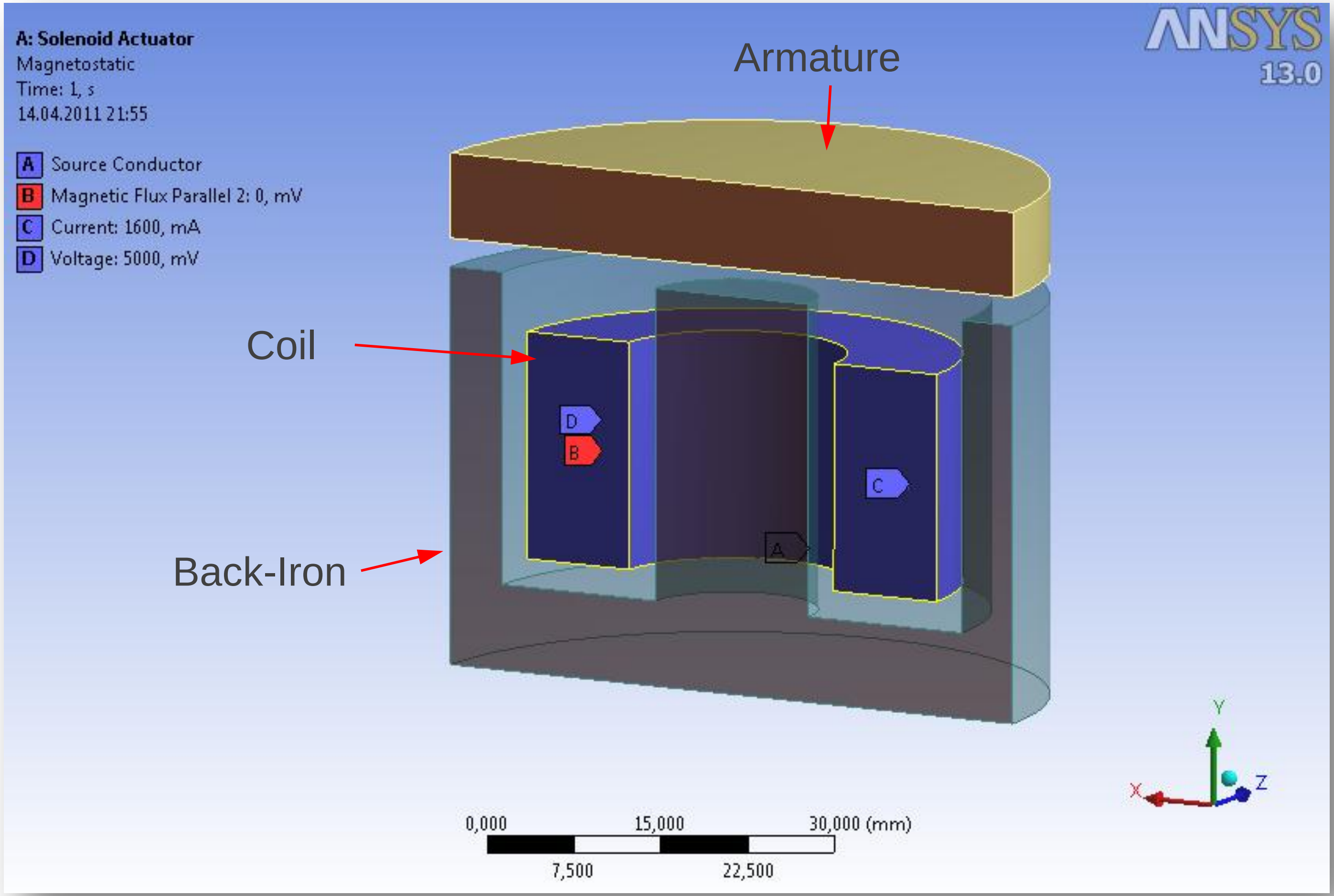
Six Sigma Design
of a
Solenoid Actuator

OptiY GmbH - Germany

Solenoid Actuator



Initial Nominal Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	⊟ Input Parameters			
3	⊟ Solenoid Actuator (A1)			
4	P4	Back Iron Inner Radius	0,0075	
5	P2	Back Iron Thickness	0,005	
6	P3	Fix Outer Radius	0,0275	
7	P5	Coil Thickness	0,01	
8	P6	Coil Distance	0,0025	
9	P12	Armature Thickness	0,0075	
10	P8	Air Gap	0,0025	
11	P9	Ground Thickness	0,0075	
12	P10	Back Iron High	0,035	
13	P11	Coil High	0,02	
14	P17	Coil Current	1600	mA
15	P18	Coil Voltage	5000	mV
16	P19	Magnetic Flux Density Scale of Material	1	
*	New input parameter	New name	New expression	
18	⊟ Output Parameters			
19	⊟ Solenoid Actuator (A1)			
20	P15	Armature Force	-8,1643	N
21	P20	Coil Flux Linkage	63,272	mWb
*	New output parameter		New expression	
23	Charts			

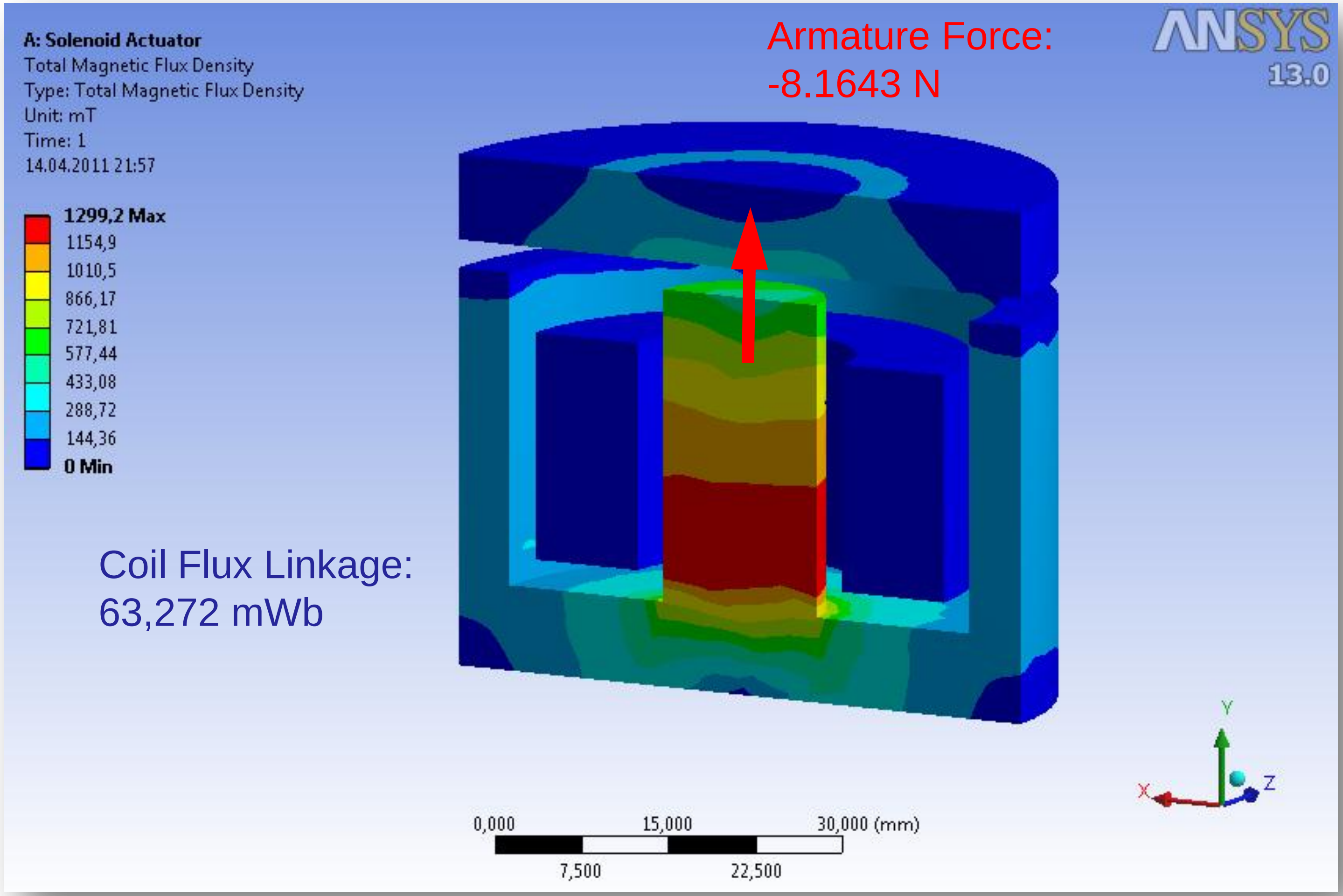
Variable Design Parameters:

- P4: Back Iron Inner Radius
- P2: Back Iron Thickness
- P5: Coil Thickness
- P6: Coil Distance
- P12: Armature Thickness
- P8: Air Gap
- P9: Back Iron Ground Thickness
- P11: Coil High

Fix Process Parameters:

- P17: Coil Current
- P18: Coil Voltage
- P19: Scale of B/H Curve

Nominal Simulation in Ansys Workbench



Design Specifications

Design Parameter Space:

• Back Iron Inner Radius	= [5, 10]	mm
• Back Iron Thickness	= [4, 6]	mm
• Coil Thickness	= [5,15]	mm
• Coil Distance	= [1.5, 3,5]	mm
• Armature Thickness	= [5, 10]	mm
• Air Gap	= [1.5, 3.5]	mm
• Ground Thickness	= [5, 10]	mm
• Coil High	= [10, 30]	mm

Geometry Tolerances = 1 mm
With Normal Distribution

Fix Process Parameters:

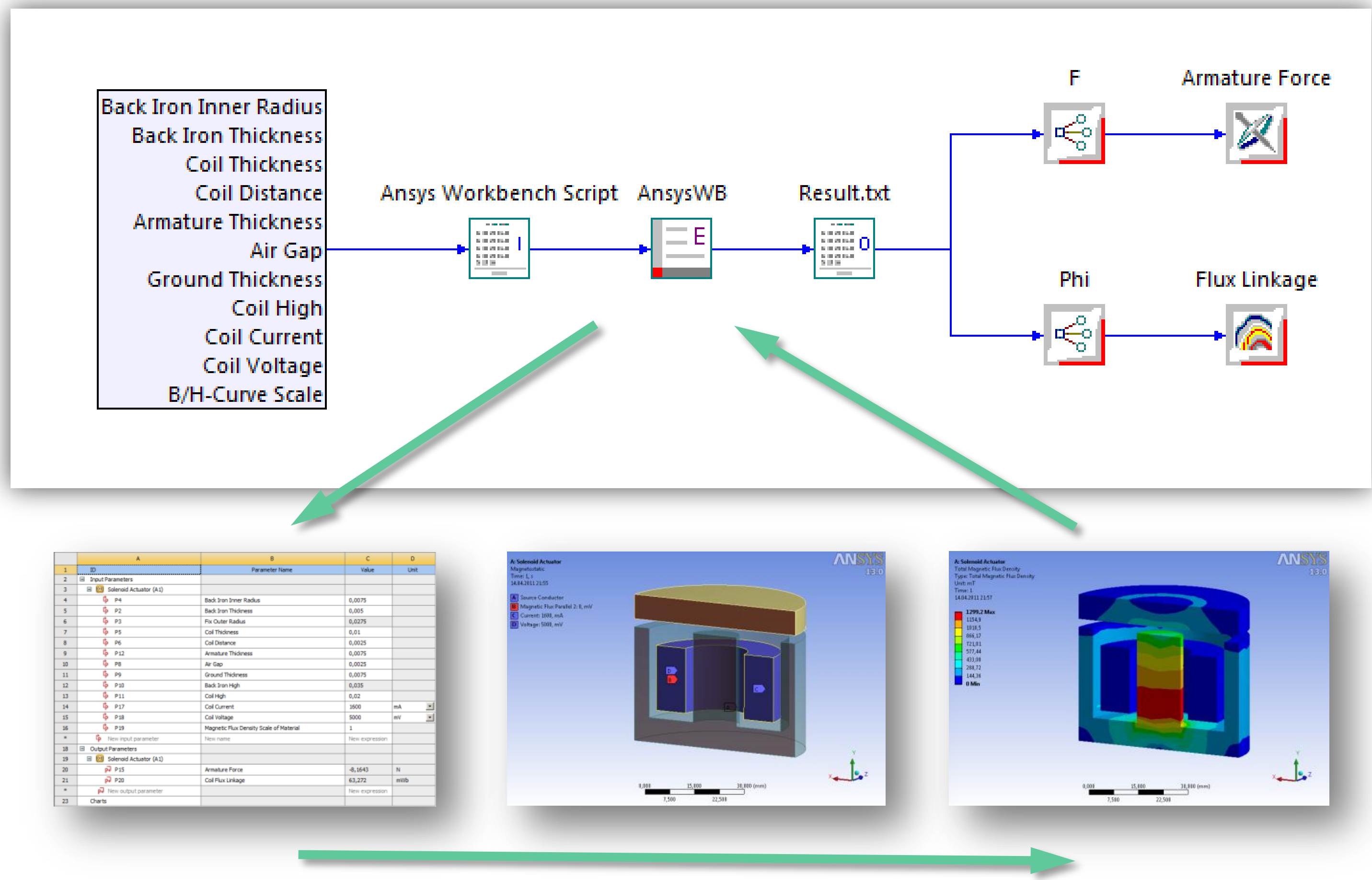
- Coil Current = 1.6 A (Source)
- Coil Voltage = 5 mV (Source)
- Scale for B/H-Curve = 1 (Material)

Uncertainties = 5%
with Normal Distribution

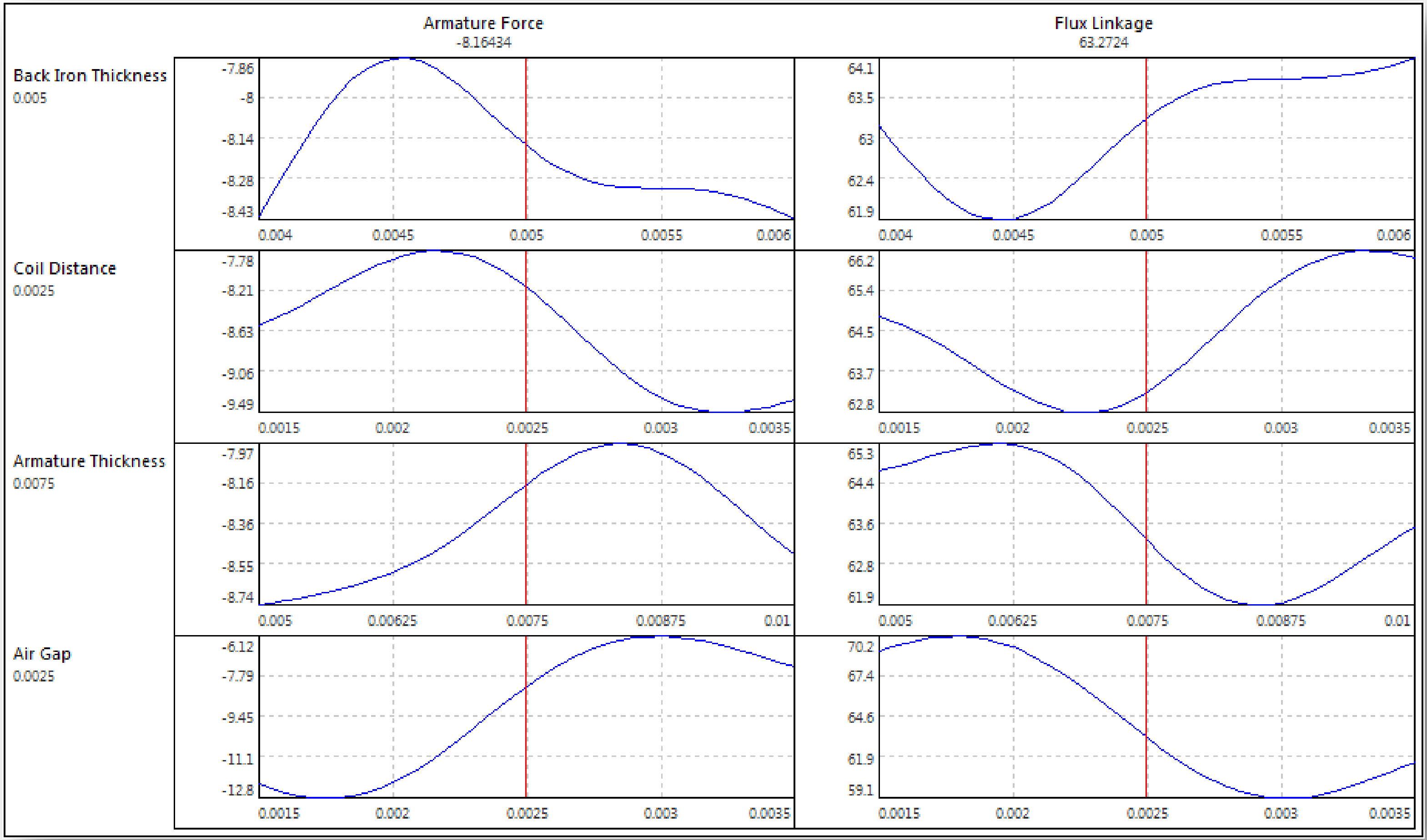
Functional Requirements:

- Armature Force = [-15 ,-10] N
- Flux Linkage = minimal as possible

Meta-Modeling in OptiY

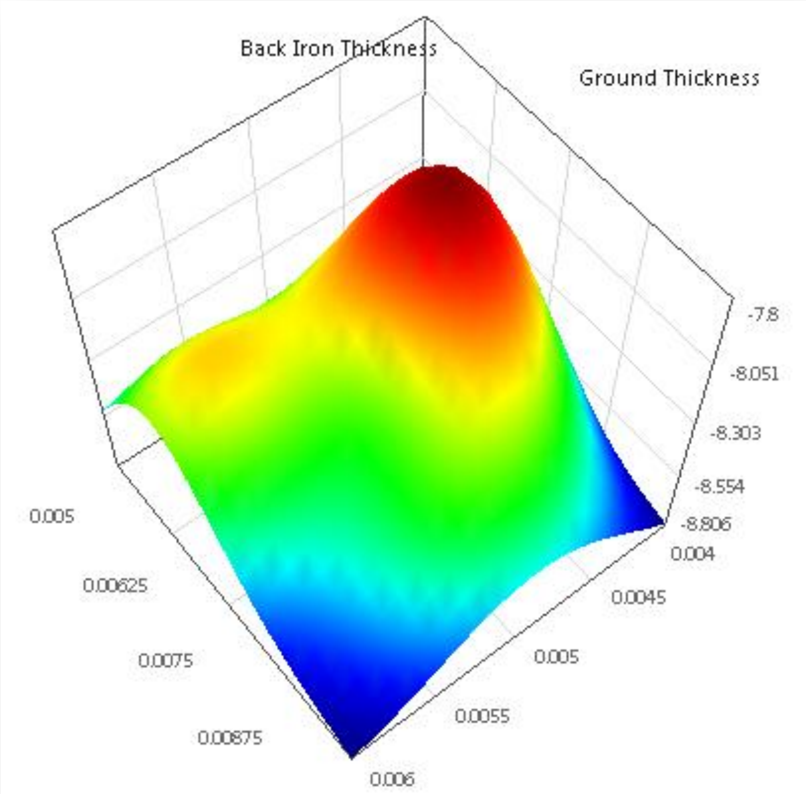


Design Space: 2D Section Diagrams

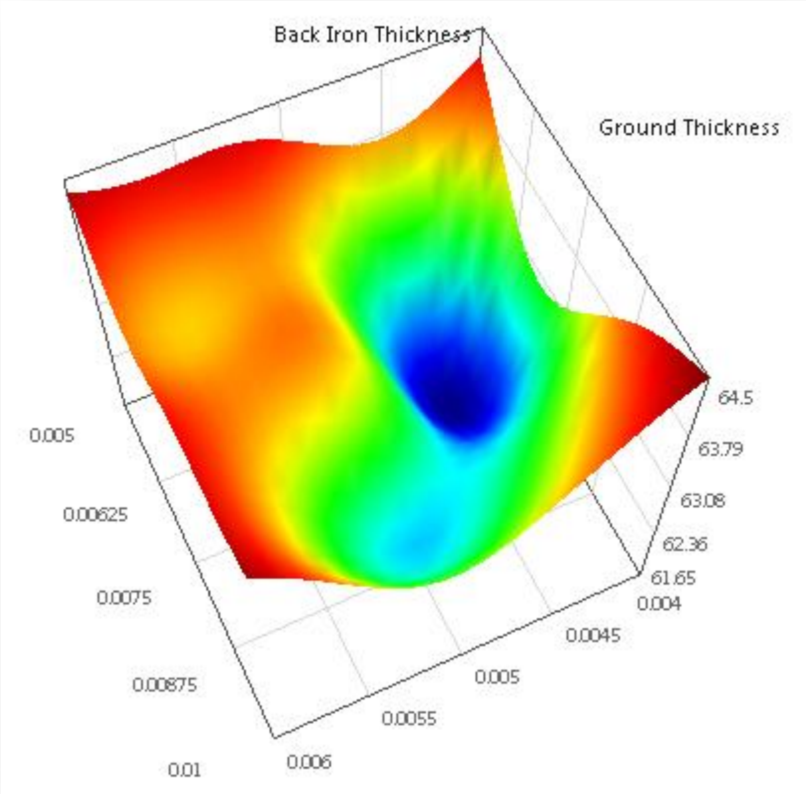


Design Space: 3D Graphics

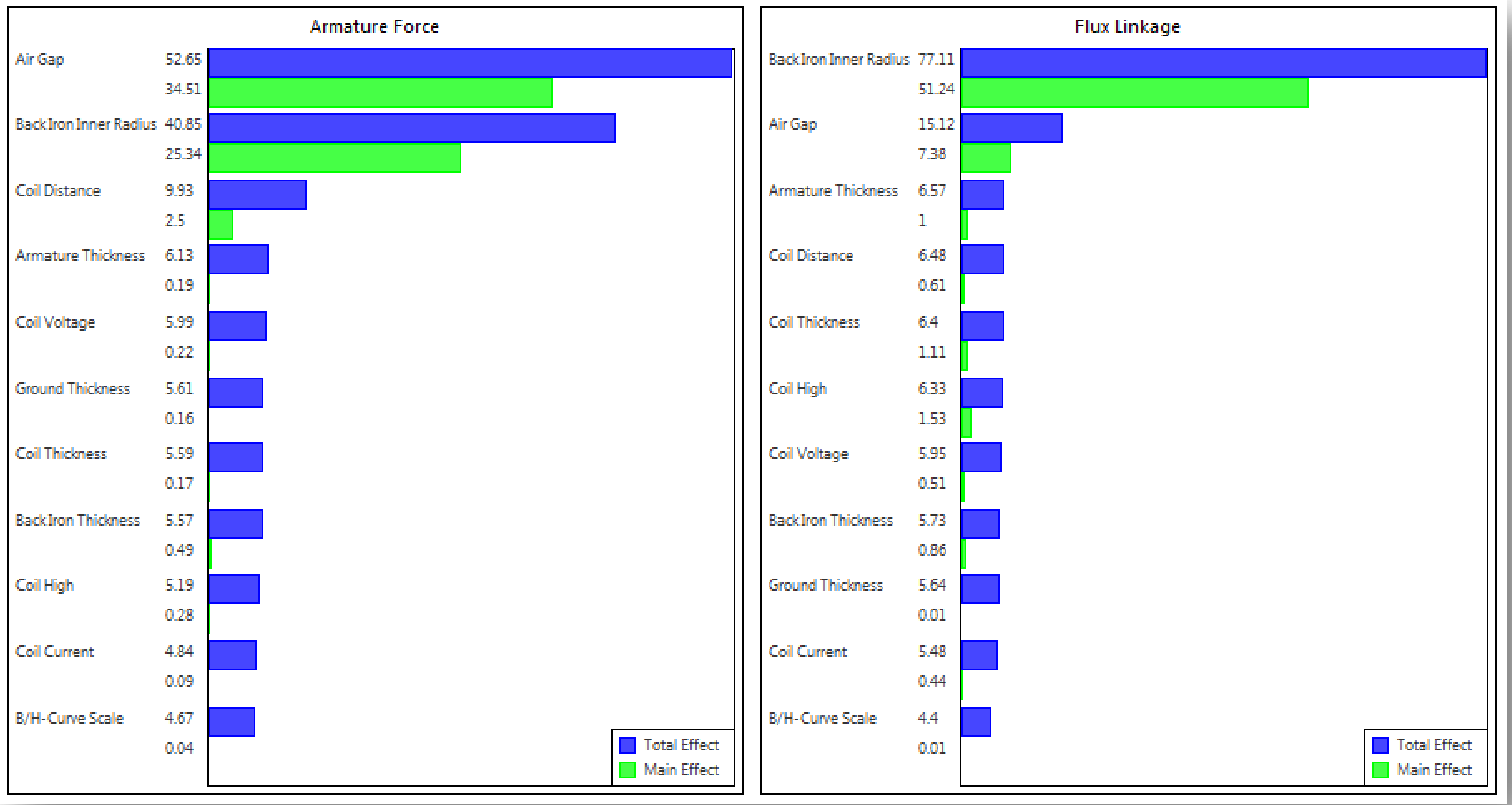
Armature Force



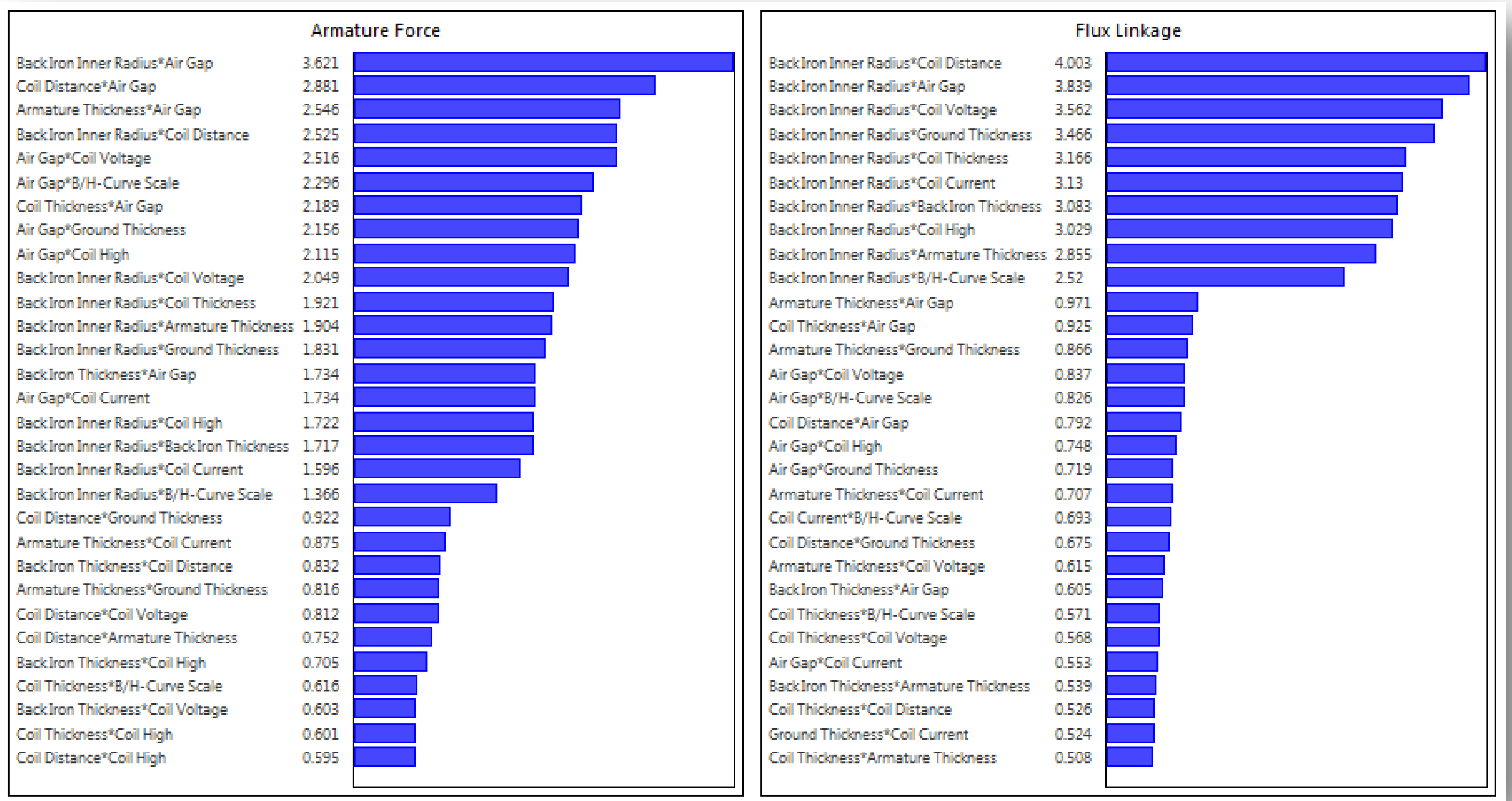
Flux Linkage



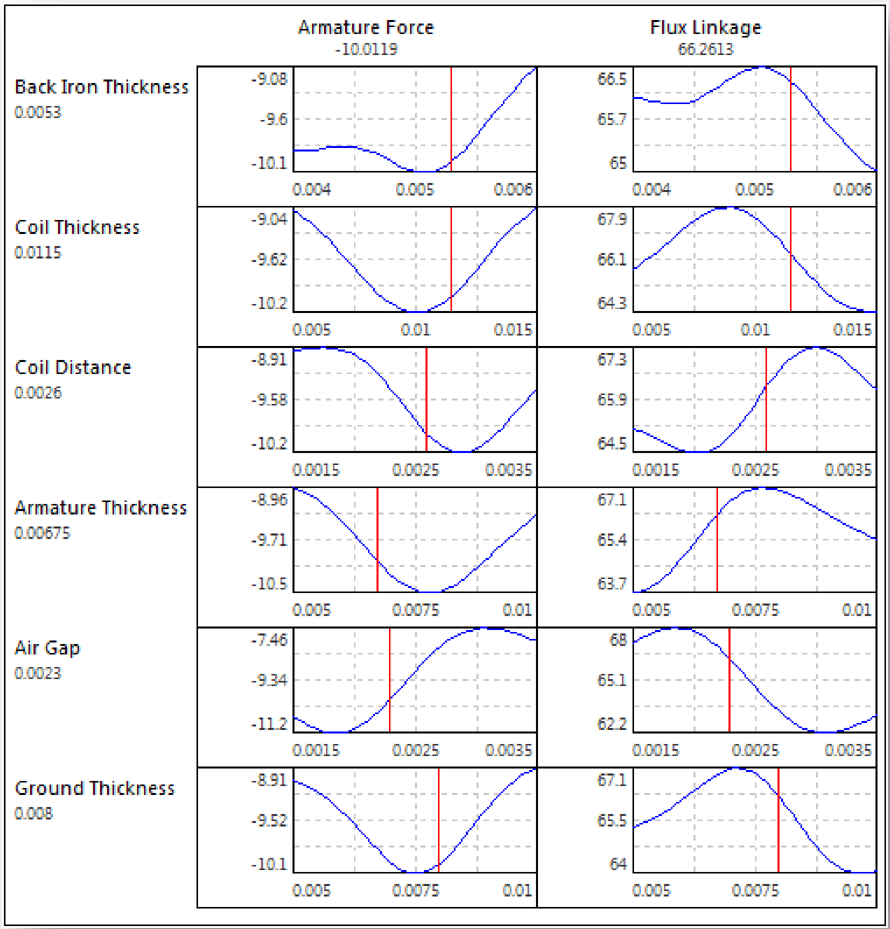
Global Sensitivity: Parameter Importance [%]



Global Sensitivity: Parameter Interaction [%]



Nominal Design Optimization



Optimization Goals:

- Constraint: -15 N ≤ Armature Force ≤ -10 N
- Criterion: Minimize Flux Linkage

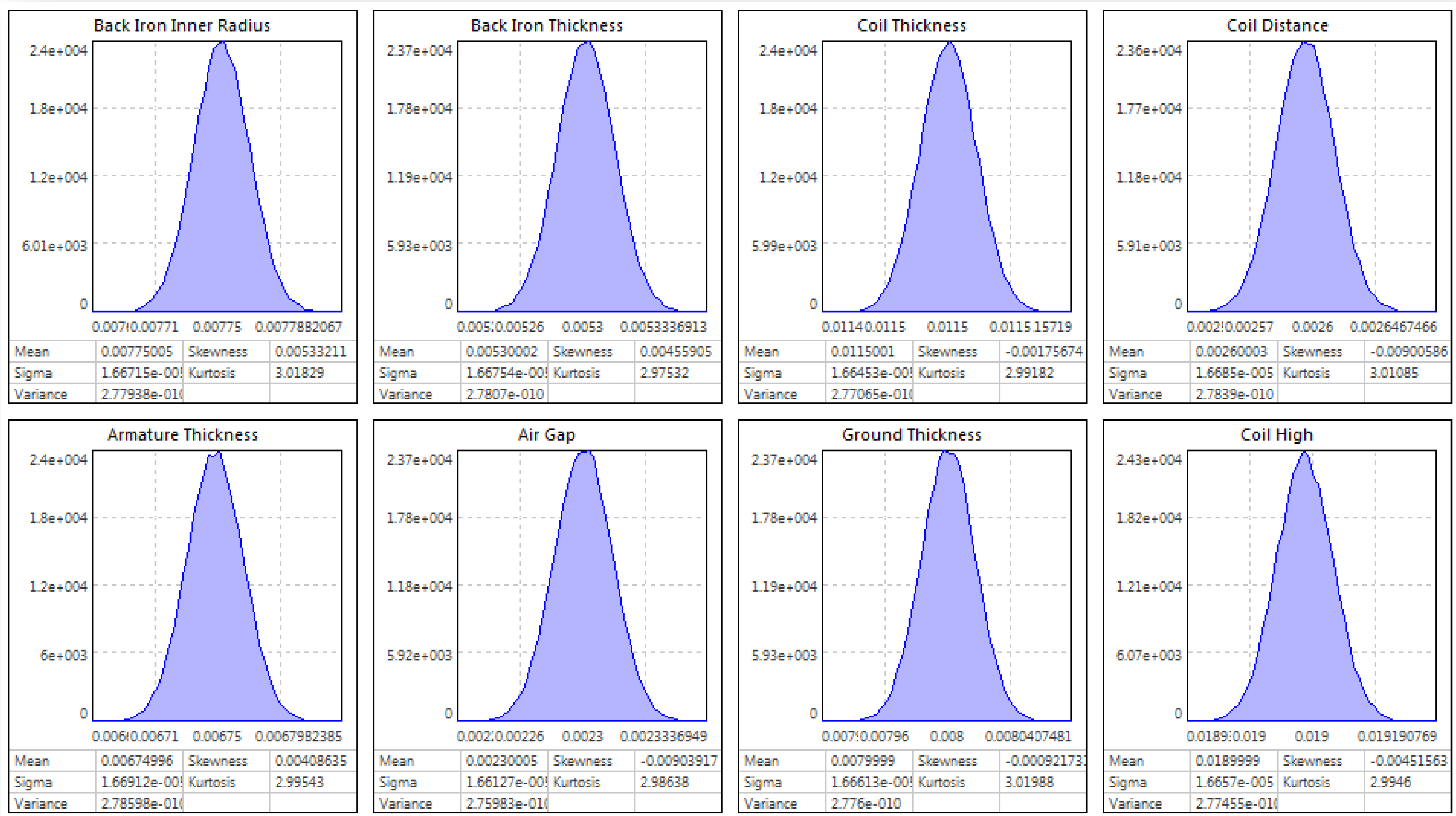
Nominal Design:

- Armature Force = -10,01 N
- Flux Linkage = 66,26 mWb

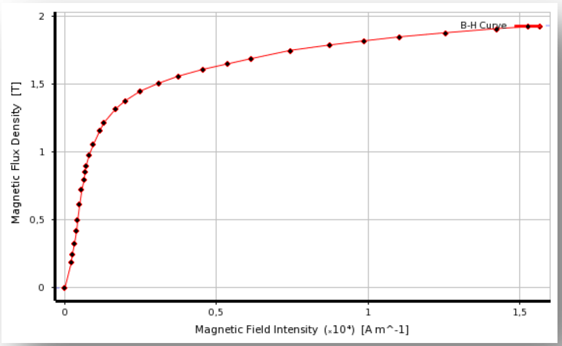
Design Parameters

Name	Nominal	Tolerance	Unit
Back Iron Inner Radius	0.00775	0.0001	m
Back Iron Thickness	0.0053	0.0001	m
Coil Thickness	0.0115	0.0001	m
Coil Distance	0.0026	0.0001	m
Armature Thickness	0.00675	0.0001	m
Air Gap	0.0023	0.0001	m
Ground Thickness	0.008	0.0001	m
Coil High	0.019	0.0001	m
Coil Current	1600	80	mA
Coil Voltage	5000	250	mV
B/H-Curve Scale	1	0.05	

Nominal Design: Geometry Tolerances

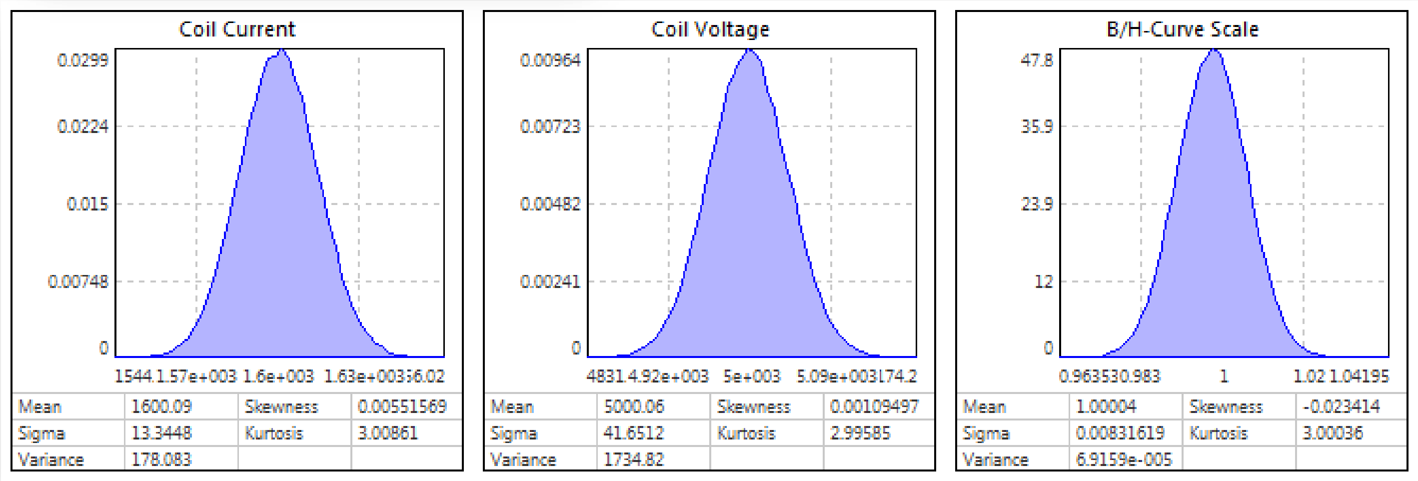


Nominal Design: Uncertainty Parameters



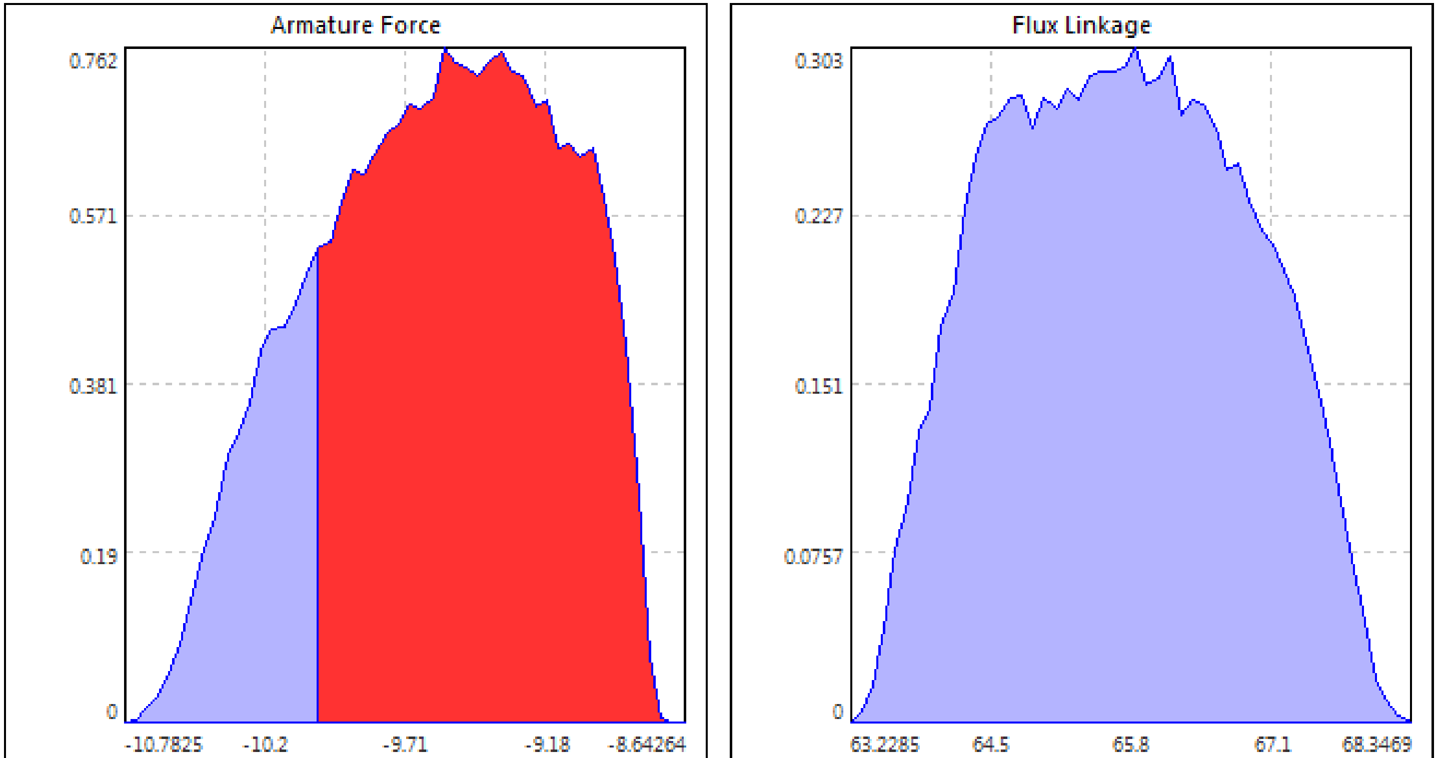
B/H-Curve for the Material
(1018 Steel 90.5 HRB)

Scale Factor = 1 (Nominal)
Uncertainty = 0.05 (Range)



Nominal Design: Reliability Analysis

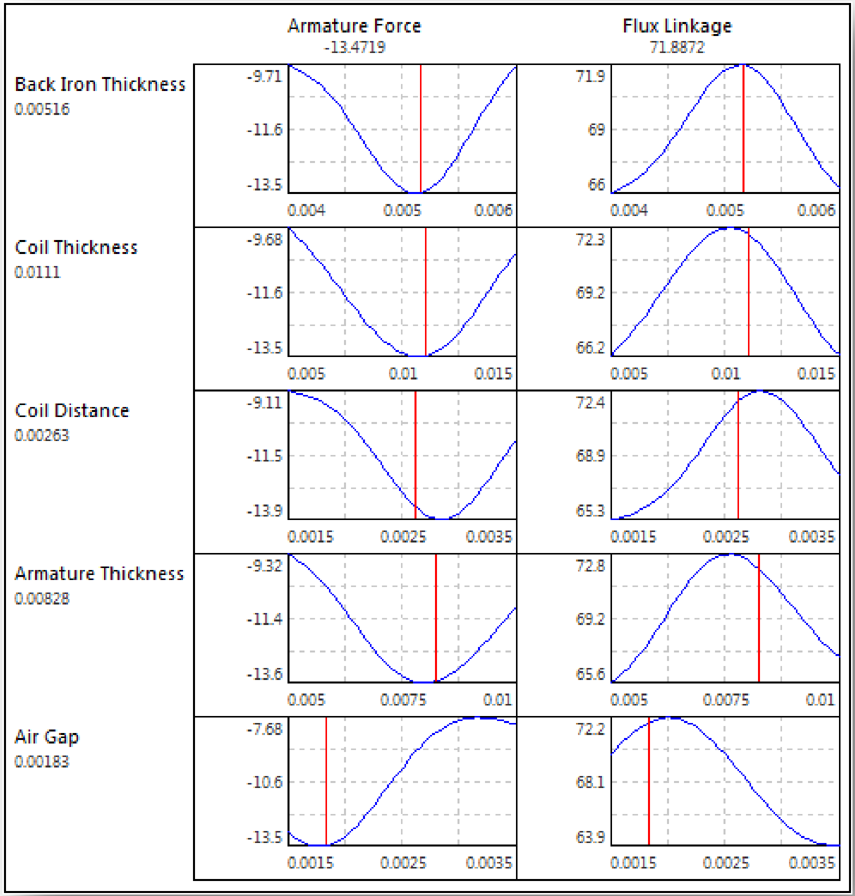
-15 N ≤ F ≤ -10N
Failure Probability = 78,93%



Mean	-9.58891	Skewness	-0.21981
Sigma	0.448846	Kurtosis	2.11534
Variance	0.201462	Failure Probability	0.78933/0.78933

Mean	65.7102	Skewness	0.0469059
Sigma	1.09236	Kurtosis	2.0632
Variance	1.19326		

Robust Design Optimization



Optimization Goal for Armature Force:
Minimize Taguchi Quality Loss Function

L = Cost*(Variance + (Mean – Target)^2)

- Cost = 1 Unit
- Target = -12.5 N (Center of [-15, -10] N)

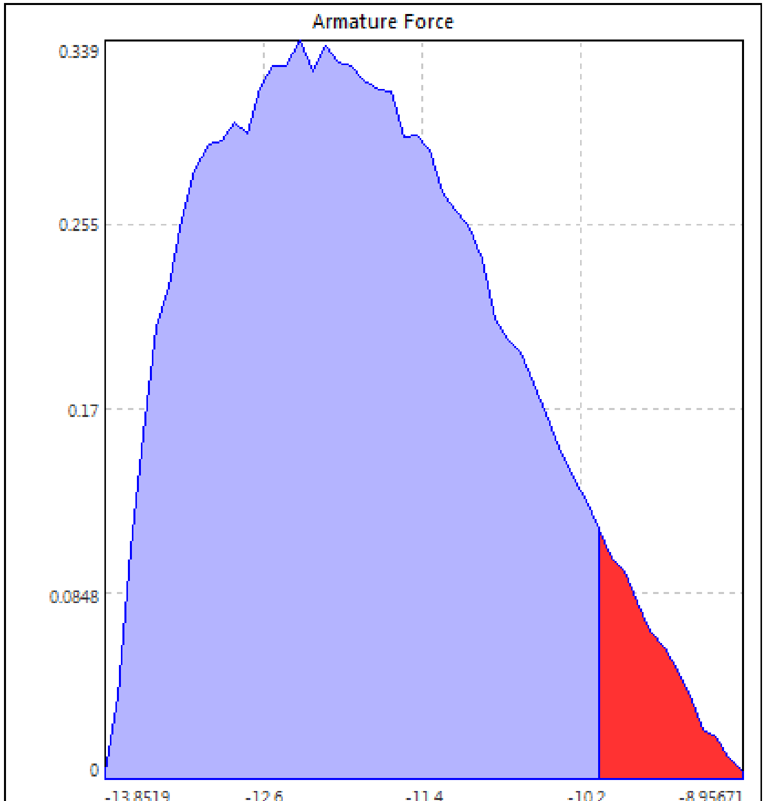
Design Parameters

Name	Nominal	Tolerance	Unit
Back Iron Inner Radius	0.00810815152	0.0001	m
Back Iron Thickness	0.00516077547	0.0001	m
Coil Thickness	0.0110754615	0.0001	m
Coil Distance	0.00262703234	0.0001	m
Armature Thickness	0.00827946693	0.0001	m
Air Gap	0.00182891033	0.0001	m
Ground Thickness	0.00737462933	0.0001	m
Coil High	0.0200907957	0.0001	m
Coil Current	1600	80	mA
Coil Voltage	5000	250	mV
B/H-Curve Scale	1	0.05	

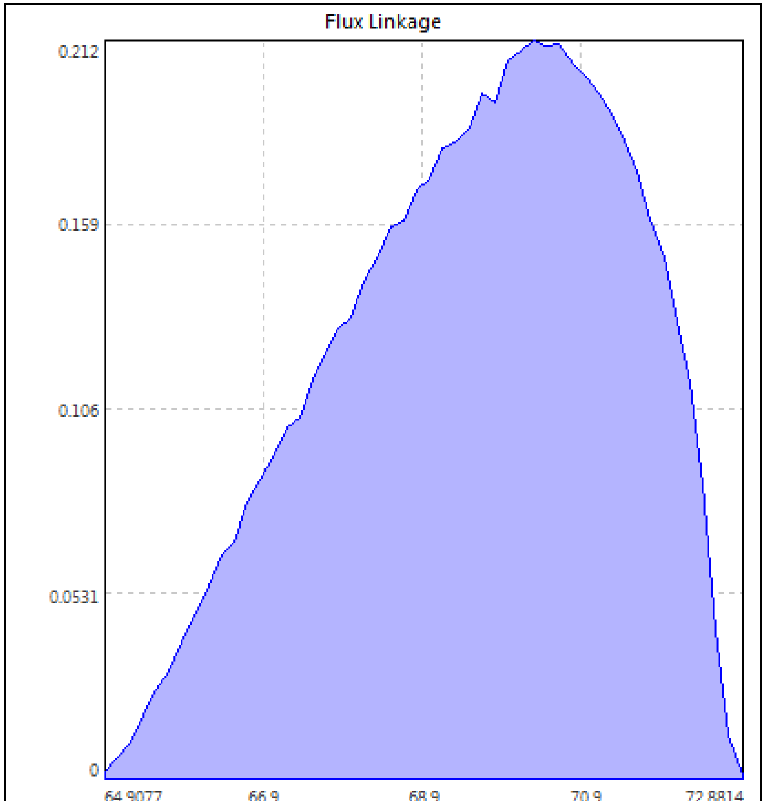
Robust Design: Reliability Analysis

-15 N ≤ F ≤ -10N

Failure Probability = 5,48 %



Mean	-11.8452	Skewness	0.330438
Sigma	1.05786	Kurtosis	2.32717
Variance	1.11907	Failure Probability	0.05481/0.05481



Mean	69.5557	Skewness	-0.347607
Sigma	1.72679	Kurtosis	2.29621
Variance	2.98182		

Conclusion

Nominal design using classical nominal simulation cannot warranty the reliability and quality of the products, because the nominal parameters are only one fix value.

Six sigma design is a power-full tool for design of reliable and quality products in the early design stage without any cost. It considers the uncertainty parameters as stochastic distributions.

In the case of the solenoid actuator, we can reduce the failure probability from **78,93%** to **5,48%** at a manufacturing process.

OptiY® is the leading software platform for six sigma design of all engineering fields using different commercial CAD/CAE-software or in-house codes.