

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

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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

PEIC: the Power Electronics Innovation Center

<u>Inter-Departmental Center</u> 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





The Synchronous Reluctance Motor Technology



Background: Synchronous Reluctance Torque



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



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Source: Pinterest

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[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





962

Year 🝷

2013 2014 2015

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

Advantages of SyR Motors

1. Standard distributed-winding stator

2. Rotor simplicity

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







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Vs Asynchronous Motors:

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







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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

Sensorless Control (no encoder)

V/Hz controlled Asynchronous counterparts are sensorless \rightarrow 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

[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





Control Challenges

Sensorless Control (no encoder) -> LUTs

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

MTPA Operation \rightarrow LUTs and manipulation

This guarantees the promised IE4 efficiency

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 $i_q[A]$

 $i_d[A]$

 $i_d[A]$

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

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Rotor barriers design -> golden rules, optimization, asymmetric poles

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

Magnetic design -> FEA-corrected design equations

• What if the stator is not given?

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

• rotor ribs scale with n_{max}^2

High number of poles \rightarrow PM-assistance

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, skew

(x,b and FEAfix)

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SyR-e: Synchronous Reluctance Evolution

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



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 opensource design resources

Downloadable under the <u>APACHE License</u>, Version 2.0

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

FEMM is at <u>www.femm.info</u>

Power Electronics Innovation Center

SVIC <u>https://github.com/SyR-e</u>





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

FEMM is at www.femm.info









SyR-e Geography

Sensorless control







t (s)



BAWP.tem JD RAWP.am

0 1000 2000 3000 4000 5000 6000 $n \, [rpm]$

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





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







 $n \, [rpm]$

Efficiency Map



40

 $[V]_{b_{i}}^{30}$

20

10

0

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

The demo in use consists of two files:

- RAWP.fem \rightarrow FEMM model
- RAWP.mat \rightarrow 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

| [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 |

| gs | | | | - Comme | | |
|---------------------|-----------|----------|---|-------------|---|----|
| Motor name | RAWP | | | | | |
| ber of 3phase sets | 1 | | | | | |
| Motor type | SR | | | | | |
| Axis type | SR | | | | | |
| Rated power | 4442.74 | [W] | | 111 | | 21 |
| Rated current | 15 | [Apk] | | | | P |
| Maximum current | 30 | [Apk] | | | | |
| DC link voltage | 565 | [V] | 1 | | | |
| Rated speed | 2252 | [rpm] | | | E | |
| Maximum speed | 5000 | [rpm] | | | | |
| Phase resistance | 0.4541 | [Ohm] | | | | |
| inding temperature | 50 | [°C] | | and a state | / | |
| PM temperature | (20 ▼) | [°C] | | | (| |
| Active length | 110 | [mm] | | | | |
| in series per phase | 120 | | | | | |
| Inertia | 0.0079578 | [kg m^2] | | | | |



Motor Ratir

Nun

Turns

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

Torque and power-factor contours 承 GUI_Syre _ \times Main Data Geometry Options Simulation Motor-CAD Windings Materials Optimization are evaluated via design equations as Load Machine Preliminary Design a function of the two key parameters: Save machine Number of pole pairs 3 syrmDesign(x,b) FEAfix • $x = \frac{r}{R}$ (rotor/stator split) Clear \tmp folder Number of slots/(pole*phase) 2 syre Current mot file is: • $b = \frac{B_g}{B_{F_o}}$ (\rightarrow iron/copper split) Range of x (rotor/stator split) [0.5 0.7] Airgap thickness [mm] 0.325 RAWP.mat ver. 3.0 Stator outer radius [mm] 87.5 Range of b (airgap/iron split) [0.4 0.6] 承 Figure 3 _ \times Airgap radius [mm] 59.5 Current overload [p.u.] 1 <u>File Edit View Insert Tools Desktop Window Help</u> 🗋 🗀 🛃 🍓 🗔 🔲 🗈 🕨 🔳 Iron Loading [T] Shaft radius [mm] 25 1.4 torque and PF tradeoff 0.6 Stack length [mm] 110 Tooth factor 0.88 $\bigcirc cos\varphi$ # of FEAfix simulations 1 Type of rotor Circular • • magnetic loading 2.0 **SELECT** \times pick up a machine? p.u. ÷ 0.45 Yes No 0.40.550.60.650.70.5x - rotor / stator split



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















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 $B_{Fe} = 1.4 \text{ T}$ (back iron and rotor flux carriers)

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





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 highperformance 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

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| 17 | <pre>% [map] = syrmDesign_SyRM(dataSet)</pre> | | | | | | | | | | | |
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| 19 | <pre>% Preliminary desi</pre> | gn for SyF | machine | es. Refe | erences: | | | | | | | |
| 20 | % - Vagati's Tutor | 1al 1994 | | | | | | | | | | |
| 21 | -% - ECCE 2018 pape | r (FEAIIX) | | | | | | | | | | |
| 22 | e innut | | | | | | | | | | | |
| 23 | if nargin==1 | | | | | | | | | | | |
| 24 | %flags for SvR | M design | | | | | | | | | | |
| 26 - | flag kw=1: | % flag k | w=0> | use Vac | rati's er | multions w | ith kw= | | sart (3 | 3)) | | |
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| 31 | | % flag_p | b=2> | hc/(df* | sk^0.5) | = constant | (reduc | ce Lfq) | | | | |
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| 3 usages | of "flag_kw" found | | US-ASC | | syrmDes | sign_SyR | | | Ln 30 | 7 Col | 11 | |



Default Rotor Design

[7] A. Vagati, M. Pastorelli, G. Francheschini, and S. C. Petrache, "Design of low-torqueripple 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

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→ Torque ripple is well minimized without need for optimization

→ Rotor and stator flux density peaks are consistent





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FEAfix: FEA-augmented Design Equations







FEAfix: FEA-augmented Design Equations





Flux Barriers Shift for Asymmetric Poles

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

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



| Main Data Geometry Options Windings Materials Optimization Simulation Motor-CAD Stator Parameters Tooth length [mm] 16.07 Tooth width [mm] 5.03 Slot shape Trapezoidal • Stator slot opening [p.u.] 0.3 Tooth tang, depth [mm] 0.6 Barriers width hc [mm] [2.15 3.67 5.19] Barriers shift dx [p.u.] [0.041 0.18] | |
|--|-----------------------------------|
| Stator Parameters Rotor Parameters Save machine Tooth length [mm] 16.07 Number of rotor barriers 3 Tooth width [mm] 5.03 Barriers angles alpha [p.u.] [0.375 0.25 0.25] Clear \tmp folder Slot shape Trapezoidal Barriers angles alpha [*] [11.25 7.5 7.5] Current mot file is: Stator slot opening [p.u.] 0.3 Barrier width hc [p.u.] [0.27 0.46 0.65] Tooth tang. depth [mm] 0.6 Barriers shift dx [p.u.] [0.41 0.18] | |
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| Tooth tang. depth [mm] 0.6 Barrier width hc [mm] [2.15 3.67 5.19] Tooth tang. angle [°] 25 Barriers shift dx [p.u.] [0 0.41 0.18] | |
| Tooth tang. depth [mm] 0.6 Barrier width hc [mm] [2.15 3.67 5.19] Tooth tang. angle [°] 25 Barriers shift dx [p.u.] [0 0.41 0.18] | |
| Tooth tang, angle [*] 25 Barriers shift dx (p.u.) [0 0.41 0.18] | |
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| Fillet at slot bottom [mm] 3.4 PM shape factor beta [p.u.] 0 | \mathbf{x} |
| Theta FBS [mech *] 5 | $\%\lambda$ |
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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

| 📣 GUI Syre | | | | |
|--|---|------------------------------------|----------------------|-------------------------|
| Main Data Geometry Options | Windings Materials Optimization | Simulation Motor-CAD | | |
| Optimization Parameters | Variables and Bounds |] | Load Machine | 5 |
| # of generations 60 | 1st barrier pos. [p.u.] [0.25 0.5] | | Save machine MN | |
| Population size 60 | Barriers positions [p.u.] [0.17 0.5] | Optimize | Clear \tmp folder | |
| Time stepping during MODE | Barrier width [p.u.] [0.2 1] | Current overload [p.u.] 2 | Current mot file is: | Syle |
| Rotor angular excursion 30 | Barrier dx [p.u.] [-0.75 0.75] | | RAWP.mat | ver. 3.0 |
| # of rotor positions 5 | Airgap thickness [mm] [0.4 0.8] | | | |
| Time stepping for Pareto front re-evaluation | PM remanence [T] [0.2 0.8] | Objectives and Penalization Limits | | |
| Rotor angular excursion 60 | Airgap radius [mm] [52 78] | Torque [Nm] -10 | | \searrow |
| # of rotor positions 30 | Tooth width [mm] [3.8 6.3] | Torque ripple (pp) [Nm] 8 | | λ |
| | Tooth lenght [mm] [15 22.5] | | | \sim |
| | Stator slot open [p.u.] [0.2 0.3] | Copper mass [kg] 0 | | ∇ |
| | Tooth tan. depth [mm] [0.8 1.2] | PM mass [kg] 1.58 | | \mathcal{A} |
| | PM shape factor [p.u.] [10 89] | | | |
| | Theta FBS [mech °] [0 10] | | | T |
| | PM dimension [p.u.] [0 1] | | | $\overline{\mathbf{D}}$ |
| | Gamma [°] [40 75] | | | |



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, <u>random</u> offset
- <u>random</u> current phase angle during optimization
- Accurate re-evaluation of the Paretooptimal 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



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

Target and estimated temperature must be equal

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

| 承 GUI_Syre | | | | | | | — 🗆 🗙 |
|--------------------------------|--------------|----------------------------|------------|--------------|---|-----------------------|-------------------|
| Main Data Geometry Options | Windings Mat | erials Optimization | Simulation | Motor-CAD | | | |
| | r | | | | | Load Machine | 52000 |
| Thermal Parameters | | | | | _ | Save machine MN | |
| Thermal loading kj [W/m2] | 2800 | Admitted copper le | oss [W] | 169.3318 | | | |
| Target copper temperature [°C] | 50 E | Estimated copper temperate | ure [°C] | 53.01 | | Clear \tmp folder | SV/r |
| | | | | | | Current mot file is: | Syl |
| Housing temperature [°C] | 40 | Current density [A | /mm^2] | 7.032 | | RAWP.mat | ver. 3.0 |
| Calculated rated current [A] | 15.767 Phas | e resistance @ target temp | erature | 0.4541 | | | |
| Mesh Control | | Structural Parameters | | | | \sim | |
| Mesh | 5 | Overspee | ed [rpm] | 3000 | - | | \searrow |
| Mesh_MOOA | 10 | Minimum mech. tolerand | ce [mm] | 0.4 | | \mathbb{D}_{Γ} | λ |
| Ribs Design | | | | | | | $\langle \rangle$ |
| Tangential ribs width [mm] [0. | 0.4 0.4 0.4] | Radial ribs widt | th [mm] | [0 0 0] | | | ∇ |
| Tangential ribs fillet [mm] | 0 | Radial ribs angl | e [deg] | [0 0 0] | - | | D |
| | | Radial ribs offs | et [mm] | [0 0 0] | = | \wedge | |
| Manual ribs | Split ribs | Radial ribs fill | let [mm] | 0.4 0.4 0.4] | = | | |
| | | | | | | | |
| | | | | | | | |



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)

This is seamlessly evaluated for each candidate design during optimization

| Surger State | | |
|--|---|-----------------|
| | | - u x |
| Main Data Geometry Options Windings Materials Optimization Simulation Motor-CAD | | Ale |
| | Load Machine | 5 |
| Thermal Parameters | | |
| Thermal loading ki IW/m21 2800 Admitted copper loss IWI 169 3318 | Save machine MN | |
| | Clear time folder | |
| Target copper temperature [°C] 50 Estimated copper temperature [°C] 53.01 | Clear (imp folder | SVIrA |
| | Current mot file is: | Syl |
| Housing temperature [°C] 40 Current density [A/mm^2] 7.032 | RAWP.mat | ver. 3.0 |
| Calculated rated ourrant (A) d5 797 Disease registrance @ target temperature 0.4544 | | |
| Calculated rated current [A] 15.767 Phase resistance @ target temperature 0.4541 | | |
| Mesh Control Structural Parameters | \sim | |
| | | |
| Mesh 5 Overspeed [rpm] 15000 | | |
| Mesh MOQA 10 Minimum mech tolerance [mm] 0.4 | /()/ | |
| | $\downarrow \downarrow \downarrow / \frown$ | \wedge |
| Ribs Design | | |
| | | $) \land \Box$ |
| Tangential ribs width [mm] [0.4 0.4 0.4] Radial ribs width [mm] [0 0.73 1.33] | | |
| Radial ribs angle [deg] | | $() \downarrow$ |
| | | |
| Radial ribs offset [mm] [0 0 0] | A MAN | |
| | | |
| Manual ribs Split ribs Radial ribs fillet [mm] [0.4 0.4 0.4] | | Fn I |
| | | |
| | | |
| | | |



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

| GUI Syre | - 🗆 X | GUI Swe | - 🗆 X |
|---|--------------------------------------|--|----------|
| Main Data Geometry Options Windings Materials Optimization Simulation Motor-CAD | Load Machine | Main Data Geometry Options Windings Materials Optimization Simulation Motor-CAD Load Machine | |
| Slot filing factor 0.45 Slot layer position Stacked • 6 slots | Save machine MN Clear tump folder | Slot filing factor 0.45 Slot layer position Stacked • 36 slots | C. A |
| Turns in series per phase 120 Number of simulated slots 6 | Current mot file Is: | Turns in series per phase 120 Number of simulated slops 36 Current mot file Is: | syre |
| Pitch shortening factor 1 Number of 3-phase sets 1 | RAWP.mat ver. 3.0 | Pitch shortening factor 1 Number of 3-phase sets 1 RAWP mat | ver. 3.0 |
| Save Configuration Slot Slot Slot Slot Slot Layer 1 1 -3 -3 2 2 Layer 2 1 -3 -3 2 2 | \sim | Save Configuration Slot Slot <td></td> | |
| | | Editable winding scheme | |
| Slot Model | | | |
| Conductor type Round Conductor radius (mm) 0.4 Insulation thickness (mm) 0.1 Conductor width (mm) 0.8 | | Conductor type Round Conductor radius (mm) 0.4 | |
| Conductor shape factor (h/w) 1 Conductor height [mm] 0.8 | | Conductor shape factor (h/w) 1 Conductor height [mm] 0.8 | |
| Number of conductors 20 Draw slot model | | Number of conductors 20 Draw slot model | |
| Frequency vector [Hz] [1 10 50 100 200 300 400 500 600 700 800 500 10C Evaluate slot model | | Prequency vector [H2] [1 10 50 100 200 300 400 500 600 700 800 900 10C] | |
| remperature vector [1:2] = ================================== | | remperature vector [1:0] DU 0621209900539 | |



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



| | | | | | | | | | | | | _ | | | | | | | | | |
|--------------|---------------------|--------|---------|----------|-----------|----------|-------------|---------|---------|--------|--------------|---|-----------------|--------|---------------|--------------------------|-----------------|---------------------|--------------|--------|---|
| 承 GUI_Syre | | | | | | | | | | | | | | | | | | | _ | | > |
| Main Data | Geometry | Option | s V | Vindings | Mate | rials | Optimizatio | on | Simula | ation | Motor-CAD | | | | | | _ | | | | |
| | | | | | | | | | | | | | | L | oad Mach | ine | | 5 | | Sec. | |
| Ş | Slot filling factor | r 🗌 | 0.45 | 5 | | | Slot I | ayer po | osition | Sta | cked 🔻 | | | Save | machine | MN | | i N. | 0 | | |
| Turns in | series per phas | se 🗌 | 120 |) | | Nu | mber of sir | nulated | d slots | | 6 | | | Cle | ar \tmp fo | older | | Q | ∕∕¥∕ ∖∕r∟ | 2 | |
| | | | | | | | | | | | | | | Cu | rrent mot f | ile is: | | $\underline{\circ}$ | yıc | , , | |
| Pitch | shortening facto | or | 1 | | | 1 | Number of | 3-phas | e sets | | 1 | | | | RAWP.ma | at | | , | ver. 3.0 | | |
| | | | | | | | | | | | | | · · | , , , | | 1 | | | | - | _ |
| Save C | onfiguration | | | Slot | Slot | Slot | Slot | Slot | Slot | | | | - | | | | | | | | |
| | | | ayer 1 | 1 | 1 | -3 | -3 | | 2 | 2 | | | | | | | | | | | |
| | Default | L | ayer 2 | 1 | 1 | -3 | -3 | | 2 | 2 | | | - | | | | | | | | |
| | | | | | | | | | | | | | 6 | | | | | | 1 | | - |
| Slot Model | | | | | | | | | | | | | 4 | | | | | | | | |
| | Conductor typ | e Ro | und | ▼ | | | Conductor | radius | s [mm] | | 0.4 | | 2 | | $\overline{}$ | $\overline{\mathcal{A}}$ | 6 | | \ | | |
| | | | | | | | | | | | | | | \cap | \boxtimes | Xr | | | | | |
| Insulation | n thickness [mn | n] | 0.1 | | | | Conducto | r width | n [mm] | | 0.8 | | - 0 - | | \bigcirc | \odot | UX | | | | |
| | | _ | | | | | | | | _ | | | -2 h | | $^{\sim}$ | \bigcirc | ∞ | | | | |
| Conductor sh | hape factor (h/v | v) | 1 | | | | Conductor | height | t [mm] | | 0.8 | _ | | | <u> </u> | | $\underline{0}$ | / | / | | |
| Numb | per of conductor | rs | 20 | | | | | Draw | slot m | odel | | | - ⁻⁴ | | | | | | | | |
| Freau | uency vector [H: | z] [1 | 10 50 1 | 00 200 3 | 00 400 50 | 0 600 70 | 0 800 900 | 100 | | | | | 60 | | 65 | | 70 | | 75 | | 8 |
| | , . | | | | | | | | E | valuat | e slot model | | | | | | | | | | |
| Temper | rature vector [°C | C] | | 50. | .66212599 | 966339 | | | | | | | - | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | | _ | _ |



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 <u>PM machines</u>





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.*

Modello in SyRe 250• 50 Hz **-**50 Hz 200• 60 Hz [M/kg] 150 -60 Hz • 100 Hz 100 Hz Specific loss [**o** 200 Hz 200 Hz **o** 400 Hz **-** 400 Hz • 700 Hz 50700 H 1.50 0.5B[T]Total Iron Loss $n = 750 \, rpm$ $n = 1500 \, rpm$ $n = 3000 \, rpm$ 200150 $P_{Fe} \; [W]$ 1005040402020 $i_q [A]$ 0 0 $i_d [A]$

The iron loss map is FEA simulated at a single speed value $n_0(\text{rpm})$

Hysteresis and classic loss terms are evaluated separately

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

The loss map is scaled speed-wise

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

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

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



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



Von Mises Stress [MPa]

0.02 0.03 0.04 0.05 0.06

[m]

Mesh for structural FEA





Stress calculated at 5000 rpm Yield strength of M600-50A is 285 MPa



0.06

0.05

0.04

0.02

).01

0.01

E 0.03

Export to Motor-CAD

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

[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





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







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

| n Scaling 9 60 | | | |
|---|--------------------------|---|--|
| Scaling & SK | ewing Torque-Speed syreD | rive Waveform | SvR-e |
| Iodels Loaded | | | Magnetic Model Manipulation |
| | | | |
| ✓ aq Model | Load | | Load Save FileCheck |
| 🖌 dqtMap Model | Load Plot | Save | New Save As Close all |
| 🖌 Iron Loss Mode | Load Plot | Save | |
| Skin Effect Mor | | Save | Current path: C:\syreGIT\ |
| | | | Motor Ratings |
| ITPA-MTPV | | | Motor name RAWP |
| MTPA/MTPV | Load Plot | Save Print | Number of 3phase sets 1 |
| | | | Motor type SR |
| | Evaluate | LUT | Axis type SR |
| | | | Rated power 4442.74 [W] |
| | - Anno 1997 - A Anno 19 | | |
| nductance and Anis | otropy maps | | Maximum current 30 [Apk] |
| Inductance and Anis | s Eval Plot | Save | Maximum current 30 [Apk] DC link voltage 565 [V] |
| Inductance and Anis | s Eval Plot |) Save | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] |
| Inductance and Anis | s | Save Short Circuit Torque | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] Maximum speed 6000 [rpm] |
| Inductance and Anis Inductance Map Current Angle Curve # of current levels | s | Save Short Circuit Torque | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] Maximum speed 6000 [rpm] Phase resistance 0.4541 [Ohm] |
| Inductance and Anis | s | Save Short Circuit Torque Evaluate | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] Maximum speed 6000 [rpm] Phase resistance 0.4541 [Ohm] Winding temperature 50 [*C] |
| Inductance and Anis Inductance Maj Inductance Inductance Maj Inductance Inductanc | s | Save Short Circuit Torque Evaluate | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] Maximum speed 6000 [rpm] Phase resistance 0.4541 [Ohm] Winding temperature 50 [°C] PM temperature 20 [°C] |
| Inductance and Anis Inductance May Current Angle Curve # of current levels nverse Model | s Eval Plot Eval Plot | Save Short Circuit Torque Evaluate Save | Maximum current 30 [Apk] DC link voltage 565 [V] Rated speed 2252 [rpm] Maximum speed 6000 [rpm] Phase resistance 0.4541 [Ohm] Winding temperature 50 [°C] PM temperature 20 [°C] Active length 110 [mm] |





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]

| Operating Limits Gyr+9 # of current levels 4 Evaluate Rating sevaluation Efficiency Map Min Max # of points Speed limits (rpm) 0 6000 11 Torque limits (Nm) 0 50 11 Winding temperature (°C) 60 Mech. loss poly 0 Iron loss No P Mioss factor 2 PM loss No P Mioss factor 1 Skin effect No Vertical LUT Number of 3phase sets 1 Motor strategy Maximum efficiency Evaluate Maximum current 30 Magnetic Model Manipulation Iron loss No 1 No Vinding temperature (°C) 60 Mech. loss poly 0 0 Iron loss No P Mioss factor 1 Number of 3phase sets 1 Skin effect No Vertical as peed 2000 MM Rated power 50000 Min Maximum current 30 Apki DC link voltage 665 M 44411 Origoiiiiiiiiiiiiiiii | ain | Scaling & Skewing | Torque-Speed | syreDrive Wavefo | m | PuD a |
|---|---------|-----------------------|------------------|--------------------------------------|------------------|------------------------------|
| # of current levels 4 Evaluate Rating sevaluation Efficiency Map Min Max # of points Speed limits (rpm) 0 6000 11 Torque limits (rpm) 0 50 11 Winding temperature (°C) 50 Methods failing seveluate Motor name RAWP Winding temperature (°C) 50 Method LUT Number of 3phase sets 1 Skin effect No PM loss factor 1 Motor failing s Skin effect No Method 1 Torque limits (rpm) 30 Axis type SR Motor stategy Maximum efficiency Evaluate Motor states 1 Maximum current 30 Apki Signage - | Opera | ation Limits | | | | Magnetic Model Manipulation |
| # of current levels 4 Evaluate Hating sevaluation Efficiency Map Min Max # of points Speed limits (rpm) 0 6000 11 Torque limits (rpm) 0 60 11 Winding temperature [°C] 60 Meth. loss poly 0 Iron loss No P Mioss factor 2 PM loss No P Mioss factor 1 Skin effect No Wethod LUT Namber of 3phase sets 1 Motor faitings 60000 Min Rated power 60000 Min Skin effect No Method LUT Nation current 30 Axis type SR Sign of the effect No Method Lut Torainate PM loss Axis type SR Sign of the effect No Method Lut Torainate PM loss | - , | | | | | |
| Min Max # of points Speed limits (rpm) 0 6000 11 Torque limits (rpm) 0 50 11 Winding temperature (°C) 50 Mech. loss poly 0 Ion loss No Vinol loss factor 2 PM loss No PM loss factor 1 Skin effect No PM loss factor 1 Skin effect No PM loss factor 1 Skin effect No Wethod LUT Torque limits (rpm) Skin effect No Wethod LUT Rated power 50000 Min Sign of the state points Image: Sign of the state points Image: Sign of the state points 1 Sign of the state points 1 1 Sign of the state points Image: Sign of the state points Image: Sign of the state points 1 1 1 1 Sign of the state points Image: Sign of the state points Image: Sign of the state points 1 1 1 1 Sign of the state points Image: Sign of the state points Image: Sign of the state points 1 1< | #1 | ofcurrent levels | 4 | Evaluate | atingsevaluation | Load Save FileCheck |
| Min Max # of points Speed limits (rpm) 0 6000 11 Torque limits (Nm) 0 60 11 Winding temperature (°C) 50 Mech. loss poly 0 Iron loss No Iron loss factor 2 PM loss No PM loss factor 1 Skin effect No PM loss factor 1 Control strategy Maximum efficiency Evaluate Maximum current 30 Maximum efficiency Evaluate Maximum current 30 Akit Maximum efficiency Evaluate Maximum current 30 Akit Maximum efficiency Evaluate Maximum current 30 Akit Maximum current 10 Maximum current 30 Akit Maximum current 0 0.4641 (hmin Phase resistance 0.4641 Minding temperature 50 (°C) (°C) (°C) (°C) (°C) Maximum current 10 Iron Iron Iron Iron Iron Maximum current | Efficie | ency Map | | | | New Save As Close all SV/ |
| Speed limits (rpm) 0 6000 11 Torque limits (Nm) 0 60 11 Winding temperature (°C) 50 Mech. loss poly 0 Iron loss No Iron loss factor 2 PM loss No PM loss factor 1 Skin effect No PM loss factor 1 Control strategy Maximum efficiency Evaluate Maximum current 30 Go Iron Iron Iron loss factor 1 Skin effect No Method LUT Rated current 15 Go Iron Iron Iron loss factor 1 Maximum current 30 Go Iron loss Iron Iron Iron Iron Iron Iron Skin effect No Method Iron Iron <td></td> <td></td> <td>Min</td> <td>Max</td> <td># of points</td> <td></td> | | | Min | Max | # of points | |
| Torque limits [Nm] 0 50 11 Winding temperature [°C] 50 Mech. loss poly 0 Iron loss No Iron loss factor 2 PM loss No PM loss factor 1 Skin effect No PM loss factor 1 Control strategy Maximum efficiency Evaluate Fated current 15 Axis type 565 Mi T-n feastble points 0 0 0 Maximum efficiency Evaluate Maximum current 30 Akit Maximum efficiency Evaluate Maximum current 30 Akit Maximum speed 60000 (rpm) Maximum speed 60000 (rpm) Maximum speed 0.4541 (hm) Phase resistance 0.4541 (hm) PM long temperature 50 (°C) PM long temperature 50 (°C) | | Speed limits [rpm] | 0 | 6000 | 11 | Current path: C:\syreGIT\ |
| Winding temperature [°C] 50 Mech. loss poly 0 Motor name RAWP Iron loss No Iron loss lactor 2 Motor type SR PM loss No PM loss factor 1 Axis type SR Skin effect No PM loss factor 1 Axis type SR Control strategy Maximum efficiency Evaluate Rated current 15 Apkl Control strategy Maximum efficiency Evaluate Maximum current 30 Apkl Maximum efficiency Evaluate Maximum current 30 Apkl Maximum speed 60000 (rpm) Maximum speed 60000 (rpm) Maximum speed 0.4541 (hm) Phase resistance 0.4541 (hm) Minding temperature 20 (°C) PM imperature 20 (°C) | | Torque limits [Nm] | 0 | 50 | 11 | Motor Ratings |
| Iron loss No Iron loss lactor 2 PM loss No PM loss lactor 1 Skin effect No PM loss factor 1 Skin effect No PM loss factor 1 Control strategy Maximum efficiency Evaluate Rated current 15 Axis type 565 Militate 0000 (Pm) Rated speed 2500 (Pm) Rated speed 2500 (Pm) Maximum current 30 Akit Akit DC link voltage 6665 Militate Maximum speed 60000 (Pm) Maximum speed 60000 (Pm) Phase resistance 0.4541 (Dhm) Phase resistance 0.4541 (Dhm) Phase resistance 0.4541 (Dhm) Phase resistance 0.4541 (Dhm) Phase resistance 0.4541 (Dhm) Philementure 20 (°C) Phase resistance 0.4541 (Dhm) Philementure 20 (°C) Phase resistance 0.4541 (Dhm) Philementure 20 (°C) <t< td=""><td>Win</td><td>ding temperature (°C)</td><td>50</td><td>Mech loss poly</td><td>0</td><td>Motor name RAWP</td></t<> | Win | ding temperature (°C) | 50 | Mech loss poly | 0 | Motor name RAWP |
| Iron loss No Iron loss tactor 2 PM loss No PM loss factor 1 Skin effect No PM loss factor 1 Skin effect No PM loss factor 1 Control strategy Maximum efficiency Evaluate Rated current 15 Axis type SR SR Motor type SR Control strategy Maximum efficiency Evaluate Maximum current 30 Akit Maximum efficiency Evaluate Maximum speed 6000 (pm) Maximum speed 00000 (pm) Maximum speed 00000 (pm) Maximum speed 0.4541 (ph) Phase resistance 0.4541 (ph) Minding temperature 20 (°C) PM immediate 20 (°C) | | | | | | Number of 3phase sets 1 |
| PM loss No PM loss factor 1 Skin effect No Method LUT Rated power SR Control strategy Maximum efficiency Evaluate Rated current 15 Apkl More T-n feasible points O Minum Maximum current 30 Apkl Maximum efficiency T-n feasible points O Maximum speed 6000 (Ipm) Maximum speed 00000 Ipminum Maximum speed 00000 (Ipm) Minding temperature 20 (°C) PM longe (°C) (°C) Minding temperature 20 (°C) PM longe (°C) (°C) Maximum speed 00000 (Ipm) Phase resistance 0.45411 (Dhm) Minding temperature 20 (°C) (°C) (°C) (°C) Minding temperature 20 (°C) (°C) (°C) (°C) Minding temperature 20 (°C) (°C) (°C) (°C) Minding temperature 20 (°C) (°C) (°C) (°C) </td <td></td> <td>Iron loss</td> <td>NO</td> <td> Iron loss factor </td> <td>2</td> <td>Motor type SR</td> | | Iron loss | NO | Iron loss factor | 2 | Motor type SR |
| Skin effect No Method LUT Rated power 5000 Mj Control strategy Maximum efficiency Evaluate Bated power 5000 Mj 50 T-n feasible points 0 15 Apkj 60 Control strategy Maximum efficiency Evaluate 30 Apkj 50 T-n feasible points 0 10 10 Maximum current 30 Apkj 6000 Irpmi 10 10 10 10 10 10 | | PMloss | No | ▼ PM loss factor | | Axis type SR |
| Control strategy Maximum efficiency Evaluate 7-n feasible points Maximum current 30 60 - - 7-n feasible points 0 8-n feasible points 10 7-n feasible point 110 7-n feasible point 110 7-n feasible point 110 | | Skin effect | No | Method | LUT 🔻 | Rated power 5000 [M] |
| 50 T-n feasible points Maximum current 30 Apgl 40 A | | Control strategy | Maximum efficier | ncy 🔻 | Evaluate | Rated current 15 [Apk] |
| 20 | | | T-n f | easible points | | Maximum current 30 [Apk] |
| 40 10 10 10 10 10 10 10 10 10 1 | 5 | | | | | Do link voltage 505 [V] |
| 30 Image: Constraint of the second of the sec | 4 | 10 | | | | Maximum eneed 6000 [rpm] |
| 5. 20 Winding temperature 50 [°C] 10 PM temperature 20 [°C] Active length 110 Immil | (m) | 30 | | | • | Phase resistance 04541 [Ohm] |
| 10 | €2 | 20 | · · · | | | Winding temperature 50 [°C] |
| Active length 110 Immi | 1 | 10 | • • | | | PM temperature (20 ▼) [°C] |
| neare lengar the philip | | | • • | | | Active length 110 [mm] |
| (1.1/1/48) | | | | | | Inertia 0.0079578 [kg.m/S |





[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)

| | – 🗆 X |
|--|--|
| Main Cooling & Skowing Torrus Speed auroDrive Waveform | |
| Control setups | SyR-e Magnetic Model Manipulation |
| Control type Torque control Flux maps model dq Model | Load Save FileCheck New Save As Close all SV/C |
| Converter data | Current path: C:\syreGIT\ |
| ON threashold 0 [V] | Motor Ratings |
| Internal resistance 0.0001 [Ohm] | Motor name RAWP |
| Dead time 1e-06 [ns] | Number of 3phase sets 1 |
| | Motor type SR |
| Seneorless control | Axis type SR |
| | Rated power 4442.74 [W] |
| | Rated current 15 [Apk] |
| Low speed region | Maximum current 30 [Apk] |
| Injected signal Sinusoidal V | DC link voltage 565 [V] |
| | Rated speed 2252 [rpm] |
| | Maximum speed 6000 [rpm] |
| High speed region | Phase resistance 0.4541 [Ohm] |
| Position error estimation APP | Winding temperature 50 [°C] |
| | PM temperature 20 ▼ [°C] |
| | Active length 110 [mm] |
| | Turns in series per phase 120 |
| | Inertia 0.0079578 [kg m^2] |





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

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 \rightarrow 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

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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
$$\mathbf{G} = \begin{bmatrix} g & 0 \\ 0 & g \end{bmatrix}$$



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| 540 ##ifdef MATLAB_MEX_FILE /* Is this file being compiled as a MEX-file? */ | | | | | | | | |
| 541 #include "simulink.c" /* MEX-file interface mechanism */ | | | | | | | | |
| 542 #else | | | | | | | | |
| 543 #include "cg_sfun.h" /* Code generation registration function */ | | | | | | | | |
| 544 L#endif | | | | | | | | |
| 545 | | | | | | | | |
| 546 Evoid FluxObserver (void) { | | | | | | | | |
| 547 | | | | | | | | |
| 548 lambda_CM_ab_km1 = lambda_CM_ab; | | | | | | | | |
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| 558 | | | | | | | | |
| 559 feedback OBS.alpha = lambda CM ab km1.alpha - lambda OBS.alpha; | | | | | | | | |
| feedback OBS.beta = lambda CM ab km1.beta - lambda OBS.beta; | | | | | | | | |
| 561 | | | | | | | | |
| 562 // Integration | | | | | | | | |
| 563 lambda_OBS.alpha += Ts*(vsab_km1.alpha - RS*isab.alpha + KOBS*feedback_OBS.alpha); | | | | | | | | |
| 564 lambda_OBS.beta += Ts*(vsab_km1.beta - RS*isab.beta + KOBS*feedback_OBS.beta); | | | | | | | | |
| 565 lambda_OBS.amp = sqrt(pow(lambda_OBS.alpha,2) + pow(lambda_OBS.beta,2)); | | | | | | | | |
| 566 | | | | | | | | |
| rot(lambda OBS, SinCos_elt, lambda_dq); | | | | | | | | |
| <pre>568 T_elt = 1.51*PP*(lambda_OBS.alpha*isab.beta - lambda_OBS.beta*isab.alpha);</pre> | | | | | | | | |
| <pre>detta = atan(tambda_dq.q/lambda_dq.d);</pre> | | | | | | | | |
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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 θ 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



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