Design the Future e-Mobility

Altair HyperWorks Electromechanical Workflow for the Design of Electric Motor Powertrain

Philippe Wendling, VP, Business Development-Electromagnetics
Richard Yen, SVP, Global Automotive and Industry Verticals Team

April 11 2019

Altair

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AGENDA

1. E-Mobility Trends and Challenges
2. Altair’s Vision and Workflow
3. E-Motor Design Process
4. Looking Forward

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MOBILITY TRENDS AND CHALLENGES

Richard Y.

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….. E-MOBILITY

Transportation OEM need sustainable technologies to meet customer demands:

Safer, Lighter, Greener, Smarter Vehicles

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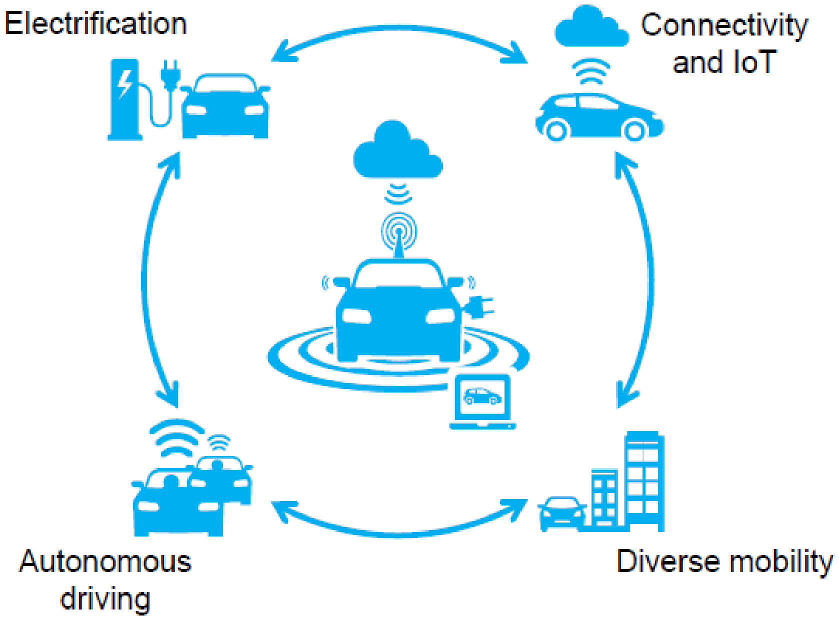
"GM's vision is a world with zero crashes, zero emissions and zero congestion."

"GM believes the future of personal mobility will be driven by the convergence of electrification, autonomous vehicles, connectivity and shared mobility services."

--Mary Barra, CEO of General Motors



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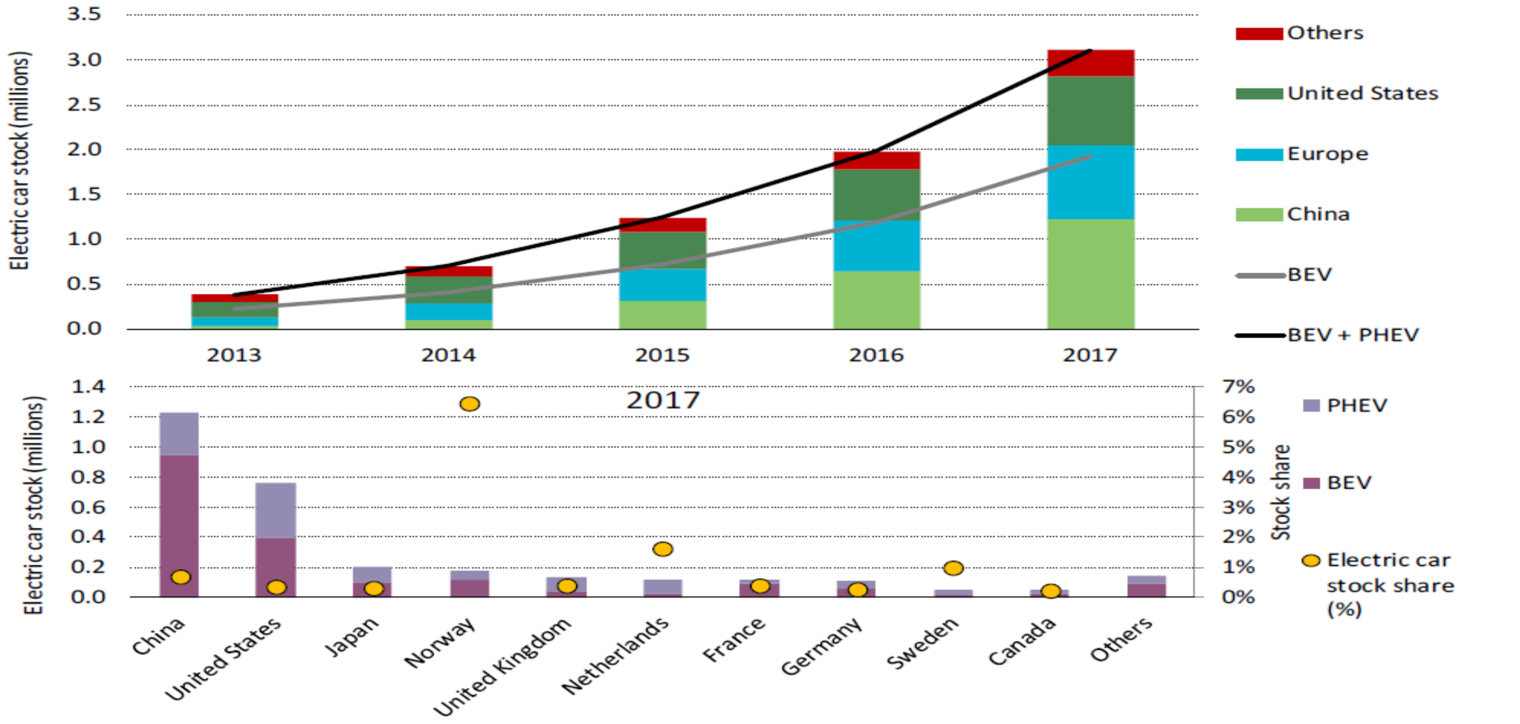
INDUSTRY TRENDS ON ELECTRIFICATION (1)



Note: BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle. Stock shares are calculated based on country submissions and estimates of the rolling vehicle stocks developed for the IEA Mobility Model. The vehicle stocks are estimated based on new vehicle registration data, lifetime range of 13-18 years, and vehicle scrappage using a survival curve that declines linearly in the last five years of the active vehicle life. Lifetimes at the low end of the range are used for countries with higher income levels (and vice versa).

Source: IEA analysis based on country submissions, complemented ACEA (2018), EAFO (2018a).

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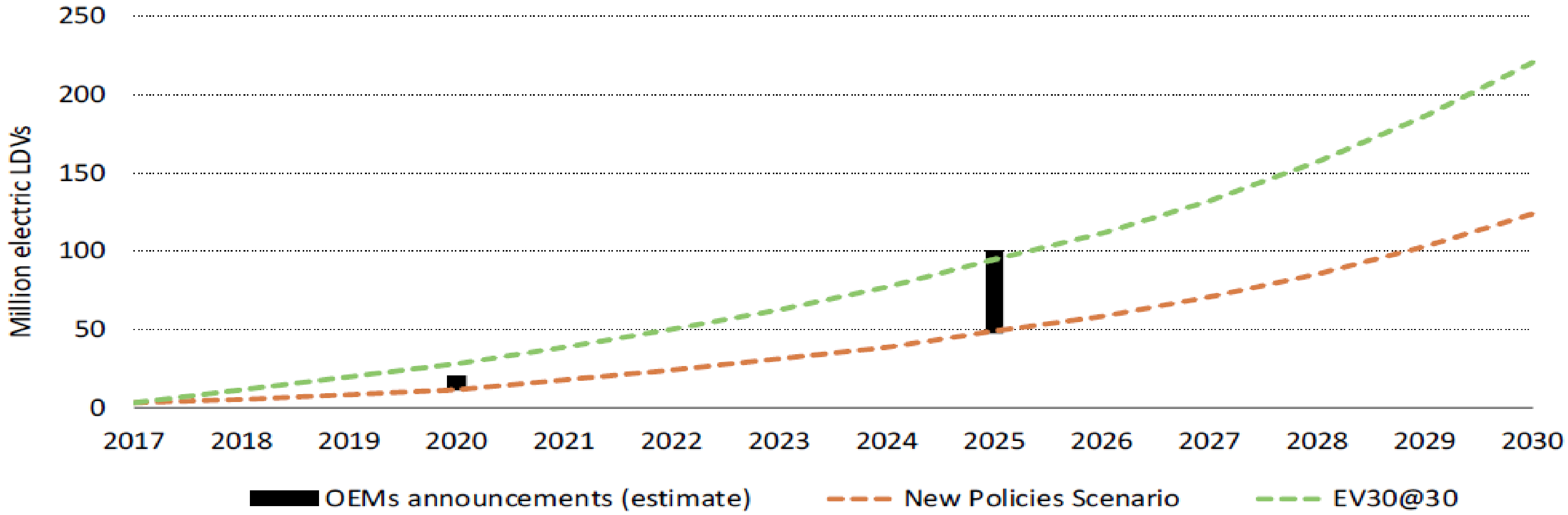
INDUSTRY TRENDS ON ELECTRIFICATION (2)



Notes: The 2020 and 2025 projections from original equipment manufacturers are based on their announcements as outlined in Table 2.5. The production capacity of OEMs in China has been capped at 5.2 million vehicles both in 2020 and 2025. This cap is calculated considering the 7.7 million vehicle capacity announced for 2020 (Liu, 2018) and a 66% capacity utilisation factor, aligned with the ratio of vehicle production in China and capacity available in recent years (IHS Markit, 2015). The lower bound of vehicle production in China for 2020 was assumed to be 2 million, well below the capacity assessed to become available in the same year. For companies that announced the deployment of a number of models, the assumptions made in this analysis consider a sales-to-model ratio range of 10 000-30 000 in the 2020 timeframe and 30 000-50 000 in 2025.

Source: IEA analysis developed with the IEA Mobility Model (IEA, 2018a).

Comparison of scenario projections and manufacturers' targets for electric LDVs, 2017-30

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AUTOMOTIVE – ALTAIR'S STRATEGIC SOLUTIONS

1. **e-Mobility**
2. **Connected and Automated Mobility**
3. **Design for Efficiency**
4. **Safety, Comfort and Perceived Quality**

➡ ***Solution* Oriented Innovation**

Industry domain knowledge + Integrated design process + Optimization

Design the Difference

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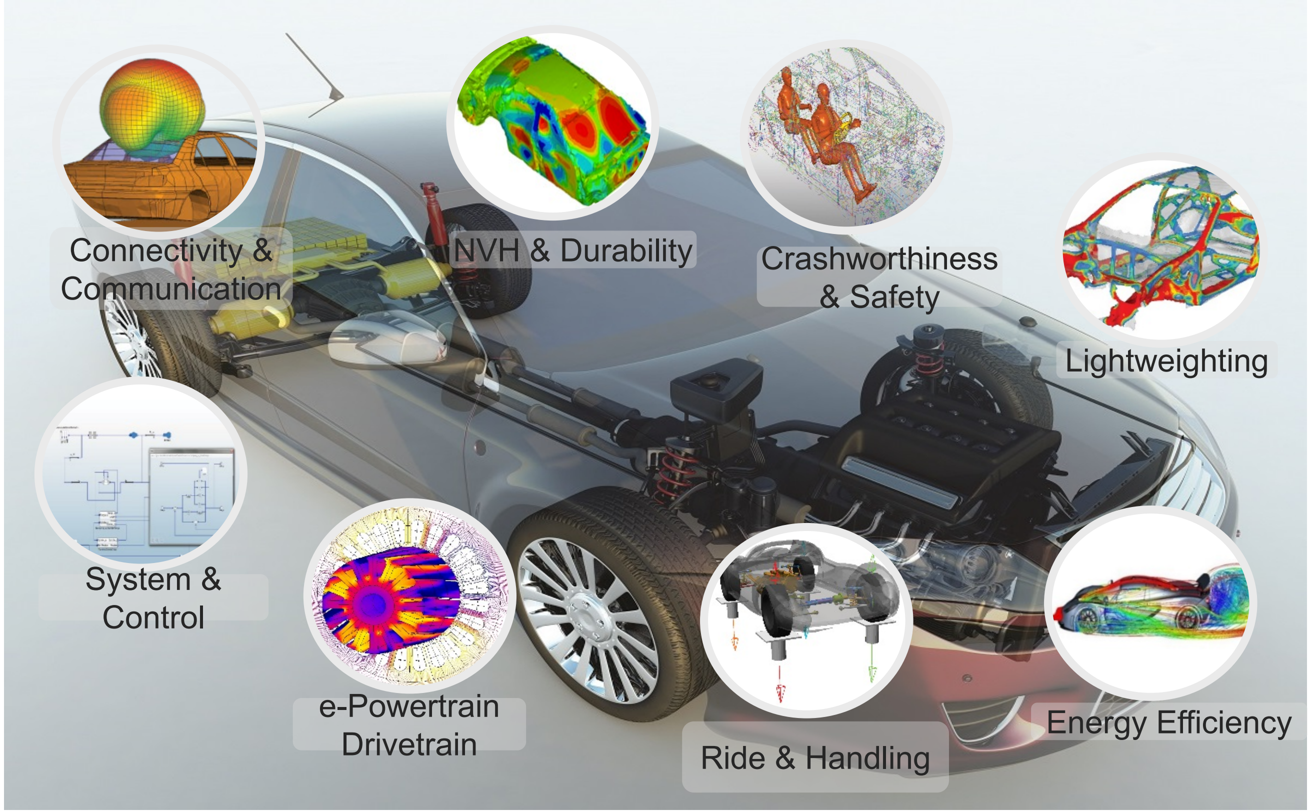
DESIGN THE FUTURE OF E-MOBILITY



New Key Elements

- Electric Motor
- Battery
- Power Electronics - Inverter
- System Modeling and Control

Challenges:

- Packaging and Weight Distribution
- New Requirements and Physics
- Complex System

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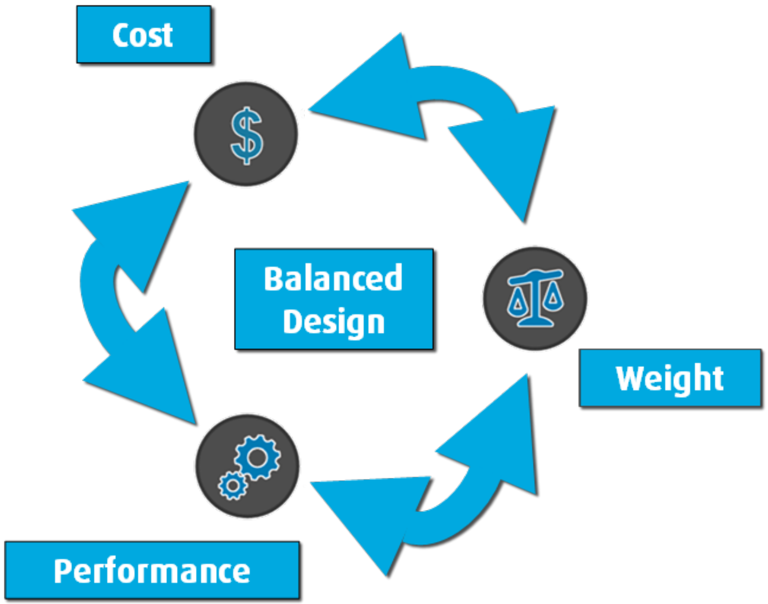
CHALLENGES FOR E-PROPULSION DESIGN

- **Stringent performance requirements** – Advanced OEMs are trying to set them apart from competition
- **Stricter regulations (WLTP)** – Maximize efficiency throughout the e-propulsion system
- **Multiphysics** design to balance **cost, time, size, weight and performance**
- **Integrated solution** across departments with different disciplinary requirements



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ALTAIR'S VISION AND WORKFLOW

Richard Y.

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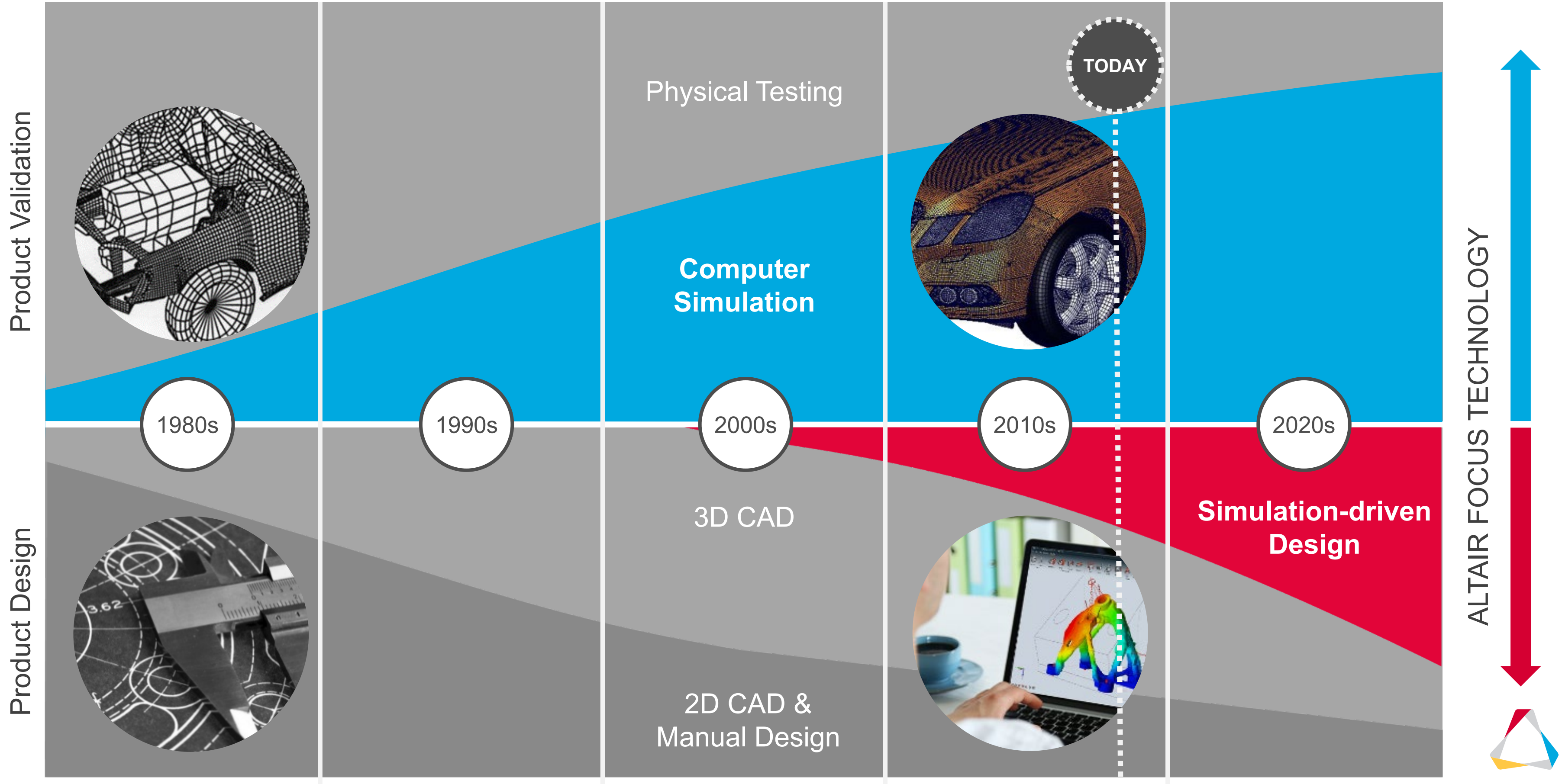
SIMULATION-DRIVEN DESIGN – AN OVERVIEW



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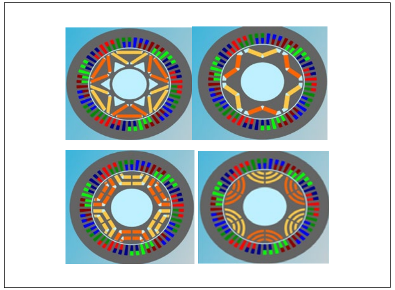
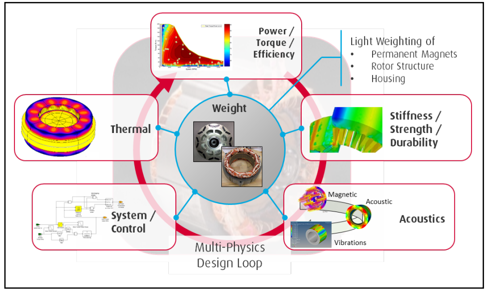
SIMULATION-DRIVEN INNOVATION

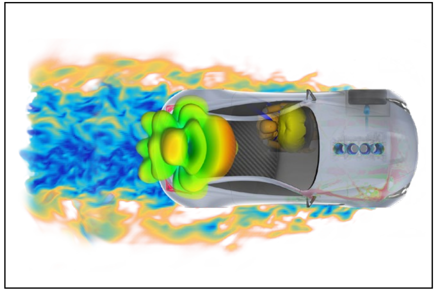
Exhaustive Design Exploration



Optimization & Multiphysics



Powerful Modeling & Visualization



Cloud Collaboration & Data Analytics

High Performance Computing

Value-based Business Model

Global Expertise

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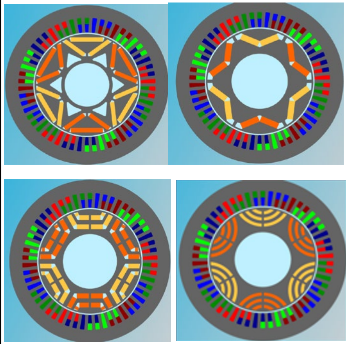
THE E-MOTOR DESIGN PROCESS

Concept Design



Rapid Design Exploration and Ranking

Detailed Design

Multi-Physics Optimization
EM, Structural, Thermal

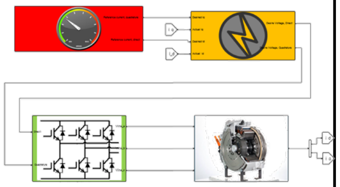
Responses
Power, Torque, Torque Ripples, Max Speed, Losses, Temperatures, Demagnetization, Stress

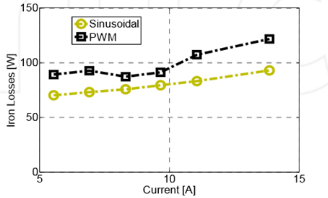
Scenario
Individual Working Points

Magnet Shape DVs

System Modeling

Add Inverter Battery Models

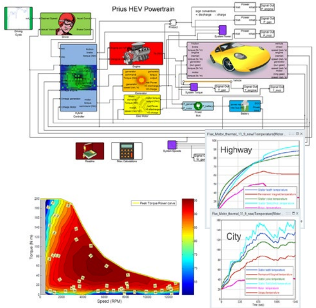




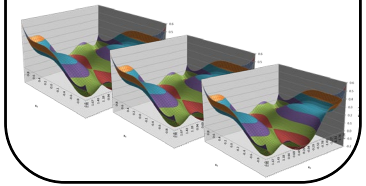
More realistic Torques and Efficiencies

System Optimization

Simulation of Drive Cycles



Reduced-Order Models



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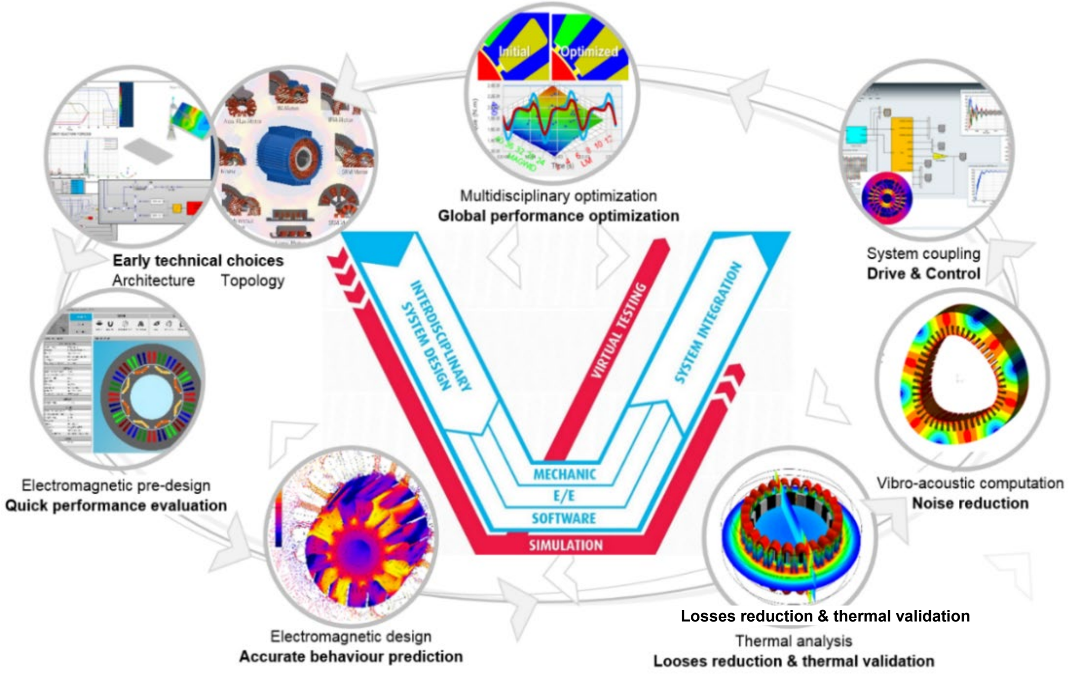
ALTAIR'S COMPLETE PLATFORM FOR E-MOTOR INNOVATION

- An **integrated** workflow for **model based multi-physics optimization** design
- **Disruptive** to traditional design process through **machine learning**
- **Speed to market** with **balanced design** and confidence
- **Flexible process** for customization and ease of use



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ALTAIR SOLVER TECHNOLOGY

Crash
Safety
Blast
Gravity
Springback

RADIOSS
Structural Explicit

OptiStruct
Structural Implicit

Durability
Vibrations
Acoustics
Buckling
Heat Transfer

Forming
Extrusion
Additive
Casting
Molding

Click2X
Manufacturing

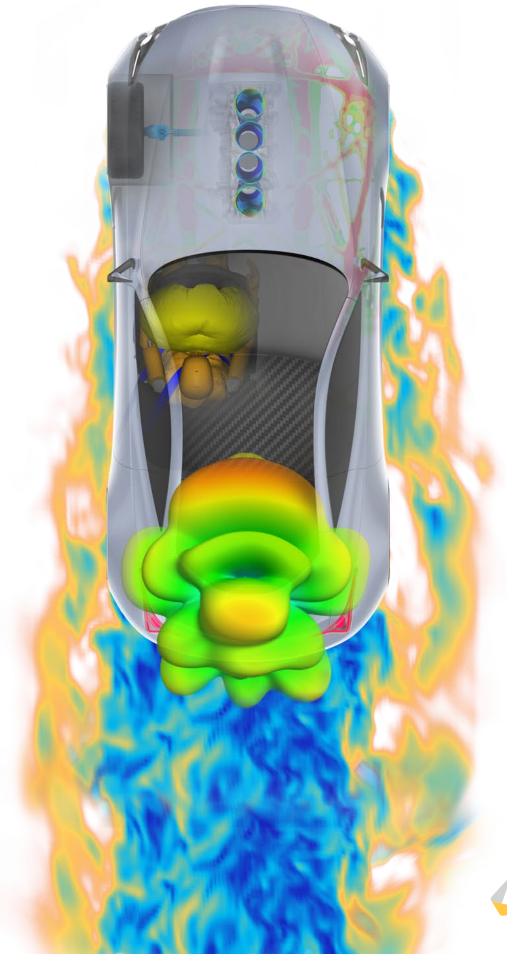
ACTIVATE
Systems

AcuSolve - FluidX
CFD and Thermal

OptiStruct
Design Optimization
-
HyperStudy
Design Exploration

FEKO - FLUX
Electromagnetism

MotionSolve
Multi-body Dynamics



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E-MOTOR DESIGN PROCESS

Philippe W.

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DESIGN SPECIFICATIONS

Specifications

- Stator diameter : DIAM
- Active length : LENGTH
- Iron fill factor : 0.92
- Magnet : Br 1.15 T
- Tmax winding 200°C
- Tmax rotor : 180°C
- Maximum speed : MAXS rpm
- Minimum power : 170kW
- Max phase voltage : 241V
- Max phase current : 300A
- DC-link voltage : 650V, 800V

Objectives

- Maximum power (base point)
- Minimize torque ripple

Constraints

- Demagnetization at base point
- Mechanical strength
- Temperature of winding lower than 200°C

The stator topology is set.

The rotor topology is open

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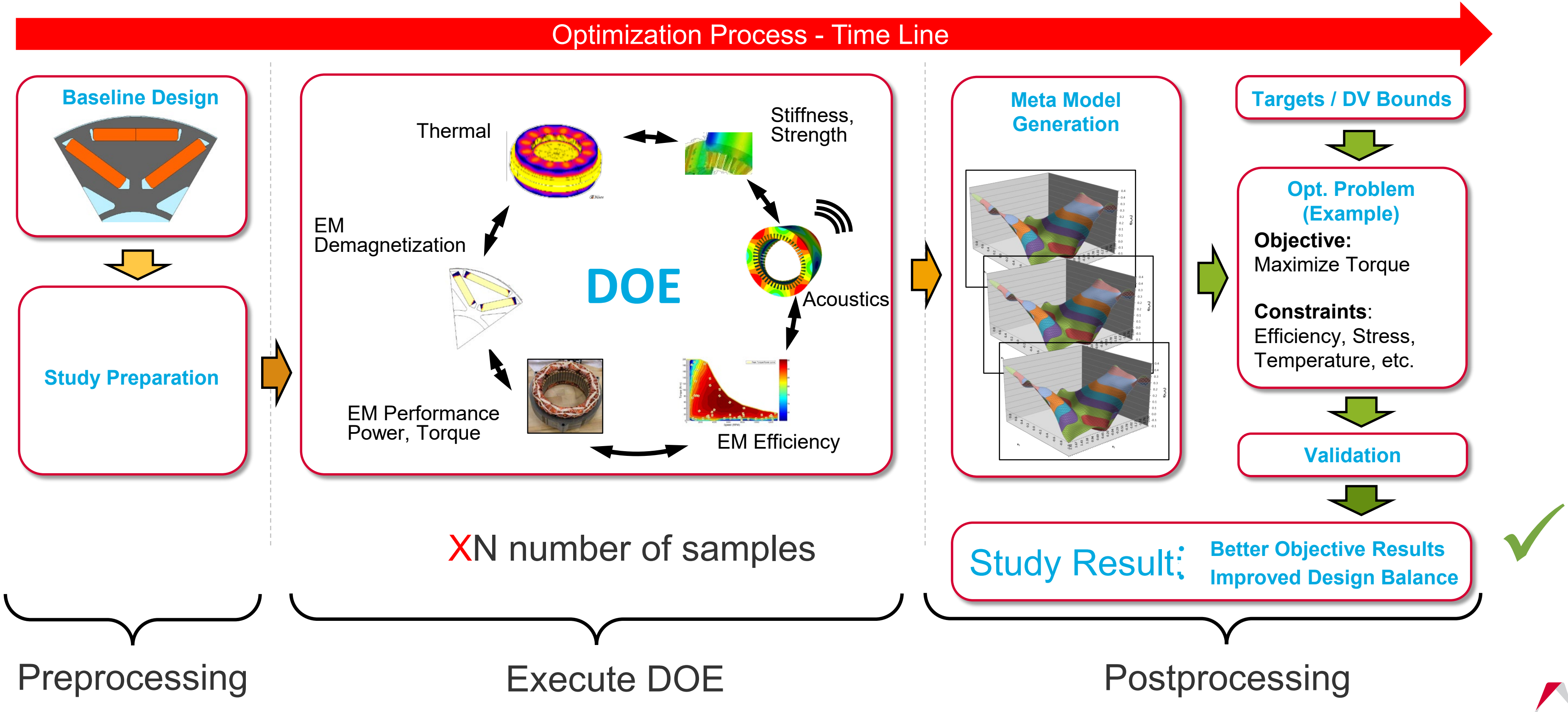
MULTI-DISCIPLINARY/PHYSICS OPTIMIZATION – GENERIC OVERVIEW



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FLUXMOTOR PROJECT
BASE DESIGN

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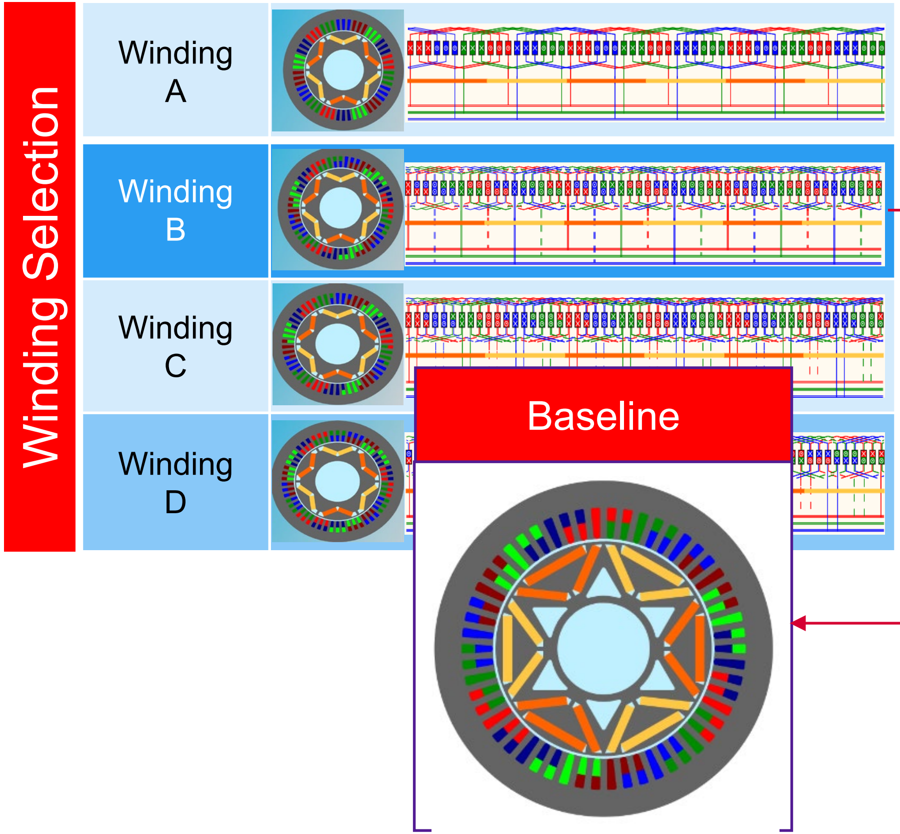
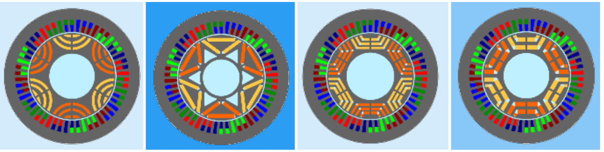
MOTOR BASELINE



Rotor Selection

	Rotor A	Rotor B	Rotor C	Rotor D
				
Current den (A/mm2)	31,1	31,1	31,1	31,1
Torque (Nm)	181	164	165	162
Power (kW)	195	186	185	180
Base speed (rpm)	10.290	10.830	10.670	10.610
Efficiency (%)	96,0	95,9	95,9	95,7
Magnet weight (Kg)	2,54	2,48	2,48	2,53

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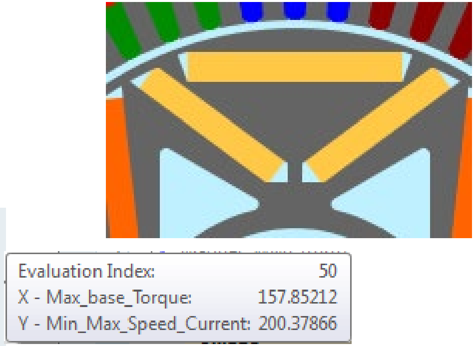
FIRST OPTIMIZATION FLUXMOTOR: MINIMIZE CURRENT

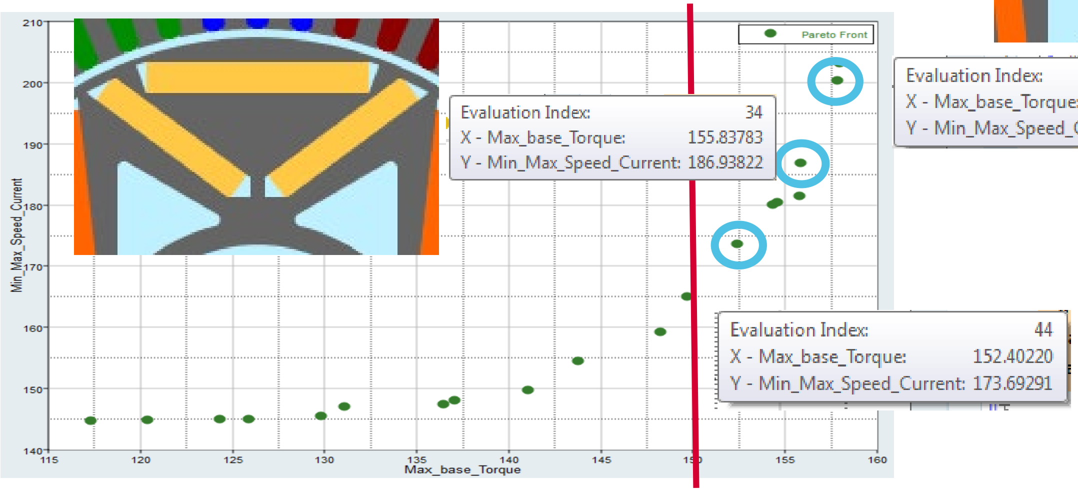
Goal:

- Maximize base torque – more than 150 N.m
- Minimize current at 100 kW (initial value 205 A)

50 runs

30 minutes





With 174 A, we obtain the target torque, helping the temperature constraints

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DOE WORKFLOW

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LOAD CASES

Base point

- Identify base point
- Average torque and torque ripple
- Short-circuit test, risk for demagnetization

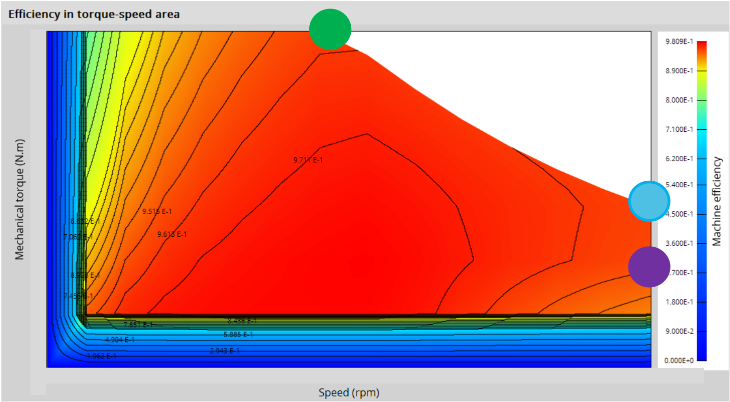
Max speed max torque

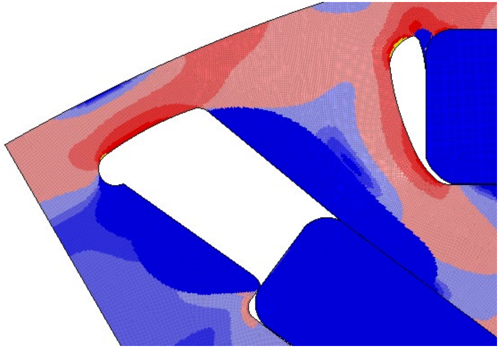
- Average torque and torque ripple, losses

Max speed 100 kW : check temperature after 2 hours

- Magnetic analysis: losses
- 2D Thermal analysis: temperature after 2 hours

Stress : check stress at MAXS rpm on rotor only





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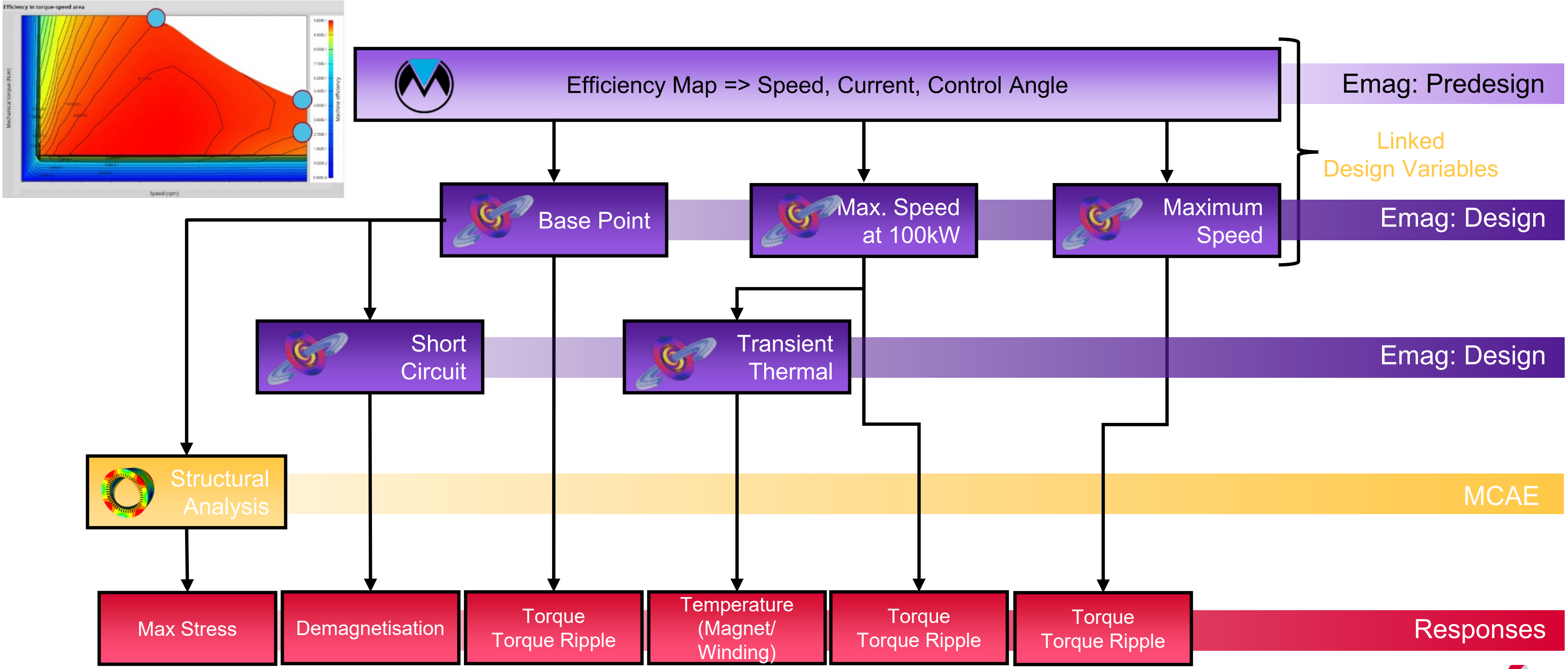
WORFLOW TO COMPUTE ONE SINGLE SAMPLE



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SETTING THE LOAD CASES

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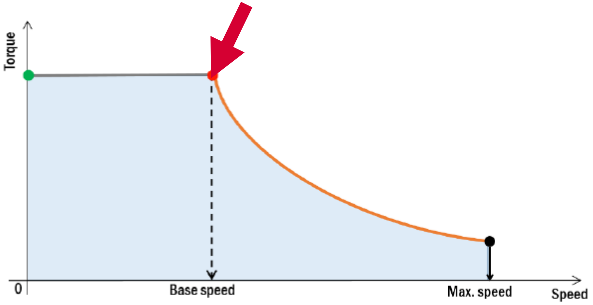
FLUX BASE POINT

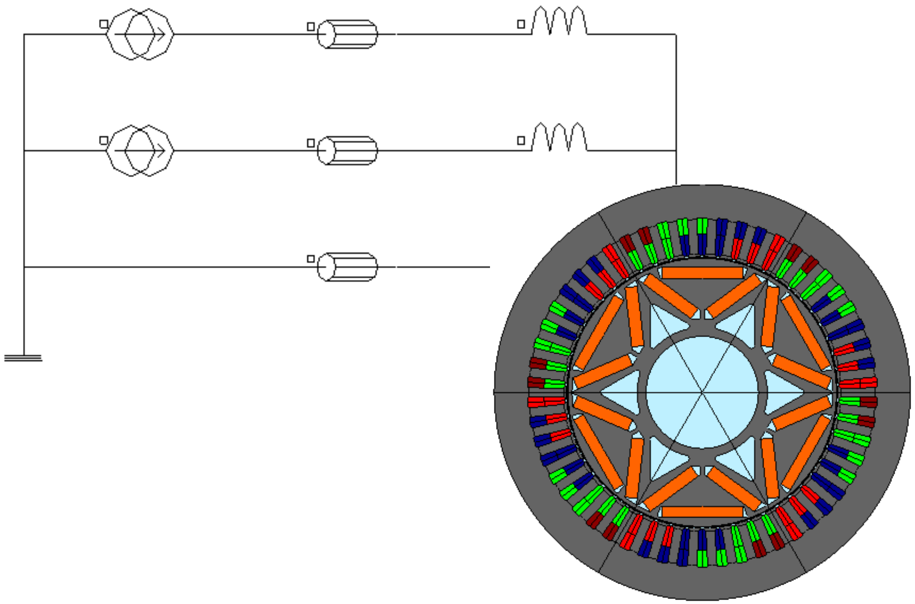


Input

- Rotor geometric parameters
- Base speed,
- Base line current,
- Base control angle

Output

- Base torque,
- Base torque ripple,
- Generate *.STEP file (for OptiStruct analysis)



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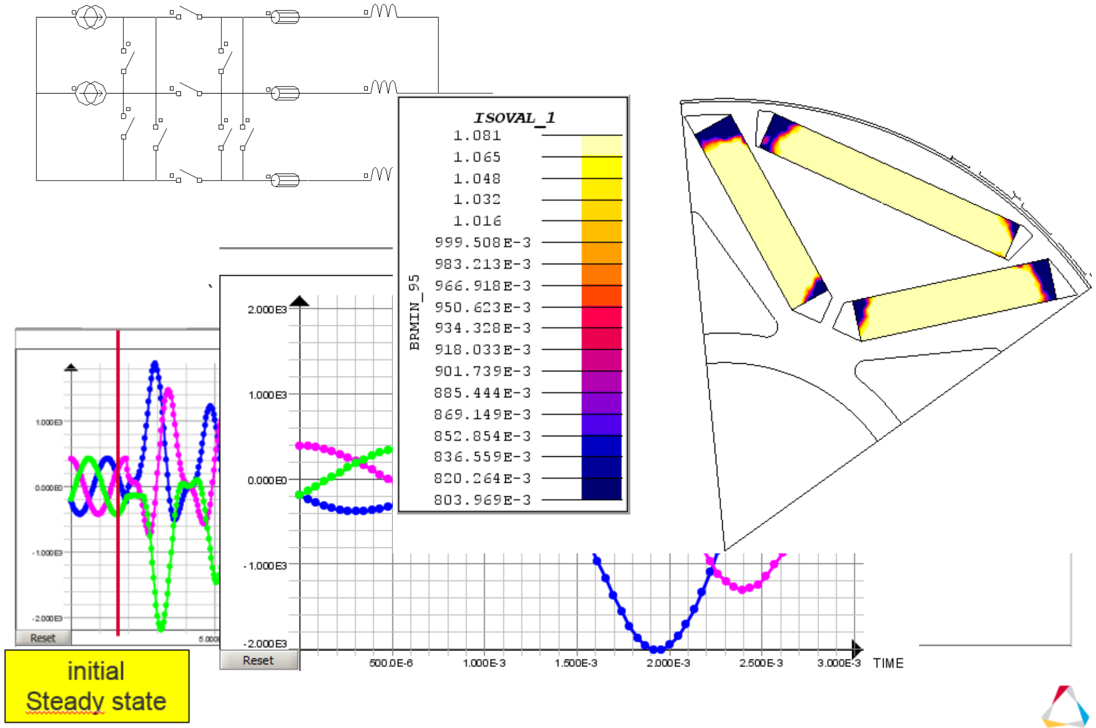
FLUX SHORT-CIRCUIT AT BASE SPEED

Input

- Rotor geometric parameters
- Speed
- Base line current,
- Base control angle

Output

- Demagnetization



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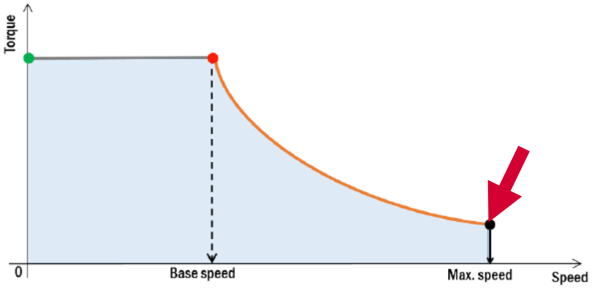
FLUX MAX SPEED

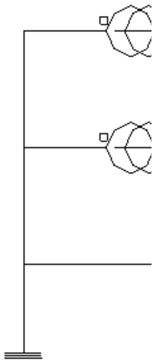
Input

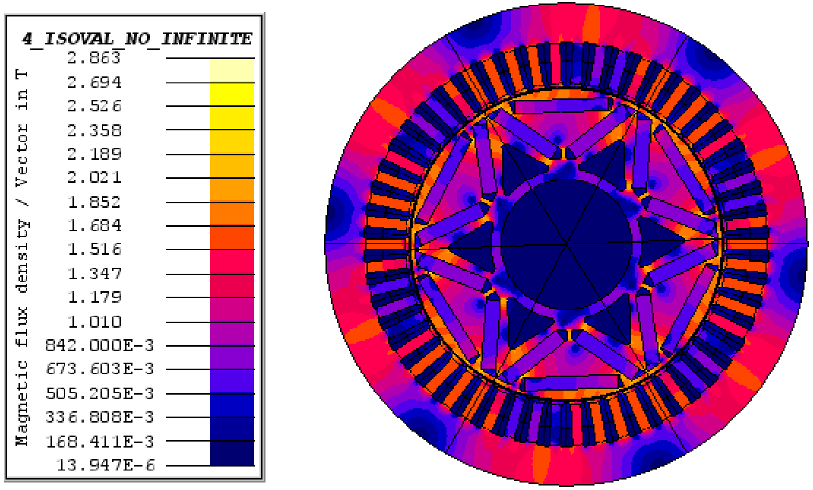
- Rotor geometric parameters
- Speed
- Max speed line current
- Max speed control angle

Output

- Max speed torque
- Max speed ripples







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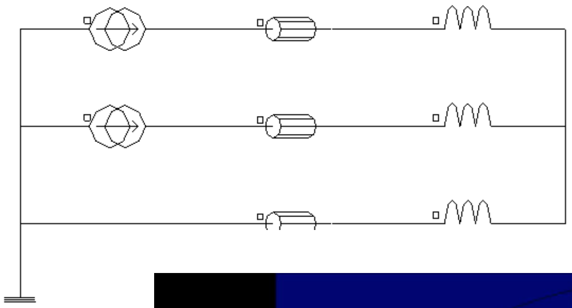
FLUX 100KW AT MAX SPEED

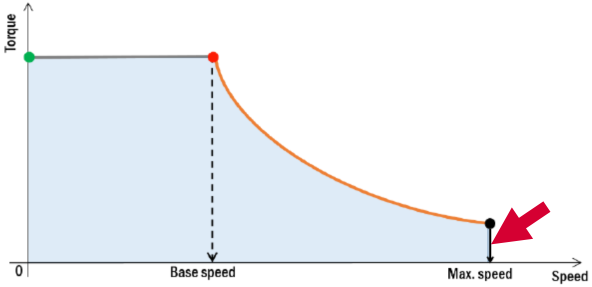
Input

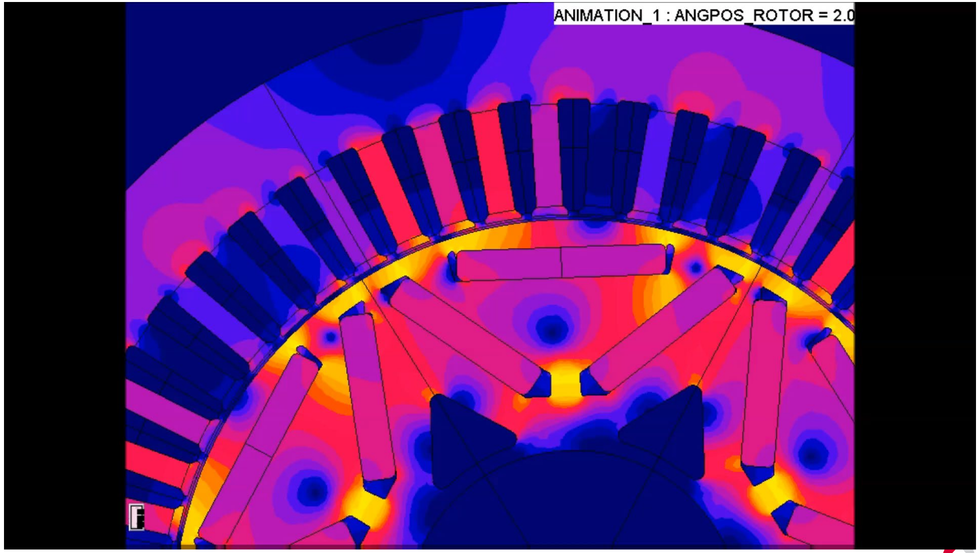
- Rotor geometric parameters
- Speed, current, angle

Output

- Losses (core losses rotor and stator, winding Joule losses, eddy current magnet)







Iron losses

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2D THERMAL ANALYSIS

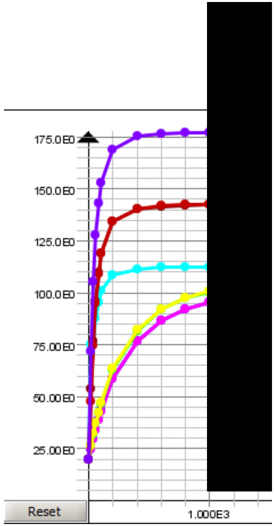
Test after 2 hours

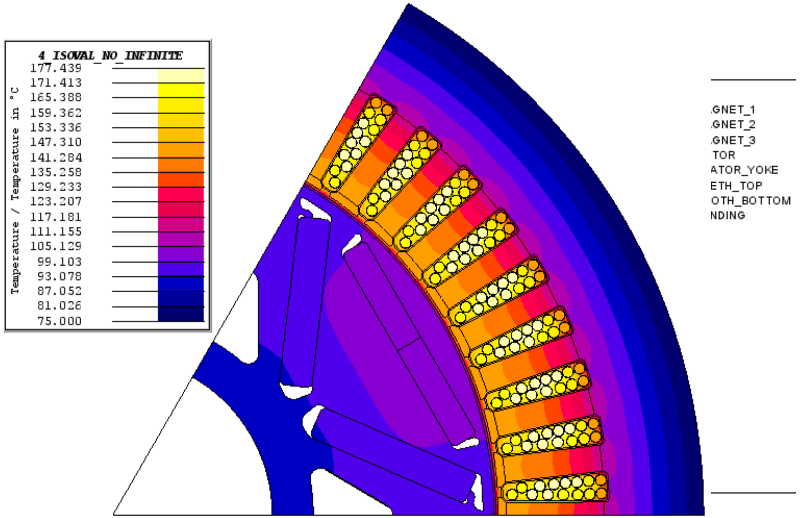
Input :

- Rotor geometric parameters
- Losses

Output

- Temperature in magnets (max)
- Temperature in winding (T < 180°C)





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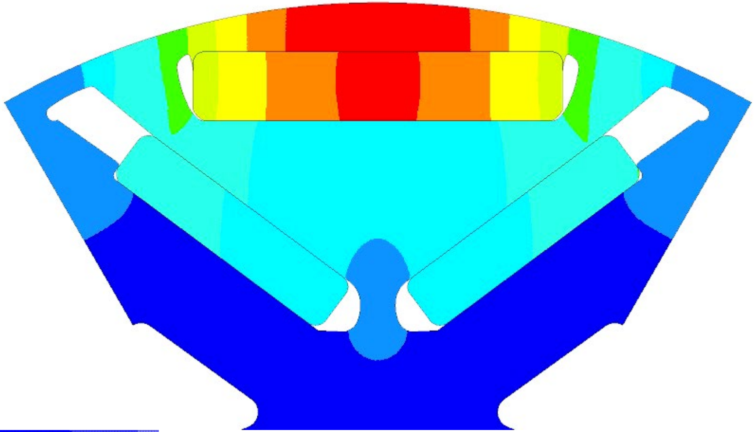
STRESS ANALYSIS MAXS



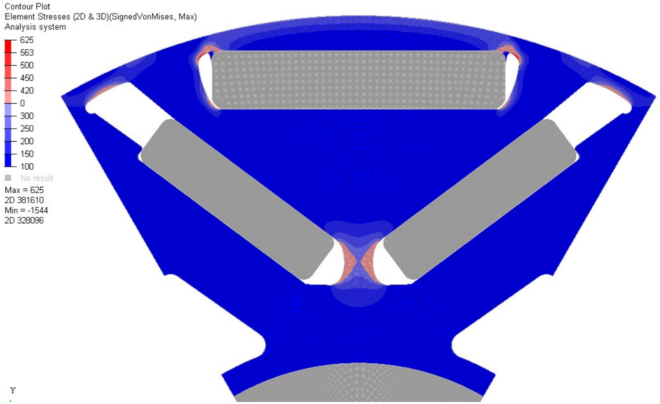
Starting from geometry in step file

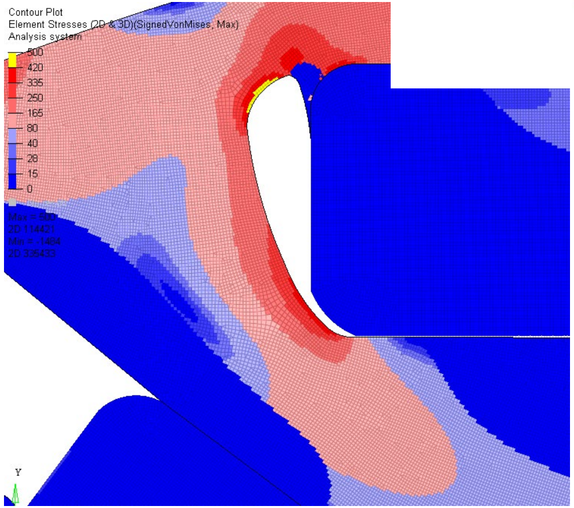
Input

- STEP file

Output

- Max value of stress (must be lower than 500 MPa)





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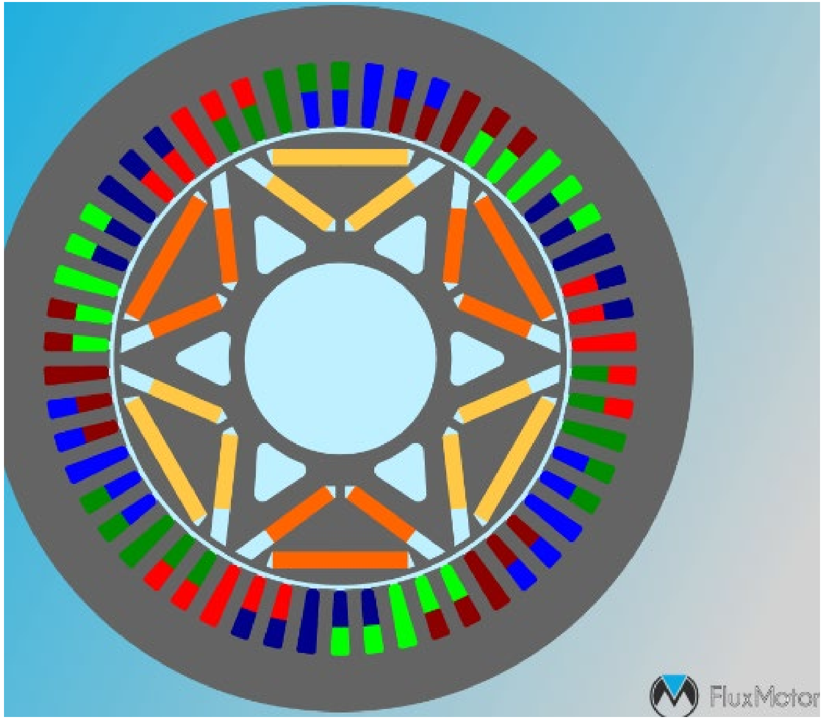
GLOBAL OPTIMIZATION

Goal:

- Maximize base torque
- Minimize torque ripple

Constraint:

- Stress lower than 500 MPa
- Winding temperature lower than 180°C
- Demagnetization lower than 5%
- Torque greater than 150 Nm



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DOE OUTLINE

Summary of Optimization Problem in HyperStudy

Add Model | Remove Model | Model Resources

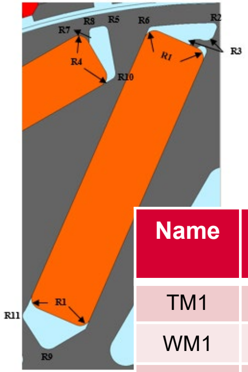
	Active	Label	Varname	Model Type	Solving time
1	☑	FluxMotor	m_1	FluxMotor	2,5 minutes
2	☑	base_speed	m_2	Flux	4 minutes
3	☑	Max_Speed	m_3	Flux	4 minutes
4	☑	Short_circuit	m_4	Flux	6 minutes
5	☑	100_kW_MAx_S...	m_5	Flux	4 minutes
6	☑	Thermal	m_6	Flux	6 minutes
7	☑	HyperMesh	m_7	Operator	10 seconds
8	☑	OptiStruct	m_8	Operator	2 minutes

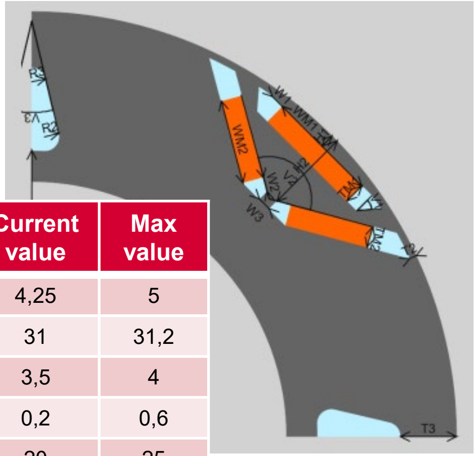
29 minutes

DOE Study

- 18 Design Variables
- Approximately 400 runs
- 18h with 15 cores in parallel

Design Space





Name	Min Value	Current value	Max value
TM1	3	4,25	5
WM1	29	31	31,2
H1	3	3,5	4
W1	0,2	0,2	0,6
V1	15	20	25
TM2	3,5	4,75	4,75
WM2	16	23	23
H2	20	20	20
W2	0,5	0,6	0,7
T2	1,1	1,5	1,6
V2	106,7	107	107,1

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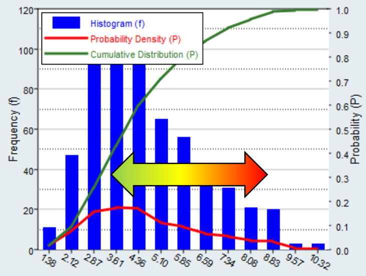
GLOBAL OPTIMIZATION

2 Objectives

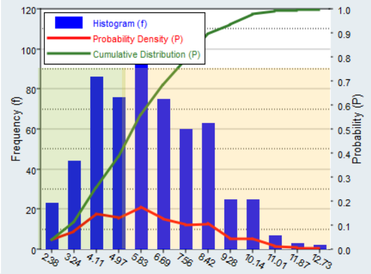
- Min Torque Ripples
- Max Power

4 Constraints

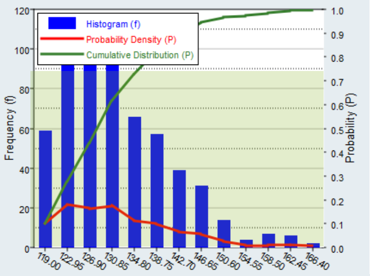
- Demagnetization < 5 %
- Base torque >= 150 Nm
- Temperature winding <180°C
- Max stress <= 500 Mpa



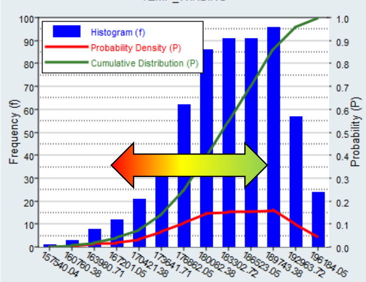
Torque Ripples



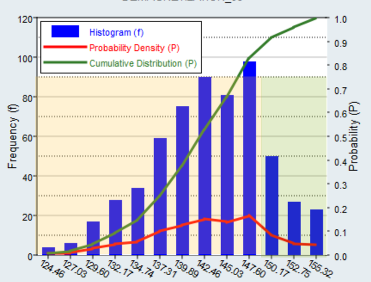
Demagnetization



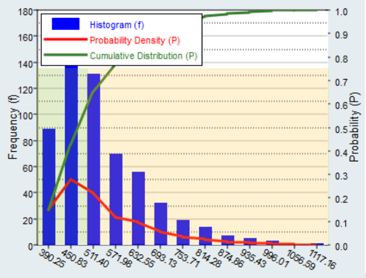
Temp Winding



Mechanical Power



Mechanical Torque



Max Stress

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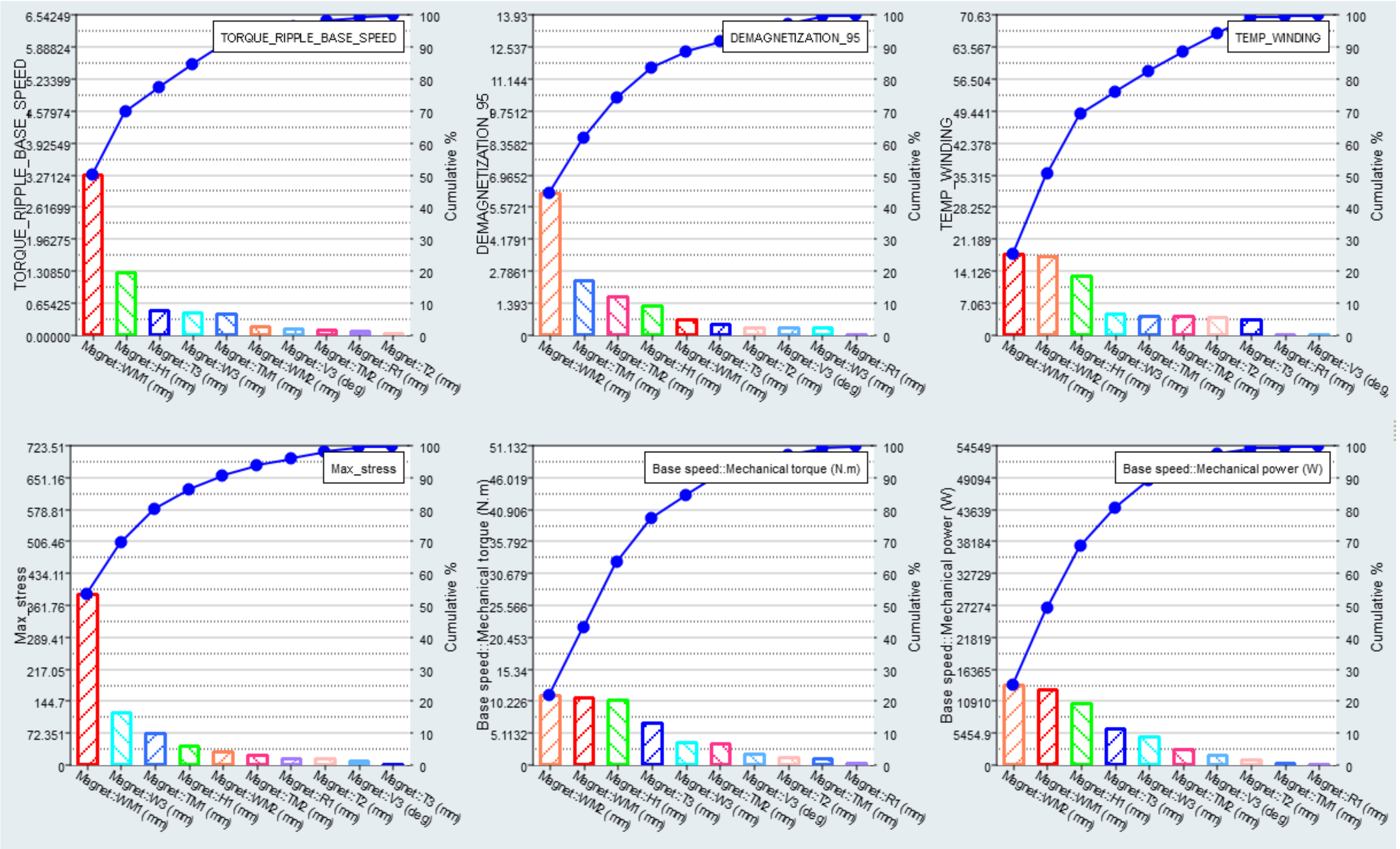
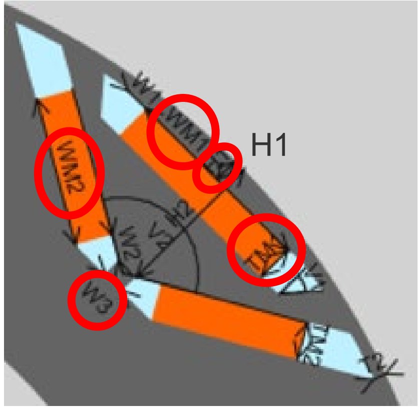
400 RUNS – SENSITIVITY





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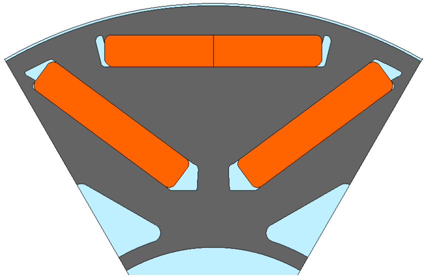
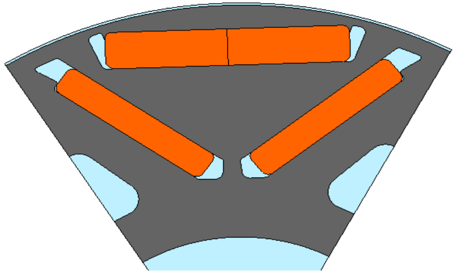
GLOBAL OPTIMIZATION : DESIGN OF EXPERIMENT

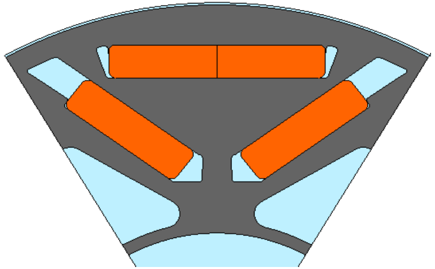
Trends from DOE



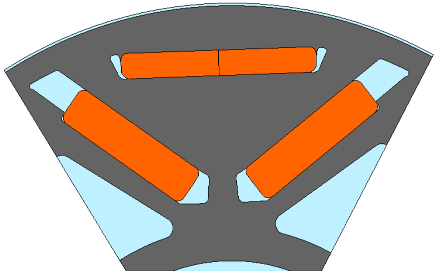
initial



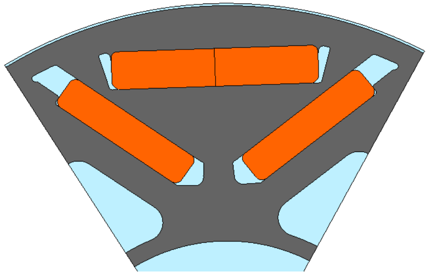
Maximum torque



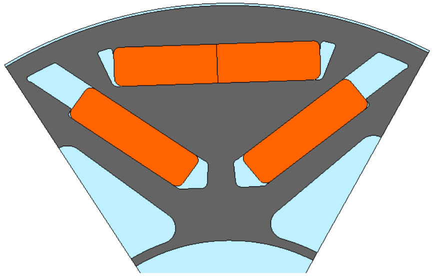
Minimum winding temperature



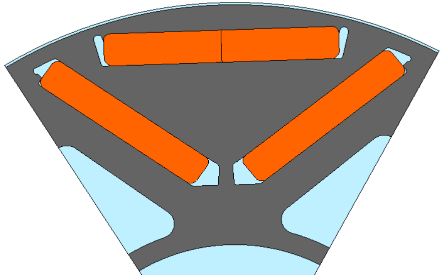
Minimum stress



Minimum torque ripple



Minimum demagnetization



Maximum power

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OPTIMIZATION

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USING FIT FOR DIFFERENT OPTIMIZATIONS

2 objectives

- Max power
- Min torque ripple

- 4 constraints
  - Max stress <= 500 MPa
  - Demagnetization <= 5 %
  - Temperature winding <180°C
  - Base torque => 150 Nm

500 iterations 12 points per iteration										
DEMAG	stress	T_winding	Torque		Objective 1	Objective 2	STRESS	DEMAG	WINDING	TORQUE
5	500	180	145	optimal	185558.05	3.3028670	500.11439	5.0013581	130.90805	**144.89983**
5	500	180	150	violated	185508.19	3.6410141	**507.49310**	**5.0686687**	129.17836	**144.97804**
5	550	180	150	violated	187568.45	3.0975566	**558.08334**	5.0524471	135.21758	**146.80096**
5	600	180	150	violated	187670.12	4.5006536	**603.67138**	5.0290165	134.09146	**148.13142**
5	650	180	150	optimal	189735.28	4.3846638	**651.65516**	5.0097176	137.21773	149.29942
6	500	180	150	violated	187886.74	3.6127883	**504.44520**	**6.0462309**	132.34385	**147.29856**
7	500	180	150	violated	189568.45	4.0627783	**502.64007**	**7.0298307**	134.11429	**148.39414**
7,5	500	180	150	optimal	190711.88	3.3218627	499.97401	**7.4943515**	136.39664	150.02709
7,2	500	180	150	optimal	190256.56	3.4551889	500.39643	**7.2047921**	135.50755	149.77043

Note: with fit, one optimization takes less than 2 minutes with 500 runs

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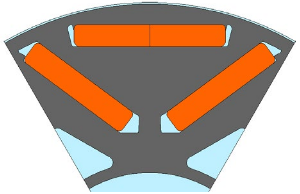
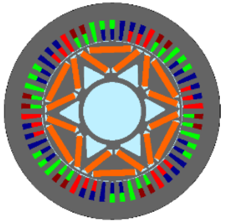
E-MOTOR OPTIMIZATION PROBLEM – FINAL RESULTS



	Initial
Base torque [Nm]	155
Base torque Ripple [Nm]	8,5
Stress [Mpa]	2.316
Winding Temp. [°C]	171
Demagnetization Factor	6,6



- **Optimization Objective:**
  - Maximize base output Power
  - Minimize base Torque Ripple
- **Constraints:**
  - Stress lower than 500 MPa
  - Winding Temperature lower than 180°C
  - Demagnetization lower than 5%
  - Base Torque greater than 150 Nm

Magnet Weight
Reduction of 40 %

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TO GO FURTHER: INCLUDE DRIVE

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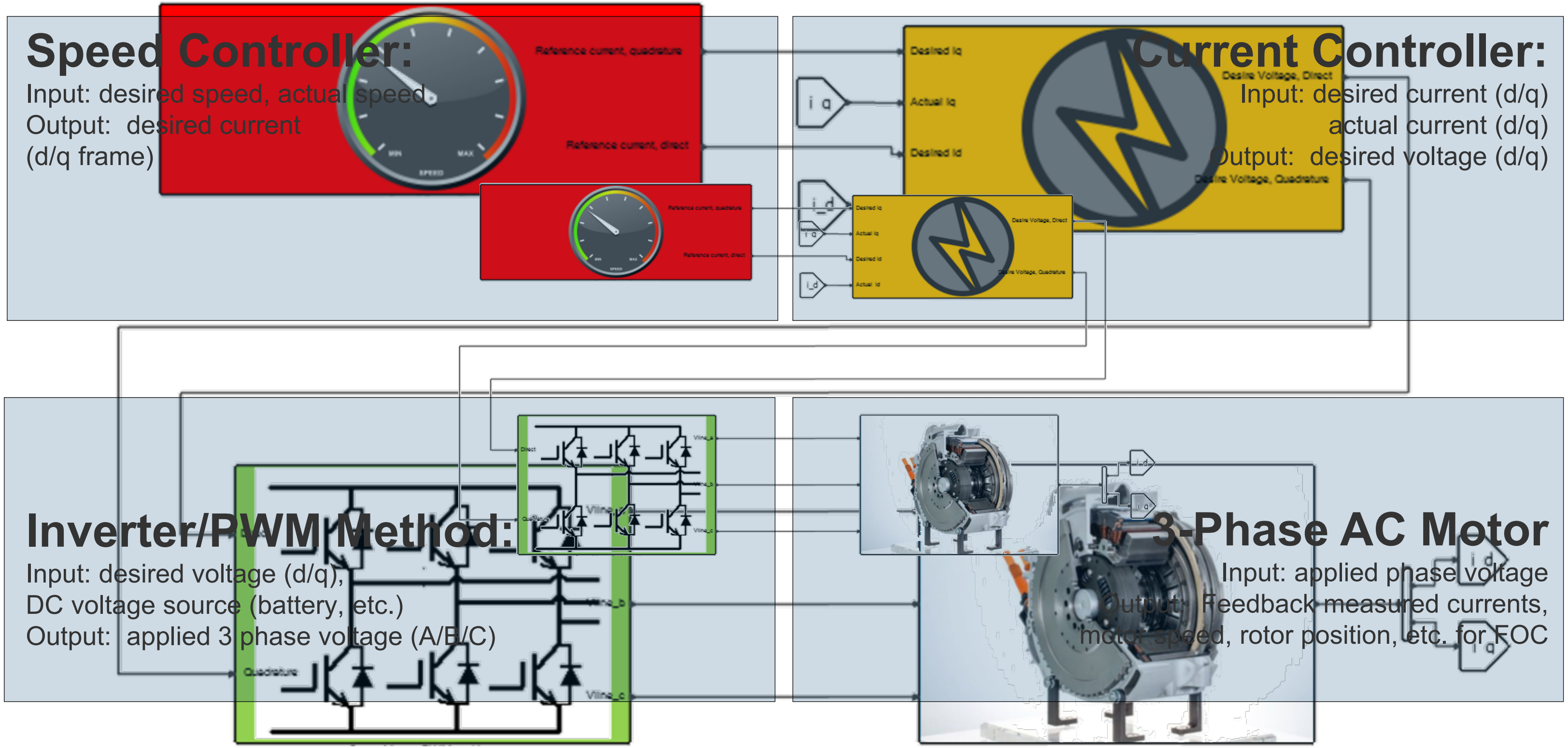
FIELD ORIENTED CONTROL STEPS: OVERVIEW



Speed Controller:
Input: desired speed, actual speed
Output: desired current (d/q frame)

Current Controller:
Input: desired current (d/q)
actual current (d/q)
Output: desired voltage (d/q)

Inverter/PWM Method:
Input: desired voltage (d/q),
DC voltage source (battery, etc.)
Output: applied 3 phase voltage (A/B/C)

3-Phase AC Motor
Input: applied phase voltage
Output: Feedback measured currents, motor speed, rotor position, etc. for FOC

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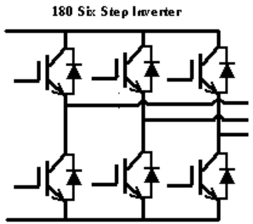
PROCESS: ACTIVATE INVERTER INPUTS TO FLUX

Flux

Motor Parameters

+



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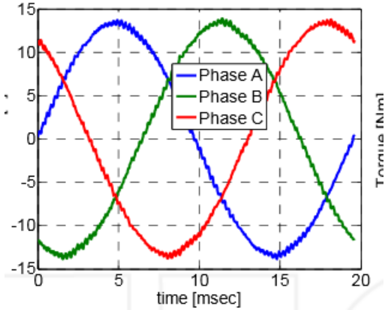
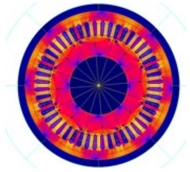


Current Waveforms

Flux



More Accurate Motor Results: Losses, Torque Ripple, etc.

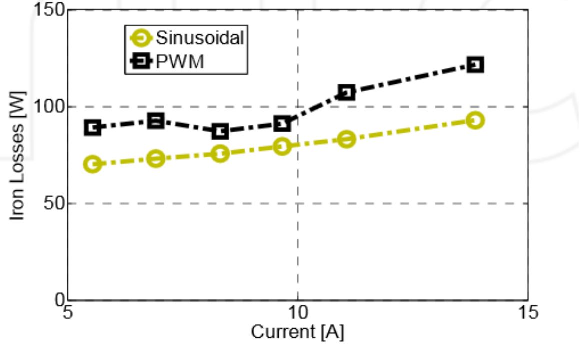


*Image Source: https://cdn.intechopen.com/pdfs-wm/39370.pdf
See notes, next slide for details

Faster process than direct co-sim:
Use simplified motor model in Activate to generate steady-state current

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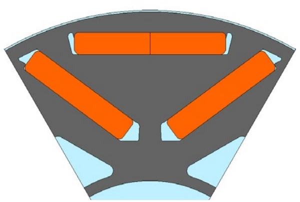
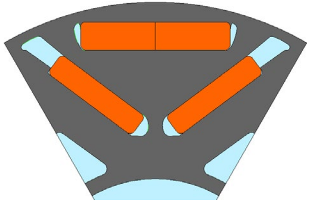
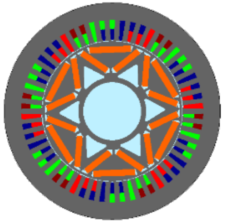
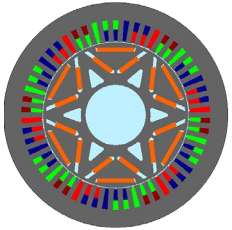
E-MOTOR OPTIMIZATION PROBLEM – FINAL RESULTS WITH PWM





	Initial	Current Optimum With Sine Current
Base torque [Nm]	155	150
Base torque Ripple [Nm]	8,5	5,4
Stress [Mpa]	2.316	500
Winding Temp. [°C]	171	139
Demagnetization Factor	6,6	5,2





Magnet Weight
Reduction of 40 %

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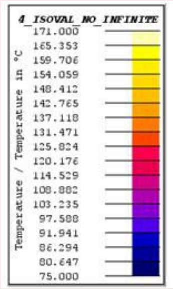
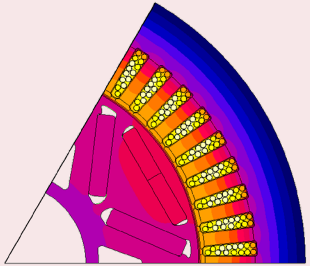
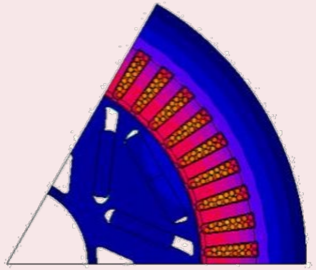
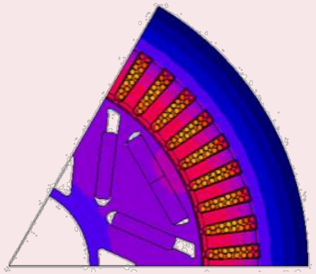
(*) TEMPERATURES USING PWM CURRENT

	Initial	Current Optimum With Sine Current	Current Optimum with PWM Current (620V – 800V)
Joule losses (W)	4.220	2.266	2.272 – 2.278
Magnet losses (W)	143,6	58	141 - 164
Iron losses stator (W)	1.157	1.096	1.173 – 1.206
Iron losses rotor (W)	230	159	196 - 208
Temp. Rotor [°C]	Tmax 118	Tmax 87	Tmax 103 - 108
 High / Low			

Added losses leads to 20 % higher temperatures in magnets and rotor yoke

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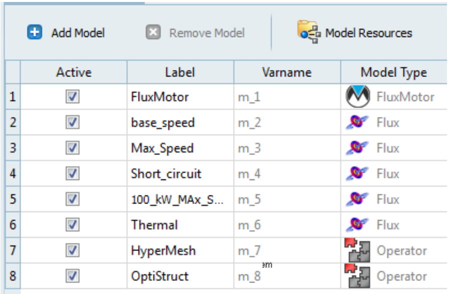
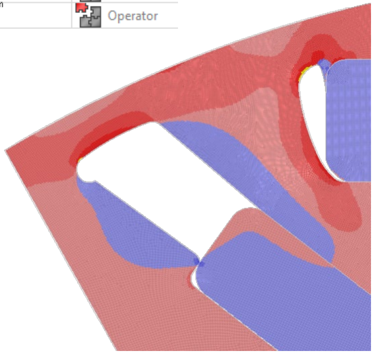
SUMMARY



	Active	Label	Varname	Model Type
1	☑	FluxMotor	m_1	FluxMotor
2	☑	base_speed	m_2	Flux
3	☑	Max_Speed	m_3	Flux
4	☑	Short_circuit	m_4	Flux
5	☑	100_kW_MAx_S...	m_5	Flux
6	☑	Thermal	m_6	Flux
7	☑	HyperMesh	m_7	Operator
8	☑	OptiStruct	m_8	Operator

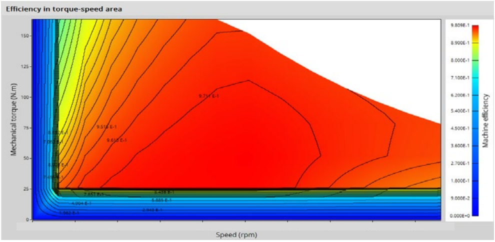
Multi-physics optimization of E-motor including:

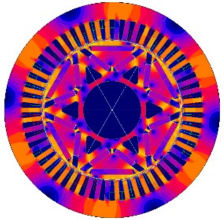
- Predesign of motor - FluxMotor
- Magnetic analysis - Flux
- Thermal analysis - Flux
- Structural analysis - OptiStruct

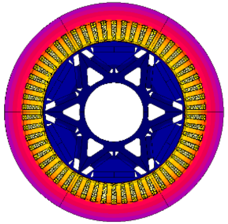


DOE and optimization driven by HyperStudy

Extension system - Activate







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LOOKING FORWARD

Richard Y.

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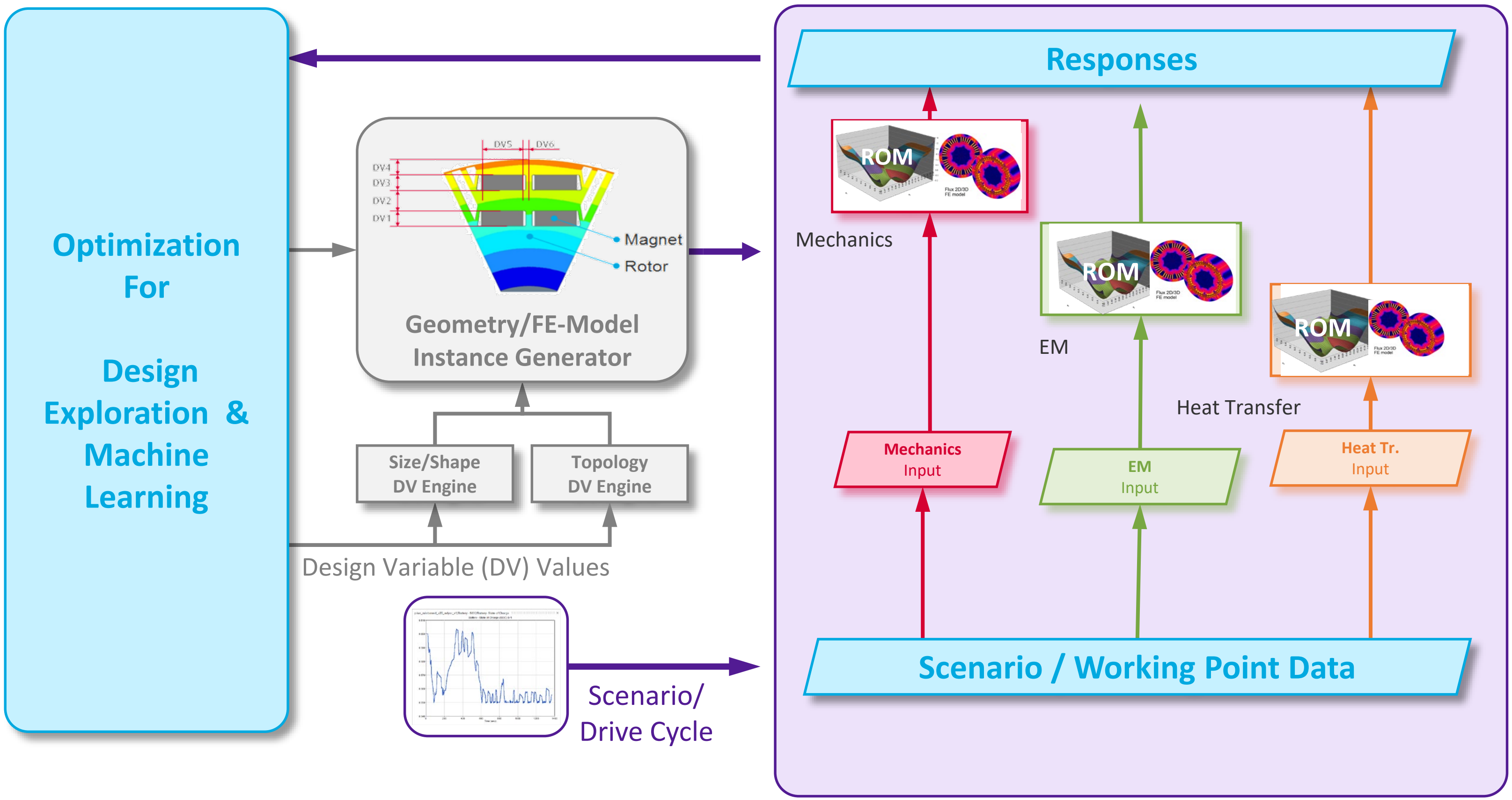
A COMPLETE MODEL BASED MULTIPHYSICS OPTIMIZATION WORKFLOW



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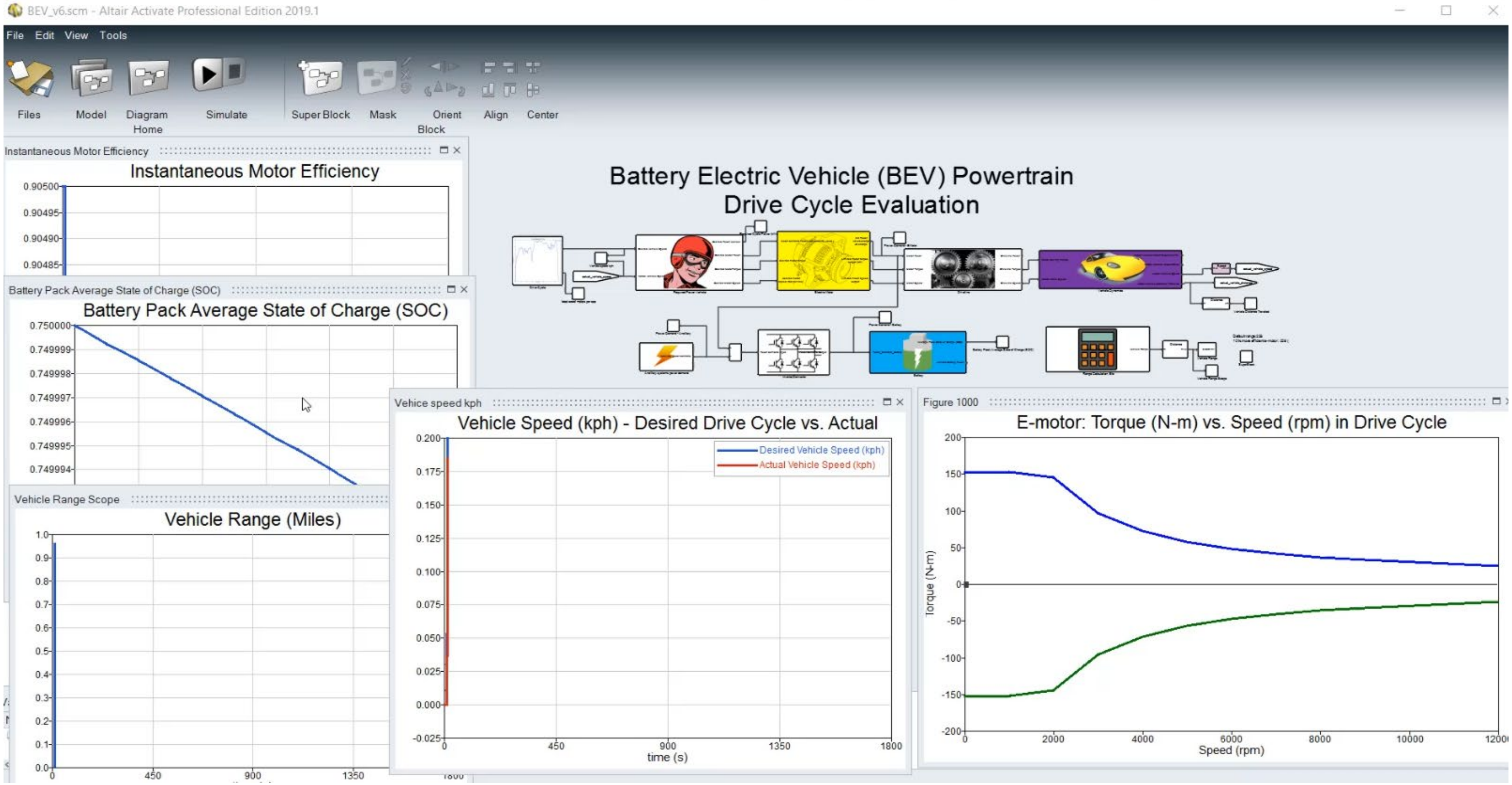
EVALUATION OF WLTP – DRIVE CYCLE EFFICIENCY



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