Performance Map Calculation of Current-Excited Synchronous Motors using optiSLang

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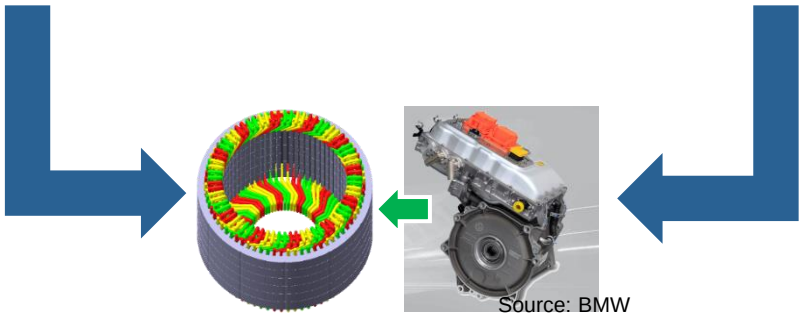
- Project Framework and Motivation
- Assessment of Performance for Variable Speed Electric Drives
  - Definition of terms
  - Torque speed curves and performance maps
  - Recapitulation of torque-speed curve calculation
- Suggested Workflow in optiSLang
  - Optimization task and its implementation optiSLang
  - Best practice core concepts
  - Issues
- Summary

Project: „ProE-Traktion“

- Machine Design
  - Identification of interdependencies with manufacturing
  - Production-oriented design
- Manufacturing
  - New manufacturing processes
  - Intelligent production line



Source: BMW

- Search for simultaneous improvement
  - Production time and cost
  - Product performance

Supported by:

Federal Ministry for Economic Affairs and Energy

on the basis of a decision by the German Bundestag

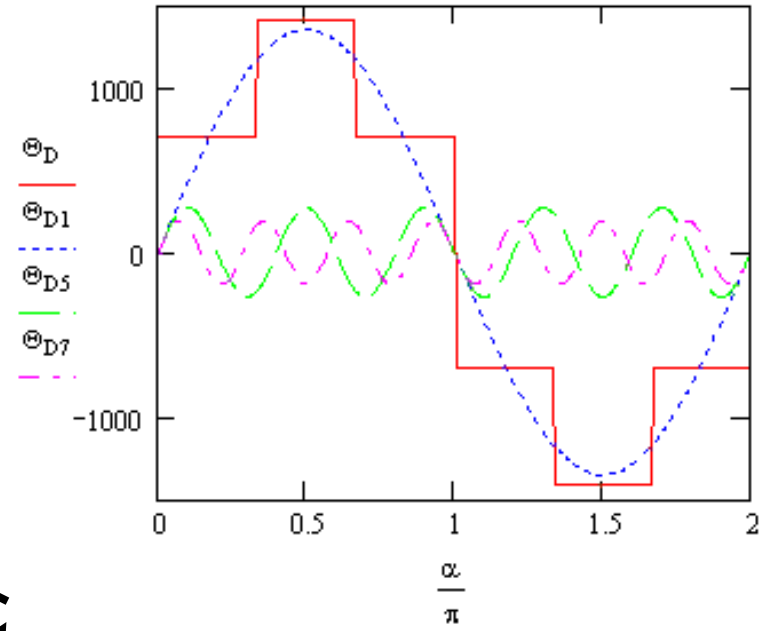
DLR Projektträger

Definition of Terms

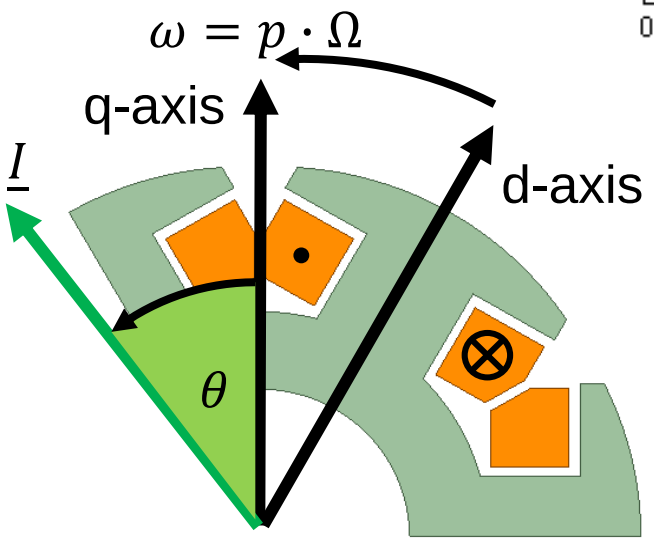
- dq-Transformation
  - Rotor oriented
  - Angle θ between q axis and current vector
  - Polar description used in present work

$$I_q = \sqrt{2} \cdot I \cos(\theta)$$

$$I_d = -\sqrt{2} \cdot I \sin(\theta)$$



- For Synchronous Machines
  - Speed directly related to f_{el}
  - T is f(I_e, I, θ, f_{el})
    not known a priori

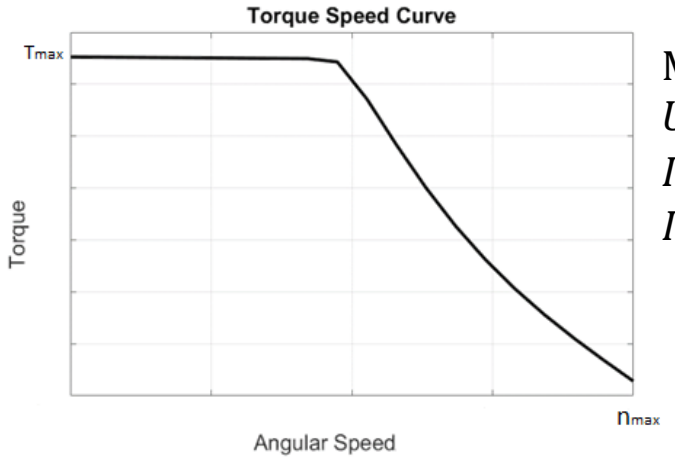


Torque-Speed Curve and Performance Maps

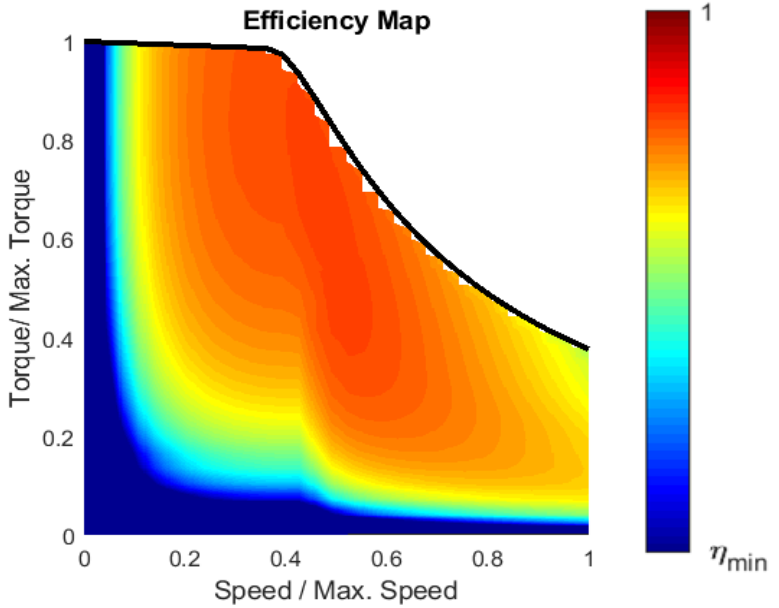
- System view
  - Electric Machine: $\mathrm{T}(I_e, I, \theta, f_{el})$
  - Power electronics
  - Control

- Torque-Speed-Curve
  - Limit of practically reachable points
  - Maximization of torque at every speed
  - Unique solution

- Performance Maps
  - Assessment of operation points
  - Non-uniqueness
  - Goal function to enforce unique solution
  - Minimization of chosen goal function

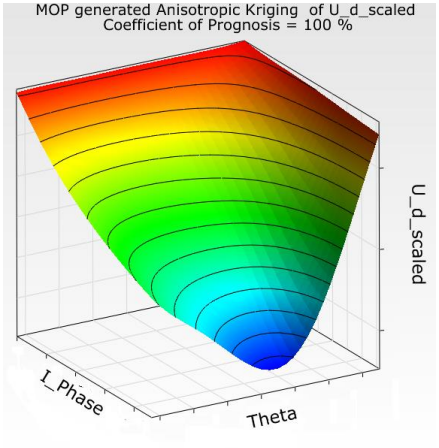


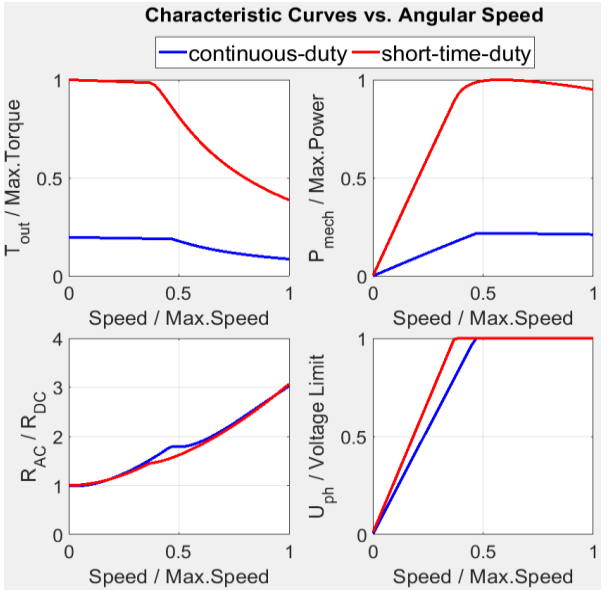
$$\text{Max } T$$
$$U_{\mathrm{ph}} \leq U_{\mathrm{max}}$$
$$I_{\mathrm{e}} \leq I_{\mathrm{e,max}}$$
$$I \leq I_{\mathrm{max}}$$

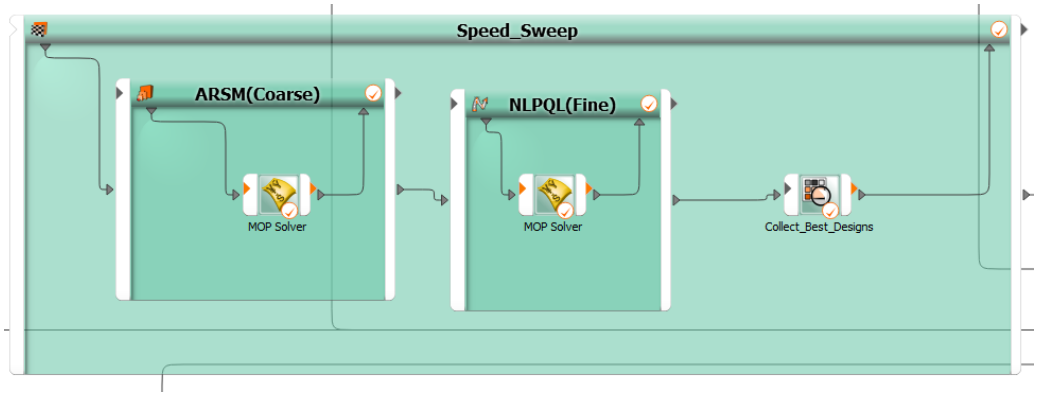


Recapitulation of Torque-Speed Curve Calculation

- FE-based calculation of envelope curves
  - Sampling of FE-Model
  - Spanning of response surfaces
- Optimization using MOPs
  - Two optimizers in series
- Careful selection of response quantities for MOP creation
  - Other results as derived quantities
  - $U_{d,q} = \Omega \cdot U^*_{d,q} + R_{AC}(P^{Stat}_{Cu}) \cdot I_{d,q}$
  - $U_{Max} \geq \sqrt{\frac{U_d^2 + U_q^2}{2}}$
- Export of text files from optiSLang scenery



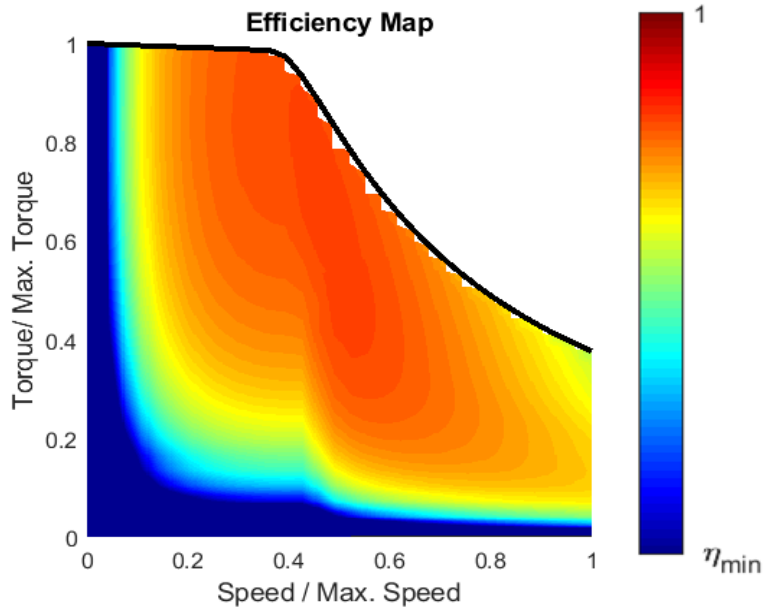




Description: Mathematical Optimization Task

- Uniqueness through objective function
  - Maximum Torque per Ampere
  - Power Factor Maximization
  - Total Loss Minimization
- Definition of T-n-points
  - Check if point is reachable
- Optimization for each reachable point in grid

$$\text{Min}\,[\mathrm{F}(I_e, I, \theta, f_{el})]$$
$$U_{\mathrm{ph}} \leq U_{\max}$$
$$I \leq I_{\max}\,;\; I_{\mathrm{e}} \leq I_{\mathrm{e,max}}$$
$$n = n_0\,; T = T_0$$



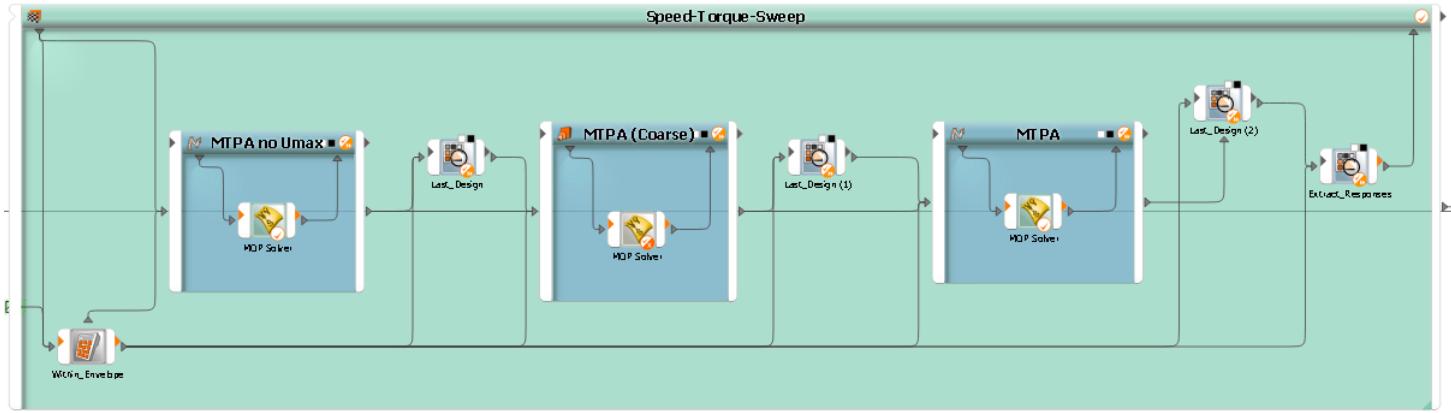
Description: Implementation in optiSLang

- Tolerance for Torque
  - Relative valued
  - Two distinct constraints

Name	Type	Expression	Criterion	Limit
MTPA	Objective	I_Goal	MIN	
Target_Torque	Constraint	-Delta	≤	Tolerance
Max_Voltage	Constraint	U_Phase_RMS/Umax	≤	1
Target_Torque2	Constraint	Delta	≤	Tolerance
Delta	Variable	(T_Target-Torque_edit)/T_Target		
Tolerance	Variable	0.01		

- Rectangular grid of T-n points
  - Check if point is reachable (“conditional execution”)

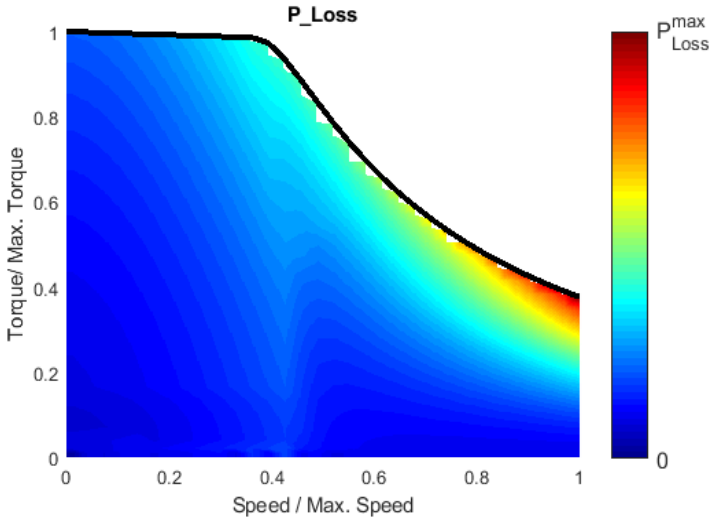
- Three optimizers in series
  1. Without voltage constraint
  2. Coarse optimization
  3. Fine optimization

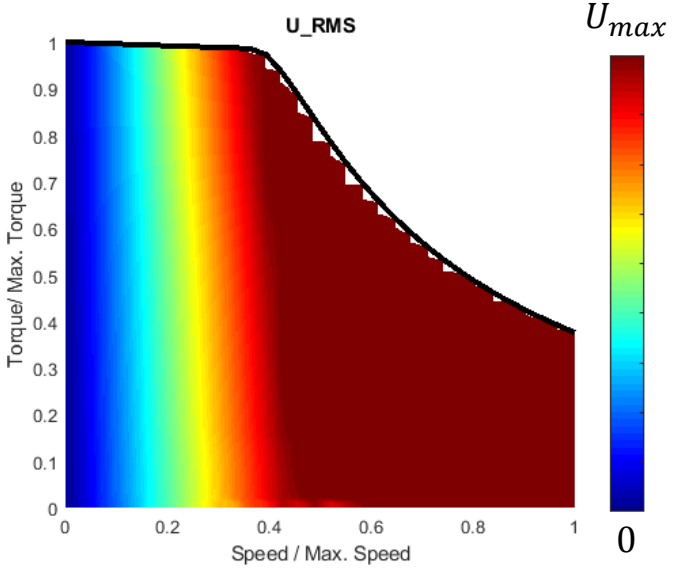


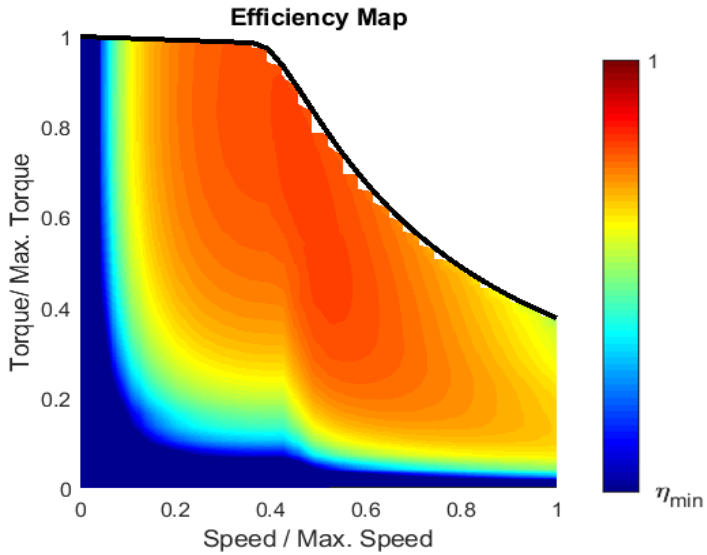
Description: Data Handling and Post-Processing

- Merging of rectangular grid points and envelope curve points

- Post-Processing in Matlab
  - Physics based extrapolation ($T = 0, n = 0$)
  - Contour plot
  - Plot of envelope curves

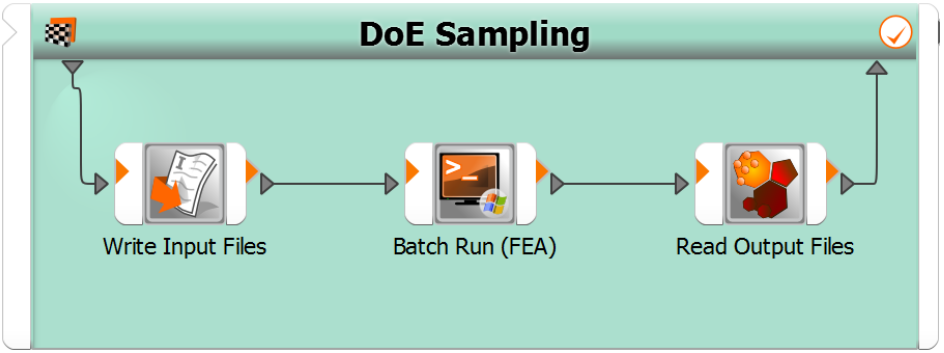






Core concepts

- Sampling of FEM-Model of Motor
  - Accounts for effects modeled in FEA
  - Separate optiSLang project
- High CoP values
  - Careful selection/normalization of responses
  - Decomposition of results into multiple terms (e.g. core losses, voltage)
  - Accurate model of simple response over uncertain model of complex response
- Definition of equality constraint using tolerance
- Series of Optimizers
  - Varying Accuracy
  - Constraints



Results for Different Control Strategies

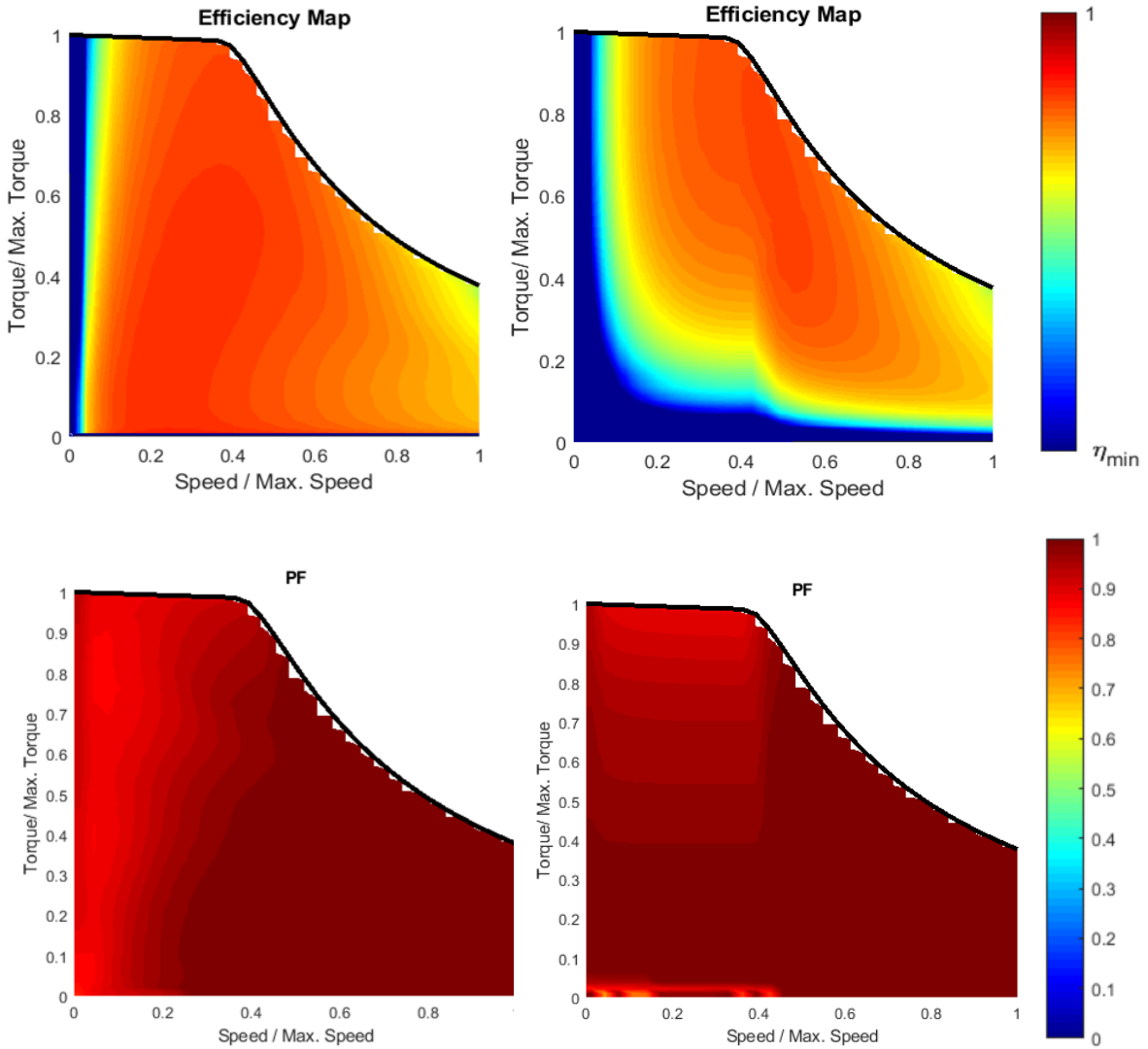
- Maps with different criteria computed using same MOP
  - No additional FEA
- Total loss minimization (left):

$$F = \sum \text{Losses}$$

- Maximum Torque Per Ampere (right):

$$F = I$$

  - Rotor losses dominant in low torque region



Results for Different Control Strategies

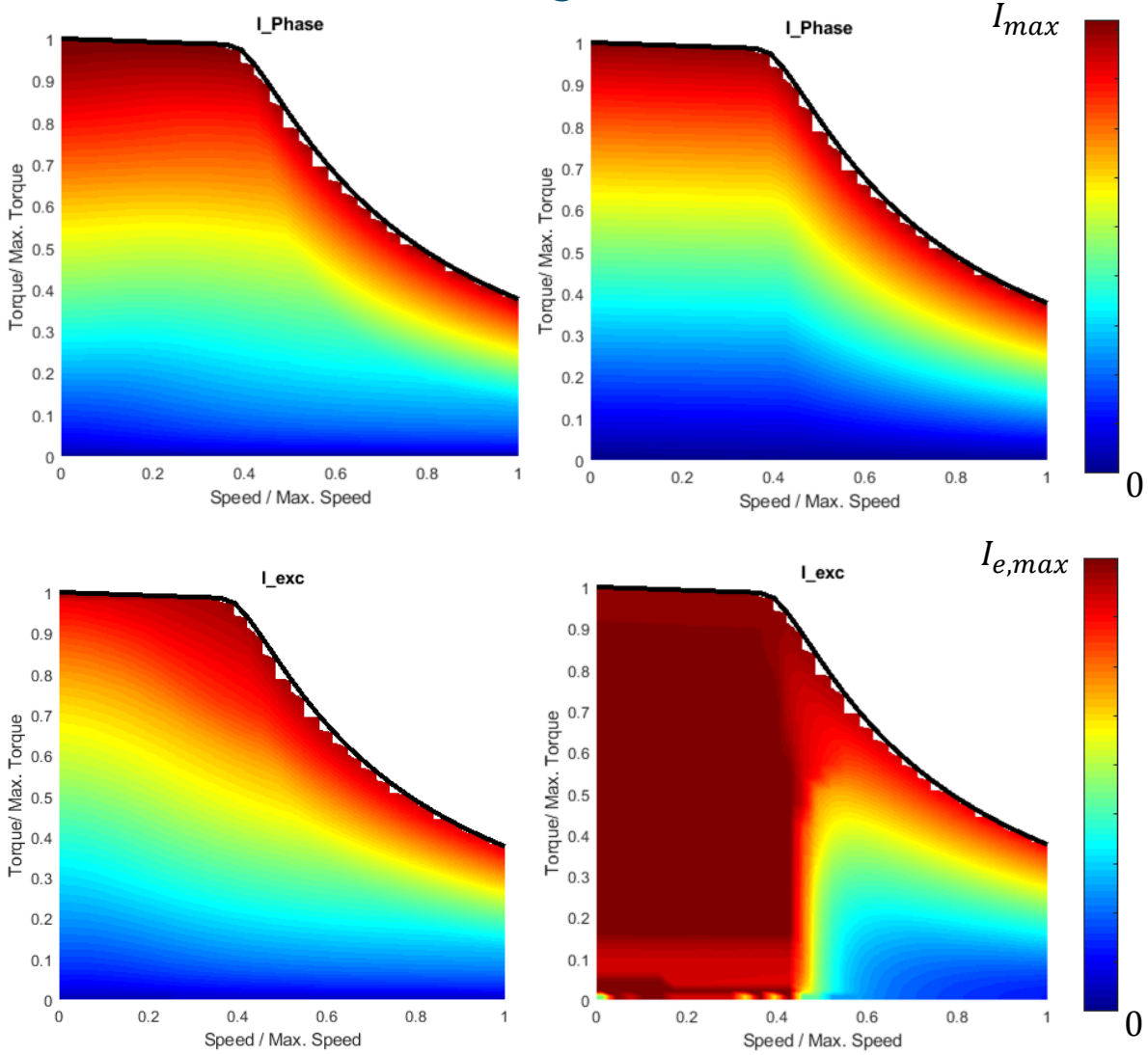
- Maps with different criteria computed using same MOP
  - No additional FEA
- Total loss minimization (left):

$$F = \sum \text{Losses}$$

- Maximum Torque Per Ampere (right):

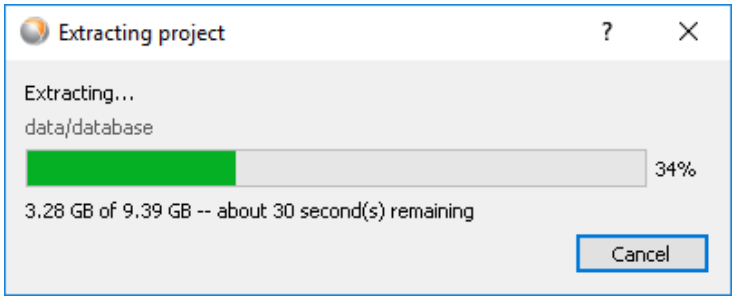
$$F = I$$

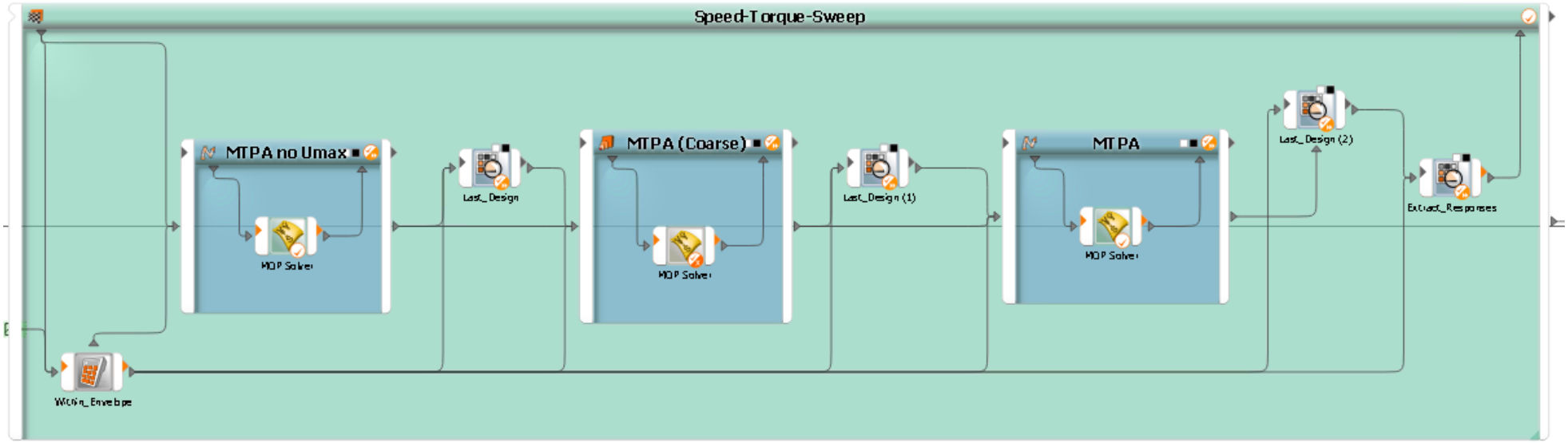
  - Rotor current maximized in base speed region



Issues: Run-time Performance

- Database
  - Storage of all iterations in all optimizers
  - Project speed issue
  - Option to store only best design missing

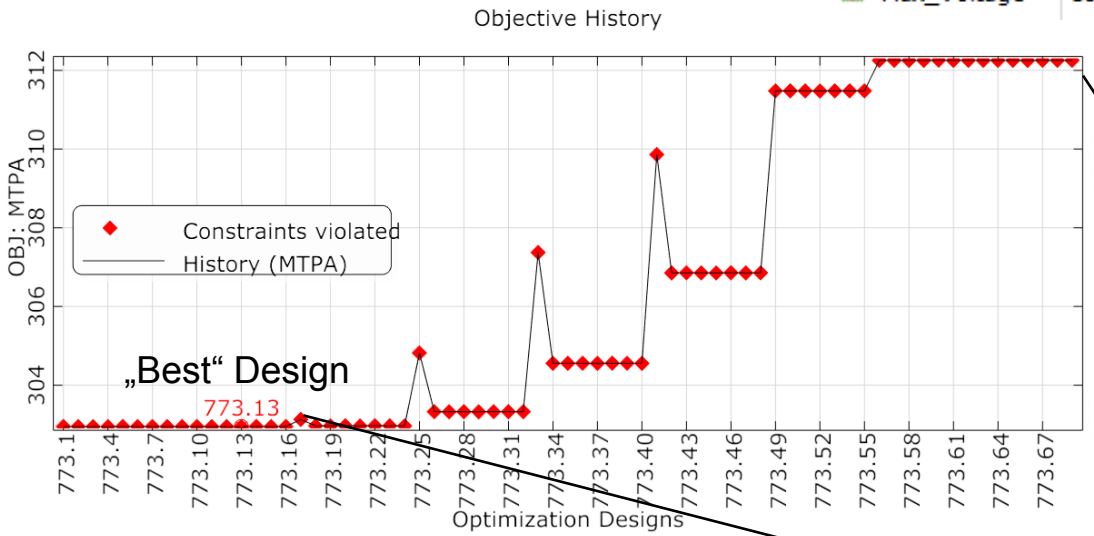


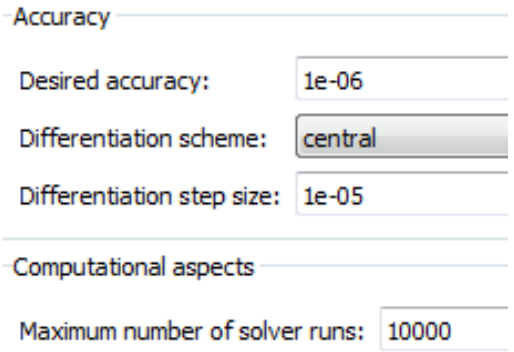


Issues: Post-Processing of Optimization

- Choosing best design
  - Issues when all iterations violate constraint

MTPA	Objective	I_Phase	MIN	
Target_Torque	Constraint	abs(Torque-T_Target)/T_Target*100	≤	1
Max_Voltage	Constraint	U_RMS/Umax	≤	1

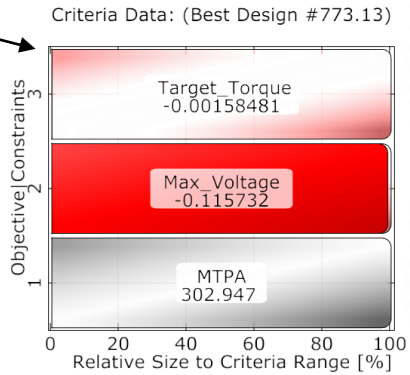


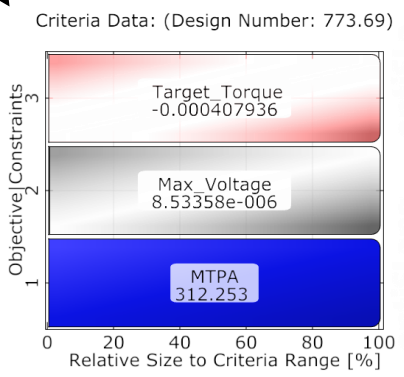


- Constraint fulfilled within certain accuracy

(amount of violation always in the order of magnitude of accuracy set)

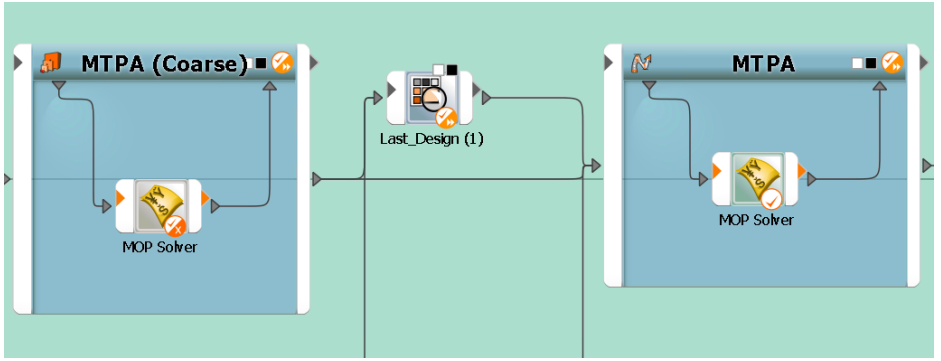
- Selector picks iteration with lowest objective function (ignores constraints)

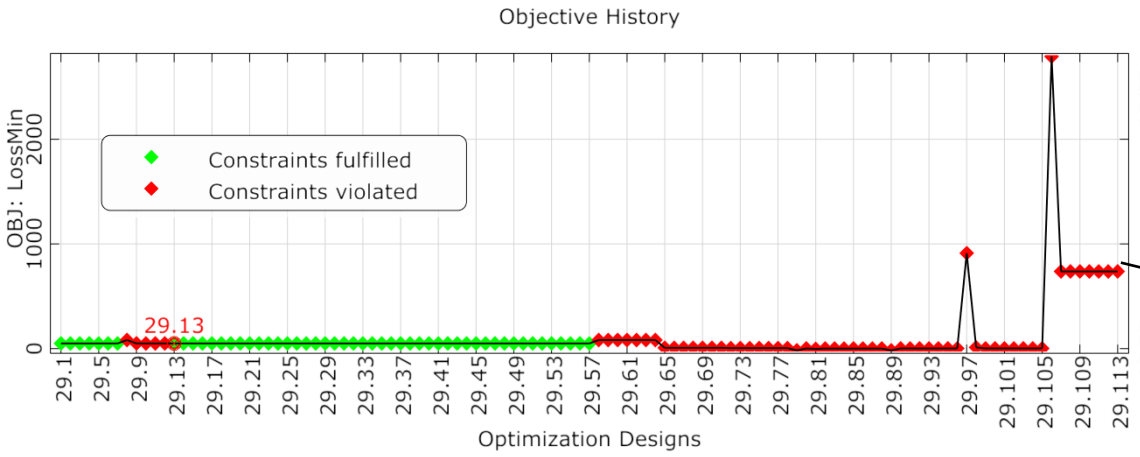


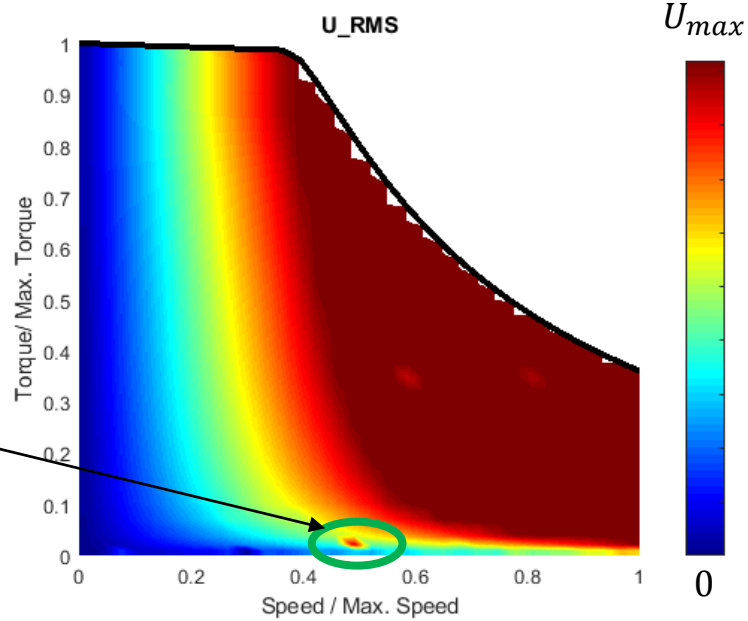


Issues: Post-Processing of Optimization

- Solution using “data mining” node
  - Last design of NLPQL optimizer forwarded
- Erroneous convergence behavior for some T-n points
  - Currently: Manual correction of text files
- Possible correction in future
  - Python script node for design selection







Summary

- Versatile tool for performance map calculation
  - Multiple effects considered (sampling of FEM)
  - MOP-assembly (accuracy check with CoP)
  - Allows optimizer chains (robust solution)
  - Highly flexible / customizable
- Assessing different strategies/limits without the need of additional FEM
  - MOP as electric machine model
  - High accuracy through careful selection/normalization of result quantities
- Issues in terms of practical handling
  - Run-time performance
  - Selection of optimization result

Special thanks to Mr. Markus Stokmaier for outstanding support.