Small-scale wind turbine systems with efficient and inexpensive generator topology for micro-grids

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Outline

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1. Introduction and motivation
   - Bund der Freunde der TUM e.V. Project
   - Preparatory work
   - Reluctance synchronous machine

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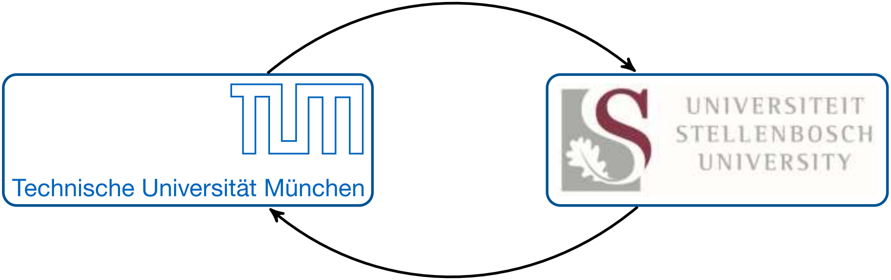
Bund der Freunde der TUM e.V. Project

International cooperation with the University of Stellenbosch, South Africa

Bund der Freunde der TUM e.V. Project

Project partners



CRES (Dr.-Ing. C. Hackl)

- Modeling and control
- Hardware-in-the-Loop (HiL) system

EMLab (Prof. M. Kamper)

- Modeling (FEM)
- Machine design and construction

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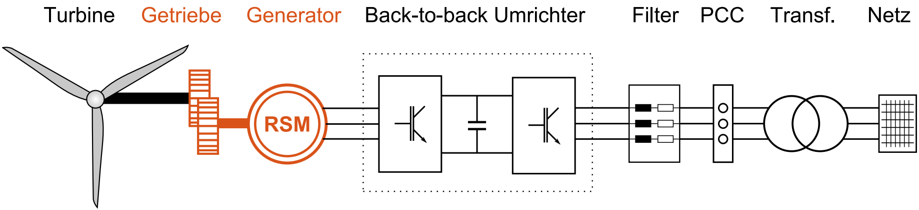
Preparatory work

Modeling, control and simulation of small-scale wind turbine system with RSM [1]



- current control (generator-side)
- maximum torque per Ampere (MTPA)
- speed control (maximum power point tracking (MPPT))
- current control (grid-side)
- DC-link voltage control
- reactive power (feedforward) control

Outline

Reluctance synchronous machine

A view into the machine

http://www.youtube.com/watch?v=69mtuom774E&index=4&list=PLg4s1do3XuVlwc1LnpyZgvfjd_o4wtA_D (cut version/duration: 0:26 min)

Reluctance synchronous machine

A viable alternative?


Traditional IE2 induction motor


IE4 SynRM motor

Losses

http://www.abb.com

advantages [2–4]:

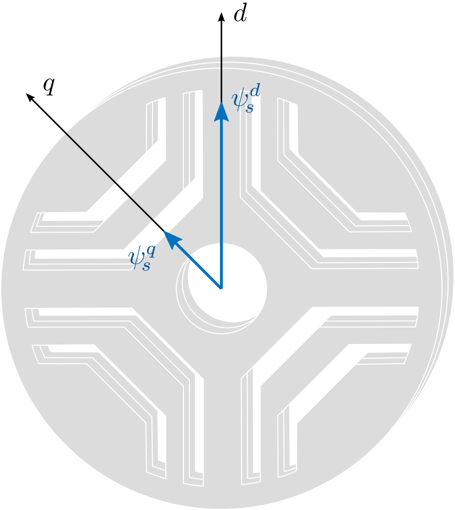
- (very) cheap
- high efficiency feasible (IE4)
- high power density and torque-per-volume ratio
- sensorless control feasible

disadvantages:

- power factor
- highly nonlinear
- inverter necessary
- (complex/nonlinear control necessary)

Reluctance synchronous machine

Flux linkage in the rotor



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2 Control of reluctance synchronous machines (RSMs)

- Nonlinear PI current control of RSMs [1, 5]
  - Generic model of RSM
  - Nonlinear PI controller design
  - Measurement results
- Maximum torque per Ampere (MTPA) [1, 5]
- Overall simulation

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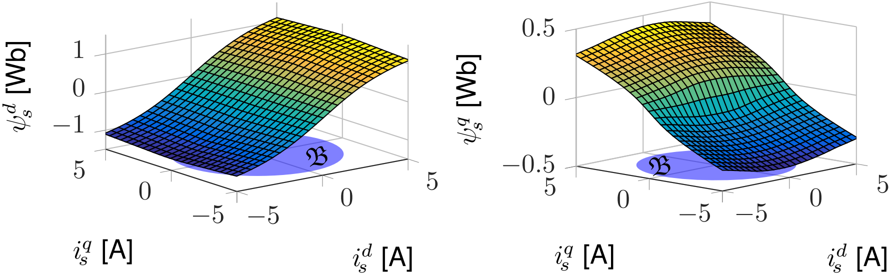
Nonlinear PI current control of RSM

Generic model with nonlinear flux linkage (without iron losses)

$$\boldsymbol{u}_s^k(t) = R_s \boldsymbol{i}_s^k(t) + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big) + \omega_k(t) \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{=:\boldsymbol{J}} \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big),$$

$$m_m(t) = \frac{3}{2} p\, \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)^\top \boldsymbol{J} \boldsymbol{i}_s^k(t)$$

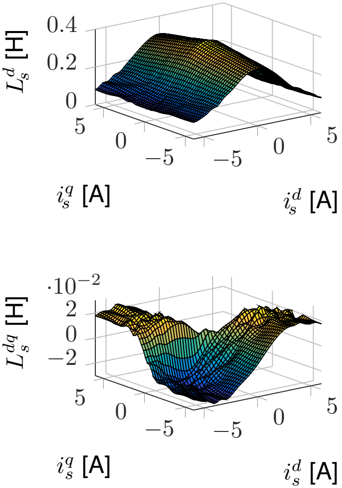


(a) d-*flux linkage* (b) q-*flux linkage*

⇒ **Nonlinear dynamical system!**

Nonlinear PI current control of RSM

Nonlinear inductances $L_s^d := \frac{\partial \psi_s^d}{\partial i_s^d}$, $L_s^q := \frac{\partial \psi_s^q}{\partial i_s^q}$, $L_s^{dq} := \frac{\partial \psi_s^d}{\partial i_s^q} = \frac{\partial \psi_s^q}{\partial i_s^d} =: L_s^{qd}$



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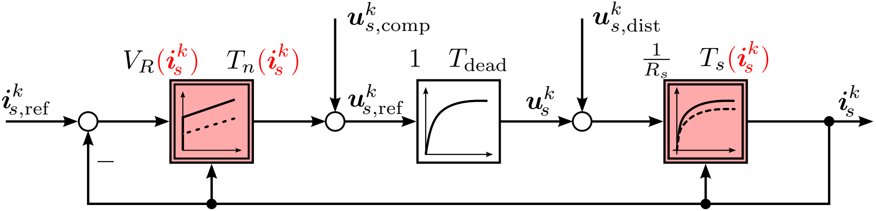
Nonlinear PI current control of RSM

Control loop (with inverter approximation) and PI controller design



where for the nonlinear case we have [1, 5]

- $T_s = T_s(L_s^{dd}(\boldsymbol{i}_s^k), L_s^{dq}(\boldsymbol{i}_s^k), L_s^{qd}(\boldsymbol{i}_s^k), L_s^{qq}(\boldsymbol{i}_s^k))$
- $T_{\mathrm{dead}} \propto f_{\mathrm{pwm}}$.
- $\boldsymbol{u}_{s,\mathrm{comp}}^k = \boldsymbol{u}_{s,\mathrm{dist}}^k$ (ideal decoupling)
- Controller design according to **Magnitude Optimum** [6]:

Gain: $V_R(\boldsymbol{i}_s^k) = \dfrac{T_s(\boldsymbol{i}_s^k) R_s}{2T_{\mathrm{dead}}}$ $[\Omega]$ $\wedge$ Time constant: $T_n(\boldsymbol{i}_s^k) = T_s(\boldsymbol{i}_s^k)$ $[\mathrm{s}]$

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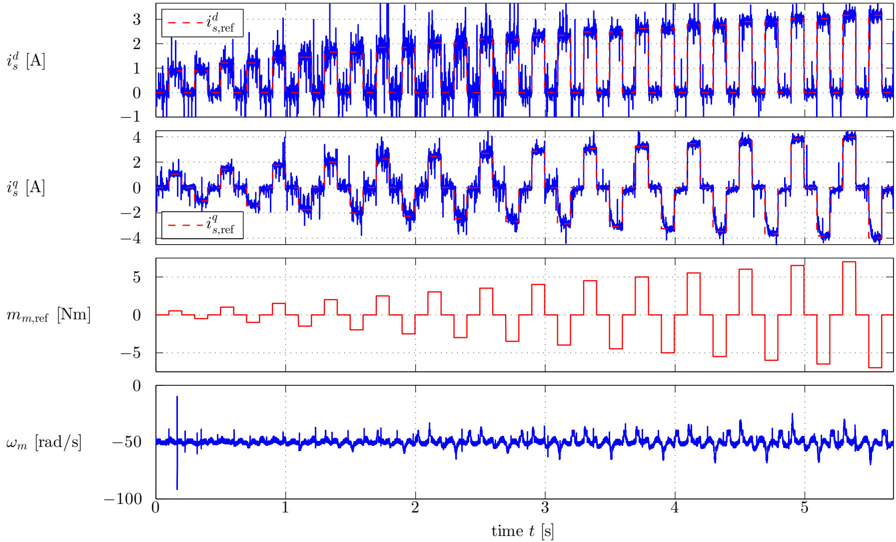
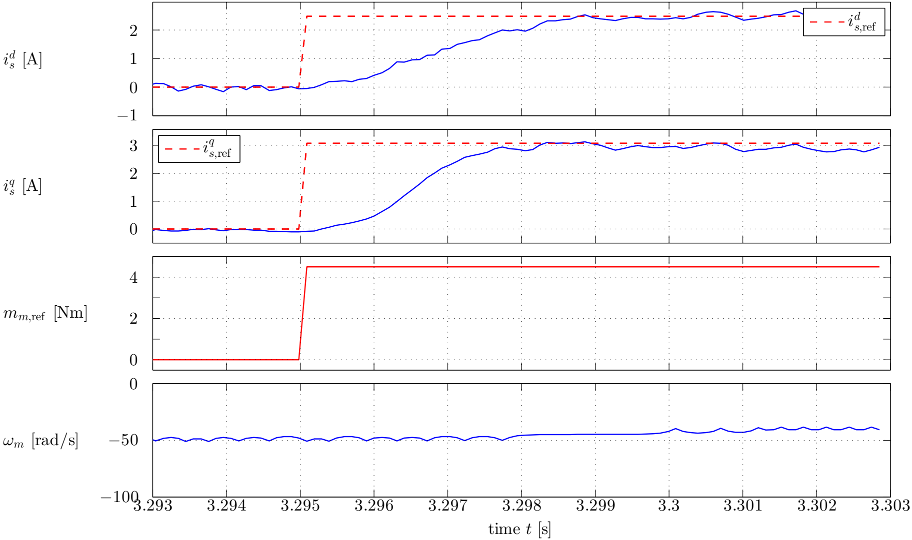
Nonlinear PI current control of RSM

Measurement results for 1,1 kW RSM



Nonlinear PI current control of RSM

Measurement results for 1,1 kW RSM (Zoom)



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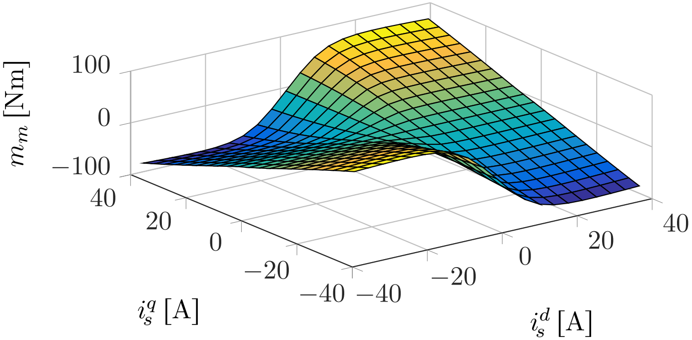
Maximum Torque per Ampere (MTPA)

Nonlinear machine torque

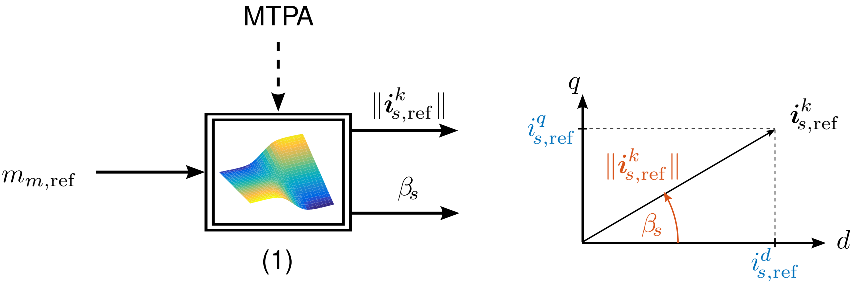


$$m_m(t) = \frac{3}{2}\, p\, \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)^\top \boldsymbol{J}\,\boldsymbol{i}_s^k(t) = \frac{3}{2}\, p \left(\psi_s^d(\boldsymbol{i}_s^k(t))\, i_s^q(t) - \psi_s^q(\boldsymbol{i}_s^k(t))\, i_s^d(t) \right) \tag{1}$$

Maximum Torque per Ampere (MTPA)

Torque (feedforward) control: Block diagram

- Goal: Current reference generation $m_{m,\mathrm{ref}} \to \boldsymbol{i}^k_{s,\mathrm{ref}}$
- Constraint: High efficiency
  $\Longrightarrow$ minimize copper losses $\frac{3}{2} R_s \|\boldsymbol{i}^k_s\|^2 = \frac{3}{2} R_s \big[(i^d_s)^2 + (i^q_s)^2\big]$
- Strategy: *Maximum Torque per Ampere* (MTPA; numerical solution)



(a) *Torque feedforward control* (b) *Current vector*

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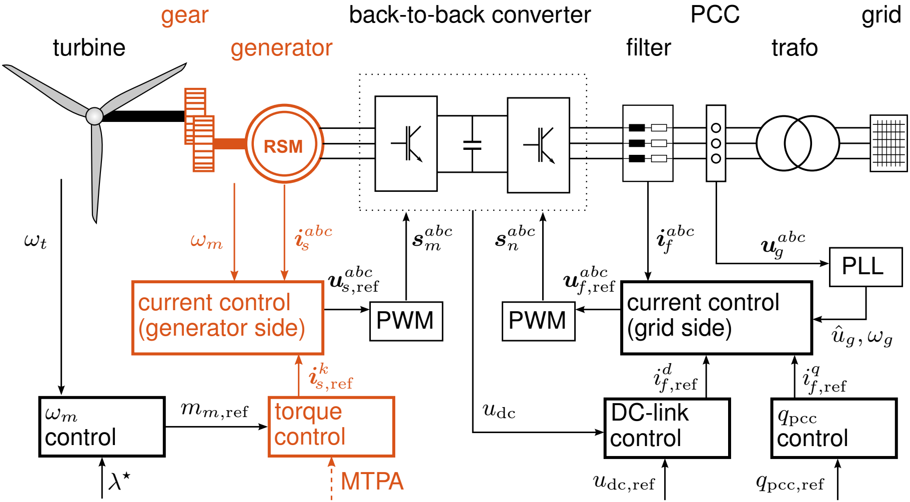
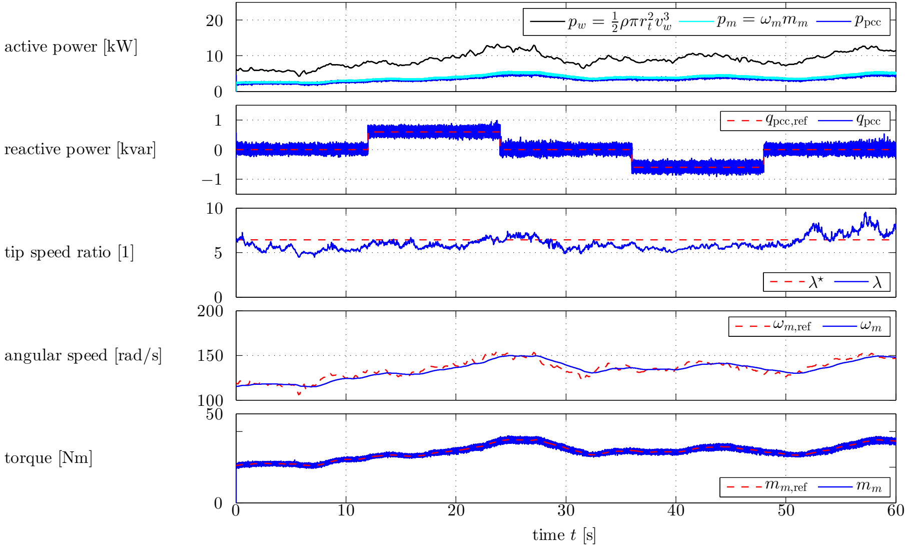
Overall simulation

Small-scale wind turbine system with reluctance synchronous machine (region II)



Overall simulation

Simulation results for overall small-scale wind turbine system (region II)



Outline

3 Next steps

Next steps

Next project phases of Bund der Freunde der TUM e.V. Project

Start → Phase 1 ↔ Phase 2 → Phase 3 → ?

Phase 1

- Modeling [1, 7] ✓
- Exchange ✓ CRES → EMLab
- Control [1, 5, 8] ✓
- Simulation [1, 7] ✓
- HiL system
  - Specification ✓
  - Construction
  - Measurements [5] (✓)
  - Validation (control, efficiency, optimization)

Phase 2

- Machine re-design (FEM)
- Exchange EMLab → CRES
- Iteration(s)
  - Modeling
  - Controller design
  - Simulation

Phase 3

- Research proposal
- Prototype
- Long-term tests (Stellenbosch / CleanTechCampus)

References I

[1] J. Kullick, “Simulation and control of a small-scale wind turbine system with reluctance synchronous generator,” Master’s thesis, Technische Universität München, MSE Research Group "Control of renewable energy systems", 2015.

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[8] C. M. Hackl, “Current PI-funnel control with anti-windup for synchronous machines,” in *submitted to 54th IEEE Conference on Decision and Control*, 2015.