

# CONFERENCE

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2024

#### Optimization and design of a stepper motor with OptiSLang

C. Hugel Thursday, 24.10.2024

#### Agenda

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- 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







#### 01 Hilite International



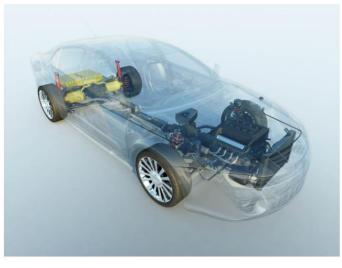
- Automotive company
- Founded in 1930
- About 1700 employees
- 8 locations on 3 continents
  About 550 Mio. € turnover



Electric, hybrid and hydrogen drives >



Engine and transmission applications >





### Introduction

Task, starting conditions and system setup



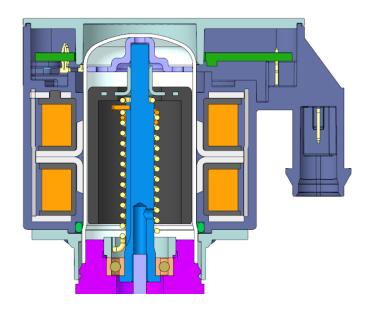
#### 01.1 Task and basic information



- 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:

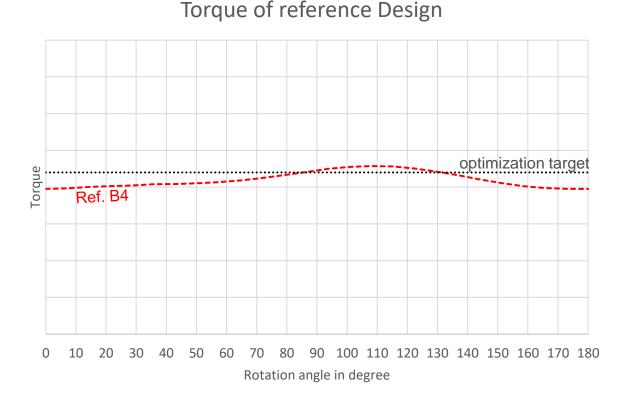
- Increase in torque (optimal design)
- Cost reduction (lower height)



#### 01.2 Computation and reference



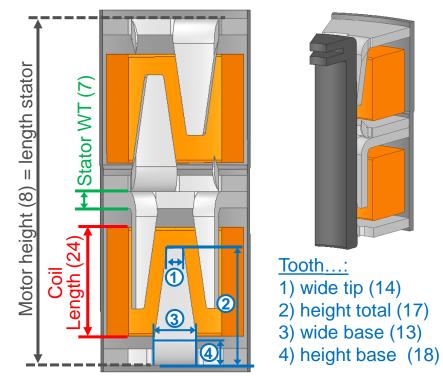
- Computation of torque with 30° 3D symmetry model in ANSYS AEDT
- Sinusoidal input of current in each coil for estimation of the dynamic torque curve
- Use of idealized magnet material
- Minimum value of torque curve as parameter for optimization
- Height of motor as second value for optimization



#### 01.3 Model and Parameterization



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



	Name	Parameter type	Constant	Operation	Value type	Resolution	Range plot
1	Wkl_max_Breite	Optimization	$\checkmark$		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	WkI_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	WkI_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**

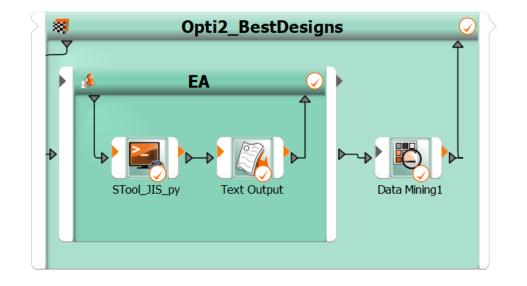
Sensitivity analysis and optimization setups





Parametric system 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)



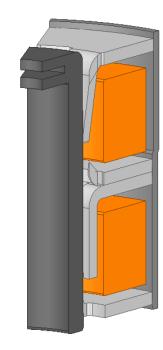


#### 02.2 External System

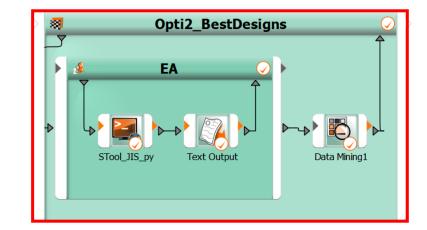


• Outer area of system for creating DoE

- •6 parameters for geometry variation
- •9 constraints for variation control



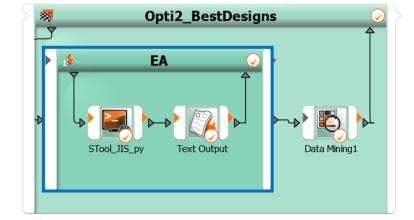
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1	Wkl_max_Breite	Optimization			REAL	Continuous	
2	Wkl_max_Dinnen	Optimization			REAL	Continuous	4
3	Wkl_max_R_Ohm	Optimization			REAL	Continuous	-
4	Wkl_max_Temp_C	Optimization			REAL	Continuous	-
5	Wkl_min_Spannung_V	Optimization			REAL	Continuous	
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		والمتعاد المتعاد المتعاد	
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	Туре	Expression	Criterion	Limit
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d constr_SpWiderstand_Min	Constraint	STool_Spulenwiderstand	≥	max_R-var_R-Wkl_max_R_plusTol
📥 constr_Strom_Max	Constraint	STool_StromIn	≤	0.5
i 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
∫w max_R	Variable	17		
∫w var_R	Variable	6		
new				

#### 02.3 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



			1 Min_Spa	inung De	ependent	8		Wkl_min_Spannung_V					
			2 Motor_h	iehe Di	ependent	23.182		Wicklung_Laenge*2+1.2*2+0.9*2+Stator_WS*4					
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			10 W_Hoeh		ependent			20.5+50807_W3-2 (W_Da-W_Di)/2					
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			12 Wid_max		ptimization		-		REAL	Continuous	5	7.5	_
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constr SpWiderstand Min	Constraint	Spulenwiderst	bnet	≥		nav R-var	R-V	Vkl_max_R_plusTol	REAL	Continuous	0	0.5	4
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						-			REAL	Continuous	1.5 0.8	1.8	
constr_Wkl_Daussen_max	Constraint	Wkl_max_Dau	issen	≤	V	V_Da			num.	Contribution		1.00	_
									REAL	Continuous	0.1	0.2	-
constr_Wkl_Dinnen_min	Constraint	Wkl_max_Din	nen	≥	v	V_Di		1					
max_R	Variable	17							REAL	Continuous	0.65	0.85	_
	Valiable	17											
obj_AmpereLaenge	Objective	AmpereLaeng	e350	MAX									
var_R	Variable	6											
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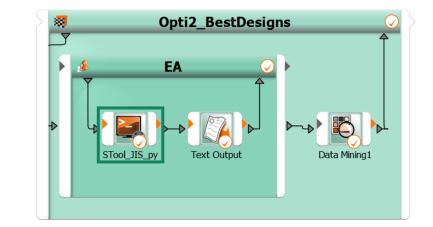
#### 02.4 Python solver / script



 Python script with search for the smallest wire diameter with valid resistance

• Use of different wire standards possible

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



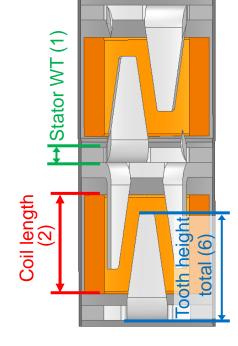
# Analysis and Optimization

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

#### 03.1 Sensitivity analysis





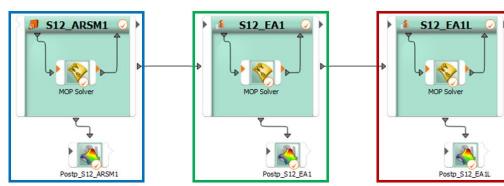


- Sensitivity analysis of 100 designs
- "Motor height" due to stator thickness (Stator WT) and coil length with great influence o the torque
- Total height of the teeth with the second largest contribution to the torque change
- Height of the base of the teeth with very little influence

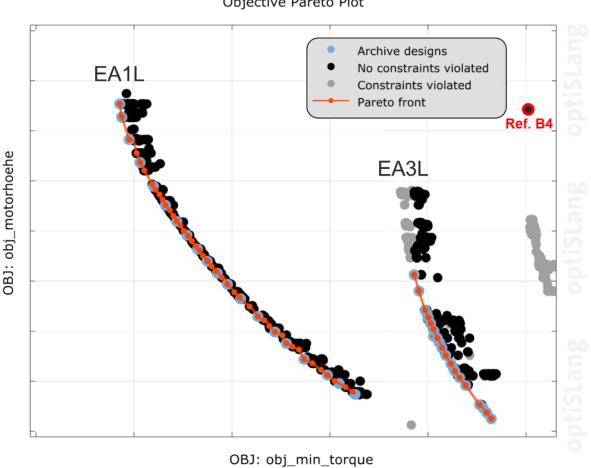
#### 03.2 Optimization: Pareto designs

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- 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



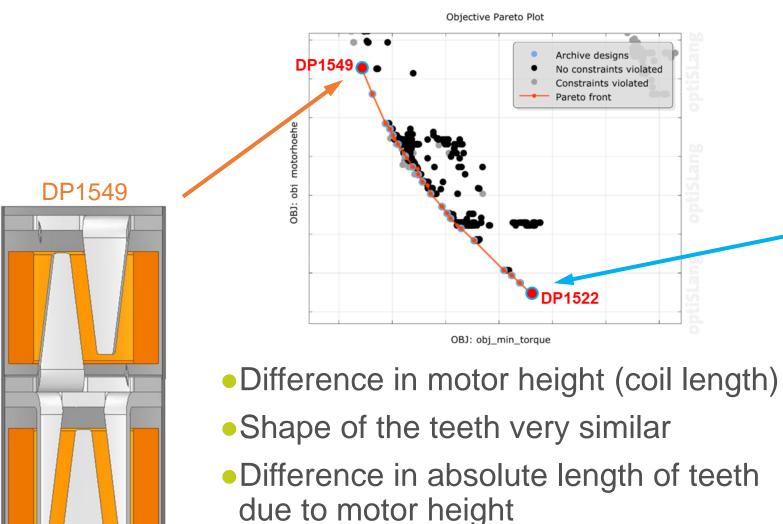
First optimization Global optimization Local optimization with **one** objective with two targets with two targets

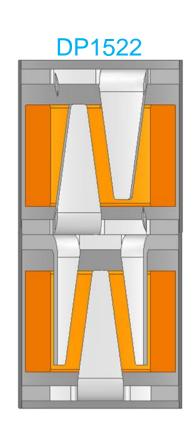


**Objective Pareto Plot** 

#### 03.3 Optimization: EA3L

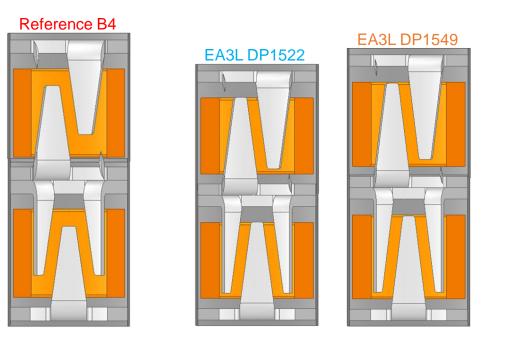
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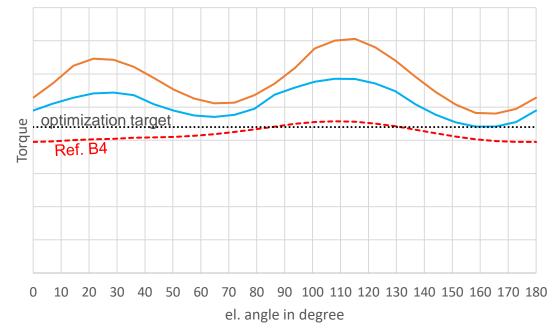


#### 03.4 Optimization: Torque curve





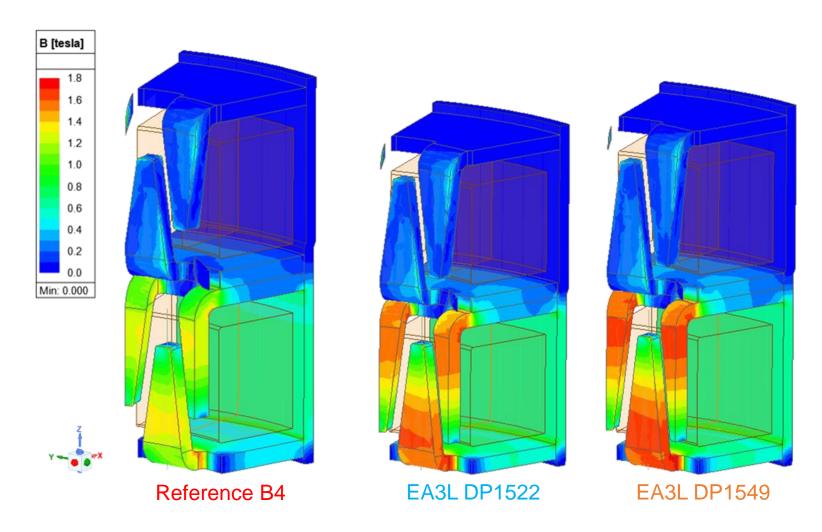
Torque of pareto optimal designs



- 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)

#### 03.5 Optimization: Magnetic Field





- 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



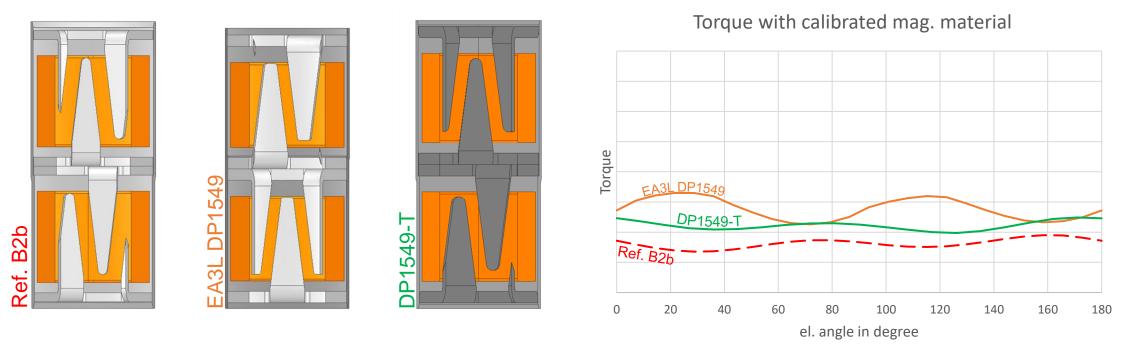
## **Realized design**

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



#### 04.1 Simulation realized design



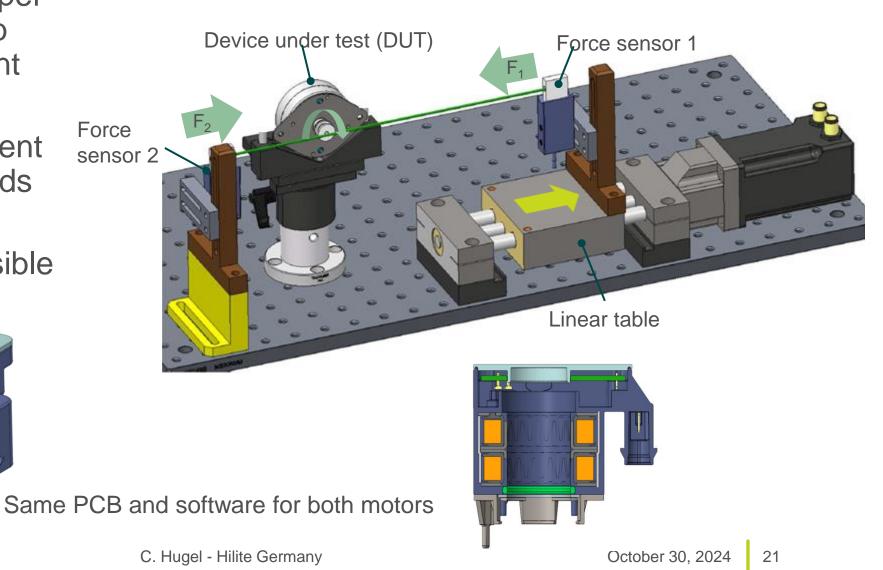


- Realization of optimized design DP1549-T from design team for testing
- Computation with use of calibrated magnet material
- 17% higher min. torque with DP1549 than Ref. B2b
- Loss of around 5% with DP1549-T but still 12% stronger than Ref. B2b

#### 04.2 Testing realized design

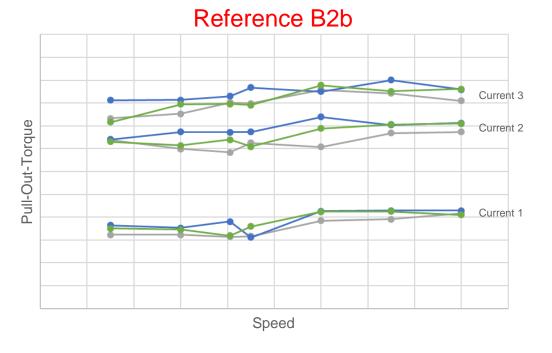


- Examination of stepper motor reference B2b and optimized variant DP1549-T
- Testing with 3 different currents and 7 speeds
- Static and dynamic measurements possible



#### 04.3 Testing realized design





- 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



#### 05.1 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



