Synchronous Reluctance Motor Drives: Introducing the Design Resource SyR-e and its new Dimension SyReDrive

February 25, 2021

gianmario.pellegrino@polito.it

Acknowledgments

This lecture is based on the precious work of all the team of the PEIC of PoliTO, as per paper cited throughout the presentation

Dr. Simone Ferrari and Dr.Anantaram Varatharajan helped preparing the material presented today

Simone Ferrari, PhD

Anantaram Varatharajan, PhD

Outline

- Introduction
  - Politecnico di Torino and the Power Electronics Innovation Center (PEIC)
  - History of the SyR Machine technology and today's opportunities and challenges
  - Motor design and drive control aspects
- SyR-e: Synchronous Reluctance Evolution
  - Overview
  - Main GUI and motor design toolchain
  - Flux Map manipulation GUI
  - syreDrive: automatic control code generation
- Conclusion

Politecnico di Torino

Founded in 1859, as Technical School for Engineers
Politecnico di Torino since 1906

Home to **Galileo Ferraris**, pioneer of electrical engineering. He was a professor here, and a Senator of the former Reign of Italy

35000 students, 800 PhD students

850 Faculty members, 890 Administrative Technical staff

Budget (2020): 263 M€
(62% State, 12% student fees, 26% projects)

Average tuition fee: < 1000 € / year (max 2000€)

Galileo Ferraris
(1847 – 1897)

PEIC: the Power Electronics Innovation Center

Power Electronics Innovation Center

http://www.peic.polito.it/

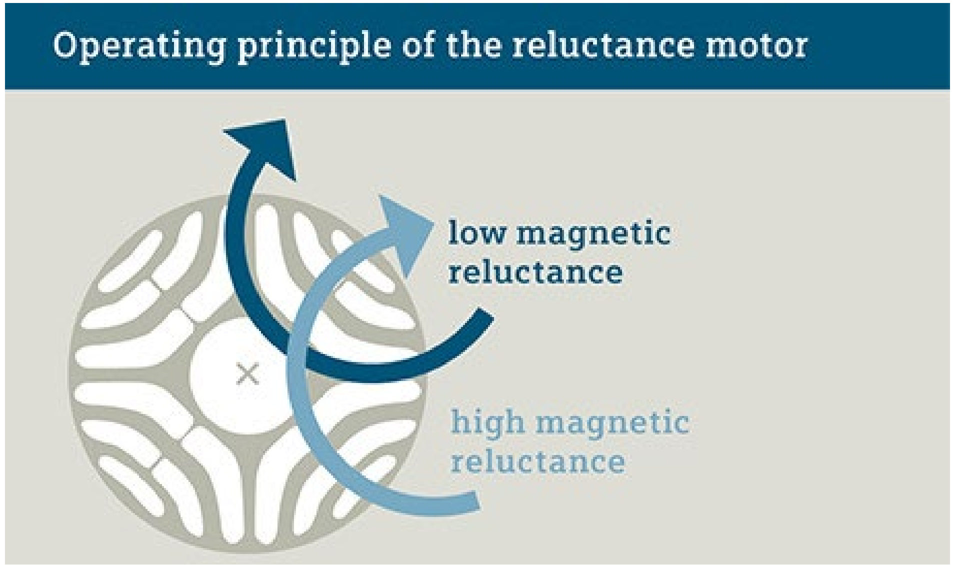
Inter-Departmental Center dedicated to Power Electronics, from Si wafer to final applications, launched in 2017

- 20 faculty members, 1 technician, 25 PhD students
- Key fields of application:
  Transportation electrification, Energy, Industry
- TRL4 demonstrators, support to higher-TRL prototyping
- E-motor drive tests up to 20.000 rpm, 500 kW pk

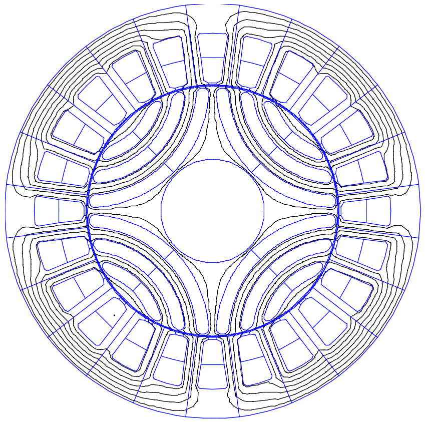
Power Electronics Innovation Center

The Synchronous Reluctance Motor Technology

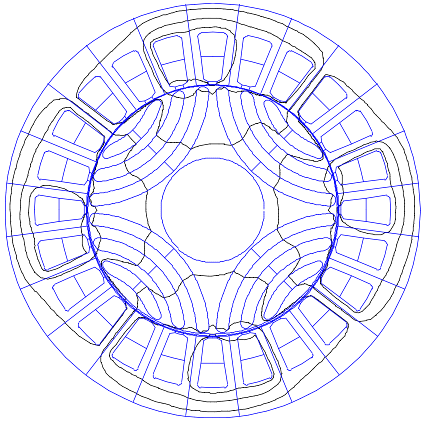
Background: Synchronous Reluctance Torque



Excitation of
***low reluctance** rotor axis*



Excitation of
***high reluctance** rotor axis*



*Reluctance motors operate according to the principle of **<u>magnetic reluctance</u>** …. The rotor consisting of air and iron has the **least possible magnetic reluctance in one direction** and the **highest possible reluctance in the direction perpendicular to that**. Because the system always moves toward the lowest magnetic reluctance, rotational movement results.*

Source: "Dynamic Energy Efficiency", in Advance 1/2015, April 2015, Siemens AG (new.siemens.com)

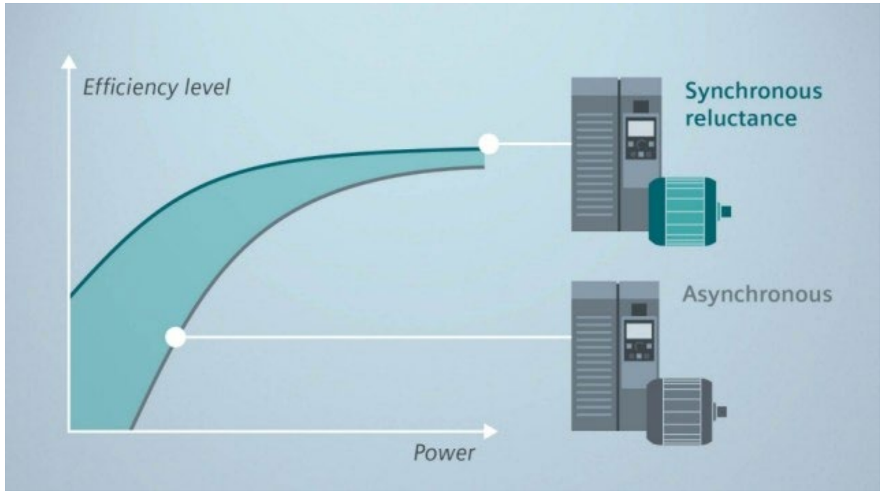
Drivers of the SyRM technology

Efficiency standards

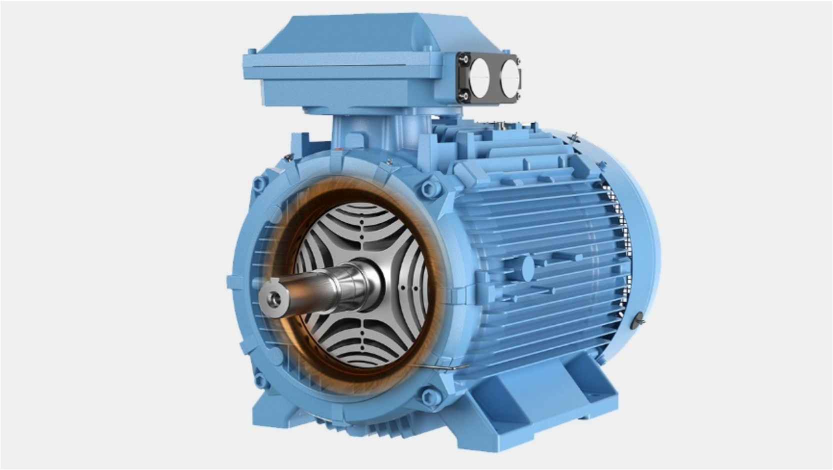
- IEC standards active since 2011
- natural IE4 replacement of IE2-IE3 IMs
- today, ABB has a line of IE5 SyR motors

Magnet-free

- peak of rare-earth metals in 2011
- motors for traction and actuators with less magnets and more reluctance torque



Source: new.siemens.com


Source: new.abb.com

Drivers of the SyRM technology

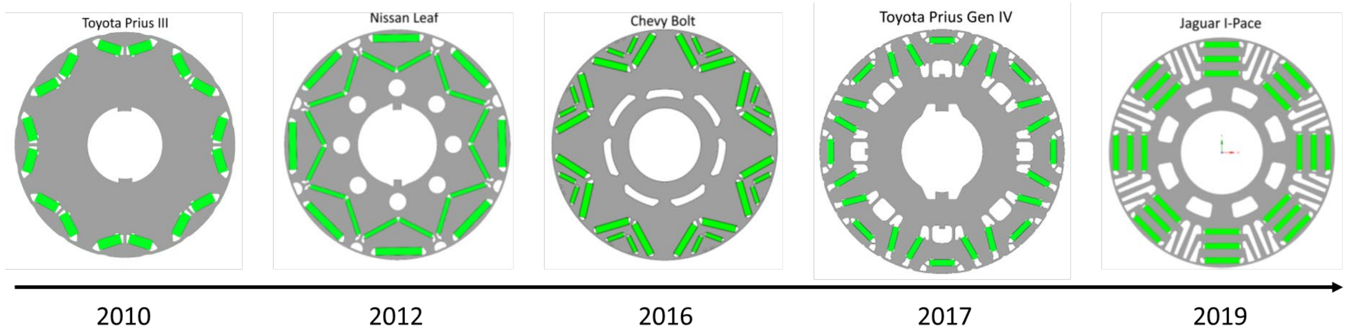
Source: Pinterest

Efficiency standards

- IEC standards active since 2011
- natural IE4 replacement of IE2-IE3 IMs
- today, ABB has a line of IE5 SyR motors

Magnet-free

- peak of rare-earth metals in 2011
- motors for traction and actuators with less magnets and more reluctance torque

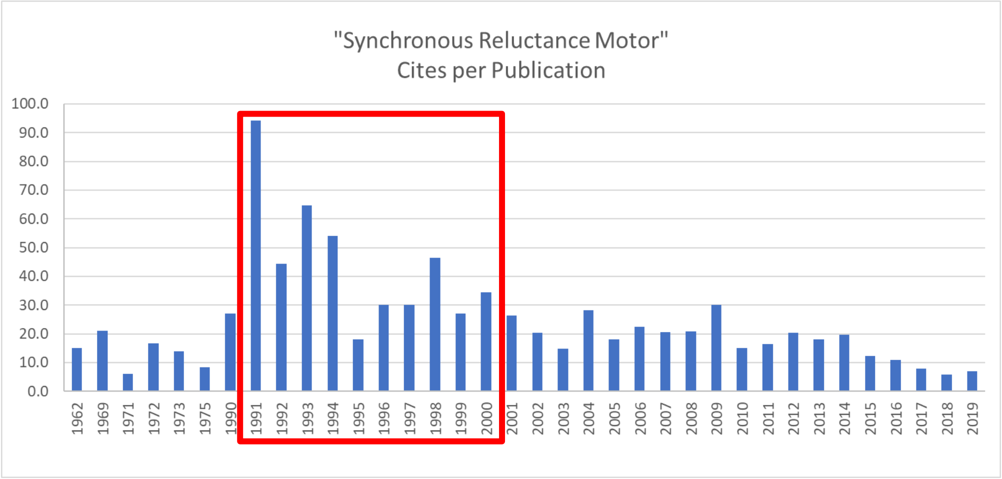


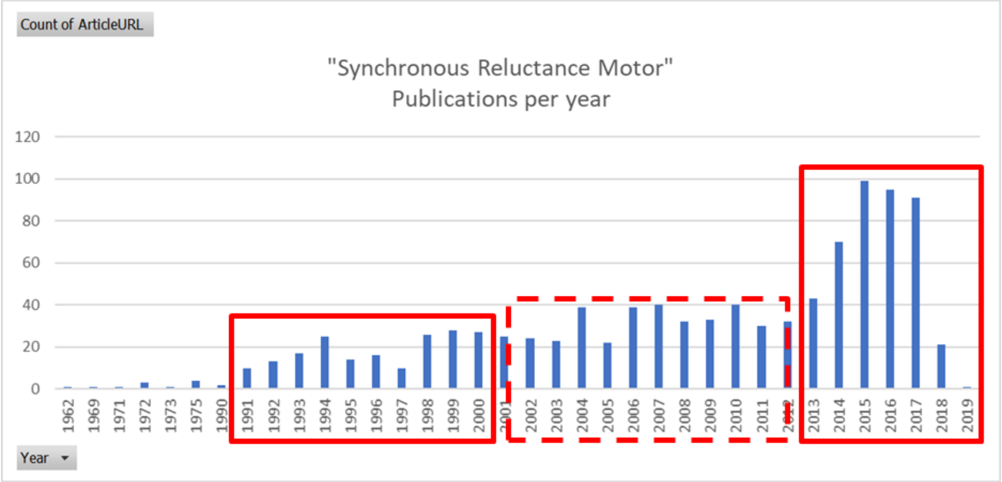
[1] A. Krings and C. Monissen, “Review and Trends in Electric Traction Motors for Battery Electric and Hybrid Vehicles,” in *2020 International Conference on Electrical Machines (ICEM)*, 2020

History: the Roaring Ninenties

The technology developed in the 1990s:
few works with high number of citations

However, it was nearly disregarded in the following decade





[2] G. Pellegrino, "Synchronous Reluctance Motor Drives: Still a Niche Technology?" in *2019 ACEMP & OPTIM*, Istanbul, Turkey, 2019

Power Electronics Innovation Center

Hype on SyR Motor Technology

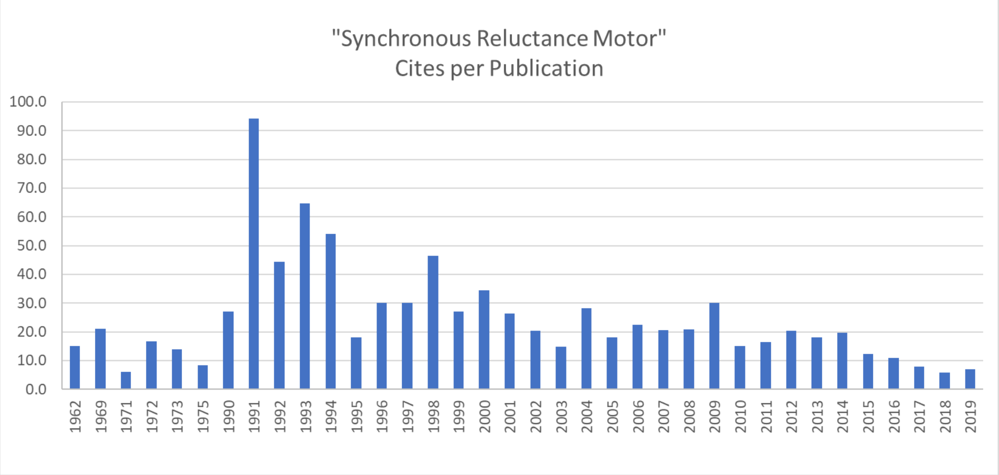
The technology developed in the 1990s:
few works with high number of citations

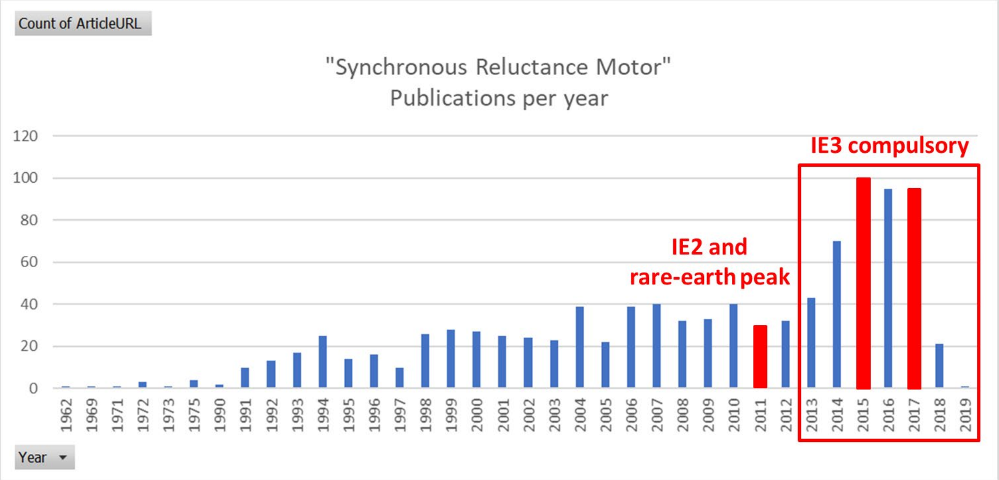
However, it was nearly disregarded in the following decade

In the 2010 decade the hype grew again (see the number of publications per year)

This relates to (*)

- ban of pre-IE2 efficiency levels and rare-earth materials price peak (both in June 2011)
- Compulsory IE3 efficiency from 2015 (> 7.5 kW) and 2017 (>0.75 kW)
- You find the ACEMP-OPTIM 2019 lecture [2] here





* IEC 60034-30 standard and EC Regulation 640/2009

[2] G. Pellegrino, "Synchronous Reluctance Motor Drives: Still a Niche Technology?" in *2019 ACEMP & OPTIM*, Istanbul, Turkey, 2019

PEIC
Power Electronics Innovation Center

Advantages of SyR Motors

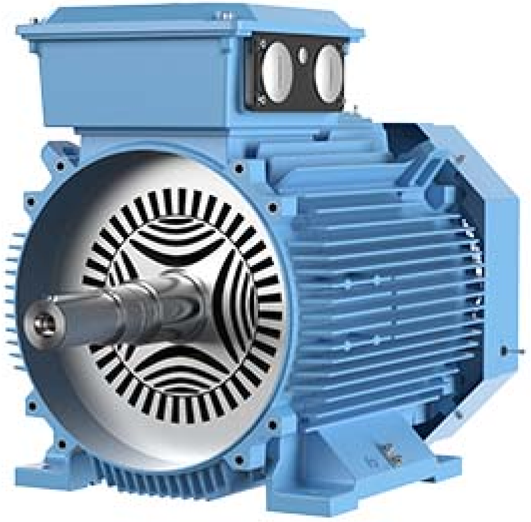
1. Standard distributed-winding stator

2. Rotor simplicity

- no windings → substantial loss reduction, ease of manufacturing

- no PMs → cost reduction, no de-magnetization, no back-emf voltage when uncontrolled

- low moment of inertia → Dynamic performance



Source: new.abb.com

Advantages of SyR Motors

1. Standard distributed-winding stator

2. Rotor simplicity

- no windings → substantial loss reduction, ease of manufacturing

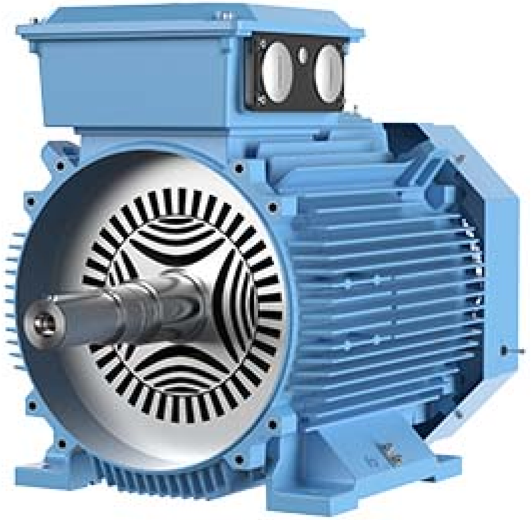
- no PMs → cost reduction, no de-magnetization, no back-emf voltage when uncontrolled

- low moment of inertia → Dynamic performance

Vs Asynchronous Motors:

- smaller frame size per continuous torque or higher efficiency in the same size

- faster speed dynamics



Source: new.abb.com

Advantages of SyR Motors

1. Standard distributed-winding stator

2. Rotor simplicity

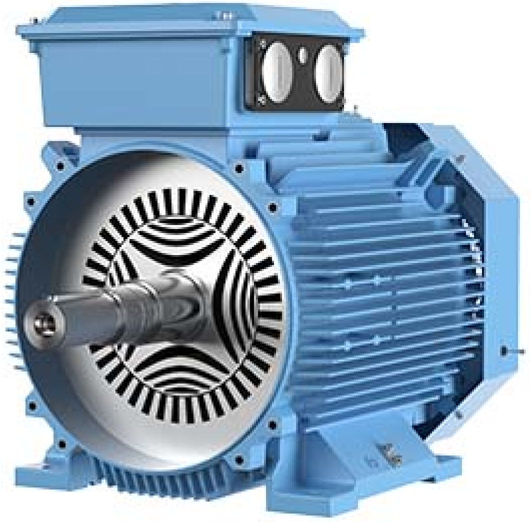
- no windings → substantial loss reduction, ease of manufacturing
- no PMs → cost reduction, no de-magnetization, no back-emf voltage when uncontrolled
- low moment of inertia → Dynamic performance

Vs Asynchronous Motors:

- smaller frame size per continuous torque or higher efficiency in the same size
- faster speed dynamics

Vs PM Synchronous Motors:

- lower cost of production (no PM cost, ease of manufacturing)
- higher transient overload capability (no risk for demagnetization)



Source: new.abb.com

Control Challenges

[3] A. Varatharajan and G. Pellegrino. “Sensorless Synchronous Reluctance Motor Drives: A General Adaptive Projection Vector Approach for Position Estimation.” *IEEE Transactions on Industry Applications*, 2020

Sensorless Control (no encoder)

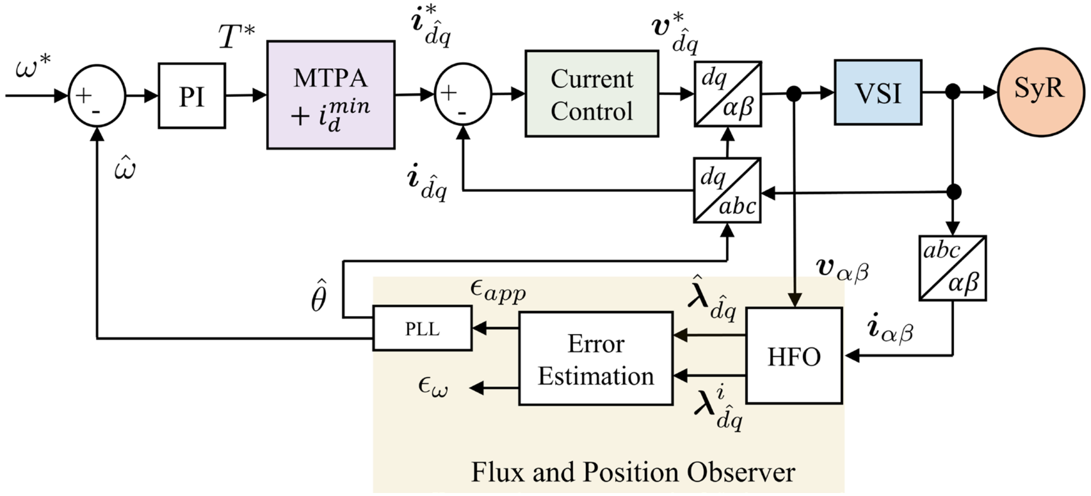
V/Hz controlled Asynchronous counterparts are sensorless → this is mandatory in most all industry applications with the exception of servo and machine tools

MTPA Operation

This guarantees the promised IE4 efficiency

Self-Commissioning + Plug and Play

Control calibration must remain under the hood, the user is not supposed to hold a PhD degree



Control Challenges

[3] A. Varatharajan and G. Pellegrino. “Sensorless Synchronous Reluctance Motor Drives: A General Adaptive Projection Vector Approach for Position Estimation.” *IEEE Transactions on Industry Applications*, 2020

Sensorless Control (no encoder) → LUTs

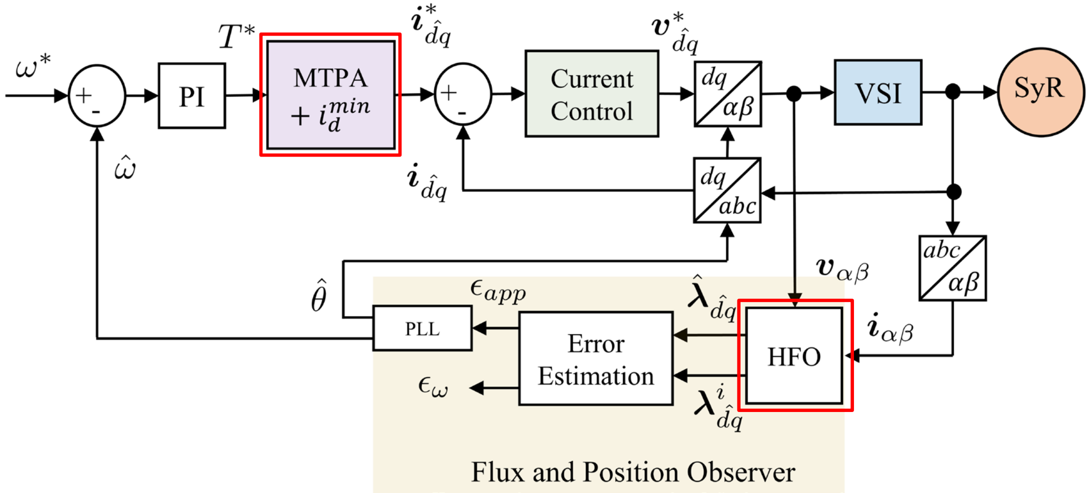
V/Hz controlled Asynchronous counterparts are sensorless → this is mandatory in most all industry applications with the exception of servo and machine tools

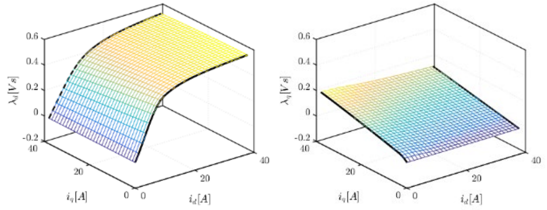
MTPA Operation → LUTs and manipulation

This guarantees the promised IE4 efficiency

Self-Commissioning + Plug and Play → LUTs

Control calibration must remain under the hood, the user is not supposed to hold a PhD degree





Motor Design Challenges

[4] S. Ferrari and G. Pellegrino. "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines." *IEEE Transactions on Industry Applications,* 2020

Rotor barriers design

- Maximization of torque and power factor
- Minimization of torque ripple

Magnetic design

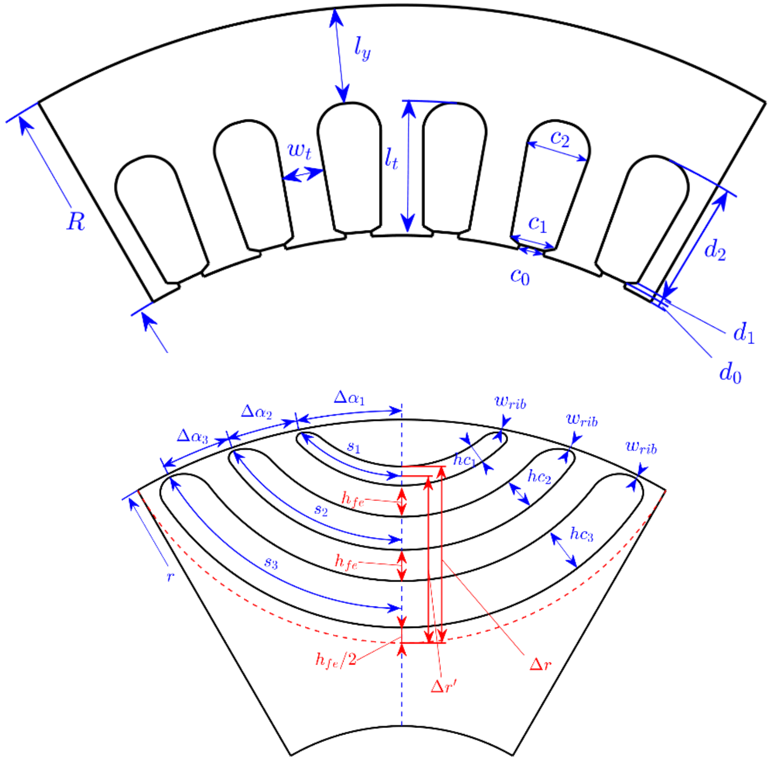
- What if the stator is not given?

Rotor ribs minimization

- rotor ribs scale with n_{max}^2

High number of poles

- This increases the p.u. excitation current



Motor Design Challenges

[4] S. Ferrari and G. Pellegrino. “FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines.” *IEEE Transactions on Industry Applications,* 2020

Rotor barriers design → **golden rules, optimization, asymmetric poles**

- Maximization of torque and power factor **, skew**
- Minimization of torque ripple

Magnetic design → **FEA-corrected design equations**

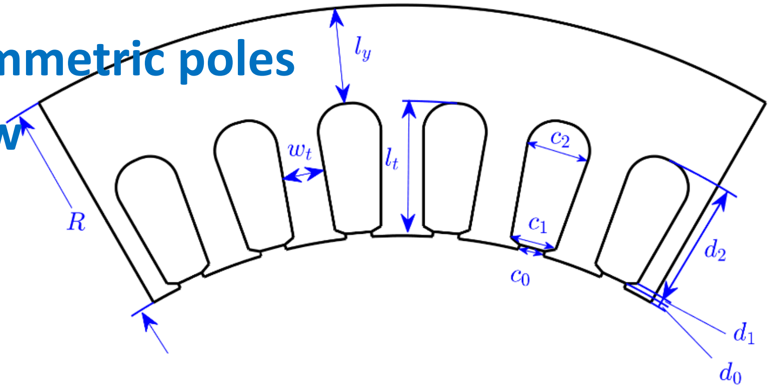
- What if the stator is not given? **(*x*,*b* and FEAfix)**

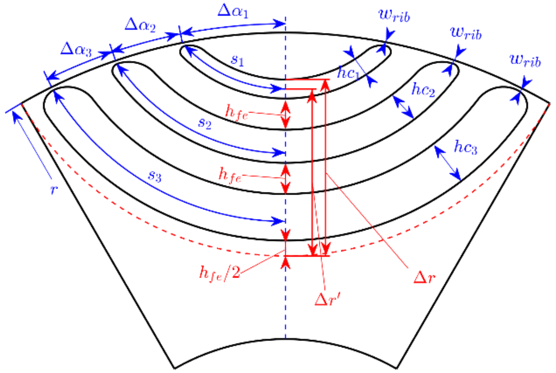
Rotor ribs minimization → **Magnetic-Structural co-design**

- rotor ribs scale with n_{max}^2

High number of poles → **PM-assistance**

- This increases the p.u. excitation current





Motor Design Challenges

[4] S. Ferrari and G. Pellegrino. "FEAfix: FEA Refinement of Design Equations for Synchronous Reluctance Machines." *IEEE Transactions on Industry Applications,* 2020

Rotor barriers design → **golden rules, optimization, asymmetric poles**

- Maximization of torque and power factor **, skew**
- Minimization of torque ripple

Magnetic design → **FEA-corrected design equations**

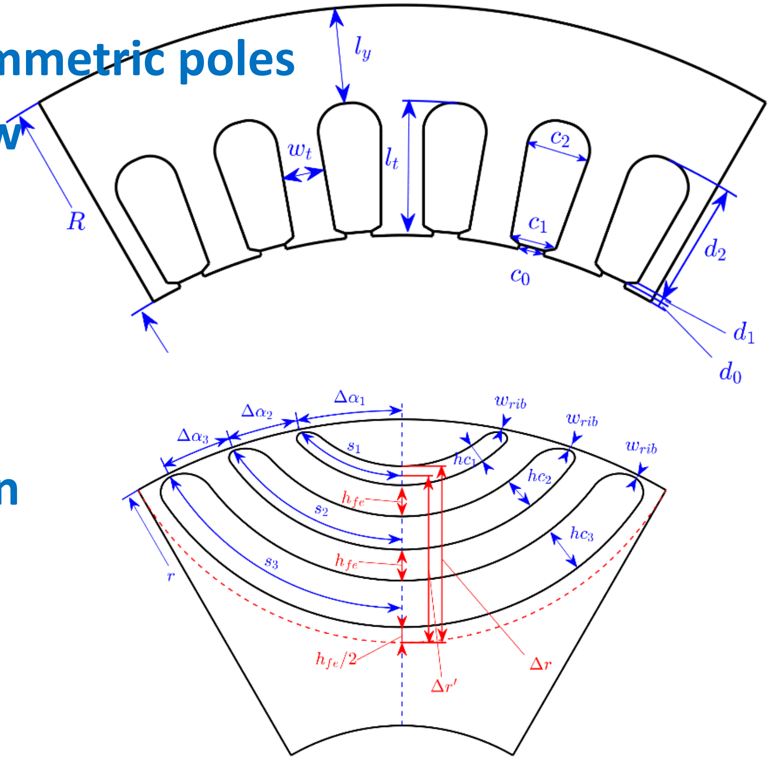
- What if the stator is not given? **(*x*,*b* and FEAfix)**

Rotor ribs minimization → **Magnetic-Structural co-design**

- rotor ribs scale with n_{max}^2

High number of poles → **~~PM-assistance~~**

- This increases the p.u. excitation current



Power Electronics Innovation Center

SyR-e: Synchronous Reluctance Evolution

https://sourceforge.net/projects/syr-e/
https://github.com/SyR-e

Power Electronics Innovation Center

What is SyR-e

SyR-e: Synchronous Reluctance – evolution is a design tool for synchronous e-machines

It runs under Matlab (or GNU Octave), using FEMM as a client for magneto-static FEA

A collaboration between Politecnico di Torino and Politecnico di Bari, in Italy, inspired by the Octave scripting library of FEMM

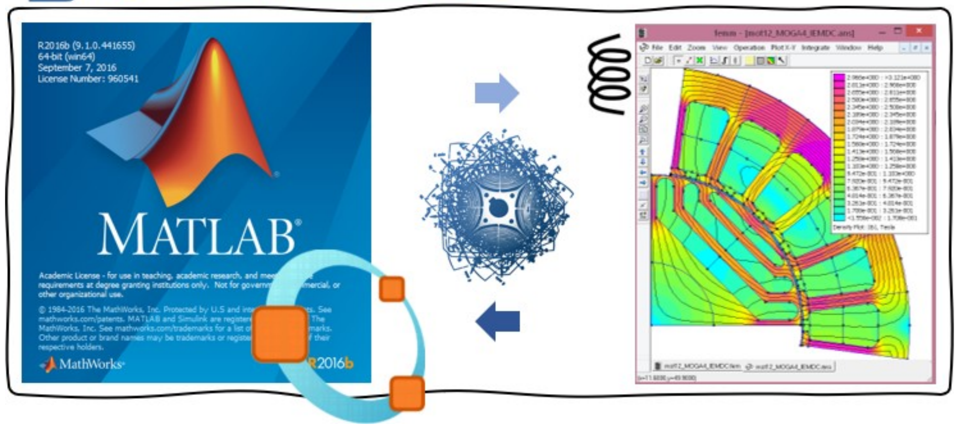
- Launched during the ECCE 2014 Tutorial in Pittsburg
- Another tutorial was organized at ECCE 2017 on open-source design resources

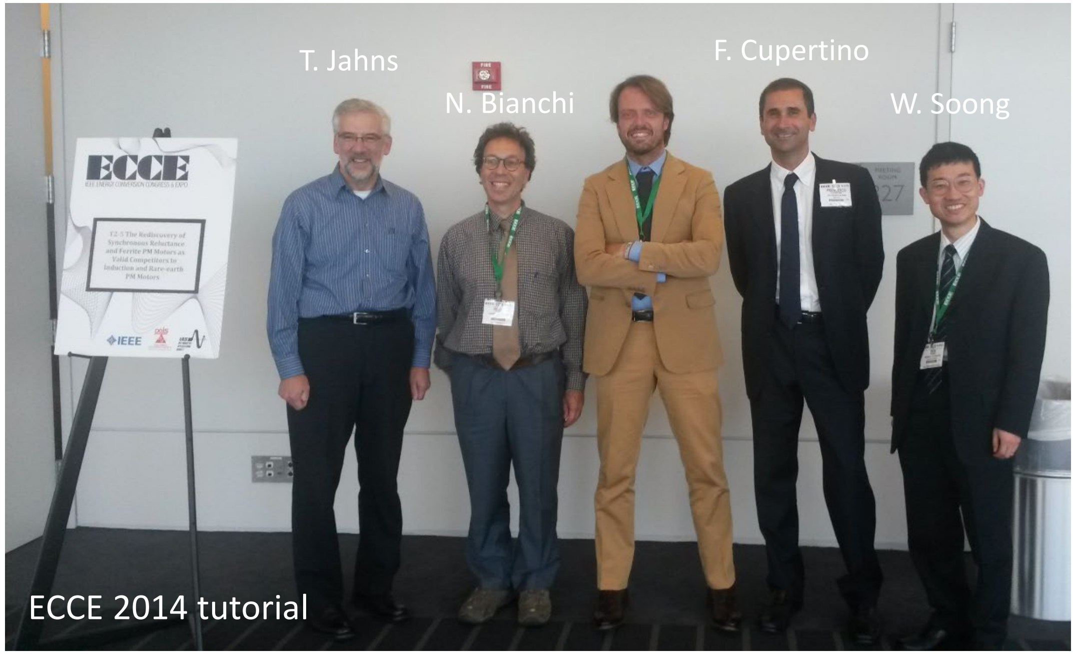
Downloadable under the APACHE License, Version 2.0

- https://sourceforge.net/projects/syr-e/
- https://github.com/SyR-e

FEMM is at www.femm.info

syre https://github.com/SyR-e





ECCE 2014 tutorial

Power Electronics Innovation Center

What is SyR-e

SyR-e: Synchronous Reluctance – evolution is a design tool for synchronous e-machines

It runs under Matlab (or GNU Octave), using FEMM as a client for magneto-static FEA

A collaboration between Politecnico di Torino and Politecnico di Bari, in Italy, inspired by the Octave scripting library of FEMM

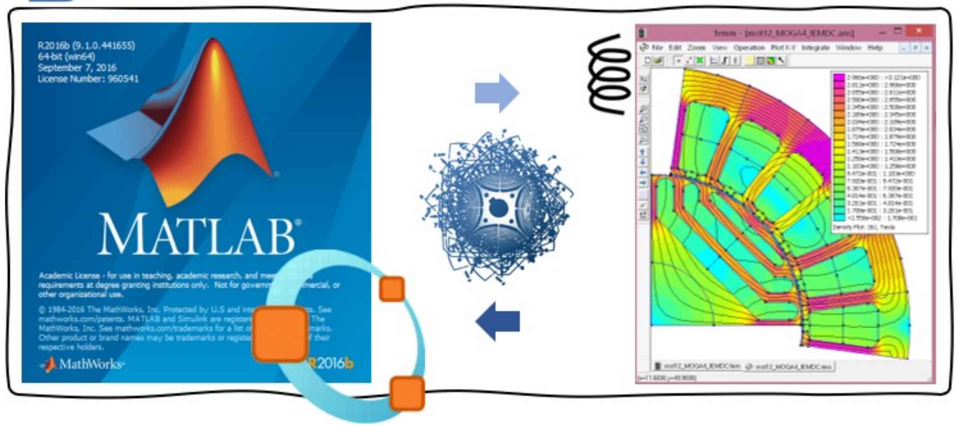
- Launched during the ECCE 2014 Tutorial in Pittsburg
- Another tutorial was organized at ECCE 2017 on open-source design resources, featuring Dave Meeker of FEMM

Downloadable under the APACHE License, Version 2.0

- https://sourceforge.net/projects/syr-e/
- https://github.com/SyR-e

FEMM is at www.femm.info

syre https://github.com/SyR-e

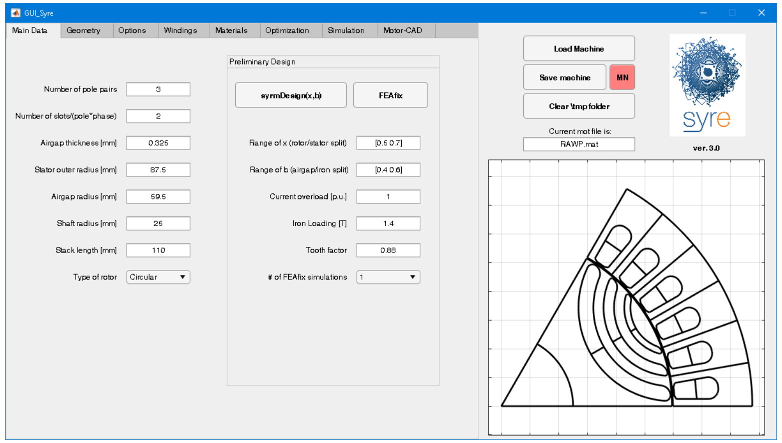


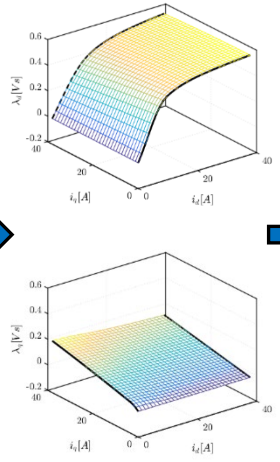
ECCE 2017, with David Meeker author of FEMM

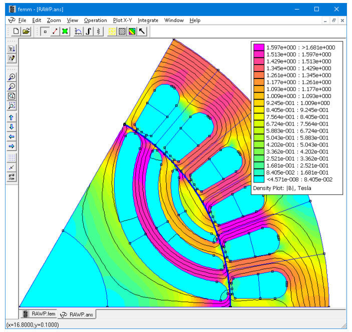
SyR-e Geography

GUI_Syre

Motor design and simulation

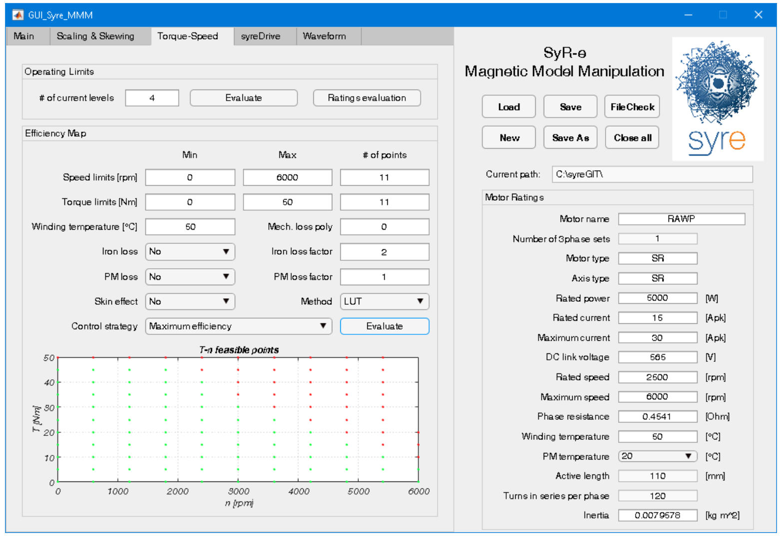




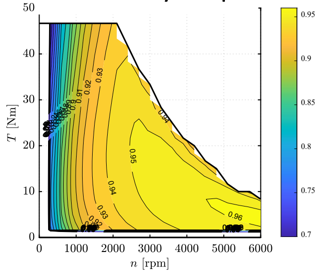


GUI_Syre_MMM

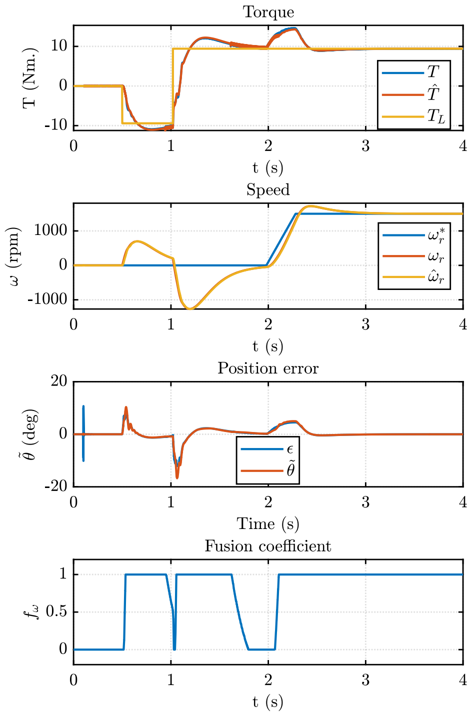
Magnetic Model Manipulation



Efficiency Map



Sensorless control simulation results



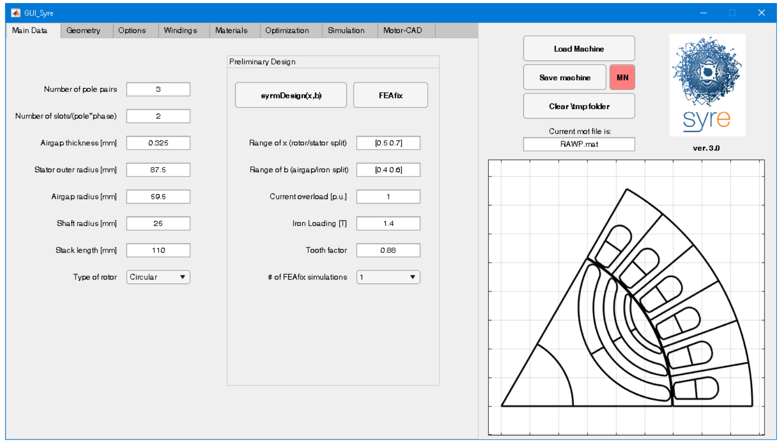
Power Electronics Innovation Center

Motor Design

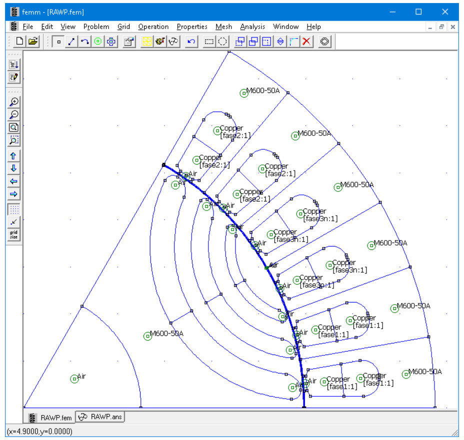
Parametric machine model and fast FEA simulation, including

- Design Equations (*x*,*b* plane) and FEAfix
- MODE optimization of selected design goals
- Simplified temperature and centrifugal stress models → embedded FEA stress model *(NEW)*
- Export to commercial CAD software (Autocad, Simcenter MagNet, MotorCAD, Ansys Maxwell)

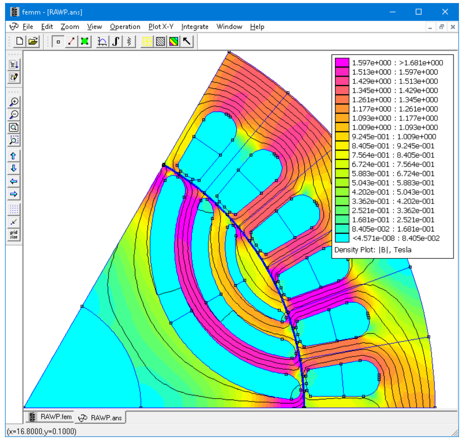
GUI_Syre: Motor design and simulation



FEA model



Simulation

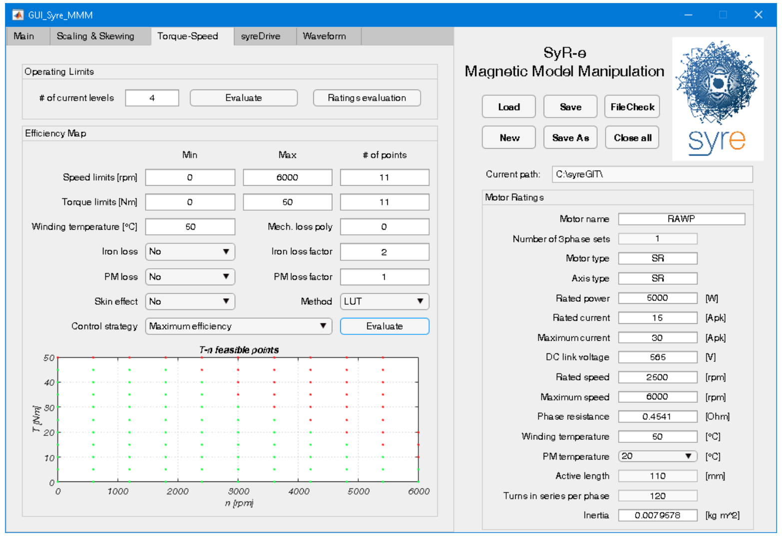


Model Manipulation

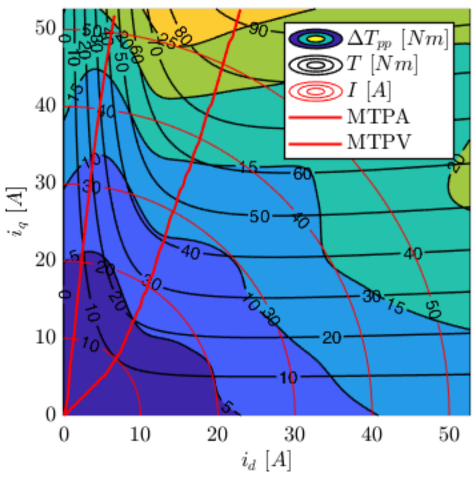
Advanced manipulation of FEA output

- Control trajectories (MTPA, MTPV)
- dq and $dq\theta$ flux maps manipulation
- Scaling and skewing
- Efficiency map evaluation
- syreDrive: generation of the Simulink model for control simulation *(NEW)*

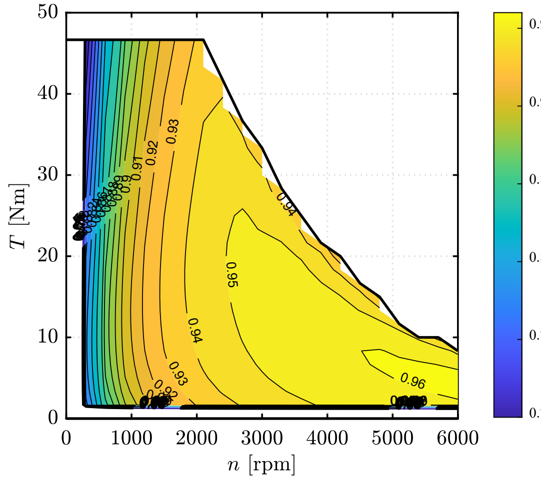
GUI_Syre_MMM: Magnetic Model Manipulation



Performance Curves



Efficiency Map

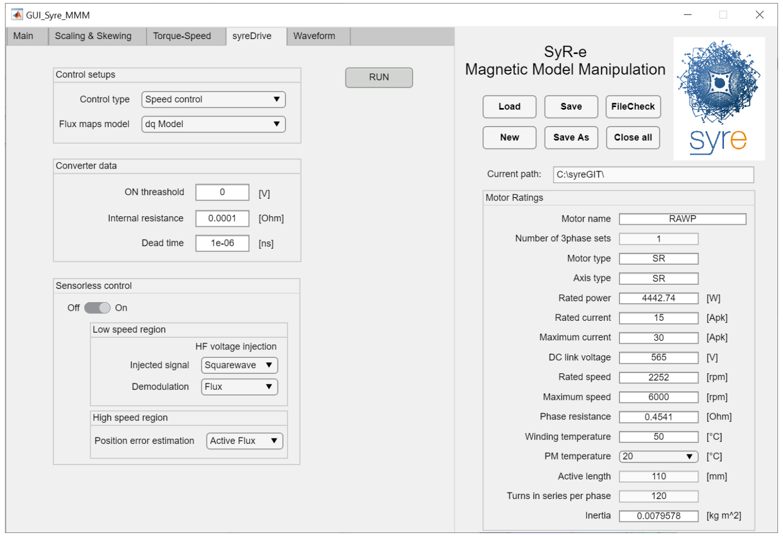


Drive Control

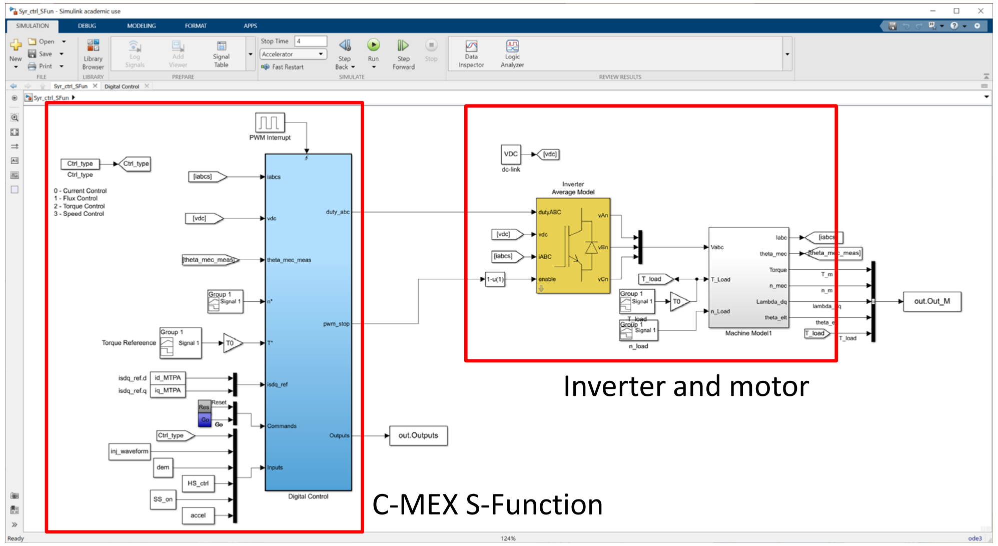
Advanced manipulation of FEA output

- Control trajectories (MTPA, MTPV)
- dq and $dq\theta$ flux maps manipulation
- Scaling and skewing
- Efficiency map evaluation
- **syreDrive**: generation of the Simulink model for control simulation
  - Torque and speed control
  - Full-speed sensorless control (Active Flux and APP)
  - Automated calibration based on flux-map LUTs
  - Floating-point C-code generation

syreDrive tab of GUI_Syre_MMM



Auto generated Simulink model



GUI_Syre

Motor Design Toolchain

Demo motor: RAWP.mat

[5] S. Ferrari, G. Pellegrino, M. Davoli, and C. Bianchini, "Reduction of Torque Ripple in Synchronous Reluctance Machines through Flux Barrier Shift," in ICEM 2018

The demo in use consists of two files:

- RAWP.fem → FEMM model
- RAWP.mat → all input data (and FEA results)

It is a 4.4 kW industrial machine derived from an IE3 induction motor stator (2.2 kW, 955 rpm)

Two SyR rotors were built for validation of the Flux-Barriers Shift (asymmetric rotor poles) features compared to rotor skewing [5]

The motor design procedure is well documented in [4], referring to the same specs of the RAWP example

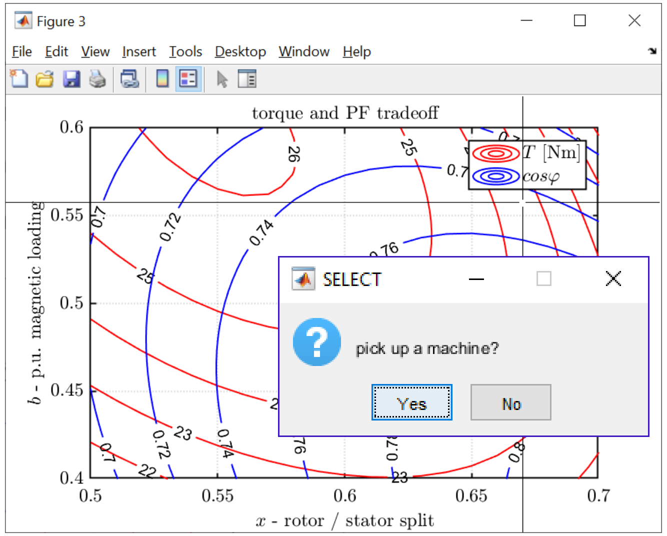
Motor Ratings

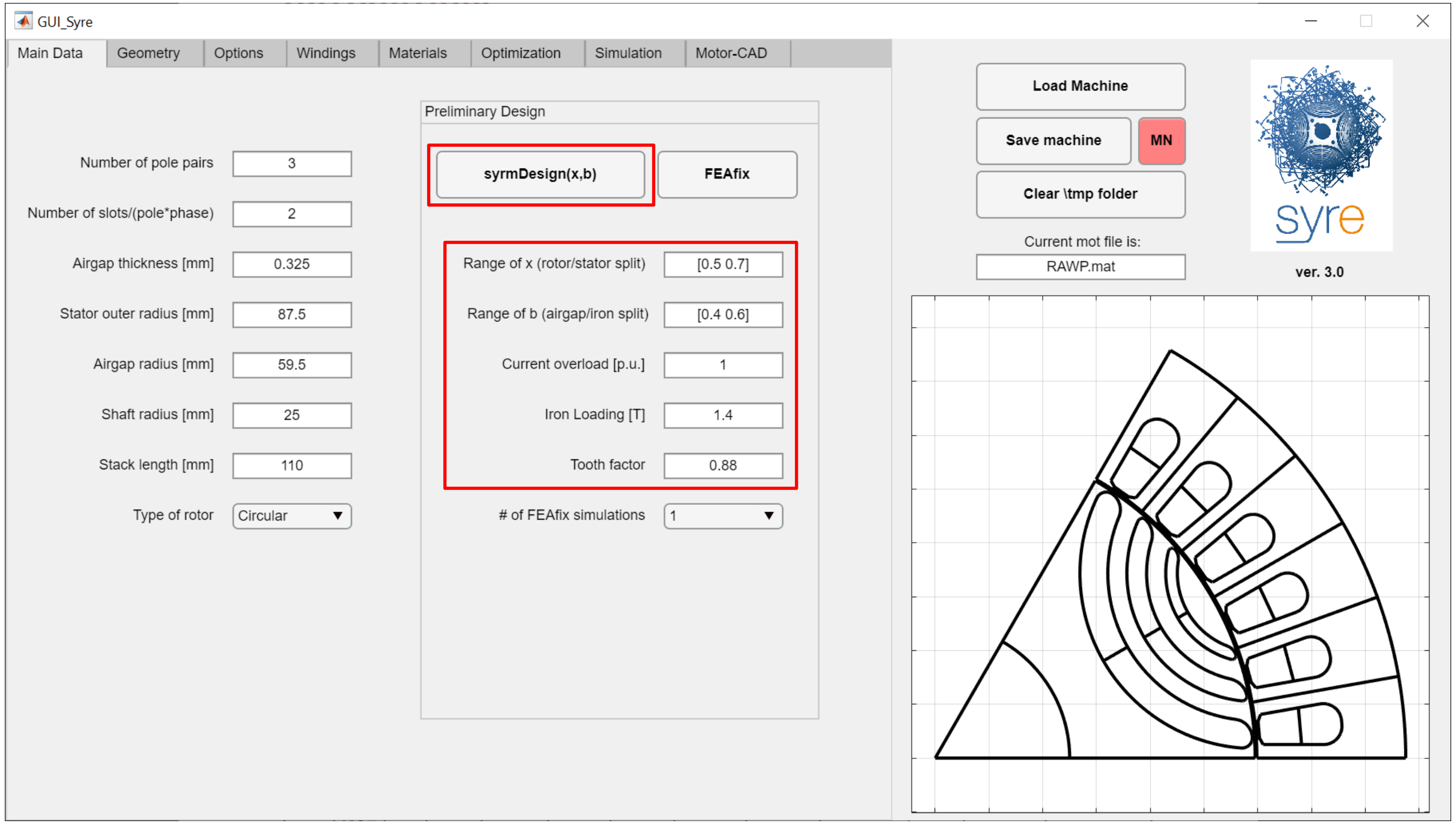
Motor name	RAWP	
Number of 3phase sets	1	
Motor type	SR	
Axis type	SR	
Rated power	4442.74	[W]
Rated current	15	[Apk]
Maximum current	30	[Apk]
DC link voltage	565	[V]
Rated speed	2252	[rpm]
Maximum speed	5000	[rpm]
Phase resistance	0.4541	[Ohm]
Winding temperature	50	[°C]
PM temperature	20	[°C]
Active length	110	[mm]
Turns in series per phase	120	
Inertia	0.0079578	[kg m^2]

syrmDesign(*x*,*b*): Design Equations

Torque and power-factor contours are evaluated via design equations as a function of the two key parameters:

- $x = \frac{r}{R}$ (rotor/stator split)
- $b = \frac{B_g}{B_{Fe}}$ (→ iron/copper split)





Power Electronics Innovation Center

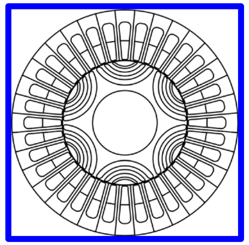
Use of the *x,b* design plane

Torque and **PF** have different trends

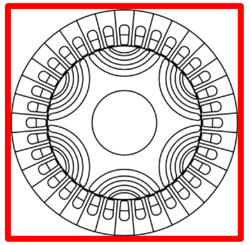
Any point of the plane corresponds to one design

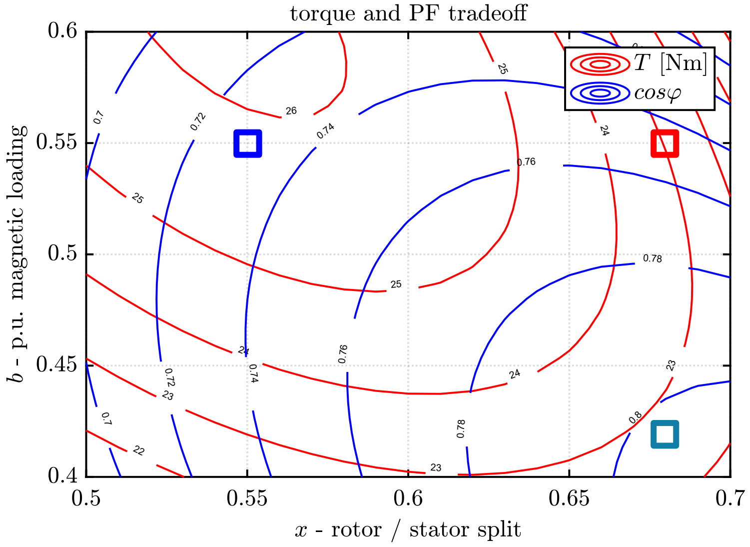
- x up: big rotor, short slots
- b down: slender iron paths

x = 0.55, b = 0.55

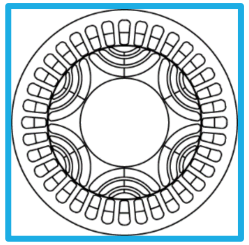


x = 0.68, b = 0.55





x = 0.68, b = 0.42



Example of Results

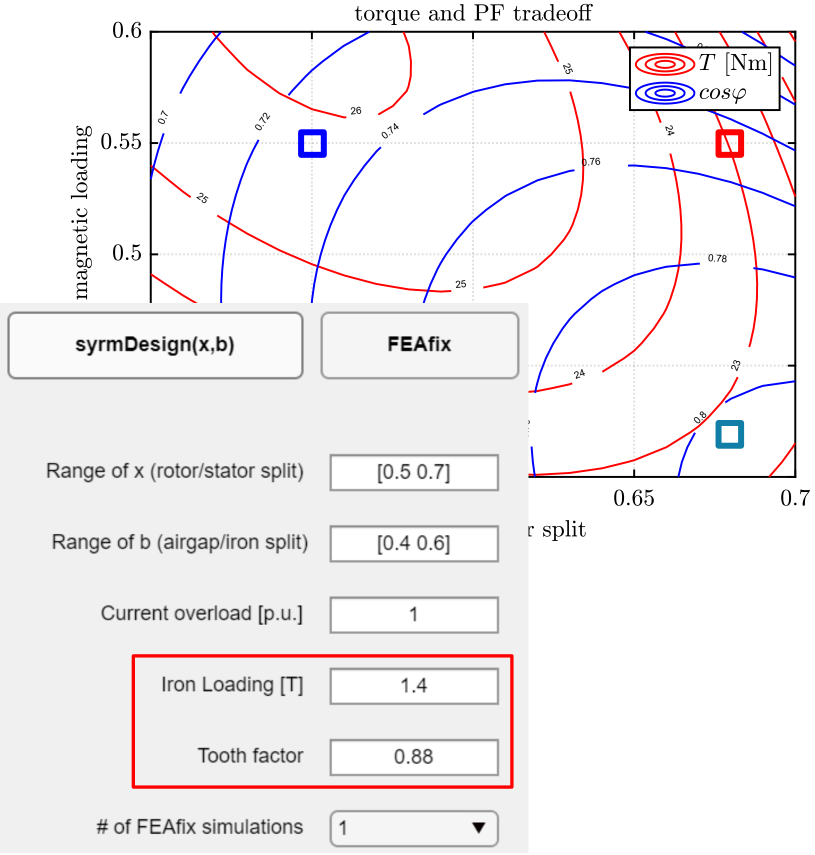
Torque and **PF** have different trends

Any point of the plane corresponds to one design

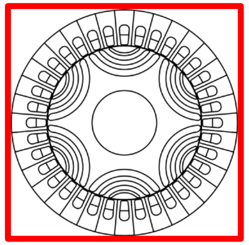
- x up: big rotor, short slots
- b down: slender iron paths

All the designs have the same peak flux density $B_{Fe} = 1.4\ \mathrm{T}$ (back iron and rotor flux carriers)

The tooth size can be calibrated separately via the dedicated parameter ($k_t = 0.88$ stands for $B_{tooth} = B_{Fe} \cdot \dfrac{1}{0.88}$



RAWP is
$x = 0.68$, $b = 0.55$



Accessible Design Equations

[6] A. Vagati, G. Franceschini, I. Marongiu, and G. P. Troglia, “Design criteria of high-performance synchronous reluctance motors,” in *Conference Record of the 1992 IEEE Industry Applications Society Annual Meeting*, Houston, TX, USA, 1992

The torque and PF vs *x,b* design equations are accessible

They derive from Vagati’s equations [6] plus recent corrections, such as the saturation coefficient [4]

Not accurate, but insightful

Initial design is very quick and quickly FEA validated

Editor - C:\syreGIT\mfiles\syrmDesign\syrmDesign_SyR.m

EDITOR PUBLISH VIEW

syrmDesign_SyR.m

```
%    limitations under the License.

function [map] = syrmDesign_SyR(dataSet,flags)
%
% [map] = syrmDesign_SyRM(dataSet)
%
% Preliminary design for SyR machines. References:
% - Vagati's Tutorial 1994
% - ECCE 2018 paper (FEAfix)

% input
if nargin==1
    %flags for SyRM design
    flag_kw=1;       % flag_kw=0 --> use Vagati's equations, with kw=pi/(2*sqrt(3))
                     % flag_kw=1 --> use the winding factor

    flag_pb=1;       % flag_pb=0 --> hc              = constant (useful for adding PMs)
                     % flag_pb=1 --> sk/hc           = constant (reduce harmonic content)
                     % flag_pb=2 --> hc/(df*sk^0.5)  = constant (reduce Lfq)

    flag_dx=1;       % flag_dx=0 --> dx=0
                     % flag_dx=1 --> constant rotor carrier width
                     % flag_dx=2 --> rotor carrier width proportional to sine integral
                     % flag_dx=3 --> rotor carrier width proportional to flux of d-axis

    flag_ks=1;       % flag_ks=0 --> no saturation factor used
                     % flag_ks=1 --> saturation factor enabled
```

3 usages of "flag_kw" found | US-ASCII | syrmDesign_SyR | Ln 307 Col 11

Default Rotor Design

[7] A. Vagati, M. Pastorelli, G. Francheschini, and S. C. Petrache, "Design of low-torque-ripple synchronous reluctance motors," *IEEE Trans. on Ind. App., 1998*

The default rotor has:

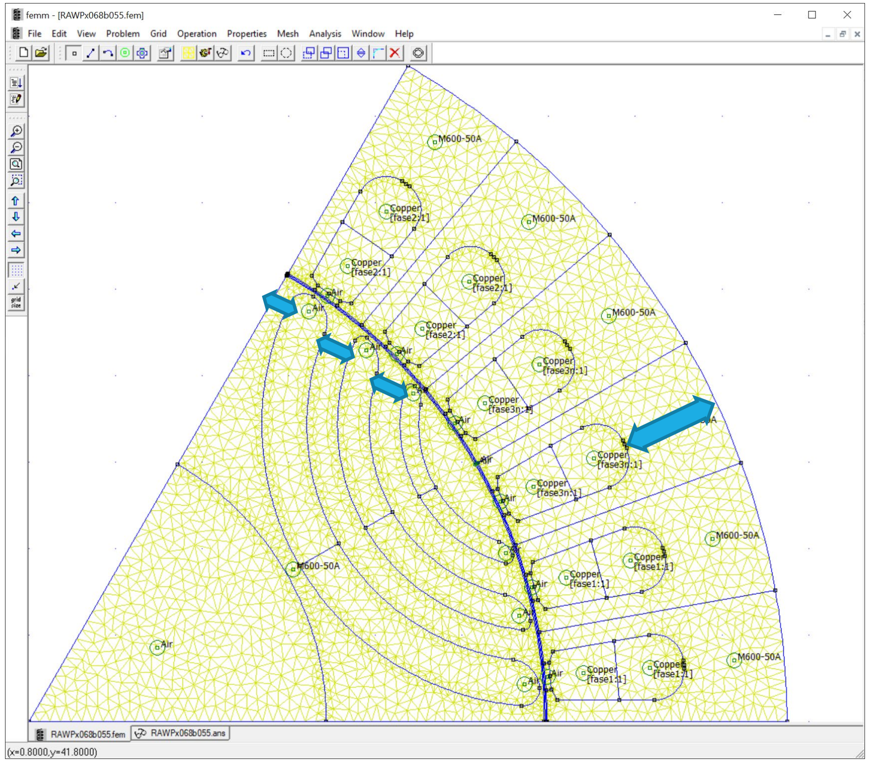
- Regular pitch for torque ripple minimization, according to the golden rule [7]

$$n_r = n_s \pm 4$$

- The flux carriers' dimension (sum of) equal to the back iron width

FEA model generated from the x,b plane

$(x = 0.55, b = 0.68)$



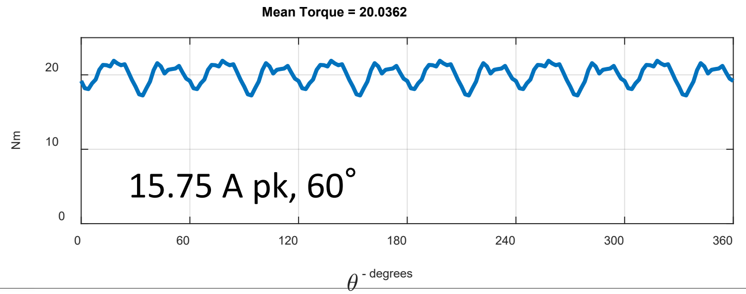
Default Rotor Design

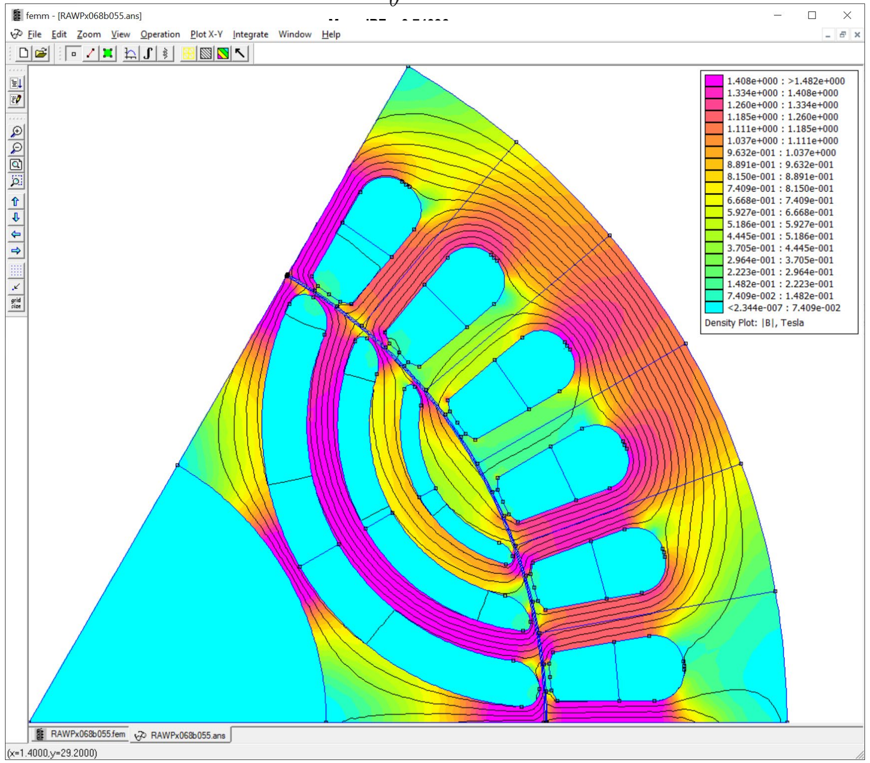
The default rotor has:

- Regular pitch for torque ripple minimization, according to the golden rule [7]
$$n_r = n_s \pm 4$$
- The flux carriers' dimension (sum of) equal to the back iron width

→ Torque ripple is well minimized without need for optimization

→ Rotor and stator flux density peaks are consistent





Default Rotor Design

The default rotor has:

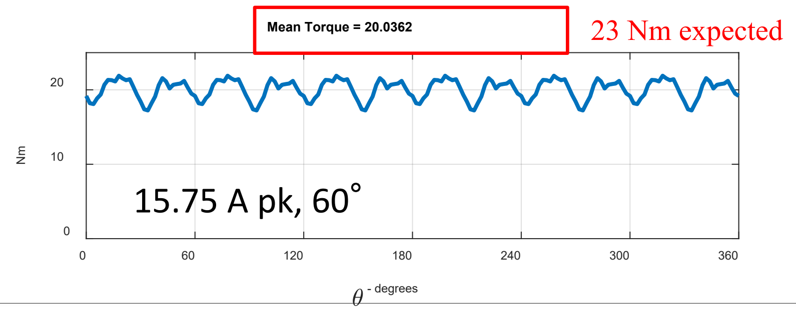
- Regular pitch for torque ripple minimization, according to the golden rule [7]

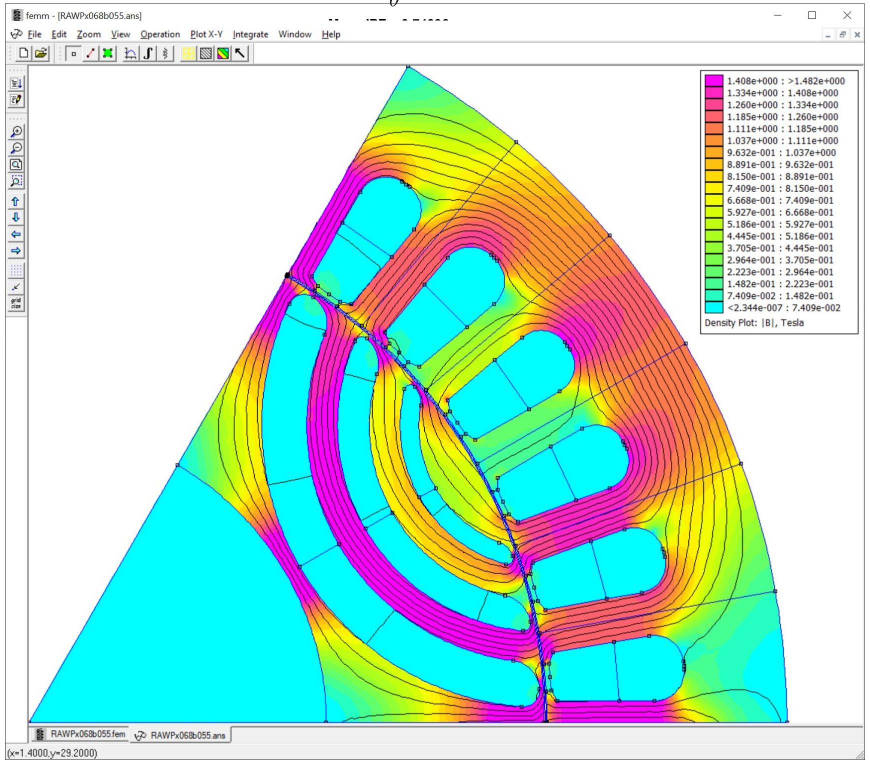
$$n_r = n_s \pm 4$$

- The flux carriers' dimension (sum of) equal to the back iron width

→ Torque ripple is well minimized without need for optimization

→ Rotor and stator flux density peaks are consistent





FEAfix: FEA-augmented Design Equations

Main design inputs + costraints

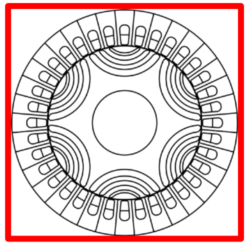
Design equations

Torque(x,b) and PF(x,b)

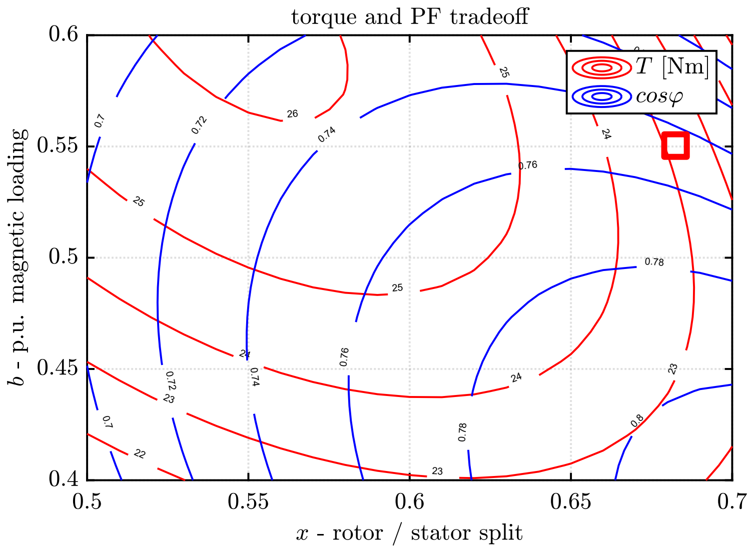
1 FEMM run (20 sec) → corr. Coefficients

FEAfix1

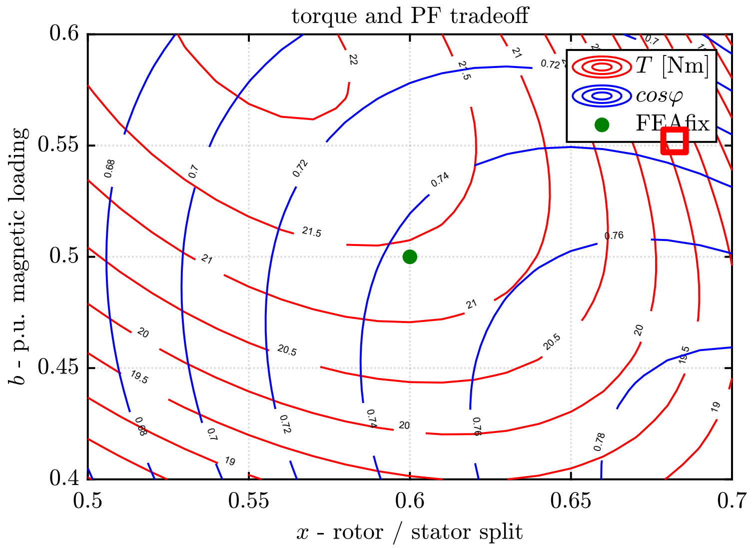
Selected design



x,b = 0.68, 0.55



Equations: 23 Nm



Equations corrected with FEAfix**1**

Closer to 20Nm

FEAfix: FEA-augmented Design Equations

Main design inputs + costraints

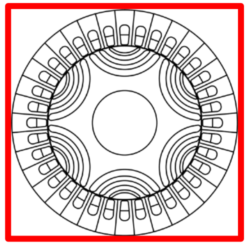
Design equations

Torque(x,b) and PF(x,b)

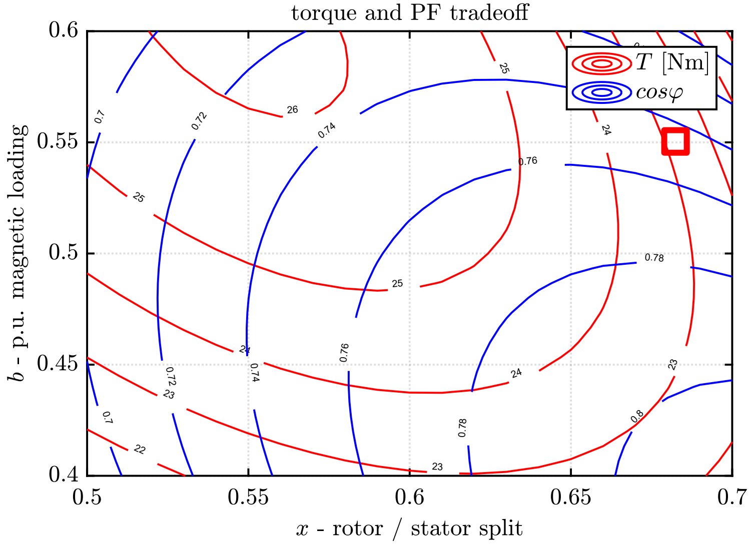
4 FEMM runs (80 sec) → revised corr. coefficients

FEAfix4

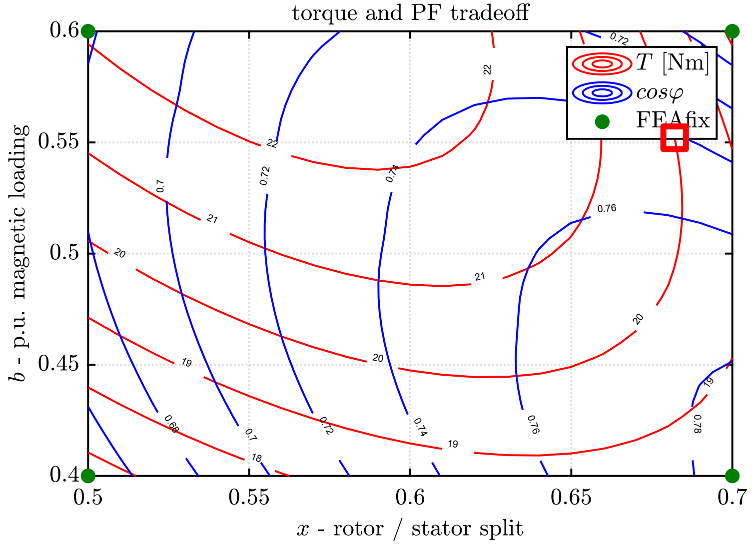
Selected design



x,b = 0.68, 0.55



Equations : 23 Nm



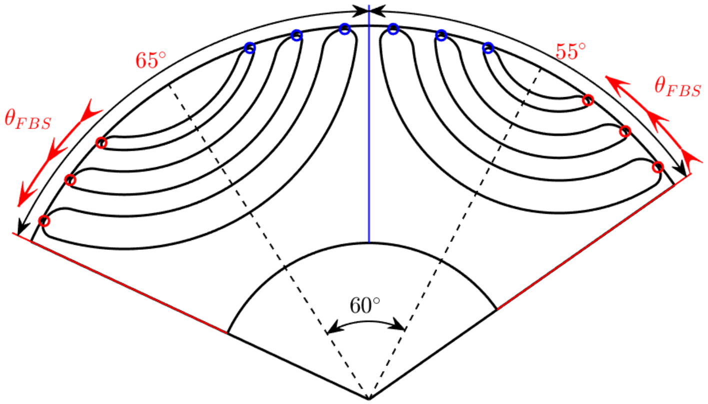
Equations corrected with FEAfix**4**

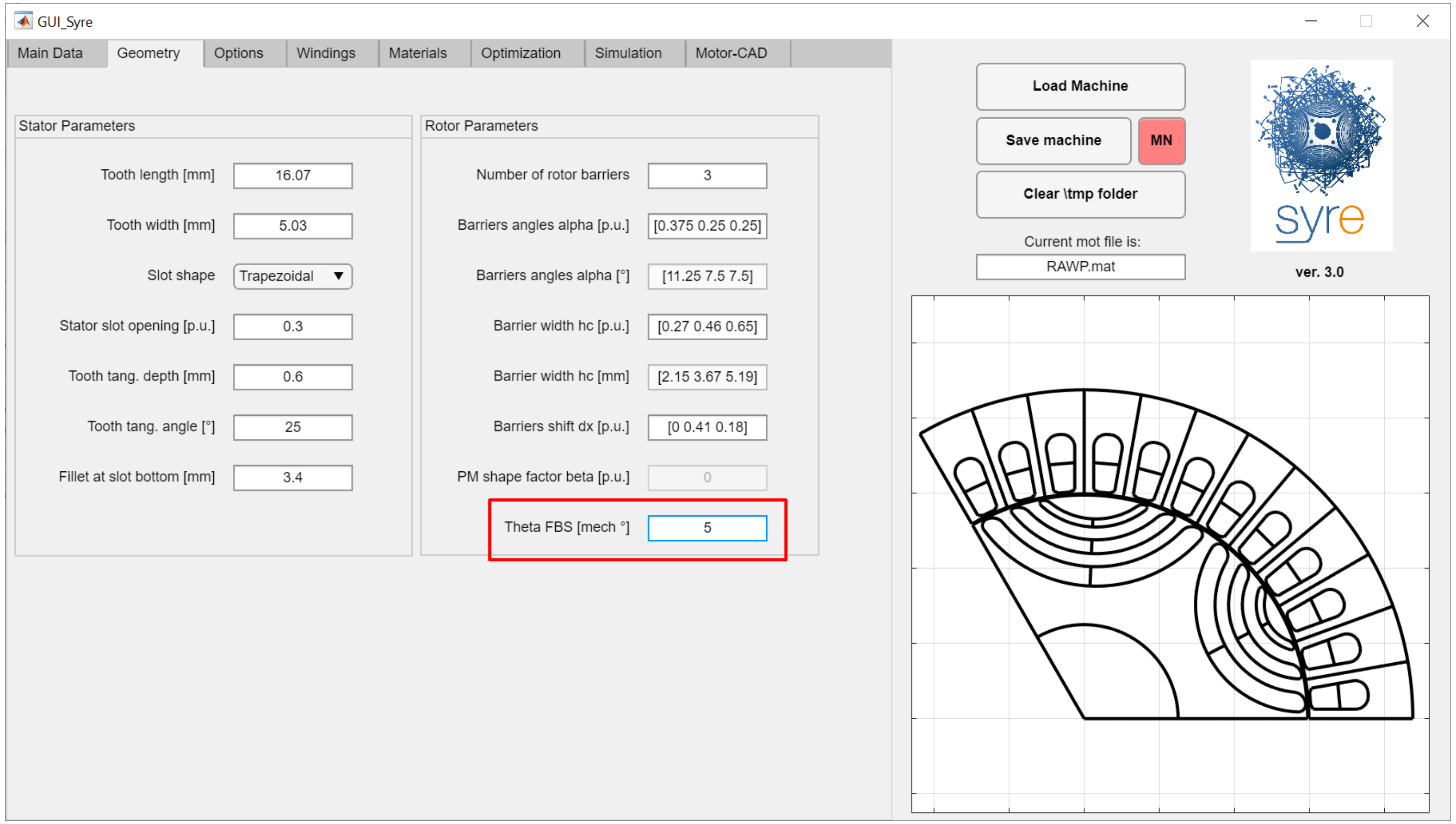
20 Nm (!)

Flux Barriers Shift for Asymmetric Poles

A straightforward method for selective torque ripple minimization (h is the target harmonic order)

$$\theta_{FBS} = \frac{360°}{2p \cdot h}$$

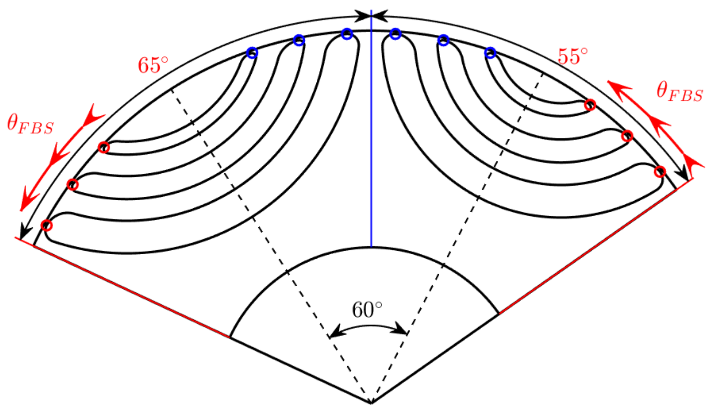




Flux Barriers Shift - Results

FEA comparison between straight and FBS machine

- The target 12th harmonic is minimized
- Less effective than skewing, at a lower manufacturing complexity



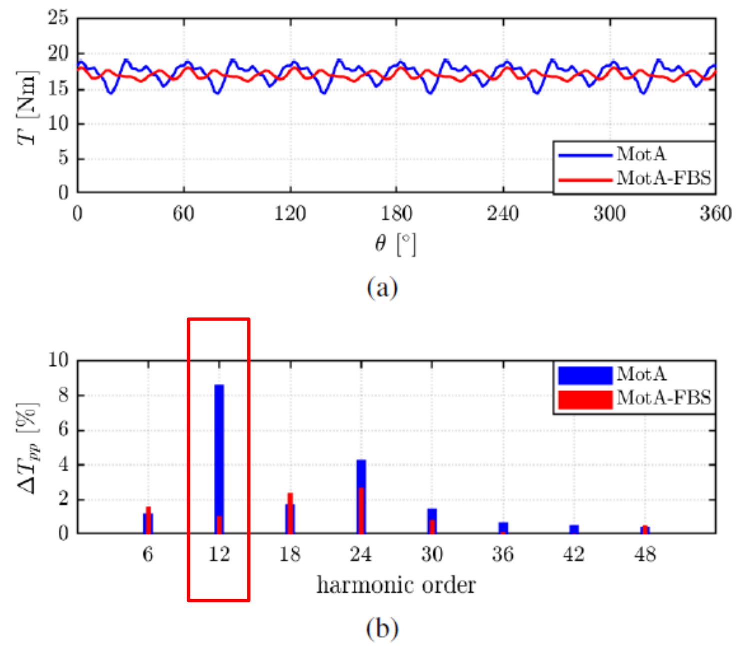
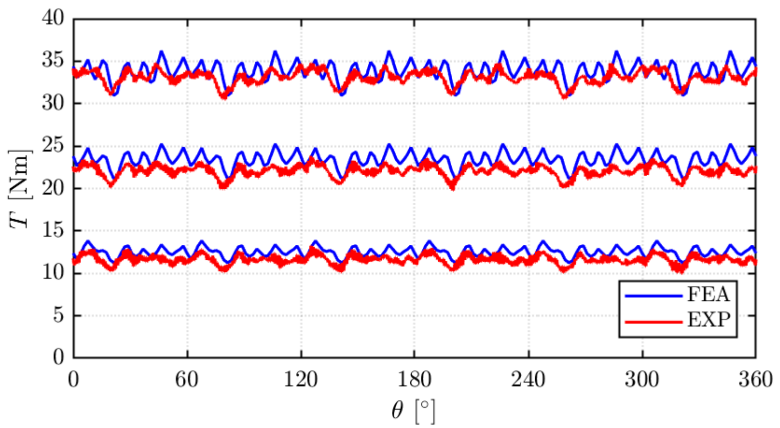


Fig. 7. Torque waveform (a) and harmonic spectrum (b) of MotA (blue) and MotA-FBS (red) at the rated current, along the MTPA



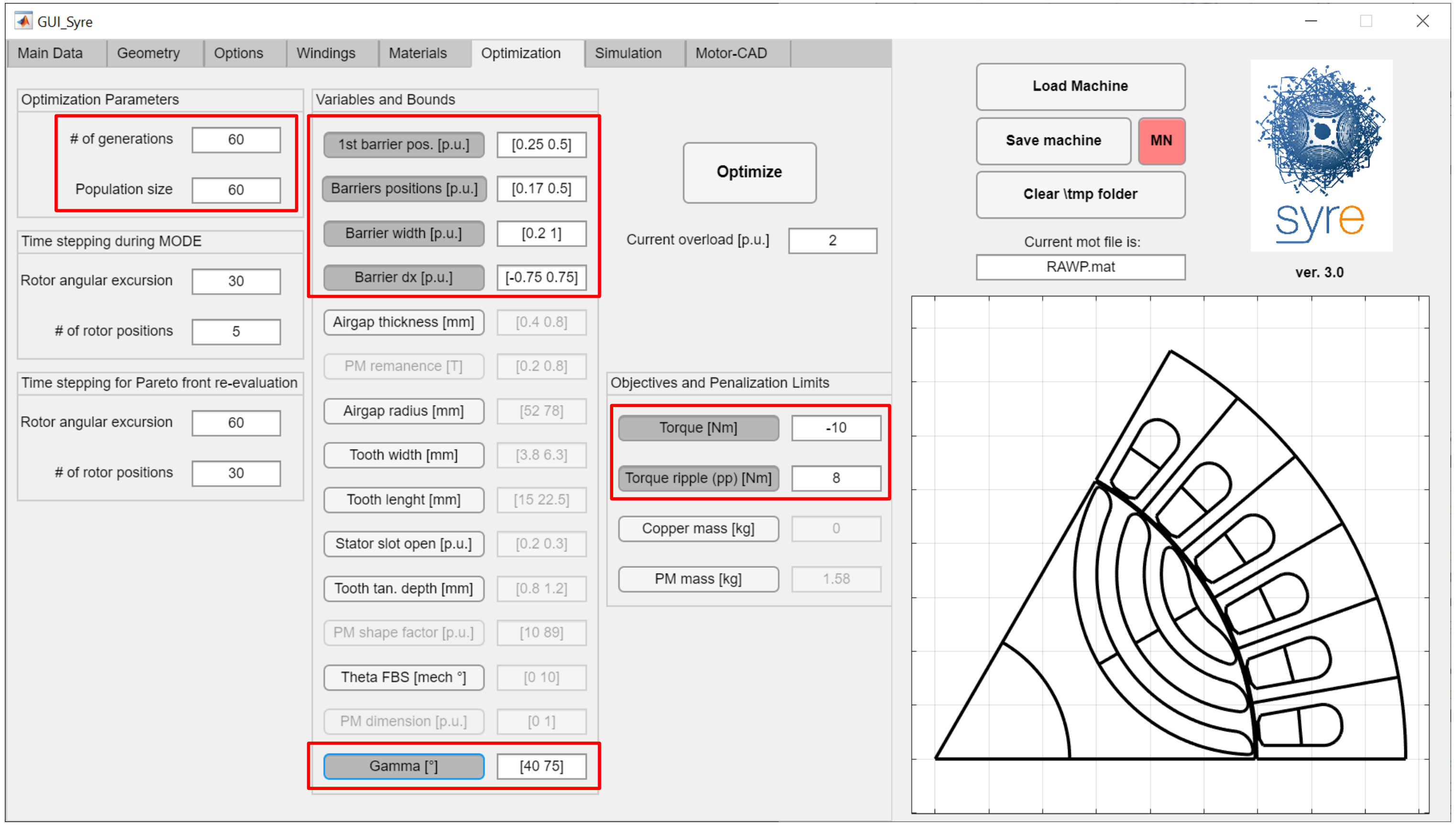
Design Optimization

[8] F. Cupertino, G. Pellegrino, and C. Gerada, “Design of Synchronous Reluctance Motors With Multiobjective Optimization Algorithms,” IEEE Trans. on Ind. App., 2014

The **Optimization** tab configures and runs the MODE optimization
(Multi-Objective Differential Evolution)

Key configuration fields:

- Population size and # of generations
- Selectable inputs
- Selectable objectives



Design Optimization

[9] G. Pellegrino, F. Cupertino, and C. Gerada, "Automatic Design of Synchronous Reluctance Motors Focusing on Barrier Shape Optimization," IEEE Trans. on Ind. App. 2015

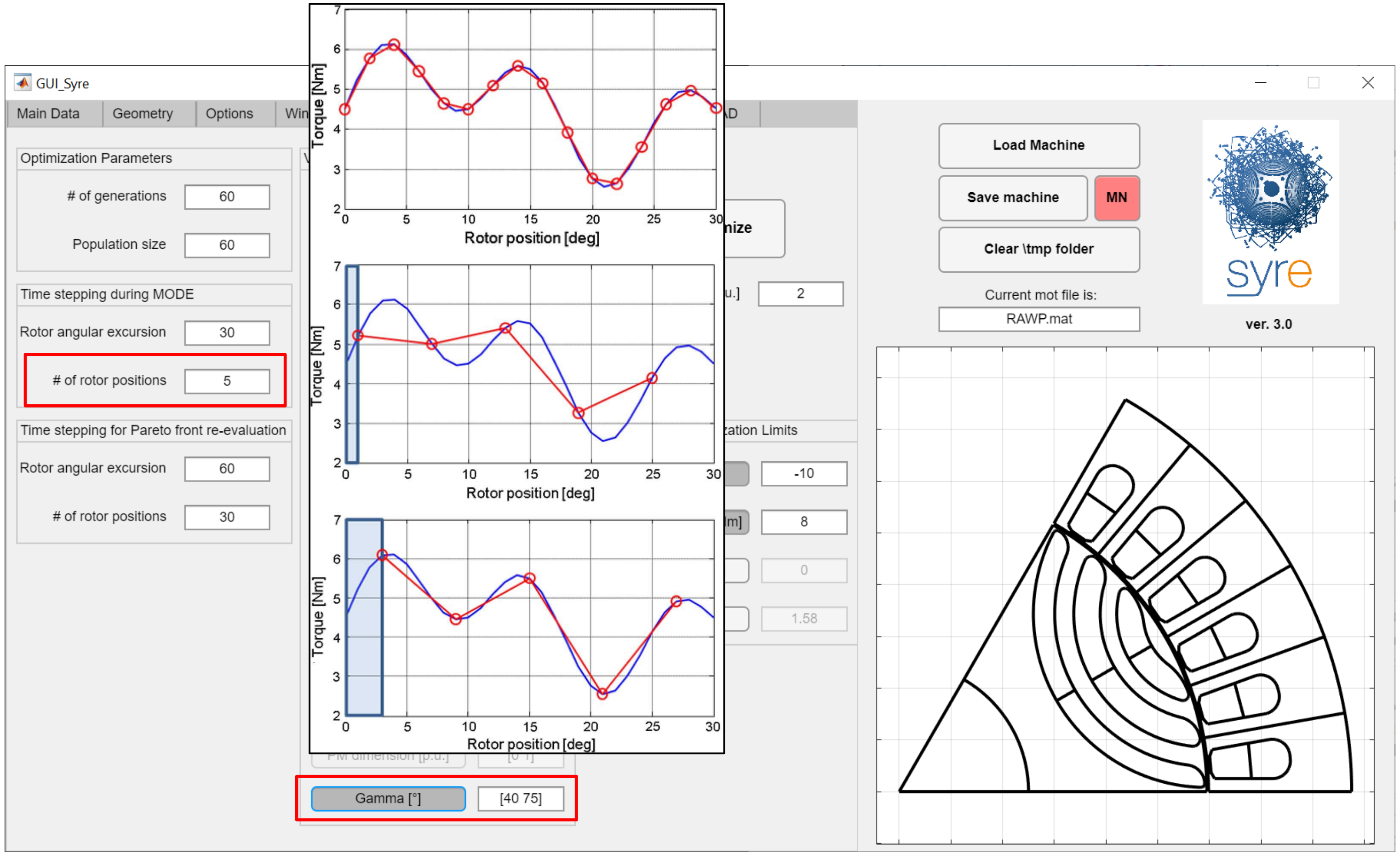
The **Optimization** tab configures and runs the MODE optimization
(Multi-Objective Differential Evolution)

Key configuration fields:

- Population size and # of generations
- Selectable inputs
- Selectable objectives

Fast FEA evaluation:

- 5 rotor positions per candidate, **random** offset
- **random** current phase angle during optimization
- Accurate re-evaluation of the Pareto-optimal designs (30 rotor positions)



Torque Ripple Optimization

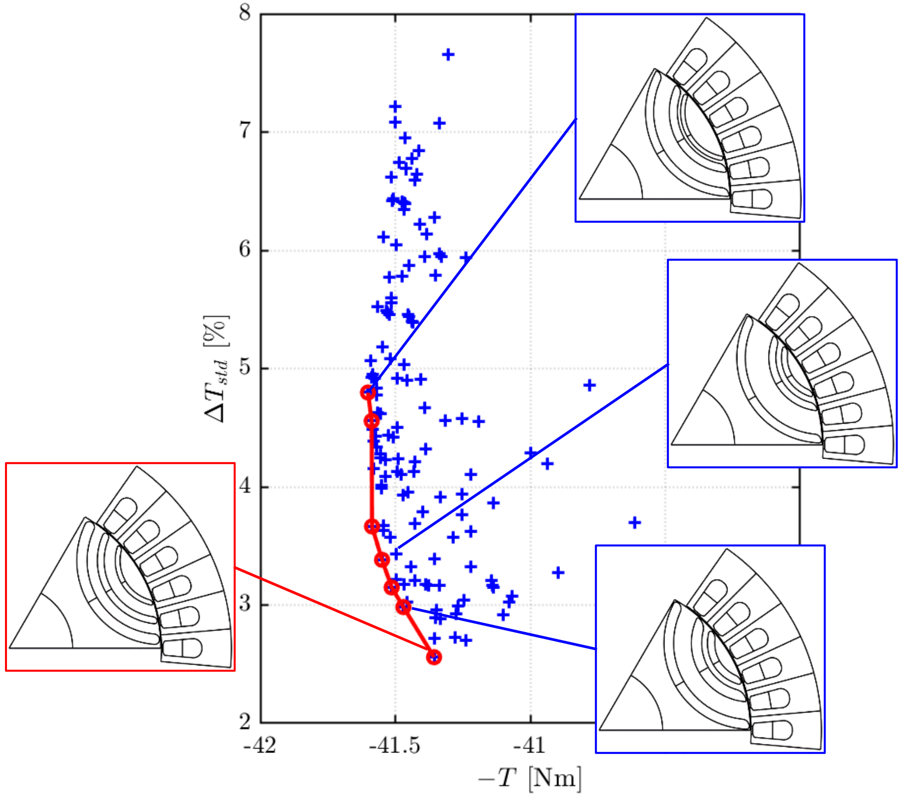
Example of automated rotor design via optimization

- Automated process, very good for non-specialist designers
- Torque ripple minimization is very effective and consistent with respect to current loading variation
- Hard to beat in terms of performance
- The optimized rotor resembles regular pitch one

✘ Computational time
(12 hours on INTEL i7-4770 PC, 3600 function evaluation)

✘ Pareto-optimal machines are not necessarily feasible

Pareto front of
Torque Vs Torque ripple optimization



Current Load and Copper Temperature Estimate

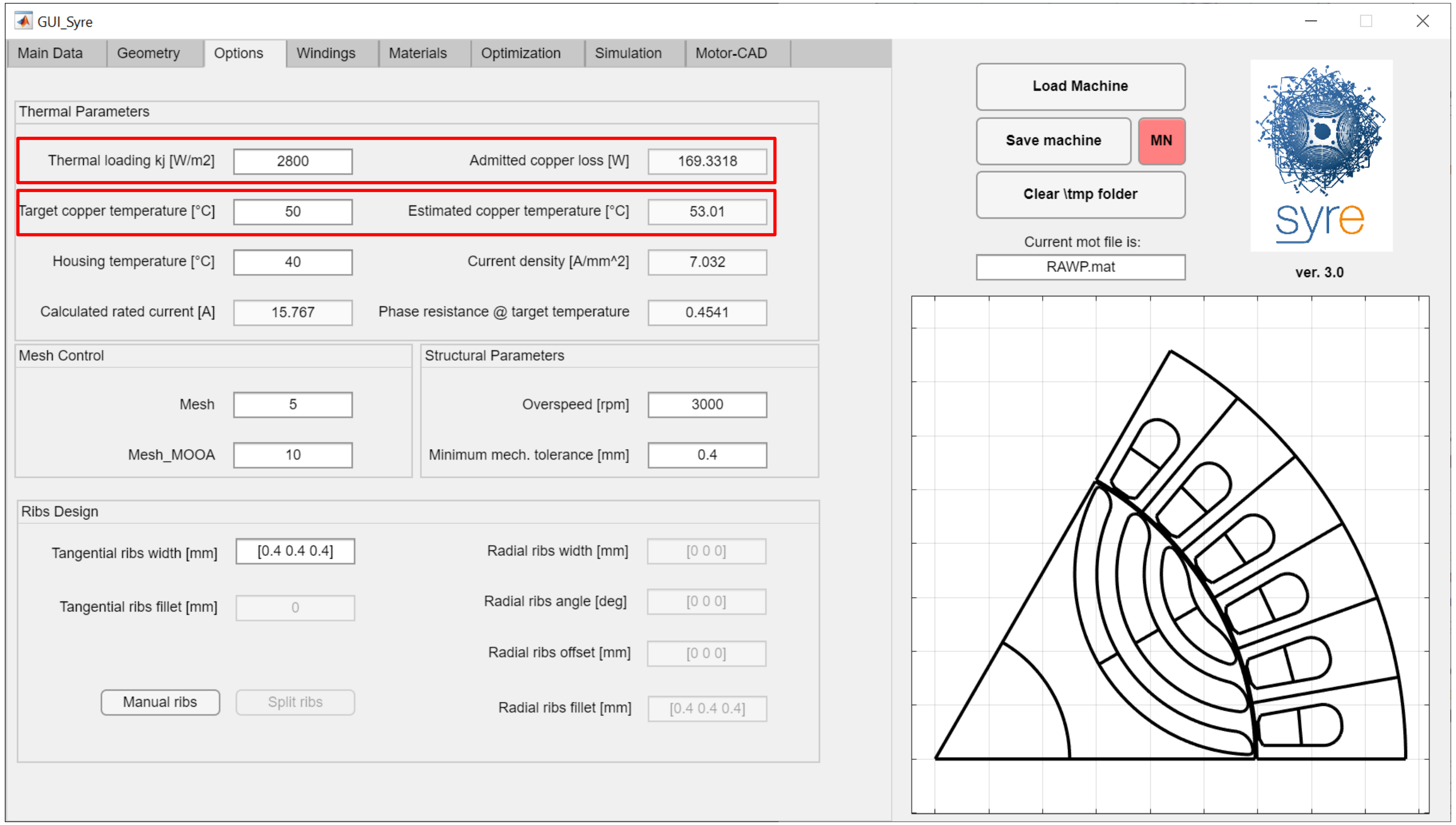
The inputs are:

- Specific copper loss (W/m2)
- Target copper temperature

A lumped parameter **thermal network** estimates the copper temperature given the housing temperature

<u>Target and estimated temperature must be equal</u>

This helps defining the current loading or current density of the initial design

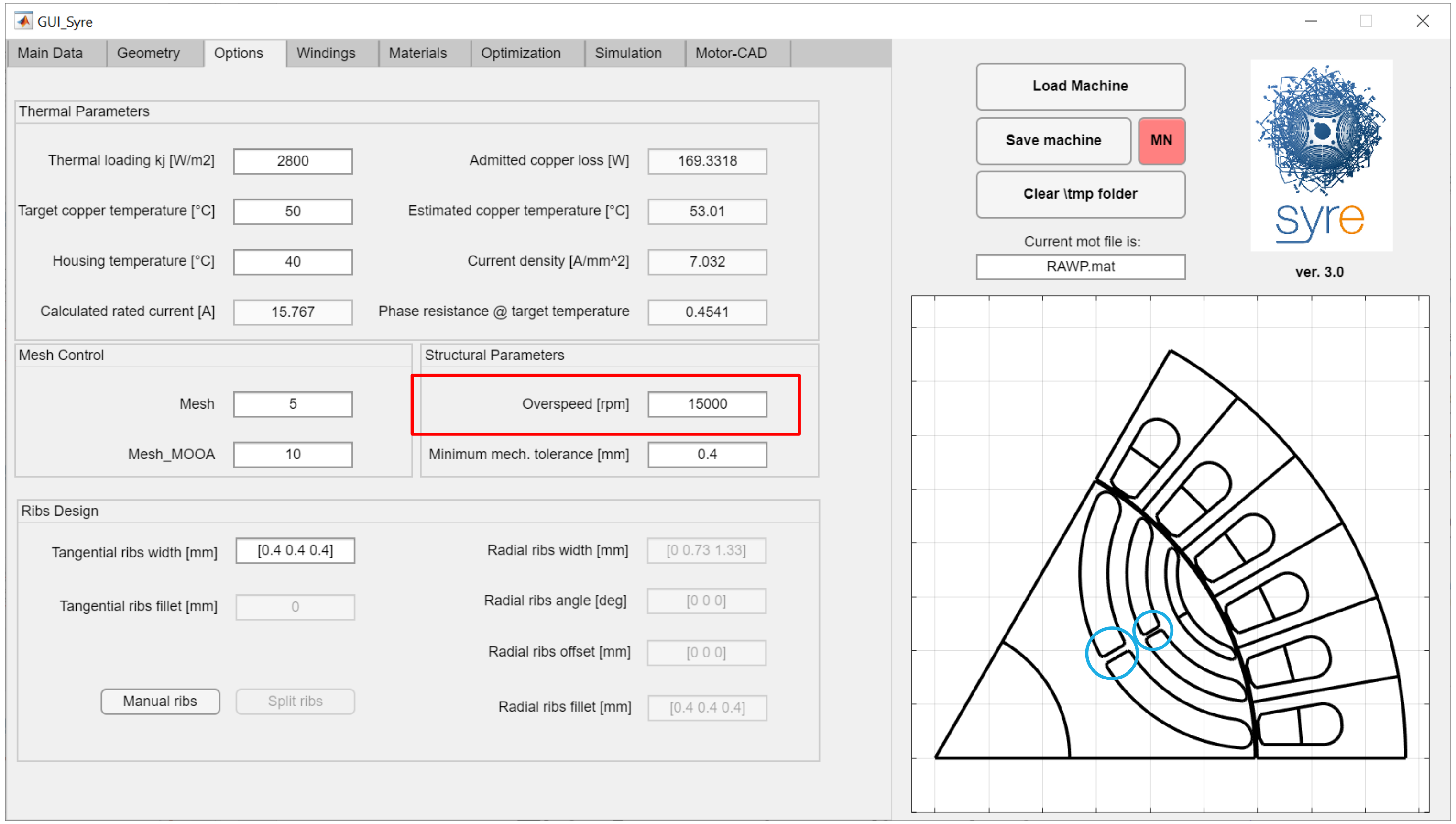


Structural co-design

The overspeed (rpm) input field determines the size of the additional internal rib

Calculated under the assumption that each rib supports all the downstream rotating mass, and imposing a stress limit equal to the yield strength of the selected silicon steel (285 MPa for M600-50A)

<u>This is seamlessly evaluated for each candidate design during optimization</u>



Windings Design

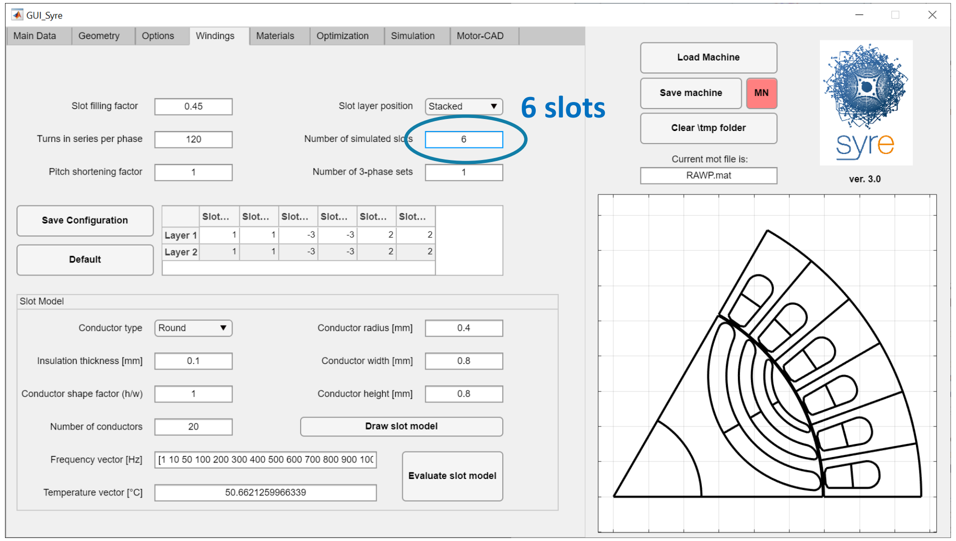
```
******************************************************************
This is koil_syre, a koil forc to be interfaced with Syre
visit koil.sourceforge.net Copyright 2009-2014 Luigi Alberti
******************************************************************
```

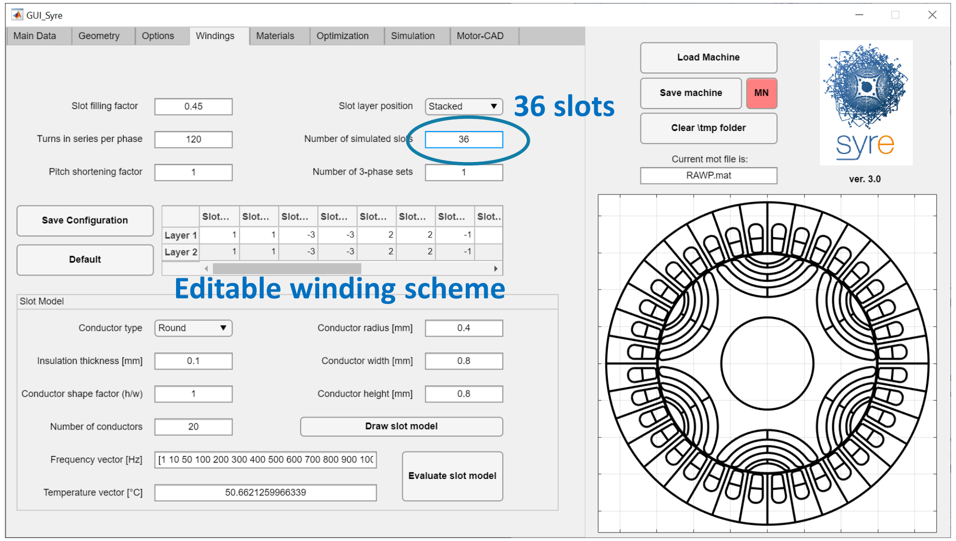
KOIL designs the winding distribution into slots automatically, given the slot/pole/phase number

- Example: p = 3 (pole pairs), q = 2 (slots/pole/phase)

Symmetry conditions are exploited: it is one rotor pole and **6 stator slots** in here

User defined windings are feasible. See for example **all 36 slots** set manually

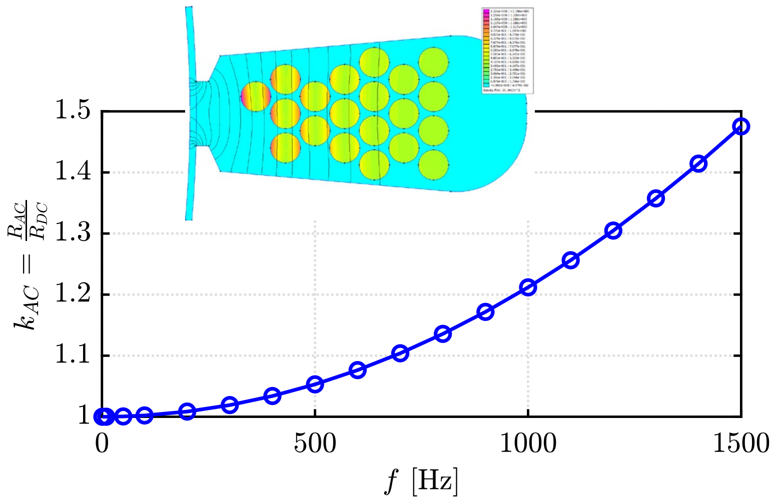


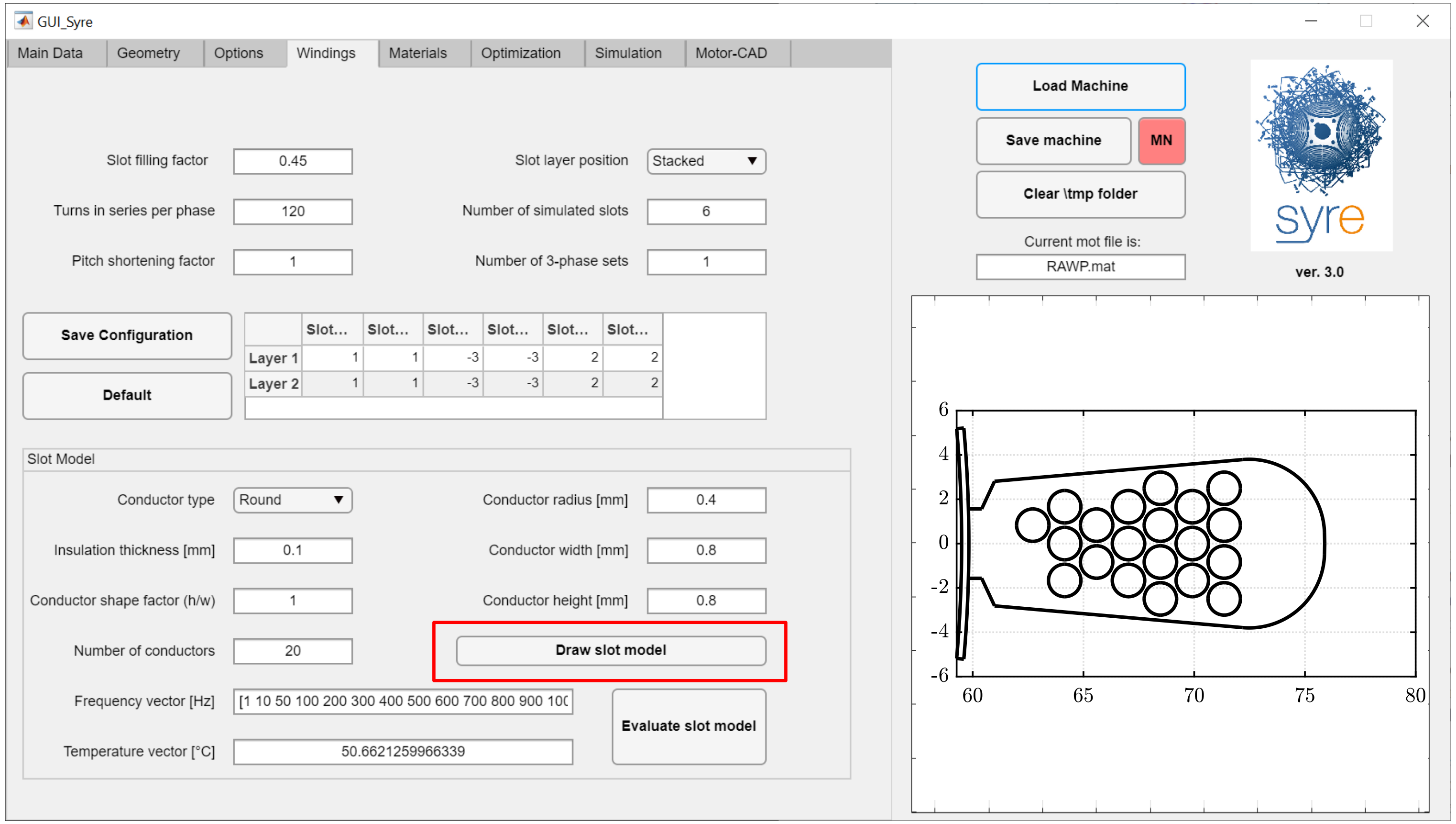


Slot model for AC loss

AC loss is FEA evaluated using AC analysis

The AC loss vs frequency characteristic contributes to the <u>efficiency map</u> evaluation





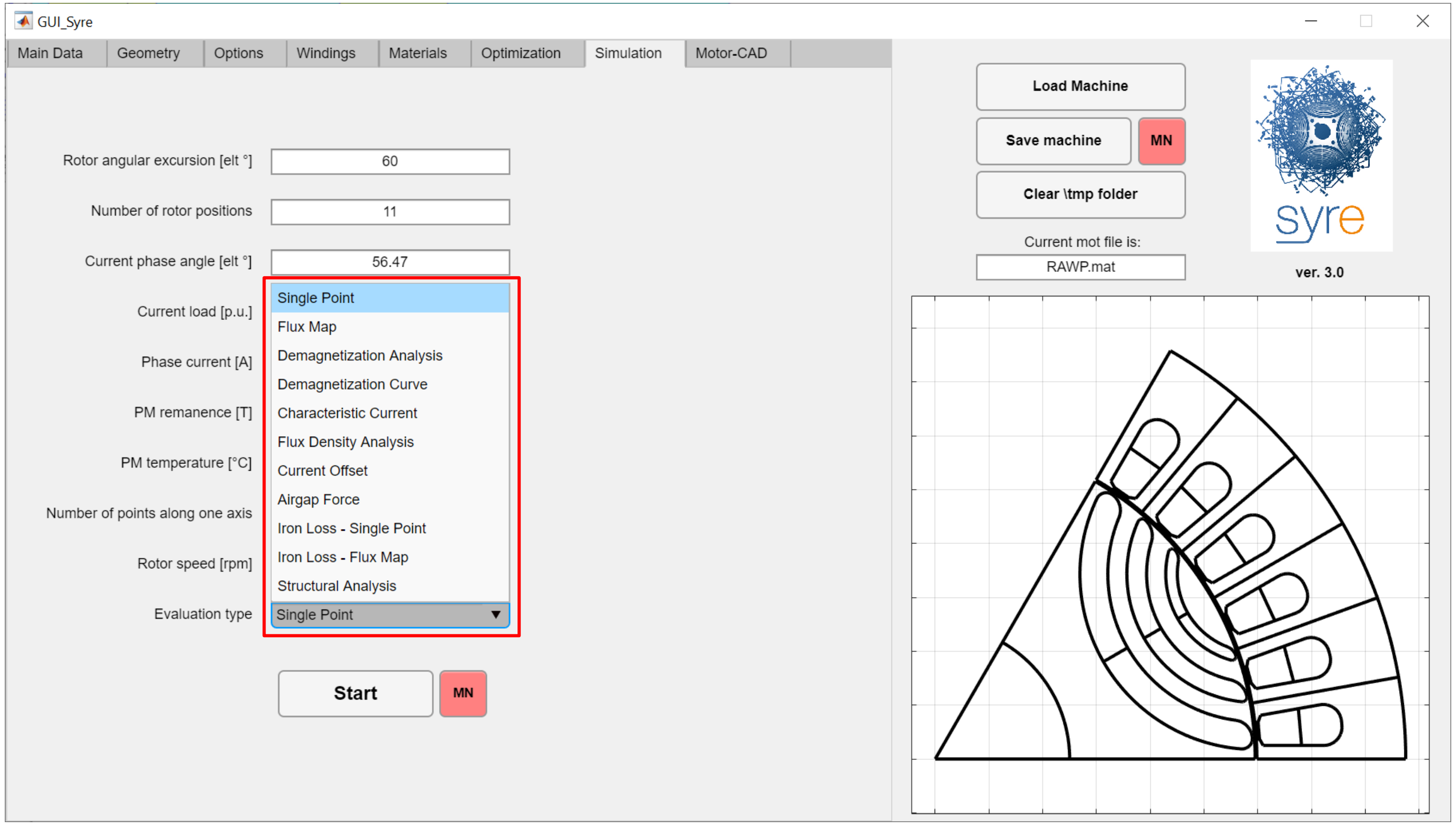
The Simulation Tab

A list of FEA simulation possibilities is given

Besides FEMM, MN stands for Simcenter MagNet 2D FEA

Export to Ansys Maxwell is in progress

Demagnetization and characteristic current refer to PM machines



Flux maps

dq flux maps, torque and torque ripple maps are calculated with magnetostatic FEMM runs

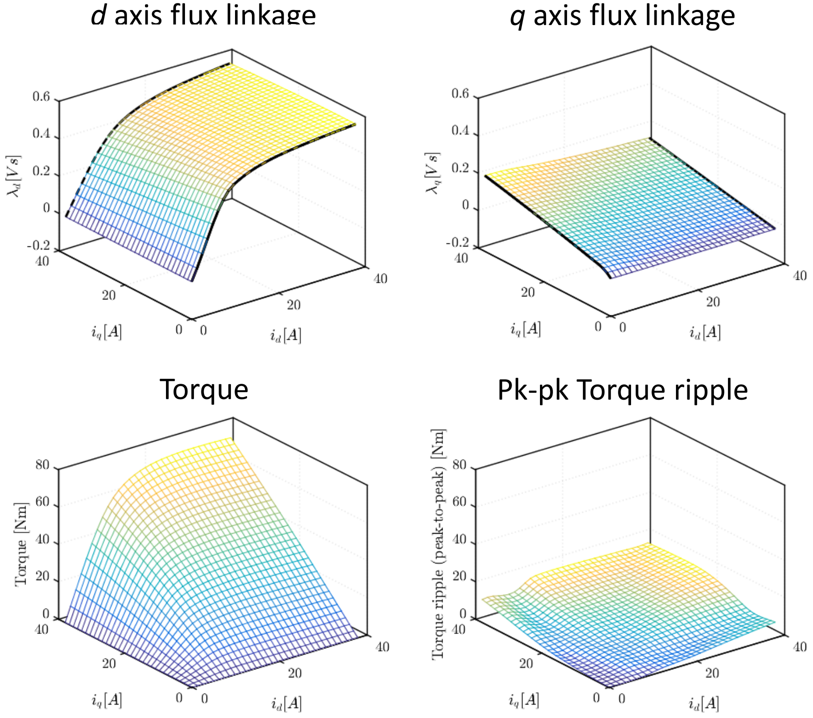
$$\lambda_d = \Lambda_d(i_d, i_q)$$
$$\lambda_q = \Lambda_q(i_d, i_q)$$

This is called the *dq* approach (fundamental component of flux linkages)

Apparent and incremental inductance maps are derived, e.g.

$$L_d(i_d, i_q) = \frac{\Lambda_d(i_d,i_q)}{i_d}, \; l_d(i_d, i_q) = \frac{\Delta\Lambda_d(i_d,i_q)}{\Delta i_d}$$

This is the key for further manipulation and vector control



Iron Loss Map

[10] K. Venkatachalam, C. R. Sullivan, T. Abdallah, and H. Tacca, "Accurate prediction of ferrite core loss with non sinusoidal waveforms using only Steinmetz parameters," in *2002 IEEE Workshop on Computers in Power Electronics, 2002.*

The iron loss map is FEA simulated at a single speed value n_0(rpm)

Hysteresis and classic loss terms are evaluated separately

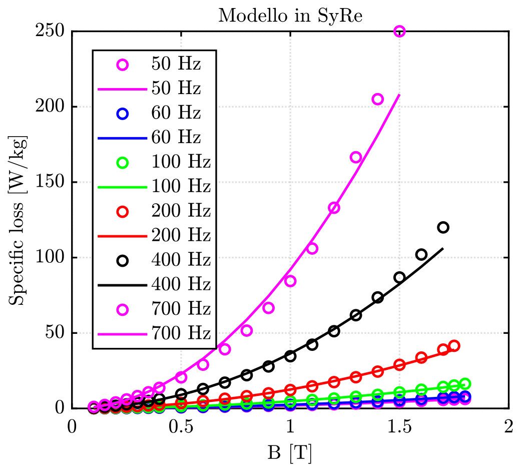
$$P_{Fe} = \underbrace{h_s\left(i_d, i_q, n_0\right) + c_s\left(i_d, i_q, n_0\right)}_{\text{stator}} + \underbrace{h_r\left(i_d, i_q, n_0\right) + c_r\left(i_d, i_q, n_0\right)}_{\text{rotor}}$$

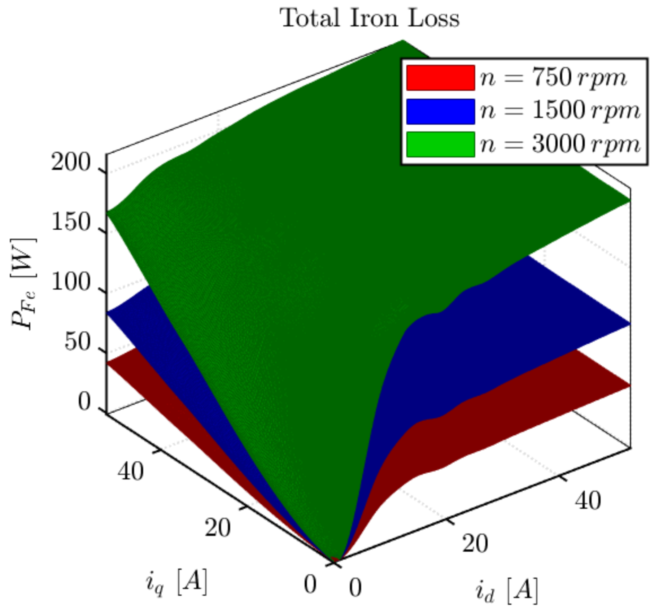
The loss map is scaled speed-wise

$$P_{Fe}\left(i_d, i_q, n\right) = \left(h_s + h_r\right) \cdot \left(\frac{n}{n_0}\right)^{\alpha} + \left(c_s + c_r\right) \cdot \left(\frac{n}{n_0}\right)^{2}$$

after the **specific loss (modified) Steinmetz model**

$$p_{Fe} = k_h f^{\alpha} B^{\beta} + k_e (fB)^{2} \left(\frac{\mathrm{W}}{\mathrm{kg}}\right)$$





Power Electronics Innovation Center

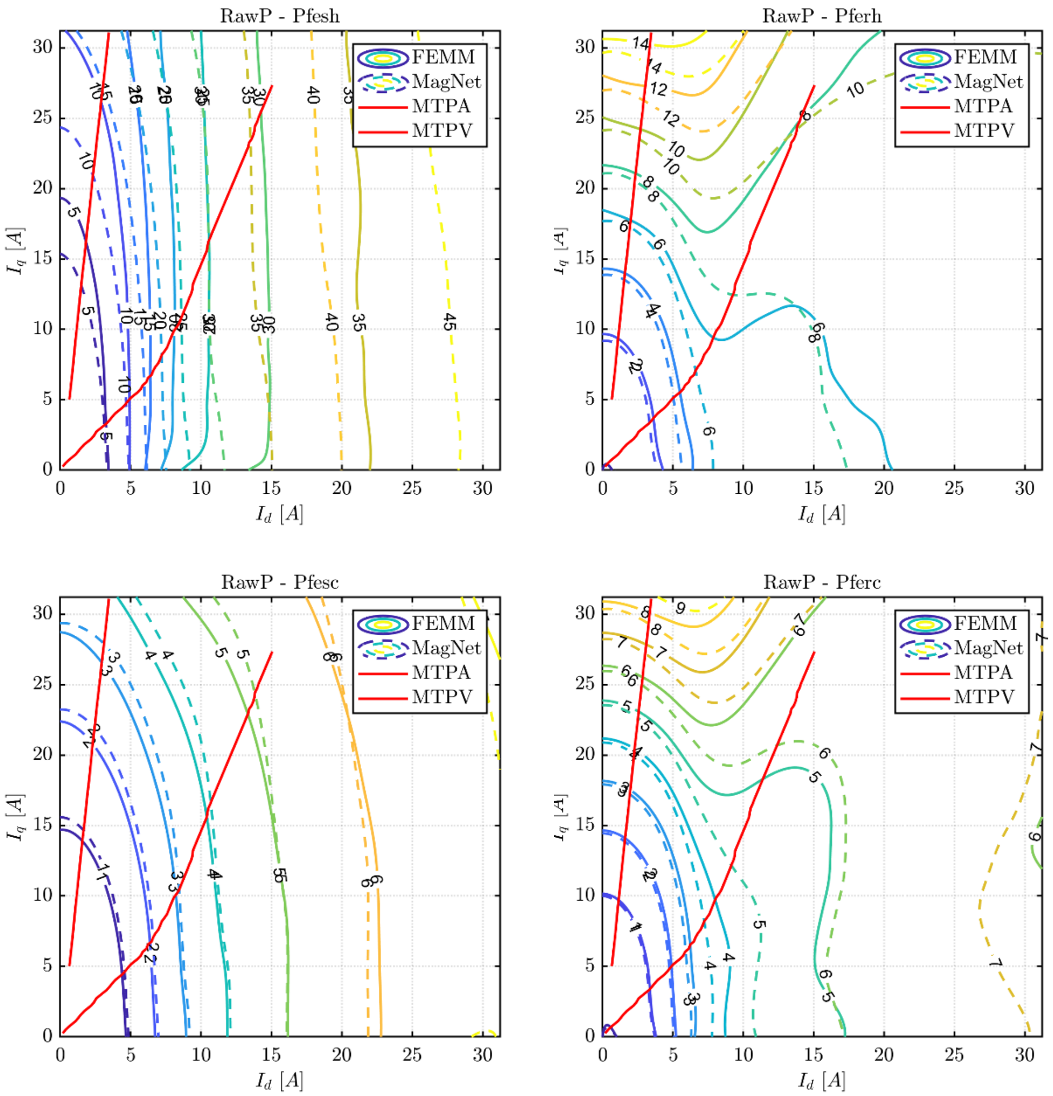
Iron Loss with FEMM and Simcenter MagNet

Simcenter MagNet transient with motion versus FEMM magnetostatic simulation

- Same iron loss data
- Simcenter Magnet: proprietary algorithm
- SyRe – FEMM: manipulation of the local field

The results are comparable

- Rotor loss discrepancy is more significant, but less of impact
- SyRe overestimates the loss, which is acceptable
- Computation wise



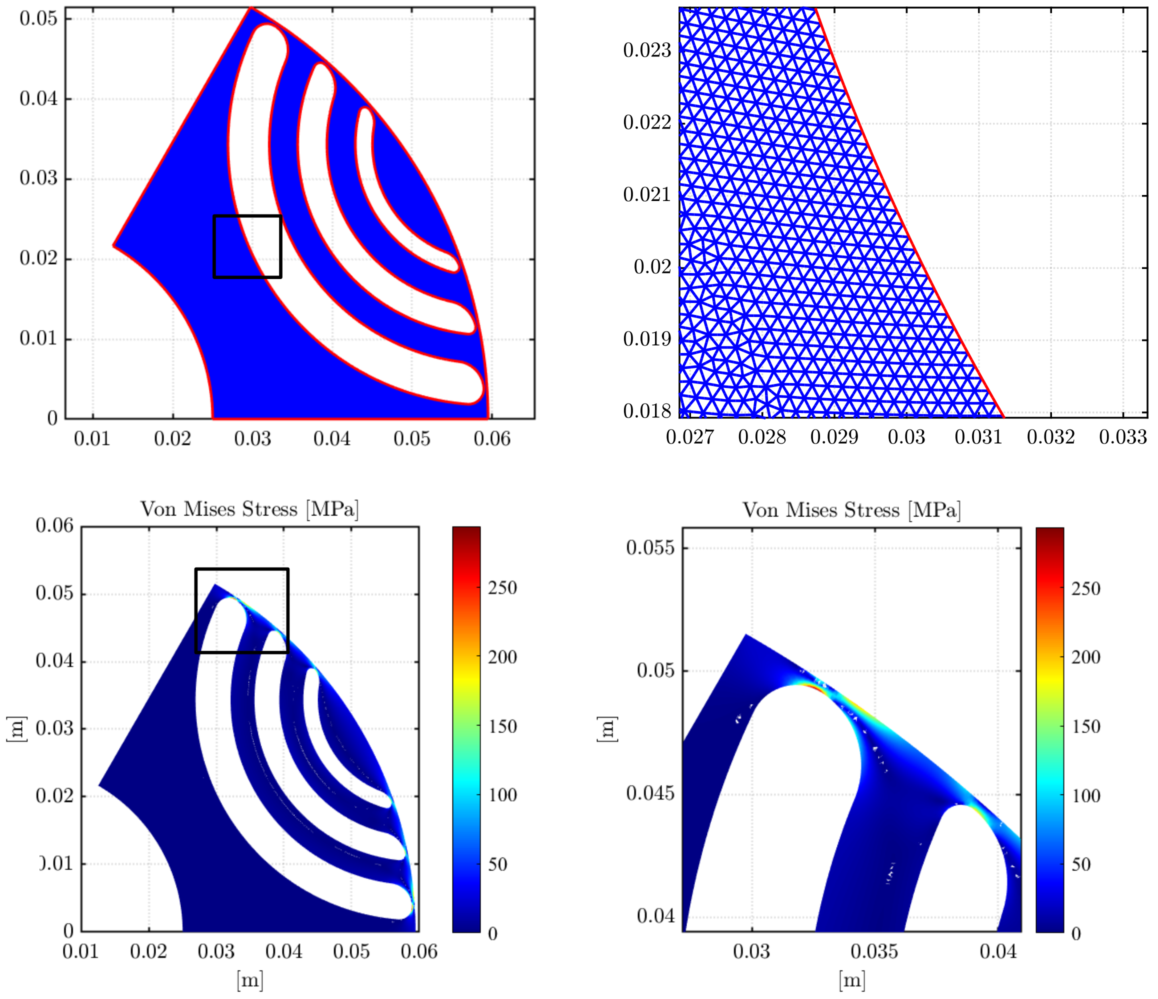
FEA Evaluation of Centrifugal Stress

Structural FEA called directly from the GUI

- Linear FEA model
- Simulation time: a few seconds

NEW: not yet online

Mesh for structural FEA

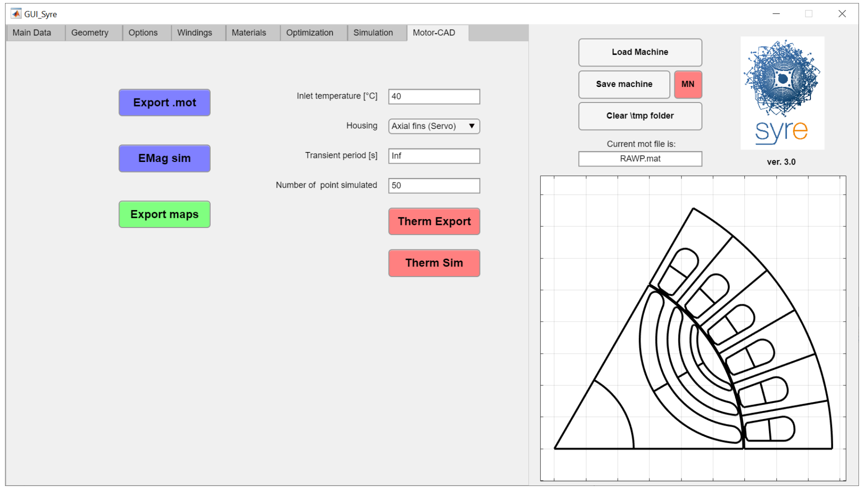


Stress calculated at 5000 rpm

Yield strength of M600-50A is 285 MPa

Export to Motor-CAD

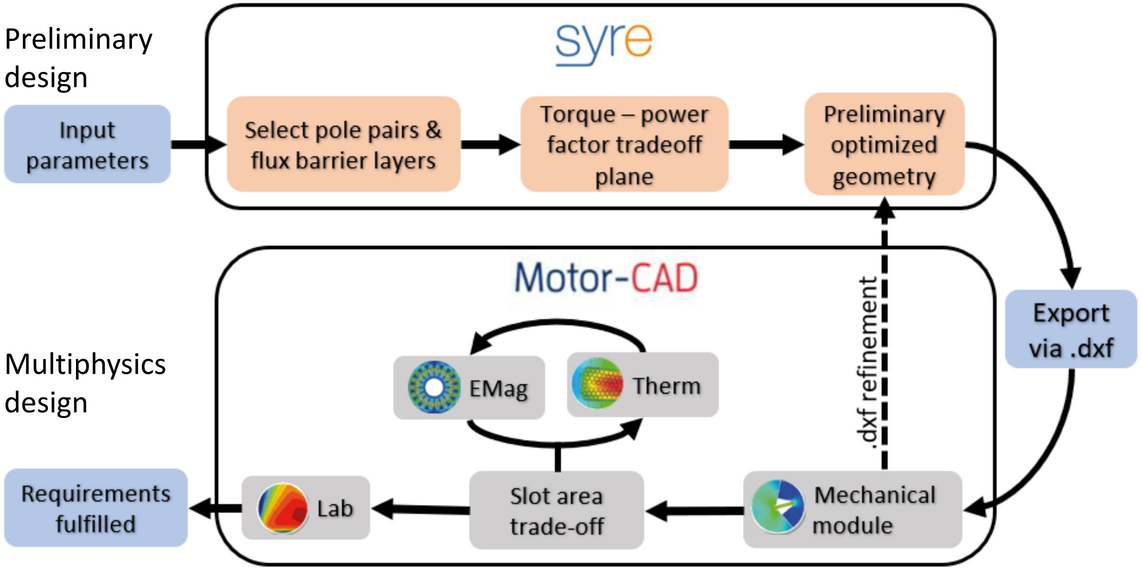
[11] P. Ragazzo, S. Ferrari, N. Riviere, M. Popescu, and G. Pellegrino, "Efficient Multiphysics Design Workflow of Synchronous Reluctance Motors," in *2020 International Conference on Electrical Machines (ICEM)*, Gothenburg, Sweden, Aug. 2020



The synergy with Motor-CAD is win-win

- Fast preliminary design features of SyR-e complement well with Motor-CAD
- The Motor-CAD suite is recognized by the industry as best-in-class for finalizing the motor design and for thermal validation

Interface towards Ansys Maxell is ongoing



GUI_Syre_MMM

Magnetic Model Manipulation

dqt model

The $dq\theta$ approach includes the effect of rotor position into the flux and torque maps

$$\lambda_d = \Lambda_d(i_d, i_q, \theta)$$

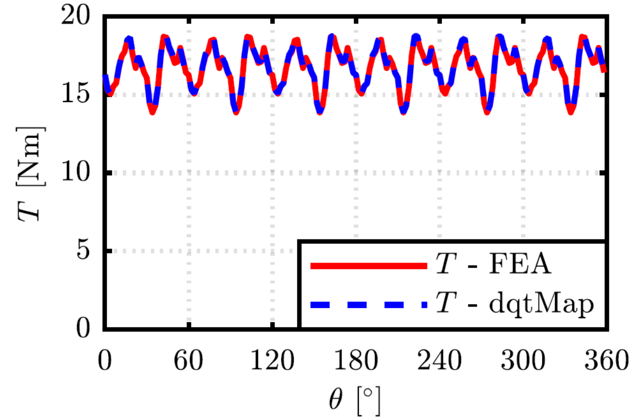
$$\lambda_q = \Lambda_q(i_d, i_q, \theta)$$

$$T_e = T_e(i_d, i_q, \theta)$$

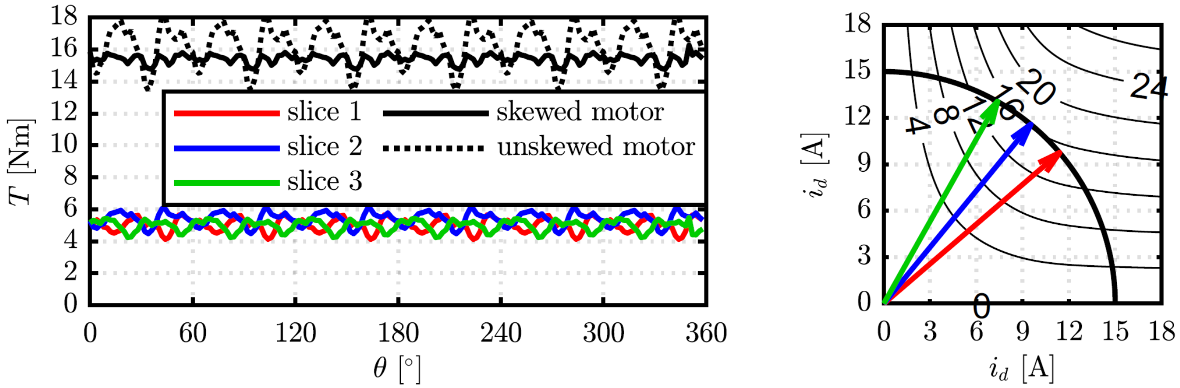
No new data, it is just the better storage and manipulation of FEA map results

- Torque waveform retrieved without a dedicated simulation
- Seamless skewing evaluation
- Machine model for control simulation

Torque waveform from *dqt map* interpolation



Torque waveform of the step-skewed machine

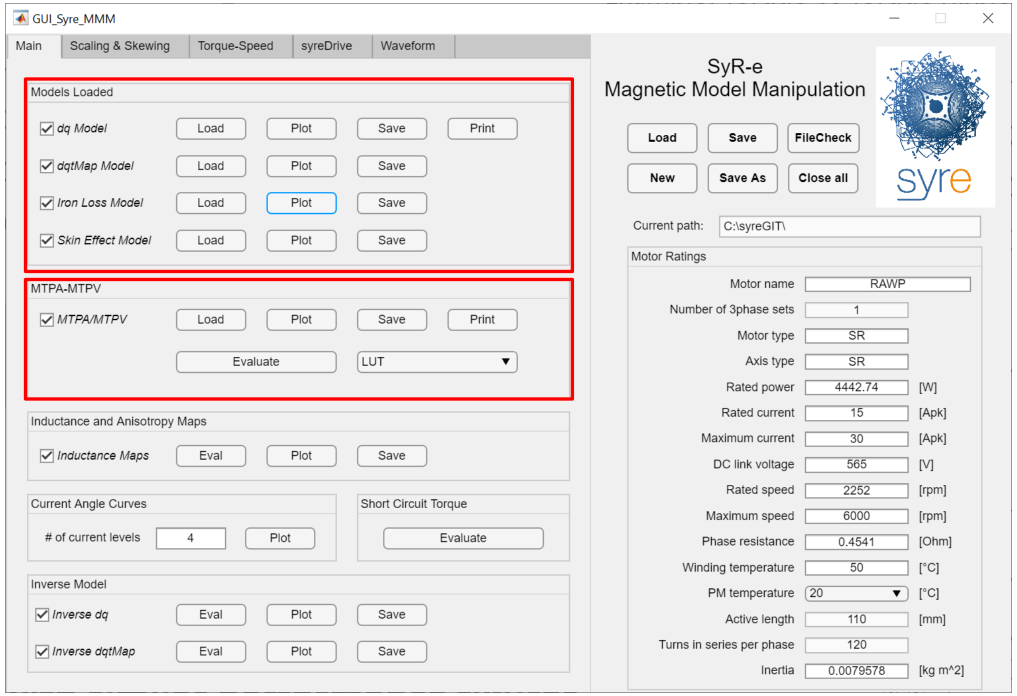


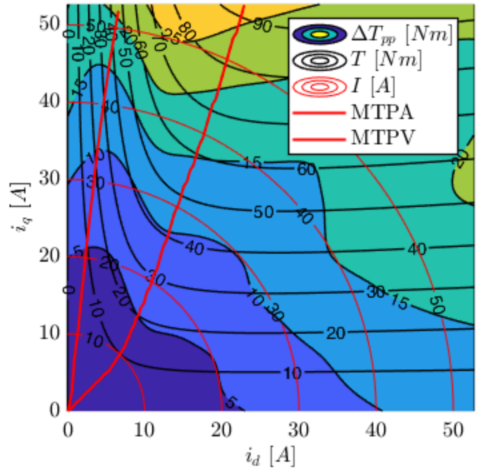
Efficiency Map Preliminaries

All maps are loaded

- Flux maps (*dq* or *dqt*)
- Iron loss map
- Slot AC loss curve (vs frequency)

The control trajectories (MTPA, MTPV) are also known, from flux map manipulation





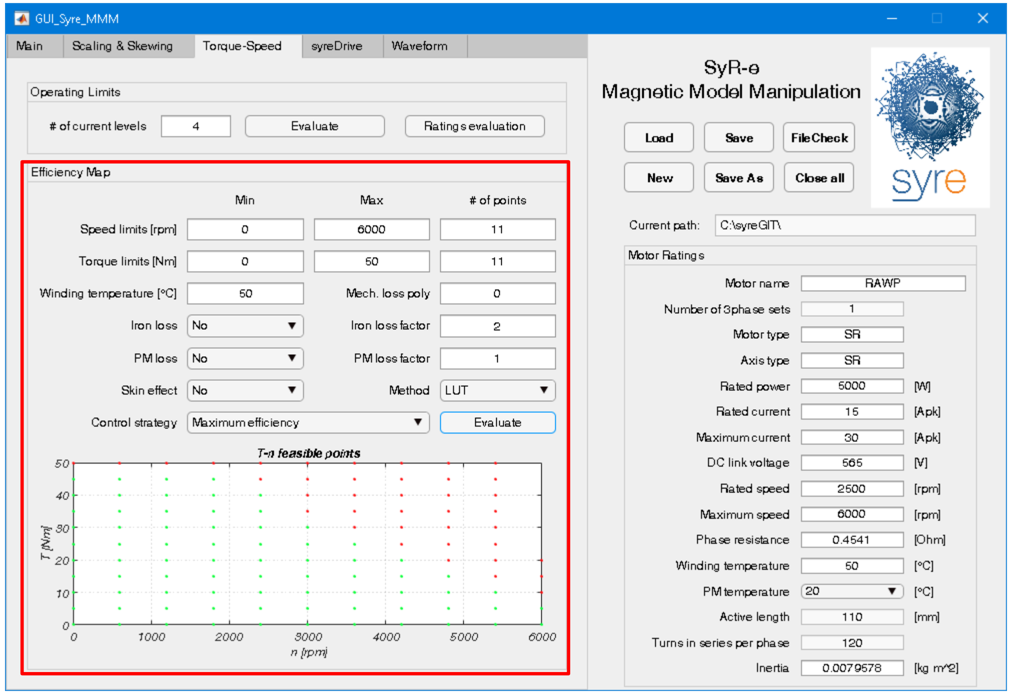
Efficiency Map Calculation

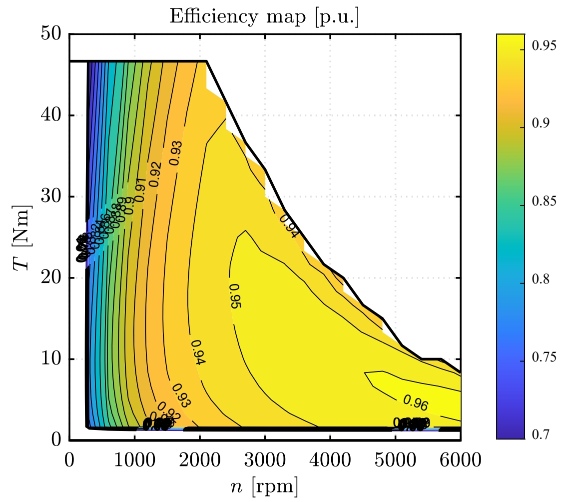
The torque vs speed domain is considered

At each speed (frequency) and torque value, the minimum loss control law is pursued

Current and voltage limits are considered

A conference contribution is under revision [12]





[12] S. Ferrari, P. Ragazzo, G. Dilevrano, and G. Pellegrino, “Flux-Map Based FEA Evaluation of Synchronous Machine Efficiency Maps”
submitted to WEMDCD 2021

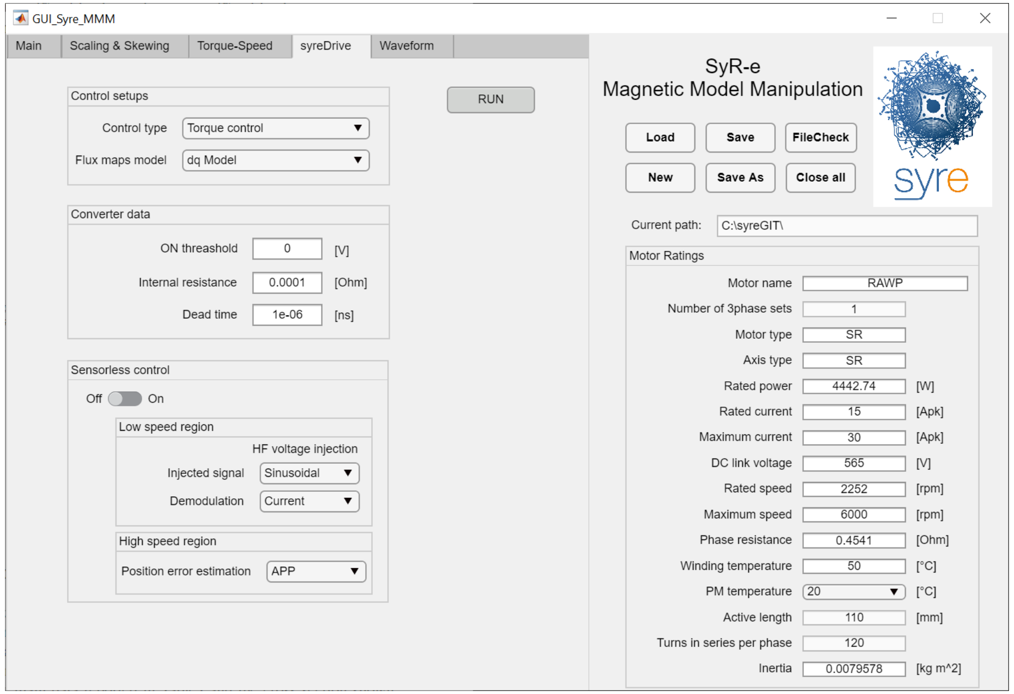
syreDrive

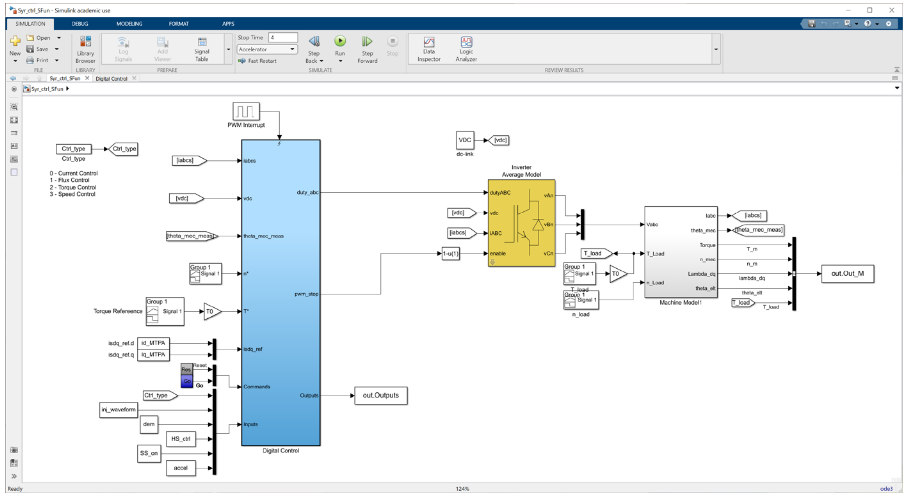
Drive control simulation

syreDrive tab

This new feature connects to Simulink for control simulation

- Discrete-time executed, C-Mex S-Function
- Average model of the inverter
- Continuous-state model of the machine (non circuital, inverse LUT based, *dq* or *dqt* compatible)





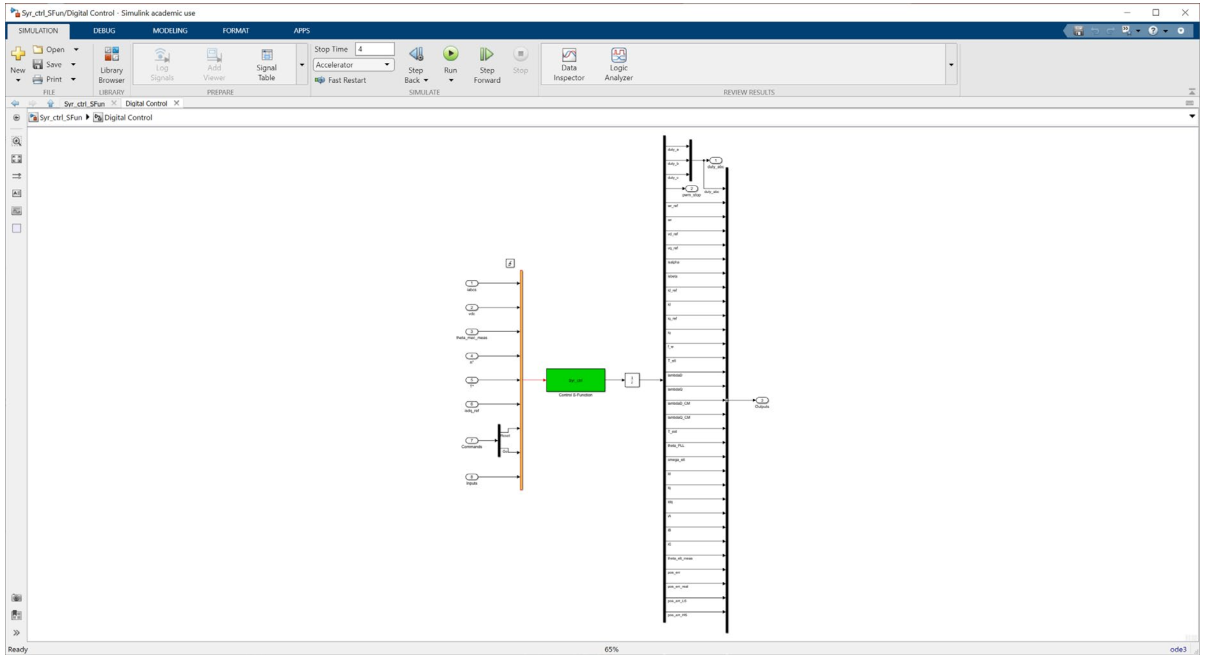
[13] D. Brunelli, A. Varatharajan, S. Ferrari and G. Pellegrino, "syreDrive: Automated Sensorless Control Code Generation for Synchronous Reluctance Motor Drives", **submitted to WEMDCD 2021**

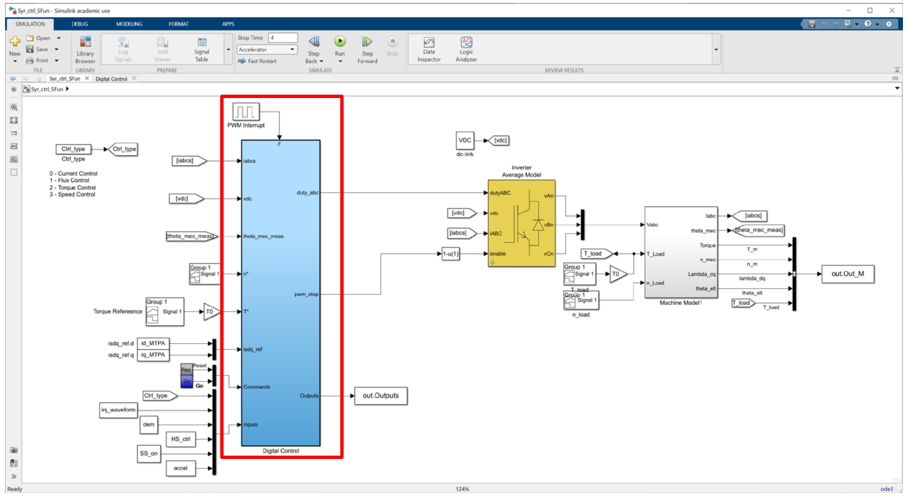
Inside the Simulink Model

The ctrl subsystem is discrete-time executed

The block contains a C-Mex S-Function and a one-step delay

The mex command of Matlab needs a C compiler to be installed, the one suggested by the Mathworks is MinGW





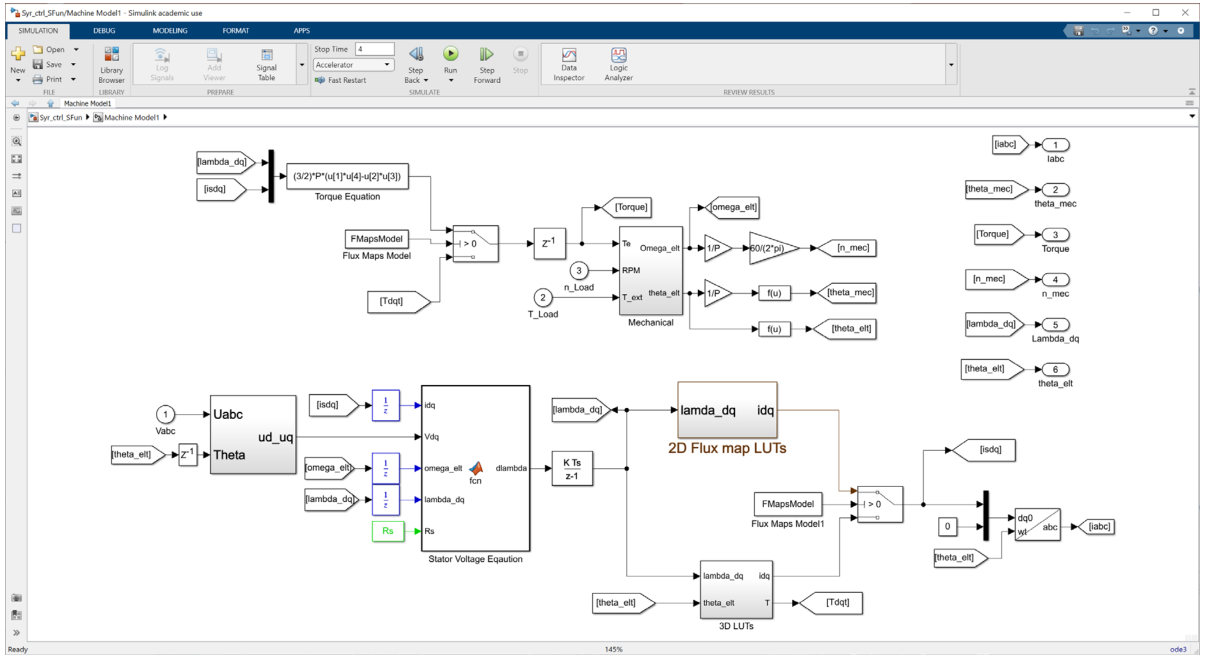
Inside the Simulink Model

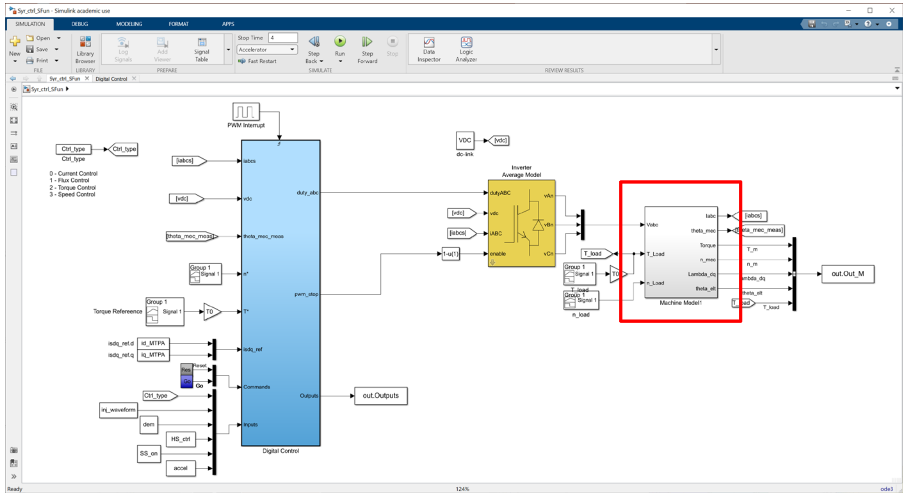
The motor subsystem is a continuous-time model based on state equations integration

It is not a circuital model:

- phase voltages are the input
- phase currents are the output

The flux map tables are used in inverse form (flux linkage → current), either *dq* or *dqt* form



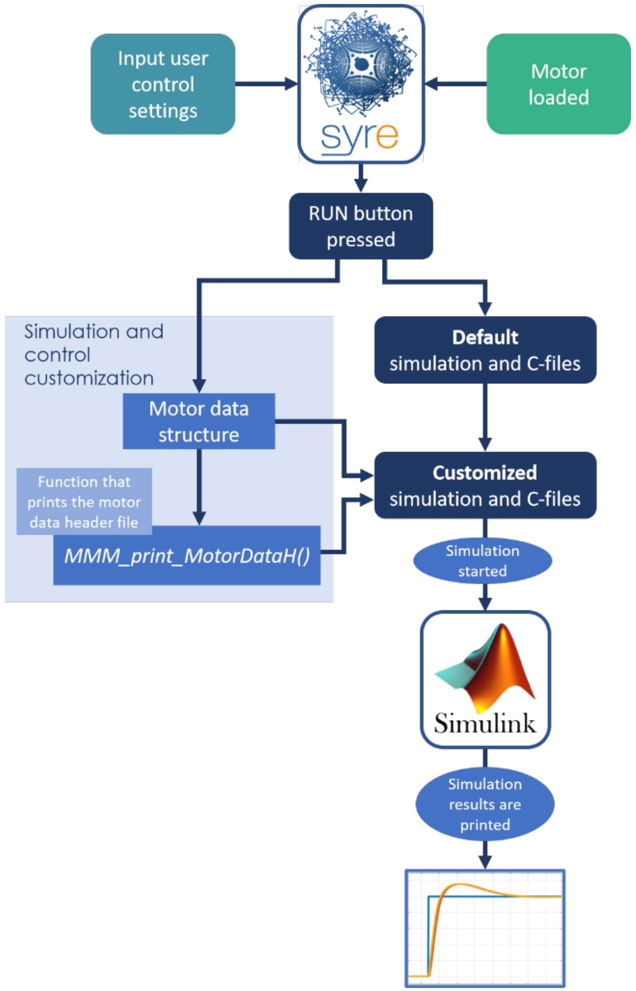


syreDrive flowchart

All necessary motor data is in the *RAWP.mat* file (structure *motorModel*)

A template Simulink model is in the SyR-e repository, the C code being part of it

Once the RUN button is pressed, a copy of the folder is configured according to the parameters of the motor under test



Files and source code

The automatically generated RAWP_ctrl folder contains

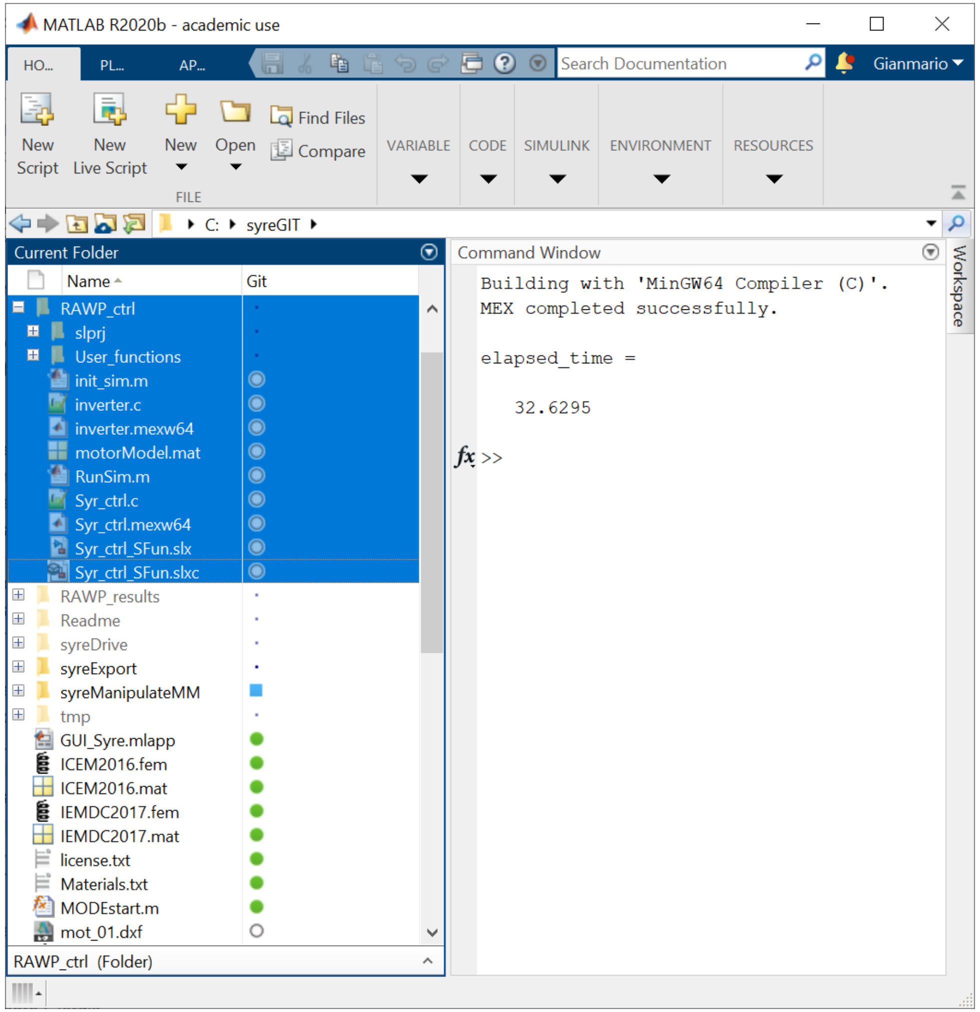
- The .slx model
- The source file *Syr_ctrl.c* and library files folder *User_functions*

The *User_constants.h* and *User-variables.h* files inside User_functions are **overwritten** according to the selected control type and the motor parameters

This is a modification of minimum impact

One simulation takes 32 sec in the example

The model can be user modified and run manually



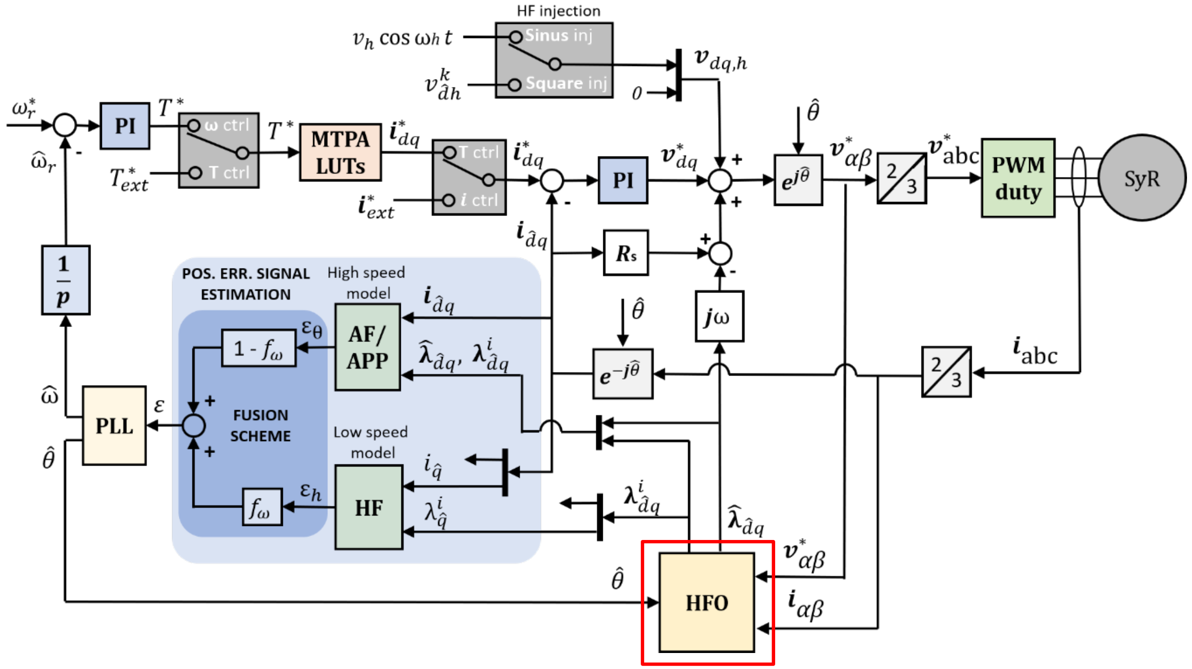
Types of Control

[14] A. Varatharajan, G. Pellegrino, E. Armando, and M. Hinkkanen, “Sensorless Synchronous Motor Drives: A Review of Flux Observer-based Position Estimation Schemes using the Projection Vector Framework,” *IEEE Trans. Power Electron.*, pp. 1–1, 2021

Selectable types of control

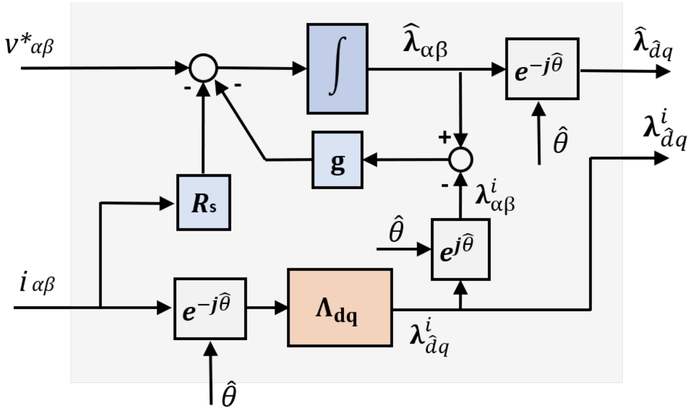
- Position sensor or sensorless
- Torque or speed
- Low speed sensorless: sin or sqw pulsating inj
- High speed sensorless: Active Flux or APP*

Example: hybrid flux observer



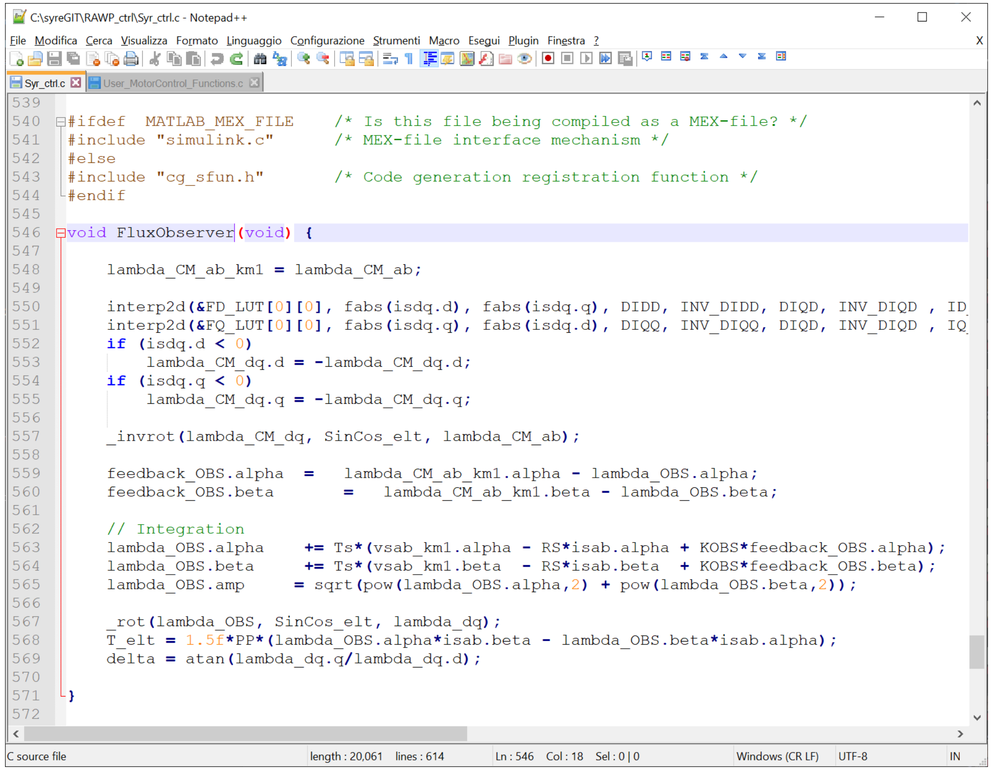
(*) APP (Adaptive Projection Vector) [14]

Hybrid Flux Observer



Common to all sensorless schemes:

- Back-emf integral (voltage model) in $\alpha\beta$ coordinates
- Obs. feedback error using the current-model flux estimate (flux-map LUTs Λ_{dq})
- Scalar obs. gain matrix $\mathbf{G} = \begin{bmatrix} g & 0 \\ 0 & g \end{bmatrix}$



```
#ifdef  MATLAB_MEX_FILE    /* Is this file being compiled as a MEX-file? */
#include "simulink.c"      /* MEX-file interface mechanism */
#else
#include "cg_sfun.h"       /* Code generation registration function */
#endif

void FluxObserver(void) {

    lambda_CM_ab_km1 = lambda_CM_ab;

    interp2d(&FD_LUT[0][0], fabs(isdq.d), fabs(isdq.q), DIDD, INV_DIDD, DIQD, INV_DIQD , ID
    interp2d(&FQ_LUT[0][0], fabs(isdq.q), fabs(isdq.d), DIQQ, INV_DIQQ, DIQD, INV_DIQD , IQ
    if (isdq.d < 0)
        lambda_CM_dq.d = -lambda_CM_dq.d;
    if (isdq.q < 0)
        lambda_CM_dq.q = -lambda_CM_dq.q;

    _invrot(lambda_CM_dq, SinCos_elt, lambda_CM_ab);

    feedback_OBS.alpha  =   lambda_CM_ab_km1.alpha - lambda_OBS.alpha;
    feedback_OBS.beta       =   lambda_CM_ab_km1.beta - lambda_OBS.beta;

    // Integration
    lambda_OBS.alpha    += Ts*(vsab_km1.alpha - RS*isab.alpha + KOBS*feedback_OBS.alpha);
    lambda_OBS.beta     += Ts*(vsab_km1.beta  - RS*isab.beta  + KOBS*feedback_OBS.beta);
    lambda_OBS.amp     = sqrt(pow(lambda_OBS.alpha,2) + pow(lambda_OBS.beta,2));

    _rot(lambda_OBS, SinCos_elt, lambda_dq);
    T_elt = 1.5f*PP*(lambda_OBS.alpha*isab.beta - lambda_OBS.beta*isab.alpha);
    delta = atan(lambda_dq.q/lambda_dq.d);

}
```

Results – Automatic calibration

Two motors of different sizes are considered

Sensorless speed control response is compared, under zero to nominal speed step and 50% nominal torque step reversal

The dynamic response in not optimized, but it guarantees stability independently of the machine size

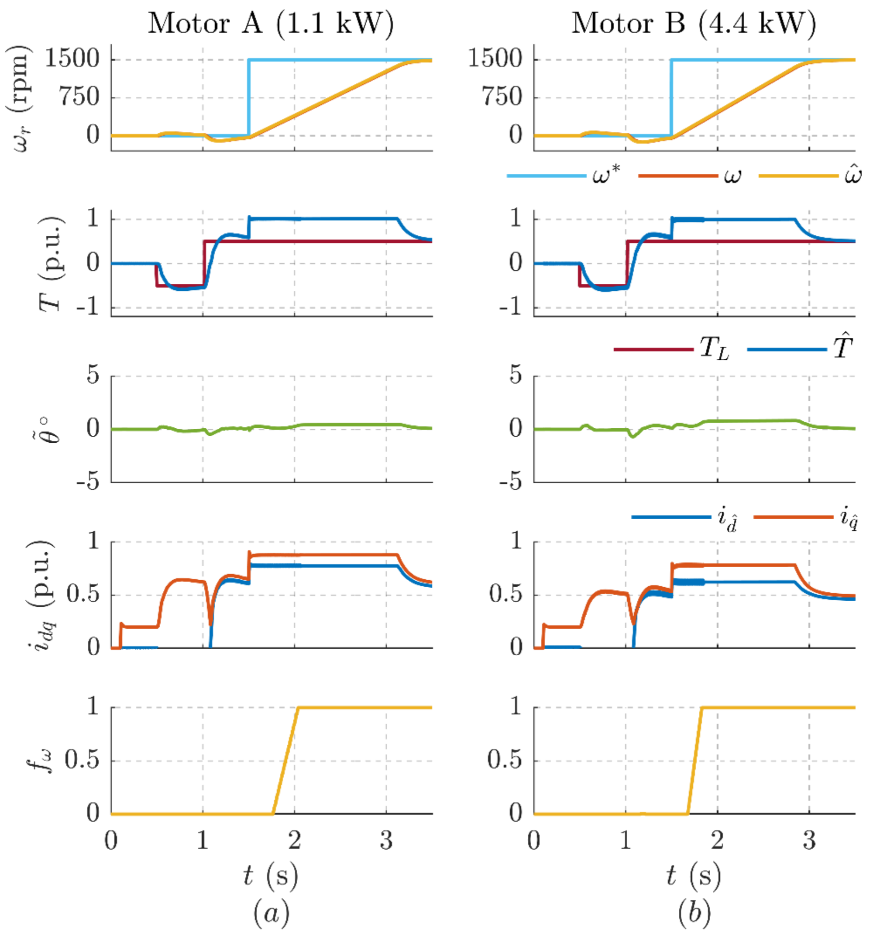


Fig. 6. Simulation result of syreDrive automated sensorless control generation using square-wave voltage injection with current-model flux demodulation at low speeds and APP at high speeds region: (a) Motor A (1.1 kW); (b) Motor B (4.4 kW).

Results – *dq* and *dqt* model comparison

The use of the *dqt* model in the control model is a step ahead in line with the model-based control design paradigm

The very preliminary results are shown here

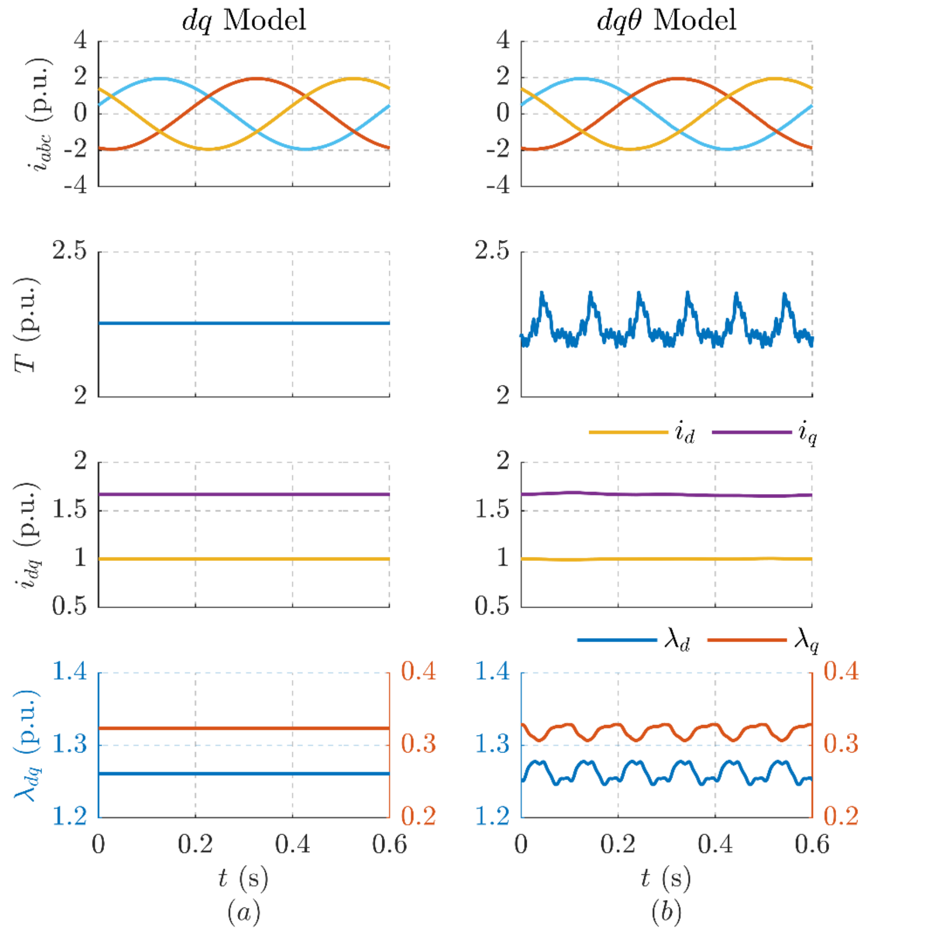


Fig. 7. Simulation result using encoder at current control and constant speed $\omega_r = 50$ rpm: (a) 2D dq flux maps; (b) 3D $dq\theta$ flux maps.

Conclusions

The literature on SyR motors and drives is rich and well established: key concepts were already known as early as in late 1990s

The technology has advantages and disadvantages, expectedly

The weakest elements of the SyR motor drives toolchain are the lack of **engineering experience** and the lack of **standardization of the design and control methodologies**

The tight connection between motor design and (sensorless) control design aspects is key to the wider success of this technology

SyR-e is designed to contribute to this process, and it is developing fast thanks to the teamwork animated by Politecnico di Torino

Thank you!

QUESTIONS, PLEASE

gianmario.pellegrino@polito.it

www.peic.polito.it

Power Electronics Innovation Center