MACCON

Parameter studies for the optimization of e-mobility traction motors with the help of FluxMotor, FLUX and HyperStudy

Dipl.-Ing. Christoph Stuckmann

MACCON: The company

MOTION UNDER CONTROL

- founded in 1982, based in Munich
- 35+ employees, mainly engineers and technicians
- specialised in high-end motion control solutions
  - development and manufacture of synchronous- (BLDC ,SR etc.) and asynchronous motors (AC)!
  - sales of electric motors, controls and drive accessories
  - in power range 100W up to >250kW!
- active in Germany, EU and Asia

Motors made to measure!

Drive Electronics to match!

Motioneering Turn-key Systems

Embedded Motion Control

Hi-Reliability MIL & Space

Extreme Environments

Multi-axis Motion Control

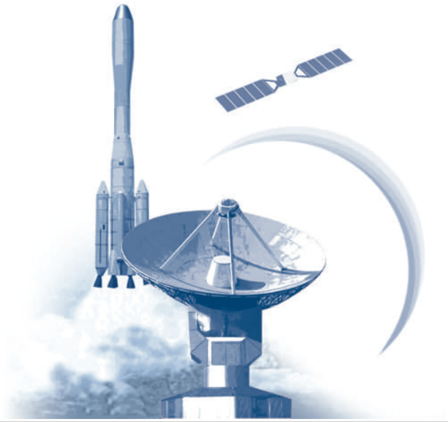
MACCON: Markets

MACCON
MOTION UNDER CONTROL

INDUSTRY

AUTOMOTIVE

AERONAUTICS



SCIENCE & SPACE

ENERGY

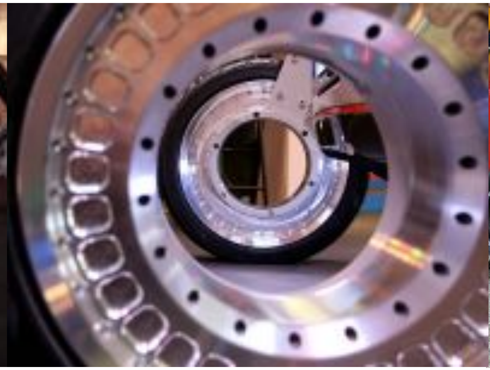
DEFENSE

INFOTAINMENT MEDICAL OPTICS SEMICONDUCTOR WHITE GOODS ETC.

CAE- SOFTWARE- SALE and ENGINEERING

Motors for electric vehicles

MACCON
MOTION UNDER CONTROL



Automotive

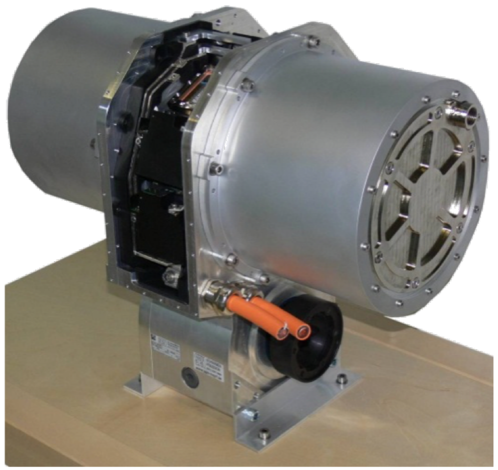
FSM- Traction motor

Single wheel- axle- drive- unit

- Includes two mechanically independent permanent magnet synchronous motors
- peak power of more than 80 kW for each motor Motors
- two mechanically independent spur gears with a fixed reduction of 7:1 adapt the torque and speed level of the electric machines to the wheel-requirement peak torque of 2.000 Nm per wheel

MACCON

- Motor design
- Complete motor manufacturing



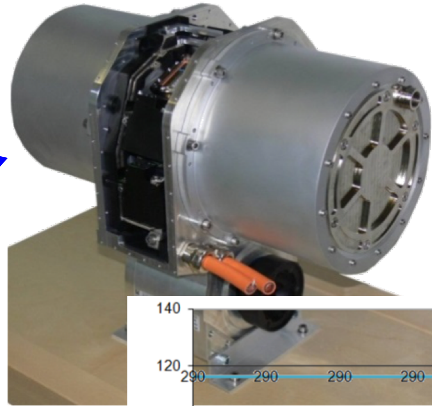
Automotive

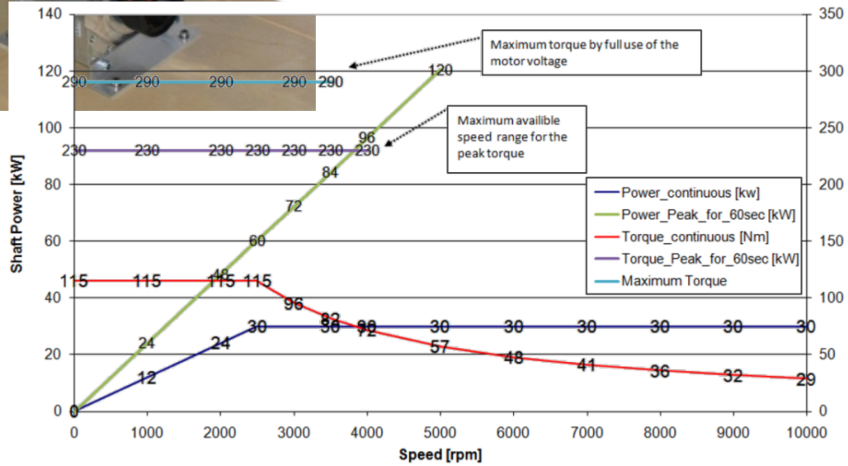
Coorparation project FraunhoferIISB / MACCON

MACCON
MOTION UNDER CONTROL

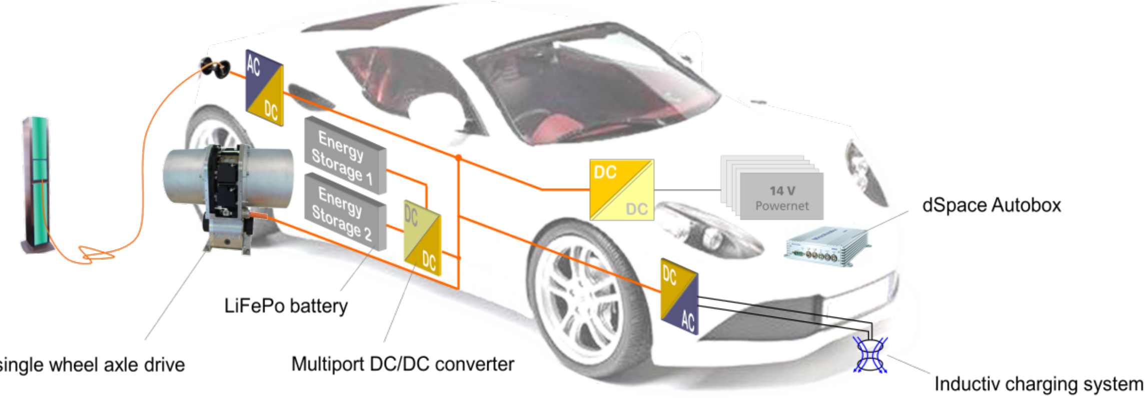
Coorparation project FraunhoferIISB / MACCON

MACCON
MOTION UNDER CONTROL





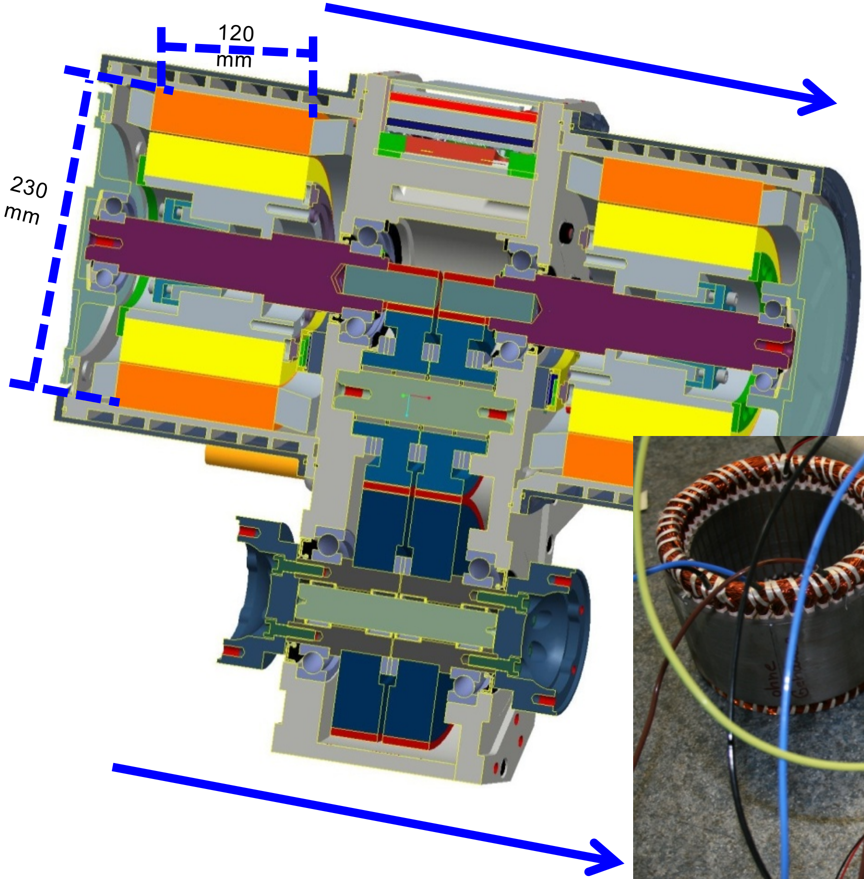
Development of a street legal electric vehicle (eArtega) fully equipped with Fraunhofer IISB components for traction-power, electric, thermal energy management and charging furthermore two highly optimized e- traction motors (designed by MACCON)

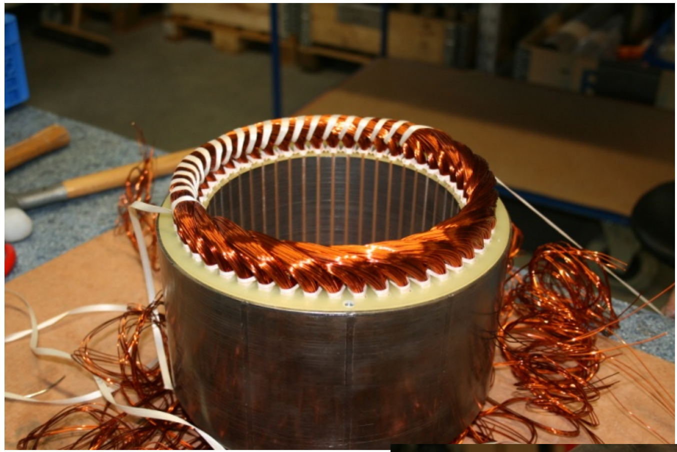


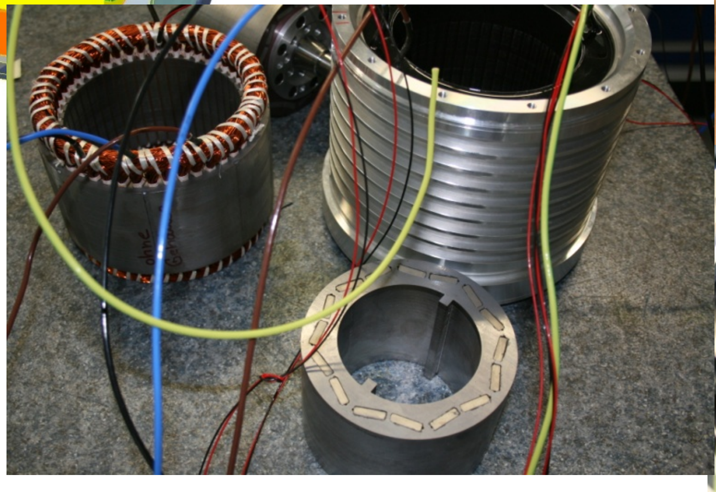
Coorparation project
FraunhoferIISB / MACCON

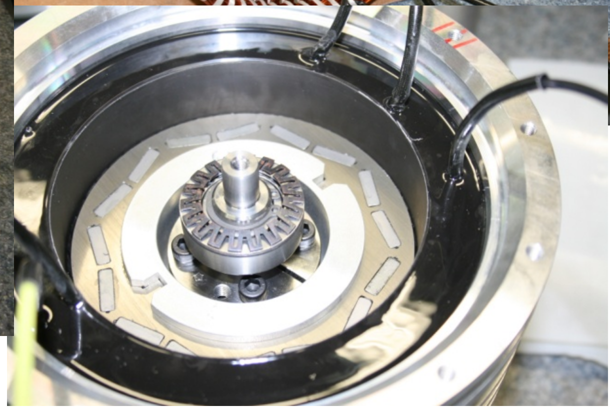
MACCON
MOTION UNDER CONTROL

Section view of the highly integrated
2x80 kW drive-unit





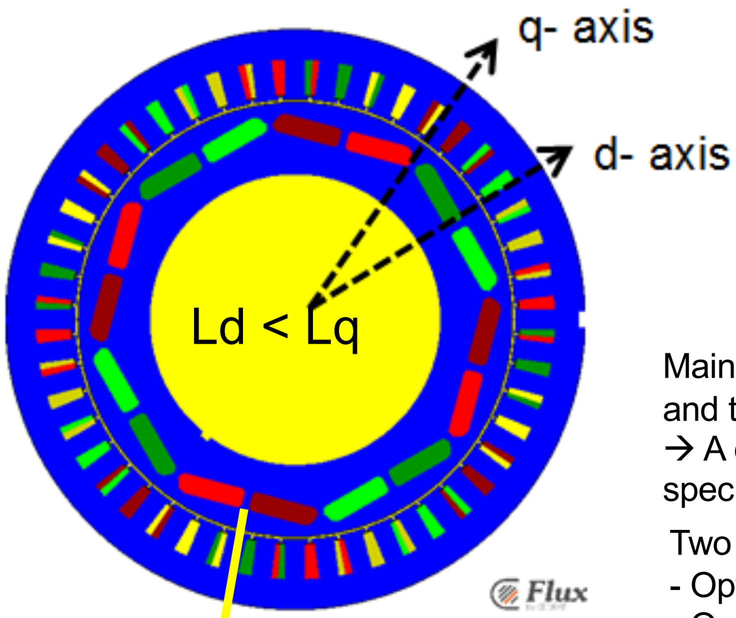


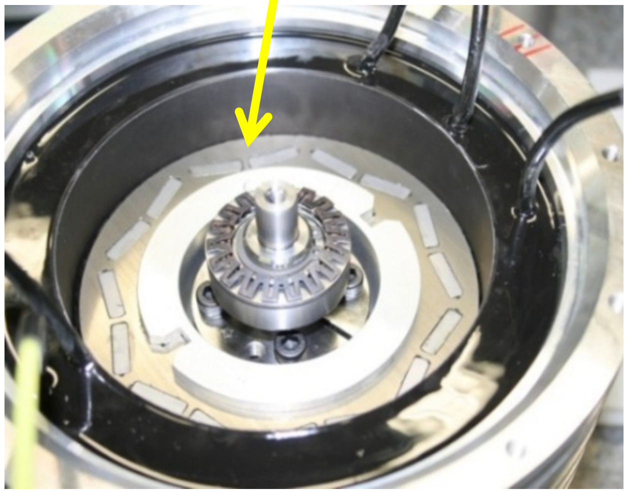


Pictures from the motor manufacturing

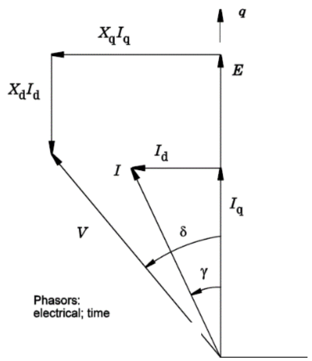
Optimization goals considering a special Torque- Speed characteristic of IPM- motors

MACCON
MOTION UNDER CONTROL



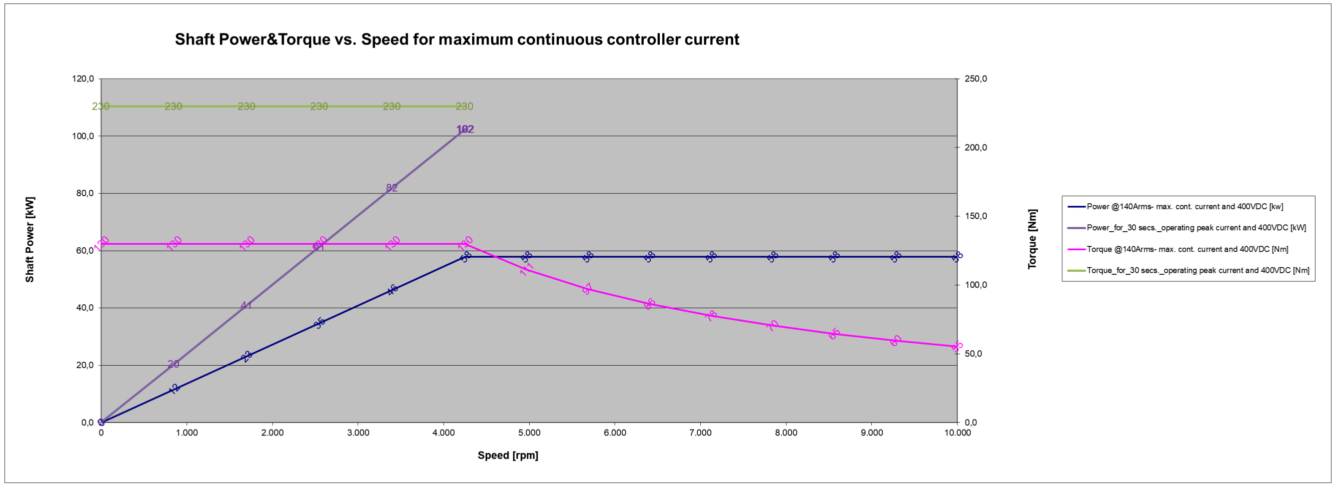


T_mag=m*p*(Ψd*Iq- Ψq*Id)
= m*p*[Ψ1Md*Iq+Id*Iq*(Ld-Lq)]
→inductances itself are depending on the respective current : Ld,Lq = f(Id,Iq, Ψ1Md)



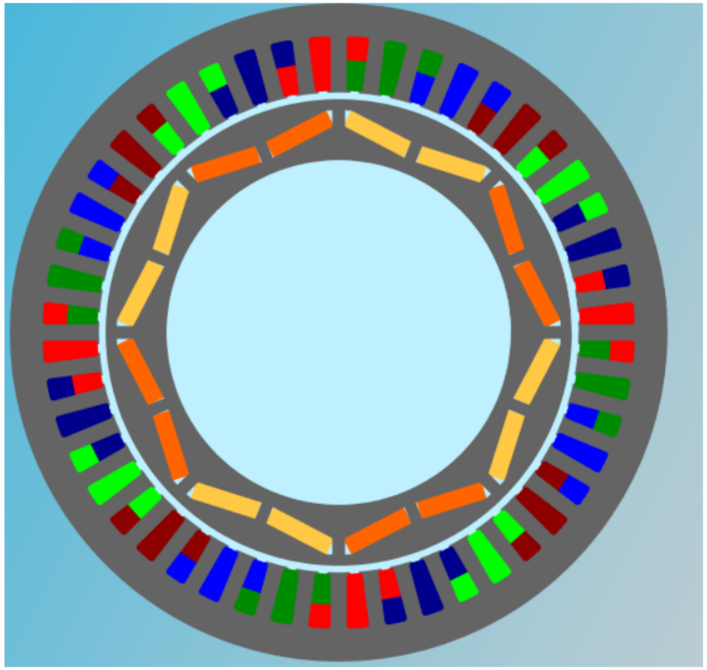
Main goal: maximization of the ratio for the rated to the maximum operating speed and therefore achieving a certain level of power density and efficiency
→ A certain operating voltage of the battery and a certain controller current limit is specified which have not to be exceeded

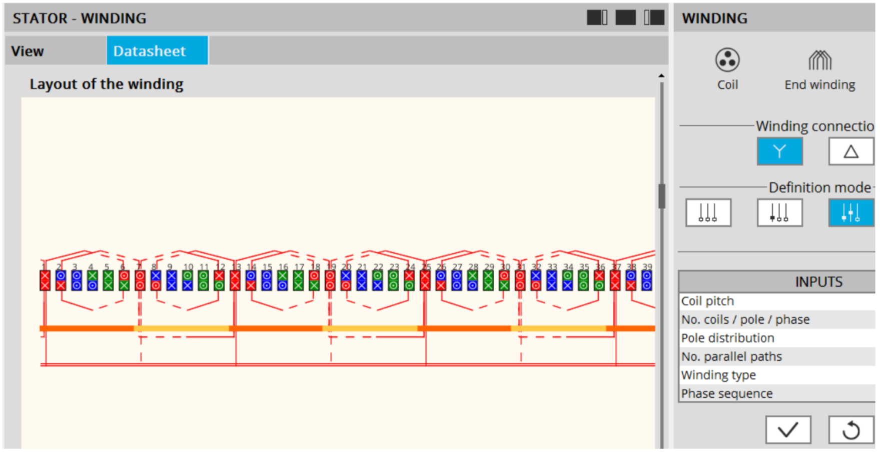
Two different approaches will be compared
- Option 1) FluxMotor and HyperStudy
- Option 2) Flux and HyperStudy



Input data for the geometry and further magnetic data needed for the FluxMotor design data table (Option 1)

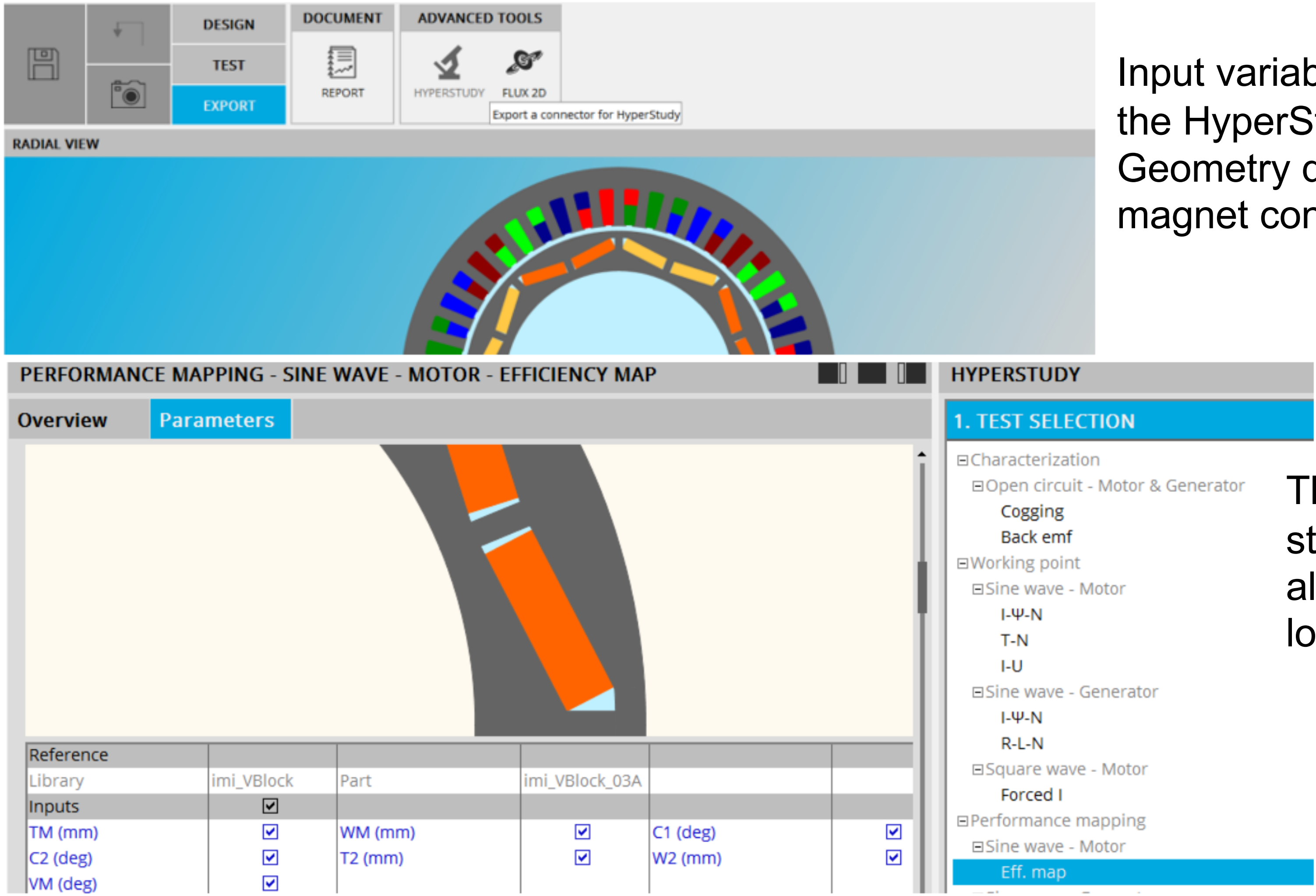
MACCON
MOTION UNDER CONTROL





Input data for the geometry and further magnetic data needed for the FluxMotor design data table (Option 1)

MOTION UNDER CONTROL

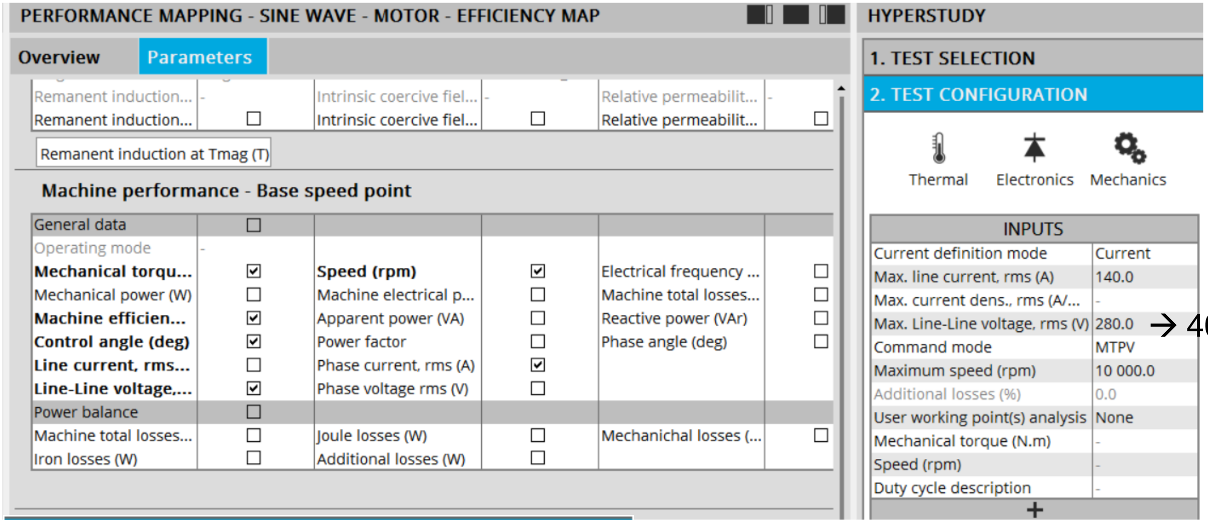


Input variable data for setup the HyperStudy- coupling file: Geometry data of the rotor and magnet configuration

The input data for the stator geometry are already fixed by the load requirements

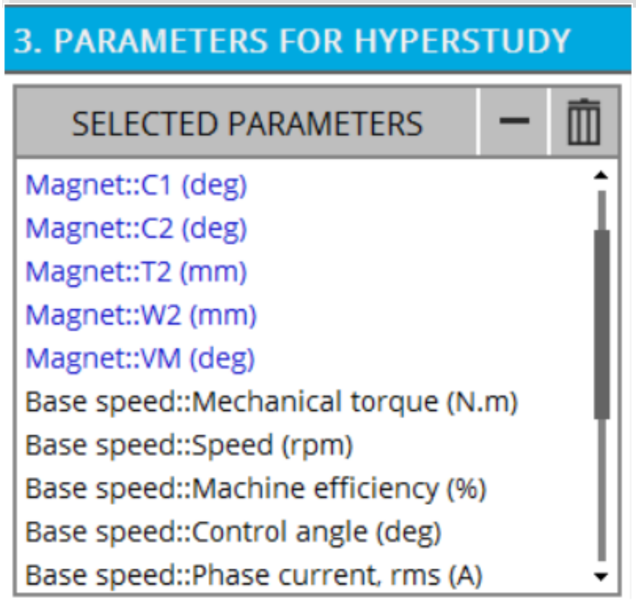
Input data for the geometry and further magnetic data needed for the FluxMotor design data table (Option 1)

MACCON
MOTION UNDER CONTROL



→ 400VDC

Output response data: Operating data for the rated and maximum operating speed for setup the HyperStudy- coupling file



Input data / output coupling data for setup the optimization process

Remark according the computation of the maximum rms- line-line- voltage:
As can be seen in the literature (e.g., DESIGN of BRUSHLESS PERMANENT MAGNET MACHINES):
a factor for the degree of modulation of 0.7 for the line-line-rms- voltage should be assumed (sine-triangle modulation with 3rd harmonic)

Input data for the geometry and further magnetic data needed for the FluxMotor design data table (Option 1)

MACCON
MOTION UNDER CONTROL

	Active	Label	Varname
1	☑	Magnet::TM (mm)	var_1
2	☑	Magnet::WM (mm)	var_2
3	☑	Magnet::C1 (deg)	var_3
4	☑	Magnet::C2 (deg)	var_4
5	☑	Magnet::T2 (mm)	var_5
6	☑	Magnet::W2 (mm)	var_6
7	☑	Magnet::VM (deg)	var_7

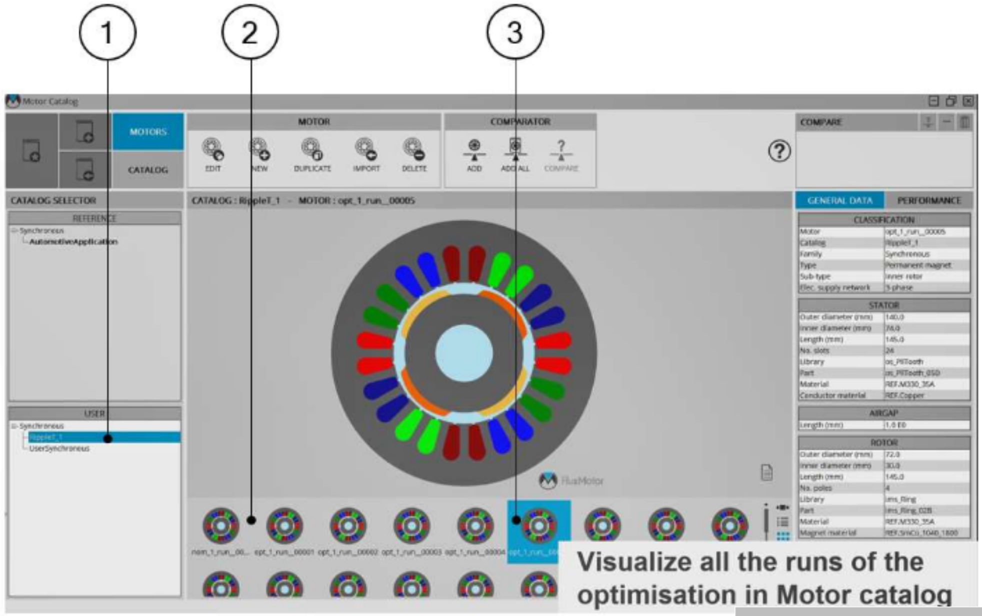
Input variable data for the HyperStudy optimization process

Output response variable data for the HyperStudy optimization process

	Active	Label	Varname	Expression	Value	Goals	Evaluate From	Output Type
1	☑	Base speed::Mechanical torque (N.m)	r_1	ds_1[0] ...	130.59782	>= 130.00000 ...	f() Expression	Real
2	☑	Base speed::Speed (rpm)	r_2	ds_2[0] ...	4213.1952	>= 4250.0000 ...	f() Expression	Real
3	☑	Base speed::Machine efficiency (%)	r_3	ds_3[0] ...	96.794317	>= 95.000000 ...	f() Expression	Real
4	☑	Base speed::Control angle (deg)	r_4	ds_4[0] ...	28.744064	Minimize ...	f() Expression	Real
5	☑	Base speed::Phase current, rms (A)	r_5	ds_5[0] ...	140.00000	<= 140.00000 ...	f() Expression	Real
6	☑	Base speed::Line-Line voltage, rms (V)	r_6	ds_6[0] ...	279.99986	<= 280.00000 ...	f() Expression	Real
7	☑	Maximum speed::Mechanical torque (N.m)	r_7	ds_7[0] ...	56.161711	>= 55.000000 ...	f() Expression	Real
8	☑	Maximum speed::Speed (rpm)	r_8	ds_8[0] ...	10000.000	>= 10000.000 ...	f() Expression	Real
9	☑	Maximum speed::Machine efficiency (%)	r_9	ds_9[0] ...	96.185798	>= 55.000000 ...	f() Expression	Real
10	☑	Maximum speed::Control angle (deg)	r_10	ds_10[0] ...	73.121551	Minimize ...	f() Expression	Real
11	☑	Maximum speed::Phase current, rms (A)	r_11	ds_11[0] ...	140.00000	<= 140.00000 ...	f() Expression	Real
12	☑	Maximum speed::Line-Line voltage, rms (V)	r_12	ds_12[0] ...	280.00001	<= 280.00000 ...	f() Expression	Real

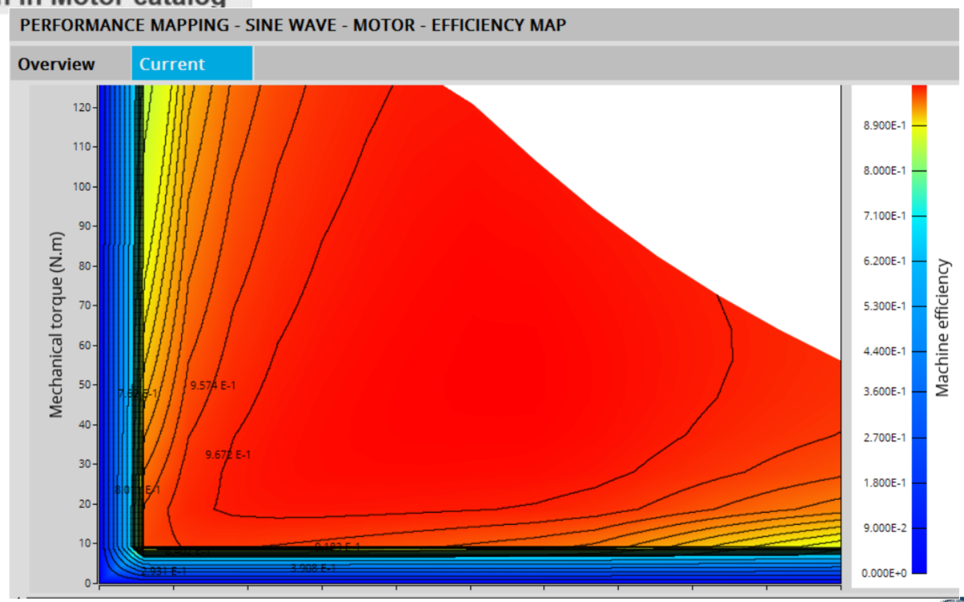
Input data for the geometry and further magnetic data needed for the FluxMotor design data table (Option 1)

MOTION UNDER CONTROL



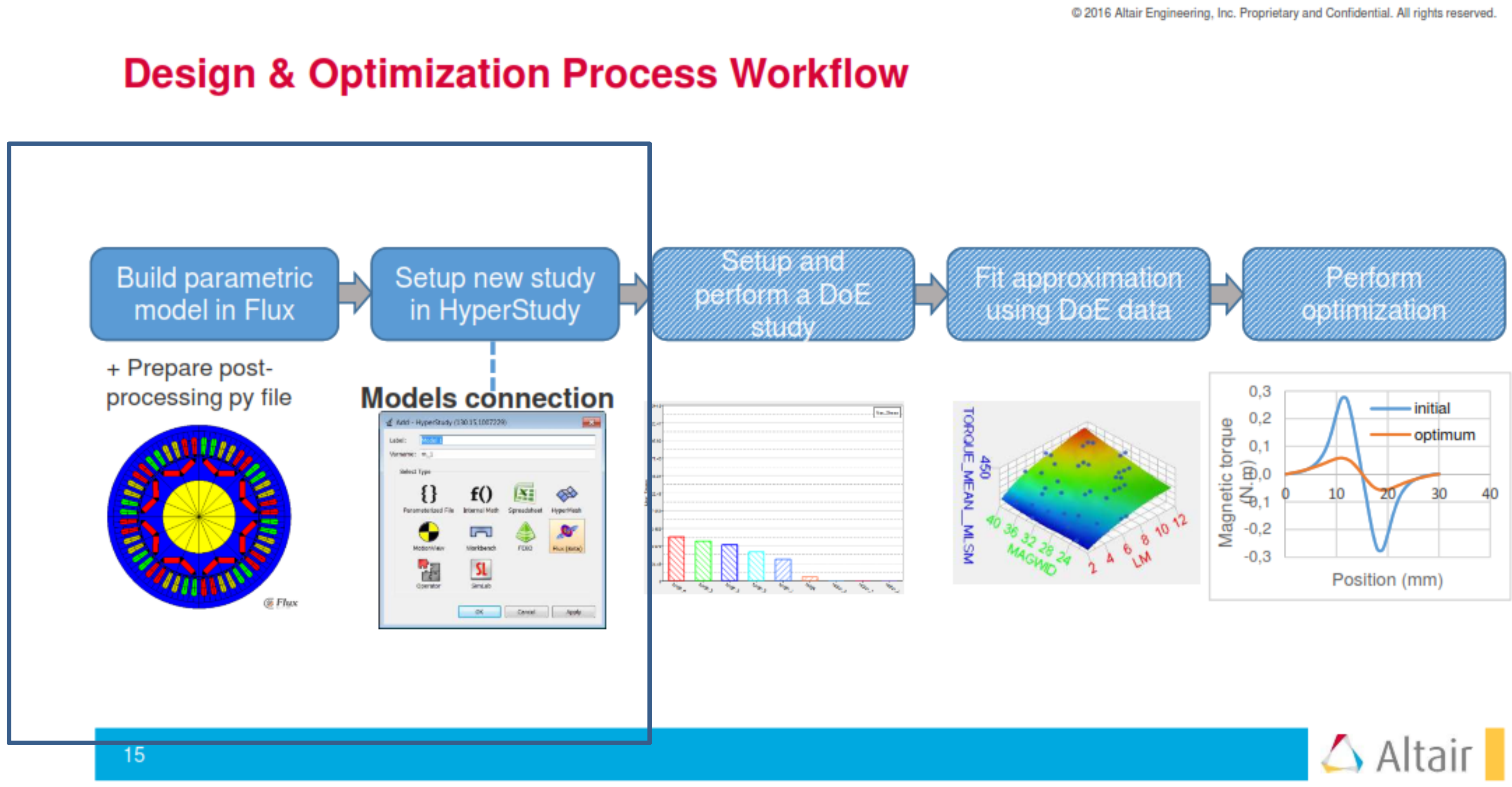
Dedicated Catalogue – stores all HyperStudy runs

Finally optimized EffMap- data



Computation of the Efficiency- Map data by using a more general approach → HyperStudy- Workflow / (Option 2)

MACCON
MOTION UNDER CONTROL



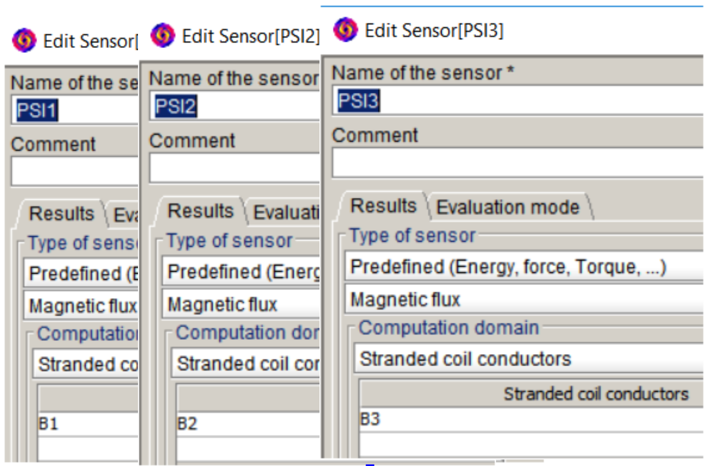
Computation of the Efficiency- Map data by using a more general approach → FLUX- coupling for DOE / (Option 2)

MACON
MOTION UNDER CONTROL

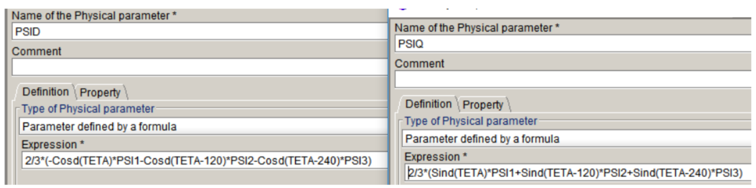
→ Approach by using FLUX and HyperStudy

Workflow to get the coupling with HyperStudy and FLUX for the DOE

Flux- model→ using 3 magnetic flux sensors



By using the Park-transformation the magnetic flux in d- and q- axis can be deduced



Coupling Flux- model with HyperStudy for the DOE

Input- variable data

Active	Label	Varname	Lower Bound	Nominal	Upper Bound	Comment
☑	ID	var_1	-300.00000 ...	10.000... ...	300.00000 ...	PHYS ...
☑	IQ	var_2	-300.00000 ...	10.000... ...	300.00000 ...	PHYS ...

Output variable data

Select Output Responses

Add Output Response   Remove Output Response   Evaluate from Fit Model

	Active	Label	Varname	Expression	Evaluate From
1	☑	PSIQ_MEAN	r_1	ds_1[0]	f0 Express...
2	☑	PSID_MEAN	r_2	ds_2[0]	f0 Express...

HyperStudy- Workflow→ DoE (Option 2)

MACCON
MOTION UNDER CONTROL

Investigate relationships

What are the critical parameters?

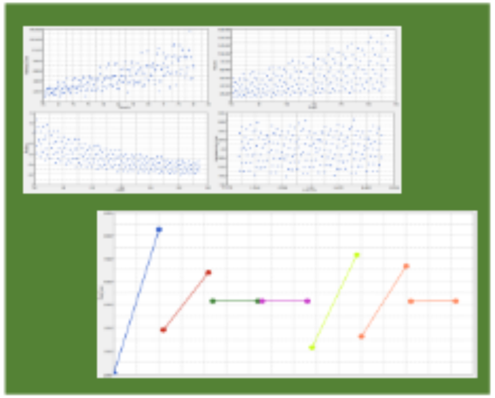
$$u_d = R_s \cdot i_d + \frac{d\Psi_d}{dt} - \omega_{el} \cdot \Psi_q = R_s \cdot i_d + L_d \cdot \frac{di_d}{dt} - \omega_{el} \cdot L_q \cdot i_q$$

$$u_q = R_s \cdot i_q + \frac{d\Psi_q}{dt} - \omega_{el} \cdot \Psi_d = R_s \cdot i_q + L_q \cdot \frac{di_q}{dt} - \omega_{el} \cdot L_d \cdot i_d$$

Equations for describing the motor behavior

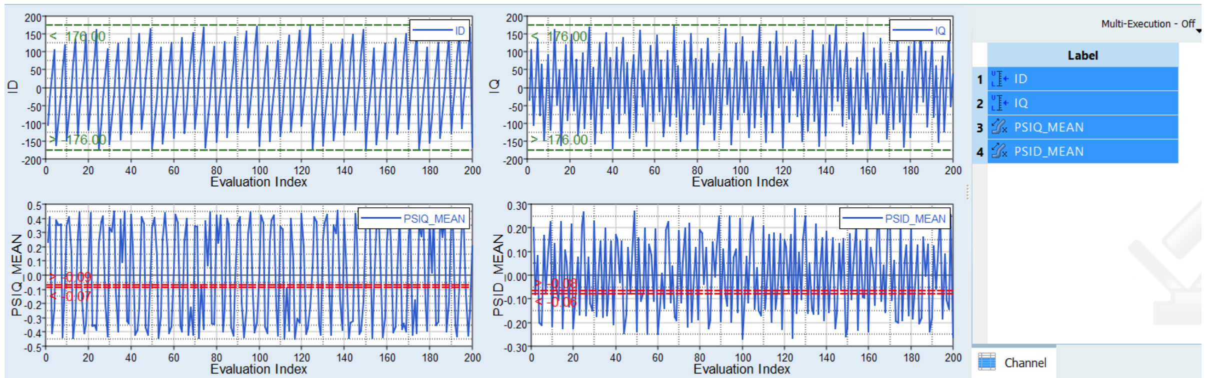
$$\Psi_d = L_d \cdot i_d$$
$$\Psi_q = L_q \cdot i_q$$

$$\Psi_d = L_d \cdot i_d + M_{dq} \cdot i_q$$
$$\Psi_q = L_q \cdot i_q + M_{qd} \cdot i_d$$



Design of Experiments

Input and output signal for the DoE-evaluation



HyperStudy- Workflow→ Fit (Option 2)

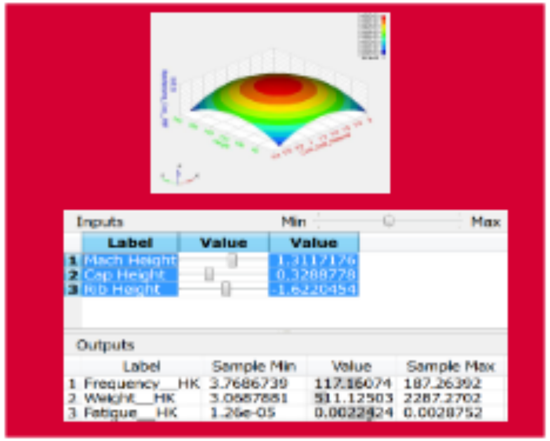
MACCON
MOTION UNDER CONTROL

Make predictions

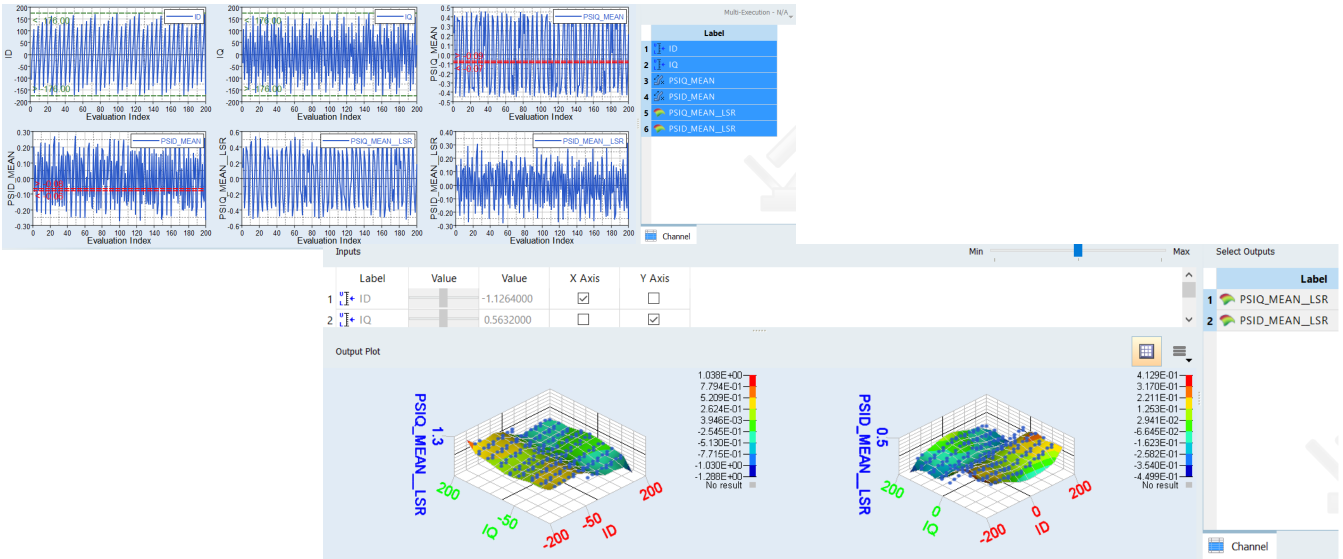
What will be the performance if?

Input matrix for the FiT- evaluation

Active	Label	Varname	Type	Matrix Source	Matrix Origin
☑	Fit Matrix 1	fitmatrix_1	Input	Hammersley (...	DoeHamme...



Output evaluation plots of the Fitting functions approximations interpolation as simulations responses



Fit

Deduced / compact regression term e.g. seventh polynomial order describing the motor behavior

1 PSIQ_MEAN_LSR

```
0.013295202619652042+(-0.010697467277629857*var_1^1)+(-8.950545774792234e-06*var_1^2)+( 1.3862731390705827e-06*var_1^3)+(
9.699311592161421e-10*var_1^4)+(-7.550827489080651e-11*var_1^5)+(-2.5554708449463794e-14*var_1^6)+( 1.3508958465608452e-15*var_1^7)
```

2 PSID_MEAN_LSR

```
-0.004889274102251369+(-2.6804174143316975e-04*var_1^1)+( 4.395358756482029e-06*var_1^2)+(
8.575694393092441e-08*var_1^3)+(-5.872199071918761e-10*var_1^4)+(-6.56221783062804e-12*var_1^5)+( 1.779321029106209e-14*var_1^6)+(
1.394610857341266e-16*var_1^7)
```

HyperStudy- Workflow→ Optimization (Option 2)

MACCON
MOTION UNDER CONTROL

The inner optimization loop has to be embedded in the outer loop

- Inner_Loop
  - Setup
    - Define Models
    - Define Input Variables
    - Specifications
    - Evaluate
    - **Define Output Responses**
    - Post-Processing
    - Report
  - Optimization 1
    - Select Input Variables
    - Select Output Responses
    - Specifications
    - Evaluate
    - Post-Processing
    - Report

Add Output Response | Remove Output Response | File Assistant

	Active	Label	Varname	
1	☑	PSIQ	PSIQ	0.007350320827406479+(-4.542217749868624e-05*ID^1)+(8.595321756416163e-04*IQ^1)+(-1.3313151435134255e-08*ID^2)+(-3
2	☑	PSID	PSID	0.08321641065616878+(3.455472192926523e-04*ID^1)+(-4.277845755377263e-05*IQ^1)+(6.547642721526293e-08*ID^2)+(1.101
3	☑	Torque_mag	Torque_mag	(PSID * IQ - PSIQ * ID) * 3 / 2 * Polzahl / 2*scale
4	☑	omega	omega	N_ist/ 60 * 2 * PI * Polzahl / 2
5	☑	Torque_abw	Torque_abw	(Torque_mag-Torque_eff)^2
6	☑	Drehz_abw	Drehz_abw	(N_soll-N_ist)^2
7	☑	Du	Du	Rphase * ID - omega * PSIQ
8	☑	Uq	Uq	Rphase * IQ + omega * PSID
9	☑	Uist	Uist	sqrt(Du ^2+ Uq ^2)
10	☑	Iist	Iist	sqrt(ID ^2 + IQ^2)
11	☑	CopperLosses	CopperLosses	3 * Rphase * Iist * Iist / 2

Add Input Variable | Remove Input Variable

	Active	Label	Varname	Lower Bound	Nominal	Upper Bound	Comment
1	☑	ID	ID	-300.00000 ...	-100.00000 ...	0.0000000 ...	...
2	☑	IQ	IQ	0.0000000 ...	200.00000 ...	300.00000 ...	...
3	☐	Polzahl	Polzahl	0.9000000 ...	8.0000000 ...	1.1000000 ...	...
4	☐	Torque_soll	Torque_soll	1.0000000 ...	130.00000 ...	200.00000 ...	...
5	☐	N_soll	N_soll	0.9000000 ...	3000.0000 ...	25000.000 ...	...
6	☐	Rphase	Rphase	0.0100000 ...	0.0200000 ...	0.0500000 ...	...
7	☑	N_ist	N_ist	1.0000000 ...	7000.0000 ...	25000.000 ...	...

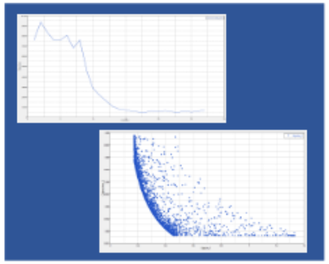
Responses | Objectives | Constraints

Add Objective | Remove Objective

	Active	Label	Varname	Type	
1	☐	Objective 1	obj_1	Minimize	Torque_abw (Torque_abw)
2	☐	Objective 2	obj_2	Minimize	Drehz_abw (Drehz_abw)
3	☑	Objective 3	obj_3	Maximize	eta (eta)

Identify best design

What is the best solution?



Optimization

Responses | Objectives | Constraints

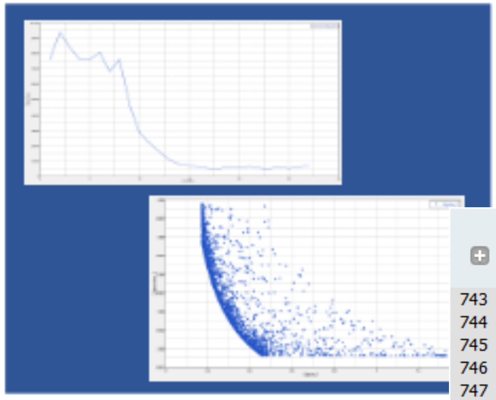
Add Constraint | Remove Constraint

	Active	Label	Varname	Type	Apply On	Bound Type	Bound Value	CDF Limit	Evaluate From
1	☑	Constraint 1	c_1	Deterministic	Torque_abw (Torque_abw)	<=	1.0000000	99.000000	Expression
2	☑	Constraint 2	c_2	Deterministic	Drehz_abw (Drehz_abw)	<=	1.0000000	99.000000	Expression
3	☑	Constraint 3	c_3	Deterministic	Uist_rms (Uist_rms)	<=	150.00000	99.000000	Expression
4	☑	Constraint 4	c_4	Deterministic	eta (eta)	>=	0.5000000	99.000000	Expression

HyperStudy- Workflow→ Optimization (Option 2)

Identify
best design

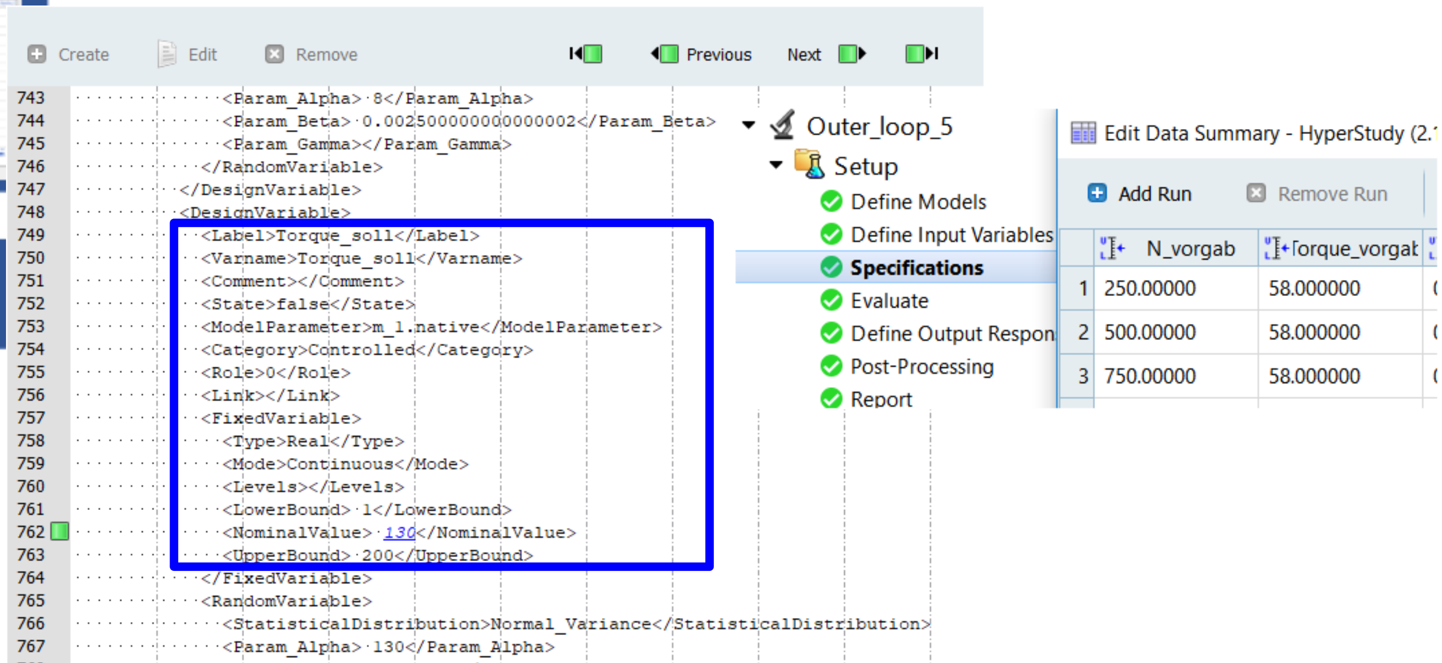
What is the best solution?



Optimization

The inner optimization loop has to be embedded in the outer loop

By the outer loop can be varied values of the inner loop:
The target torque values of the torque- speed characteristic → maximum torque and partial torque values / maximum speed and partial speed values: in order to compute intermediate values too for the interpolation algorithm



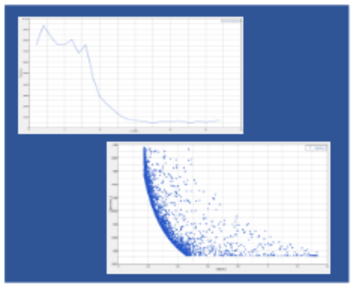
HyperStudy- Workflow→ Optimization (Option 2)

Results of the maximum torque range computation

	N_vorgab	Torque_vorga	ID	IQ	Torque_mag	eta	gamma	Ist_rms	Uist_rms	cos_phi	P_iron
2	1000.0000	130.00000	-94.742222	186.41283	130.94944	0.9069835	26.941441	147.86114	44.176490	0.7710582	93.669733
3	1500.0000	130.00000	-102.62085	175.25635	129.21484	0.9367632	30.350982	143.60680	63.255570	0.7952870	133.15699
4	2000.0000	130.00000	-122.86566	158.18919	129.08495	0.9515828	37.836514	141.63296	78.544608	0.8517107	172.64425
5	2500.0000	130.00000	-93.353942	184.28631	129.24879	0.9577507	26.865413	146.07601	106.70731	0.7554021	212.13150
6	3000.0000	130.00000	-123.32193	157.70835	129.00158	0.9653576	38.024053	141.56310	116.31675	0.8496707	251.61876
7	3500.0000	130.00000	-115.22674	164.79483	129.44138	0.9692607	34.960013	142.21266	139.21098	0.8321899	291.10602
8	4000.0000	130.00000	-132.10488	151.47048	129.02657	0.9722541	41.093284	142.11793	149.99071	0.8694412	330.59327
9	4100.0000	130.00000	-139.41188	146.58636	128.99948	0.9725024	43.562993	143.04411	149.99691	0.8849342	338.49073
10	4200.0000	130.00000	-146.63986	142.17500	129.04792	0.9726205	45.885680	144.42468	149.99659	0.8980066	346.38818
11	4250.0000	130.00000	-151.10490	139.59936	129.08646	0.9725799	47.266478	145.46593	149.56010	0.9051842	350.33690
12	4500.0000	130.00000	-168.86948	129.94124	128.99950	0.9723003	52.422534	150.66789	149.07565	0.9280188	370.08053
13	5000.0000	117.00000	-171.09104	112.50906	116.07748	0.9733019	56.671175	144.79370	149.90939	0.9591385	409.56779
14	5500.0000	106.00000	-172.89542	98.498274	105.01114	0.9736447	60.329897	140.70312	149.98431	0.9810320	449.05504
15	6000.0000	98.000000	-177.43169	87.655036	96.997989	0.9734303	63.709647	139.93822	149.99998	0.9942345	488.54230
16	6500.0000	90.000000	-178.56144	78.326655	88.999472	0.9731939	66.315158	137.87540	149.99984	1.0032772	528.02956
17	7000.0000	84.000000	-184.28667	71.224644	84.037617	0.9725488	68.869066	139.70420	150.04292	1.0071185	567.51682
18	7500.0000	78.000000	-182.65046	64.079174	76.999683	0.9721702	70.667623	136.87098	150.00384	1.0098528	607.00407
19	8000.0000	73.000000	-184.24858	58.344990	72.010206	0.9715400	72.428853	136.65957	149.99736	1.0096443	646.49133
20	8500.0000	69.000000	-186.83411	53.491259	67.998416	0.9708227	74.023397	137.41961	149.99997	1.0081694	685.97859
21	9000.0000	65.000000	-188.09742	49.023222	64.000134	0.9701001	75.392152	137.44802	149.98934	1.0052782	725.46584
22	9500.0000	62.000000	-190.91596	45.316135	61.011484	0.9693398	76.647283	138.74879	150.04486	1.0026758	764.95310

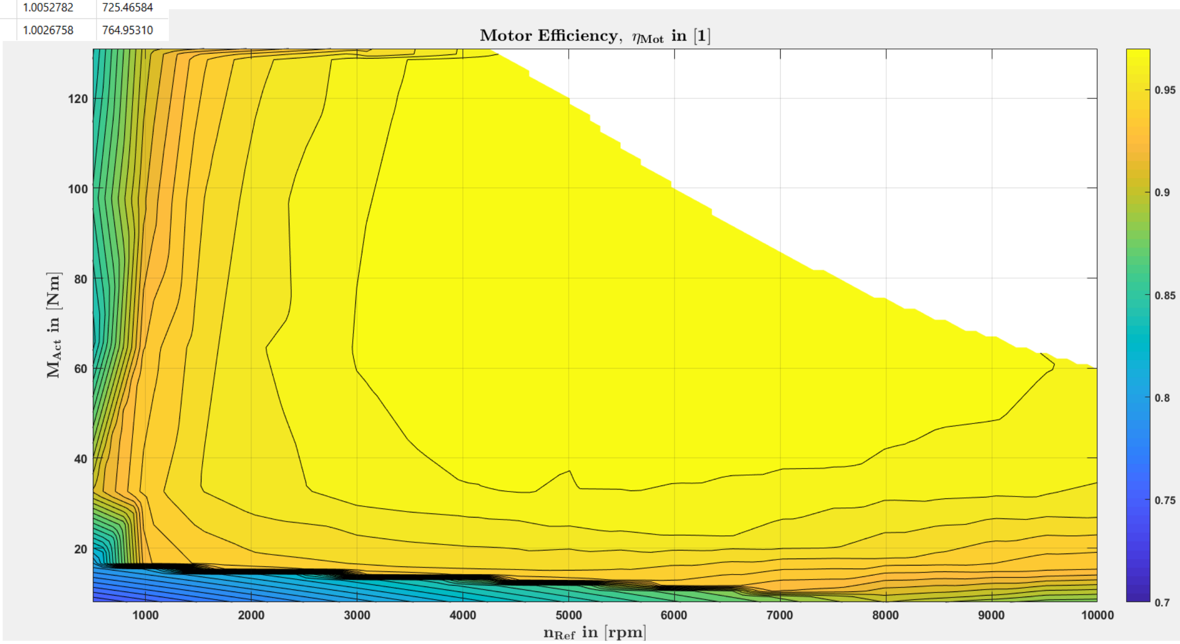
Identify
best design

What is the best solution?



Optimization

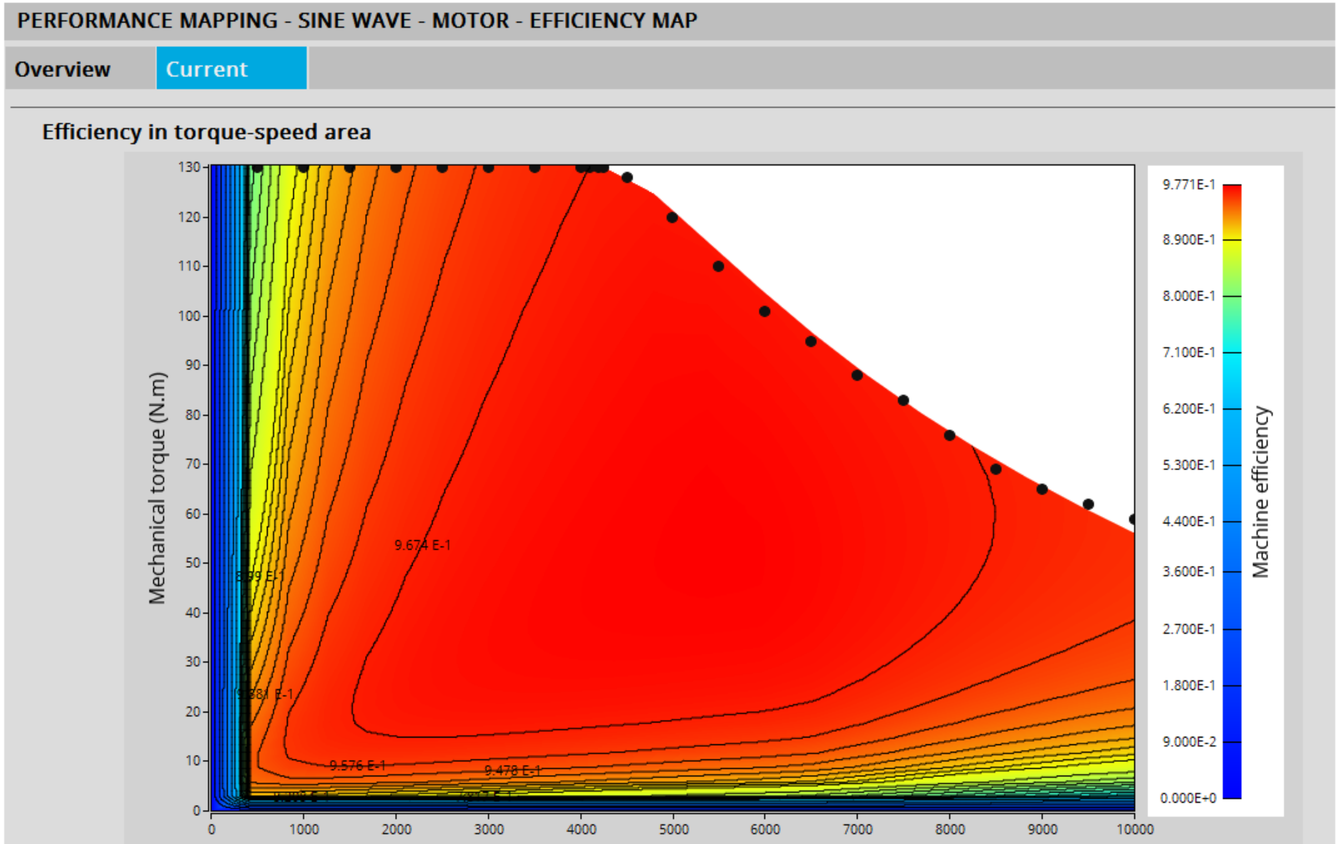
Resulting interpolated efficiency map (therefore partial data values were computed in addition)



Comparison of both approaches (option 1 versus option 2)

MACCON
MOTION UNDER CONTROL

The black marked points were computed by the method of using FLUX and HyperStudy furthermore these points were verified by measurements on a test bench / the main plot were generated by FluxMotor



Both approaches are having very similar results. Furthermore the consistency of the results are confirmed by measurements. Consequently, both solutions can be used, with each approach having its strengths.

Comparison of both approaches (option 1 versus option 2)

MOTION UNDER CONTROL

Summary:

The approach by using FluxMotor and HyperStudy works very fast and can easily be setup. The solution by using FLUX and HyperStudy results in the highest degree of flexibility and gives furthermore a basis for a motor model setup by using the replacement function. By the help of this model the complex behaviour of the motor can be embedded in system simulation models.

→ FluxMotor is very well suited for a first parameter study. Further design considerations should be done with the help of FLUX, HyperStudy and further Altair software- tools.

MACCON

MOTION UNDER CONTROL

Thank you for attention.

We look forward to working with you!

Motors
made to measure!

Drive Electronics
to match!

Motioneering
Turn-key Systems

Embedded Motion
Control

Hi-Reliability
MIL & Space

Extreme
Environments

Multi-axis
Motion Control