Hochschule
München (HM)
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

Modern electrical drives

Nonlinear Modelling, Dynamic Simulation, High-Performance Control and Optimal Operation

Christoph M. Hackl (with whole LMRES team)
christoph.hackl@hm.edu

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ISES

Outline

1 Introduction

2 Motivation

3 Nonlinear modelling

4 Dynamic simulation

5 High-performance control

6 Optimal operation

7 Conclusion

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1 Introduction
- HM research environment
- LMRES research activities
- LMRES research interests

Introduction: HM research environment

HM (www.hm.edu), ISES (ises.hm.edu) and LMRES (lmres.ee.hm.edu)

HM – Munich University of Applied Sciences

- 14 departmens
- >18.000 students
- ~480 professors
- 3 campuses

ISES – Institute for Sustainable Energy Systems

- 8 research labs (8 professors)
- 34 PhD candidates

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

- International team
- 15 PhD candidates (status 2024)
- >150 publications / >8.3 Mio. € raised

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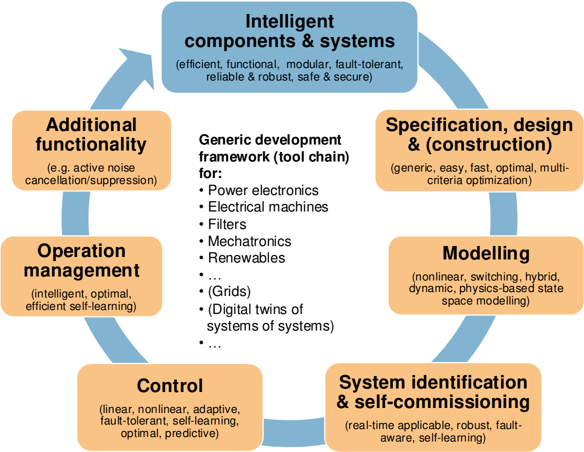
Introduction: LMRES research activities

Research projects and research goals (funding: > 8.3 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)



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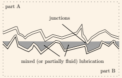
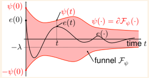
Introduction: LMRES research interests

Interdisciplinary expertise & publications

System identification [9–26]



Fric-tion [27–29]



Non-identifier based adaptive control [14, 27, 30–46]

Paper coating machines [4–8]

Supervision & teaching (Award) [157–163]

Mechatronics & robotics [27, 28, 40, 46–58]

Mechatronic and renewable energy systems

Electro-active polymers [1–3]

Power electronics [19–21, 46, 58–88]

Wind energy, renewables & smart grid [13–15, 44, 46, 57, 58, 60, 61, 67, 68, 70–72, 74, 79, 85, 93–95, 98, 100, 107, 112, 120, 132, 136, 139–156]

Electrical machines & drives [13, 15, 17, 23–27, 30, 32, 33, 45, 46, 51, 55, 57, 69, 77, 78, 80, 89–138]

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- Emerging applications of electrical drives
- Electrical machines — widely-used, compact and efficient actuators
- Core components of mechatronic system
- Motion control via mechatronic actuators
- Block diagram of mechatronic actuator
- Overall control system

Motivation

Emerging applications of electrical drives: Electrical drives are **the** mechatronic actuators of the future

(a) Full-electric vehicles (e-mobility).

(b) Mobile (industrial) robots.

(c) Autonomous, full-electric tractor (farming).

(d) Full-electric aircraft.

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Motivation

Electrical machines — widely-used, compact and efficient actuators


www.miele.de


www.farmwood.co.uk


www.abb.com (from video)


www.siemens.com


www.bmw.de


www.siemens.com


www.siemens.com


www.lilium.com

- household and buildings (e.g. wasching machines, air conditioning or fans)
- industrial applications (e.g. pumps, milling, grinding)
- traction drives (e.g. electric vehicles, trains, etc.)
- power generation (e.g. conventional power plants or wind turbine systems)
- (more) electric aircrafts
- ...

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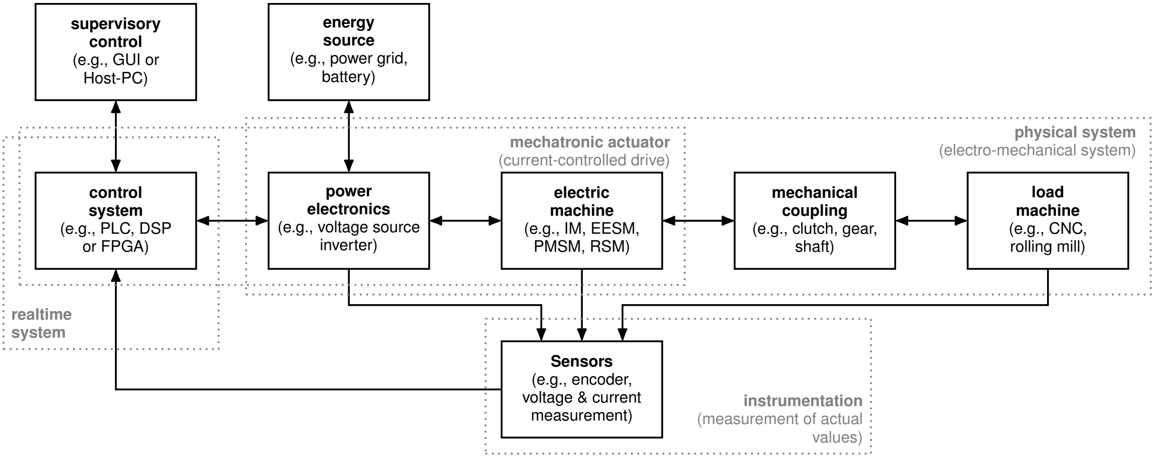
Motivation

Core components of mechatronic system



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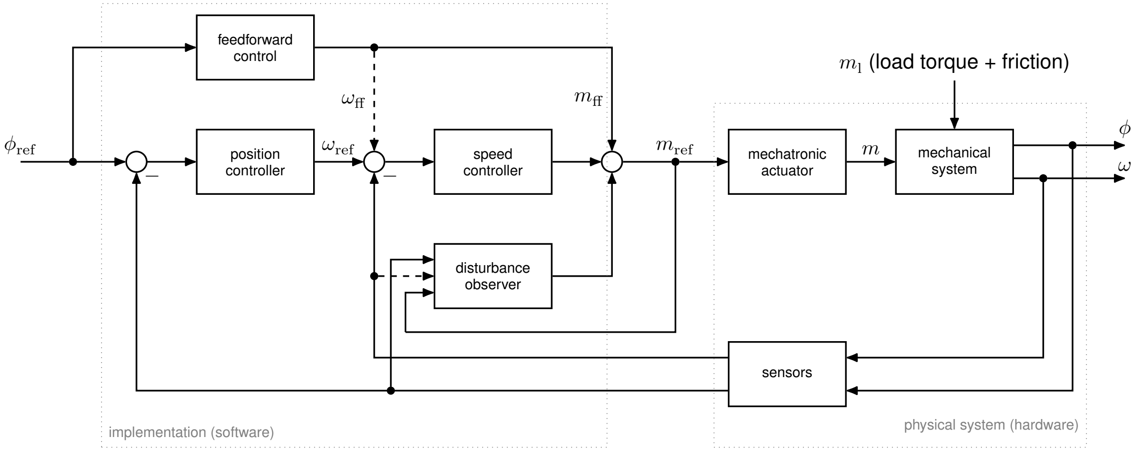
Motion control via mechatronic actuators



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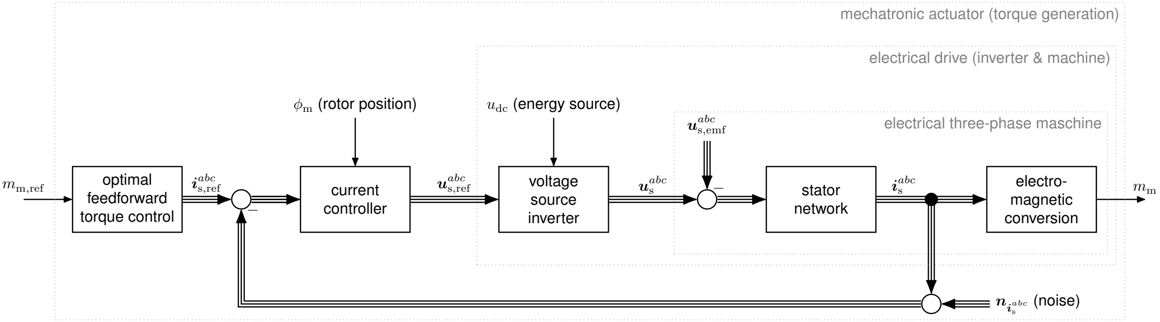
Motivation

Block diagram of mechatronic actuator (e.g., with electrical three-phase machine)



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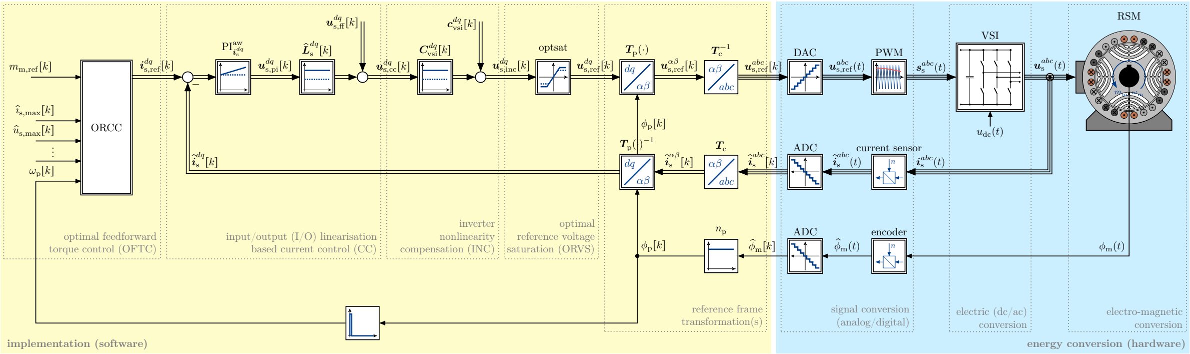
Motivation

Overall control system (e.g., for Reluctance Synchronous Machine (RSM))



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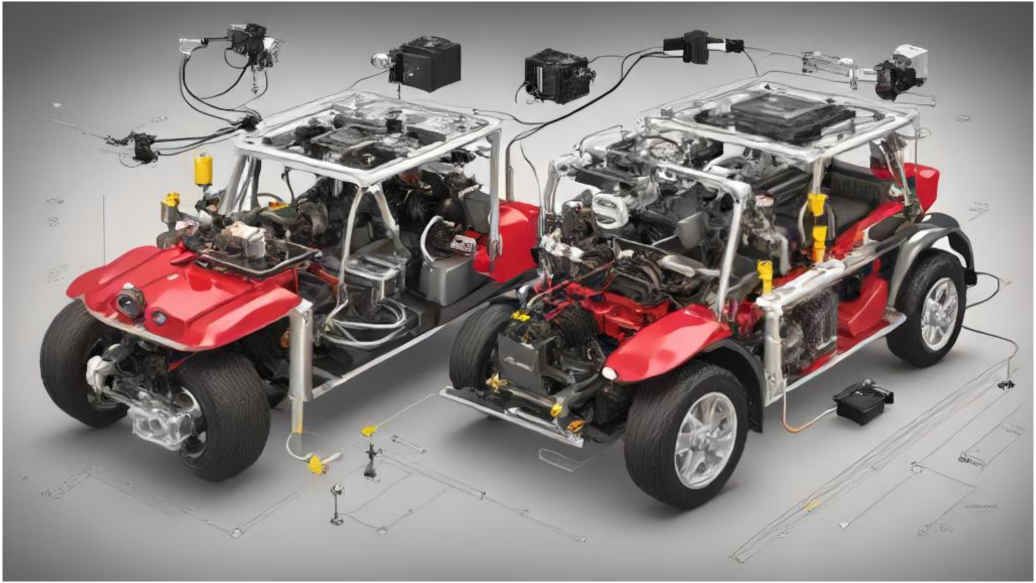
- Two-level voltage source inverter (2L-VSI)
  - Electrical circuit
  - Switching model
  - Modulation
  - Dynamics and its approximation
- Electrical machine
  - Key equations
  - Reference frames
  - Generic machine dynamics
  - Equivalent circuit

Nonlinear modelling: Motivation

Output of DeepAI Figure Generator (prompted with “Electric vehicle with motor, power electronics & battery”)



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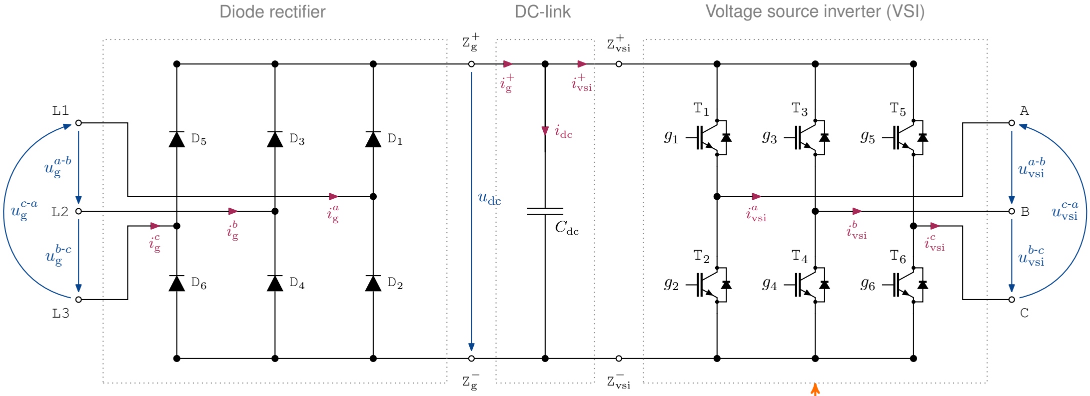
Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

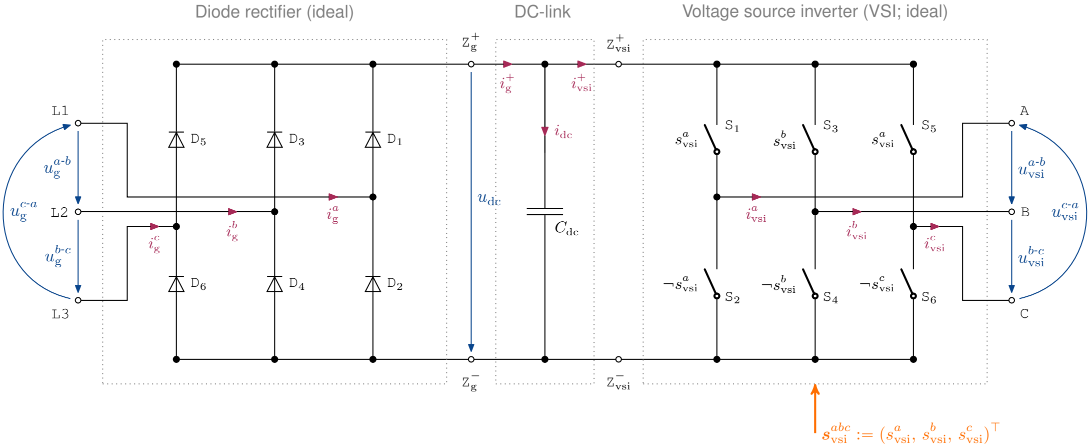
Electrical circuit with rectifier



$\boldsymbol{g} := (g_1, g_2, \ldots, g_5, g_6)^\top$

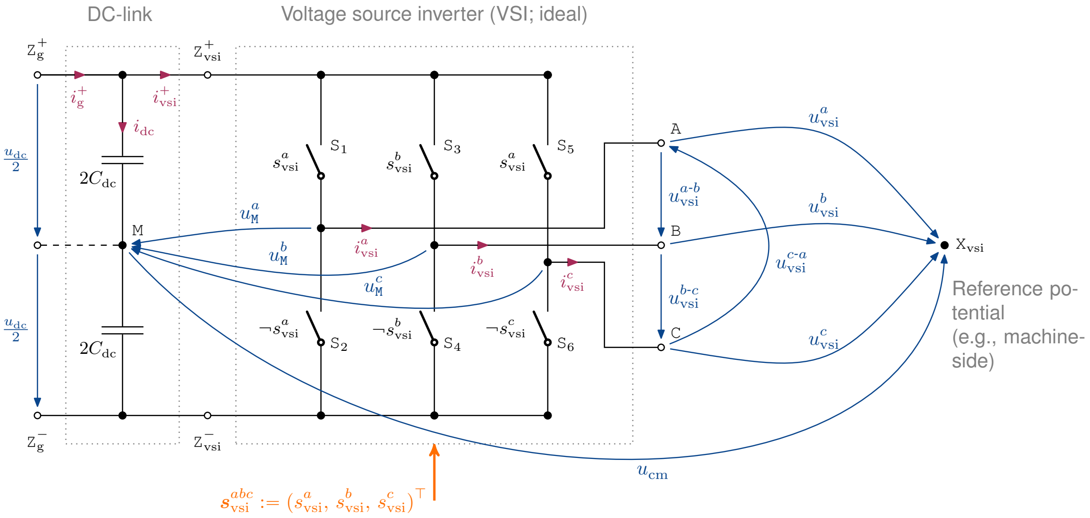
Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Electrical circuit with rectifier (ideal semi-conductors)



Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Electrical circuit with split dc-link and mid-point voltages (ideal switches)



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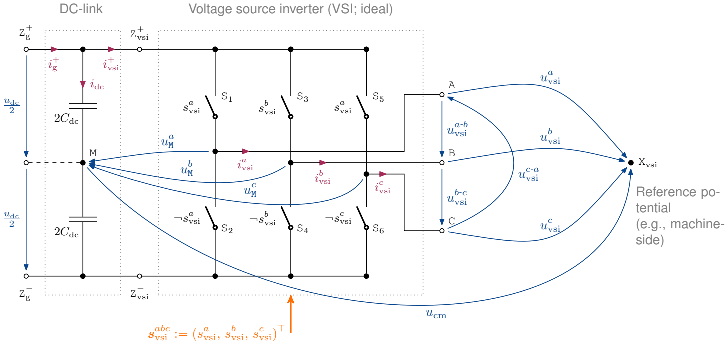
Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Switching model (as matrix-vector product)



☞ **This model can easily and modularly be extended to include conduction and switching losses as well [164].**

$$u_{vsi}^{a\text{-}b\text{-}c} = \begin{pmatrix} u_{vsi}^{a\text{-}b} \\ u_{vsi}^{b\text{-}c} \\ u_{vsi}^{c\text{-}a} \end{pmatrix} = u_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \boldsymbol{s}_{vsi}^{abc}$$

$$u_{vsi}^a + u_{vsi}^b + u_{vsi}^c = 0 \Longrightarrow \quad \boldsymbol{u}_{vsi}^{abc} = \frac{u_{dc}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \boldsymbol{s}_{vsi}^{abc} = \underbrace{u_{dc}\left(\boldsymbol{s}_{vsi}^{abc} - \tfrac{1}{2}\mathbf{1}_3\right)}_{=:\boldsymbol{u}_M^{abc}} + \mathbf{1}_3 u_{cm}$$

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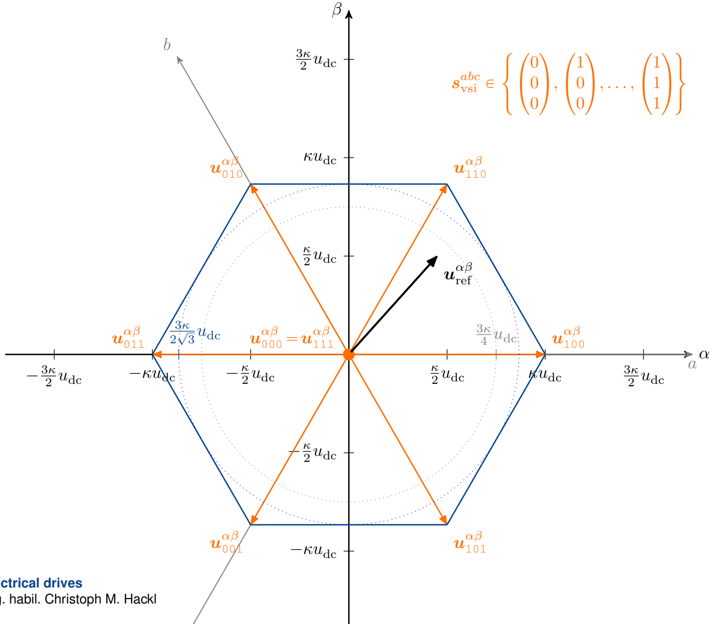
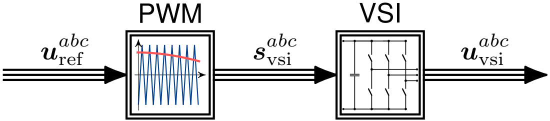
Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

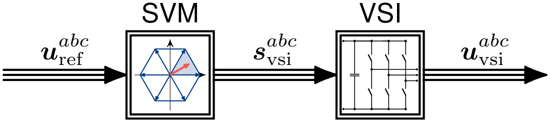
Modulation: Voltage hexagon



Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Modulation: Pulse Width Modulation (PWM) and Space Vector Modulation (SVM)





Switching signal vector

$$\boldsymbol{s}_{\mathrm{vsi}}^{abc} = \begin{pmatrix} s_{\mathrm{vsi}}^{a} \\ s_{\mathrm{vsi}}^{b} \\ s_{\mathrm{vsi}}^{c} \end{pmatrix} = \begin{pmatrix} \sigma\left(\frac{u_{\mathrm{ref}}^{a}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \\ \sigma\left(\frac{u_{\mathrm{ref}}^{b}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \\ \sigma\left(\frac{u_{\mathrm{ref}}^{c}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \end{pmatrix}$$

with Heaviside function

$$\sigma(x) := \begin{cases} 1 & , \quad x \geqslant 0 \\ 0 & , \quad x < 0 \end{cases}$$

Switching signal vector

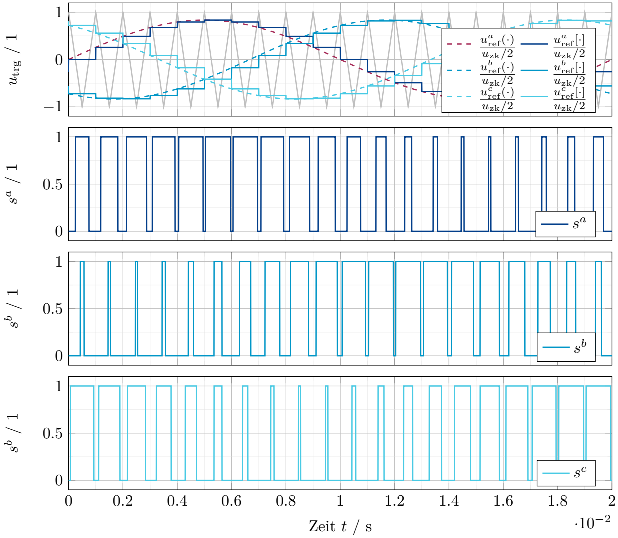
$$\boldsymbol{s}_{\mathrm{vsi}}^{abc} = \begin{pmatrix} \sigma\left(\frac{u_{\mathrm{ref,svm}}^{a}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \\ \sigma\left(\frac{u_{\mathrm{ref,svm}}^{b}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \\ \sigma\left(\frac{u_{\mathrm{ref,svm}}^{c}}{u_{\mathrm{dc}}/2} - u_{\mathrm{car}}\right) \end{pmatrix}$$

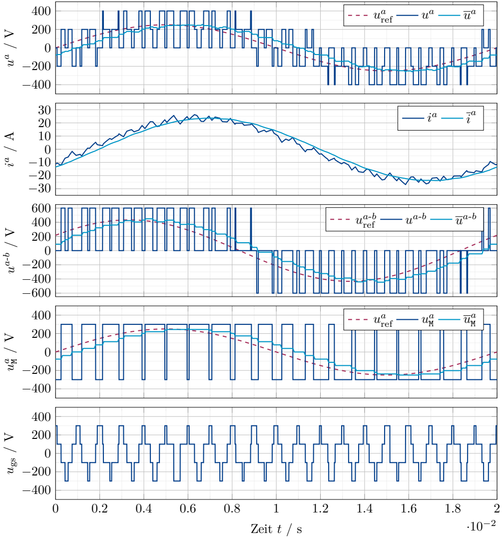
with extended reference voltages

$$\boldsymbol{u}_{\mathrm{ref,svm}}^{abc} := \boldsymbol{u}_{\mathrm{ref}}^{abc} - \begin{pmatrix} \frac{\max(\boldsymbol{u}_{\mathrm{ref}}^{abc}) + \min(\boldsymbol{u}_{\mathrm{ref}}^{abc})}{2} \\ \frac{\max(\boldsymbol{u}_{\mathrm{ref}}^{abc}) + \min(\boldsymbol{u}_{\mathrm{ref}}^{abc})}{2} \\ \frac{\max(\boldsymbol{u}_{\mathrm{ref}}^{abc}) + \min(\boldsymbol{u}_{\mathrm{ref}}^{abc})}{2} \end{pmatrix}$$

Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Modulation (example): Symmetrical PWM and averaged delay





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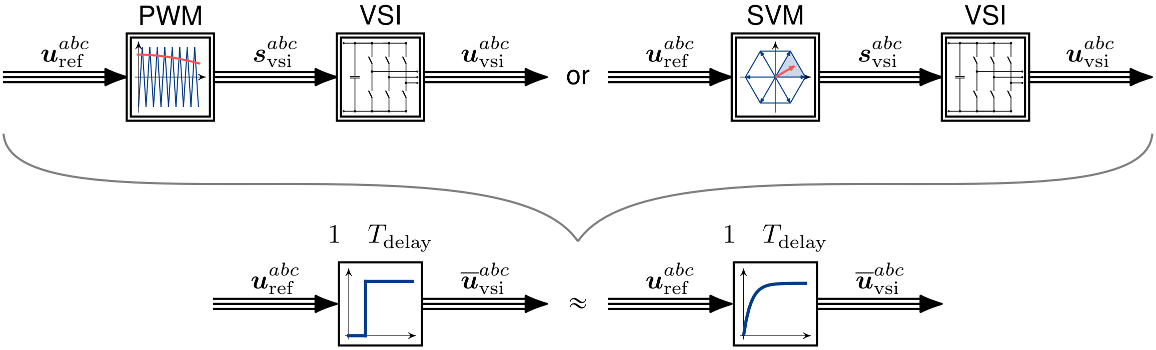
Nonlinear modelling: Two-level voltage source inverter (2L-VSI)

Dynamics and its approximation



Delay depends on switching frequency $\frac{1}{T_{\mathrm{sw}}}$ and implementation of PWM or SVM:

$$T_{\mathrm{delay}} \propto T_{\mathrm{sw}} \quad \Longrightarrow \quad F_{\mathrm{vsi}}(s) := \frac{\overline{\boldsymbol{u}}_{\mathrm{vsi}}^{abc}(s)}{\boldsymbol{u}_{\mathrm{ref}}^{abc}(s)} = e^{-sT_{\mathrm{delay}}} \approx \frac{1}{1 + sT_{\mathrm{delay}}}$$

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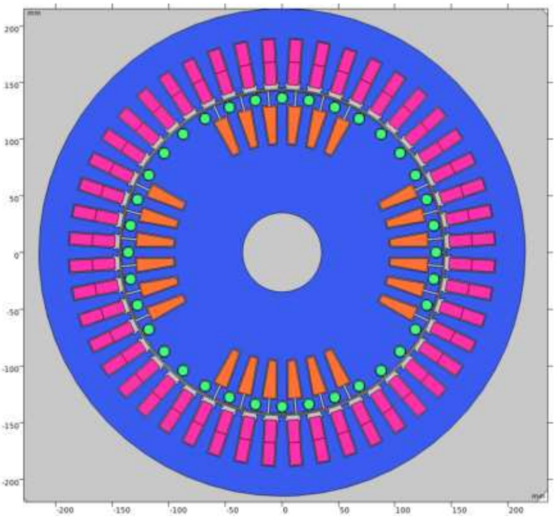
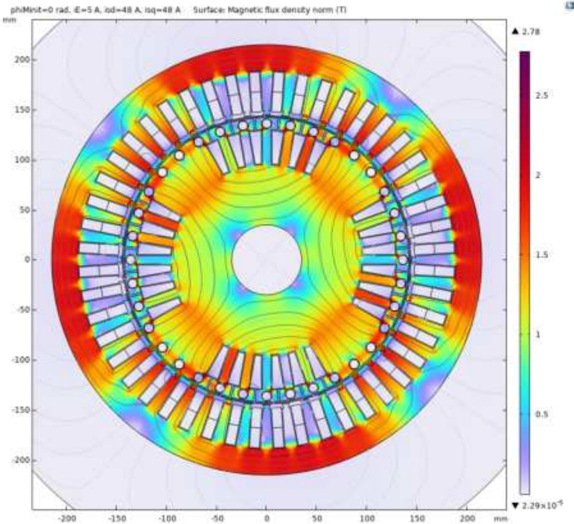
Nonlinear modelling: Electrical machine

Exemplary 2D-FEM design of Electrically-Excited Synchronous Machine (**EESM**) with damper windings





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Nonlinear modelling: Electrical machine

Key equations: Dependencies for each winding of an electric machine (holds for transformer or rotatory machine)

Kirchhoff's voltage equation:

- single-phase: $u = R\,i + \frac{\mathrm{d}}{\mathrm{d}t}\psi \quad \iff \quad \frac{\mathrm{d}}{\mathrm{d}t}\psi = u - R\,i$
- three-phase: $\boldsymbol{u}_\mathrm{z}^{abc} = \boldsymbol{R}_\mathrm{z}^{abc}\boldsymbol{i}_\mathrm{z}^{abc} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_\mathrm{z}^{abc} \quad \iff \quad \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_\mathrm{z}^{abc} = \boldsymbol{u}_\mathrm{z}^{abc} - \boldsymbol{R}_\mathrm{z}^{abc}\boldsymbol{i}_\mathrm{z}^{abc}, \quad \mathrm{z} \in \{\mathrm{s}, \mathrm{Fe}, \mathrm{r}, \mathrm{e}, \dots\}$

where

- applied winding voltage u (arbitrary shape) or $\boldsymbol{u}_\mathrm{z}^{abc} := (u_\mathrm{z}^a, u_\mathrm{z}^b, u_\mathrm{z}^c)^\top \in \mathbb{R}^3$
- winding current i (arbitrary shape) or $\boldsymbol{i}_\mathrm{z}^{abc} := (i_\mathrm{z}^a, i_\mathrm{z}^b, i_\mathrm{z}^c)^\top \in \mathbb{R}^3$
- winding resistance $R := R(i, \phi, \omega, \vartheta, \dots)$ or $\boldsymbol{R}_\mathrm{z}^{abc} := \boldsymbol{R}_\mathrm{z}^{abc}(\boldsymbol{i}_\mathrm{z}^{abc}, \phi, \omega, \boldsymbol{\vartheta}_\mathrm{z}^{abc}, \dots) \in \mathbb{R}^{3\times 3}$
- flux linkage $\psi := \psi(i, \phi, \omega, \vartheta, \dots)$ or $\boldsymbol{\psi}_\mathrm{z}^{abc} := (\psi_\mathrm{z}^a, \psi_\mathrm{z}^b, \psi_\mathrm{z}^c)^\top = \boldsymbol{\psi}_\mathrm{z}^{abc}(\boldsymbol{i}_\mathrm{z}^{abc}, \phi, \omega, \boldsymbol{\vartheta}_\mathrm{z}^{abc}, \dots) \in \mathbb{R}^3$

***Remark**: Resistance R and flux linkage ψ may depend on states $\boldsymbol{x} := (i, \phi, \omega, \vartheta, \dots)^\top \in \mathbb{R}^{N_{\boldsymbol{x}}}$ such as e.g. current(s) i, angle ϕ, angular frequency ω and temperature(s) ϑ to cover iron losses, magnetic saturation & cross-coupling, anisotropy, harmonics, proximity & skin effect, slip rings or winding asymmetries, etc.*

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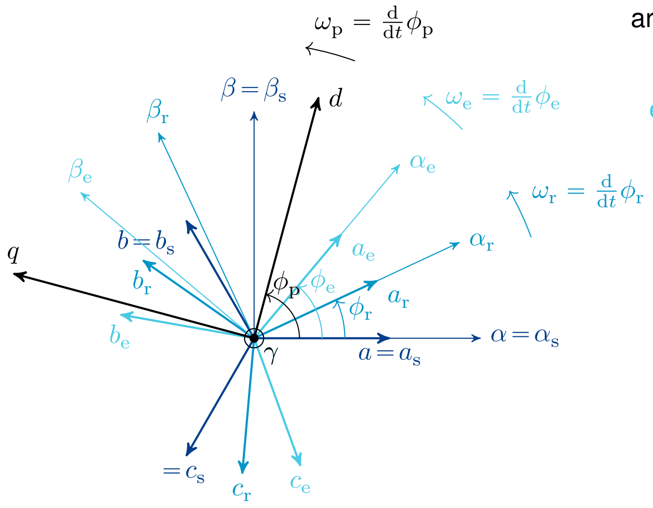
Nonlinear modelling: Electrical machine

Reference frames (considering of γ-component might be crucial [165])



arbitrarily rotating (d, q, γ)-reference frame

excitor-fixed $(\alpha_e, \beta_e, \gamma)$-reference frame

rotor-fixed $(\alpha_r, \beta_r, \gamma)$-reference frame

stator-fixed (α, β, γ)-reference frame

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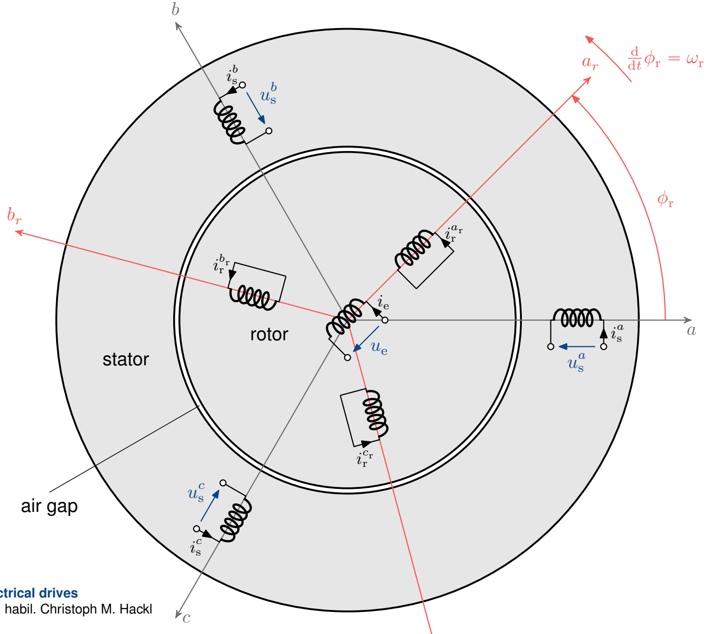
Nonlinear modelling: Electrical machine

Generic machine dynamics: Three-phase machine model (cross-sectional view; without iron losses)



Nonlinear modelling: Electrical machine

Generic machine dynamics: Three-phase machine model in (d, q, γ)-reference frame [after Clarke and (arbitrary) Park transformation]

$$
\left.
\begin{array}{lrcll}
\text{Stator:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} & -\omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}, \\
\text{Stator iron:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq\gamma} & = & - \boldsymbol{R}_{\mathrm{s,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma} & -\omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq\gamma}, \\
\text{Rotor:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{r}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{r}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{r}}^{dq\gamma}\boldsymbol{i}_{\mathrm{r}}^{dq\gamma} & -(\omega_{\mathrm{p}} - \omega_{\mathrm{r}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{r}}^{dq\gamma}, \\
\text{Rotor iron:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{r,Fe}}^{dq\gamma} & = & - \boldsymbol{R}_{\mathrm{r,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma} & -(\omega_{\mathrm{p}} - \omega_{\mathrm{r}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{r,Fe}}^{dq\gamma}, \\
\text{Excitor:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{e}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{e}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{e}}^{dq\gamma}\boldsymbol{i}_{\mathrm{e}}^{dq\gamma} & -(\omega_{\mathrm{p}} - \omega_{\mathrm{e}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{e}}^{dq\gamma}, \\
\text{Mechanical subsystem:} & \frac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathrm{m}} & = & \frac{1}{\Theta_{\mathrm{m}}}\Big(m_{\mathrm{m}} - \mathfrak{F}\omega_{\mathrm{m}} + m_{\mathrm{l}}\Big) & \\
 & \frac{\mathrm{d}}{\mathrm{d}t}\phi_{\mathrm{m}} & = & \omega_{\mathrm{m}} &
\end{array}
\right\} \tag{1}
$$

with machine torque $m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{r}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{e}}^{dq\gamma}, \boldsymbol{\psi}_{\mathrm{pm}}^{dq\gamma}, \phi_{\mathrm{m}}, \dots)$ and rotation matrix (by $\pi/2$)

$$
\boldsymbol{J}_0 := \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
$$

***Remark**: Please note that consideration of γ-component might be crucial to allow for e.g. currents including third-order harmonics as possibly present in delta-connected or grounded star-point configurations [165].*

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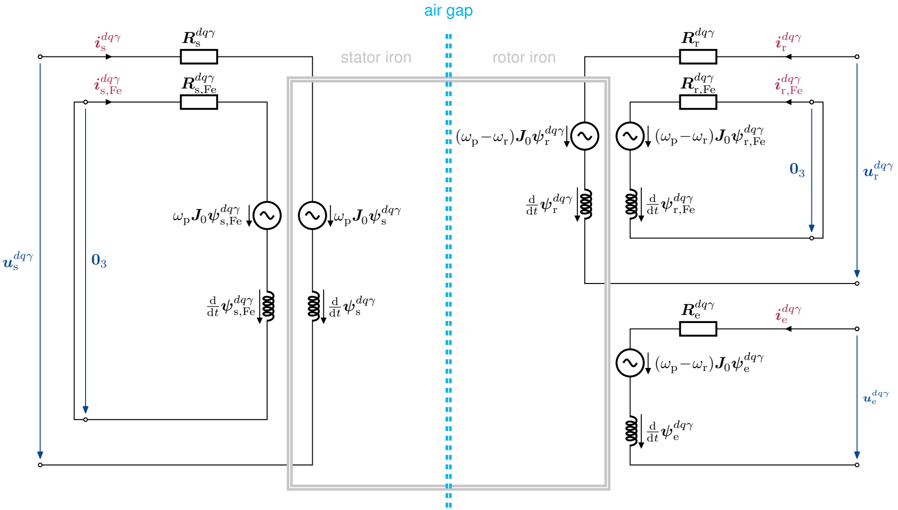
Nonlinear modelling: Electrical machine

Equivalent circuit of generic three-phase machine model in (d, q, γ)-reference frame



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4 Dynamic simulation
- Electrical machine dynamics
- Required system knowledge
- Exemplary implementation results

Dynamic simulation: Electrical machine dynamics

Possible implementations of electrical dynamics in (d, q, γ)-reference frame [for simplicity: only considering stator currents]

- Flux linkage dynamics with inverse interpolation $\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{f}_{\psi}^{-1}(\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}, \dots)$

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} \tag{2}$$

- Current dynamics with differential inductances and flux linkages

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = (\boldsymbol{L}_{\mathrm{s}}^{dq\gamma})^{-1}\Big(\boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} + \underbrace{\frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial\phi_{\mathrm{m}}}\omega_{\mathrm{m}} + \frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial\vartheta}\frac{\mathrm{d}}{\mathrm{d}t}\vartheta + \dots}_{=:\boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma}}\Big) \tag{3}$$

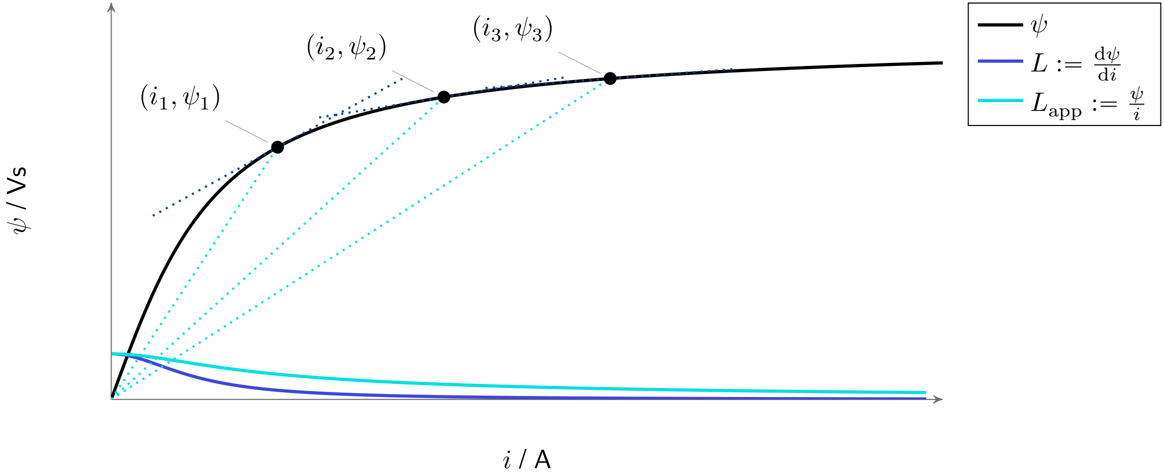
- Current dynamics with differential and apparent inductances and permanent-magnet flux linkages

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = (\boldsymbol{L}_{\mathrm{s}}^{dq\gamma})^{-1}\Big(\boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0(\boldsymbol{L}_{\mathrm{s,app}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} + \boldsymbol{\psi}_{\mathrm{pm}}^{dq\gamma}) + \boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma}\Big) \tag{4}$$

***Remark**: Important to note that* $\boldsymbol{L}_{\mathrm{s}}^{dq\gamma} := \frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\mathrm{d}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}} \neq \boldsymbol{L}_{\mathrm{s,app}}^{dq\gamma} := \frac{\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma},\dots) - \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}(\boldsymbol{0}_3,\dots)}{\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}}$

Dynamic simulation: Electrical machine dynamics

Crucial distinction: Illustration of differential inductance L (tangent) and apparent inductance L_{app} (secant)



Outline

4 Dynamic simulation
- Electrical machine dynamics
- Required system knowledge
- Exemplary implementation results

Dynamic simulation: Required system knowledge

Required system data and execution times for high-fidelity simulation of different dynamics implementations

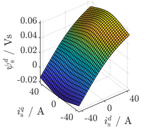
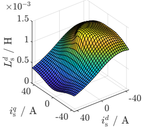
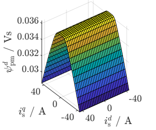
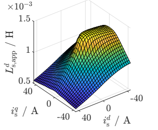
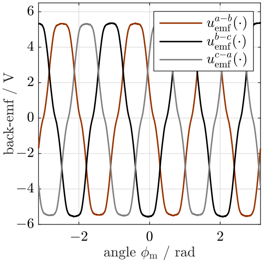
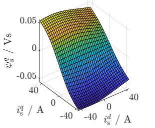
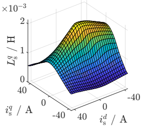
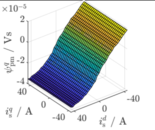
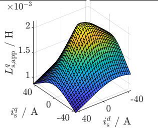
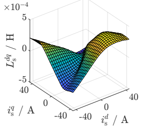
	FLD+II	**CD+DI&FL**	**CD+DAI&PMFL**
$\boldsymbol{R}_{\mathrm{s}}^{dq(\gamma)}(\boldsymbol{x})$	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{L}_{\mathrm{s}}^{dq(\gamma)}(\boldsymbol{x})$	–	$3\ (+3) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+3) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{L}_{\mathrm{s,app}}^{dq(\gamma)}(\boldsymbol{x})$	–	–	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{\psi}_{\mathrm{pm}}^{dq(\gamma)}(\boldsymbol{x})$	–	–	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{\psi}_{\mathrm{s}}^{dq(\gamma)}$	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs	–
$\boldsymbol{f}_{\psi}(\cdot)^{-1}$	yes	no	no
t_{exec} (in p.u.)	$1.00^{\star}$ / $1.07^{\dagger}$ / $2.55^{\ddagger}$	1.55	1.83

***Remark**: The states $\boldsymbol{x} := (\boldsymbol{i}_{\mathrm{x}}^{abc}, \phi_{\mathrm{m}}, \phi_{\mathrm{p}}, \omega_{\mathrm{m}}, \omega_{\mathrm{p}}, \boldsymbol{\vartheta}_{\mathrm{x}}^{abc}, \ldots)^{\top} \in \mathbb{R}^{N_{\boldsymbol{x}}}$ comprise currents, machine and/or transformation angles, machine and/or transformation angular frequencies and temperatures to allow for proper simulation/emulation of iron losses, magnetic saturation and cross-coupling, anisotropy, proximity and/or skin effect, slip rings or winding asymmetries, etc.; $N_{\boldsymbol{x}}$ represents the dimension of the considered states. *: Bilinear Inversion (reference as fastest), †: pre-processed LUTs for inverse interpolation of flux*

☞ **LMRES (HM) is working with several academic/industrial partners on fast, accurate and overall machine identification approaches in order to allow for even more sophisticated machine simulation and/or emulation.**

Dynamic simulation: Required system knowledge

Examples of identified stator/permanent-magnet flux linkages, differential/apparent inductances and back-emf harmonics

	$\psi_s^{dq}(i_s^{dq})$	$L_s^{dq}(i_s^{dq})$	$\psi_{pm}^{dq}(i_s^{dq})$	$L_{s,app}^{dq}(i_s^{dq})$	$\delta_s^{dq\gamma} = \frac{\partial \psi_s^{dq\gamma}}{\partial \phi_m}\omega_m$
d					
q					
dq/qd	–		–	–	

Remark: *For simplicity, only the dependencies on* $i_s^{dq} := (i_s^d, i_s^q)^\top$ *are shown, i.e.* $x := (i_s^d, i_s^q)^\top$ *with* $N_x = 2$.

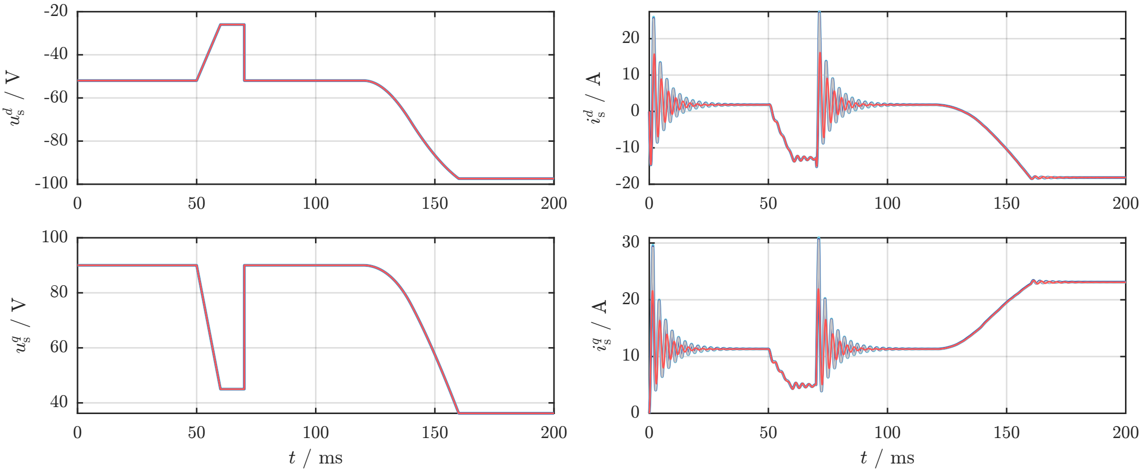
Outline

4 Dynamic simulation
- Electrical machine dynamics
- Required system knowledge
- Exemplary implementation results

Dynamic simulation: Exemplary implementation results

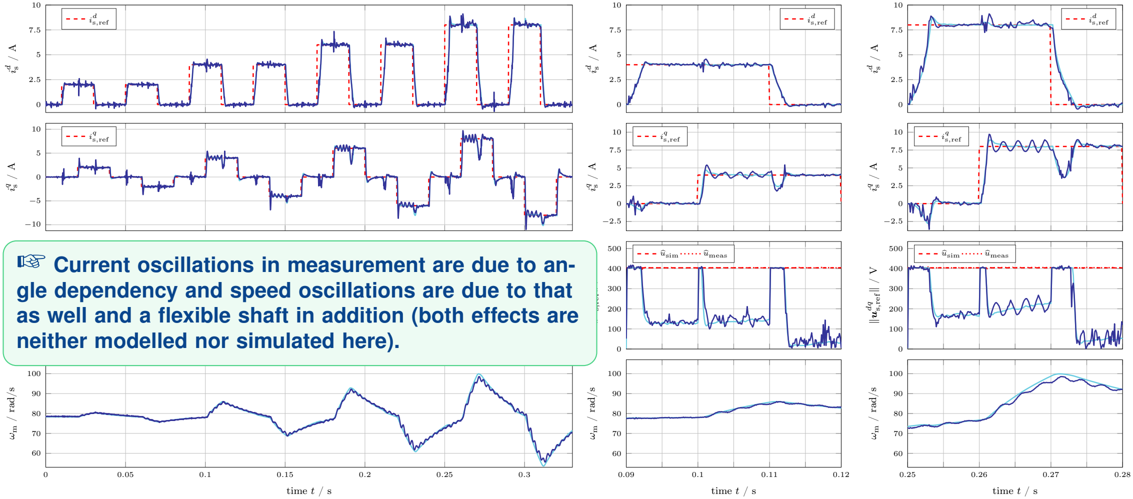
Open-loop current responses for diff. dynamics implementations (3.8 kW IPMSM @ $\omega_{\mathrm{m,R}} = 576\,\frac{\mathrm{rad}}{\mathrm{s}}$):

[——] FLD+II (bil. Inv.), [——] CD+DI&FL, [——] CD+DAI&FL, [——] CD+DAI&FL ($\boldsymbol{L}_{\mathrm{s}}^{dq} = \boldsymbol{L}_{\mathrm{s,app}}^{dq}$; wrong implement.!)



Dynamic simulation: Exemplary implementation results

Comparison of closed-loop nonlinear electrical drive system (4.0 kW RSM @ $\omega_{\rm m} \approx 80\,\frac{\rm rad}{\rm s}$):
[——] simulation (CD+DI&FL), [——] measurement

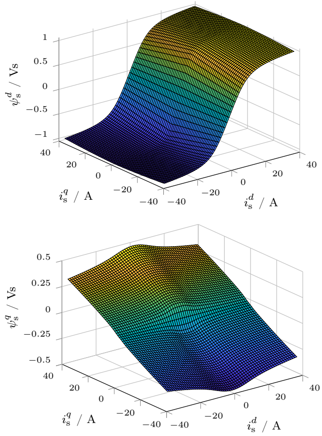


☞ **Current oscillations in measurement are due to angle dependency and speed oscillations are due to that as well and a flexible shaft in addition (both effects are neither modelled nor simulated here).**

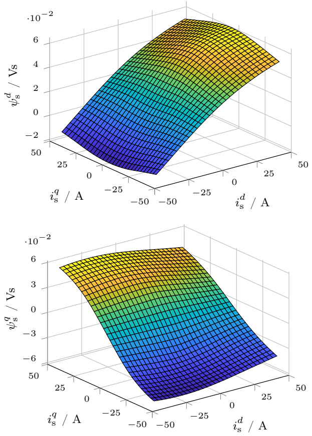
Dynamic simulation: Exemplary implementation results

Flux Linkage Prototype Functions (**FLPFs**) [25] – Analytic functions for flux linkage representation

$\psi_{\mathrm{s}}^{d/q}$ of typ. RSM



$\psi_{\mathrm{s}}^{d/q}$ of typ. IPMSM



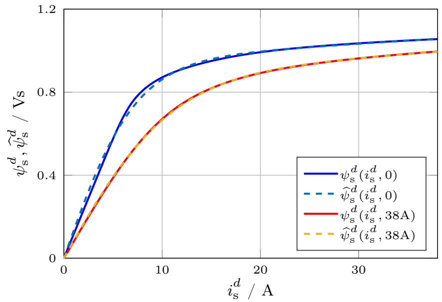
General FLPF idea

$$\widehat{\psi}_{\mathrm{s}}^{d}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}) = \widehat{\psi}_{\mathrm{s,self}}^{d}(i_{\mathrm{s}}^{d}) - \widehat{\psi}_{\mathrm{s,cross}}^{d}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})$$

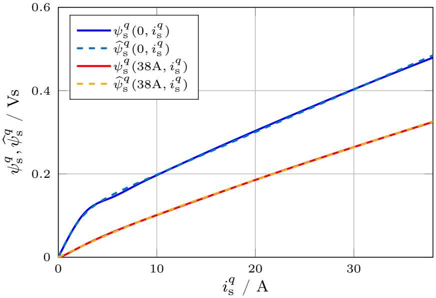
$$\widehat{\psi}_{\mathrm{s}}^{q}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}) = \widehat{\psi}_{\mathrm{s,self}}^{q}(i_{\mathrm{s}}^{d}) - \widehat{\psi}_{\mathrm{s,cross}}^{q}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})$$

Dynamic simulation: Exemplary implementation results

Flux Linkage Prototype Functions (**FLPFs**) [25] – Observation for self-axis effects ($9.6\,$kW RSM)



(a) d-axis flux linkage ψ_s^d v.s. d-axis current i_s^d

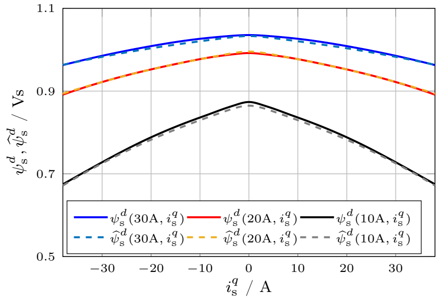


(b) q-axis flux linkage ψ_s^q v.s. q-axis current i_s^q

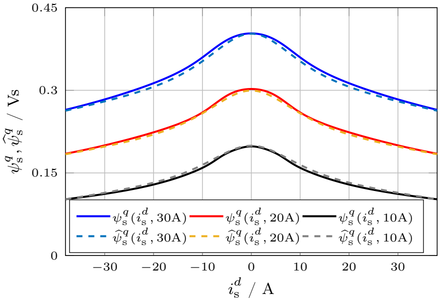
e.g., $\widehat{\psi}^{d,q}_{s,\mathrm{self}}(i_s^d) \propto \tanh(i_s^{d/q}) + i_s^{d/q}$

Dynamic simulation: Exemplary implementation results

Flux Linkage Prototype Functions (**FLPFs**) [25] – Observation for cross-coupling effects (9.6 kW RSM)



(a) d-axis flux linkage ψ_s^d v.s. q-axis current i_s^q

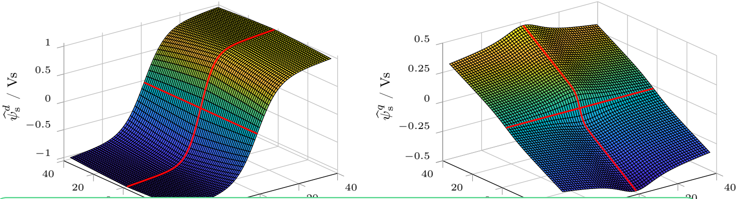


(b) q-axis flux linkage ψ_s^q v.s. d-axis current i_s^d

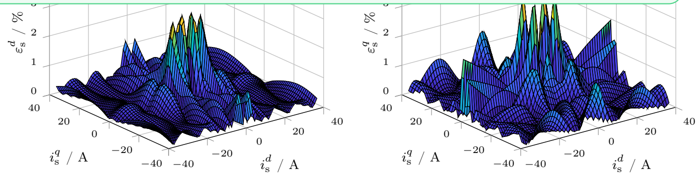
e.g., $\widehat{\psi}^{d/q}_{s,\mathrm{cross}} \propto -\ln\left(\cosh(i_s^{d/q})\right)$ or $\widehat{\psi}^{d/q}_{s,\mathrm{cross}} \propto \exp\left(-(i_s^{d/q})^2\right)$

Dynamic simulation: Exemplary implementation results

Flux Linkage Prototype Functions (**FLPFs**) [25] – Estimation accuracy & properties ($9.6\,\mathrm{kW}$ RSM)



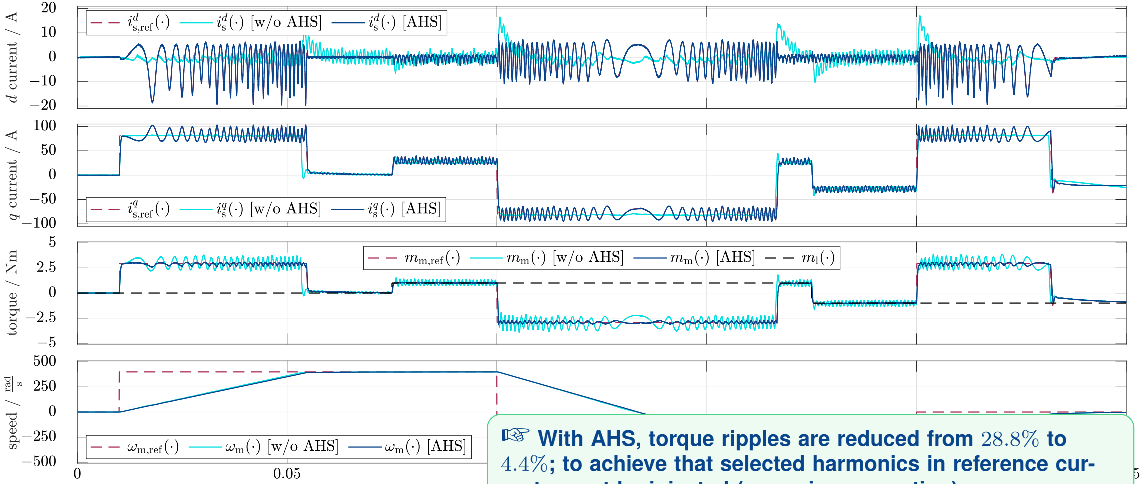
☞ **Flux linkage prototype functions (FLPFs) can also be used for self-commissioning [166] or in the framework of Artificial Neuronal Networks (ANNs) to identify inverter and machine simultaneously [138].**



- **Flux linkages** approximated by FLPFs $\widehat{\psi}_s^d(i_s^d, i_s^q)$ & $\widehat{\psi}_s^q(i_s^d, i_s^q)$ with high accuracy (usually $\geqslant 95\%$)
- **Energy conservation** assured, i.e. $\frac{\partial \widehat{\psi}_s^d(i_s^d, i_s^q)}{\partial i_s^q} = \frac{\partial \widehat{\psi}_s^q(i_s^d, i_s^q)}{\partial i_s^d}$ (reciprocity)
- **Few parameters** to be fitted (only $10 \sim 20$ parameters needed)
- **Differentiability** allows to derive differential inductances analytically
- **Inter-/extrapolation capability** due to analytical function evaluation (no numerical inaccuracies or oscillations)
- **Extensibility** ensures applicability to different SMs (e.g., RSMs, IPMSMs or even EESMs)

Dynamic simulation: Exemplary implementation results

Active Harmonics Suppression (**AHS**) in $2.6\,$kW BLDC machine (compensating for $\boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma} = \frac{\partial \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial \phi_{\mathrm{m}}}\omega_{\mathrm{m}}$)



☞ **With AHS, torque ripples are reduced from 28.8% to 4.4%; to achieve that selected harmonics in reference currents must be injected (paper in preparation).**

Outline

1 Introduction

2 Motivation

3 Nonlinear modelling

4 Dynamic simulation

5 High-performance control

6 Optimal operation

7 Conclusion

Outline

5 High-performance control

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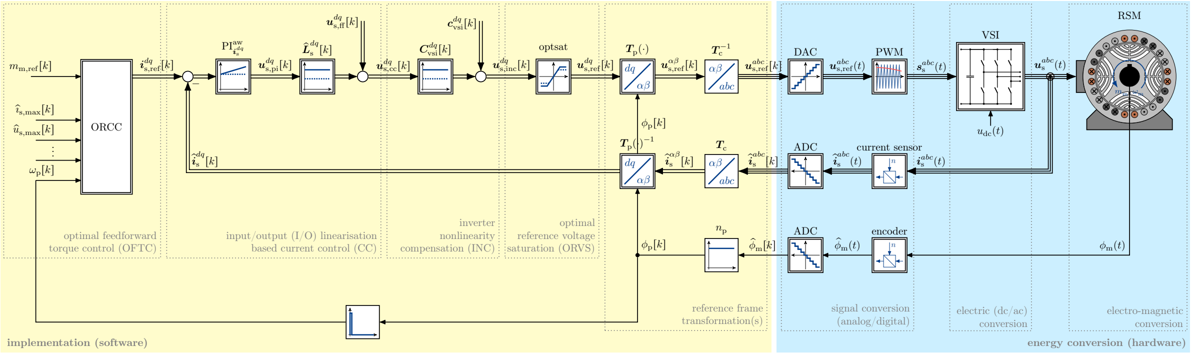
  - Controller structure of input/output (I/O) linearization based nonlinear current control system
  - Principle idea of I/O linearization
  - Closed-loop system with reference current filter
  - Controller tuning via pole placement
  - Vector-valued PI controller with anti-windup (conditional integration)
- Inverter nonlinearity compensation
  - Problem statement
  - Nonlinear voltage drops
  - Average model
  - Dead-time effects
  - Transformation to (d, q)-reference frame
  - Validation
- Optimal reference voltage saturation
  - Problem statement
  - Proposed solution
  - Input/ouput (I/O) linearization (recap)
  - PI controller design with anti-windup (recap)
  - Reference voltage saturation
  - Validation

High-performance control

Overview



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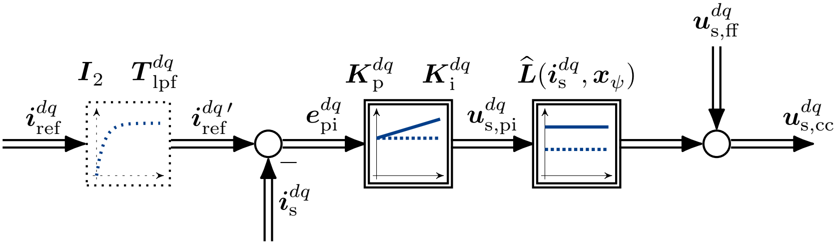
High-performance control: Nonlinear current control

Controller structure of input/output (I/O) linearization based nonlinear current control system



Nonlinear (vector-valued) PI controller

$$
\begin{aligned}
\boldsymbol{u}_{\mathrm{s,cc}}^{dq} &= \overbrace{\boldsymbol{K}_{\mathrm{p}}^{dq}\boldsymbol{e}_{\mathrm{pi}}^{dq} + \boldsymbol{K}_{\mathrm{i}}^{dq}\boldsymbol{x}_{\mathrm{i}}^{dq}}^{=:\boldsymbol{u}_{\mathrm{s,pi}}^{dq}} + \overbrace{\widehat{\boldsymbol{R}}_{\mathrm{s}}^{dq}\boldsymbol{i}_{\mathrm{s}}^{dq} + \omega_{\mathrm{p}}\boldsymbol{J}\widehat{\boldsymbol{\psi}}_{\mathrm{s}}^{dq} + \widehat{\boldsymbol{\delta}}_{\mathrm{s}}^{dq}}^{=:\boldsymbol{u}_{\mathrm{s,ff}}^{dq}}, \\
\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{i}}^{dq} &= f_{\mathrm{aw}}\left(\widehat{u}_{\mathrm{s,max}}, \boldsymbol{u}_{\mathrm{s,ref}}^{dq}\right)\boldsymbol{e}_{\mathrm{pi}}^{dq}
\end{aligned}
$$

with feedforward term $\boldsymbol{u}_{\mathrm{s,ff}}^{dq}$ and integral state $\boldsymbol{x}_{\mathrm{i}}^{dq}$, gain matrices $\boldsymbol{K}_{\mathrm{p}}^{dq} := \mathrm{diag}(k_{\mathrm{p}}^{d}, k_{\mathrm{p}}^{q})$ and $\boldsymbol{K}_{\mathrm{i}}^{dq} := \mathrm{diag}(k_{\mathrm{i}}^{d}, k_{\mathrm{i}}^{q})$ and anti-windup (“conditional integration”) with

$$
f_{\mathrm{aw}}\left(\widehat{u}_{\mathrm{s,max}}, \boldsymbol{u}_{\mathrm{s,ref}}^{dq}\right) = \begin{cases} 0, & \text{if } \|\boldsymbol{u}_{\mathrm{s,ref}}^{dq}\| > \widehat{u}_{\mathrm{s,max}}, \\ 1, & \text{else.} \end{cases}
$$

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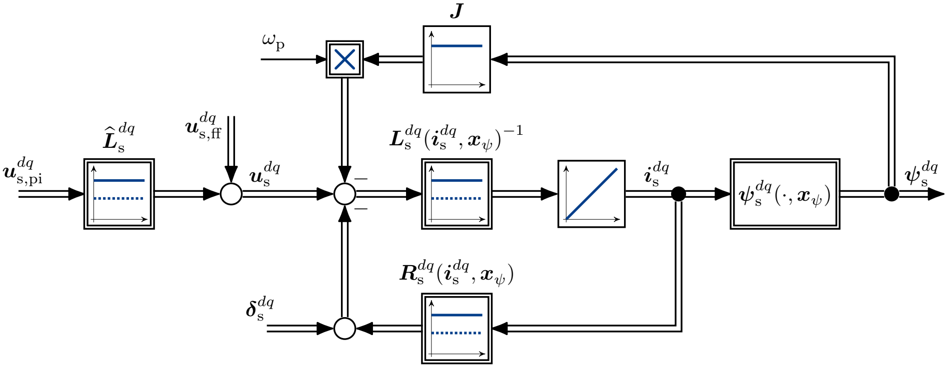
High-performance control: Nonlinear current control

Principle idea of I/O linearization (ideal conditions, i.e., $\boldsymbol{u}_{\mathrm{s,cc}}^{dq} = \boldsymbol{u}_{\mathrm{s}}^{dq}$, $\widehat{\boldsymbol{R}}_{\mathrm{s}}^{dq} = \boldsymbol{R}_{\mathrm{s}}^{dq}$, $\widehat{\boldsymbol{L}}_{\mathrm{s}}^{dq} = \boldsymbol{L}_{\mathrm{s}}^{dq}$ and $\widehat{\boldsymbol{\delta}}_{\mathrm{s}}^{dq} = \boldsymbol{\delta}_{\mathrm{s}}^{dq}$)



$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq} = (\boldsymbol{L}_{\mathrm{s}}^{dq})^{-1}\Big[\underbrace{\widehat{\boldsymbol{L}}_{\mathrm{s}}^{dq}\boldsymbol{u}_{\mathrm{s,pi}}^{dq} + \overbrace{\boldsymbol{R}_{\mathrm{s}}^{dq}\boldsymbol{i}_{\mathrm{s}}^{dq} + \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} + \boldsymbol{\delta}_{\mathrm{s}}^{dq}}^{=:\boldsymbol{u}_{\mathrm{s,ff}}^{dq}}}_{\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\approx\boldsymbol{u}_{\mathrm{s}}^{dq}} - \boldsymbol{R}_{\mathrm{s}}^{dq}\boldsymbol{i}_{\mathrm{s}}^{dq} - \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq} - \boldsymbol{\delta}_{\mathrm{s}}^{dq}\Big] = \boldsymbol{u}_{\mathrm{s,pi}}^{dq}$$

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5 High-performance control

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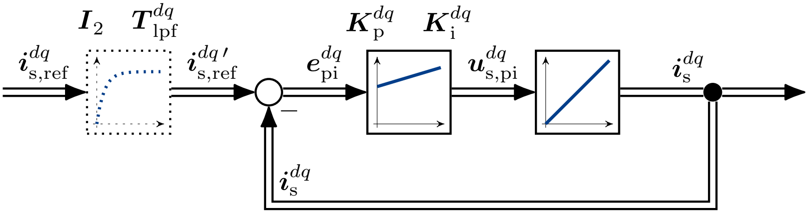
High-performance control: Nonlinear current control

Closed-loop system with reference current filter (after ideal I/O-linearization and without anti-windup)



Reference current filter (optional; set $\boldsymbol{T}_{\mathrm{lpf}}^{dq} = \mathrm{diag}(T_{\mathrm{lpf}}^{d}, T_{\mathrm{lpf}}^{q}) = \boldsymbol{O}_{2\times 2}$ if not used)

$$F_{\mathrm{lpf}}(s) = \frac{i_{\mathrm{s,ref}}^{d/q\,\prime}}{i_{\mathrm{s,ref}}^{d/q}} = \frac{1}{1 + s\,T_{\mathrm{lpf}}^{d/q}} \quad \text{with} \quad T_{\mathrm{lpf}}^{d/q} := \frac{k_{\mathrm{p}}^{d/q}}{k_{\mathrm{i}}^{d/q}}$$

Current closed-loop system (neglecting anti-windup)

$$F_{\mathrm{cl}}(s) = \frac{i_{\mathrm{s}}^{d/q}}{i_{\mathrm{s,ref}}^{d/q}} = \frac{k_{\mathrm{p}}^{d/q}\, s + k_{\mathrm{q}}^{d/q}}{s^2 + k_{\mathrm{p}}^{d/q}\, s + k_{\mathrm{q}}^{d/q}} = \frac{1 + \frac{k_{\mathrm{p}}^{d/q}}{k_{\mathrm{i}}^{d/q}}\, s}{1 + \frac{k_{\mathrm{p}}^{d/q}}{k_{\mathrm{i}}^{d/q}}\, s + \frac{1}{k_{\mathrm{i}}^{d/q}}\, s^2}$$

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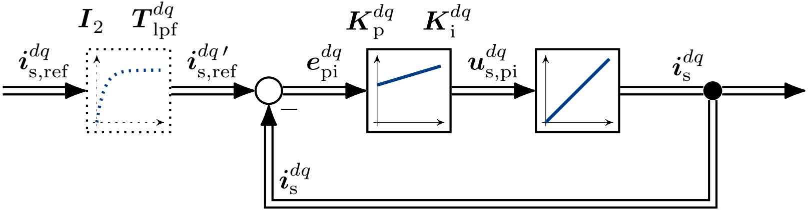
High-performance control: Nonlinear current control

Controller tuning via pole placement



Pole placement by comparing coefficients (separately for d & q possible!)

$$\chi^{d/q}_{\mathrm{ref}}(s) := s^2 + 2D^{d/q}\omega_0^{d/q}\, s + 1 \stackrel{!}{=} s^2 + k_{\mathrm{p}}^{d/q}\, s + k_{\mathrm{q}}^{d/q} =: \chi^{d/q}_{\mathrm{cl}}(s)$$

Obtained controller parameters (for given bandwidth $\omega_0^{d/q}$ and damping D^{dq})

$$\Longrightarrow \quad k_{\mathrm{p}}^{d/q} = 2D^{d/q}\omega_0^{d/q} \quad \text{and} \quad k_{\mathrm{i}}^{d/q} = \left(\omega_0^{d/q}\right)^2$$

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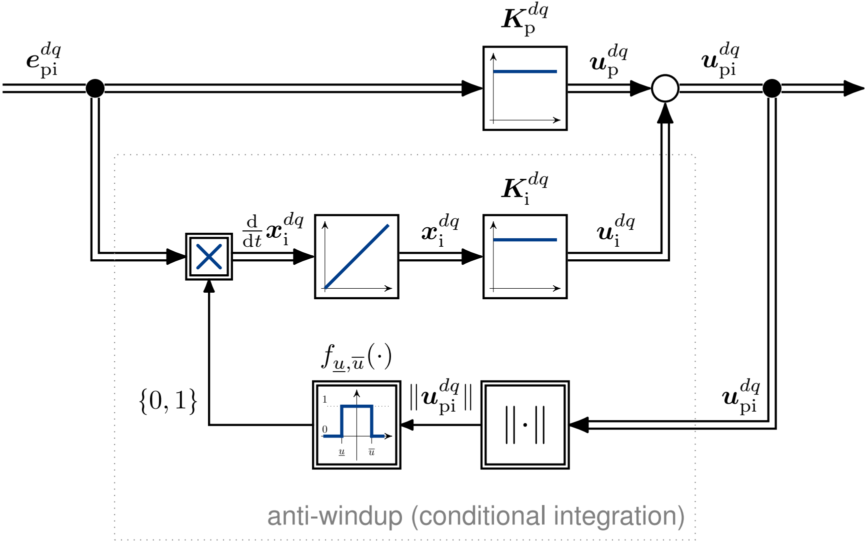
High-performance control: Nonlinear current control

Vector-valued PI controller with anti-windup (conditional integration)



Outline

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- Nonlinear current control
  - Controller structure of input/output (I/O) linearization based nonlinear current control system
  - Principle idea of I/O linearization
  - Closed-loop system with reference current filter
  - Controller tuning via pole placement
  - Vector-valued PI controller with anti-windup (conditional integration)
- Inverter nonlinearity compensation
  - Problem statement
  - Nonlinear voltage drops
  - Average model
  - Dead-time effects
  - Transformation to (d, q)-reference frame
  - Validation
- Optimal reference voltage saturation
  - Problem statement
  - Proposed solution
  - Input/ouput (I/O) linearization (recap)
  - PI controller design with anti-windup (recap)
  - Reference voltage saturation
  - Validation

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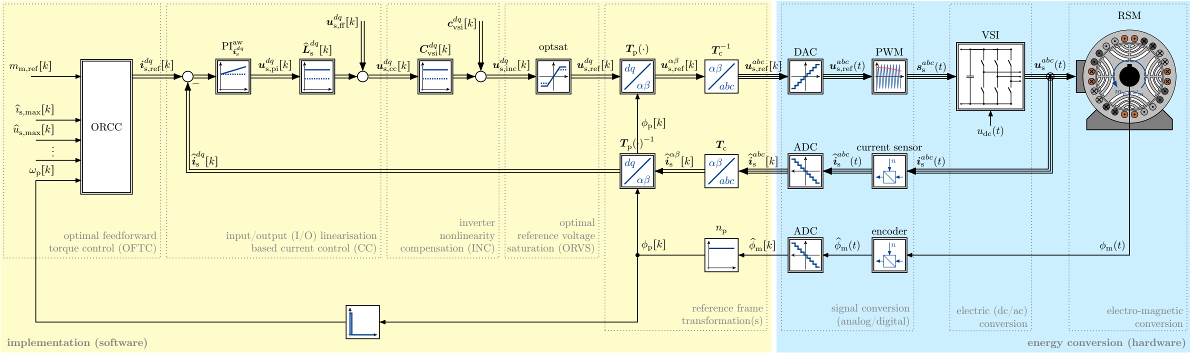
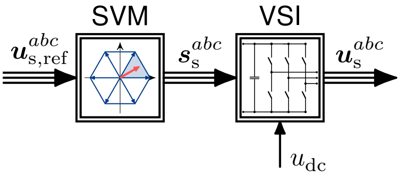
High-performance control

Inverter nonlinearity compensation: Overview



High-performance control: Inverter nonlinearity compensation

Problem statement: Drawbacks of voltage source inverters



Any voltage source inverter (VSI) suffers from *four* inevitable drawbacks (D_i):

(D_1) voltage deterioration due to nonlinear current-dependent voltage drops over semiconductors [167],

(D_2) voltage ripples due to the switching behavior of the power electronic devices [168],

(D_3) delayed voltage response due to modulation [169], and

(D_4) output voltage constraints due to a limited dc-link voltage.

$\Longrightarrow$ Here we will discuss and solve the first and third problem! For each drawback, several improvements or compensation strategies exist. This subsection focuses on the first and third drawback and its impact, in particular, on the output voltage by the inverter nonlinearity which leads to a deteriorates from the desired VSI voltage. The second drawback can be tackled by optimal pulse pattern and/or increased switching frequency [117, 128, 129].

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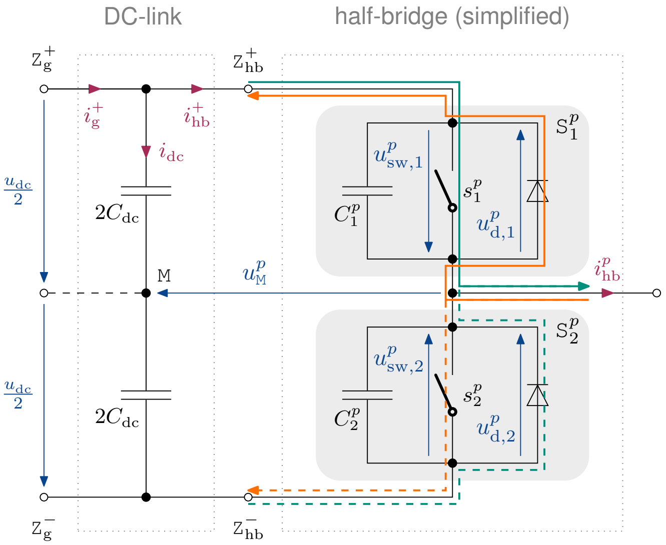
High-performance control: Inverter nonlinearity compensation

Nonlinear voltage drops in a half-bridge



Mid-point voltage varies with switching state and current direction (this holds for any phase $p \in \{a, b, c\}$)

$$u_M^p = \begin{cases} \frac{u_{dc}}{2} - u_{sw,1}^p & , s_1^p = 1 \wedge i_{hb}^p \geqslant 0 \\ \frac{u_{dc}}{2} + u_{d,1}^p & , s_1^p = 1 \wedge i_{hb}^p < 0 \\ -\frac{u_{dc}}{2} - u_{d,2}^p & , s_1^p = 0 \wedge i_{hb}^p \geqslant 0 \\ -\frac{u_{dc}}{2} + u_{sw,2}^p & , s_1^p = 0 \wedge i_{hb}^p < 0 \end{cases}$$

***Remark**: Important to note that voltage drops $u_{sw,1/2}^p$ and $u_{d,1/2}^p$ over power switch and power diodes, respectively, usually depend on currents and temperatures. Moreover, they may be different for each upper and/or lower branch (index 1 & 2) and each phase $p \in \{a, b, c\}$.*

High-performance control: Inverter nonlinearity compensation

Nonlinear voltage drops in a three-phase VSI

Assuming $u_{\rm sw}^p := u_{{\rm sw},1}^p = u_{{\rm sw},2}^p$ and $u_{\rm d}^p := u_{{\rm d},1}^p = u_{{\rm d},2}^p$, one obtains (for all $p \in \{a,b,c\}$)

$$u_{\rm M}^p = \left(u_{\rm dc} - u_{\rm sw}^p + u_{\rm d}^p\right)\left(s_1^p - \tfrac{1}{2}\right) - \tfrac{1}{2}\,{\rm sgn}(i_{\rm hb}^p)\left(u_{\rm sw}^p + u_{\rm d}^p\right),$$

where

$${\rm sgn}(x) := \begin{cases} 1 & , \text{ if } x \geqslant 1 \\ -1 & , \text{ if } x < 1. \end{cases}$$

For a 2L-VSI, we have three phases $p \in \{a,b,c\}$, switching vector $\boldsymbol{s}_{\rm vsi}^{abc} = (s_1^a, s_1^b, s_1^c)^\top$ and current vector $\boldsymbol{i}_{\rm vsi}^{abc} = (i_{\rm hb}^a, i_{\rm hb}^b, i_{\rm hb}^c)^\top$, which yields the mid-point voltage vector

$$\boldsymbol{u}_{\tt M}^{abc} = {\rm diag}\left[u_{\rm dc}\mathbf{1}_3 - \boldsymbol{u}_{\rm sw}^{abc} + \boldsymbol{u}_{\rm d}^{abc}\right]\left(\boldsymbol{s}_{\rm vsi}^{abc} - \tfrac{1}{2}\mathbf{1}_3\right) - \tfrac{1}{2}\,{\rm diag}\left[{\rm sgn}(\boldsymbol{i}_{\rm vsi}^{abc})\right]\left(\boldsymbol{u}_{\rm sw}^{abc} + \boldsymbol{u}_{\rm d}^{abc}\right).$$

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High-performance control: Inverter nonlinearity compensation

Average model

Assuming **constant voltages** $\boldsymbol{u}_{\mathrm{sw}}^{abc}$, $\boldsymbol{u}_{\mathrm{d}}^{abc}$ and u_{dc} and **identical signs** $\mathrm{sgn}(\boldsymbol{i}_{\mathrm{vsi}}^{abc})$ **of the currents** over one switching period $T_{\mathrm{sw}} = \frac{1}{f_{\mathrm{sw}}}$, the **average mid-point voltages** at sampling instant k (i.e., $t = kT_{\mathrm{sw}}$) are given by

$$\begin{aligned}\overline{\boldsymbol{u}}_{\mathrm{M}}^{abc}[k] \quad &:= \quad \frac{1}{T_{\mathrm{sw}}}\int_{(k-1)T_{\mathrm{sw}}}^{kT_{\mathrm{sw}}} \boldsymbol{u}_{\mathrm{M}}^{abc}(\tau)\,\mathrm{d}\tau \\ &= \quad \mathrm{diag}\Big[u_{\mathrm{dc}}[k]\mathbf{1}_3 - \boldsymbol{u}_{\mathrm{sw}}^{abc}[k] + \boldsymbol{u}_{\mathrm{d}}^{abc}[k]\Big]\Big(\boldsymbol{d}_{\mathrm{vsi}}^{abc}[k] - \tfrac{1}{2}\mathbf{1}_3\Big) \\ &\qquad -\tfrac{1}{2}\,\mathrm{diag}\Big[\mathrm{sgn}(\boldsymbol{i}_{\mathrm{vsi}}^{abc}[k])\Big]\Big(\boldsymbol{u}_{\mathrm{sw}}^{abc}[k] + \boldsymbol{u}_{\mathrm{d}}^{abc}[k]\Big)\end{aligned} \tag{5}$$

with the duty cycle vector

$$\boldsymbol{d}_{\mathrm{vsi}}^{abc}[k] := \frac{1}{T_{\mathrm{sw}}}\int_{(k-1)T_{\mathrm{sw}}}^{kT_{\mathrm{sw}}} \boldsymbol{s}_{\mathrm{vsi}}^{abc}(\tau)\,\mathrm{d}\tau = \frac{\boldsymbol{t}_{\mathrm{on}}^{abc}[k]}{T_{\mathrm{sw}}}, \tag{6}$$

which depends on the on-time vector $\boldsymbol{t}_{\mathrm{on}}^{abc}[k] := (T_{\mathrm{on}}^{a}[k], T_{\mathrm{on}}^{b}[k], T_{\mathrm{on}}^{c}[k])^\top$ (e.g., as consequence of modulation).

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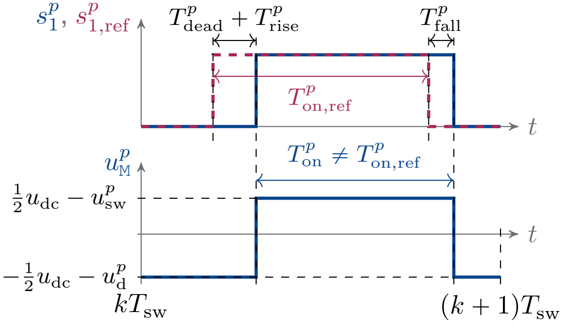
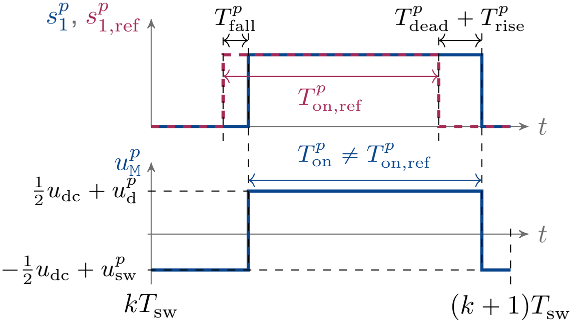
High-performance control: Inverter nonlinearity compensation

Dead-time effects in a half-bridge



positive current (i.e., $i_{\mathrm{hb}^p} \geqslant 0$)



negative current (i.e., $i_{\mathrm{hb}}^p < 0$)

Hence, for each half-bridge / each phase $p \in \{a, b, c\}$, one obtains

$$T_{\mathrm{on}}^p = T_{\mathrm{on,ref}}^p - \left(T_{\mathrm{dead}}^p + T_{\mathrm{rise}}^p - T_{\mathrm{fall}}^p\right)\mathrm{sgn}\left(i_{\mathrm{hb}}^p\right).$$

High-performance control: Inverter nonlinearity compensation

Dead-time effects in a three-phase 2L-VSI

For $\boldsymbol{i}^{abc}_{\mathrm{vsi}} := (i^a_{\mathrm{hb}}, i^b_{\mathrm{hb}}, i^c_{\mathrm{hb}})^\top$, $\boldsymbol{t}^{abc}_{\mathrm{on}} := (T^a_{\mathrm{on}}, T^b_{\mathrm{on}}, T^c_{\mathrm{on}})^\top$, $\boldsymbol{t}^{abc}_{\mathrm{dead}} := (T^a_{\mathrm{dead}}, T^b_{\mathrm{dead}}, T^c_{\mathrm{dead}})^\top$, $\boldsymbol{t}^{abc}_{\mathrm{rise}} := (T^a_{\mathrm{rise}}, T^b_{\mathrm{rise}}, T^c_{\mathrm{rise}})^\top$ and $\boldsymbol{t}^{abc}_{\mathrm{fall}} := (T_{\mathrm{fall}}, T^b_{\mathrm{fall}}, T^c_{\mathrm{fall}})^\top$, the three-phase 2L-VSI result is

$$\boldsymbol{t}^{abc}_{\mathrm{on}} = \boldsymbol{t}^{abc}_{\mathrm{on,ref}} - \mathrm{diag}\Big[\mathrm{sgn}\big(\boldsymbol{i}^{abc}_{\mathrm{vsi}}\big)\Big]\Big(\boldsymbol{t}^{abc}_{\mathrm{dead}} + \boldsymbol{t}^{abc}_{\mathrm{rise}} - \boldsymbol{t}^{abc}_{\mathrm{fall}}\Big). \tag{7}$$

Inserting $\boldsymbol{d}^{abc}_{\mathrm{vsi}}[k] = \frac{\boldsymbol{t}^{abc}_{\mathrm{on}}[k]}{T_{\mathrm{sw}}}$ (i.e., (6)) with (7) into (5) and recalling that

$$\overline{\boldsymbol{u}}^{abc}_{\mathrm{M,ref}}[k] = \left(\frac{\boldsymbol{t}^{abc}_{\mathrm{on,ref}}[k]}{T_{\mathrm{sw}}} - \frac{1}{2}\mathbf{1}_3\right) u_{\mathrm{dc}}[k] \quad \Longleftrightarrow \quad \frac{\boldsymbol{t}^{abc}_{\mathrm{on,ref}}[k]}{T_{\mathrm{sw}}} = \frac{\overline{\boldsymbol{u}}^{abc}_{\mathrm{M,ref}}[k]}{u_{\mathrm{dc}}[k]} + \frac{1}{2}\mathbf{1}_3$$

yields (details omitted and argument $[k]$ neglected)

$$\begin{aligned}\overline{\boldsymbol{u}}^{abc}_{\mathrm{M}} \overset{(5),(6),(7)}{=} & \underbrace{\mathrm{diag}\left[\mathbf{1}_3 - \frac{1}{u_{\mathrm{dc}}}\big(\boldsymbol{u}^{abc}_{\mathrm{sw}} - \boldsymbol{u}^{abc}_{\mathrm{d}}\big)\right]}_{=:[\boldsymbol{C}^{abc}_{\mathrm{vsi}}]^{-1}} \overline{\boldsymbol{u}}^{abc}_{\mathrm{M,ref}} \\ & - \underbrace{\mathrm{diag}\Big[\mathrm{sgn}\big(\boldsymbol{i}^{abc}_{\mathrm{vsi}}\big)\Big]\left(\mathrm{diag}\Big[u_{\mathrm{dc}}\mathbf{1}_3 - \boldsymbol{u}^{abc}_{\mathrm{sw}} + \boldsymbol{u}^{abc}_{\mathrm{d}}\Big]\frac{\boldsymbol{t}^{abc}_{\mathrm{dead}} + \boldsymbol{t}^{abc}_{\mathrm{rise}} - \boldsymbol{t}^{abc}_{\mathrm{fall}}}{T_{\mathrm{sw}}} + \frac{1}{2}\big(\boldsymbol{u}^{abc}_{\mathrm{sw}} + \boldsymbol{u}^{abc}_{\mathrm{d}}\big)\right)}_{=:\boldsymbol{c}^{abc}_{\mathrm{vsi}}}\end{aligned} \tag{8}$$

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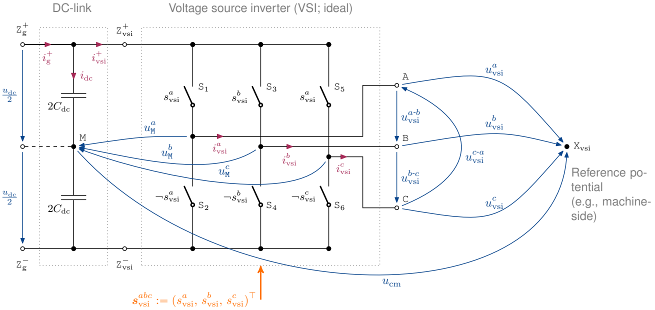
High-performance control: Inverter nonlinearity compensation

Transformation to (d, q)-reference frame (# 1)



Clearly, the following holds

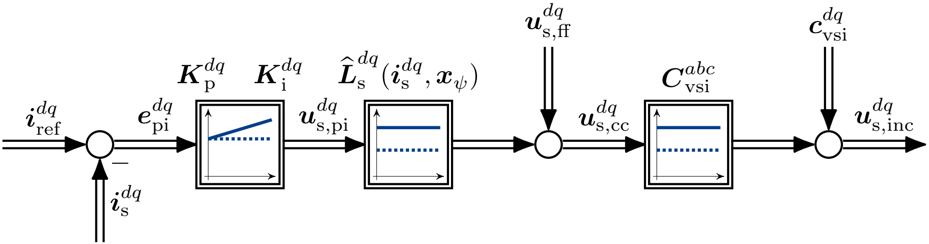
$$\boldsymbol{u}_{vsi}^{abc} = \boldsymbol{u}_{M}^{abc} + u_{cm}\mathbf{1}_3 \quad \text{or} \quad \boldsymbol{u}_{ref}^{abc} = \boldsymbol{u}_{M,ref}^{abc} + u_{cm,ref}\mathbf{1}_3,$$

which implies

$$\boldsymbol{u}_{vsi}^{\alpha\beta} = \boldsymbol{T}_c\boldsymbol{u}_{vsi}^{abc} = \underbrace{\boldsymbol{T}_c\boldsymbol{u}_{M}^{abc}}_{=\boldsymbol{u}_M^{\alpha\beta}} + \underbrace{\boldsymbol{T}_c u_{cm}\mathbf{1}_3}_{=\mathbf{0}_2} \quad \text{or} \quad \boldsymbol{u}_{ref}^{\alpha\beta} = \boldsymbol{T}_c\boldsymbol{u}_{ref}^{abc} = \underbrace{\boldsymbol{T}_c\boldsymbol{u}_{M,ref}^{abc}}_{=\boldsymbol{u}_{M,ref}^{\alpha\beta}} + \underbrace{\boldsymbol{T}_c u_{cm,ref}\mathbf{1}_3}_{=\mathbf{0}_2},$$

High-performance control: Inverter nonlinearity compensation

Transformation to (d, q)-reference frame (# 2)



$$\boldsymbol{u}^{dq}_{\mathrm{s,cc}} \overset{!}{=} \boldsymbol{u}^{dq}_{\mathrm{vsi}} = \boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})^{-1}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{u}^{abc}_{\mathrm{vsi}} = \boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})^{-1}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{u}^{abc}_{\mathtt{M}} + \boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})^{-1}\underbrace{\boldsymbol{T}_{\mathrm{c}}u_{\mathrm{cm}}\boldsymbol{1}_3}_{=\boldsymbol{0}_2}$$

$$\overset{(8)}{=} \underbrace{\boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})^{-1}\boldsymbol{T}_{\mathrm{c}}[\boldsymbol{C}^{abc}_{\mathrm{vsi}}]^{-1}\boldsymbol{T}_{\mathrm{c}}^{-1}\boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})}_{=:[\boldsymbol{C}^{dq}_{\mathrm{vsi}}]^{-1}}\boldsymbol{u}^{dq}_{\mathrm{ref}} - \underbrace{\boldsymbol{T}_{\mathrm{p}}(\phi_{\mathrm{p}})^{-1}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{c}^{abc}_{\mathrm{vsi}}}_{=:\boldsymbol{c}^{dq}_{\mathrm{vsi}}}$$

$$\Longrightarrow \quad \boldsymbol{u}^{dq}_{\mathrm{s,inc}} := \boldsymbol{u}^{dq}_{\mathrm{ref}} = \boldsymbol{C}^{abc}_{\mathrm{vsi}}\boldsymbol{u}^{dq}_{\mathrm{s,cc}} + \boldsymbol{c}^{dq}_{\mathrm{vsi}} \tag{9}$$

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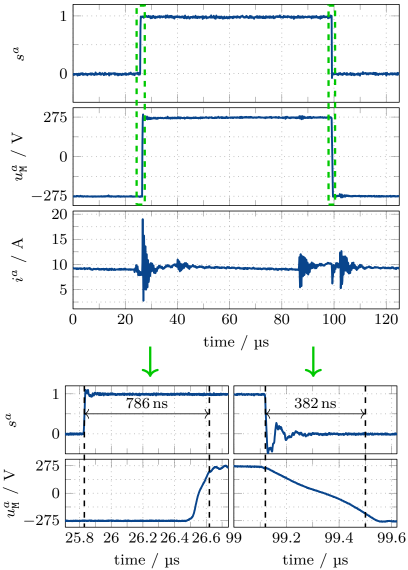
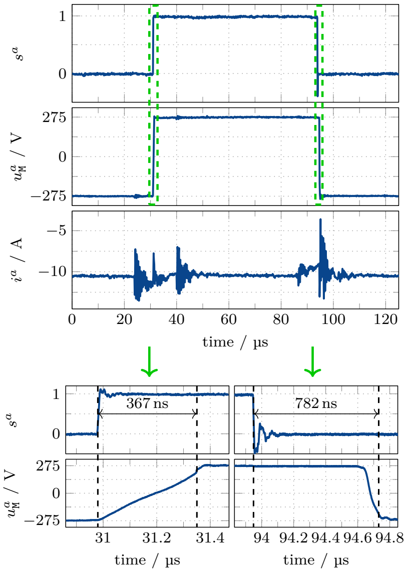
High-performance control: Inverter nonlinearity compensation

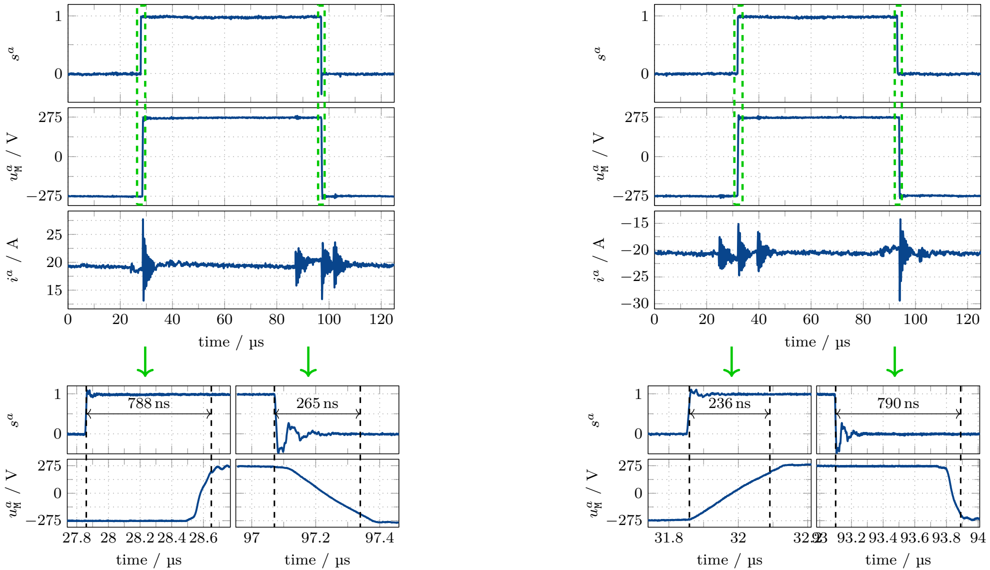
Validation: Measured voltage response of SEMIKRON SKiiP 83 AC 12 in SEW MDX61B0220 at ± 10 A





High-performance control: Inverter nonlinearity compensation

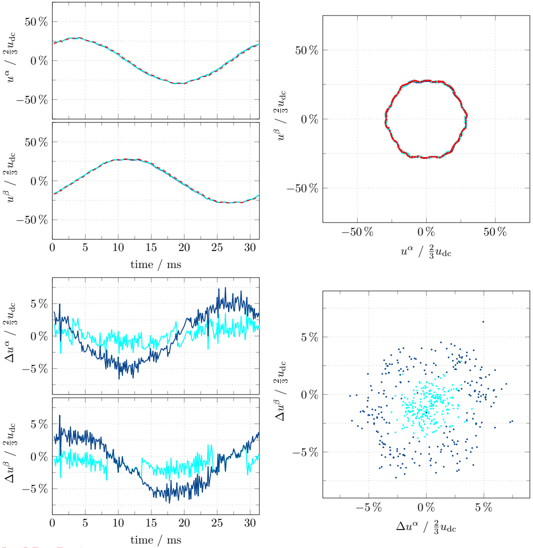
Validation: Measured voltage response of SEMIKRON SKiiP 83 AC 12 in SEW MDX61B0220 at ± 20 A



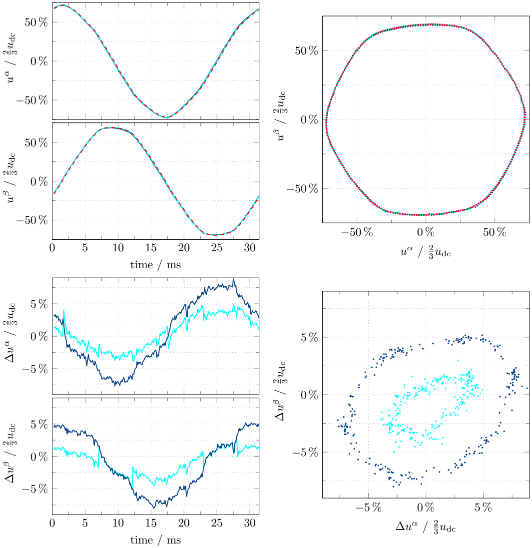
High-performance control: Inverter nonlinearity compensation

Validation: Measurement results [blue line] without INC and [cyan line] with INC

Low-voltage measurements



High-voltage measurements



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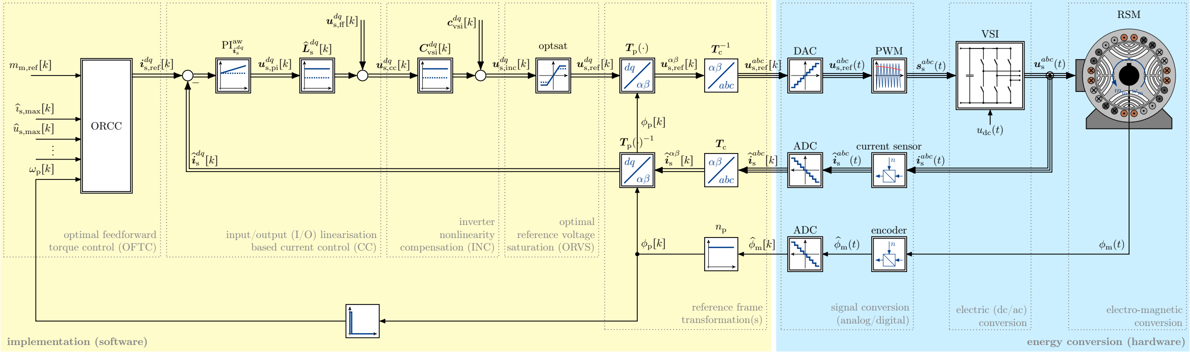
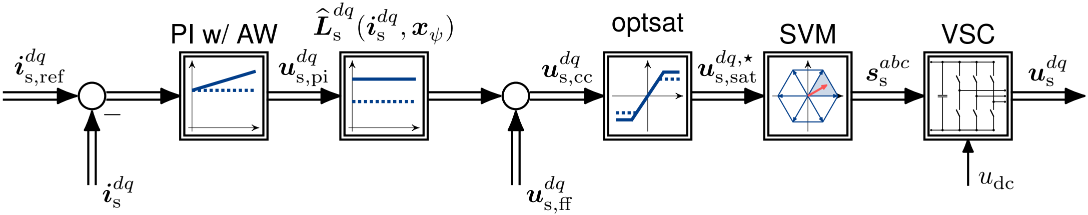
High-performance control

Optimal reference voltage saturation: Overview



High-performance control: Optimal reference voltage saturation

Problem statement: Drawbacks of converters



Any voltage source converter (VSC) suffers from *four* inevitable drawbacks (D_i):

(D_1) voltage deterioration due to nonlinear current-dependent voltage drops over semiconductors [167],

(D_2) voltage ripples due to the switching behavior of the power electronic devices [168],

(D_3) delayed voltage response due to modulation [169], and

(D_4) output voltage constraints due to a limited dc-link voltage.

$\Longrightarrow$ Now we will discuss and solve the last problem in an optimal way ("optsat") in order to reduce its impact, in particular, on proportional-integral (PI) based control methods which still represent the vast majority in industrial applications. For more advanced control methods like model predictive control, the voltage constraints can directly be considered during controller design and/or the optimization stage [135, 170, 171].

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High-performance control: Optimal reference voltage saturation

Proposed solution Optimal Reference Voltage Saturation (ORVS)

Goal of ORVS:
Minimization of the deviation between the desired current dynamics $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s,pi}}^{dq})$ (time derivative of the currents) obtained for the control action $\boldsymbol{u}_{\mathrm{s,pi}}^{dq}$ computed by the PI control system if the voltage constraints were not present and the feasible current dynamics $\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s,sat}}^{dq,\star}, \widehat{u}_{\mathrm{s,max}})$ due to the active voltage constraint $\widehat{u}_{\mathrm{s,max}}$, i.e.

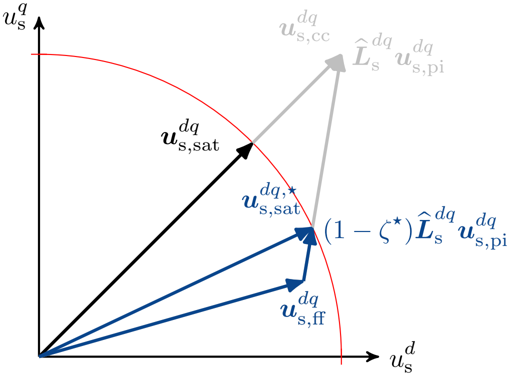
$$\boldsymbol{u}_{\mathrm{s,sat}}^{dq,\star} = \arg\min_{\boldsymbol{u}_{\mathrm{s}}^{dq}} \left\| \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s,pi}}^{dq}) - \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s}}^{dq}, \widehat{u}_{\mathrm{s,max}}) \right\| = \begin{cases} \boldsymbol{u}_{\mathrm{s,cc}}^{dq} \frac{\widehat{u}_{\mathrm{s,max}}}{\|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\|}, & \text{if } \|\boldsymbol{u}_{\mathrm{s,ff}}^{dq}\| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,ff}}^{dq} + (1-\zeta^\star)\,\widehat{\boldsymbol{L}}_{\mathrm{s}}^{dq}\boldsymbol{u}_{\mathrm{s,pi}}^{dq}, & \text{if } \|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,cc}}^{dq}, & \text{else} \end{cases}$$

In contrast to **no saturation** or **conventional saturation**

$$\boldsymbol{u}_{\mathrm{s,sat}}^{dq} := \begin{cases} \boldsymbol{u}_{\mathrm{s,cc}}^{dq} \frac{\widehat{u}_{\mathrm{s,max}}}{||\boldsymbol{u}_{\mathrm{s,cc}}^{dq}||}, & \text{if } ||\boldsymbol{u}_{\mathrm{s,cc}}^{dq}|| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,cc}}^{dq}, & \text{else,} \end{cases}$$

High-performance control: Optimal reference voltage saturation

Proposed solution Illustration of the idea of **Optimal Reference Voltage Saturation (ORVS)**



☞ Consideration of **voltage hexagon** as constraint is possible! (another paper in preparation)

$$\widehat{u}_{s,\max}(u_{dc}) := \begin{cases} \frac{u_{dc}}{2}, & \text{for PWM,} \\ \frac{u_{dc}}{\sqrt{3}}, & \text{for SVM.} \end{cases}$$

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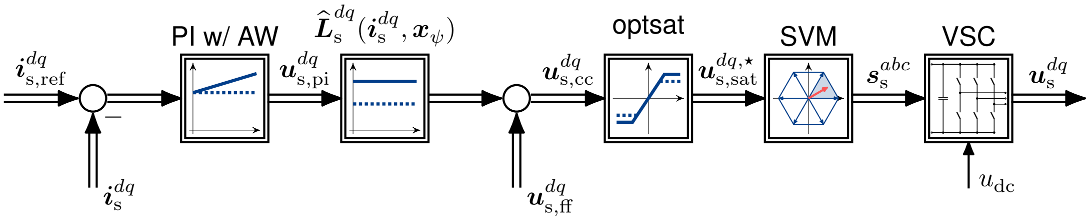
High-performance control: Optimal reference voltage saturation

Input/ouput (I/O) linearization (recap)



I/O linearization approach

$$u^{dq}_{s} \approx u^{dq}_{s,cc} := \widehat{L}^{dq}_{s} u^{dq}_{s,pi} + \underbrace{R^{dq}_{s} i^{dq}_{s} + \omega_p J \psi^{dq}_{s} + \delta^{dq}_{s}}_{=: u^{dq}_{ff}}, \tag{10}$$

gives simple **integral current dynamics** $\frac{d}{dt} i^{dq}_{s} = u^{dq}_{s,pi}$ and allows for simple PLL-like **tuning by pole placement** (recall last slides).

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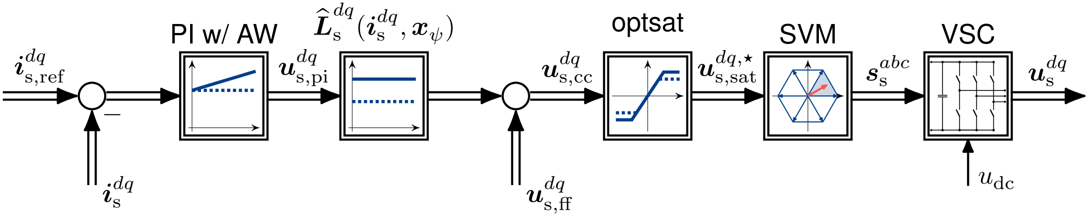
High-performance control: Optimal reference voltage saturation

PI controller design with anti-windup (recap)



Current control system

$$\left.\begin{aligned} \boldsymbol{u}_{\mathrm{s,pi}}^{dq} &= \boldsymbol{K}_{\mathrm{p}}^{dq}\left(\boldsymbol{i}_{\mathrm{s,ref}}^{dq} - \boldsymbol{i}_{\mathrm{s}}^{dq}\right) + \boldsymbol{K}_{\mathrm{i}}^{dq}\boldsymbol{x}_{\mathrm{i}}^{dq}, \\ \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{x}_{\mathrm{i}}^{dq} &= f_{\mathrm{aw}}\left(\widehat{u}_{\mathrm{s,max}}, \boldsymbol{u}_{\mathrm{s,cc}}^{dq}\right)\left(\boldsymbol{i}_{\mathrm{s,ref}}^{dq} - \boldsymbol{i}_{\mathrm{s}}^{dq}\right) \end{aligned}\right\} \qquad (11)$$

with integral state $\boldsymbol{x}_{\mathrm{i}}^{dq}$, gain matrices $\boldsymbol{K}_{\mathrm{p}}^{dq}$ & $\boldsymbol{K}_{\mathrm{i}}^{dq}$ and anti-windup (“conditional integration”) with

$$f_{\mathrm{aw}}\left(\widehat{u}_{\mathrm{s,max}}, \boldsymbol{u}_{\mathrm{s,cc}}^{dq}\right) = \begin{cases} 0, & \text{if } \left\|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\right\| > \widehat{u}_{\mathrm{s,max}}, \\ 1, & \text{else.} \end{cases}$$

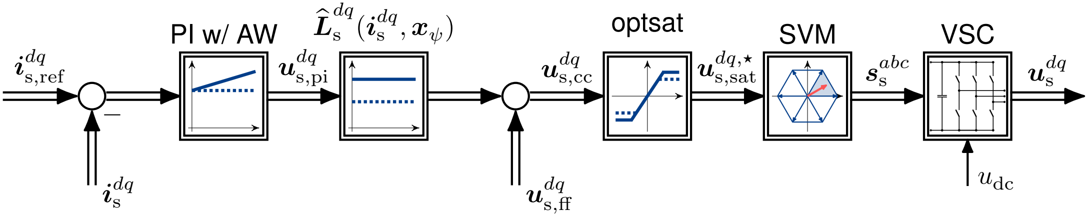
Outline

5 High-performance control

- Overview
- Nonlinear current control
- Inverter nonlinearity compensation
- Optimal reference voltage saturation
  - Problem statement
  - Proposed solution
  - Input/ouput (I/O) linearization (recap)
  - PI controller design with anti-windup (recap)
  - Reference voltage saturation
  - Validation

High-performance control: Optimal reference voltage saturation

Reference voltage saturation: Comparison of different approaches



- **optimal reference voltage saturation** [——] with

$$\boldsymbol{u}_{\mathrm{s,sat}}^{dq,\star} := \arg\min_{\boldsymbol{u}_{\mathrm{s}}^{dq}} \left\| \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s,pi}}^{dq}) - \tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq}(\boldsymbol{u}_{\mathrm{s}}^{dq}, \widehat{u}_{\mathrm{s,max}}) \right\| = \begin{cases} \boldsymbol{u}_{\mathrm{s,cc}}^{dq} \frac{\widehat{u}_{\mathrm{s,max}}}{\|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\|}, & \text{if } \|\boldsymbol{u}_{\mathrm{s,ff}}^{dq}\| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,ff}}^{dq} + (1-\zeta^\star)\, \widehat{\boldsymbol{L}}_{\mathrm{s}}^{dq} \boldsymbol{u}_{\mathrm{s,pi}}^{dq}, & \text{if } \|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,cc}}^{dq}, & \text{else} \end{cases}$$

- **conventional saturation** [——] with $\boldsymbol{u}_{\mathrm{s,sat}}^{dq} := \begin{cases} \boldsymbol{u}_{\mathrm{s,cc}}^{dq} \frac{\widehat{u}_{\mathrm{s,max}}}{\|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\|}, & \text{if } \|\boldsymbol{u}_{\mathrm{s,cc}}^{dq}\| \geqslant \widehat{u}_{\mathrm{s,max}}, \\ \boldsymbol{u}_{\mathrm{s,cc}}^{dq}, & \text{else,} \end{cases}$

- **no saturation (and no anti-windup)** [——]

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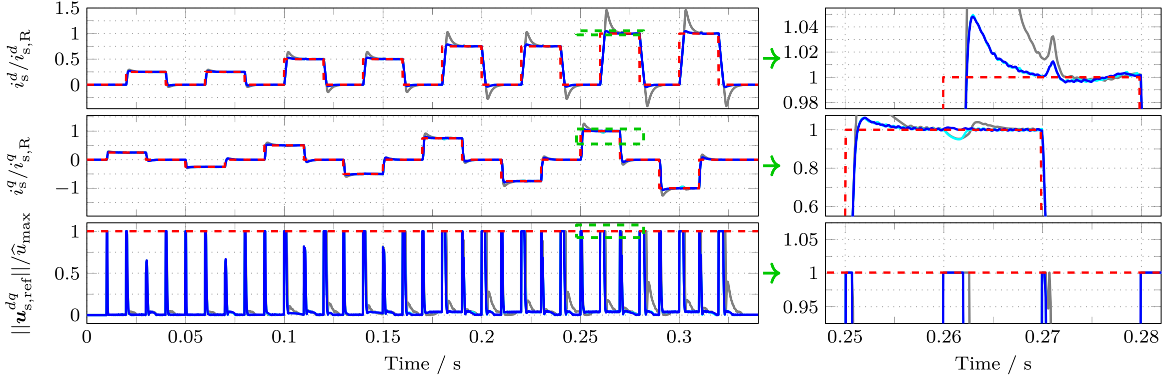
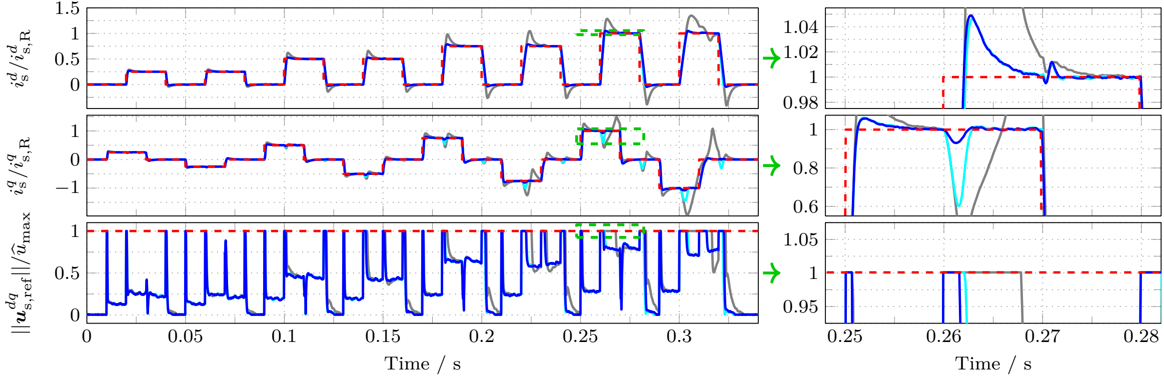
High-performance control: Optimal reference voltage saturation

Validation: Simulation results at standstill ($\omega_{\mathrm{m}} = 0$): Control system *with* ORVS [——], *with* conventional saturation [——] and *without* saturation and anti-windup [——]



High-performance control: Optimal reference voltage saturation

Validation: Simulation results at rated speed ($\omega_{\rm m} = \omega_{\rm m,R}$): Control system *with* ORVS [——], *with* conventional saturation [——] and *without* saturation and anti-windup [——]



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1 Introduction

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3 Nonlinear modelling

4 Dynamic simulation

5 High-performance control

6 Optimal operation

7 Conclusion

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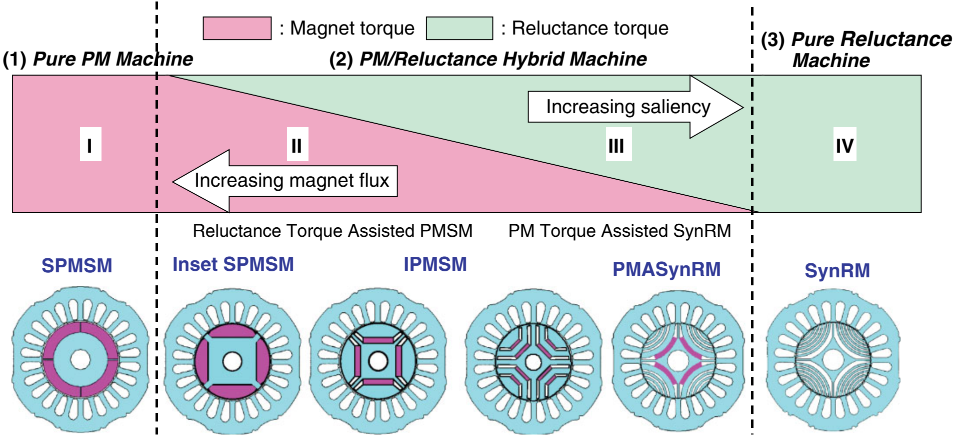
Optimal operation: Motivation

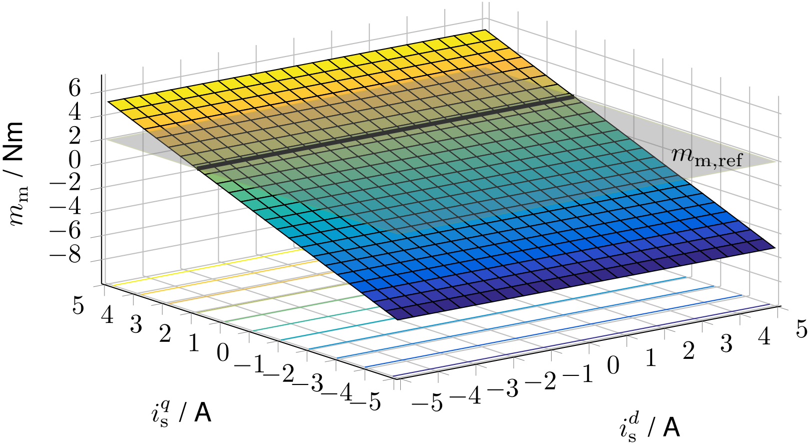
Examples of anisotropic synchronous machines [172] with "saliency ratio" $L_s^d / L_s^q \neq 1$ ($\Leftrightarrow L_{s,app}^d / L_{s,app}^q \neq 1$)



$$m_m(i_s^d, i_s^q) = \frac{2n_p}{3\kappa^2} (\boldsymbol{i}_s^{dq})^\top \boldsymbol{J} \boldsymbol{\psi}_s^{dq} = \frac{2n_p}{3\kappa^2} \Big[\underbrace{\psi_{pm}^d i_s^q - \psi_{pm}^q i_s^d}_{\text{magnetic torque}} + \underbrace{\big(L_{s,app}^d - L_{s,app}^q\big) i_s^d i_s^q}_{\text{reluctance torque}} + \underbrace{L_{s,app}^{dq}\big((i_s^q)^2 - (i_s^d)^2\big)}_{\text{cross-coupling torque}} \Big]$$

Optimal operation: Motivation

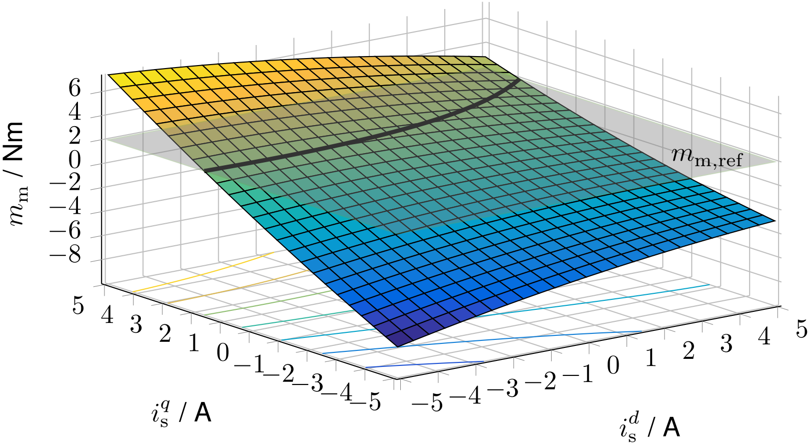
Optimal Feedforward Torque Control (**OFTC**) problem: **Isotropic, linear PMSM** (without iron losses)



$$m_{\mathrm{m,ref}} \overset{!}{=} m_{\mathrm{m}}\left(i_{\mathrm{s}}^{d},\, i_{\mathrm{s}}^{q}\right) = \frac{2n_{\mathrm{p}}}{3\kappa^2}\,\psi_{\mathrm{pm}} i_{\mathrm{s}}^{q} \Longrightarrow \boxed{\boldsymbol{i}_{\mathrm{s,ref}}^{dq} := \left(i_{\mathrm{s,ref}}^{d},\, i_{\mathrm{s,ref}}^{q}\right)^\top = \left(0,\ \frac{3\kappa^2\, m_{\mathrm{m,ref}}}{2n_{\mathrm{p}}\psi_{\mathrm{pm}}}\right)^\top}$$

Optimal operation: Motivation

<u>O</u>ptimal <u>F</u>eedforward <u>T</u>orque <u>C</u>ontrol (**OFTC**) problem: **Anisotropic, affine PMSM** (without iron losses)

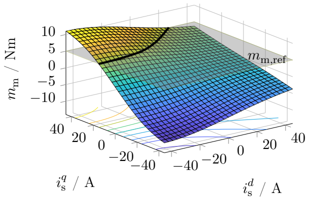


$$m_{\mathrm{m,ref}} \overset{!}{=} \underbrace{\frac{2n_{\mathrm{p}}}{3\kappa^2}\Big[\psi_{\mathrm{pm}}^{d} i_{\mathrm{s}}^{q} - \psi_{\mathrm{pm}}^{q} i_{\mathrm{s}}^{d} + \big(L_{\mathrm{s,app}}^{d} - L_{\mathrm{s,app}}^{q}\big) i_{\mathrm{s}}^{d} i_{\mathrm{s}}^{q} + L_{\mathrm{s,app}}^{dq}\big((i_{\mathrm{s}}^{q})^2 - (i_{\mathrm{s}}^{d})^2\big)\Big]}_{m_{\mathrm{m}}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})} \implies \boxed{\boldsymbol{i}_{\mathrm{s,ref}}^{dq} := (?, ?)^{\top}}$$

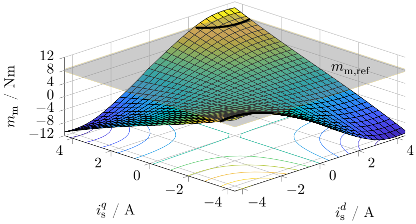
Optimal operation: Motivation

Optimal Feedforward Torque Control (**OFTC**) problem: **Identical for all nonlinear machines**

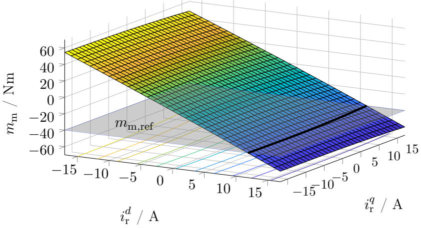
Nonlinear IPMSM (3.9 kW@5 500 rpm)



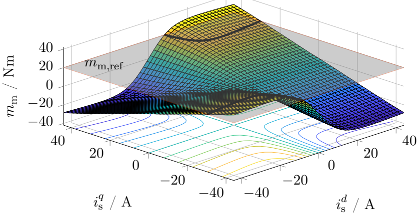
Nonlinear IM (3 kW@1 445 rpm)



Nonlinear DFIM (10 kW@1 500 rpm)



Nonlinear RSM (9.6 kW@1 500 rpm)



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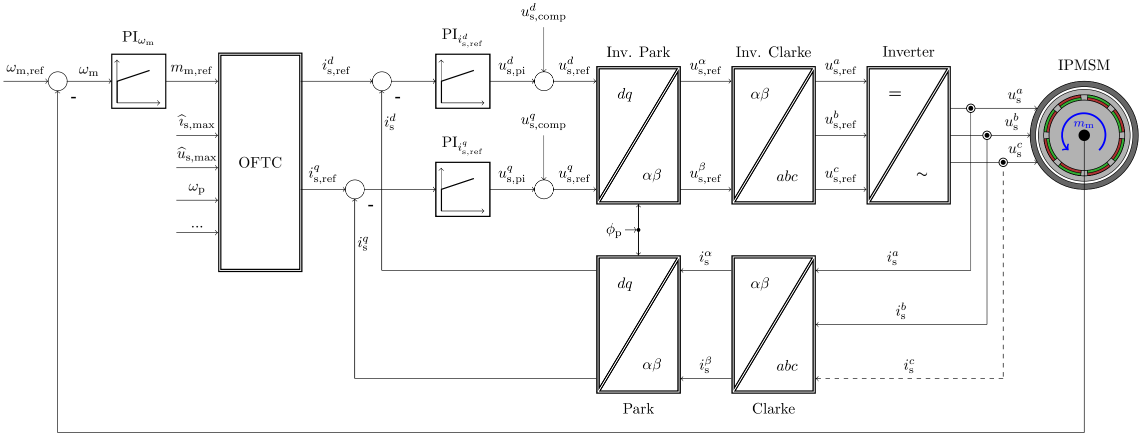
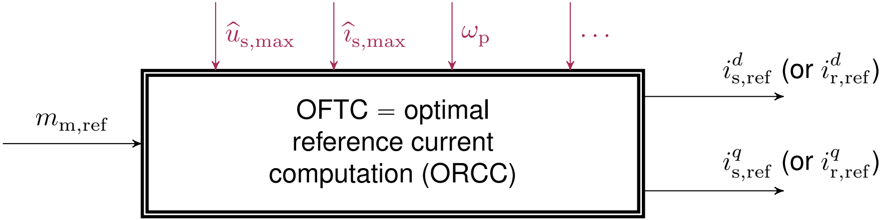
Optimal operation: Problem statement and proposed solution

Optimal Feedforward Torque Control (**OFTC**) within the control system



Optimal operation: Problem statement and proposed solution

Optimal Feedforward Torque Control (**OFTC**) problem: Optimal reference current computation (ORCC)



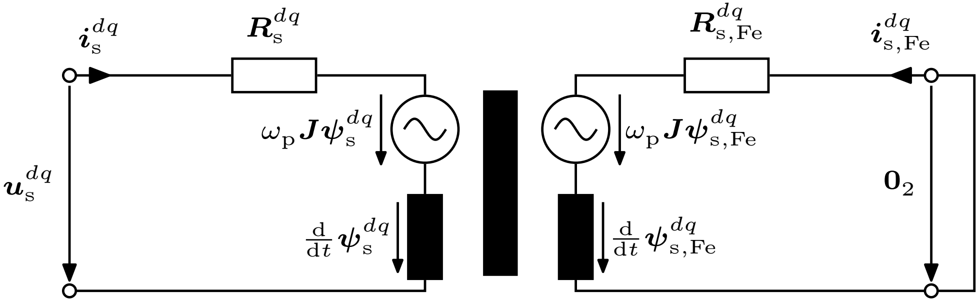
$$\boldsymbol{i}^{dq}_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \dots) = \begin{pmatrix} i^d_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \dots) \\ i^q_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \dots) \end{pmatrix}$$

- ✓ 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 $R_{\mathrm{s}} = 0$, $R_{\mathrm{s,Fe}} = 0$ and/or $L_{\mathrm{s,m}} = 0$, etc.)

Optimal operation: Problem statement and proposed solution

Considered anisotropic synchronous machines with iron losses: **Nonlinear transformer model**



with $\boldsymbol{\psi}_{\mathrm{s}}^{dq} = \boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq}$ (single assumption!) and (possibly) *nonlinear*

- *current, angle, speed* and *temperature* dependent stator resistance, i.e. $\boldsymbol{R}_{\mathrm{s}}^{dq} := \boldsymbol{R}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \phi_{\mathrm{p}}, \omega_{\mathrm{p}}, \vartheta_{\mathrm{s}})$
- *current, angle, speed* and *temperature* dependent iron resistance, i.e. $\boldsymbol{R}_{\mathrm{s,Fe}}^{dq} := \boldsymbol{R}_{\mathrm{s,Fe}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \phi_{\mathrm{p}}, \omega_{\mathrm{p}}, \vartheta_{\mathrm{s}})$
- *current, angle, speed* and *temperature* dependent flux linkages, i.e. $\boldsymbol{\psi}_{\mathrm{s}}^{dq} := \boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \phi_{\mathrm{p}}, \omega_{\mathrm{p}}, \vartheta_{\mathrm{s}})$

Optimal operation: Problem statement and proposed solution

Considered anisotropic synchronous machines with iron losses: **Nonlinear machine dynamics** ($\Longrightarrow$ steady-state model)

Stator:
$$\underbrace{\begin{pmatrix} u_s^d \\ u_s^q \end{pmatrix}}_{=:\boldsymbol{u}_s^{dq}} = \underbrace{\begin{bmatrix} R_s^d & R_s^{dq} \\ R_s^{qd} & R_s^q \end{bmatrix}}_{=:\boldsymbol{R}_s^{dq}} \underbrace{\begin{pmatrix} i_s^d \\ i_s^q \end{pmatrix}}_{=:\boldsymbol{i}_s^{dq}} + \omega_p \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{=:\boldsymbol{J}} \underbrace{\begin{pmatrix} \psi_s^d \\ \psi_s^q \end{pmatrix}}_{=:\boldsymbol{\psi}_s^{dq}} + \cancel{\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^{dq}}$$

Iron:
$$\underbrace{\begin{pmatrix} 0 \\ 0 \end{pmatrix}}_{=:\boldsymbol{0}_2} = \underbrace{\begin{bmatrix} R_{s,Fe}^d & R_{s,Fe}^{dq} \\ R_{s,Fe}^{qd} & R_{s,Fe}^q \end{bmatrix}}_{=:\boldsymbol{R}_{s,Fe}^{dq}} \underbrace{\begin{pmatrix} i_{s,Fe}^d \\ i_{s,Fe}^q \end{pmatrix}}_{=:\boldsymbol{i}_{s,Fe}^{dq}} + \omega_p \boldsymbol{J}\boldsymbol{\psi}_s^{dq} + \cancel{\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^{dq}}$$

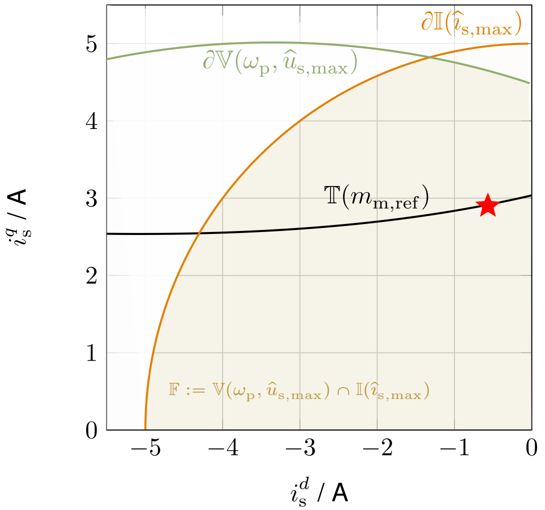
$$\boldsymbol{i}_{s,Fe}^{dq} = -(\boldsymbol{R}_{s,Fe}^{dq})^{-1}\left[\omega_p \boldsymbol{J}\boldsymbol{\psi}_s^{dq} + \cancel{\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_s^{dq}} \right]$$

Mech.:
$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{1}{\Theta_m}(m_m + m_l) \quad \text{with} \quad \omega_p = n_p \omega_m$$
$$m_m = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_s^{dq} + \boldsymbol{i}_{s,Fe}^{dq}\right)^\top \boldsymbol{J}\boldsymbol{\psi}_s^{dq}$$

Losses:
$$p_{s,loss} = \underbrace{\frac{2}{3\kappa^2}(\boldsymbol{i}_s^{dq})^\top \boldsymbol{R}_s^{dq}\boldsymbol{i}_s^{dq}}_{=:p_{s,Cu}} + \underbrace{\frac{2}{3\kappa^2}(\boldsymbol{i}_{s,Fe}^{dq})^\top \boldsymbol{R}_{s,Fe}^{dq}\boldsymbol{i}_{s,Fe}^{dq}}_{=:p_{s,Fe}}$$

Optimal operation: Problem statement and proposed solution

Optimal Reference Current Computation (**ORCC**): Optimization problem(s) with multiple constraints



$\max_{\boldsymbol{i}_s^{dq} \in \mathbb{F}} \; -f(\boldsymbol{i}_s^{dq})$ subject to

- $\|\boldsymbol{i}_s^{dq}\|^2 \leqslant \widehat{\imath}_{s,\max}^2$, (current circular area)
- $\|\boldsymbol{u}_s^{dq}(\boldsymbol{i}_s^{dq}, \omega_p, \ldots)\|^2 \leqslant \widehat{u}_{s,\max}^2$, (voltage elliptical area)
- $|m_m(\boldsymbol{i}_s^{dq}, \omega_p, \ldots)| \leqslant |m_{m,ref}|$, and $\mathrm{sign}(m_{m,ref}) = \mathrm{sign}(m_m(\boldsymbol{i}_s^{dq}))$.

$\Longrightarrow$ e.g. minimize copper losses, i.e., $-f(\boldsymbol{i}_s^{dq}) = -\|\boldsymbol{i}_s^{dq}\|^2$.

$\Longrightarrow$ $\boldsymbol{i}_{s,ref}^{dq} = \boldsymbol{i}_{s,MTPC}^{dq}$ at ★, i.e., MTPC with $m_{m,ref} = m_m(\boldsymbol{i}_{s,ref}^{dq})$ feasible.

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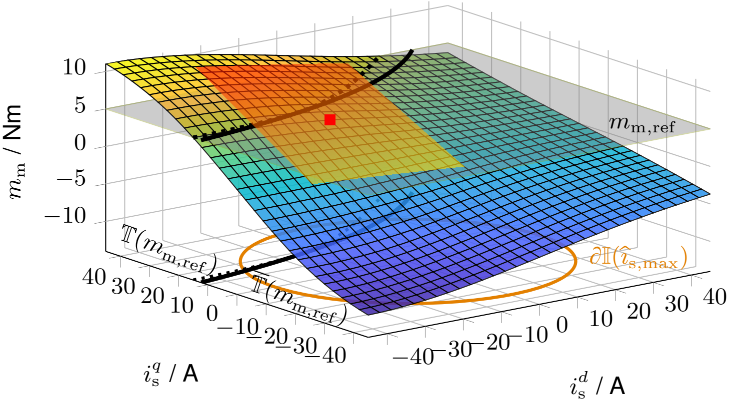
Optimal operation: OFTC with analytical ORCC

Sequential Quadratic Programming (SQP): Linearization, implicit formulation, optimization & intersection points

Step 1: Online linearization of flux linkages, machine torque, iron resistance, etc.: for example:

- **flux linkages** (first-order Taylor approximation around operating point $\bar{\boldsymbol{i}}_s^{dq}$ [■])
- **machine torque** (second-order Taylor approximation around operating point $\bar{\boldsymbol{i}}_s^{dq}$ [■])



- ...

Optimal operation: OFTC with analytical ORCC

Sequential Quadratic Programming (SQP): Linearization, implicit formulation, optimization & intersection points

Step 2: Derivation of quadrics $Q_A(\boldsymbol{i}_s^{dq}) := (\boldsymbol{i}_s^{dq})^\top \boldsymbol{A}\, \boldsymbol{i}_s^{dq} + 2\boldsymbol{a}^\top \boldsymbol{i}_s^{dq} + \alpha$:

- Current circular area: $(i_s^d)^2 + (i_s^q)^2 \leqslant \widehat{\imath}_{s,\max}^2 \iff \|\boldsymbol{i}_s^{dq}\|^2 = (\boldsymbol{i}_s^{dq})^\top \boldsymbol{I}_2 \boldsymbol{i}_s^{dq} \leqslant \widehat{\imath}_{s,\max}^2$

$$\implies \quad \mathbb{I}(\widehat{\imath}_{s,\max}) := \left\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_s^{dq})^\top \boldsymbol{I}_2 \boldsymbol{i}_s^{dq} - \widehat{\imath}_{s,\max}^2 \leqslant 0 \right\}$$

- (Linearized) Voltage elliptical area: $(u_s^d)^2 + (u_s^q)^2 \leqslant \widehat{u}_{s,\max}^2 \iff \|\boldsymbol{u}_s^{dq}(\boldsymbol{i}_s^{dq}, \omega_p, \ldots)\|^2 = \ldots \leqslant \widehat{u}_{s,\max}^2$

$$\implies \quad \overline{\mathbb{V}}(\widehat{u}_{s,\max}) := \left\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{V}}(\overline{\omega}_p)\, \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{v}}(\overline{\omega}_p)^\top \boldsymbol{i}_s^{dq} + \overline{\nu}(\overline{\omega}_p, \widehat{u}_{s,\max}) \leqslant 0 \right\}$$

- (Linearized) Reference torque hyperbola: $m_m(\boldsymbol{i}_s^{dq}, \omega_p, \ldots) = \frac{3}{2} n_p (\boldsymbol{i}_s^{dq} + \boldsymbol{i}_{s,\mathrm{Fe}}^{dq})^\top \boldsymbol{J} \boldsymbol{\psi}_s^{dq} \overset{!}{=} m_{m,\mathrm{ref}} \iff \ldots$

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

- ...

Optimal operation: OFTC with analytical ORCC

Sequential Quadratic Programming (SQP): Linearization, implicit formulation, optimization & intersection points

Step 3: Optimization problem with equality constraint

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

$\Longrightarrow$ Hyperbolas for e.g. MTPC, MTPL or MTPV (with $R_s, R_{s,Fe} \neq 0$ & $L_{s,m} \neq 0$, etc.)

Step 4: Intersection of two quadrics (e.g. voltage ellipse and current circle)

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

$\Longrightarrow$ Optimal operation point ★ (reference current; iteration possibly necessary)

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 [173])

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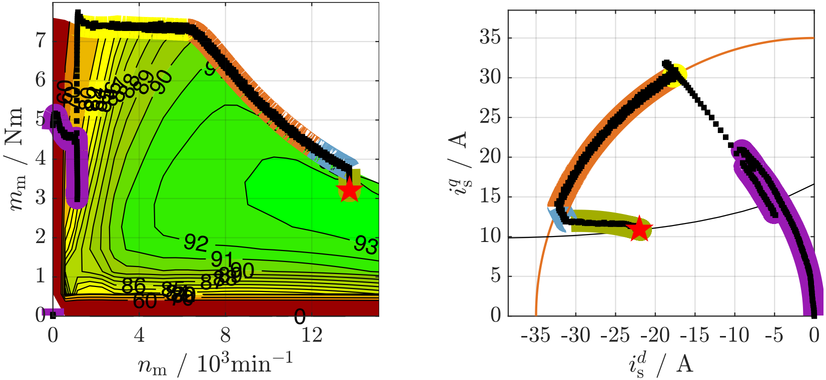
Optimal operation: OFTC with analytical ORCC

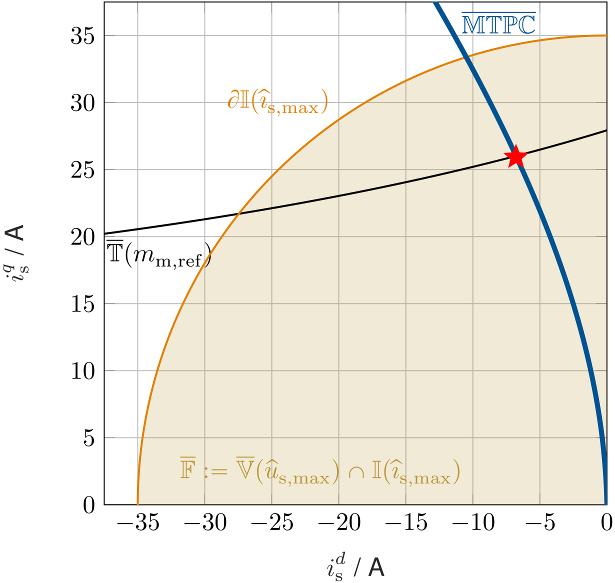
Operation strategies: Overview



- Maximum Torque per Losses (MTPL) [ ] (or Maximum Torque per Current (MTPC) [ ])
- Maximum Current (MC) [ ] and Maximum Current extended (MC_{ext}) [ ]
- Maximum Torque per Voltage (MTPV) [ ] (or Maximum Torque per Flux (MTPF)))
- Field Weakening (FW) [ ]

Optimal operation: OFTC with analytical ORCC

Operation strategies: Maximum Torque per Current (**MTPC** @ $0 \cdot \omega_{\mathrm{m,R}}$; $m_{\mathrm{m,ref}}$ **feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{dq} \in \overline{\mathbb{F}}} -p_{\mathrm{s,Cu}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) \quad \text{s.t.}$$

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

Solution set

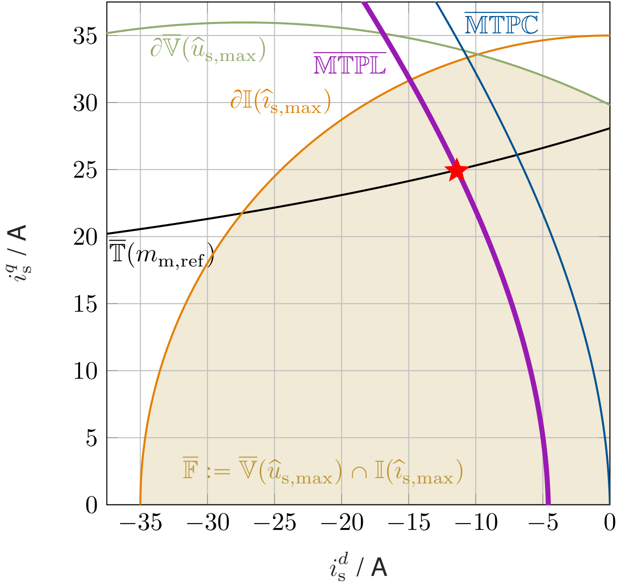
$$\overline{\mathbb{MTPC}}(\overline{\boldsymbol{i}}_{\mathrm{s}}^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots) := \Big\{ \boldsymbol{i}_{\mathrm{s}}^{dq} \in \mathbb{R}^2 \ \Big| \ (\boldsymbol{i}_{\mathrm{s}}^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{C}}\, \boldsymbol{i}_{\mathrm{s}}^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{C}}^\top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

Optimal reference currents (★)

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

Optimal operation: OFTC with analytical ORCC

Operation strategies: Maximum Torque per Losses (**MTPL** @ $1 \cdot \omega_{\mathrm{m,R}}$; $m_{\mathrm{m,ref}}$ **feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{dq} \in \overline{\mathbb{F}}} -p_{\mathrm{s,Cu}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) - p_{\mathrm{s,Fe}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) \quad \text{s.t.}$$

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

Solution set

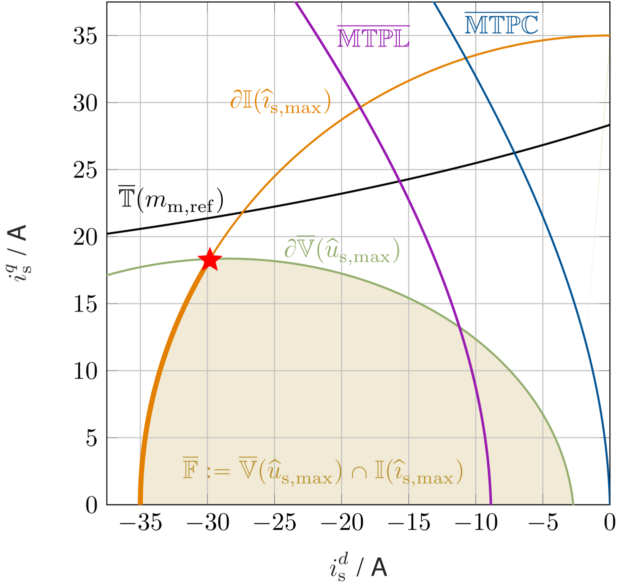
$$\overline{\mathrm{MTPL}}(\overline{\boldsymbol{i}}_{\mathrm{s}}^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots) := \Big\{ \boldsymbol{i}_{\mathrm{s}}^{dq} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_{\mathrm{s}}^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{L}}\, \boldsymbol{i}_{\mathrm{s}}^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{L}}^\top \boldsymbol{i}_{\mathrm{s}}^{dq} + \overline{\mu}_{\mathrm{L}} = 0 \Big\}$$

Optimal reference currents (★)

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

Optimal operation: OFTC with analytical ORCC

Operation strategies: Maximum Current (**MC** @ $2 \cdot \omega_{\mathrm{m,R}}$; $m_{\mathrm{m,ref}}$ **not feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_s^{dq} \in \overline{\mathbb{F}}} |(m_m(\boldsymbol{i}_s^{dq}))| \quad \text{s.t.}$$

$$\mathrm{sign}(m_m) = \mathrm{sign}(m_{m,\mathrm{ref}})$$

Feasible set

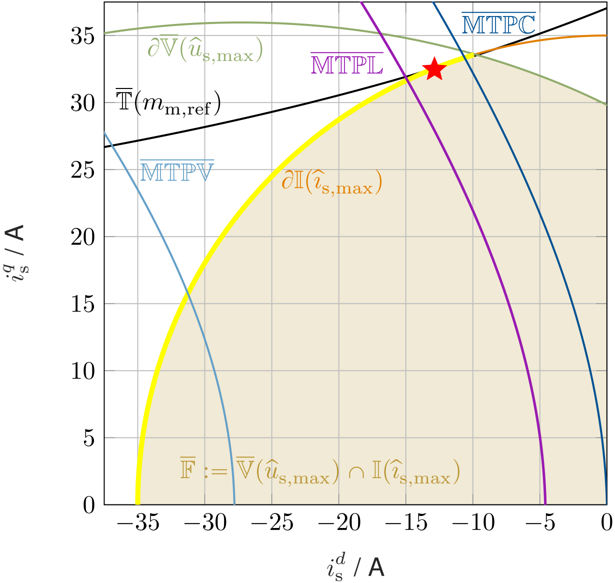
$$\overline{\mathbb{MC}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_p, \ldots, \widehat{u}_{s,\max}, \widehat{\imath}_{s,\max}) := \overline{\mathbb{V}}(\widehat{u}_{s,\max}) \cap \partial\mathbb{I}(\widehat{\imath}_{s,\max})$$

Optimal current reference (★)

$$\boldsymbol{i}_{s,\mathrm{MC}}^{dq} = \partial\overline{\mathbb{V}}(\widehat{u}_{s,\max}) \cap \partial\mathbb{I}(\widehat{\imath}_{s,\max})$$

Optimal operation: OFTC with analytical ORCC

Operation strategies: Maximum Current extended (**MC**$_{\rm ext}$ @ $1 \cdot \omega_{\rm m,R}$; $m_{\rm m,ref}$ **feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_{\rm s}^{dq} \in \overline{\mathbb{F}}} |(m_{\rm m}(\boldsymbol{i}_{\rm s}^{dq}))| \quad \text{s.t.}$$

$$\text{sign}(m_{\rm m}) = \text{sign}(m_{\rm m,ref})$$

Solution set

$$\overline{\mathbb{MC}}_{\rm ext}(\overline{\boldsymbol{i}}_{\rm s}^{dq}, \overline{\omega}_{\rm p}, \ldots, \widehat{u}_{\rm s,max}, \widehat{\imath}_{\rm s,max}) := \overline{\mathbb{V}}(\widehat{u}_{\rm s,max}) \cap \partial\mathbb{I}(\widehat{\imath}_{\rm s,max})$$

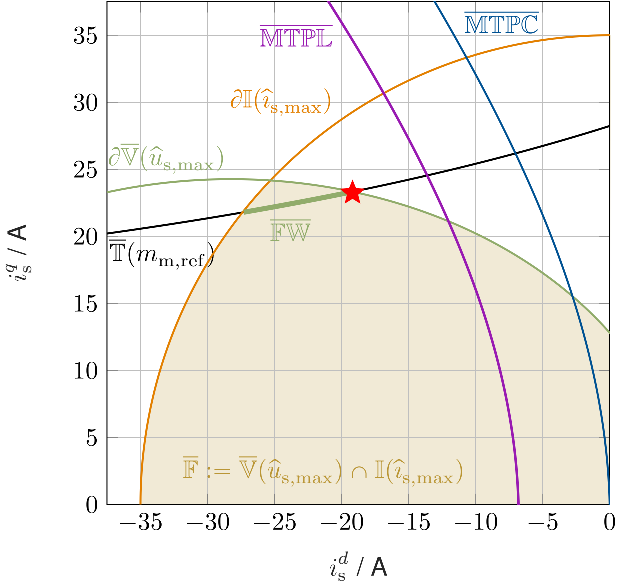
Optimal current reference (★)

$$\boldsymbol{i}_{\rm s,MC_{ext}}^{dq} = \overline{\mathbb{T}}(m_{\rm m,ref}) \cap \partial\mathbb{I}(\widehat{\imath}_{\rm s,max})$$

with $i_{\rm s,MTPL}^{d} < i_{\rm s,MC_{ext}}^{d}$

Optimal operation: OFTC with analytical ORCC

Operation strategies: Field Weakening (**FW** @ $1.40 \cdot \omega_{\mathrm{m,R}}$; $m_{\mathrm{m,ref}}$ **feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_{\mathrm{s}}^{dq} \in \overline{\mathbb{F}}} -p_{\mathrm{s,Cu}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) - p_{\mathrm{s,Fe}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) \quad \text{s.t.}$$

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

Feasible set

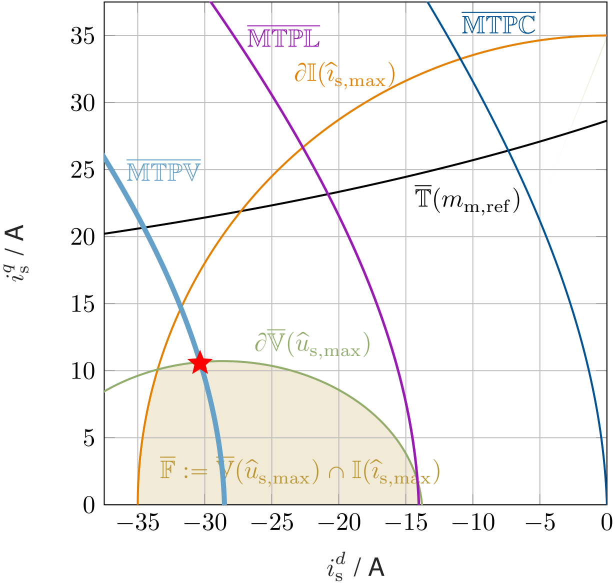
$$\overline{\mathbb{FW}}(\bar{\boldsymbol{i}}_{\mathrm{s}}^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots, m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) := \overline{\mathbb{F}}(\widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) \cap \overline{\mathbb{T}}(m_{\mathrm{m,ref}})$$

Optimal reference currents (★)

$$\boldsymbol{i}_{\mathrm{s,FW}}^{dq} = \partial\overline{\mathbb{V}}(\widehat{u}_{\mathrm{s,max}}) \cap \overline{\mathbb{T}}(m_{\mathrm{m,ref}})$$

Optimal operation: OFTC with analytical ORCC

Operation strategies: Maximum Torque per Voltage (**MTPV** @ $3.50 \cdot \omega_{\mathrm{m,R}}$; $m_{\mathrm{m,ref}}$ **not feasible**)



Optimization problem

$$\max_{\boldsymbol{i}_s^{dq} \in \overline{\mathbb{F}}} -\left\|\boldsymbol{u}_s^{dq}(\boldsymbol{i}_s^{dq})\right\|^2 \quad \text{s.t.}$$

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

Solution set

$$\overline{\mathbb{MTPV}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_{\mathrm{p}}, \cdots) := \left\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\middle|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{V}}\, \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{V}}^\top \boldsymbol{i}_s^{dq} + \overline{\mu}_{\mathrm{V}} = 0 \right\}$$

Optimal reference currents (★)

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

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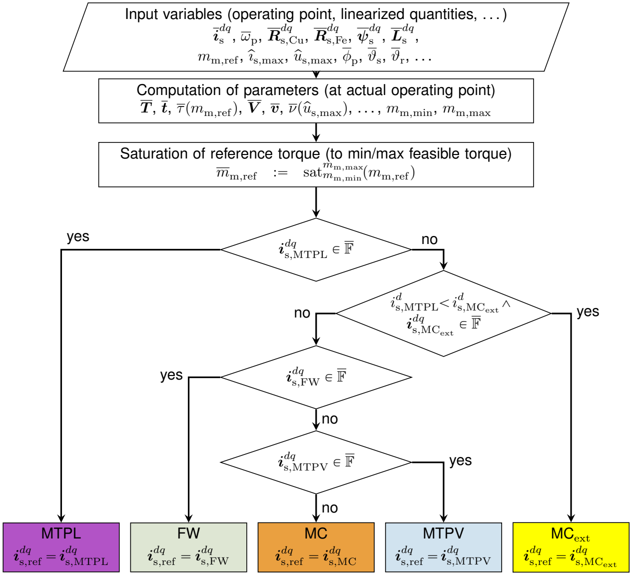
- OFTC with ANN-based ORCC

Optimal operation: OFTC with analytical ORCC

Operation management: Decision tree



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Optimal operation: OFTC with analytical ORCC

Implementation results: Exemplary laboratory setup

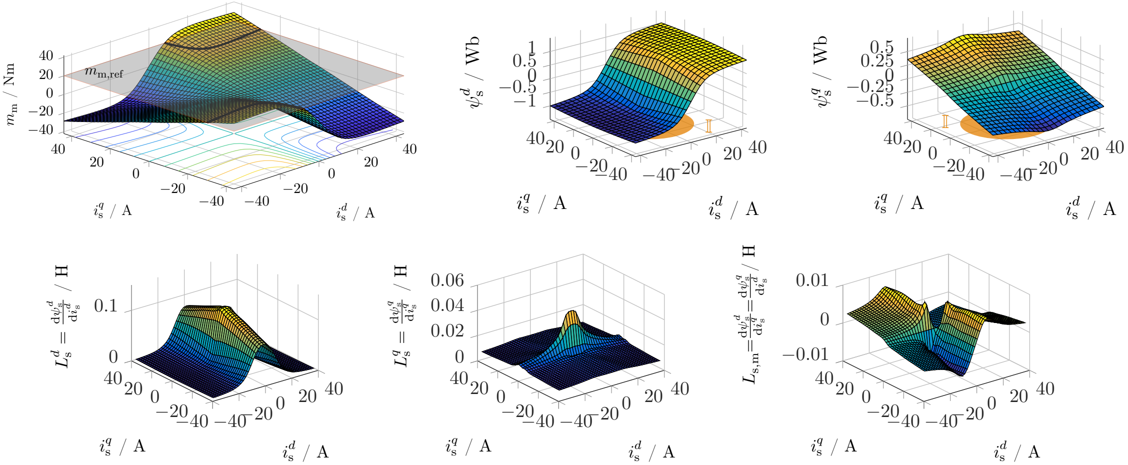
Reluctance SM (RSM) and Permanent-magnet SM

Host PC (rapid prototyping)

Real-time system and VSIs

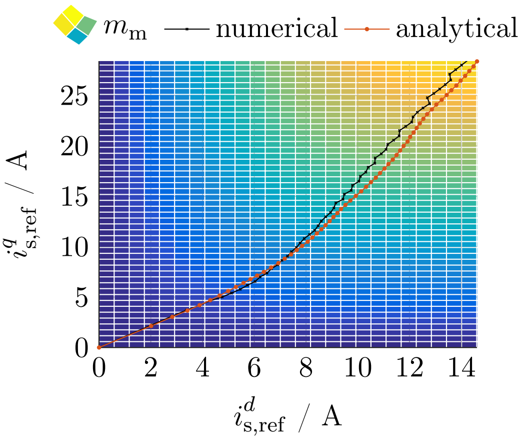
Optimal operation: OFTC with analytical ORCC

Implementation results: Nonlinear maps of torque, flux linkages and differential inductances of RSM ($9.6\,\mathrm{kW}@1\,500\,\mathrm{rpm}$)

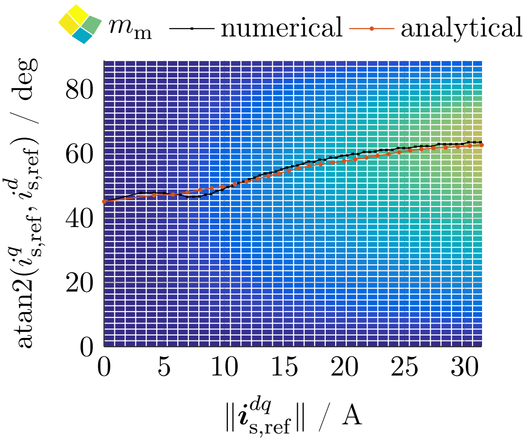


Optimal operation: OFTC with analytical ORCC

Implementation results: Comparison of numerical and analytical solutions for MTPC of RSM (9.6 kW@1 500 rpm)



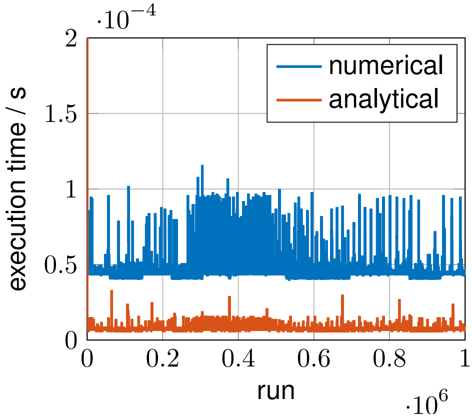
Cartesian coordinates

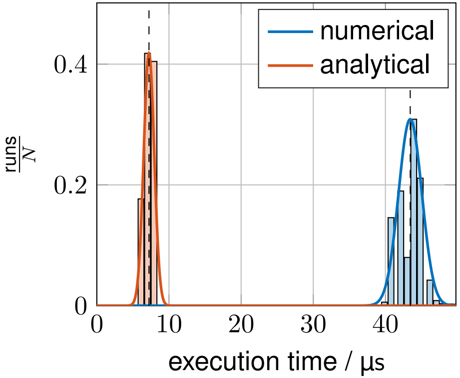


polar coordinates

Optimal operation: OFTC with analytical ORCC

Implementation results: Comparison of computational load (Euler's solution for fourth-order polynomials)



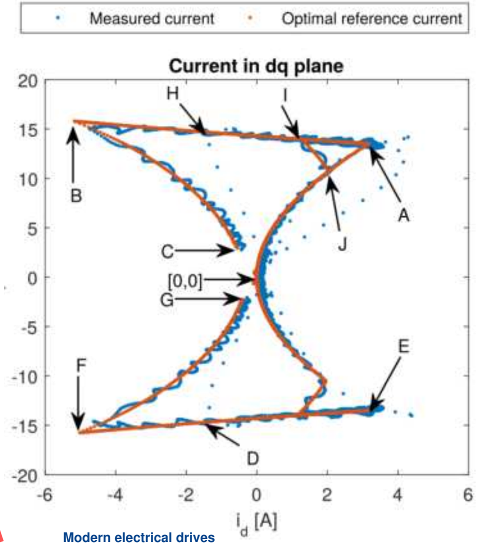


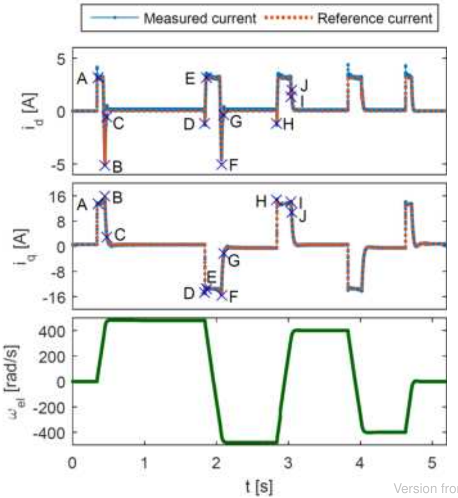
- Execution times for $N = 10^6$ runs (downsampled by factor 100)
- Standard deviations $\sigma_n = 1.61 \cdot 10^{-6}$ s and $\sigma_a = 0.73 \cdot 10^{-6}$ s
- Average execution times $\mu_n = 43.4 \cdot 10^{-6}$ s and $\mu_a = 7.23 \cdot 10^{-6}$ s ($>$**6x faster**)

Optimal operation: OFTC with analytical ORCC

Implementation results: Implementation by colleagues for PME-RSM $(4.5\,\mathrm{kW}@1\,500\,\mathrm{rpm})$

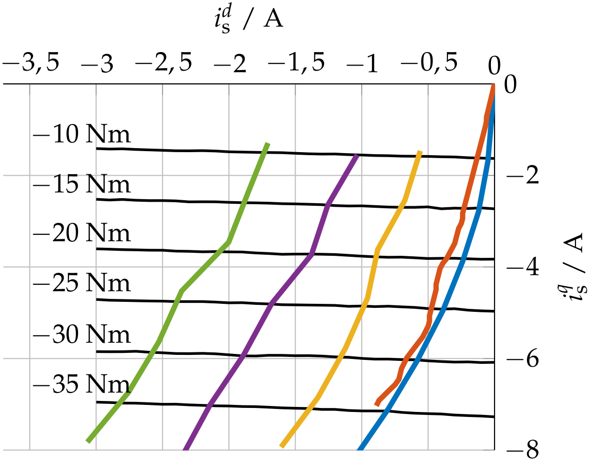
$[\max\left(L_{\mathrm{s}}^{d}(\boldsymbol{i}_{\mathrm{s}}^{dq})/L_{\mathrm{s}}^{q}(\boldsymbol{i}_{\mathrm{s}}^{dq})\right) = 1.43]$ [174]

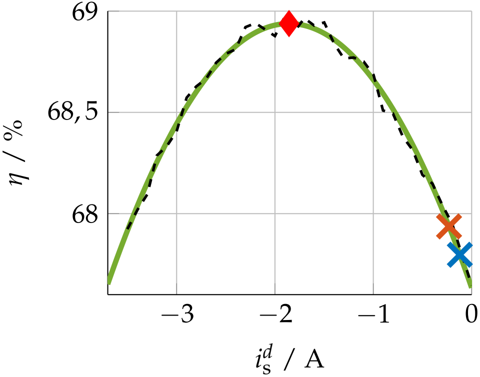




Optimal operation: OFTC with analytical ORCC

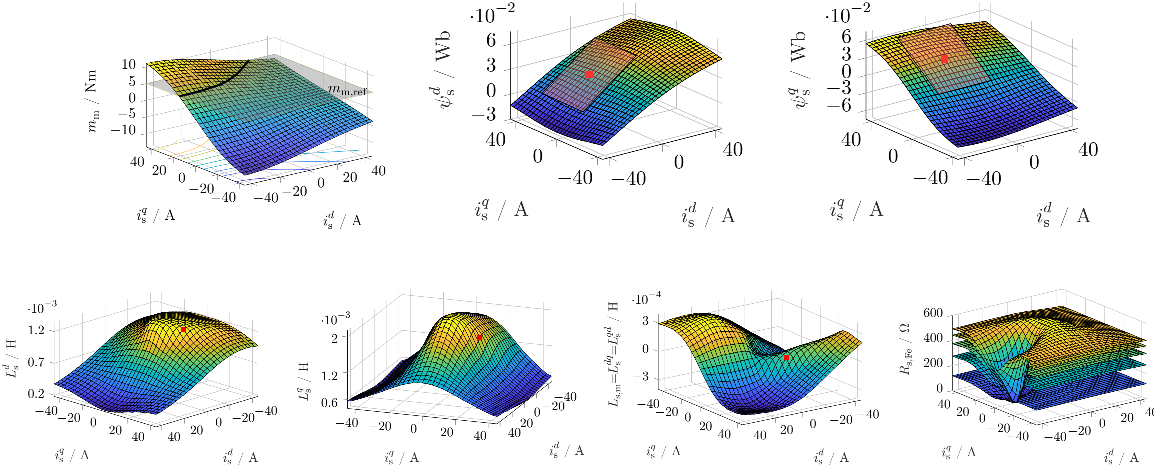
Implementation results: Efficiency enhancements considering iron losses for IPMSM (generator mode) [15]





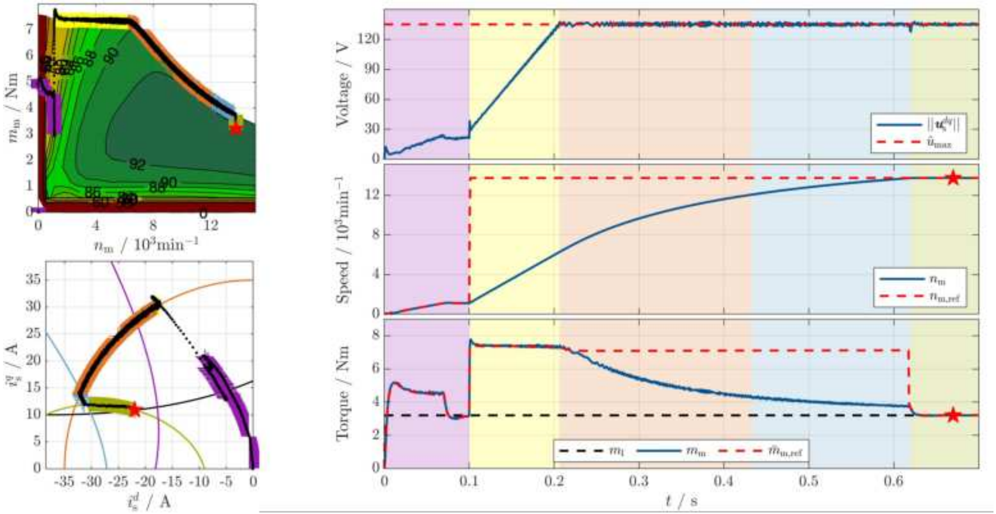
Optimal operation: OFTC with analytical ORCC

Implementation results: Nonlinear maps of torque, flux linkages, differential inductances and iron resistance of IPMSM ($3.9\,$kW@$5\,500\,$rpm)



Optimal operation: OFTC with analytical ORCC

Implementation results: Animation of optimal operation of IPMSM ($3.9\,\mathrm{kW}@5\,500\,\mathrm{rpm}$)



MTPL [ ]

$\mathrm{MC_{ext}}$ [ ]

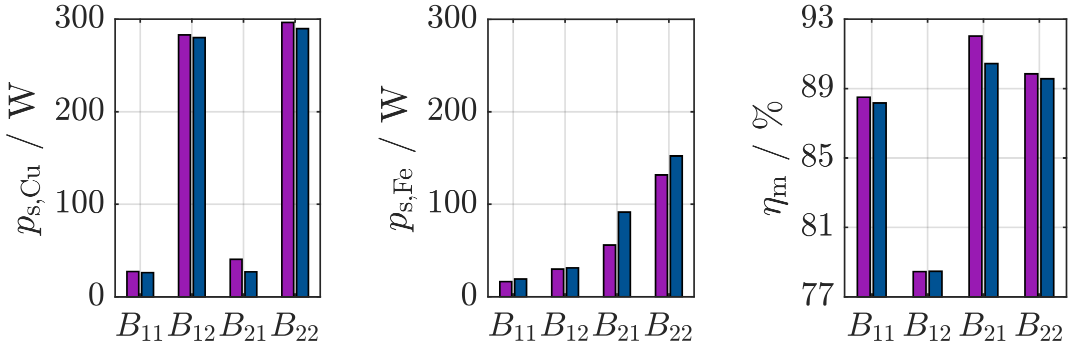
MC [ ]

MTPV [ ]

FW [ ]

Optimal operation: OFTC with analytical ORCC

Implementation results: Comparison of MTPL [ ] & MTPC [ ] for **four** operating points (OPs) of IPMSM (3.9 kW@$5\,500$ rpm)



OP	Speed	Torque
B_{11}	$30\%\, n_{m,R}$	$30\%\, m_{m,R}$
B_{12}	$30\%\, n_{m,R}$	$100\%\, m_{m,R}$
B_{21}	$100\%\, n_{m,R}$	$30\%\, m_{m,R}$
B_{22}	$100\%\, n_{m,R}$	$100\%\, m_{m,R}$

- Copper losses increase with torque
- Iron losses increase with speed *and* torque
- MTPL outperforms MTPC for three OPs (equal for B_{12})
- highest efficiency enhancement for high speeds and low(er) torque (i.e., B_{21} with $\Delta\eta_m > 2\%$)

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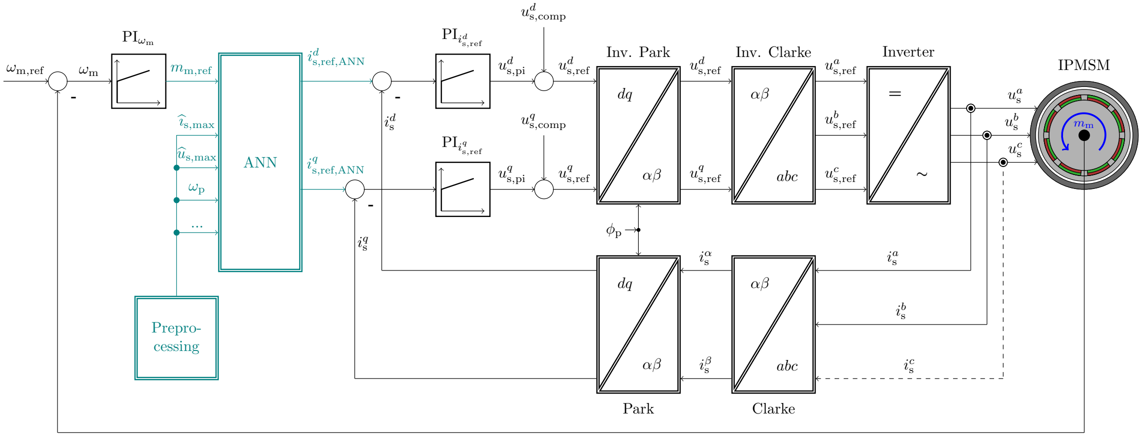
Optimal operation: OFTC with ANN-based ORCC

Overview: OFTC with Artificial Neural Network (ANN)-based ORCC within the control system



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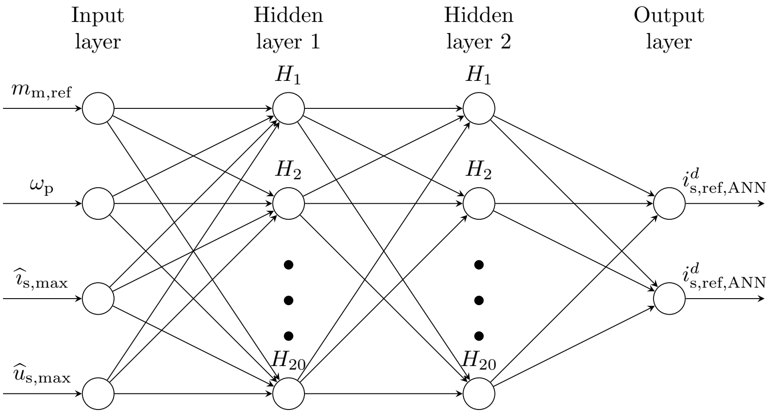
Optimal operation: OFTC with ANN-based ORCC

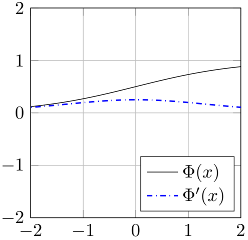
Artificial Neural Network Design: Used ANN topology



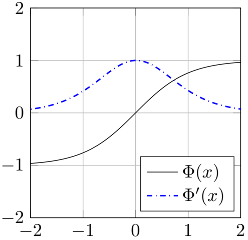
$$\hat{\boldsymbol{y}} = \begin{pmatrix} i^d_{\mathrm{ref,ANN}} \\ i^q_{\mathrm{ref,ANN}} \end{pmatrix} = \boldsymbol{\Phi}_4\Big(\boldsymbol{W}_4\boldsymbol{\Phi}_3\Big(\boldsymbol{W}_3\boldsymbol{\Phi}_2\Big(\boldsymbol{W}_2\boldsymbol{\Phi}_1\Big(\boldsymbol{W}_1 \underbrace{\begin{pmatrix} m_{\mathrm{m,ref}} \\ \omega_{\mathrm{p}} \\ \widehat{\imath}_{\mathrm{s,max}} \\ \widehat{u}_{\mathrm{s,max}} \end{pmatrix}}_{=:\boldsymbol{x}} + \boldsymbol{b}_1\Big) + \boldsymbol{b}_2\Big)\Big) + \boldsymbol{b}_3\Big) + \boldsymbol{b}_4\Big).$$

Optimal operation: OFTC with ANN-based ORCC

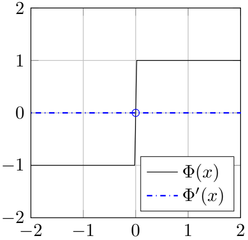
Artificial Neural Network Design: Possible and used ANN activation function(s)



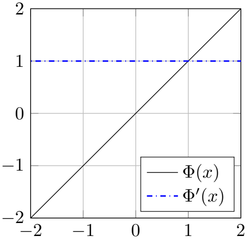
(a) Sigmoid.



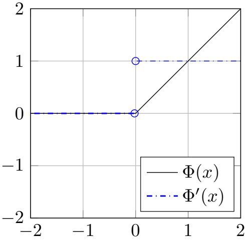
(b) Tangens hyperbolicus.



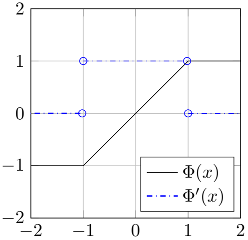
(c) Signum (sign).



(d) **Identity**.



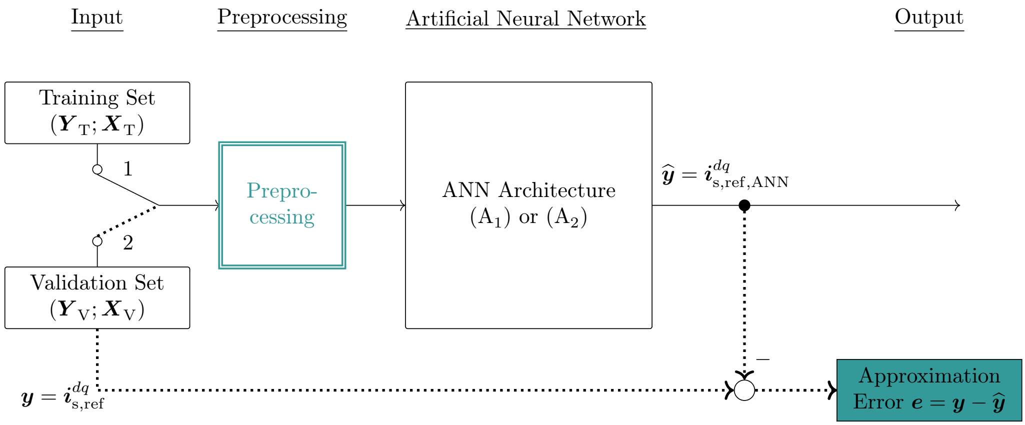
(e) **Rectified Linear Unit (ReLU)**.



(f) Saturation.

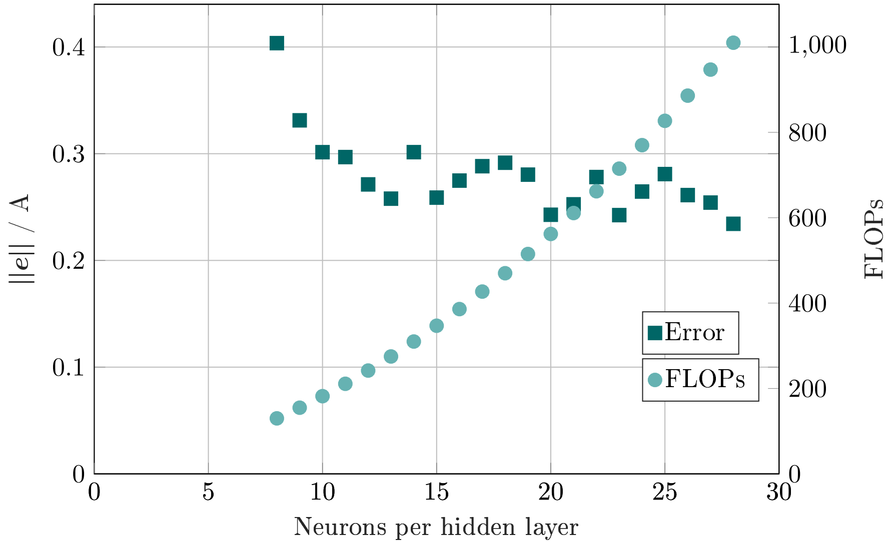
Optimal operation: OFTC with ANN-based ORCC

Artificial Neural Network Design: ANN training and validation



Optimal operation: OFTC with ANN-based ORCC

Artificial Neural Network Design: Estimation accuracy (norm of estimation error) versus floating point operations



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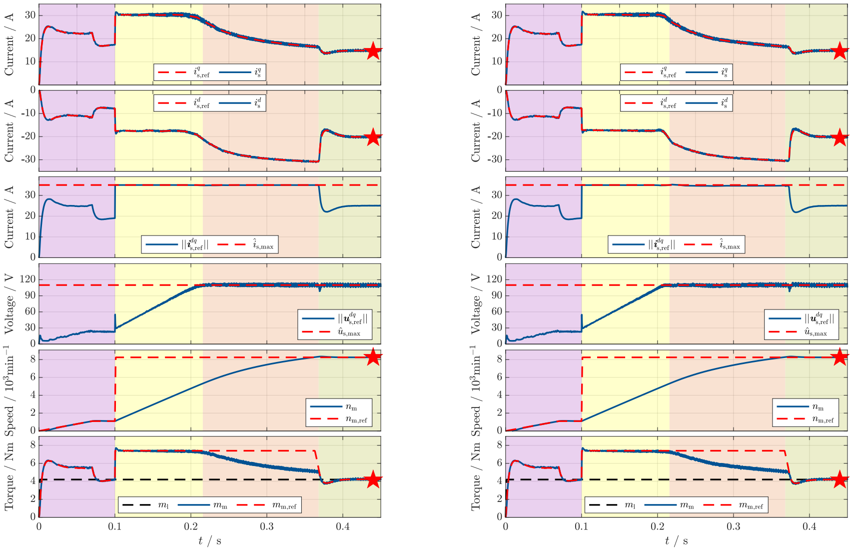
Optimal operation: OFTC with ANN-based ORCC

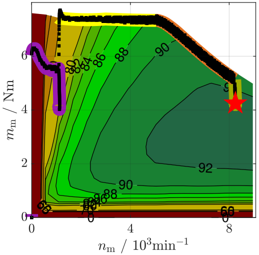
Implementation results: Time series



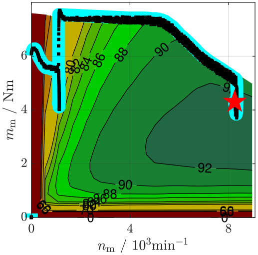
(a) OFTC with analytical ORCC ($\mathrm{OFTC_{ANA}}$). (b) ANN-based OFTC ($\mathrm{OFTC_{ANN}}$).

Optimal operation: OFTC with ANN-based ORCC

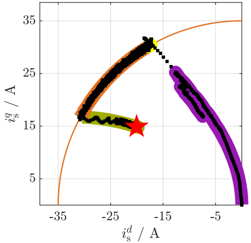
Implementation results: Speed-torque map



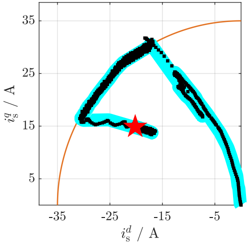
(a) Speed-torque map ($\mathrm{OFTC_{ANA}}$).



(b) Speed-torque map ($\mathrm{OFTC_{ANN}}$).



(c) Current locus ($\mathrm{OFTC_{ANA}}$).



(d) Current locus ($\mathrm{OFTC_{ANN}}$).

Optimal operation: OFTC with ANN-based ORCC

Implementation results: Performance comparison and execution times

Performance measure	**X=OFTC$_{\mathrm{LUT}}$**	**X=OFTC$_{\mathrm{NUM}}$**	**X=OFTC$_{\mathrm{ANA}}$**	**X=OFTC$_{\mathrm{ANN}}$**
$\int \lvert i^d_{\mathrm{s,ref,OFTC_{NLP}}} - i^d_{\mathrm{s,ref,X}} \rvert \mathrm{d}t$	$0.176\,\mathrm{As}$	$0.186\,\mathrm{As}$	$0.384\,\mathrm{As}$	$0.227\,\mathrm{As}$
$\int \lvert i^q_{\mathrm{s,ref,OFTC_{NLP}}} - i^q_{\mathrm{s,ref,X}} \rvert \mathrm{d}t$	$0.195\,\mathrm{As}$	$0.207\,\mathrm{As}$	$0.256\,\mathrm{As}$	$0.213\,\mathrm{As}$
$\int \lvert m_{\mathrm{ref,X}} - m_{\mathrm{m}} \rvert \mathrm{d}t$	$0.018\,\mathrm{Nms}$	$0.017\,\mathrm{Nms}$	$0.026\,\mathrm{Nms}$	$0.020\,\mathrm{Nms}$
$\int \lvert \widehat{u}_{\mathrm{s,max}} - \lVert \boldsymbol{u}^{dq}_{\mathrm{s,ref,X}} \rVert \rvert \mathrm{d}t$	$0.445\,\mathrm{Vs}$	$0.446\,\mathrm{Vs}$	$0.454\,\mathrm{Vs}$	$0.459\,\mathrm{Vs}$
$\int \lvert \widehat{\imath}_{\mathrm{s,max}} - \lVert \boldsymbol{i}^{dq}_{\mathrm{s,ref,X}} \rVert \rvert \mathrm{d}t$	$0.010\,\mathrm{As}$	$0.000\,\mathrm{As}$	$0.000\,\mathrm{As}$	$0.059\,\mathrm{As}$
$\int \lvert n_{\mathrm{m,ref}} - n_{\mathrm{m,X}} \rvert \mathrm{d}t$	$752.4\,\frac{\mathrm{s}}{\mathrm{min}}$	$750.9\,\frac{\mathrm{s}}{\mathrm{min}}$	$752.6\,\frac{\mathrm{s}}{\mathrm{min}}$	$757.8\,\frac{\mathrm{s}}{\mathrm{min}}$
$\bar{t}_{\mathrm{exec,X}}$	$2\,734.782\,\mu\mathrm{s}$	$448.745\,\mu\mathrm{s}$	$439.671\,\mu\mathrm{s}$	$5.855\,\mu\mathrm{s}$

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4 Dynamic simulation

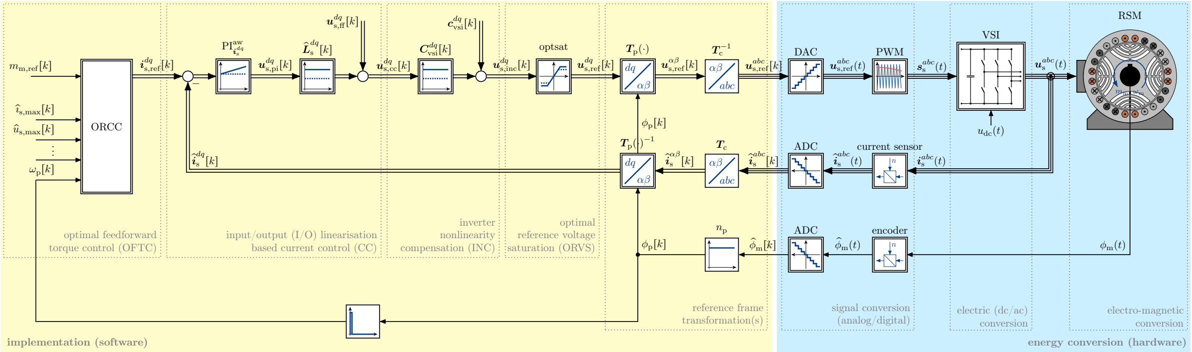
5 High-performance control

6 Optimal operation

7 Conclusion

Conclusion

Summary and future work



To take home

- **Generic** approach to modern electrical drive systems
  - **Nonlinear modelling**
  - **Dynamic simulation**
  - **High-performance control**
  - **Optimal operation**

Future work

- more extensive experimental validation
- impact of (parameter/modelling/alignment) uncertainties
- new book series **“Moderne elektrische Antriebe” with Springer** in preparation (first volume to appear in 2026)

References

Journal article (published 2022; see doi: 10.3390/en15051838)

energies

MDPI

Article

Artificial Neural Network Based Optimal Feedforward Torque Control of Interior Permanent Magnet Synchronous Machines: A Feasibility Study and Comparison with the State-of-the-Art

Max A. Buettner †, **Niklas Monzen** † and **Christoph M. Hackl** *

Department of Electrical Engineering and Information Technology, Hochschule München (HM) University of Applied Sciences, Lothstr. 64, 80335 München, Germany; max.buettner@hm.edu (M.A.B.); niklas.monzen@hm.edu (N.M.)

* Correspondence: christoph.hackl@hm.edu

† These authors contributed equally to this work.

Abstract: A novel Artificial Neural Network (ANN) Based Optimal Feedforward Torque Control (OFTC) strategy is proposed which, after proper ANN design, training and validation, allows to analytically compute the optimal reference currents (minimizing copper and iron losses) for Interior Permanent Magnet Synchronous Machines (IPMSMs) with highly operating point dependent nonlinear electric and magnetic characteristics. In contrast to conventional OFTC, which either utilizes large look-up tables (LUTs; with more than three input parameters) or computes the optimal reference currents numerically or analytically but iteratively (due to the necessary online linearization), the proposed ANN-based OFTC strategy does not require iterations nor a decision tree to find the optimal operation strategy such as e.g., Maximum Torque per Losses (MTPL), Maximum Current (MC) or Field Weakening (FW). Therefore, it is (much) faster and easier to implement while (i) still

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References

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A unified theory for optimal feedforward torque control of anisotropic synchronous machines

Hisham Eldeeb[a], Christoph M. Hackl[a,*], Lorenz Horlbeck[b] and Julian Kullick[a]

[a]Research Group 'Control of Renewable Energy Systems (CRES)', Munich School of Engineering (MSE), Technical University of Munich (TUM), Munich, Germany; [b]Institute of Automotive Technology (FTM), Technical University of Munich (TUM), Munich, Germany

ABSTRACT
A unified theory for optimal feedforward torque control of anisotropic synchronous machines with *non-negligible stator resistance* and *mutual inductance* is presented which allows to *analytically* compute (1) the optimal direct and quadrature reference currents for all operating strategies, such as maximum torque per current (MTPC), maximum current, field weakening, maximum torque per voltage (MTPV) or maximum torque per flux (MTPF), and (2) the transition points indicating when to switch between the operating strategies due to speed, voltage or current constraints. The analytical solutions allow for an (almost) instantaneous selection and computation of actual operation strategy and corresponding reference currents. Numerical methods (approximating these solutions only) are *no longer* required. The unified theory is based on one simple idea: all optimisation problems, their respective constraints and the computation of the intersection point(s) of voltage ellipse, current circle or torque, MTPC, MTPV, MTPF hyperbolas are reformulated implicitly as *quadrics* which allows to invoke the Lagrangian formalism and to find the roots of fourth-order polynomials analytically. The proposed theory is suitable for any anisotropic synchronous machine. Implementation and measurement results illustrate effectiveness and applicability of the theoretical findings in real world.

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KEYWORDS
Maximum torque per ampere (MTPA); maximum torque per current (MTPC); maximum torque per voltage (MTPV); maximum torque per flux (MTPF); maximum current (MC); field weakening (FW); analytical solution; optimal feedforward torque control; efficiency; copper losses; anisotropy; synchronous machine; interior

References

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Generic loss minimization for nonlinear synchronous machines by analytical computation of optimal reference currents considering copper and iron losses

Christoph Hackl, Julian Kullick and Niklas Monzen
Laboratory for Mechatronic and Renewable Energy Systems (LMRES)
Munich University of Applied Sciences (MUAS)
Munich, Germany
{christoph.hackl, julian.kullick, niklas.monzen}@hm.edu

***Abstract*—The unified theory introduced in [1] allows to solve *analytically* the optimal feedforward torque control (OFTC) problem of anisotropic synchronous machines (SMs). In this paper, the theory is extended by considering relevant machine nonlinearities and incorporating copper *and* iron losses, thus minimizing the overall (steady-state) losses in the machine. Instead of the well known maximum torque per current (MTPC) operation strategy, *maximum torque per losses (MTPL)* is realized. The unified theory for the derivation of the analytical solution is briefly recapitulated. Moreover, current *and* speed dependent iron losses, as well as magnetic saturation and cross-coupling effects are considered. The resulting nonlinear optimization problem is solved via online linearization of the relevant expressions.**

for synchronous machines (SMs) with anisotropic rotor designs, e.g. interior permanent magnet synchronous machines (IPMSMs), reluctance synchronous machines (RSMs) or PM-assisted RMSs (PMA-RSMs), efficiency can be increased by optimal feedforward torque control (OFTC) [3, 4].

The main idea of OFTC is to exploit the ambiguity in the selection of the stator current's *direct* and *quadrature* components (producing the same amount of torque), such that losses are minimized while physical constraints are satisfied (e.g. current or voltage limits). Depending on the actual operating conditions, different optimization problems may be formulated

References

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Optimal feedforward torque control for nonlinear induction machines considering stator & rotor copper losses and current & voltage limits

Andre Thommessen, Christoph Hackl
Laboratory for Mechatronic and Renewable Energy Systems (LMRES)
Munich University of Applied Sciences (MUAS)
Munich, Germany
{andre.thommessen, christoph.hackl}@hm.edu

***Abstract*—In order to *analytically* solve the optimal feedforward torque control (OFTC) problem of induction machines (IMs), the unified theory for synchronous machine introduced in [1] is extended by considering relevant IM *nonlinearities* and incorporating stator *and* rotor copper losses. Instead of the well known *Maximum Torque per (stator) Current* (MTPC) operation strategy, *Maximum Torque per (copper) Losses* ($\mathrm{MTPL_{Cu}}$) is realized and extended by the *Maximum (rotor) Current* ($\mathrm{MC_{r,\,ext}}$) strategy due to stator *and* rotor current limitations. Modeling magnetic saturation and cross-coupling effects leads to a constrained *nonlinear* optimization problem which is solved based on the idea of *sequential quadratic programming* (SQP). The second order Taylor approximations are formulated in implicit**

generic approach can also be applied to other types of inverter-fed IMs, such as squirrel-cage induction machines (SCIMs).

The highest priority of the OFTC is to provide the reference torque while minimizing losses. In a wide operating range, there usually exist (infinitely many) different combinations of reference currents resulting in the same torque. Thus, an optimal reference current computation (ORCC) is desirable which minimizes the current-dependent IM losses while reaching the reference torque and taking into account operating (e.g. current & voltage) limits. To do so, this paper proposes a physics-based nonlinear IM model for analytical ORCC.

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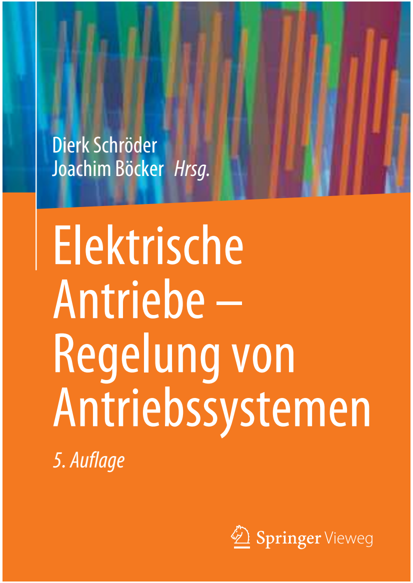
Chapter 6.9 in [175] (published in 2020 in Schröder “Elektrische Antriebssysteme”; doi: 10.1007/978-3-662-62700-6)



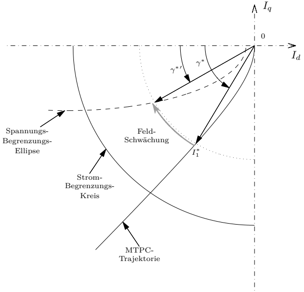


Abb. 6.101 Wirkungsweise der Feldschwächregelung mit Spannungsrückkopplung

6.9 Optimale Betriebsführung von nichtlinearen Synchronmaschinen

C. M. Hackl, J. Kullick, N. Monzen

Der folgende Abschnitt basiert auf den Publikationen [HH16; Eld+16; EHK16; Eld+17b; Hac+17; Eld+17a]. Darin wurde die erste allgemeine Theorie zur analytischen Berechnung der optimalen (verlustminimierenden) Sollströme für anisotrope Synchronmaschinen mit konstanter Erregung vorgestellt. Die weithin verbreiteten und vereinfachenden Annahmen wie z. B. die Vernachlässigung des Statorwiderstandes oder der magnetischen Kreuzkopplung konnten aufgehoben werden. Zusätzlich erlaubt die Theorie die Berücksichtigung von Eisenverlusten und Nicht-

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