HILITE INTERNATIONAL

Optimization and design of a stepper motor with OptiSLang

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Thursday, 24.10.2024

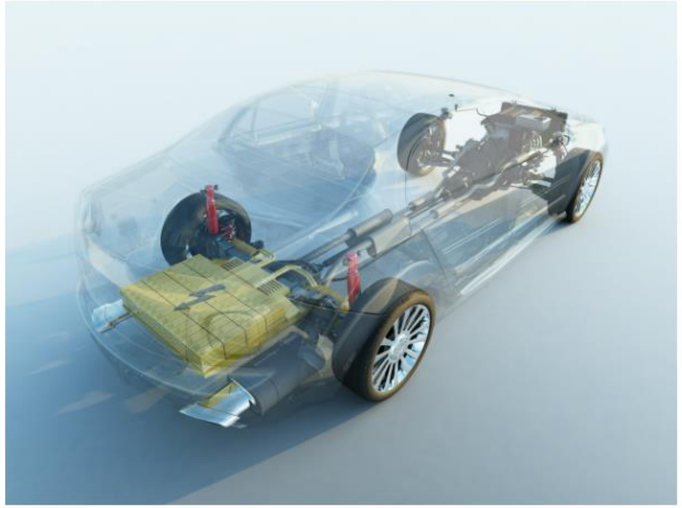
Agenda

1. Short introduction of Hilite
2. Introduction to the task
3. Details of the optiSLang system
4. Analysis and optimization
5. Test of the realized design
6. Conclusion

Hilite International

- Automotive company
- Founded in 1930
- About 1700 employees
- 8 locations on 3 continents
- About 550 Mio. € turnover

Electric, hybrid and hydrogen drives ›



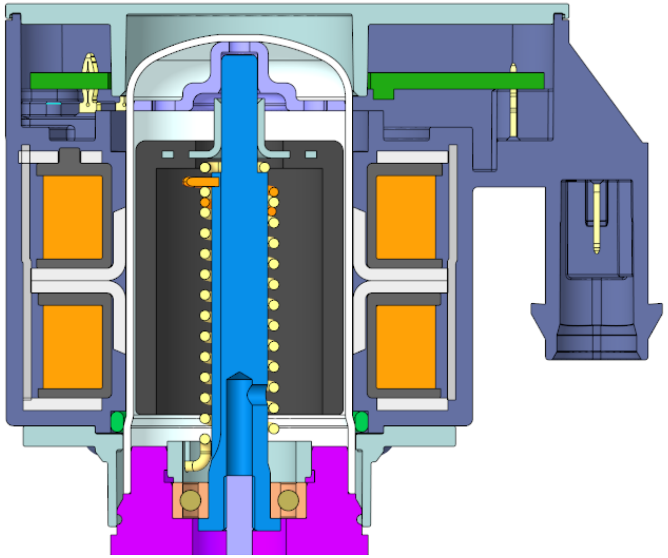
Engine and transmission applications ›

Introduction

Task, starting conditions and system setup

Task and basic information

- Analysis and optimization of a stepper motor
- Specific criteria for minimal torque and installation space given by system and customer
- Use of best current concept (B4) for optimization and current test design (B2b) for comparisons
- Worst-Case constraints for analysis and optimization

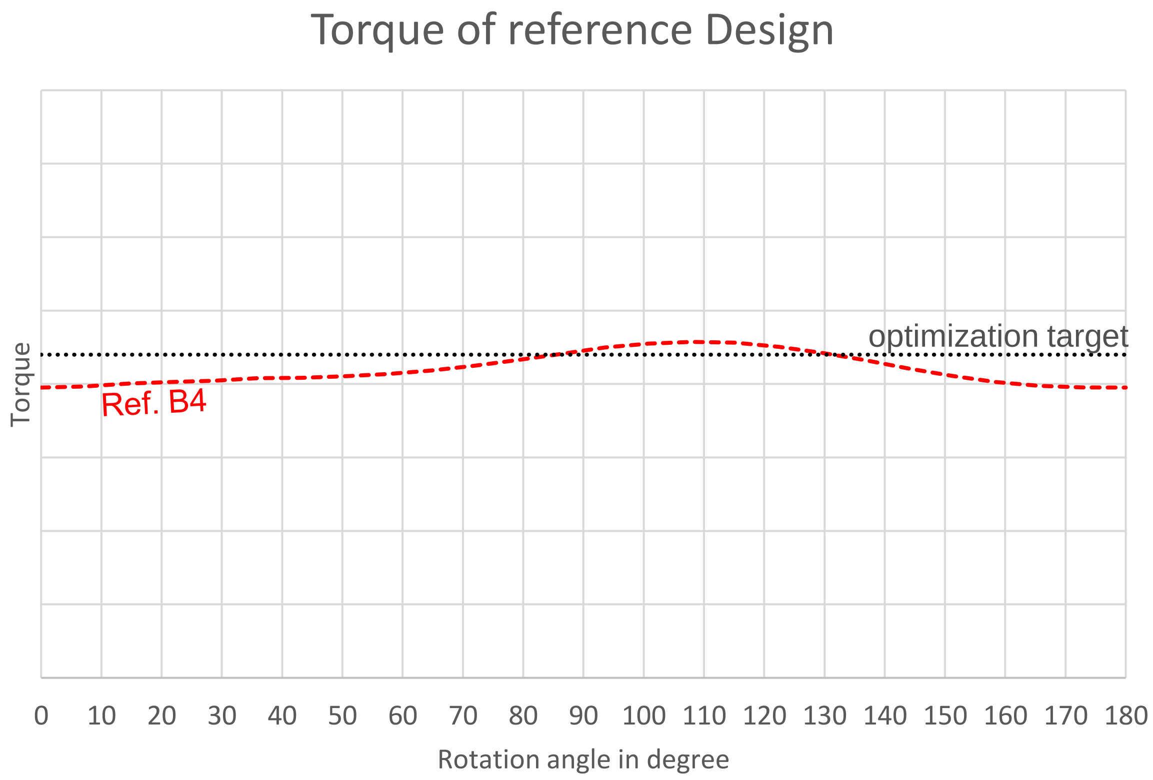


Target of optimization is:

- Increase in torque (optimal design)
- Cost reduction (lower height)

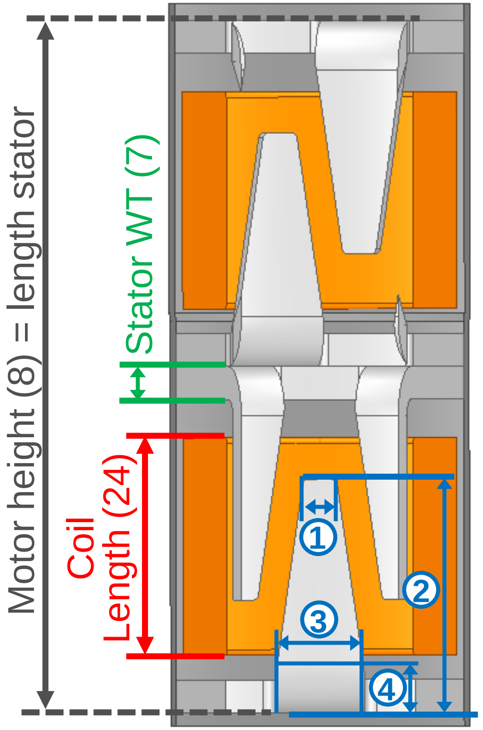
01.2 Computation and reference

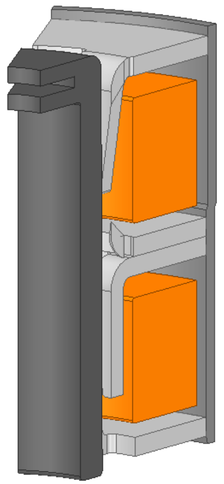
- Computation of torque with 30° 3D symmetry model in ANSYS AEDT
- Sinusoidal input of current in each coil for estimation of the dynamic torque curve
- Use of idealized magnet material
- Minimum value of torque curve as parameter for optimization
- Height of motor as second value for optimization



Model and Parameterization

- 6 geometry parameters
- Optimized coil design for every variation
- Height of teeth dependent on „motor height“
- Rotor dependent on „motor height“





Tooth…:
1) wide tip (14)
2) height total (17)
3) wide base (13)
4) height base (18)

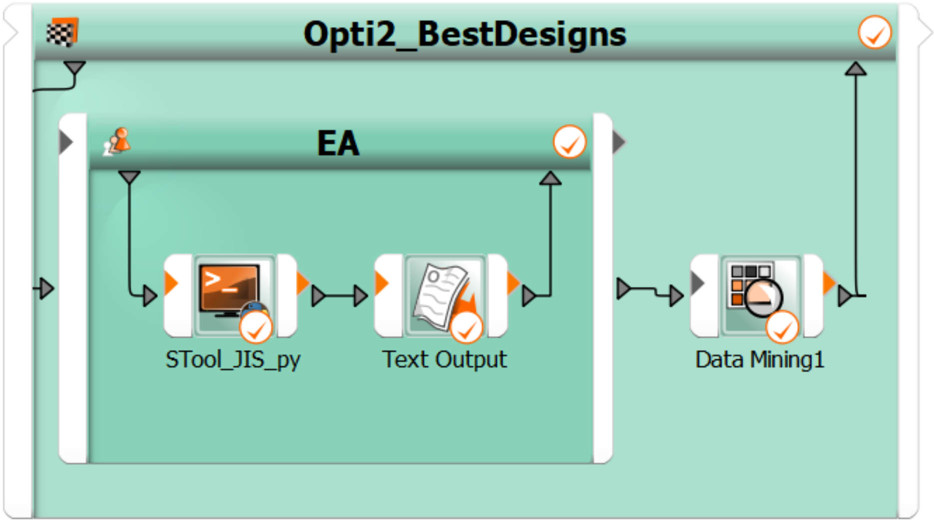
	Name	Parameter type	Constant	Operation	Value type	Resolution	Range plot
1	Wkl_max_Breite	Optimization	☑		REAL	Continuous	
2	Wkl_max_Dinnen	Optimization	☑		REAL	Continuous	
3	Wkl_max_R_Ohm	Optimization	☑		REAL	Continuous	
4	Wkl_max_Temp_C	Optimization	☑		REAL	Continuous	
5	Wkl_min_Spannung_V	Optimization	☑		REAL	Continuous	
6	Wkl_max_Daussen	Optimization	☑		REAL	Continuous	
7	Stator_WS	Optimization	☐		REAL	Ordinal discrete (by index)	
8	Motor_hoehe	Dependent	☐	Wicklung_Laenge*2+1.2*2+0.9*2+Stator_WS*4			
9	W_Breite	Dependent	☐	Wicklung_Laenge			
10	W_Di	Dependent	☐	24.2+Stator_WS*2			
11	W_Da	Dependent	☐	38.5			
12	W_Hoehe	Dependent	☐	(W_Da-W_Di)/2			
13	Zahn_breite_Basis	Optimization	☐		REAL	Continuous	
14	Zahn_breite_Spitze	Optimization	☐		REAL	Continuous	
15	Zahn_hoehe_Basis	Dependent	☐	Motor_hoehe/2*Zahn_hoehe_Basis_pz			
16	Zahn_hoehe_Gesamt	Dependent	☐	Motor_hoehe/2*Zahn_hoehe_Gesamt_pz			
17	Zahn_hoehe_Gesamt_pz	Optimization	☐		REAL	Continuous	
18	Zahn_hoehe_Basis_pz	Optimization	☐		REAL	Continuous	
19	Wkl_max_R_plusTol	Optimization	☑		REAL	Continuous	
20	Temp_Strom1	Optimization	☑		REAL	Continuous	
21	Temp_Strom2	Optimization	☑		REAL	Continuous	
22	Strom	Optimization	☑		REAL	Continuous	
23	Min_Spannung	Dependent	☐	Wkl_min_Spannung_V			
24	Wicklung_Laenge	Optimization	☐		REAL	Continuous	

OptiSLang systems

Sensitivity analysis and optimization setups

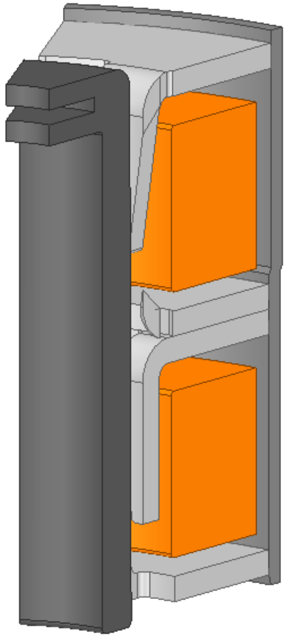
Parametric System

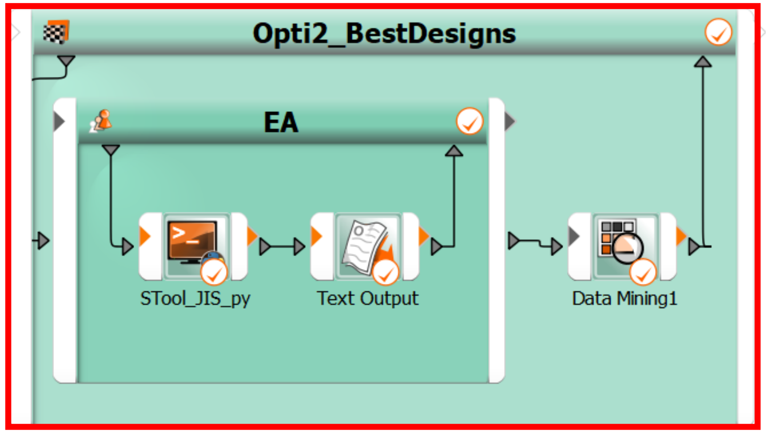
- Parametric system with internal optimization
- Primary use of creating design of experiment (DoE) due to stability and performance
- Computation of the DoE with ANSYS Maxwell (AEDT)
- Analysis and optimization with python tools and OptiSLang (postprocessing and MOP)



02.2 External System

- Outer area of system for creating DoE
  - 6 parameters for geometry variation
  - 9 constraints for variation control





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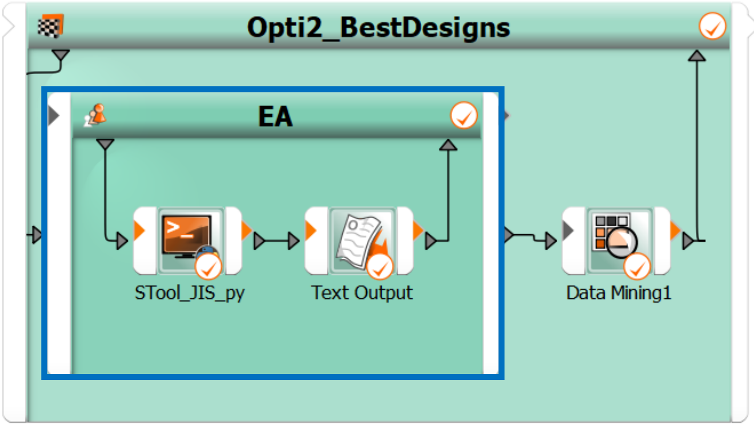
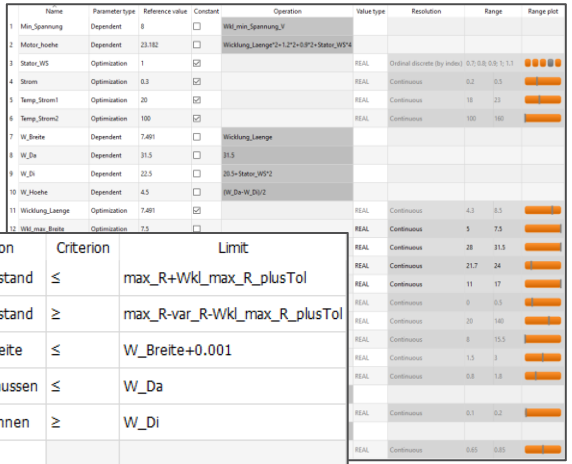
1	Wkl_max_Breite	Optimization	☑		REAL	Continuous	
2	Wkl_max_Dinnen	Optimization	☑		REAL	Continuous	
3	Wkl_max_R_Ohm	Optimization	☑		REAL	Continuous	
4	Wkl_max_Temp_C	Optimization	☑		REAL	Continuous	
5	Wkl_min_Spannung_V	Optimization	☑		REAL	Continuous	
6	Wkl_max_Daussen	Optimization	☑		REAL	Continuous	
7	Stator_WS	Optimization	☐		REAL	Ordinal discrete (by index)	
8	Motor_hoehe	Dependent	☐	Wicklung_Laenge*2+1.2*2+0.9*2+Stator_WS*4			
9	W_Breite	Dependent	☐	Wicklung_Laenge			
10	W_Di	Dependent	☐	24.2+Stator_WS*2			
11	W_Da	Dependent	☐	38.5			
12	W_Hoehe	Dependent	☐	(W_Da-W_Di)/2			
13	Zahn_breite_Basis	Optimization	☐		REAL	Continuous	
14	Zahn_breite_Spitze	Optimization	☐		REAL	Continuous	
15	Zahn_hoehe_Basis	Dependent	☐	Motor_hoehe/2*Zahn_hoehe_Basis_pz			
16	Zahn_hoehe_Gesamt	Dependent	☐	Motor_hoehe/2*Zahn_hoehe_Gesamt_pz			
17	Zahn_hoehe_Gesamt_pz	Optimization	☐		REAL	Continuous	
18	Zahn_hoehe_Basis_pz	Optimization	☐		REAL	Continuous	
19	Wkl_max_R_plusTol	Optimization	☑		REAL	Continuous	
20	Temp_Strom1	Optimization	☑		REAL	Continuous	
21	Temp_Strom2	Optimization	☑		REAL	Continuous	
22	Strom	Optimization	☑		REAL	Continuous	
23	Min_Spannung	Dependent	☐	Wkl_min_Spannung_V			
24	Wicklung_Laenge	Optimization	☐		REAL	Continuous	

Name	Type	Expression	Criterion	Limit
constr_SpWiderstand_Max	Constraint	STool_Spulenwiderstand	≤	max_R+Wkl_max_R_plusTol
constr_SpWiderstand_Min	Constraint	STool_Spulenwiderstand	≥	max_R-var_R-Wkl_max_R_plusTol
constr_Strom_Max	Constraint	STool_StromIn	≤	0.5
constr_Strom_Min	Constraint	STool_StromIn	≥	0.2
constr_W_Breite_max	Constraint	STool_W_Laenge_Ist	≤	W_Breite+0.001
constr_W_Daussen_max	Constraint	STool_W_Daussen_Ist	≤	W_Da
constr_W_Dinnen_min	Constraint	STool_W_Dinnen_Ist	≥	W_Di
constr_ZHB	Constraint	Zahn_hoehe_Basis	≥	Stator_WS+0.05
constr_ZHG	Constraint	Zahn_hoehe_Gesamt	≤	Wicklung_Laenge+Stator_WS+0.9+1.4
max_R	Variable	17		
var_R	Variable	6		
new				

Internal optimization

- Inner area of system for optimizing coil design (python script for calculation max. windings)
  - 4 variable parameters for coil configuration
  - 1 objective value for optimization
  - Optimization of „ampere-length“ (max current x wire length)
  - 5 constraints for variation control

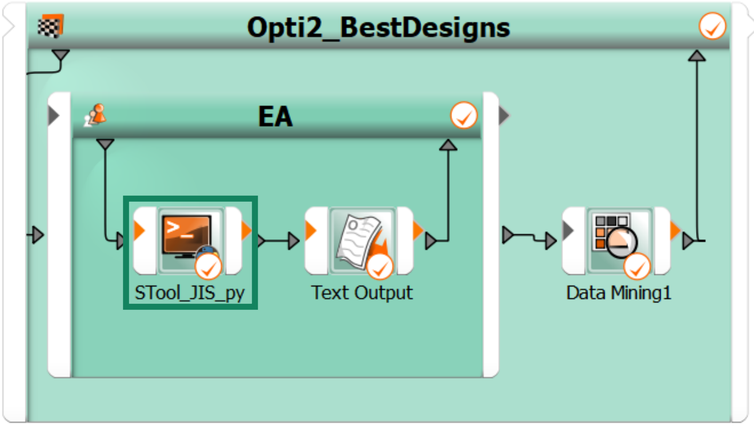


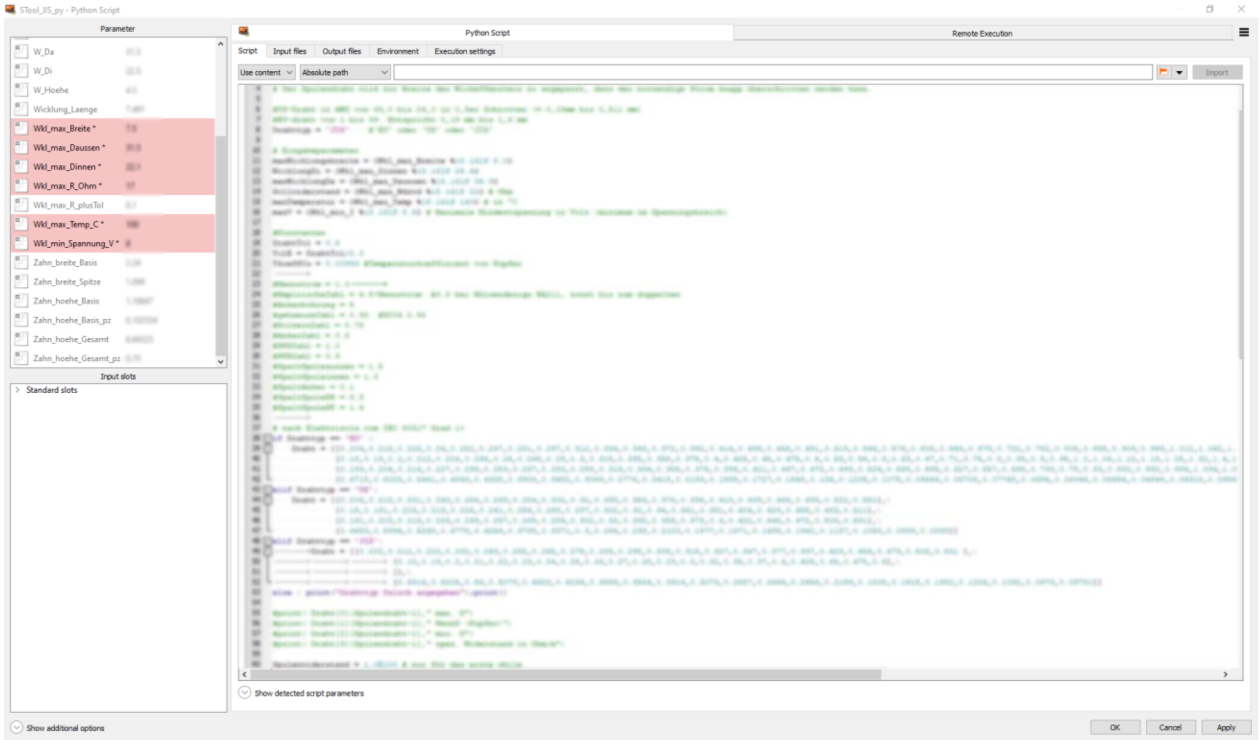


Name	Type	Expression	Criterion	Limit
constr_SpWiderstand_Max	Constraint	Spulenwiderstand	≤	max_R+Wkl_max_R_plusTol
constr_SpWiderstand_Min	Constraint	Spulenwiderstand	≥	max_R-var_R-Wkl_max_R_plusTol
constr_Wkl_Breite_max	Constraint	Wkl_max_Breite	≤	W_Breite+0.001
constr_Wkl_Daussen_max	Constraint	Wkl_max_Daussen	≤	W_Da
constr_Wkl_Dinnen_min	Constraint	Wkl_max_Dinnen	≥	W_Di
max_R	Variable	17		
obj_AmpereLaenge	Objective	AmpereLaenge350	MAX	
var_R	Variable	6		
new				

02.4 Python solver / script

- Python script with search for the smallest wire diameter with valid resistance
- Use of different wire standards possible





- Constraints and parameters
  - Winding width
  - Inner diameter
  - Outer diameter
  - Nominal resistance
  - Max. temperature
  - Min. voltage

Analysis and Optimization

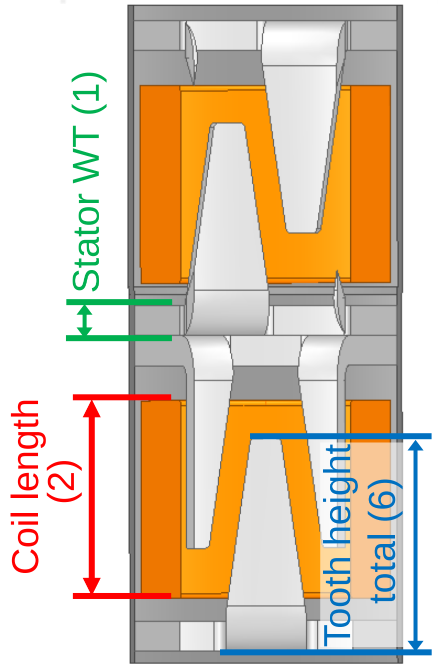
Sensitivity analysis with identification of the most important parameters and optimization of the stepper motor

03.1 Sensitivity analysis

Models

	M_T000	M_T002	M_T004	M_T006	M_T008	M_T010	M_T012	M_T014	M_T016	M_T018	M_T020	M_T022	M_T024
Stator_WS_mm	14.4 %	10.6 %	7.2 %	7.1 %	8.0 %	10.4 %	12.5 %	14.8 %	19.9 %	21.9 %	21.2 %	19.4 %	15.9 %
Wicklung_laenge_mm	69.1 %	65.6 %	64.5 %	62.9 %	62.1 %	59.9 %	56.4 %	54.4 %	58.1 %	60.4 %	59.3 %	67.1 %	75.6 %
Zahn_breite_Basis_mm	2.9 %	2.9 %	1.4 %	0.8 %	0.4 %	1.0 %	3.0 %	3.6 %	4.8 %	3.9 %	3.4 %	2.3 %	1.8 %
Zahn_breite_Spitze__mm	5.1 %	4.7 %	2.6 %	1.7 %	1.1 %	0.9 %	1.0 %	2.2 %	2.7 %	4.2 %	7.4 %	6.6 %	6.5 %
Zahn_hoehe_Basis_pz											0.7 %	1.0 %	1.1 %
Zahn_hoehe_Gesamt_pz	23.1 %	28.4 %	30.8 %	32.8 %	33.9 %	34.1 %	33.7 %	33.0 %	25.7 %	23.6 %	22.9 %	19.3 %	19.3 %
Total	98.1 %	98.5 %	98.1 %	98.1 %	98.1 %	98.2 %	97.9 %	98.2 %	97.7 %	97.5 %	98.1 %	98.1 %	98 %

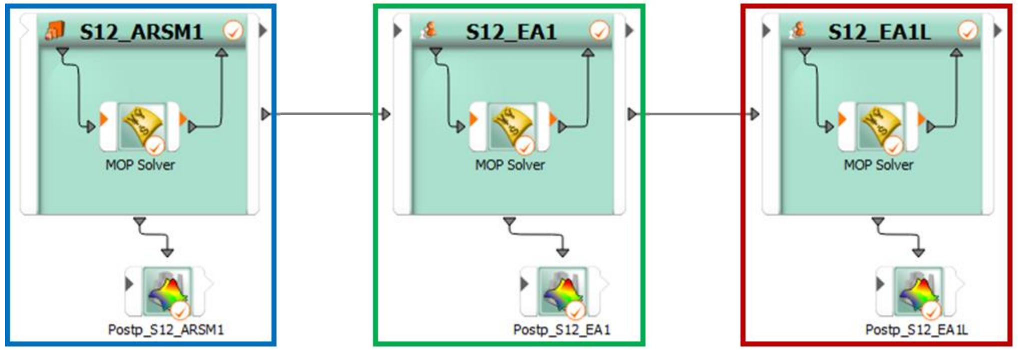
	M_T026	M_T028	M_T030	M_T032	M_T034	M_T036	M_T038	M_T040	M_T042	M_T044	M_T046	M_T048	M_T050
Stator_WS_mm	10.1 %	8.9 %	10.2 %	8.9 %	11.0 %	9.8 %	16.8 %	17.8 %	15.5 %	23.4 %	18.2 %	17.8 %	14.3 %
Wicklung_laenge_mm	79.0 %	78.5 %	73.3 %	82.1 %	76.8 %	78.6 %	83.1 %	83.0 %	75.2 %	62.0 %	76.8 %	70.5 %	67.5 %
Zahn_breite_Basis_mm	0.8 %	1.2 %	1.4 %	1.1 %	1.2 %	1.0 %	1.5 %	3.1 %	4.4 %	5.0 %	3.7 %	3.4 %	2.9 %
Zahn_breite_Spitze__mm	3.4 %	1.5 %	1.3 %	1.2 %	1.2 %	0.8 %	2.6 %	2.1 %	1.3 %	4.5 %	2.4 %	5.3 %	4.7 %
Zahn_hoehe_Basis_pz			0.0 %	0.4 %			0.4 %	0.2 %	0.5 %	0.8 %	0.9 %		
Zahn_hoehe_Gesamt_pz	14.2 %	13.9 %	12.6 %	10.3 %	9.7 %	9.4 %	8.8 %	7.2 %	10.6 %	12.1 %	18.7 %	17.9 %	22.7 %
Total	98.2 %	97.8 %	98.4 %	98.5 %	98.6 %	98.6 %	98.4 %	98.2 %	98.3 %	98.2 %	98.2 %	97.9 %	98.1 %



- Sensitivity analysis of 100 designs
- “Motor height“ due to stator thickness *(Stator WT)* and coil length with great influence o the torque
- Total height of the teeth with the second largest contribution to the torque change
- Height of the base of the teeth with very little influence

03.2 Optimization: Pareto designs

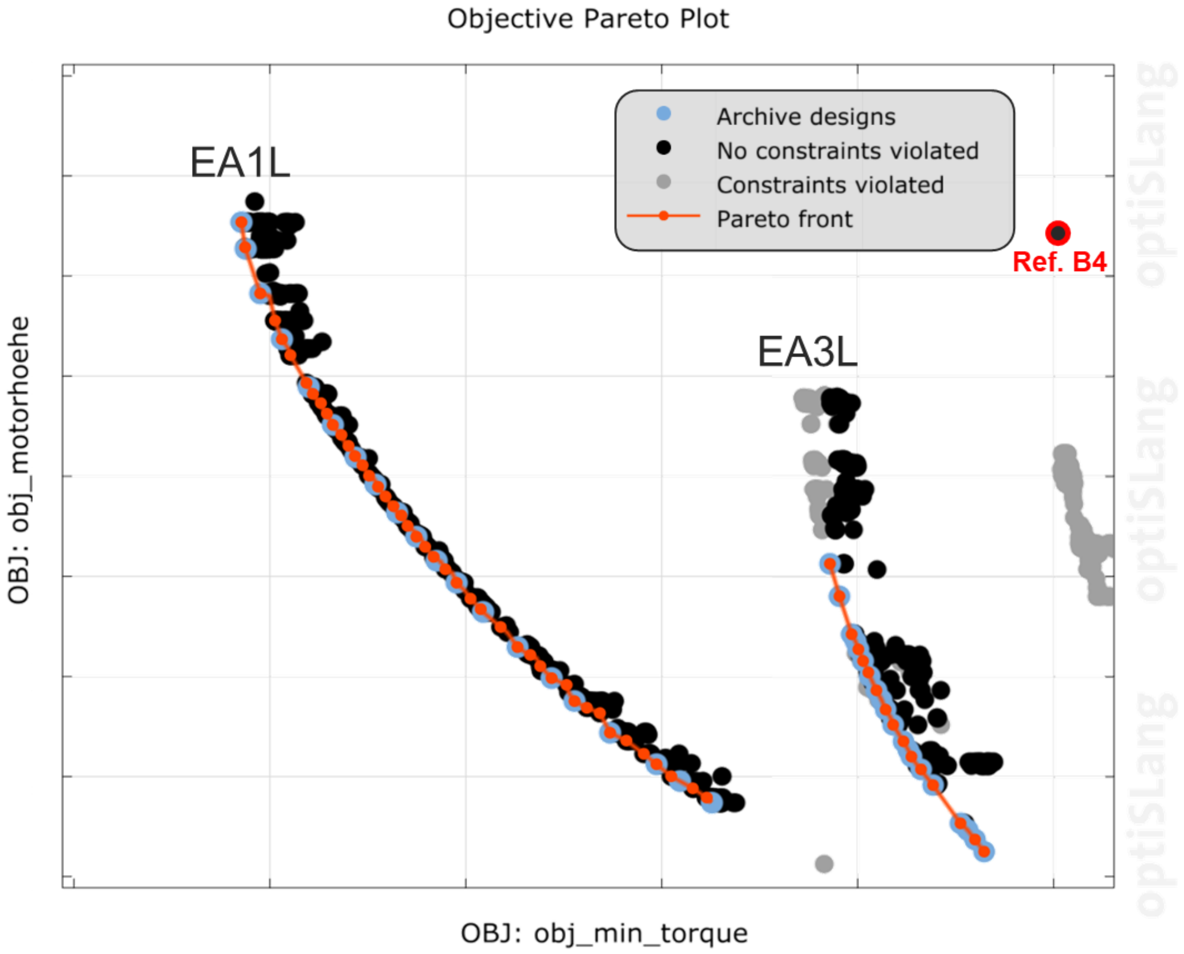
- Pareto optimal designs with motor height and minimum torque as optimization targets
- EA1 without manufacturing restrictions on the geometry
- EA3 with manufacturing restrictions
- Reduction of possible motor height and torque in EA3



First optimization with **one** objective

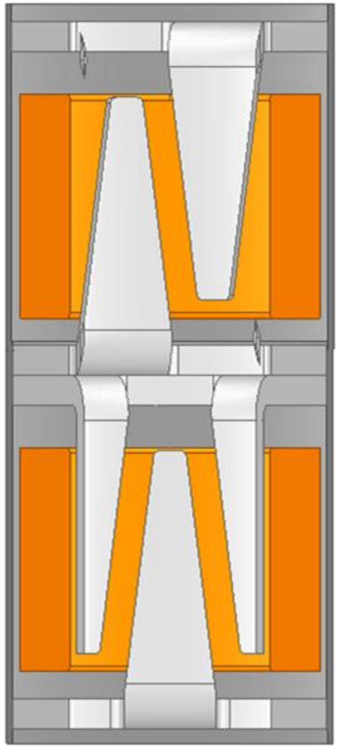
Global optimization with two targets

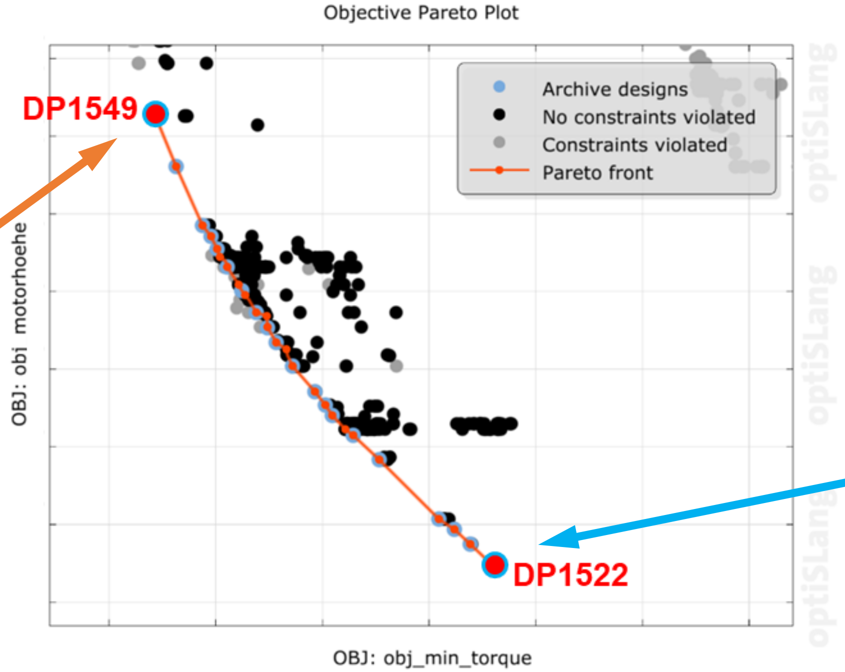
Local optimization with two targets



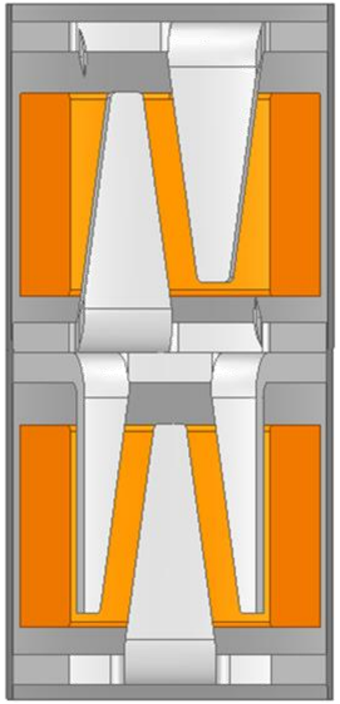
03.3 Optimization: EA3L

DP1549



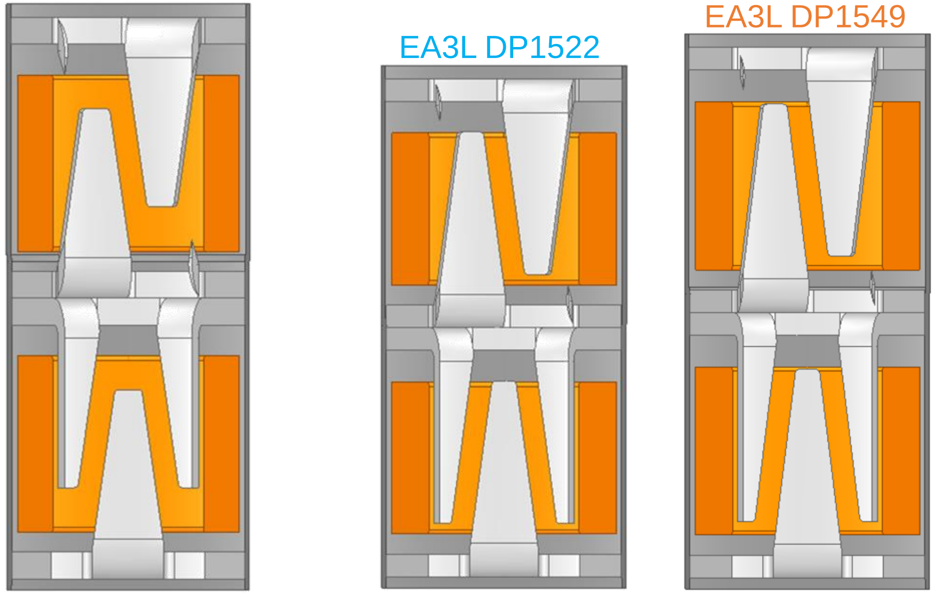


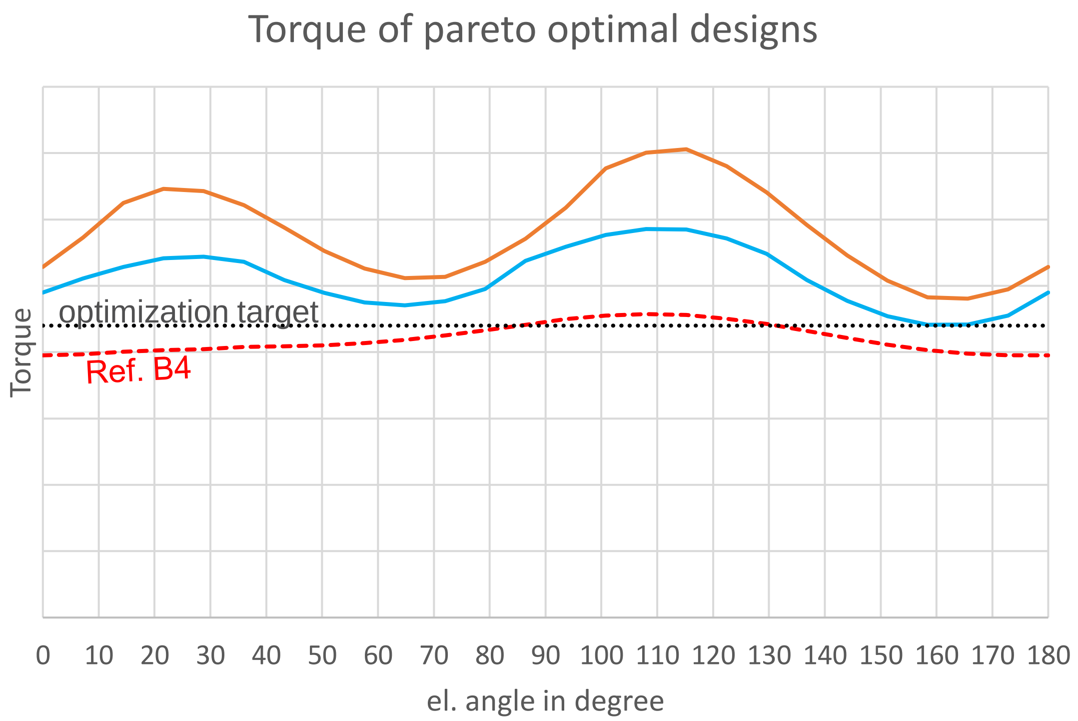
DP1522



- Difference in motor height (coil length)
- Shape of the teeth very similar
- Difference in absolute length of teeth due to motor height

Optimization: Torque curve

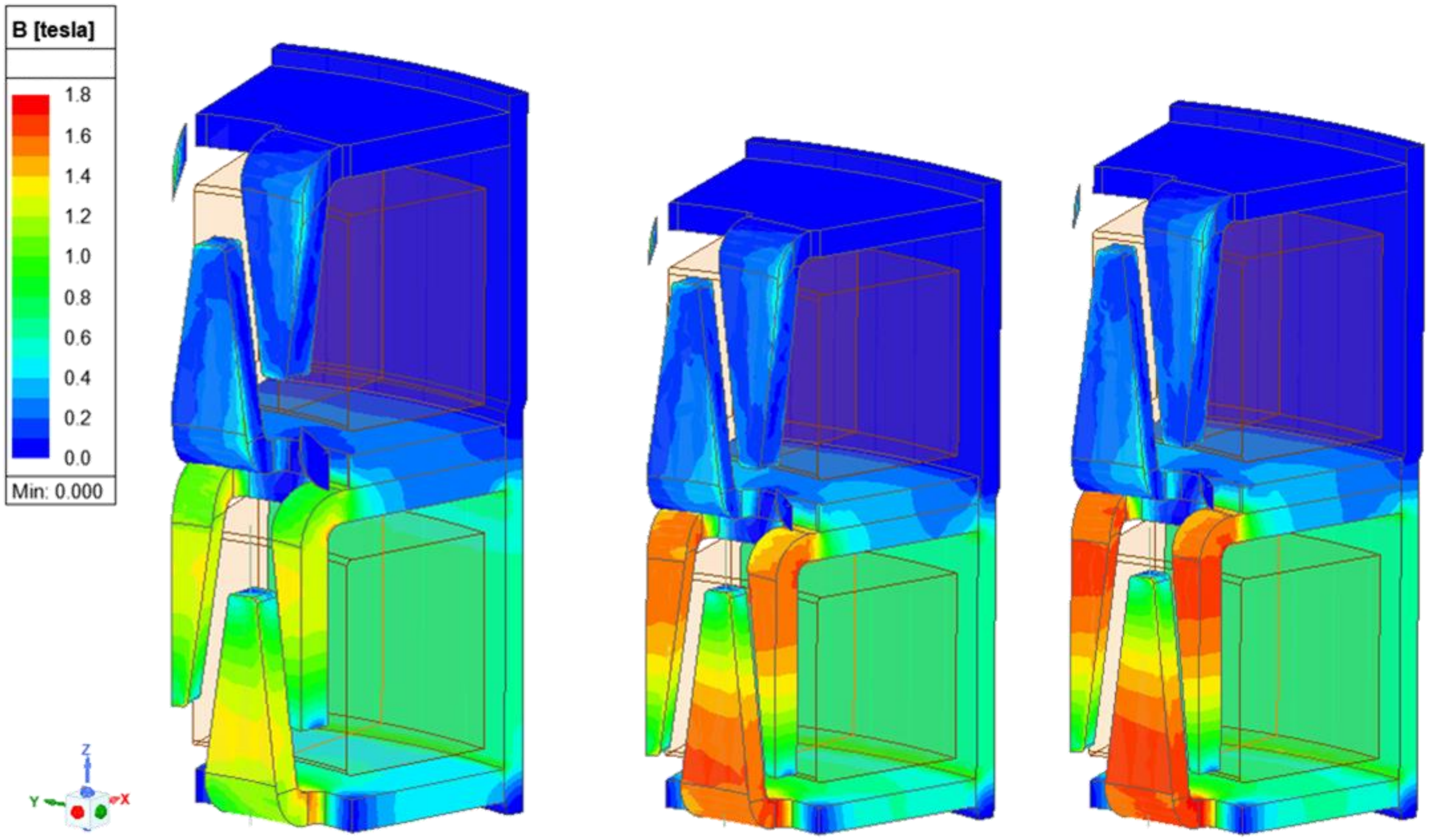




- Improvement of the reference design
- Recalculation of MOP optimization
- Using the parametric system for coil design

- Improvement in min. torque between 6% DP1522 and 11% DP1549 (comp. to Ref. B4)
- Reduction of motor height between 6% DP1549 and 12% DP1522 (comp. to Ref. B4)

Optimization: Magnetic Field



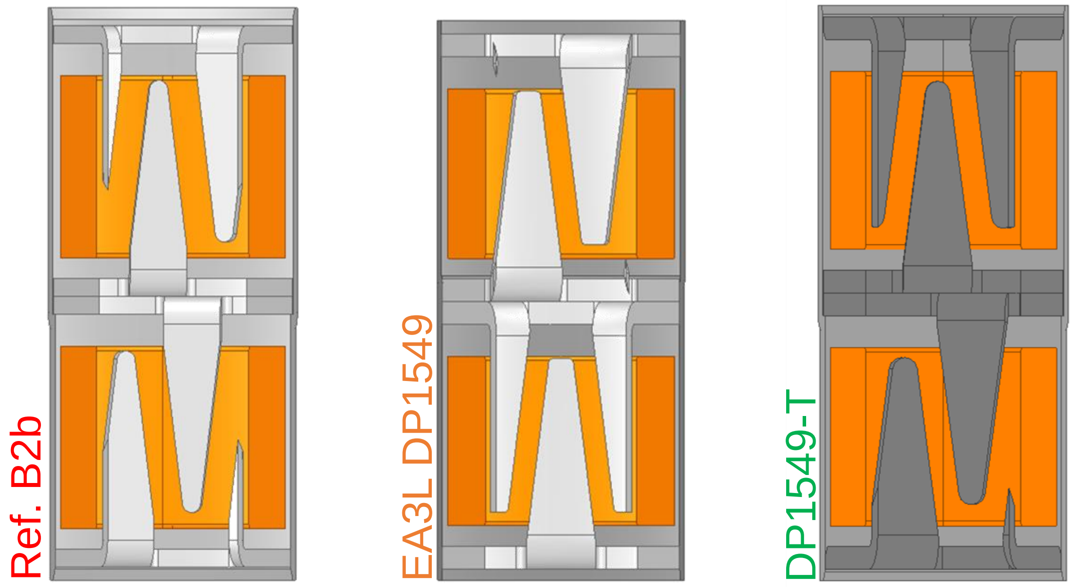
Reference B4 EA3L DP1522 EA3L DP1549

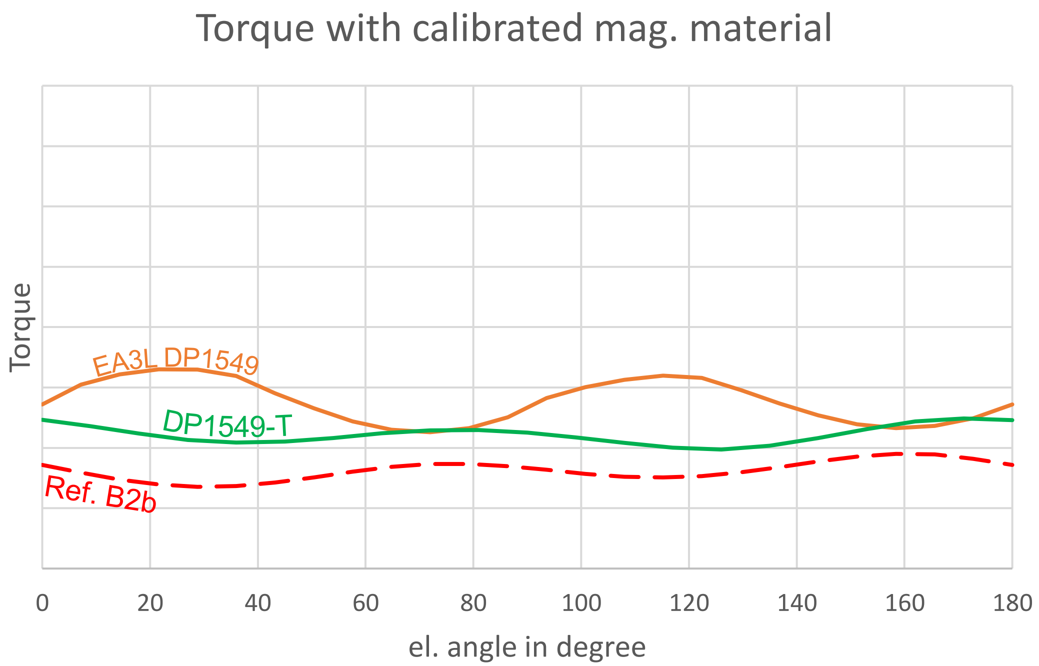
- Magnetic B-Field at 5.4° rotor angle (largest value in teeth)
- No oversaturation with current coil design
- Reference B4 with the lowest B-field in the teeth
- Optimized designs with similar saturation, independent of torque
- Extreme values in the corners and curves of the stators

Realized design

Comparison of simulation and test results of the motor design created for testing

Simulation realized design

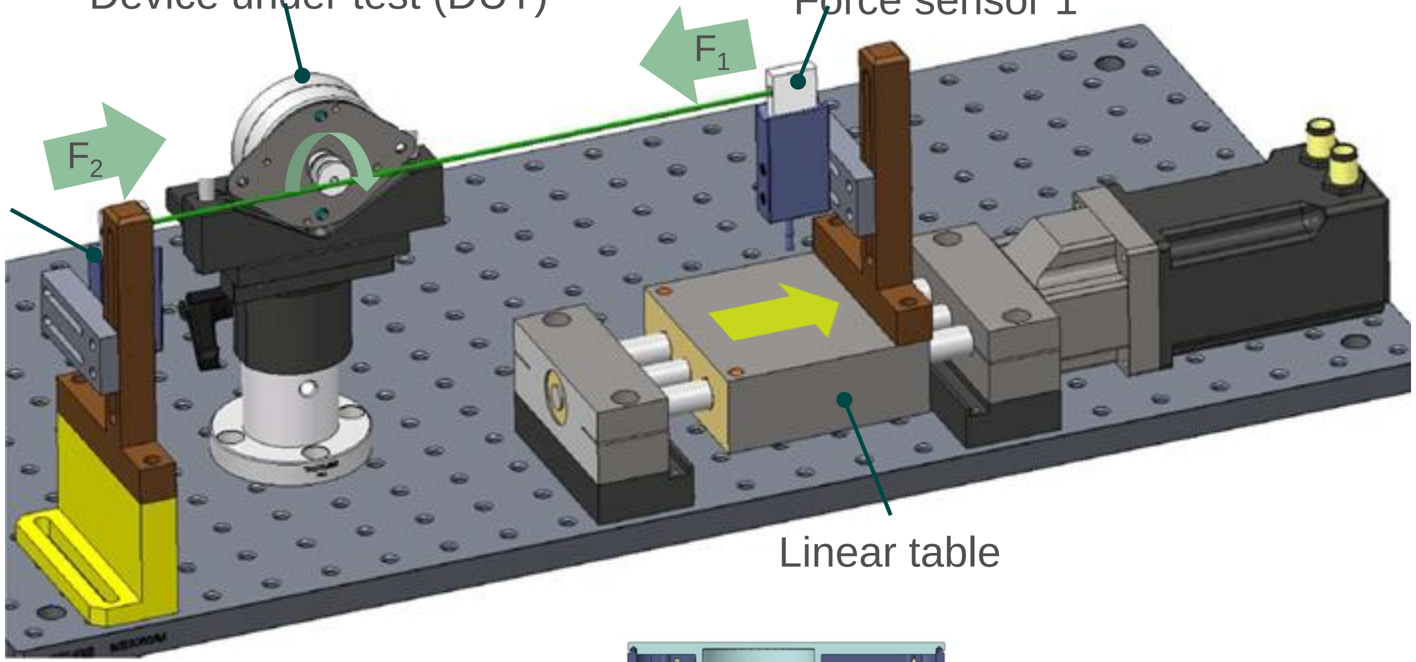


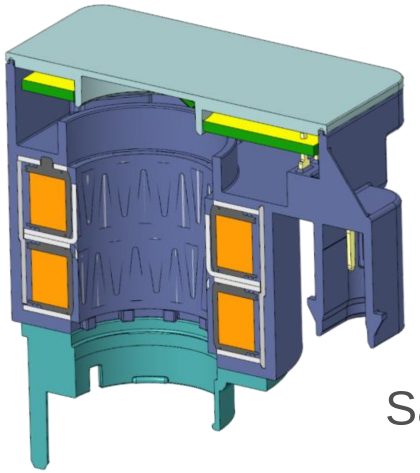


- Realization of optimized design DP1549-T from design team for testing
- Computation with use of calibrated magnet material
- 17% higher min. torque with DP1549 than Ref. B2b
- Loss of around 5% with DP1549-T but still 12% stronger than Ref. B2b

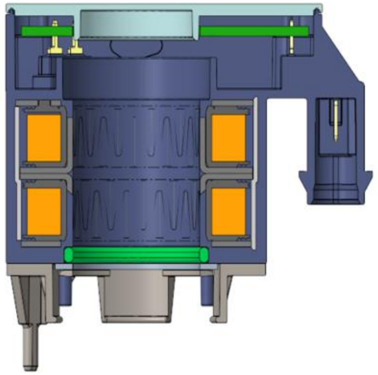
Testing realized design

- Examination of stepper motor reference B2b and optimized variant DP1549-T
- Testing with 3 different currents and 7 speeds
- Static and dynamic measurements possible



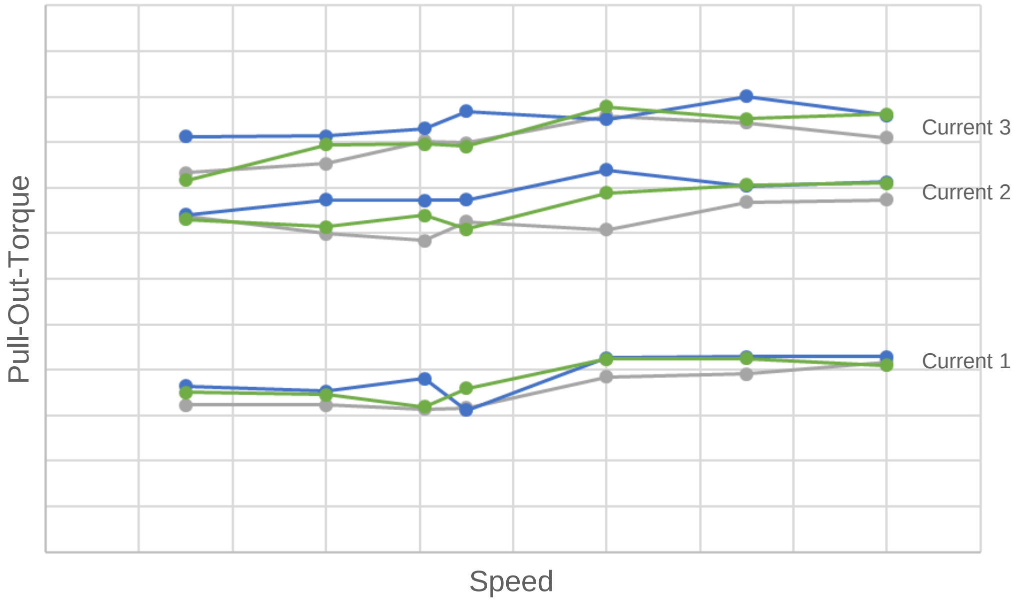


Same PCB and software for both motors

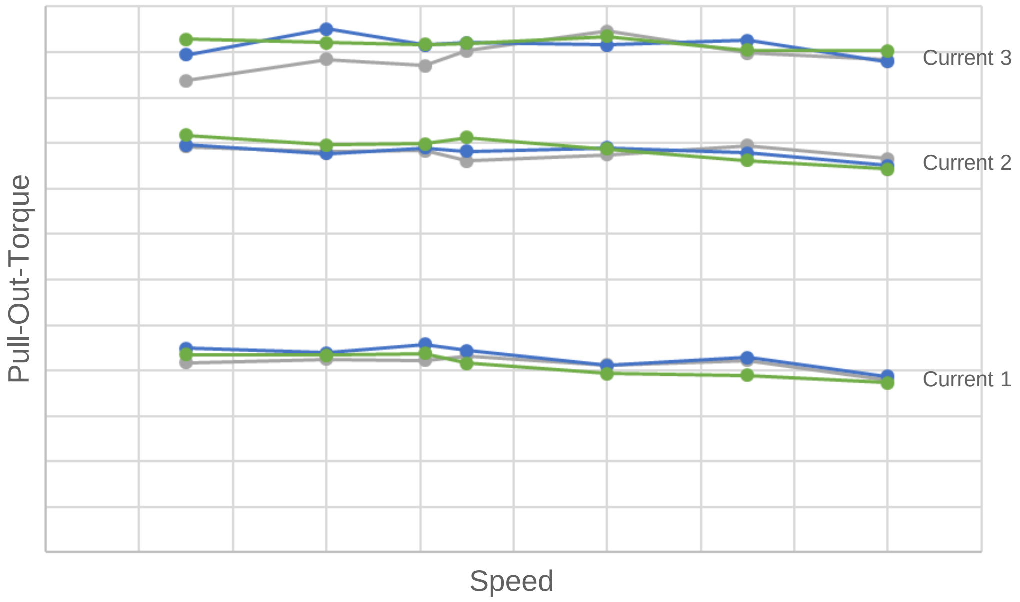


Testing realized design

Reference B2b



DP1549-T



- Test of dynamic “Pull-Out-Torque” with 3 samples
- Performance difference increasing with current

- Tested speed with minor influence on the torque
- 12% higher torque average at max. current for DP1549-T confirms simulation

Conclusion

Summary of the analysis and optimization

Conclusion and forecast

- In order to optimize a stepper motor a new, more complex optimization system as been successfully implemented
- A first design for the coil in every variation can automatically be generated
- A sensitivity analysis was able to determine the most important geometry parameters
- With help of the new system an optimization found a design with increased performance and possible cost reduction
- The performance increase was confirmed by testing

Thank you for your attention!