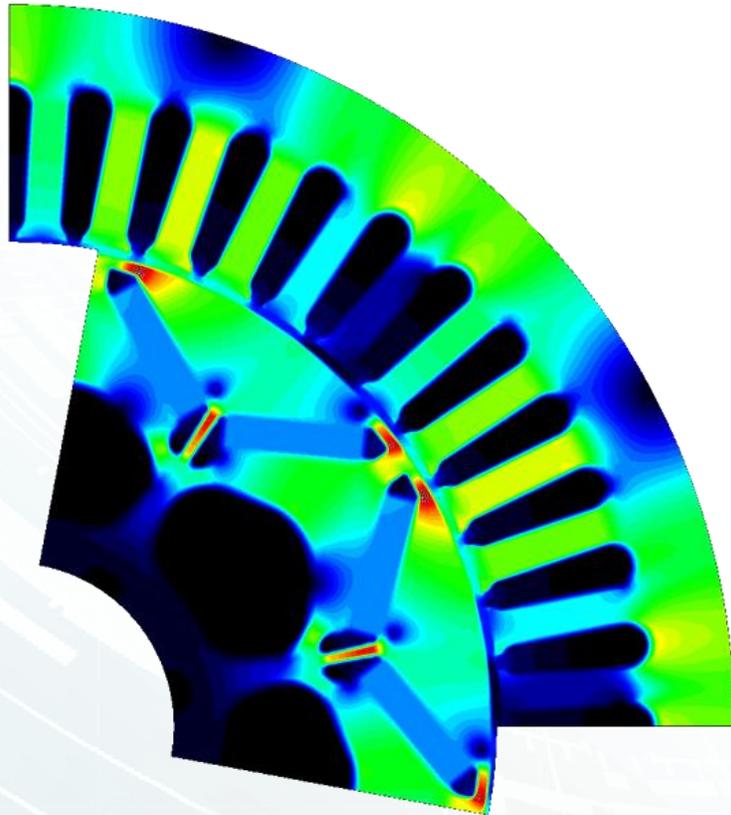


AVL



Introduction to AVL eSUITE, e-motor design concept & electro-magnetic analysis

AVL NA Simulation Conference 2019



- Introduction AVL eSUITE
- E-motor Solution Overview
- Concept Designer
- Electromagnetic Analysis
- Parameter Study
- Summary & Outlook

Future Powertrains

Electrified

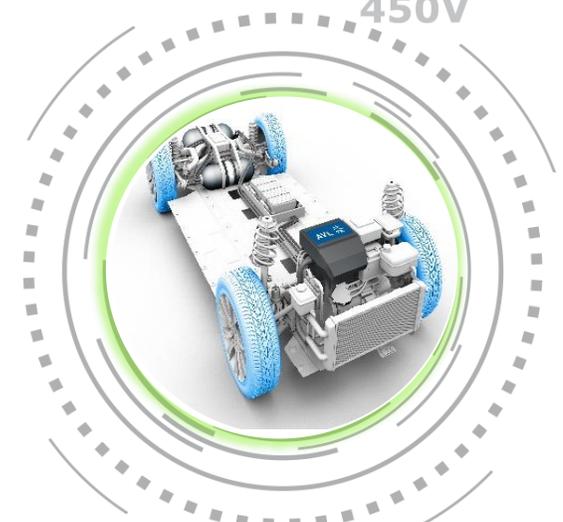
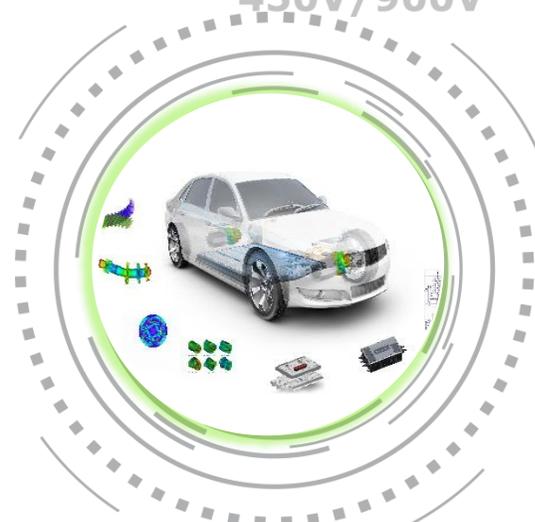
Fully Electric

(M)HEV
48V

PHEV
450V

BEV
450V/900V

FCEV
450V

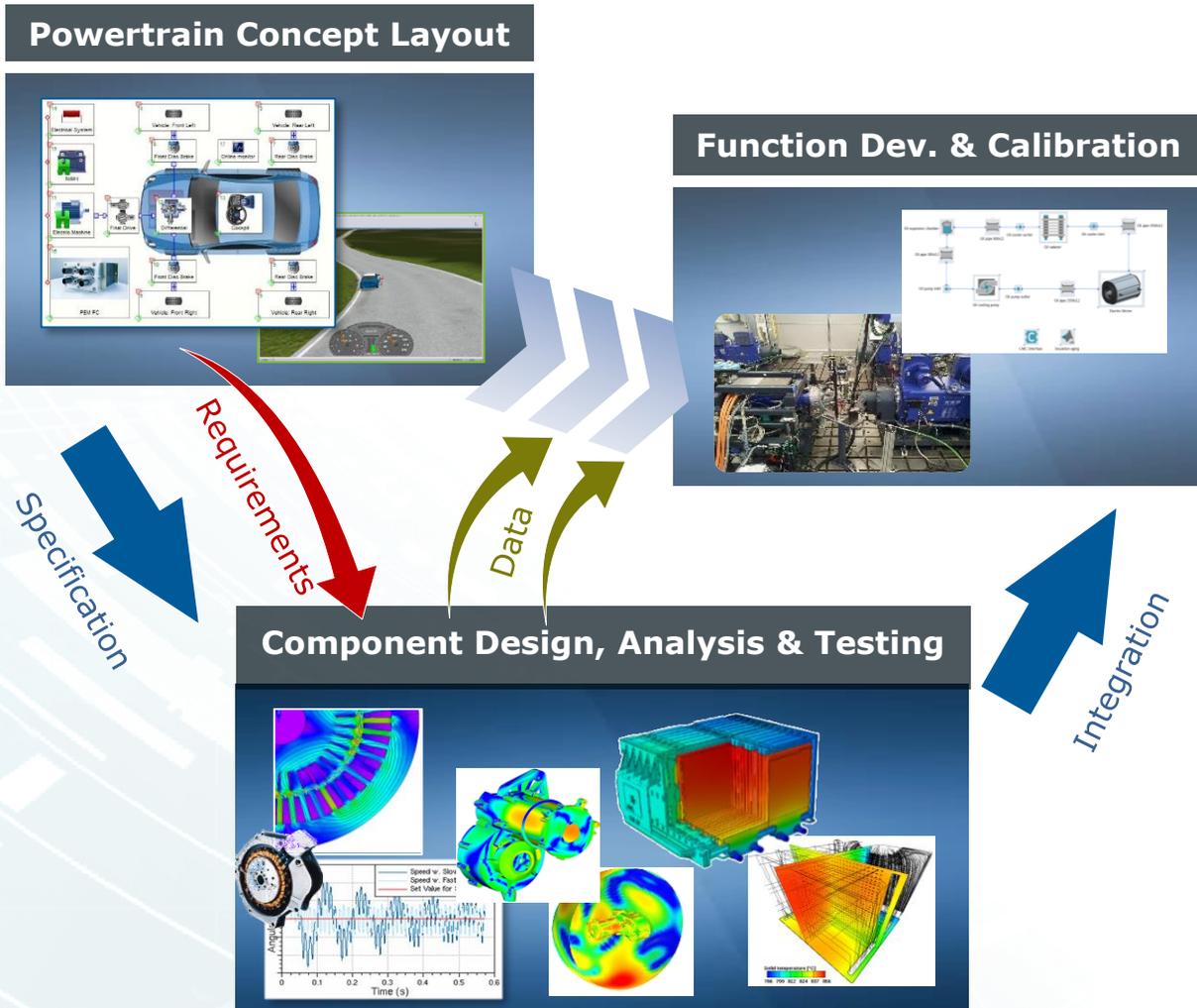


Fossil Fuel

Electric Energy

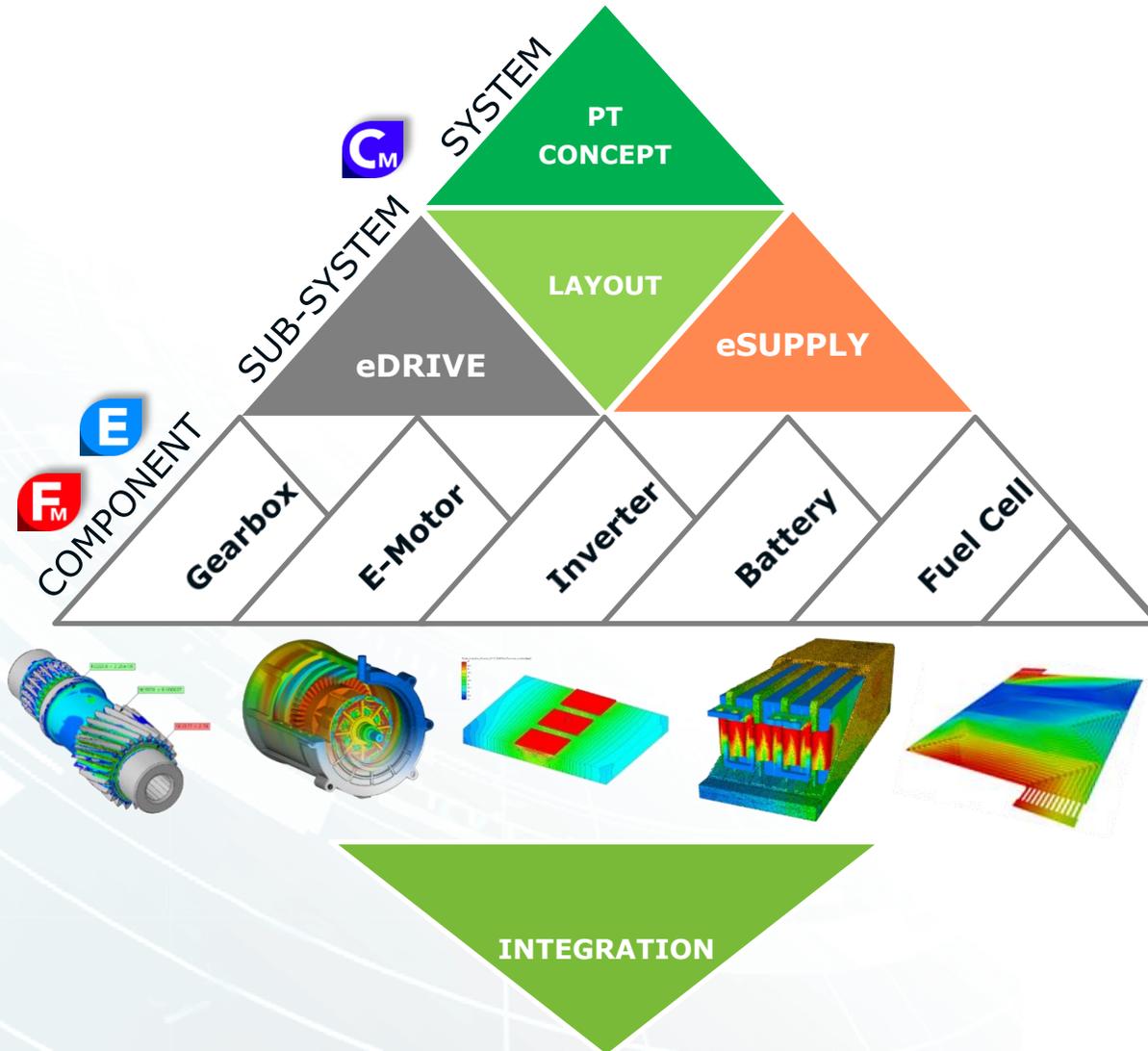
Hydrogen

Electrification Development Process



- Vertical integration from system to component level (concept, system layout, detailed 3D analysis)
- Horizontal integration from specification (office) till testing and calibration (TB, HiL)
- Seamless simulation model evolution over the whole development process

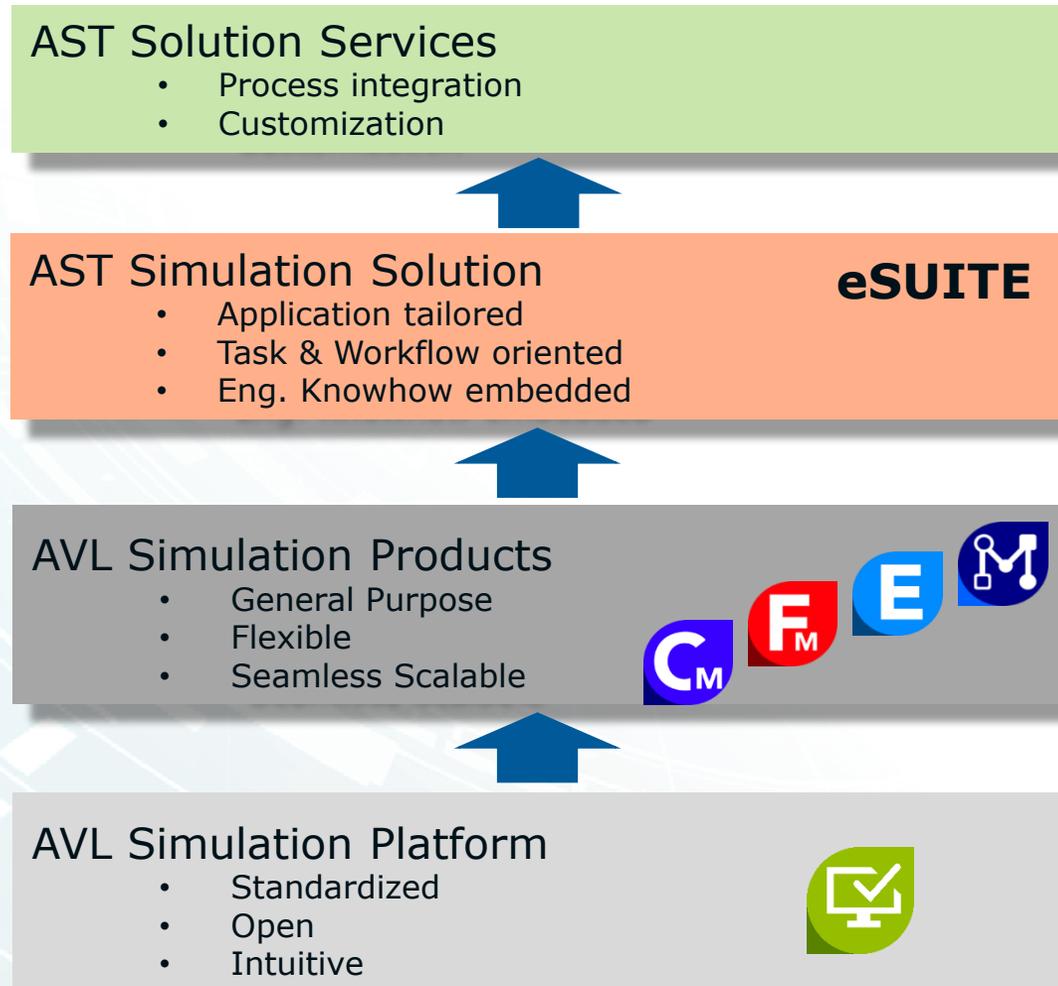
Powertrain Electrification supported by AVL eSUITE™



System and Sub-System Simulation
 (cooling circuit, electric network,
 mechanical driveline) based on **AVL
 CRUISE™ M**

Component Analysis
 based on **AVL EXCITE™**
 and **AVL FIRE™ M**

AVL Solution Structure



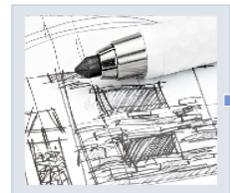
4 Level Concept

- **AVL Software Platform:** Simulation Desktop (SDT) acts as the platform
- **AVL Software Products** offers the simulation capabilities
- **AVL Software Solutions:** Application tailored solution focusing on engineering tasks
- **AVL Services:** Customer specific process integration and software customization

AVL Workflow for E-Motor Simulation

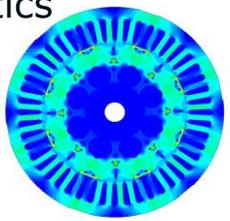
Seamless E-Motor Simulation Workflow

AVL E-Motor Tool



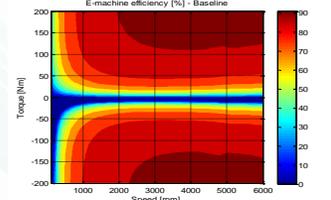
Concept Designer

Electro-magnetics



AVL FIRE™ M

Current Strategy, Efficiency Map

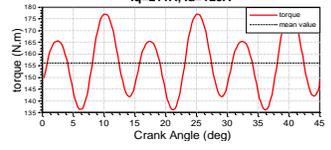


Losses

Temperature

FL, Force, Torque

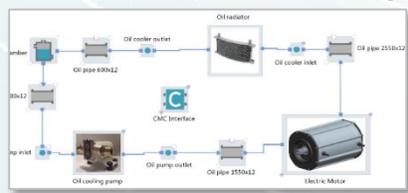
$I_q=211A, I_d=123A$



Tooth Forces and moments



Integration (mechanical, thermal, electrical)



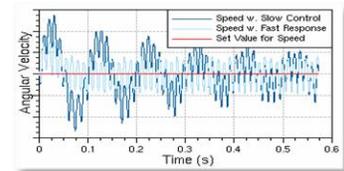
AVL CRUISE™ M

Thermal Analysis



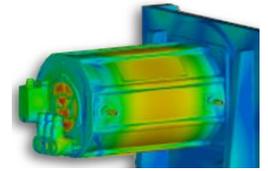
AVL FIRE™ M

Rotor Dynamics



AVL EXCITE™

Acoustic Analysis



AVL EXCITE™ Acoustics

Performance Tasks

C_M **F_M**

Basic Layout

BH Curves

— 35H210
— M330-35A
— M250-35A

E

C_M **F_M**

Maps & Strategies

Inverter-driven E-Motor are current controlled

Torque [Nm]

Current angle [deg]

MTPA sets the current tables by maximizing the torque

E

C_M **F_M**

Sensitivities

Rotor force [N]

angle [deg]

— F_x
— F_y

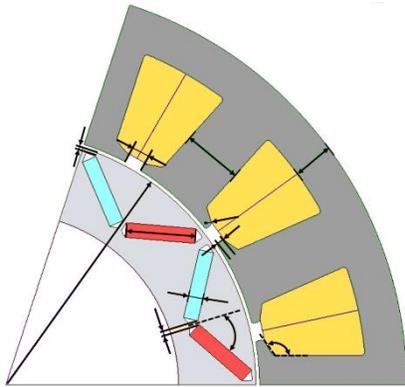
E

Performance Workflow

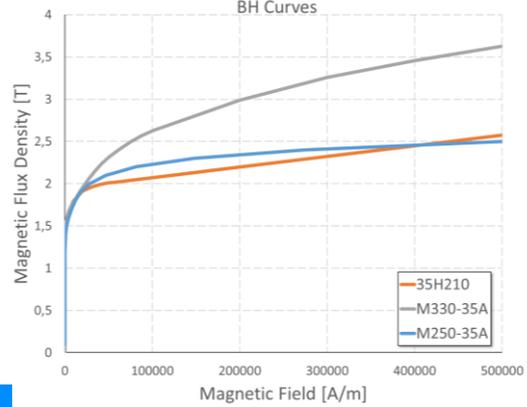
C_M

F_M

Basic Layout

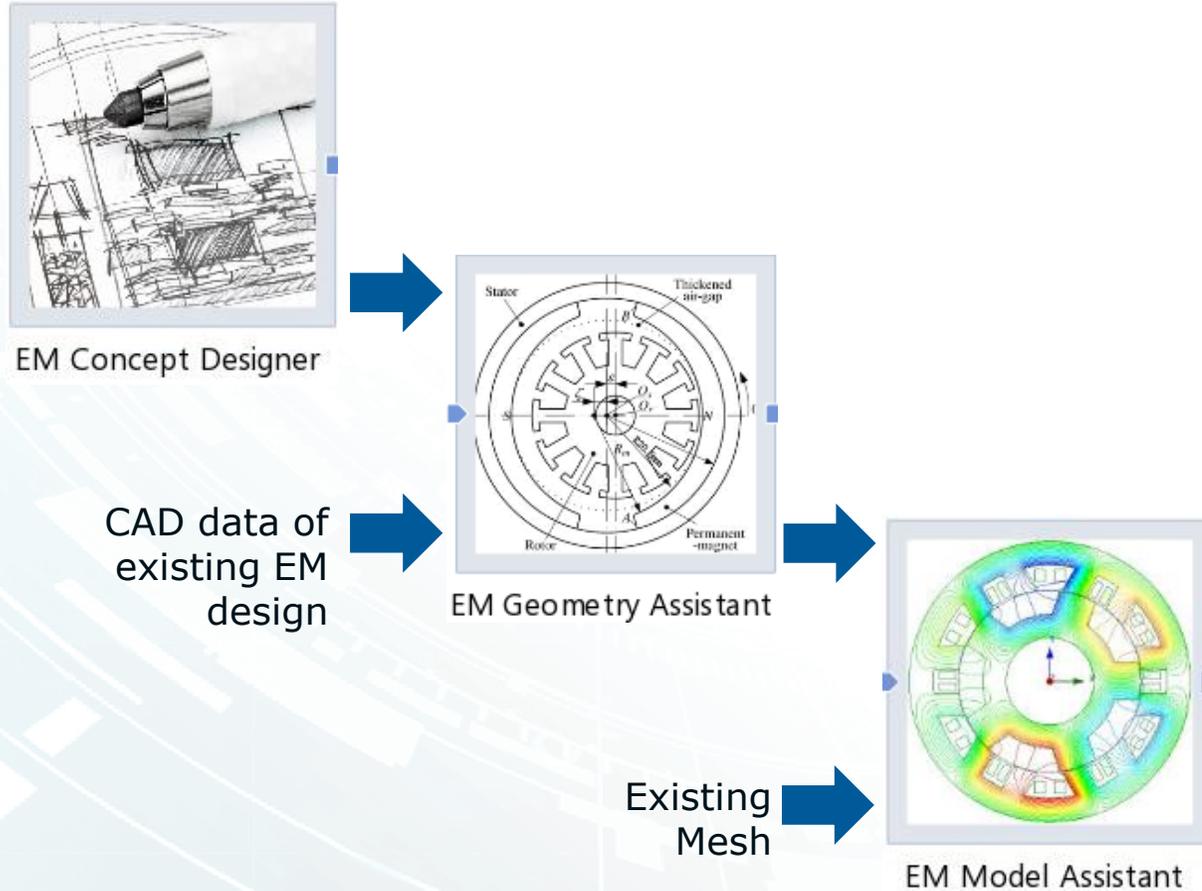


BH Curves



E

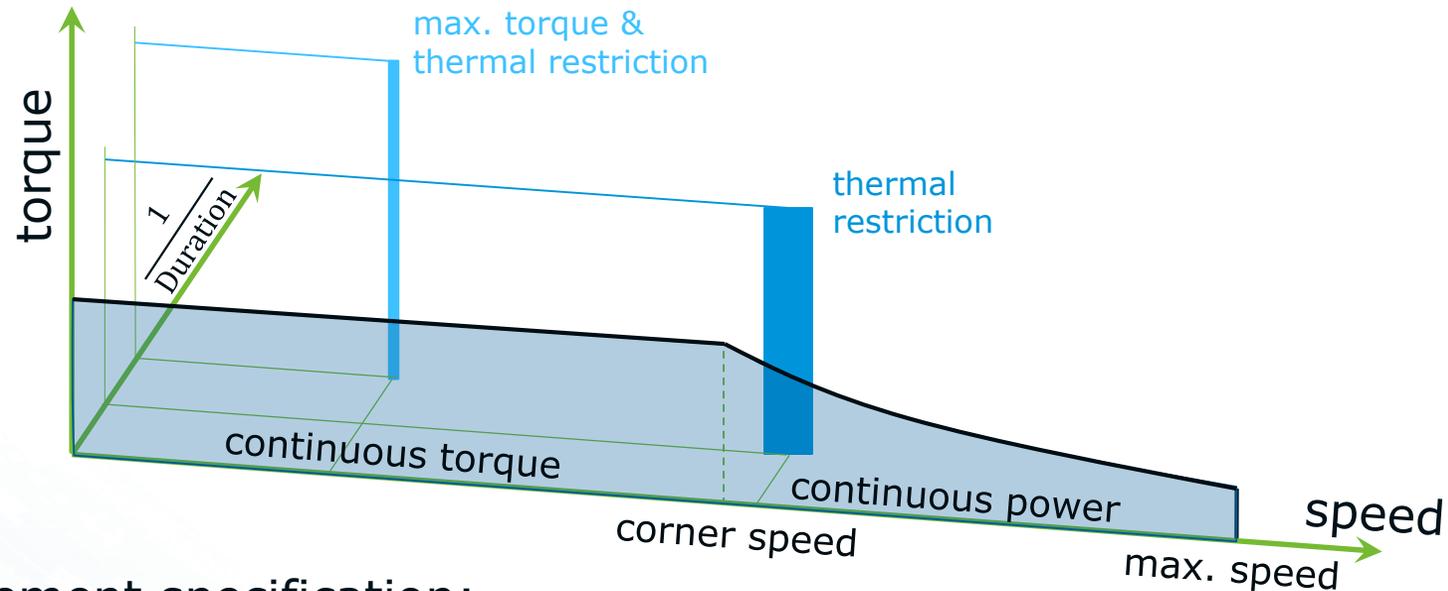
E-Motor Tool (EMT), Purpose and Goals



AVL EMT provides **assistance for the E-motor**

- **Concept definition** in the early development stage based on target settings
- Electro-magnetic analysis for EM **performance and efficiency**
- EM current **control strategy** definition
- **Power loss density** evaluation for thermal analysis
- **Load determination** for rotor dynamic and NVH analysis

Input for EM tool



Requirement specification:

- Minimum **supply voltage** and
- **Continuous torque and power**, max. speed and optional
- One or more cycles defined by **overload** power at speed for duration and base load for recovery time

Example:

- 300V
- 100Nm continuous, 50kW continuous, 10.000rpm max. speed ■
- 100kW at 6.000rpm for 10s and 10kW for 130s ■
- 25kW at 2.000rpm for 2s and 1kW for 300s ■

AVL EMT, Concept Designer

COMPOSE 1 Workflow



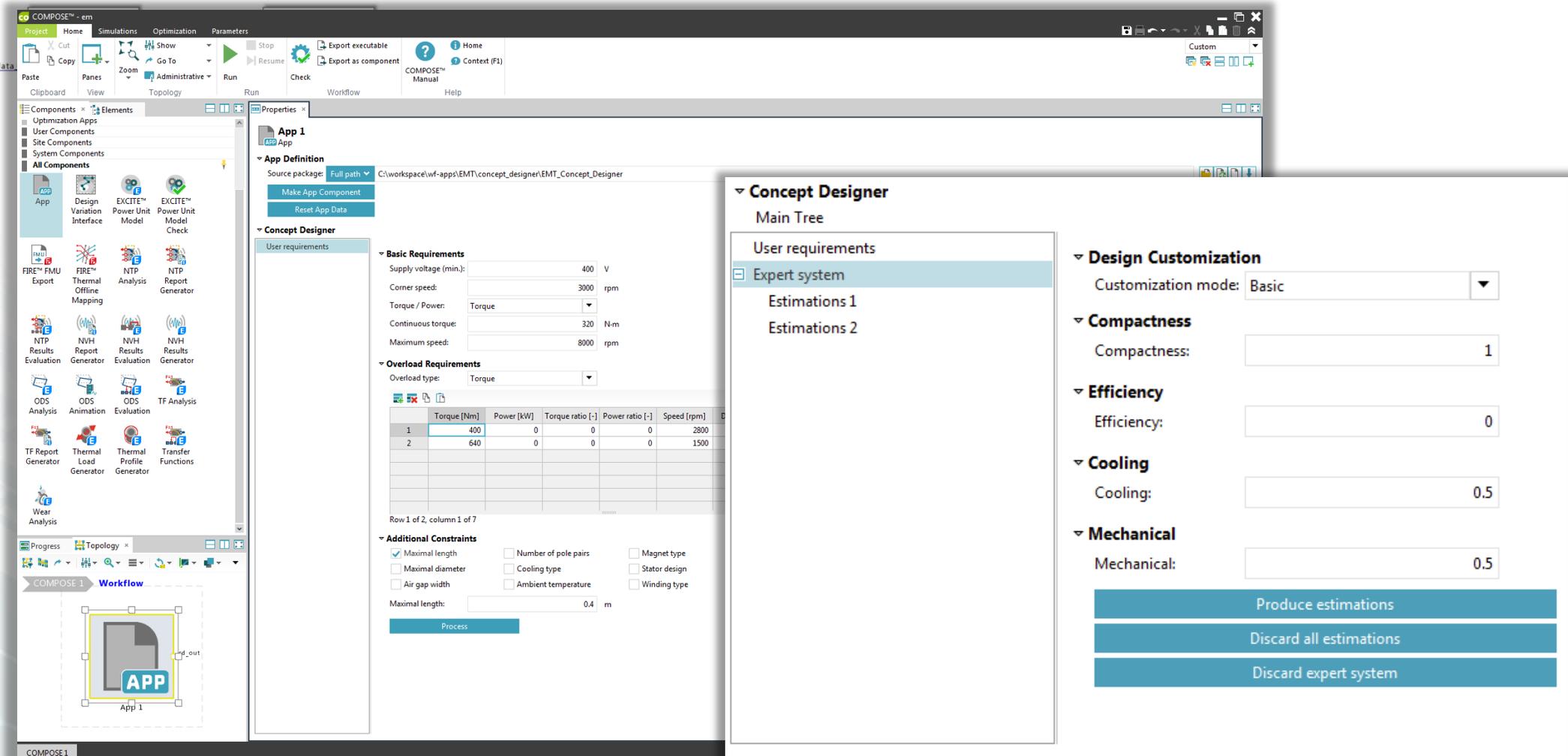
The screenshot displays the AVL EMT Concept Designer software interface. The main window is titled 'COMPOSE™ - em' and features a menu bar with options like Project, Home, Simulations, Optimization, and Parameters. A toolbar contains icons for Cut, Copy, Paste, Zoom, and Run. The left sidebar shows a 'Components' tree with categories like Optimization Apps, User Components, and System Components. Below this is a 'Library' of various analysis tools such as EXCITE™ Power Unit Model Check, FIRE™ FMU Export, and NVH Report Generator. The main workspace is divided into several sections:

- App Definition:** Shows the source package path and buttons for 'Make App Component' and 'Reset App Data'.
- Concept Designer:** Contains 'User requirements' and 'Basic Requirements' (Supply voltage: 400 V, Corner speed: 3000 rpm, Continuous torque: 320 N·m, Maximum speed: 8000 rpm).
- Overload Requirements:** Includes an 'Overload type' dropdown and a table of operating points.
- Additional Constraints:** A list of checkboxes for parameters like Maximal length, Maximal diameter, Air gap width, Number of pole pairs, Cooling type, Ambient temperature, Magnet type, Stator design, Winding type, Stator slot opening, and Rotor design.
- Power Plot:** A 3D plot showing torque [Nm] vs speed [rpm] with a curve and a shaded volume representing the operating region. The plot includes labels for 'cont.', '120s', and '10s'.

At the bottom of the interface, there is a 'Progress' bar and a 'Topology' view showing a 3D model of the motor components. The status bar at the bottom indicates 'COMPOSE 1' and '0.15 s 633.30 MiB'.

AVL EMT, Concept Designer

COMPOSE 1 Workflow

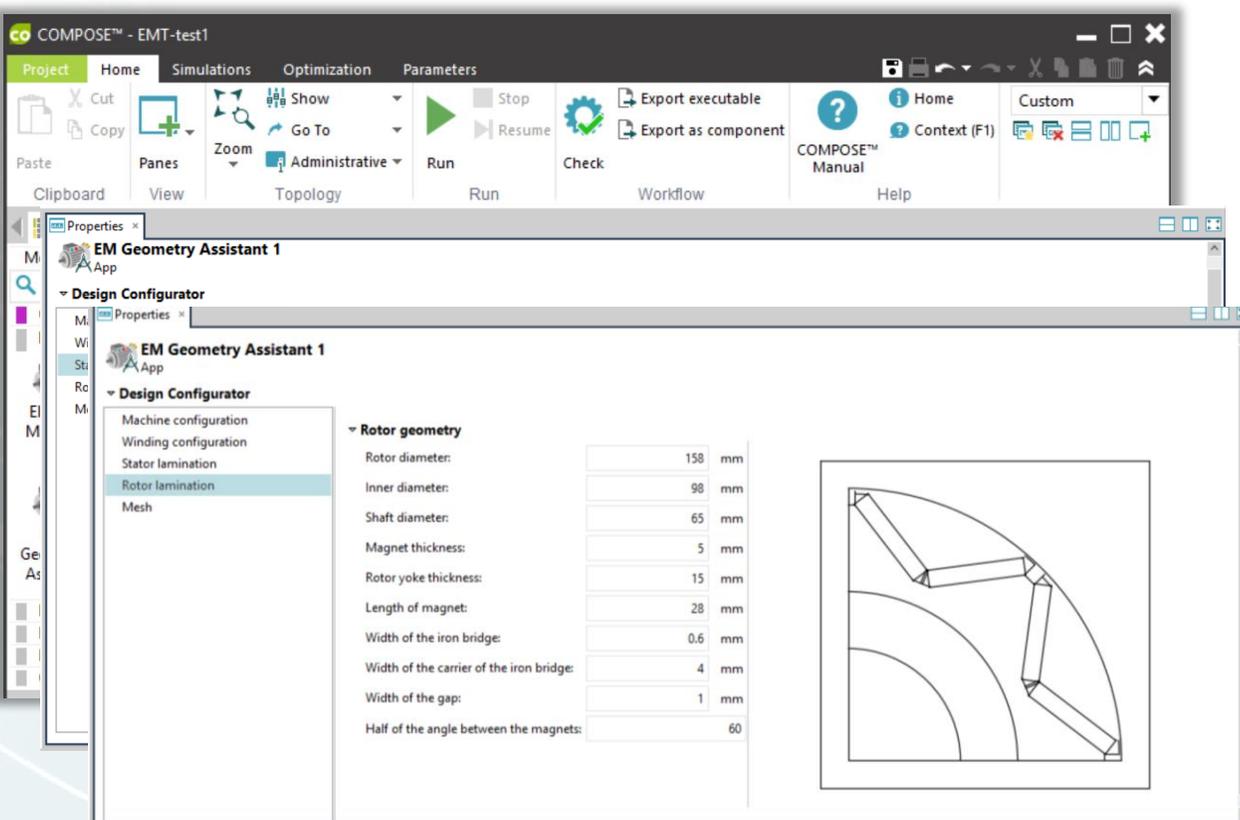
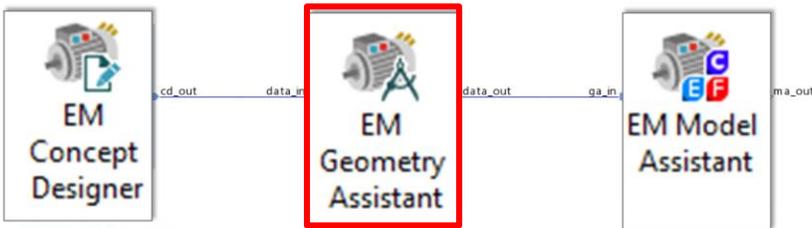
The screenshot displays the AVL EMT Concept Designer software interface. The main window is titled "COMPOSE™ - em" and shows a "Workflow" view. The interface is divided into several panels:

- Left Panel (Components):** A tree view showing "Optimization Apps" and "All Components". The "All Components" list includes various analysis tools like "Design Variation Interface", "EXCITE™ Power Unit Model", "NTP Report Generator", "NVH Results Evaluation", "ODS Analysis", "TF Report Generator", and "Wear Analysis".
- Properties Panel (App 1):** Shows the "App Definition" and "Concept Designer" settings. The "App Definition" section includes "Source package" and "Full path". The "Concept Designer" section includes "User requirements" and "Basic Requirements" (Supply voltage, Corner speed, Torque / Power, Continuous torque, Maximum speed) and "Overload Requirements" (Overload type). A table shows torque and power data for two rows.
- Table (Overload Requirements):**

	Torque [Nm]	Power [kW]	Torque ratio [-]	Power ratio [-]	Speed [rpm]
1	400	0	0	0	2800
2	640	0	0	0	1500
- Additional Constraints:** A list of checkboxes for constraints such as "Maximal length", "Maximal diameter", "Air gap width", "Number of pole pairs", "Cooling type", "Ambient temperature", "Magnet type", "Stator design", and "Winding type".
- Design Customization Panel (Right):** A panel titled "Concept Designer Main Tree" showing a tree view with "User requirements", "Expert system", "Estimations 1", and "Estimations 2". Below this are several settings:
 - Design Customization:** Customization mode: Basic
 - Compactness:** Compactness: 1
 - Efficiency:** Efficiency: 0
 - Cooling:** Cooling: 0.5
 - Mechanical:** Mechanical: 0.5
- Action Buttons:** Three buttons at the bottom right: "Produce estimations", "Discard all estimations", and "Discard expert system".

AVL EMT, Geometry Assistant

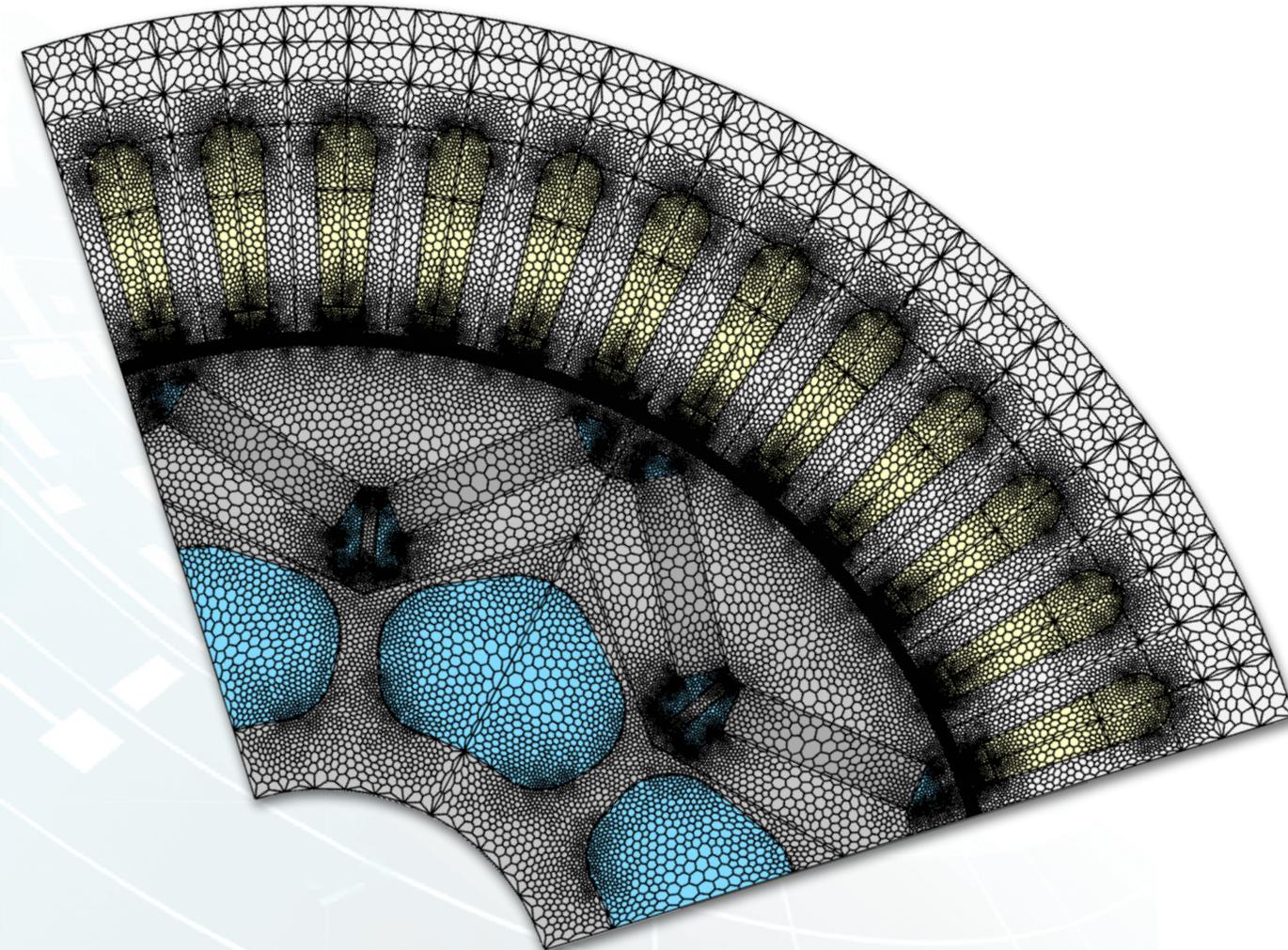
COMPOSE 1 Workflow



Key features:

- Concept Designer **automatically provide input** data for the **E-motor configuration** and parametrization
- Parameters **can be adjusted** according to specific preferences
- E-motor **configuration** and parameters **can be defined manually**
- Definition or **adjustment** of stator and rotor parameters
- **Dynamic sketched** show geometry based in input data

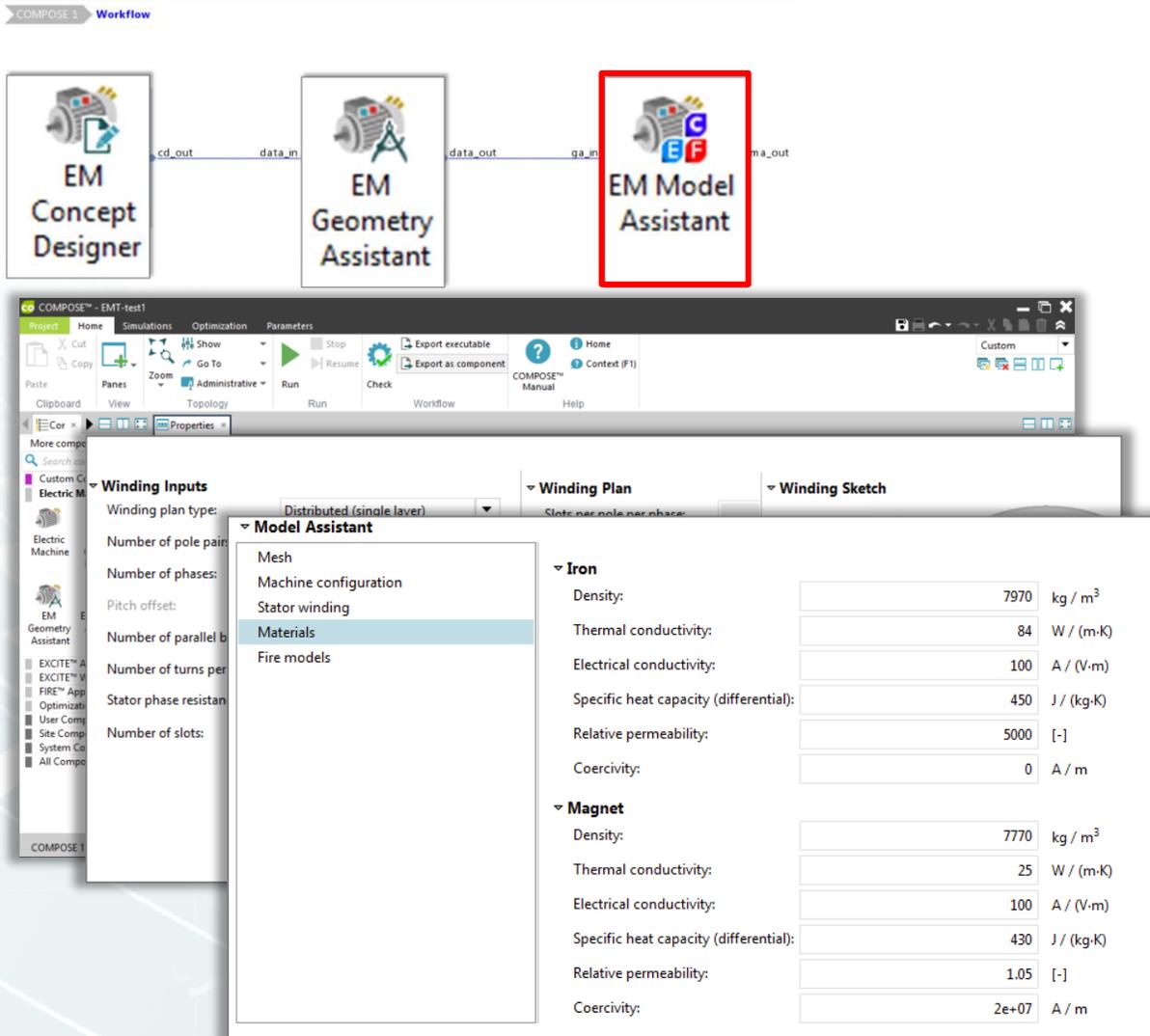
AVL EMT, Mesh preparation



Key features:

- **Automatic** generated high quality mesh (no user interaction required)
- **Polyhedral elements** with block topology in air gap
- AVL EMT dynamically generates topologies (**no CAD required**)
- **CAD import** to analyze complex geometries
- Sliding rotor for full flexibility in angular step control (**arbitrary rotor position possible**)
- Support of rotor and magnet eccentricity (**only one topology required**)

AVL EMT, Model Assistant



Key features:

- Model Assistant **allows** the **import of an existing mesh**
- Setup** of EM winding plan, material properties and operating range (mech & electr.)
- Create** FIRE M model **and launch simulations** for electro-magnetics

Model assistant

Map-based model

- Used for later system analysis (CRUISE M)
- Evaluation of power losses and efficiency

Fundamental wave model (linear and saturated)

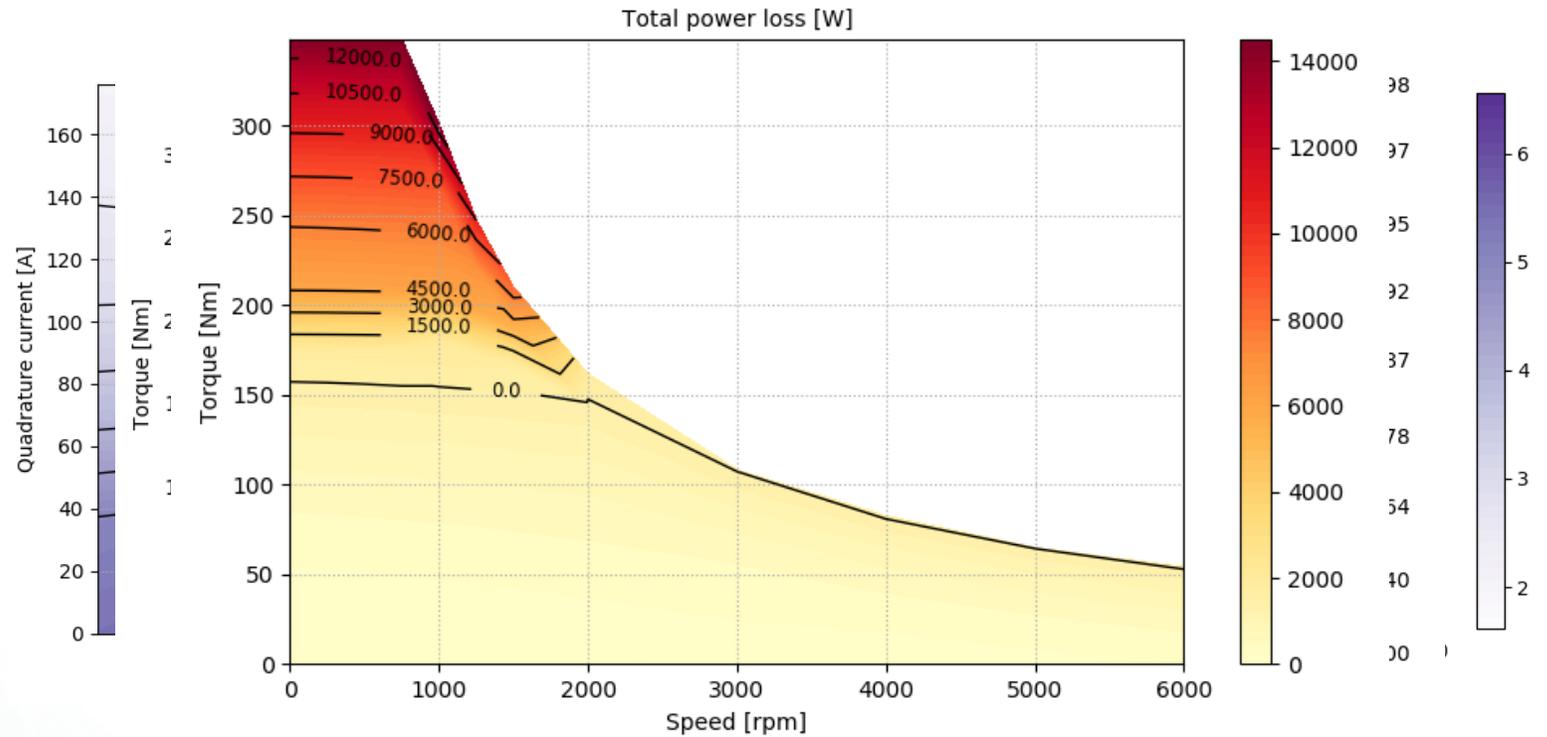
- Sinusoidal distribution of magnetic field in the air gap
- Calculation of inductances
- Main flux linkage
- Torque vs Speed characteristics

MFC-model

- Used for NVH (Excite)
- Includes harmonics due to slotting
- Torque ripple and forces for NVH

Results

- Inductances (direct and quadrature)
- Main flux linkage
- Torque vs speed characteristic
- Efficiency
- Power loss



Loss map

Data from electromagnetic simulation

Heat_Winding_Front

Heat loss

Cond_Stat

Heat_Stator

PowerLoss_Stator_f(speed, torque)

Speed ↑ Torque ↑

e-motor

Edit Properties - PowerLoss_Stator_f(speed, torque)

Settings

- Frequency of evaluation: Low
- Map mode: Regular map
- Output:

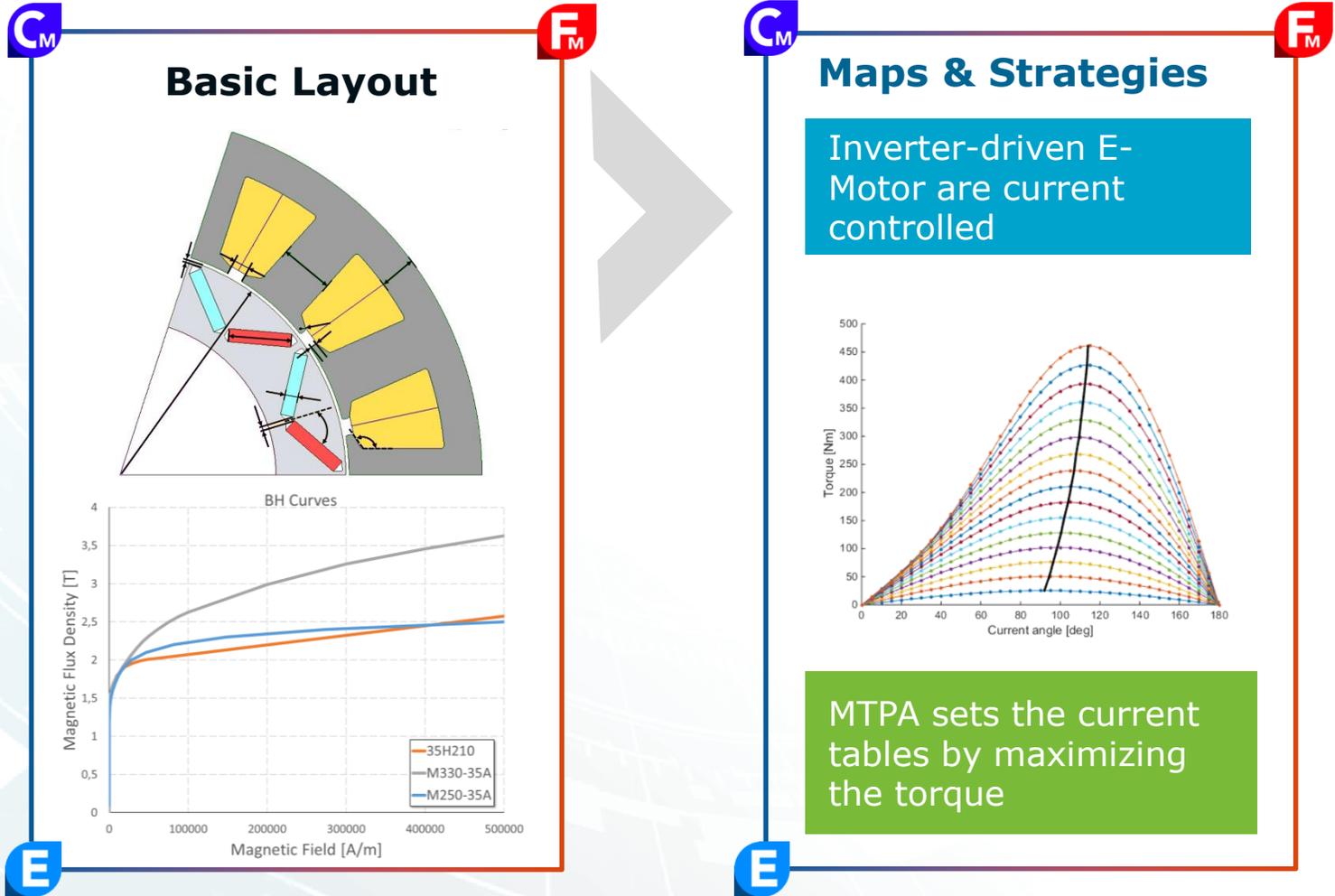
Extended Parameter Settings

Regular Map

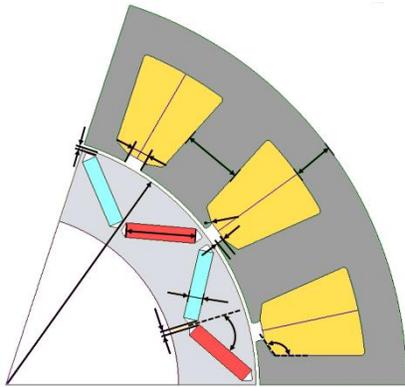
Power Loss (W)		Torque (N.m)					
		0	316	632	948	1260	1580
Speed (rpm)		1	2	3	4	5	6
0	1	0	0	0	0	0	0
1000	2	127	274	314	324	333	341
2000	3	394	849	972	1000	1030	1060
3000	4	762	1640	1880	1940	1990	2040
4000	5	1220	2620	3010	3100	3190	3260
5000	6	1750	3770	4330	4460	4580	4690
6000	7	2360	5080	5820	6000	6170	6320
7000	8	3030	6530	7480	7720	7930	8120
8000	9	3770	8120	9300	9590	9850	10100

Close

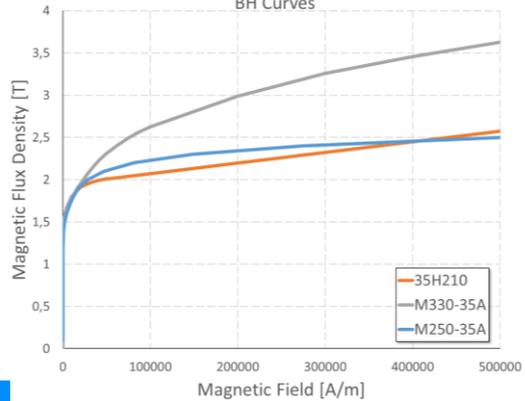
Performance Workflow



Basic Layout

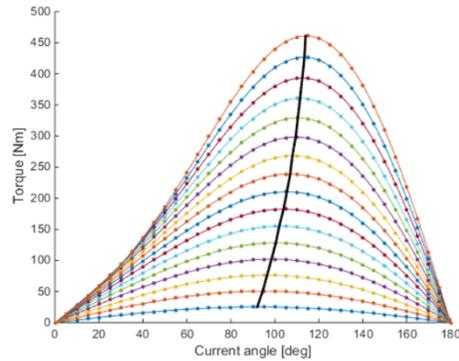


BH Curves



Maps & Strategies

Inverter-driven E-Motor are current controlled

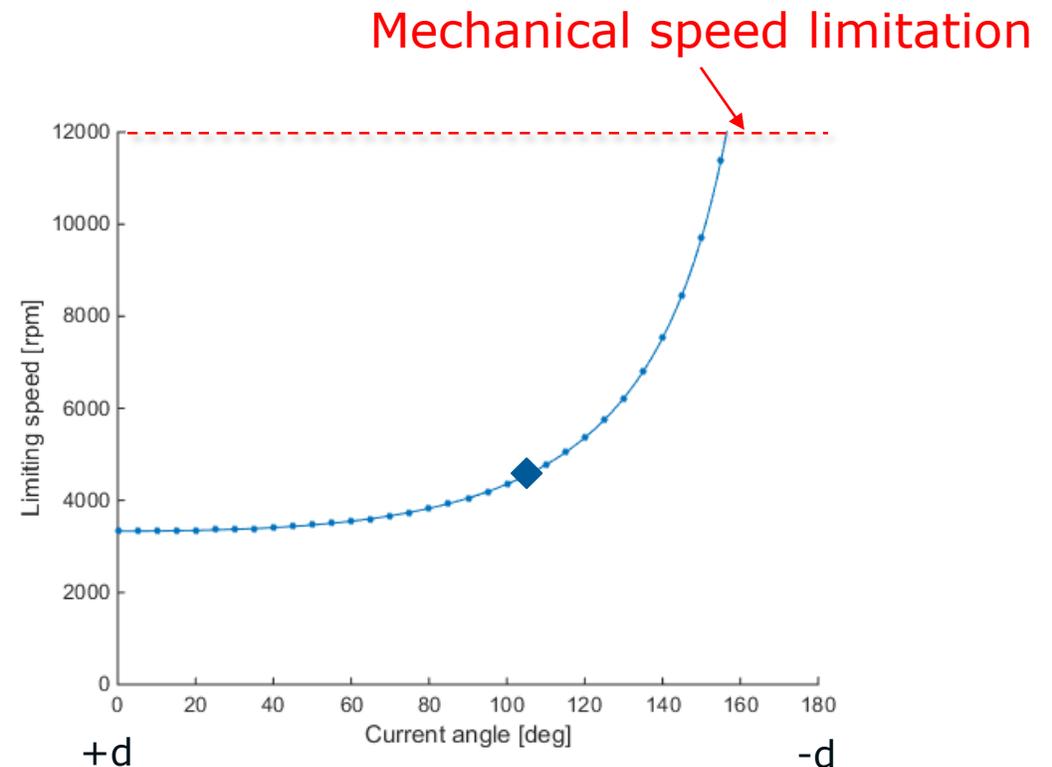
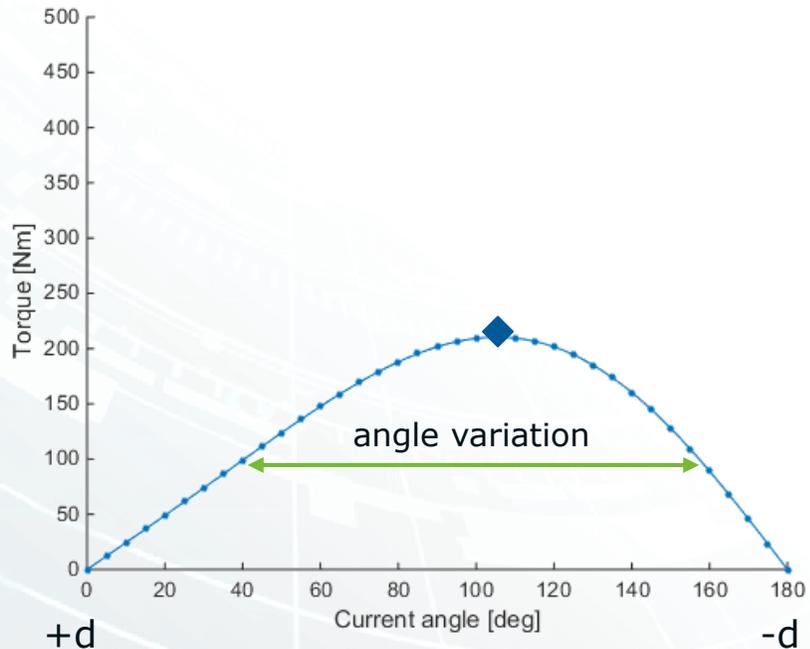


MTPA sets the current tables by maximizing the torque

MTPA – Maximum Torque Per Amperage

Principle of method

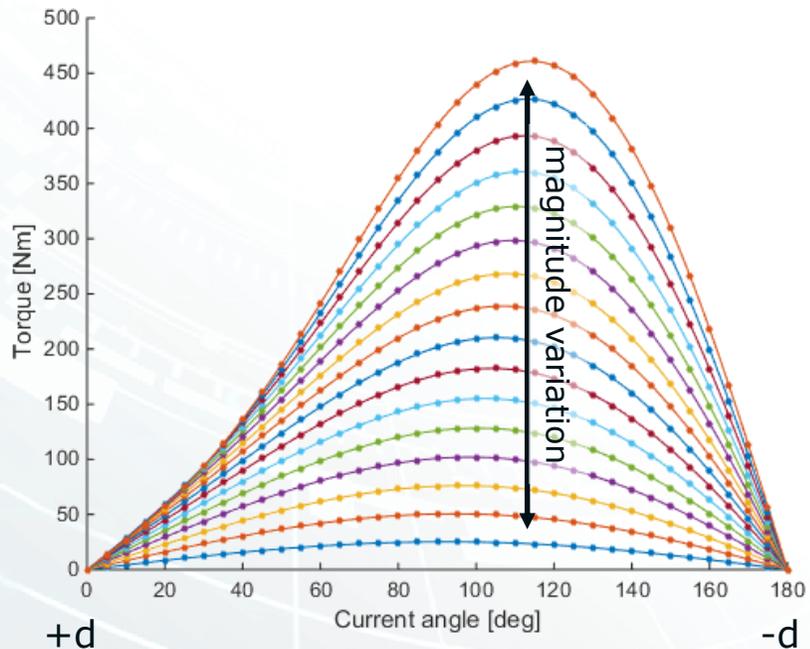
- Evaluation of torque and limiting speed (induced voltage < supply voltage)
- Sweep over current angles



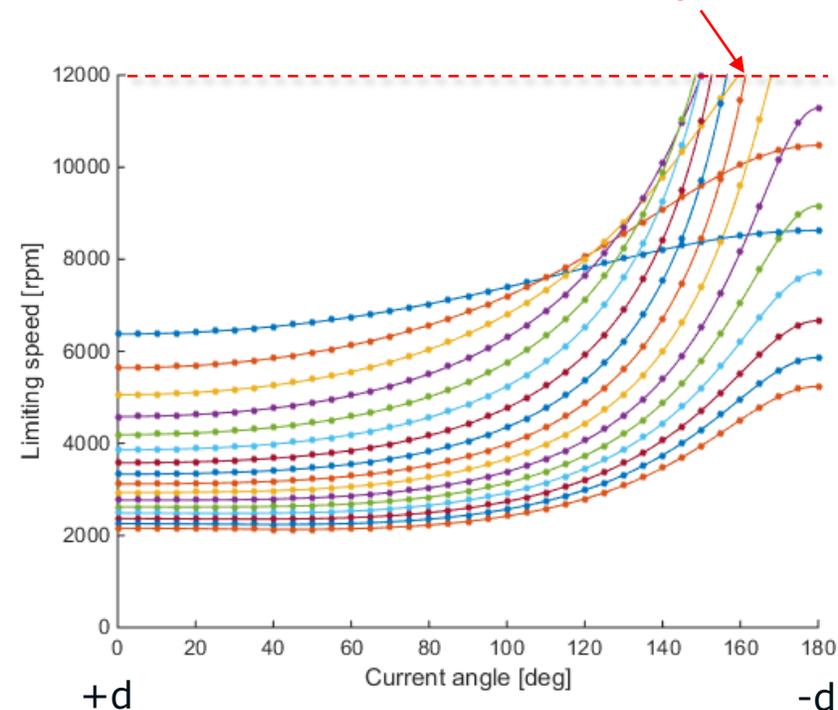
MTPA – Maximum Torque Per Amperage

Principle of method

- Evaluation of torque and limiting speed (induced voltage < supply voltage)
- Sweep over current angles and magnitudes



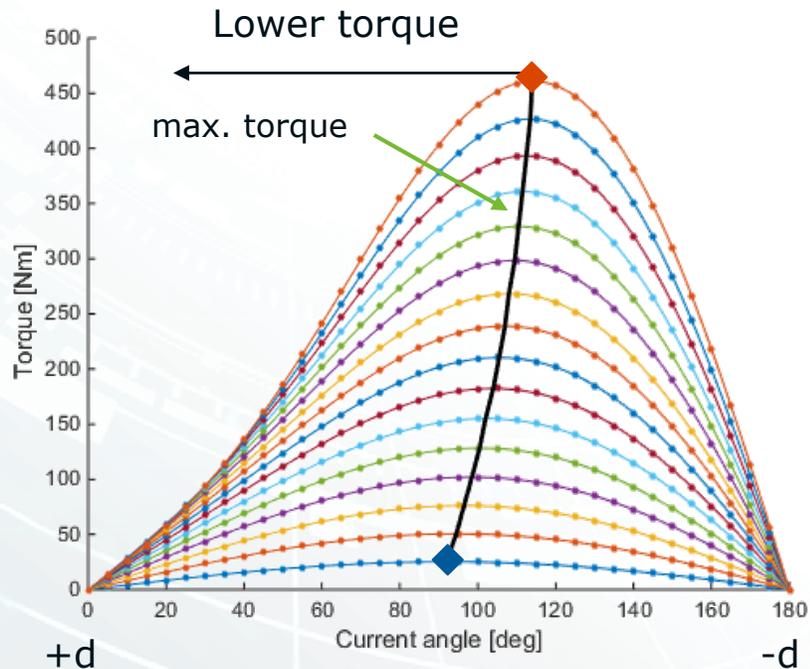
Mechanical speed limitation



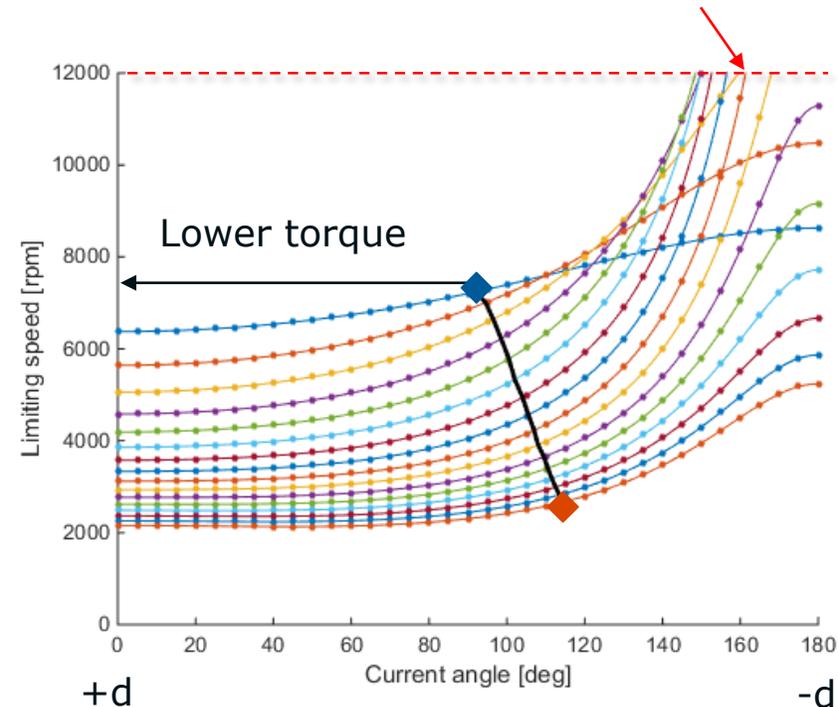
MTPA – Maximum Torque Per Amperage

Principle of method

- Evaluation of torque and limiting speed (induced voltage < supply voltage)
- Sweep over current angles and magnitudes
- Evaluation of maximum torque



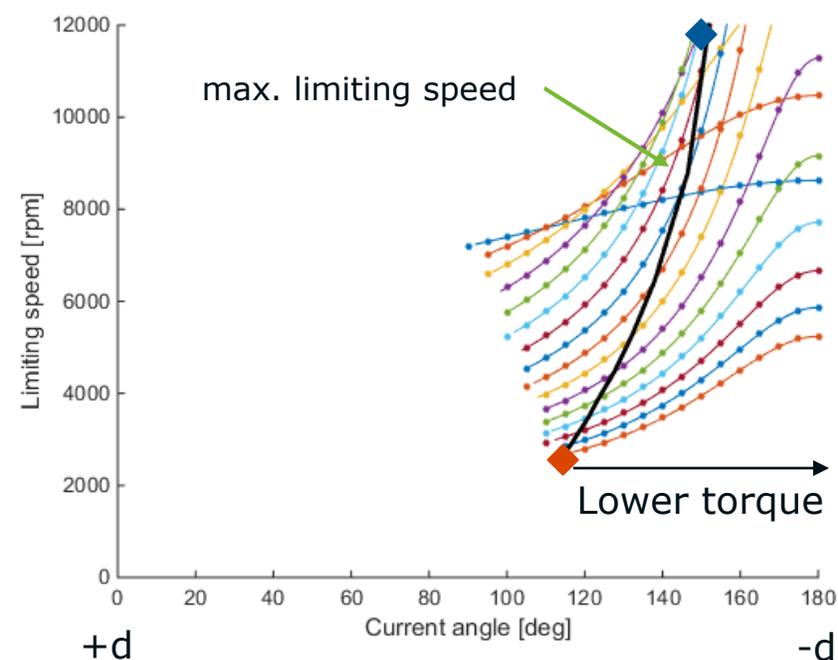
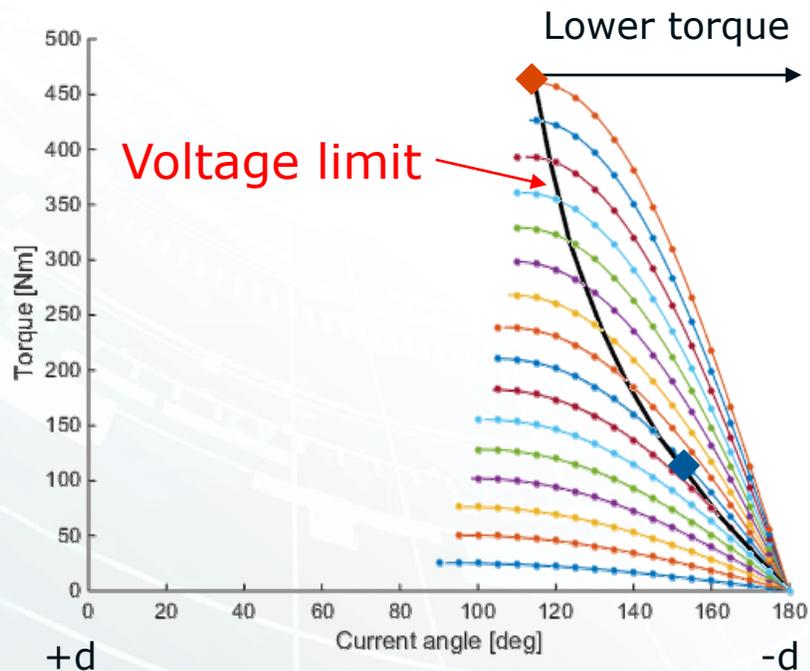
Mechanical speed limitation



MTPA – Maximum Torque Per Amperage

Principle of method

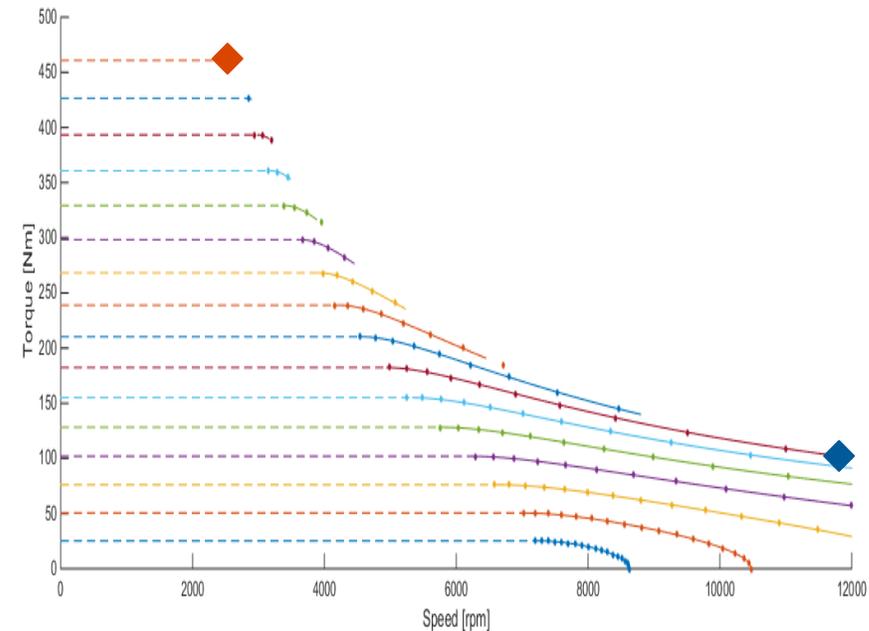
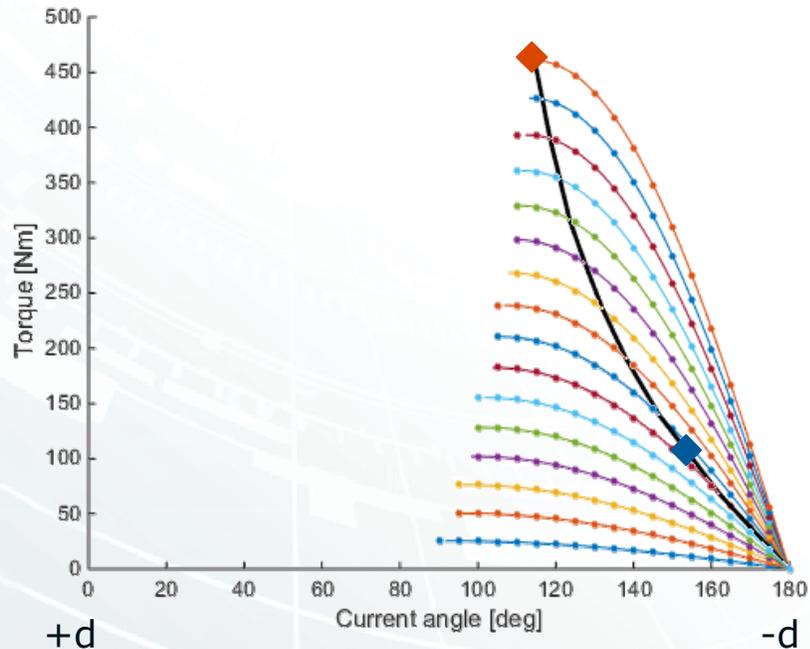
- Evaluation of torque and limiting speed (induced voltage < supply voltage)
- Sweep over current angles and magnitudes
- Evaluation of maximum torque and limiting speed



MTPA – Maximum Torque Per Amperage

Principle of method

- Evaluation of torque and limiting speed (induced voltage < supply voltage)
- Sweep over current angles and magnitudes
- Evaluation of maximum torque and limiting speed
- Combination of torque and speed vs. current magnitude and angle



Performance Workflow

C_M **Basic Layout** **F_M**

BH Curves

— 35H210
— M330-35A
— M250-35A

E

C_M **Maps & Strategies** **F_M**

Inverter-driven E-Motor are current controlled

Torque [Nm]

Current angle [deg]

MTPA sets the current tables by maximizing the torque

E

C_M **Sensitivities** **F_M**

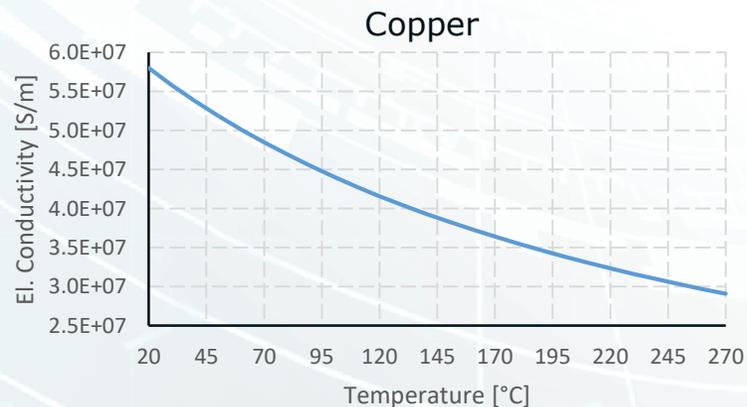
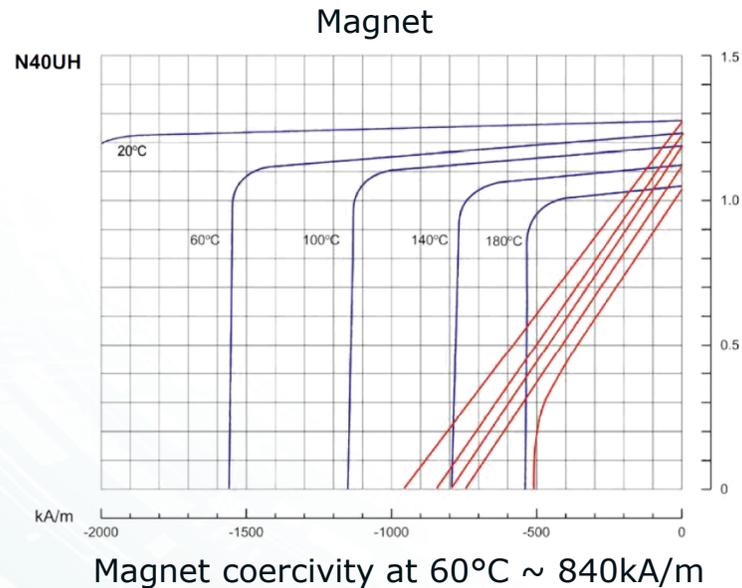
Rotor force [N]

angle [deg]

— F_x
— F_y

E

Performance dependency



Temperature

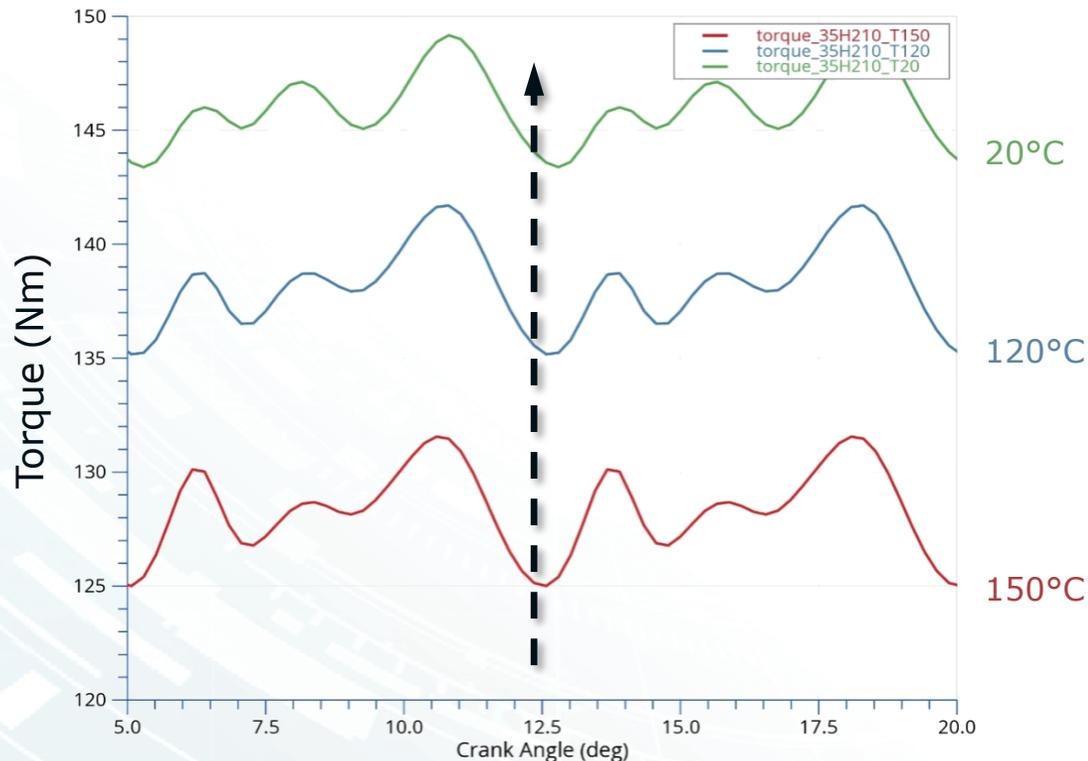
- A higher magnet temperature weakens the magnetic force which also reduces the resulting torque
- A higher copper temperature increases the copper resistivity and consequently increases the copper loss.

Influence on:

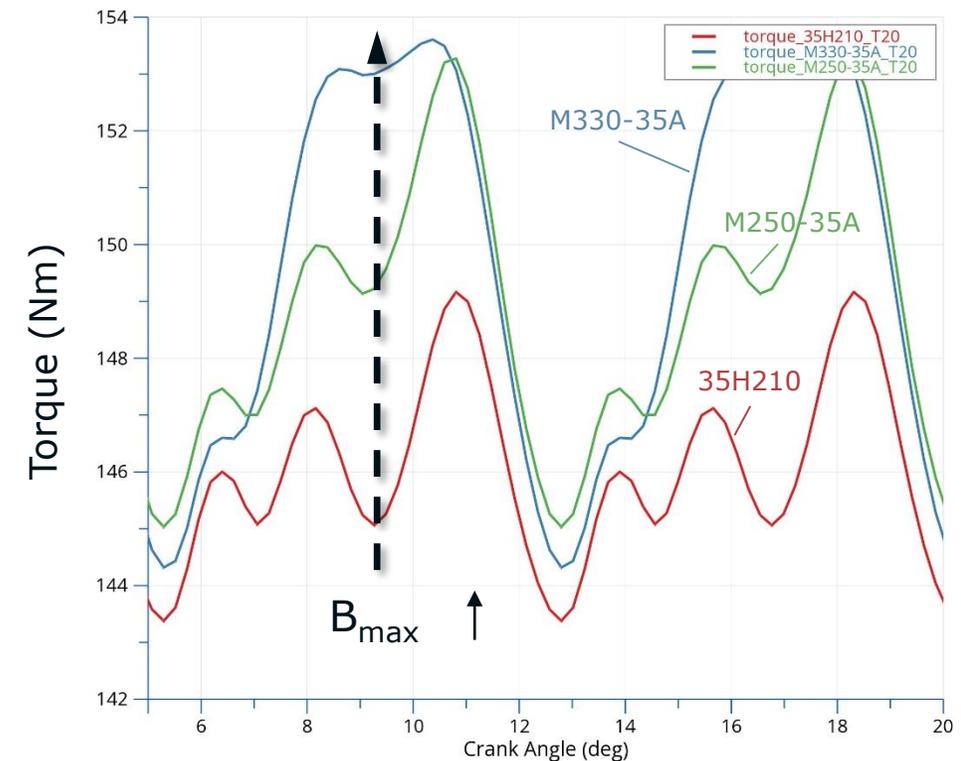
- Torque,
- Copper and Magnet losses

Torque depending on temperature

Temperature variation



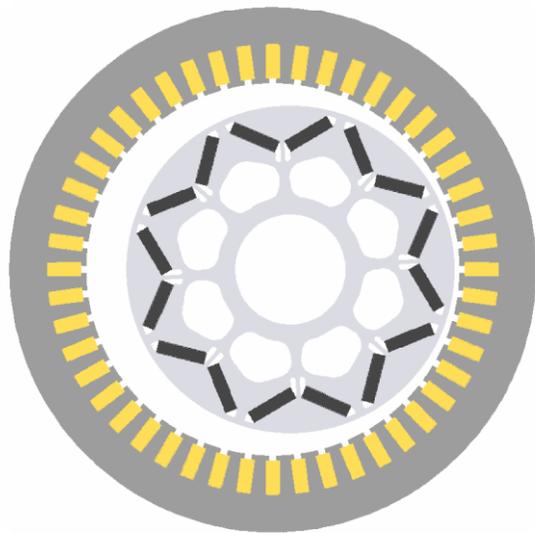
Material variation



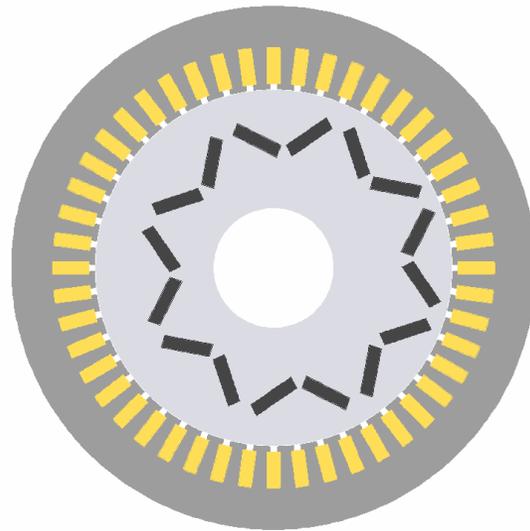
- The mean torque increases with decreasing temperature (stronger magnets).
- With a higher saturation flux density also the mean torque increases. Simultaneously the torque ripple increases.

Eccentricity investigations

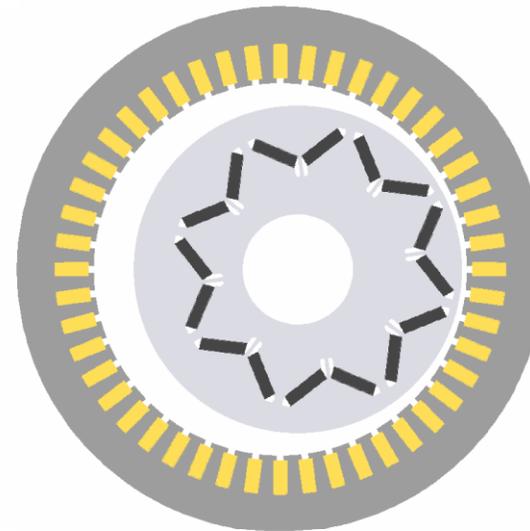
Rotor offset



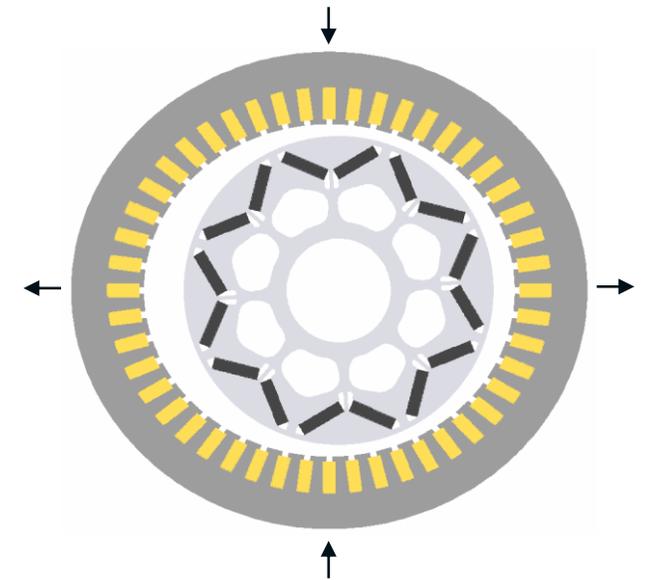
Magnet offset



Magnet + Rotor offset

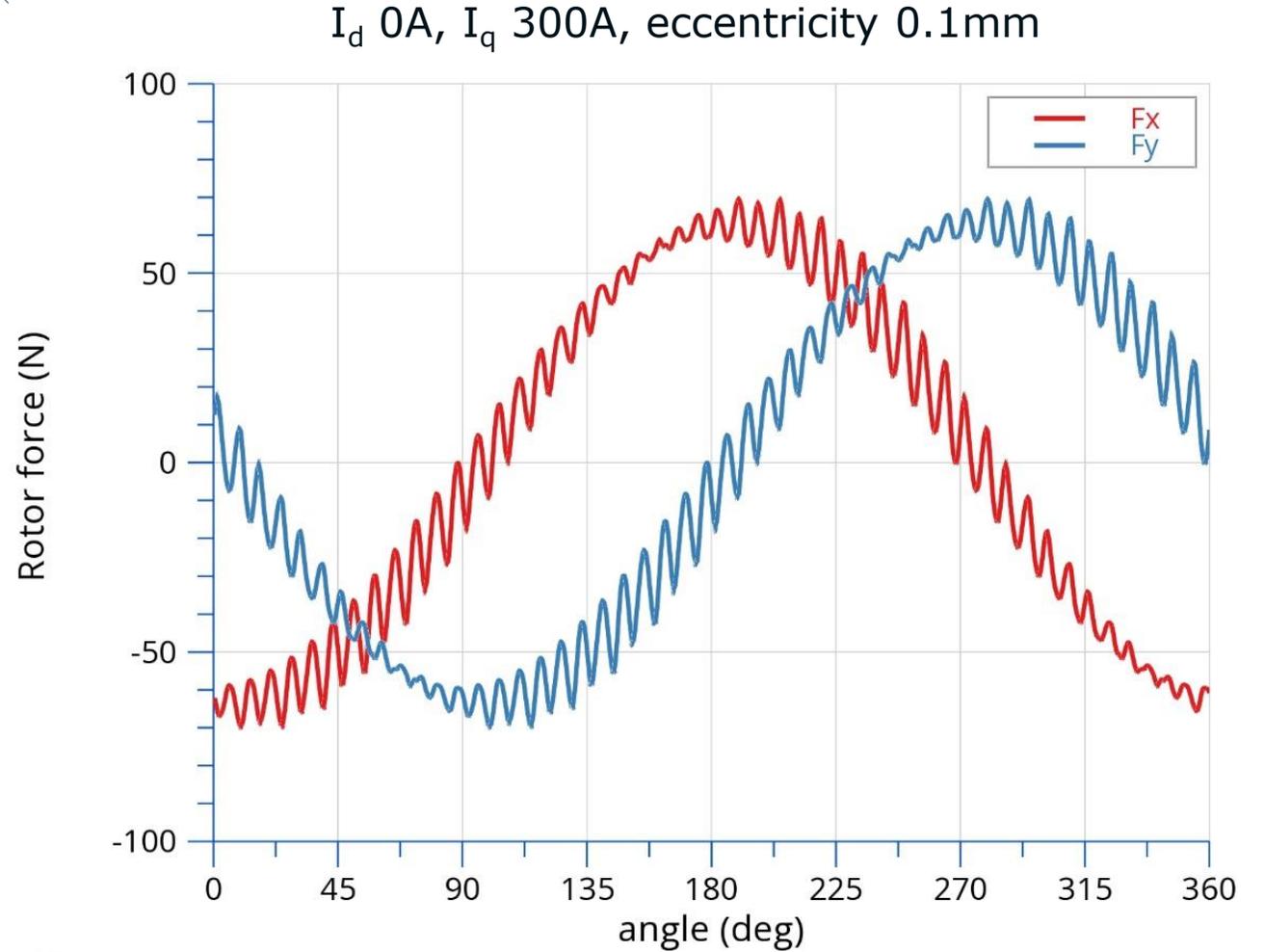
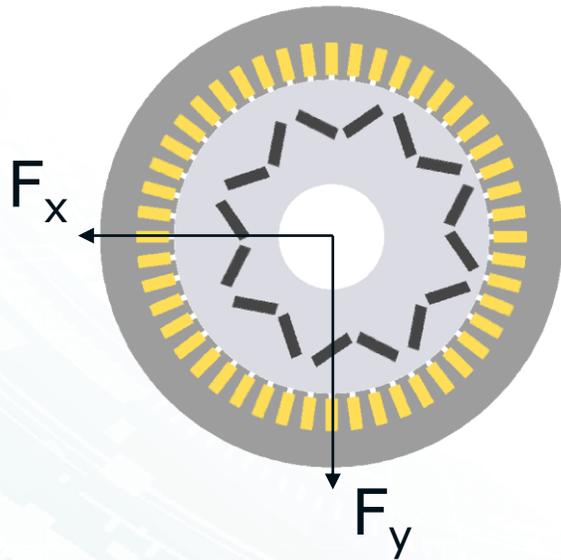


Stator deformation + Rotor offset



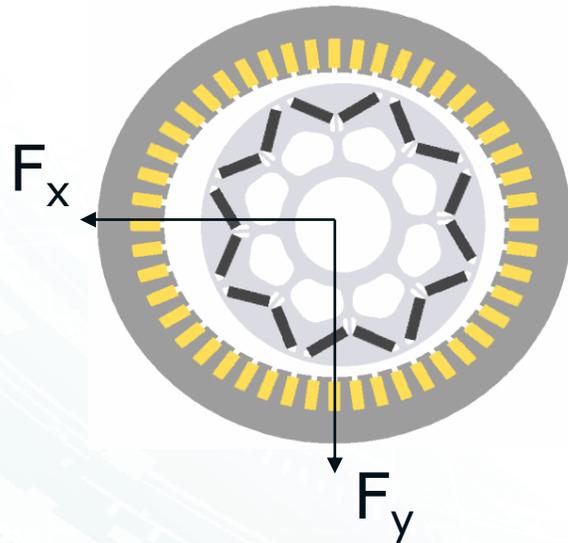
Altogether over **1100 configurations** (current variation + geometry matrix) are examined and compared. Only one basic geometry is required. The eccentricity and consequent deformation is automatically taken into account by deformation of the base geometry

Magnet Offset, Rotor Force

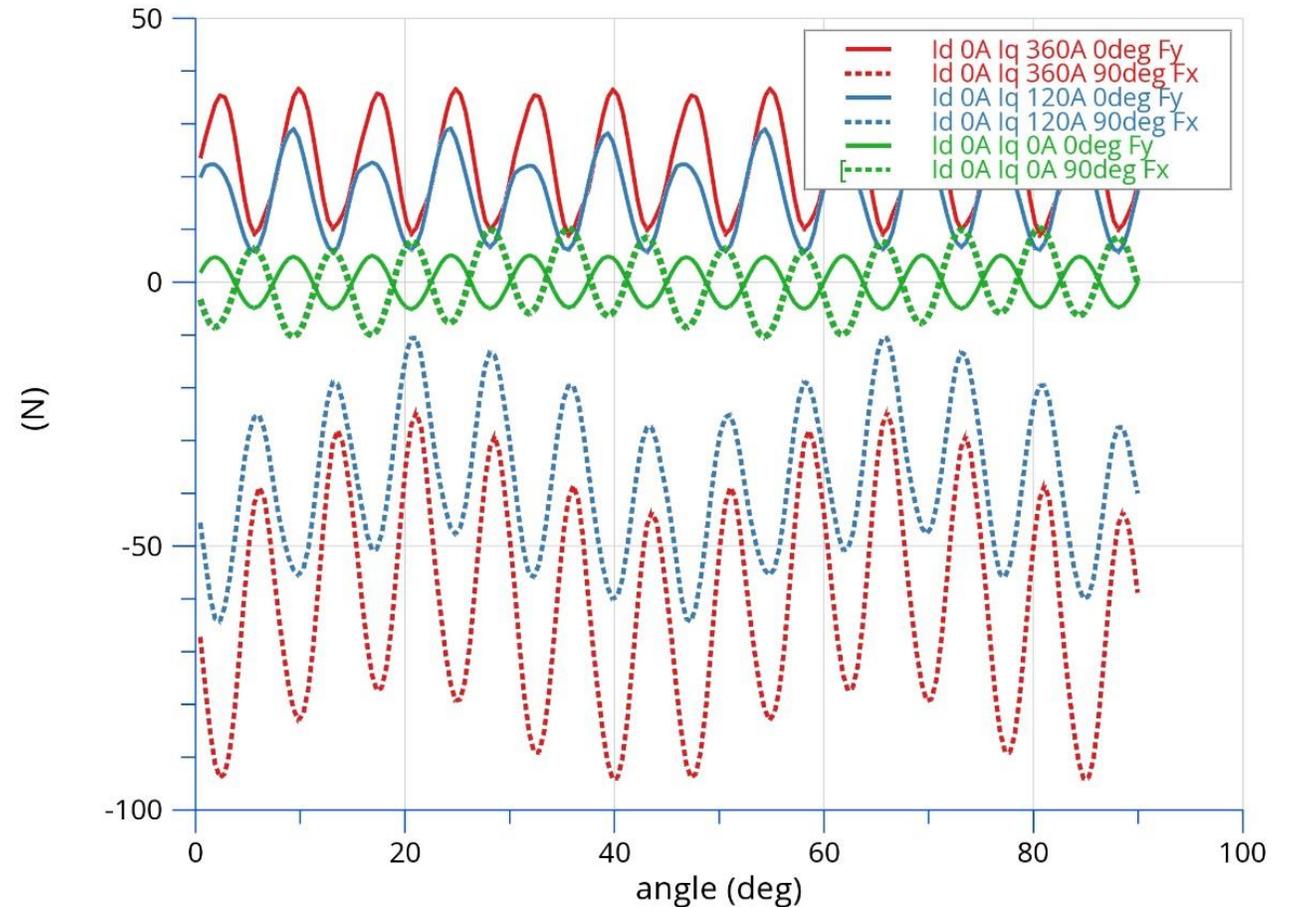


➤ The rotor force has a period of 360deg

Stator out of Roundness, Rotor Force



I_d 0A, I_q 300A, eccentricity 0.1mm



- Due to the prescribed current the mean X component is not zero at 90deg, and the Y component is not zero at 0deg offset.
- The force offset increases with the motor current/torque.

Summary

At a glance

- **E-motor** concept and layout **tool**. Can be used **with or without CAD input**
- **No** need to care about **grid generation**. AVL EMT does everything **automatically** in the background and **depending on** the required **simulation task** (system simulation, NVH, ect.)
- **MTBA** analysis and **loss maps** included in workflow
- **Easy data exchange** (e.g. forces, losses) and **automatic handover** to AVL FIRE™ M and AVL CRUISE™ M for further investigations
- **Easy handling of sensitivity investigations** (manufacturing tolerances) and consideration of **rotor misalignment**

Thank You



www.avl.com

