Modeling and control of renewable energy systems

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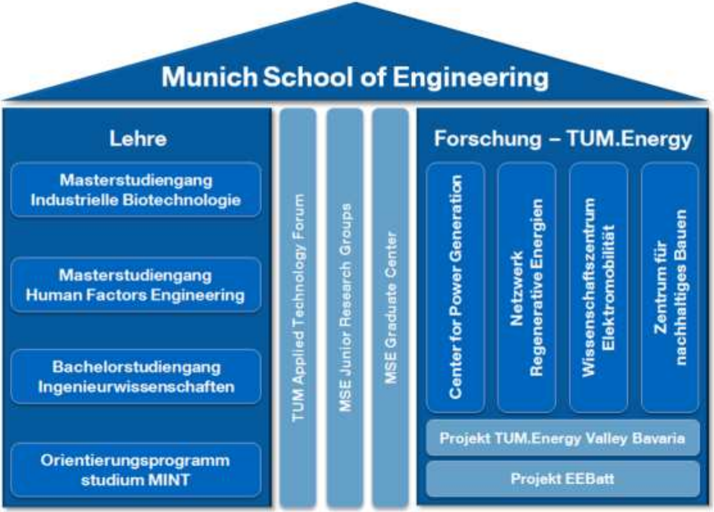
Outline

Outline

Munich School of Engineering (MSE)

Integrative research center



Group “Control of renewable energy systems (CRES)”

Team

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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

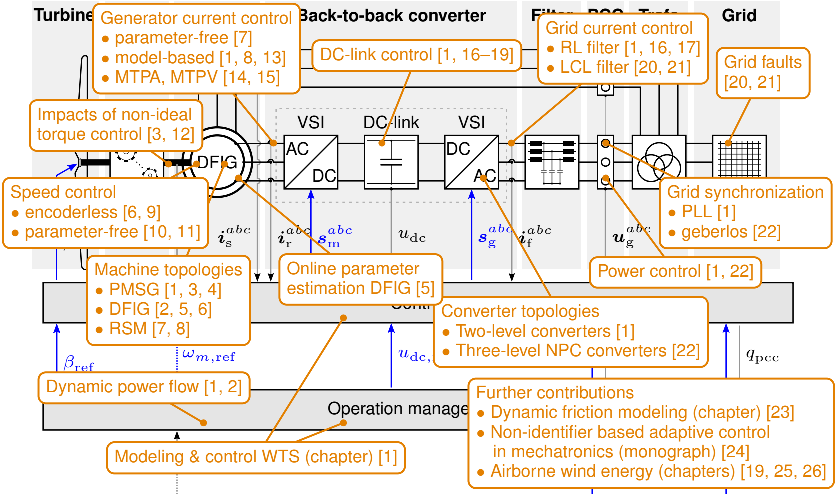
Focus: Fault-tolerant control

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



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Laboratory setup

Reluctance and Permanent-magnet SMs

Electrically-excited SM and doubly-fed IM

Real-time system and VSIs

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]:

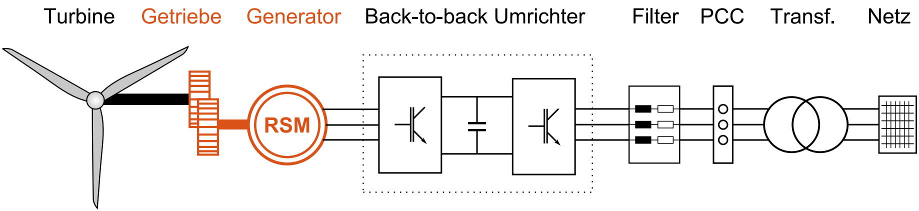
- (very) cheap
- high efficiency feasible (IE4)
- high power density and torque-per-volume ratio
- sensorless control feasible

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]

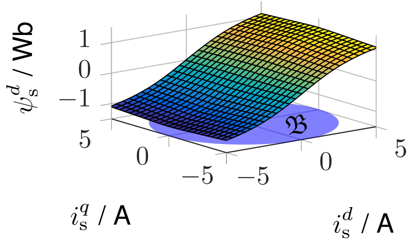


- current control (generator-side)
- maximum torque per Ampere (MTPA)
- speed control (maximum power point tracking (MPPT))
- current control (grid-side)
- DC-link voltage control
- reactive power (feedforward) control

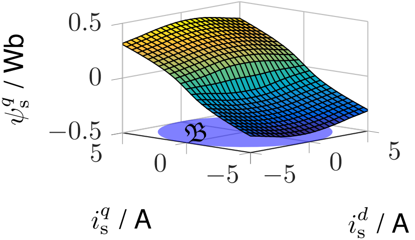
Generic model of RSM

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

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



(a) d-flux linkage (1kW RSM)

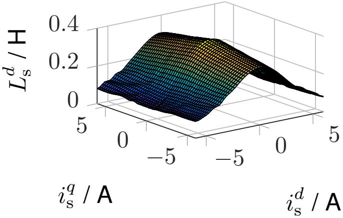


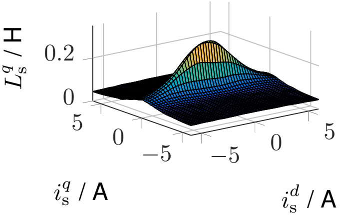
(b) q-flux linkage (1kW RSM)

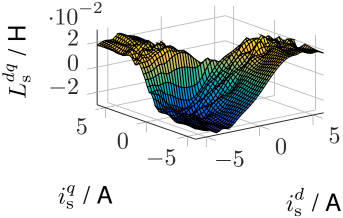
$\Rightarrow$ **Nonlinear dynamical system!**

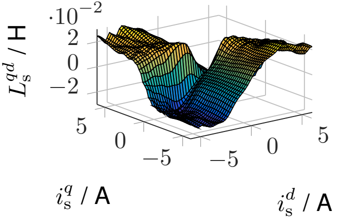
Generic model of RSM

Nonlinear differential inductances $L_\mathrm{s}^d := \frac{\partial \psi_\mathrm{s}^d}{\partial i_\mathrm{s}^d}$, $L_\mathrm{s}^q := \frac{\partial \psi_\mathrm{s}^q}{\partial i_\mathrm{s}^q}$, $L_\mathrm{s}^{dq} := \frac{\partial \psi_\mathrm{s}^d}{\partial i_\mathrm{s}^q} = \frac{\partial \psi_\mathrm{s}^q}{\partial i_\mathrm{s}^d} =: L_\mathrm{s}^{qd}$



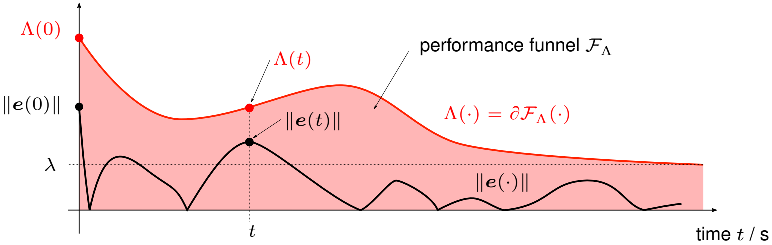






Current PI-funnel control with anti-windup for RSMs

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]):

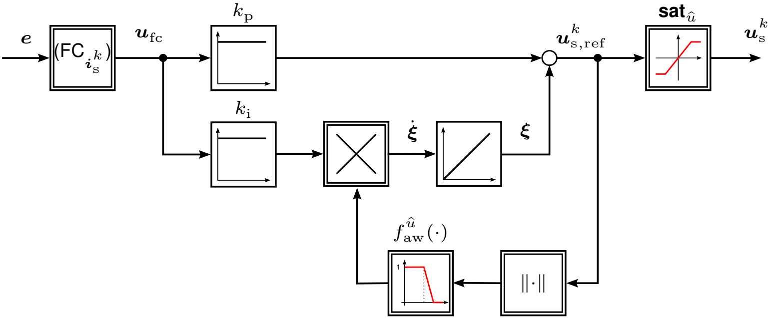
$$\boxed{\boldsymbol{u}_{\text{fc}}(t) = \kappa(t)\boldsymbol{e}(t)} \quad \Longrightarrow \quad \boxed{\|\boldsymbol{e}(t)\| < \Lambda(t)} \qquad (\text{FC}_{\boldsymbol{i}_s^k})$$

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



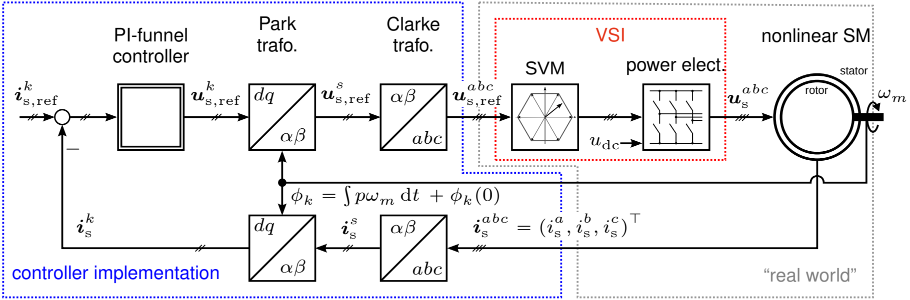
$$\left.\begin{aligned} \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\xi}(t) &= k_i\, f_{aw}^{\hat{u}}\Big(\boldsymbol{\xi}(t) + k_p\, \boldsymbol{u}_{fc}(t)\Big)\, \boldsymbol{u}_{fc}(t), & \boldsymbol{\xi}(0) &= \boldsymbol{\xi}^0 \in \mathbb{R}^n \\ \boldsymbol{u}_{s,ref}^k(t) &= \boldsymbol{\xi}(t)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

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

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

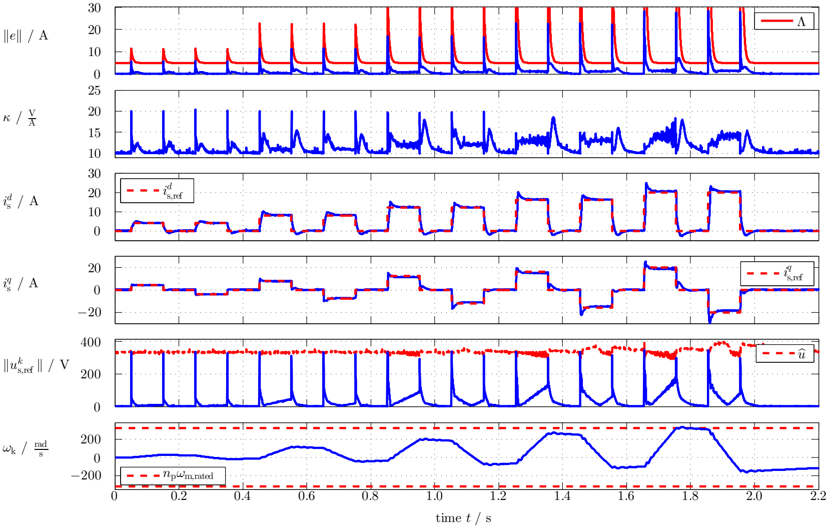
Current PI-funnel control with anti-windup for RSMs

Control-loop and implementation (9.6kW RSM)



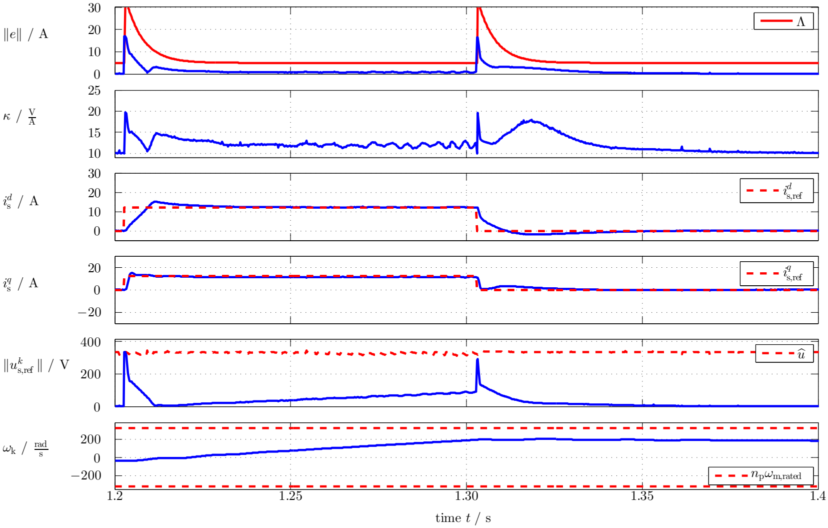
Current PI-funnel control with anti-windup for RSMs

Measurement results for 9,6 kW RSM



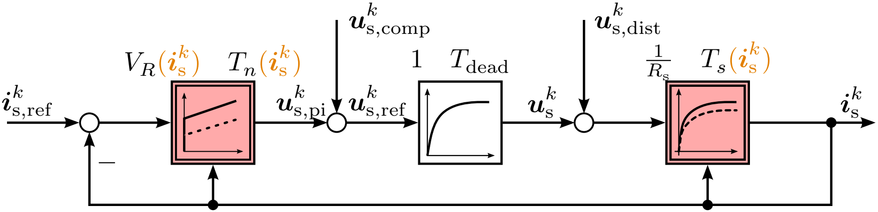
Current PI-funnel control with anti-windup for RSMs

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



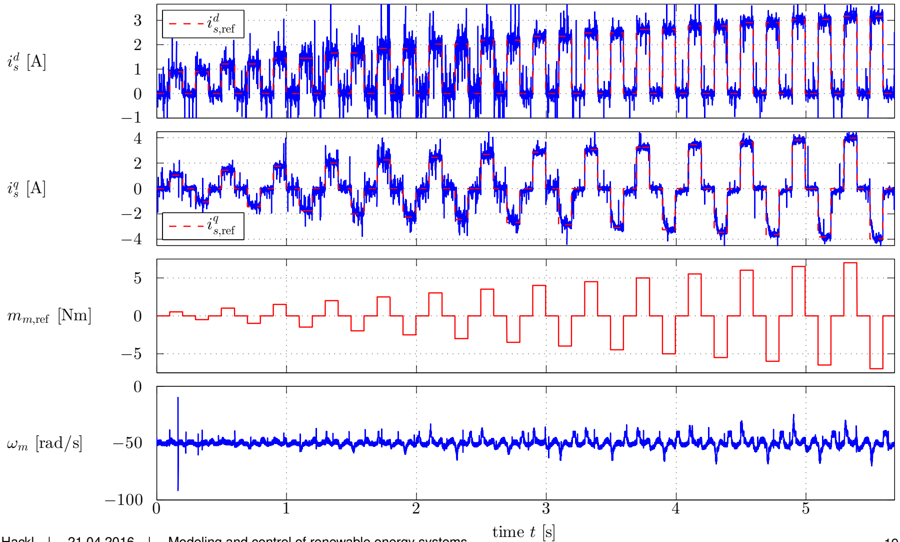
where for the nonlinear case we have [8, 14]

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

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

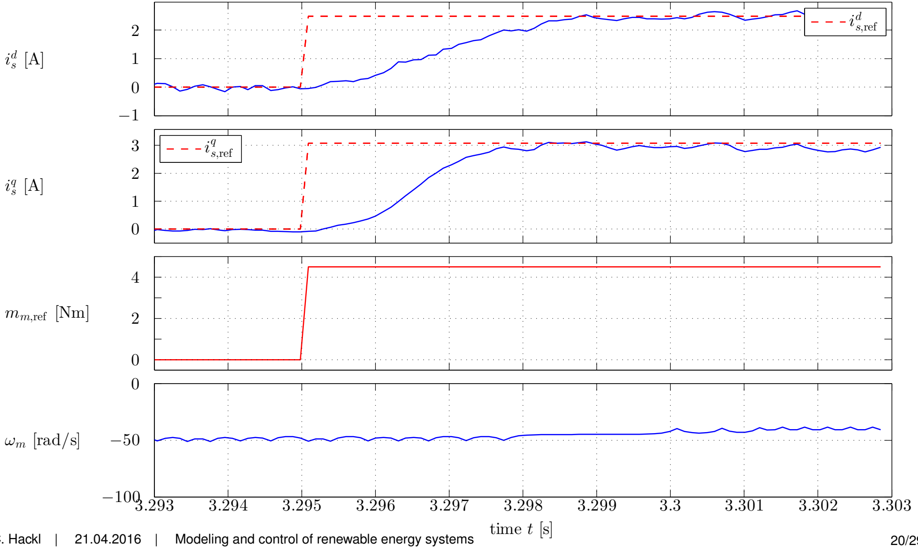
Nonlinear PI current control of RSMs

Measurement results for 1,1 kW RSM



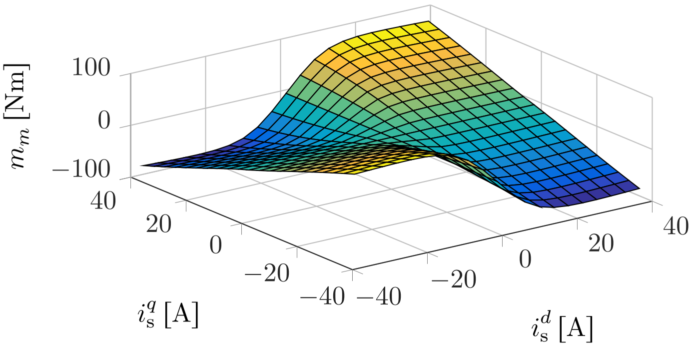
Nonlinear PI current control of RSM

Measurement results for 1,1 kW RSM (Zoom)



Maximum Torque per Ampere (MTPA)

Nonlinear machine torque

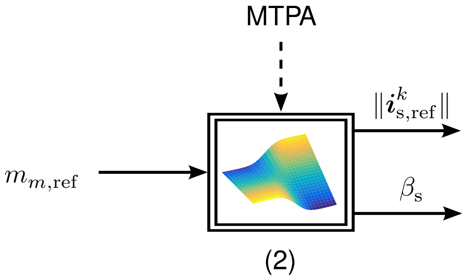


$$m_m(t) = \frac{3}{2}\, p\, \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)^\top \boldsymbol{J}\, \boldsymbol{i}_s^k(t) = \frac{3}{2}\, p \Big(\psi_s^d(\boldsymbol{i}_s^k(t))\, i_s^q(t) - \psi_s^q(\boldsymbol{i}_s^k(t))\, i_s^d(t)\Big) \qquad (2)$$

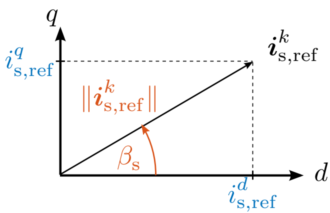
Maximum Torque per Ampere (MTPA)

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 $\frac{3}{2}R_\mathrm{s}\|\boldsymbol{i}^k_\mathrm{s}\|^2 = \frac{3}{2}R_\mathrm{s}\left[(i^d_\mathrm{s})^2 + (i^q_\mathrm{s})^2\right]$
- Strategy: *Maximum Torque per Ampere* (MTPA; numerical solution)



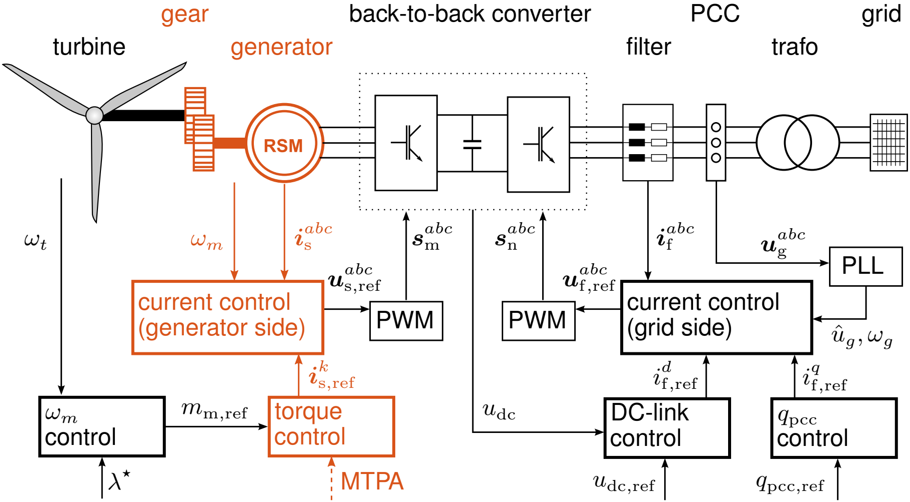
(a) Torque feedforward control



(b) Current vector

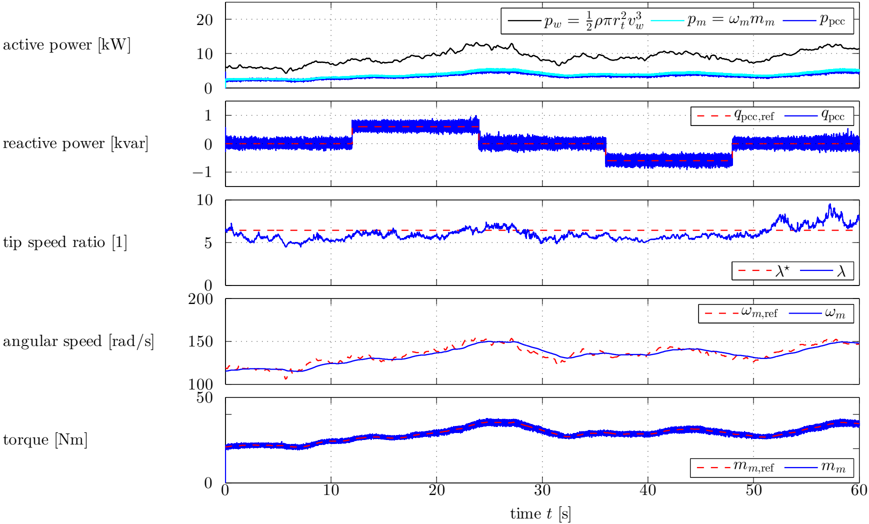
Overall simulation

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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