Optimal feedforward torque control of anisotropic synchronous machines with analytical solution considering stator resistance and cross-coupling inductance

Christoph Hackl

IEEE Senior Member

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

www.cres.mse.tum.de

01.08.2017

Technische Universität Kaiserslautern

Outline

1. Scientific background

2. Optimal feedforward torque control of anisotropic synchronous machines with analytical solution [1–4]

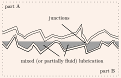
Outline

1. Scientific background
   - Interdisciplinary expertise
   - Research group “Control of renewable energy systems (CRES)”
   - Running projects and third-party funding
   - Teaching experience

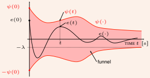
Scientific background

Interdisciplinary expertise (> 90 peer-reviewed publications, e.g. one monograph)

System identification [13–17]



Dynamic friction [18, 19]



Non-identifier based adaptive control [18, 20–35]

Paper coating machines [8–12]

Teaching (EOF Award ’13) [35, 95–101]

Robotics / mechatronics [18, 19, 35–46]

Systems & control
(dynamical systems)

Electro-active polymers [5–7]

Power electronics [35, 35, 47–66]

Renewable energy systems [17, 32, 34, 35, 48, 49, 52, 56, 57, 59–61, 63, 65, 66, 71–73, 76, 78, 84–94]

Electrical drives (machines/generators) [17, 18, 20, 22, 23, 33, 35, 41, 45, 58, 67–84]

Scientific background

Head of CRES research group (since 2014): 9 PhD students, 1 Post-Doc (& 3 PhD collaborations)

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)

C. Ladisla, M.Sc.
(CRES, 01/2018)

External PhD students

M. Landerer, M.Sc.
(CRES, 06/2016)

Z. Zhang, Dr.-Ing.
(CRES/EAL,07/2015)

K. Bär, M.Sc.
(THI, 07/2017)

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

S. Krüner, M.Sc.
(SINNPower,11/2015)

Scientific background

Running projects & third-party funding (> 2 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)

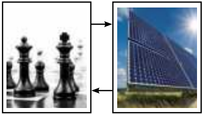
Large-scale WTS

Efficiency+Reliability

Small-scale WTS

Reluctance SM

Model predictive control for RES



Real-time applicability

Airborne Wind Energy

Fault-tolerant control

Geothermal energy

Fault-tolerant control

Wave energy (SinnPower)

Efficiency+Reliability

Electric vehicles (BMW)

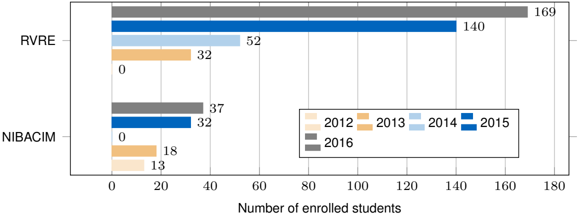
Efficiency+Reliability

Electrical power system

Three-phase four-wire system dynamics

Scientific background

Teaching experience (since 2004)



- Lectures, tutorials, practical courses & student projects, e.g.
  - "**R**egelung **v**on **r**egenerativen **E**nergiesystemen" (WS, 3SWS; since 2013)
  - "**N**on-**i**dentifier **b**ased **a**daptive **c**ontrol in **m**echatronics" (SS, 4SWS; since 2012)
  - "Projektstudium Antriebstechnik" [99–101] (EOF Lehrpreis 2013, WS1415)
- International / PhD teaching activities
  - Lecture & Seminar on "Modeling and control of renewable energy systems" (TUM-CREATE, Singapore; May-July 2017)
  - EU H2020 ITN Workshop "Electrical Drives and Predictive Control" (2016)
  - MSE Winter School "Holistic Modeling and Control of Energy Systems" (2015)
  - Block course on "Modeling and control of wind turbine systems: An introduction" (South Africa, University of Stellenbosch, 2014)

Outline

2 Optimal feedforward torque control of anisotropic synchronous machines with analytical solution [1–4]

- Motivation
- Problem statement and proposed solution
- Operation management and operation strategies
- Analytical solution
- Implementation
- Conclusion

Motivation

Synchronous machines: Widely-used, compact and efficient actuators

www.bmw.de

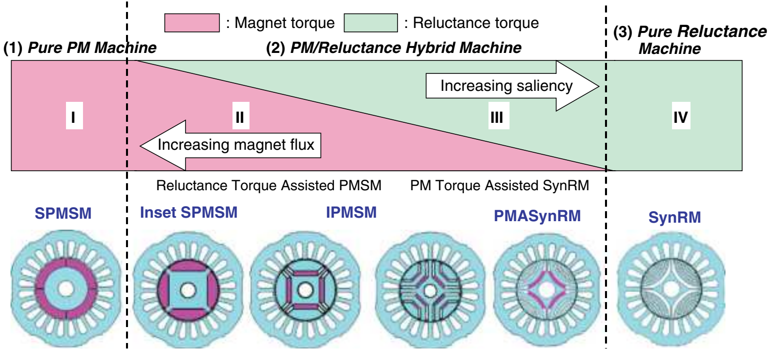
www.farmwood.co.uk

www.abb.com (from video)

- traction drives (e.g. electric vehicles or trains)
- air conditioning/fans
- pumps
- conventional power plants (e.g. hydro power plants)
- renewable energy systems (e.g. direct-drive wind turbine systems)

Motivation

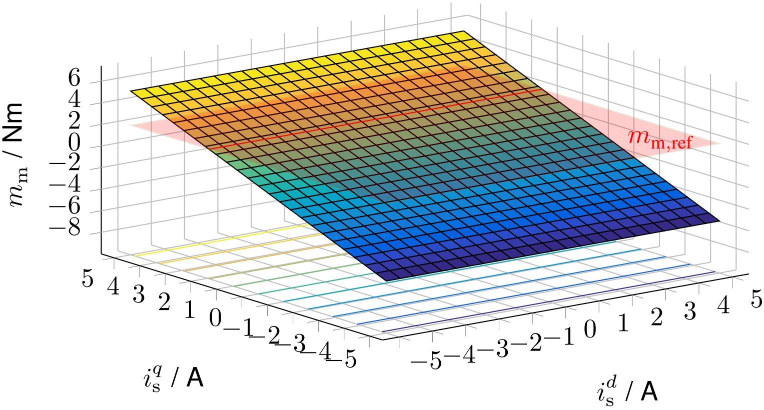
Examples of anisotropic synchronous machines [102] with "saliency ratio" $L_s^d / L_s^q \neq 1$



$$m_m(i_s^d, i_s^q) = \frac{3}{2} n_p \Big[\underbrace{\psi_{pm} i_s^q}_{\text{magnetic torque}} + \underbrace{\left(L_s^d - L_s^q\right) i_s^d i_s^q}_{\text{reluctance torque}} + \underbrace{L_m\left((i_s^q)^2 - (i_s^d)^2\right)}_{\text{cross-coupling torque}} \Big]$$

Motivation

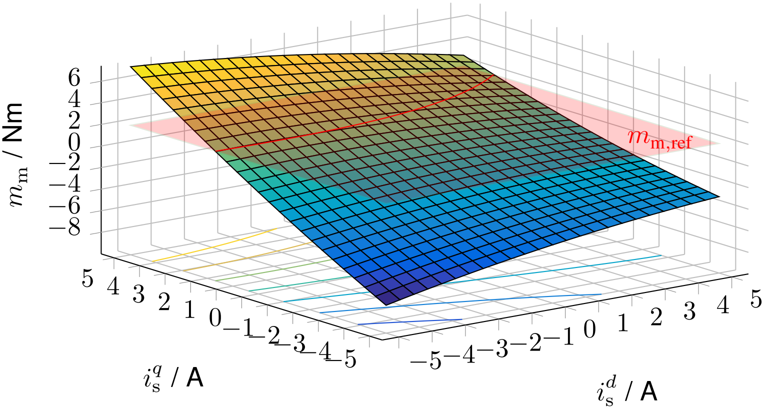
Optimal feedforward torque control problem: **Isotropic machine**



$$m_{\mathrm{m,ref}} \overset{!}{=} m_{\mathrm{m}}\left(i_{\mathrm{s}}^{d},\, i_{\mathrm{s}}^{q}\right) = \frac{3}{2}\, n_{\mathrm{p}}\, \psi_{\mathrm{pm}} i_{\mathrm{s}}^{q} \quad \left(\Longrightarrow\; i_{\mathrm{s,ref}}^{q} = \frac{2\, m_{\mathrm{m,ref}}}{3 n_{\mathrm{p}} \psi_{\mathrm{pm}}}\right)$$

Motivation

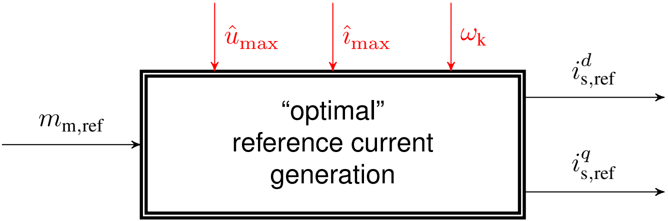
Optimal feedforward torque control problem: **Anisotropic machine**



$$m_{\mathrm{m,ref}} \overset{!}{=} m_{\mathrm{m}}\left(i_{\mathrm{s}}^{d},\, i_{\mathrm{s}}^{q}\right) = \frac{3}{2}\, n_{\mathrm{p}} \left[\psi_{\mathrm{pm}} i_{\mathrm{s}}^{q} + \left(L_{\mathrm{s}}^{d} - L_{\mathrm{s}}^{q}\right) i_{\mathrm{s}}^{d} i_{\mathrm{s}}^{q} + L_{\mathrm{m}}\left(\left(i_{\mathrm{s}}^{q}\right)^{2} - \left(i_{\mathrm{s}}^{d}\right)^{2}\right)\right]$$

Motivation

Optimal feedforward torque control problem: **Goal**



$$\boldsymbol{i}^k_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \hat{u}_{\max}, \hat{\imath}_{\max}, \omega_{\mathrm{k}}) = \begin{pmatrix} i^d_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \hat{u}_{\max}, \hat{\imath}_{\max}, \omega_{\mathrm{k}}) \\ i^q_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \hat{u}_{\max}, \hat{\imath}_{\max}, \omega_{\mathrm{k}}) \end{pmatrix}$$

- ✓ Numerical solutions and/or look-up tables
  (but: limited storage, accuracy, real-time applicability)
- **?** Analytical solutions (some do exist but impose simplifying assumptions such as $\cancel{R_{\mathrm{s}} = 0 \text{ and/or } L_{\mathrm{m}} = 0}$)

Problem statement and proposed solution

Considered machines: Anisotropic synchronous machines (steady-state model)

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

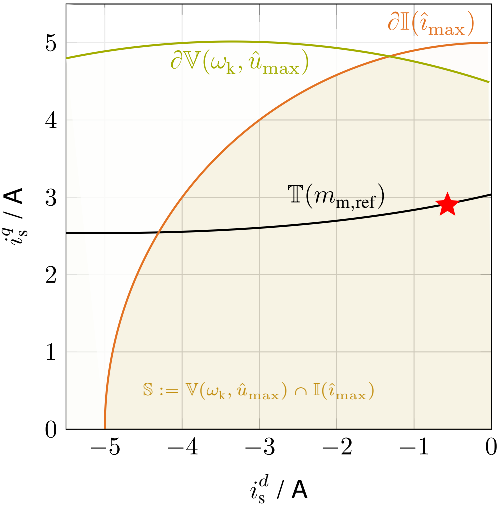
$$\begin{aligned} m_m(\boldsymbol{i}_s^k) &= \tfrac{3}{2} n_p (\boldsymbol{i}_s^k)^\top \boldsymbol{J} \boldsymbol{\psi}_s^k(\boldsymbol{i}_s^k) \\ &= \tfrac{3}{2} n_p \left[\psi_{pm} i_s^q + (L_s^d - L_s^q) i_s^d i_s^q + L_m \left((i_s^q)^2 - (i_s^d)^2 \right) \right] \end{aligned}$$

Assumption (Affine flux linkage (at least locally))

$$\boldsymbol{\psi}_s^k(\boldsymbol{i}_s^k) = \underbrace{\begin{bmatrix} L_s^d & L_m \\ L_m & L_s^q \end{bmatrix}}_{=:\boldsymbol{L}_s^k \in \mathbb{R}^{2\times 2}} \boldsymbol{i}_s^k + \underbrace{\begin{pmatrix} \psi_{pm} \\ 0 \end{pmatrix}}_{=:\boldsymbol{\psi}_{pm}^k} \quad \text{with } \boldsymbol{L}_s^k = (\boldsymbol{L}_s^k)^\top > 0$$

Problem statement and proposed solution

Feedforward torque control: Optimization problem(s) with multiple constraints



$$\max_{\boldsymbol{i}_s^k \in \mathbb{S}} \; -f(\boldsymbol{i}_s^k) \quad \text{subject to}$$

$$\begin{cases} \|\boldsymbol{i}_s^k\|^2 \leqslant \hat{\imath}_{\max}^2, \\ \text{(current circular area)} \\ \|\boldsymbol{u}_s^k(\boldsymbol{i}_s^k, \omega_k)\|^2 \leqslant \hat{u}_{\max}^2, \\ \text{(voltage elliptical area)} \\ |m_m(\boldsymbol{i}_s^k)| \leqslant |m_{m,\text{ref}}|, \text{ and} \\ \operatorname{sign}(m_{m,\text{ref}}) = \\ \operatorname{sign}(m_m(\boldsymbol{i}_s^k)). \end{cases}$$

e.g. $-f(\boldsymbol{i}_s^k) = -\|\boldsymbol{i}_s^k\|^2$ (minimize copper losses) $\Longrightarrow \; \boldsymbol{i}_{s,\text{ref}}^k$ at ★

Problem statement and proposed solution

Proposed solution: Implicit formulation (quadrics), optimization and intersection points

Step 1: Derivation of quadrics $Q_A(\boldsymbol{i}_\mathrm{s}^k) := (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{A}\, \boldsymbol{i}_\mathrm{s}^k + 2\boldsymbol{a}^\top \boldsymbol{i}_\mathrm{s}^k + \alpha$:

- Current circular area: $(i_\mathrm{s}^d)^2 + (i_\mathrm{s}^q)^2 \leqslant \hat{\imath}_\mathrm{max}^2 \iff \|\boldsymbol{i}_\mathrm{s}^k\|^2 = (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{I}_2 \boldsymbol{i}_\mathrm{s}^k \leqslant \hat{\imath}_\mathrm{max}^2$

$$\Longrightarrow \quad \mathbb{I}(\hat{\imath}_\mathrm{max}) := \left\{ \boldsymbol{i}_\mathrm{s}^k \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{I}_2 \boldsymbol{i}_\mathrm{s}^k - \hat{\imath}_\mathrm{max}^2 \leqslant 0 \right\}$$

- Voltage elliptical area: $(u_\mathrm{s}^d)^2 + (u_\mathrm{s}^q)^2 \leqslant \hat{u}_\mathrm{max}^2 \iff \|\boldsymbol{u}_\mathrm{s}^k(\boldsymbol{i}_\mathrm{s}^k, \omega_\mathrm{k})\|^2 = \ldots \leqslant \hat{u}_\mathrm{max}^2$

$$\Longrightarrow \quad \mathbb{V}(\omega_\mathrm{k}, \hat{u}_\mathrm{max}) := \left\{ \boldsymbol{i}_\mathrm{s}^k \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{V}(\omega_\mathrm{k})\, \boldsymbol{i}_\mathrm{s}^k + 2\,\boldsymbol{v}(\omega_\mathrm{k})^\top \boldsymbol{i}_\mathrm{s}^k + \nu(\omega_\mathrm{k}, \hat{u}_\mathrm{max}) \leqslant 0 \right\}$$

- Reference torque hyperbola: $m_\mathrm{m}(\boldsymbol{i}_\mathrm{s}^k) = \frac{3}{2} n_\mathrm{p} (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{J} \boldsymbol{\psi}_\mathrm{s}^k(\boldsymbol{i}_\mathrm{s}^k) \overset{!}{=} m_\mathrm{m,ref} \iff \ldots$

$$\Longrightarrow \quad \mathbb{T}(m_\mathrm{m,ref}) := \left\{ \boldsymbol{i}_\mathrm{s}^k \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_\mathrm{s}^k)^\top \boldsymbol{T} \boldsymbol{i}_\mathrm{s}^k + 2\,\boldsymbol{t}^\top \boldsymbol{i}_\mathrm{s}^k - m_\mathrm{m,ref} = 0 \right\}$$

- ...

Problem statement and proposed solution

Proposed solution: Implicit formulation (quadrics), optimization and intersection points (cont'd)

Step 2: Optimization problem with equality constraint

$$\max_{\boldsymbol{i}_{\rm s}^k} -\Big(\underbrace{(\boldsymbol{i}_{\rm s}^k)^\top \boldsymbol{A}\boldsymbol{i}_{\rm s}^k + 2\boldsymbol{a}^\top \boldsymbol{i}_{\rm s}^k + \alpha}_{=:Q_A(\boldsymbol{i}_{\rm s}^k)}\Big) \text{ s.t. } \underbrace{(\boldsymbol{i}_{\rm s}^k)^\top \boldsymbol{B}\boldsymbol{i}_{\rm s}^k + 2\boldsymbol{b}^\top \boldsymbol{i}_{\rm s}^k + \beta}_{=:Q_B(\boldsymbol{i}_{\rm s}^k)} = 0$$

$\Longrightarrow$ Hyperbolas for MTPC, MTPV and MTPF (with $R_{\rm s} \neq 0$ & $L_{\rm m} \neq 0$!)

Step 3: Intersection of two quadrics (e.g. voltage ellipse and current circle)

$$\boldsymbol{i}_{\rm s,ref}^k := \arg\min_{\|\boldsymbol{i}_{\rm s}^k\|} \left\{ \boldsymbol{i}_{\rm s}^k \in \mathbb{R}^2 \,\middle|\, Q_A(\boldsymbol{i}_{\rm s}^k) = 0 \;\wedge\; Q_B(\boldsymbol{i}_{\rm s}^k) = 0 \right\}$$

$\Longrightarrow$ Optimal operation point ★ (reference current)

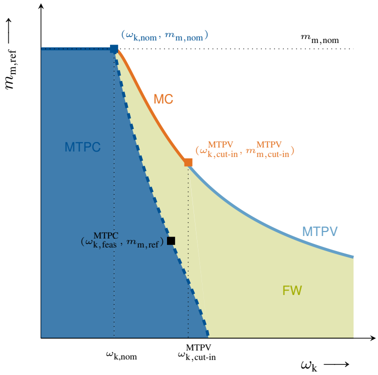
Both lead to subproblem of solving a fourth-order (quartic) polynomial

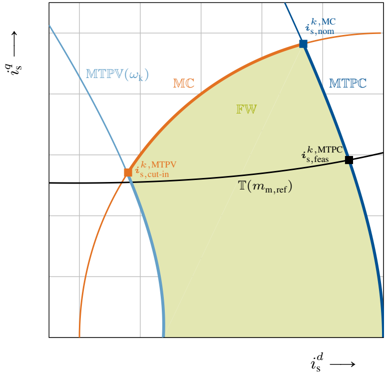
$$\chi(\lambda) := c_4\,\lambda^4 + c_3\,\lambda^3 + c_2\,\lambda^2 + c_1\,\lambda + c_0 \stackrel{!}{=} 0$$

$\Longrightarrow$ Analytical solutions exist (e.g. Euler's solution, see [103])

Operation management and operation strategies

Operation management: Operation strategies and transition points

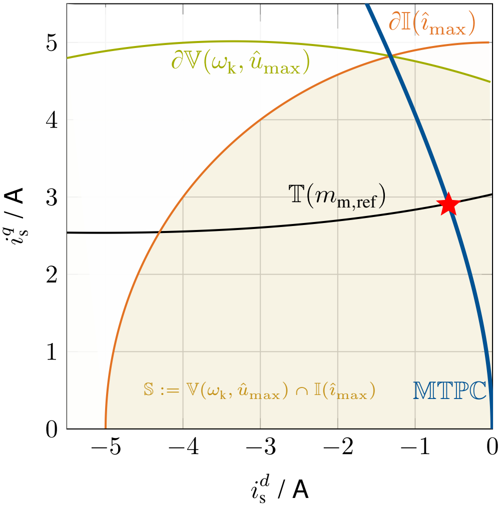




- Maximum Torque per Current (MTPC): $\omega_{\mathrm{k}} \leqslant \omega_{\mathrm{k,feas}}^{\mathrm{MTPC}}(m_{\mathrm{m,ref}})$ (and $m_{\mathrm{m,ref}} \leqslant m_{\mathrm{m,nom}}$)
- Field Weakening (FW): $\omega_{\mathrm{k,feas}}^{\mathrm{MTPC}}(m_{\mathrm{m,ref}}) < \omega_{\mathrm{k}}$ and $m_{\mathrm{m,ref}} < m_{\mathrm{m,feas}}^{\mathrm{FW}}(\omega_{\mathrm{k}})$
- Maximum Current (MC): $\omega_{\mathrm{k,nom}} < \omega_{\mathrm{k}} < \omega_{\mathrm{k,cut\text{-}in}}^{\mathrm{MTPV}}$ and $m_{\mathrm{m,ref}} \geqslant m_{\mathrm{m,feas}}^{\mathrm{FW}}(\omega_{\mathrm{k}})$
- Maximum Torque per Voltage (MTPV): $\omega_{\mathrm{k}} > \omega_{\mathrm{k,cut\text{-}in}}^{\mathrm{MTPV}}$ and $m_{\mathrm{m,ref}} \geqslant m_{\mathrm{m,cut\text{-}in}}^{\mathrm{MTPV}}(\omega_{\mathrm{k}})$

Operation management and operation strategies

Maximum Torque per Current (**MTPC**): Reference torque feasible



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{k} \in \mathbb{S}} -\|\boldsymbol{i}_{\mathrm{s}}^{k}\|^2 \quad \text{s.t.}$$

$$\underbrace{(\boldsymbol{i}_{\mathrm{s}}^{k})^\top \boldsymbol{T} \boldsymbol{i}_{\mathrm{s}}^{k} + 2\,\boldsymbol{t}^\top \boldsymbol{i}_{\mathrm{s}}^{k}}_{=m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{k})} - m_{\mathrm{m,ref}} = 0$$

Solution set

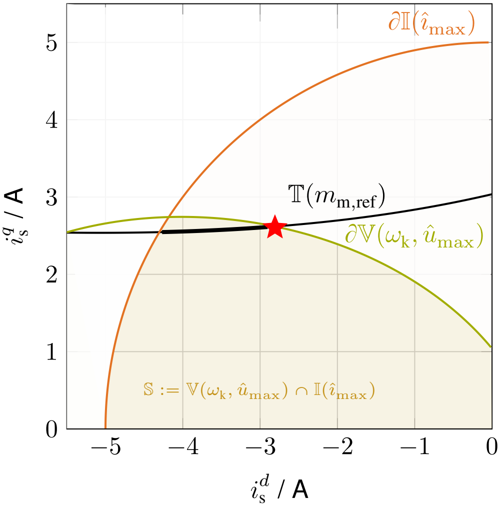
$$\mathbb{MTPC} := \Big\{ \boldsymbol{i}_{\mathrm{s}}^{k} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_{\mathrm{s}}^{k})^\top \boldsymbol{M}_{\mathrm{C}}\, \boldsymbol{i}_{\mathrm{s}}^{k} + 2\,\boldsymbol{m}_{\mathrm{C}}^\top \boldsymbol{i}_{\mathrm{s}}^{k} = 0 \Big\}$$

Optimal current reference (★)

$$\boldsymbol{i}_{\mathrm{s,ref}}^{k} = \mathbb{MTPC} \cap \mathbb{T}(m_{\mathrm{m,ref}})$$

Operation management and operation strategies

Field Weakening (**FW**): Reference torque feasible



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{k} \in \mathbb{S}} -\|\boldsymbol{i}_{\mathrm{s}}^{k}\|^2 \quad \text{s.t.}$$

$$\underbrace{(\boldsymbol{i}_{\mathrm{s}}^{k})^{\top}\boldsymbol{T}\boldsymbol{i}_{\mathrm{s}}^{k} + 2\,\boldsymbol{t}^{\top}\boldsymbol{i}_{\mathrm{s}}^{k}}_{=m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{k})} - m_{\mathrm{m,ref}} = 0$$

Feasible set

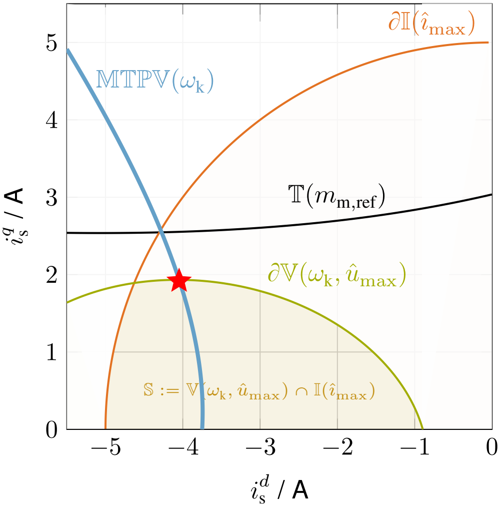
$$\mathbb{FW}(m_{\mathrm{m,ref}}, \omega_{\mathrm{k}}, \hat{u}_{\max}) := \mathbb{S}(\omega_{\mathrm{k}}, \hat{u}_{\max}, \hat{\imath}_{\max}) \cap \mathbb{T}(m_{\mathrm{m,ref}})$$

Optimal current reference (★)

$$\boldsymbol{i}_{\mathrm{s,ref}}^{k} = \partial\mathbb{V}(\omega_{\mathrm{k}}, \hat{u}_{\max}) \cap \mathbb{T}(m_{\mathrm{m,ref}})$$

Operation management and operation strategies

Maximum Torque per Voltage (**MTPV**): Reference torque **not** feasible



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{k} \in \mathbb{S}} -\|\boldsymbol{u}_{\mathrm{s}}^{k}(\boldsymbol{i}_{\mathrm{s}}^{k})\|^2 \quad \text{s.t.}$$

$$\underbrace{(\boldsymbol{i}_{\mathrm{s}}^{k})^\top \boldsymbol{T} \boldsymbol{i}_{\mathrm{s}}^{k} + 2\,\boldsymbol{t}^\top \boldsymbol{i}_{\mathrm{s}}^{k}}_{=m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{k})} - m_{\mathrm{m,ref}} = 0$$

Solution set

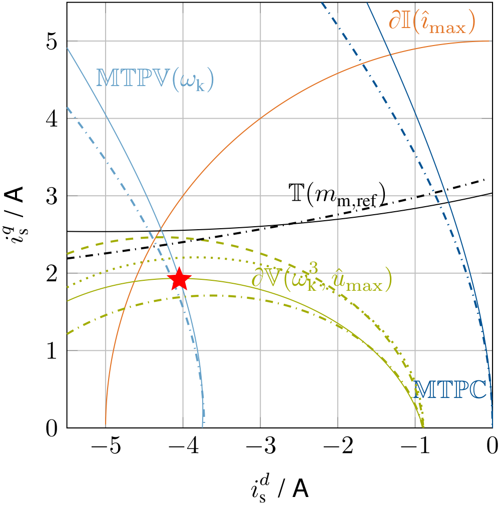
$$\mathrm{MTPV}(\omega_{\mathrm{k}}) := \Big\{ \boldsymbol{i}_{\mathrm{s}}^{k} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_{\mathrm{s}}^{k})^\top \boldsymbol{M}_{\mathrm{V}}\, \boldsymbol{i}_{\mathrm{s}}^{k} + 2\,\boldsymbol{m}_{\mathrm{V}}^\top \boldsymbol{i}_{\mathrm{s}}^{k} + \mu_{\mathrm{V}} = 0 \Big\}$$

Optimal current reference (★)

$$\boldsymbol{i}_{\mathrm{s,ref}}^{k} = \mathrm{MTPV}(\omega_{\mathrm{k}}) \cap \partial\mathbb{V}(\omega_{\mathrm{k}}, \hat{u}_{\max})$$

Operation management and operation strategies

Illustration of the effect of neglecting R_s and/or L_m



$R_\mathrm{s} = 0$ (and $L_\mathrm{m} \neq 0$)

$L_\mathrm{m} = 0$ (and $R_\mathrm{s} \neq 0$)

$R_\mathrm{s} = 0$ and $L_\mathrm{m} = 0$

$\Longrightarrow$ **Reduced efficiency**! (and wrong torque and/or possibly wrong operation strategies)

Analytical solution

Example: Analytical solution for intersection points of two quadrics

Problem

$$\mathbb{X} := \left\{ \boldsymbol{x} \in \mathbb{R}^2 \;\middle|\; \underbrace{\boldsymbol{x}^\top \boldsymbol{A}\boldsymbol{x} + 2\boldsymbol{a}^\top \boldsymbol{x} + \alpha}_{=:Q_A(\boldsymbol{x})} = 0 \;\wedge\; \underbrace{\boldsymbol{x}^\top \boldsymbol{B}\boldsymbol{x} + 2\boldsymbol{b}^\top \boldsymbol{x} + \beta}_{=:Q_B(\boldsymbol{x})} = 0 \right\}$$

Solution: Relate both (e.g., if $\alpha \neq 0$ and $\beta \neq 0$)

$$Q_D(\boldsymbol{x}) := \frac{Q_A(\boldsymbol{x})}{\alpha} - \frac{Q_B(\boldsymbol{x})}{\beta} = \boldsymbol{x}^\top \underbrace{\left(\frac{\boldsymbol{A}}{\alpha} - \frac{\boldsymbol{B}}{\beta}\right)}_{=:\boldsymbol{D}} \boldsymbol{x} + 2 \underbrace{\left(\frac{\boldsymbol{a}}{\alpha} - \frac{\boldsymbol{b}}{\beta}\right)^\top}_{=:\boldsymbol{d}^\top} \boldsymbol{x} + \underbrace{\left(\frac{\alpha}{\alpha} - \frac{\beta}{\beta}\right)}_{=0} = 0$$

and note that

$$Q_D(\boldsymbol{x}) := \boldsymbol{x}^\top \big(\underbrace{\boldsymbol{D}\boldsymbol{x} + 2\boldsymbol{d}}_{\overset{!}{=}\lambda \boldsymbol{J}\boldsymbol{x}} \big) \overset{!}{=} 0 \quad \iff \quad \boldsymbol{x}^\star(\lambda) = -2\big(\boldsymbol{D} - \lambda \boldsymbol{J}\big)^{-1} \boldsymbol{d}$$

Analytical solution

Example: Analytical solution for intersection points of two quadrics (cont'd)

then insert $\boldsymbol{x}^\star(\lambda)$ in $Q_A(\boldsymbol{x})$ (or $Q_B(\boldsymbol{x})$), i.e.

$$Q_A(\boldsymbol{x}^\star(\lambda)) =$$

$$4\boldsymbol{d}^\top\big(\boldsymbol{D}-\lambda\boldsymbol{J}\big)^{-\top}\boldsymbol{A}\big(\boldsymbol{D}-\lambda\boldsymbol{J}\big)^{-1}\boldsymbol{d} - 4\boldsymbol{a}^\top\big(\boldsymbol{D}-\lambda\boldsymbol{J}\big)^{-1}\boldsymbol{d} + \alpha = 0 \,\Big|\, \cdot \Big[\underbrace{\det\big(\boldsymbol{D}-\lambda\boldsymbol{J}\big)}_{\propto\lambda^2}\Big]^2$$

$$\Longrightarrow \boxed{\chi(\lambda) := c_4\,\lambda^4 + c_3\,\lambda^3 + c_2\,\lambda^2 + c_1\,\lambda + c_0 \overset{!}{=} 0}$$

$\Longrightarrow$ Analytical (real) solutions $\lambda^\star \in \{\lambda_1, \ldots, \lambda_4\}$ can be computed [103]:

$$\Longrightarrow \boxed{\boldsymbol{x}^\star(\lambda^\star) = -2\big(\boldsymbol{D} - \lambda^\star\boldsymbol{J}\big)^{-1}\,\boldsymbol{d}}$$

Implementation results

Laboratory setup

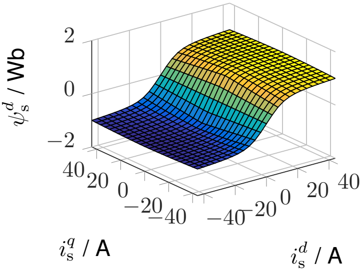
Reluctance SM (RSM) and Permanent-magnet SM

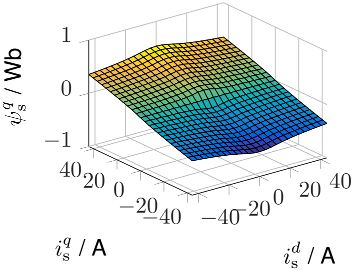
Host PC (rapid prototyping)

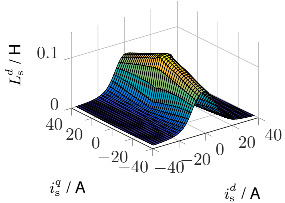
Real-time system and VSIs

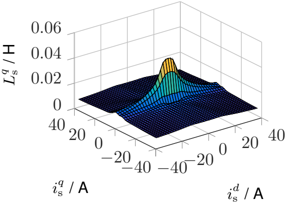
Implementation results

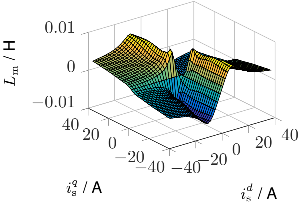
Nonlinear flux linkages and inductances of RSM





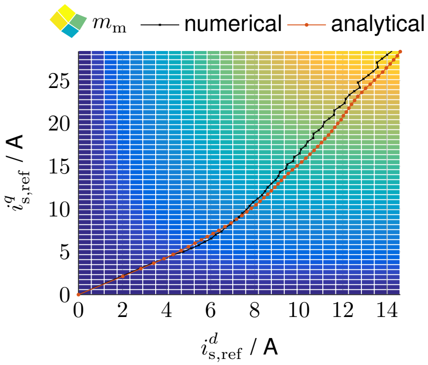




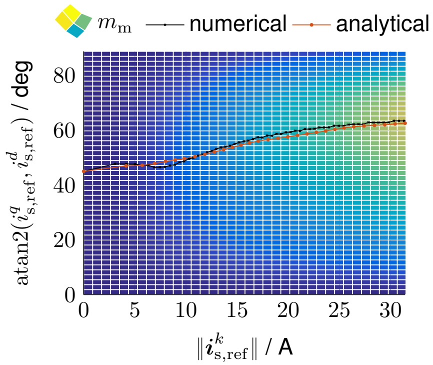


Implementation results

Comparison of numerical and analytical solutions for MTPC



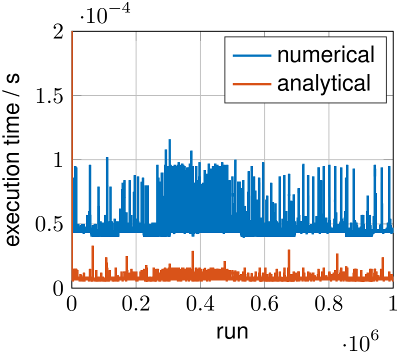
Cartesian coordinates

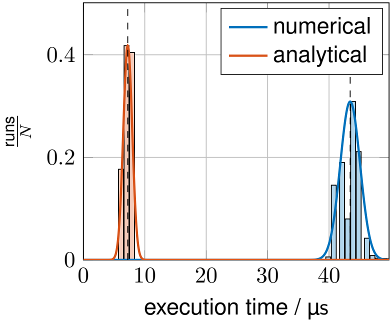


polar coordinates

Implementation results

Comparison of the computational load (Euler's solution for fourth-order polynomials)

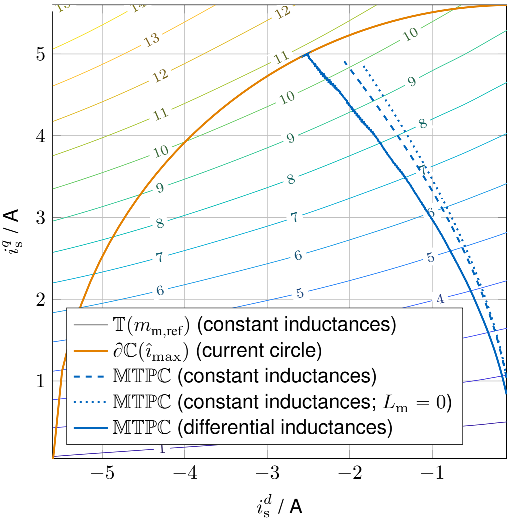




- Execution times for $N = 10^6$ runs (downsampled by factor 100);
- Average execution times $\mu_n = 43{,}4 \cdot 10^{-6}$ s and $\mu_a = 7{,}23 \cdot 10^{-6}$ s; and
- Standard deviations $\sigma_n = 1{,}61 \cdot 10^{-6}$ s and $\sigma_a = 0{,}73 \cdot 10^{-6}$ s.

Implementation results

MTPC at a IPMSM with non-negligible mutual inductance and nonlinear flux linkage



Conclusion

Summary and future work

To take home

- **unified** theory for MTPC, FW, MTPV/MTPF or MC based on
  - **quadrics** (implicit formulation),
  - **optimization problems** with **equality constraint**, and
  - **intersection** of two quadrics
- **analytical** solution for reference currents (& transition points)
- $R_\mathrm{s} \neq 0$ and $L_\mathrm{m} \neq 0$ (both can be considered **simultaneously**)
- **fast(er)** and **more accurate** computation
- **applicable** in real-world (nonlinear RSM and IPMSM)

Future work

- convergence (mathematical proof or consideration of nonlinear flux linkages)
- consideration of iron losses (including e.g. $R_\mathrm{fe}(\omega_\mathrm{k})$; article in preparation)
- impact of parameter uncertainty (e.g. $R_\mathrm{s}^a \neq R_\mathrm{s}^b \neq R_\mathrm{s}^c$; article in preparation)

References

Monograph published May 2017

References I

[1] Lorenz Horlbeck and Christoph Hackl. Analytical solution for the MTPV hyperbola including the stator resistance. In *Proceedings of the IEEE International Conference on Industrial Technology (ICIT 2016)*, pages 1060–1067, Taipei, Taiwan, 2016.

[2] Hisham Eldeeb, Christoph M. Hackl, and Julian Kullick. Efficient operation of anisotropic synchronous machines for wind energy systems. In *Proceedings of the 6th edition of the conference "The Science of Making Torque from Wind" (TORQUE 2016)*, Open access Journal of Physics: Conference Series 753 (2016) 112005, Munich, Germany, 2016.

[3] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. On the optimal feedforward torque control problem of anisotropic synchronous machines: Quadrics, quartics and analytical solutions. *arXiv:1611.01629 (see https://arxiv.org/pdf/1611.01629)*, 2016.

[4] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. A unified theory for optimal feedforward torque control of anisotropic synchronous machines. *submitted to International Journal of Control*, 2017.

[5] Christoph M. Hackl. A physics-based model of electro-active polymer actuators as the bases for a Gopinath-style motion state observer. Bachelorthesis, Lehrstuhl für Elektrische Antriebssysteme, Technische Universität München, Germany & Department of Mechanical Engineering and Department of Electrical & Computer Engineering, University of Wisconsin-Madison, USA, 2003.

[6] Christoph Hackl, H.-Y. Tang, R.D. Lorenz, L.-S. Turng, and Dierk Schröder. A multiphysics model of planar electro-active polymer actuators. In *Conference Record of the 39th IEEE Industrial Application Society Annual Meeting*, volume 3, pages 2125–2130. Institute of Electrical and Electronics Engineers (IEEE), 2004.

References II

[7] Christoph Hackl, H.-Y. Tang, R.D. Lorenz, L.-S. Turng, and Dierk Schröder. A multidomain model of planar electro-active polymer actuators. *IEEE Transactions on Industry Applications*, 41(5):1142–1148, sep 2005.

[8] Christoph M. Hackl and Beatrix Mair. Optimale Bahnzugregelung am Beispiel einer Papierstreichanlage. In *Konferenzband des 9. Bahnlaufseminar*, TU Chemnitz, Deutschland, 2007.

[9] Christoph M. Hackl and Beatrix Mair. Optimierung der Bahnspannungsregelung durch dezentrale Regelsysteme auf der Basis von moderner Mikroelektronik und intelligenter Software zur Steigerung der Produktionssicherheit und der Produktivität von Papierstreichanlagen. Abschlussbericht zum Forschungsvorhaben AiF/IGF 14140N, Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guerick" (AiF), 2007.

[10] Beatrix Mair and Christoph M. Hackl. Optimierung der Bahnspannungsregelung durch dezentrale Regelsysteme auf der Basis von moderner Mikroelektronik und intelligenter Software zur Steigerung der Produktionssicherheit und der Produktivität von Papierstreichanlagen. PTS Forschungsbericht, The Paper Technology Specialists, Hessstr. 134, 80797 München, Germany, 2007.

[11] Christoph M. Hackl and Beatrix Mair. Besser Bahnen ziehen – Optimale Bahnzugregelung mit dSPACE-Prototyping-System. *dSPACE Magazine*, 2:40–45, 2008.

[12] Christoph M. Hackl and Beatrix Mair. Smoothing the tension - optimal web tension control with a dSPACE prototyping system. *dSPACE Magazine*, 2:40–45, 2008.

[13] Christian Endisch, Christoph Hackl, and Dierk Schröder. Optimal brain surgeon for general dynamic neural networks. In José Neves, Manuel Filipe Santos, and José Manuel Machado, editors, *Progress in Artificial Intelligence*, volume 4974/2007 of *Lecture Notes in Artificial Intelligence*, pages 15–28. Springer-Verlag, Berlin, 2007.

References III

[14] Christian Endisch, Christoph Hackl, and Dierk Schröder. System identification with general dynamic neural networks and network pruning. *International Journal of Computational Intelligence*, 4(3):187–195, 2007.

[15] Christian. Endisch, Peter Stolze, Peter Endisch, Christoph M.. Hackl, and Ralph M. Kennel. Levenberg-Marquardt-based OBS algorithm using adaptive pruning interval for system identification with dynamic neural networks. In *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, pages 3402–3408, San Antonio, TX, USA, oct 2009. Institute of Electrical and Electronics Engineers (IEEE).

[16] C. Endisch, P. Stolze, C. Hackl, and D. Schröder. Comments on “Backpropagation algorithms for a broad class of dynamic networks”. *IEEE Transactions on Neural Networks*, 20(3):540–541, mar 2009.

[17] Mohamed Abdelrahem, Christoph M. Hackl, and Ralph Kennel. Application of extended Kalman filter to parameter estimation of doubly-fed induction generators in variable-speed wind turbine systems. In *Proceedings of the 5th International Conference on Clean Electrical Power (ICCEP 2015)*, pages 236–243, Taormina, Italy, 2015.

[18] Christoph M. Hackl. *Contributions to High-gain Adaptive Control in Mechatronics*. PhD thesis, Lehrstuhl für Elektrische Antriebssysteme und Leistungselektronik, Technische Universität München (TUM), Germany, 2012.

[19] Christoph M. Hackl. Dynamische Reibungsmodellierung: Das Lund-Grenoble (LuGre) Reibmodell. In Dierk Schröder, editor, *Elektrische Antriebe – Regelung von Antriebssystemen*, chapter 25, pages 1615–1657. Springer-Verlag, 2015.

References IV

[20] Hans Schuster, Christoph M. Hackl, Christian Westermaier, and Dierk Schröder. Funnel-control for electrical drives with uncertain parameters. In *Proceedings of the 7th International Power Engineering Conference (IPEC)*, pages 15–22, Singapore, 2005. Institute of Electrical and Electronics Engineers (IEEE).

[21] Christoph M. Hackl and Dierk Schröder. Extension of high-gain controllable systems for improved accuracy. In *Proceedings of the 2006 IEEE International Conference on Control Applications (CCA 2006)*, pages 2231–2236, Munich, Germany, oct 2006. Institute of Electrical and Electronics Engineers (IEEE).

[22] Christoph M. Hackl and Dierk Schröder. Funnel-control for nonlinear multi-mass flexible systems. In *Proceedings of the 32nd Annual Conference on IEEE Industrial Electronics*, pages 4707–4712. Institute of Electrical and Electronics Engineers (IEEE), nov 2006.

[23] Christoph M. Hackl, Hans Schuster, Christian Westermaier, and Dierk Schröder. Funnel-control with integrating prefilter for nonlinear, time-varying two-mass flexible servo systems. In *Proceedings of the 9th International Workshop on Advanced Motion Control*, pages 456–461, Istanbul, Turkey, 2006. Institute of Electrical and Electronics Engineers (IEEE).

[24] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Enhanced funnel-control with improved performance. In *Proceedings of the 15th Mediterranean Conference on Control and Automation*, pages Paper T01–016, Athens, Greece, jun 2007. Institute of Electrical and Electronics Engineers (IEEE).

[25] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Funnel-control with constrained control input compensation. In *Proceedings of the 9th IASTED International Conference CONTROL AND APPLICATIONS*, pages 147–152, Montreal, Quebec, Canada, 2007.

References V

[26] Christoph M. Hackl, Yang Ji, and Dierk Schröder. Nonidentifier-based adaptive control with saturated control input compensation. In *Proceedings of the 15th Mediterranean Conference on Control and Automation*, pages Paper T01–15, Athens, Greece, jun 2007. Institute of Electrical and Electronics Engineers (IEEE).

[27] Christoph M. Hackl and Dierk Schröder. Funnel-control with online foresight. In *Proceedings of the 26th IASTED International Conference MODELLING, IDENTIFICATION AND CONTROL*, pages 171–176, Innsbruck, Austria, 2007.

[28] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Specially designed funnel-control in mechatronics. In *Proceedings of the 5th International Conference on Computational Intelligence, Robotics and Autonomous Systems*, pages 59–64, 2008.

[29] Christoph M. Hackl. Funnel Control: Implementierung, Erweiterung und Anwendung. In Dierk Schröder, editor, *Intelligente Verfahren: Systemidentifikation und Regelung nichtlinearer Systeme*, pages 697–760. Springer-Verlag, Berlin, 2010.

[30] Christoph M. Hackl and Stephan Trenn. The bang-bang funnel controller: An experimental verification. *PAMM*, 12(1):735–736, dec 2012.

[31] Christoph M. Hackl, Norman Hopfe, Achim Ilchmann, Markus Mueller, and Stephan Trenn. Funnel control for systems with relative degree two. *SIAM Journal on Control and Optimization*, 51(2):965–995, jan 2013.

[32] Christoph M. Hackl. Funnel control for wind turbine systems. In *Proceedings of the 2014 IEEE International Conference on Control Applications (CCA 2014)*, pages 1377–1382, Antibes, France, oct 2014. Institute of Electrical and Electronics Engineers (IEEE).

References VI

[33] Christoph M. Hackl. Current PI-funnel control with anti-windup for synchronous machines. In *Proceedings of the 54th IEEE Conference on Decision and Control (CDC 2015)*, pages 1997–2004, Osaka, Japan, dec 2015. Institute of Electrical and Electronics Engineers (IEEE).

[34] Christoph M. Hackl. Speed funnel control with disturbance observer for wind turbine systems with elastic shaft. In *Proceedings of the 54th IEEE Conference on Decision and Control (CDC 2015)*, pages 2005–2012, Osaka, Japan, 2015.

[35] Christoph M. Hackl. *Non-identifier based adaptive control in mechatronics: Theory and Application*. Number 466 in Lecture Notes in Control and Information Sciences. Springer International Publishing, Berlin, 2017.

[36] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Applicability of funnel-control in robotics. In *Proceedings of the 5th International Conference on Computational Intelligence, Robotics and Autonomous Systems*, pages 65–70, Linz, Austria, 2008.

[37] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Funnel-control in robotics: An introduction. In *Proceedings of the 16th Mediterranean Conference on Control and Automation*, pages 913–919, Ajaccio, France, jun 2008. Institute of Electrical and Electronics Engineers (IEEE).

[38] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Contributions to non-identifier based adaptive control in mechatronics. *Robotics and Autonomous Systems, Elsevier*, 57(10):996–1005, 2009.

[39] Christoph M. Hackl and Dierk Schröder. Non-identifier based adaptive control in robotics: An introduction. In Salvatore Pennacchio, editor, *Recent adavances in Control Systems, Robotics and Automation*, volume 1. INTERNATIONALSAR International Society for Advanced Research, Palermo, Italy, third edition, 2009.

References VII

[40] Christoph M. Hackl. High-gain adaptive position control. *International Journal of Control*, 84(10):1695–1716, oct 2011.

[41] Christoph M. Hackl, Andreas G. Hofmann, Rik W. De Doncker, and Ralph M. Kennel. Funnel control for speed & position control of electrical drives: A survey. In *Proceedings of the 19th Mediterranean Conference on Control & Automation (MED)*, pages 181–188, Corfu Island, Greece, jun 2011. Institute of Electrical and Electronics Engineers (IEEE).

[42] Christoph M. Hackl, Andreas G. Hofmann, and Ralph M. Kennel. Funnel control in mechatronics: An overview. In *Proceedings of the 50th IEEE Conference on Decision and Control (CDC) and European Control Conference (ECC)*, pages 8000–8007, Orlando, FL, USA, dec 2011. Institute of Electrical and Electronics Engineers (IEEE).

[43] Christoph M. Hackl. 'Funnel control' zur Positionsregelung von starren Drehgelenkrobotern mit grob bekannter Trägheitsmatrix. In *Tagungsband des GMA-Fachausschuss 1.40*, pages 302–310, Anif, Austria, 2012.

[44] Christoph M. Hackl and Ralph M. Kennel. Position funnel control for rigid revolute joint robotic manipulators with known inertia matrix. In *Proceedings of the 20th Mediterranean Conference on Control and Automation*, pages 615–620, Barcelona, Spain, jul 2012. Institute of Electrical and Electronics Engineers (IEEE).

[45] Christoph M. Hackl and Ralph M. Kennel. Position funnel control with linear internal model. In *Proceedings of 2012 IEEE International Conference on Control Applications (CCA 2012)*, pages 1334–1339, Dubrovnik, Croatia, oct 2012. Institute of Electrical and Electronics Engineers (IEEE).

References VIII

[46] Timm Faulwasser and Christoph M. Hackl. Path-following funnel control for rigid-link revolute-joint robotic systems. In *Proceedings of the 21st International Symposium on Mathematical Theory of Networks and Systems*, pages 1044–1051, Groningen, Netherlands, 2014.

[47] Christoph M. Hackl, Florian Larcher, Alexander Dötlinger, and Ralph. M. Kennel. Is multiple-objective model-predictive control "optimal"? In *Proceedings of the 2013 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE 2013)*, pages 1–8, Munich, Germany, oct 2013. Institute of Electrical and Electronics Engineers (IEEE).

[48] Z. Zhang, C. Hackl, F. Wang, Z. Chen, and R. Kennel. Encoderless model predictive control of back-to-back converter direct-drive permanent-magnet synchronous generator wind turbine systems. In *Proceedings of 15th European Conference on Power Electronics and Applications*, pages 1–10. Institute of Electrical and Electronics Engineers (IEEE), sep 2013.

[49] Mohamed Abdelrahem, Christoph M. Hackl, and Ralph Kennel. Sensorless control of doubly-fed induction generators in variable-speed wind turbine systems. In *Proceedings of the 5th International Conference on Clean Electrical Power (ICCEP)*, pages 423–430, Taormina, Italy, jun 2015. Institute of Electrical and Electronics Engineers (IEEE).

[50] Christian Dirscherl, Josef Fessler, Christoph Hackl, and Hanko Ipach. State-feedback control and observer design of grid-connected power inverters with LCL-filter. In *Proceedings of the 5th Colloquium of the Munich School of Engineering*, Garching, Germany, 2015.

[51] Christian Dirscherl, Josef Fessler, Christoph M. Hackl, and Hanko Ipach. State-feedback controller and observer design for grid-connected voltage source power converters with LCL-filter. In *Proceedings of the 2015 IEEE International Conference on Control Applications (CCA 2015)*, pages 215–222, Sydney, Australia, sep 2015. Institute of Electrical and Electronics Engineers (IEEE).

References IX

[52] Christian Dirscherl, Christoph Hackl, and Korbinian Schechner. Modellierung und Regelung von modernen Windkraftanlagen: Eine Einführung (see https://arxiv.org/abs/1703.08661 for the english translation). In Dierk Schröder, editor, *Elektrische Antriebe – Regelung von Antriebssystemen*, chapter 24, pages 1540–1614. Springer-Verlag, 2015.

[53] Christian Dirscherl, Christoph Hackl, and Korbinian Schechner. Explicit model predictive control with disturbance observer for grid-connected voltage source power converters. In *Proceedings of the 2015 IEEE International Conference on Industrial Technology (ICIT 2015)*, pages 999–1006. Institute of Electrical and Electronics Engineers (IEEE), mar 2015.

[54] Christian Dirscherl, Christoph M. Hackl, and Korbinian Schechner. Pole-placement based nonlinear state-feedback control of the DC-link voltage in grid-connected voltage source power converters: A preliminary study. In *Proceedings of the 2015 IEEE International Conference on Control Applications (CCA 2015)*, pages 207–214, Sydney, Australia, sep 2015. Institute of Electrical and Electronics Engineers (IEEE).

[55] Christoph M. Hackl. MPC with analytical solution and integral error feedback for LTI MIMO systems and its application to current control of grid-connected power converters with LCL-filter. In *Proceedings of the 2015 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE 2015)*, pages 61–66, Valparaiso, Chile, oct 2015. Institute of Electrical and Electronics Engineers (IEEE).

[56] Zhenbin Zhang, Hue Xu, M. Xue, Z. Chen, T. Sun, Ralph Kennel, and Christoph Hackl. Predictive control with novel virtual flux estimation for back-to-back power converters. *IEEE Transactions on Industrial Electronics*, 62(5):2823–2834, may 2015.

References X

[57] Ayman Ayad, Mohamed Hashem, Christoph Hackl, and Ralph Kennel. Proportional-resonant controller design for quasi-Z-source inverters with LC filters. In *Proceedings of the 42nd IEEE Industrial Electronics Conference (IECON 2016)*, Firenze, Italy, 2016.

[58] Christoph M. Hackl. On the equivalence of proportional-integral and proportional-resonant controllers with anti-windup. 2016.

[59] Josh C. Mitchell, Maarten J. Kamper, and Christoph M. Hackl. Small-scale reluctance synchronous generator variable speed wind turbine system with DC transmission linked inverters. In *Proceedings of the IEEE Energy Conversion Congress & Exposition (ECCE)*, pages xxxx–xxxx, Milwaukee, WI, USA, 2016.

[60] Zhenbin Zhang, Christoph Hackl, Mohamed Abdelrahem, and Ralph Kennel. Voltage sensorless direct model predictive control of 3L-NPC back-to-back power converter PMSG wind turbine systems with fast dynamics. In *Proceedings of the Power Electronics Student Summit (PESS 2016)*, Aachen, Germany, 2016.

[61] Zhenbin Zhang, Christoph Hackl, and Ralph Kennel. Computationally efficient DMPC for three-level NPC back-to-back converters in wind turbine systems with PMSG. *IEEE Transactions on Power Electronics*, 32:8018–8034, 2017.

[62] Zhenbin Zhang, Christoph Hackl, and Ralph Kennel. FPGA based direct model predictive current control of PMSM drives with 3L-NPC power converters. In *Proceedings of the PCIM Europe 2016*, Nuremberg, Germany, 2016.

References XI

[63] Zhenbin Zhang, Ralph Kennel, and Christoph Hackl. Computationally efficient direct model predictive control for three-level NPC back-to-back converter PMSG wind turbine systems. In *Proceedings of the 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2016)*, pages 1045–1050, Anacapri, Italy, jun 2016. Institute of Electrical and Electronics Engineers (IEEE).

[64] Zhenbin Zhang, Ralph Kennel, and Christoph M. Hackl. Performance-enhanced direct multiple-vector model predictive power control for grid-tied AFEs. In *Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, pages 2904–2909, Hefei, China, may 2016. Institute of Electrical and Electronics Engineers (IEEE).

[65] Florian Bauer, Christoph M. Hackl, Keyue Ma Smedley, and Ralph M. Kennel. Multicopter with series connected propeller drives. *IEEE Transactions on Control Systems Technology*, pages 1–12, 2017.

[66] Korbinian Schechner, Florian Bauer, and Christoph M. Hackl. Nonlinear DC-link PI control for airborne wind energy systems during pumping mode. In Roland Schmehl, editor, *Airborne Wind Energy: Advances in Technology Development and Research*. Springer Singapore, 2017.

[67] Christoph M. Hackl, Christian Endisch, and Dierk Schröder. Error reference control of nonlinear two-mass flexible servo systems. In *Proceedings of the 16th Mediterranean Conference on Control and Automation*, pages 1047–1053, Ajaccio, France, jun 2008. Institute of Electrical and Electronics Engineers (IEEE).

[68] Peter Landsmann, Christoph M. Hackl, and Ralph M. Kennel. Eliminating all machine parameters in encodersless predictive torque control without signal injection. In *Proceedings of the 2011 IEEE International Electric Machines and Drives Conference*, pages 1259–1264. Institute of Electrical and Electronics Engineers (IEEE), may 2011.

References XII

[69] Christoph M. Hackl. Funnel control with disturbance observer for two-mass systems. In *Proceedings of the 52nd IEEE Conference on Decision and Control (CDC)*, pages 6244–6249, Florence, Italy, dec 2013. Institute of Electrical and Electronics Engineers (IEEE).

[70] Christoph M. Hackl. PI-funnel control with Anti-windup and its application for speed control of electrical drives. In *Proceedings of the 52nd IEEE Conference on Decision and Control (CDC)*, pages 6250–6255, Florence, Italy, dec 2013. Institute of Electrical and Electronics Engineers (IEEE).

[71] Christian Dirscherl, Christoph M. Hackl, and Korbinian Schechner. Modeling and control of wind turbine systems with permanent-magnet synchronous generators (PMSG) and doubly fed induction generators (DFIG). In *Proceedings of the 4th Colloquium of the Munich School of Engineering*, Garching, Germany, 2014.

[72] Christoph M. Hackl. Klein-Windkraftanlagen mit effizienter und kostengünstiger Generatortopologie für Micro-Grids: Eine Voruntersuchung. In *Poster auf der Jahresversammlung des Bundes der Freunde der Technischen Universität München e.V.*, Munich, Germany, 2014.

[73] Christoph Hackl and Korbinian Schechner. Non-ideal torque control in wind turbine systems: Causes and impacts. In *Proceedings of the 5th Colloquium of the Munich School of Engineering*, Garching, Germany, 2015.

[74] Christoph M. Hackl, Maarten J. Kamper, Julian Kullick, and Joshua Mitchell. Nonlinear PI current control of reluctance synchronous machines. 2015.

[75] Christoph M. Hackl and Korbinian Schechner. Non-ideal torque control in wind turbine systems: Causes and impacts. In *Proceedings of the 5^{th} MSE-Kolloquium on "Innovations for Energy Systems, Mobility, Buildings and Materials"*, Munich, Germany, 2015.

References XIII

[76] Mohamed Abdelrahem, Christoph M. Hackl, and Ralph Kennel. Encoderless model predictive control of doubly-fed induction generators in variable-speed wind turbine systems. In *Proceedings of the 6th edition of the conference "The Science of Making Torque from Wind" (TORQUE 2016)*, Open access Journal of Physics: Conference Series 753 (2016) 112005, Munich, Germany, 2016.

[77] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. On the optimal feedforward torque control problem of anisotropic synchronous machines: Quadrics, quartics and analytical solutions. 2016.

[78] Hisham Eldeeb, Christoph M. Hackl, and Julian Kullick. Efficient operation of anisotropic synchronous machines for wind energy systems. In *Proceedings of the 6th edition of the conference "The Science of Making Torque from Wind" (TORQUE 2016)*, Open access Journal of Physics: Conference Series 753 (2016) 112005, Munich, Germany, 2016.

[79] Christoph M. Hackl, Maarten J. Kamper, Julian Kullick, and Joshua Mitchell. Current control of reluctance synchronous machines with online adjustment of the controller parameters. In *Proceedings of the 2016 IEEE International Symposium on Industrial Electronics (ISIE 2016)*, pages 153–160, Santa Clara, CA, USA, jun 2016. Institute of Electrical and Electronics Engineers (IEEE).

[80] Lorenz Horlbeck and Christoph M. Hackl. Analytical solution for the MTPV hyperbola including the stator resistance. In *Proceedings of the IEEE International Conference on Industrial Technology (ICIT 2016)*, pages 1060–1067, Taipei, Taiwan, mar 2016. Institute of Electrical and Electronics Engineers (IEEE).

[81] Zhenbin Zhang, Ralph Kennel, and Christoph M. Hackl. Two direct torque and power control methods for back-to-back power converter PMSG wind turbine systems. In *Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, pages 1515–1520, Hefei, China, may 2016. Institute of Electrical and Electronics Engineers (IEEE).

References XIV

[82] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. A unified theory for optimal feedforward torque control of anisotropic synchronous machines. *International Journal of Control*, 2017.

[83] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. Analytical solutions for the optimal reference currents for MTPC/MTPA, MTPV and MTPF control of anisotropic synchronous machines. In *Proceedings of the IEEE International Electric Machines & Drives Conference (IEMDC 2017)*, pages xxx–xxx, Miami, FL, USA, 2017.

[84] Mohamed Abdelrahem, Christoph Michael Hackl, and Ralph Kennel. Implementation and experimental investigation of a sensorless field-oriented control scheme for permanent-magnet synchronous generators. *Electrical Engineering*, may 2017.

[85] Florian Bauer, Christoph M. Hackl, and Korbinian Schechner. DC-link control for airborne wind energy systems during pumping mode. In *Proceedings of the Airborne Wind Energy Conference (AWEC 2015)*, Delft, Netherlands, 2015.

[86] Mohamed Abdelrahem, Christoph M. Hackl, and Ralph Kennel. Model predictive control of permanent magnet synchronous generators in variable-speed wind turbine systems. In *Proceedings of the Power Electronics Student Summit (PESS 2016)*, Aachen, Germany, 2016.

[87] Mohamed Abdelrahem, Christoph Michael Hackl, and Ralph Kennel. Simplified model predictive current control without mechanical sensors for variable-speed wind energy conversion systems. *Electrical Engineering*, 99(1):367–377, 2016.

[88] Mohamed Abdelrahem, Christoph M. Hackl, Zhenbin Zhang, and Ralph Kennel. Sensorless control of permanent magnet synchronous generators in variable-speed wind turbine systems. In *Proceedings of the Power Electronics Student Summit (PESS 2016)*, Aachen, Germany, 2016.

References XV

[89] Florian Bauer, Christoph M. Hackl, Keyue Smedley, and Ralph Kennel. Crosswind kite power with tower. In Roland Schmehl, editor, *Airborne Wind Energy: Advances in Technology Development and Research*. Springer-Verlag, 2016.

[90] Florian Bauer, Christoph M. Hackl, Keyue Smedley, and Ralph Kennel. On multicopter-based launching and landing of lift power kites. In Roland Schmehl, editor, *Airborne Wind Energy: Advances in Technology Development and Research*. Springer-Verlag, 2016.

[91] Florian Bauer, Christoph M. Hackl, K. Smedley, and Ralph Kennel. Virtual-power-hardware-in-the-loop simulations in crosswind kite power with ground generation. In *Proceedings of the 2016 American Control Conference (ACC)*, pages 4071–4076, Boston, FL, USA, jul 2016. Institute of Electrical and Electronics Engineers (IEEE).

[92] Christian Dirscherl and Christoph M. Hackl. Dynamic power flow in wind turbine systems with doubly-fed induction generator. In *Proceedings of the 2016 IEEE International Energy Conference (ENERGYCON 2016)*, pages 1–6, Leuven, Beglium, apr 2016. Institute of Electrical and Electronics Engineers (IEEE).

[93] Christoph M. Hackl and Korbinian Schechner. Non-ideal feedforward torque control of wind turbines: Impacts on annual energy production & gross earnings. In *Proceedings of the 6th edition of the conference "The Science of Making Torque from Wind" (TORQUE 2016)*, volume 753 of *Open access Journal of Physics: Conference Series 753 (2016) 112005*, page 112010, Munich, Germany, sep 2016. IOP Publishing.

[94] Christoph M. Hackl and Korbinian Schechner. Non-ideal torque control of wind turbine systems: Impacts on annual energy production. 2016.

[95] D. Schröder and C.M. Hackl. Grundlagen der Regelungstechnik. IHK Schwaben, Mechatronik Weiterbildung, 2009.

References XVI

[96] Christoph Hackl. *Bewegungssteuerung durch geregelte elektrische Antriebe (Übung)*. Lehrstuhl für Elektrische Antriebe und Leistungselektronik – Technische Universität München, 2013.

[97] Christoph M. Hackl. Projektbezogen Studieren – Aktives Lernen im Team: Projektstudium Antriebstechnik (Vorlesungsskriptum und Versuchsanleitung). online, 2014. Lehrmaterialien zur Umsetzung des Ernst-Otto Fischer Lehrpreises 2013 im Wintersemester 2014/2015 an der Technischen Universität München.

[98] Christoph M. Hackl. Regelung von regenerativen Energiesystemen (Vorlesungsskriptum und Übungsaufgaben). online, 2014. Lehrmaterialien zur Veranstaltung "Regelung von regenerativen Energiesystemen" im Wintersemester 2013/2014 an der Technischen Universität München.

[99] Christoph Hackl, Ellen Taraba, and Anne-Marie Fleischmann. Projektbezogen Studieren – Aktives Lernen im Team: Fachliche und überfachliche Kompetenzen von Studierenden fördern. In *Proceedings of the 2. HD-MINT-Symposium Hochschuldidaktik für MINT-Fächer (Nürnberg, Germany)*, 2015.

[100] Christoph M. Hackl, Anne-Marie Fleischmann, and Ellen Taraba. Projektstudium Antriebstechnik: Projektbezogen Studieren – Aktives Lernen im Team. In *Tagungsband des 5. VDI Qualitätsdialogs Lehre - Studienerfolg verbessern*, Tagungswerk Jerusalemkirche, Berlin, Germany, 2015.

[101] Christoph Hackl, Anne-Marie Lickert, and Ellen Taraba. Projektbezogen Studieren – Aktives Lernen im Team. In *Neues Handbuch Hochschullehre*, volume 76, pages 31–44. DUZ Medienhaus, 2016.

[102] Shigeo Morimoto. Trend of permanent magnet synchronous machines. *IEEJ Transactions on Electrical and Electronic Engineering*, 2(2):101–108, mar 2007.

[103] R.W.D Nickalls. The quartic equation: Invariants and Euler's solution revealed. *Mathematical Gazette*, 93(526):66–75, 2009.