From Geometric Model to System Simulation: Physical Modeling and Control of Electric Motors with Simulink and Simscape

Feng He, Mathworks (fenghe@mathworks.com)

Simone Ferrari, Politecnico di Torino (simone.ferrari@polito.it)

Content

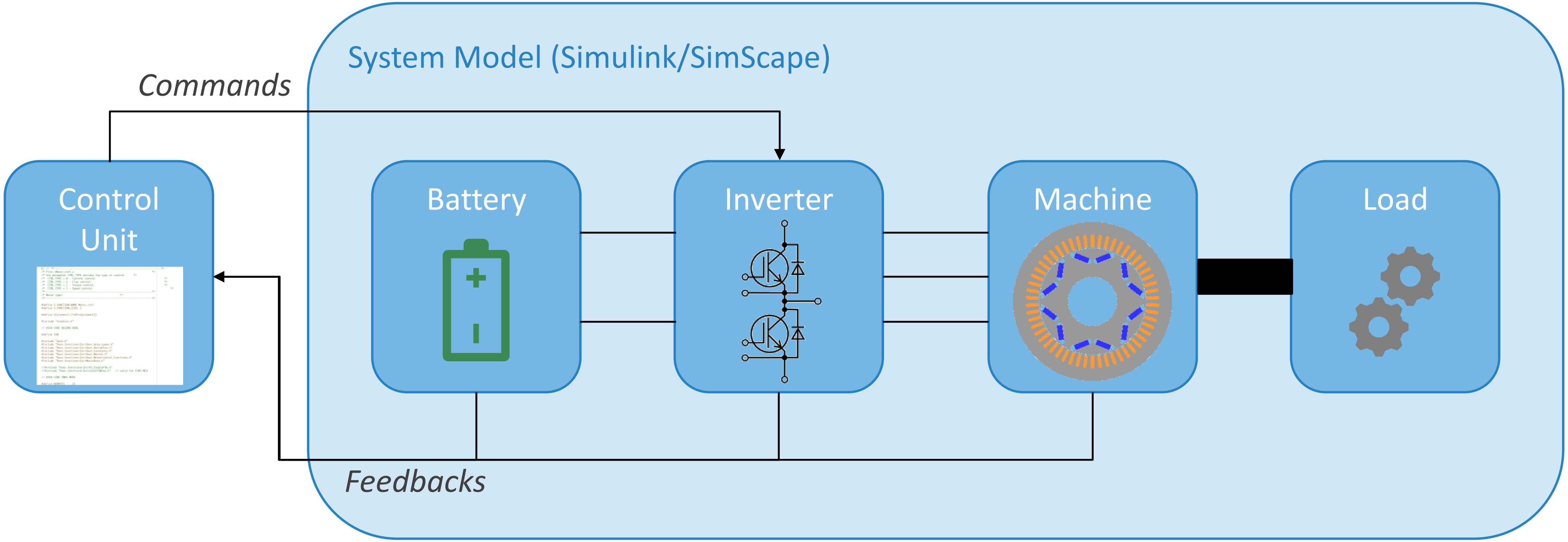
- Introduction
- Part 1: Electric Motor Modeling, Feng He (45 min)
- Part 2: SyR-e environment for eMotor Design and Analysis, Simone Ferrari (40 min)
- Part 3: Beyond the Electric Motor, Feng He (45 min)
- Conclusions
- Q&A (20 min)

About the speakers

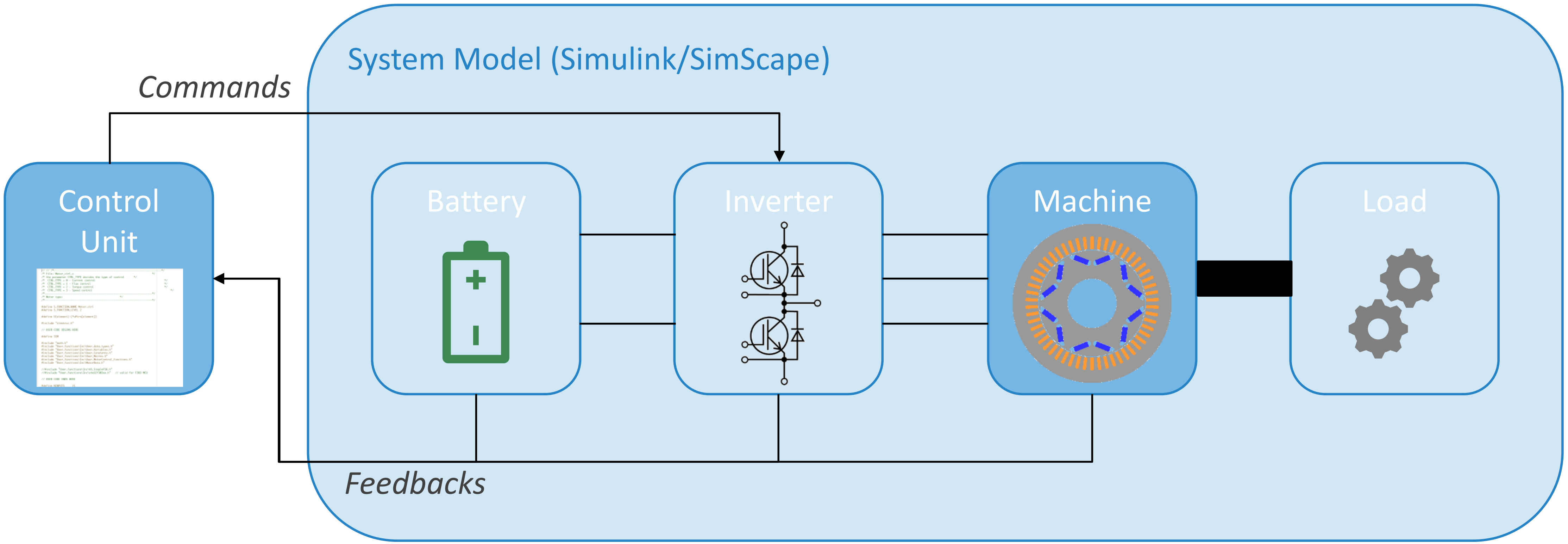
Feng He is an Application Engineer at MathWorks. He holds a M. Sc in Automation Engineering and Control of Complex Systems from Università degli Studi di Catania. Before joining MathWorks, he worked in the automotive industry: five years at General Motors as Application Software and Algorithm Development Engineer implementing the next generation thermal control for internal combustion engines; two years at Plastic Omnium (Austria) deploying a Model Based Design toolchain for the Fuel Cell control, simulation, and target HW integration.

Simone Ferrari (Member, IEEE) receive the Ph.D. degree “cum laude” in 2020 from Politecnico di Torino, where he is currently an Assistant Professor. From July to December 2018, he was a Visiting Scholar at North Carolina State University, Raleigh, NC, USA. He is one of the authors of SyR-e, an open-source design tool for synchronous reluctance and permanent magnet machines. From 2021 he is also one of the responsible of the eDrive testing infrastructure TEST-eDRIVE managed from Energy Department and the Power Electronics Innovation Center of Politecnico di Torino. His research interests include electrical machine design and testing, and multi-physical evaluation of electrical machines, with a focus on synchronous reluctance and permanent magnet machines.

Tutorial Map

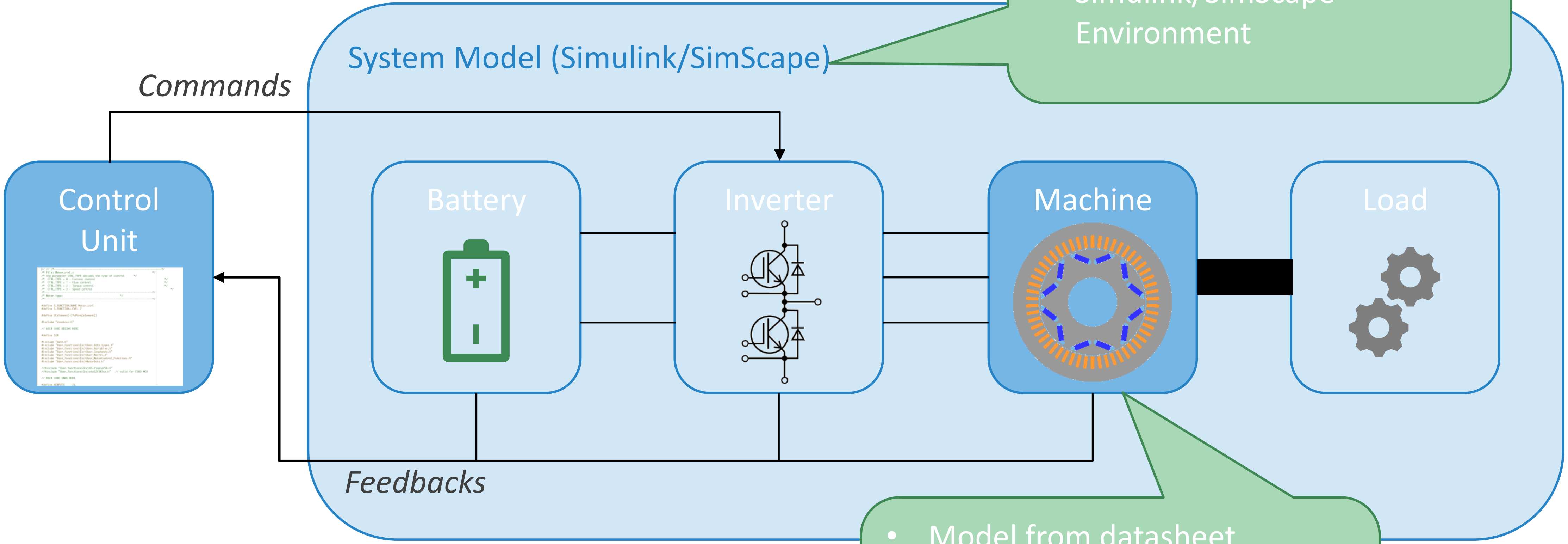


Tutorial Map



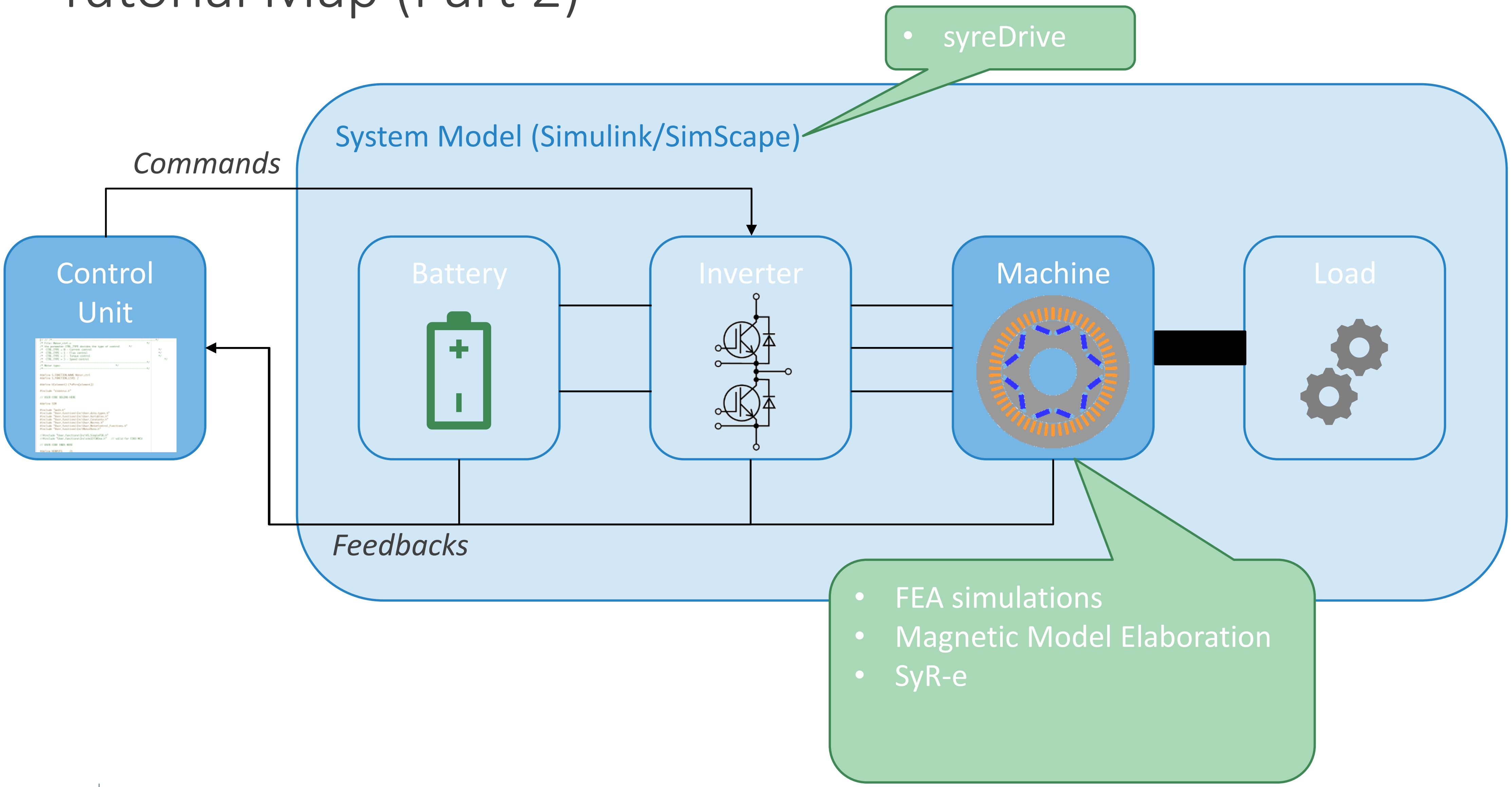
Tutorial Map (Part 1)

- Introduction to system modeling
- Simulink/SimScape Environment

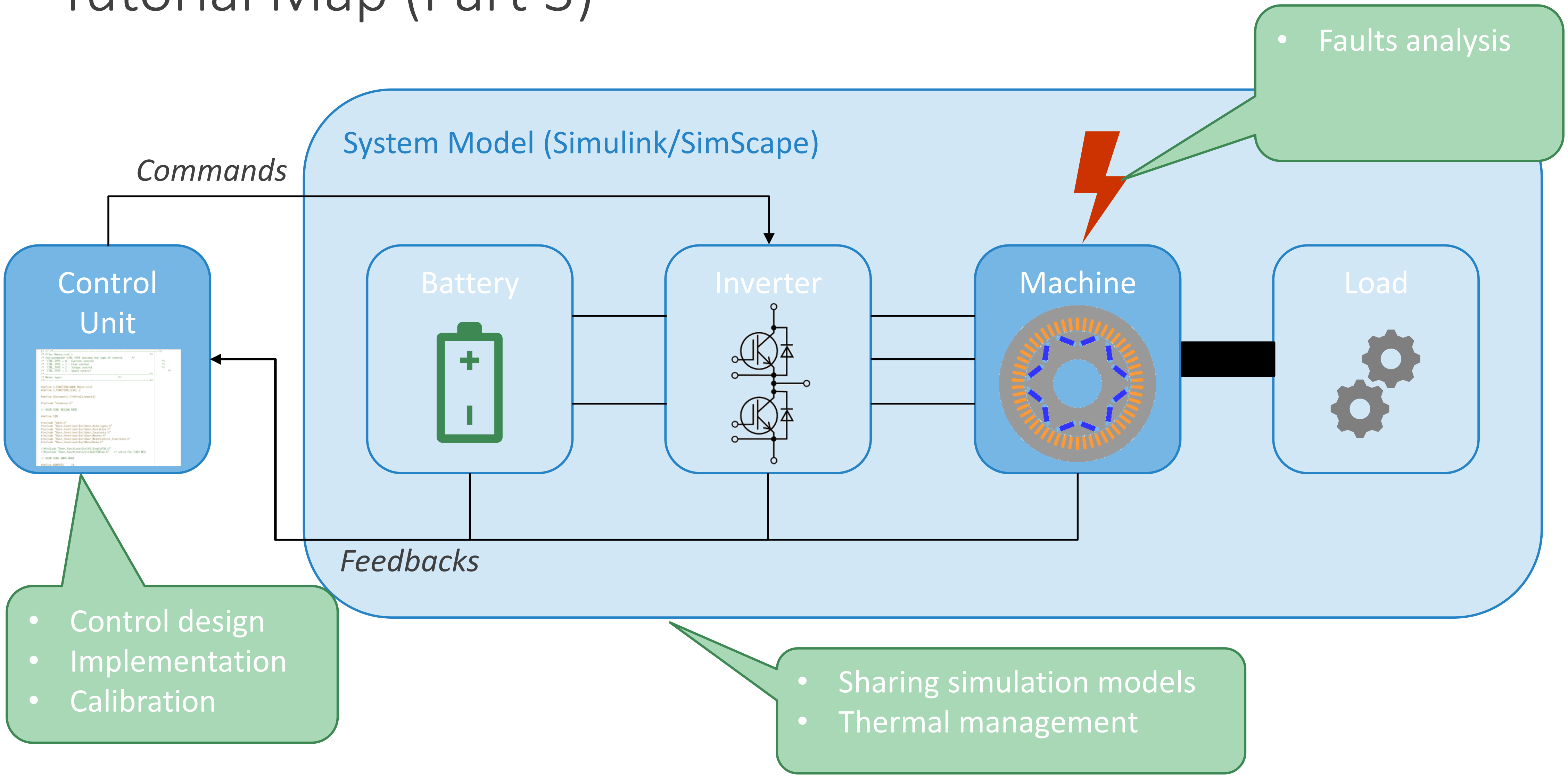


- Model from datasheet
- System identification
- Model from lab data
- Simple model (symbolic)
- Import from external software

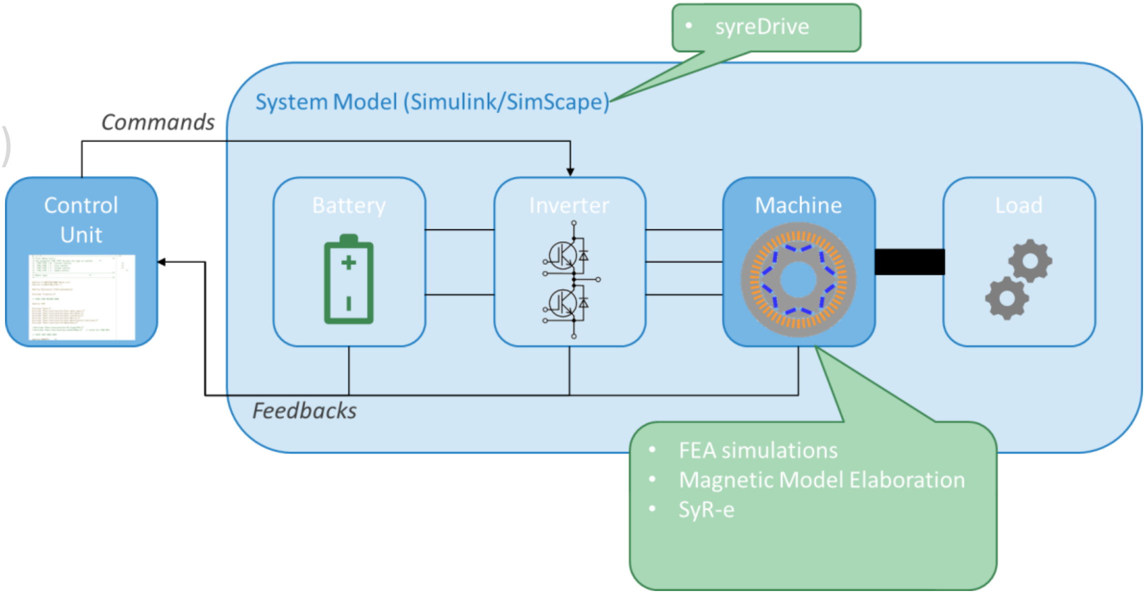
Tutorial Map (Part 2)



Tutorial Map (Part 3)



Content



syreDrive
System Model (Simulink/SimScape)
Commands
Control Unit
Battery
Inverter
Machine
Load
Feedbacks
FEA simulations
Magnetic Model Elaboration
SyR-e

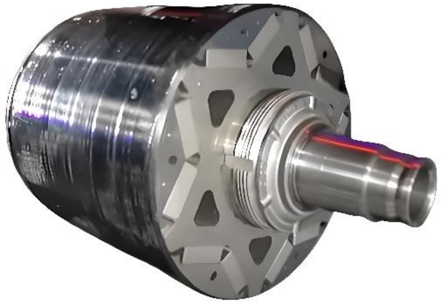
Why FEA and not just Circuital Model?

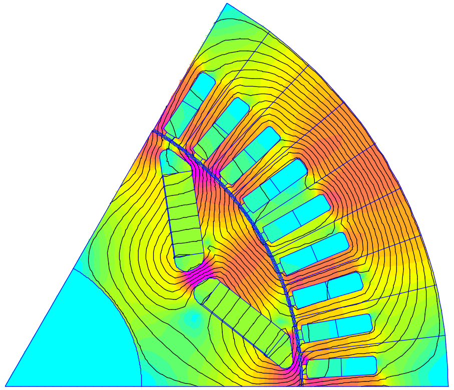
In the eMachine (magnetic) modeling, **FEA is mandatory** for accurate results:

- Complex geometry
- Non-linear behaviors (iron saturation)
- Local saturation + cross-saturation

When the **eDrive** (EM+PE+control) is simulated, the motor modeling is even more critical

B. Sarlioglu, C. T. Morris, D. Han and S. Li, "Benchmarking of electric and hybrid vehicle electric machines, power electronics, and batteries," 2015 Intl Aegean Conference on Electrical Machines & Power Electronics (ACEMP), 2015 Intl Conference on Optimization of Electrical & Electronic Equipment (OPTIM) & 2015 Intl Symposium on Advanced Electromechanical Motion Systems (ELECTROMOTION), Side, Turkey, 2015, pp. 519-526, doi: 10.1109/OPTIM.2015.7426993





eMachine Modeling

One of the most accurate methods to <u>include the motor in the eDrive model</u> is the **co-simulation**

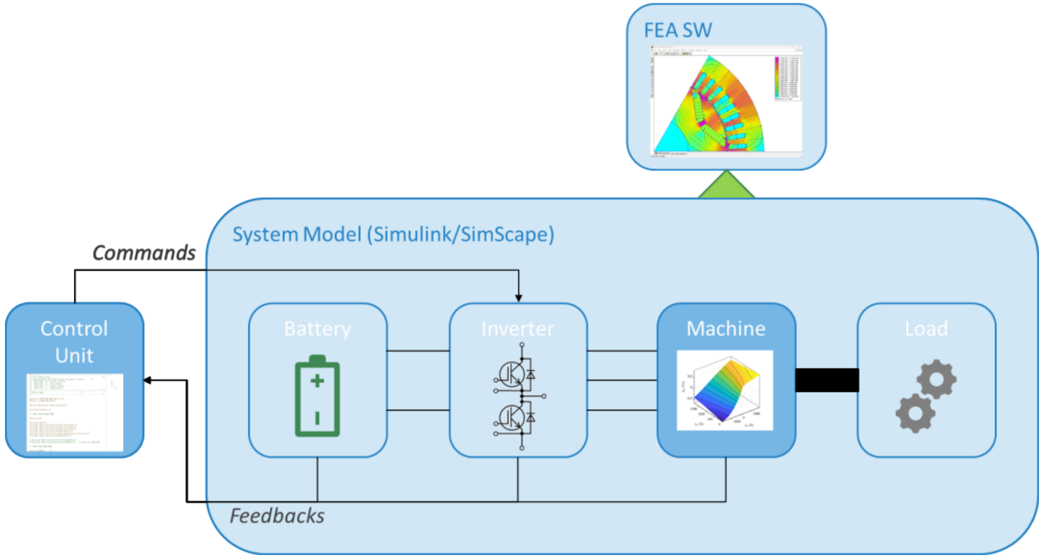
- FEA launched iteratively with eDrive model
- High computational burden

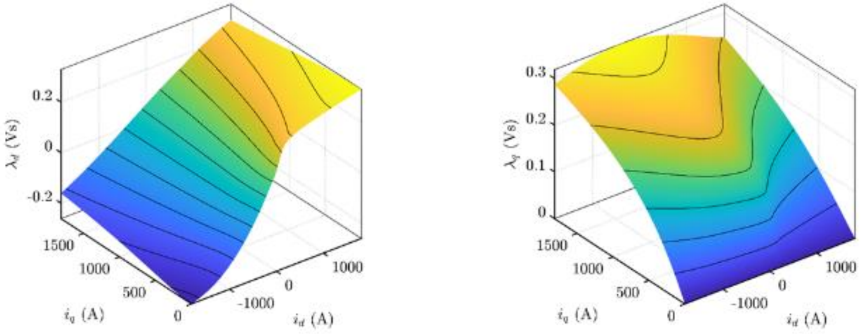
A fast and accurate alternative is to model the motor with **flux maps**:

- dq rotating frame
- Express flux linkages function of the currents
- Can be measured or FEA-simulated

With flux maps, it is possible to perform:

- <u>Off-line elaboration</u> (mainly steady-state figures)
- <u>Accurate eDrive simulation</u>, w/o co-simulation
- …



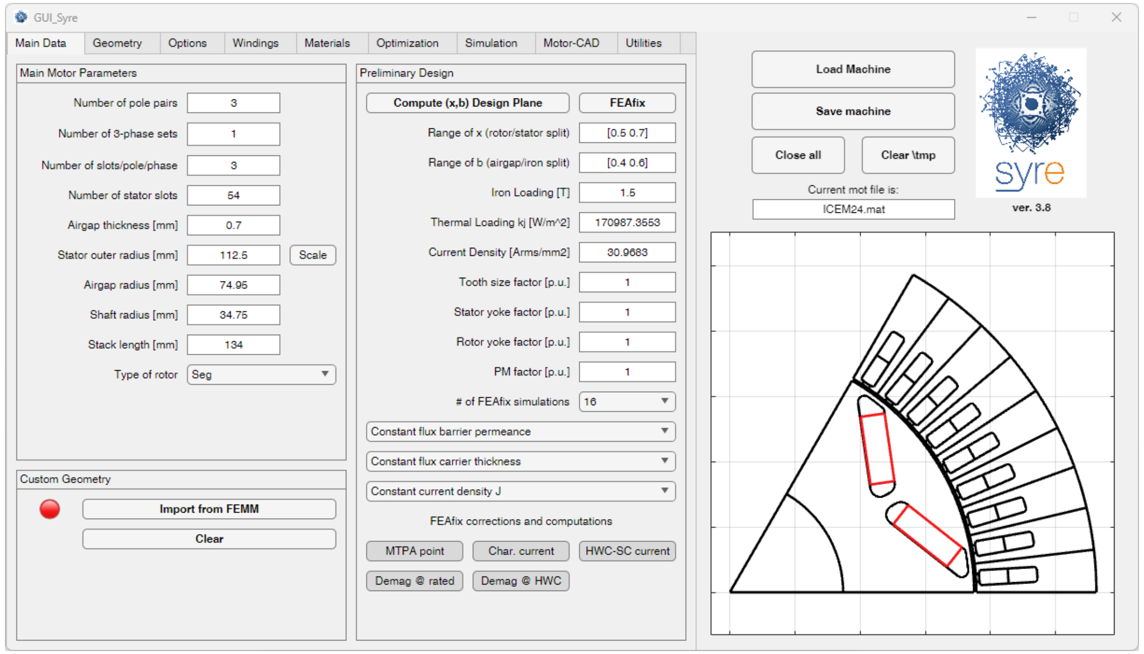


Design and Analysis Environment: SyR-e

SyR-e is an open-source design and analysis environment for synchronous machines

- Developed in Matlab and based on FEMM for electromagnetic FEA simulations
- Include **preliminary design** procedure for SyRM and PMSM
- Automatic **flux maps** and **machine model evaluation**, included elaboration routines
- **Fast scaling methodology** for the full motor model (flux maps, loss, …)
- Interface with eDrive model (Simulink/SimScape)
- Available on GitHub and Matlab File Exchange
- Can work with Matlab Online (no FEA)

NB: new release **v3.8.1**



Try the last release!

SyR-e Team

SyR-e is developed by a group of researchers and PhD students at the Power Electronics Innovation Center of Politecnico di Torino

G. Pellegrino, PhD
Full Professor
Co-founder and Leader

S. Ferrari, PhD
Assistant Professor
Team Leader eMotor Design

M. Mirazimi
Research Assistant
eMotor Design

P. Pescetto, PhD
Assistant Professor
eDrive Control

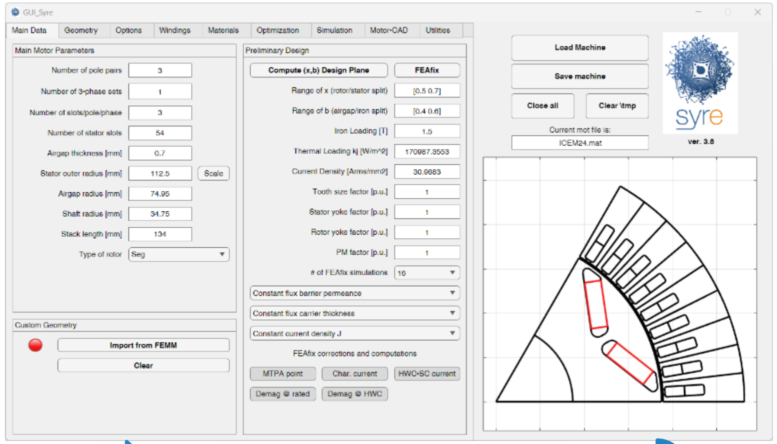
A. Bojoi
PhD student
eDrive Control

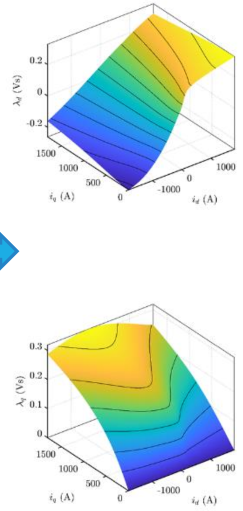
Many MSc student and former PhD students contribute to the project in the last years

SyR-e Geography

GUI_Syre

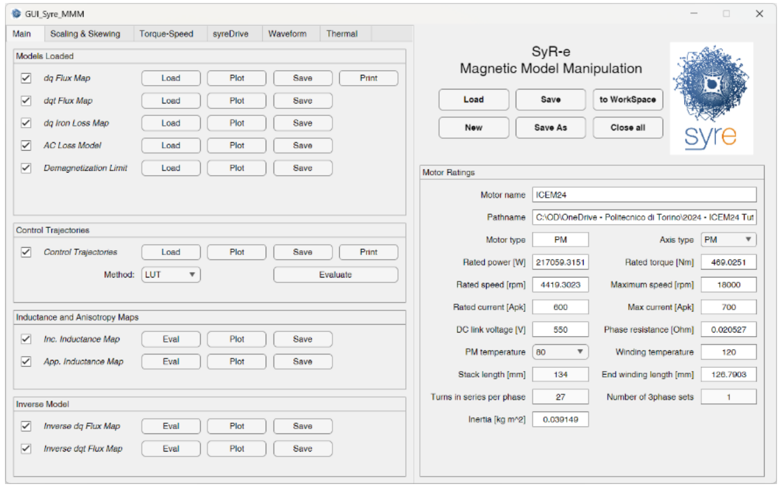
Motor design and simulation

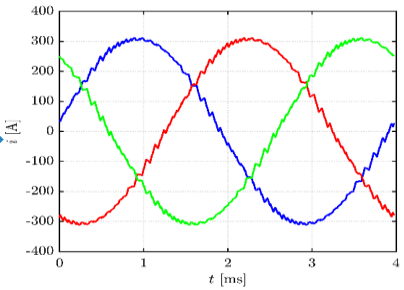


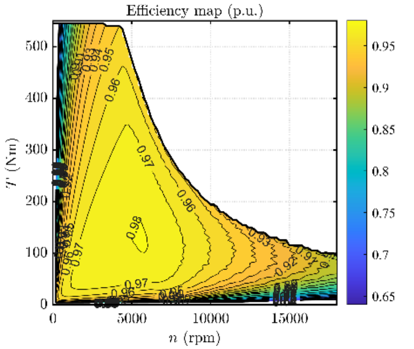


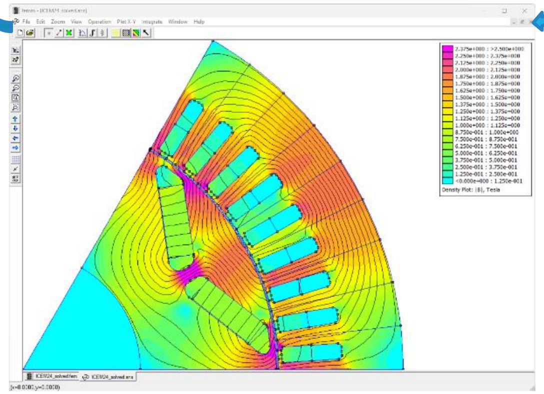
GUI_Syre_MMM

Magnetic Model Manipulation

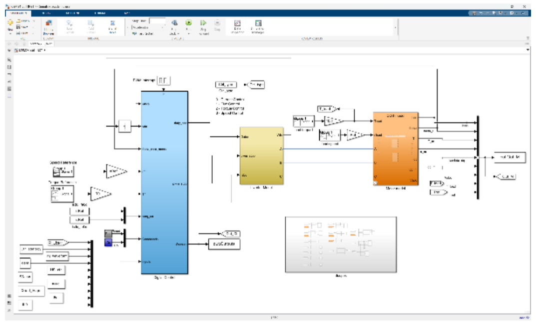








FEMM



SIMULINK®

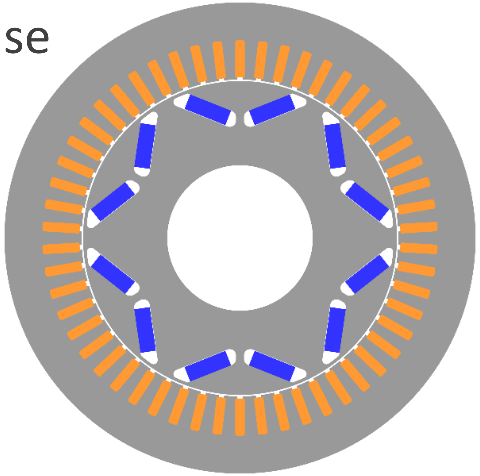
Electrical
Battery
Fluids
Multibody
Driveline
Simscape

Case Study

Today, the selected case study is an IPMSM, based on the Tesla Model Y 3D6 electric motor

- V-type rotor
- NdFeB PMs
- Hairpin windings
- Cooling system unknown → focus on electromagnetic and mechanical

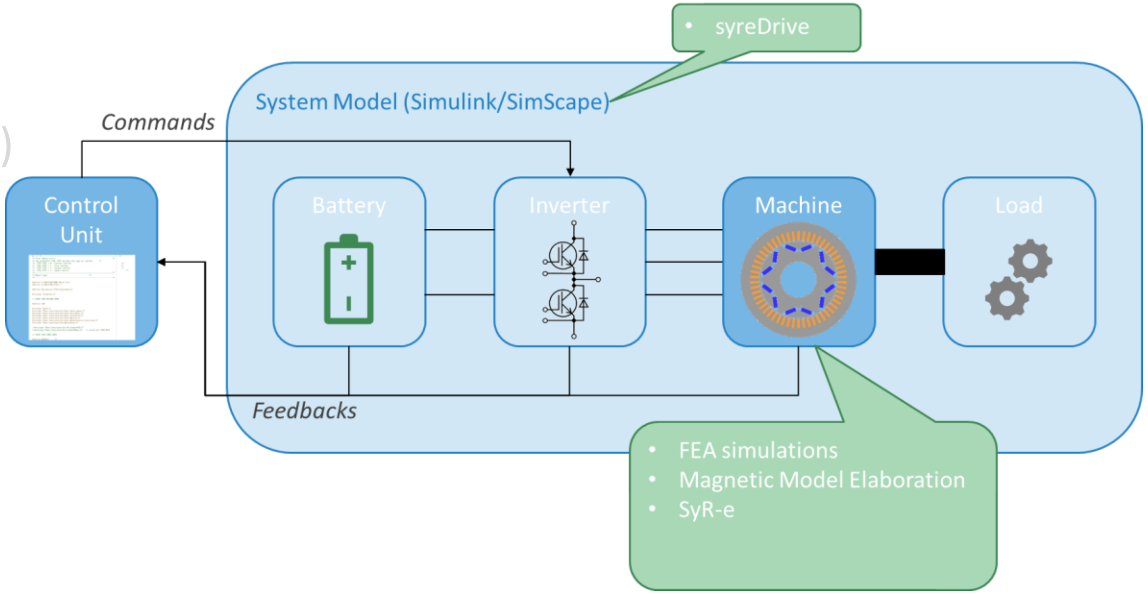
The model is reconstructed in SyR-e and uploaded as example in the last release (**ICEM24.mat / .fem**)



ICEM24.mat / ICEM24.fem		
Peak torque	(Nm)	460
Peak power	(kW)	210
Base speed	(rpm)	~4000
Maximum speed	(rpm)	18000
Peak phase current	(Apk)	600
DC link voltage	(Vdc)	550
Stator outer diameter	(mm)	225
Stack length	(mm)	134
Number of pole pairs		3
Number of stator slots		54
Number of slots/pole/phase		3
Number of turns in series per phase		27
Number of pins per slot		6

Content

- Introduction
- Part 1: Electric Motor Modeling, Feng He (45 min)
- Part 2: SyR-e environment for eMotor Design and Analysis, Simone Ferrari (40 min)
  - Introduction
  - **FEA simulation of PMSM**
  - Motor Modeling
  - eDrive Model: syreDrive
  - Examples
  - Conclusions
- Part 3: Beyond the Electric Motor, Feng He (45 min)
- Q&A (20 min)

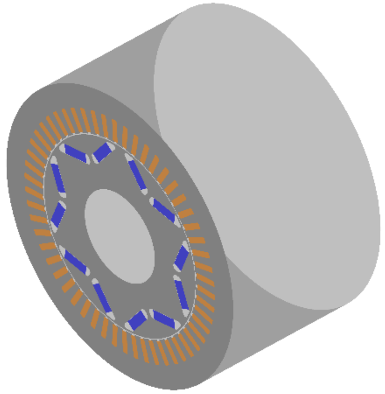


FEA Simulation of PMSM

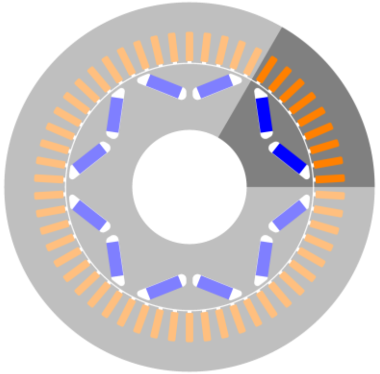
Computational time is a crucial aspect for FEA simulation. To reduce the model complexity:

- 2D model instead of 3D model is adopted
- Periodic or anti-periodic condition (based on adopted winding)
- Rotation of less than 1 period, thanks to electric symmetry
- Time-Step Static FEA simulation → FEMM
- Current-controlled simulation (already in steady-state)

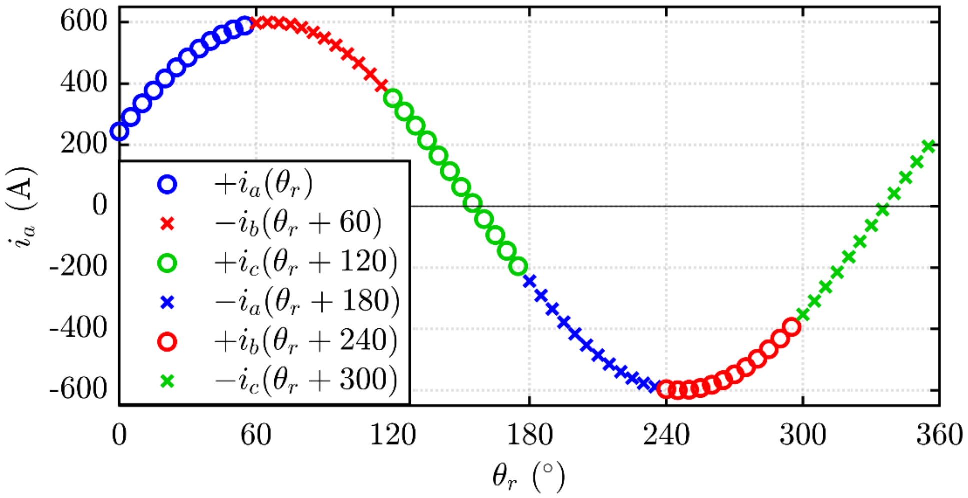
3D→2D



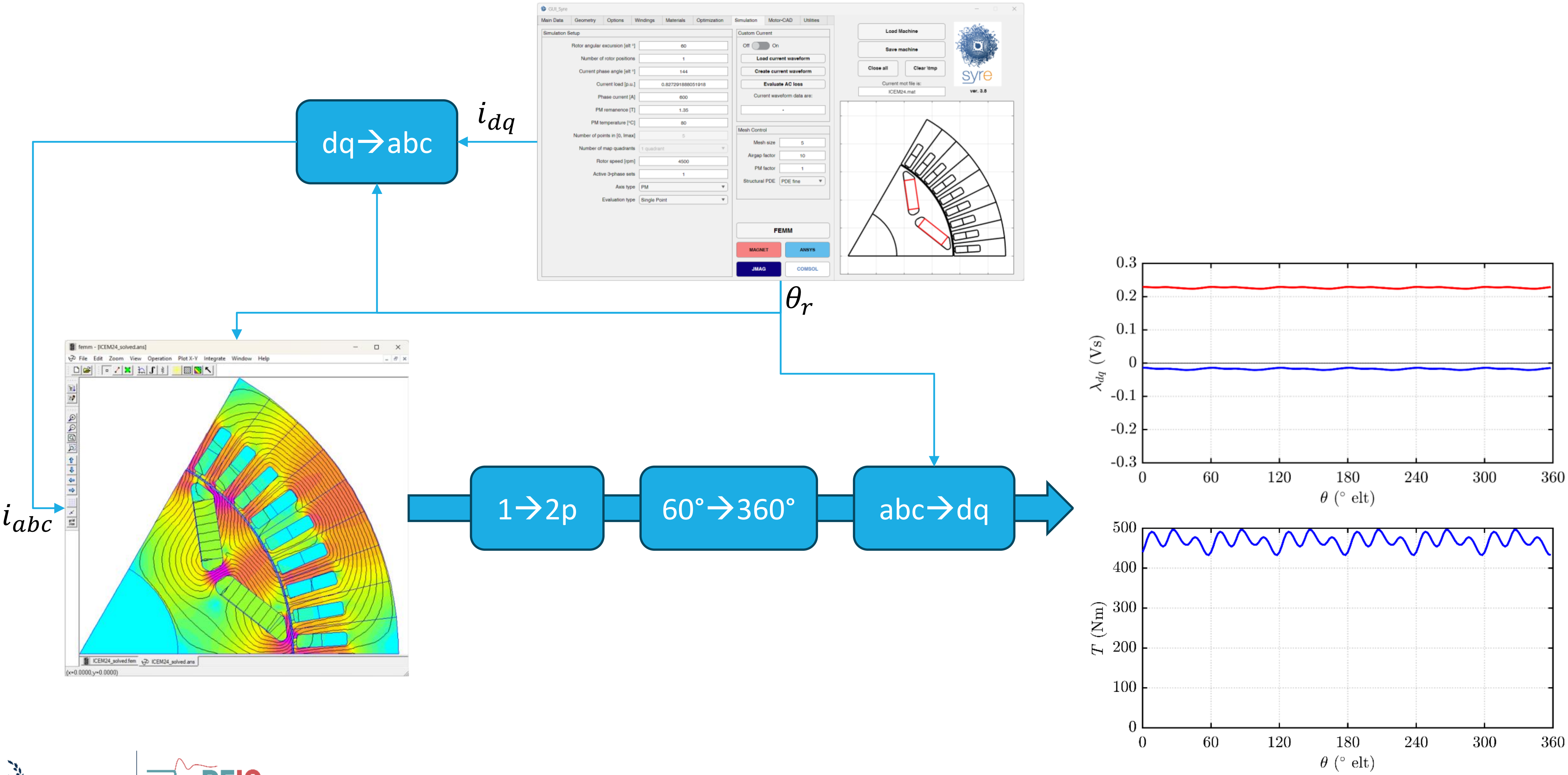
2p→1



360°→60°



Operating Point FEA Simulation

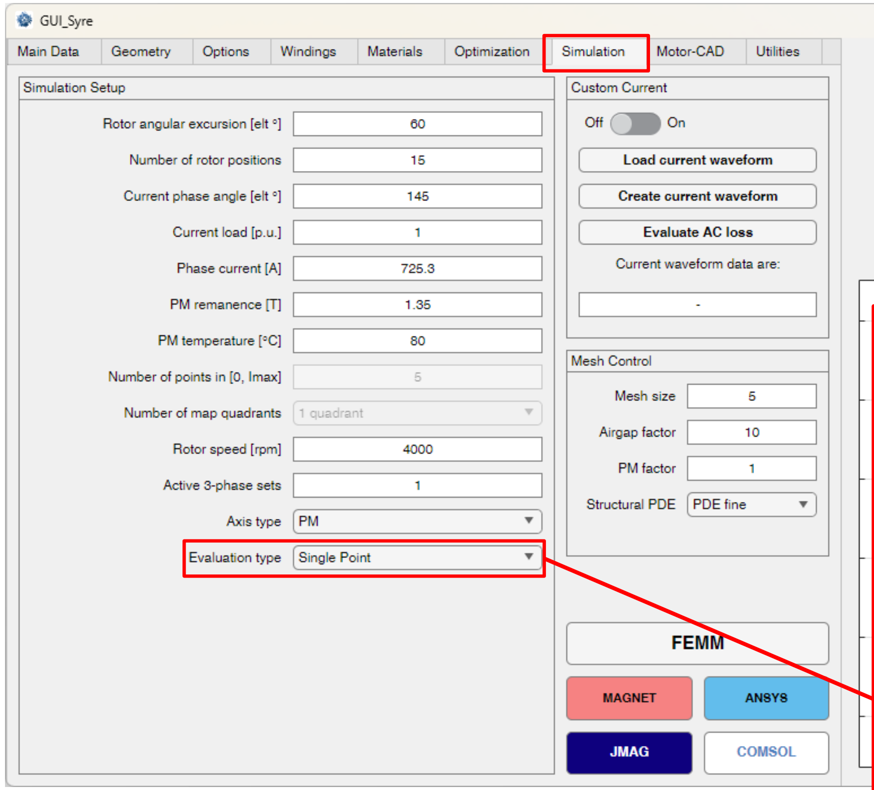


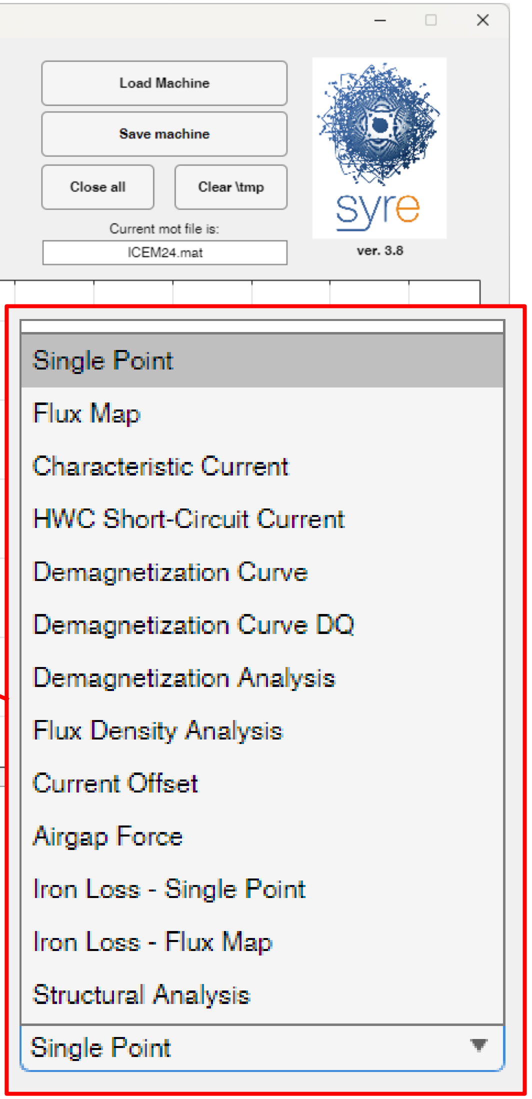
FEA Simulations with SyR-e

FEA simulations are launched from the **dedicated tab** on the main GUI

Several **evaluation types** possible:

- Single operating point
- Flux maps
- Demagnetization analysis
- Flux density analysis
- Structural analysis
- HWC peak short-circuit current
- …



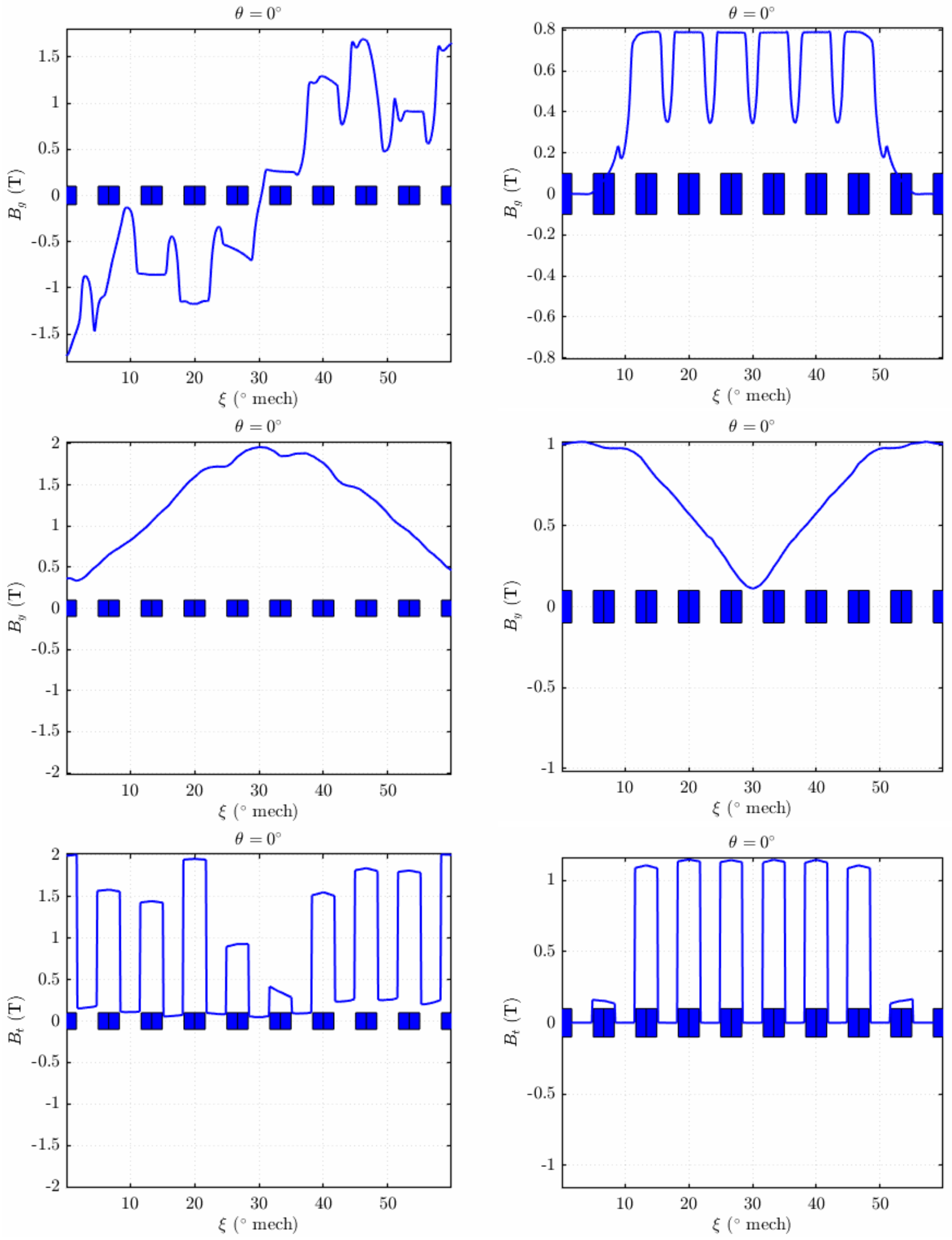


Besides FEMM, some **FEA commercial SW** are supported

Results: Flux Density Waveform

From the same FEA simulations, the **airgap flux density waveform** can be extracted for each rotor position.

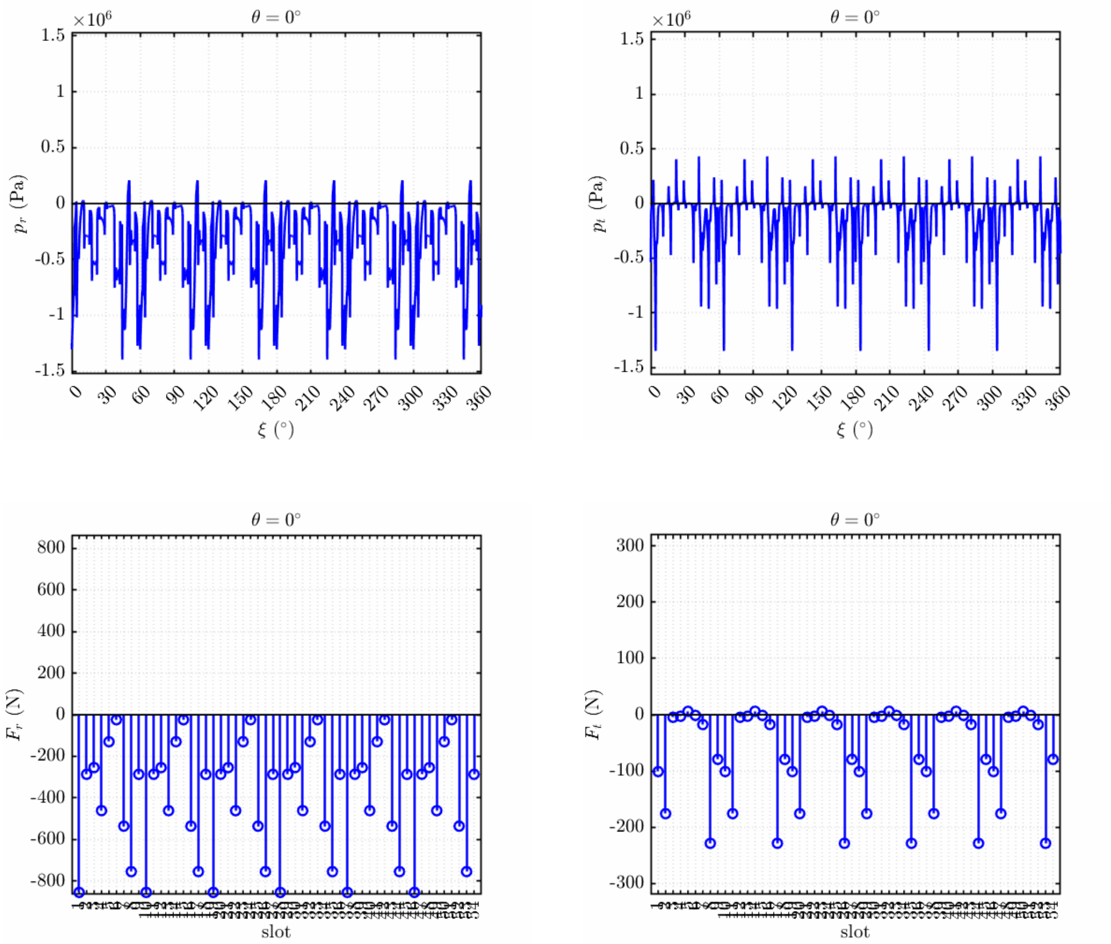
- Not included in standard eDrive models, but advanced models can be implemented
- Important for design verification
- The data can be further manipulated to get the harmonic content
- Stator yoke and tooth flux density can be extracted, too

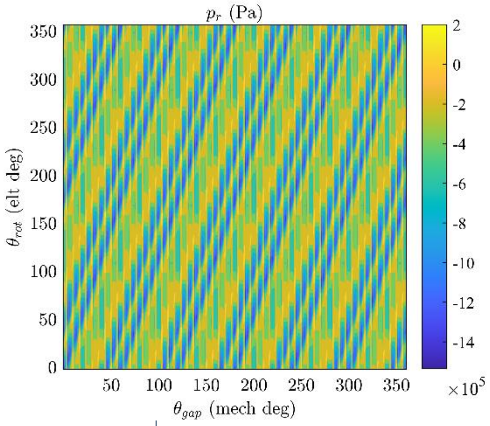


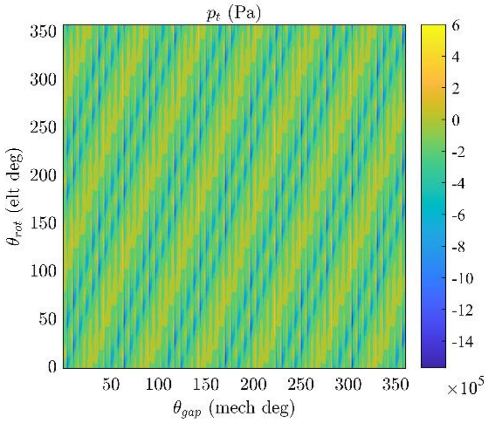
Results: Airgap Magnetic Pressure (NVH)

The **airgap magnetic pressure** is one of the sources of eNVH issues.

- Not included in the standard eMotor model, but mandatory for NVH analysis
- Symmetry conditions are adopted to get the full motor / full period characteristic
- Tooth forces are computed by integration of the magnetic pressure over one tooth







Results: Iron and PM Loss

Iron and PM loss are computed offline, after the FEA simulation

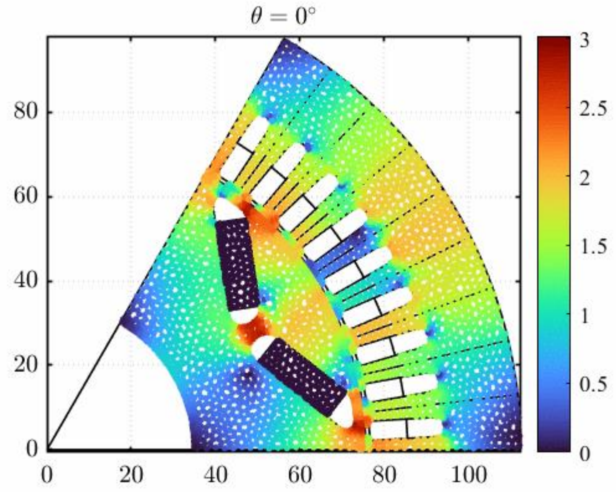
The data are imported in Matlab for each mesh element and rotor position:

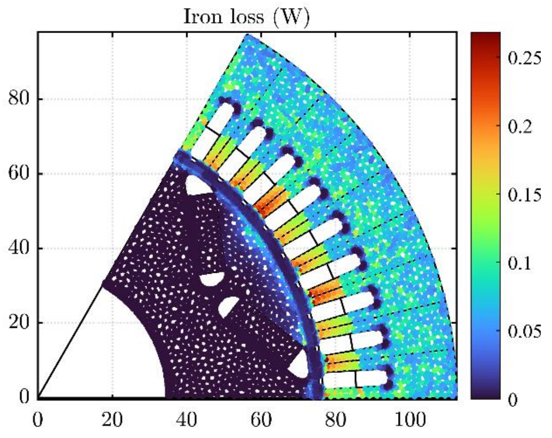
- The flux density for lamination elements
- The magnetic potential for PM elements

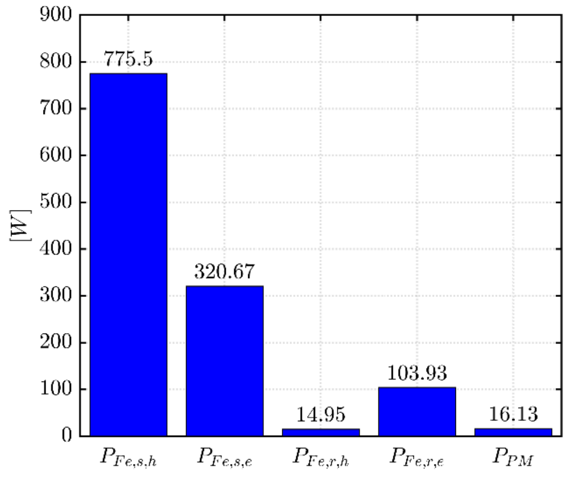
The iron loss are computed with iGSE:

- Hysteresis loss are obtained from main and minor loops and the related loss coefficient
- Eddy-current loss are obtained from FFT and the related loss coefficient
- PM loss are obtained by from FFT and the PM conductivity

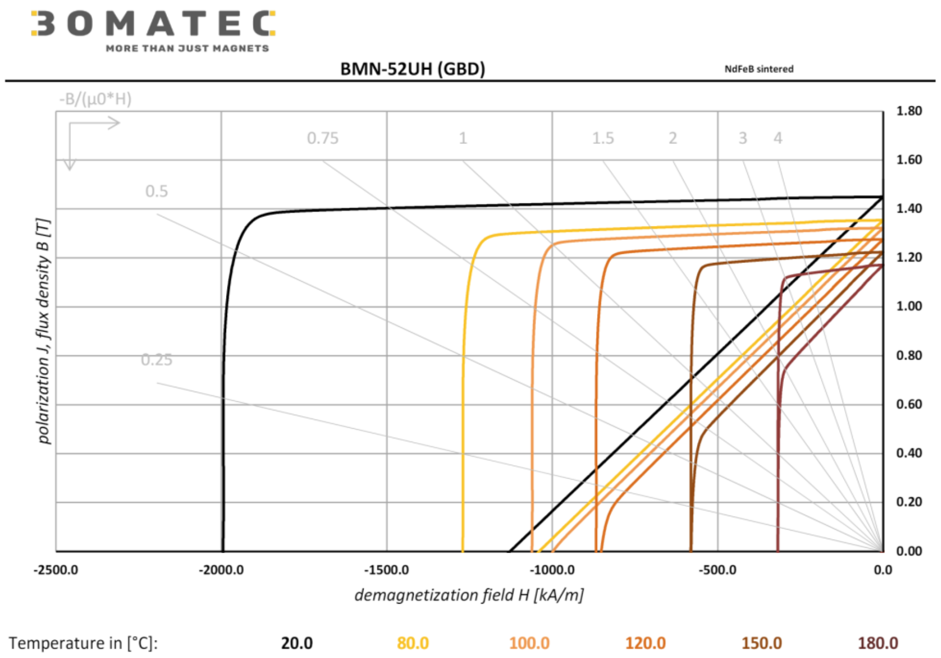
Computational time: ~5min







Demagnetization Analysis



Demagnetization is a critical problem for PMSM

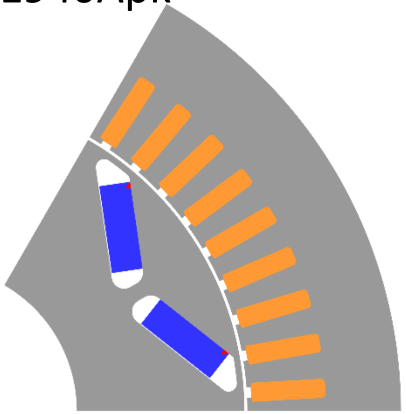
In general, FEA uses **linear PM curves**

- **Knee point** is identified as limit for correct modeling
- If non-conventional PMs are adopted, the non-linear BH curve must be considered

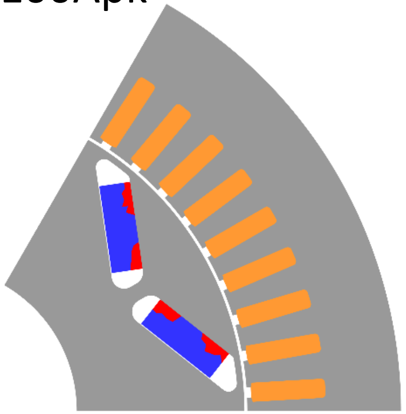
The demagnetization analysis is performed at **given temperature and current**

- The flux density in each PMs mesh element is considered and compared with the knee point
- Magnetization direction only is considered

80°C, 1940Apk



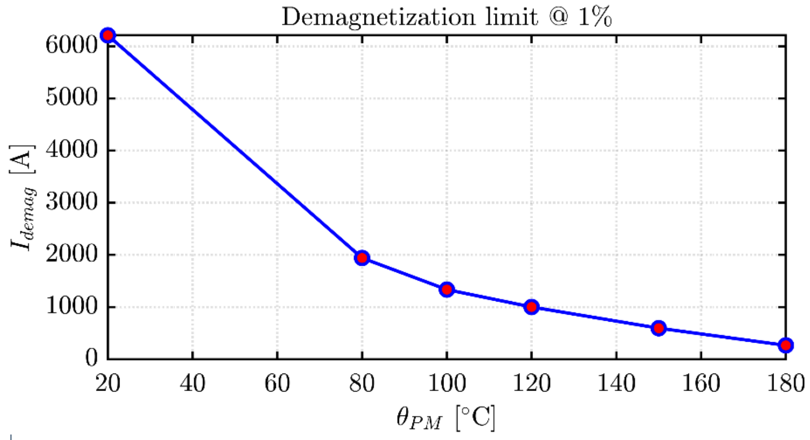
80°C, 3100Apk

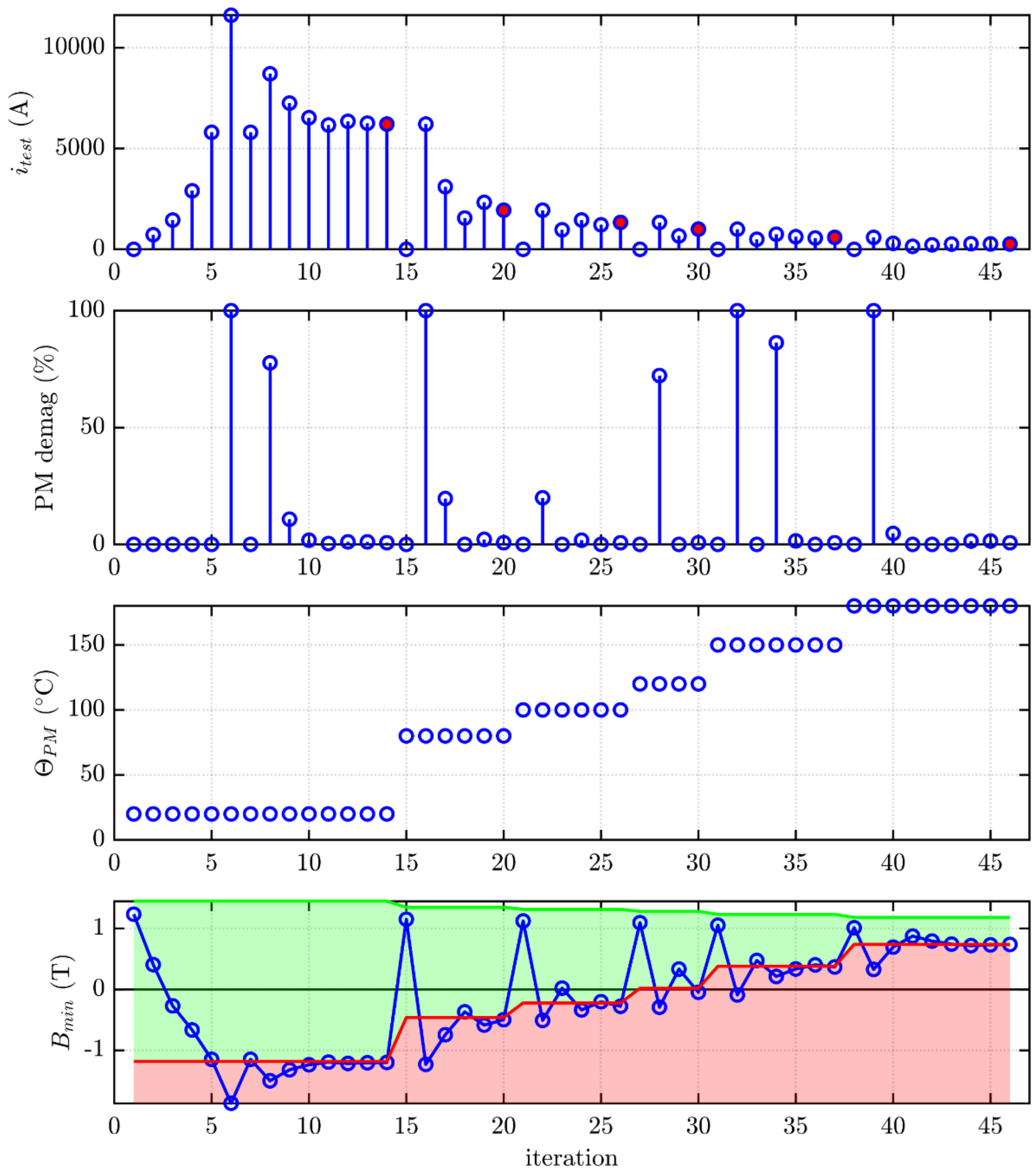


Demagnetization Limit

Besides the single point, a useful information is the **demagnetization limit**:

- maximum current, injected against the PM flux linkage, that irreversibly demagnetize 1% of the PMs volume
- Identifiedin SyR-e through an iterative process
- Function of the PM temperature
- NB: the shape and slope of the curve is function of PM material andnmotor geometry!





AC Loss Modeling

For **hairpin winding**, loss due to AC effects (skin effect and proximity) are crucial

AC loss is computed in SyR-e with time-harmonic FEA over a (f, Θ_{Cu}) map

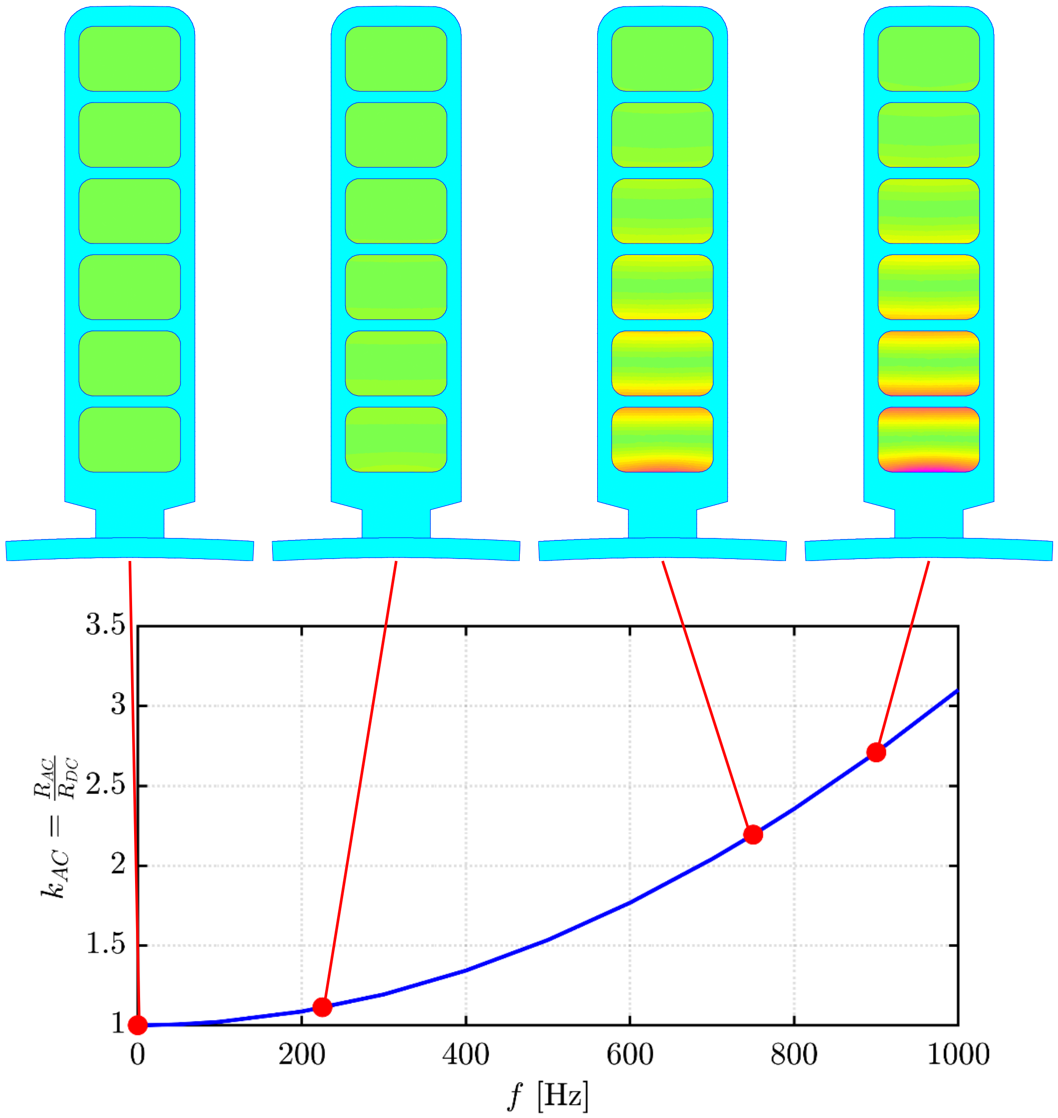
- Unsaturated iron
- Active section only

The result is the AC factor, defined as:

$$k_{AC} = \frac{P_{Cu,AC}}{P_{Cu,DC}}$$

Computational times:

- Less than 1s for a single simulation
- About 36s for the entire map (parallel computing)



Centrifugal Stress

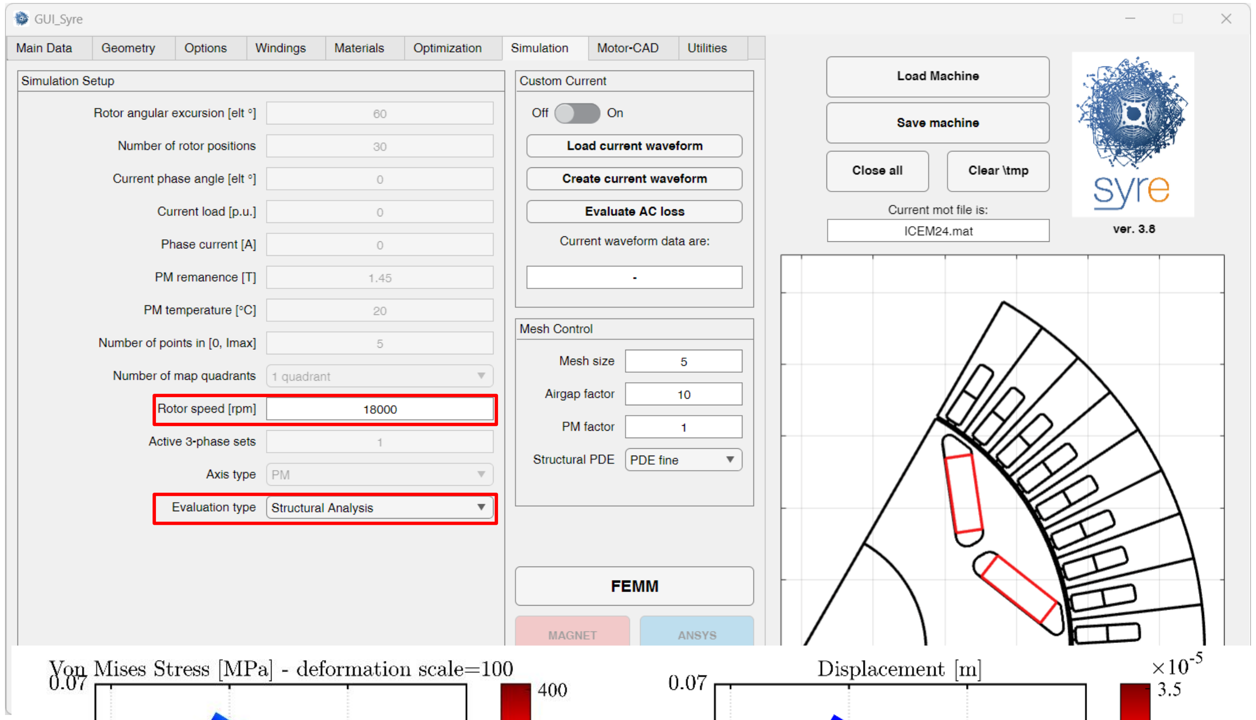
Structural validation is crucial for **high-speed machines**

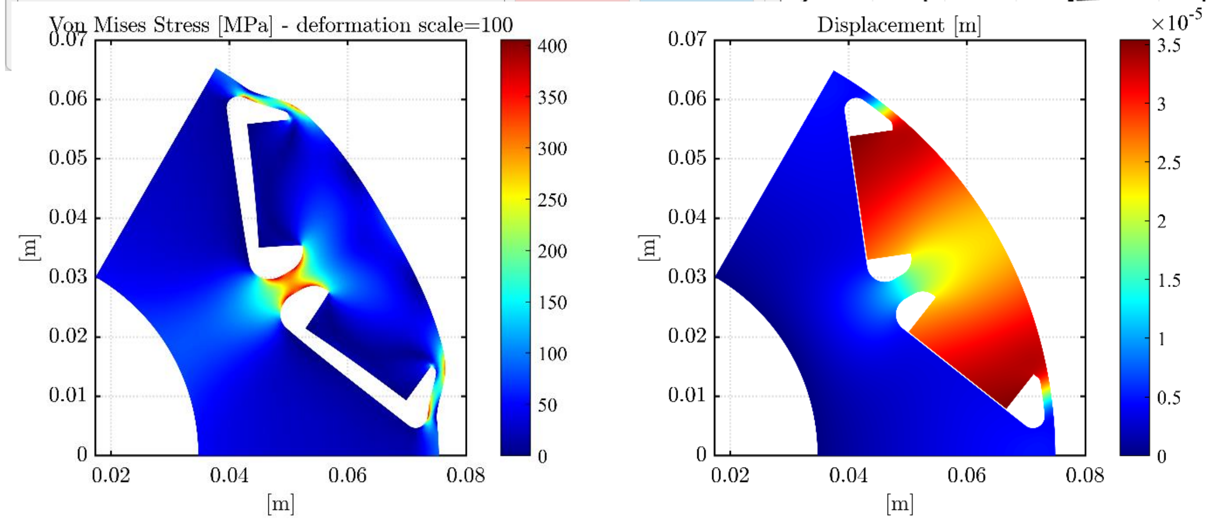
Simplified structural model:

- Just centrifugal stress considered
- Periodic symmetry over 1 pole

SyR-e embeds a **simplified structural FEA simulations**:

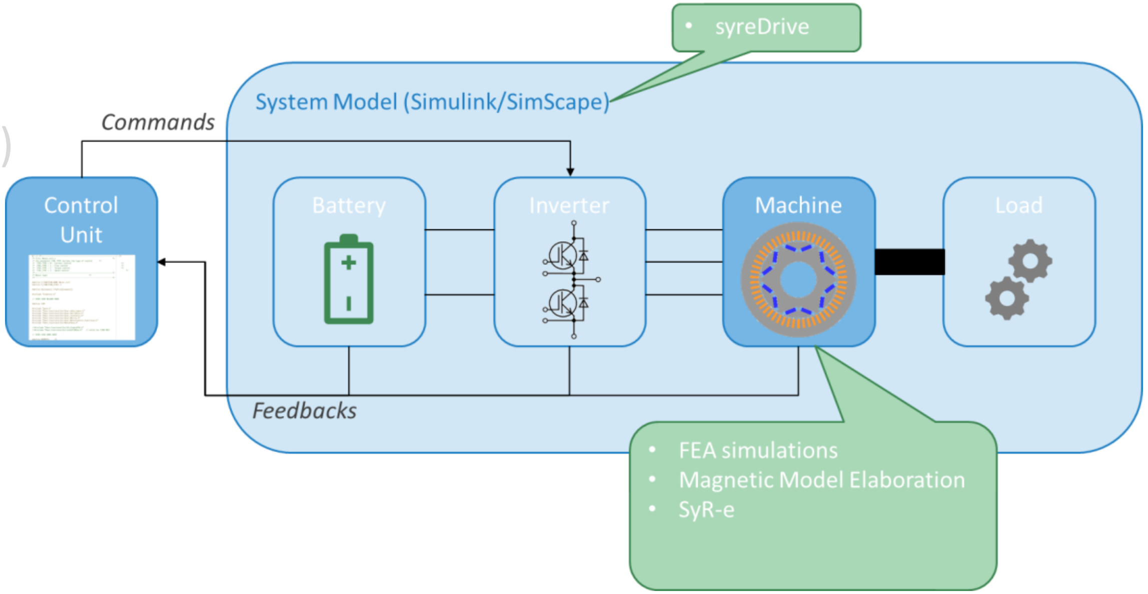
- Developed with PDE Toolbox
- Single-body model
- No pre-stress considered
- Linear model → yield stress is the limit!
- Validation typically done in overspeed condition



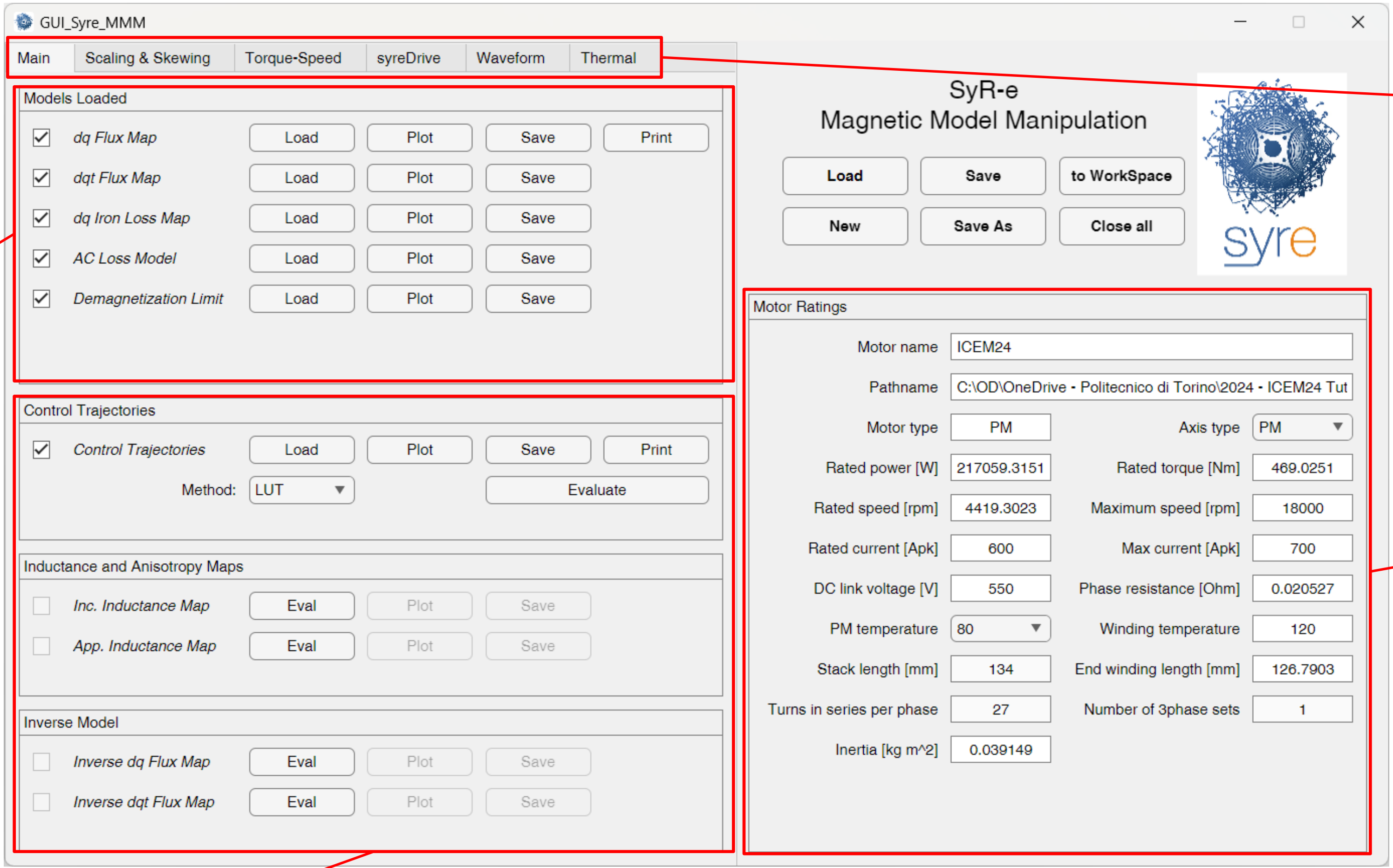


Content

- Introduction
- Part 1: Electric Motor Modeling, Feng He (45 min)
- Part 2: SyR-e environment for eMotor Design and Analysis, Simone Ferrari (40 min)
  - Introduction
  - FEA simulation of PMSM
  - **Motor Modeling**
  - eDrive Model: syreDrive
  - Examples
  - Conclusions
- Part 3: Beyond the Electric Motor, Feng He (45 min)
- Q&A (20 min)



Motor Modeling, from FEA to MMM



Additional elaboration
+
syreDrive interface

Data from FEA

Ratings

Flux maps elaborations

Magnetic Model

The magnetic model is based on **flux maps**:

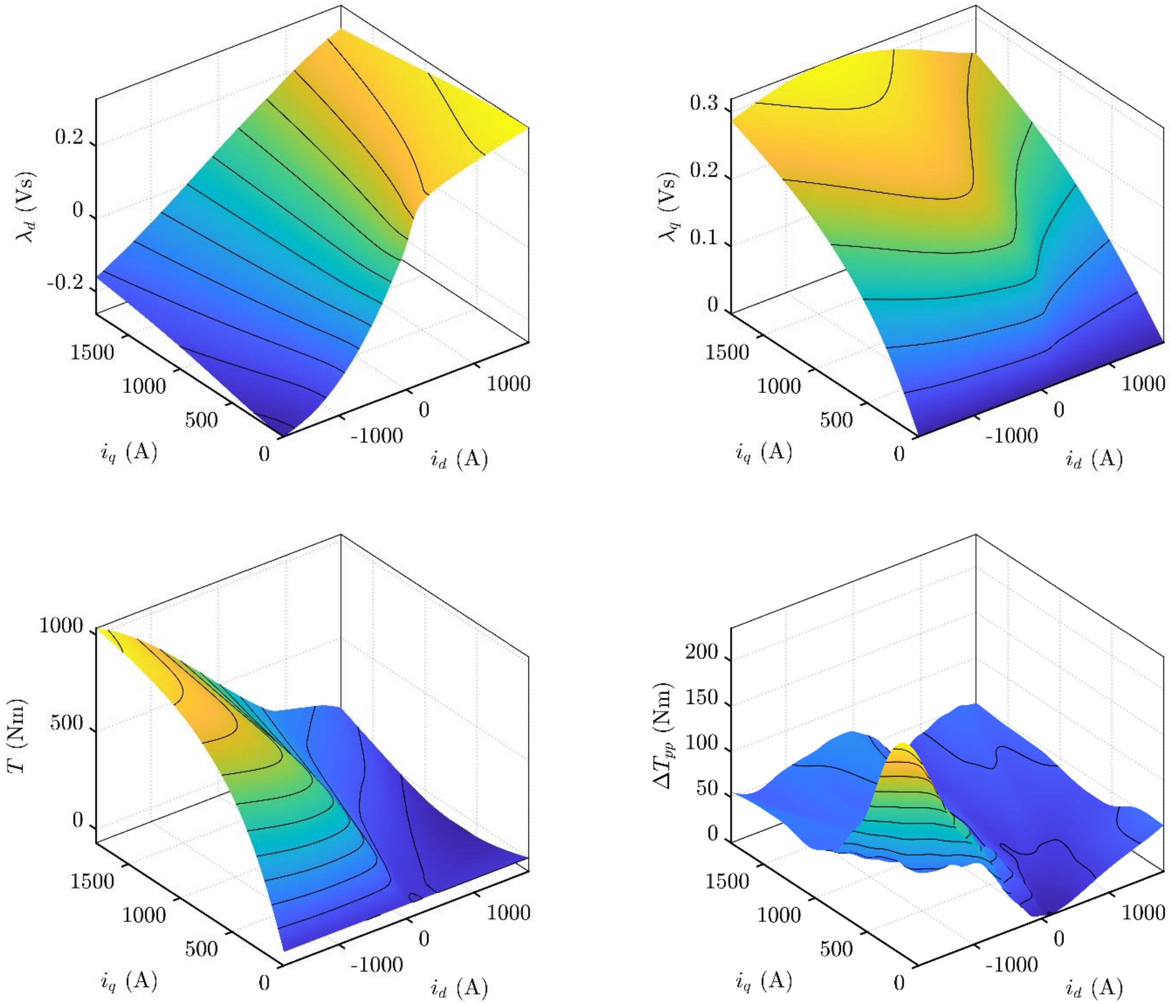
- Constant PM temperature
- Computed on square or rectangular domain
- 1Q or 2Q (4Q by symmetry, if needed)
- Can be measured on the prototype

Flux linkages are expressed function of the $\boldsymbol{dq}$ **currents**, additional quantities can be saved

- $\Lambda_d(i_d, i_q)$ and $\Lambda_q(i_d, i_q)$
- $T(i_d, i_q) = \frac{3}{2} \cdot p \cdot (\Lambda_d \odot I_q - \Lambda_q \odot I_d)$
- Torque ripple map $\Delta T_{pp}(i_d, i_q)$, $\Delta T_{rms}(i_d, i_q)$
- …

Computational effort (parallel computing):

- Accurate map (15x15, 30pos): ~25min
- Fast map (15x15, 12pos): ~10min



Politecnico di Torino 1859

PEIC Power Electronics Innovation Center

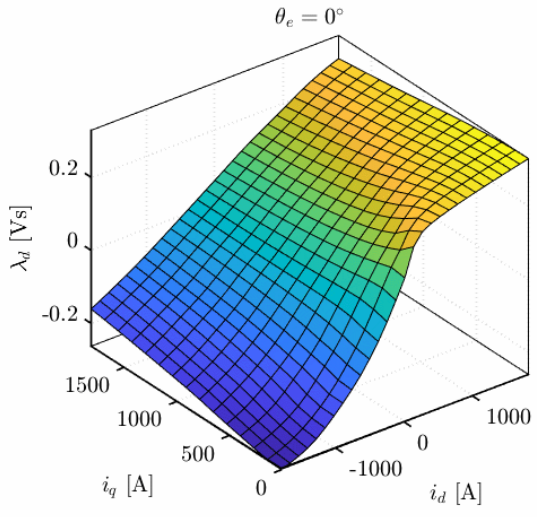
Magnetic Model

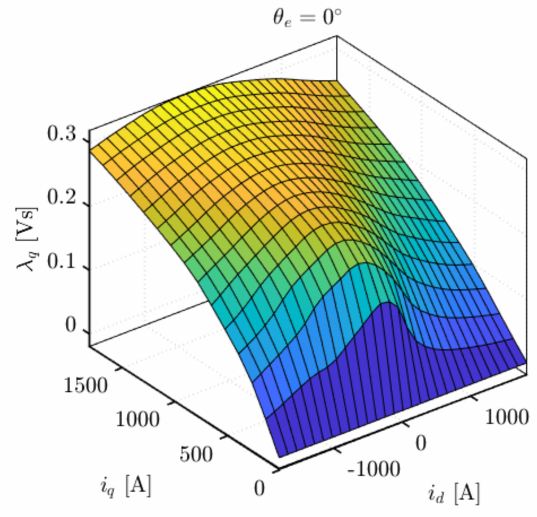
The $dq\theta$ **model** can be considered (if FEA simulation was enough accurate): flux linkage and torque maps function of rotor position, too:

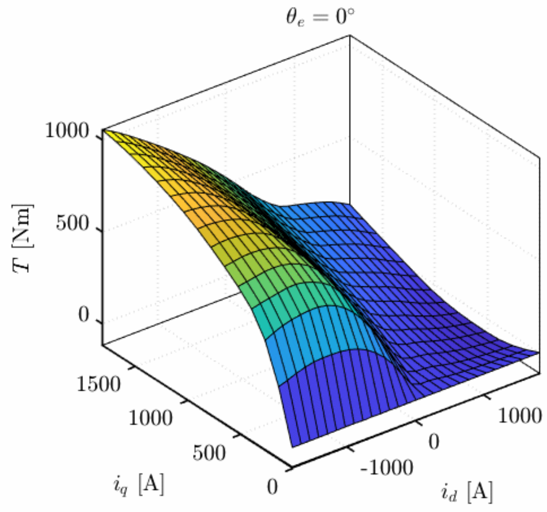
- $\Lambda_d(i_d, i_q, \theta_r)$
- $\Lambda_q(i_d, i_q, \theta_r)$
- $T(i_d, i_q, \theta_r)$

Advantages:

- No additional computational effort (standard ~25min simulation)
- Waveform evaluation offline, w/o FEA
- Skewing computation
- Motor harmonic content in the eDrive model







Iron and PM Loss Model

Iron Loss is based on iSGE and the 2-terms Steinmetz equation

$$p_{Fe} = k_h \cdot f^{\alpha} \cdot B^{\beta} + k_e \cdot (f \cdot B)^2$$

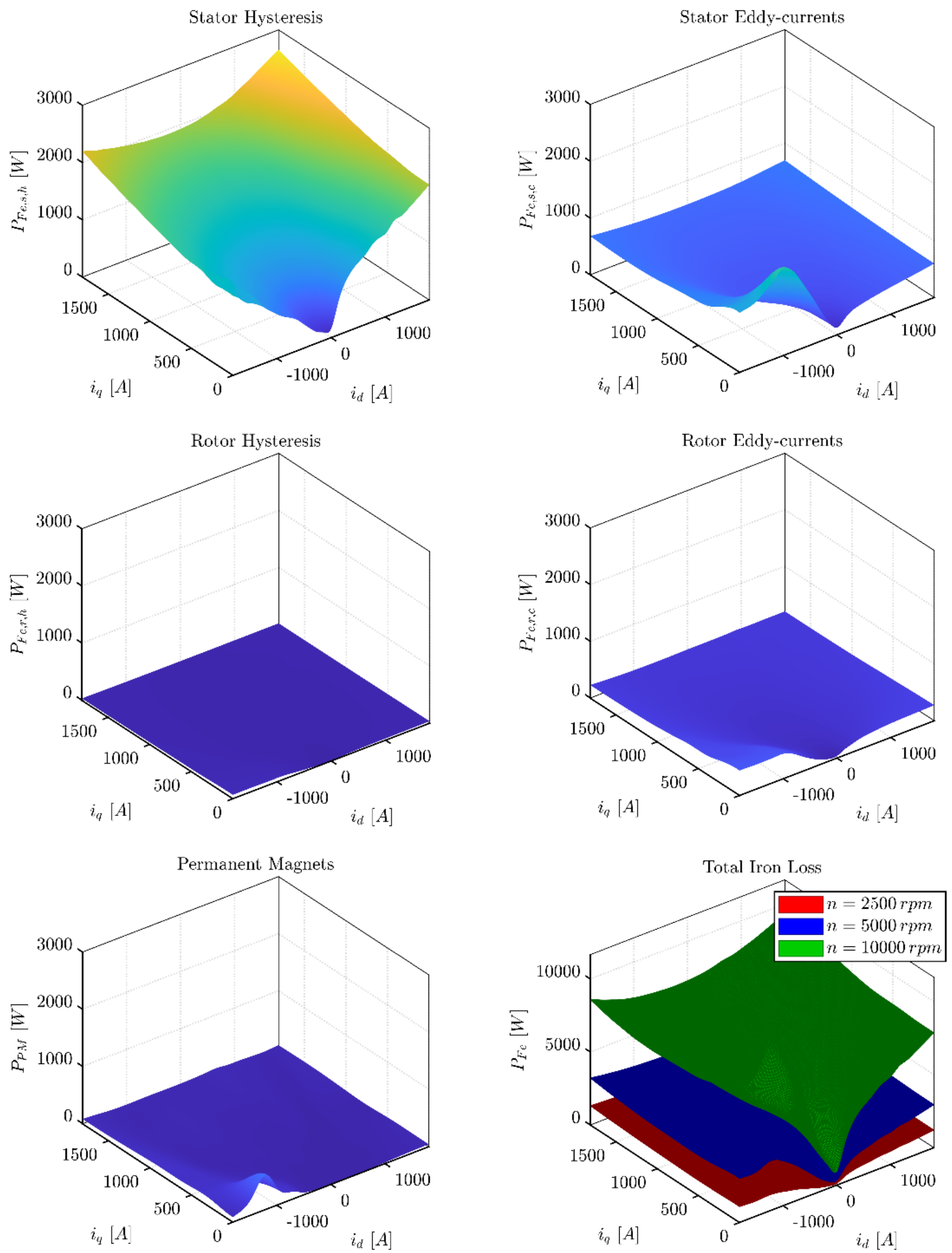
The iron loss are mapped at <u>constant speed</u> over the <u>*dq* plane</u> and the hysteresis and eddy-current terms are saved separately.

PM loss are considered as additional loss term

Iron and PM loss are then scaled in speed:

$$P_{Fe+PM} = P_{Fe,h,0} \cdot \left(\frac{n}{n_0}\right)^{\alpha} + P_{Fe,e,0} \cdot \left(\frac{n}{n_0}\right)^{2} + P_{PM,0} \cdot \left(\frac{n}{n_0}\right)^{2}$$

<u>NB: sinusoidal current supply!</u>



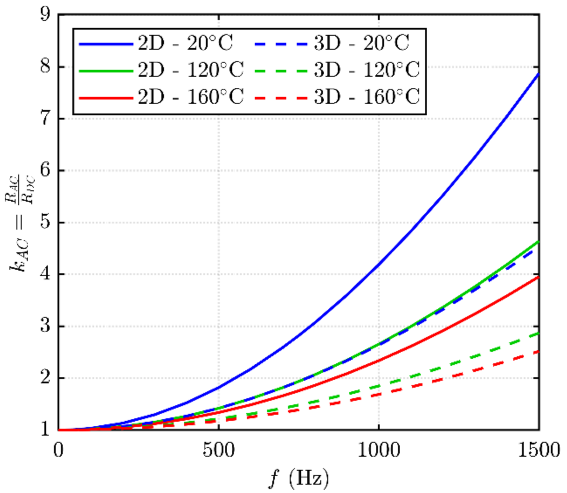
AC Loss Model

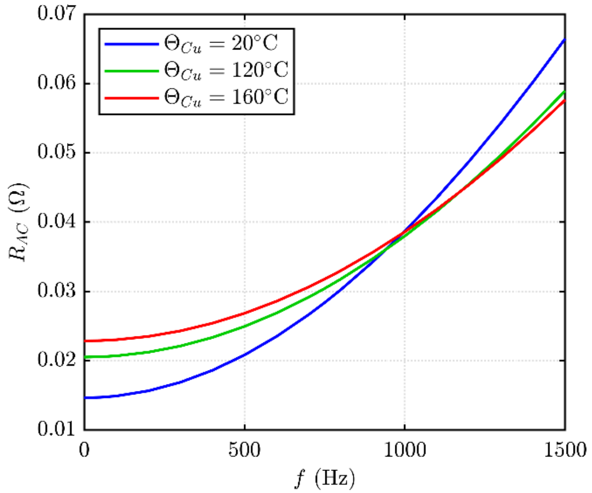
FEA-computed **AC loss factor** is applied just on the active section

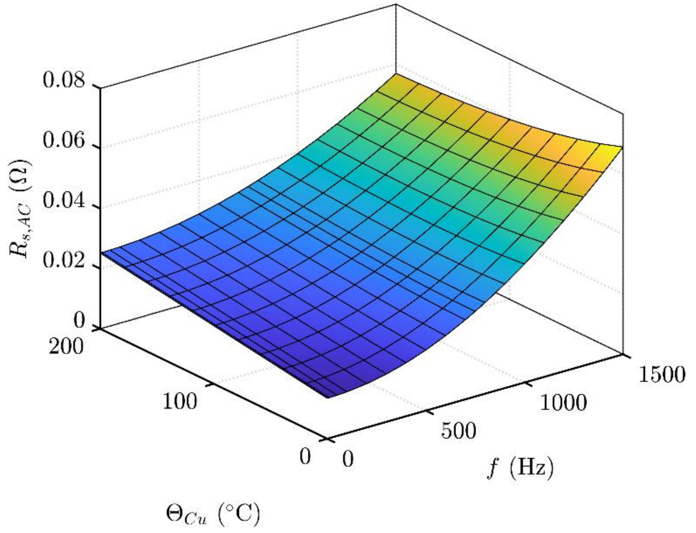
- End-windings have almost no AC effect
- Effective AC factor is computed
- In some cases, the AC factor of the end-winding can be defined (via 3D FEA or experimental results)

Phase resistance map is computed

- Function of temperature and frequency
- Account for both AC loss and temperature effects on DC resistance







Inductance Maps Computation

Inductance maps can be adopted for eMotor dynamic modeling (e.g. VBR)

Two models are typically considered:

- Apparent inductances (Vs/A ratio)

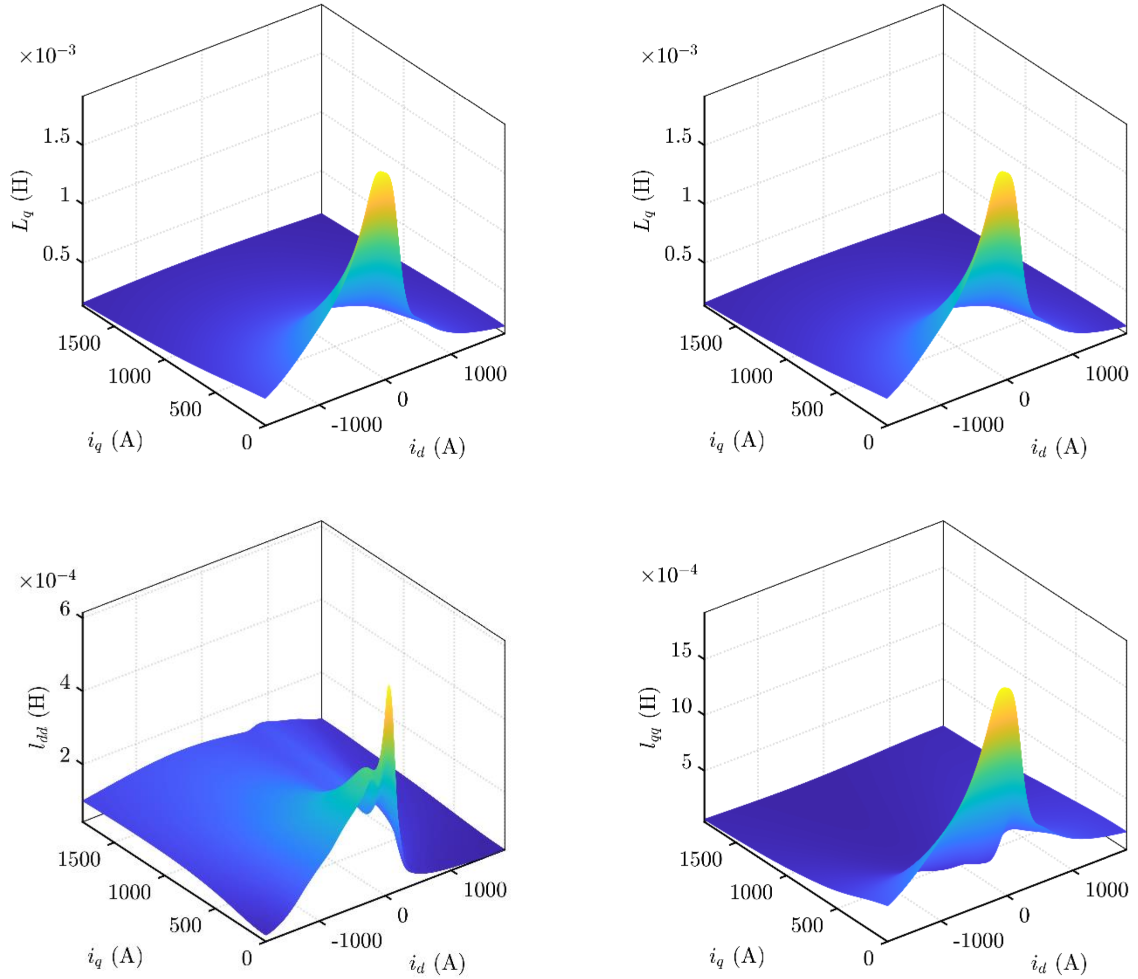
$$\lambda_m = \lambda_m(i_q), L_d = \frac{\Lambda_d(i_d, i_q) - \lambda_m(i_q)}{i_d}, L_q = \frac{\Lambda_q(i_d, i_q)}{i_q}$$

- Incremental inductances (differentiation)

$$l_{dd} = \frac{\partial\Lambda_d(i_d, i_q)}{\partial i_d}, l_{qq} = \frac{\partial\Lambda_q(i_d, i_q)}{\partial i_q}$$

$$l_{dq} = \frac{\partial\Lambda_d(i_d, i_q)}{\partial i_q} = l_{qd} = \frac{\partial\Lambda_q(i_d, i_q)}{\partial i_d}$$

Both inductances modeling can be computed through dq flux maps elaboration with SyR-e



Inverse Model Computation

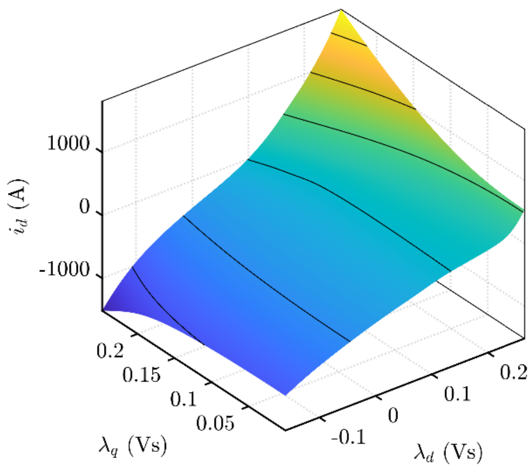
Inverse flux maps are another useful framework for eMotor modeling (e.g. CCG).

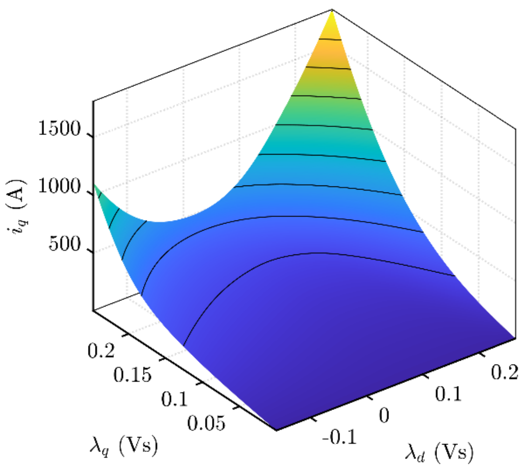
- Currents and torque are expressed function of flux linkages
- Both dq and $dq\theta$ inverse model

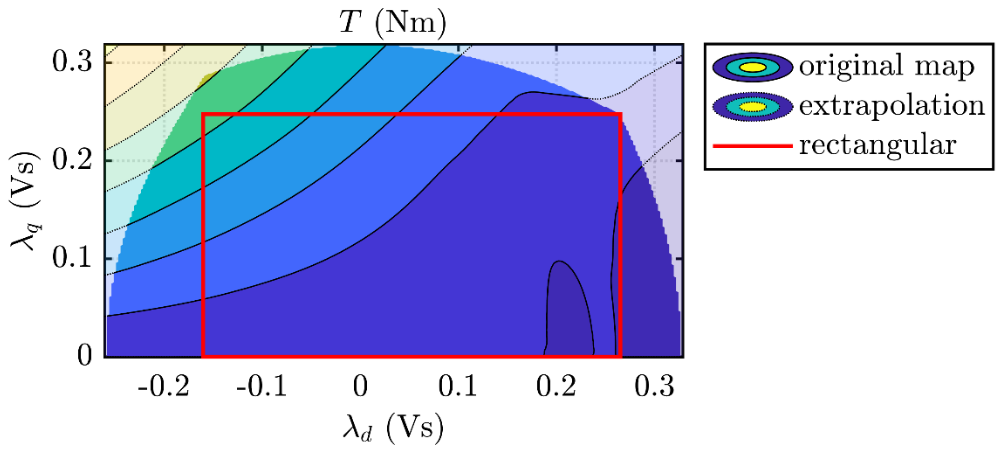
The model inversion is performed with *scatteredInterpolant* Matlab function

The **maps limits** must be carefully considered:

- If rectangular domain is pursued → data loss
- Extrapolation should be avoided
- For loss-less inversion → non-rectangular domain
- Normalization techniques can be implemented to avoid data loss







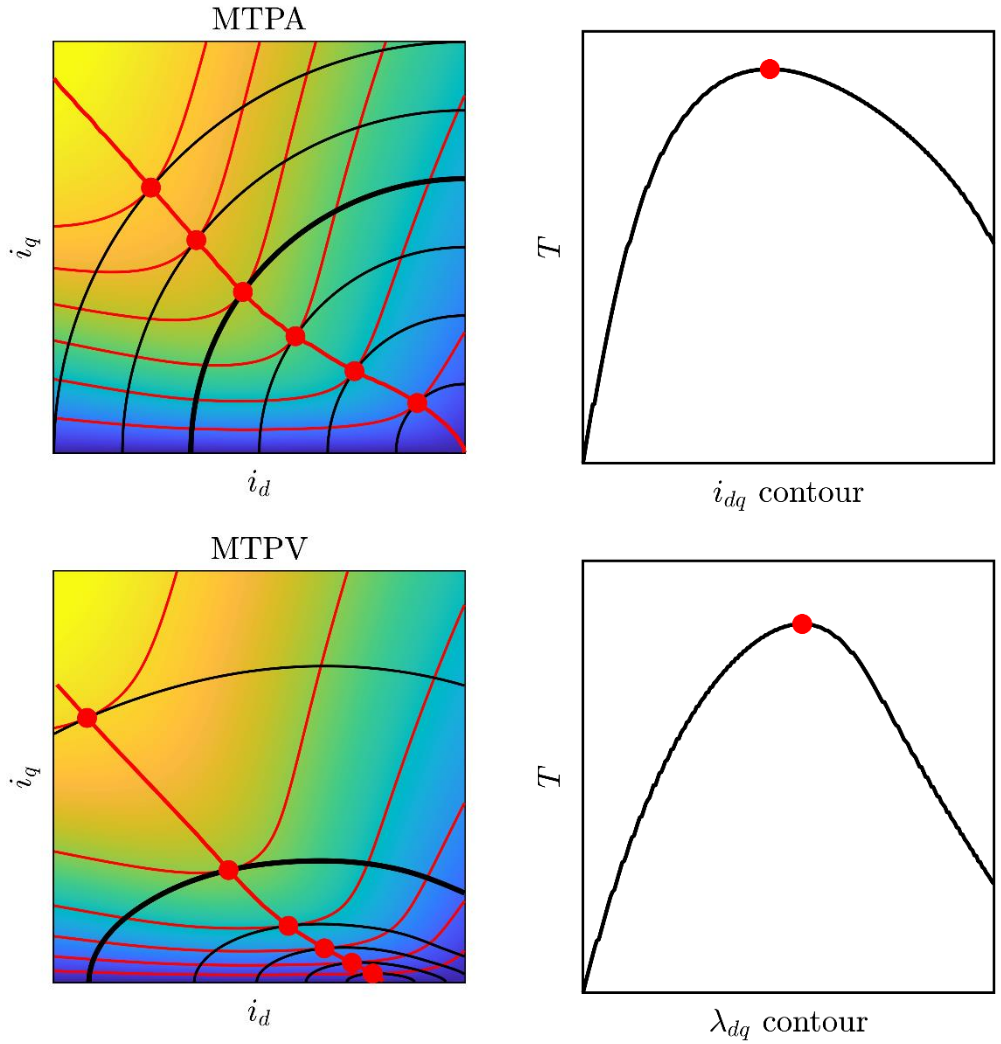
Computation of Control Trajectories

<u>Control trajectories are directly computed from dq flux and torque maps</u>

- MTPA: Maximum Torque per Ampere
- MTPV: Maximum Torque per Voltage (~flux)

The same **evaluation routine** is adopted:

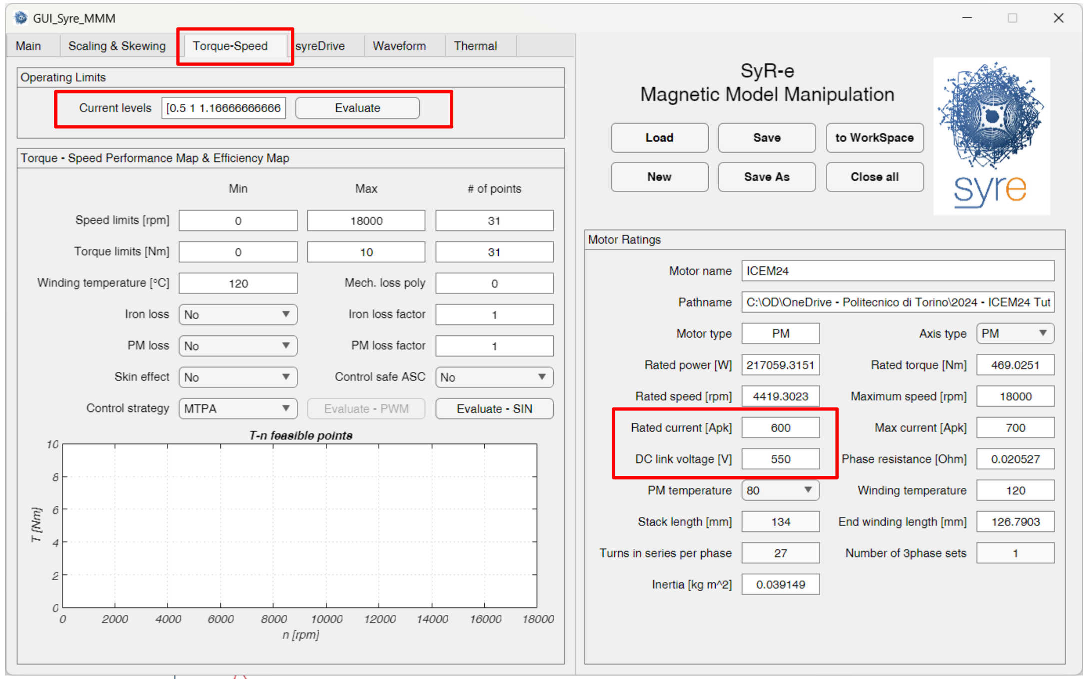
- A vector of currents (or flux linkages) amplitudes is considered
- For each current (or flux linkage) level, the maximum torque is identified and the corresponding (i_d, i_q) coordinates are stored

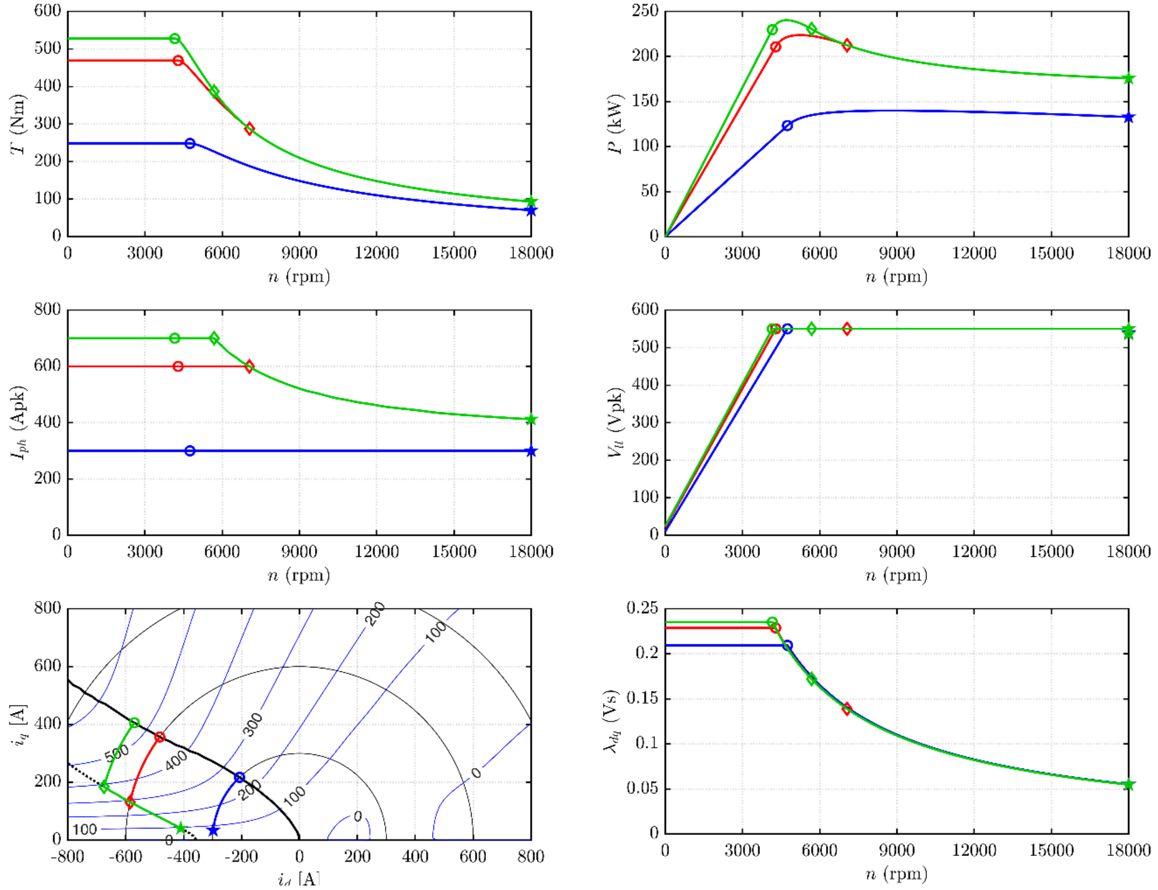


Torque – Speed Limits

With the control trajectories and the inverter ratings, the **operating limits** can be identified, almost istantaneously

- Different current and voltage limits
- Loss-less condition





Efficiency Maps Computation

Efficiency maps are computed over a <u>torque-speed regular grid</u>

Several **loss components** can be included

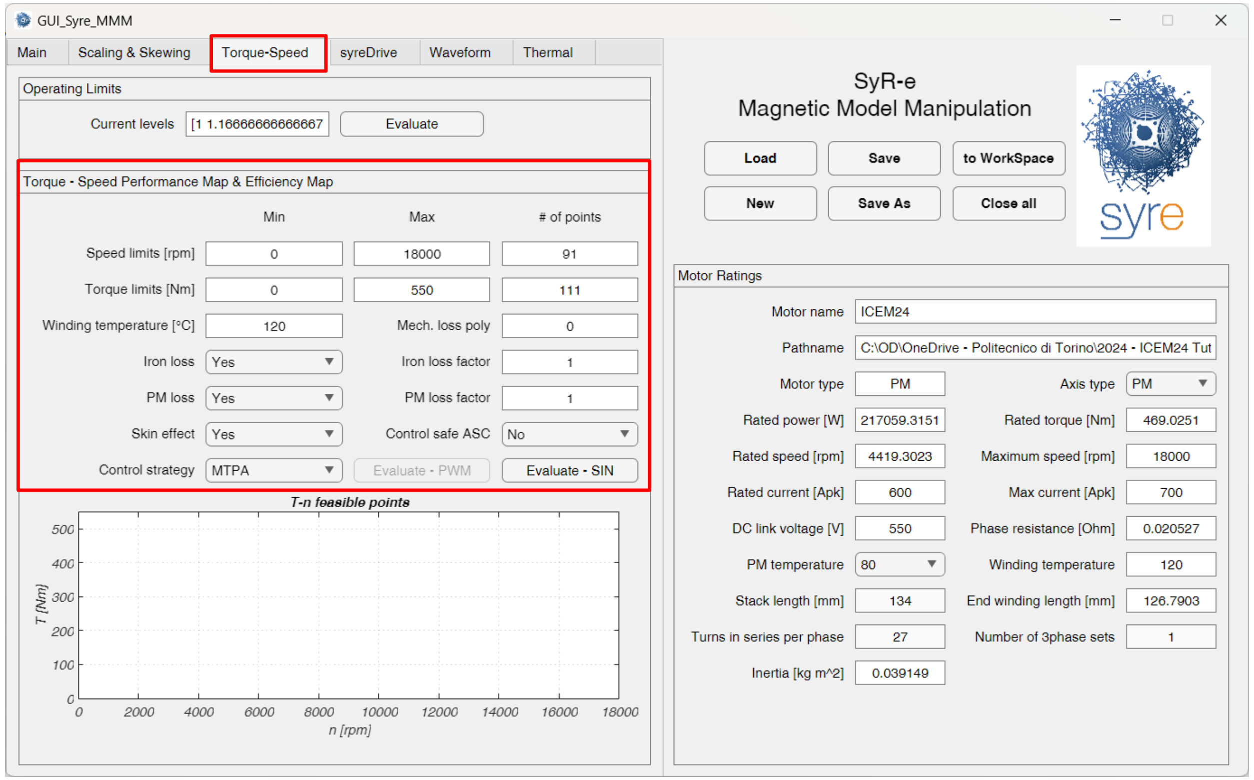
- Copper loss (DC and AC components)
- Iron and PM loss can be considered (SIN supply)
- Mechanical loss can be included

Inverter limits are considered

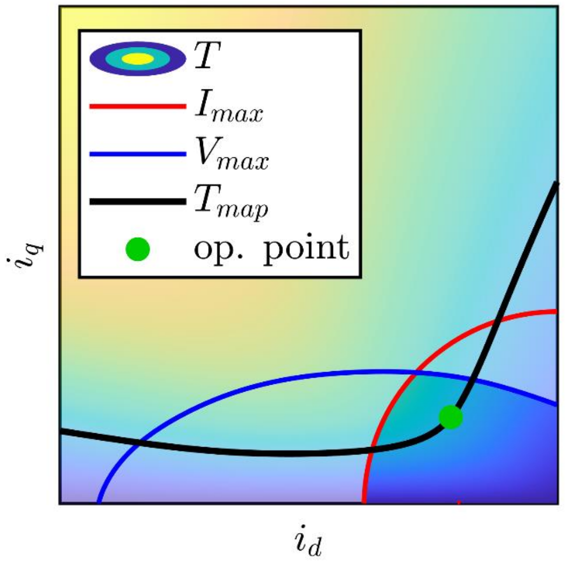
Post-fault conditions (ASC and OC) are considered and evaluated

Computational time:

- About 13 min for 10201 points (101x101 grid)
- Lower discretization can be adopted
- Parallel computing not (yet) implemented

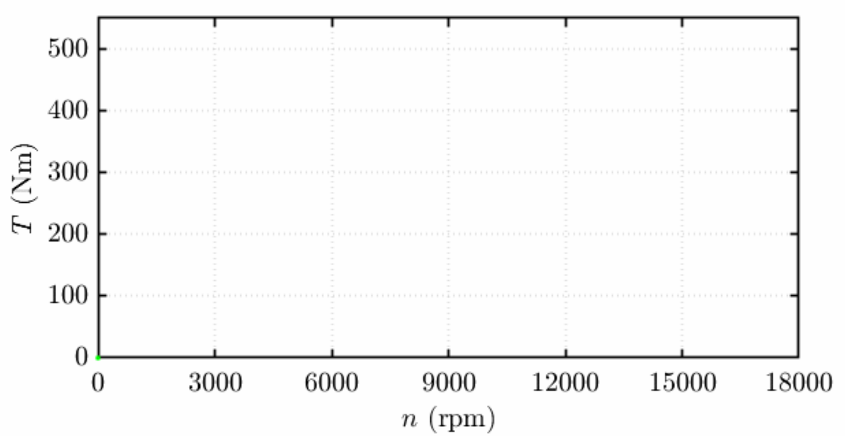


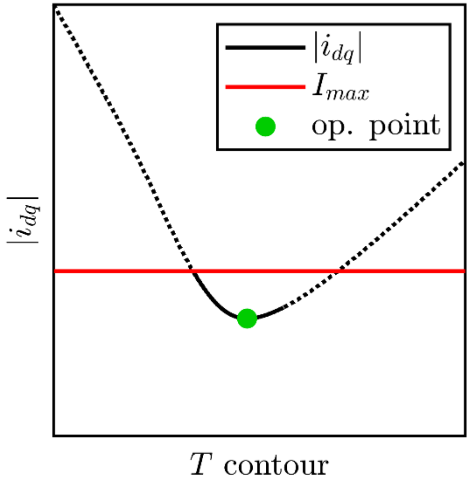
Efficiency Maps Computation

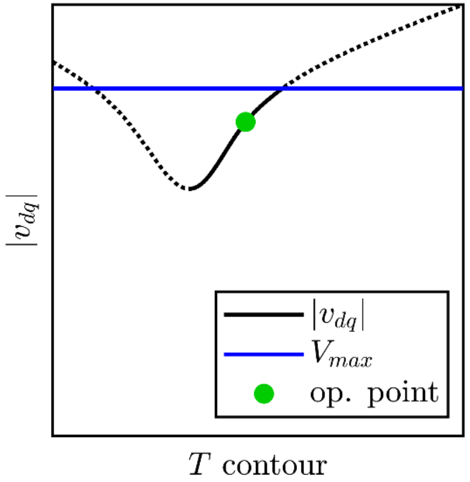


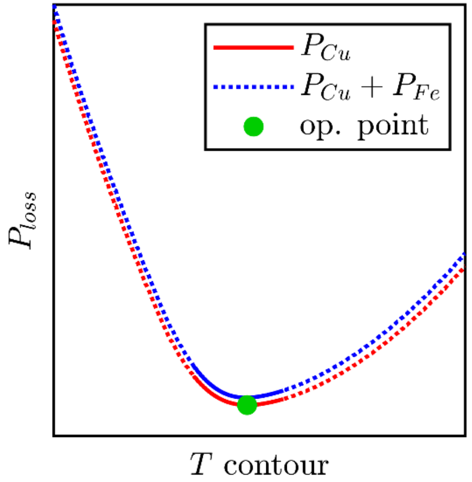
For each (T, n) point, the flux and loss maps are scaled and the (i_d, i_q) operating point is computed

- Point that are not compatible with the inverter are dropped
- The minimum copper loss point is identified









Symmetric Short-Circuit Condition

Symmetric **short-circuit** condition (3-phase short-circuit) can be modeled through **flux maps**

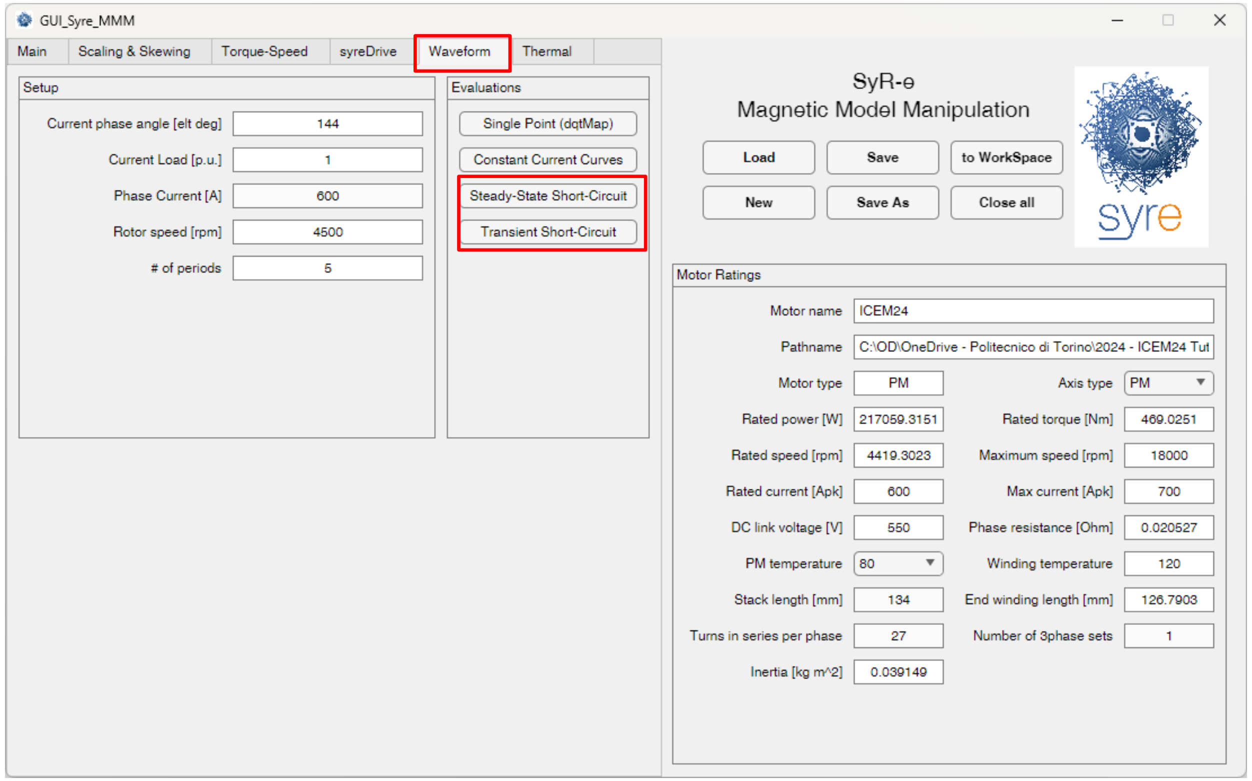
- Valid for all the motors modeled in this framework

Steady-state short-circuit (SSSC):

- Torque and current function of speed
- Voltage maps computed over the dq plane and SC point identified

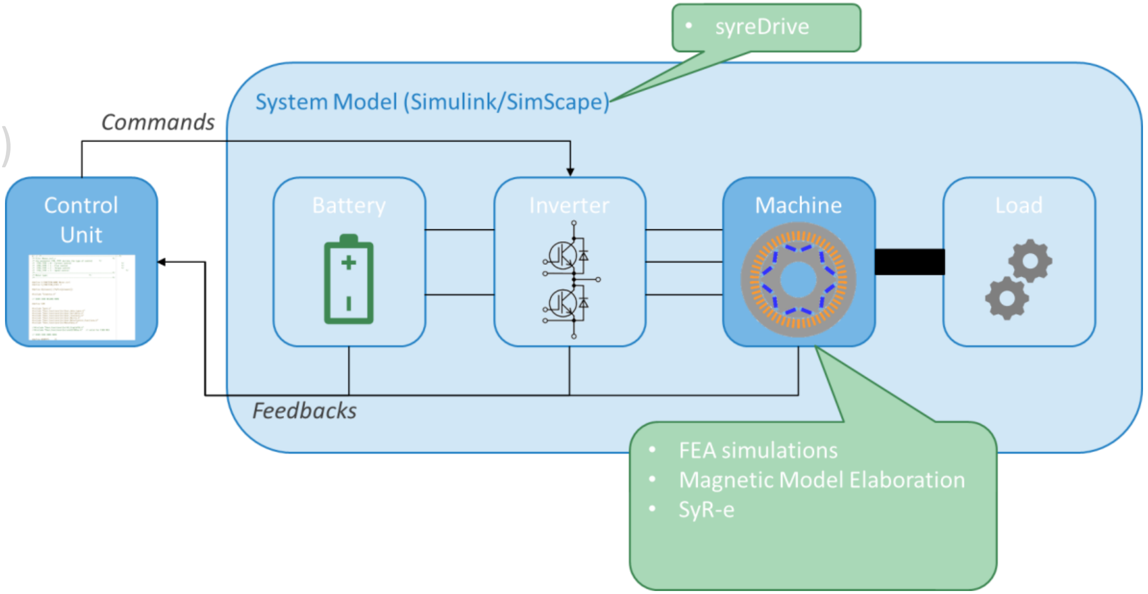
Transient short-circuit (TSC):

- Torque and current function of time
- Inverse maps needed
- Differential equation discretized and solved with back-Euler method
- Pre-fault condition must be set



Content

- Introduction
- Part 1: Electric Motor Modeling, Feng He (45 min)
- Part 2: SyR-e environment for eMotor Design and Analysis, Simone Ferrari (40 min)
  - Introduction
  - FEA simulation of PMSM
  - Motor Modeling
  - **eDrive Model: syreDrive**
  - Examples
  - Conclusions
- Part 3: Beyond the Electric Motor, Feng He (45 min)
- Q&A (20 min)

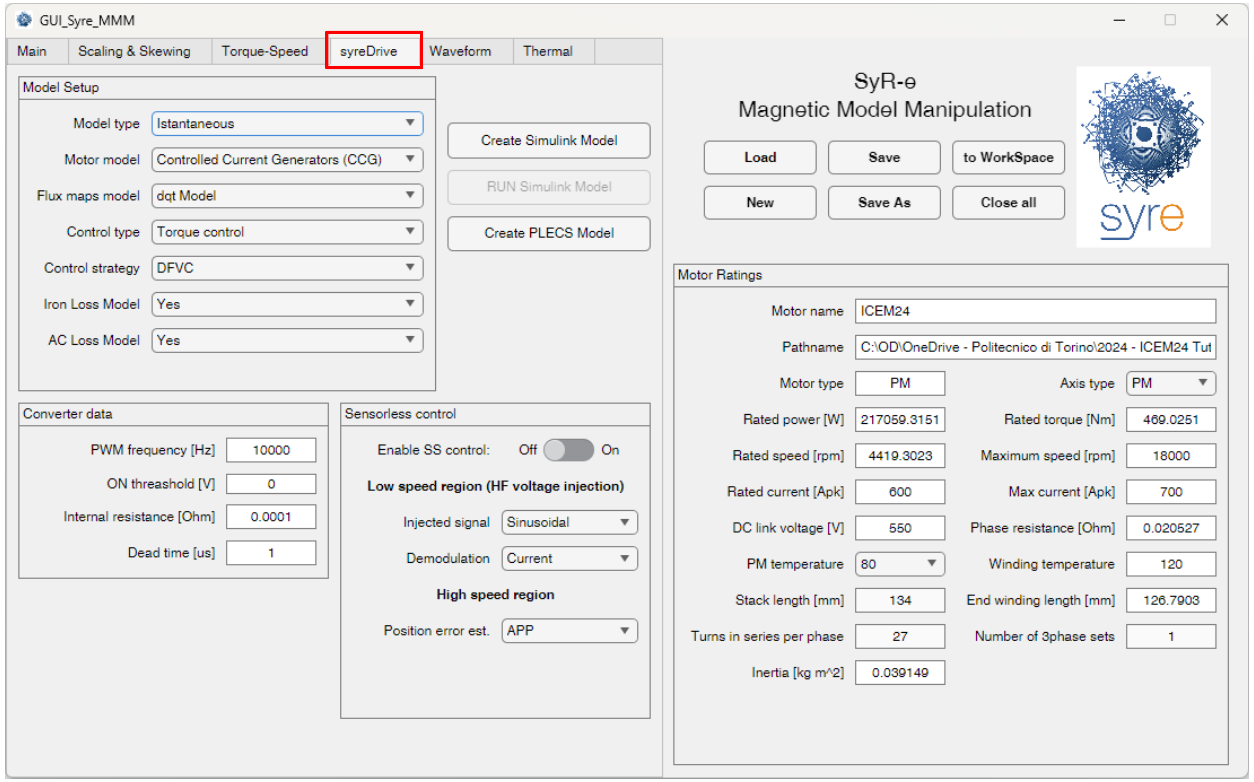


eDrive Dynamic Model

eDrive modeling is implemented in Simulink/SimScape or other similar environment

syreDrive: direct interface between eMotor design, FEA simulation and the eDrive dynamic model

- Inverter modeled with SimScape block (AVG or PWM)
- Different eMotor models
- C-based control algorithm, current, torque and speed control available and auto-tuned
- Sensorless control scheme included



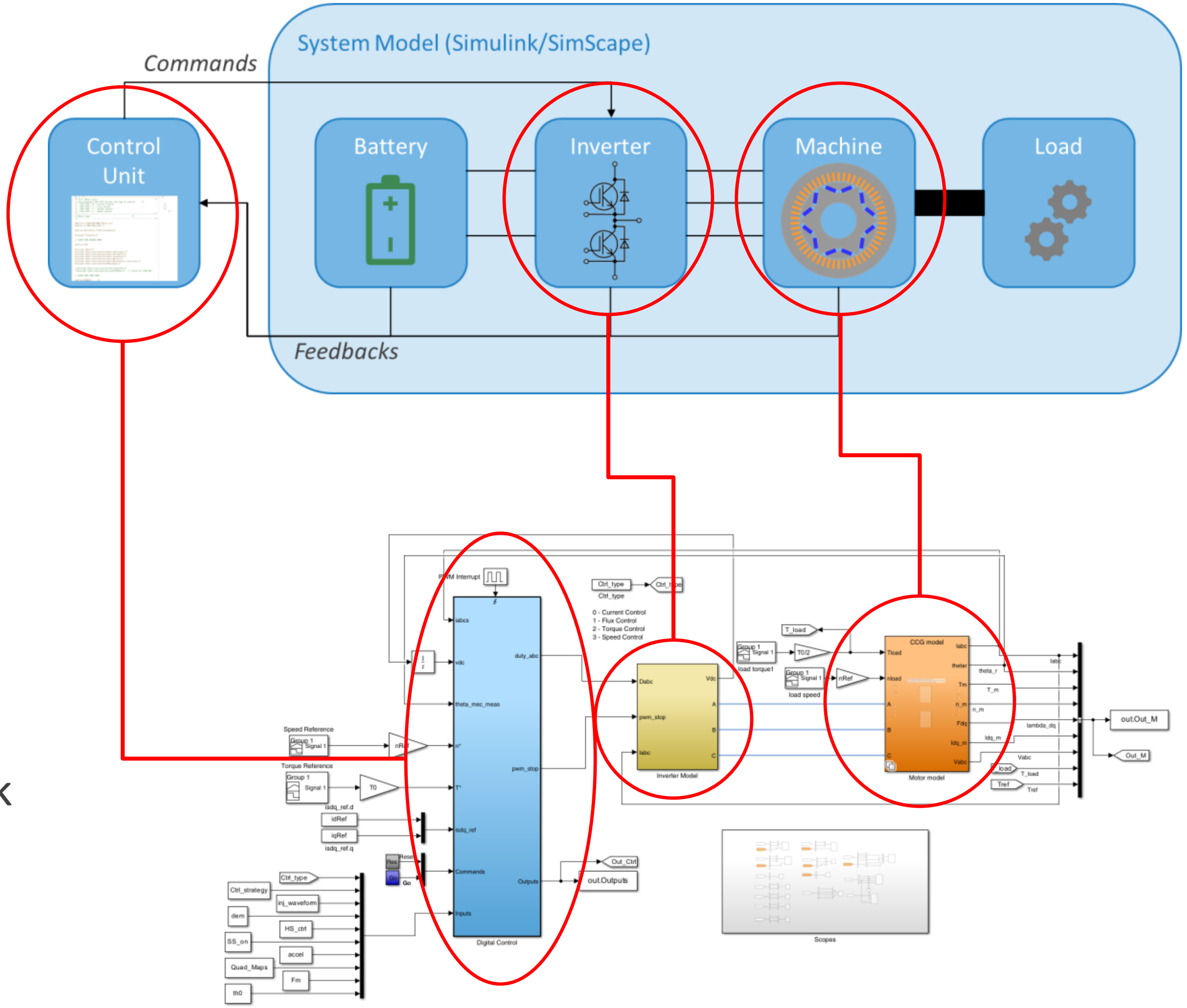
eDrive Dynamic Model

All the eDrive blocks must be included:

- Control unit is included with C-file S-function
- Inverter included through SimScape Electrical block and can be average or instantaneous (with PWM)
- Motor is modeled with flux maps. Different models possible

Some elements are less detailed:

- Battery (or DC-link) is assumed ideal and embedded in the inverter block
- Mechanical load is embedded in the motor block and assumed ideal (constant speed or torque, based on the motor control algorithm)



eDrive Dynamic Model – eMotor

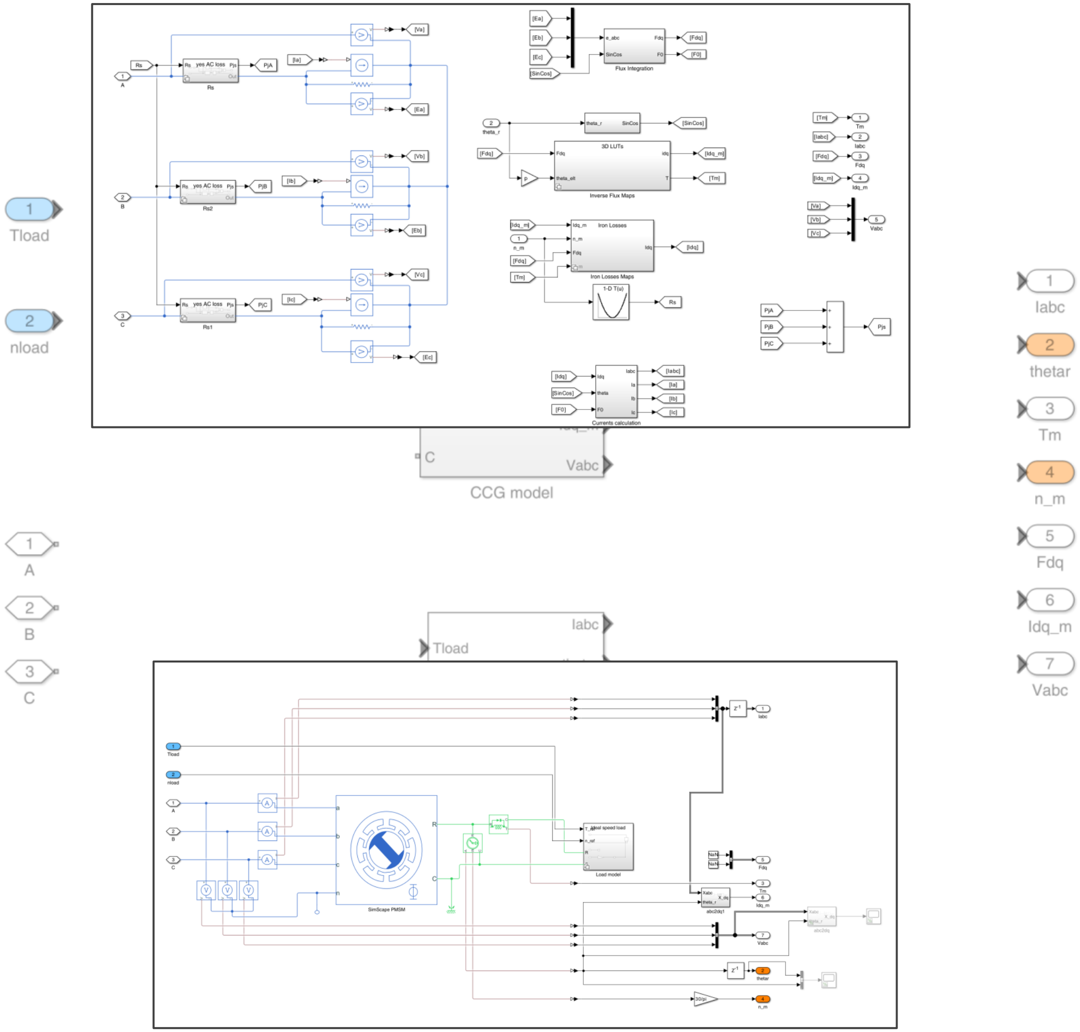
Variant subsystem in Simulink can switch between the different models:

- Controlled Current Generator (CCG)
- Voltage-Behind-Reactance (VBR) → WIP
- FEM-based SimScape PMSM block

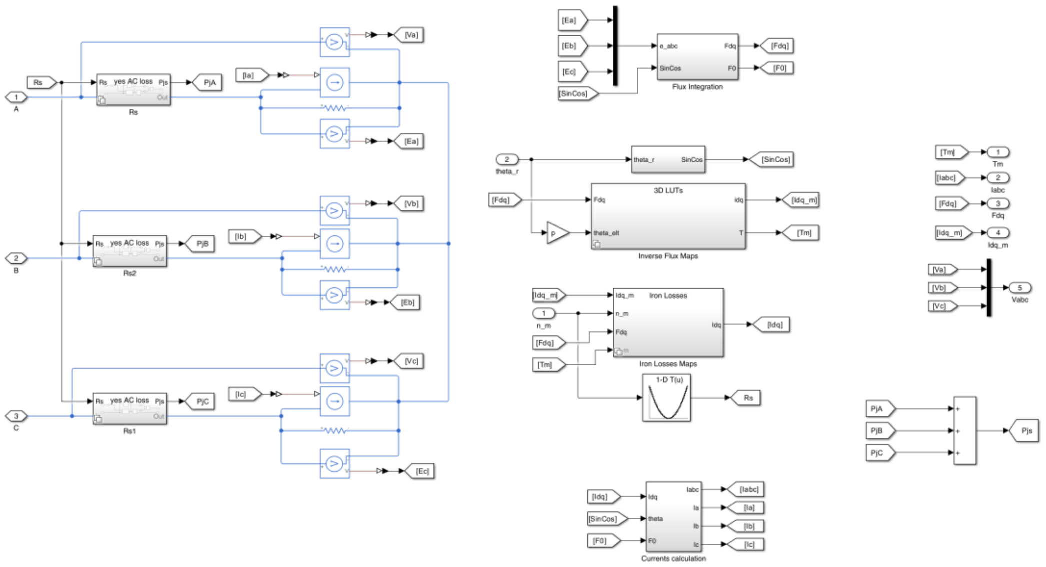
Dealing with the type of model, different degrees of complexity can be selected:

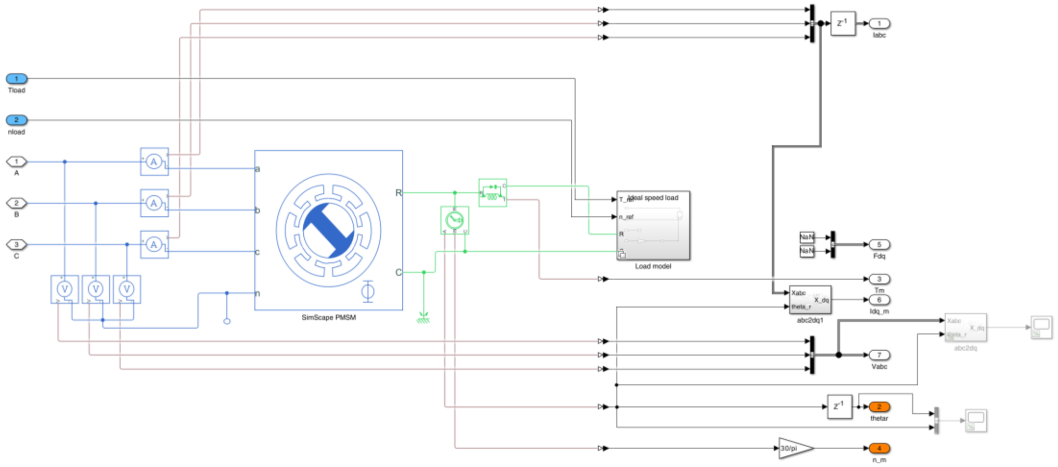
- Loss-less or lossy model
- Fundamental (dq) or harmonic ($dq\theta$) model

Accuracy – computational time trade-off



eDrive Dynamic Model – eMotor





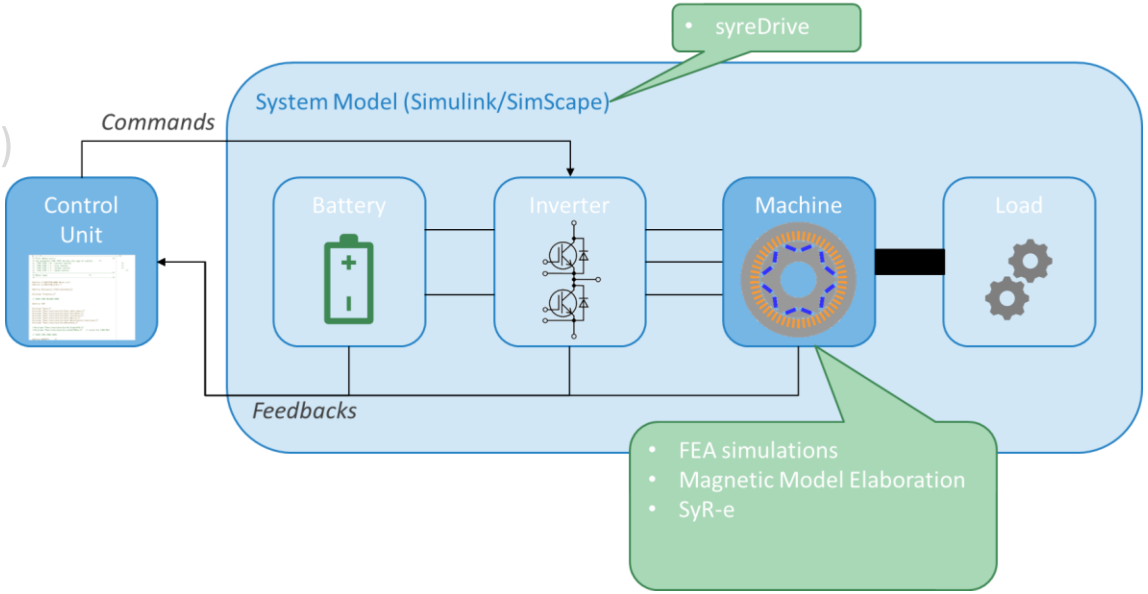
CCG:

- Implemented with SimScape blocks
- Based on inverse maps
- Fundamental or harmonic model
- Model iron and AC copper loss (if needed)
- Flux linkages and all the model internal variables are available
- Mechanical load implemented with Simulink blocks

SimScape FEM-parametrized PMSM

- From built-in SimScape Electrical blocks
- Based on direct flux maps
- Harmonic model only
- Allow iron loss, not AC copper loss
- Flux linkages and internal variables are not available
- Mechanical load implemented with SimScape blocks

Content



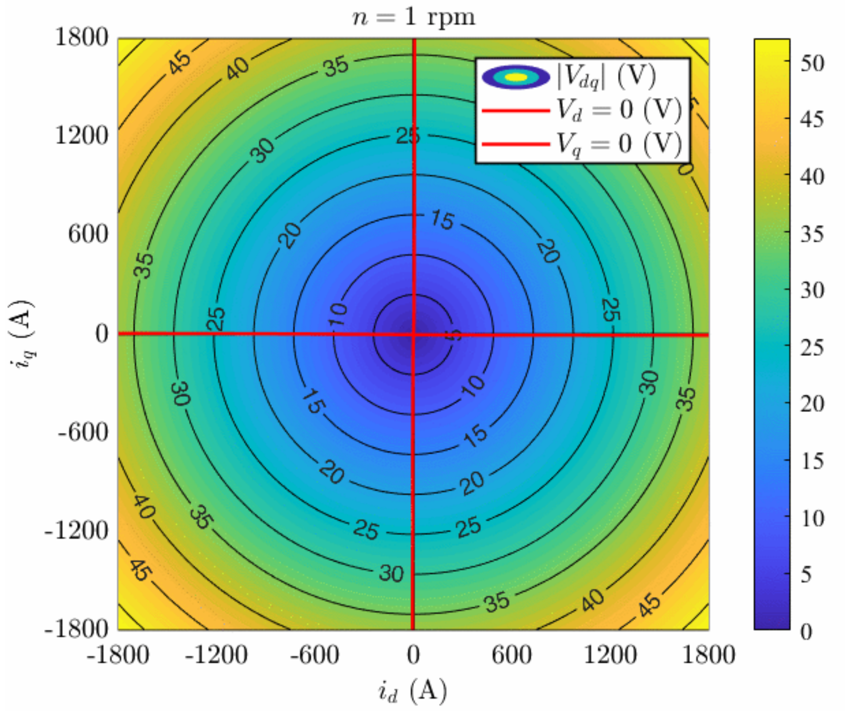
syreDrive
System Model (Simulink/SimScape)
Commands
Control Unit
Battery
Inverter
Machine
Load
Feedbacks
FEA simulations
Magnetic Model Elaboration
SyR-e

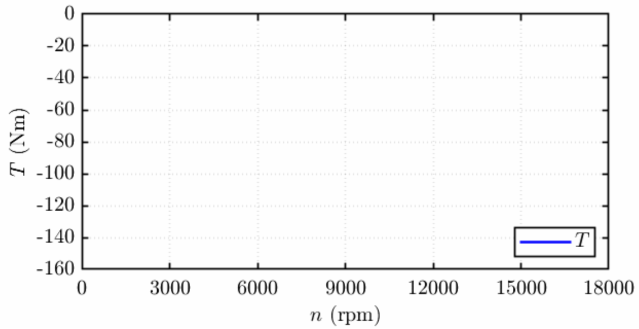
Example #1: Short-Circuit Analysis

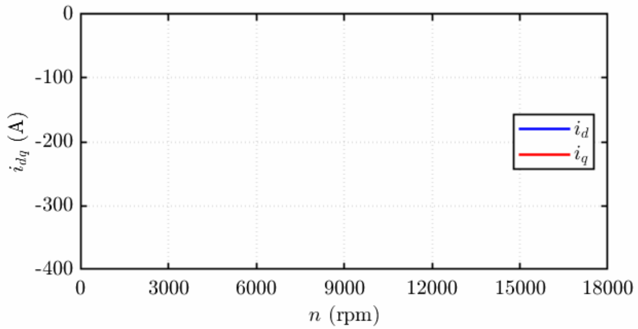
First, **Steady-State Short-Circuit** is considered
- Rated temperature
- Curves function of speed

At low speed:
- Voltage is given by phase resistance drop
- Back-emf is null
- SSSC is at zero current

At high speed:
- Phase resistance voltage drop is negligible, voltage given by back-emf
- SSSC is at characteristic current
- Braking torque is low



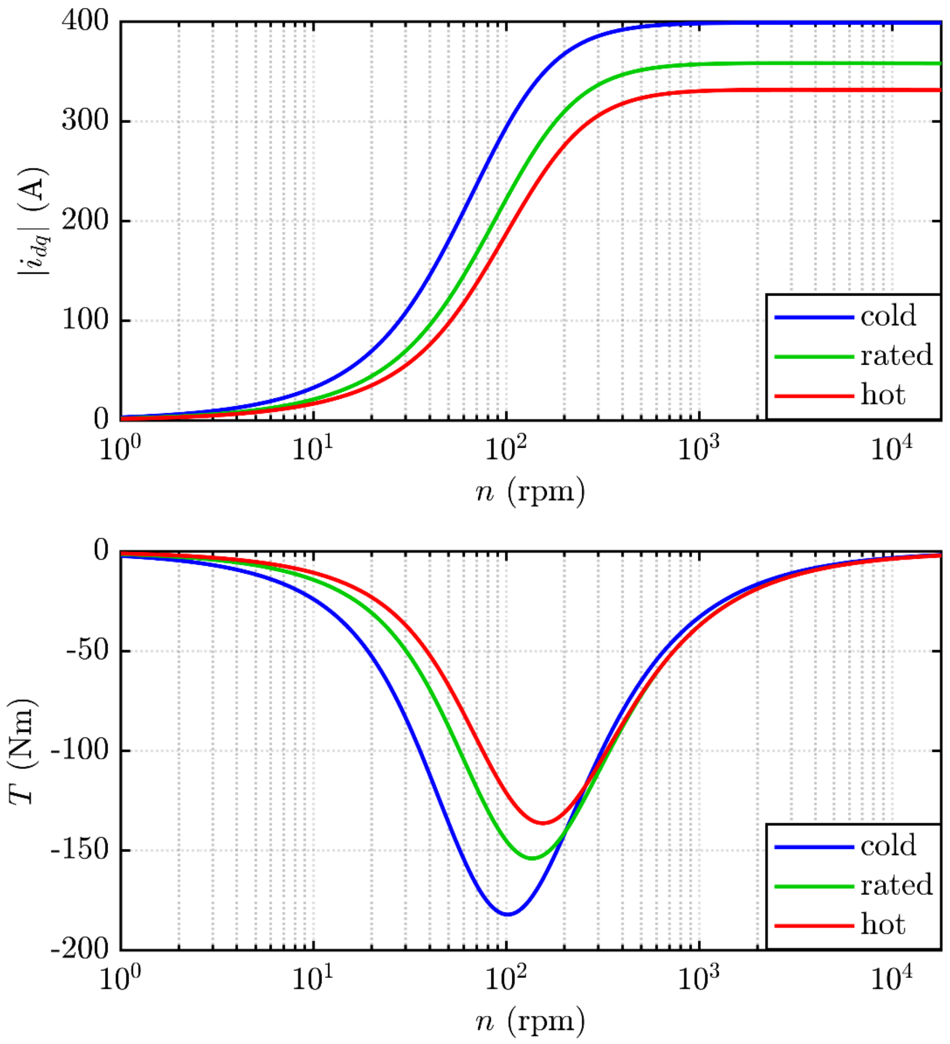




Example #1: Short-Circuit Analysis

Investigation on the **short-circuit behaviors** and the effects of **temperatures**

- High-speed steady-state current reduces with temperature increase → PM flux linkage and characteristic current changes
- Peak breaking torque change in amplitude and speed → different effect of back-emf and resistance voltage drop



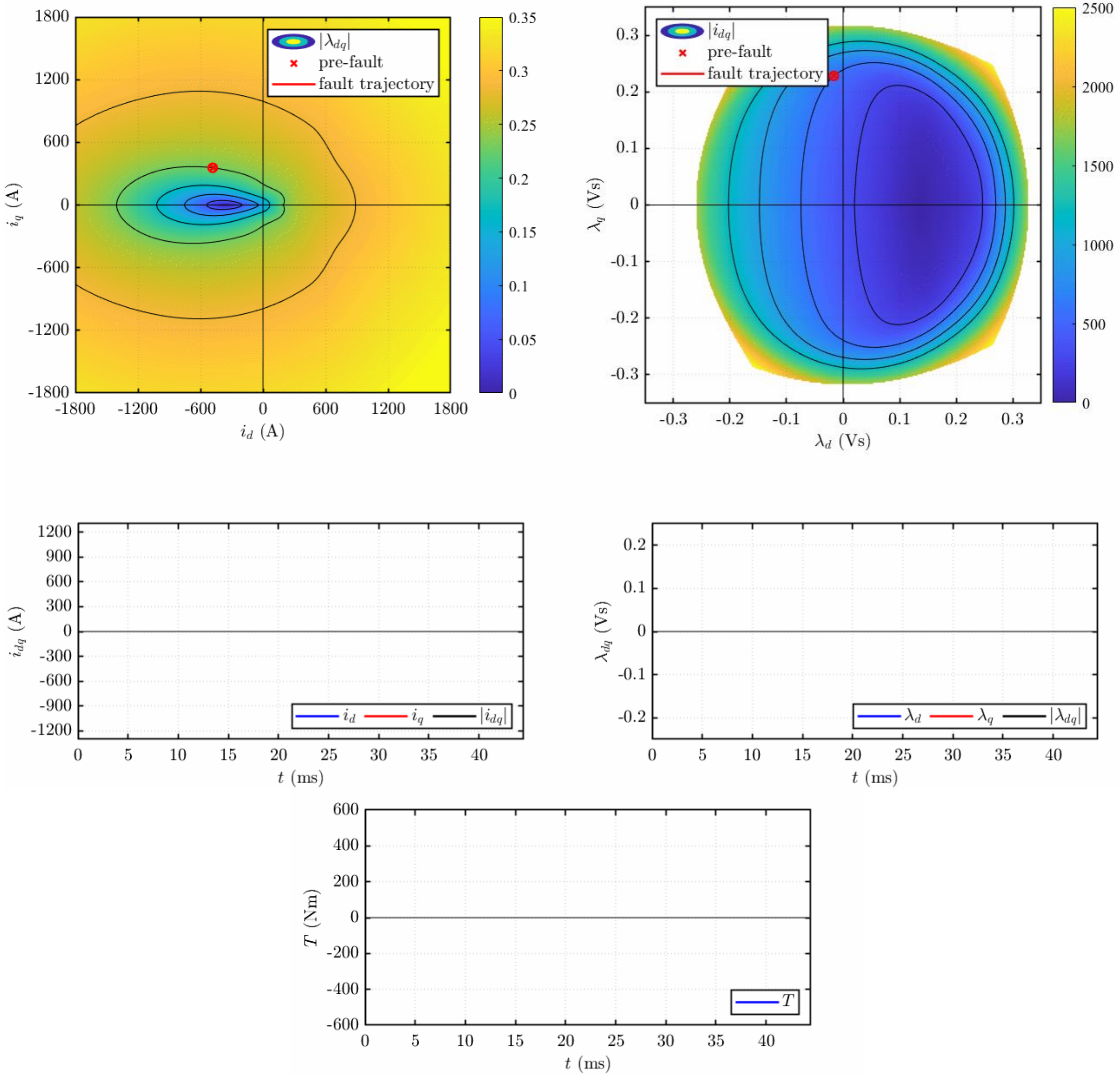
Example #1: Short-Circuit Analysis

Transient Short-Circuit is then considered:

- Rated temperature
- Pre-fault point: max torque at base speed

TSC trajectory:

- Follows a spiral in the (λ_d, λ_q) domain
- Damping due to copper loss
- In the (i_d, i_q) domain, the trajectory is ellyptical, centered on the SSSC point



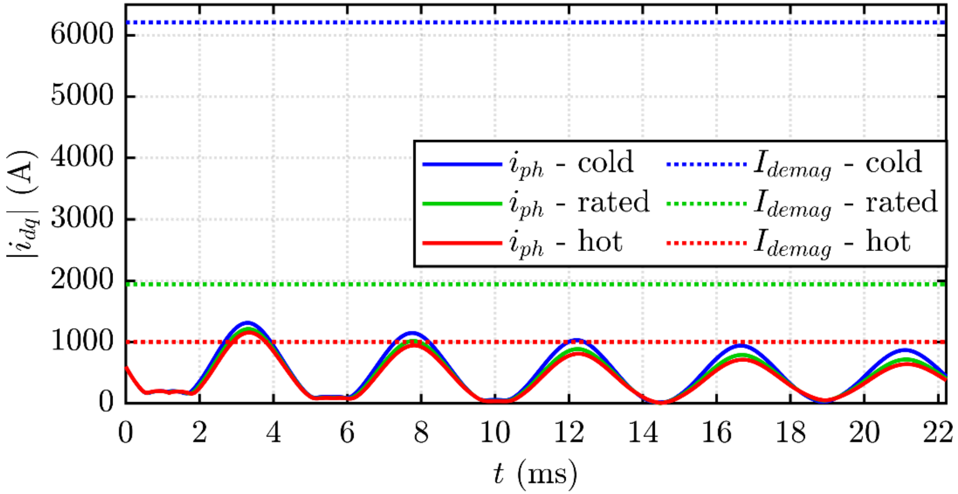
Example #1: Short-Circuit Analysis

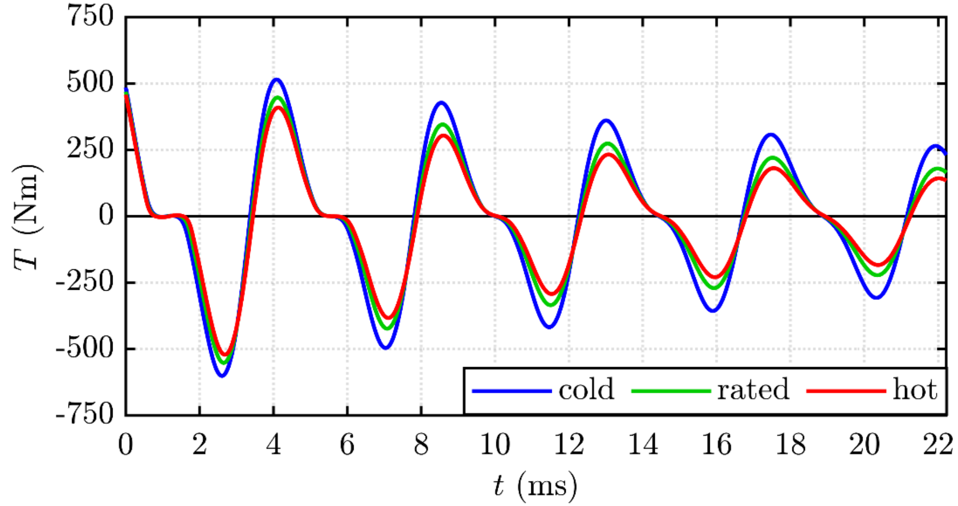
Temperature effect is studied in **transient conditions**

- Pre-fault at base speed and peak torque

The effect is coherent with the SSSC

- Higher temperture reduce the peak current and torque
- Hot condition is critical for **demagnetization** issue (limit current drastically decreased with temperature)





Example #1: Short-Circuit Analysis

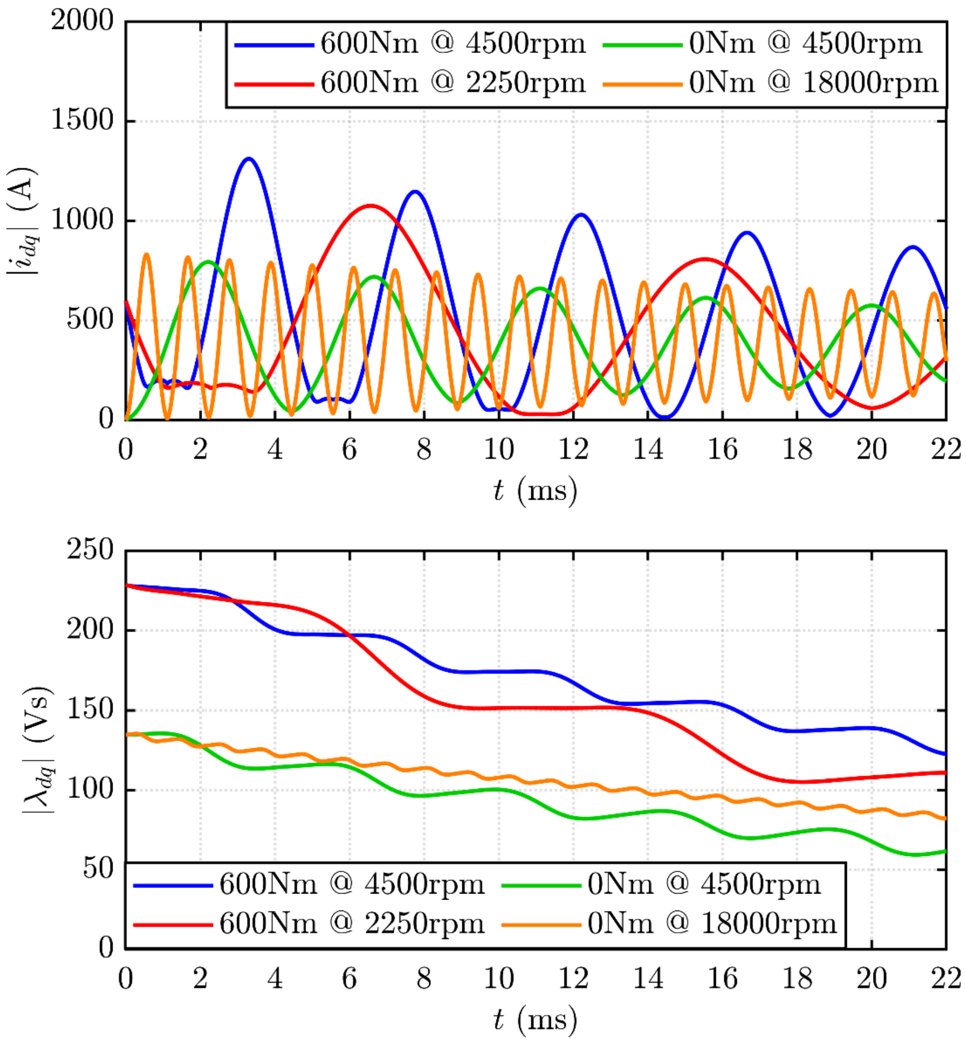
Pre-fault condition is investigated at rated temperature

Four points are considered:

- Peak torque, rated speed
- Peak torque half rated speed
- No load, rated speed
- No load maximum speed

Results

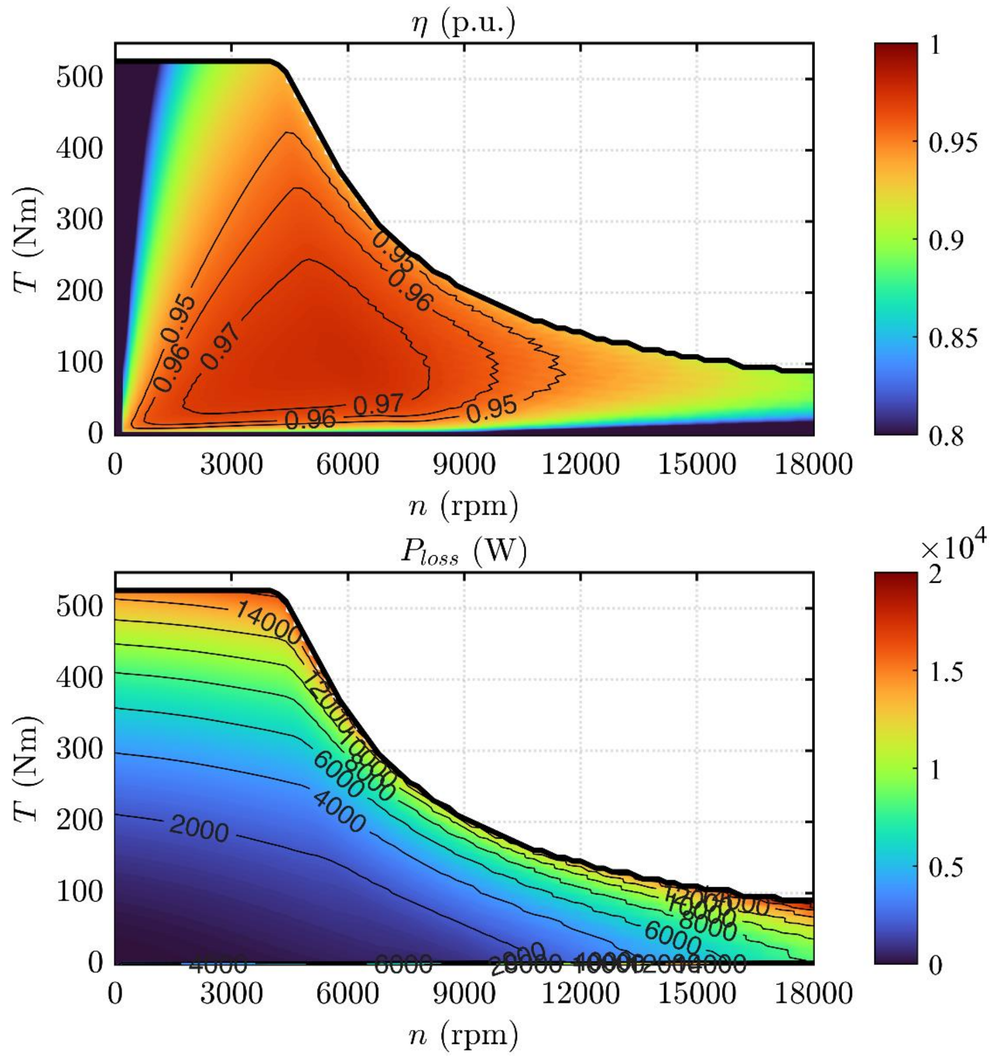
- Peak current is function of the pre-fault flux linkage
- At given flux linkage, lower the speed, lower the peak current (more time for damping)



Example #2: Efficiency and Loss Maps

The efficiency maps are computed with sinusiudal current

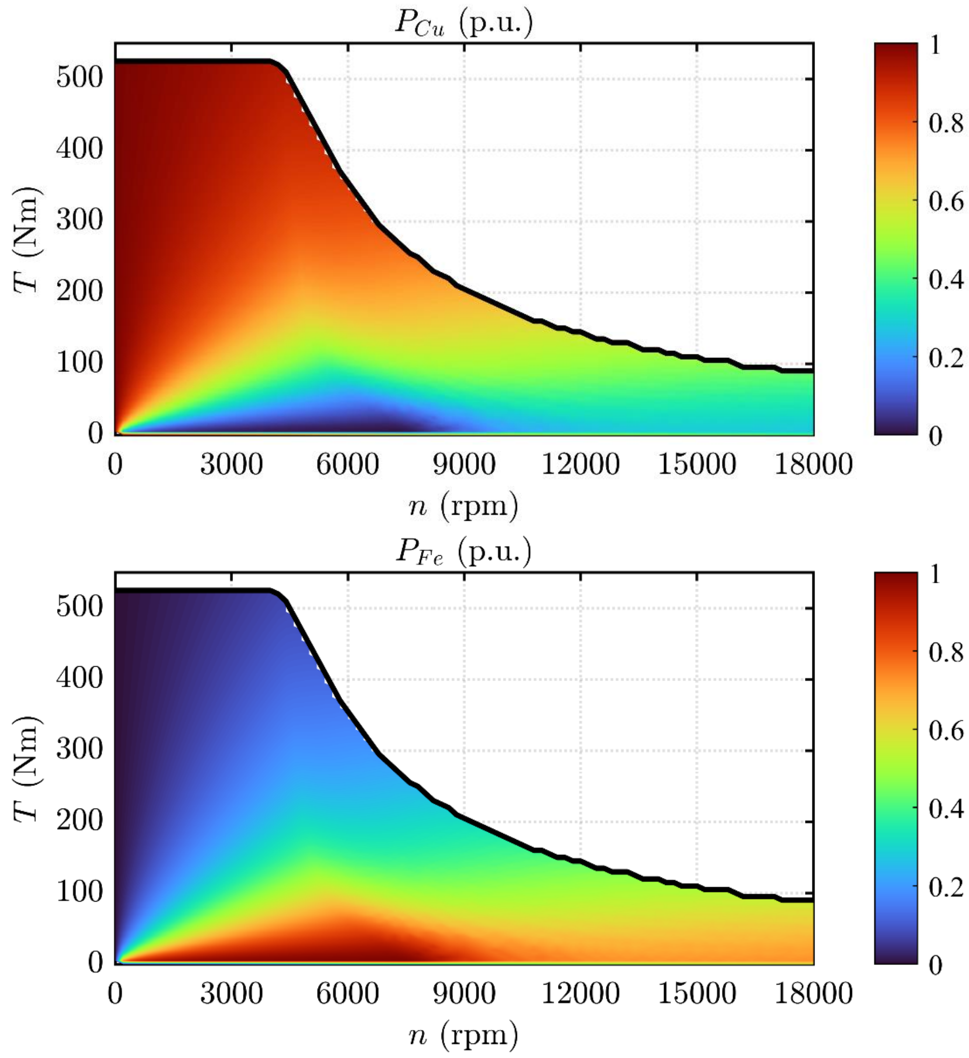
- Imposed inverter limits
- Constant Cu and PM temperature
- MTPA + field weakening is implemented
- Different loss terms can be considered



Example #2: Efficiency and Loss Maps

Loss components can be studied and separated:

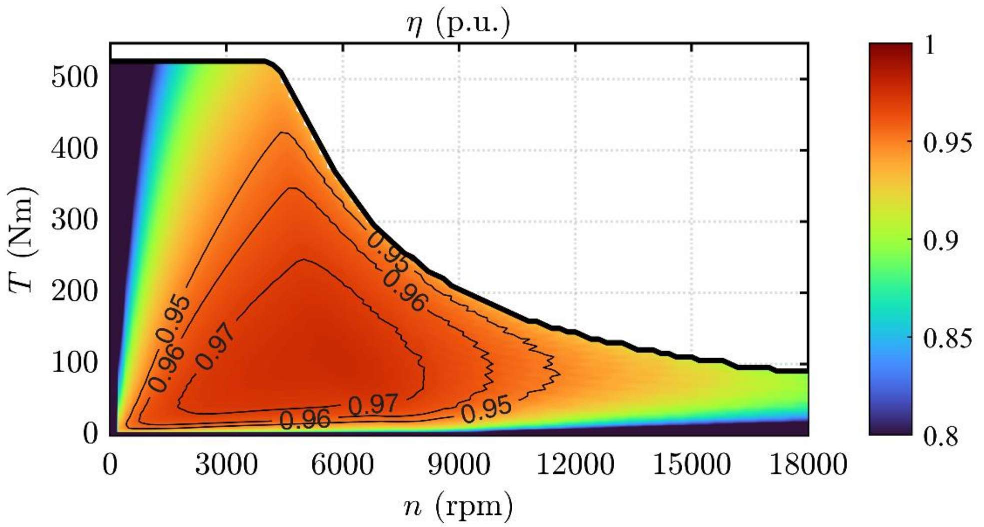
- Copper loss
- AC effect on copper loss
- Iron loss
- PM loss
- Mechanical loss
- …

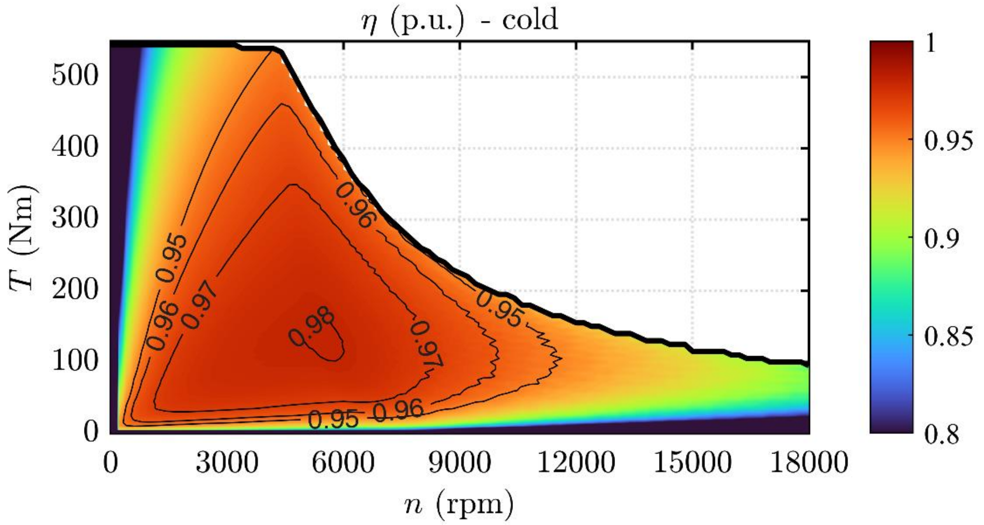


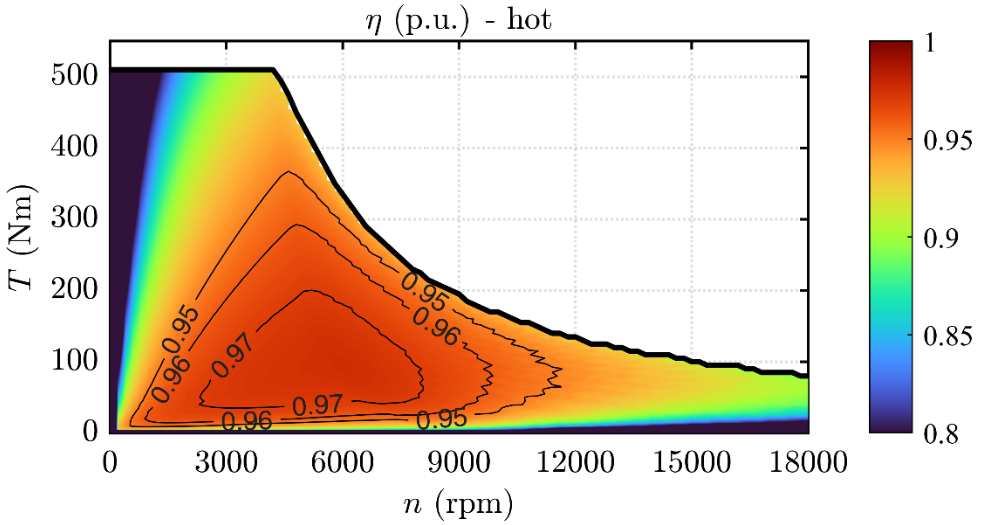
Example #2: Efficiency and Loss Maps

The maps can be computed at **different temperatures**, to understand the effect on:

- Peak torque
- Peak power
- Efficiency



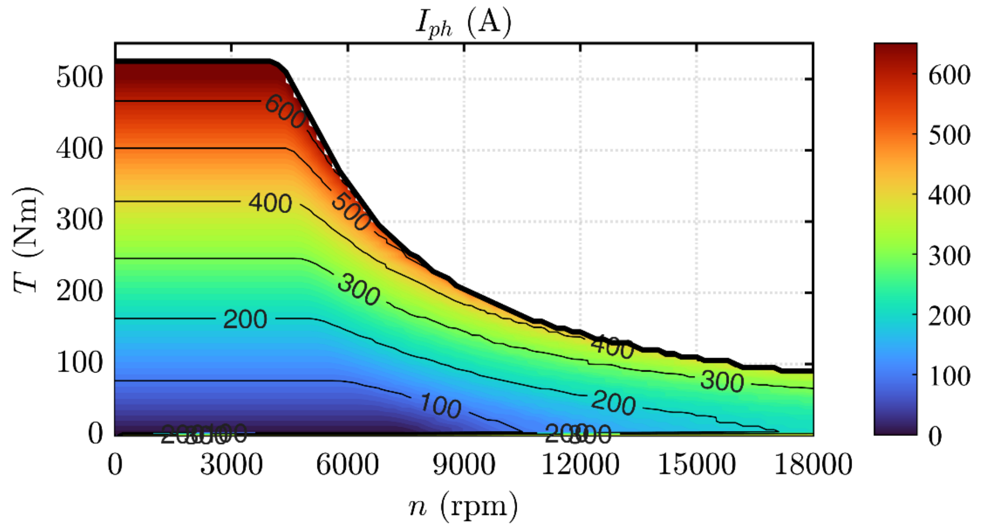


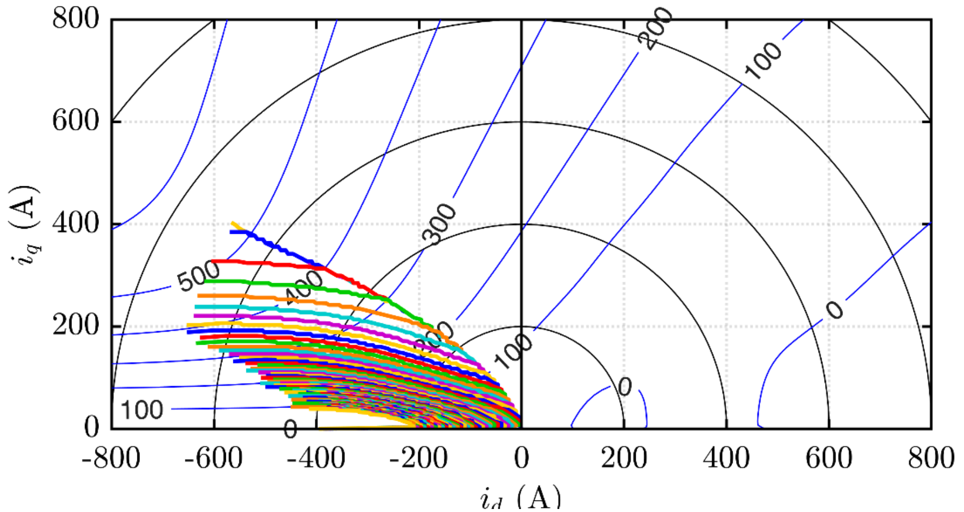


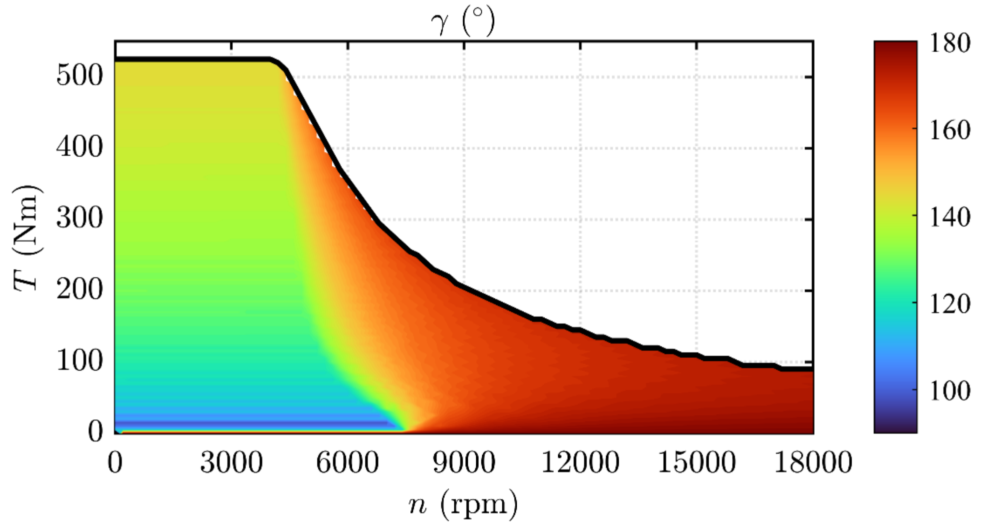
Example #2: Efficiency and Loss Maps

The **control algorithm** is automatically implemented:

- Control locus are retrieved for each (T, n) point
- Different control strategies can be considered, included loss minimization



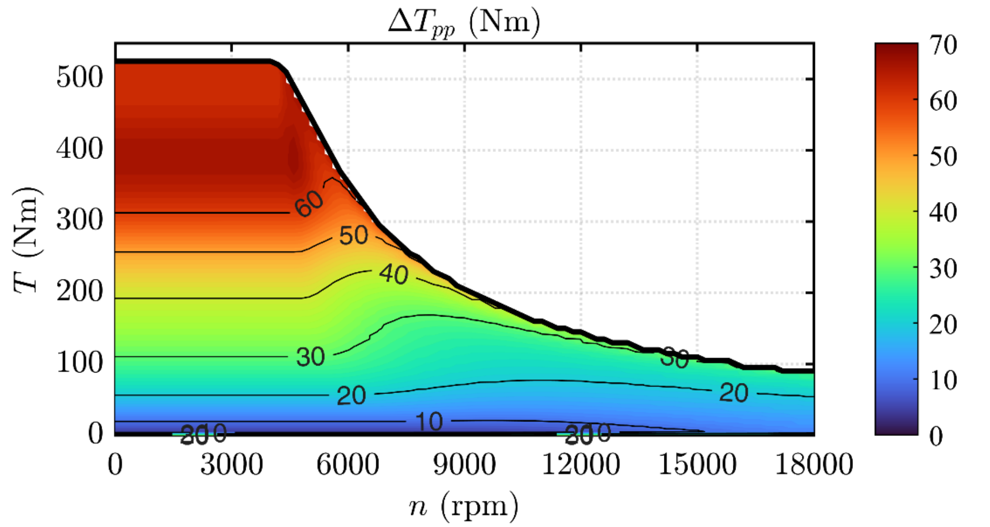


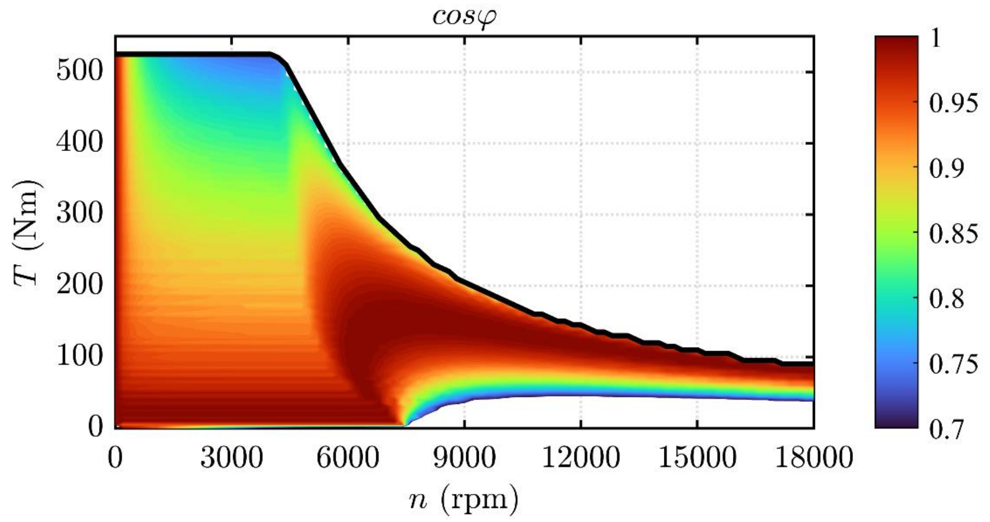


Example #2: Efficiency and Loss Maps

With the dq currents, all the quantities from flux and loss maps can be retrieved:

- Flux linkages
- Torque ripple
- Power factor
- Phase current and voltage
- …





Example #2: Efficiency and Loss Maps

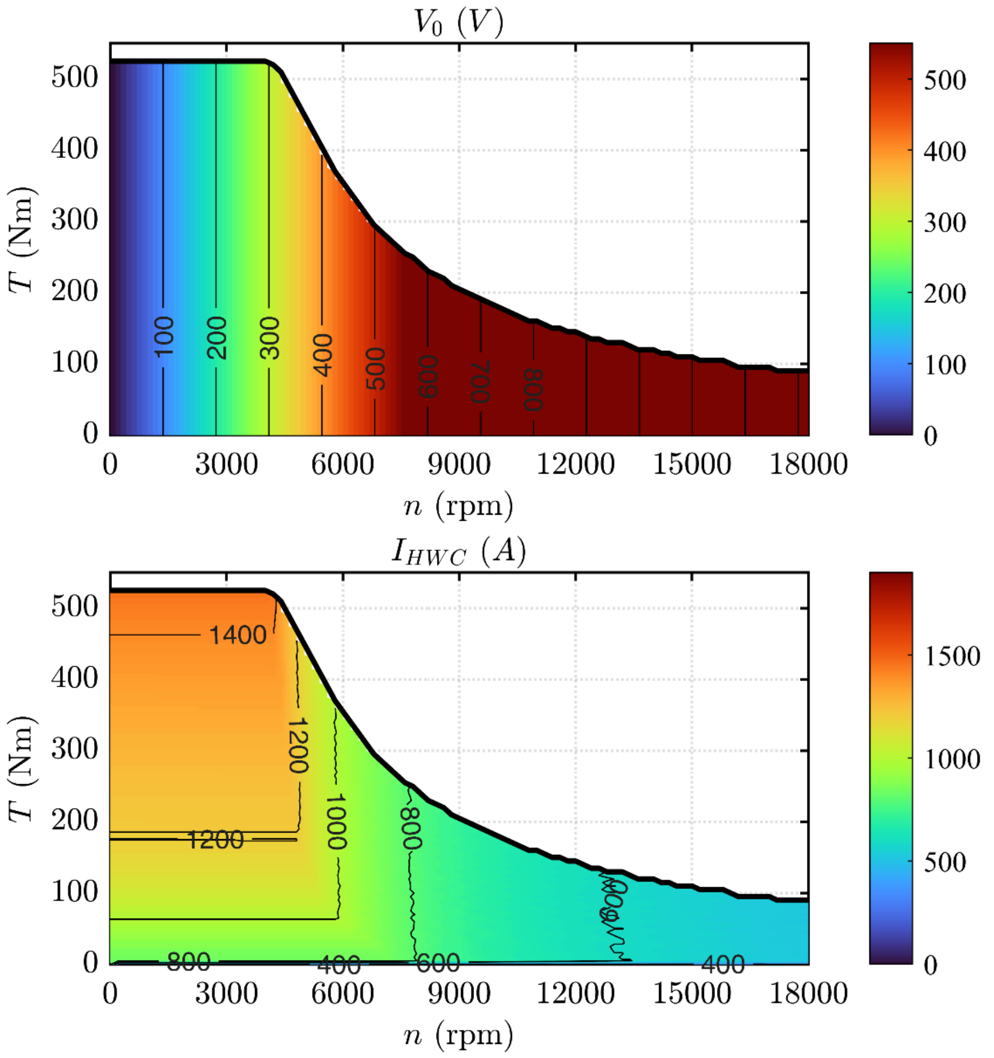
Post-fault safe state condition can be estimated over the plane:

- **OC**: the no-load voltage must be lower than the DC link (otherwise, UGO happens)
- **ASC**: peak short circuit current (HWC for computational burden) must be lower than the demagnetization limit

At rated temperature:

- ASC is always safe
- OC is dangerous above about 7000rpm

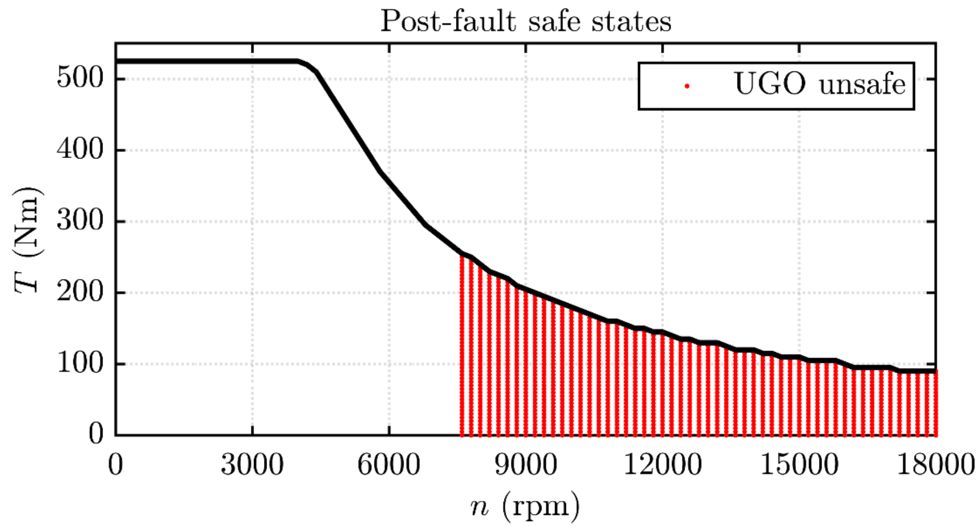
The turn-off modes changes with temperature!

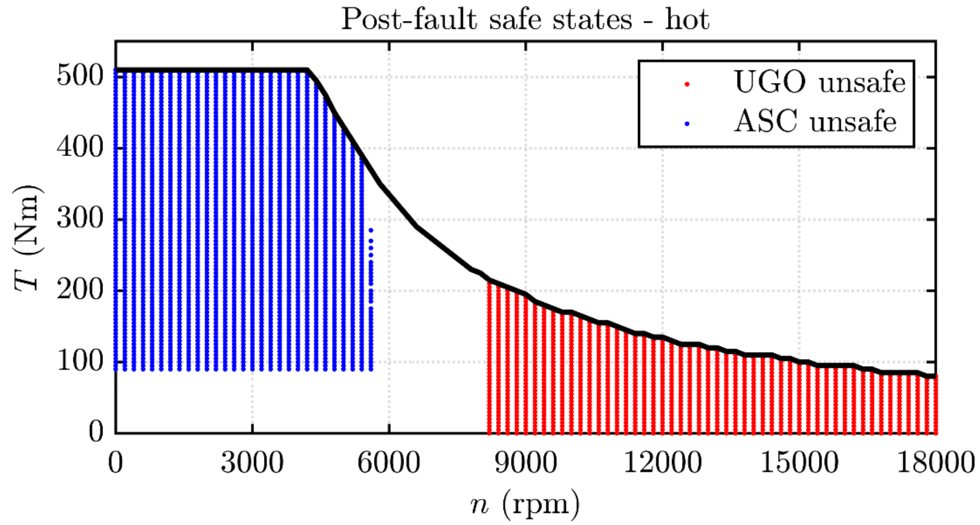


Example #2: Efficiency and Loss Maps

The safe states change with temperature.
Increasing temperature:

- PM flux linkage reduces → OC unfeasible area reduces
- Demag limit reduces → ASC unfeasible area increase

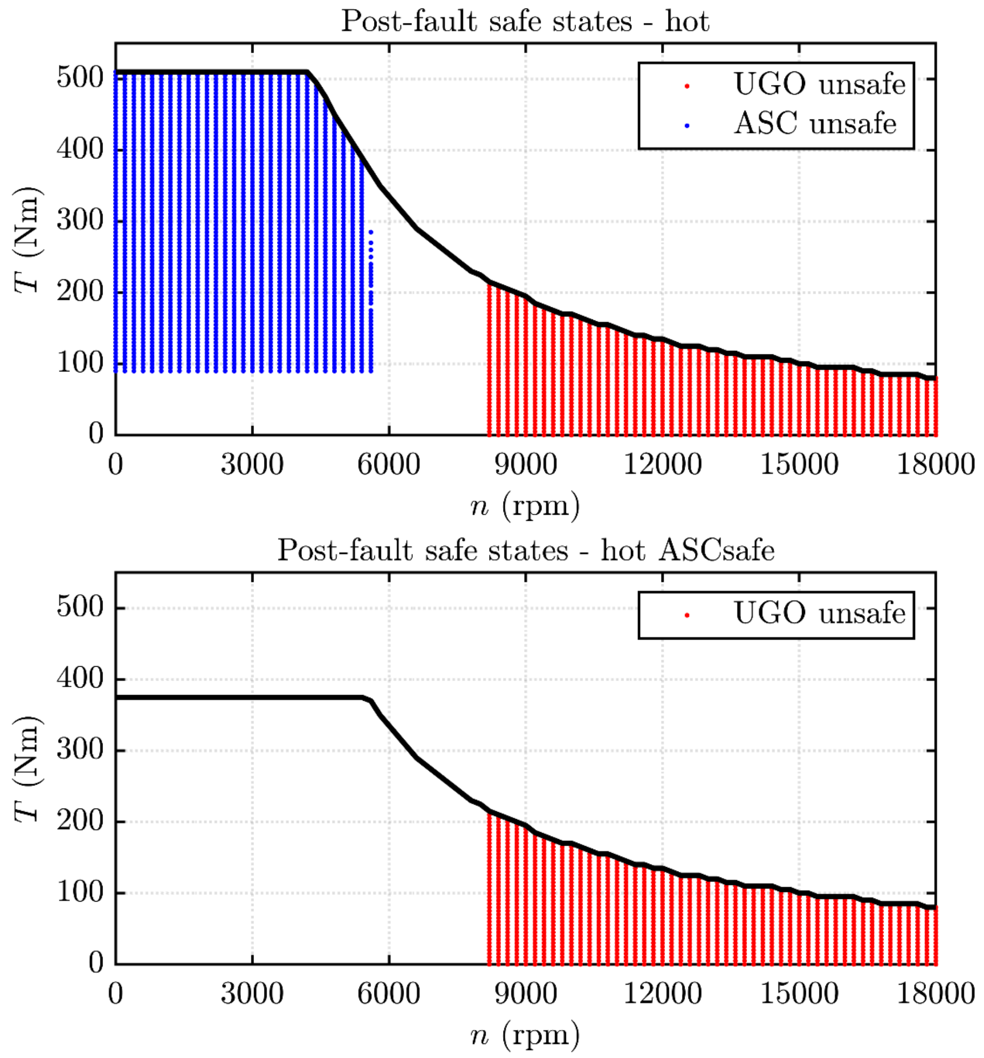




Example #2: Efficiency and Loss Maps

The ASC unsafe area can be reduced by control, by limiting the pre-fault flux linkage:

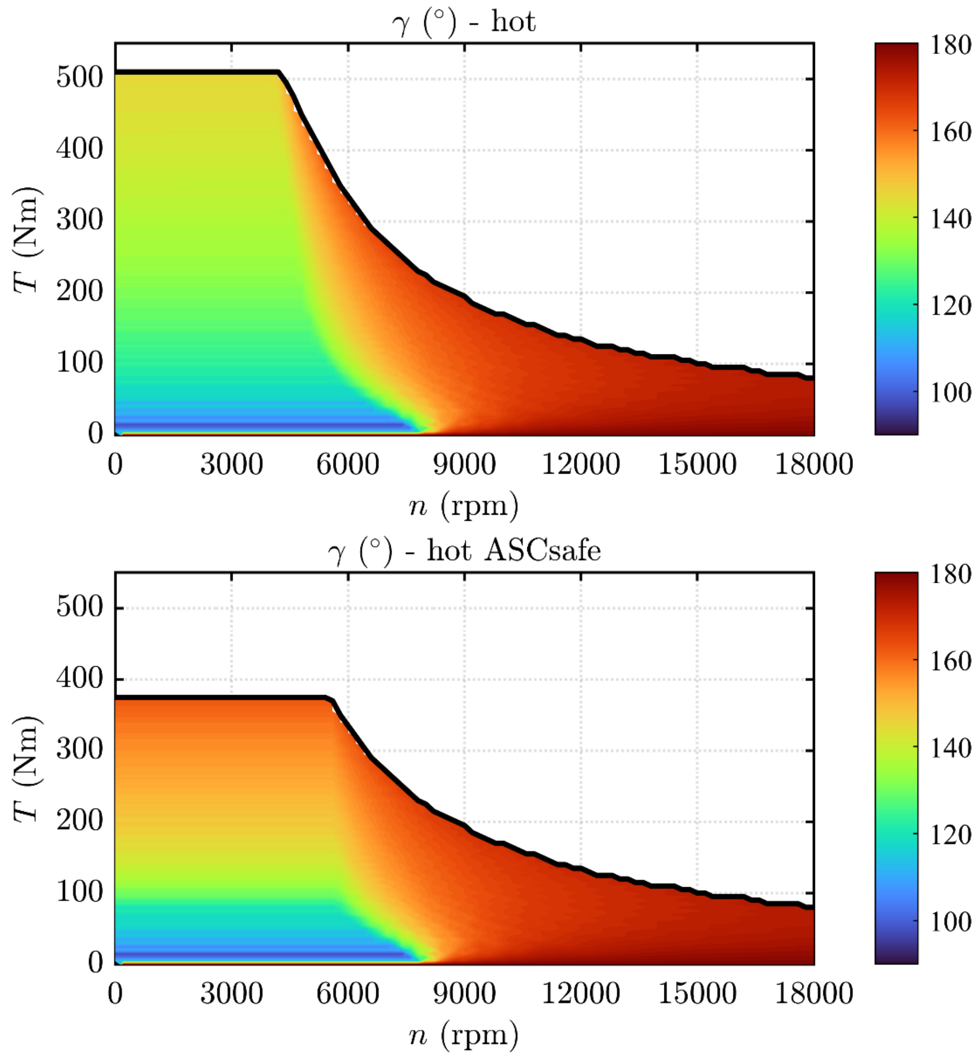
- Torque limitation (no MTPA at high load)
- Efficiency detriment
- Modification just at low speed (when flux linkage is high)



Example #2: Efficiency and Loss Maps

The ASC unsafe area can be reduced by control, by limiting the pre-fault flux linkage:

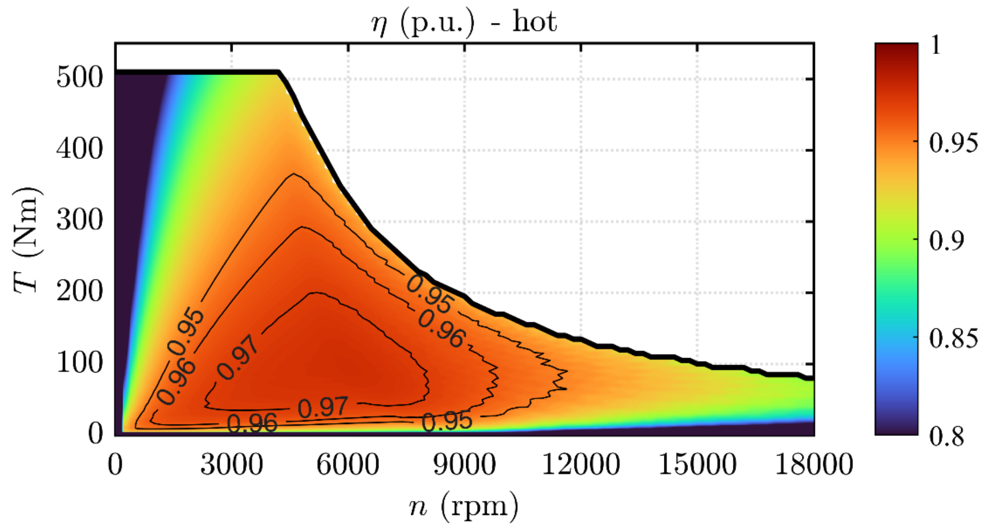
- Torque limitation (no MTPA at high load)
- Efficiency detriment
- Modification just at low speed (when flux linkage is high)

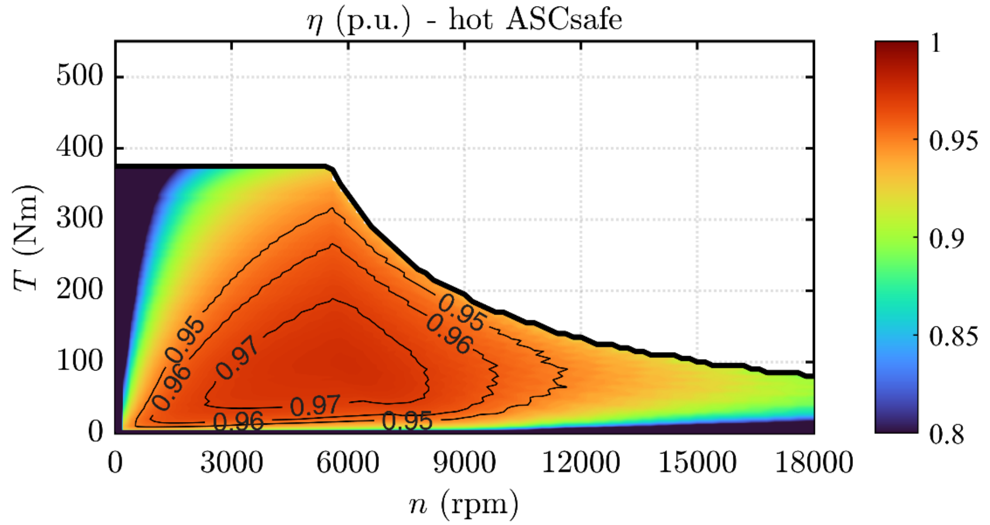


Example #2: Efficiency and Loss Maps

The ASC unsafe area can be reduced by control, by limiting the pre-fault flux linkage:

- Torque limitation (no MTPA at high load)
- Efficiency detriment
- Modification just at low speed (when flux linkage is high)





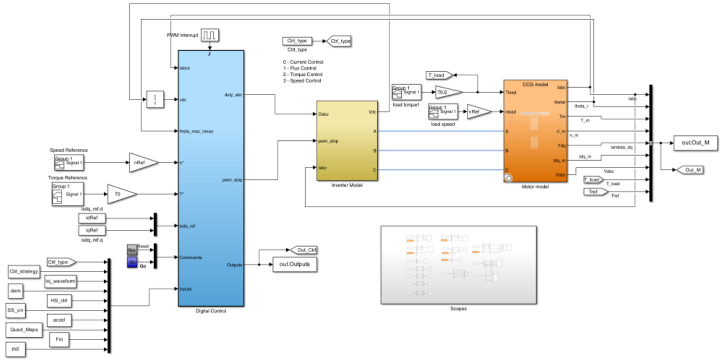
Example #3: Torque Control with syreDrive

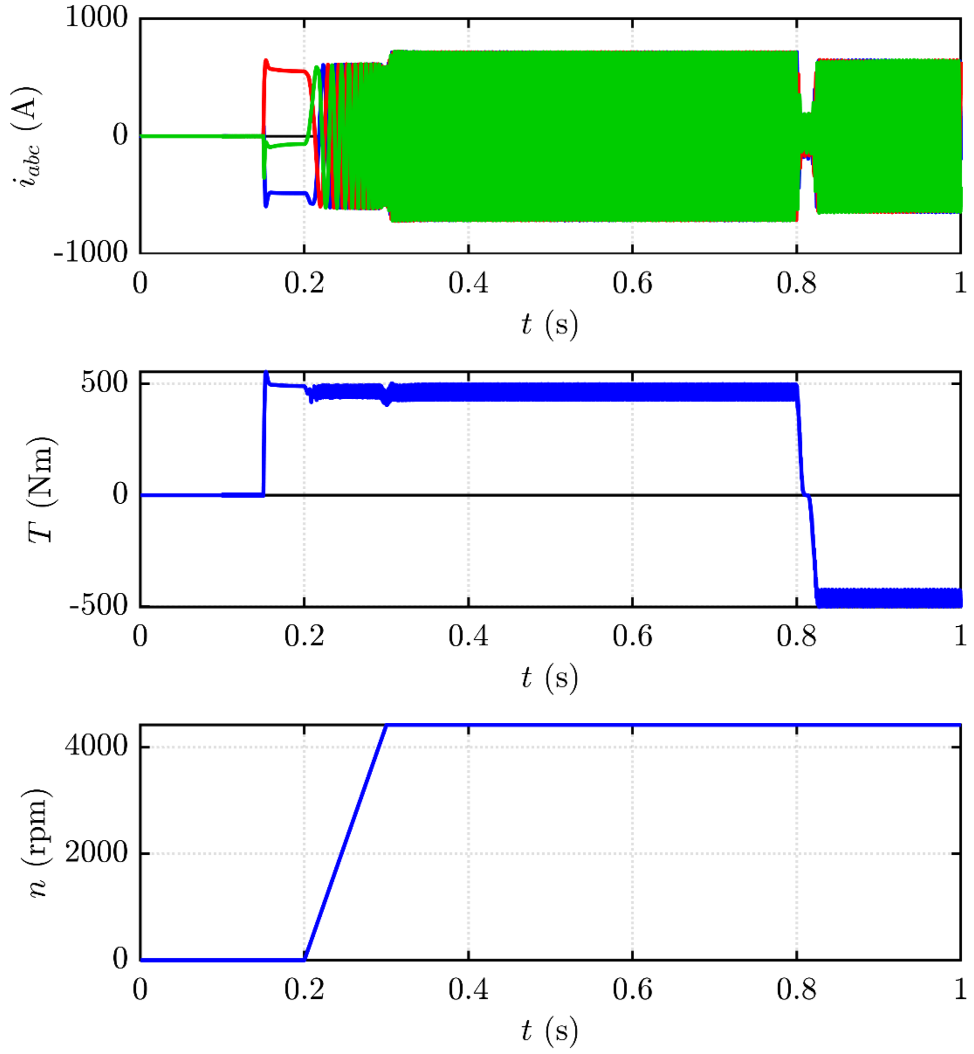
eDrive model is created in Simulink/SimScape

Torque control is automatically implemented with Direct Flux Vector Control (DFVC) and pre-calibrated

Torque and speed references can be changed from the Simulink model

Current, torque and speed from the motor are computed

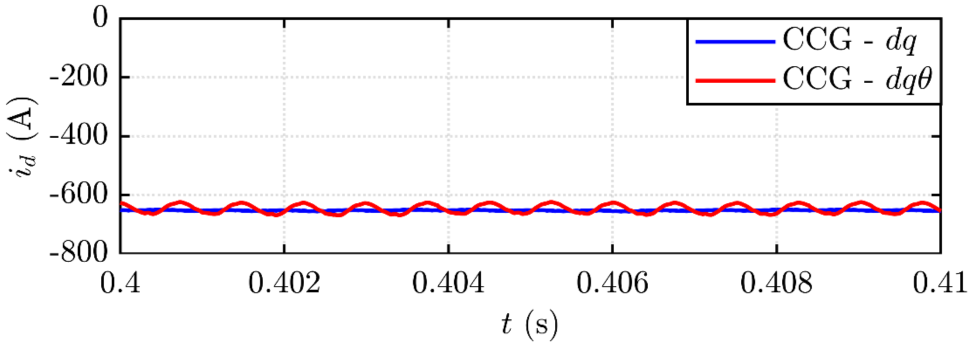


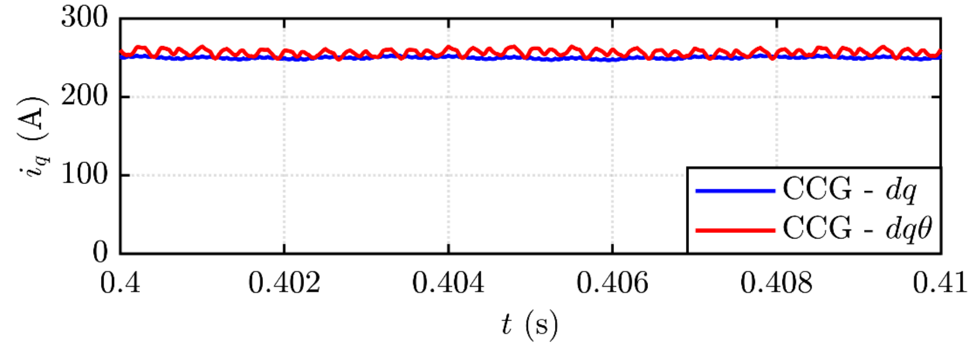


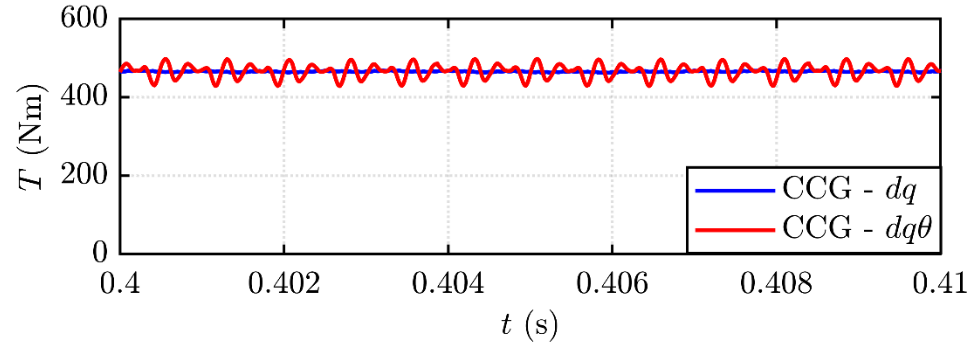
Example #3: Torque Control with syreDrive

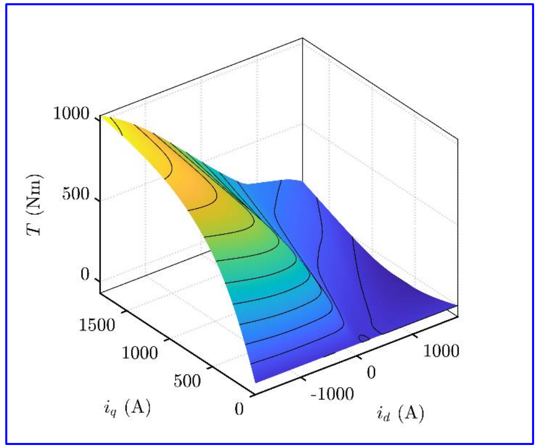
With CCG modeling, fundamental (dq) and harmonic ($dq\theta$) motor models are compared

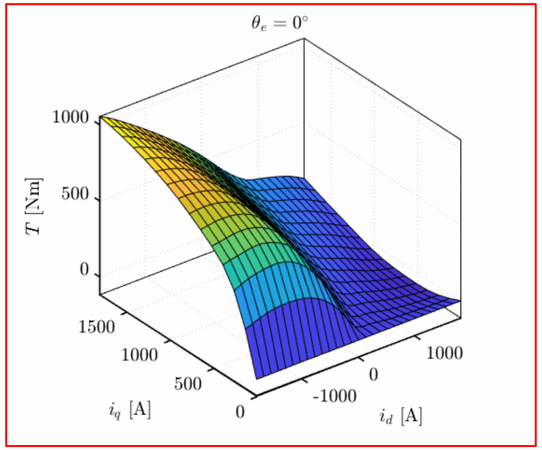
- Torque ripple is visible with $dq\theta$
- Spatial harmonic are visible also on the currents → controller must be calibrated accounting also for harmonics
- Slight computational time increase (13s versus 18s)











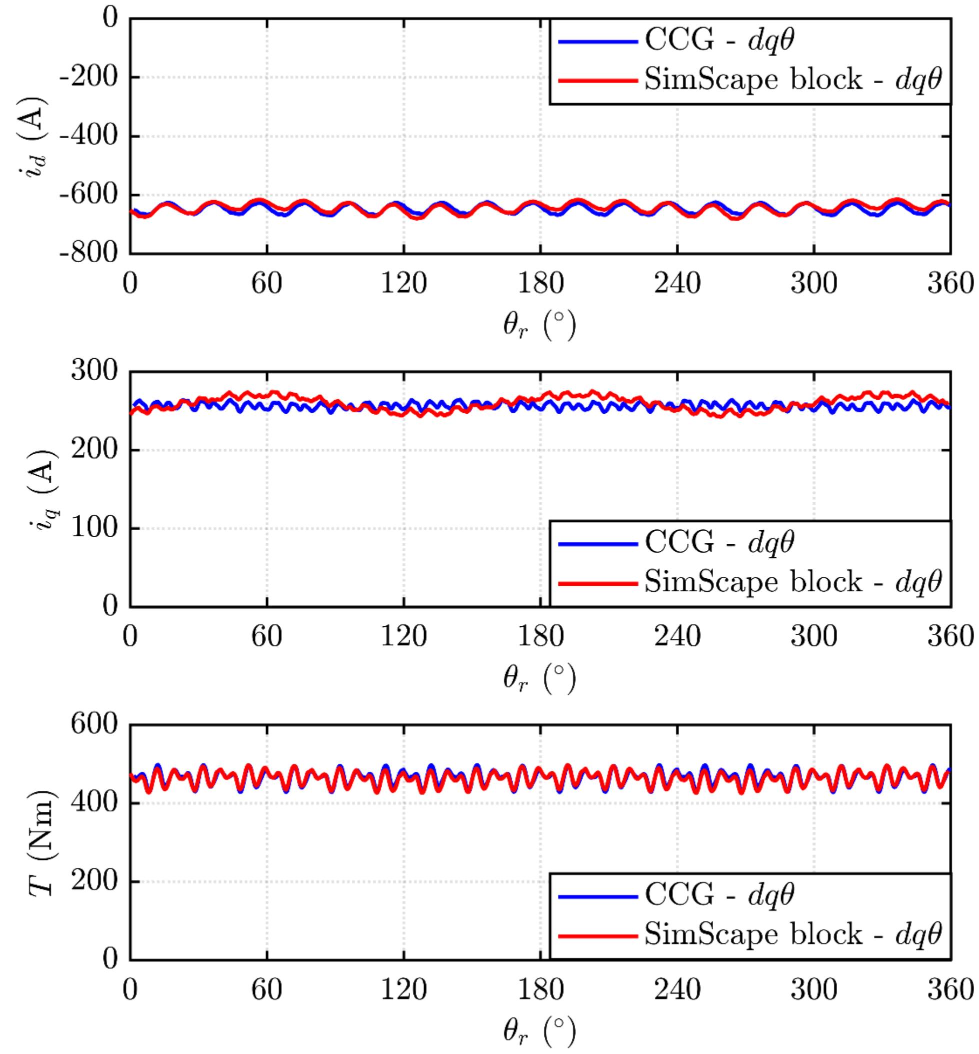
Example #3: Torque Control with syreDrive

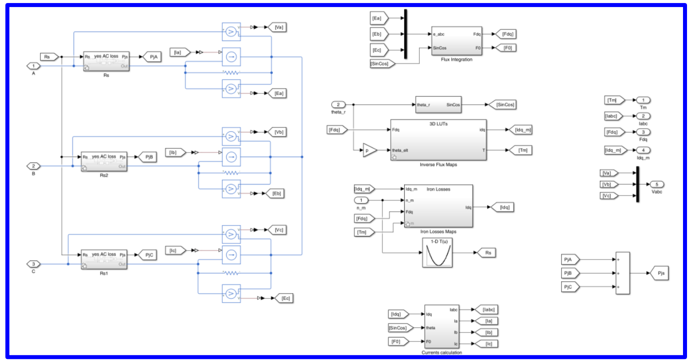
CCG model is compared with SimScape FEM-parametrized PMSM block

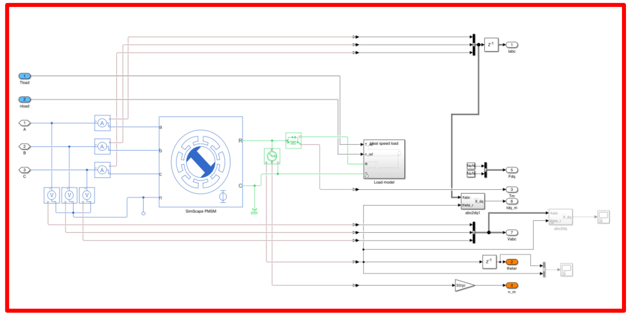
- Results are consistent ($dq\theta$ model)
- No direct availability of flux linkages of SimScape block → instrument-like modeling

Similar computational time:

- CCG=18s
- FEM-parametrized PMSM=14s







Example #3: Torque Control with syreDrive

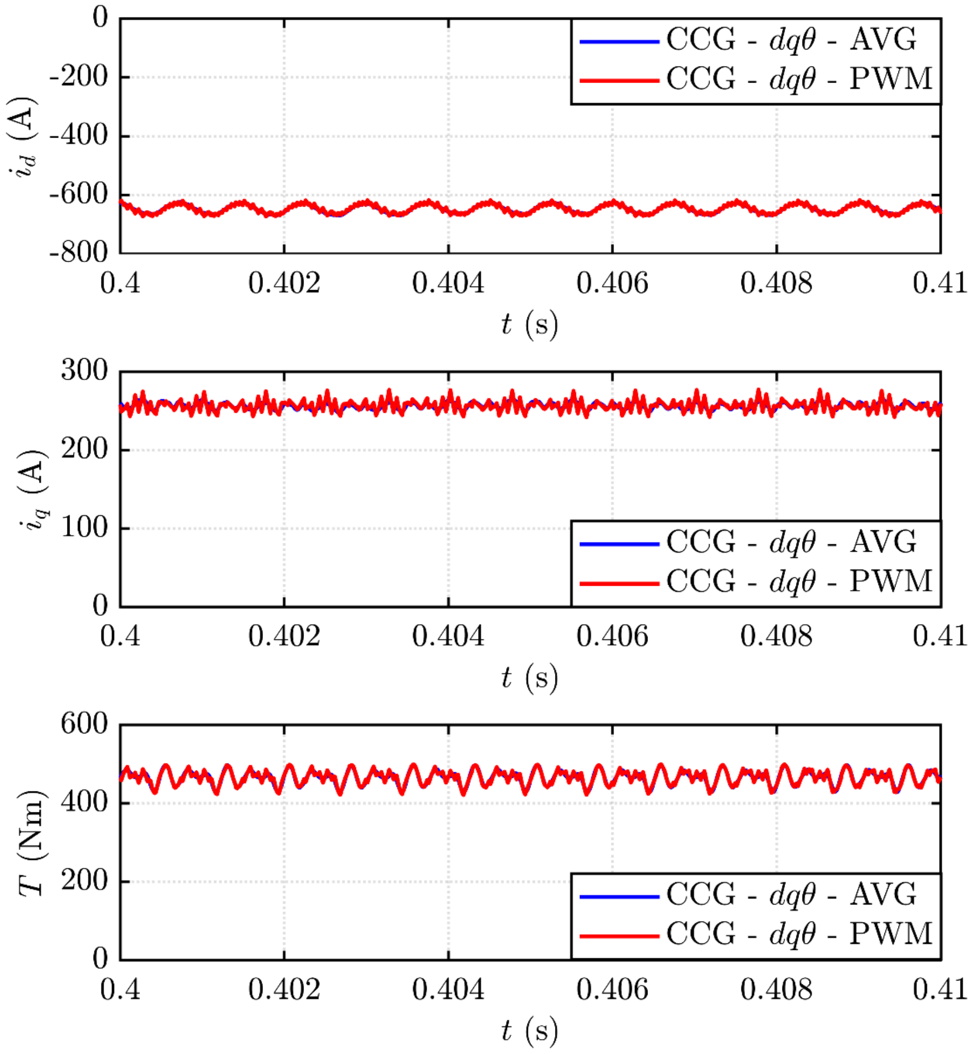
CCG model is adopted with PWM inverter

- PWM-induced current ripple is visible
- Small to no effects on torque ripple
- The effect change with speed and load!

Computational time are increase:

- AVG inverter: 18s
- PWM inverter: 36s
- Computational effort is increased also with SimScape PMSM block

NB: additional loss MUST be re-computed with dedicated FEA simulations!



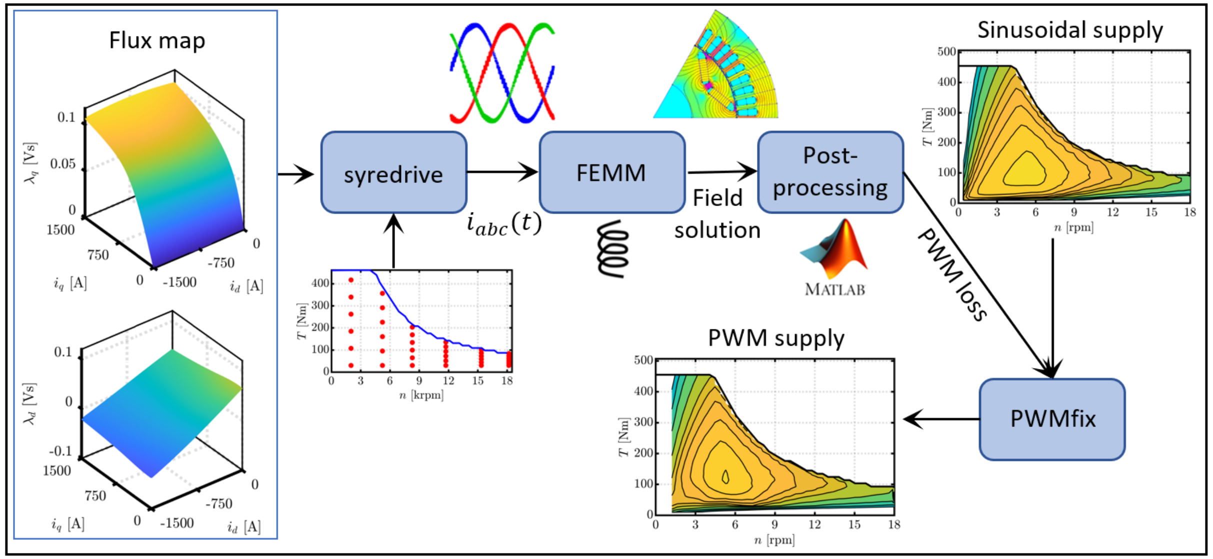
Example #4: PWM Effect and Loss

Efficiency maps was computed with sinusoidal supply, however, PWM can affect losses

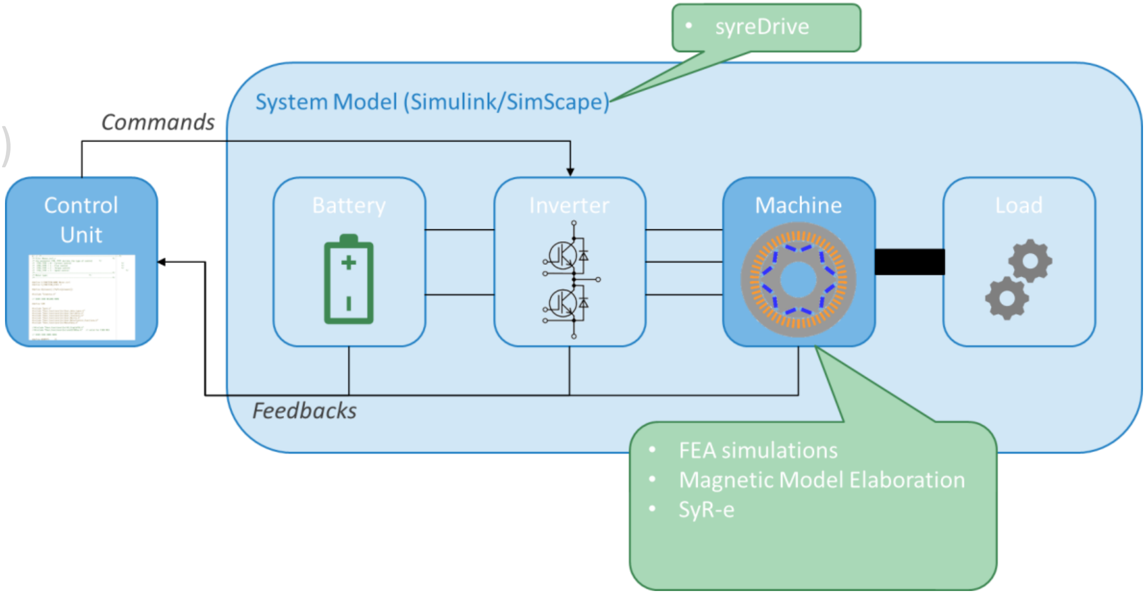
eDrive model cannot properly estimate the iron loss (loss model based on sinusoidal supply)

Solution: **PWMfix procedure**

- Some points of the (T, n) domain are evaluated with eDrive model and currents with PWM ripple are retrieved
- Dedicated FEA simulations are performed with custom currents to compute the PWM-induced loss
- Correction factors are computed and extended to the whole efficiency map



Content



syreDrive
System Model (Simulink/SimScape)
Commands
Control Unit
Battery
Inverter
Machine
Load
Feedbacks
FEA simulations
Magnetic Model Elaboration
SyR-e

Recap and Conclusions

The SyR-e approach in the motor modeling is presented

The **motor modeling** is based on **flux** and **loss maps**, in the dq reference frame. Detailed FEA simulations can be performed for specific motor behaviors

Magnetic model elaboration based on **flux and loss maps** are implemented for several motor metrics evaluation

syreDrive is the interface with **eDrive model** in Simulink. It is automatic and based on the same flux and maps previously computed. The user can select **several modeling apporach**, from the simplest (average inverter and motor, lossless) to the most complex (PWM inverter, motor with spatial harmonics, with loss).

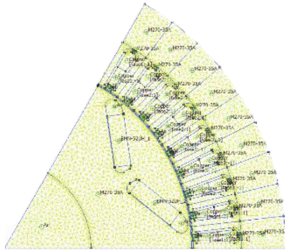
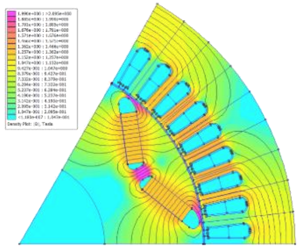
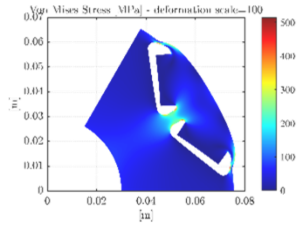
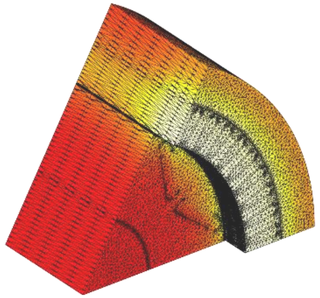
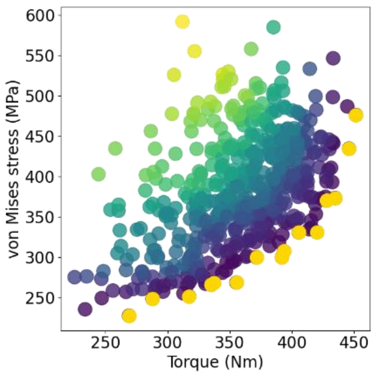
A model of traction PMSM is added to the SyR-e repository as a demo from today's tutorial

SyR-e is constantly evolving under the push of industry and new research challenges

We invite you to try SyR-e and cooperate with SyR-e Team!

Galileo Ferraris' Contest

Comparing Data-Driven Methodologies for the Multi-Physics Simulation of Traction Electrical Machines

The **Galileo Ferraris Contest** provides a platform for testing various machine learning techniques on a set of benchmark cases.

Organizers will generate and share multi-physical results datasets through a well-defined procedure in an open environment.

What will be available to participants: complete result datasets of electromagnetic, structural and thermal analyses on a family of traction motors will be published.

What will be requested from participants: try their data-driven procedures on these result datasets extrapolating motor performance on new data.

Who will win the Contest: a set of quality index are defined and the groups providing better modelling performance will win the Contest.

Awards will be given to recognize the best results, considering both accuracy and computational efficiency. Winners will be presented at COMPUMAG 2025 in Naples.

https://cadema-polito.github.io/GalFer_contest/

under patronage of

International Compumag Society (ICS)

IEEE MAGNETICS ITALY CHAPTER

sponsored by

MathWorks