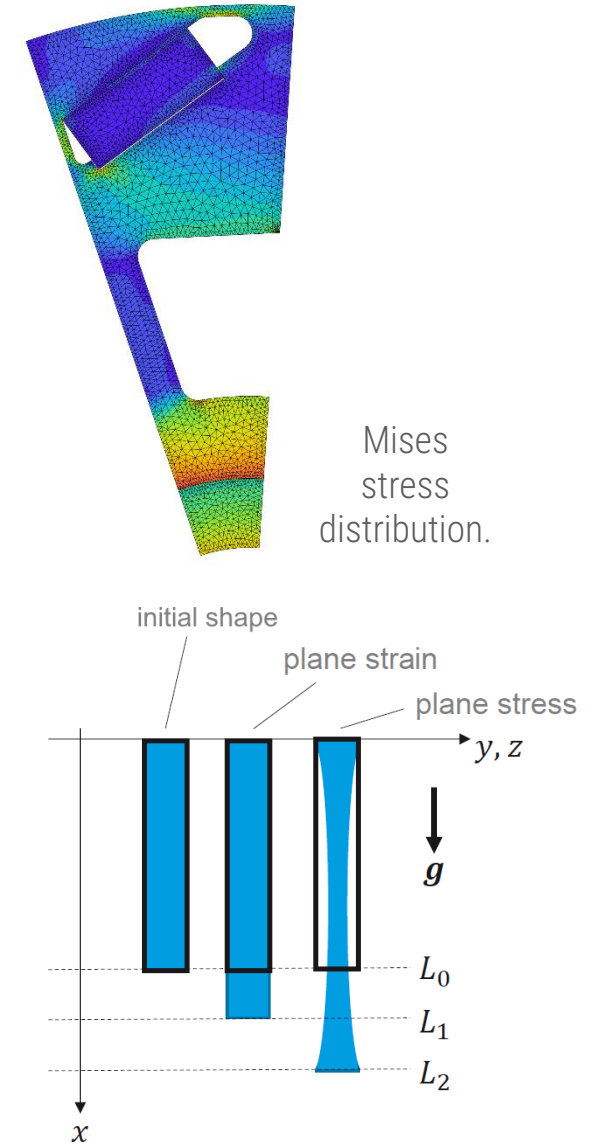
- Heat conduction problem is solved in 2D with finite element method (FEA)
→ steady-state temperature distribution.
- Parameters for equivalent thermal circuit are calculated from FEA solution.
- Thermal elements to consider 3D effects (end winding, ...) are added.
- Transient thermal simulation is based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



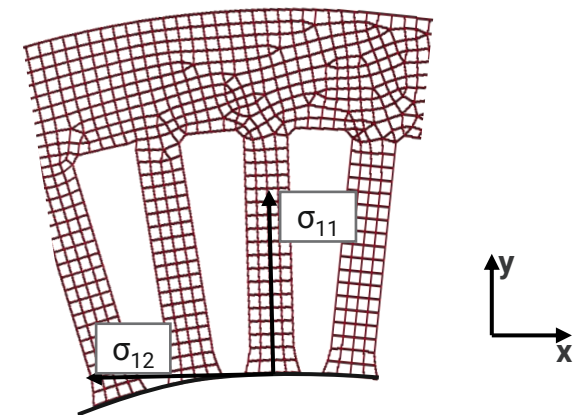
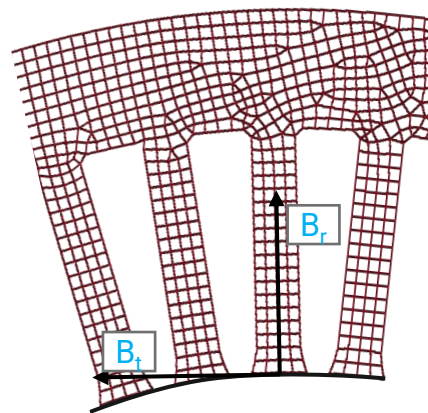
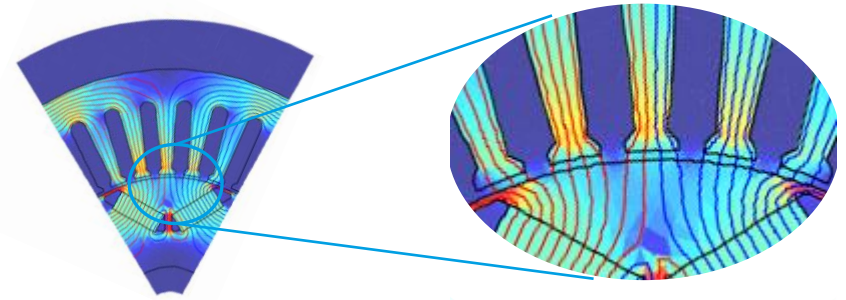
Noise Vibration Harshness (NVH) Simulation

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

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

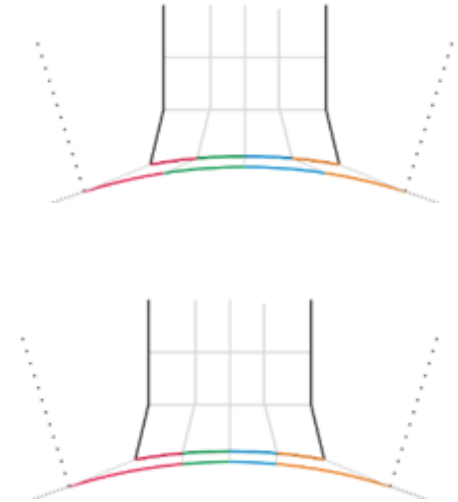
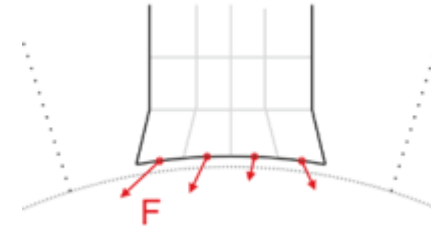
- Normal and tangential components of flux densities produce stress in normal and tangential directions on the rotor surface.



NVH Simulation

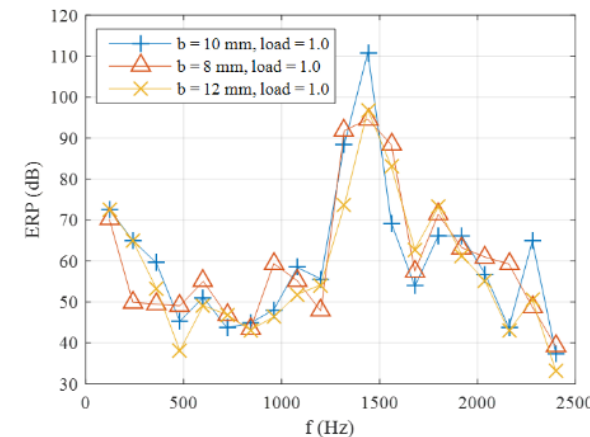
Mapping of magnetic forces onto stator teeth

- **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.

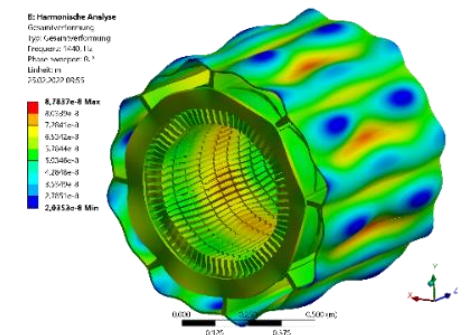


Integration methods.

- **Prediction of Noise Vibration Harshness (NVH)**
 - Harmonic mechanical simulation for excited frequencies.
 - Assessment of Equivalent Radiated Power (ERP) on the housing surface.

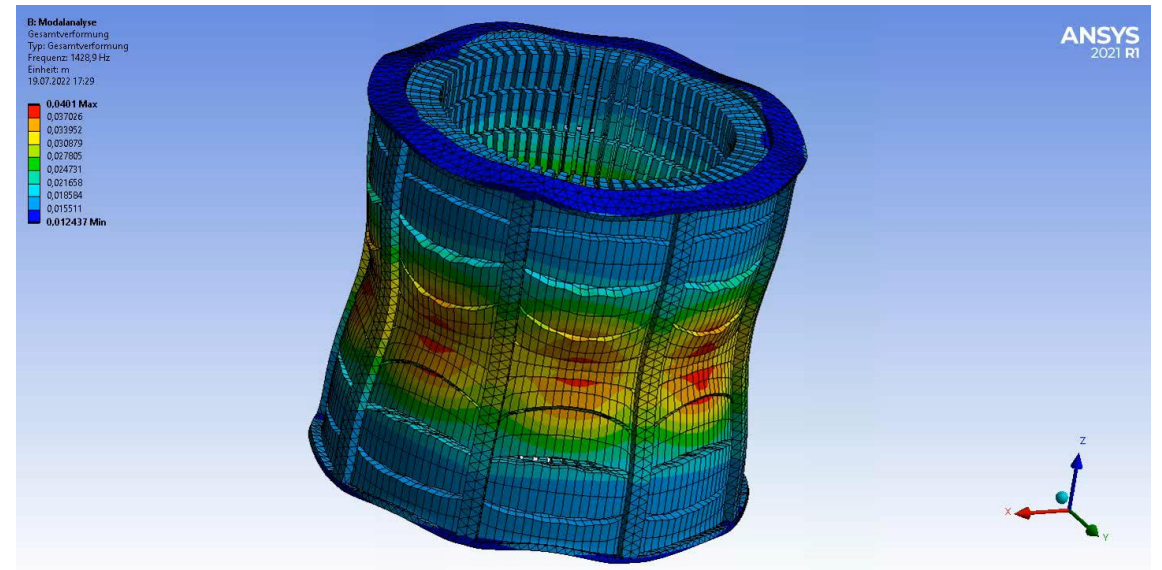
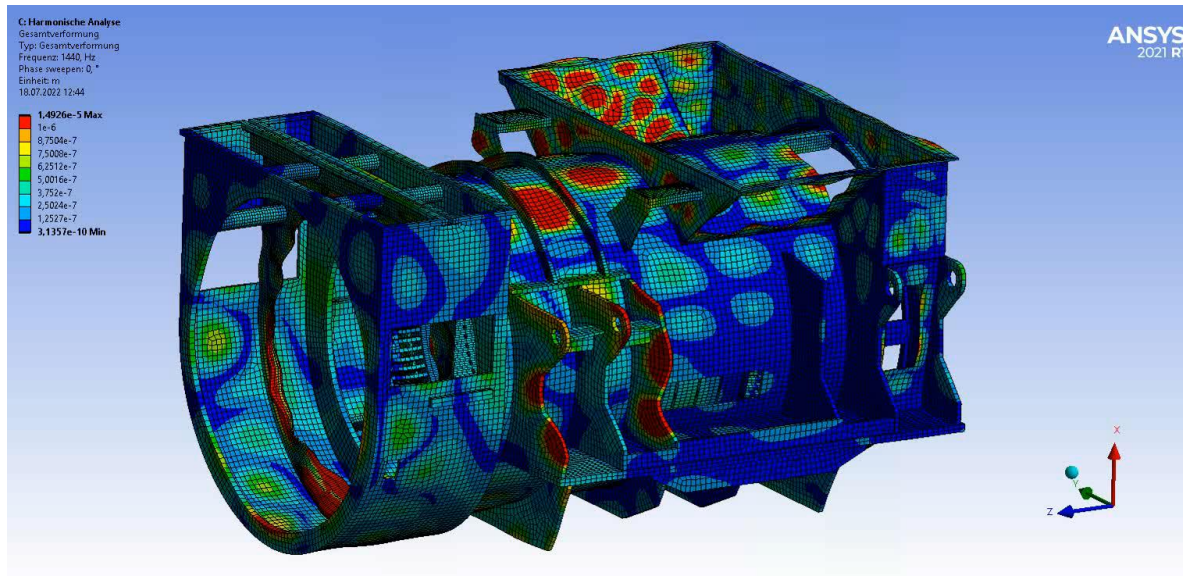


ERP as a function of excitation frequency.



NVH Simulation

Examples



Customization
Prototyping
Development
Research
Science

