

Global efficiency and torque accuracy optimization for an EESM

Lecturer



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- 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

1 What is the Challenge

2 EESM – External Excited Synchronous Machine

Properties and possibilities with this machine

3 How we get the Solution

How did we face the challenge and what was the solution

4 Results

Were we able to get satisfactory results?

5 Q&A

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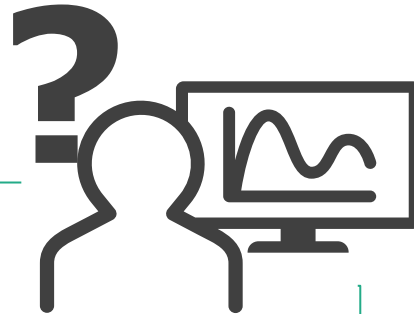
5 Q&A

Challenge

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

Create a global model to
characterize the EESM
Speed, Torque, U_{DC} , I_{dr} , I_{qr} + I_f

Generate optimized data
With best efficiency and max torque accuracy



Near the MTPF line
Fast increase in temperature
Modulation Index

In a defined temperature range
Stator temperature in a certain tolerance ($\pm 5^\circ\text{C}$)
Rotor Temperature $< T_{\max}$

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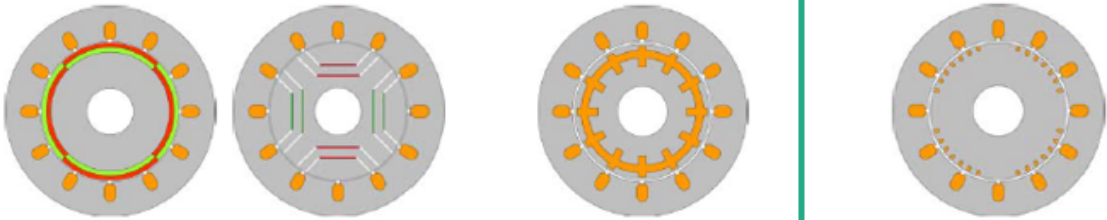
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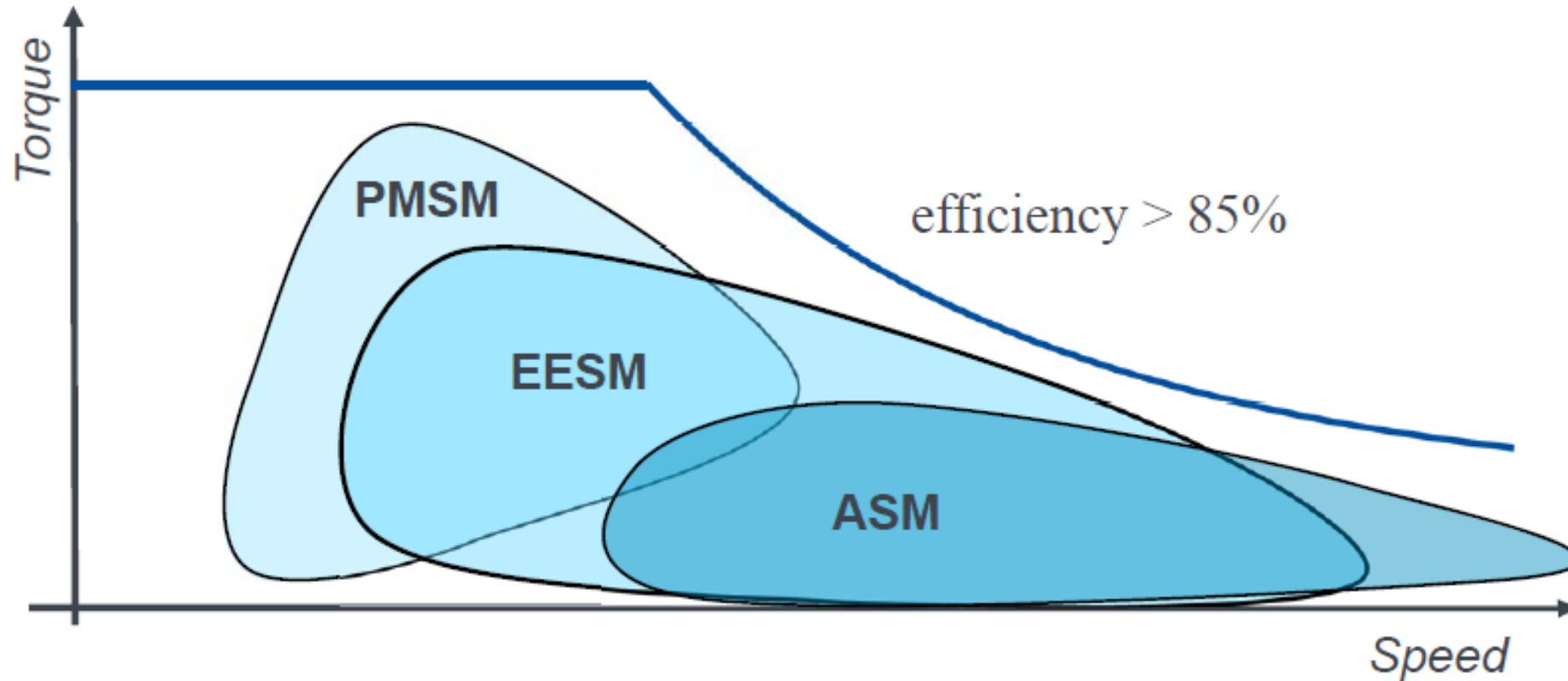
EESM – Characteristics I

- 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

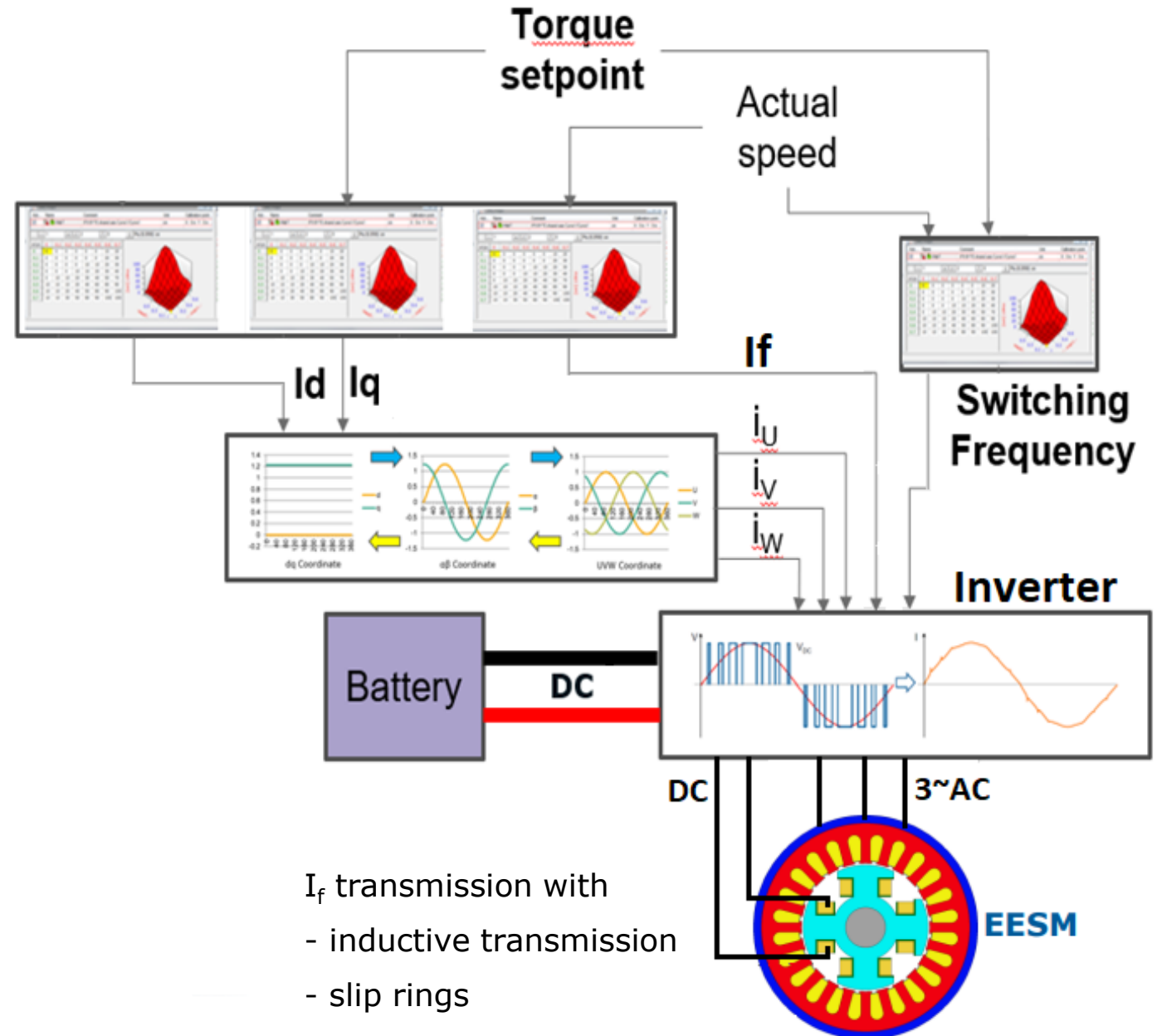
EESM – Characteristics II



EESM – I_f

With I_f we...

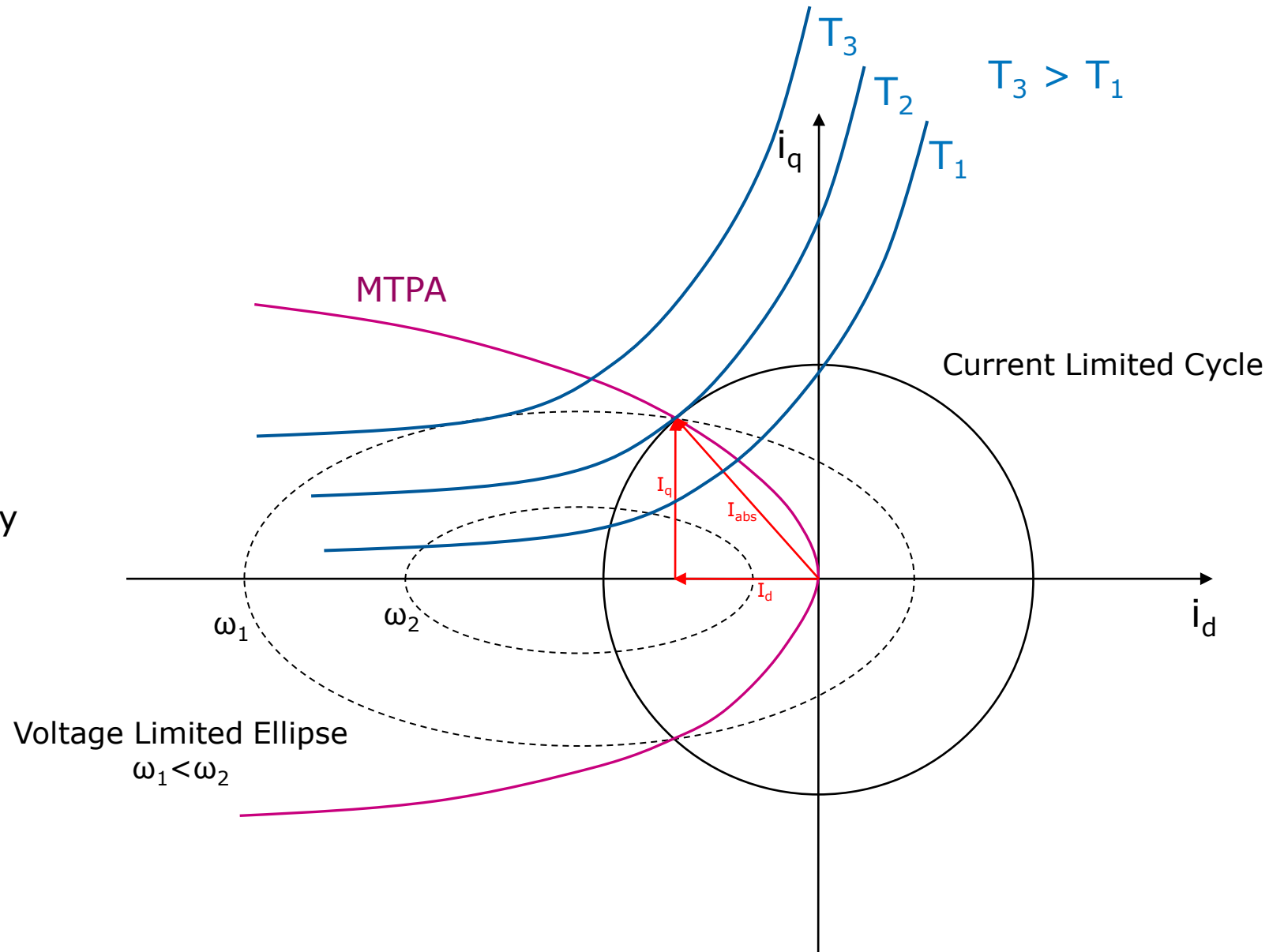
- have a temperature model for Rotor Temperature
- can influence the field weakening
- have no magnets



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 \rightarrow 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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1 **What is the Challenge**

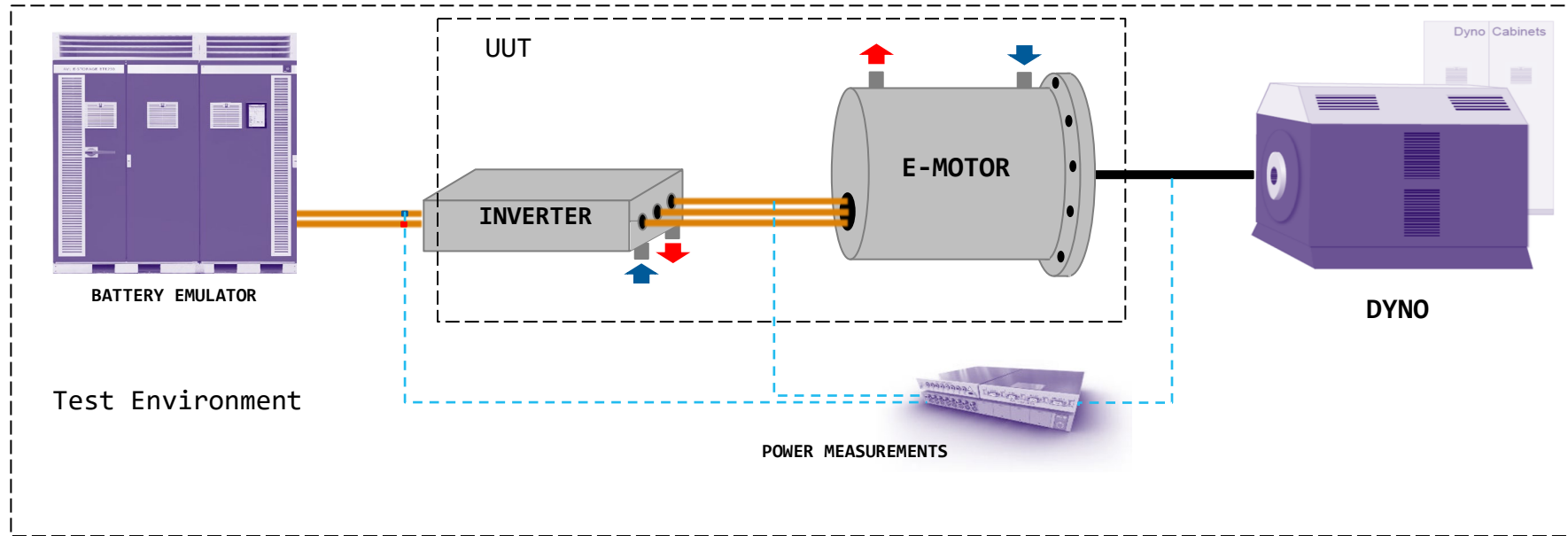
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How we get the solution?



AVL Toolchain



CAMEO

Smart Calibration
and Validation



PUMA

Automation



XION

Power Analyzer



Concerto

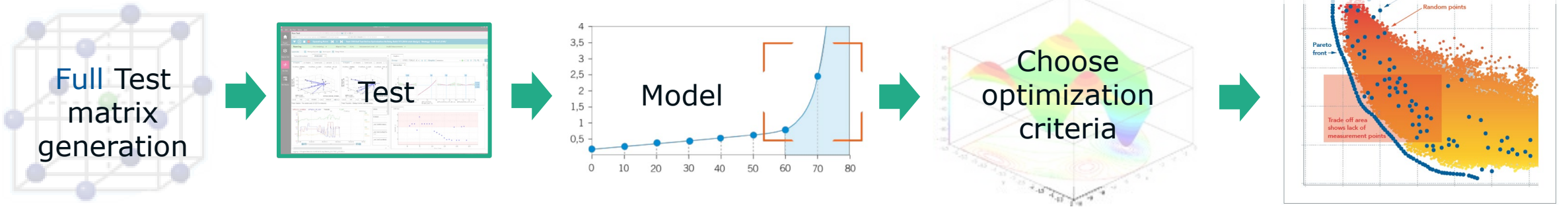
Post processing

Active DoE Workflow

Traditional DoE

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

Standard DoE workflow



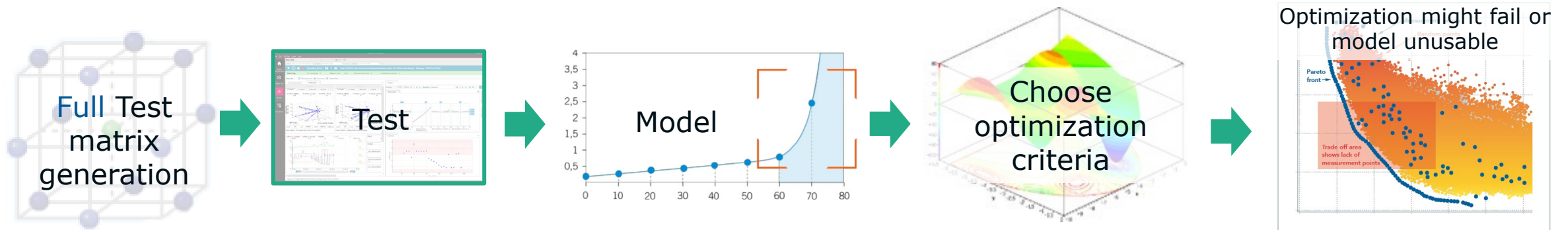
For high numbers of input dimensions or highly non-linear systems, even standard DoE has its limits

Minimizing time per test

Active DoE

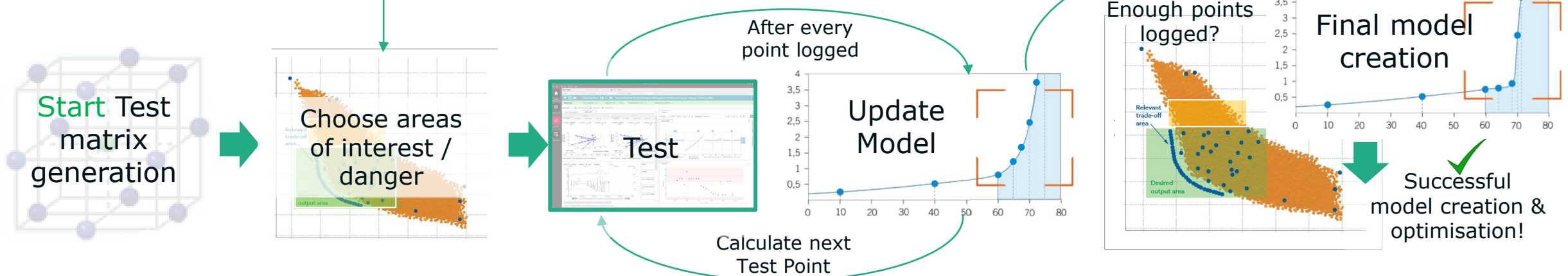
Model and Predict *during* the test: Bring Knowledge forward to the testing phase

Standard DoE workflow



AI Active DoE workflow

Bring knowledge forward



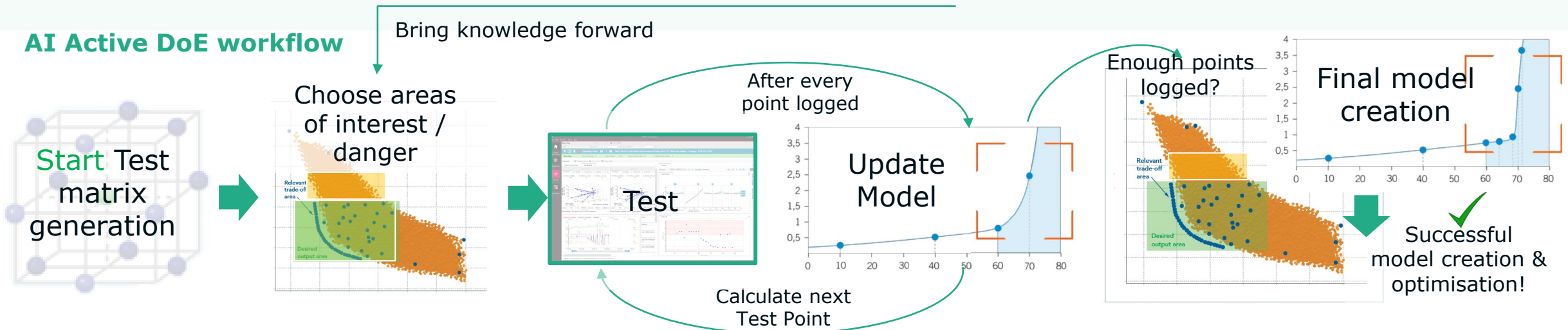
Minimizing time per test

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

Test Vorbereitung
 Test: 02b_Global DoE max efficienc Version: 05 - 2000 to 14000rpm - 330V- Ergebnis: ✖
 04:16:41 0 Fehler 26 Warnungen

Betriebspunktgrafik
 Betriebspunkte: ✔ ⚠ ✖ Typ: All Types Gruppe: ✔ ⚠ ✖

Testrun Plan
 Operating Points Graphic
 Operating Points: ✔ ⚠ ✖ Typ: All Types Gruppe: ✔ ⚠ ✖

Channels:

No.	Name	Area	Min	From	Start	To	Max	Stab. Time	Set Mode	Base Data	Set Order	Ramp Tir
1	L_sp_dummy		0	1	1	2	3	1	Absolute	<none>	1	
2	Psi_sp_dummy		0	1	1	2	3	1	Absolute	<none>	1	
3	If_dummy		0	1	1	2	3	1	Absolute	<none>	1	

Variation List:

No.	<input checked="" type="checkbox"/>		L_sp_dummy	Psi_sp_dummy	If_dummy	Indi. Stab. Time	Model Verification Flag	Type	Sub-Test
1	<input checked="" type="checkbox"/>		0	0	0	0	0	1	
2	<input checked="" type="checkbox"/>		1	2	1	0	0	1	
3	<input checked="" type="checkbox"/>		2	0	1	0	0	1	

2 Layer Test

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

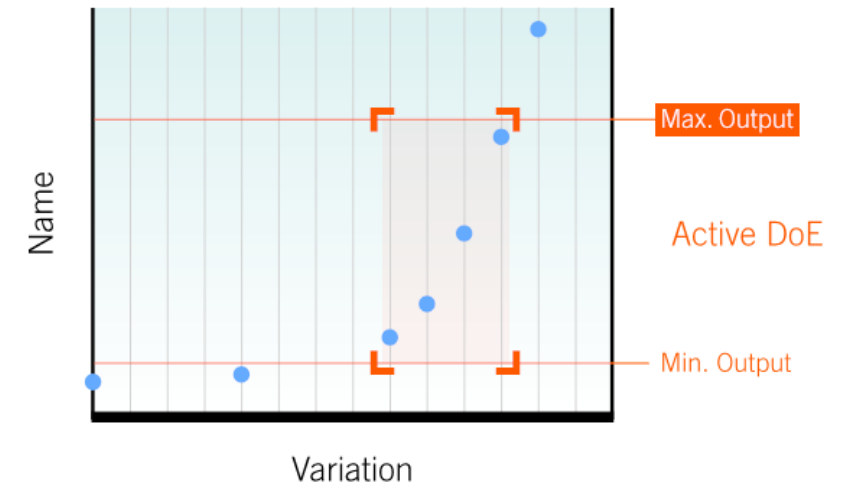
Active DoE Test in CAMEO

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	<input checked="" type="checkbox"/>	expected_tq_start-3	expected_tq_start+3	Standard
2	Mod.Ratio	Mean	2	1	0.05	∞	0	<input checked="" type="checkbox"/>	- Infinity	Max.Ratio	ModelLimit
3	.EFFICIENCY_3	Mean	2	1	0.05	∞	0	<input checked="" type="checkbox"/>	80	100	Standard
4	.EFFICIENCY_4	Mean	2	1	0.05	∞	0	<input checked="" type="checkbox"/>	80	100	Standard
5	.MECA_POWER	Mean	2	1	0.05	∞	0	<input checked="" type="checkbox"/>	0	180	Standard
6	List of Measurements	GlobalList	2	1	0.05	∞	0	<input type="checkbox"/>			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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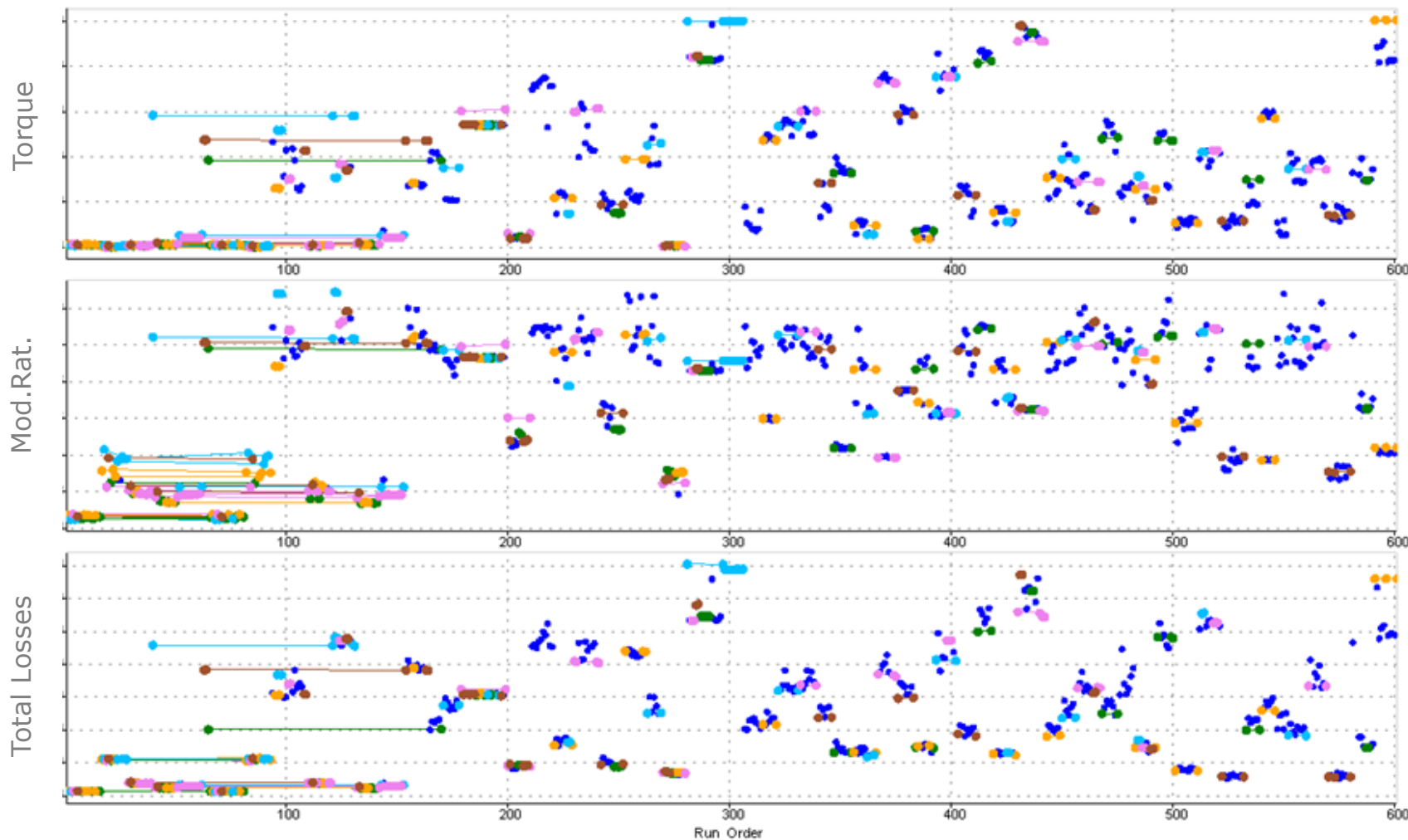
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Raw Data Analysis

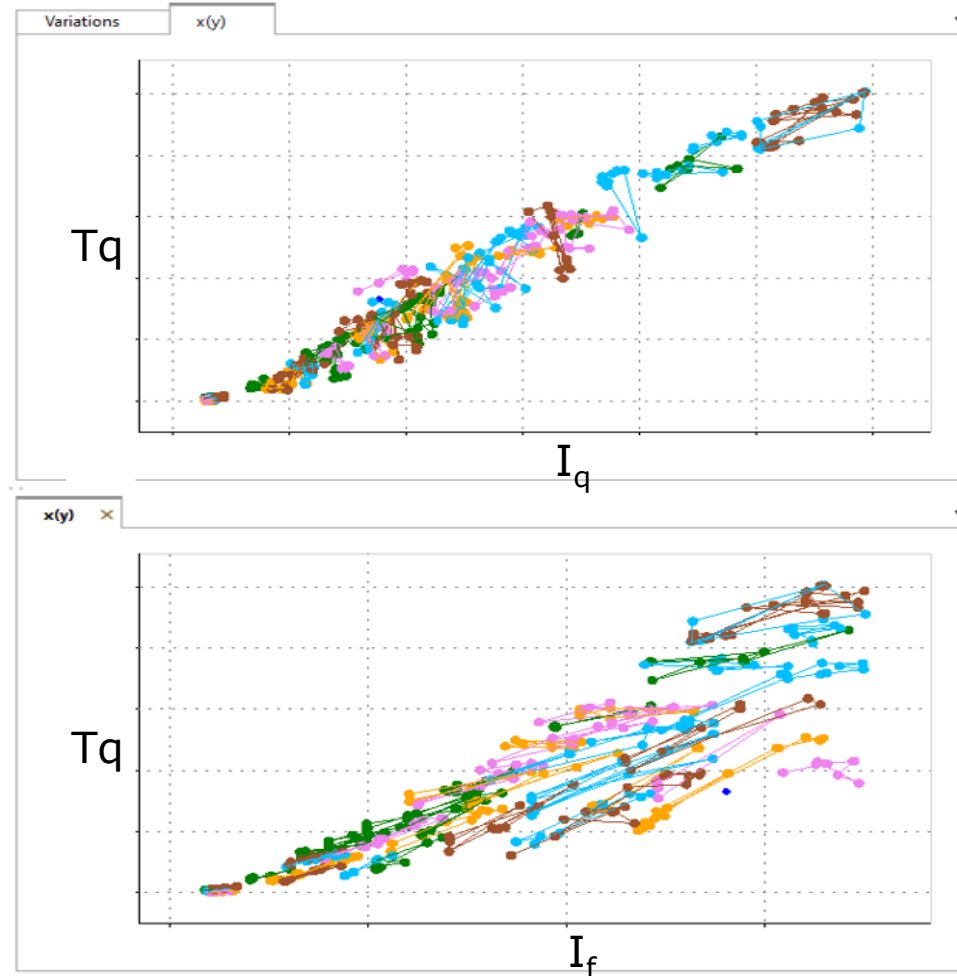
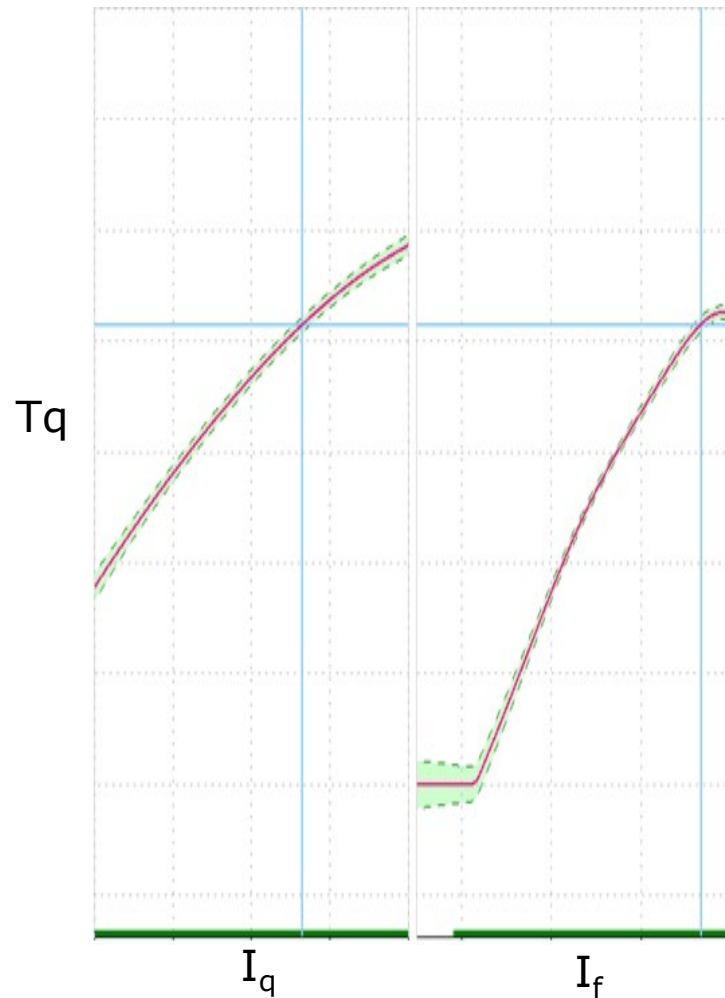
Repeatability measurements



Repeatability:

- Same color for the points with same Speed, I_d , I_q and I_f
- $$\text{ModRat}_{\text{calc}} = \frac{\sqrt{V_d^2 + V_q^2}}{\frac{U_{\text{batt}}}{\sqrt{3}}}$$
- 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

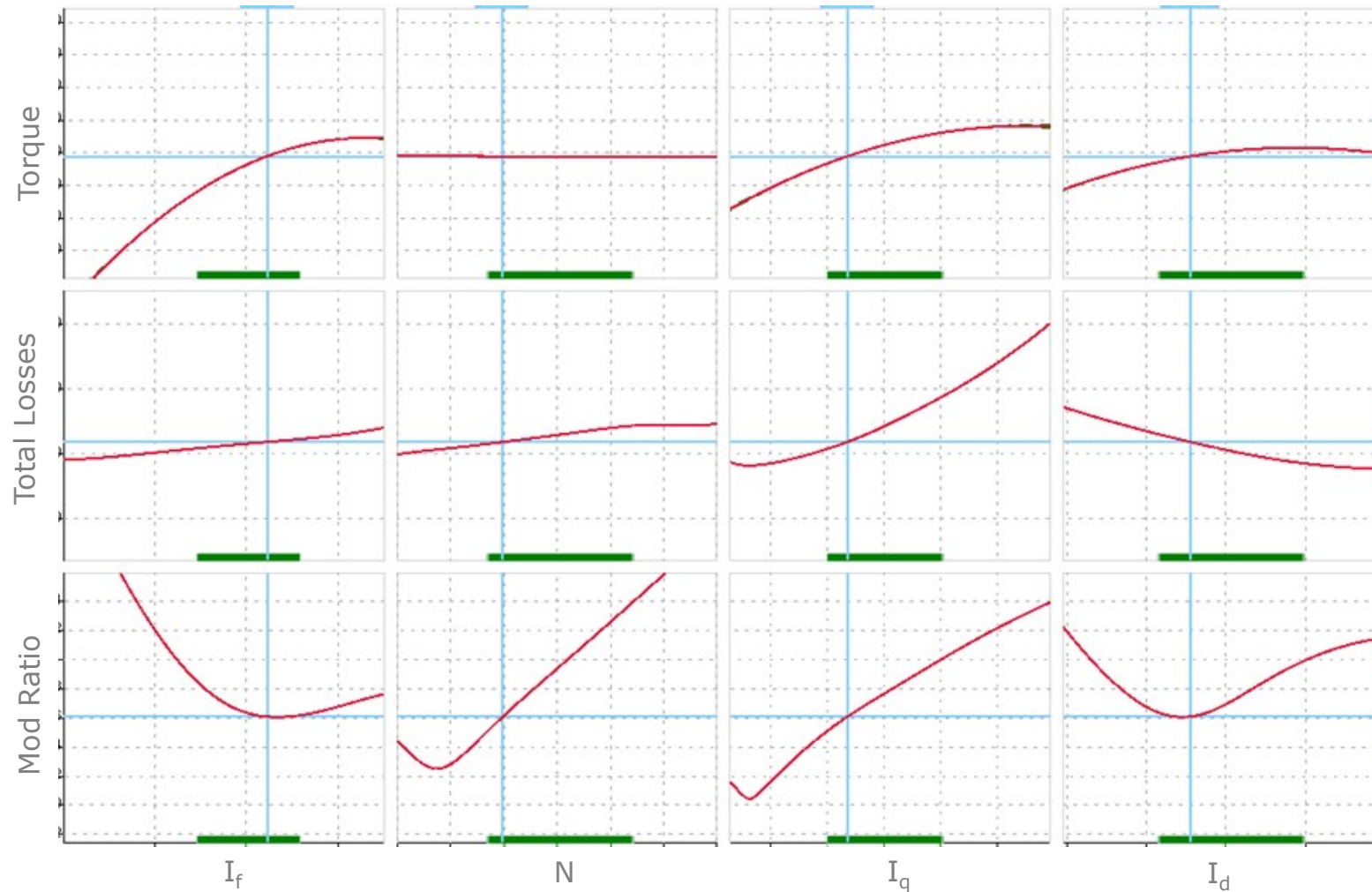
Influence of I_f on Torque



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

Optimization

Model Evaluation: 01b_Model Evaluation and Op Variant: Variant 2c Copy new brake po Result: 1) Local optimization Dummy

Definition Graphics Trade-Off Results Table of Results Root Cause Analysis

Optimization: Type: Local (OLD 4R2 Legacy vers.) Create Samples Optimize Optimization Sequence

Target Functions: + x

No.	Channel	Divisor	Type	Weight
1	TotalLosses_Modelformula	1	Minimize	

Optimization Points: + x Local Constraints: + Use Design Space

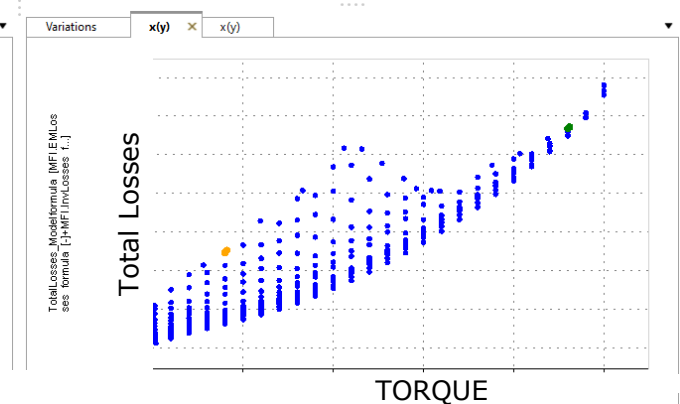
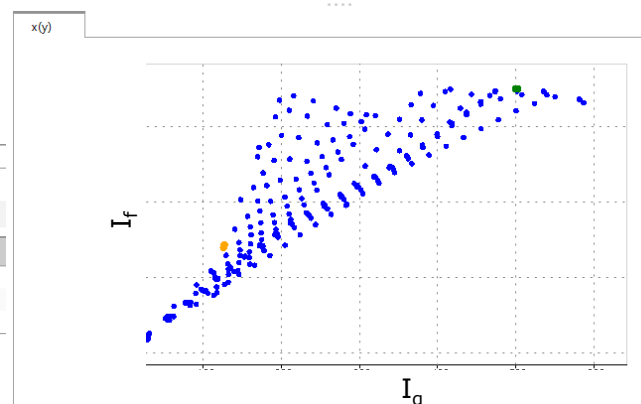
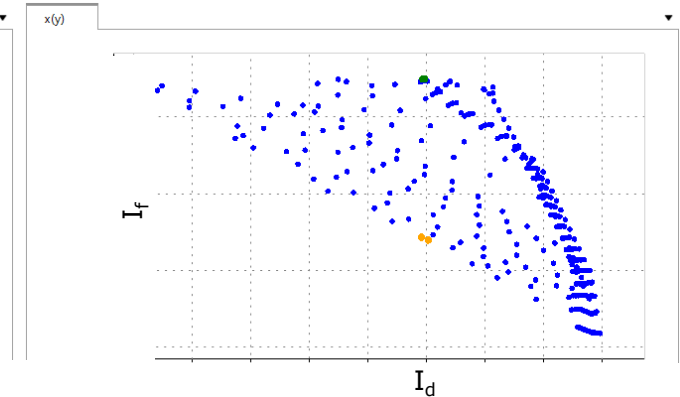
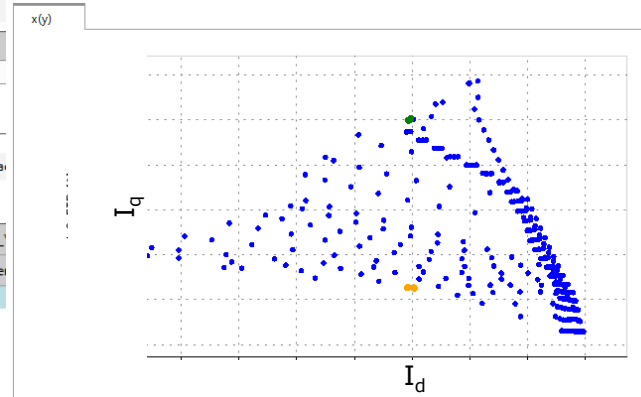
Channel X: SPEED Channel Y: Dummy

No.		Data Group	Channel X Values	Channel Y Values	Cycle Weight	Target Weight	Design Space [%]	TORQUE_Lower
1	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	0.1
2	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	2.7
3	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	7.29
4	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	13.5
5	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	27
6	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	40.5
7	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	54
8	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	67.5
9	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	81
10	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	94.5
11	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	121.5
12	<input checked="" type="checkbox"/>	Manual Group 1	2400	1	1	1	100	135

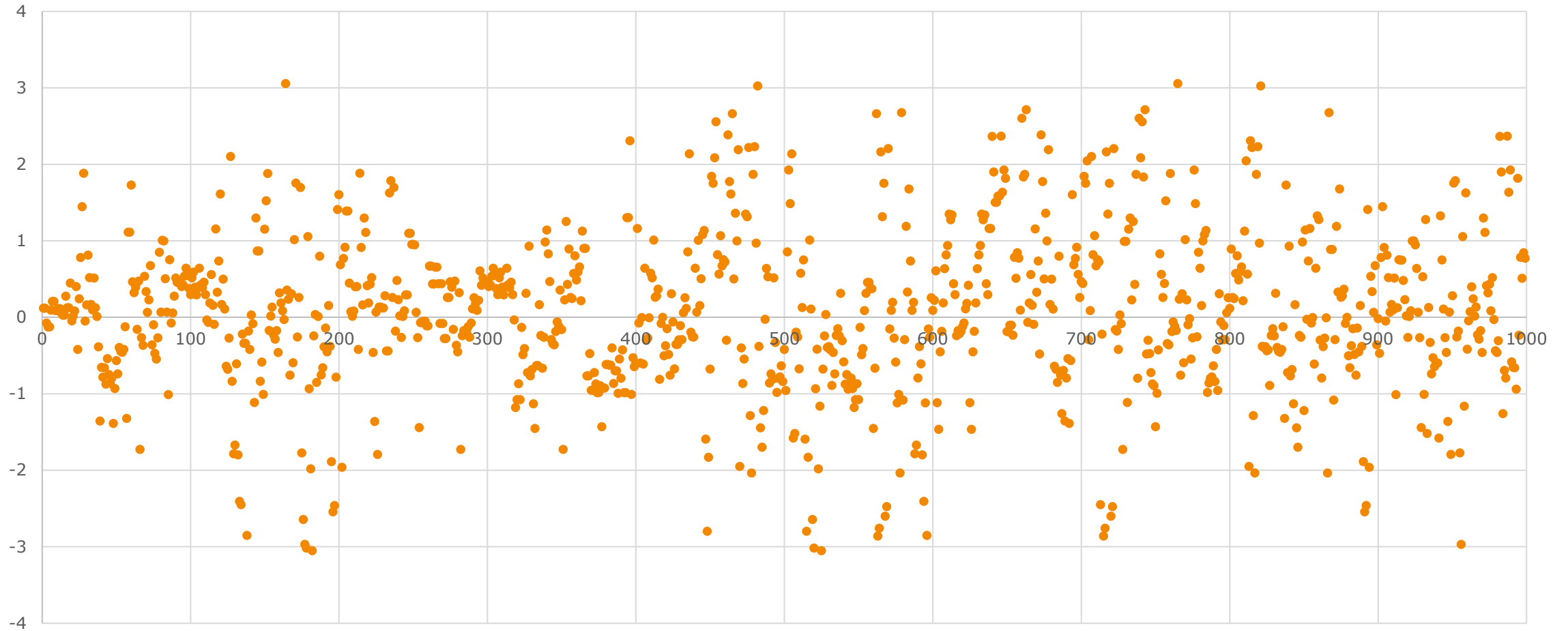
Variation Constraints

Variation Constraints: []

No.	Channel	Lower Bound	Upper Bound	Discrete
1	I_D	-404.4375	-1.4375	<input type="checkbox"/>
2	I_F	0.046875	17.517578125	<input type="checkbox"/>
3	I_Q	28.375	593.8125	<input type="checkbox"/>

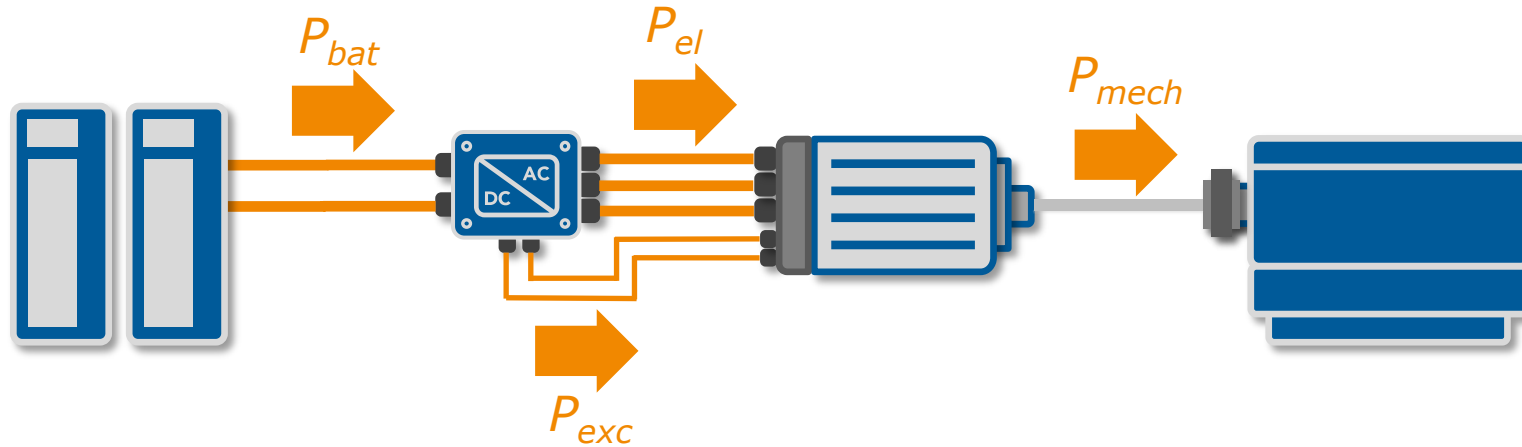


Torque Accuracy



Mean Value: 0,06125

Total System Efficiency / Total Losses



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

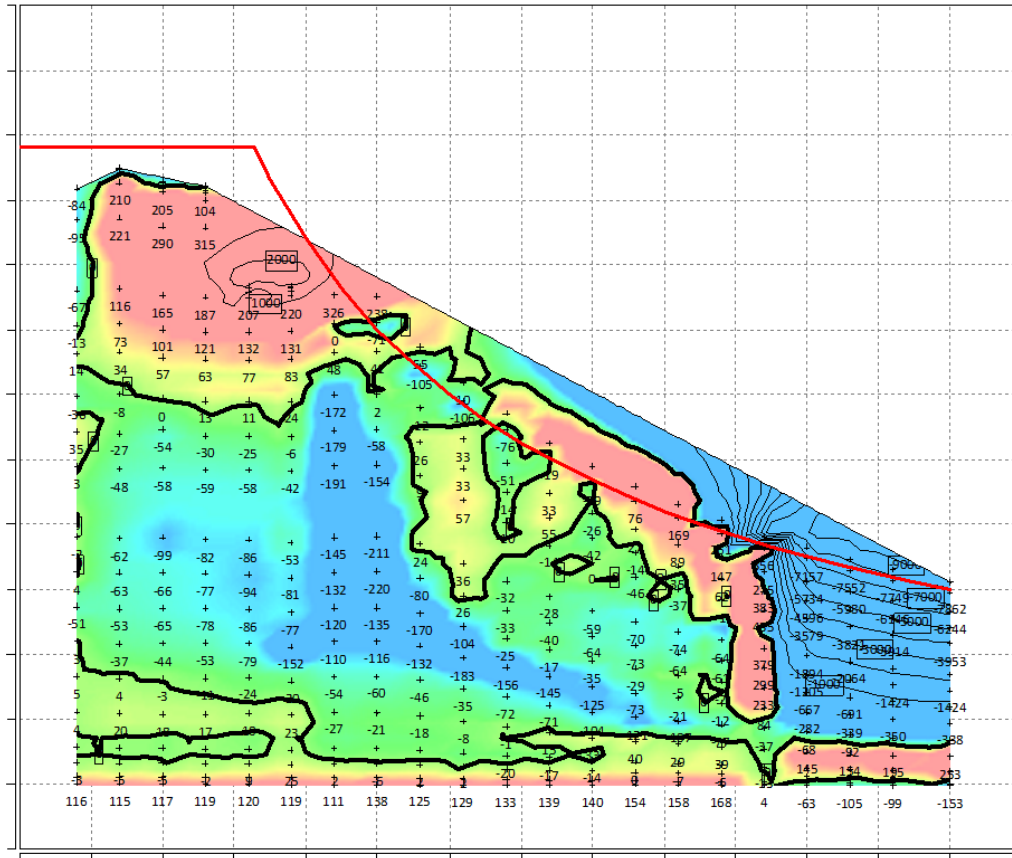
$$\text{Motor Losses} = P_{el} - P_{mech}$$

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

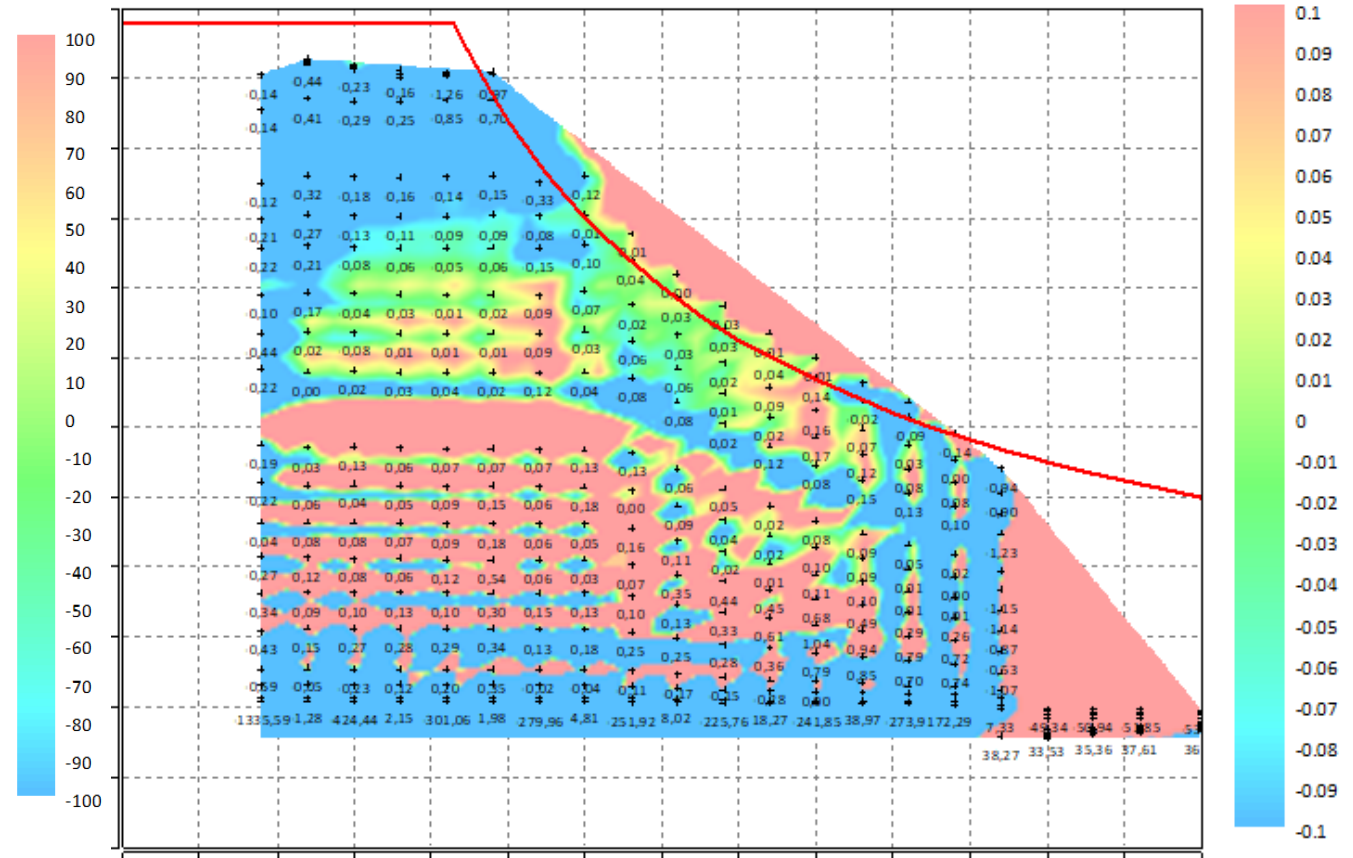
$$\text{Total Losses} = \text{Inverter Losses} + \text{Motor Losses} + P_{exc}$$

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

Validation of Efficiency

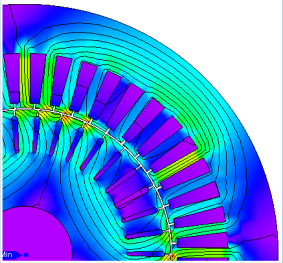


Total Losses Difference [W]



Total System Efficiency Difference [%]

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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