Hochschule
München (HM)
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

HM

Artificial Neural Network (ANN) based Optimal Feedforward Torque Control (OFTC) of Synchronous Machines (SMs)

Christoph M. Hackl
(with M. Buettner, H. Eldeeb, L. Horlbeck, J. Kullick, N. Monzen and A. Thommessen)
christoph.hackl@hm.edu

30.03.2022 – Stellenbosch University, South Africa

ISES

Outline

Outline

Introduction

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

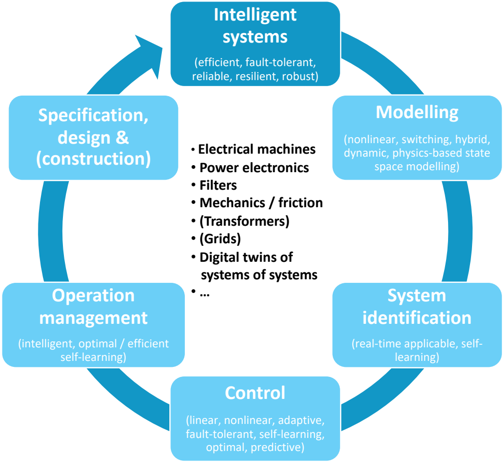
- 5 research labs
- 5 professors
- 25 PhD candidates

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

- International team
- 14 PhD candidates

Introduction

LMRES Activities



Outline

Motivation

Electrical machines: Widely-used, compact and efficient actuators

www.farmwood.co.uk

www.abb.com (from video)

www.bmw.de

www.siemens.com

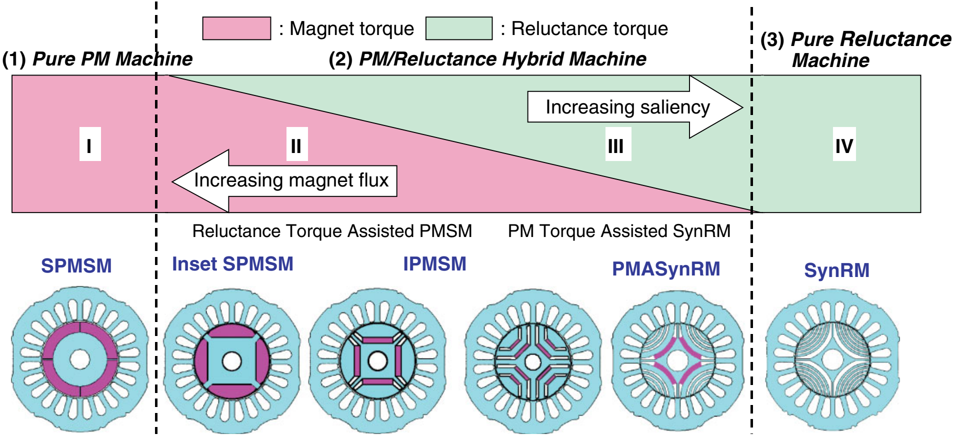
www.lilium.com

...

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

Motivation

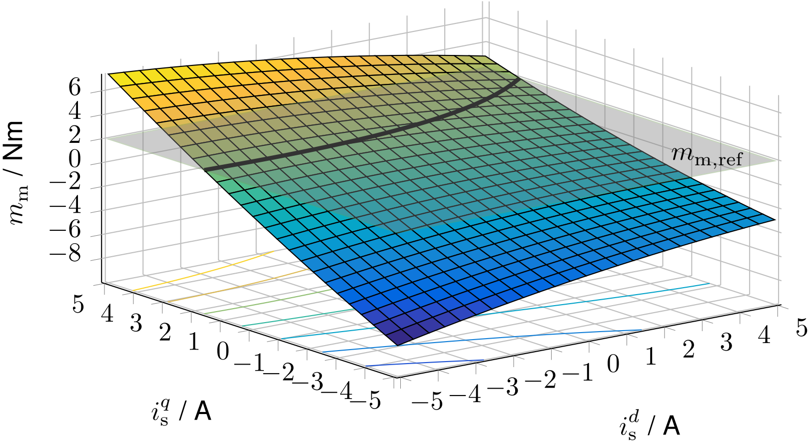
Examples of anisotropic synchronous machines [1] with "saliency ratio" $L_s^d / L_s^q \neq 1$



$$m_m\left(i_s^d, i_s^q\right) = \frac{2n_p}{3\kappa^2}\left(\boldsymbol{i}_s^{dq}\right)^\top \boldsymbol{J}\boldsymbol{\psi}_s^{dq} \overset{\text{(const. Para.)}}{=} \frac{2n_p}{3\kappa^2}\Big[\underbrace{\widetilde{\psi}_{pm} i_s^q}_{\text{magnetic torque}} + \underbrace{\left(\widetilde{L}_s^d - \widetilde{L}_s^q\right) i_s^d i_s^q}_{\text{reluctance torque}} + \underbrace{\widetilde{L}_{s,m}\left((i_s^q)^2 - (i_s^d)^2\right)}_{\text{cross-coupling torque}}\Big]$$

Motivation

Optimal feedforward torque control problem: **Anisotropic, affine PMSM** (without iron losses)

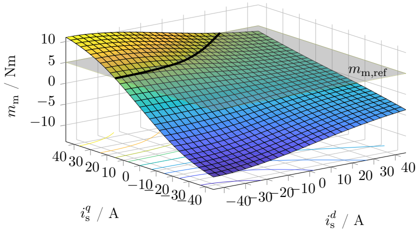


$$m_{\rm m,ref} \stackrel{!}{=} m_{\rm m}\left(\boldsymbol{i}_{\rm s}^{dq}\right) = \frac{2n_{\rm p}}{3\kappa^2}\left[\widetilde{\psi}_{\rm pm} i_{\rm s}^q + \left(\widetilde{L}_{\rm s}^d - \widetilde{L}_{\rm s}^q\right) i_{\rm s}^d i_{\rm s}^q + \widetilde{L}_{\rm s,m}\left(\left(i_{\rm s}^q\right)^2 - \left(i_{\rm s}^d\right)^2\right)\right] \Longrightarrow \boxed{\boldsymbol{i}_{\rm s,ref}^{dq} := (?,?)^\top}$$

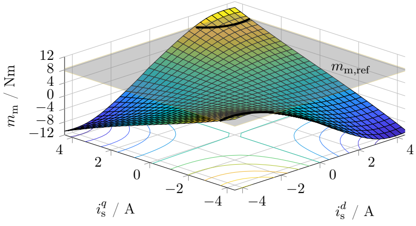
Motivation

Optimal feedforward torque control problem: **Identical for all nonlinear machines**

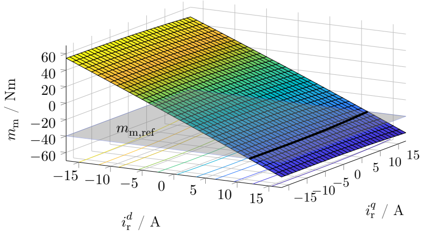
Nonlinear IPMSM (3.9 kW@5 500 rpm)



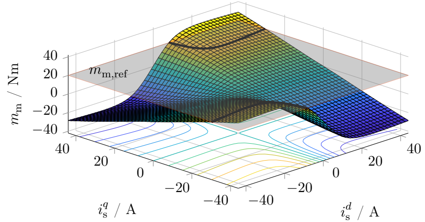
Nonlinear IM (3 kW@1 445 rpm)



Nonlinear DFIM (10 kW@1 500 rpm)



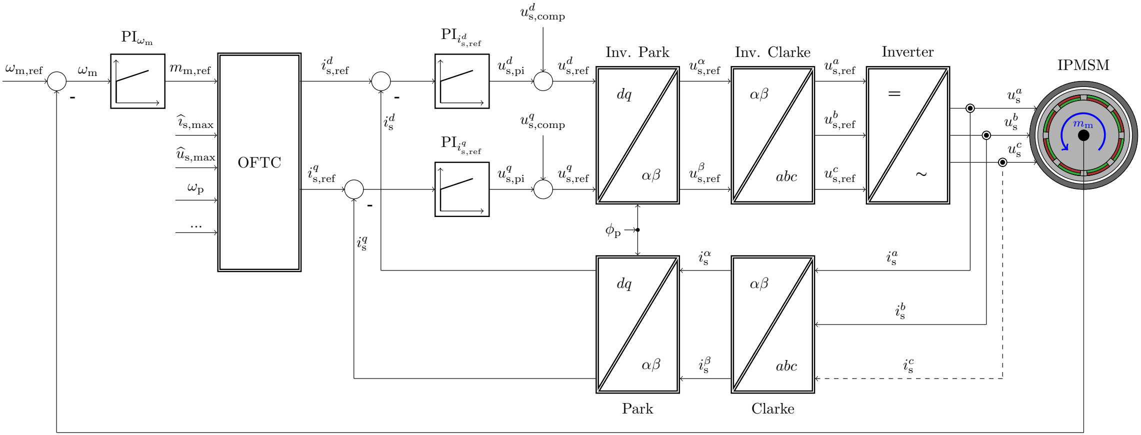
Nonlinear RSM (9.6 kW@1 500 rpm)



Outline

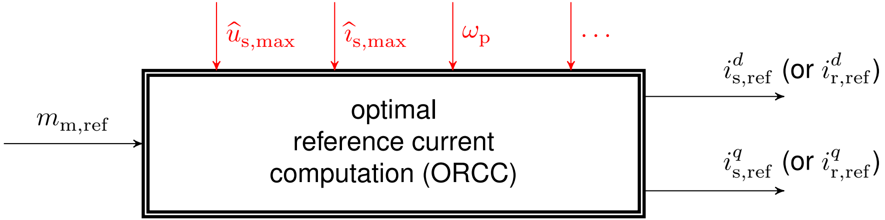
Problem statement and proposed solution

Optimal feedforward torque control (OFTC) within the control system



Problem statement and proposed solution

Optimal feedforward torque control (OFTC) problem: Optimal reference current computation (ORCC)



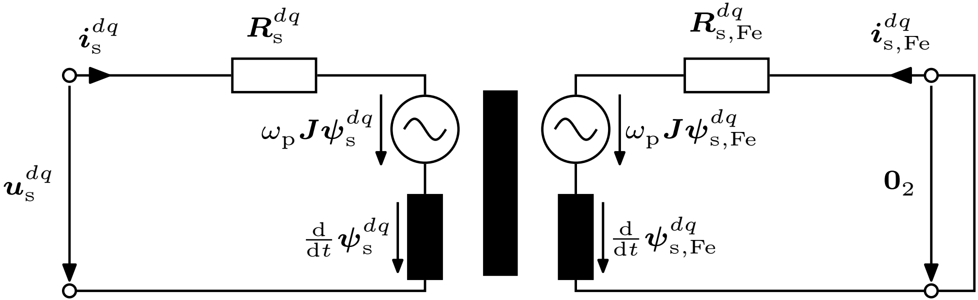
$$\boldsymbol{i}^{dq}_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \ldots) = \begin{pmatrix} i^d_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \ldots)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

- ✓ 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.~~)

Problem statement and proposed solution

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

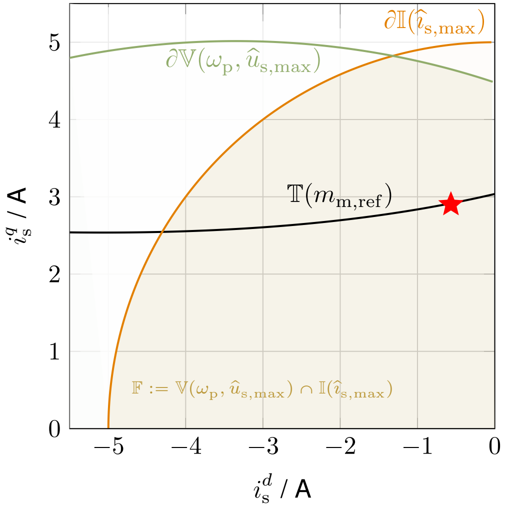


with $\boldsymbol{\psi}_{\mathrm{s}}^{dq} = \boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq}$ (single assumption!) and (possibly) *nonlinear*

- *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. $\boldsymbol{\psi}_{\mathrm{s}}^{dq} := \boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \phi_{\mathrm{p}}, \omega_{\mathrm{p}}, \vartheta_{\mathrm{s}})$

Problem statement and proposed solution

Optimal reference current computation (ORCC): Optimization problem(s) with multiple constraints



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

$$\begin{cases} \|\boldsymbol{i}_{\mathrm{s}}^{dq}\|^2 \leqslant \widehat{\imath}_{\mathrm{s,max}}^2, \\ \text{(current circular area)} \\ \|\boldsymbol{u}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \omega_{\mathrm{p}}, \dots)\|^2 \leqslant \widehat{u}_{\mathrm{s,max}}^2, \\ \text{(voltage elliptical area)} \\ |m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \omega_{\mathrm{p}}, \dots)| \leqslant |m_{\mathrm{m,ref}}|, \\ \text{and } \operatorname{sign}(m_{\mathrm{m,ref}}) = \\ \operatorname{sign}(m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq})). \end{cases}$$

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

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

Outline

4 OFTC with analytical ORCC

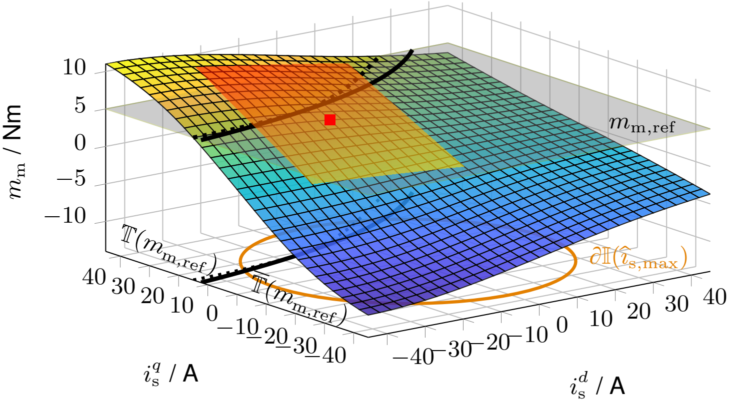
- Analytical computation
- Operation strategies
- Implementation results

OFTC with analytical ORCC: Analytical computation

Sequential Quadratic Programming (SCP): 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 $\bar{\boldsymbol{i}}_{\mathrm{s}}^{dq}$ [■])
- **machine torque** (second-order Taylor approximation around operating point $\bar{\boldsymbol{i}}_{\mathrm{s}}^{dq}$ [■])



- ...

OFTC with analytical ORCC: Analytical computation

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

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

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

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

- (Linearized) Voltage elliptical area: $(u_\mathrm{s}^d)^2 + (u_\mathrm{s}^q)^2 \leqslant \widehat{u}_{\mathrm{s,max}}^2 \iff \|\boldsymbol{u}_\mathrm{s}^{dq}(\boldsymbol{i}_\mathrm{s}^{dq}, \omega_\mathrm{p}, \dots)\|^2 = \dots \leqslant \widehat{u}_{\mathrm{s,max}}^2$

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

- (Linearized) Reference torque hyperbola: $m_\mathrm{m}(\boldsymbol{i}_\mathrm{s}^{dq}, \omega_\mathrm{p}, \dots) = \frac{3}{2} n_\mathrm{p} (\boldsymbol{i}_\mathrm{s}^{dq} + \boldsymbol{i}_{\mathrm{s,Fe}}^{dq})^\top \boldsymbol{J} \boldsymbol{\psi}_\mathrm{s}^{dq} \stackrel{!}{=} m_{\mathrm{m,ref}} \iff \dots$

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

- ...

OFTC with analytical ORCC: Analytical computation

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

Step 3: Optimization problem with equality constraint

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

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

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

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

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

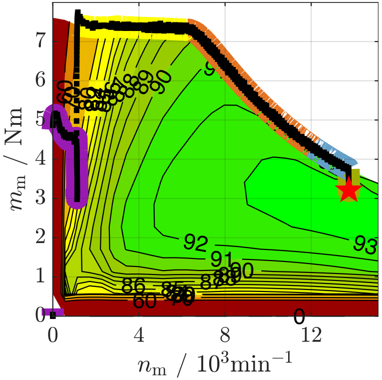
Both lead to subproblem of solving a fourth-order (quartic) polynomial

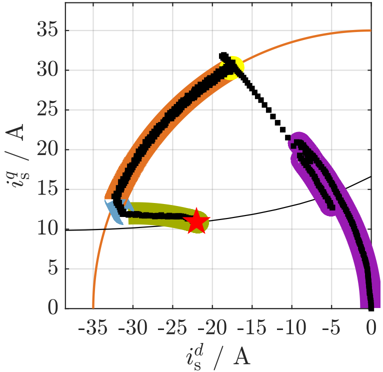
$$\chi(\lambda) := c_4\,\lambda^4 + c_3\,\lambda^3 + c_2\,\lambda^2 + c_1\,\lambda + c_0 \overset{!}{=} 0$$

$\implies$ Analytical solutions exist (e.g. Euler's solution, see [2])

OFTC with analytical ORCC: Operation strategies

Overview

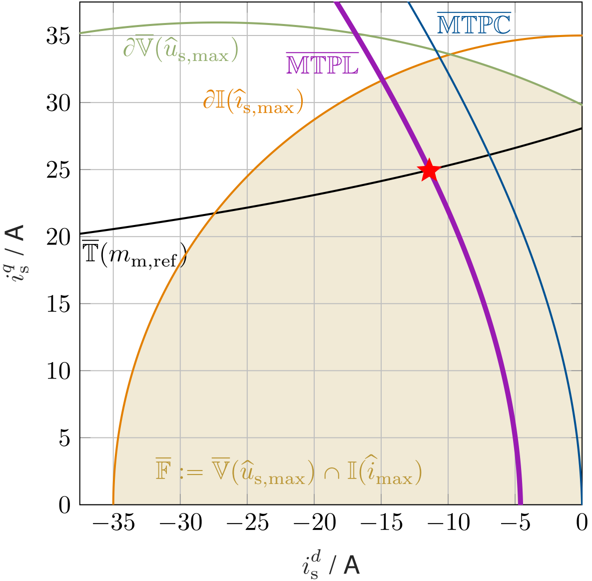




- Maximum Torque per Losses (MTPL) [ ] (or Maximum Torque per Current (MTPC) [ ])
- Maximum Current (MC) [ ] and Maximum Current extended ($\mathrm{MC_{ext}}$) [ ]
- Maximum Torque per Voltage (MTPV) [ ] (or Maximum Torque per Flux (MTPF)))
- Field Weakening (FW) [ ]

OFTC with analytical ORCC: Operation strategies

Maximum Torque per Losses (**MTPL** @ $1 \cdot \omega_{\mathrm{m,R}}$): Reference torque **feasible**



Optimization problem

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

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

Solution set

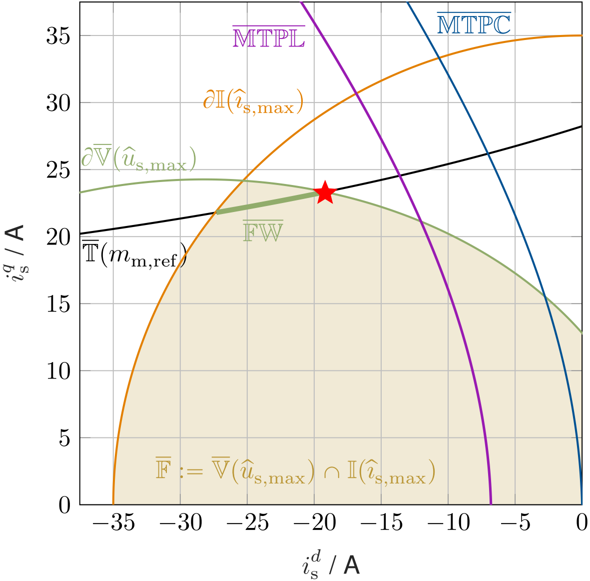
$$\overline{\mathrm{MTPL}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots) := \Big\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{L}}\, \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{L}}^\top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

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

Field Weakening (**FW** @ $1.40 \cdot \omega_{\mathrm{m,R}}$): Reference torque **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

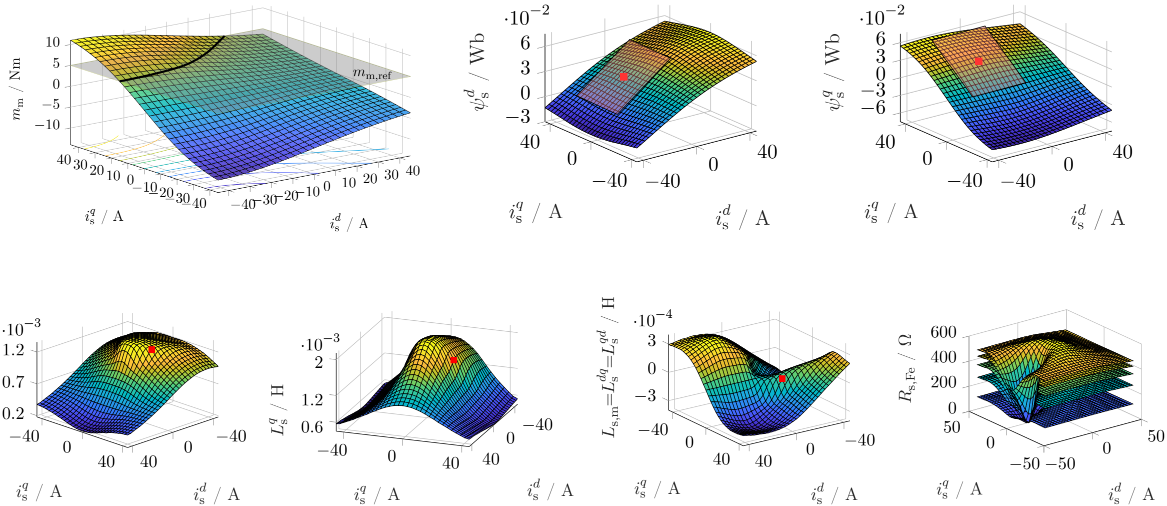
$$\overline{\mathbb{FW}}(\overline{\boldsymbol{i}}_{\mathrm{s}}^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots, m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) := \overline{\mathbb{F}}(\widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) \cap \overline{\mathbb{T}}(m_{\mathrm{m,ref}})$$

Optimal reference currents (★)

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

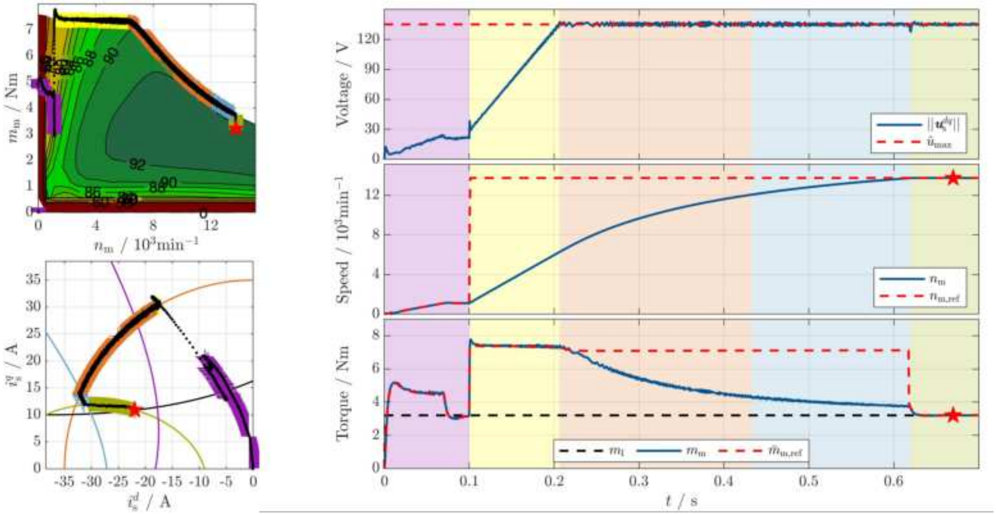
OFTC with analytical ORCC: Implementation results

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



OFTC with analytical ORCC: Implementation results

IPMSM ($3.9\,\mathrm{kW}@5\,500\,\mathrm{rpm}$): Animation



MTPL []

MC$_{\mathrm{ext}}$ []

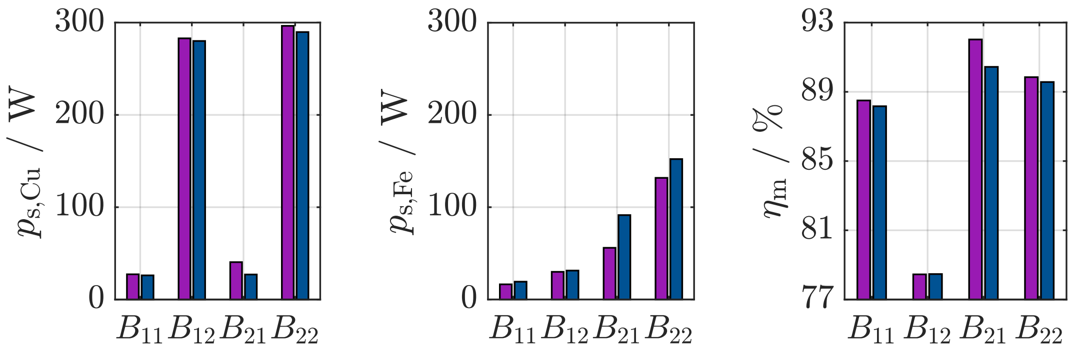
MC []

MTPV []

FW []

OFTC with analytical ORCC: Implementation results

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



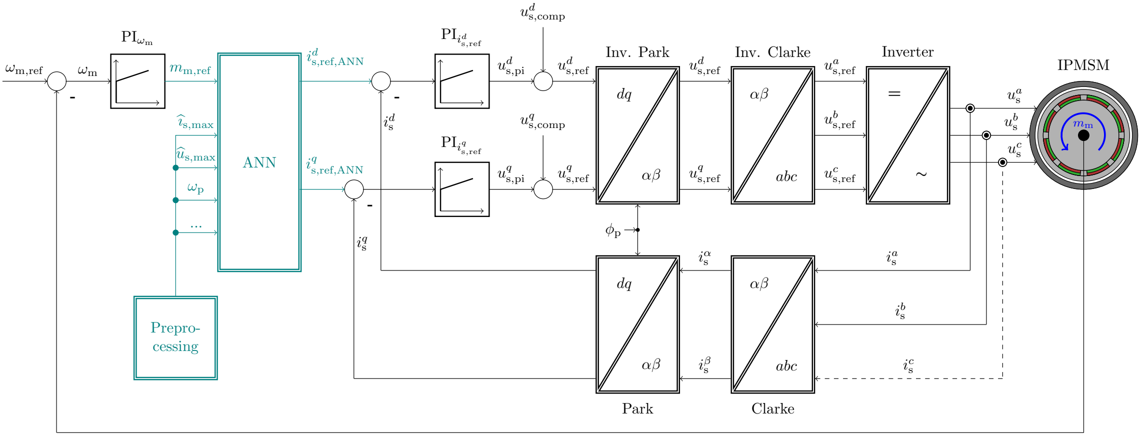
OP	Speed	Torque
B_{11}	$30\%\, n_{\mathrm{m,R}}$	$30\%\, m_{\mathrm{m,R}}$
B_{12}	$30\%\, n_{\mathrm{m,R}}$	$100\%\, m_{\mathrm{m,R}}$
B_{21}	$100\%\, n_{\mathrm{m,R}}$	$30\%\, m_{\mathrm{m,R}}$
B_{22}	$100\%\, n_{\mathrm{m,R}}$	$100\%\, m_{\mathrm{m,R}}$

- 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 $\Delta\eta_{\mathrm{m}} > 2\%$)

Outline

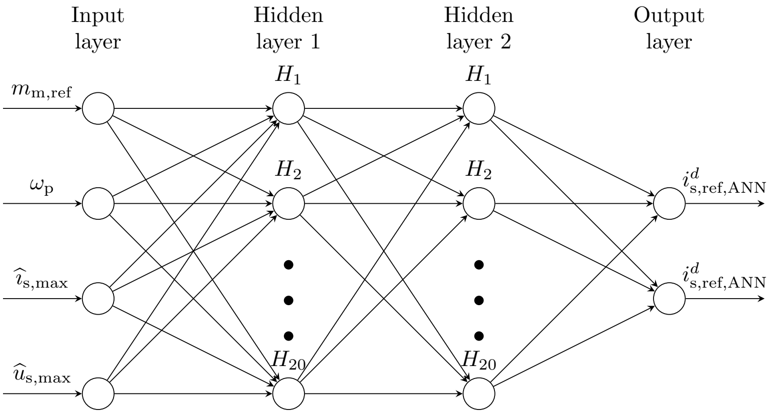
OFTC with ANN-based ORCC: Overview

Optimal feedforward torque control (OFTC) with ANN-based ORCC within the control system



OFTC with ANN-based ORCC: Artificial Neural Network Design

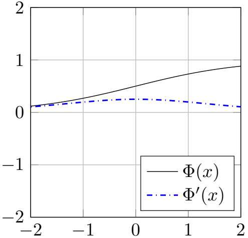
Used ANN topology



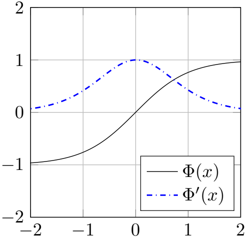
$$\widehat{\boldsymbol{y}} = \begin{pmatrix} i^d_{\mathrm{ref,ANN}} \\ i^q_{\mathrm{ref,ANN}} \end{pmatrix} = \boldsymbol{\Phi}_4\Big(\boldsymbol{W}_4\boldsymbol{\Phi}_3\Big(\boldsymbol{W}_3\boldsymbol{\Phi}_2\Big(\boldsymbol{W}_2\boldsymbol{\Phi}_1\Big(\boldsymbol{W}_1 \underbrace{\begin{pmatrix} m_{\mathrm{m,ref}}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

OFTC with ANN-based ORCC: Artificial Neural Network Design

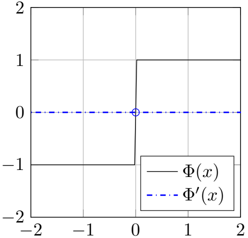
Possible and used ANN activation function



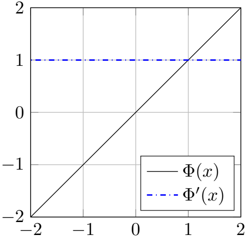
(a) Sigmoid.



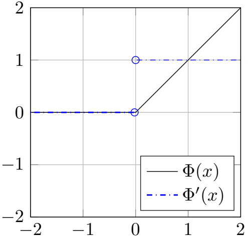
(b) Tangens hyperbolicus.



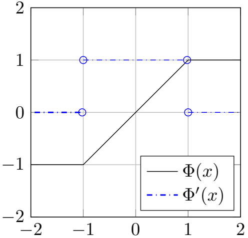
(c) Signum (sign).



(d) **Identity**.



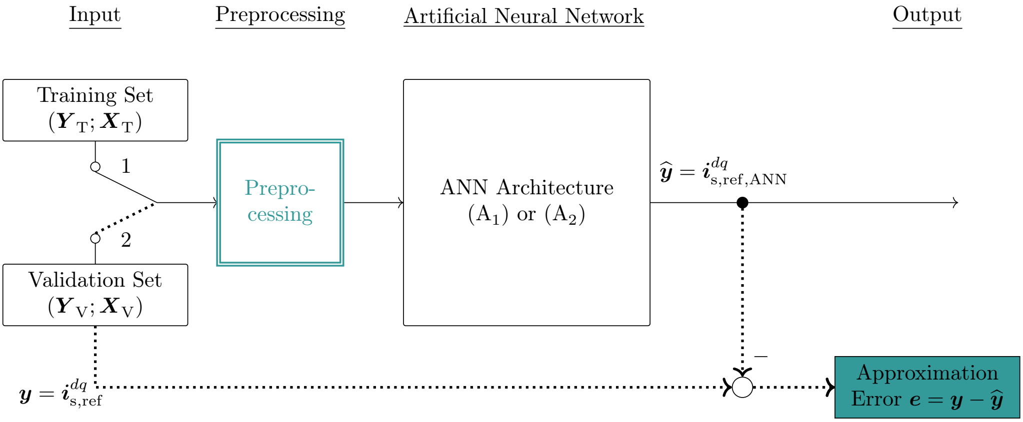
(e) **Rectified Linear Unit (ReLU)**.



(f) Saturation.

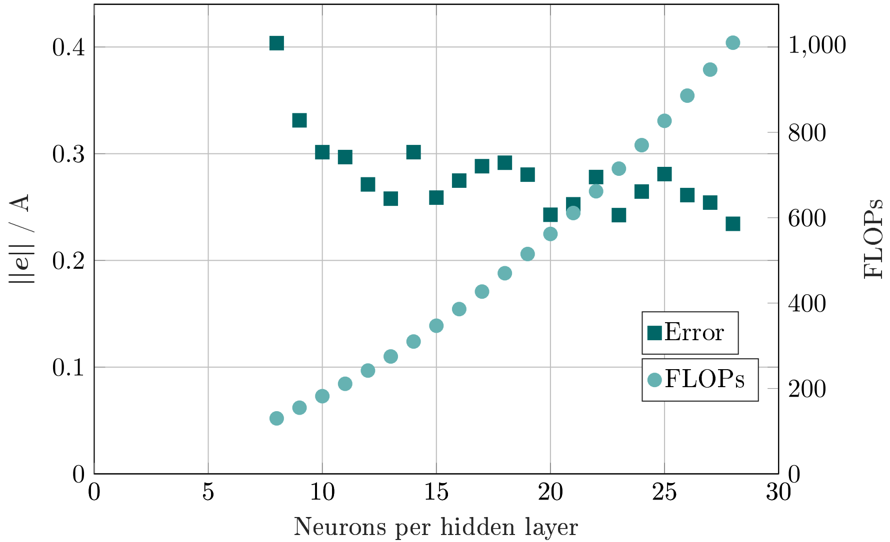
OFTC with ANN-based ORCC: Artificial Neural Network Design

ANN training and validation



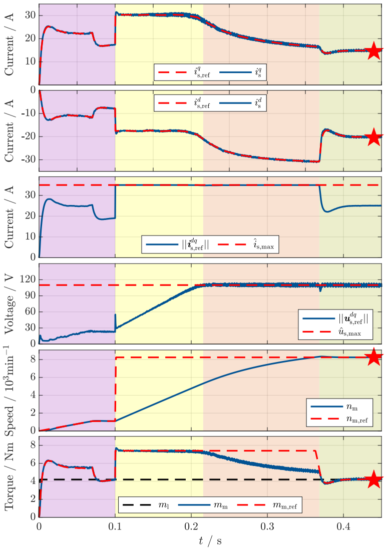
OFTC with ANN-based ORCC: Artificial Neural Network Design

Estimation accuracy (norm of estimation error) versus floating point operations

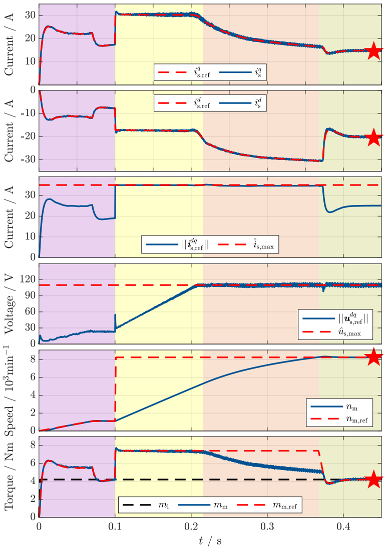


OFTC with ANN-based ORCC: Implementation results

Time series



(a) OFTC with analytical ORCC ($\mathrm{OFTC_{ANA}}$).



(b) ANN-based OFTC ($\mathrm{OFTC_{ANN}}$).

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

Outline

6 Conclusion

Conclusion

Summary and future work

To take home

- **Unified** framework for OFTC with analytical ORCC for MTPL (MTPC), FW, MC$_{\mathrm{(ext)}}$ & MTPV (MTPF) based on [3–7] and [8, Chapt. 6.9]
  - **online linearization**,
  - **quadrics** (implicit formulation),
  - **optimization problems** with **equality constraint**, and
  - **intersection** of two quadrics
- **Novel** OFTC with **analytical but ANN-based** ORCC (no decision tree required)
- Performance aspects:
  - Consideration of $R_{\mathrm{s}} \neq 0$, $R_{\mathrm{s,Fe}} \neq 0$ and $L_{\mathrm{s,m}} \neq 0$ and current, speed, angle & temperature dependency (all **feasible** and **simultaneously**)
  - **fast(er)** and **more accurate** computation (ANN the fastest)
  - **applicable** in real-world (e.g. nonlinear RSM, PME-RSM or IPMSM; also IMs or DFIMs)

Future work

- more extensive experimental validation
- impact of (parameter/modelling/alignment) uncertainties
- consideration of *rotor* iron losses (e.g. for IMs), *current transients* and *multi-phase* machines
- combination with minimization of *conduction and switching losses* [9]

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

Citation: Buettner, M.A.; Monzen, N.;

References

Journal article [4] (published 2017; doi: 10.1080/00207179.2017.1338359)

INTERNATIONAL JOURNAL OF CONTROL, 2017
https://doi.org/10.1080/00207179.2017.1338359

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

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.

ARTICLE HISTORY
Received 18 March 2017
Accepted 31 May 2017

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

Conference publication (published in ICIT 2021 proceedings; see doi: 10.1109/icit46573.2021.9453497)

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

Conference publication (published in ISIE 2021 proceedings; see doi: 10.1109/ISIE45552.2021.9576186)

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

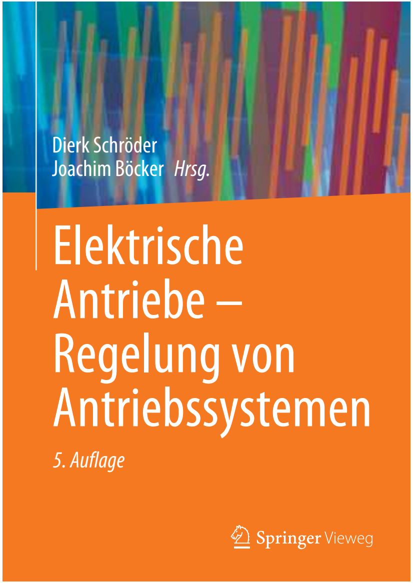
***Abstract*—In order to *analytically* solve the optimal feedforward torque control (OFTC) problem of induction machines (IMs), the unified theory for synchronous machine introduced in [1] is extended by considering relevant IM *nonlinearities* and incorporating stator *and* rotor copper losses. Instead 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**

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-

References

Chapter 6.9 in [8] (published in 2020 in Schröder “Elektrische Antriebssysteme”; doi: 10.1007/978-3-662-62700-6)



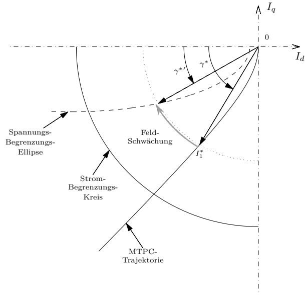


Abb. 6.101 Wirkungsweise der Feldschwächregelung mit Spannungsrückkopplung

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-

References

Monograph [10] (published May 2017; doi: 10.1007/978-3-319-55036-7)

References I

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

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

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

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

[5] C. M. Hackl, J. Kullick, H. Eldeeb, and L. Horlbeck. Analytical computation of the optimal reference currents for MTPC/MTPA, MTPV and MTPF operation of anisotropic synchronous machines considering stator resistance and mutual inductance. In *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, pages P.1–P.10, Sept 2017.

[6] Hisham Eldeeb, Christoph M. Hackl, Lorenz Horlbeck, and Julian Kullick. Analytical solutions for the optimal reference currents for MTPC/MTPA, MTPV and MTPF control of anisotropic synchronous machines. In *Proceedings of the IEEE International Electric Machines & Drives Conference (IEMDC 2017)*, pages 1–6, Miami, FL, USA, 2017.

[7] C. M. Hackl, J. Kullick, and N. Monzen. Generic loss minimization for nonlinear synchronous machines by analytical computation of optimal reference currents considering copper and iron losses. In *2021 IEEE International Conference on Industrial Technology (ICIT)*. IEEE, mar 2021.

[8] Dierk Schröder and Joachim Böcker, editors. *Elektrische Antriebe – Regelung von Antriebssystemen*. Springer Berlin Heidelberg, 2020.

[9] M. Fakharmanesh, C. M. Hackl, and R. Perini. Instantaneous conduction and switching losses in two-level voltage source inverters. In *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, pages 1–6, June 2017.

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