Global efficiency and torque accuracy optimization for an EESM

Lecturer

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- Senior Application Engineer for CAMEO
- In AVL since 2007
- Application Engineer & Personal Agent
- CAMEO on Testbed, CAMEO for E-Drive
- Married, two Daughters
- MTB (without E-Drive), Piano, RC - Model Building

Agenda

Agenda

Challenge

Full coverage of the whole area
In a short time (limited test bed time)

Near the MTPF line
Fast increase in temperature
Modulation Index

Create a global model to characterize the EESM
Speed, Torque, U_{DC}, I_d, I_q + $\mathbf{I_f}$,

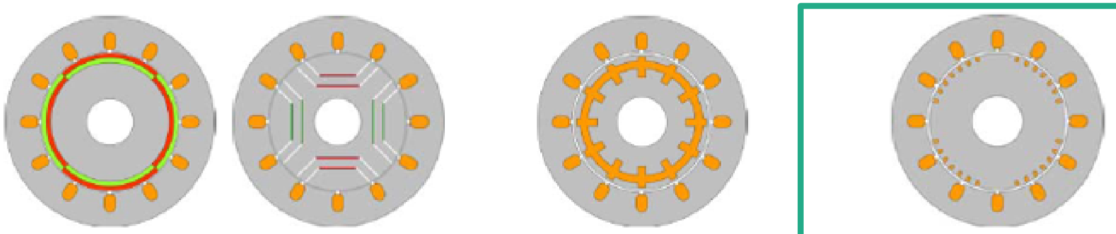
In a defined temperature range
Stator temperature in a certain tolerance (+/- 5°C)
Rotor Temperature < T_{max}

Generate optimized data
With best efficiency and max torque accuracy

Agenda

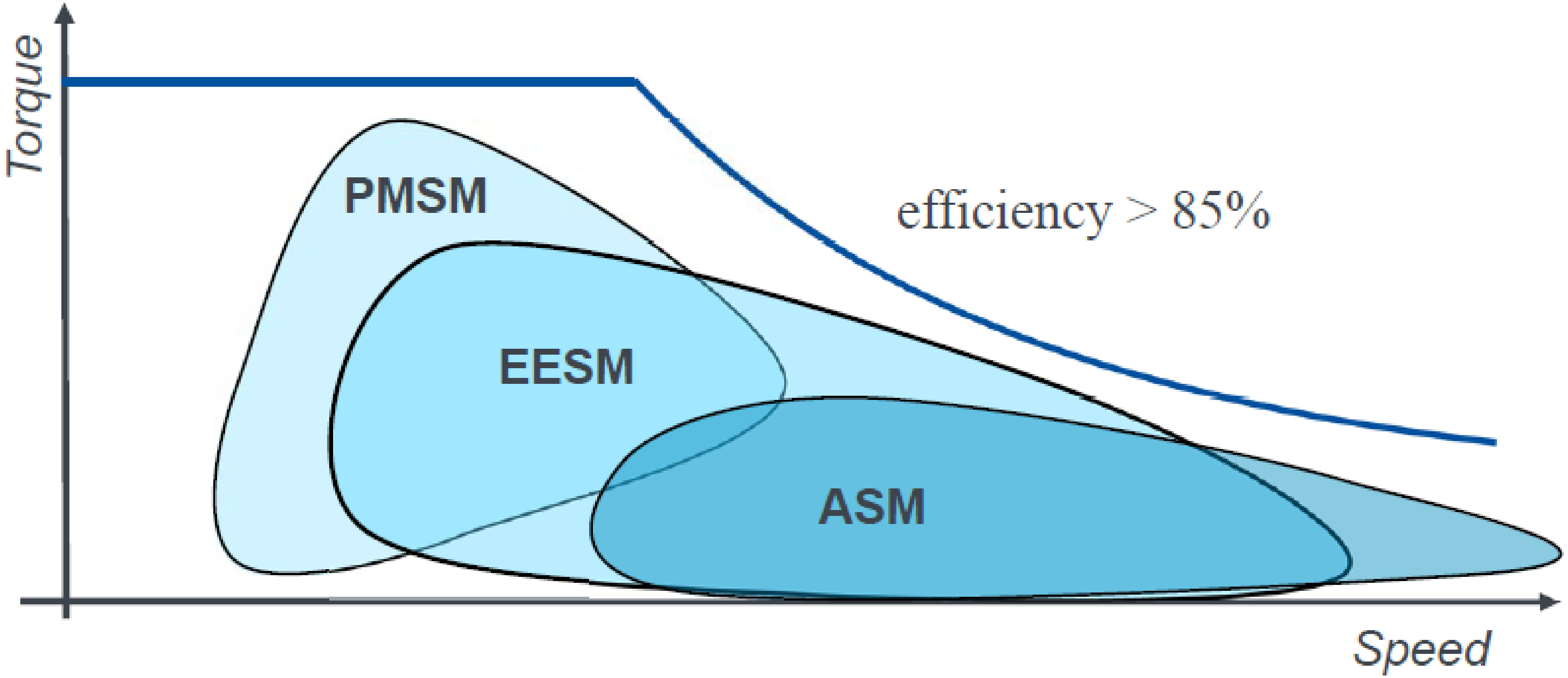
EESM – Characteristics I

- Good behavior in every speed
- No magnets
- Slip rings (alternative: Induction coils)
- Switch off possible
- Fail safe
- Uncritical temperature sensitivity



	PMSM	ASM	EESM
$n < n_n$	high efficiency	disadvantages in efficiency	good efficiency
$n > n_n$	low efficiency	advantages in efficiency	high efficiency
costs	higher production costs than ASM (magnet material)	design is simple and cheap (aluminium die-cast rotor)	Lower production costs than PMSM (no magnets)
durability	low maintenance	low maintenance	Slip rings
fault	critical (overvoltage, braking torque)	Uncritical	Uncritical
temperature sensitivity	critical (permanent magnets)	uncritical	Uncritical

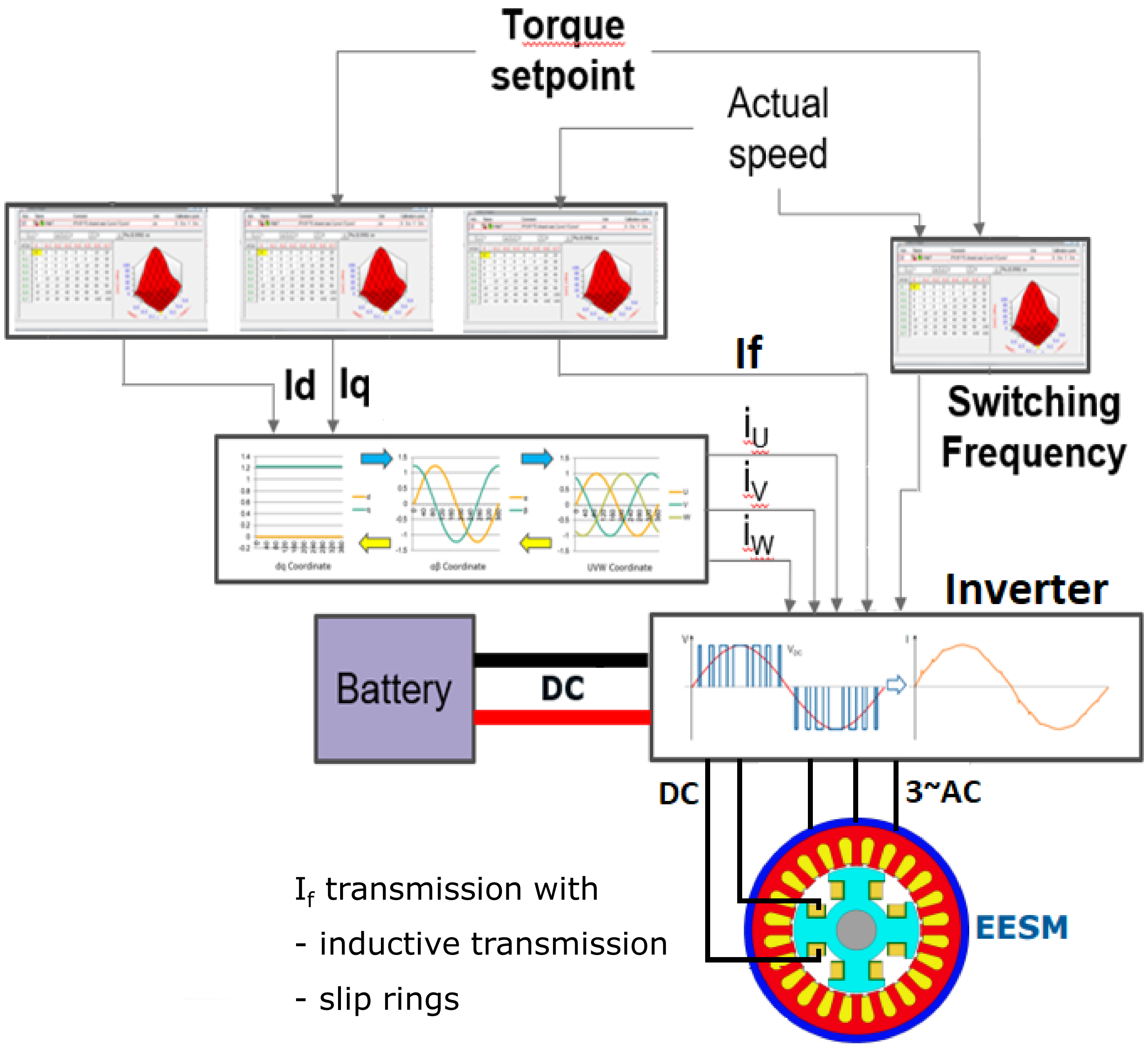
EESM – Characteristics II



EESM – I_f

With I_f we…

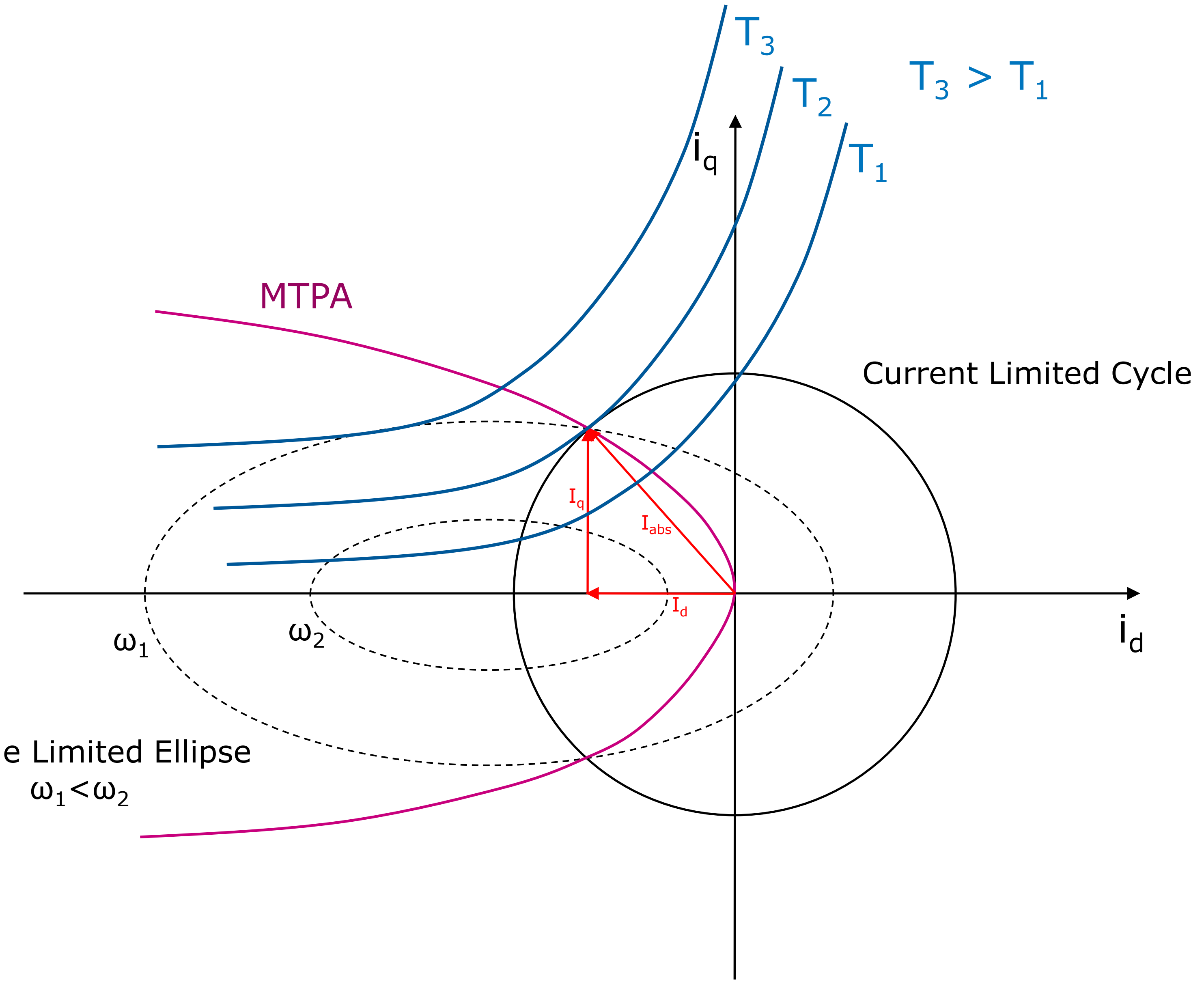
- have a temperature model for Rotor Temperature
- can influence the field weakening
- have no magnets



I_f transmission with
- inductive transmission
- slip rings

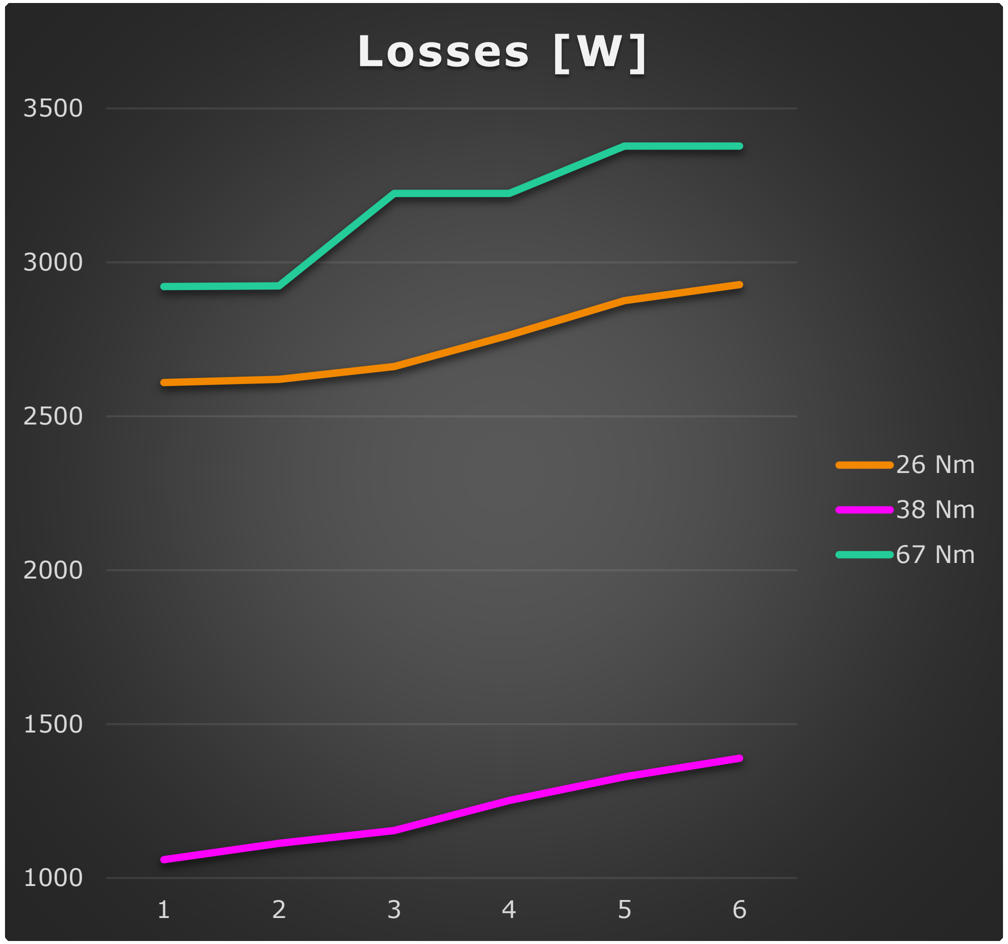
I_d-I_q - Plot

- Temperature influences the Voltage Ellipse
- I_f influences the magnetic field of the rotor → the Torque Lines
- So, with I_f you have the possibility to depict different PMSMs



Variations for Torque

Torque [Nm]	Tot. Losses [W]	I_f [A]	I_q [A]	I_d [A]	ModIndex
25.59	2610	4.60	103.44	-56.56	1.09
25.59	2620	4.37	99.56	-64.03	0.88
25.59	2662	4.06	105.47	-59.34	0.87
25.59	2764	3.30	115.78	-77.31	0.69
25.59	2876	4.51	115.09	-73.09	0.89
25.59	2928	4.75	116.31	-75.56	0.92
38.13	1060	3.31	113.59	-7.88	0.27
38.13	1113	4.09	113.91	-8.84	0.31
38.13	1154	4.16	116.19	-7.97	0.31
38.13	1252	3.29	133.31	-11.06	0.28
38.13	1329	4.76	129.09	-10.00	0.34
38.13	1389	4.98	133.53	-10.44	0.35
66.91	2922	6.23	177.94	-55.31	0.92
66.91	2924	7.49	171.28	-61.94	0.96
66.91	3224	4.96	203.41	-67.31	0.82
66.91	3224	4.96	203.41	-67.31	0.82
66.91	3378	7.46	201.56	-72.88	0.97
66.91	3378	7.46	201.56	-72.88	0.97



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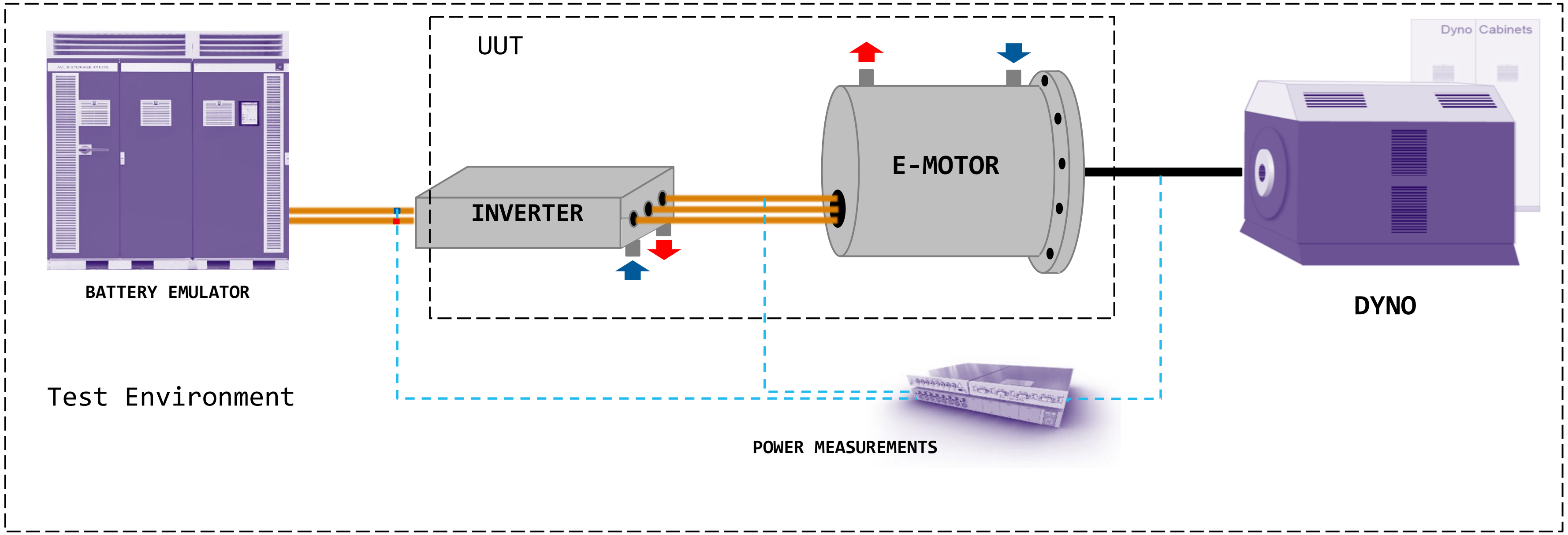
How we get the solution?



AVL Toolchain

CAMEO
Smart Calibration and Validation

PUMA
Automation

XION
Power Analyzer

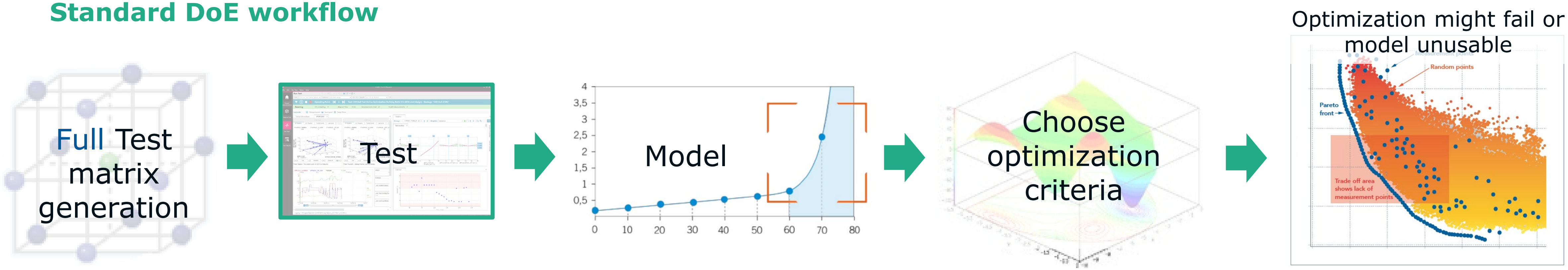
Concerto
Post processing

Active DoE Workflow

Traditional DoE

- Test – Model – Predict – Optimize: Too late for knowledge gained after testing to improve the testing phase

Standard DoE workflow



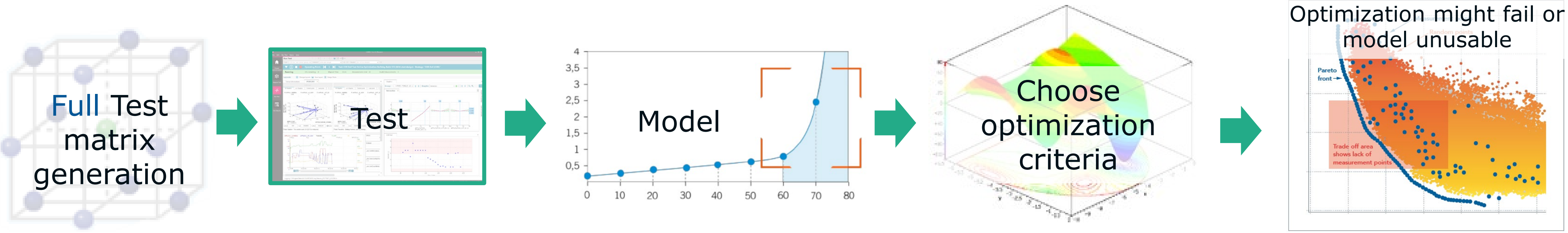
For high numbers of input dimensions or highly non-linear systems, even standard DoE has its limits

Minimizing time per test

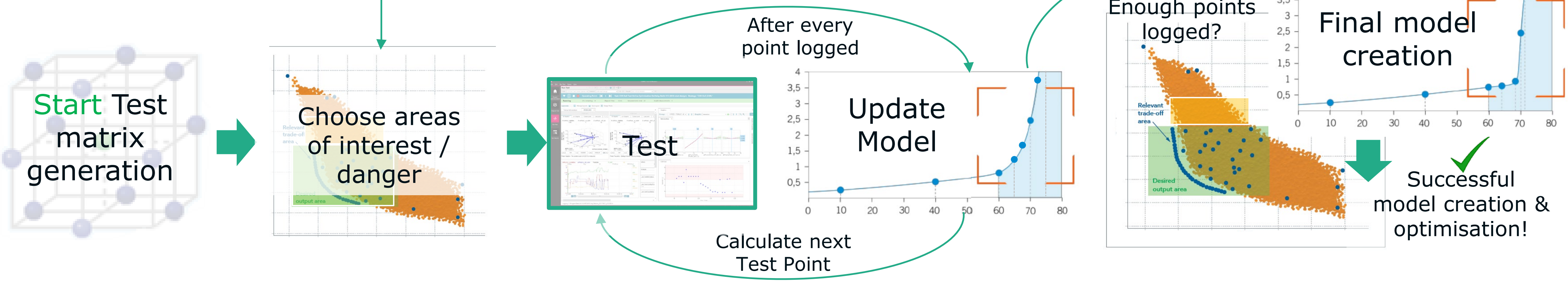
Active DoE

- Model and Predict *during* the test: Bring Knowledge forward to the testing phase

Standard DoE workflow



AI Active DoE workflow



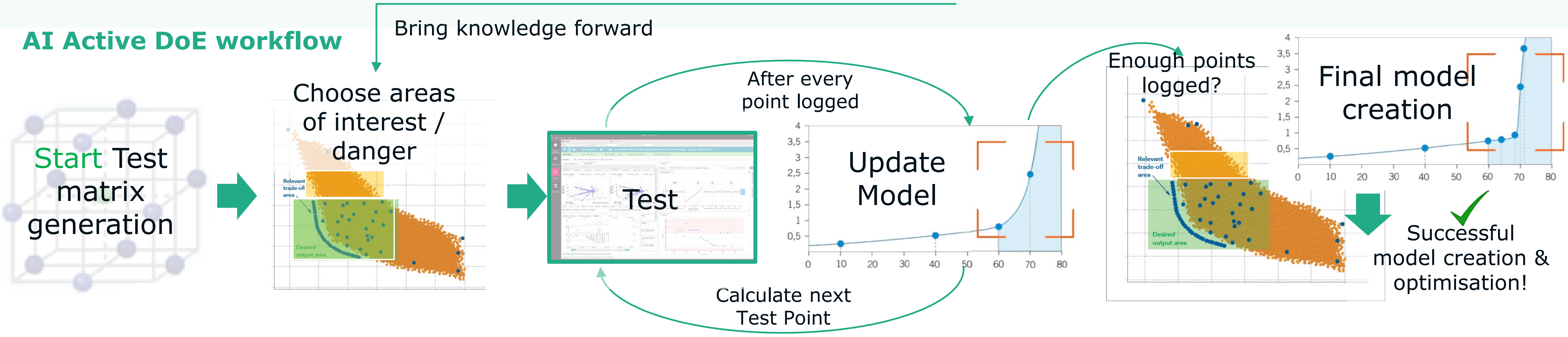
Minimizing time per test

Active DoE benefits

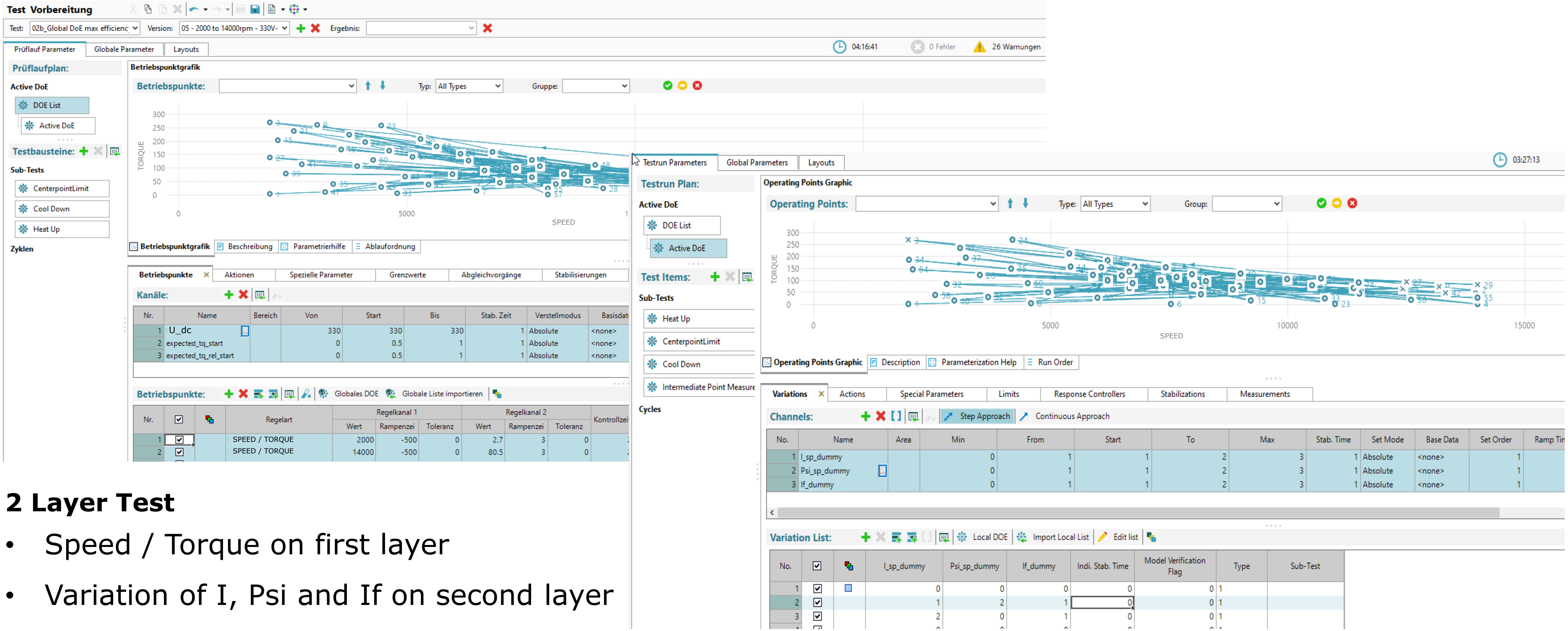
Predictive Intelligence during testing

- Intelligently focus testing on target areas
- Reduce points logged by >30% (for 5+ inputs)
- Auto-stop test when enough data gathered
- Avoid dangerous or uninteresting areas
- Improve model quality

AI Active DoE workflow



Active DoE Test in CAMEO



2 Layer Test

- Speed / Torque on first layer
- Variation of I, Psi and If on second layer
- Global DoE Design

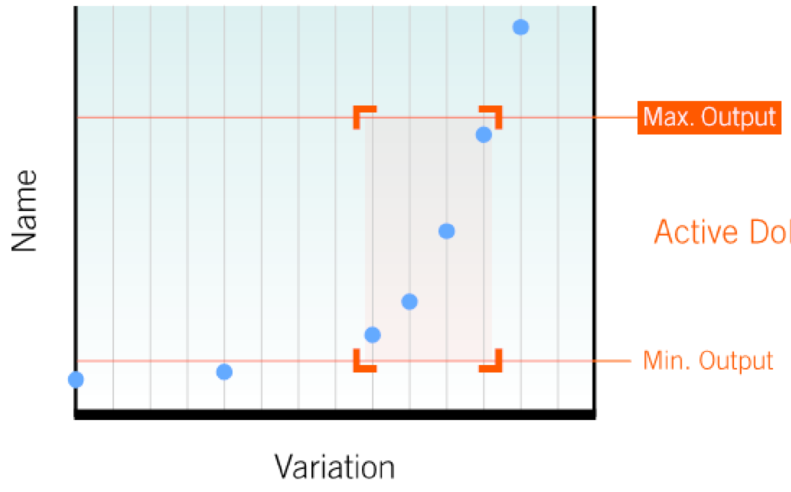
Active DoE Test in CAMEO

Measurements and DoE Conditions

Measurements: Step Approach | Continuous Approach

No.	Name	Type	Meas. Time	Sample Time	Drift Tolerance [%]	Max Std. Dev.	Alive Tol.	Active DoE	Minimum Output	Maximum Output	Active DoE Type
1	TORQUE	Mean	2	1	0.05	∞	0	☑	expected_tq_start-3	expected_tq_start+3	Standard
2	Mod.Ratio	Mean	2	1	0.05	∞	0	☑	- Infinity	Max.Ratio	ModelLimit
3	.EFFICIENCY_3	Mean	2	1	0.05	∞	0	☑	80	100	Standard
4	.EFFICIENCY_4	Mean	2	1	0.05	∞	0	☑	80	100	Standard
5	.MECA_POWER	Mean	2	1	0.05	∞	0	☑	0	180	Standard
6	List of Measurements	GlobalList	2	1	0.05	∞	0	☐			Standard

- Active DOE (multi-criteria approach)
- While test is running the Stator- Rotor-Temperature, Modulation Index and Maximum Current are monitored all the time with certain reactions.
- With predefined Variation areas AND multiple Criteria it is possible to create a test design in an easy way



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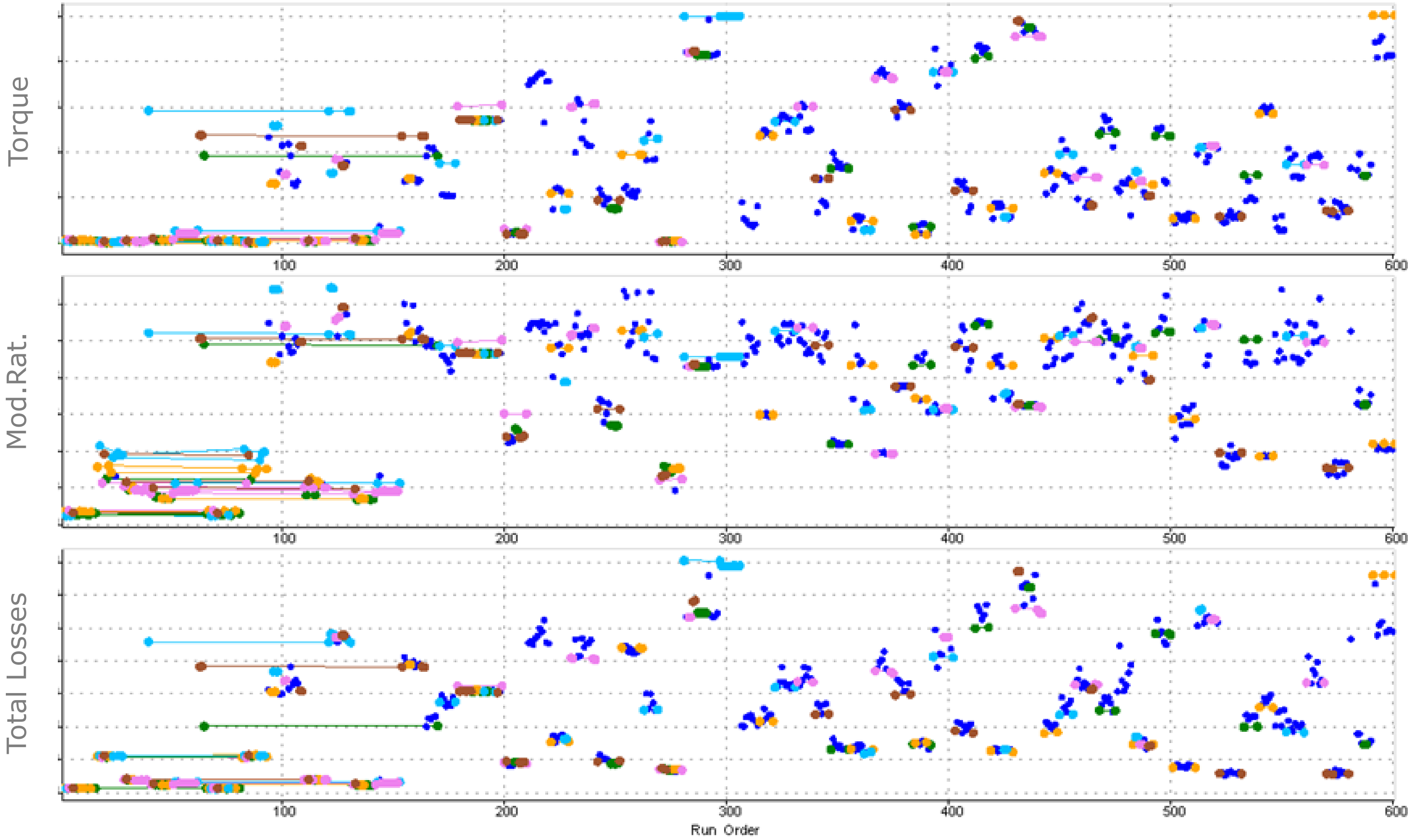
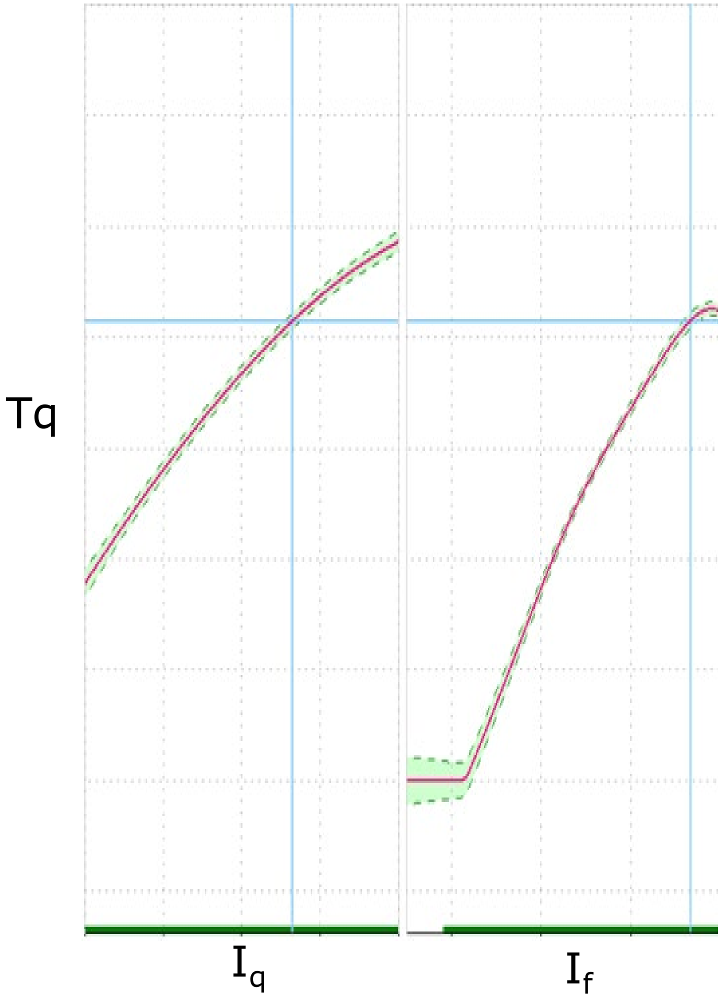
Raw Data Analysis
Repeatability measurements

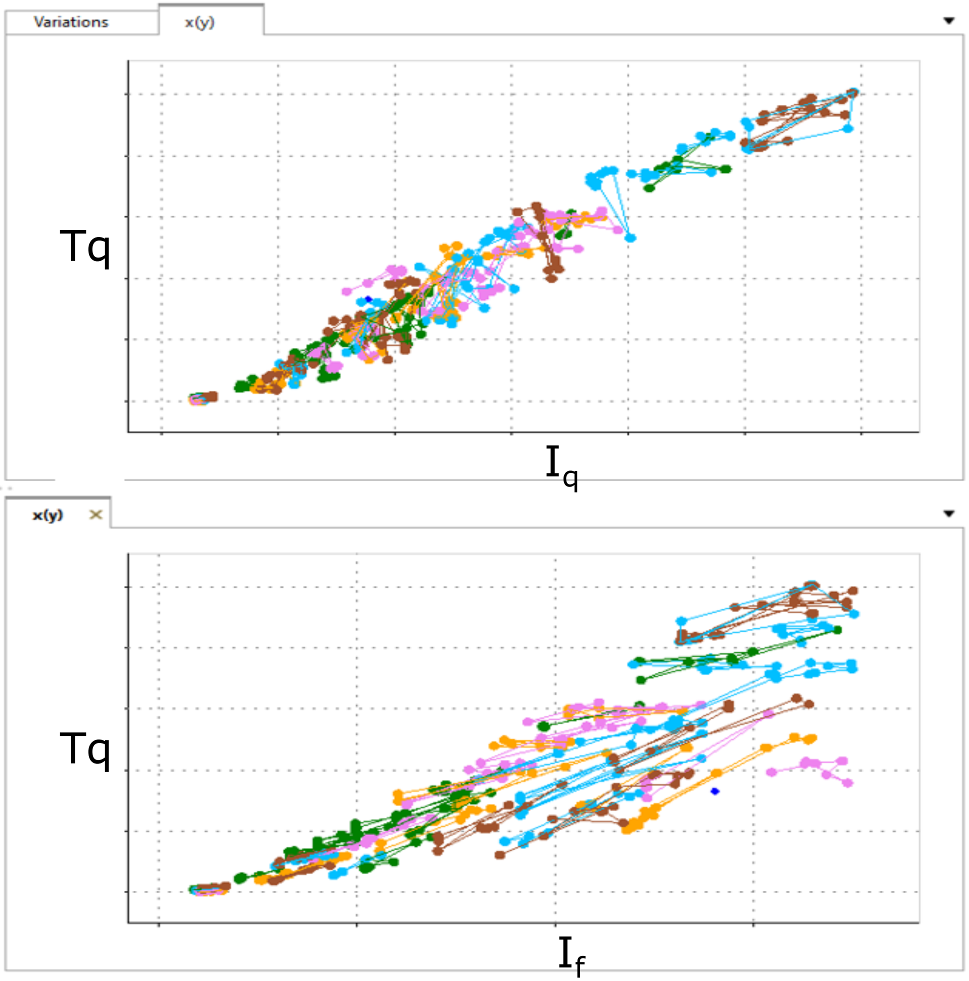


Repeatability:

- Same color for the points with same Speed, I_d, I_q and I_f
- $\mathrm{ModRat}_{\mathrm{calc}} = \frac{\sqrt{{V_d}^2 + {V_q}^2}}{\frac{U_{batt}}{\sqrt{3}}}$
- Check of repeatability for torque, modulation ratio calculated and total losses
- This was done also for U_d, U_q
- Repeatability shows how good is the stability of the whole system
- Good repeatability avoids model overfitting
- Optimization results can't be better than the repeatability

Influence of I_f on Torque

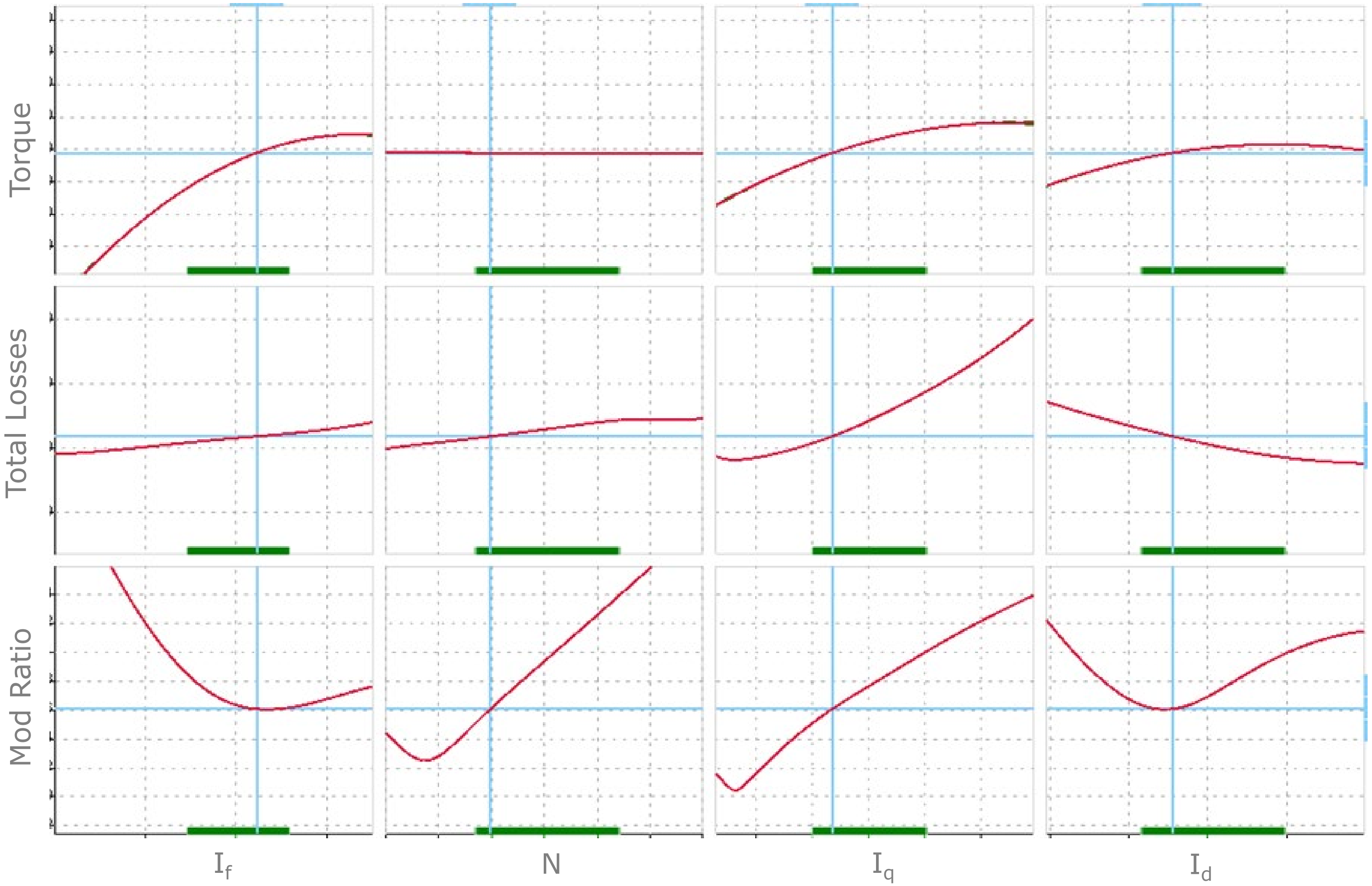




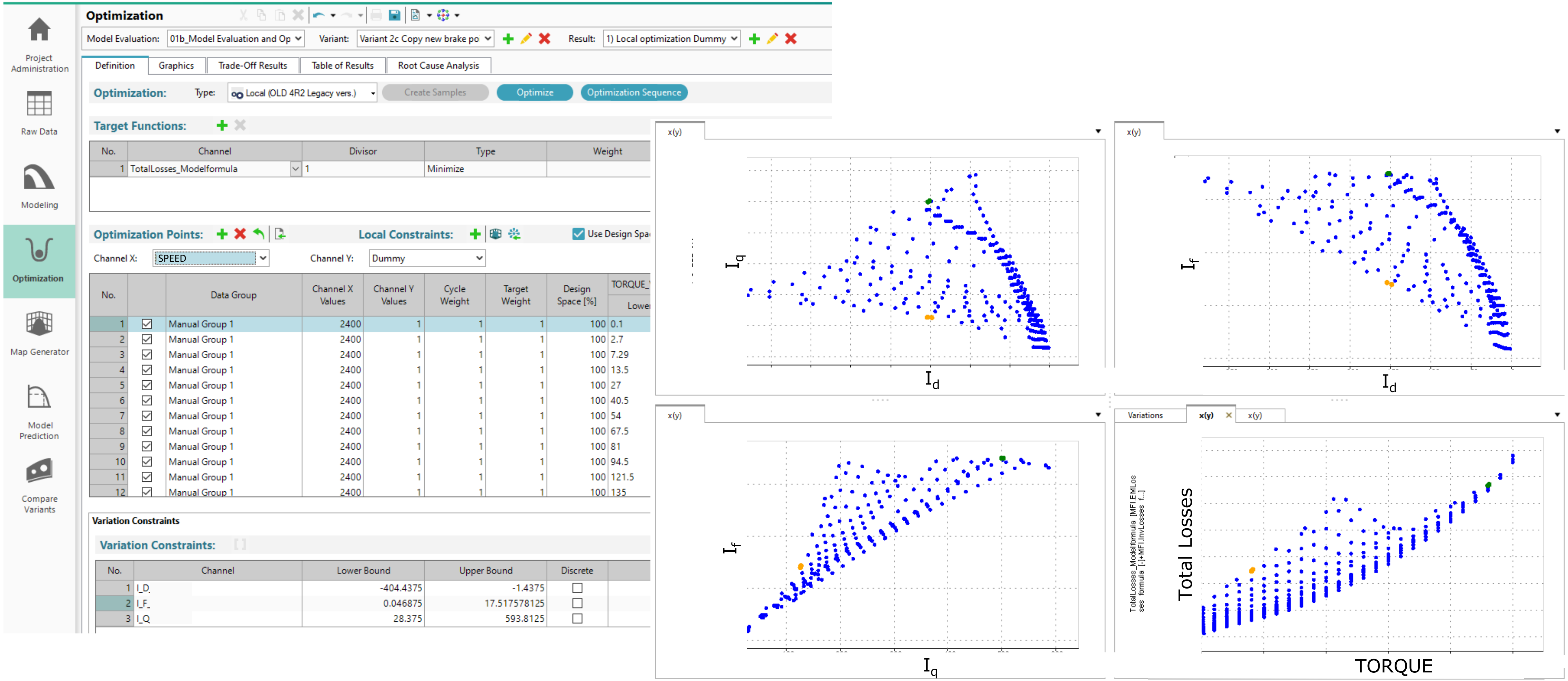
Same color means same initial requested speed/torque points. Due to the variations in I_d/I_q/I_f, this graphic shows the range of different values we can reach for:

- Torque vs I_q
- Torque vs I_f

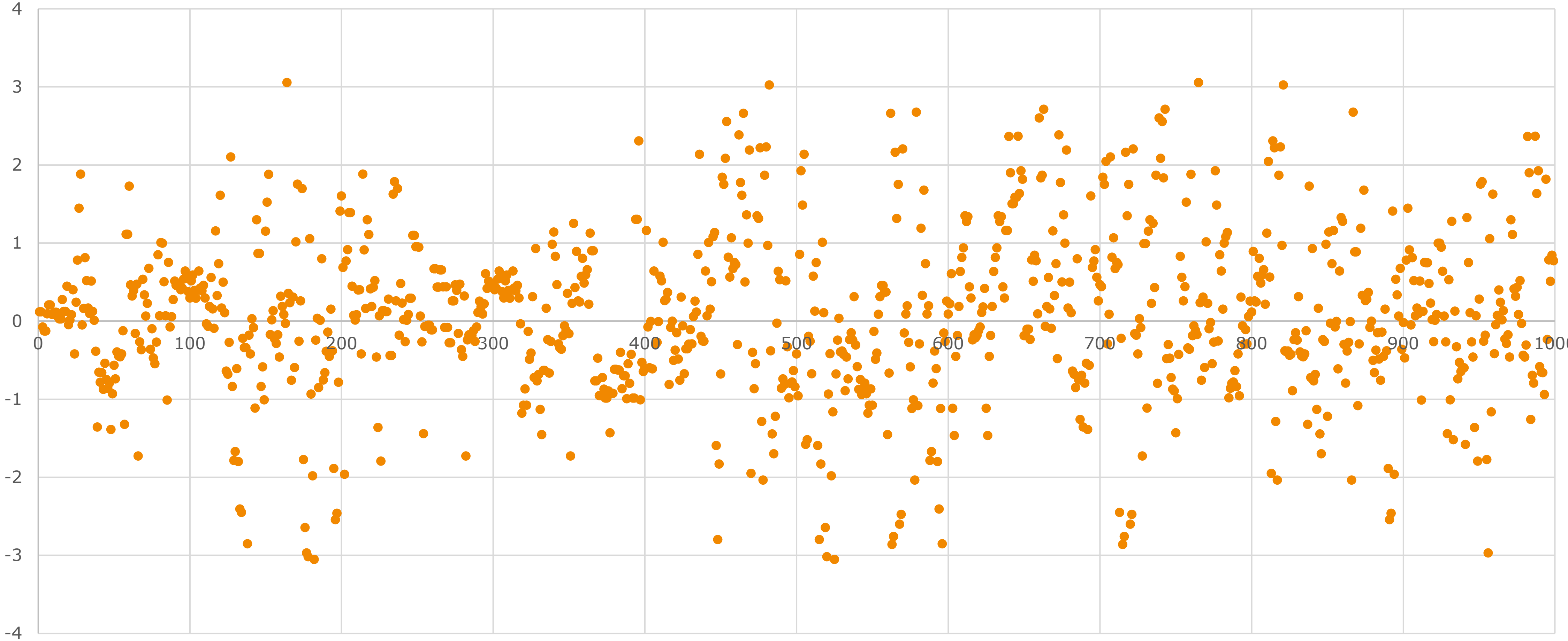
Modeling – Intersection Plot



Optimization

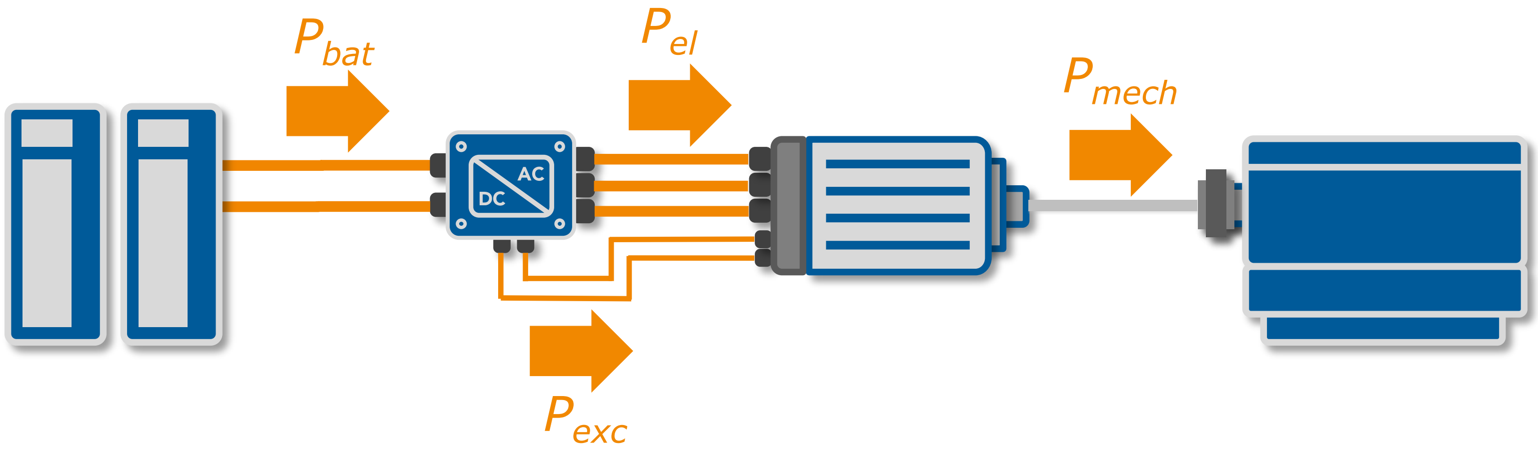


Torque Accuracy



Mean Value: 0,06125

Total System Efficiency / Total Losses



$$Inverter\ Losses = P_{bat} - (P_{el} + P_{exc})$$

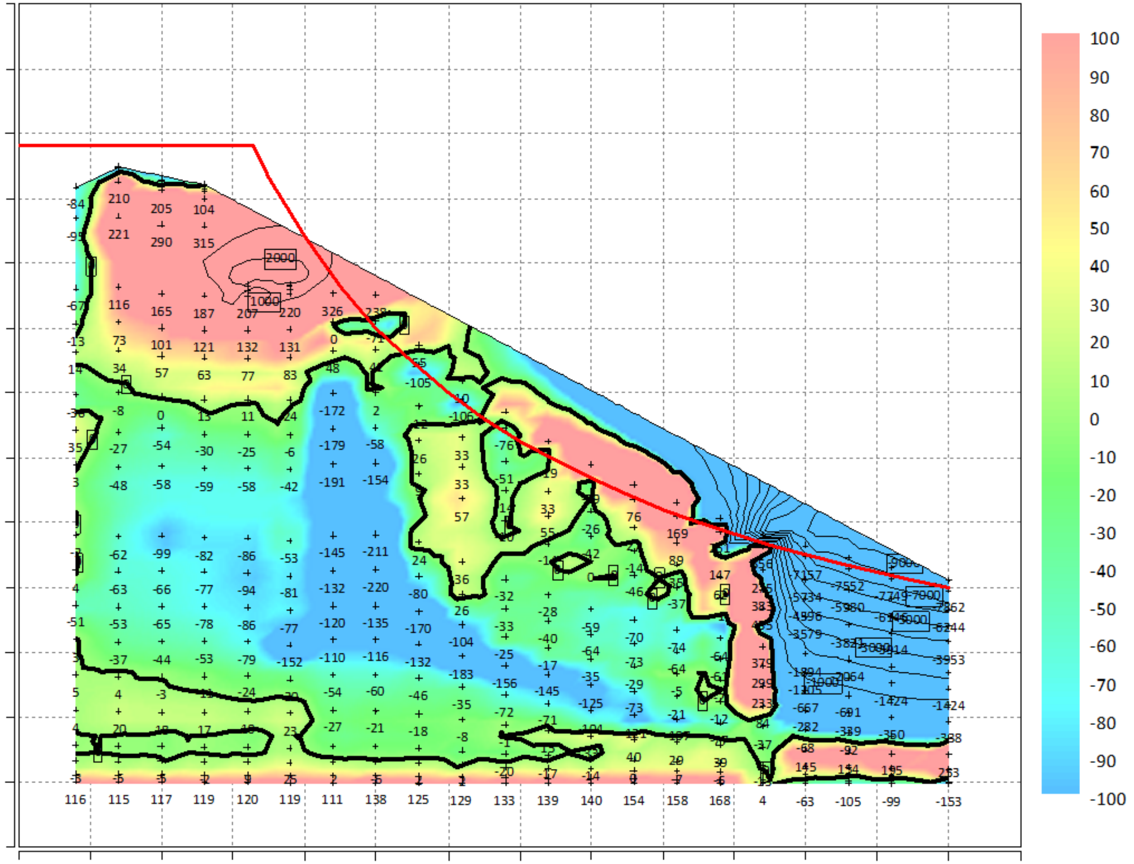
$$Motor\ Losses = P_{el} - P_{mech}$$

$$Total\ Losses = P_{bat} - P_{mech}$$

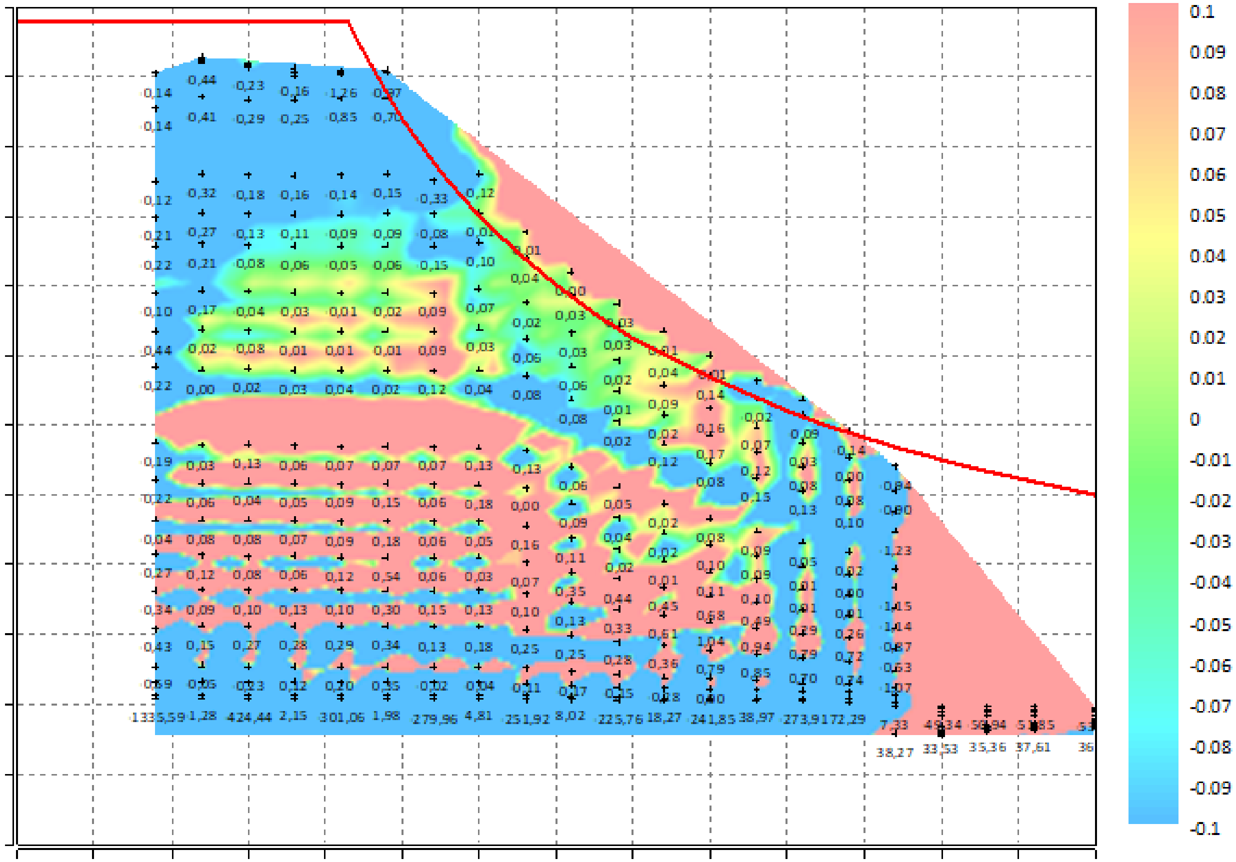
$$Total\ Losses = Inverter\ Losses + Motor\ Losses + P_{exc}$$

$$Total\ System\ Efficiency = \frac{P_{mech}}{P_{bat}}$$

Validation of Efficiency



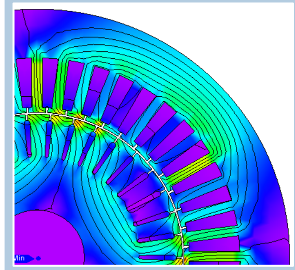
Total Losses Difference [W]



Total System Efficiency Difference [%]

AVL

Take Away Points/ Benefits



- Less know how needed about inverter and E-Motor.
- Reliable results
- Time saving through “Active DoE” and loop reduction.
- More stable against noisy results.
- Keep system in stable conditions.
- Interrelations are presented clearly and simply
- Reusable Data
- Well representable
- Traceability

If there is a better way to do it - find it.
Thomas Alva Edison (1847-1931)

Contact

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