Nonlinear control of renewable energy systems

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Duac UC
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Outline

Outline

1 Introduction

- Technical University of Munich (TUM)
  - Students and staff
  - Main campuses
  - Organigram
- Munich School of Engineering (MSE)
  - Organigram
  - Recent research foci
- MSE Research group “Control of Renewable Energy Systems (CRES)”
  - Team
  - Research
  - Laboratory setup

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)

Main campuses

Departments

154 programs - 13 departments - 3 locations

Munich

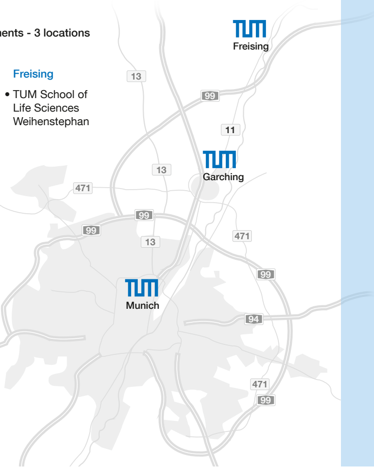
- Architecture
- Civil, Geo and Environ-mental Engineering
- Electrical, Electronic and Computer Engineering
- TUM School of Medicine
- Sport and Health Sciences
- TUM School of Education
- TUM School of Management

Freising

- TUM School of Life Sciences Weihenstephan

Garching

- Chemistry
- Informatics
- Mathematics
- Mechanical Engineering
- Physics



Locations & Networks

TUM science network

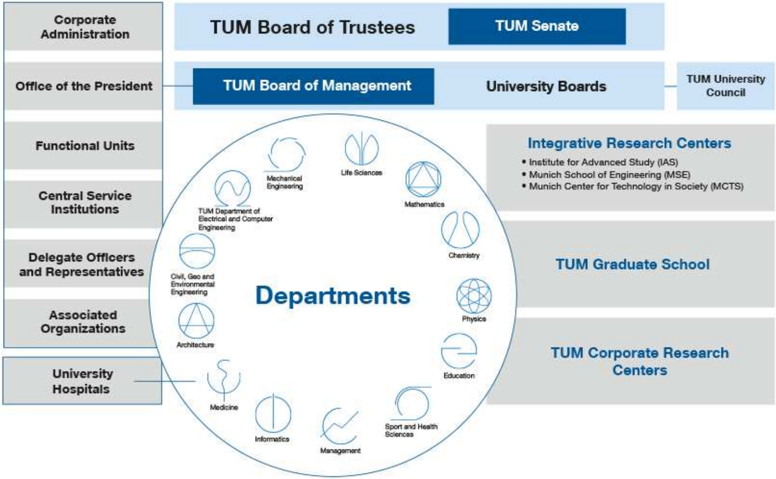
- Max Planck Institutes: Garching Martinsried Munich
- Helmholtz Zentrum München
- iwb Anwenderzentrum Augsburg
- Fraunhofer Institutes: Holzkirchen Freising

TUM locations

- Munich
- Garching
- Freising
- Iffeldorf
- Obernach
- Straubing
- Wettzell
- Singapore: TUM Asia
- Beijing
- Brussels
- Cairo
- Mumbai
- São Paulo

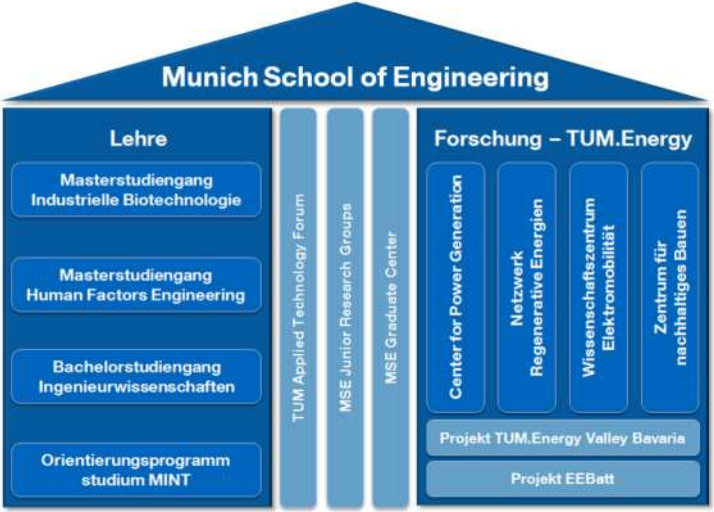
Technical University of Munich (TUM)

Organigram



Munich School of Engineering (MSE)

Integrative research center (Organigram)



Munich School of Engineering (MSE)

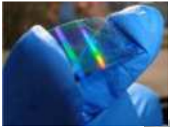
Recent research foci

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

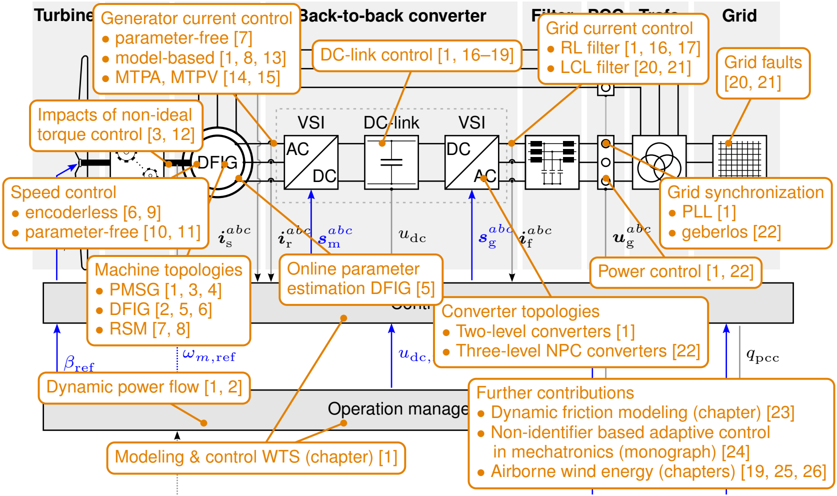
Focus: Fault-tolerant control

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



Group “Control of renewable energy systems (CRES)”

Laboratory setup

Reluctance and Permanent-magnet SMs

Electrically-excited SM and doubly-fed IM

Real-time system and VSIs

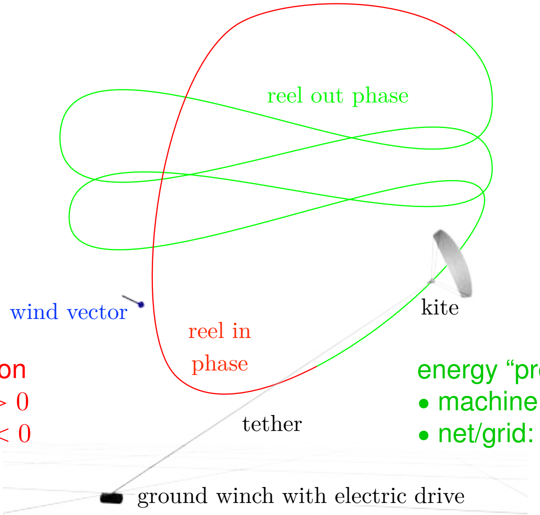
Outline

2 Nonlinear DC-link control in airborne wind energy systems

- Problem formulation
  - Airborne wind energy systems during pumping mode
  - Overview of grid-side control system
- Classical DC-link PI controller
  - Grid-side control structure in voltage orientation
  - “Structurally varying” (linearized) system
  - Root locus and local stability analysis
- Nonlinear DC-link PI controller
  - Grid-side control structure in voltage orientation
  - Simulation results

Problem formulation

Airborne wind energy systems during pumping mode $\Longrightarrow$ **Bidirectional** power flow



energy dissipation

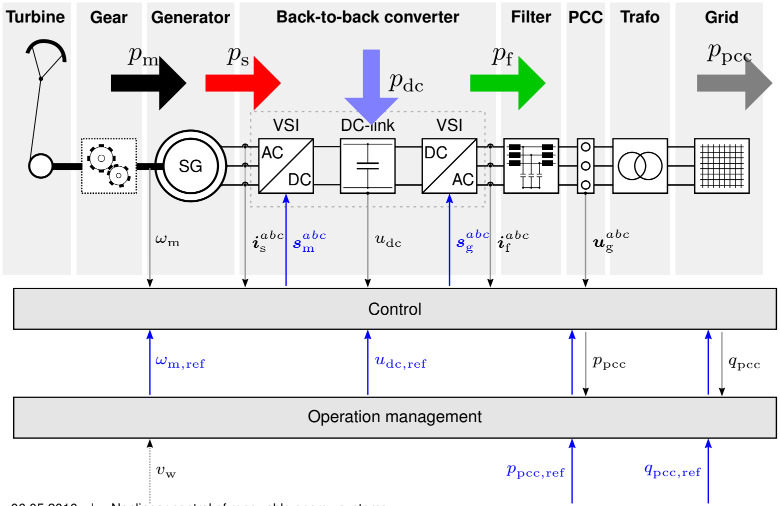
- machine: $p_{\mathrm{m}} > 0$
- net/grid: $p_{\mathrm{pcc}} < 0$

energy "production"

- machine: $p_{\mathrm{m}} < 0$
- net/grid: $p_{\mathrm{pcc}} > 0$

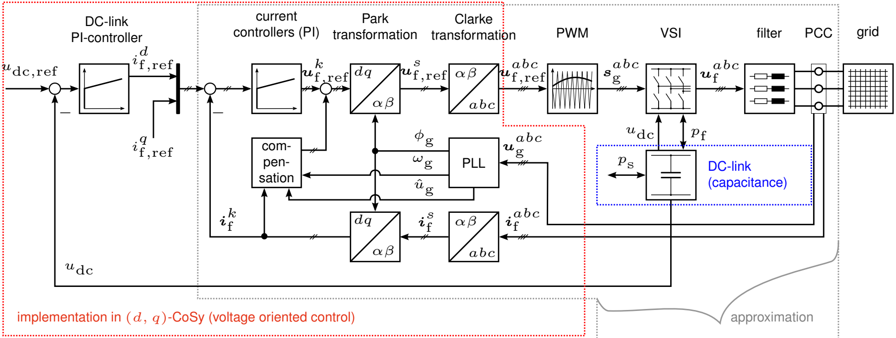
Problem formulation

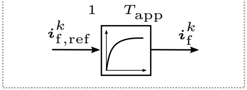
Overview of grid-side control system



Classical DC-link PI controller

Grid-side control structure in voltage orientation with *constant* PI controller



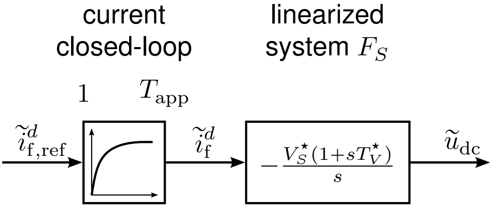


PI controller with constant gains:

$$
\begin{aligned}
e(t) &:= u_{\mathrm{dc,ref}}(t) - u_{\mathrm{dc}}(t) \\
i_{\mathrm{f,ref}}^{d}(t) &= V_{\mathrm{r}}\, e(t) + \frac{V_{\mathrm{r}}}{T_{\mathrm{n}}} \int_0^t e(\tau)\,\mathrm{d}\tau\,, \quad V_{\mathrm{r}},\, T_{\mathrm{n}} > 0
\end{aligned}
$$

Classical DC-link PI controller

"Structurally varying" (linearized) system [1]



(Case 1) $p_{\mathrm{f}} = 0 \implies i_{\mathrm{f}}^{d,\star} = 0 \implies T_V^\star = 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^{d}_{\mathrm{f,ref}}(s)} = \dfrac{V_S^\star}{s(1+sT_{\mathrm{app}})}$

(Case 2) $p_{\mathrm{f}} > 0 \implies i_{\mathrm{f}}^{d,\star} > 0 \implies T_V^\star > 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^{d}_{\mathrm{f,ref}}(s)} = \dfrac{V_S^\star(1+sT_V^\star)}{s(1+sT_{\mathrm{app}})}$

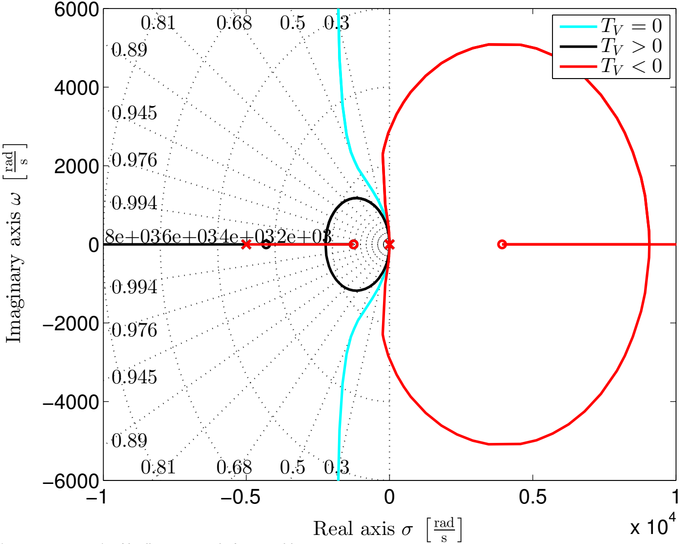
(minimum-phase)

(Case 3) $p_{\mathrm{f}} < 0 \implies i_{\mathrm{f}}^{d,\star} < 0 \implies T_V^\star < 0 \implies \dfrac{\tilde{u}_{\mathrm{dc}}(s)}{\tilde{i}^{d}_{\mathrm{f,ref}}(s)} = \dfrac{V_S^\star(1-s|T_V^\star|)}{s(1+sT_{\mathrm{app}})}$

(**non**minimum-phase)

Classical DC-link PI controller

Root locus ($T_V = T_V^\star$ depends on equilibrium!)



Classical DC-link PI controller

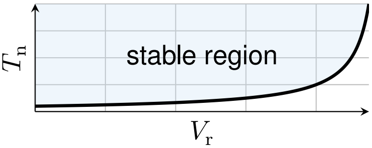
Local stability analysis: Hurwitz criterion

Transfer function of (linearized) closed-loop system

$$F_{CL}(s) = \frac{u_{\mathrm{dc}}(s)}{u_{\mathrm{dc,ref}}(s)} = \frac{V_{\mathrm{r}} V_S^{\star}(1 + sT_{\mathrm{app}})(1 + sT_V^{\star})}{s^3 \underbrace{T_{\mathrm{n}} T_{\mathrm{app}}}_{=:a_3} + s^2 \underbrace{T_{\mathrm{n}}(1 + T_V^{\star} V_S^{\star} V_{\mathrm{r}})}_{=:a_2} + s \underbrace{(T_V^{\star} + T_{\mathrm{n}}) V_S^{\star} V_{\mathrm{r}}}_{=:a_1} + \underbrace{V_{\mathrm{r}} V_S^{\star}}_{=:a_0}}$$

Sufficient condition for *local* stability

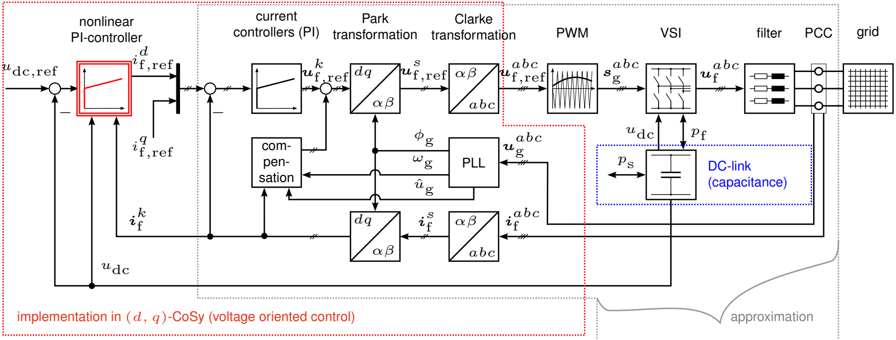
- $0 < V_{\mathrm{r}} < \frac{1}{|T_V^{\star}| V_S^{\star}}$
- $T_{\mathrm{n}} > \frac{T_{\mathrm{app}}}{1 - V_{\mathrm{r}} V_S^{\star} |T_V^{\star}|} + |T_V^{\star}| > 0$

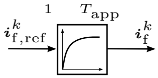


$\Longrightarrow a_0, a_1, a_2, a_3 > 0$ and $D_2 := a_2 a_1 - a_3 a_0 > 0$.

Nonlinear DC-link PI controller

Control system in voltage orientation with **nonlinear** PI controller



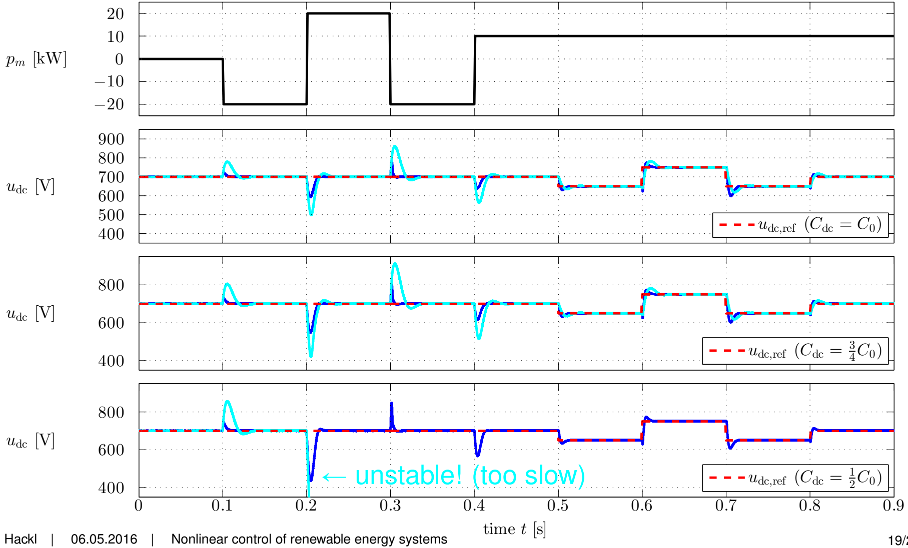


Nonlinear PI controller

$$
\begin{aligned}
e(t) &:= u_{\mathrm{dc,ref}}(t) - u_{\mathrm{dc}}(t) \\
i^d_{\mathrm{f,ref}}(t) &= V_{\mathrm{r}}(\boldsymbol{i}^k_{\mathrm{f}}, u_{\mathrm{dc}})\, e(t) + \frac{V_{\mathrm{r}}(\boldsymbol{i}^k_{\mathrm{f}}, u_{\mathrm{dc}})}{T_{\mathrm{n}}(\boldsymbol{i}^k_{\mathrm{f}}, u_{\mathrm{dc}})} \int_0^t e(\tau)\, \mathrm{d}\tau
\end{aligned}
$$

Nonlinear PI-control for DC-link voltage

Simulation results for 20 kW AWE system: —— constant PI, —— nonlinear PI



Outline

3 Conclusion

Conclusion and future work

To take home:

- DC-link voltage control
  - nonlinear system dynamics with structurally varying nature
  - **non**minimum-phase behavior during reel-in phase
  - very conservative classical PI controller design necessary
- nonlinear PI controller
  - design based on pole placement and online parameter adjustment
  - faster tracking and disturbance rejection
  - smaller DC-link capacitance feasible ($\rightarrow$ cheaper)

Future work:

- Lyapunov-based stability analysis
- Measurement results (construction of test bench in progress)

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