# Nonlinear methods for renewable energy systems

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May 13$^{\mathrm{th}}$, 2016

ENER16 — Simposio Energías Renovables
Curicó, Chile

# Outline

# Outline

1 Introduction

- Technical University of Munich (TUM)
  - Students and staff
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- Munich School of Engineering (MSE)
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- MSE Research group “Control of Renewable Energy Systems (CRES)”
  - Team
  - Research

# Technical University of Munich (TUM)

## Students and staff

**Students & Programs**

| | |
|---|---|
| **Students** | **35.979** |
| men | 24.078 |
| women | 11.901 |
| **International students** | **7.203** |
| 1. China | 1.057 |
| 2. Austria | 585 |
| 3. Italy | 421 |
| 4. India | 415 |
| 5. Turkey | 405 |
| **Programs** | **154** |
| *among these* | |
| Bachelor | 42 |
| Master | 95 |
| English-language master and PhD | 23 |
| **Programs at TUM Asia in Singapore** | **5** |
| **Newly enrolled students** | **11.673** |
| **Graduates** | **7.113** |

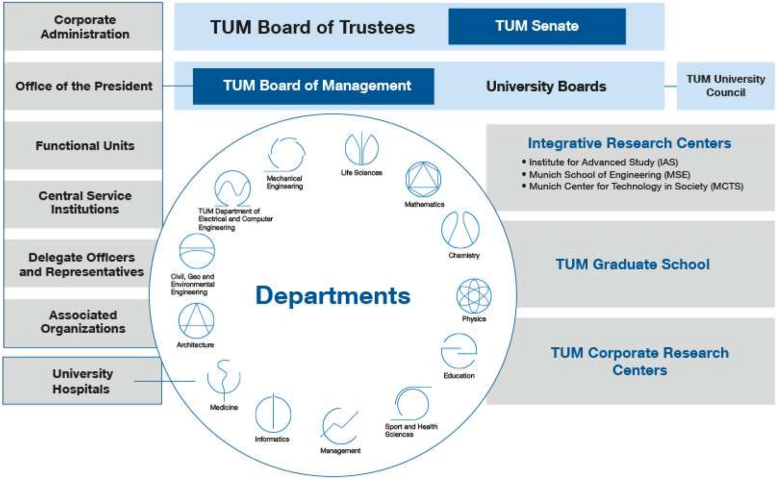
Data as of Dec. 1, 2013

**TUM Members**

| | |
|---|---|
| **Professors** (including university hospital) | **501** |
| Proportion of women | 16 % |
| **New appointments 2013** | **29** |
| **Other teaching staff** (including university hospital) | **6.168** |
| Proportion of women | 33 % |
| **Non-teaching staff** (not-including university hospital) | **3.232** |
| Proportion of women | 58 % |

# Technical University of Munich (TUM)

## Organigram



# Munich School of Engineering (MSE)

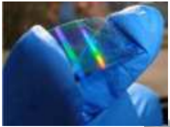
## Recent research foci

CPG Center for Power Generation

- flexible power plant technologies
- synthetic energy carriers
- technologies for energy storage
- energy studies and concepts
- solarthermal power plants

NRG Network for Renewable Energy

- carbon neutral energy generation
- novel energy materials
- conversion of raw materials to energy sources
- local energy storage



TUM.Energy

- interdisciplinary development of electric vehicles
- investigation of mobility behavior
- development of new mobility concept

Science Center for Electromobility

- sustainable urban development
- sustainable buildings
- energy optimized building envelopes
- energy efficient building technology

ENPB **Center for Sustainable Building**

# Group “Control of renewable energy systems (CRES)”

## Team


H. Eldeeb, M.Sc.
(CRES,09/2015)


C. Dirscherl, M.Sc.
(CRES,01/2014)


C. Hackl, Dr.-Ing.
(CRES,01/2014)


J. Kullick, M.Sc.
(CRES,10/2015)


K. Schechner, M.Sc.
(CRES,01/2014)


Z. Zhang, M.Sc.
(CRES/EAL,07/2015)

## External PhD candidates


S. Krüner, M.Sc.
(SINNPower,11/2015)


A. Birda, M.Sc.
(BMW,04/2016)

## . . . and collaborations with EAL (Prof. Kennel)


F. Bauer, M.Sc.
(EAL)


M. Abdelrahem,
M.Sc. (EAL)


A. Ayad,
M.Sc. (EAL)

# Group “Control of renewable energy systems (CRES)”

## Research projects

**Classical wind turbine systems**

Focus: Efficiency and reliability

**Airborne wind energy systems**

Focus: Fault-tolerant control

**Small-scale wind turbines**

Focus: Use of RSMs ($\leqslant$ 50 kW)

**Wave converters (SINN Power)**

Focus: Efficiency and reliability

**Geothermal power systems**

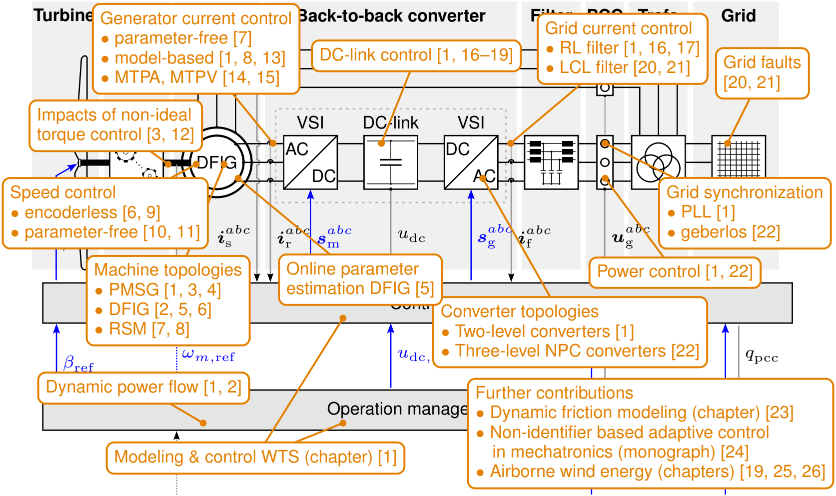
Focus: Fault-tolerant control

**Electric vehicles (BMW)**

Focus: Optimal control

# Group “Control of renewable energy systems (CRES)”

Point of view and publications: **Electrical** components of e.g. large-scale wind turbine systems



# Outline

2 Small-scale wind turbine systems with reluctance synchronous machines

- Motivation
- Preparatory work
- Generic model of RSM
- Current PI-funnel control with anti-windup for RSMs (model-free [7])
  - PI-funnel control with anti-windup
  - Implementation and results
- Nonlinear PI current control of RSMs (model-based [8, 13, 14])
  - Nonlinear PI controller design
  - Measurement results
- Maximum torque per Ampere (MTPA)
- Overall simulation

# Motivation

International cooperation with the University of Stellenbosch (Prof. M. Kamper), South Africa

# Motivation

## Reluctance synchronous machine (RSM): A viable alternative?


http://www.abb.com

**advantages [27–29]**:

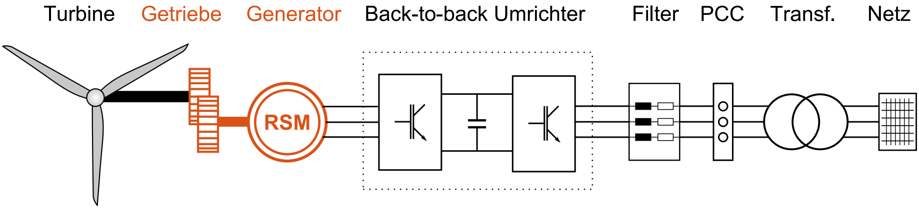
- (very) cheap
- high efficiency feasible (IE4)
- high power density and torque-per-volume ratio
- sensorless control feasible

**disadvantages:**

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

# Preparatory work

## Modeling, control and simulation of small-scale wind turbine system with RSM [14]

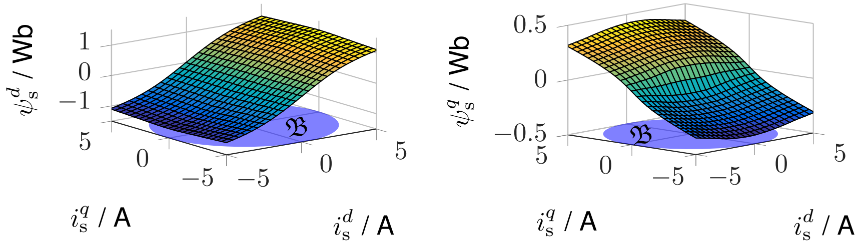



- current control (generator-side)
- maximum torque per Ampere (MTPA)
- speed control (maximum power point tracking (MPPT))
- current control (grid-side)
- DC-link voltage control
- reactive power (feedforward) control

# Generic model of RSM

Reluctance synchronous machine with nonlinear flux linkage (without iron losses)

$$\left.\begin{aligned} \boldsymbol{u}_{\mathrm{s}}^k(t) &= R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{s}}^k(t) + \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^k\big(\boldsymbol{i}_{\mathrm{s}}^k(t)\big) + \omega_k(t)\underbrace{\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}}_{=:\boldsymbol{J}}\boldsymbol{\psi}_{\mathrm{s}}^k\big(\boldsymbol{i}_{\mathrm{s}}^k(t)\big), \\ m_m(t) &= \tfrac{3}{2}p\,\boldsymbol{i}_{\mathrm{s}}^k(t)^\top \boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^k\big(\boldsymbol{i}_{\mathrm{s}}^k(t)\big) \end{aligned}\right\} \tag{1}$$

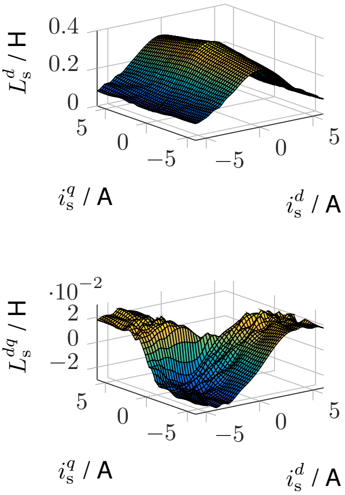



(a) $d$-flux linkage (1kW RSM) (b) $q$-flux linkage (1kW RSM)

**⇒ Nonlinear dynamical system!**

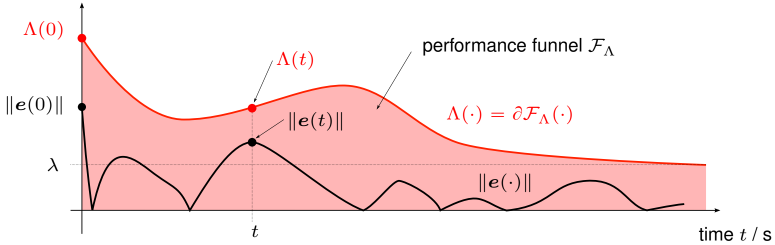
# Generic model of RSM

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



# Current PI-funnel control with anti-windup for RSMs

Tracking with prescribed transient accuracy (model-free: **no** system parameters required!)




Controller (applicable if feasibility condition $\hat{u} \geqslant \hat{u}_{\text{feas}}$ holds, see [7, Th. IV.2]):

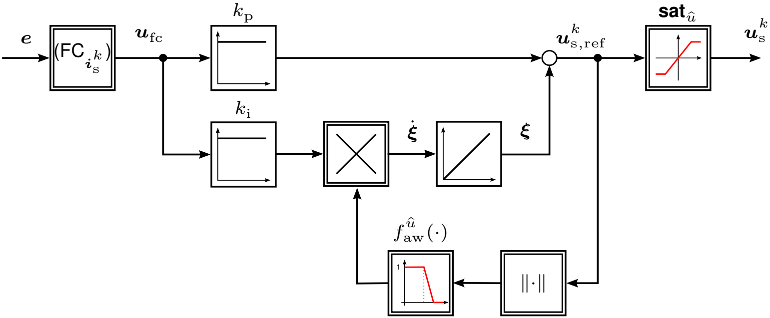
$$\boxed{\boldsymbol{u}_{\text{fc}}(t) = \kappa(t)\boldsymbol{e}(t)} \quad \Longrightarrow \quad \boxed{\|\boldsymbol{e}(t)\| < \Lambda(t)} \qquad (\text{FC}_{\boldsymbol{i}_s^k})$$

where

- $\boldsymbol{e}(t) = (e_s^d(t),\, e_s^q(t))^\top = \boldsymbol{i}_{\text{s,ref}}^k(t) - \boldsymbol{i}_{\text{s}}^k(t)$
- $\kappa(t) = \dfrac{1}{\Lambda(t) - \|\boldsymbol{e}(t)\|} \geqslant \dfrac{1}{\Lambda(t)}$ and $\|\boldsymbol{e}(t)\| = \sqrt{e_s^d(t)^2 + e_s^q(t)^2}$

# Current PI-funnel control with anti-windup for RSMs

## PI-funnel control with anti-windup



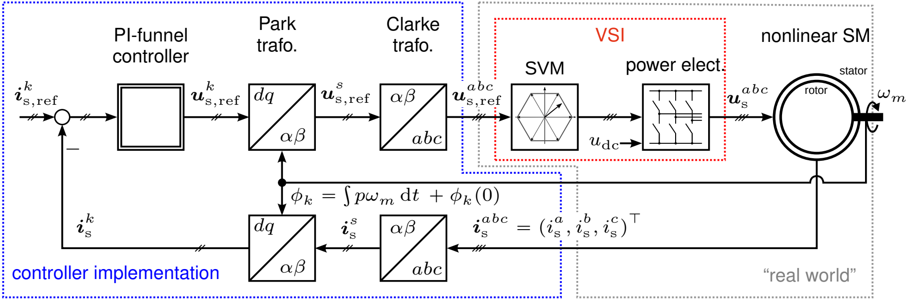

$$\left.\begin{aligned} \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\xi}(t) &= k_i\, f_{aw}^{\hat{u}}\Big(\boldsymbol{\xi}(t) + k_p\,\boldsymbol{u}_{fc}(t)\Big)\,\boldsymbol{u}_{fc}(t), \qquad && \boldsymbol{\xi}(0) = \boldsymbol{\xi}^0 \in \mathbb{R}^n \\ \boldsymbol{u}_{s,ref}^k(t) &= \boldsymbol{\xi}(t) + k_p\,\boldsymbol{u}_{fc}(t), && \text{where } k_p > 0, k_i \geqslant 0. \end{aligned}\right\} \quad (\mathrm{PI}^{\mathrm{aw}})$$

$\Longrightarrow$ $\xi(\cdot)$ acts as bounded input disturbance (see [7, Lem. III.1])

$\Longrightarrow$ PI-like extension for steady state accuracy

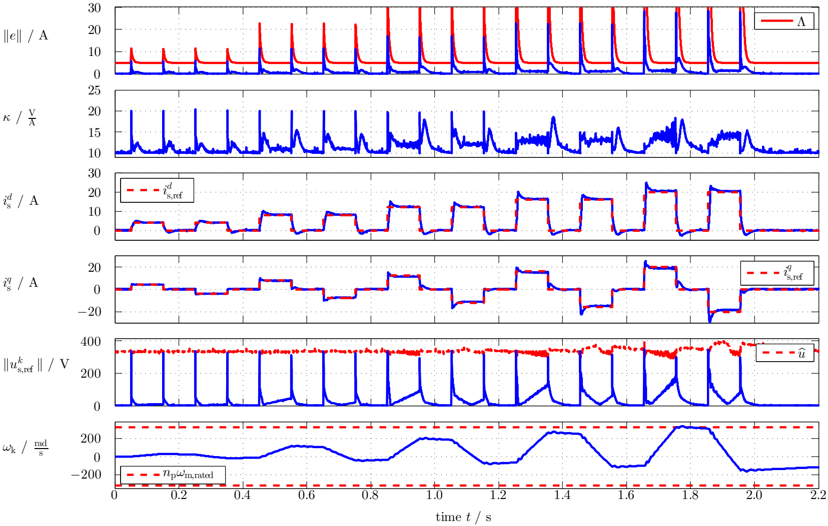
# Current PI-funnel control with anti-windup for RSMs

## Control-loop and implementation (9.6kW RSM)



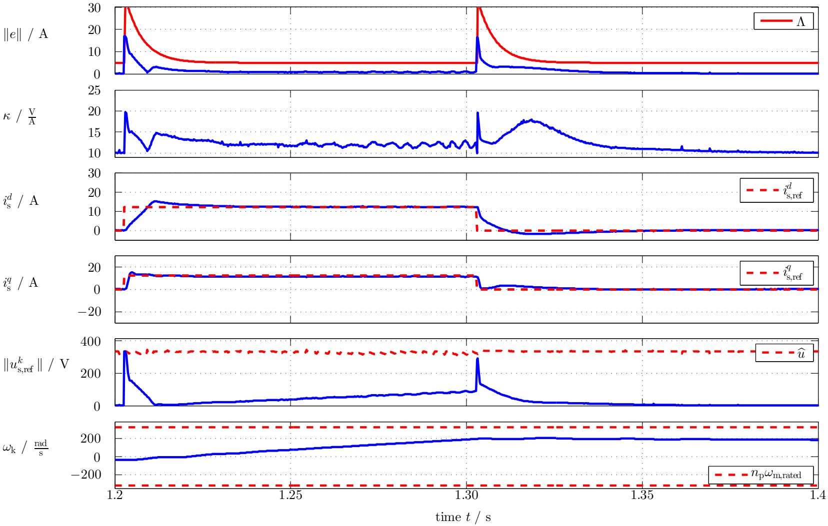
# Current PI-funnel control with anti-windup for RSMs

## Measurement results for 9,6 kW RSM



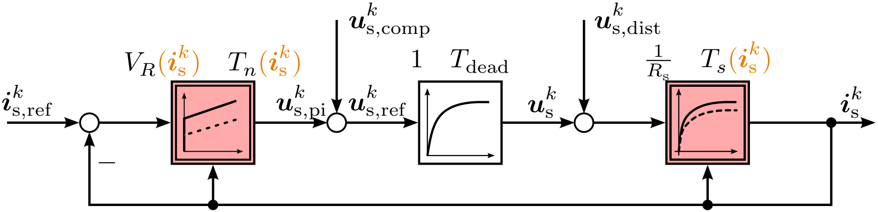
# Current PI-funnel control with anti-windup for RSMs

## Measurement results for 9,6 kW RSM (Zoom)



# Nonlinear PI current control of RSMs (model-based)

## Control loop (with inverter approximation) and PI controller design



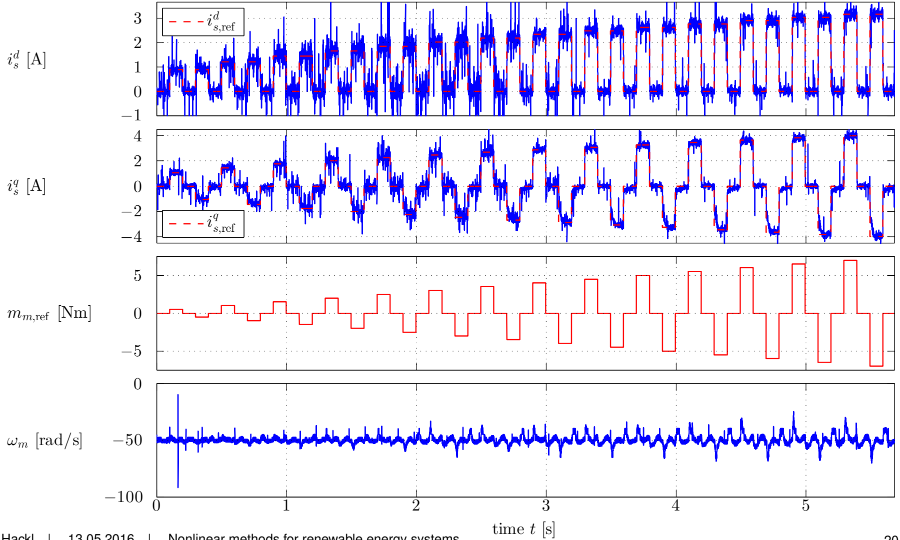

where for the nonlinear case we have [8, 14]

- $T_s = T_s(L_s^{dd}(\boldsymbol{i}_s^k), L_s^{dq}(\boldsymbol{i}_s^k), L_s^{qd}(\boldsymbol{i}_s^k), L_s^{qq}(\boldsymbol{i}_s^k))$
- $T_{dead} \propto f_{pwm}$.
- $\boldsymbol{u}_{s,comp}^k = \boldsymbol{u}_{s,dist}^k$ (ideal decoupling)
- Controller design according to **Magnitude Optimum** [30]:

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

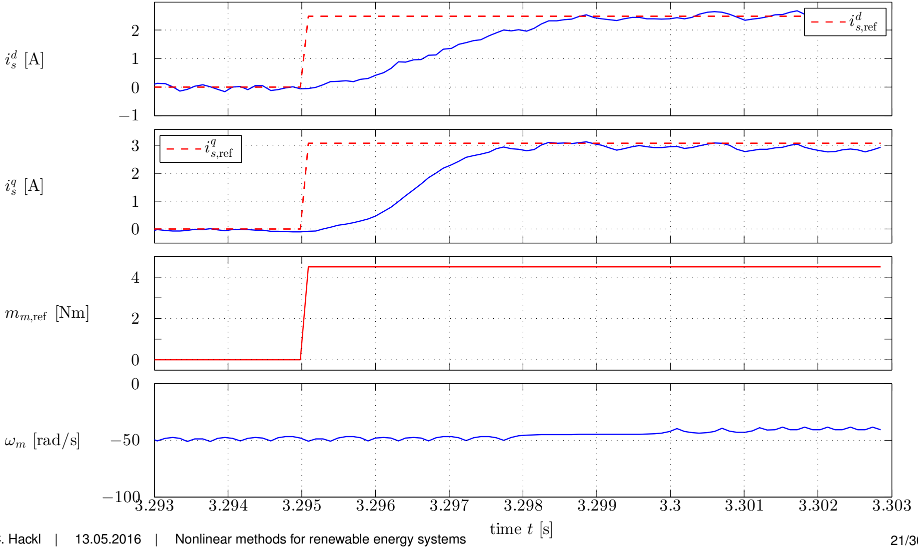
# Nonlinear PI current control of RSMs

## Measurement results for 1,1 kW RSM



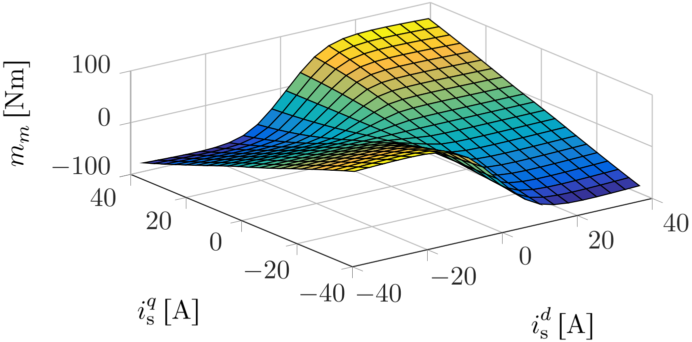
# Nonlinear PI current control of RSM

## Measurement results for 1,1 kW RSM (Zoom)



# Maximum Torque per Ampere (MTPA)

## Nonlinear machine torque

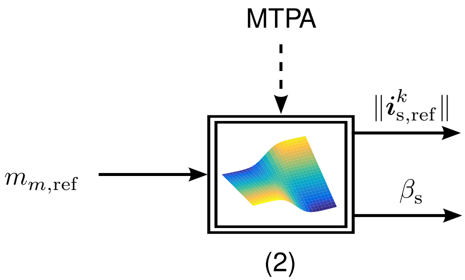



$$m_m(t) = \frac{3}{2}\,p\,\boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)^\top \boldsymbol{J}\,\boldsymbol{i}_s^k(t) = \frac{3}{2}\,p\,\Big(\psi_s^d(\boldsymbol{i}_s^k(t))i_s^q(t) - \psi_s^q(\boldsymbol{i}_s^k(t))i_s^d(t)\Big) \qquad (2)$$

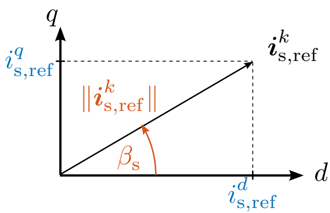
# Maximum Torque per Ampere (MTPA)

## Torque (feedforward) control: Block diagram

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



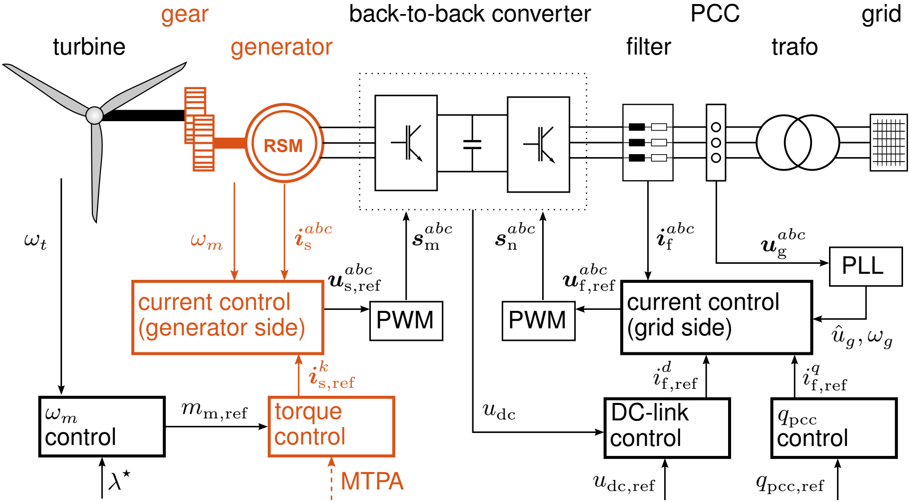

(a) Torque feedforward control




(b) Current vector

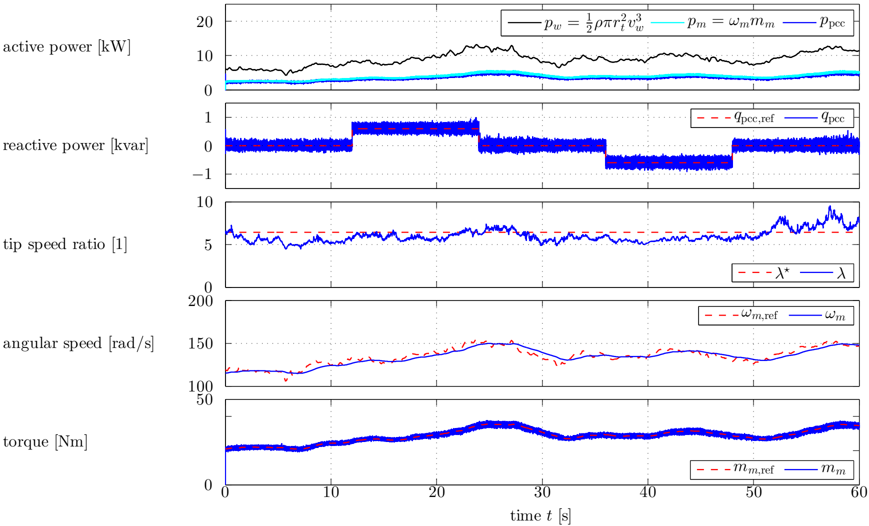
# Overall simulation

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 Conclusion

# Conclusion

**Control** is

- essential (in particular: *nonlinear control* $\Longleftrightarrow$ *state space* analysis)
- improves efficiency
- guarantees optimal operation (e.g. for different wind speeds)
- protects system (combined with operation management)

**Future challenges** for “Renewable Energy Systems” (see also [31])

- Reduction of levelized costs of Energy
  $\Longrightarrow$ “Energiewende” economically feasible?
- Improving reliability and increasing fault tolerance
  (in particular, controls and electrical sub-system are fault-prone)
- Flexible and robust grid connection
- Emerging technologies (e.g. new generator / converter topologies)

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