Nonlinear control and parameter estimation of renewable energy systems

Christoph Hackl

Technische Universität München (TUM)
Munich School of Engineering (MSE)
Research group “Control of Renewable Energy Systems (CRES)”

09.10.2015

DIE University of Chile

Santiago de Chile, Chile

Outline

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  - Team and facts
  - Research foci
  - Interdisciplinarity
  - Point of view: Electrical sub-system(s)
  - Laboratory setups
  - Contributions this far ...

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Technische Universität München (TUM)

Students and staff

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

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 %

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Technische Universität München (TUM)

Main campuses

154 programs - 13 departments - 3 locations

Munich

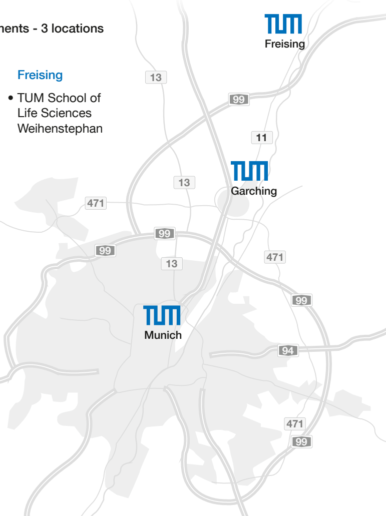
- Architecture
- Civil, Geo and Environ-mental Engineering
- Electrical, Electronic and Computer Engineering
- TUM School of Medicine
- Sport and Health Sciences
- TUM School of Education
- TUM School of Management

Garching

- Chemistry
- Informatics
- Mathematics
- Mechanical Engineering
- Physics

Freising

- TUM School of Life Sciences Weihenstephan



TUM science network

- Max Planck Institutes: Garching Martinsried Munich
- Helmholtz Zentrum München
- iwb Anwenderzentrum Augsburg
- Fraunhofer Institutes: Holzkirchen Freising

TUM locations

- Munich
- Garching
- Freising

- Iffeldorf
- Obernach
- Straubing
- Wettzell

- Singapore: TUM Asia
- Beijing
- Brussels
- Cairo
- Mumbai
- São Paulo

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Munich School of Engineering (MSE)

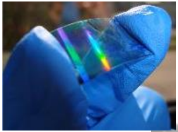
Integrative Research Center: TUM's bundled expertise on "Energy Research"

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

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Control of renewable energy systems (CRES)

Team and facts

- Team

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

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

C. Hackl, Dr.-Ing.
(Head of CRES)

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

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

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

- Group founded January 2014
- Interdisciplinary approach (control theory & renewable energy systems)
- Contact
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  - WWW: `http://www.cres.mse.tum.de`

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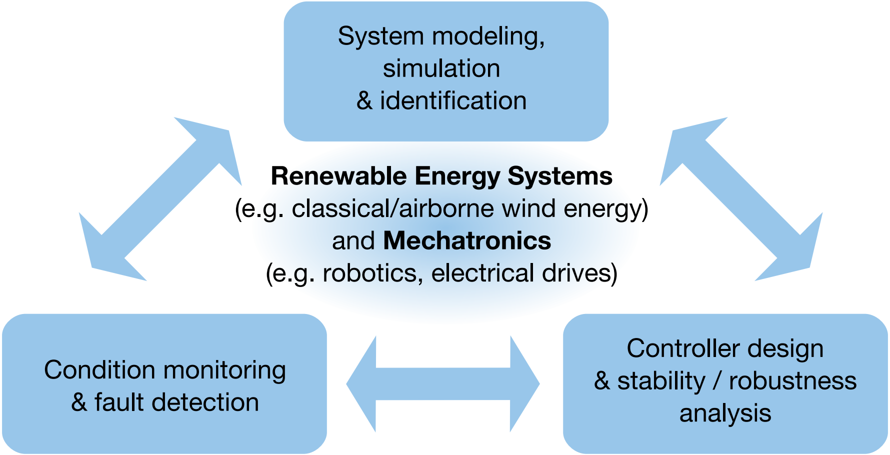
Control of renewable energy systems (CRES)

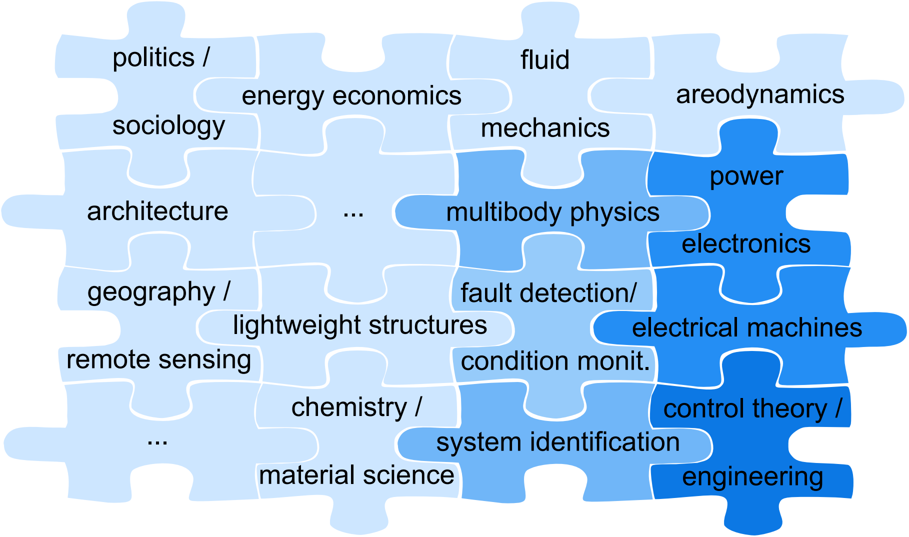
Research foci



Outline

Control of renewable energy systems (CRES)

(Energy-)Research = Interdisciplinarity



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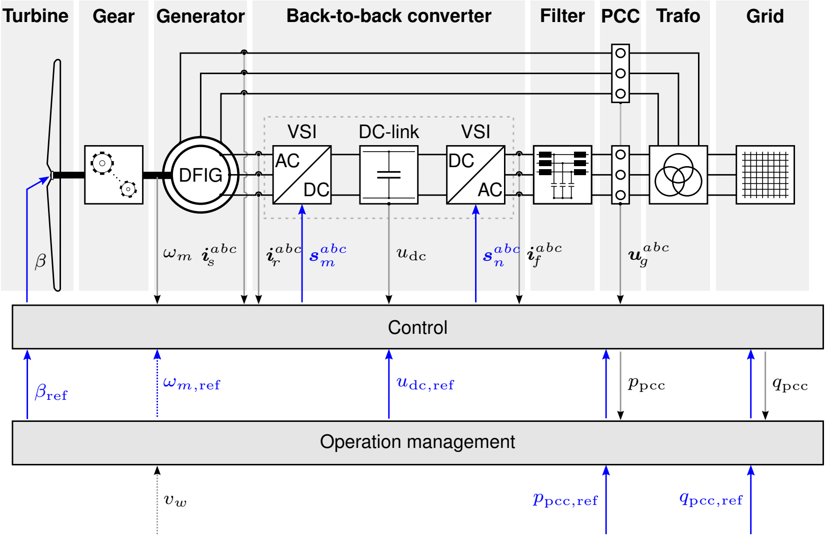
Control of renewable energy systems (CRES)

Point of view: Electrical sub-system(s) of e.g. WTS with DFIG



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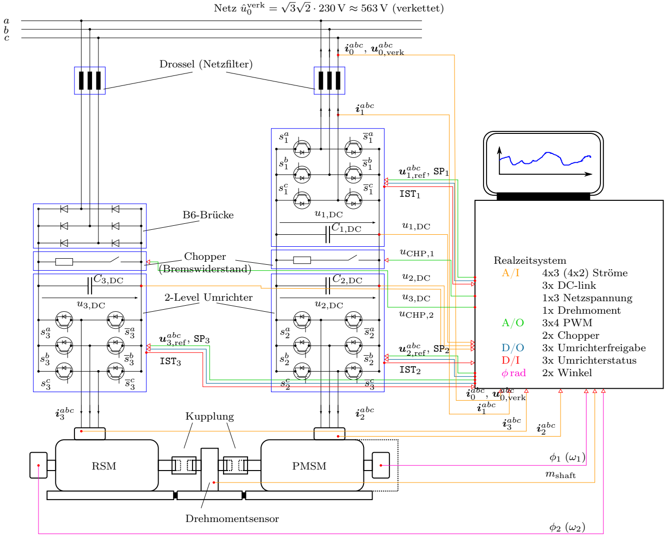
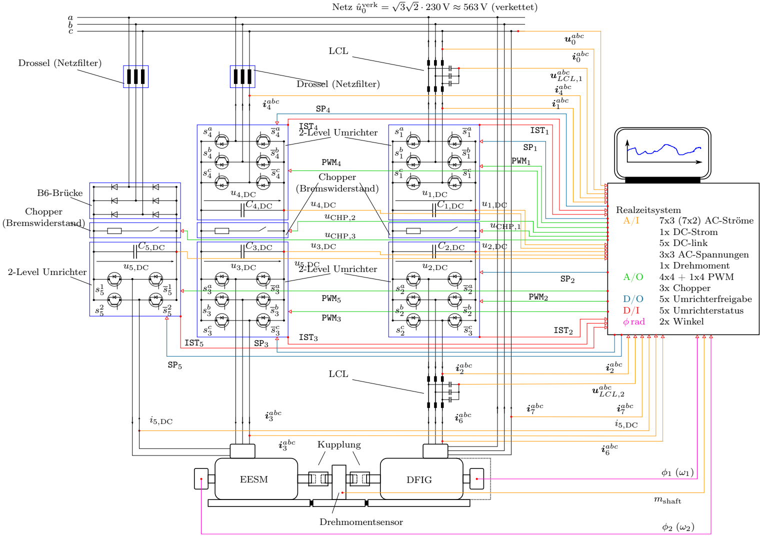
Control of renewable energy systems (CRES)

Lab setup 1: Reluctance synchronous machine and permanent-magnet synchronous machine



Control of renewable energy systems (CRES)

Lab setup 2: Electrically-excited synchronous machine and doubly-fed induction machine



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Control of renewable energy systems (CRES)

Contributions this far ...

Renewable energy systems:

- Chapter on “Modeling and control of modern wind turbine systems” (German): [1]
- Model predictive control of PMSG and grid connection: [2–5], [6][1]
- Sensorless control of PMSG and DFIG: [2, 7]
- Online estimation of DFIG parameters (Extended Kalman Filter): [8]
- State-feedback control with observer for LCL filters: [9]
- Sensorless control of grid connection (Virtual Flux): [10]
- DC-link control: [4, 11], [12]
- Model-free generator speed control of wind turbine systems: rigid [13], elastic [14]
- Model-based *and* model-free current control of RSM: [15] and [16]
- Non-ideal torque control in wind turbine systems: Causes and impacts [17]
- Dynamic power flow in WTS with DFIG [18]

Mechatronics:

- Chapter on dynamic friction modeling (German): [19]
- Model-free position and speed control of electrical drives and robots: [20–27]
- Monograph on non-identifier based adaptive control in mechatronics [28]

[1] submitted/under review/in preparation

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- Motivation
  - International cooperation with the University of Stellenbosch, South Africa
  - RSM: A viable alternative?
  - Preparatory work
- Modeling and control of reluctance synchronous machine [15, 29]
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  - Nonlinear PI controller design
  - Measurement results
  - Maximum torque per Ampere (MTPA) [15, 29]
- Overall simulation

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Small-scale WTS with RSM

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

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Small-scale WTS with RSM

RSM: A viable alternative?

http://www.abb.com

advantages [30–32]:

- (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)

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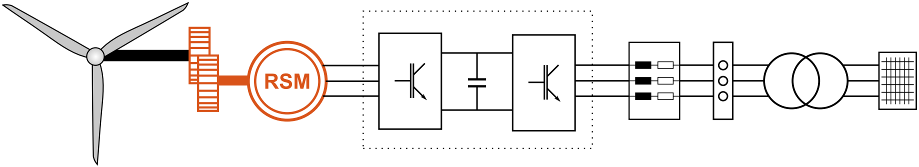
Small-scale WTS with RSM

Preparatory work: Modeling, control and simulation of small-scale WTS with RSM [29]



- 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

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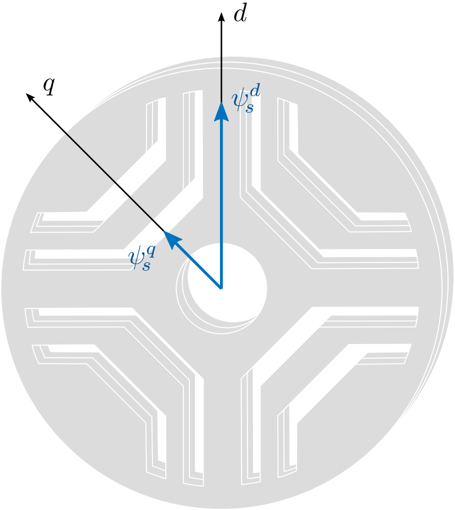
Nonlinear PI current control of RSM

Flux linkage in the rotor of the RSM

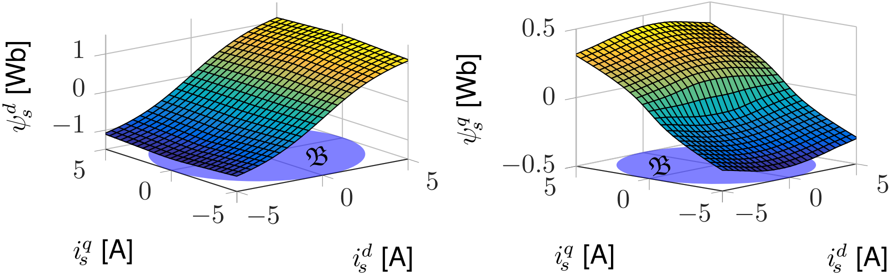


Nonlinear PI current control of RSM

Generic model with nonlinear flux linkage (without iron losses)

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

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

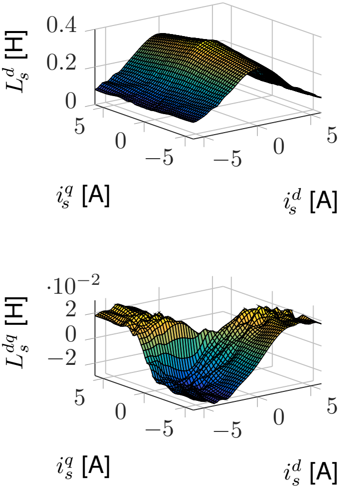


(a) d-flux linkage (b) q-flux linkage

⇒ **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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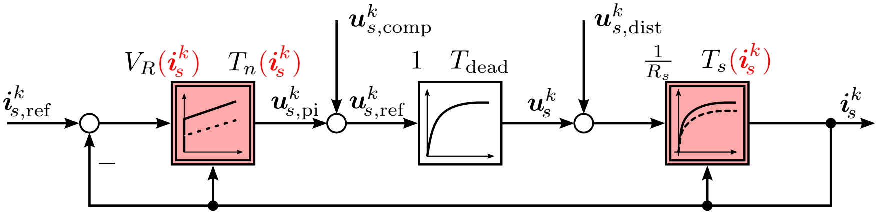
Nonlinear PI current control of RSM

Control loop (with inverter approximation) and PI controller design



where for the nonlinear case we have [15, 29]

- $T_s = T_s(L_s^{dd}(\boldsymbol{i}^k_s), L_s^{dq}(\boldsymbol{i}^k_s), L_s^{qd}(\boldsymbol{i}^k_s), L_s^{qq}(\boldsymbol{i}^k_s))$
- $T_{\mathrm{dead}} \propto f_{\mathrm{pwm}}$.
- $\boldsymbol{u}^k_{s,\mathrm{comp}} = \boldsymbol{u}^k_{s,\mathrm{dist}}$ (ideal decoupling)
- Controller design according to **Magnitude Optimum** [33]:

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

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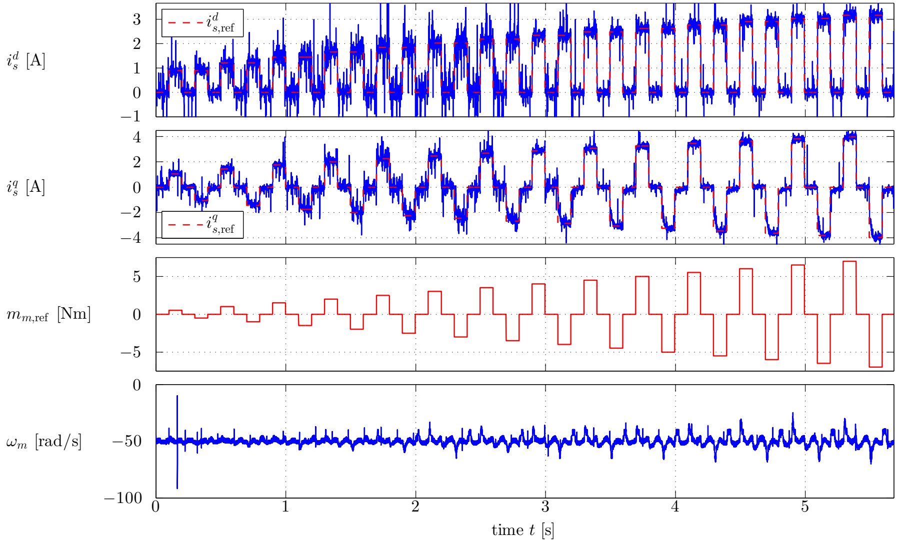
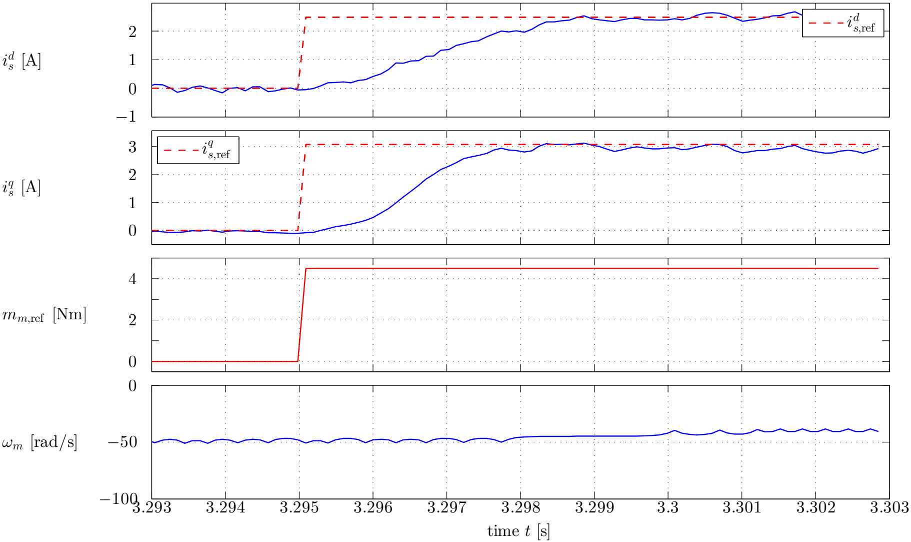
Nonlinear PI current control of RSM

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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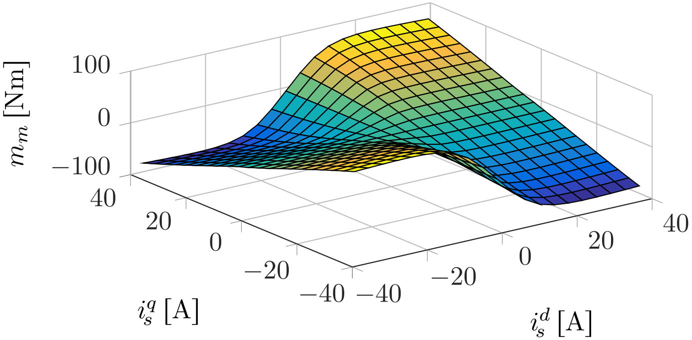
Maximum Torque per Ampere (MTPA)

Nonlinear machine torque

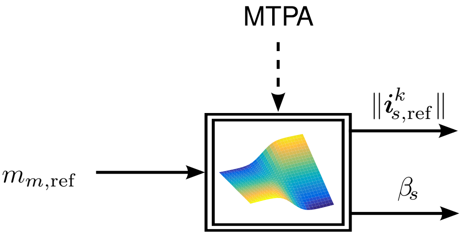


$$m_m(t) = \frac{3}{2}\, p\, \boldsymbol{\psi}_s^k\big(\boldsymbol{i}_s^k(t)\big)^\top \boldsymbol{J}\, \boldsymbol{i}_s^k(t) = \frac{3}{2}\, p\left(\psi_s^d(\boldsymbol{i}_s^k(t))\, i_s^q(t) - \psi_s^q(\boldsymbol{i}_s^k(t))\, i_s^d(t)\right) \qquad (1)$$

Maximum Torque per Ampere (MTPA)

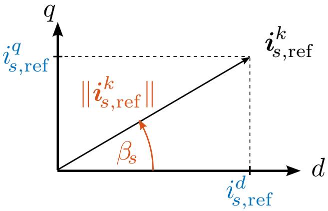
Torque (feedforward) control: Block diagram

- 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)



(1)

(a) Torque feedforward control



(b) Current vector

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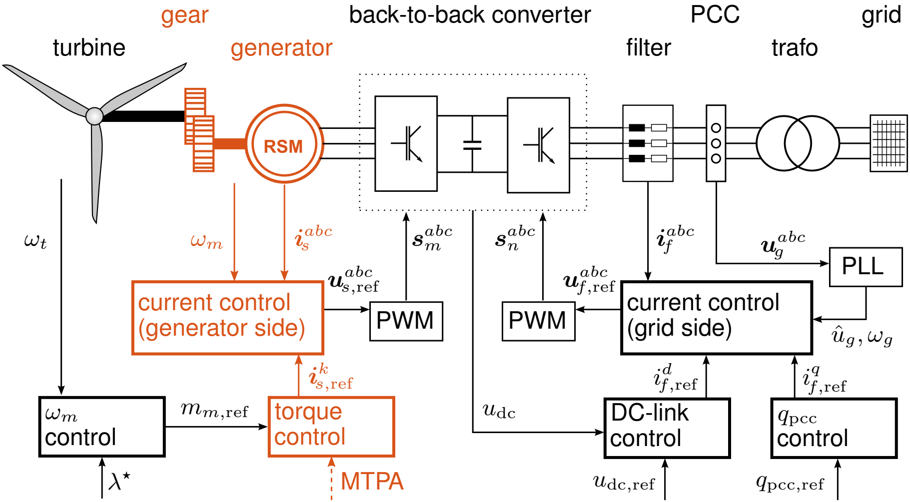
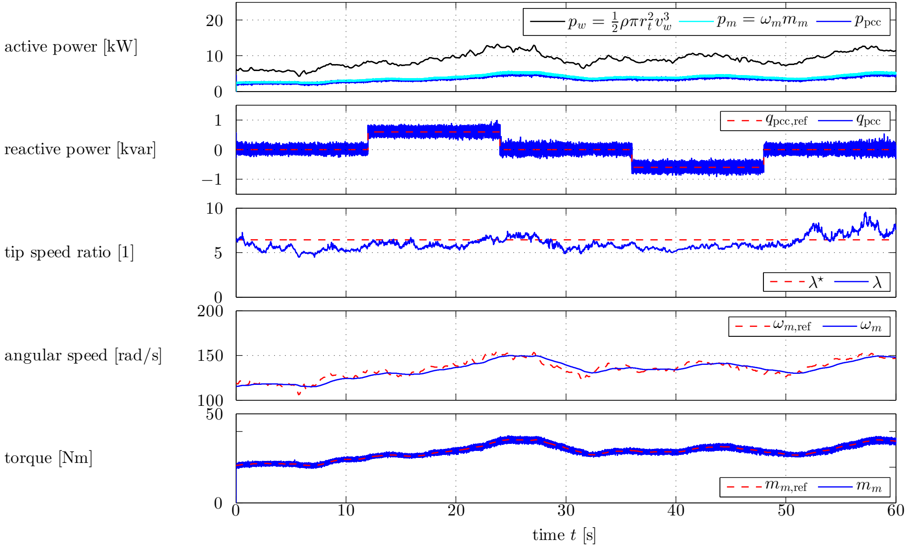
Overall simulation

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 WTS with DFIG

- Overview and modeling depth
- Dynamic power flow [18]
- Control of WTS with DFIG
- Online estimation of DFIG parameters [8]
  - Extended nonlinear model of DFIG
  - Implementation
  - Algorithm
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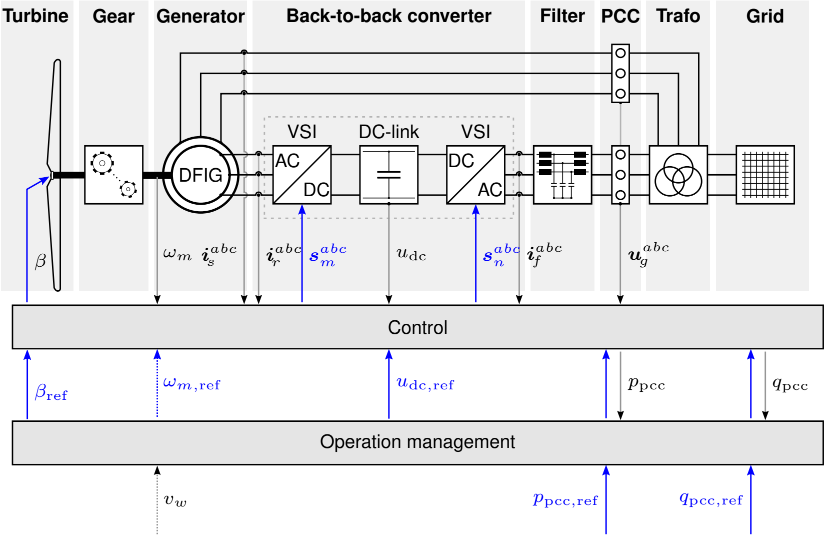
WTS with DFIG

Overview and modeling depth



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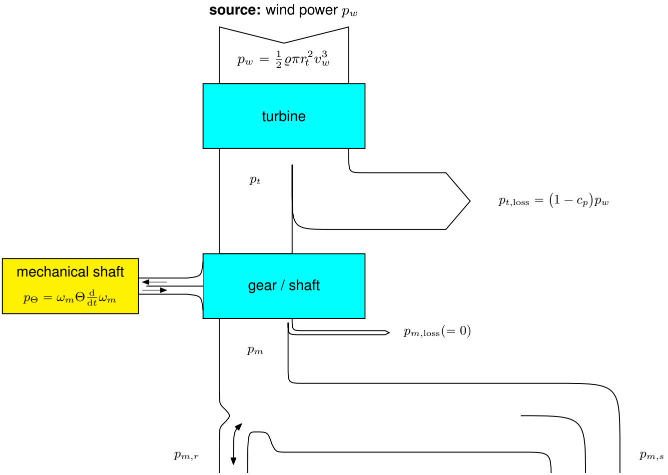
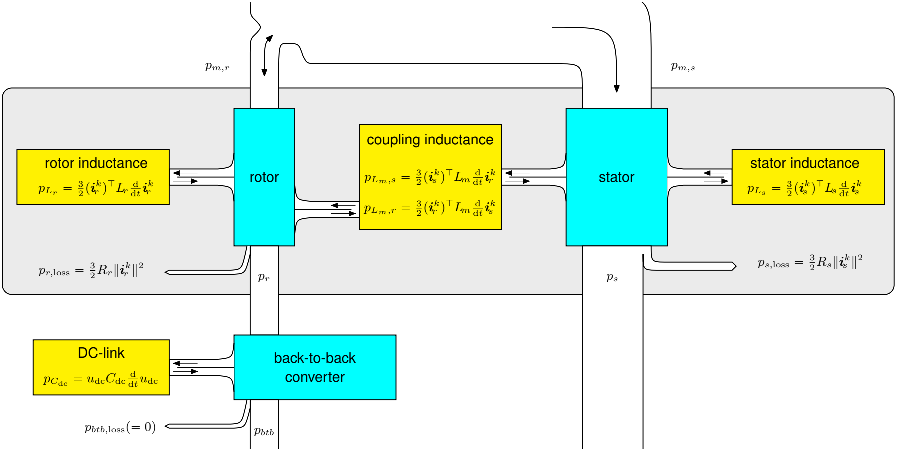
Dynamic power flow [18]

Part 1



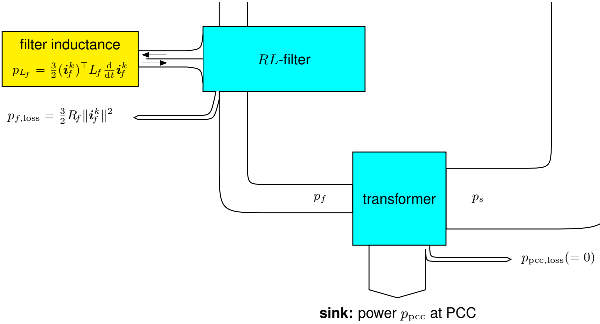
Dynamic power flow [18]

Part 2



Dynamic power flow [18]

Part 3



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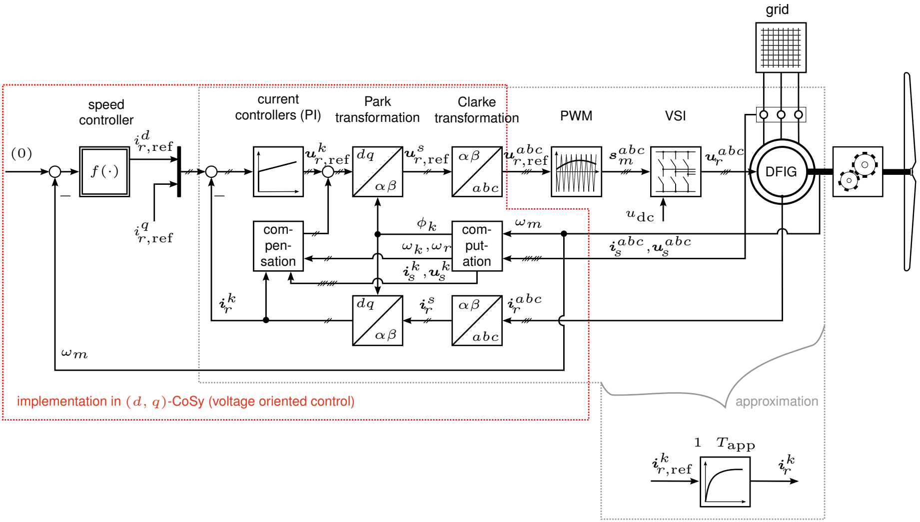
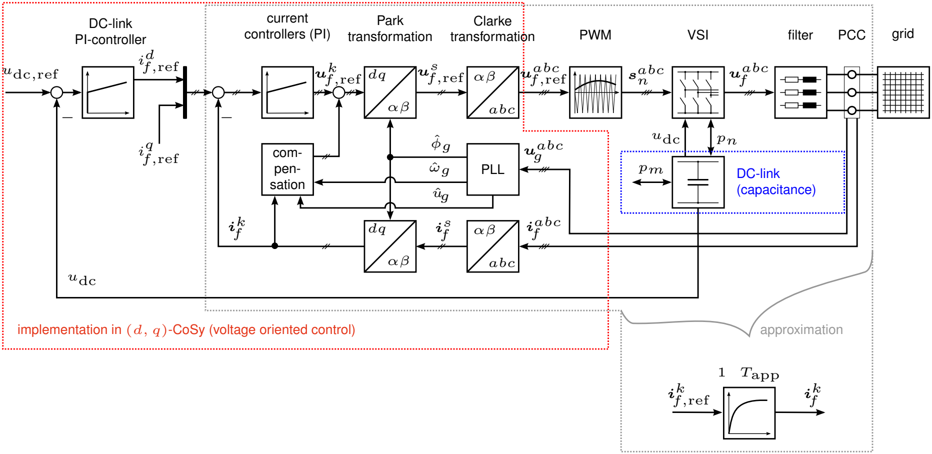
Control of WTS with DFIG

Rotor side controller structure



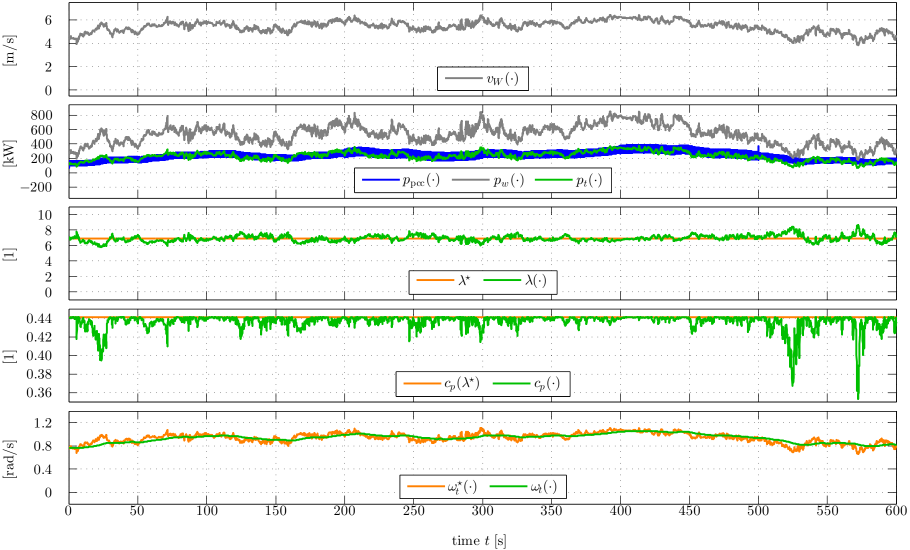
Control of WTS with DFIG

Grid side controller structure



Control of WTS with DFIG

Simulation results



Outline

3 WTS with DFIG

- Overview and modeling depth
- Dynamic power flow [18]
- Control of WTS with DFIG
- Online estimation of DFIG parameters [8]
  - Extended nonlinear model of DFIG
  - Implementation
  - Algorithm
  - Simulation results

Outline

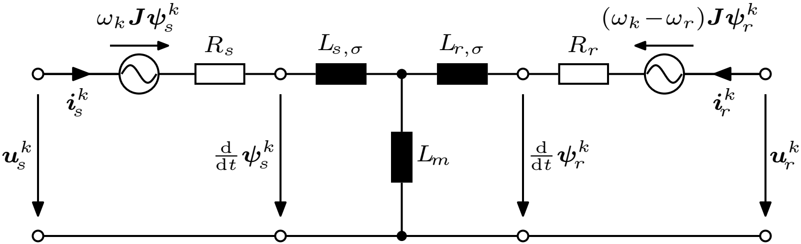
WTS with DFIG

Generic model of DFIG (after Clarke transformation)

$$
\left.
\begin{array}{rrcll}
\text{stator:} & \boldsymbol{u}_s^s(t) &=& R_s \boldsymbol{i}_s^s(t) + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^s(t), & \boldsymbol{\psi}_s^s(0) = \boldsymbol{\psi}_s^{s,0} \\
\text{rotor:} & \boldsymbol{u}_r^r(t) &=& R_r \boldsymbol{i}_r^r(t) + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_r^r(t), & \boldsymbol{\psi}_r^r(0) = \boldsymbol{\psi}_r^{r,0} \\
\text{flux linkage:} & \boldsymbol{\psi}_s^s(t) &=& \boldsymbol{\psi}_s^s\big(\boldsymbol{i}_s^s(t),\, \boldsymbol{i}_r^s(t), \phi_m(t)\big) & \\
\text{(general)} & \boldsymbol{\psi}_r^r(t) &=& \boldsymbol{\psi}_r^r\big(\boldsymbol{i}_r^r(t),\, \boldsymbol{i}_s^r(t), \phi_m(t)\big) & \\
\text{mechanics:} & \frac{\mathrm{d}}{\mathrm{d}t}\omega_m(t) &=& \frac{1}{\Theta}\left(m_m(t) + \frac{m_t(t)}{g_r} - (\mathfrak{F}\omega_m)(t)\right), & \omega_m(0) = \omega_m^0 \\
& \frac{\mathrm{d}}{\mathrm{d}t}\phi_m(t) &=& \omega_m(t), & \phi_m(0) = \phi_m^0 \\
\text{torque:} & m_m(t) &=& \frac{3}{2} p\, \boldsymbol{\psi}_s^s(t)^\top \boldsymbol{J} \boldsymbol{i}_s^s(t) &
\end{array}
\right\} \quad \text{(DFIG)}
$$

WTS with DFIG

Electrical circuit of DFIG (linear flux linkage)



$$
\left.
\begin{array}{rrcll}
\text{stator:} & \boldsymbol{u}_s^s(t) & = & R_s \boldsymbol{i}_s^s(t) + \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{\psi}_s^s(t), & \boldsymbol{\psi}_s^s(0) = \boldsymbol{\psi}_s^{s,0} \\
\text{rotor:} & \boldsymbol{u}_r^r(t) & = & R_r \boldsymbol{i}_r^r(t) + \frac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{\psi}_r^r(t), & \boldsymbol{\psi}_r^r(0) = \boldsymbol{\psi}_r^{r,0} \\
& & & & \\
\text{flux linkage:} & \boldsymbol{\psi}_s^s(t) & = & L_s \boldsymbol{i}_s^s(t) + L_m \boldsymbol{i}_r^s(t), & L_s = L_{s,\sigma} + L_m \\
\text{(linear)} & \boldsymbol{\psi}_r^r(t) & = & L_r \boldsymbol{i}_r^r(t) + L_m \boldsymbol{i}_s^r(t), & L_r = L_{r,\sigma} + L_m
\end{array}
\right\} \quad (2)
$$

Online estimation of DFIG parameters [8]

Extended nonlinear model of DFIG

Extended nonlinear model of DFIG including

- electrical parameters are additional system states
- uncertainties for model $\boldsymbol{w}$ and measurement $\boldsymbol{v}$

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}(t) = \boldsymbol{g}\big(\boldsymbol{x}(t), \boldsymbol{u}(t)\big) + \boldsymbol{w}(t), \qquad \boldsymbol{x}(0) = \boldsymbol{x}_0 \in \mathbb{R}^{10} \tag{3}$$

$$\boldsymbol{y}(t) = \boldsymbol{h}\big(\boldsymbol{x}(t)\big) + \boldsymbol{v}(t), \tag{4}$$

where

$$\left.\begin{array}{lcl} \boldsymbol{x} & = & \Big((\boldsymbol{\psi}_s^k)^\top, \; (\boldsymbol{\psi}_r^k)^\top, \; \omega_m, \; R_s, \; R_r, \; L_{s,\sigma}, \; L_{r,\sigma}, \; L_m\Big)^\top \in \mathbb{R}^{10}, \\ \boldsymbol{y} & = & \Big((\boldsymbol{i}_s^k)^\top, \; (\boldsymbol{i}_r^k)^\top, \; \omega_m\Big)^\top \in \mathbb{R}^5, \\ \boldsymbol{u} & = & \Big((\boldsymbol{u}_s^k)^\top, \; (\boldsymbol{u}_r^k)^\top\Big)^\top \in \mathbb{R}^4. \end{array}\right\} \tag{5}$$

Outline

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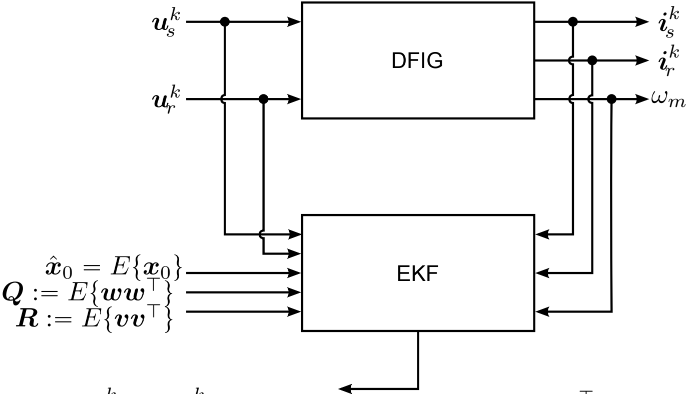
Online estimation of DFIG parameters [8]

Implementation: Block diagram of DFIG and Extended Kalman Filter (EKF)



$$\hat{\boldsymbol{x}} = \left((\hat{\boldsymbol{\psi}}_s^k)^\top, (\hat{\boldsymbol{\psi}}_r^k)^\top, \hat{\omega}_m, \hat{R}_s, \hat{R}_r, \hat{L}_{s,\sigma}, \hat{L}_{r,\sigma}, \hat{L}_m\right)^\top \in \mathbb{R}^{10}$$

Outline

Online estimation of DFIG parameters [8]

Algorithm: Extended Kalman Filter (EKF)

Step I: Initialization for $k = 0$:

$$\hat{\boldsymbol{x}}[0] = E\{\boldsymbol{x}_0\}, \boldsymbol{P}_0 := \boldsymbol{P}[0] = E\{(\boldsymbol{x}_0 - \hat{\boldsymbol{x}}[0])(\boldsymbol{x}_0 - \hat{\boldsymbol{x}}[0])^\top\},$$
$$\boldsymbol{K}_0 := \boldsymbol{K}[0] = \boldsymbol{P}[0]\boldsymbol{C}[0]^\top\big(\boldsymbol{C}[0]\boldsymbol{P}[0]\boldsymbol{C}[0]^\top + \boldsymbol{R}\big)^{-1}$$

where, for $k \geqslant 0$, $\boldsymbol{C}[k] := \frac{\partial \boldsymbol{h}(\boldsymbol{x})}{\partial \boldsymbol{x}}\Big|_{\hat{\boldsymbol{x}}^-[k]}$

Step II: Time update ("a priori prediction") for $k \geqslant 1$:

(a) State prediction

$$\hat{\boldsymbol{x}}^-[k] = \boldsymbol{f}(\hat{\boldsymbol{x}}[k-1], \boldsymbol{u}[k-1])$$

(b) Error covariance matrix prediction

$$\boldsymbol{P}^-[k] = \boldsymbol{A}[k]\boldsymbol{P}[k-1]\boldsymbol{A}[k]^\top + \boldsymbol{Q}$$

where $\boldsymbol{A}[k] := \frac{\partial \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u})}{\partial \boldsymbol{x}}\Big|_{\hat{\boldsymbol{x}}^-[k]}$

Step III: Verification of (local) observability $k \geqslant 1$:

$$n_o[k] := \mathrm{rank}\,\big(\boldsymbol{S}_o[k]\big) \text{ with } \boldsymbol{S}_o[k]$$

Step IV: Computation of Kalman gain for $k \geqslant 1$

$$\boldsymbol{K}[k] = \boldsymbol{P}^-[k]\boldsymbol{C}[k]^\top\big(\boldsymbol{C}[k]\boldsymbol{P}^-[k]\boldsymbol{C}[k]^\top + \boldsymbol{R}\big)^{-1}$$

Step V: Measurement update ("correction") for $k \geqslant 1$:

(a) Estimation update with measurement

$$\hat{\boldsymbol{x}}[k] = \hat{\boldsymbol{x}}^-[k] + \boldsymbol{K}[k](\boldsymbol{y}[k] - \boldsymbol{h}(\hat{\boldsymbol{x}}^-[k]))$$

(b) Error covariance matrix update

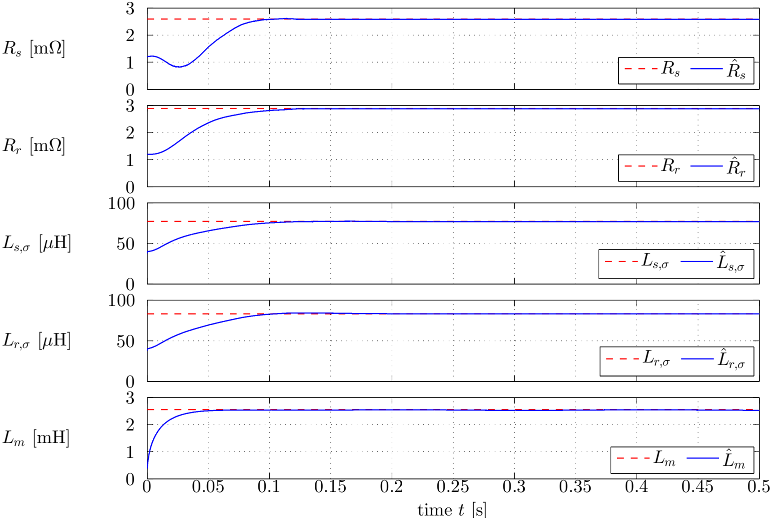
$$\boldsymbol{P}[k] = \boldsymbol{P}^-[k] - \boldsymbol{K}[k]\boldsymbol{C}[k]\boldsymbol{P}^-[k]$$

Step V: Go back to Step II (use $\boldsymbol{C}[k]$).

Outline

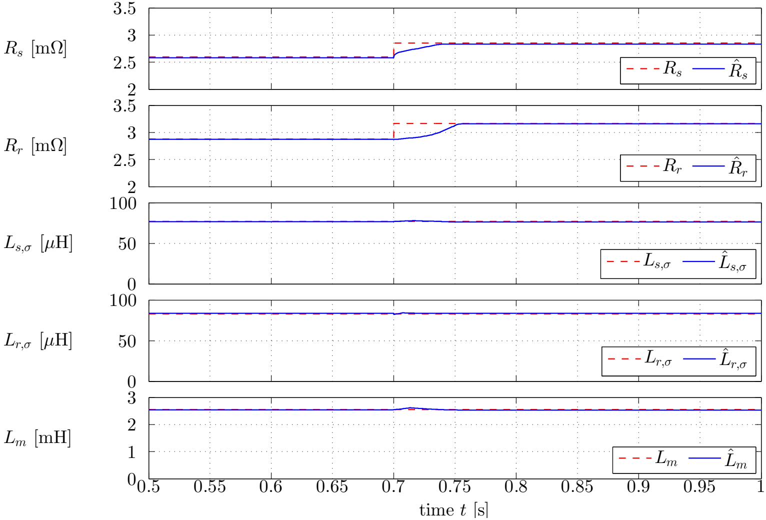
Online estimation of DFIG parameters [8]

Simulation results: Parameter estimation of nominal values



Online estimation of DFIG parameters [8]

Simulation results: Parameter estimation of resistance changes of $+10\%$



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