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ACCELERATED MULTI-CRITERIA DESIGN OPTIMIZATION OF AXIAL FLUX MOTORS WITH 3D FEA

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JMAG Advanced eMotor Design Conference
Westin, Southfield, MI | Thursday, June 5, 2025

We pioneer motion

Agenda

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1 OVERVIEW OF SCHAEFFLER

2 DESIGN CONSIDERATIONS

3 SCRIPTING WITH JMAG DESIGNER

4 AFM DESIGN OPTIMIZATION

5 CONCLUSION

Accelerated Multi-Criteria Design Optimization of AFM with 3D FEA

Overview of Schaeffler

1

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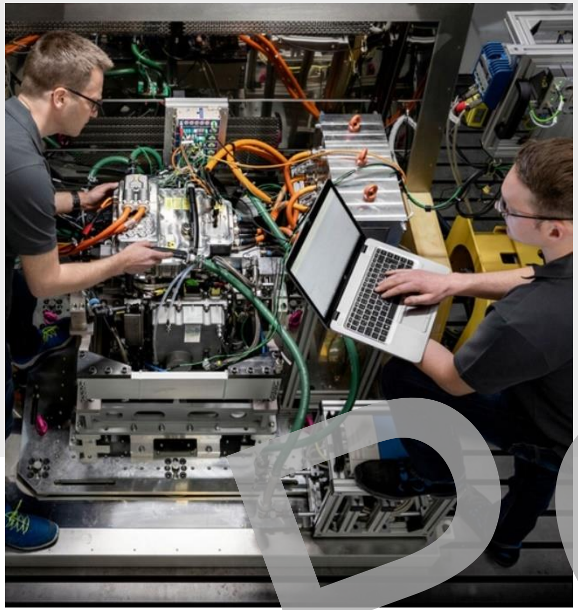
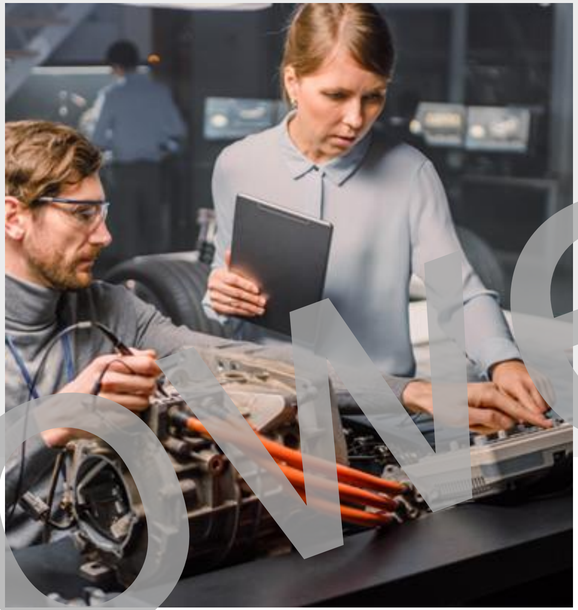
Four Divisions of Schaeffler

E-Mobility



Modular and scalable solutions for all types of electric drives.

Powertrain & Chassis



Innovative solutions for powertrain and chassis systems.

Vehicle Lifetime Solutions

Tailored solutions for the mobility ecosystem.

Bearings & Industrial Solutions

Products and solutions for the industry of the future.

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Local Vertical Integration

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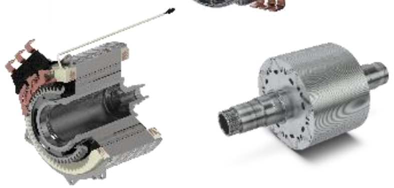
E-Motors

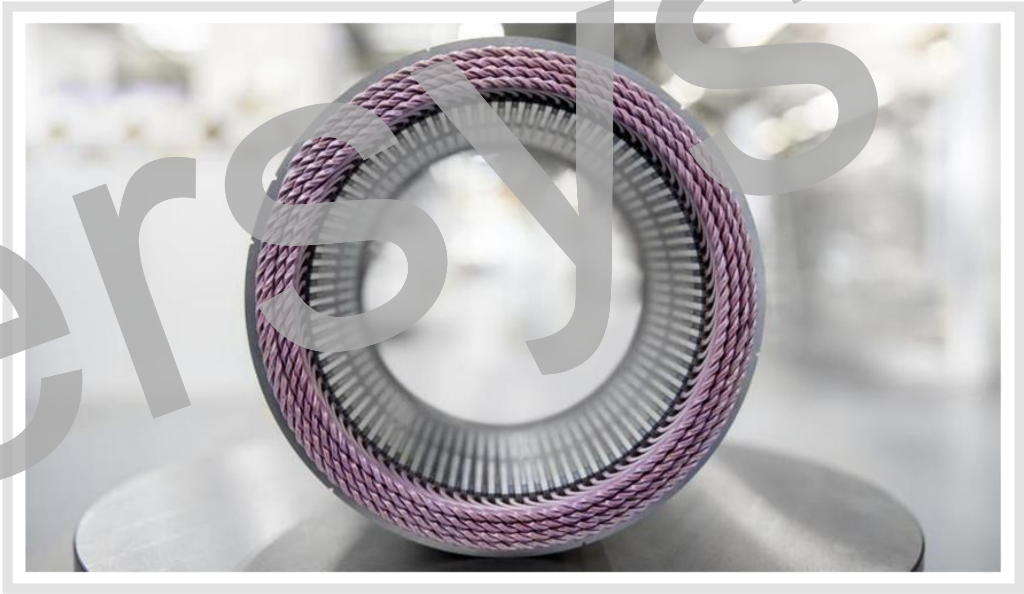
E-Motor sub-assemblies

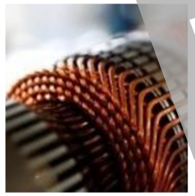


E-Motor components

Winding machinery

ELMOTEC STATOMAT





Winding

- Concentrated
- Hairpin
- Wave Winding

Stamping & Stacking

- Lamination stamping
- Interlock stacking + compressing
- Backlack stacking
- Welding

Capsulation & Isolation

- Trickling
- Flooding
- Powder Coating
- Potting

Injection Molding

- Insert Molding
- Leakage Resistance Overmolding

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e-Motor Products – Americas

48 V P1	400 V P2	400 V P3 (DHT)	400 V P4	800 V P4	800 V P4	800 V P4
Concentrated Winding	Concentrated Winding	Hairpin Winding	Hairpin Winding	ASM Hairpin Winding	Cont. Hairpin Winding	Hairpin Winding
OD 305 mm / AL 37 mm	OD 273 mm / AL 34 mm	OD 253 mm / AL 68 mm	OD 220 mm / AL 130 mm	OD 220 mm / AL 140 mm	OD 240 mm / AL 90 mm	OD 280 mm / AL 171 mm
20 kW / 13 kW	66.5 kW / 35 kW	120 kW / 75 kW	115 kW / 70 kW	225 kW / 80 kW	170 kW / 127 kW	310 kW / 180 kW
200 Nm / 97 Nm	196 Nm / 90 Nm	316 Nm / 227 Nm	306 Nm / 175 Nm	450 Nm / 110 Nm	340 Nm / 230 Nm	1000 Nm / 600 Nm

48 V | 400V | 800 V

20 kW → 125 kW → > 300 kW

Water cooled | Oil cooled | Water cooled | Oil cooled | Water cooled

+ Advanced innovation projects: EESM, rare-earth-free PMa SynRM, AFM, IM, etc.

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Rare-Earth-Free PM Motors

Rare-Earth PM Solutions

NdFeB, SmCo, SmFeN

IPMSM

PMa SynRM

Rare-Earth-Free PM Solutions

Ferrites, FeN, MnBi

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EMR Family

AFM

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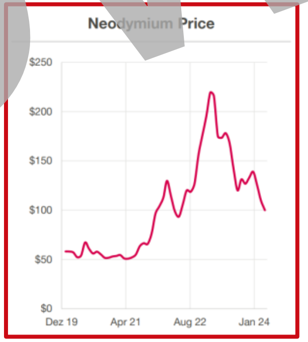
Prototype Motor

2025+ Activities

Project REFORM (NSERC-Mitacs)

University of Windsor

- Standard solution in automotive sector
  - Highest power density
- Price volatility of NdFeB magnets
  - Uncertainty, supply chain risks
  - Sustainability concerns



- Ongoing investigation of alternative solutions
  - R&D over a wide spectrum: **reduced & rare-earth-free PM**
- Reduced reliance on rare-earth PMs
  - Targeting future N.A. market
  - More sustainable choices

Accelerated Multi-Criteria Design Optimization of AFM with 3D FEA

Design Considerations

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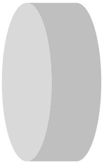
Traction Electric Motors

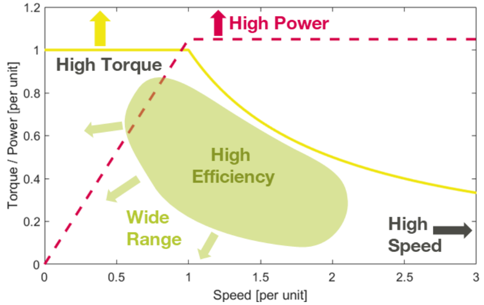
Design Factors

Physical Limits

- Outer diameter
- Axial length
- Critical ratios



Perform. Metrics

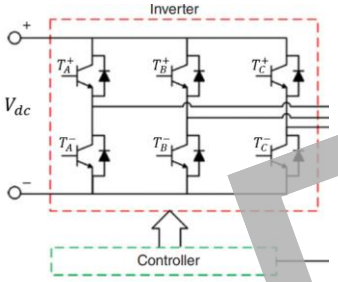


- Torque-speed
- Power-speed
- Back EMF
- Efficiency

Part Spacing

- Conductor area
- Magnet dimensions
- Magnet segmentation
- Lamination dimensions

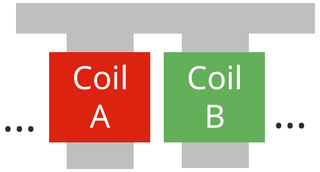
Inverter Limits



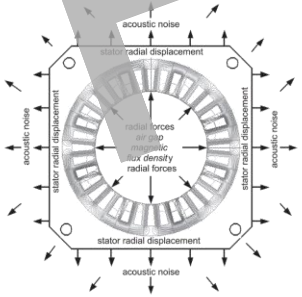
- Phase current
- DC link voltage
- Switching freq.

Winding Design

- Current density
- Number of layers
- Winding layout
- Parallel paths



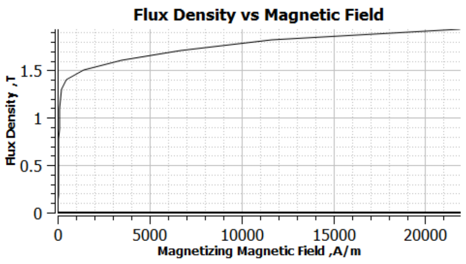
NVH



- Cogging torque
- Acoustic noise
- Campbell diagram
- Vibration harmonics

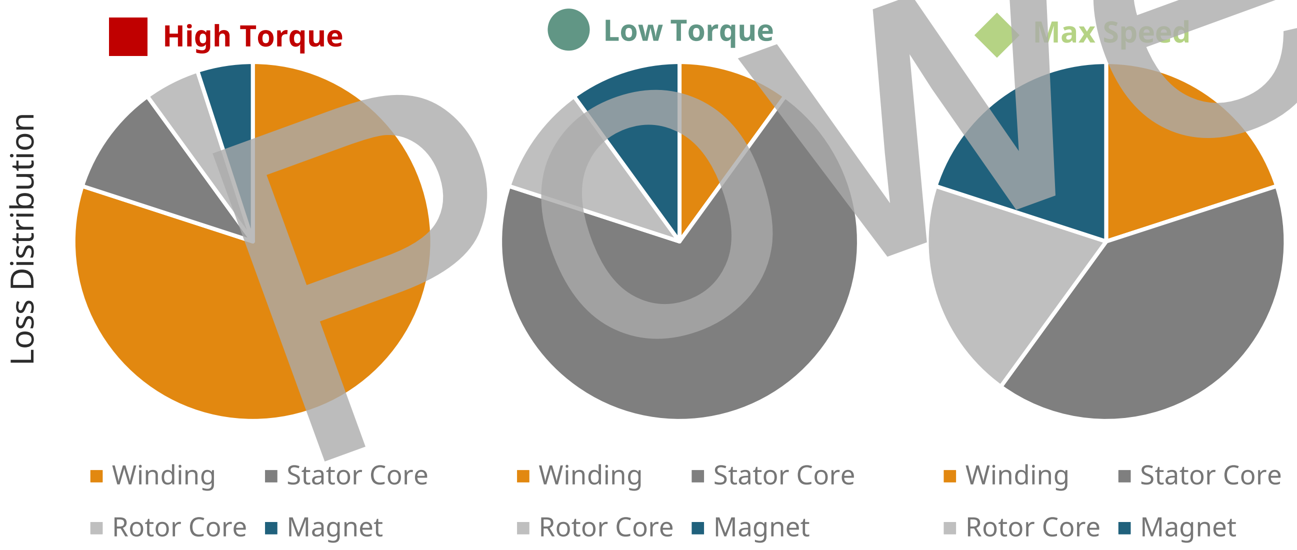
Material Property

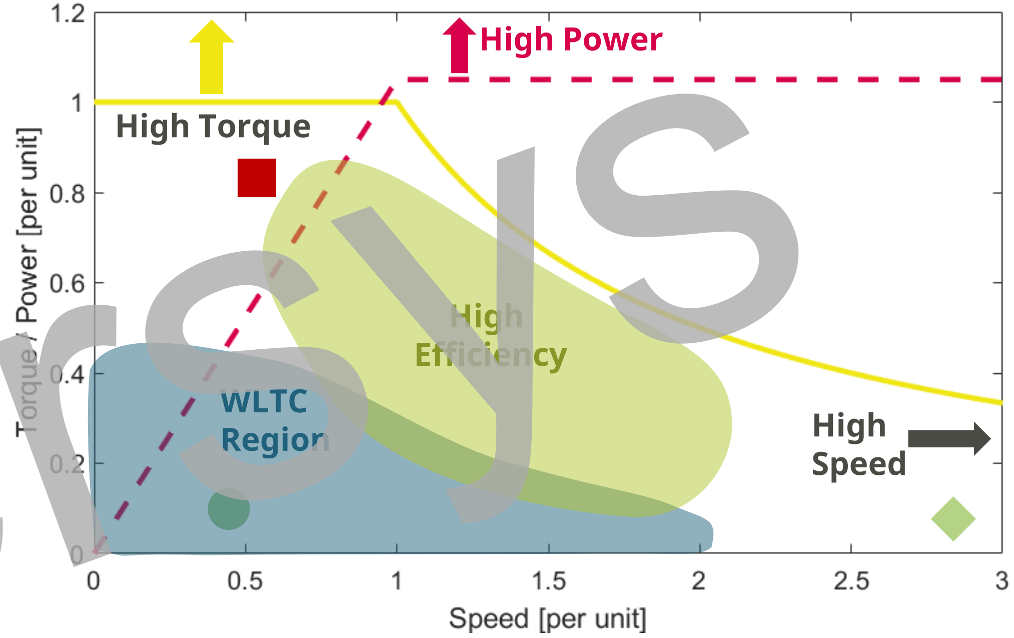
- BH magnetic curves
- Power loss curves
- Max. energy product
- Demagnetization
- Sustainability



Importance of Multi-Criteria Optimization

- Conflicting tradeoffs for design objectives
  - Peak torque vs. Peak power vs. Efficiency vs. …
- Distinct loss distribution for different operating points
  - Depends on e-motor topology (PMSM, IM, EESM)
  - Insufficient overlap of high efficiency & WLTC regions





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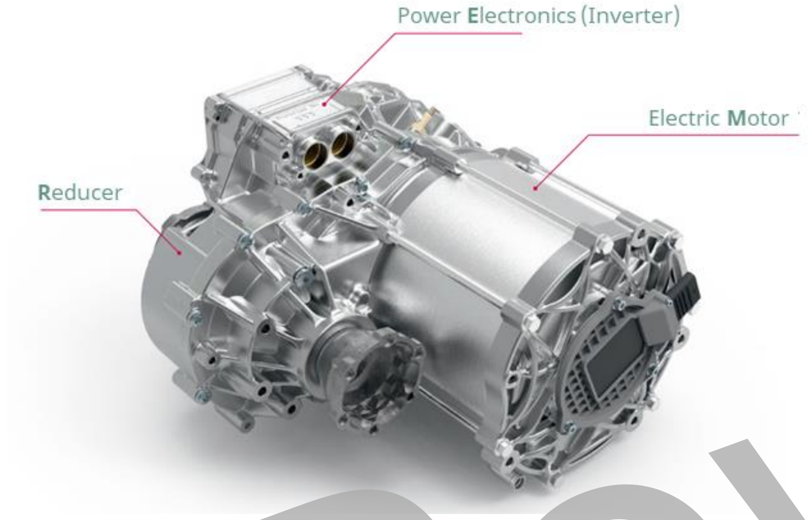
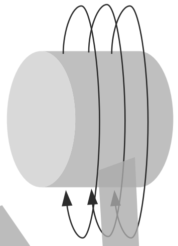
Challenges of Designing Axial Flux Motors

Radial Flux Motors (industry standard)



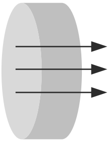


4th generation **EMR** e-axle drive

Torque	∝ Diameter² × Length ∝ Supply Current ∝ Num. Poles
Speed	∝ 1 / (Length × Num. Turns) ∝ Supply Voltage ∝ 1 / Num. Poles

- Can scale by varying stack length & keeping same cross-section
- Standard process for mass-manufacturing
- Different topologies in-production

Axial Flux Motors (alternative technology)



Prototype display of rotor-stator-rotor **AFM** concept

Torque	∝ Diameter³ ∝ Supply Current ∝ Num. Poles
Speed	∝ 1 / Num. Turns ∝ Supply Voltage ∝ 1 / Num. Poles

- Scaling not as straightforward…
- New manufacturing processes needed
- Mostly yokeless stator & surface-mounted PM rotor

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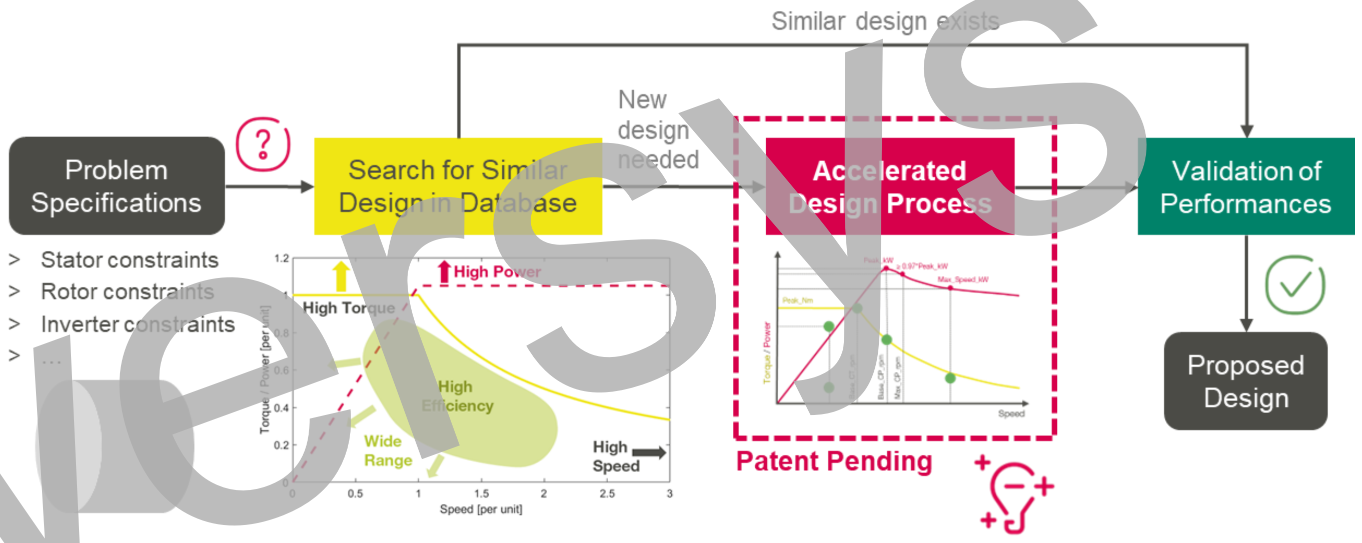
Accelerated Design Process

- **Accelerated Design Process** tailored for traction electric machines (RFM & AFM)
- Thousands of designs in **significantly less time** than typical approaches
- Rapid development of new designs for various applications
- Incorporates physical targets & constraints & target any set of requirements
- **Open to partnership & collaboration on existing R&D projects**



Reduced Time to Design Motors for New Applications!

Accelerated Multi-Criteria Design Optimization of AFM with 3D FEA

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Scripting with JMAG Designer

2D Model Setup

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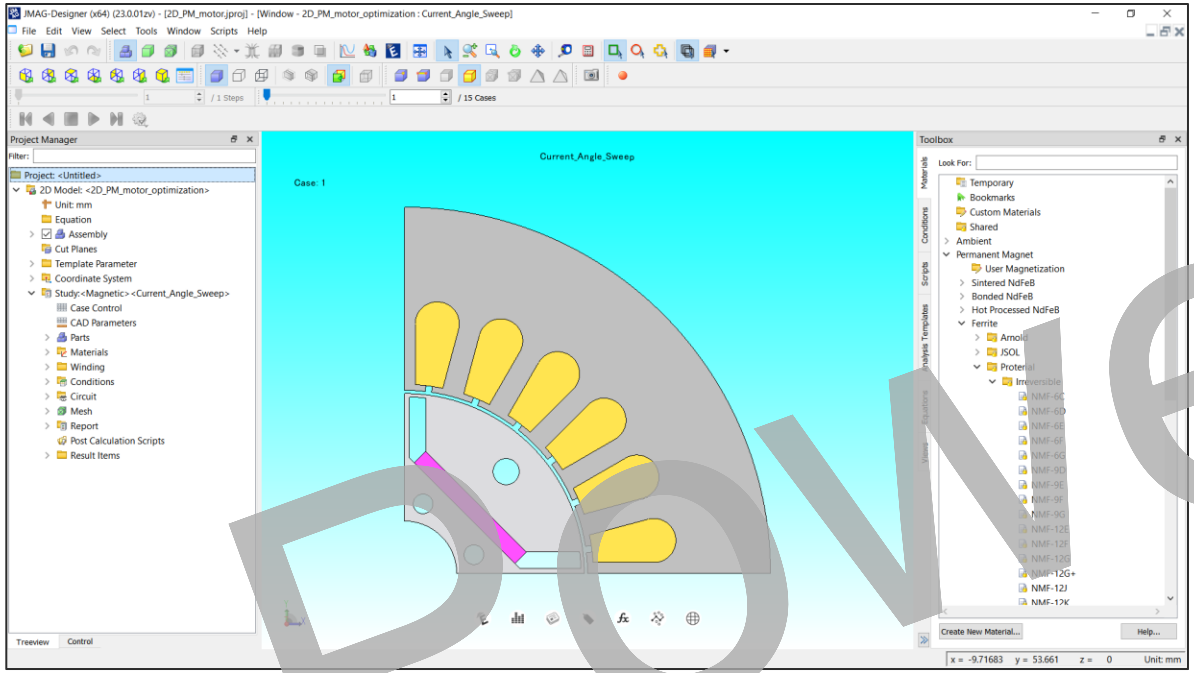
1) 2D Model from JMAG Example

PM Motor >> 2D Analysis

2D_PM_motor.jproj



2) Equations for Parameter Sweep

JMAG-Designer: Equations

	Variable	Type	Expression
1	MachineRPM	value	1800
2	NumPoles	value	4
3	ElectricFrequency	Expression	MachineRPM * NumPoles / 120
4	ElectricPeriod	Expression	1 / ElectricFrequency
5	PhaseAdvance	value	0
6	IPeak	value	0
7	NumCycles	Expression	1 / 1
8	NumPointsPerCycle	Expression	6 * NumCycles * NumTorquePoints
9	TimeStep	Expression	ElectricPeriod * NumCycles / NumPointsPerCycle
10	TimeStop	Expression	ElectricPeriod * NumCycles
11	NumSteps	Expression	NumCycles * NumPointsPerCycle
12	NumTorquePoints	value	12

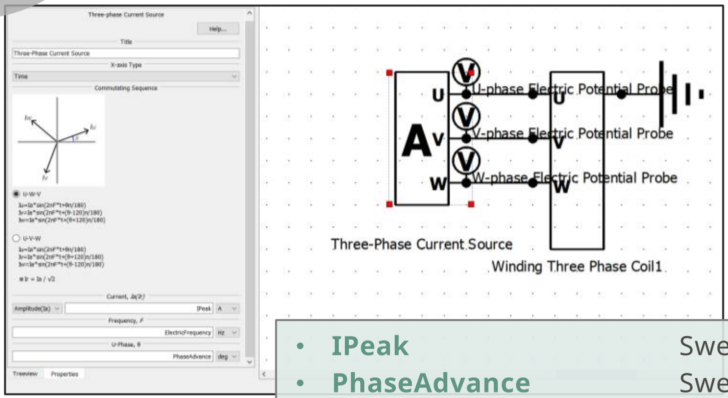
- MachineRPM
- IPeak
- PhaseAdvance
- TimeStep
- NumSteps

3) Transient Time Step Setting

Step Control

Number of Steps:	NumSteps
Step Interval Definition Type:	Time Interval
Time Step:	TimeStep s
Start Time:	0 s

4) Parametric 3-Phase Current-Driven Source



5) Create Cases for Current & Angle Sweep

JMAG-Designer: Design Table

Case	Label	Geometry	Groups	IPeak	PhaseAdvance
1				0	0
2				2	0
3				2	15
4				2	30
5				2	45
6				2	60
7				2	75
8				2	90
9				4	0
10				4	15
11				4	30
12				4	45
13				4	60
14				4	75
15				4	90

- **IPeak** Sweep 0 : 2 : 4 A (1+2 variations)
- **PhaseAdvance** Sweep 0º : 15º : 90º (7 variations)
- Number of cases 1 + 2*7 = 15 cases (1 for 0 A case)

2D Model Run

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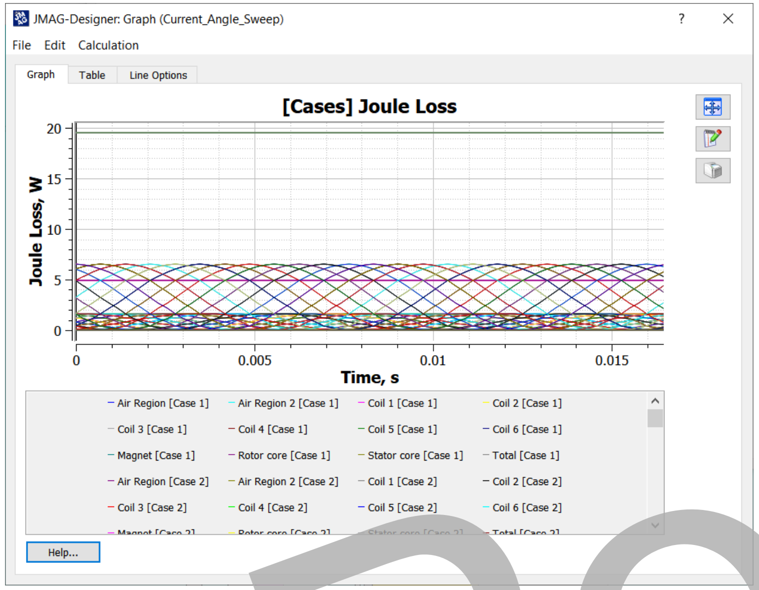
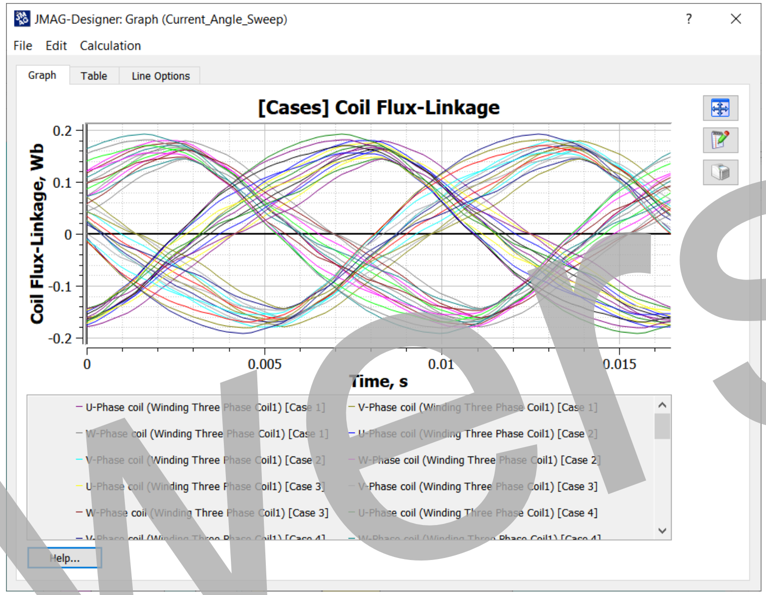
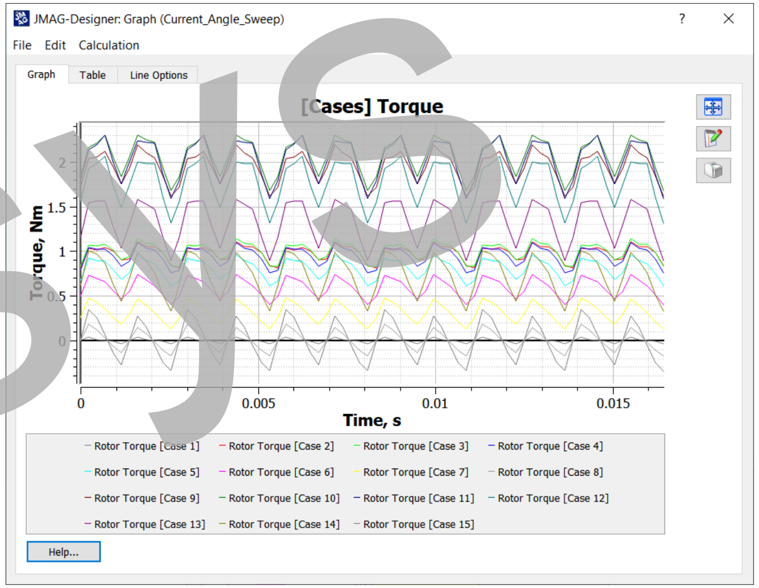
7a) Joule Losses for All Cases



7b) Flux Linkages for All Cases

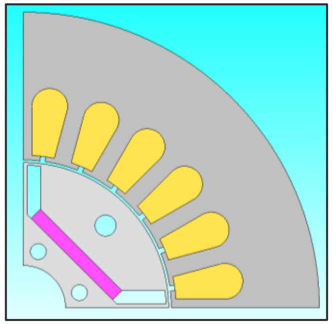


7c) Electromagnetic Torque for All Cases



6. Sweep input excitation & run all cases with **JMAG Scheduler**
   a) Variations of **IPeak** & **PhaseAdvance**
   b) Distribute cases over SMP

7. Save time-domain results as CSV files
   a) Extract **Joule loss** to calculate phase resistance
   b) Extract **Coil Flux-Linkage** to calculate DQ flux linkages
   c) Extract **Torque** to verify DQ torque



2D_PM_motor.jproj

- jmag_flux_linkages.csv
- jmag_inputs.csv
- jmag_joule_losses.csv
- jmag_torque.csv

2D Model Scripting & Post-Processing via MATLAB

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8) MATLAB Interface to JMAG V23.0

```
%% Load JMAG Model V23.0
if config.solve_jmag==1
    designer = actxserver('designer.Application.230');
    designer.Show();
    designer.Load(motor_data.path_project + motor_data.model_name)

    app = designer;
    app.GetModel(0).GetStudy(0).CheckForNewResults()
    designer.SetCurrentStudy(0)
    designer.GetModel(0).GetStudy(0).RunAllCases()
    designer.GetModel(0).GetStudy(0).GetDesignTable().Export(motor_data.path_project + "jmag_inputs.csv")
    designer.GetDataManager().GetGraphModel(0).WriteTable(motor_data.path_project + "jmag_flux_linkages.csv")
    designer.GetDataManager().GetGraphModel(1).WriteTable(motor_data.path_project + "jmag_joule_losses.csv")
    designer.GetDataManager().GetGraphModel(2).WriteTable(motor_data.path_project + "jmag_torque.csv")
    app.Quit()
end
```

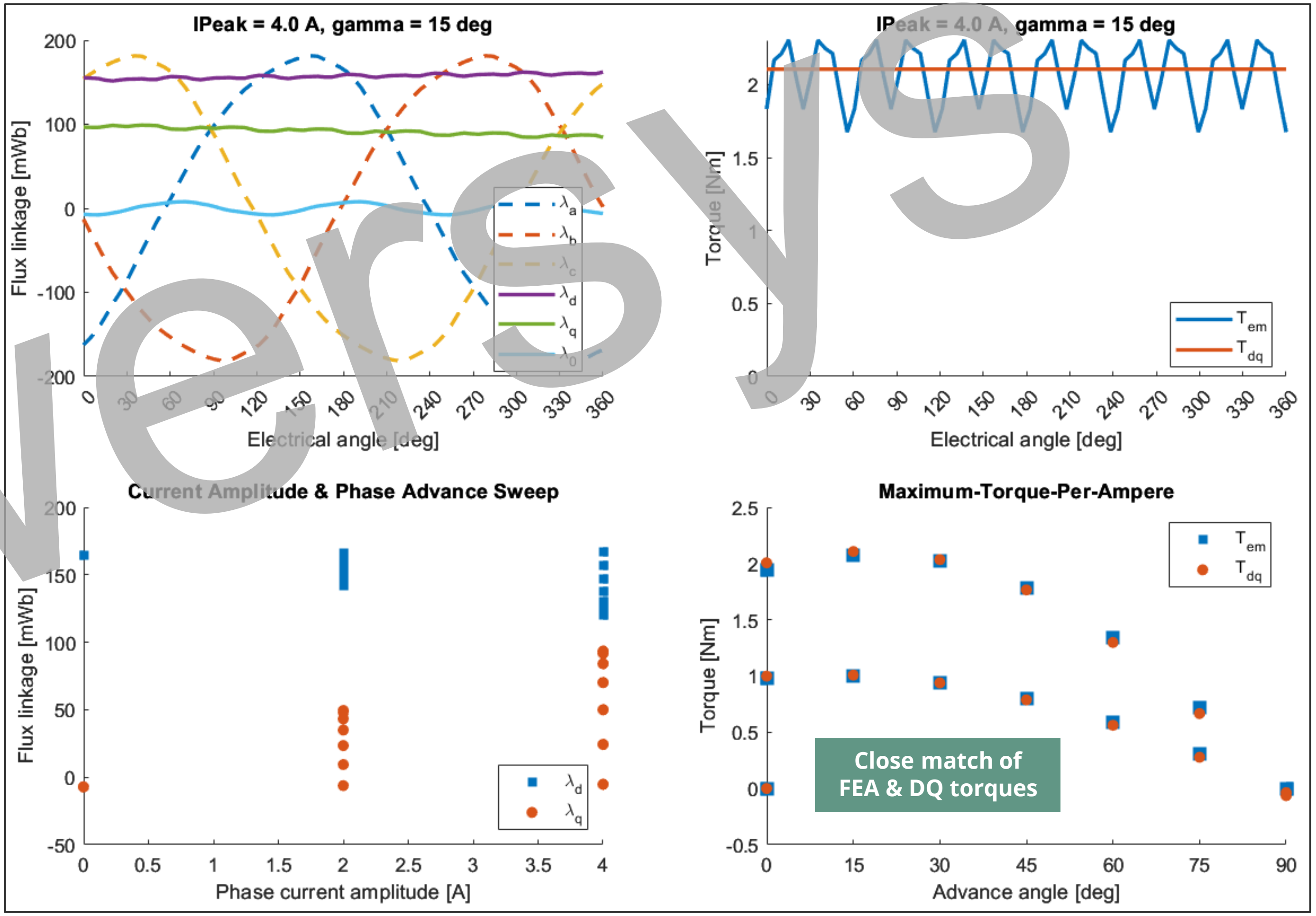
Successful implementation of scripting in MATLAB & Python

9) DQ Table for Post-Processing

	A	B	C	D	E	F
1	IPeak [A]	PhaseAdva	Ad [mWb]	Aq [mWb]	Tem [Nm]	Rph [mOhms]
2	0	0	164.0928	0.018298	5.54E-06	Inf
3	2	0	163.8977	56.61735	0.978734	813.9983506
4	2	15	158.5709	55.03499	0.999797	814.0013599
5	2	30	153.49	49.94802	0.942991	813.9985482
6	2	45	148.9811	41.4533	0.804365	813.9982766
7	2	60	145.3843	29.80936	0.588495	814.0004279
8	2	75	143.0446	15.60932	0.311191	814.0019392
9	2	90	142.2301	-0.00358	-2.77E-06	813.9959712
10	4	0	162.7003	100.5433	1.945164	814.0017095
11	4	15	152.8309	98.49772	2.06969	814.0003583
12	4	30	143.261	90.38219	2.023193	813.9997785
13	4	45	134.5655	76.03694	1.780224	813.9994776
14	4	60	127.3247	55.56636	1.336586	813.9999605
15	4	75	122.3109	29.6302	0.720939	813.9995848
16	4	90	120.4848	0.003353	3.02E-05	814.0011495

jmag_dq.csv

10) Output Verification of DQ Model



Extending Procedure to 3D AFM Model

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Saved Data from JMAG

- Geometry image as PNG
- Input design table as CSV
- Phase flux linkages as CSV
- Phase currents as CSV
- Phase voltages as CSV
- Electrical power as CSV
- Electromagnetic torque as CSV
- Joule losses as CSV
- Iron losses as CSV
- Hysteresis losses as CSV

Post-Processed Data using MATLAB

- Magnetostatic / Magnetotransient dq as CSV
- Part volumes as CSV

Simulation Overview

- Current & phase advance swept well
- Close match between FEA & DQ torques
- Stable flux linkages with 1D interpolation

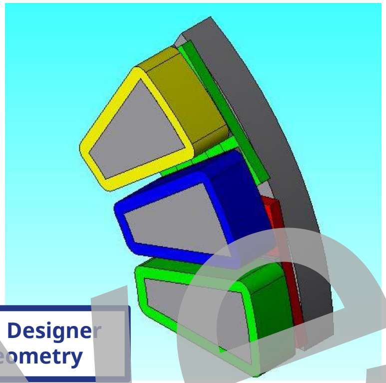
Initialization → Read DOE Table from CSV → Open JMAG Designer via Win32

- Load JMAG Model
- Set JMAG Objects

→ Loop for All Design Samples

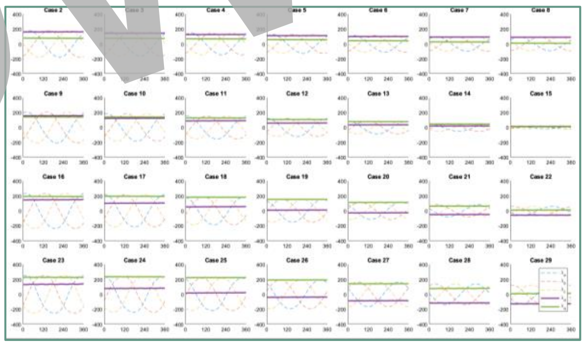
- Set Phase Current from Current Density
- Set Design Table for All Cases
- Check Feasibility & Export Image
- Create Mesh & Run for All Cases
- Export CSV Results for All Cases

→ Close JMAG Designer

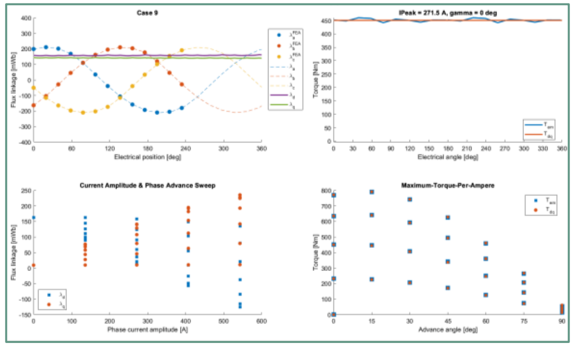


JMAG Designer 3D Geometry

Flux Linkage Waveforms



Verification of DQ Model



Test Sample Run for 3D AFM Model

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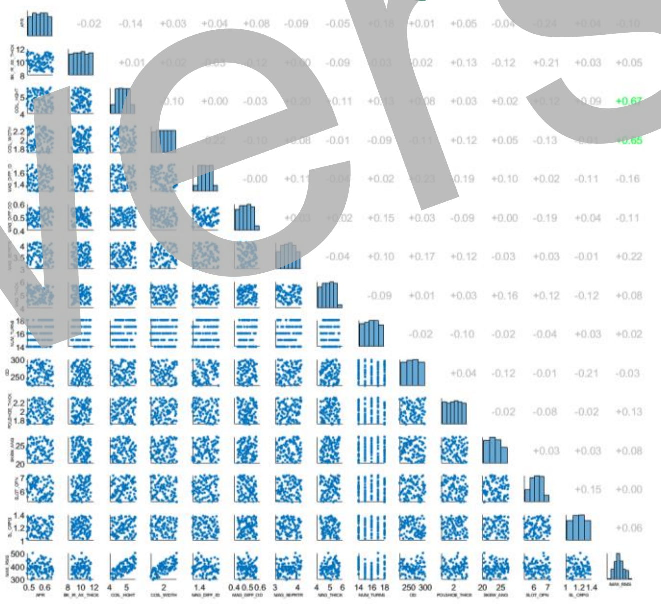
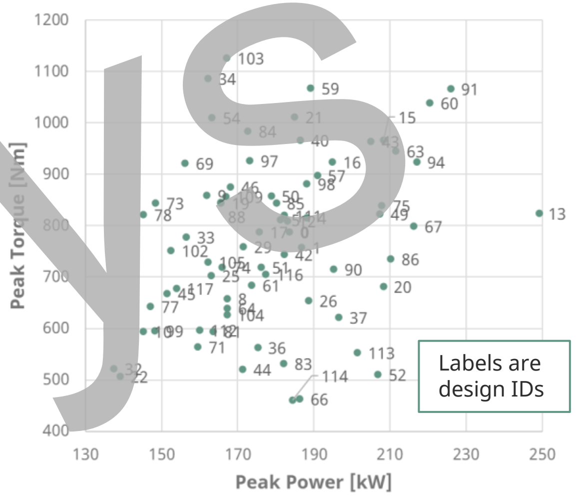
- **14 Independent Design Variables**
  - Outer diameter, Aspect ratio, Slot opening, Pole shoe thickness, Coil height, Coil width, Number of turns, Rotor back iron thickness, PM ID/OD offsets, PM separation, PM thickness, Skew angle, etc.
- **Latin Hypercube Sampling**
  - 100 samples, ±15% variation around baseline
  - Peak current density: 40 A_{rms}/mm^2
  - Integer number of turns
- **Simulation Observations**
  - 13 steps over 2/3rd e-period for 1+4x7=29 points
    - Phase current: [0%, 25%, 50%, 75%, 100%]
    - Phase advance: [0º,15º, 30º, ... , 75º, 90º]
  - 35 mins on average w/12 SMP & 1 job
    - 24 physical cores, 32 logical cores
    - Can improve via parallelization of cases & simulation settings

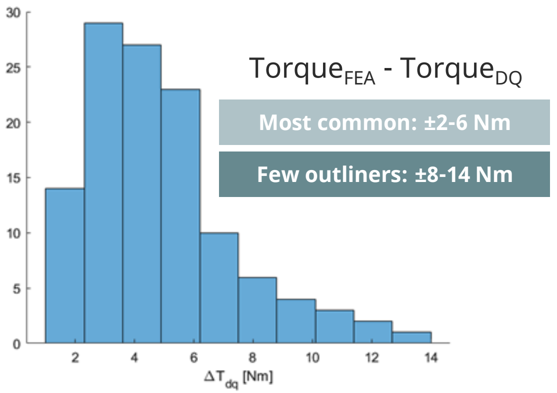
Correlation Plot of Design Variables



Initial Post-Processed Results



Histogram of MTPA Deviations



Accelerated Multi-Criteria Design Optimization of AFM with 3D FEA

AFM Design Optimization

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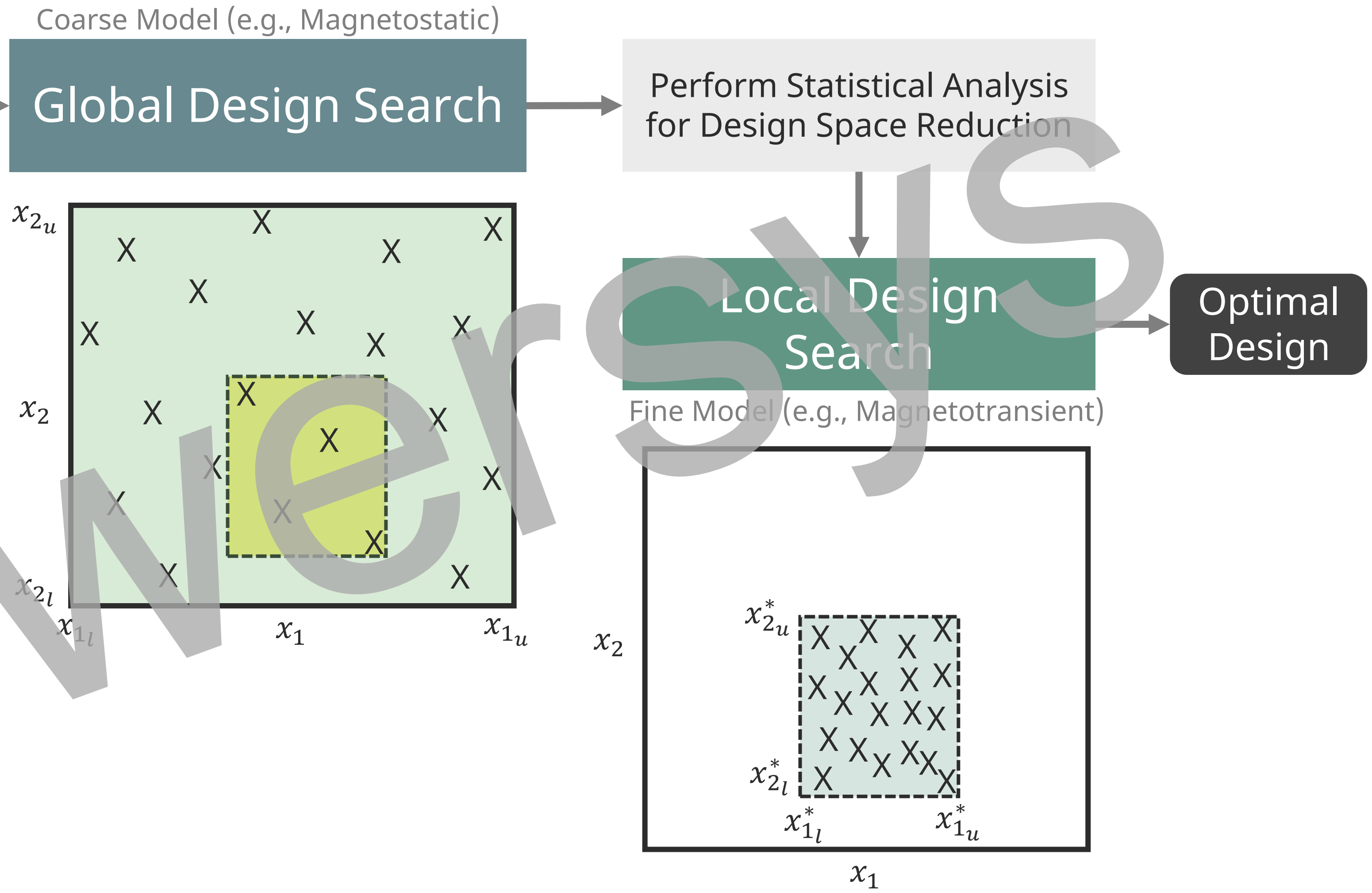
Design Process Overview

Motivation

- Global design search enables exploring a wide design space to help eliminate non-interesting design regions
  - Use coarse & cheap model to quickly evaluate KPI's (e.g., magnetostatic)

- High-performing regions identified via statistical analysis

- Reduced design space resampled for a local design search using a finer model
  - Use **computational budget effectively** in a relevant design region



Example problem with 2 design variables
Each X represents a sample (design variation)

Multi-Stage Process for Design Optimization

2 Passes Needed
1. Sensitivity Analysis
2. Initial Optimization

Workflow tested & being used across multiple regions

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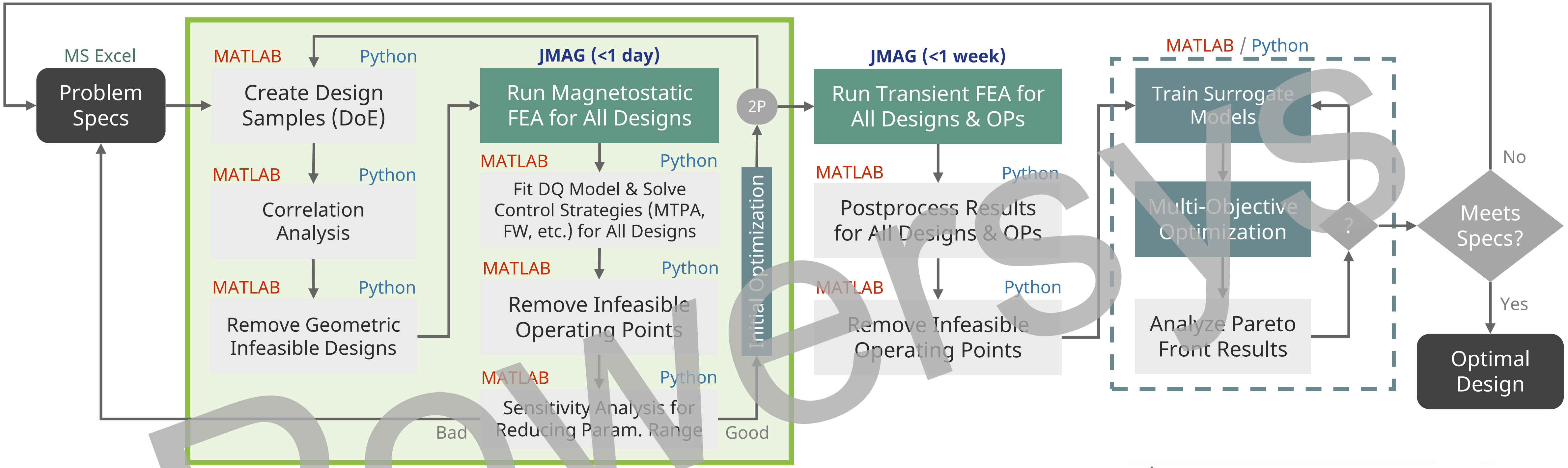


<u>Requirements</u>
- Torque/power density
- Magnet mass
- Efficiency...

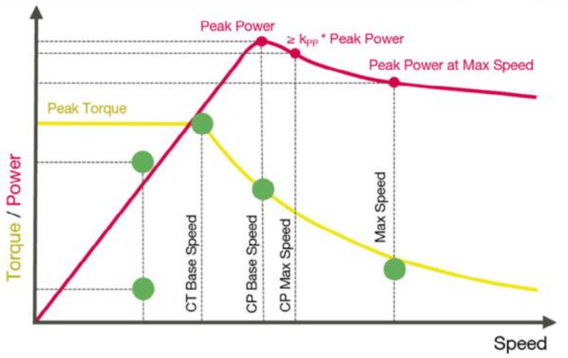
<u>Operating Points</u>
1. Peak torque
2. Max speed
3. Partial load (WLTC)

<u>Verify Range of Constraints</u>
- Stator outer diameter
- Magnet mass
- ...

<u>Design Parameters</u>
- Stator/Rotor geometry
- Material properties
- ...

<u>Evaluate KPI's</u>
- Average torque
- Torque/power density
- Phase voltage
- Losses (Cu DC)
- Cost functions
- ...

<u>Evaluate KPI's</u>
- Average torque
- Torque ripple
- Power factor
- Phase voltage
- Losses (Cu, Fe, PM)
- Demagnetization
- ...



DQ Model for Post-Processing Results

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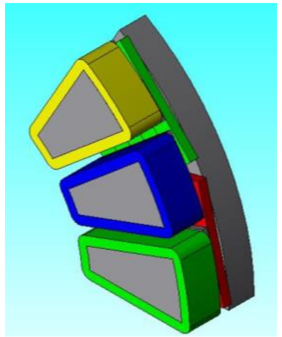
1) FEA Magnetostatic



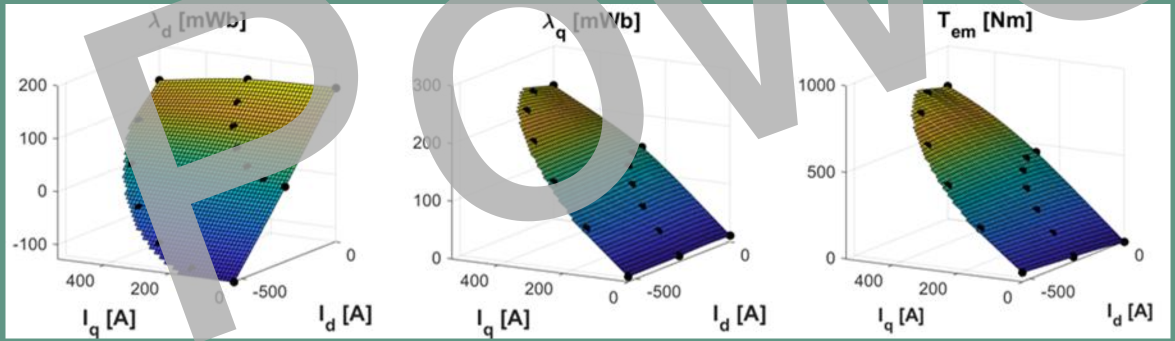
Axial Flux PMSM (**JMAG Designer 3D**)
Modeled by Ajith P. K. (SAG Germany)

2) Nonlinear DQ Data

- Inputs:
  DQ current sweep I_d, I_q
  (needed for saturation & cross-coupling effects)
- Outputs:
  DQ flux linkages λ_d, λ_q
  Phase resistance R_s

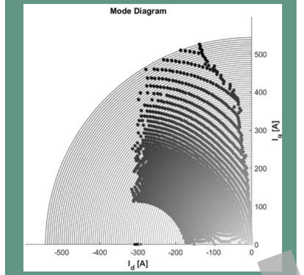
3) Fit DQ Model

d-axis Flux Linkage $\lambda_d(I_d, I_q)$ q-axis Flux Linkage $\lambda_q(I_d, I_q)$ DQ Torque $T_{em}(I_d, I_q)$



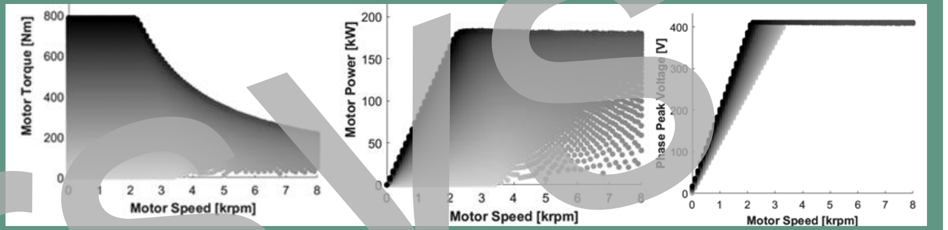
M. H. Mohammadi and D. A. Lowther, "A Computational Study of Efficiency Map Calculation for Synchronous AC Motor Drives including Cross-Coupling and Saturation Effects," *IEEE Transactions on Magnetics*, vol. 53, no. 6, Jun. 2017.

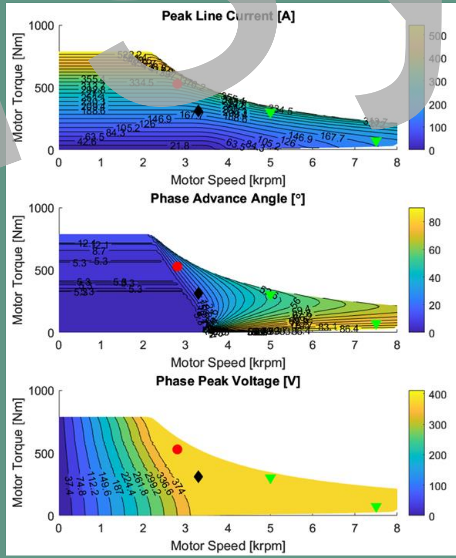
4) Solve Control Strategies



5) Performance Curves

Torque vs. Speed Power vs. Speed Voltage vs. Speed





Lookup Tables to Evaluate Different Operating Points

- Consider different gear ratios for representative operating conditions
- Check for **feasibility** of operating points (OPs)
- Ignore a design if OPs are not feasible!

Note: A random design sample is shown as an example

Visualizing Tradeoffs of KPIs

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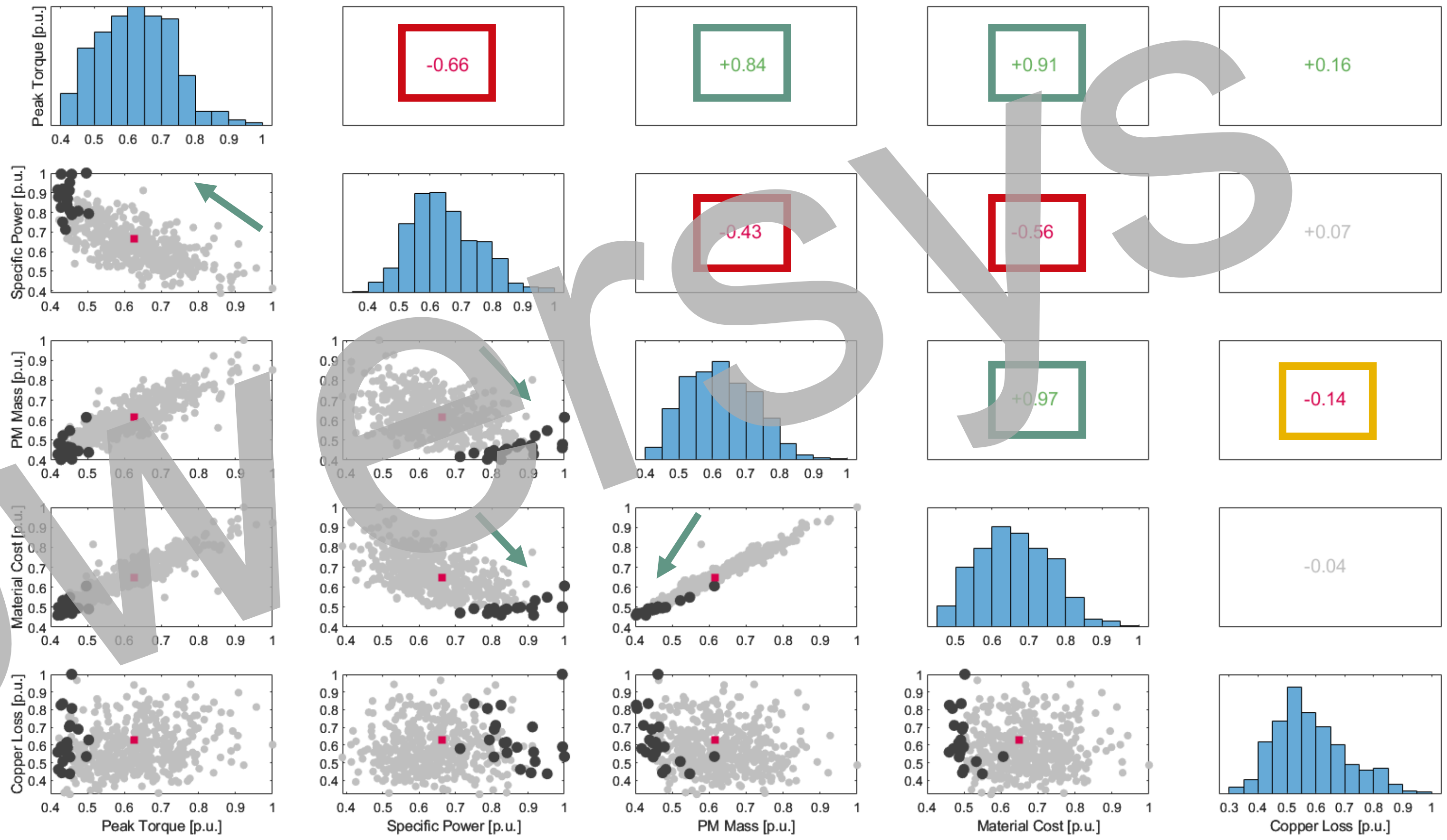
- **Simulation Statistics**
  - 14 independent design variables
  - 90+ KPIs computed using DQ models, part volumes & masses, losses, material pricing, desired OPs, etc.
  - 487 design samples from 3D FEA
    - 1 simulation week on 2 towers
    - 457 feasible designs in grey (OPs met)

- **Correlation Plot of KPIs**
  - Lower diagonal: pairwise scatter plots
    - Baseline design as **red square**
    - 21 optimal designs as **black circles**
  - Diagonal: histograms of KPIs
  - Upper diagonal: Spearman correlation coefficients (positive, negative)

max. Specific Power [kW/kg], min. Material Cost [$]



Design tradeoffs among KPIs... → Can set other objectives & filters to select designs for different targets

Accelerated Multi-Criteria Design Optimization of AFM with 3D FEA

Conclusion

5

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Conclusion

Data-driven design process based on 3D FEA simulations (coarse & fine) in **JMAG Designer** & representative models

Demonstrated **computationally-efficient design optimization** for 3D AFM & 2D RFMs (IPMSM, PMa SynRM, etc.)

Reduced engineering time by rapid design tool across different regions

Open to partnerships & collaboration on **R&D + advanced projects**

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