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MULTIPHYSICS DESIGN OPTIMIZATION OF AN EEAFM

POWERSYS Advanced eMotor Design Conference

Lukas Kirzinger | October 2025 | Stuttgart

We pioneer motion

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Introduction

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Motivation

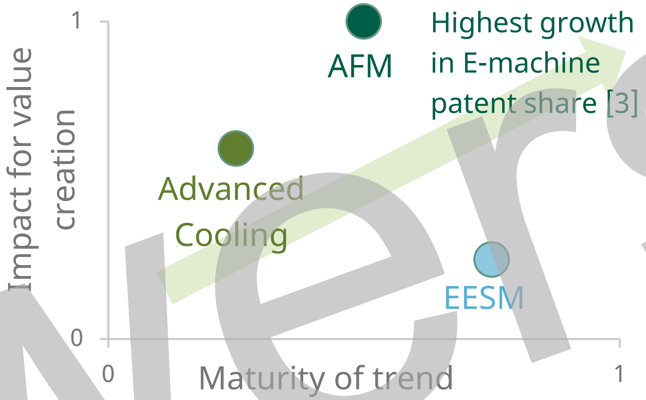
Status E-Motor Market

Magnet price development [2]

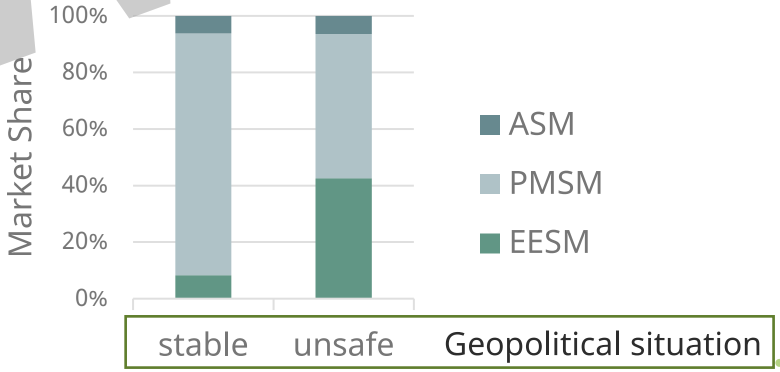
- Increasing BEV demand worldwide
- High price volatility
- 6% lower GWP of EESM vs PMSM [2]
- Strategic dependency from China [3]
  - 98% of rare earth material
  - 85% of magnets

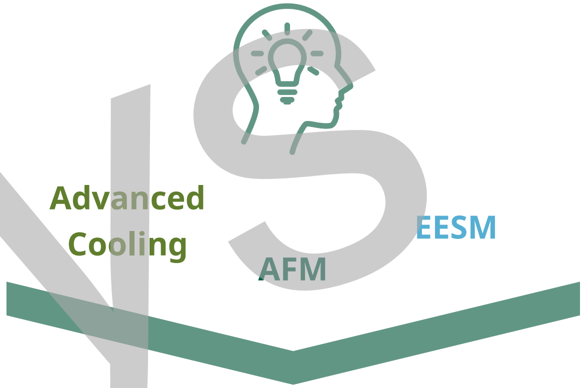
Market & Research Responses

Technology trends and future scopes [1]

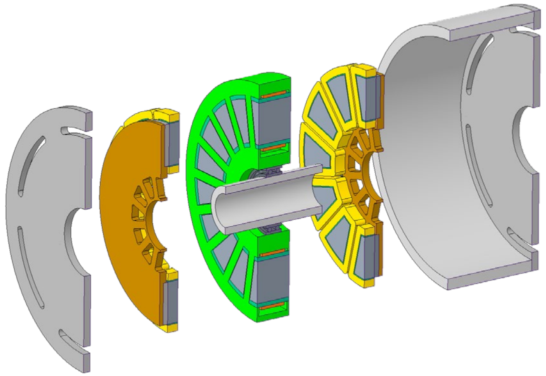


Scenarios for global EESM market 2030 [2]





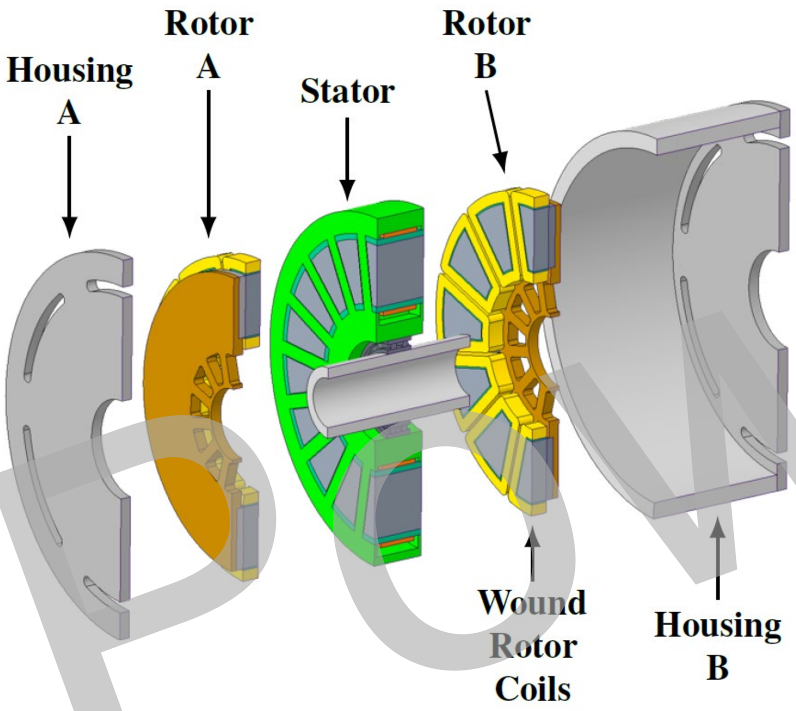
EEAFM



ASM: ASynchronous Machine, PMSM: Permanent Magnet Synchronous Machine , EESM: Externally Excited Synchronous Machine, AFM: Axial Flux Machine, EEAFM: Externally Excited Axial Flux Machine

Introduction EEAFM

Externally Excited Axial Flux Machine (EEAFM)



Exploded view EEAFM [5]

Benefits

- Rare earth free topology
  - Sustainability increased (CO_2 potential)
  - Supply chain risks decreased
  - Cost risk reduced
- Wide constant power region
- No functional safety issues

Challenges

- Temperature and load dependent rotor copper losses → thermal behaviour
- Additional weight due to rotor coils
  - Bending
  - Mechanical failure
- Simulation time
- Scalability

EEAFM: Externally Excited Axial Flux Machine, PMAFM: Permanent Magnet Axial Flux Machine

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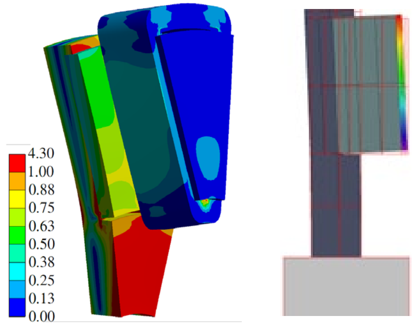
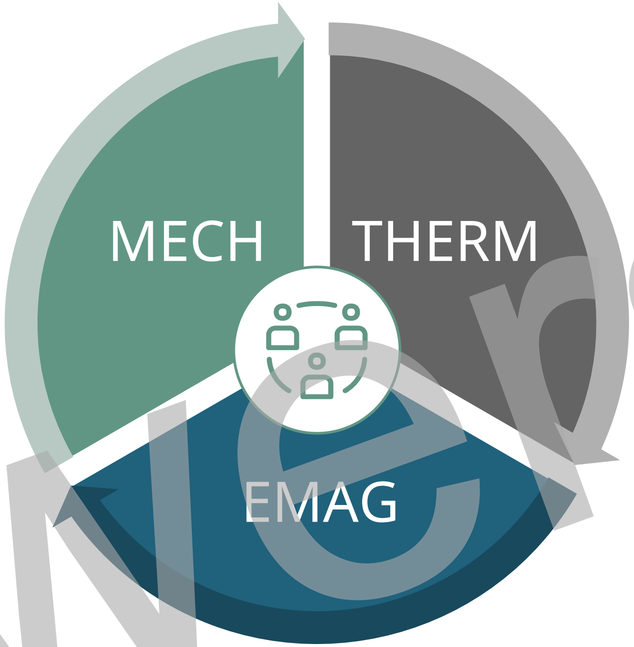
Multiphysics in the design procedure

MECHANICAL DESIGN

- **Innovative 2D approach** to include in Multiphysics optimization

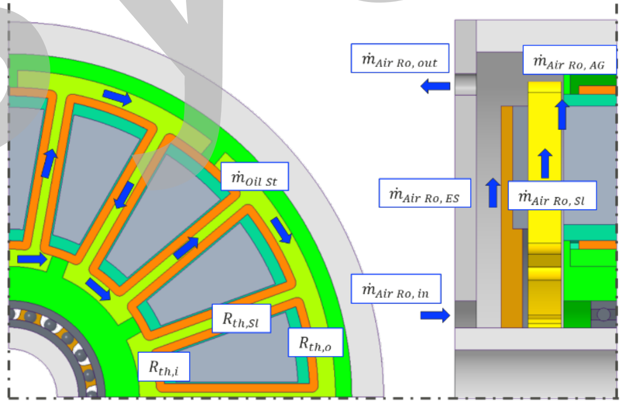


Mechanical FEM models [6]



THERMAL DESIGN

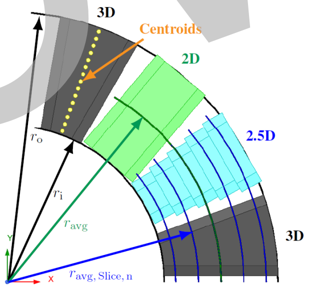
- Direct oil cooling for stator winding
- Self ventilated rotor (air) cooling
- Thermal network adaptable all parameter variations validated with CFD
- **Drag losses based on CFD**

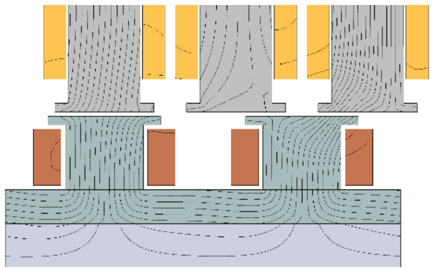


Schematic fluid flow [5]

EMAG DESIGN

- 2D FEM calculation –
  30x Speed up compared to 3D
- AC and PWM losses included
- **Gear ratio based optimization workflow**
- **Target: WLTC efficiency**





EMAG FEM models [4,6]

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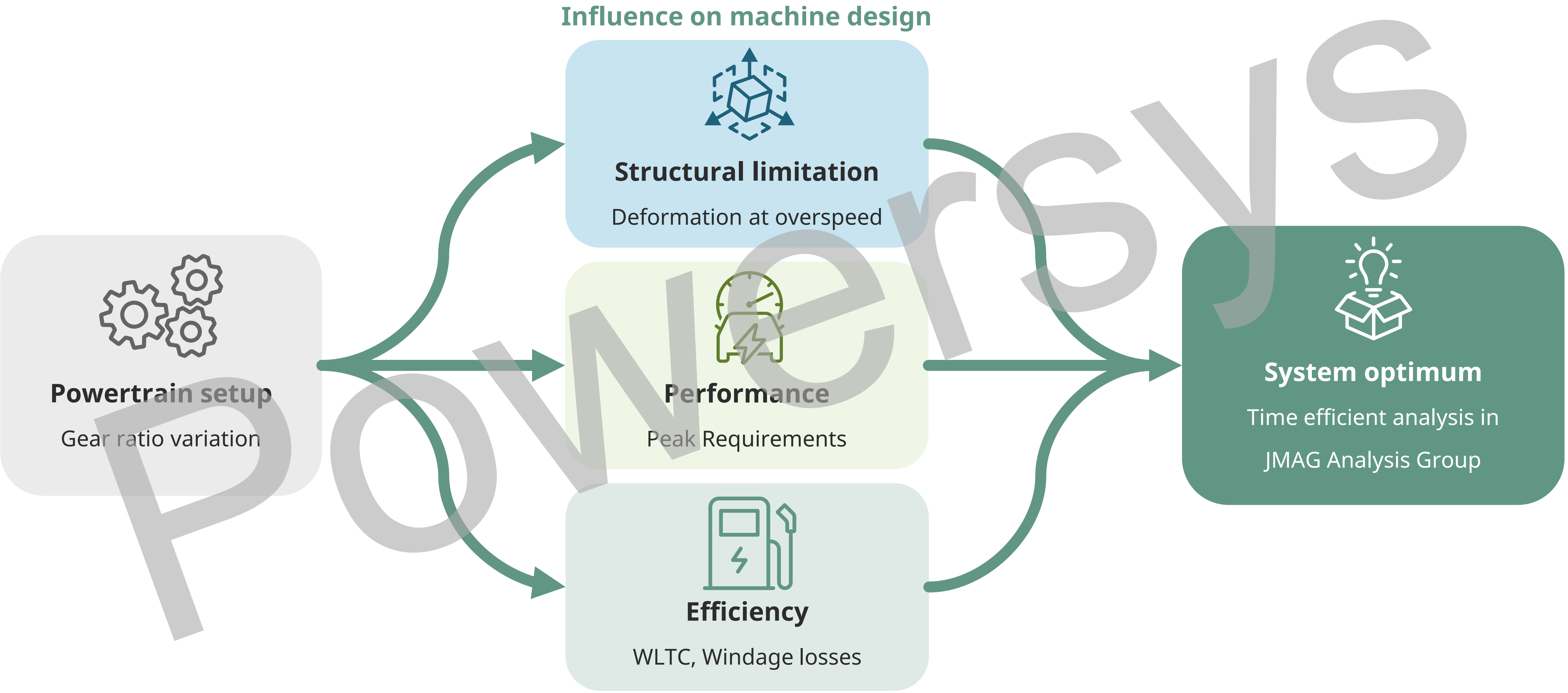
Multiphysics design optimization - Setup



Electromagnetics

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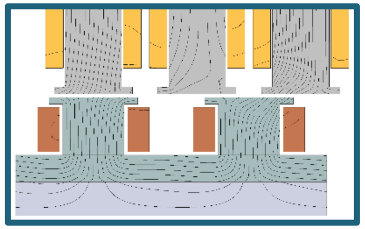
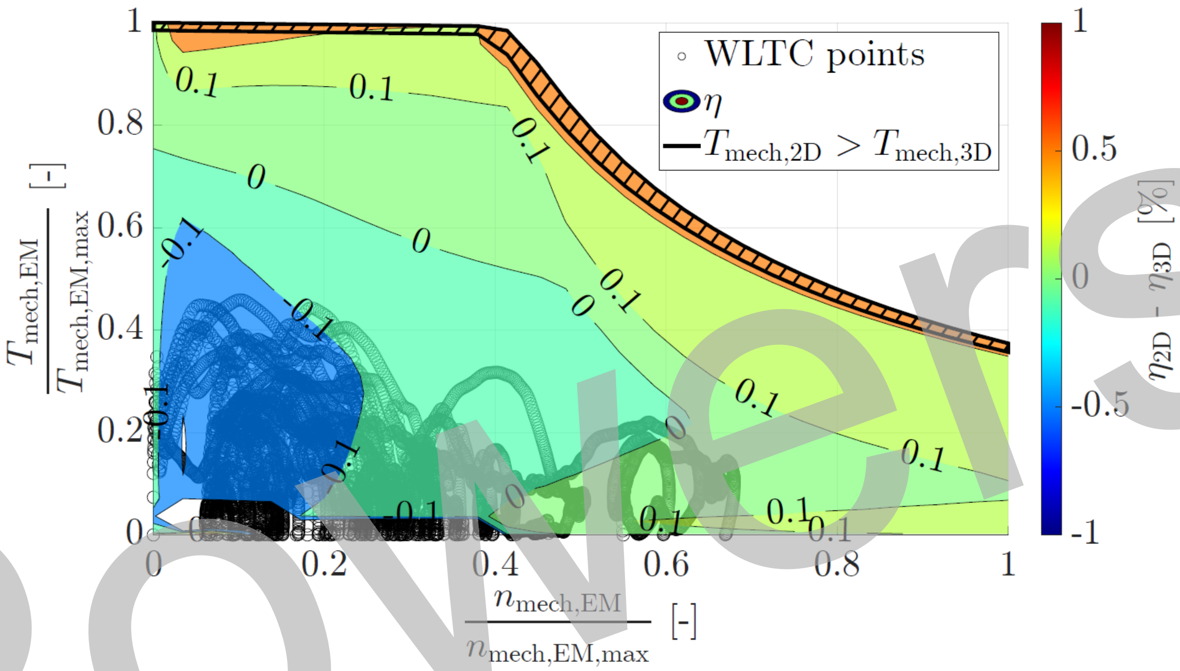
2D vs 3D FEM comparison



2D FEM [6]



Efficiency difference EEAFM - 2D FEM vs 3D[6]

Map comparison

- Discrepancy in maximum torque prediction (2D>3D)
- Efficiency differences rather small (wide area $-0.1\% < \Delta\eta < 0.1\%$)
- WLTC points in partial load area → majority of points within low difference area
- Accumulated losses in duty cycle

$$\frac{E_{WLTC,3D} - E_{WLTC,2D}}{E_{WLTC,3D}} \leq 0.02$$

2D FEM suitable for fast EMAG optimization

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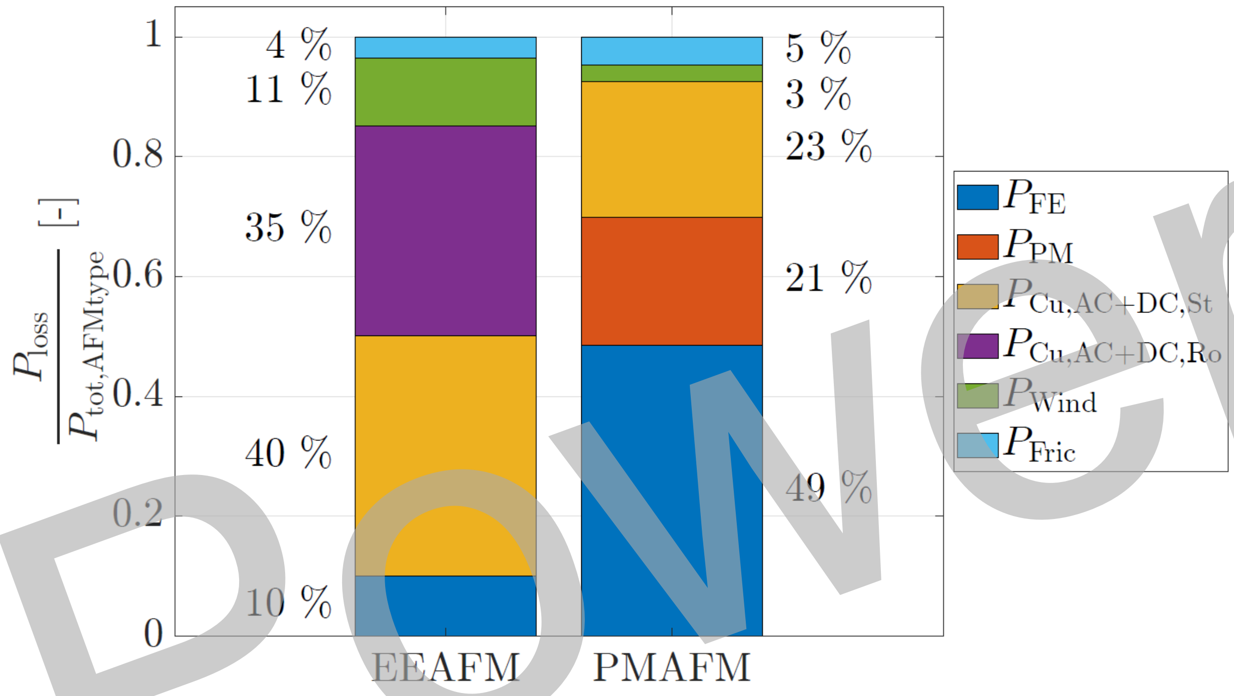
Typical WLTC loss distribution



Cycle efficiency – Loss distribution EEAFM vs PMAFM[6]

Optimization should focus on copper (AC+DC) and drag losses

WLTC loss distribution

Both machine types

- With self ventilated rotor
- In RSR config
- Same performance target
- Loss shares normalized to individual total loss amount

EEAFM

- **Increased windage losses** → ventilating surfaces
- Iron losses reduced → rotor field control)
- **Copper losses major parts** → reduction leads potentially to increased mass
- PWM losses show only little significance
- **AC losses** also of high importance → Especially Stator

1) Rotor Stator Rotor

Fluid dynamics

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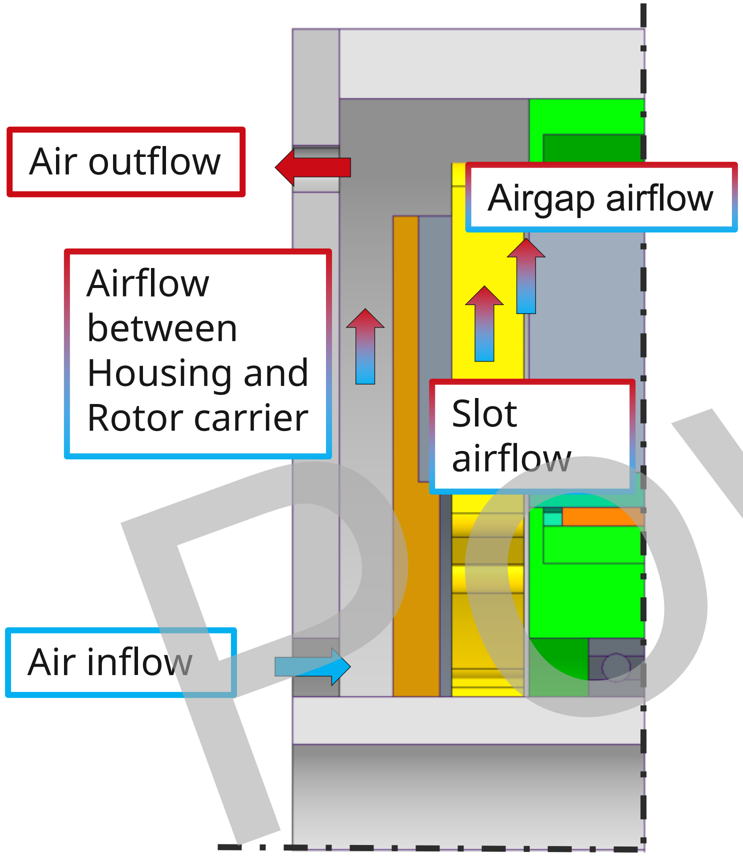
Windage loss estimation

CFD DoE



Rotor air flow [5]

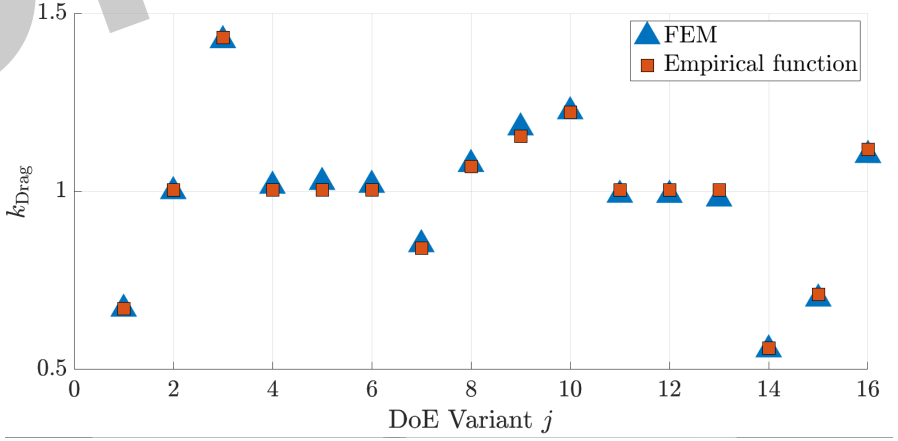
Data Analysis & Fit Function (Parameters in [6])

$$P_{\mathrm{Wind}} = k_{\mathrm{Drag}} P_{\mathrm{Wind,0}}$$

$$P_{\mathrm{Wind}} \propto n_{\mathrm{EM}}^{3} V_{\mathrm{Hull,Rot}}$$

$$k_{\mathrm{Drag}} = (p_{00} x^{p_{01}}) \cdot (p_{12} y^{2} + p_{11} y + p_{10}) \cdot (p_{22} z^{2} + p_{21} z + p_{20})$$

Empirical expression for windage losses for JMAG



Very good fit to 3D CFD results

Structural analysis

“Classic” 3D model

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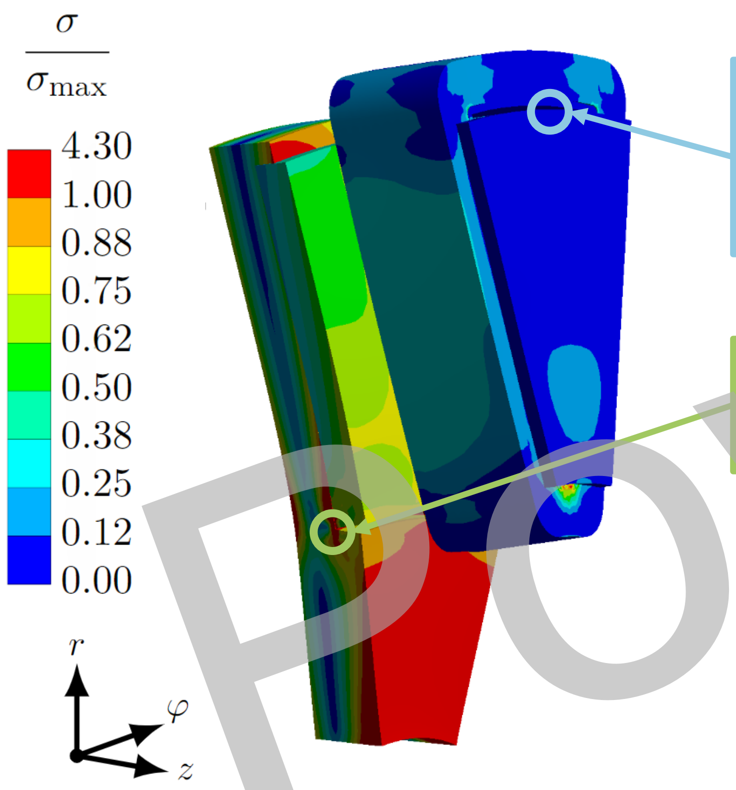
Normalized (individual material limit) **von-Mises stress distribution**



Maximum airgap axial displacement $\Delta\epsilon_{AG,max}$

Maximum stress $\sigma_{RoCar,max}$

3D structural model [6]

+ Accuracy FEM benchmark
- Long simulation duration

Structural FEA model **constraints**

Evaluated

- Deformation at overspeed ($1.2\ n_{max,EM}$)
- Stress at burst speed ($1.2^2\ n_{max,EM}$)

Contacts

- Carrier-yoke bonded contact
- Remaining contacts pairs friction

Linearized and isotropic material models

Findings

Maximum stress in rotor carrier

- Mainly radial and tangential components

Rotor deformation

- Mainly axial and radial

Axial displacement in airgap

- worsening EM performance
- main deformation part

2D Simulation proposal

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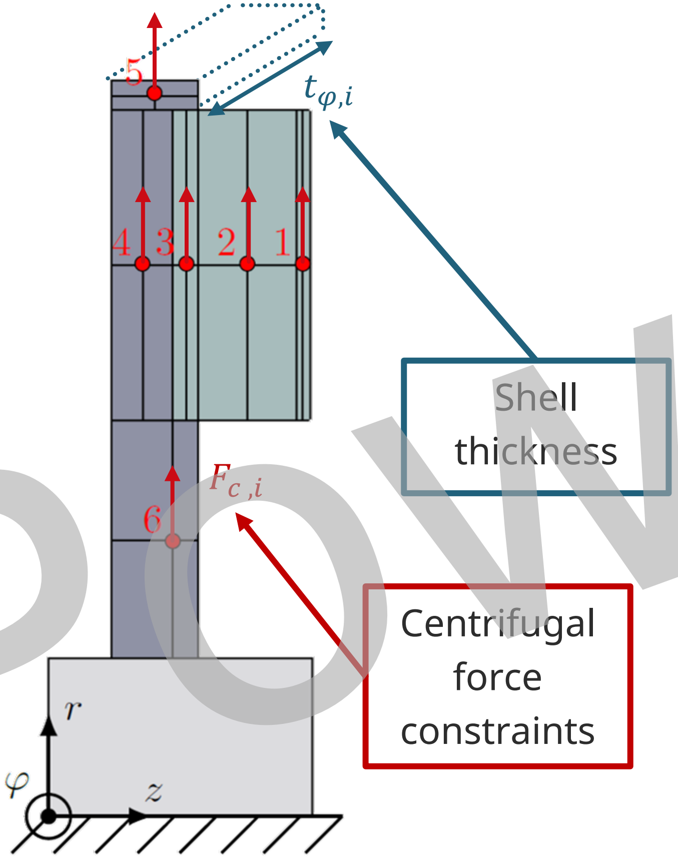
2D FEM model setup in **r-z plane**



2D structural model [6]

Setup

Contact and material identical to 3D

Discretized load constraints

- Face centred nodes (1-6)
- Load as equation-based node forces [6]

$$F_{\mathrm{c,i}} = m_{\mathrm{i}}\omega^2 r_{\mathrm{i}} = \rho_{\mathrm{i}} V_{\mathrm{i}} \omega^2 r_{\mathrm{i}}$$

- Shell thickness based on tangential expansion [6]

$$t_{\varphi,\mathrm{i}} \approx \tau_i(r_i) = \frac{2\pi r_i}{2p} - W_i$$

Findings

Shortened simulation duration

- **30 min 3D to seconds in 2D**
- fitting large scale DoE or optimization

Decreased accuracy

- Mathematical improvement needed

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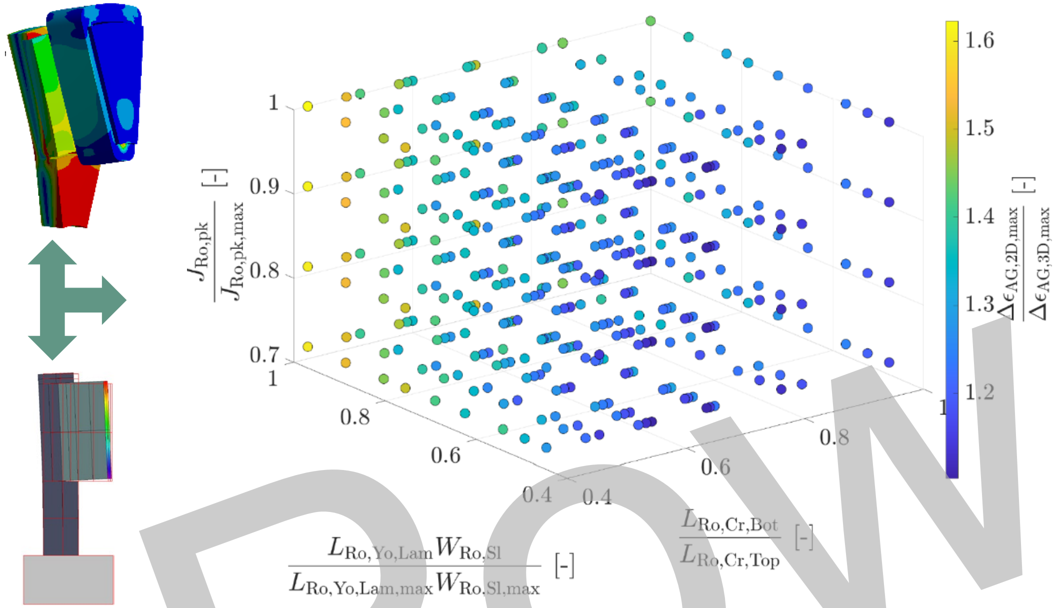
Statistical analysis of 2D 3D difference

2D vs 3D DoE

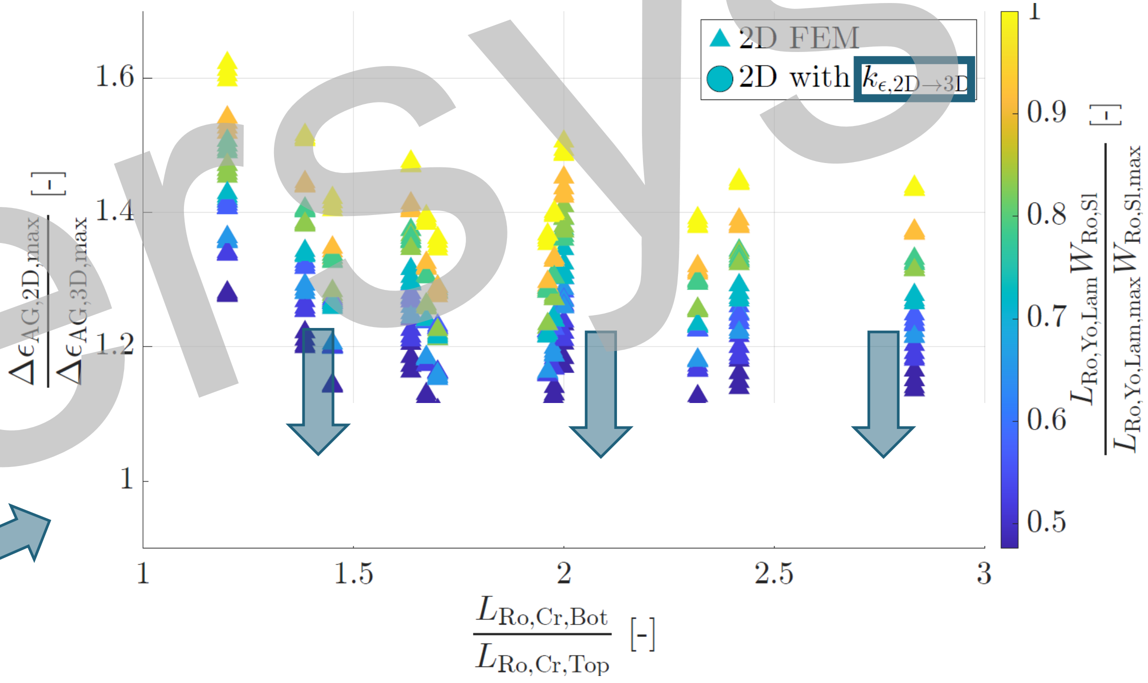


2D 3D Transfer function for implementation in JMAG [6]

$$k_{\epsilon,2D\rightarrow 3D} = \frac{\Delta\epsilon_{AG,3D,max}}{\Delta\epsilon_{AG,2D,max}}$$

$$k_{Struct,2D3D} = p_{00} + p_{10}x + p_{01}y + p_{11}xy + p_{20}x^2 + p_{02}y^2 + p_{21}x^2y + p_{12}xy^2 + p_{30}x^3$$

Maximum Axial (Airgap) Displacement vs main parameter



Transfer function improves accuracy
Easy implementation into JMAG

5 Multiphysical optimization

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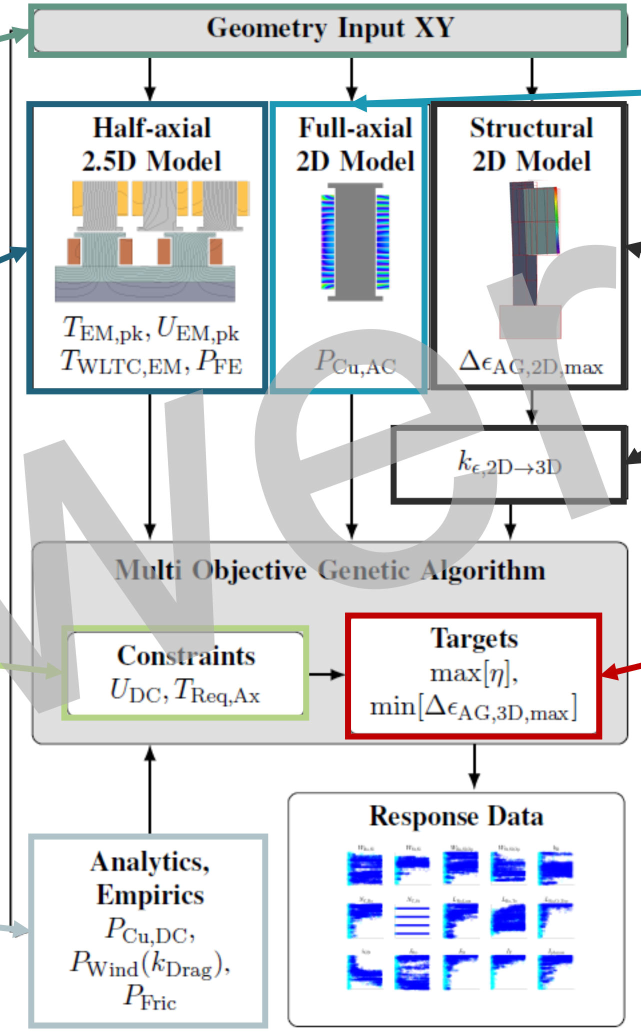
JMAG Analysis group setup – combining all phenomena in <u>one</u> co-simulation [6]

Parameter setup:
- Geometrical variation
- Definition of gear ratio

Operation point calculation:
- Full load point → Peak constraints
- Partial load points → Efficiency

Constraints:
- Gear ratio and requirement dependent

Analytical Equations:
- DC resistance → copper losses
- Equations for friction and windage losses



AC loss calculation:
- Partial load efficiency

Mechanical simulation:
- Focus bending rotor
- Improved by transfer function

Optimization targets:
- Geometry suitability
- Feedback loop for new geometries
- Collection of results

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Results

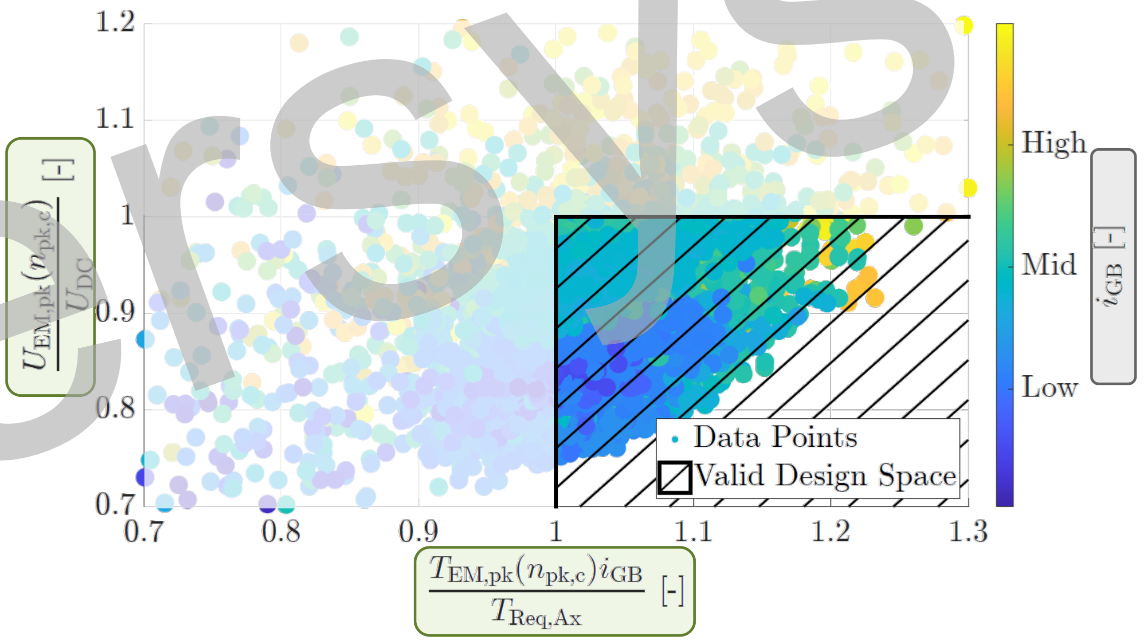
Powertrain setup
Gear ratio variation

Structural limitation
Deformation at overspeed

Performance
Peak Requirements

Efficiency
WLTC, Windage losses

Valid Design Space – Axle Requirements



Design Space Analysis – voltage vs peak torque requirement [6]

Tendency for "mid" – "low" gear ratio

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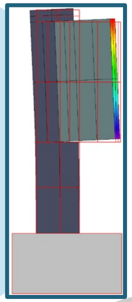
Results

Powertrain setup

Gear ratio variation

Structural limitation

Deformation at overspeed



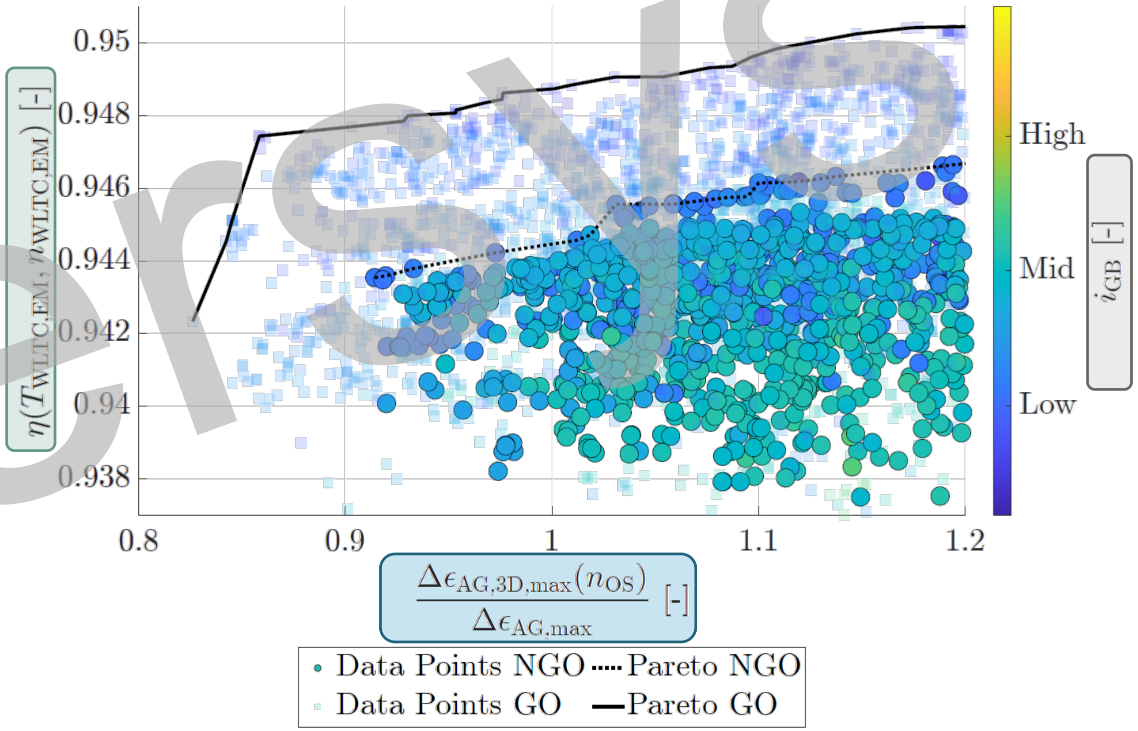
Performance

Peak Requirements

Efficiency

WLTC, Windage losses

Pareto Front – Optimum Efficiency



Pareto front – benchmark efficiency vs airgap enlargement [6]

Ensuring mechanical feasibility with optimum powertrain setting

GO: Grain Oriented Electrical Steel, NGO: Non-Grain Oriented Electrical Steel

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Summary

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Summary

Simulation time effective optimization for EEAFM

New 2D calculation methods

Workflow enables investigation on optimum gear ratio

Cycle analysis shows relevant losses → included and minimized in optimization

Targeting major issues of machine topology

Increased feasibility of future design by ensuring structural integrity

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References

#	Reference
1	Stanek, R.; et al.: „Wertschöpfungspotenziale von E-Motoren für den Automobilbereich in Baden-Württemberg“. In: Themenpapier Cluster Elektromobilität Süd-West Scale-UpE-Drive (Juli 2021).
2	Mühlberg, G.; Spas, S.: „Magnetfreier Rotor als Option für die EMR4-Plattform“.In: MTZ - Motortechnische Zeitschrift 85.5 (Mai 2024), S. 16–23. issn: 0024-8525,2192-8843. doi: 10.1007/s35146-024-1922-6.
3	Nankemann, M.; Hasselwander, S.; Frieske, B.; Spielmann, H.; Ulrich, C.: „Technologische Trends E-Motor“. In: Transformations-Factsheet Scale-Up E-Drive.2 (Sep. 2023)
4	Kirzinger, L.; Bruell, M.; Gerling, D.: „Fast Modelling, Sizing and Mapping Techniques for Permanent Magnet and Externally Excited Axial Flux Machines“. In: 2023 25thEuropean Conference on Power Electronics and Applications (EPE’23 ECCE Europe). Aalborg, Denmark: IEEE, Sep. 2023, S. 1–8.
5	Kirzinger, L.; Schwartz, E.; Gebhardt, X.; Brüll, M.; Gerling, D.: „Thermal Behaviour and Its Design Impact for Externally Excited Axial Flux Machines“. In: 2024 International Congress Exhibition SIA Powertrain. Lille, France, Juni 2024, S. 312–319
6	Kirzinger, L.; Lehmayr, B.; Gerling, D.: „Multiphysics Design Optimization of an Externally Excited Axial Flux Machine“. In: PEMD Europe 2025. Turin, Italy, Juni2025

LET'S START THE CONVERSATION

THANK YOU

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