PLECS CONFERENCE 2022
Real-Time Simulation of Power Electronics

September 20 • 8:30 to
September 21 • 16:30

Technopark Zurich
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Phone +41 44 533 51 00 • Email info@plexim.com

Integration of PLECS Circuital Models into the Open-Source Design Suite syreDrive

gianmario.pellegrino@polito.it

Politecnico di Torino, Turin, Italy

About the speaker

Gianmario Pellegrino is Professor of Power Converters, Electrical Machines and Drives at Politecnico di Torino.

He is constantly engaged in research projects with the industry in several fields of application. He is the co-founder of the open-source project SyR-e (https://github.com/SyR-e) and of the Power Electronics Innovation Center (https://www.peic.polito.it/) of Politecnico di Torino.

He was a visiting fellow at Aalborg University, Denmark, the University of Nottingham, UK, and the University of Wisconsin-Madison, USA.

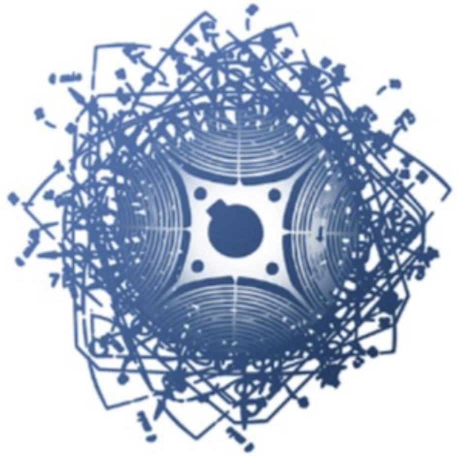
He has 60+ IEEE journal papers, five patents and nine Best Paper Awards.

He is and IEEE Fellow and the recipient of the 8th Grand Nagamori Award in 2022.

SyR-e team

This is the SyR-e team of the PEIC at PoliTO, a group of young e-motor design and e-drive control experts

Gratitude goes to the group for their contributions to the material presented today



syre team

Gruppo · 5 partecipanti

S. Ferrari, PhD
Team Leader

G. Dilevrano
3rd year PhD candidate

P. Ragazzo
3rd year PhD candidate

A. Bojoi
1st year PhD candidate

Today’s Content

Introduction

- Politecnico di Torino
- PEIC: Power Electronics Innovation Center

SyR-e and syreDrive

- SyR-e geography
- Main tools for design and modelling
- Case study: Tesla Model 3 rear axle IPM machine
- CCG and VBR approaches
- Direct and inverse flux maps
- Computational time comparison

Conclusion

Politecnico di Torino

Technical School for Engineers founded in 1959, Politecnico di Torino since 1906

Home to **Galileo Ferraris**, pioneer of electrical engineering

35000 BSc and MSc, 800 PhD students

1000 Faculty members
900 Administrative and Technical staff

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

Tuition fee: 0 - 2600€,
depending on family income and merit

Galileo Ferraris
(1847 – 1897)

PEIC: the Power Electronics Innovation Center

The **Inter-Departmental Center** dedicated to Power Electronics, from the Si-SiC-GaN device to the final application, established in 2017

- 20+ faculty, 2 technicians, 25 PhD students
- Main fields of application:
  Transportation, Energy, Industry and Home App.
- TRL4 demonstrators, support to higher-TRL prototypes
- E-motor drive tests up to 20.000 rpm, 500 kW pk

Power Electronics Innovation Center

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

PEIC: the Power Electronics Innovation Center

Since 2017

- 2 new IEEE Fellows (5 total)
- 1 Nagamori and 1 Grand Nagamori awardees
- Several best paper awards
- 10+ patent applications

Opportunities of collaboration

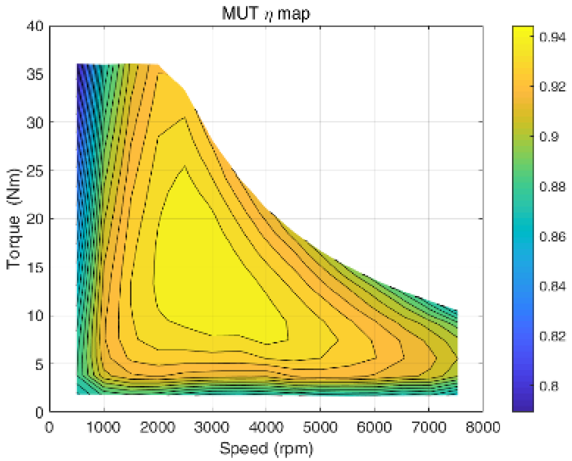
- Funded and co-funder PhD grants
- Research contracts
- EU funded projects: Horizon Europe, MSCA, Clean Aviation

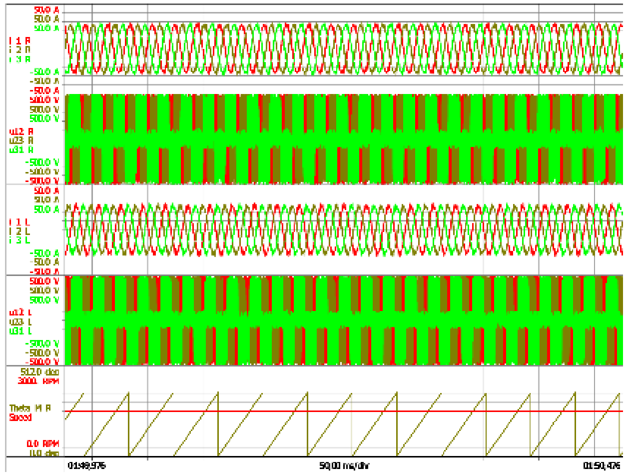
http://www.peic.polito.it/

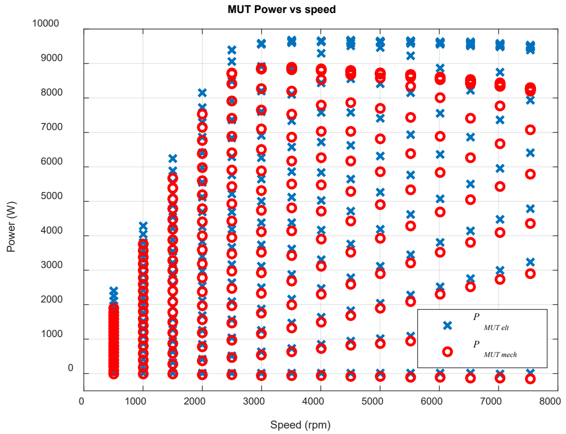
eDrives testing

Test -eDrive facility (video)

- Experimental flux maps, cold and hot motor operating conditions (PoliTo benchmark methods)
- Efficiency maps
- HBM Data recorders and torque sensor T12HP
- Automotive test rig: 150 kW, 200Nm, 20,000 rpm, controlled cooling conditions (0-85 °C)







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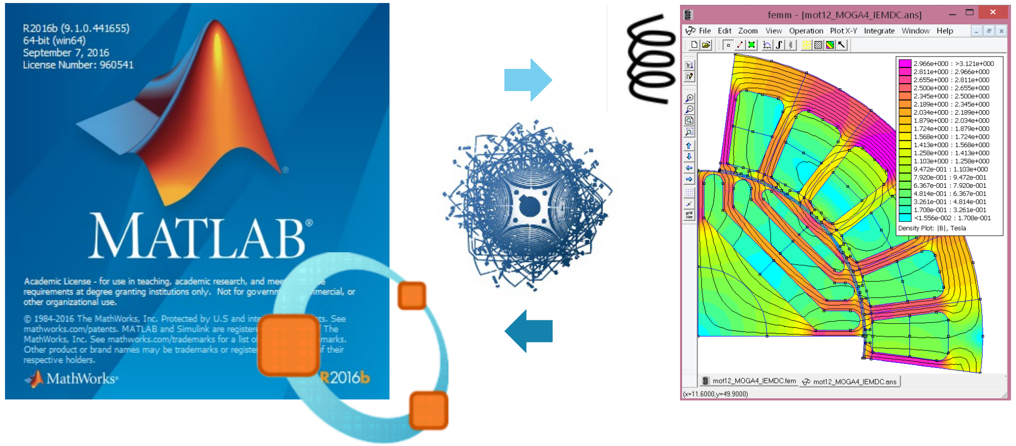
- **SyR-e geography**
- **Main tools for design and modelling**
- **Case study: Tesla Model 3 rear axle IPM machine**
- **CCG and VBR approaches**
- **Direct and inverse flux maps**
- **Computational time comparison**

Conclusion

https://github.com/SyR-e

SyR-e

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



Synchronous Reluctance evolution

Open-source design tool for e-machines and their control, Matlab and FEMM based

Features

- FEAfix: FEA-calibrated design equations
- Fast FEA model manipulation
- Preliminary design of e-machine complement for CAD suites (Ansys, Altair, Simcenter, JMAG)
- **syreDrive** control simulation model
  - No need for time consuming FEA co-simulation in Simulink
  - Open-source C control code
  - *NEW* **PLECS model generation**

Gratitude to Dave Meeker of FEMM

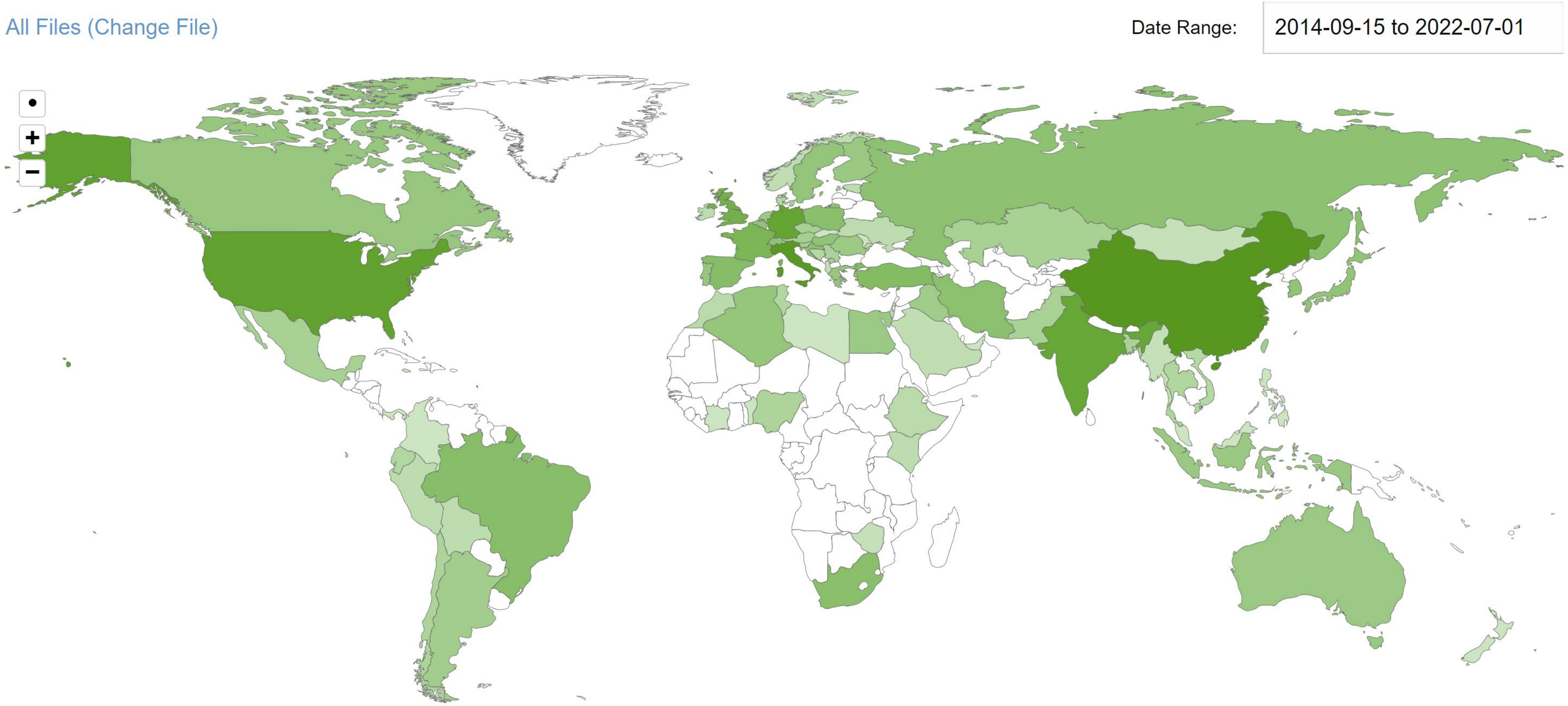
ECCE 2017, tutorial with David Meeker and Francesco Cupertino

Global Impact of SyR-e

GitHub

8,000+ downloads in 86 countries, since September 2014

Used by partner- (GE Avio, Eldor Corporation, Volvo Cars) and non-partner- companies and academia



syre

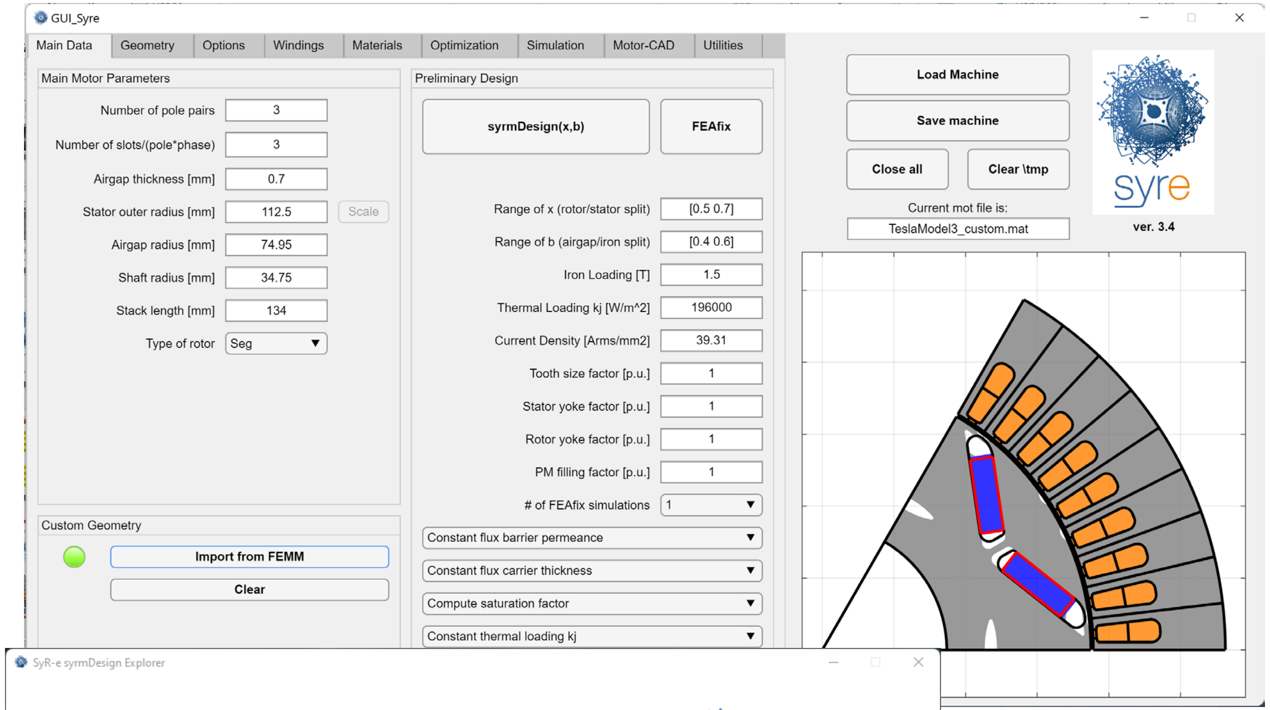
New Public Release

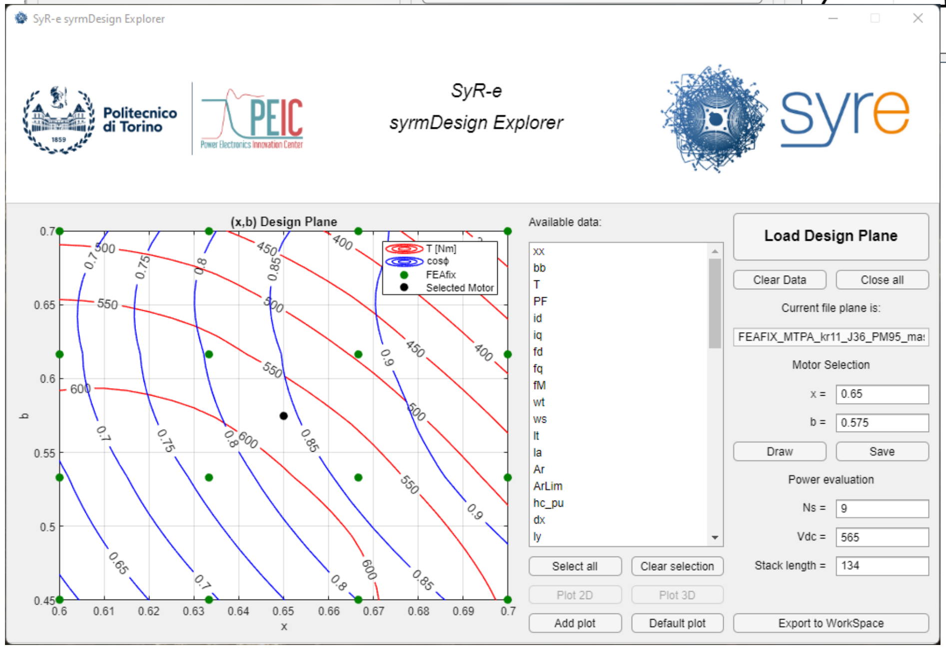
v3.4 on GitHub, September 2022

New SyR-e release with ICEM'22 updates!

- Improved (x,b) design plane (ICEM22 paper)
- Improved scaling rules (ECCE22 paper)
- **New demo TeslaModel3_custom**
- 3rd GUI syrmDesignExplorer
- **syreDrive improved**
- Improved structural simulation
- Preliminaries of Induction Motor

PLECS model generation not yet public



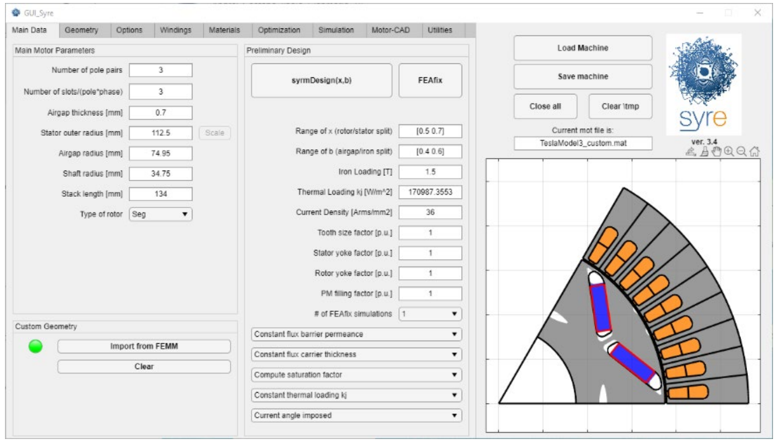


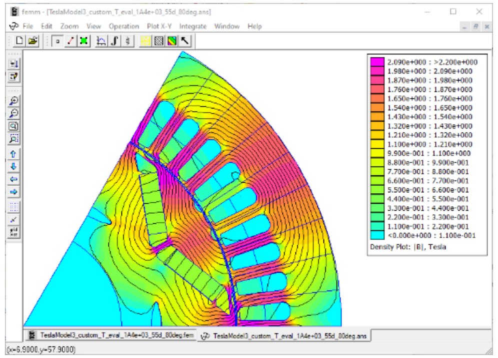
GitHub

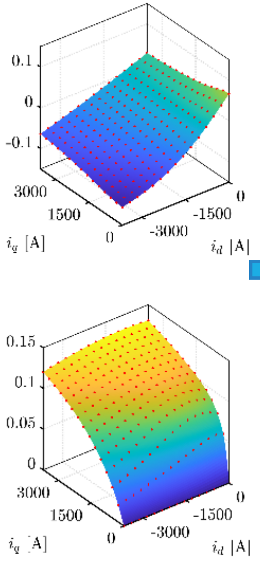
SyR-e Geography

GUI_Syre

Motor design and simulation

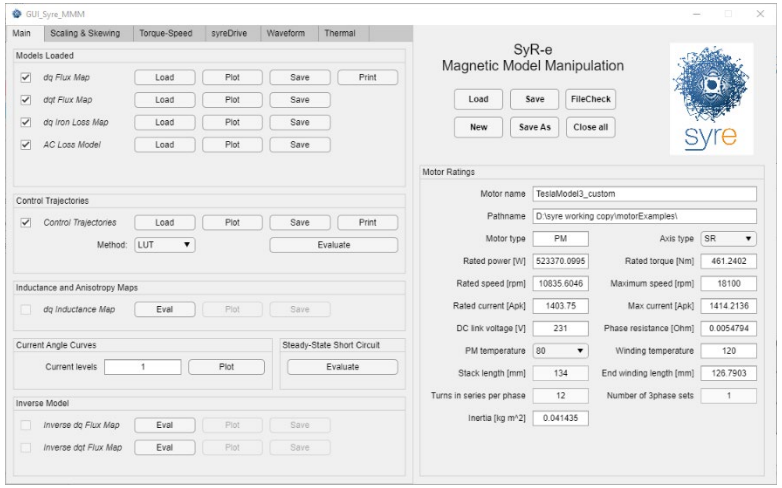




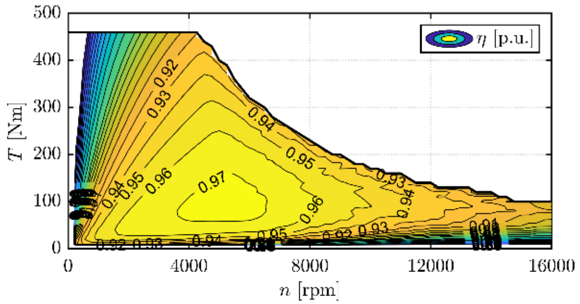


GUI_Syre_MMM

Magnetic Model Manipulation



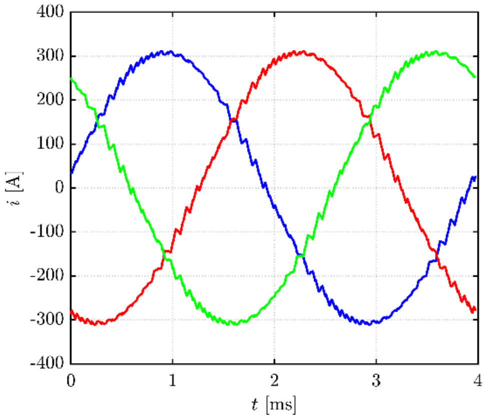
Efficiency Map



syreDrive

Phase currents, PWM ripple

NEW



syreDrive: Control Simulation

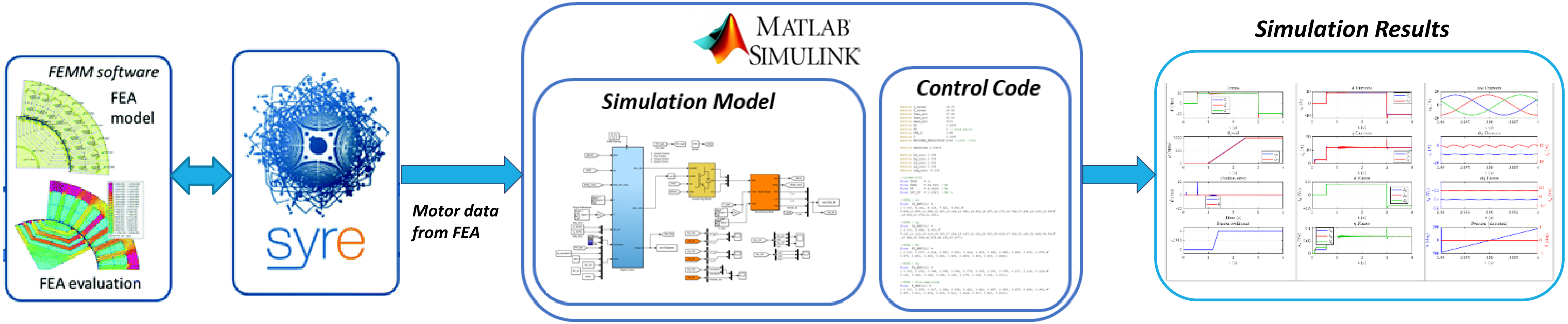
[1] A. Varatharajan, D. Brunelli, S. Ferrari, P. Pescetto and G. Pellegrino, "syreDrive: Automated Sensorless Control Code Generation for Synchronous Reluctance Motor Drives," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Modena, Italy, 2021, pp. 192-197.

The Simulink and now PLECS model of the e-drive is automatically generated

Floating-point ANSI-C control code is also provided: hand-written, fully parametrized

The tool is meant for

- Control code simulation, development and debug → rapid prototyping and HiL
- PWM current waveforms evaluation for FEM re-evaluation of e-motor loss
- Simulation of fault conditions



PWM waveforms and loss

[2] G. Pellegrino and S. Ferrari, "Design, Identification and Simulation of PM Synchronous Machines for Traction," Tutorial Notes, ICEM 2022, Valencia

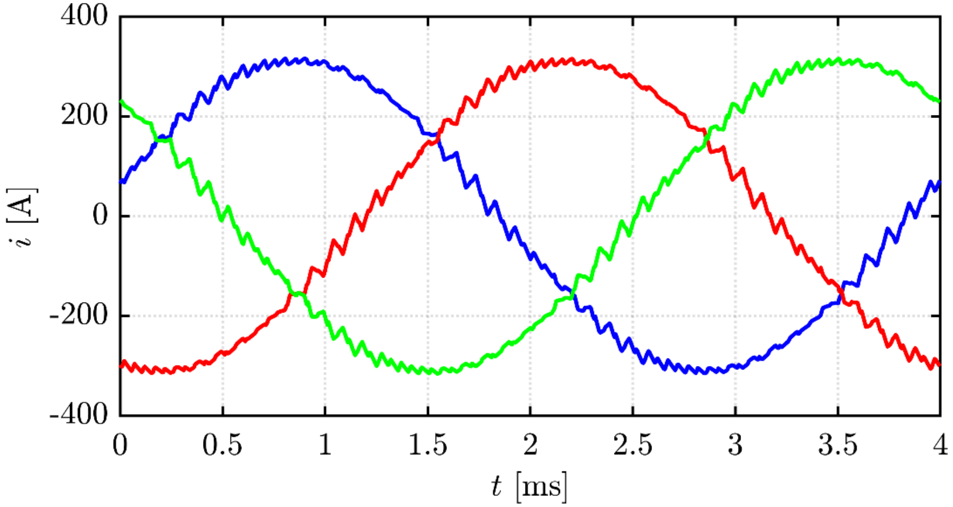
PWM loss computed at 100Nm, 5000rpm

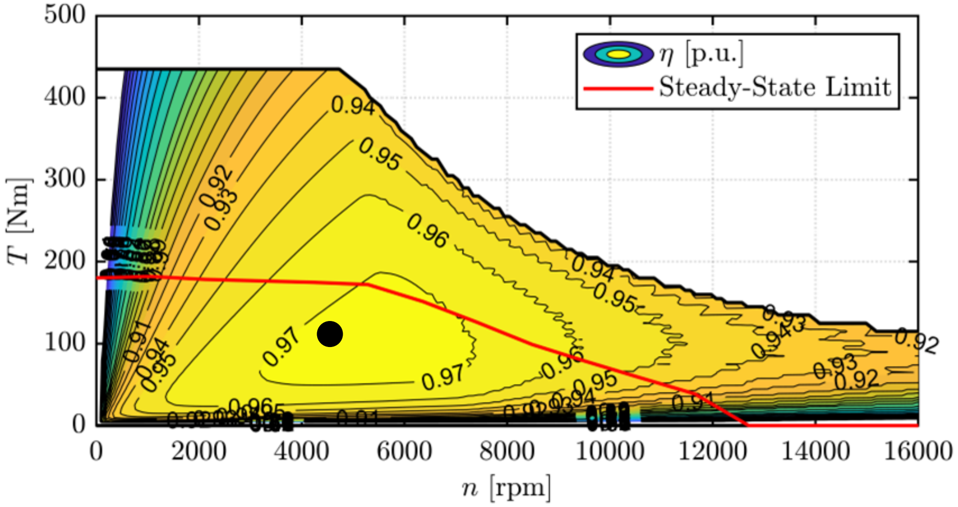
- Additional loss (except PM) is 172W (+14%)
- Mostly on the stator (eddy current term)

PM loss explodes due to PWM:

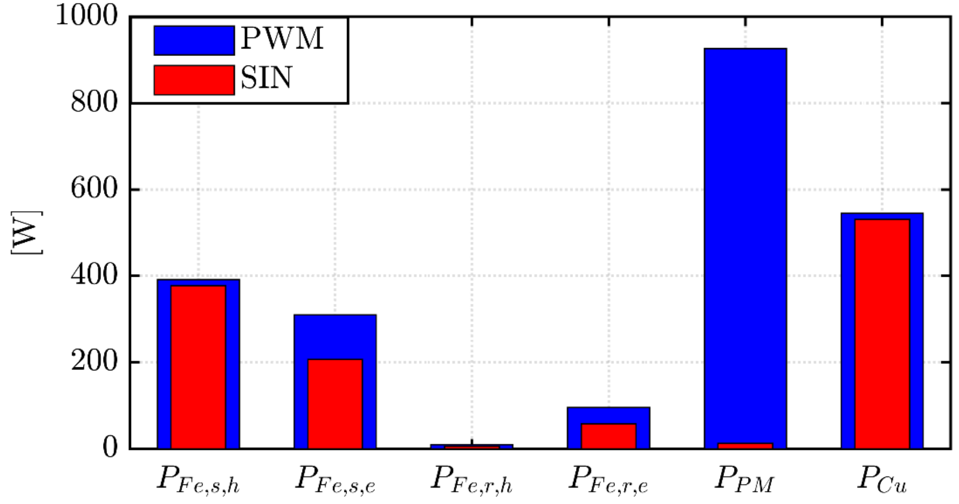
- **Segmentation and refinement with transient FEA**

Phase currents at 5000 rpm, 10kHz PWM



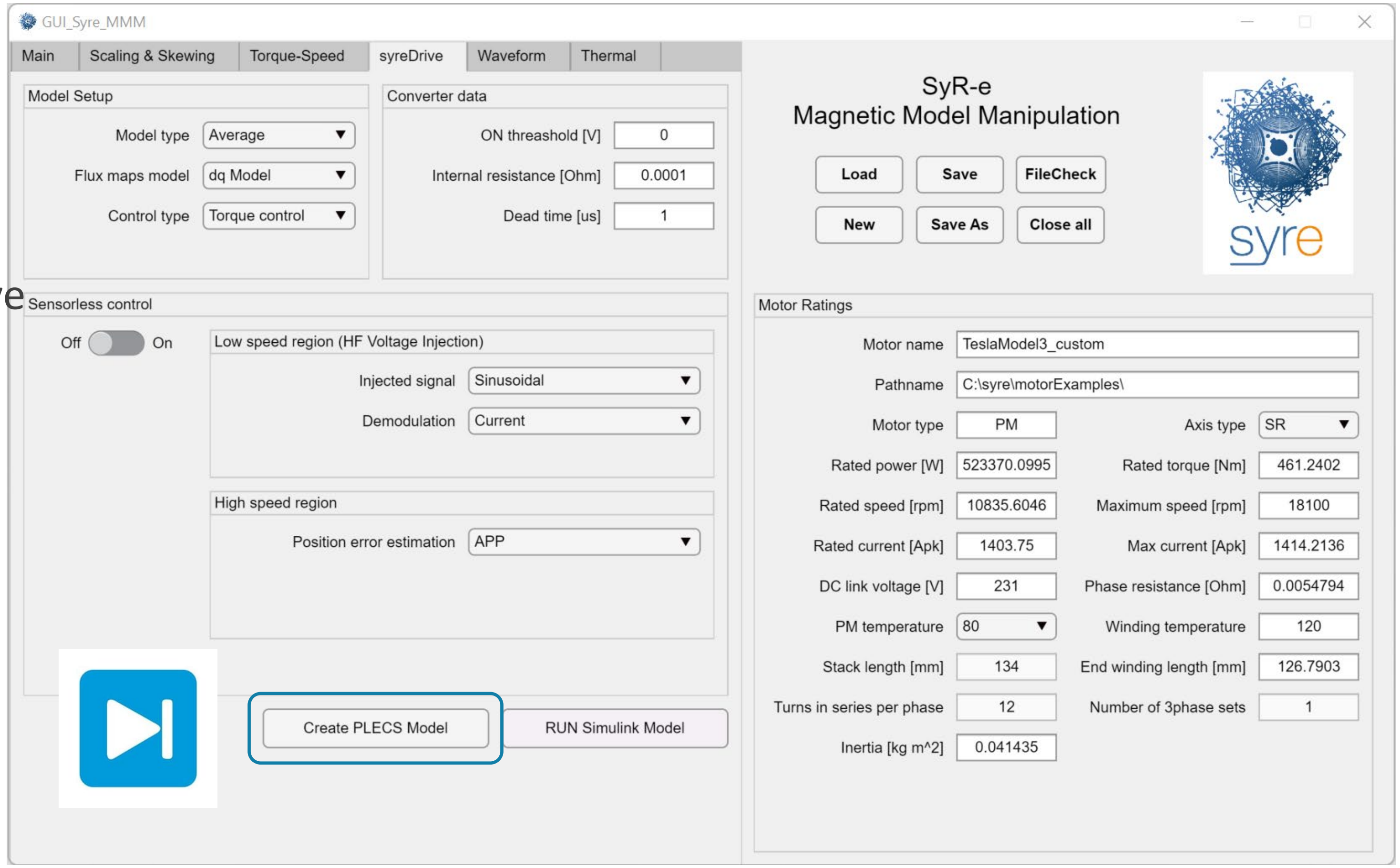


Loss breakdown



syreDrive tab

syreDrive tab of GUI_Syre_MMM



PLECS model created

- PLECS model of the e-drive
- Copy and paste a template PLECS file
- Calibrated with SyR-e data of the e-drive

Main features

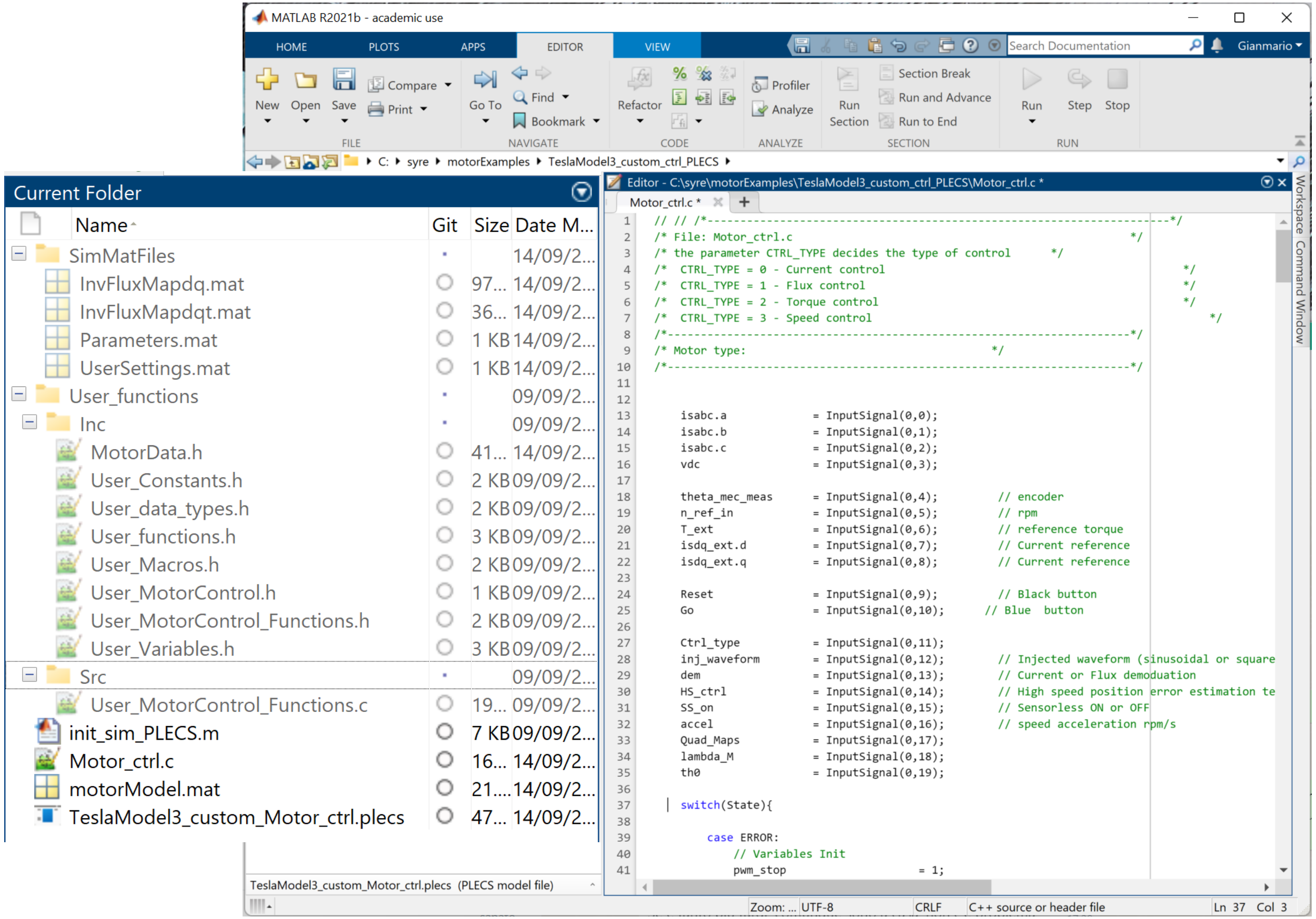
- Circuital motor model
- Flux-map based
  - 2D (dq) or 3D (dq-theta) maps
  - time-average or instantaneous PWM
- Discrete-time control
- Open ANSI-C control code
  - Torque control, speed control, current control
  - Sensorless control of SyR machines

PLECS Model Folder

Content of the new folder TeslaModel3_custom_ctrl_PLECS

The generated folder contains

- The PLECS model
- Mat files imported from SyRe
- Source C code
  - Motor_ctrl.c (main C-script)
  - User_functions library

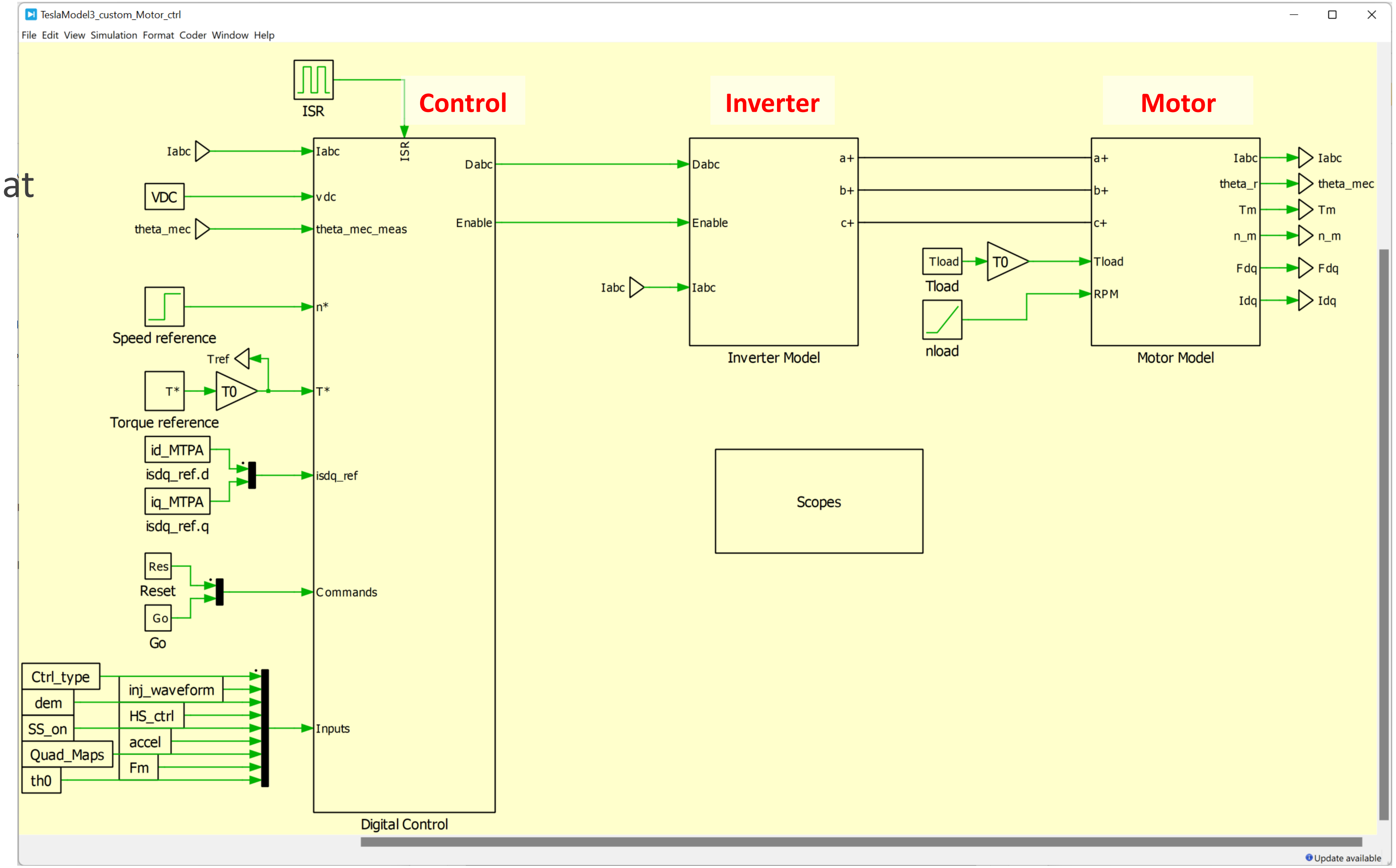


E-Drive Model Overview

PLECS model generated by syreDrive

Control block subsystem triggered at $T_s = T_{PWM}$

The inverter and motor blocks are circuital



Control Subsystem

Triggered sub-system executed at $T_s = T_{PWM}$

One-step actuation delay

C-Script control code with user-defined library calls

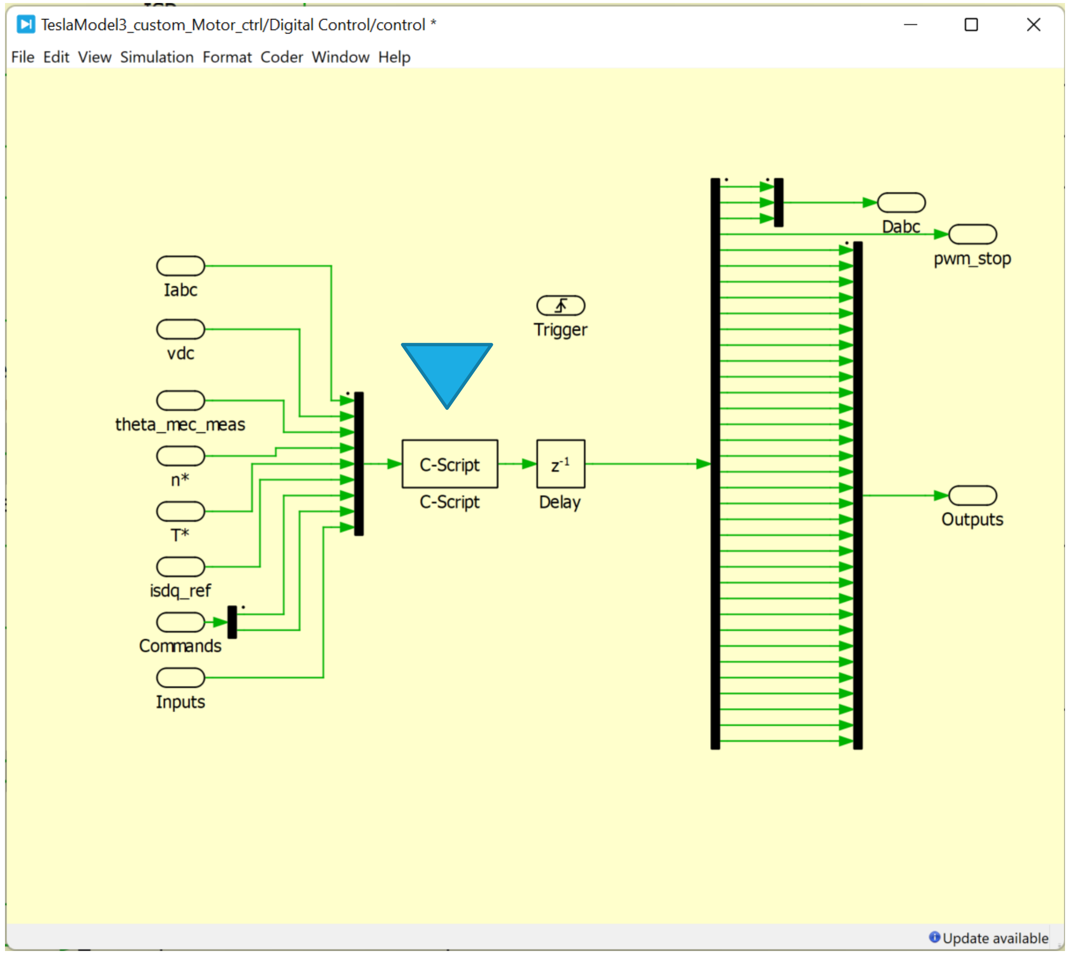
C source code

- automatically calibrated using the machine parameters existing in SyRe, same as for the e-motor model
- Open access

Copy of hand-written code (not a generated code)

The control code is portable to dSPACE and ARM based MCUs (e.g. SMT32)

Content of the triggered sub-system Digital Control

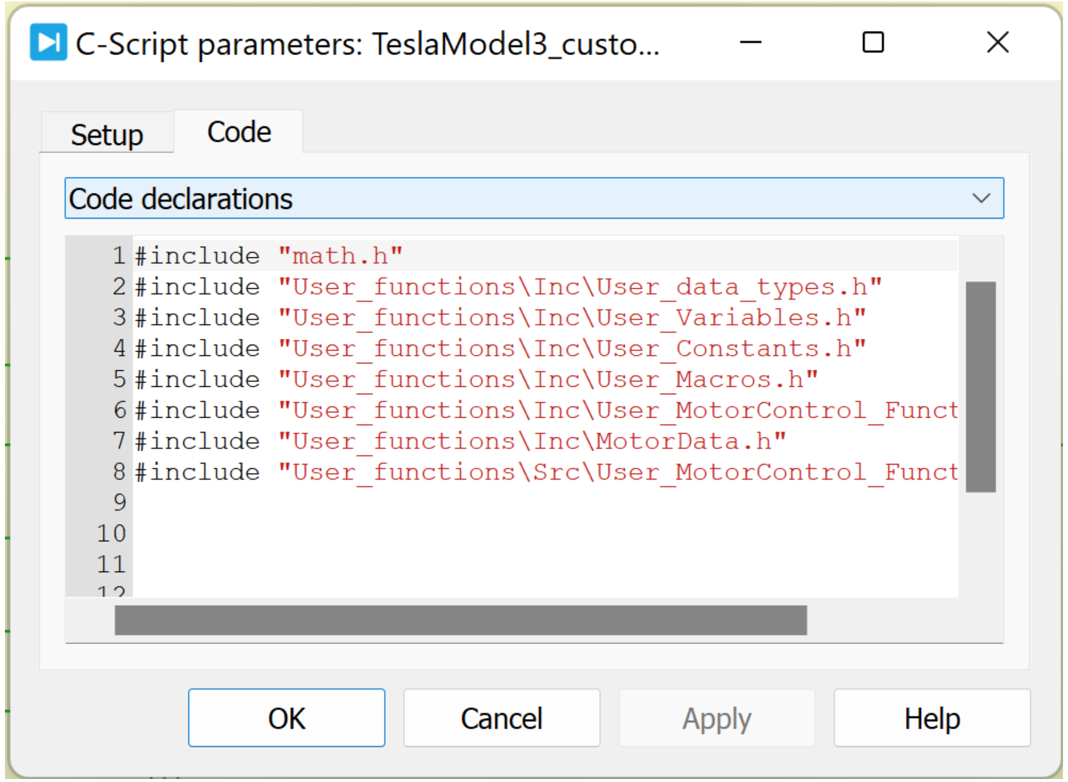


User-Defined Motor Control Library

C-script code declarations

The header files of a User_functions folder are included in the Code declarations section of the C-script block

Besides data types, constants and variables definitions, **the file MotorData.h contains the motor parameters for control (LUTs for MTPA, flux maps LUTs for flux observer, etc ..)**

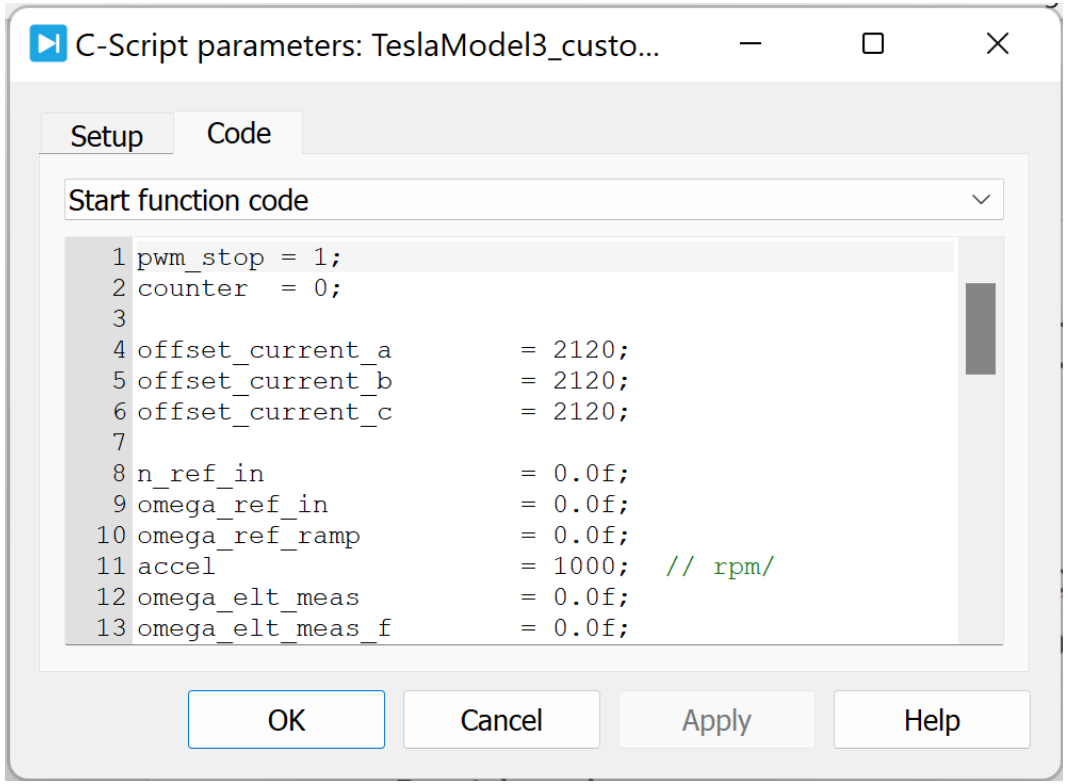


User-Defined Motor Control Library

C-script code initialization

Once again, the variables are initialized according to the parameters of the e-drive (current measurements A/D resolution, acceleration rate ..) defined in SyR-e

All such variables are editable directly in PLECS



Motor Control Function

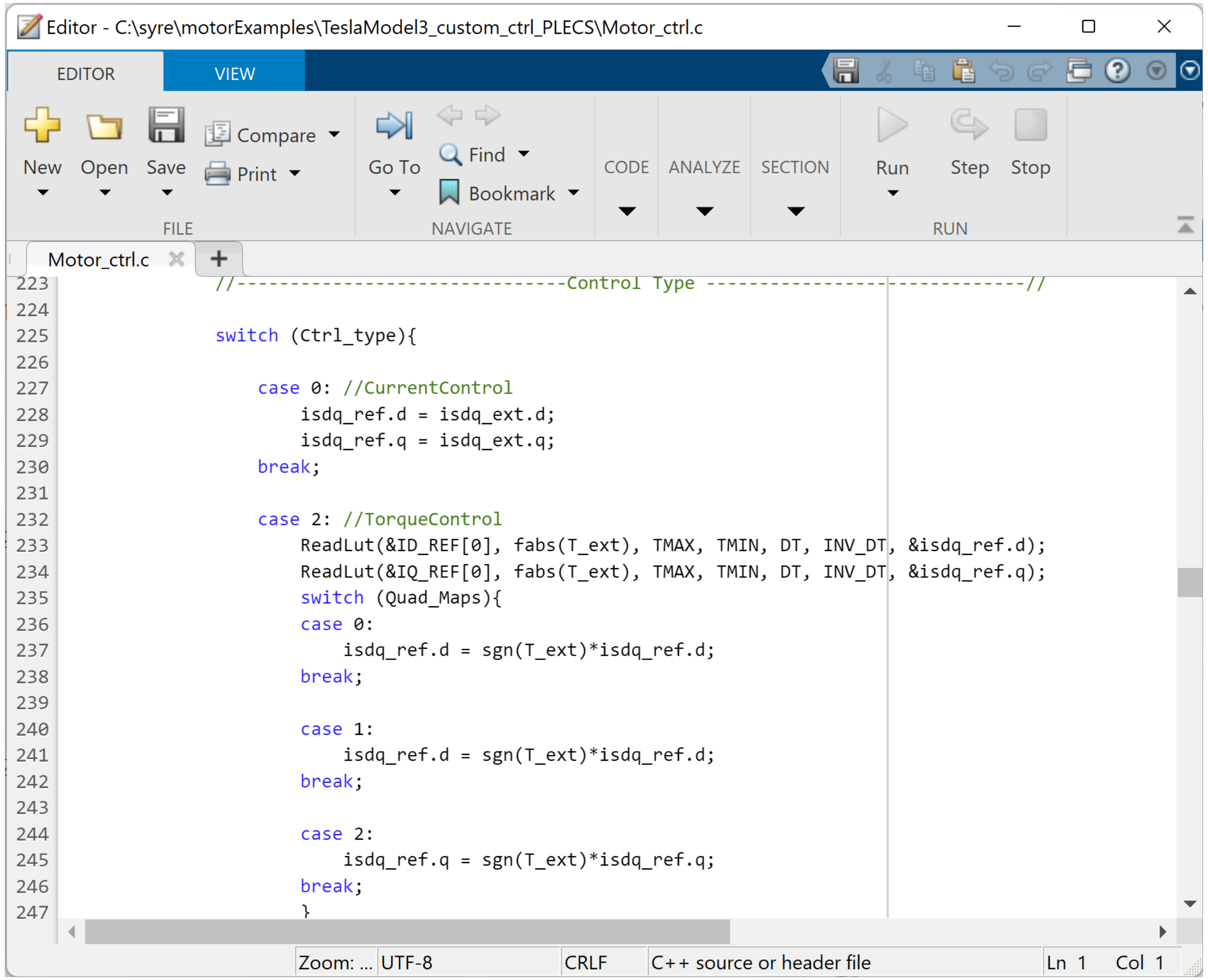
The function Motor_ctrl.c contains the FOC source code

Current vector control, with several options

- Torque control / speed control / i_d, i_q control
- Sensorless control (for SyR machines)

LUT-based MTPA (Maximum Torque per Ampere) law is included, from SyRe data

Motor_ctrl.c function for torque and speed control



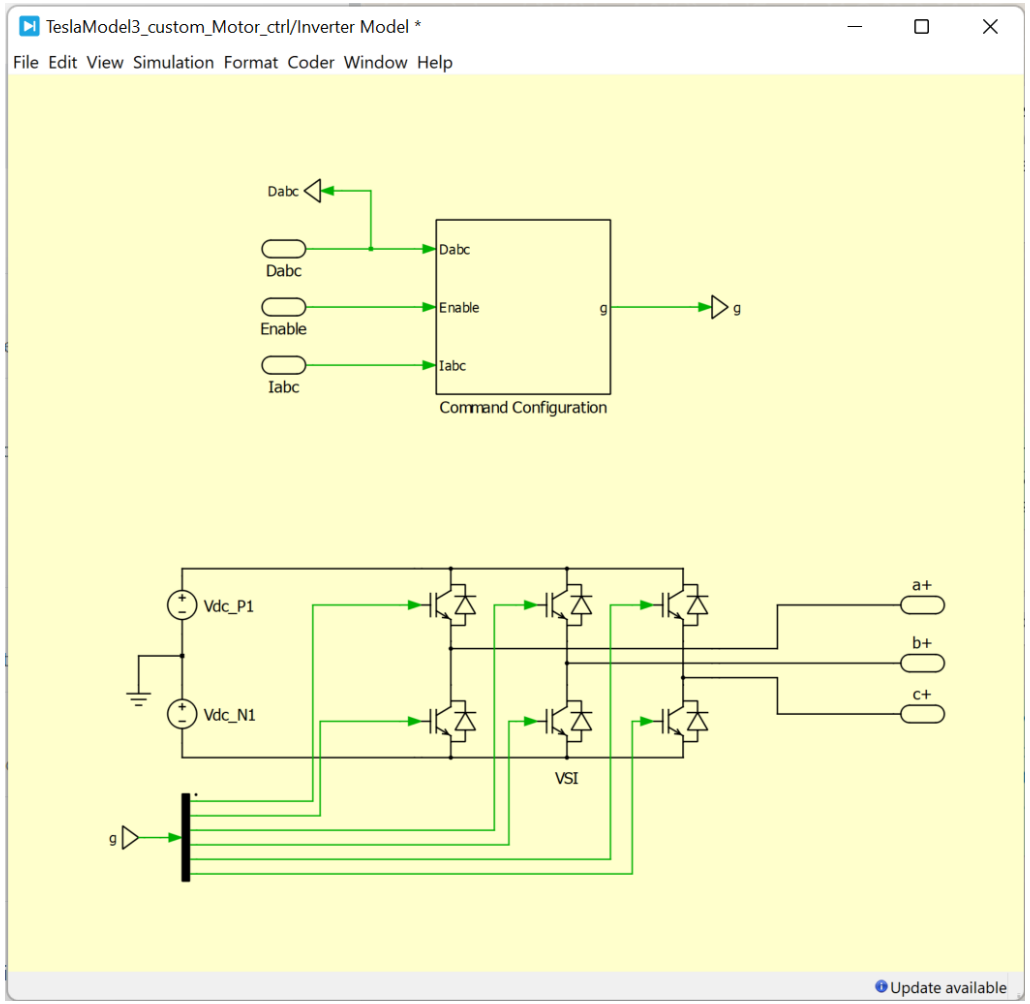
Inverter Subsystem

Based on library **3-ph 2-level Voltage Source Inverter** of PLECS

- Instantaneous or time-averaged switches
- Dead-time modeled also in the average model
- **Sub-cycle average** model type is comfortably used for either instantaneous and average simulation

The circuital model is compatible with simulation of fault conditions (uncontrolled converter, active short circuit, ph-to-ph short, etc ..)

Content of the Inverter Model subsystem



Sub-Cycle Average

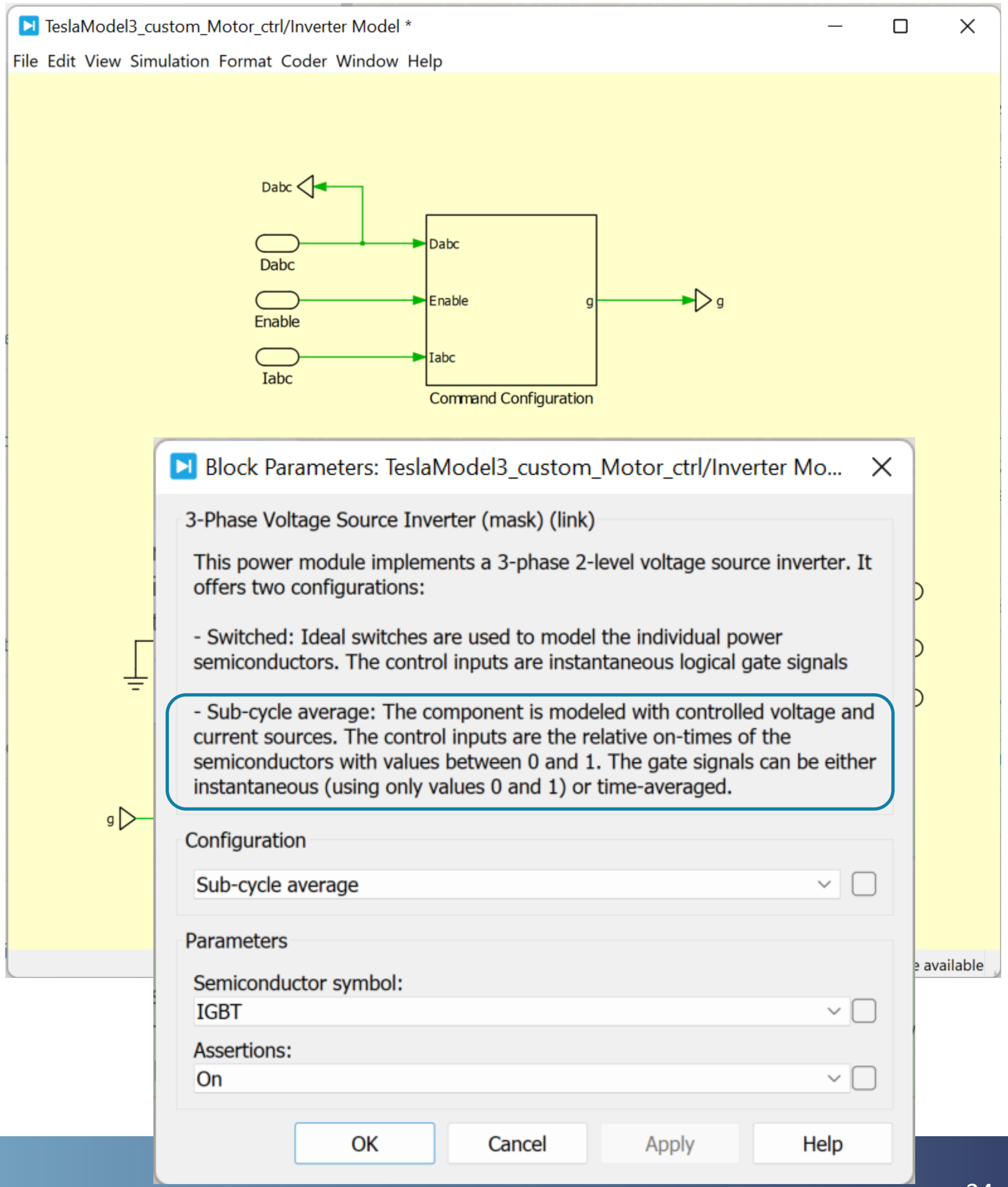
- Switched: Ideal switches are used to model the individual power semiconductors. The control inputs are instantaneous logical gate signals

- Sub-cycle average: The component is modeled with controlled voltage and current sources. The control inputs are the relative on-times of the semiconductors with values between 0 and 1. The gate signals can be either instantaneous (using only values 0 and 1) or time-averaged.

Full circuital, non idealized, approach

Comfortable: flexible use in instantaneous and average models

Content of the Inverter Model subsystem

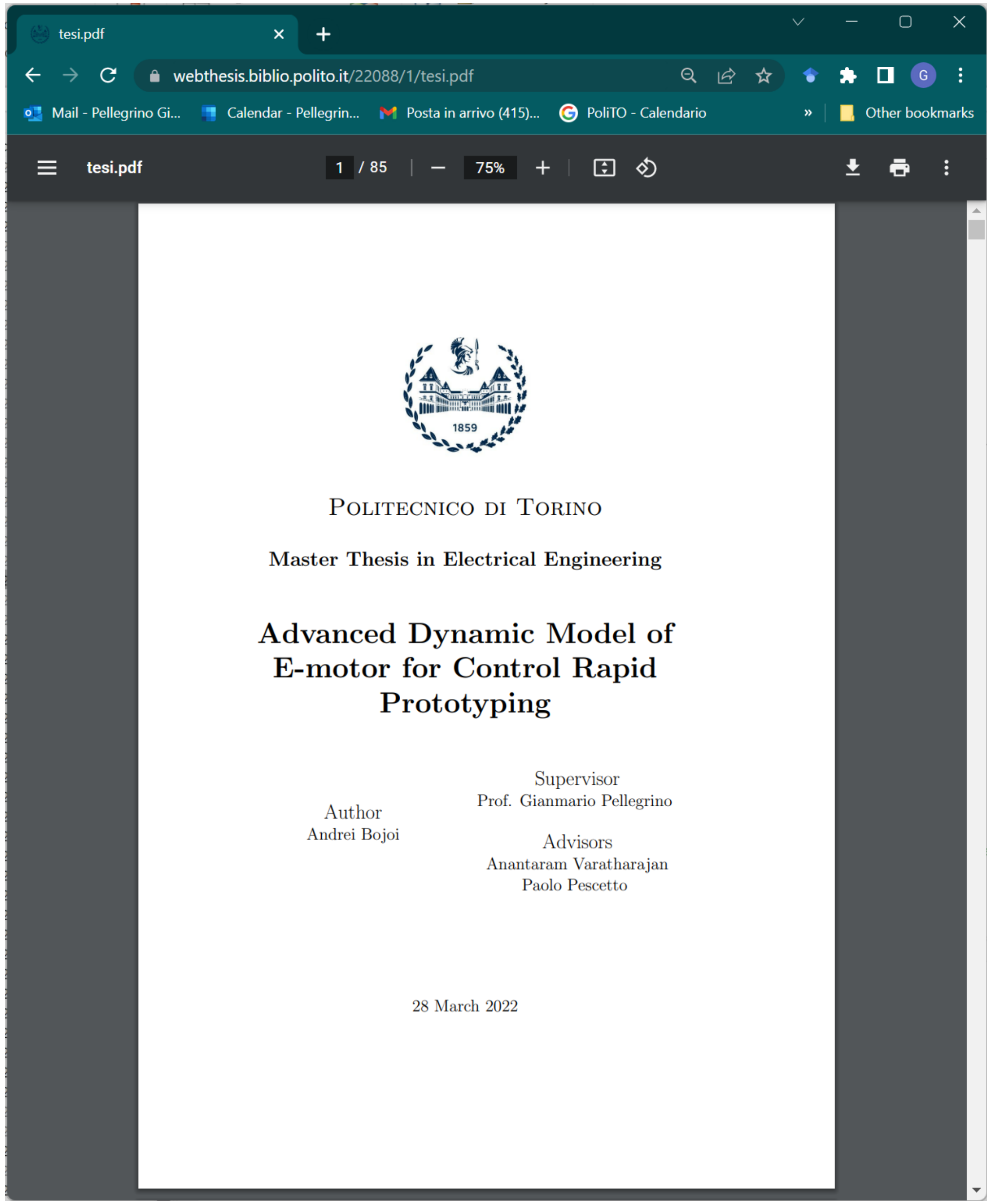


Insight on the e-motor model

MSc Thesis by A. Bojoi in early 2022 on LUT-based circuital models of synchronous e-machines

Two modelling approaches were compared and tested in Simulink and PLECS

- VBR: voltage behind reactance
- CCG: controlled current generators



1859

POLITECNICO DI TORINO

Master Thesis in Electrical Engineering

Advanced Dynamic Model of E-motor for Control Rapid Prototyping

Supervisor
Prof. Gianmario Pellegrino

Author
Andrei Bojoi

Advisors
Anantaram Varatharajan
Paolo Pescetto

28 March 2022

[3] A. Bojoi, “Advanced Dynamic Model of E-motor for Control Rapid Prototyping [MSc Thesis]”, Politecnico di Torino, 2022, https://webthesis.biblio.polito.it/22088/1/tesi.pdf

What is PLECS recommending?

The Reference PLECS library models are:

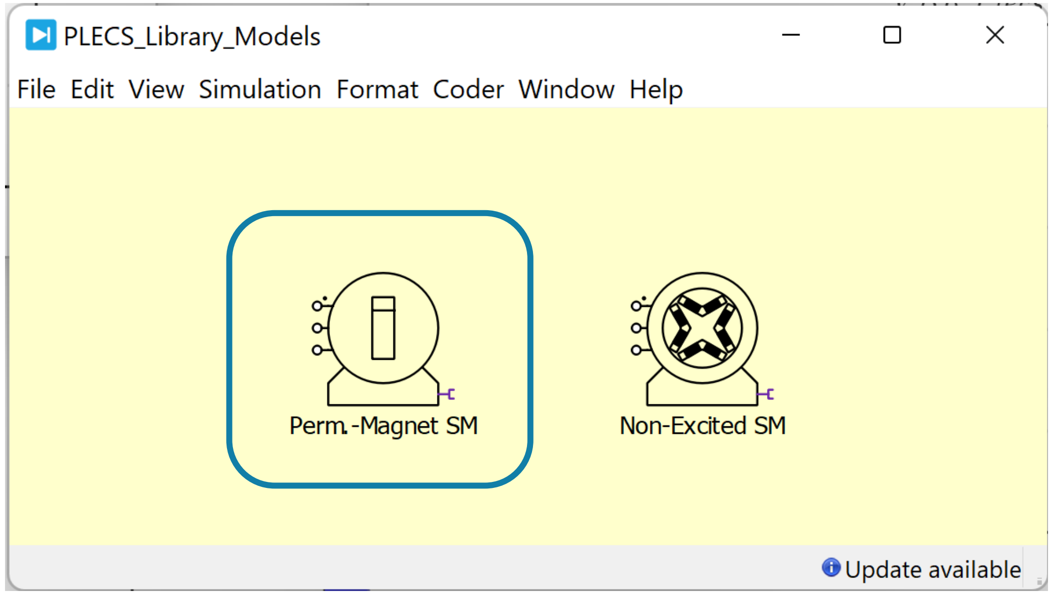
Permanent Magnet SM

- VBR or Rotor Reference Frame (CCG) approaches
- Constant parameters (L_d, L_q, PM flux linkage), no LUTs
- i_d, i_q are the state variables

Non-excited SM

- VBR approach based on flux map LUTs

PLECS library models

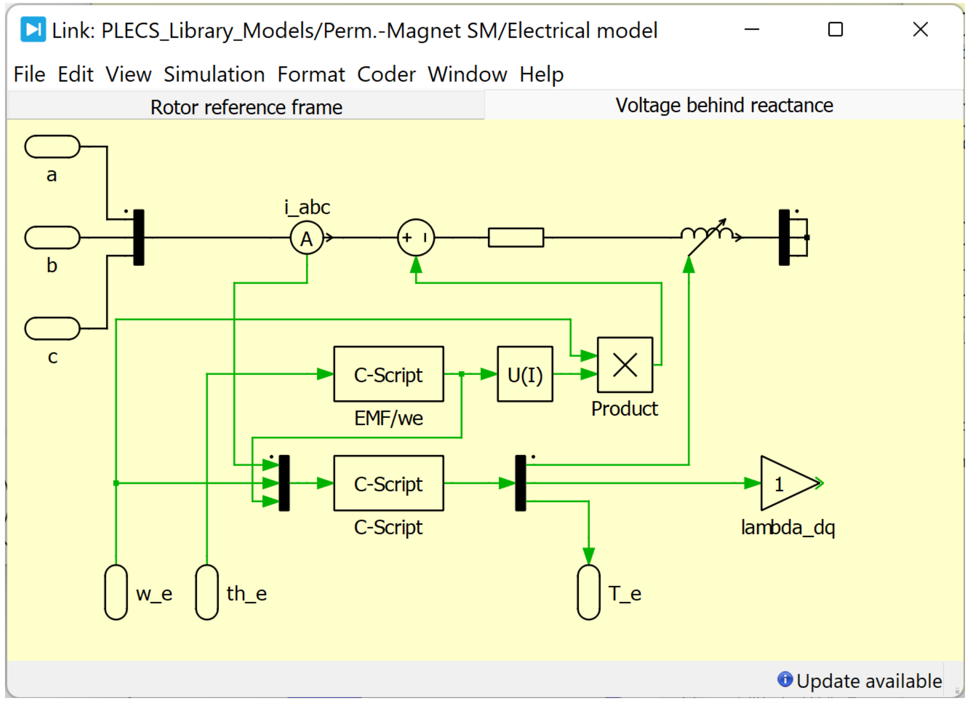


VBR or CCG approaches

- **no LUTs: constant L_d, L_q, PM flux linkage**
- **i_d, i_q are the state variables**
- **Non-excited SM uses VBR with flux-map LUTs**

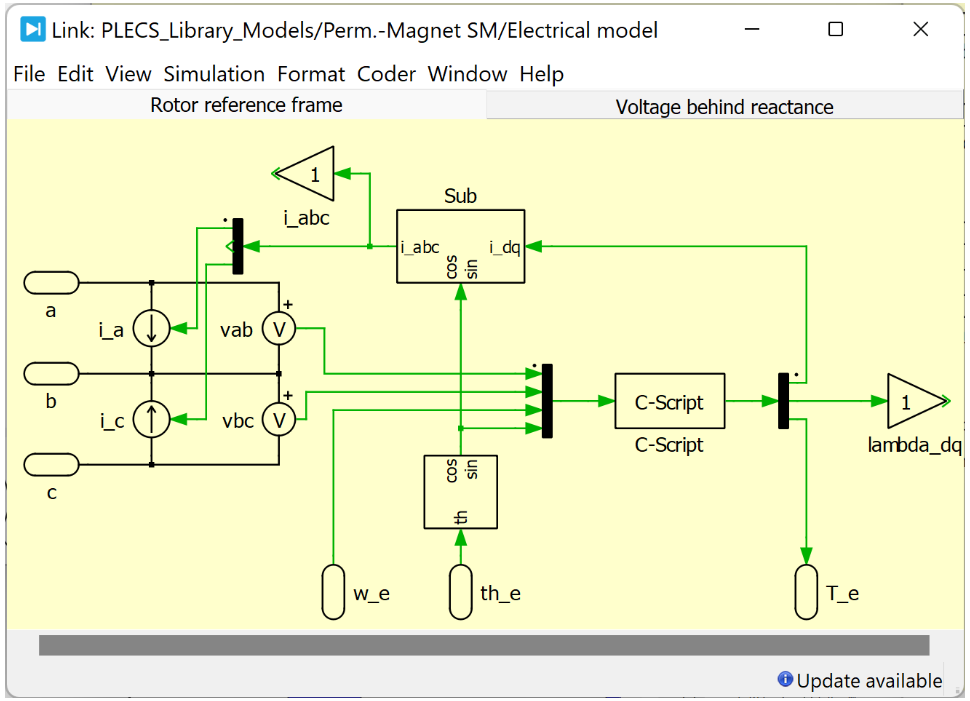
Voltage Behind Reactance:

- 3-phase RLE circuit (abc coordinates)
- Controlled voltage source E and inductance L



Controlled Current Generators

- Controlled current sources
- State equations integrated into the C-script



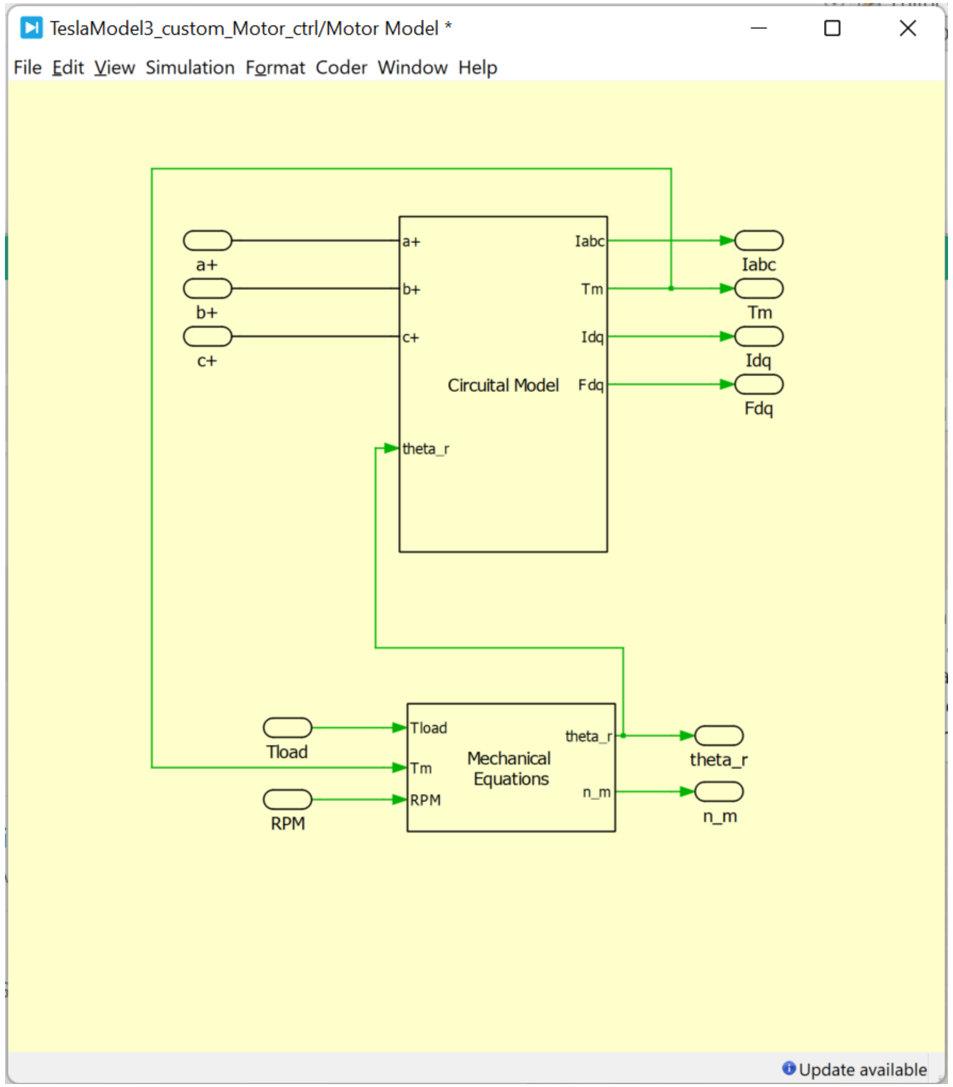
syreDrive motor model

Custom model inspired to PLECS and Simulink library models

After comparison of VBR and CCG approaches, CCG was selected for use in syreDrive, for reason of better computational time

Work is in progress; we might change decisions for the future

Content of the Motor Model subsystem



Motor Subsystem

Controlled current generators (CCG) approach

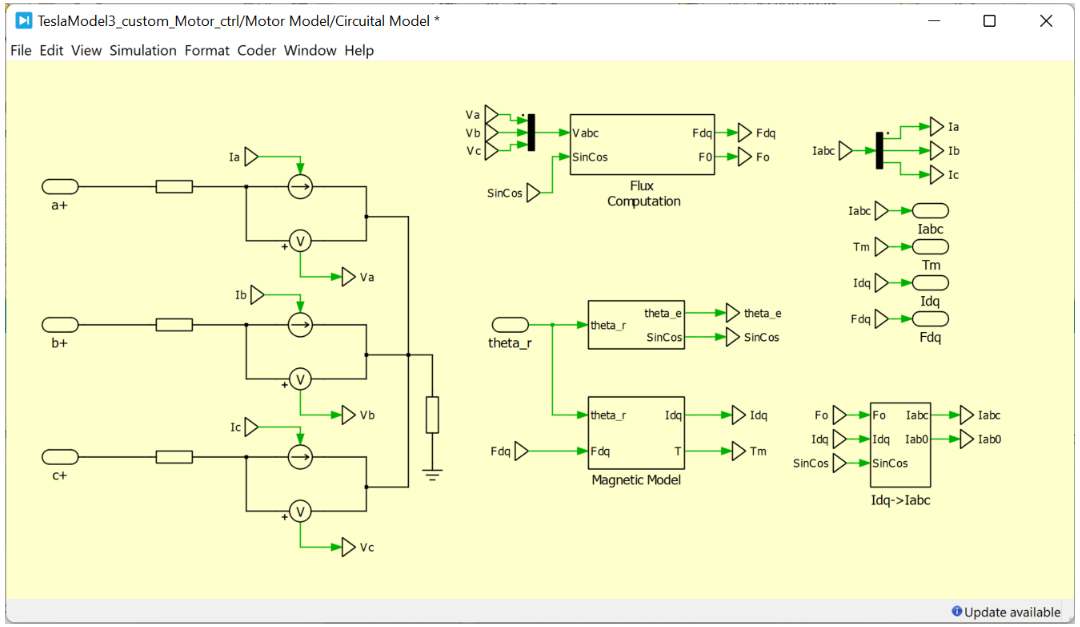
Phase currents are calculated by manipulation of current generators' voltages, using the motor parameters and flux maps

Flux linkages in *dq* frame as state variables

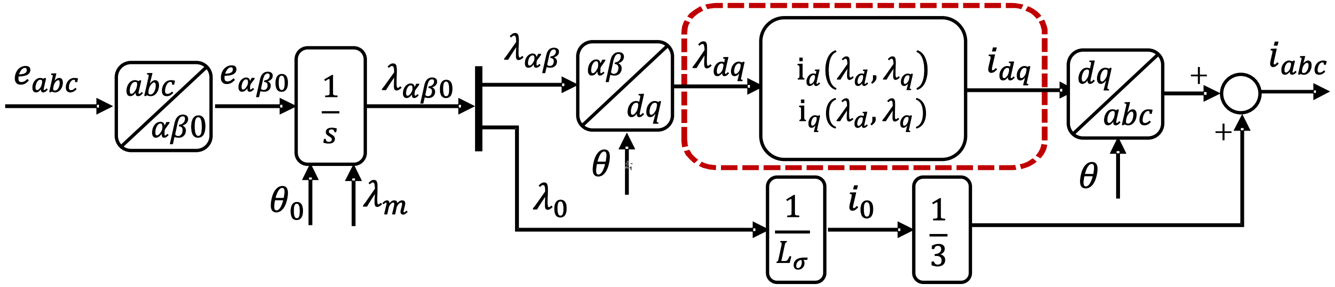
<u>Inverse</u> flux maps need (flux in, current out)

$$i_d = f(\lambda_d, \lambda_q)$$
$$i_q = g(\lambda_d, \lambda_q)$$

Content of the Circuital Model subsystem



Inverse flux maps



Limits of the CCG approach

Direct flux maps

$$\lambda_d = f'(i_d, i_q)$$
$$\lambda_q = g'(i_d, i_q)$$

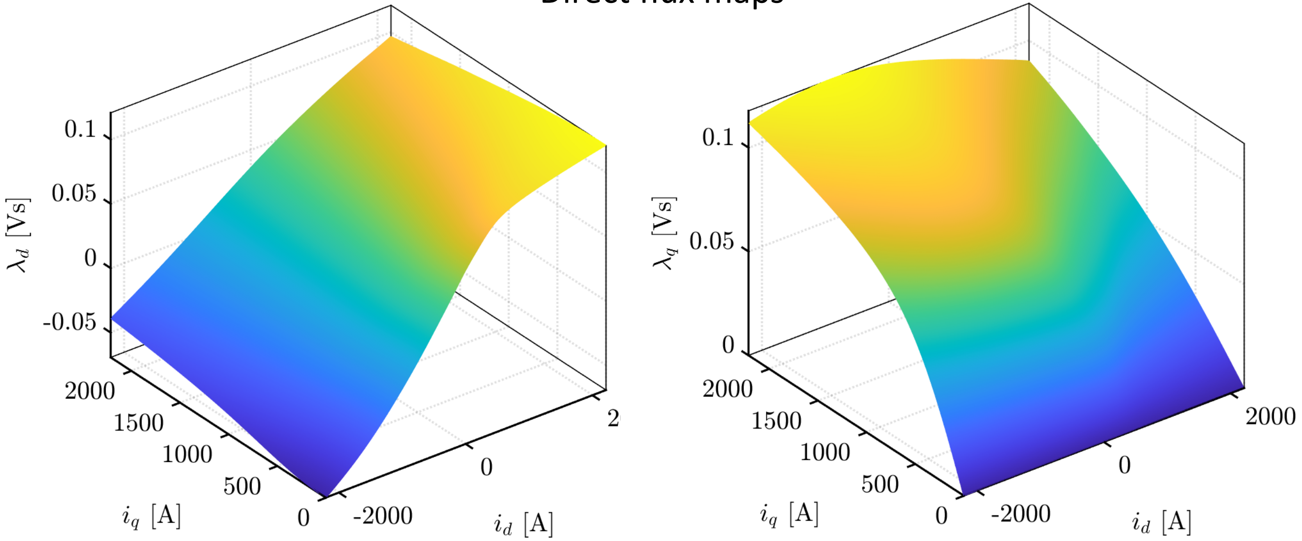
This is the output of experiments or FEM

<u>Inverse</u> flux maps

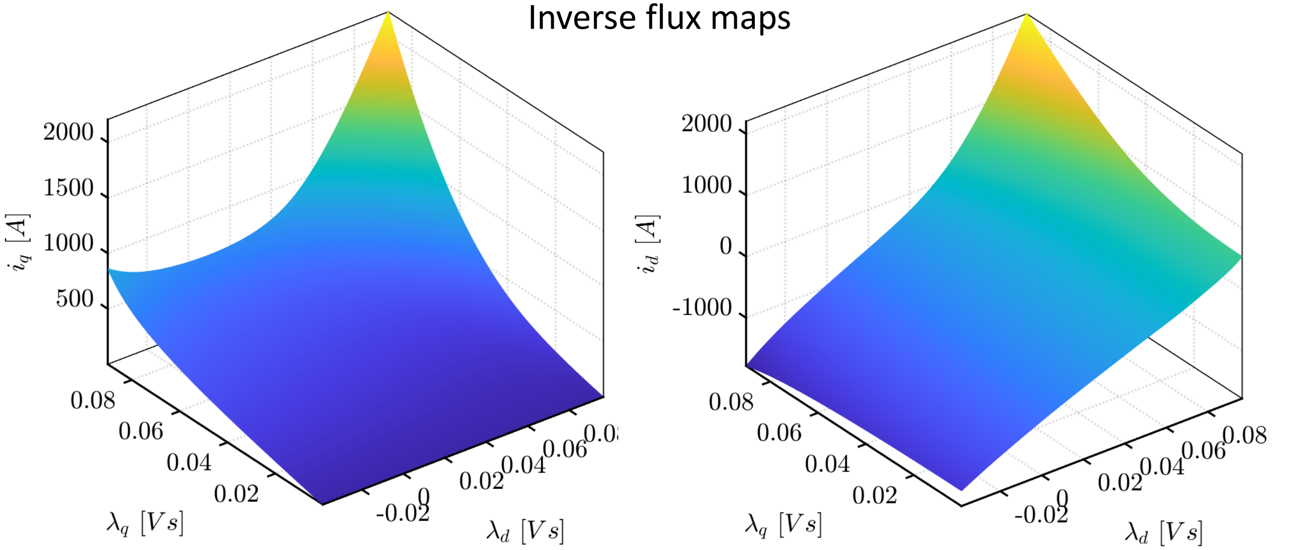
$$i_d = f(\lambda_d, \lambda_q)$$
$$i_q = g(\lambda_d, \lambda_q)$$

This is obtained via numerical manipulation

Direct flux maps



Inverse flux maps



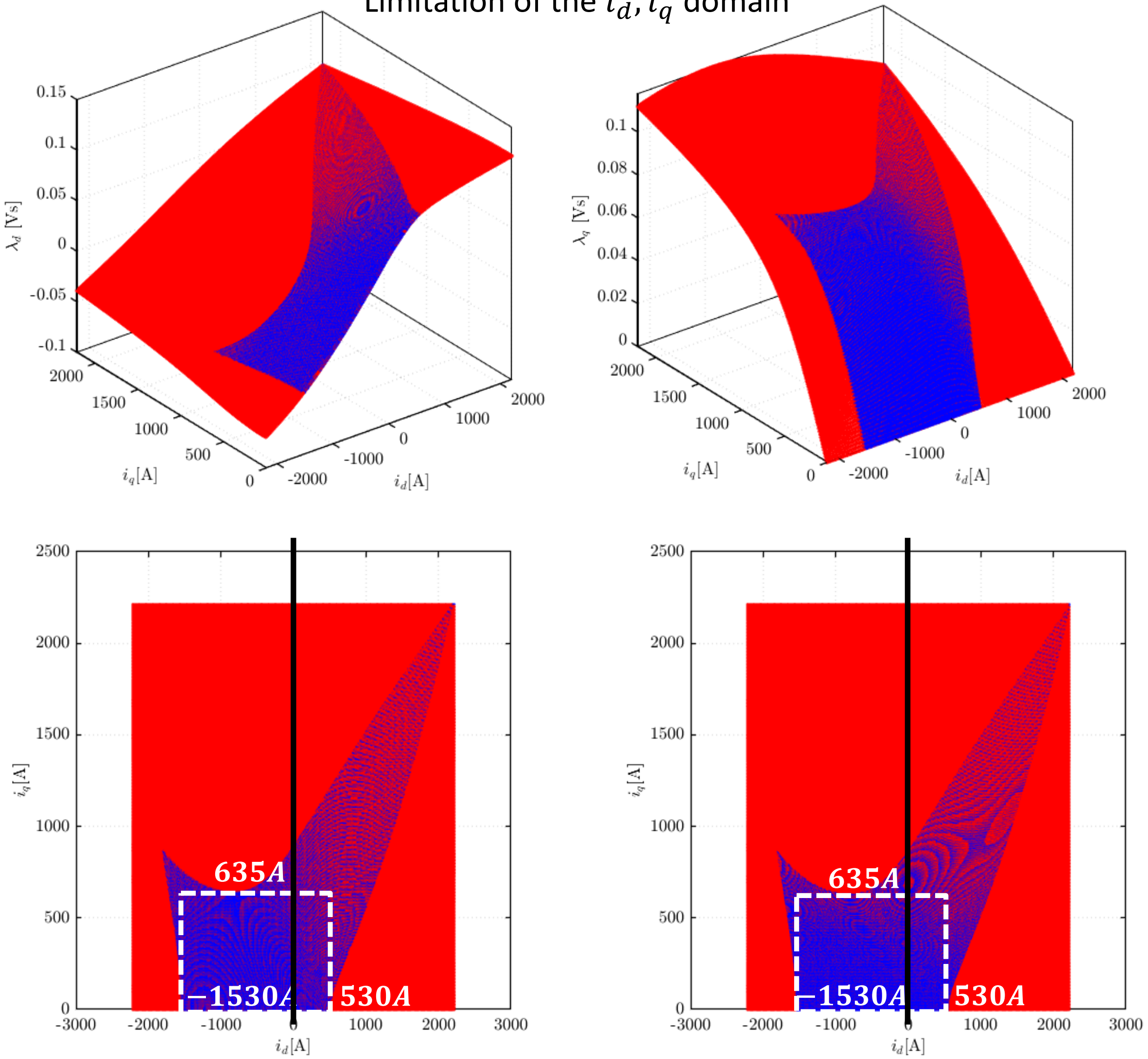
Example

The use of the inverse flux maps limits the i_d, i_q domain of identification of the machine under test

- This can be overcome with FEA
- **Strong limitation with experimental flux maps**

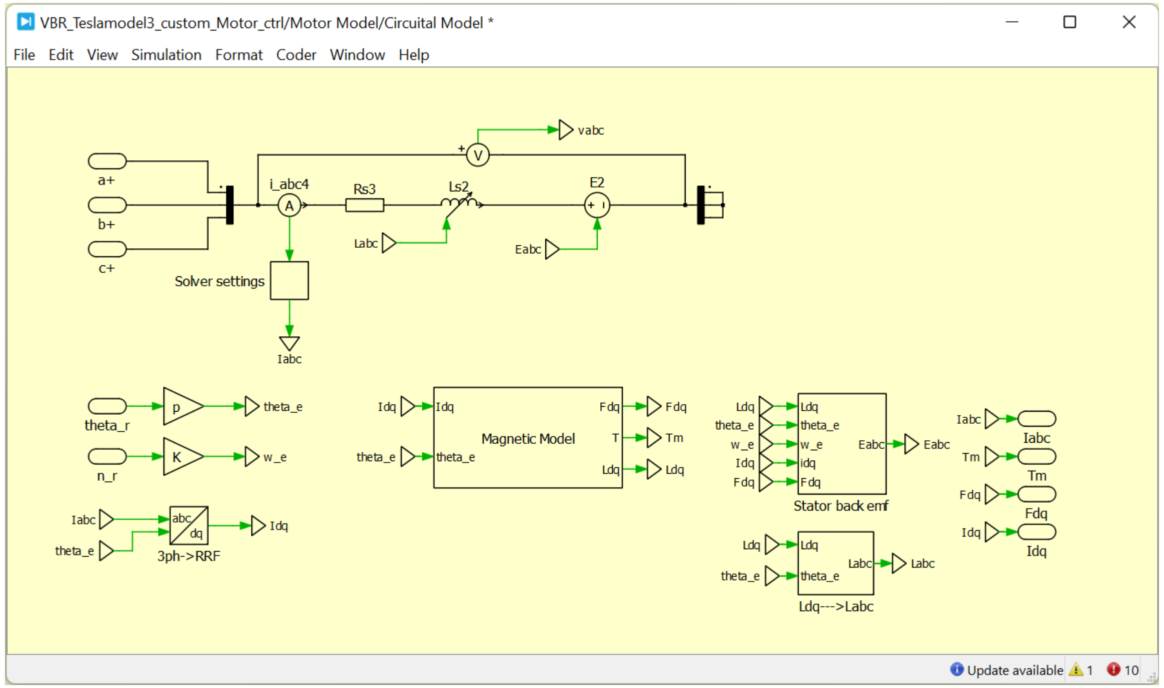
The figure is exaggerated: with the 2nd quadrant only, the limitation is within 70%

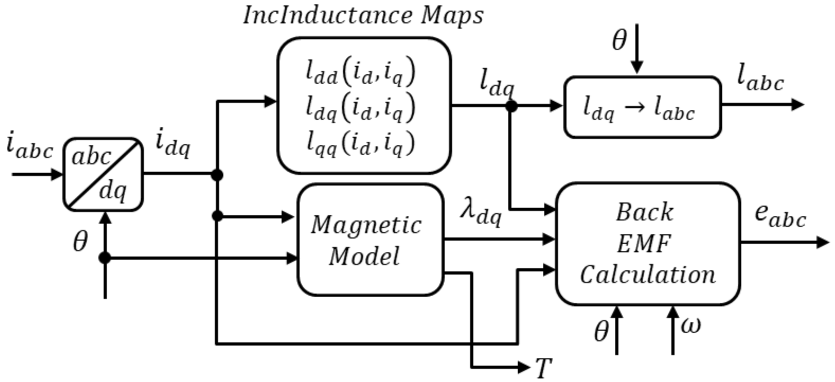
Limitation of the i_d, i_q domain



VBR approach

VBR model of the motor





Voltage Behind Reactance (VBR) approach

Phase quantities (abc), state equations solved within the circuit

Direct flux maps used for back-EMF calculation

Incremental inductance maps used for adjusting the inductance term

5x 2D-LUTs instead of 2x 2D-LUTs of CCG

- Direct flux maps (2x) - λ_d, λ_q
- Incremental inductance maps (3x) - l_d, l_q, l_{dq}

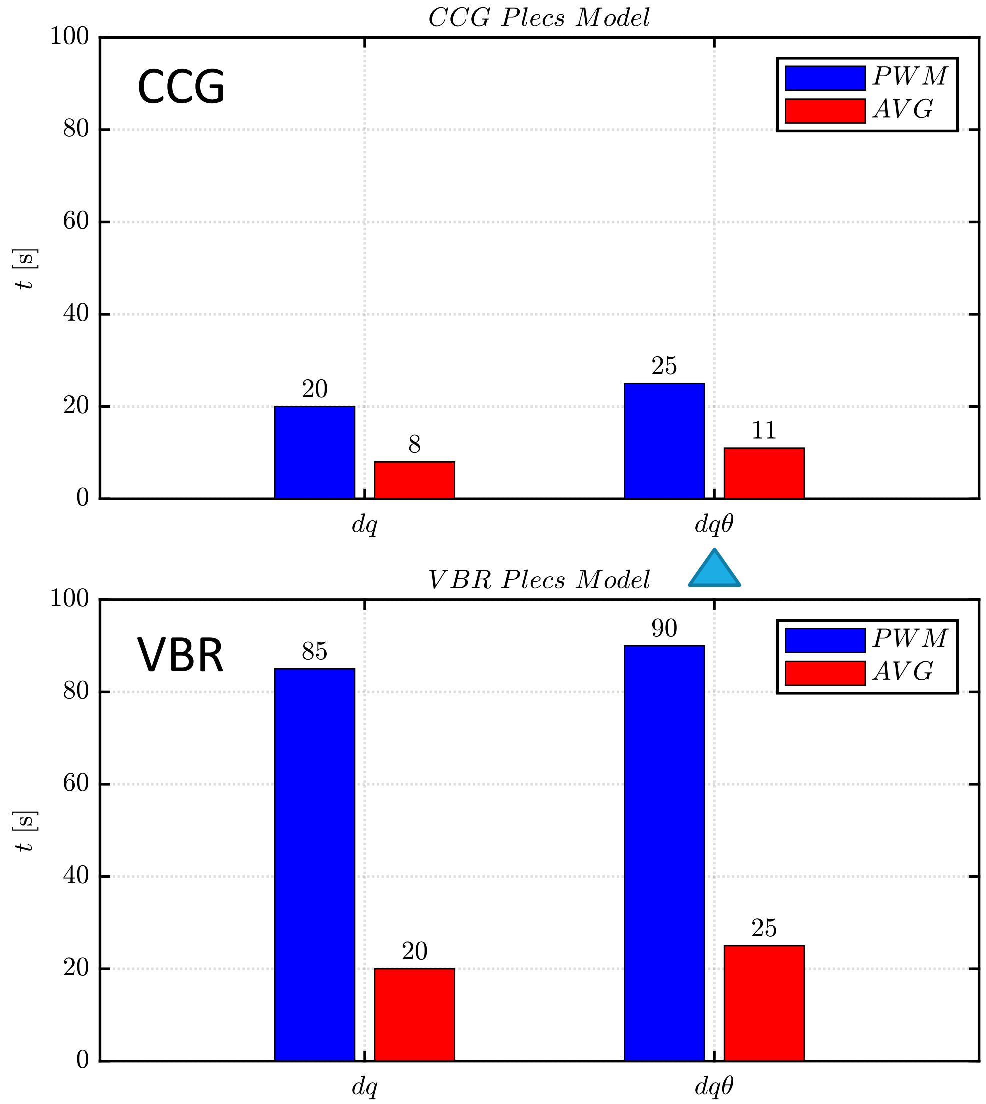
Comparison of CCG and VBR

A standardized speed and torque cycle of 1.0s is used as reference in the following

Computational time comparison

- VBR takes 2.3-2.5x longer than CCG in avg mode
- 3.6-4.5x longer in intantaneous mode

The most accurate dq-theta approach comes at a limited extra computational cost



Windows laptop, 6-core Intel i7-10750H CPU, 2.60GHz, 16GB RAM

Dq-theta model

[4] S. Ferrari, G. Dilevrano, P. Ragazzo and G. Pellegrino, "The dq-theta Flux Map Model of Synchronous Machines," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021

3-dimensional representation of flux maps, including the rotor phase angle input

$$\lambda_d = f'(i_d, i_q, \theta)$$

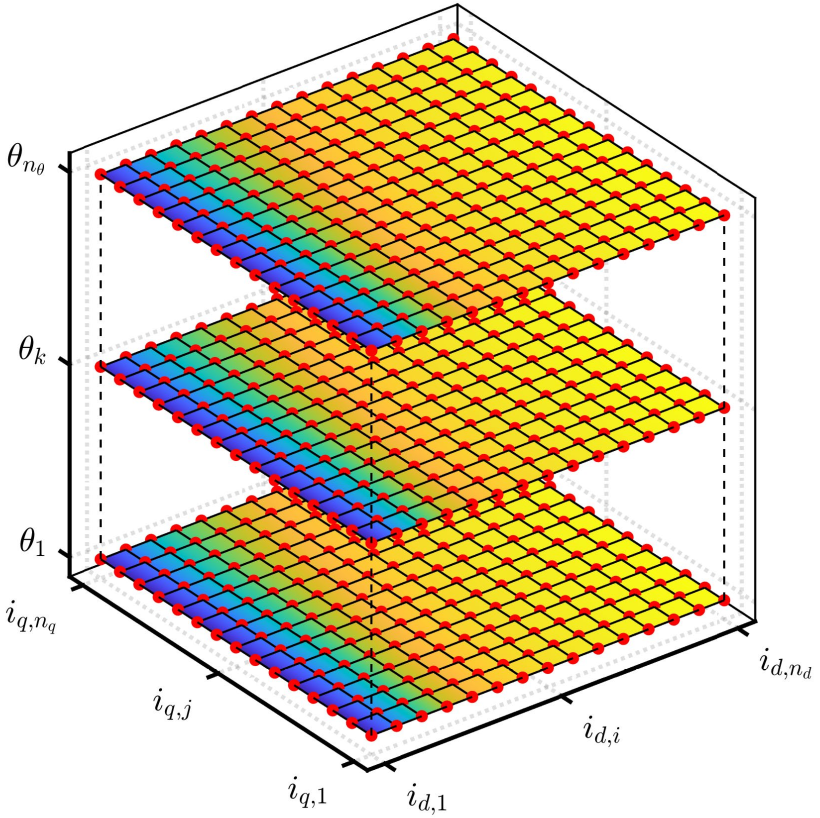
$$\lambda_q = g'(i_d, i_q, \theta)$$

- dq maps are called the fundamental model
- dq-theta includes space harmonic effects, giving birth to back-emf and torque undulation

The 3D maps are natively retrieved from FEA simulations (just by manipulation)

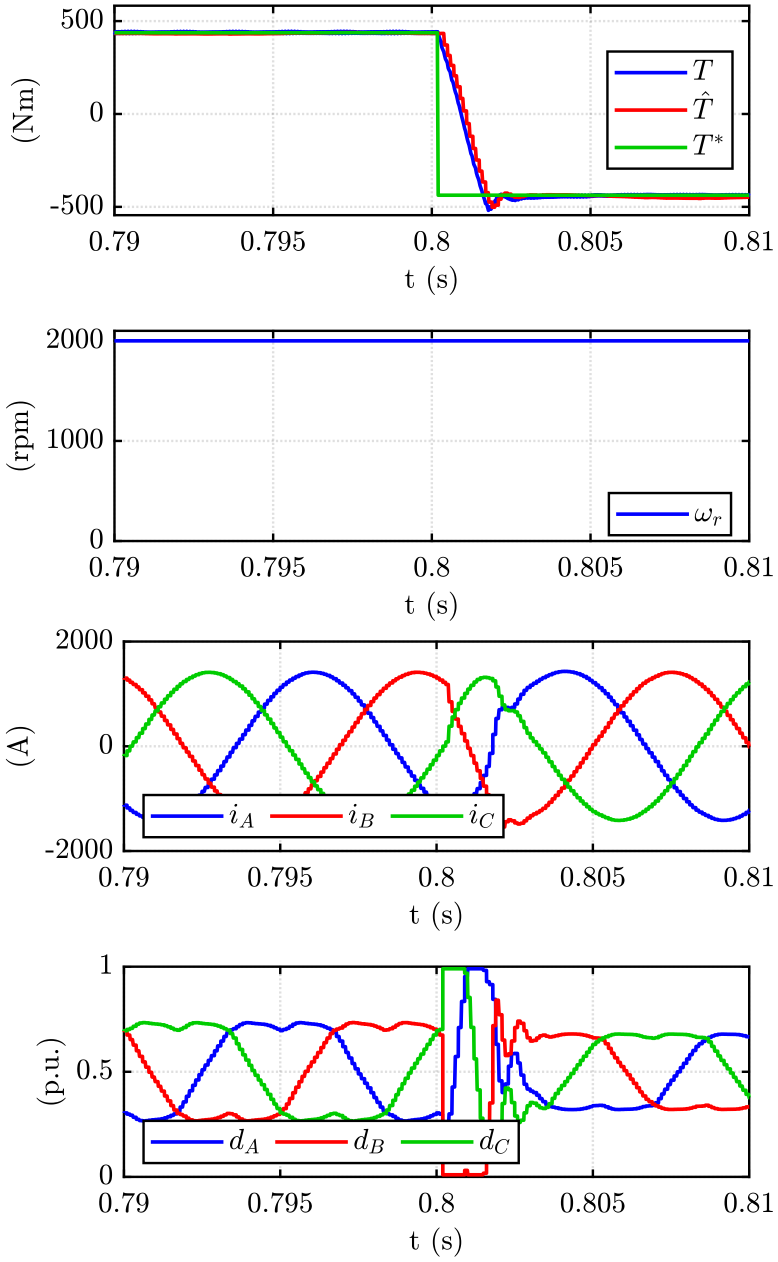
Same approach used with experimental flux maps, using raw data points (e.g. from HBM data recorder)

Organization of the dq-theta maps



Waveforms example

Torque reversal, **dq** model



Peak torque reversal is shown at 2000 rpm

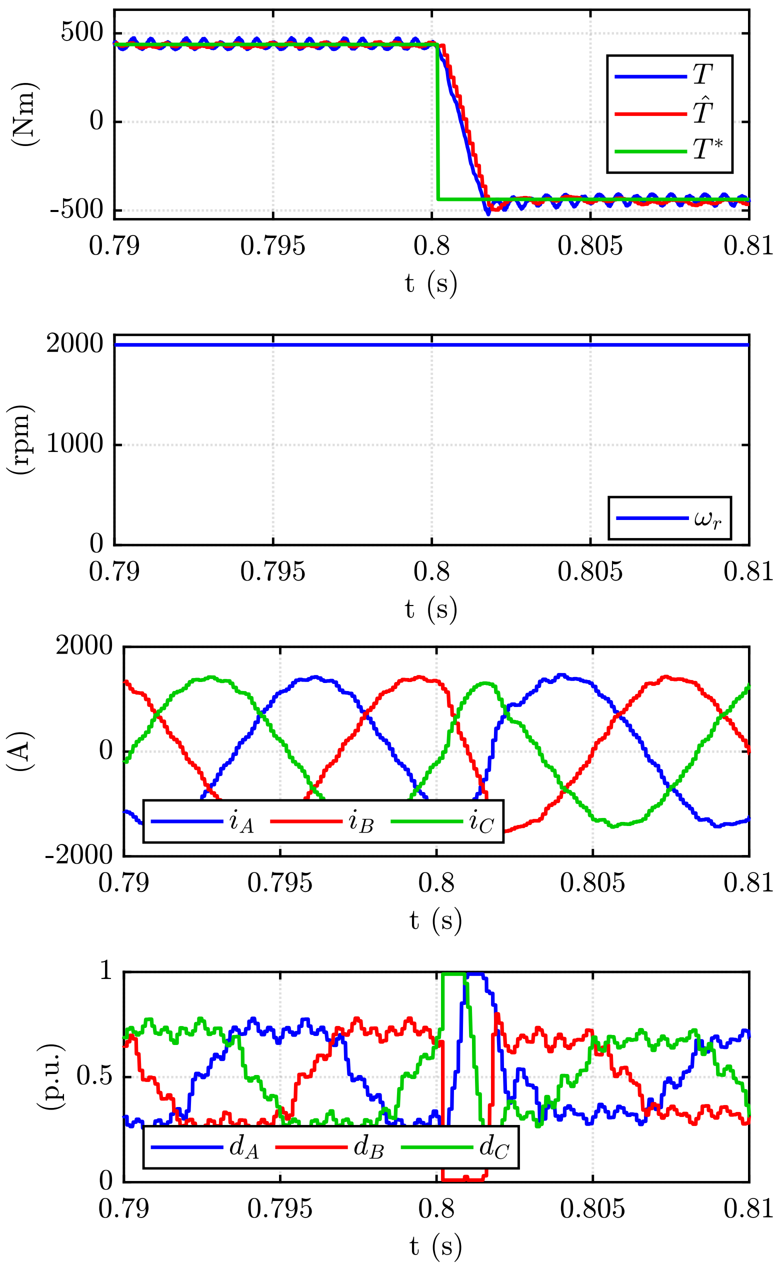
- FOC control with MTPA id, iq references
- Sampled phase current waveforms

This example uses the **dq model of the machine** (no ripple effect), based on inverse dq flux maps (CCG)

Under proper current control, currents are sinusoidal, and torque is smooth

dq-theta model

Torque reversal, **dq-theta** model



Peak torque reversal is shown at 2000 rpm

- FOC control with MTPA id, iq references
- **Sampled phase current waveforms**

The **dq-theta model** of the machine is used this time, including the flux linkage and torque harmonic effects

Currents no longer sinusoidal, torque ripple is evident

High-fidelity model for model-based control design, HiL, digital twin, ..

Comparison to Simulink

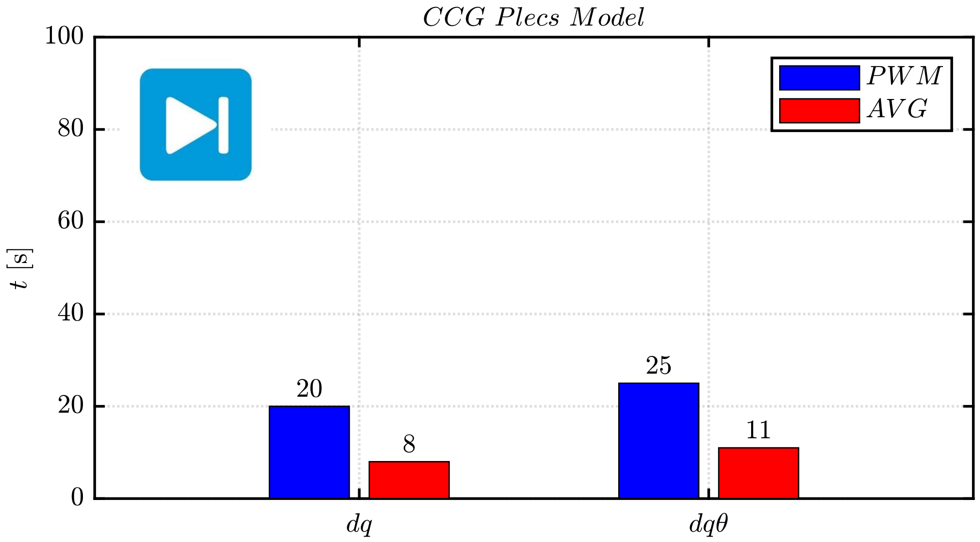
The same 1.0s duty cycle is used

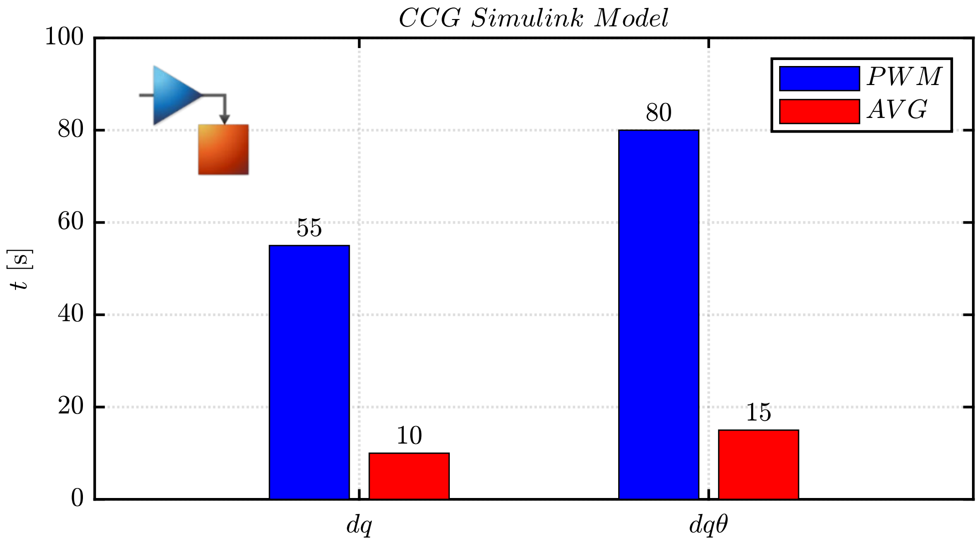
Computational time comparison (CCG)

- The instantaneous PLECS model is way faster (2.75 with dq, 3.2 with dq-theta)
- AVG models are comparable

Besides faster computation, PLECS shows better consistency w.r.t. changes between PWM and AVG and between dq and dq-theta

Simulation settings
Instantaneous: variable step solver, Tmax 2us, average: variable step solver, Tmax 10us. Switching frequency 10 kHz, single sampling, single update



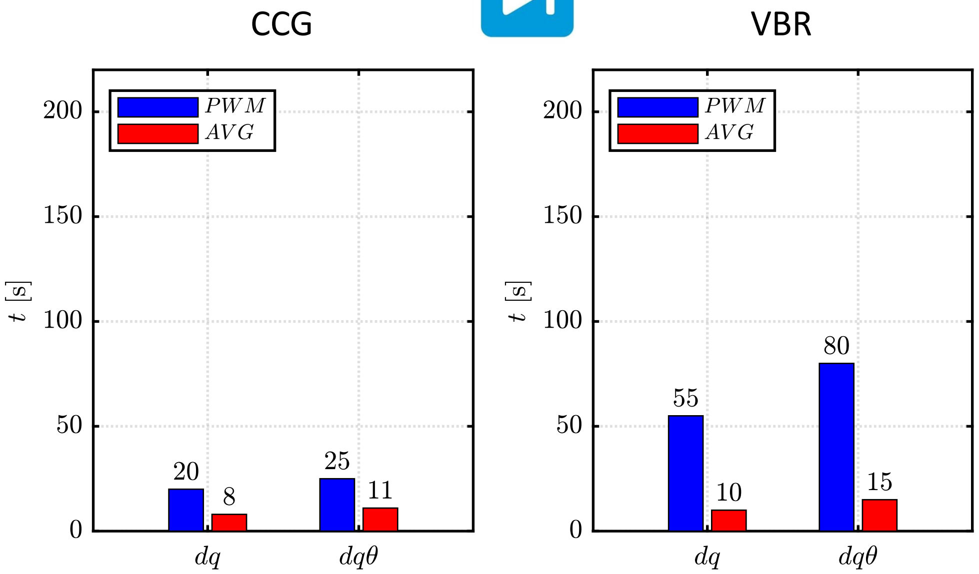


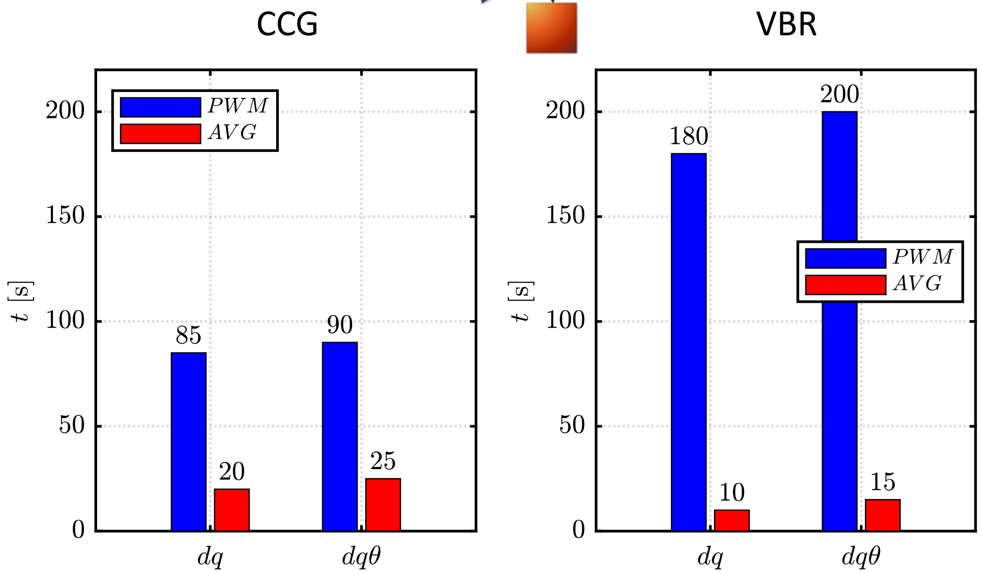
Summary: CCG vs VBR and PLECS vs SImulink

The respective VBR models are included in the comparison

Trends of longer simulation time by Simulink are confirmed

Also, the trend of less consistency is confirmed: unexpectedly, the AVG model is faster with VBR than CCG (contrary to the assumption of more time related to more LUTs)





Conclusion

syreDrive, the SyR-e approach to control simulation for PM synchronous machines was presented, using the IPM motor drive of Tesla Model3 as reference case

SyR-e is about to include PLECS models generation, beyond Simulink ones

The CCG and VBR approaches were compared, and advanced LUT-based modelling features have been presented, such as the dq-theta approach

Computational time comparison was shown and commented

Inverse flux maps dictate a tradeoff between current domain (VBR is best) and time (CCG is best)

The dq-theta model adds accuracy at limited cost

Work is in progress

We invite you to try syreDrive and collaborate with us!

References

[1] A. Varatharajan, D. Brunelli, S. Ferrari, P. Pescetto and G. Pellegrino, "syreDrive: Automated Sensorless Control Code Generation for Synchronous Reluctance Motor Drives," 2021 IEEE Workshop on Electrical Machines Design, Control and Diagnosis (WEMDCD), Modena, Italy, 2021, pp. 192-197.

[2] G. Pellegrino and S. Ferrari, "Design, Identification and Simulation of PM Synchronous Machines for Traction," Tutorial Notes, ICEM 2022, Valencia

[3] A. Bojoi, "Advanced Dynamic Model of E-motor for Control Rapid Prototyping [MSc Thesis]", Politecnico di Torino, 2022, https://webthesis.biblio.polito.it/22088/1/tesi.pdf

[4] S. Ferrari, G. Dilevrano, P. Ragazzo and G. Pellegrino, "The dq-theta Flux Map Model of Synchronous Machines," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021

syre

https://github.com/SyR-e

Thank you!

Questions are very welcome

gianmario.pellegrino@polito.it

www.peic.polito.it