Hochschule
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University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

HM

T3 – Advanced optimal feedforward torque control and operation management of electrical drives

Christoph M. Hackl
(with M. Buettner, H. Eldeeb, L. Horlbeck, J. Kullick, N. Monzen, A. Thommessen and J. Rossmann)
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19.06.2023 – ISIE 2023, Aalto University, Helsinki

ISES

Outline

1 Introduction

2 Advanced optimal feedforward torque control (OFTC) and operation management of electrical drives

3 Conclusion

Outline

1 Introduction
- Research environment
- Research projects and expertise
- Selected research results

Outline

1 Introduction
- Research environment
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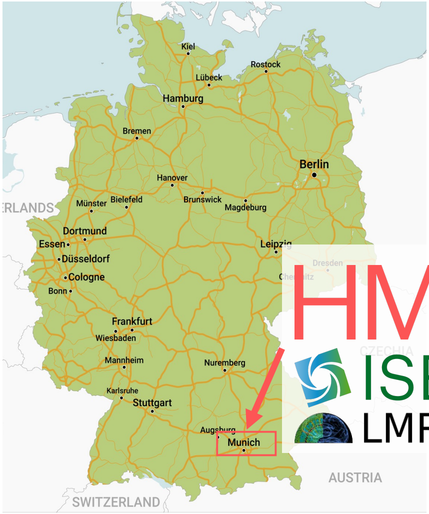
Introduction

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

- 6 research labs (6 professors)
- 27 PhD candidates

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

- International team
- 13 PhD candidates (status 2023)
- >150 publications / >5.4 Mio. € raised

Outline

1 Introduction
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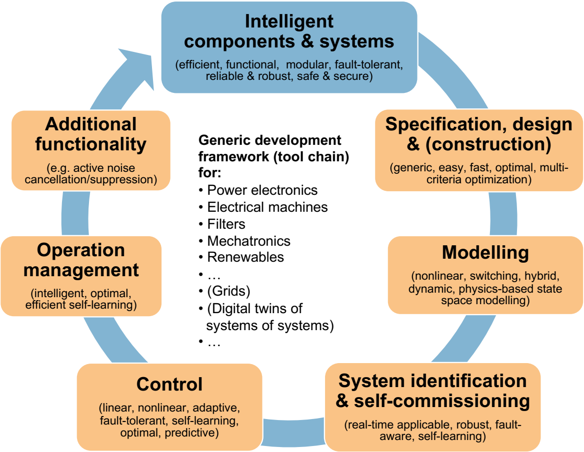
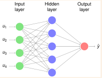
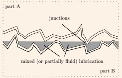
Introduction

LMRES – Research projects and research goals

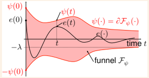




System identification [9–26]



Friction [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, 87, 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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Introduction

LMRES – Selected research results: Electrical/industrial/traction drives (reliability) [115]

6746 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 66, NO. 9, SEPTEMBER 2019

Postfault Full Torque–Speed Exploitation of Dual Three-Phase IPMSM Drives

Hisham M. Eldeeb, Ayman S. Abdel-Khalik, *Senior Member, IEEE*, and Christoph Michael Hackl, *Senior Member, IEEE*

***Abstract*—This paper exploits the torque–speed operating limits of a dual three-phase interior permanent magnet synchronous machine (ADT-IPMSM) during postfault operation for different neutral configurations. To achieve the maximum permissible torque–speed limits, the study proposes software and hardware modifications to the latest fault-tolerant techniques using: an offline optimization that takes into account simultaneously the voltage and current constraints during postfault operation and a simple hardware addition that modifies the neutral points configuration to either isolatede (1N) or connected (2N) based on the operating torque and/or speed. Compared to the literature, the proposed study considers the field-weakening operation, extending the permissible achievable speeds. A 2.5-kW ADT-IPMSM prototype validates the theoretical findings.**

***Index Terms*—Dual three phase, fault-tolerance, interior permanent magnet synchronous machine (IPMSM), postfault control.**

Nomenclature

Notation

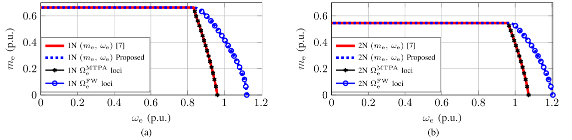
$\mathbb{R}, \mathbb{N}$	Set of real and natural numbers.
$n, m \in \mathbb{N}$	Number of rows and columns.
$\zeta \in \mathbb{R}$	Real scalar.
$\boldsymbol{\zeta} \in \mathbb{R}^n$	Real vector (bold), expressed as $\boldsymbol{\zeta} = (\zeta_1, \zeta_2, \ldots, \zeta_n)^\top$.
$\|\|\boldsymbol{\zeta}\|\|$	Euclidean norm of $\boldsymbol{\zeta}$.

Subscripts and superscripts

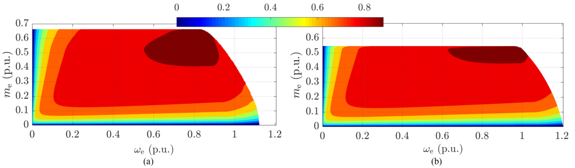
$\square^\top$	Transpose operator applied to vector or matrix.
$\underline{\square}$	Phasor description of a variable at *steady state*.
$\square_s$	Subscript "s" denotes referencing to the stator.
$\square_s^{\Lambda\lambda}$	Superscripts "Λ" and "λ" are arbitrary variables representing the coordinates of a subspace ($\Lambda \in \{dq, XY, 0^+0^-\}$, $\lambda \in \{dq, XY, 0^+0^-\}$, and $\Lambda \neq \lambda$).

General

$\boldsymbol{T}_{\mathrm{VSD}} \in \mathbb{R}^{6\times6}$	Vector space decomposition matrix.
$\boldsymbol{T}_p(\phi) \in \mathbb{R}^{2\times2}$	Park's transformation with angle $\phi \in \mathbb{R}$.
$\boldsymbol{T}_k \in \mathbb{R}^{6\times2}$	Optimization matrix.
$k_\Gamma^\alpha, k_\Gamma^\beta$	Scalar optimization parameters in $\boldsymbol{T}_k$ of the $\Gamma \in \{X, Y\}$ coordinate.
$J \in \mathbb{R}^{2\times2}$	Rotation matrix.
u	Electrical voltage (V).
i	Electrical current (A).
ψ	Flux linkage (Wb).
$\boldsymbol{\zeta}_s^{a_1\to c_2} \in \mathbb{R}^6$	Stator space vector expressed in the $(a_1b_1c_1$-$a_2b_2c_2)$ frame, where $\boldsymbol{\zeta} \in \{\boldsymbol{u}, \boldsymbol{\psi}, \boldsymbol{i}\}$.
u_{dc}	DC-link voltage (V).
m_e	Electromechanical torque (N·m).
$m_{e,\max}$	Maximum torque for a given neutral point configuration (N·m).
m_{load}	Load torque (N·m).



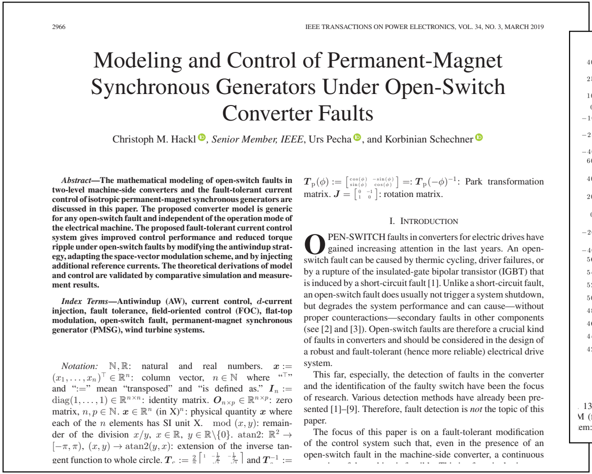
'ostfault comparison of the permissible (m_e, ω_e) characteristics between the presented algorithm in [7] and proposed optim -C with respect to the (a) 1N and (b) 2N neutral configurations, showing the enhancement in terms of extending the permissit



'ostfault efficiency maps of (a) 1N and (b) 2N connections within the (m_e, ω_e) range of the proposed optimization in Section III-

Introduction

LMRES – Selected research results: Wind energy systems & power electronics (reliability; VDE Award) [78]



Modeling and Control of Permanent-Magnet Synchronous Generators Under Open-Switch Converter Faults

Christoph M. Hackl, *Senior Member, IEEE*, Urs Pecha, and Korbinian Schechner

***Abstract*—The mathematical modeling of open-switch faults in two-level machine-side converters and the fault-tolerant current control of isotropic permanent-magnet synchronous generators are discussed in this paper. The proposed converter model is generic for any open-switch fault and independent of the operation mode of the electrical machine. The proposed fault-tolerant current control system gives improved control performance and reduced torque ripple under open-switch faults by modifying the antiwindup strategy, adapting the space-vector modulation scheme, and by injecting additional reference currents. The theoretical derivations of model and control are validated by comparative simulation and measurement results.**

***Index Terms*—Antiwindup (AW), current control, *d*-current injection, fault tolerance, field-oriented control (FOC), flat-top modulation, open-switch fault, permanent-magnet synchronous generator (PMSG), wind turbine systems.**

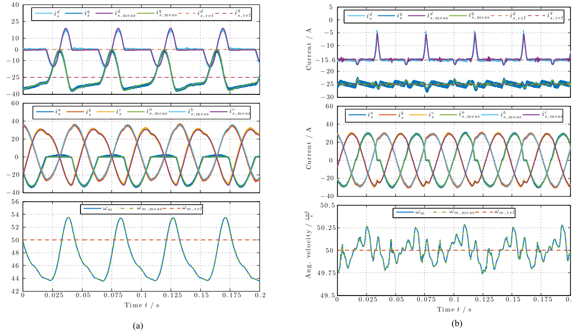
Notation: $\mathbb{N}, \mathbb{R}$: natural and real numbers. $\boldsymbol{x} := (x_1, \ldots, x_n)^\top \in \mathbb{R}^n$: column vector, $n \in \mathbb{N}$ where "$\top$" and ":=" mean "transposed" and "is defined as." $\boldsymbol{I}_n := \mathrm{diag}(1, \ldots, 1) \in \mathbb{R}^{n\times n}$: identity matrix. $\boldsymbol{O}_{n\times p} \in \mathbb{R}^{n\times p}$: zero matrix, $n, p \in \mathbb{N}$. $\boldsymbol{x} \in \mathbb{R}^n$ (in X)^n: physical quantity $\boldsymbol{x}$ where each of the n elements has SI unit X. $\bmod (x, y)$: remainder of the division x/y, $x \in \mathbb{R}$, $y \in \mathbb{R}\setminus\{0\}$. atan2: $\mathbb{R}^2 \to [-\pi, \pi)$, $(x, y) \to \mathrm{atan2}(y, x)$: extension of the inverse tangent function to whole circle. $\boldsymbol{T}_c := \frac{2}{3}\left[\begin{smallmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ \ldots\end{smallmatrix}\right]$ and $\boldsymbol{T}_c^{-1} :=$ … $\boldsymbol{T}_\mathrm{p}(\phi) := \left[\begin{smallmatrix}\cos(\phi) & -\sin(\phi)\\ \sin(\phi) & \cos(\phi)\end{smallmatrix}\right] =: \boldsymbol{T}_\mathrm{p}(-\phi)^{-1}$: Park transformation matrix. $\boldsymbol{J} = \left[\begin{smallmatrix}0 & -1\\ 1 & 0\end{smallmatrix}\right]$: rotation matrix.

I. Introduction

OPEN-SWITCH faults in converters for electric drives have gained increasing attention in the last years. An open-switch fault can be caused by thermic cycling, driver failures, or by a rupture of the insulated-gate bipolar transistor (IGBT) that is induced by a short-circuit fault [1]. Unlike a short-circuit fault, an open-switch fault does usually not trigger a system shutdown, but degrades the system performance and can cause—without proper counteractions—secondary faults in other components (see [2] and [3]). Open-switch faults are therefore a crucial kind of faults in converters and should be considered in the design of a robust and fault-tolerant (hence more reliable) electrical drive system.

This far, especially, the detection of faults in the converter and the identification of the faulty switch have been the focus of research. Various detection methods have already been presented [1]–[9]. Therefore, fault detection is *not* the topic of this paper.

The focus of this paper is on a fault-tolerant modification of the control system such that, even in the presence of an open-switch fault in the machine-side converter, a continuous …



. 13. Comparison of simulation and measurement results for standard control system and fault-tolerant control system with extended AW, modifi… M (flat-top modulation), and optimally injected d-current. (a) Experiment (E_1): Comparison of simulation and measurement results for standard contr… em: $\mathrm{THD}_{i_s^a} = 41.8\,\%$ (simulation) versus $\mathrm{THD}_{i_s^a,\mathrm{meas}} = 45.4\,\%$ (measurement). (b) Experiment (E_2): Comparison of simulation and measurement resu…

Introduction

LMRES – Selected research results: Traction drives & power electronics (efficiency; Cooperation with BMW) [128]

3760 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 68, NO. 5, MAY 2021

Synchronous Optimal Pulsewidth Modulation for Synchronous Machines With Highly Operating Point Dependent Magnetic Anisotropy

Athina Birda, Joerg Reuss, and Christoph M. Hackl, *Senior Member, IEEE*

***Abstract*—The performance of synchronous optimal pulsewidth modulation is investigated for the control of an automotive low voltage electrical drive system, which consists of a two-level voltage source inverter and an interior permanent magnet synchronous motor. The machine magnetic anisotropy varies due to magnetic saturation and cross-saturation effects and depends on the motor operating point. The main objective of this article is to investigate the influence of the varying magnetic anisotropy on the optimized half-wave symmetric inverter pulse patterns. For this purpose, the optimized inverter switching angles are derived by minimizing the current harmonic distortion of an isotropic and anisotropic permanent magnet synchronous motor. Their performance is evaluated and compared by experimental results.**

***Index Terms*—Electric vehicle, magnetic anisotropy, permanent magnet synchronous motor (PMSM), synchronous optimal pulsewidth modulation (SOPWM).**

I. Introduction

As PART of the global effort to reduce the CO2 emissions, the interest of the automotive industry over the last years focused on the concept of electric mobility. Still, the limited operating range and increased price of electric vehicles remain the most important obstacles for their wide spread. The efficiency of the electrical drive system and, by that, the operating range of electric vehicles can be improved by optimizing the inverter compromising the motor current quality. To this end, the optimized inverter pulse patterns are determined, which minimize the harmonic distortion of the phase currents. The optimization procedure is conducted offline and the resulting optimized switching angles are stored in lookup tables (LUTs). Since the switching frequency f_{sw} is synchronized with the fundamental stator frequency f_r, the pulse number

$$q := f_{\mathrm{sw}}/f_r \qquad (1)$$

is always an integer [1].

SOPWM is primarily employed in medium voltage high power induction motor drive applications, where the reduction of switching losses is of utmost importance [1], [2]. Moreover, it is a common modulation strategy for operating electric rail traction converters adopted by GE [3] and SIEMENS [4]. On the contrary, little research has been conducted when the SOPWM strategy is employed for the control of synchronous motor drives [5]–[13]. Especially, SOPWM has not yet been explored for automotive low-voltage interior permanent magnet synchronous motor (IPMSM) drives with highly operating point (OP) dependent magnetic anisotropy. This is the main motivation of this article.

In [5]–[7], the current harmonic content of an isotropic permanent magnet synchronous motor (PMSM) drive is min-

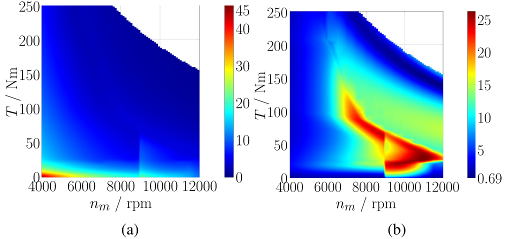


Fig. 9. Numerical performance evaluation of the optimization results. (a) $I_{s,\mathrm{THD}}(\boldsymbol{\alpha}_{\mathrm{aniso}})/\%$. (b) $I_{s,\mathrm{THD,dev}}/\%$.

Introduction

LMRES – Selected research results: Electrical drives & renewables (operation management; Geothermal Energy) [23]

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 70, NO. 1, JANUARY 2023 211

Nonlinear Modeling, Identification, and Optimal Feedforward Torque Control of Induction Machines Using Steady-State Machine Maps

Julian Kullick and Christoph M. Hackl, *Senior Member, IEEE*

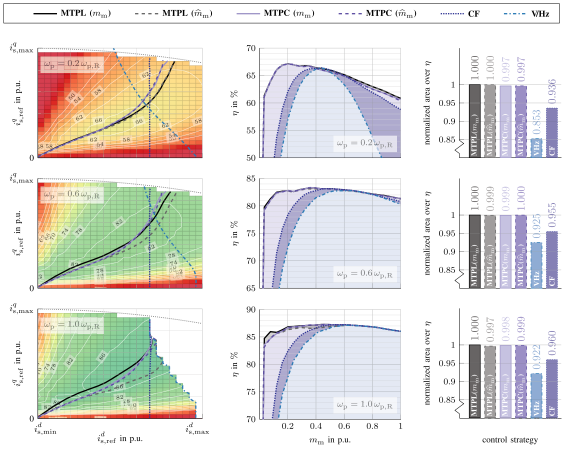
Abstract—**A novel but simple machine map-based modeling, identification, and optimal feedforward torque control (OFTC) approach for induction machines (IMs) is presented. It is based on, first, a generic, nonlinear transformer-like machine model considering nonlinear flux linkages (with magnetic saturation and cross coupling) and iron losses in the stator laminations in a novel, arbitrarily rotating but unique, robust, and reproducible (d, q)-reference frame; second, a holistic machine identification procedure, which evaluates steady-state measurements over a grid of (d, q) stator currents and produces temperature and frequency dependent machine maps, for example, flux linkages, torque, iron resistance, and efficiency; and third, a numerical offline optimization and extraction of different OFTC look-up tables (LUTs) for *optimal* current reference generation depending on reference torque and electrical frequency (and temperature). During the identification, stator winding temperature and electrical stator frequency of the IM are kept constant by an intelligent temperature and the speed control system. The presented measurement results for a squirrel-cage IM confirm that compared to constant flux operation or scalar V/Hz control, efficiency can be increased particularly in part-load operation by up to 7 % by Maximum Torque Per Losses minimizing copper *and* iron losses.**

Index Terms—**Efficiency, flux linkages, induction machine (IM), iron resistance, machine identification, MTPA**

$\|\boldsymbol{x}\| := \sqrt{\boldsymbol{x}^\top \boldsymbol{x}} = \sqrt{x_1^2 + \dot{s} + x_n^2}$: Euclidean norm of $\boldsymbol{x}$; $\boldsymbol{X} \in \mathbb{R}^{n\times n}$: matrix ($n$ rows & columns); $\boldsymbol{X}^{-1}$, $\boldsymbol{X}^{-\top}$: inverse, inverse transpose of $\boldsymbol{X}$ (if exist), resp.; $\boldsymbol{I}_n := \mathrm{diag}(1, \ldots, 1) \in \mathbb{R}^{n\times n}$: identity matrix; $\boldsymbol{0}_n := (0, \dot{s}, 0)^\top \in \mathbb{R}^n$: zero vector; $\boldsymbol{x}^{dq} := (x^d, x^q)^\top \in \mathbb{R}^2$: stator or rotor (iron) current, voltage, flux linkage vectors, i.e., $\boldsymbol{x} \in \{\boldsymbol{i}^{dq}_{s/r(,Fe)}, \boldsymbol{u}^{dq}_{s/r}, \boldsymbol{\psi}^{dq}_{s/r}, \dot{s}\}$; $\boldsymbol{X}^{dq} := \begin{bmatrix} X^d & X^{dq} \\ X^{qd} & X^q \end{bmatrix} \in \mathbb{R}^{2\times 2}$: stator/rotor (iron) resistance matrix, i.e., $\boldsymbol{R}_{s/r(,Fe)}$; $\vartheta_{s/r}$: stator/rotor temperature; x_{ref}: reference value of, e.g., temperature, electrical frequency, and currents, i.e., $x \in \{\vartheta_{s,ref}, \omega_{p,ref}, i^d_{s,ref}, i^q_{s,ref}, \dot{s}\}$; $T_{r/f}$: rotor/filter time constant; n_p: pole pair number; $m_{m/l}$: machine/load torque; Θ_m: machine inertia; ω_m: mechanical angular velocity; ϕ_p and $\omega_p = \frac{d}{dt}\phi_p$: Park transformation angle and angular velocity; $\boldsymbol{J} := \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$: rotation matrix (by $\frac{\pi}{2}$).

I. Motivation and Contributions

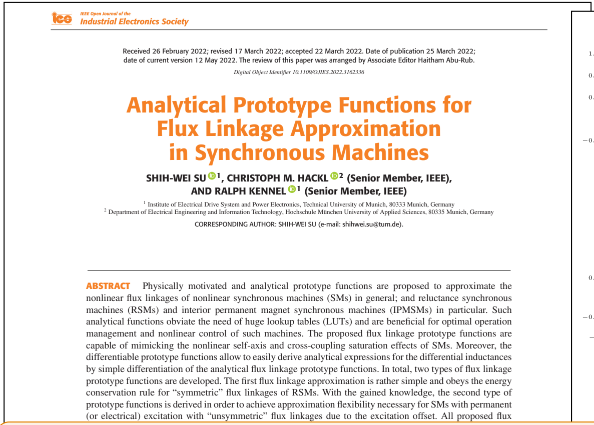
Maximum efficiency operation (or loss minimizing control) of induction machines has been subject to extensive research in



. 12. Efficiency comparison for $\omega_p \in [0.2, 0.6, 1] \cdot \omega_{p,N}$ (from top to bottom), with efficiency contour plots in current locus (left colum
ciency-over-torque plots (middle column) and overall performance bar plots (right column).

Introduction

LMRES – Selected research results: Electrical/industrial/traction drives (self-commissioning) [25]



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Analytical Prototype Functions for Flux Linkage Approximation in Synchronous Machines

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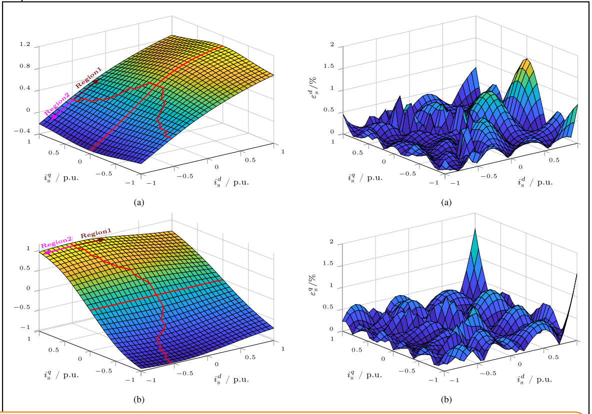
[1] Institute of Electrical Drive System and Power Electronics, Technical University of Munich, 80333 Munich, Germany
[2] Department of Electrical Engineering and Information Technology, Hochschule München University of Applied Sciences, 80335 Munich, Germany

CORRESPONDING AUTHOR: SHIH-WEI SU (e-mail: shihwei.su@tum.de).

ABSTRACT Physically motivated and analytical prototype functions are proposed to approximate the nonlinear flux linkages of nonlinear synchronous machines (SMs) in general; and reluctance synchronous machines (RSMs) and interior permanent magnet synchronous machines (IPMSMs) in particular. Such analytical functions obviate the need of huge lookup tables (LUTs) and are beneficial for optimal operation management and nonlinear control of such machines. The proposed flux linkage prototype functions are capable of mimicking the nonlinear self-axis and cross-coupling saturation effects of SMs. Moreover, the differentiable prototype functions allow to easily derive analytical expressions for the differential inductances by simple differentiation of the analytical flux linkage prototype functions. In total, two types of flux linkage prototype functions are developed. The first flux linkage approximation is rather simple and obeys the energy conservation rule for "symmetric" flux linkages of RSMs. With the gained knowledge, the second type of prototype functions is derived in order to achieve approximation flexibility necessary for SMs with permanent (or electrical) excitation with "unsymmetric" flux linkages due to the excitation offset. All proposed flux



☞ **TT 04-2 Electrical Machines and Drives (Y405)**
Monday, 19 June 2023 @ 17:20-17:40 (ISIE23-000129)
B. Pfeifer et al, "A simple disturbance observer for stator flux linkage estimation of nonlinear synchronous machines"

Introduction

LMRES – Selected research results: Smart grid/renewables/power systems (grid synchronisation) [22]

Modified Second-Order Generalized Integrators With Modified Frequency Locked Loop for Fast Harmonics Estimation of Distorted Single-Phase Signals

Christoph M. Hackl, *Senior Member, IEEE*, and Markus Landerer

***Abstract*—This article proposes *modified second-order generalized integrators* (mSOGIs) for a fast estimation of all harmonic components of arbitrarily distorted single-phase signals, such as voltages or currents in power systems. The estimation is based on the internal model principle leading to an overall observer consisting of parallelized mSOGIs. The observer is tuned by pole placement. For a constant fundamental frequency, the observer is capable of estimating all harmonic components with prescribed settling time by choosing the observer poles appropriately. For time-varying fundamental frequencies, the harmonic estimation is combined with a *modified frequency locked loop* (mFLL) with gain normalization, sign-correct antiwindup, and rate limitation. The estimation performances of the proposed parallelized mSOGIs with and without mFLL are illustrated and validated by measurement results. The results are compared to standard approaches such as parallelized standard SOGIs (sSOGIs) and adaptive notch filters (ANFs).**

***Index Terms*—Amplitude estimation, frequency estimation, frequency-locked loop (FLL), phase estimation, second-order generalized integrator (SOGI).**

Notation

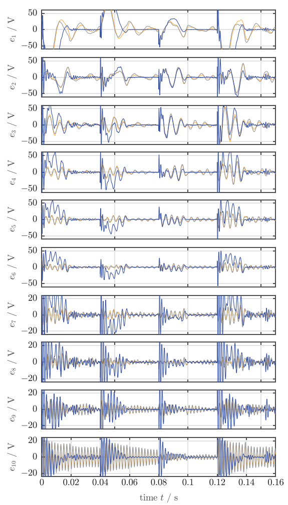
$\mathbb{N}, \mathbb{R}, \mathbb{C}, \mathbb{Q}$: natural, real, complex and rational numbers. For the following, let $n, m \in \mathbb{N}$. $\boldsymbol{x} := (x_1, \ldots, x_n)^\top \in \mathbb{R}^n$: column vector (where := means "is defined as" and $^\top$ means "transposed"). $\boldsymbol{0}_n := (0, 0, \ldots, 0)^\top \in \mathbb{R}^n$: zero vector. $\|\boldsymbol{x}\| := \sqrt{\boldsymbol{x}^\top \boldsymbol{x}}$: Euclidean norm of $\boldsymbol{x}$. $\boldsymbol{A} \in \mathbb{R}^{n \times m}$: real (non-square) matrix. $\mathrm{diag}(\boldsymbol{a}) \in \mathbb{R}^{n \times n}$: diagonal matrix with

I. Introduction

A. Motivation and Literature Review

In view of the increasing number of decentralized generation units with power electronics-based grid connection and the decreasing number of large-scale generators, the overall inertia in the grid is diminishing. This results in faster and more abrupt frequency fluctuations and significant harmonic distortion of physical quantities (such as currents or voltages) of the power system [1]. Fast frequency fluctuations endanger stability of the power grid. Significant harmonic distortions of voltages and currents can degrade power quality and lead to damage or even destruction of grid components. To be capable of taking appropriate countermeasures such as 1) improving system stability and power quality and 2) compensating for such deteriorated operation conditions, it is crucial to detect and estimate fundamental and higher harmonic components of the considered quantities in real time as fast and accurate as possible. Modern power electronic devices (e.g., flexible ac transmission systems or grid-connected converters of decentralized renewable energy systems) can then be used to implement such countermeasures. That is why, grid state estimation became of particular interest to the research community in the past years and has been studied extensively (see e.g., [2]–[24] to name a few).

It is well known that a signal with significant harmonic



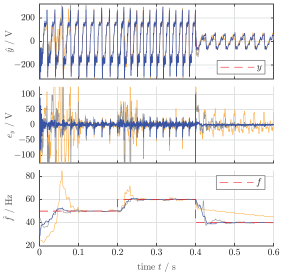


Fig. 11. Measurement results for Scenario (S_4): Comparison of the estimation performances of *parallelized* mSOGIs (——), sSOGIs (——), and ANFs (——) *without* FLL. Signals shown from top to bottom are: Harmonic signals y_1 to y_{10} (- - -) and their estimates $\hat{y}_1$ to $\hat{y}_{10}$ and harmonic estimation errors $e_1 = y_1 - \hat{y}_1$ to $e_{10} = y_{10} - \hat{y}_{10}$.

frequency are identical for this scenario. Therefore, the estimation performances purely can be compared according to the respective observer tunings only. The fundamental signal $y = y_1$ undergoes step-like changes in amplitude, phase and amplitude and phase as described above.

The estimation performances of fundamental mSOGI (——), fundamental sSOGI (——), and fundamental ANF (——) are shown in Fig. 7. The first and second subplots show input signal $y = y_1$ (- - -) and its estimates $\hat{y} = \hat{y}_1$ and the estimation errors $e_y = y_1 - \hat{y}_1$, respectively. All three observers are capable of estimating the input signal y. All estimation errors $e_y \to 0$ tend to

Outline

2 Advanced optimal feedforward torque control (OFTC) and operation management of electrical drives

- Motivation
- Problem statement and proposed solution
- OFTC with analytical ORCC
  - Analytical computation
  - Operation strategies
  - Operation management and decision tree
  - Implementation results
- OFTC with ANN-based ORCC
  - Overview
  - Artificial Neural Network Design
  - Implementation results

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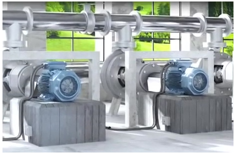
Motivation

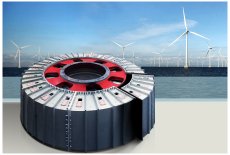
Electrical machines: Widely-used, compact and efficient actuators


www.miele.de


www.farmwood.co.uk


www.abb.com (from video)


www.siemens.com

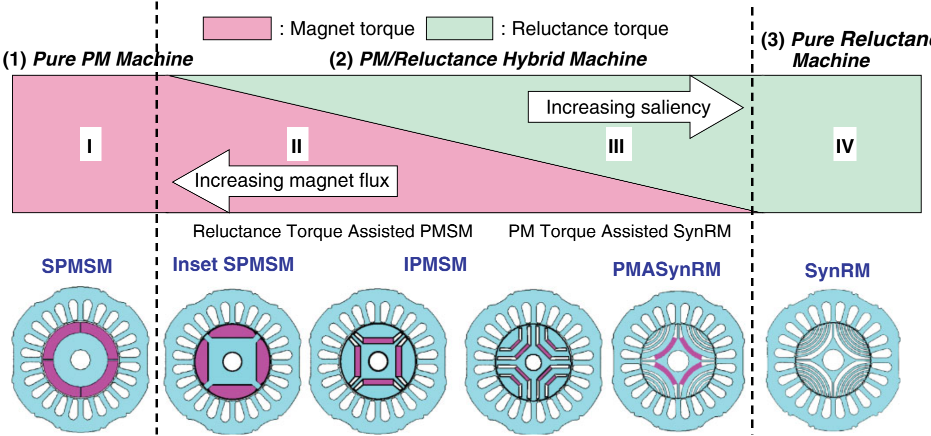


☞ **TT 05-2 Power Electronics & Energy Conversion (C Hall)**
Monday, 19 June 2023 @ 11:00-11:20 (ISIE23-000045)
L. Testa et al, "A generic Lyapunov-based Observer for Double-Star-Chopper-Cell/Bridge-Cell Modular-Multilevel-Cascade-Converters"

☞ **TT 05-5 Power Electronics (C Hall)**
Tuesday, 20 June 2023 @ 09:00-09:20 (ISIE23-000108)
O. Kalmbach et al, "I/O-Linearization Based Current Decoupling Control of Modular Multilevel Cascade Converters"

Motivation

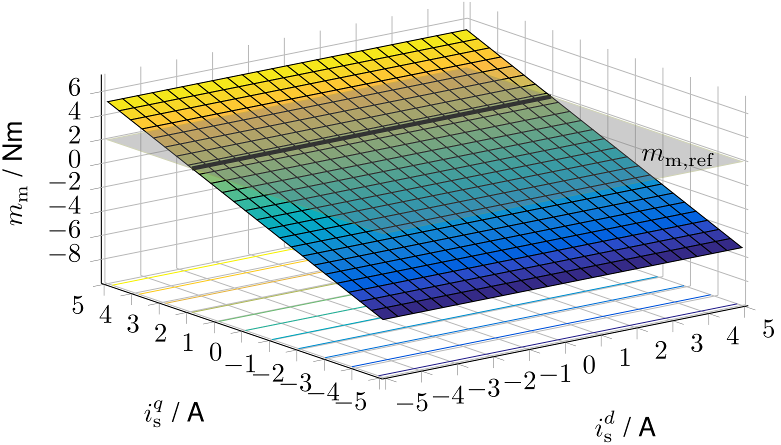
Examples of anisotropic synchronous machines [164] with "saliency ratio" $L_s^d / L_s^q \neq 1$



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

Motivation

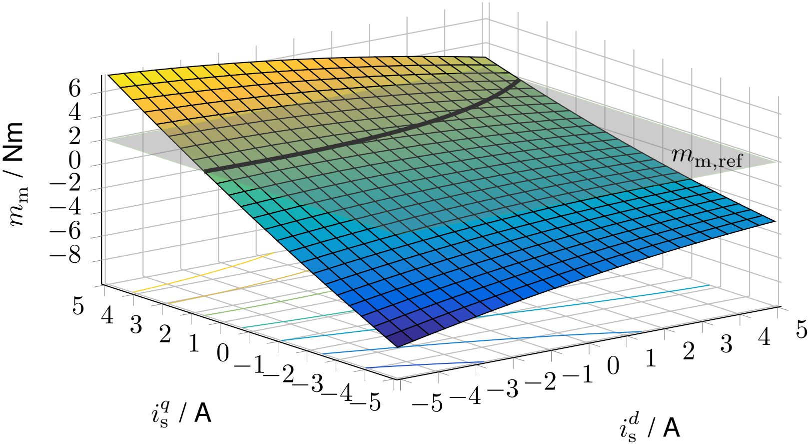
Optimal feedforward torque control problem: **Isotropic, linear PMSM** (without iron losses)



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

Motivation

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

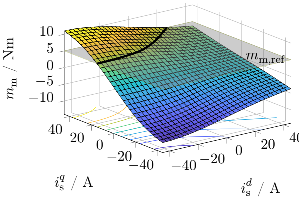


$$m_{m,ref} \overset{!}{=} m_m\big(\boldsymbol{i}_s^{dq}\big) = \frac{2n_p}{3\kappa^2}\Big[\widetilde{\psi}_{pm} i_s^q + \big(\widetilde{L}_s^d - \widetilde{L}_s^q\big) i_s^d i_s^q + \widetilde{L}_{s,m}\big((i_s^q)^2 - (i_s^d)^2\big)\Big] \Longrightarrow \boxed{\boldsymbol{i}_{s,ref}^{dq} := (?,?)^\top}$$

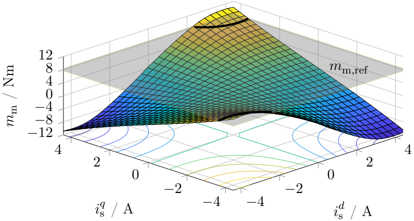
Motivation

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)



☞ **TT 04-2 Electrical Machines and Drives (Y405)**
Monday, 19 June 2023 @ 16:20-16:40 (ISIE23-000071)
J. Rossmann et al, "Nonlinear Three-Phase Reluctance Synchronous Machine Modeling With Extended Torque Equation"

☞ **TT 03-2 Power Systems and the Smart Grid, Renewable Energy Systems and Smart Grid (D Hall)**
Monday, 19 June 2023 @ 16:40-17:00 (ISIE23-000035)
A. Thommessen et al, "Combining virtual synchronous machine and feedforward torque control for doubly-fed induction machine based wind energy conversion systems"

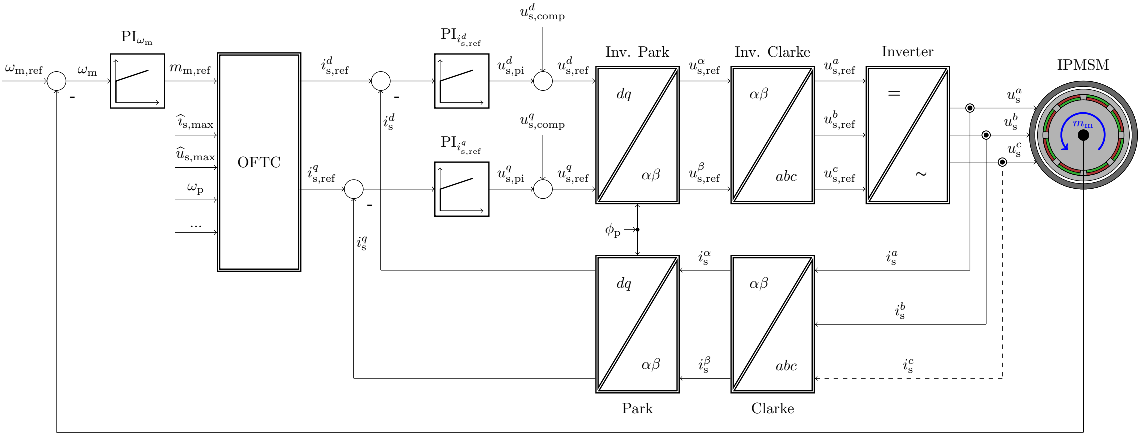
Outline

2 Advanced optimal feedforward torque control (OFTC) and operation management of electrical drives

- Motivation
- Problem statement and proposed solution
- OFTC with analytical ORCC
  - Analytical computation
  - Operation strategies
  - Operation management and decision tree
  - Implementation results
- OFTC with ANN-based ORCC
  - Overview
  - Artificial Neural Network Design
  - Implementation results

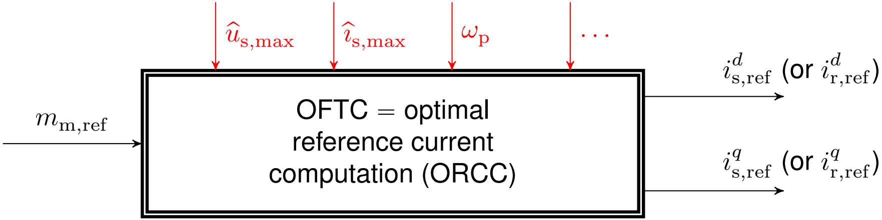
Problem statement and proposed solution

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)



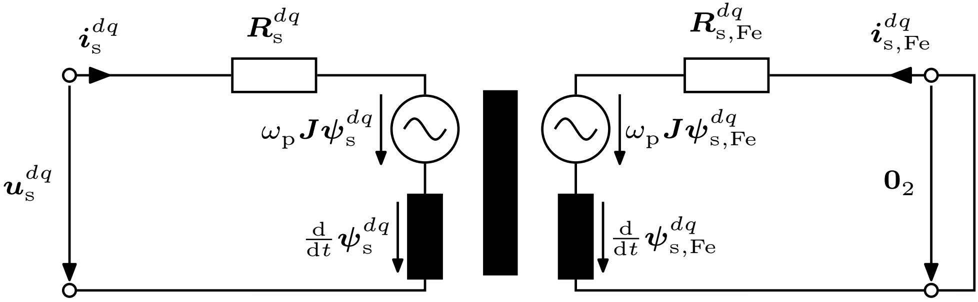
$$\boldsymbol{i}^{dq}_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \ldots) = \begin{pmatrix} i^d_{\mathrm{s,ref}}(m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}, \omega_{\mathrm{p}}, \ldots)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

- ✓ 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

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

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

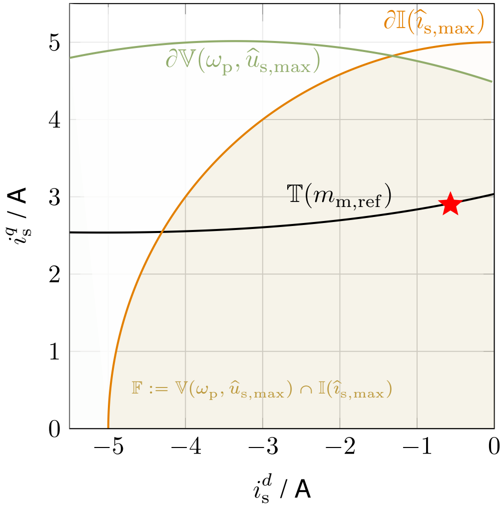
Mech.:
$$\frac{\mathrm{d}}{\mathrm{d}t}\omega_m = \frac{1}{\Theta_m}(m_m + m_l) \quad \text{with} \quad \omega_p = n_p \omega_m$$

$$m_m = \frac{2}{3\kappa^2}\left(\boldsymbol{i}_s^{dq} + \boldsymbol{i}_{s,Fe}^{dq}\right)^\top \boldsymbol{J}\boldsymbol{\psi}_s^{dq}$$

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

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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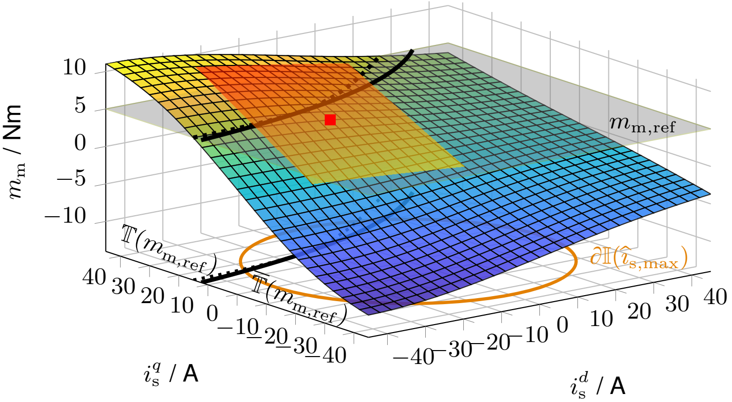
OFTC with analytical ORCC: Analytical computation

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 $Q_{\boldsymbol{A}}(\boldsymbol{i}_\mathrm{s}^{dq}) := (\boldsymbol{i}_\mathrm{s}^{dq})^\top \boldsymbol{A}\, \boldsymbol{i}_\mathrm{s}^{dq} + 2\boldsymbol{a}^\top \boldsymbol{i}_\mathrm{s}^{dq} + \alpha$:

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

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

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

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

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

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

- ...

OFTC with analytical ORCC: Analytical computation

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

Step 3: Optimization problem with equality constraint

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

$\Longrightarrow$ 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)

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

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

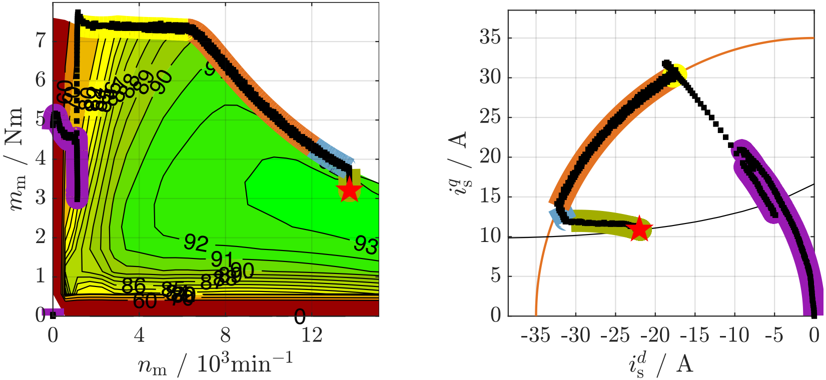
Both lead to subproblem of solving a fourth-order (quartic) polynomial

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

$\Longrightarrow$ Analytical solutions exist (e.g. Euler's solution, see [165])

OFTC with analytical ORCC: Operation strategies

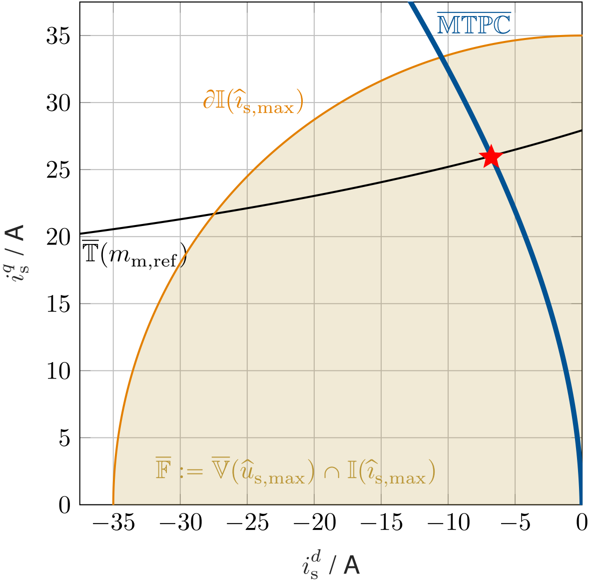
Overview



- 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) [ ]

OFTC with analytical ORCC: Operation strategies

Maximum Torque per Current (**MTPC** @ $0 \cdot \omega_{m,R}$): Reference torque **feasible**



Optimization problem

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

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

Solution set

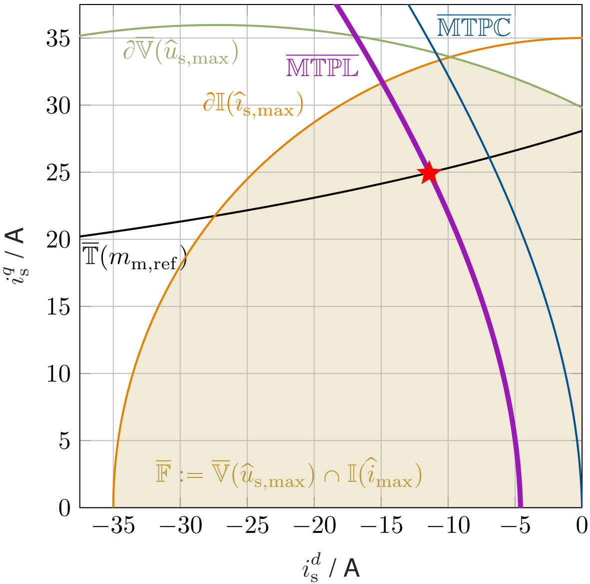
$$\overline{\mathbb{MTPC}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_p, \dots) := \{\, \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{M}}_C\, \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{m}}_C^\top \boldsymbol{i}_s^{dq} = 0 \}$$

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

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

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

Solution set

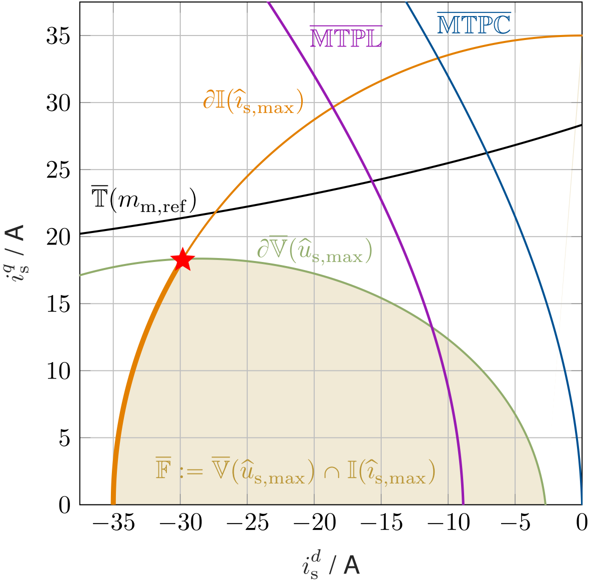
$$\overline{\mathrm{MTPL}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_{\mathrm{p}}, \dots) := \Big\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{L}}\, \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{L}}^\top \boldsymbol{i}_s^{dq}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

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

Maximum Current (**MC** @ $2 \cdot \omega_{\mathrm{m,R}}$): Reference torque **not feasible**



Optimization problem

$$\max_{\boldsymbol{i}_s^{dq} \in \overline{\mathbb{F}}} |(m_{\mathrm{m}}(\boldsymbol{i}_s^{dq}))| \quad \text{s.t.}$$
$$\mathrm{sign}(m_{\mathrm{m}}) = \mathrm{sign}(m_{\mathrm{m,ref}})$$

Feasible set

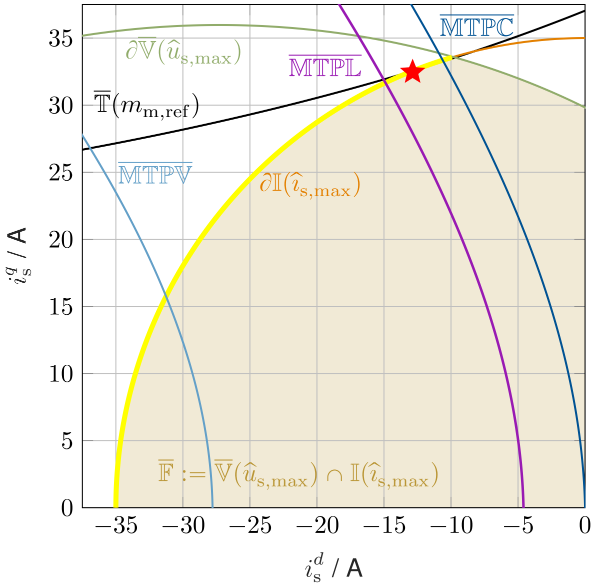
$$\overline{\mathbb{MC}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots, \hat{u}_{\mathrm{s,max}}, \hat{\imath}_{\mathrm{s,max}}) := \overline{\mathbb{V}}(\hat{u}_{\mathrm{s,max}}) \cap \partial\mathbb{I}(\hat{\imath}_{\mathrm{s,max}})$$

Optimal current reference (★)

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

OFTC with analytical ORCC: Operation strategies

Maximum Current extended (**MC**$_{\rm ext}$ @ $1 \cdot \omega_{\rm m,R}$): Reference torque **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

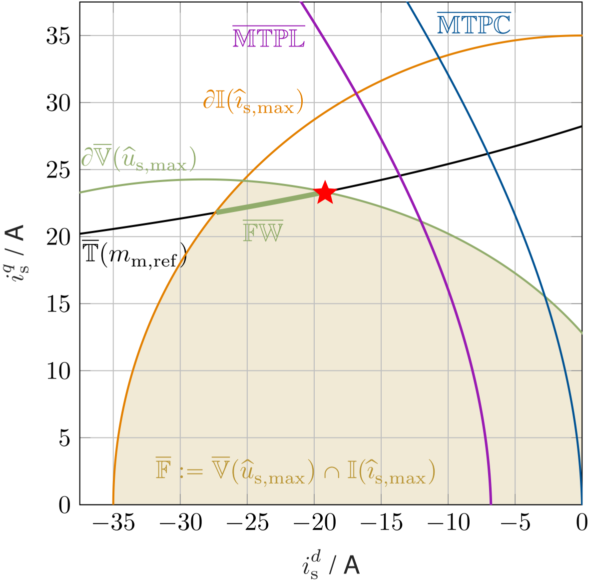
$$\overline{\rm MC}_{\rm ext}(\bar{\boldsymbol{i}}_{\rm s}^{dq}, \overline{\omega}_{\rm p}, \ldots, \widehat{u}_{\rm s,max}, \widehat{\imath}_{\rm s,max}) := \overline{\mathbb{V}}(\widehat{u}_{\rm s,max}) \cap \partial\mathbb{I}(\widehat{\imath}_{\rm s,max})$$

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

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

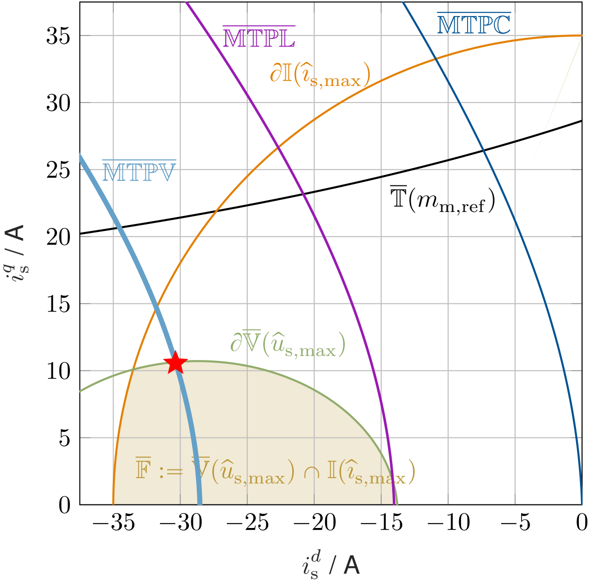
$$\overline{\mathbb{FW}}(\bar{\boldsymbol{i}}_{\mathrm{s}}^{dq}, \overline{\omega}_{\mathrm{p}}, \ldots, m_{\mathrm{m,ref}}, \widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) := \overline{\mathbb{F}}(\widehat{u}_{\mathrm{s,max}}, \widehat{\imath}_{\mathrm{s,max}}) \cap \overline{\mathbb{T}}(m_{\mathrm{m,ref}})$$

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

Maximum Torque per Voltage (**MTPV** @ $3.50 \cdot \omega_{\mathrm{m,R}}$): Reference torque **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

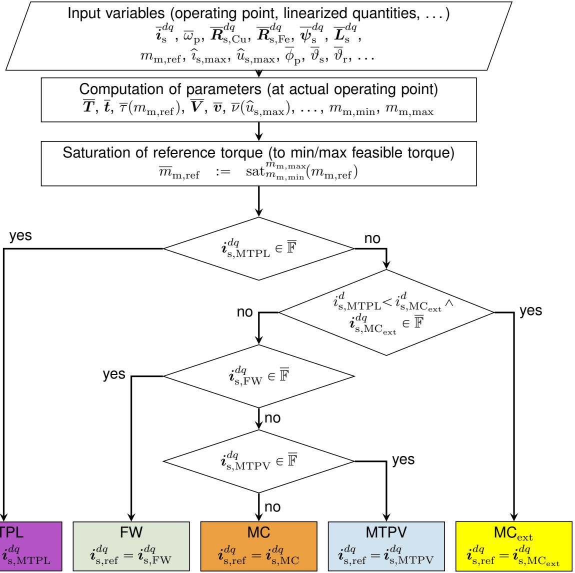
$$\overline{\mathrm{MTPV}}(\overline{\boldsymbol{i}}_s^{dq}, \overline{\omega}_{\mathrm{p}}, \cdots) := \Big\{ \boldsymbol{i}_s^{dq} \in \mathbb{R}^2 \;\Big|\; (\boldsymbol{i}_s^{dq})^\top \overline{\boldsymbol{M}}_{\mathrm{V}} \boldsymbol{i}_s^{dq} + 2\,\overline{\boldsymbol{m}}_{\mathrm{V}}^\top \boldsymbol{i}_s^{dq}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

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation management

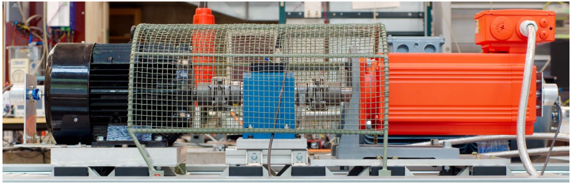
Decision tree



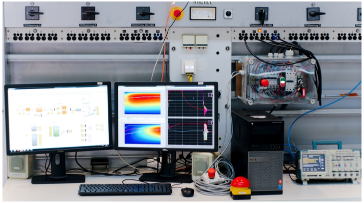
OFTC with analytical ORCC: Implementation results

Exemplary laboratory setup

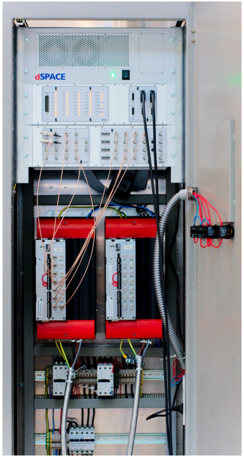
Reluctance SM (RSM) and Permanent-magnet SM



Host PC (rapid prototyping)

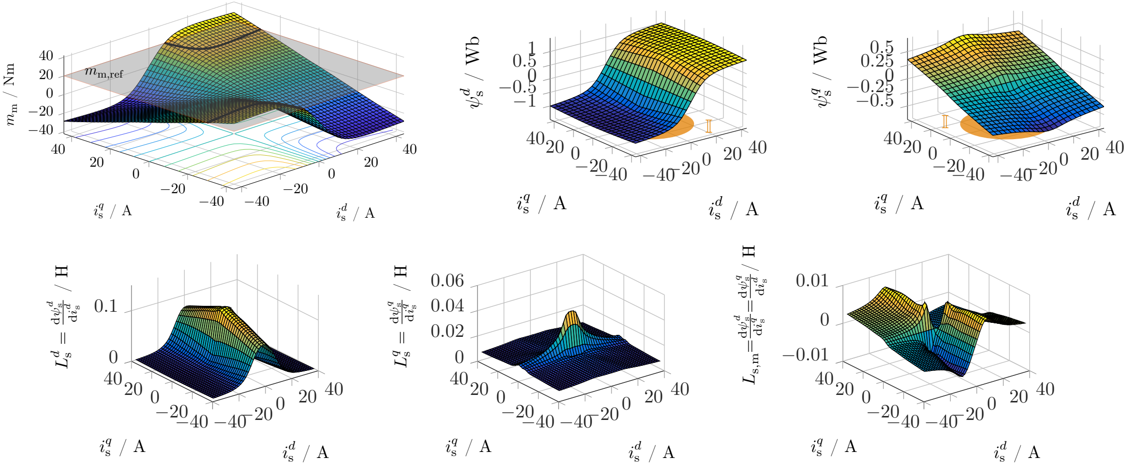


Real-time system and VSIs



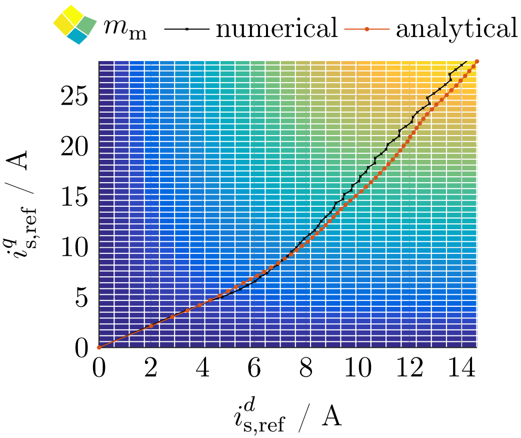
OFTC with analytical ORCC: Implementation results

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

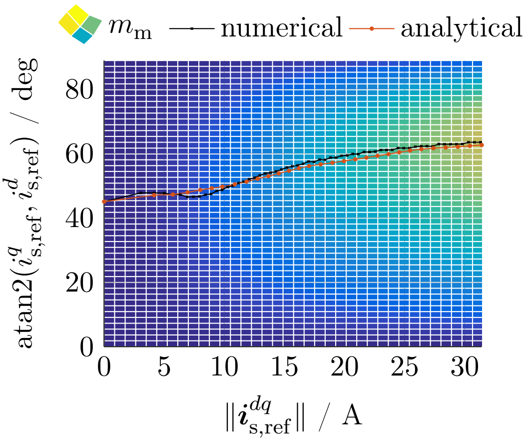


OFTC with analytical ORCC: Implementation results

RSM ($9.6\,\mathrm{kW}$@$1\,500\,\mathrm{rpm}$): Comparison of numerical and analytical solutions for MTPC



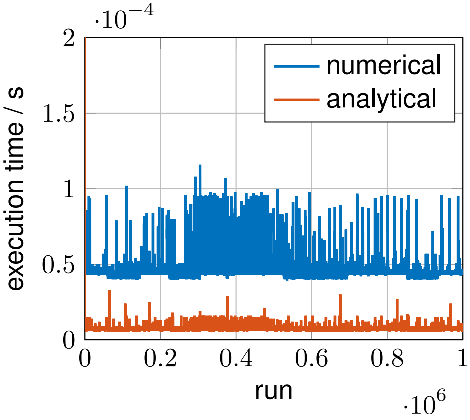
Cartesian coordinates

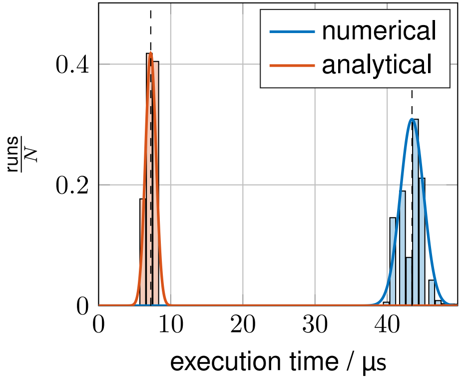


polar coordinates

OFTC with analytical ORCC: Implementation results

RSM (9.6 kW@$1\,500$ rpm): Comparison of computational load (Euler's solution for fourth-order polynomials)

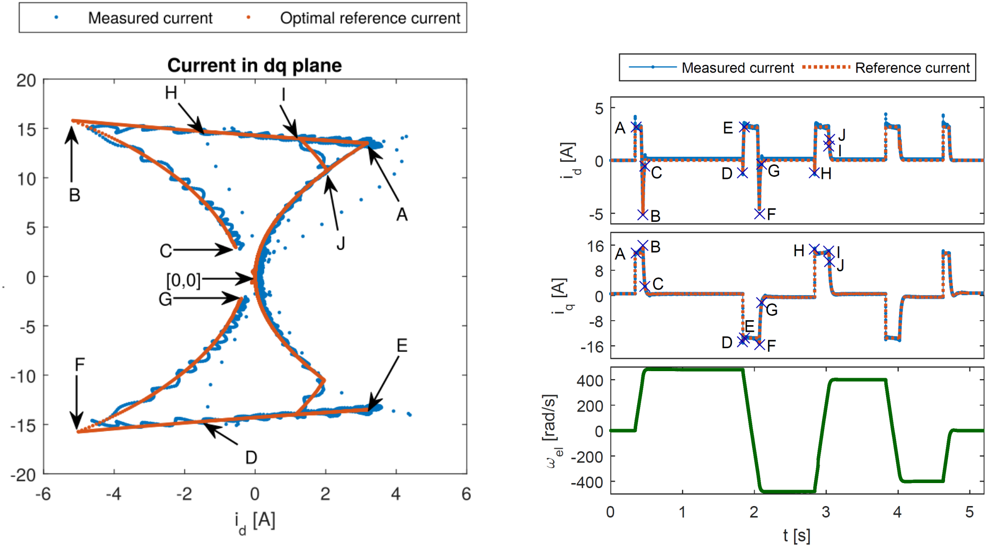




- Execution times for $N = 10^6$ runs (downsampled by factor 100)
- Standard deviations $\sigma_n = 1.61 \cdot 10^{-6}$ s and $\sigma_a = 0.73 \cdot 10^{-6}$ s
- Average execution times $\mu_n = 43.4 \cdot 10^{-6}$ s and $\mu_a = 7.23 \cdot 10^{-6}$ s ($>$**6x faster**)

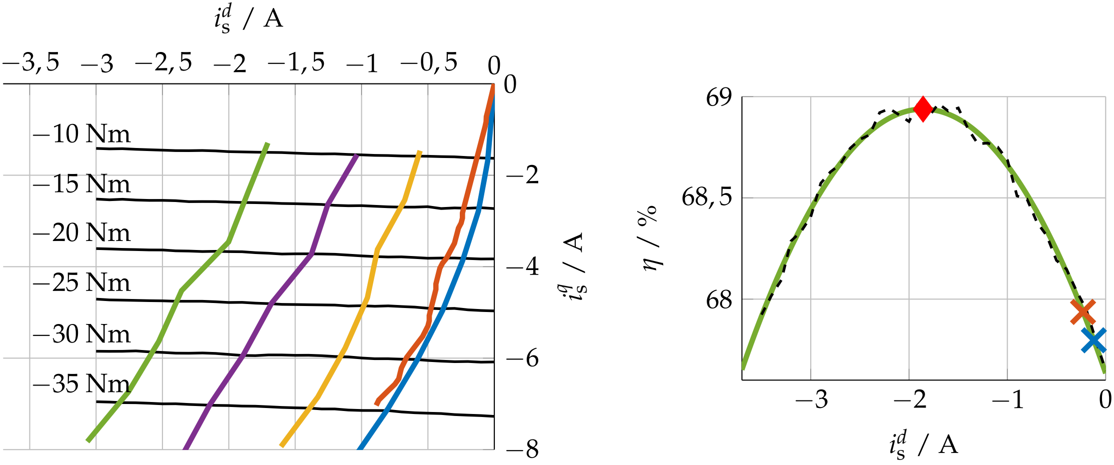
OFTC with analytical ORCC: Implementation results

PME-RSM (4.5 kW@1 500 rpm): Implementation by colleagues $[\max\left(L_s^d(\boldsymbol{i}_s^{dq})/L_s^q(\boldsymbol{i}_s^{dq})\right) = 1.43]$ [166]



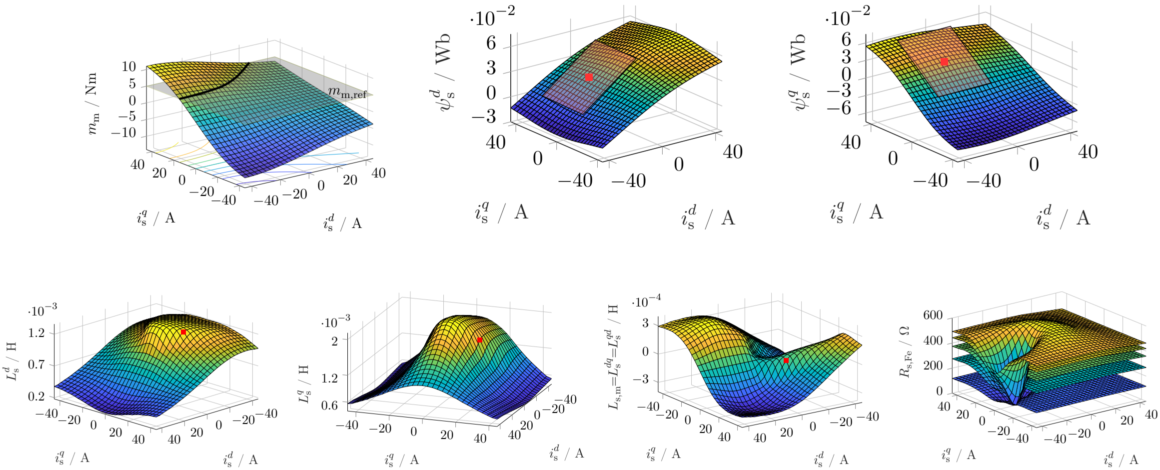
OFTC with analytical ORCC: Implementation results

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



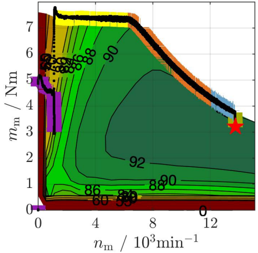
OFTC with analytical ORCC: Implementation results

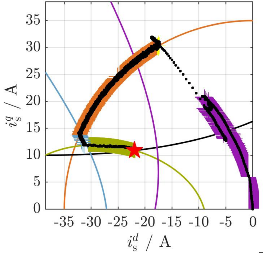
IPMSM ($3.9\,$kW@$5\,500\,$rpm): Nonlinear maps of torque, flux linkages, differential inductances and iron resistance

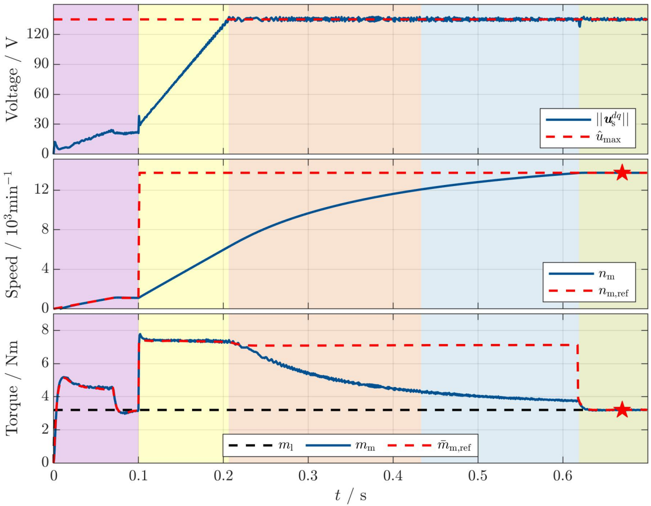


OFTC with analytical ORCC: Implementation results

IPMSM (3.9 kW@5 500 rpm): Animation







MTPL [ ]

MC_{ext} [ ]

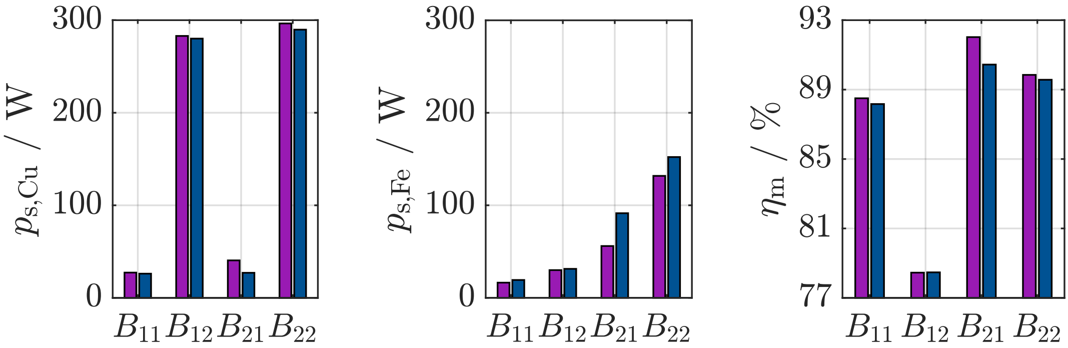
MC [ ]

MTPV [ ]

FW [ ]

OFTC with analytical ORCC: Implementation results

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



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 $\Delta\eta_m > 2\%$)

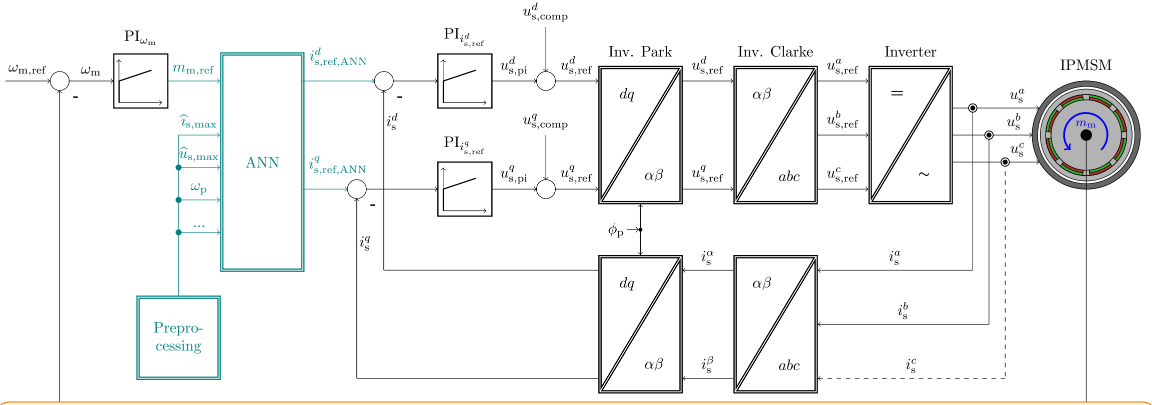
Outline

2 Advanced optimal feedforward torque control (OFTC) and operation management of electrical drives

- Motivation
- Problem statement and proposed solution
- OFTC with analytical ORCC
  - Analytical computation
  - Operation strategies
  - Operation management and decision tree
  - Implementation results
- OFTC with ANN-based ORCC
  - Overview
  - Artificial Neural Network Design
  - Implementation results

OFTC with ANN-based ORCC: Overview

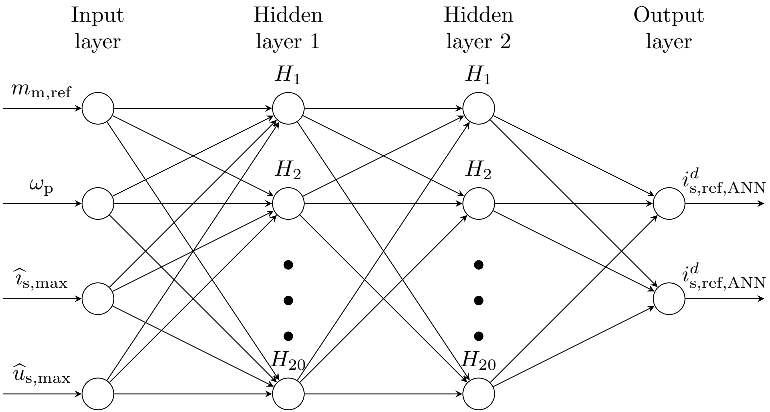
Optimal feedforward torque control (OFTC) with ANN-based ORCC within the control system



☞ **TT 04-2 Electrical Machines and Drives (Y405)**
Monday, 19 June 2023 @ 17:40-18:00 (ISIE23-000130)
N. Monzen et al, "Artificial neural network based optimal feedforward torque control of electrically excited synchronous machines"

OFTC with ANN-based ORCC: Artificial Neural Network Design

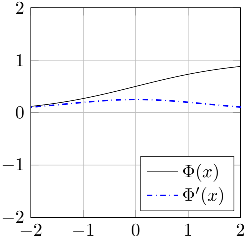
Used ANN topology



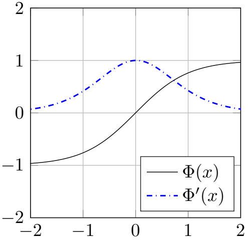
$$\widehat{\boldsymbol{y}} = \begin{pmatrix} i^d_{\mathrm{ref,ANN}} \\ i^q_{\mathrm{ref,ANN}} \end{pmatrix} = \boldsymbol{\Phi}_4\Bigg(\boldsymbol{W}_4\boldsymbol{\Phi}_3\Bigg(\boldsymbol{W}_3\boldsymbol{\Phi}_2\Bigg(\boldsymbol{W}_2\boldsymbol{\Phi}_1\Bigg(\boldsymbol{W}_1 \underbrace{\begin{pmatrix}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

OFTC with ANN-based ORCC: Artificial Neural Network Design

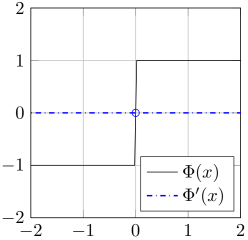
Possible and used ANN activation function



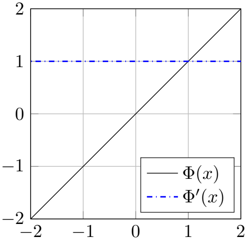
(a) Sigmoid.



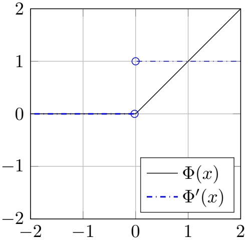
(b) Tangens hyperbolicus.



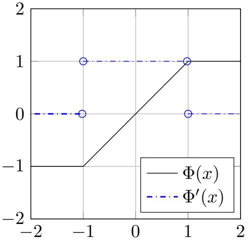
(c) Signum (sign).



(d) **Identity**.



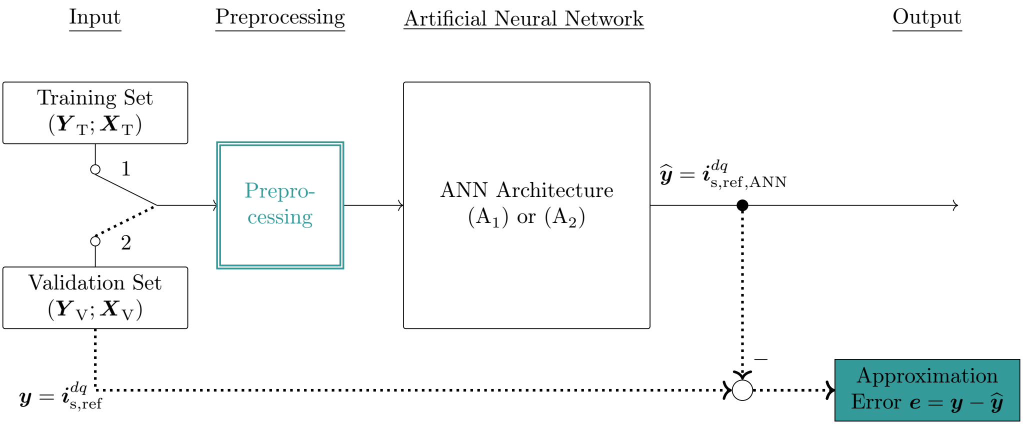
(e) **Rectified Linear Unit (ReLU)**.



(f) Saturation.

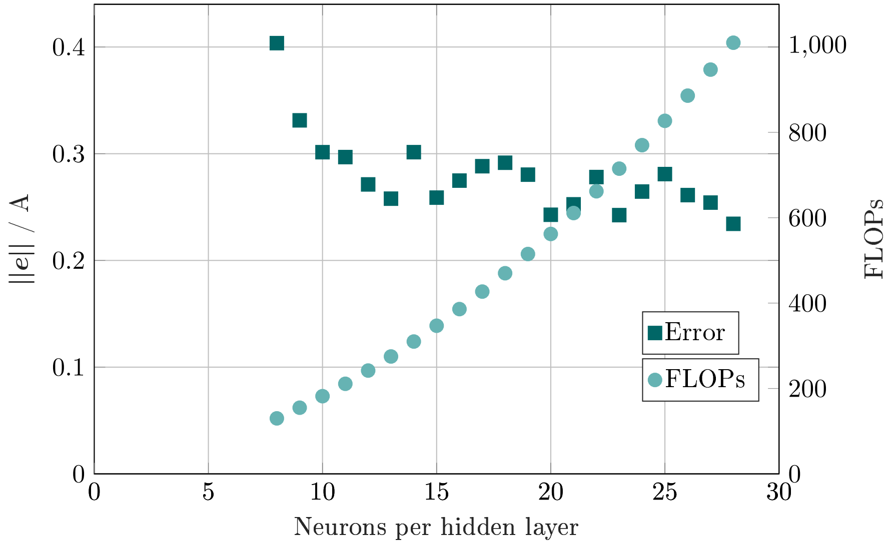
OFTC with ANN-based ORCC: Artificial Neural Network Design

ANN training and validation



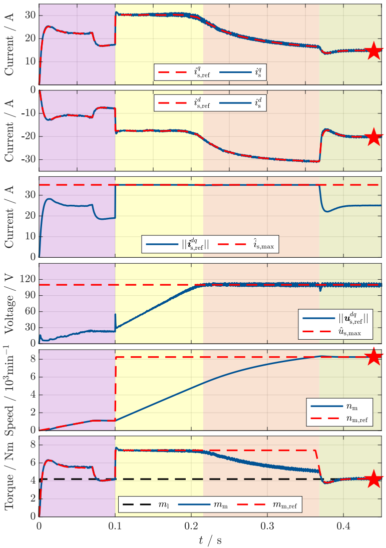
OFTC with ANN-based ORCC: Artificial Neural Network Design

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

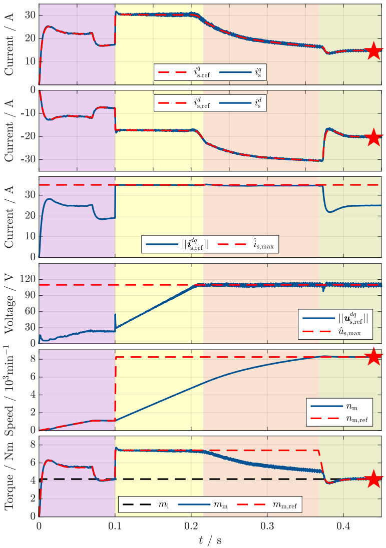


OFTC with ANN-based ORCC: Implementation results

Time series



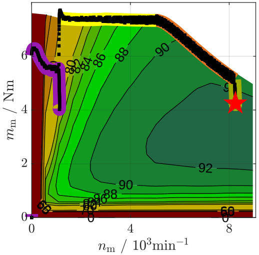
(a) OFTC with analytical ORCC ($\mathrm{OFTC}_{\mathrm{ANA}}$).



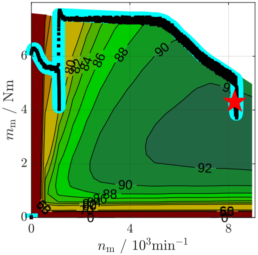
(b) ANN-based OFTC ($\mathrm{OFTC}_{\mathrm{ANN}}$).

OFTC with ANN-based ORCC: Implementation results

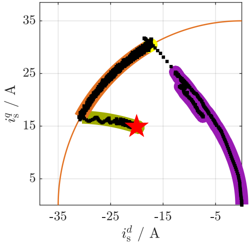
Speed-torque map



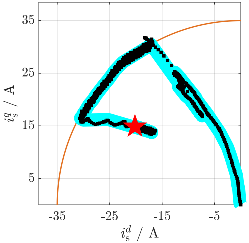
(a) Speed-torque map ($\mathrm{OFTC_{ANA}}$).



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



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



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

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

Outline

3 Conclusion

Conclusion

Summary and future work

To take home

- **Unified** framework for OFTC with analytical ORCC for MTPL (MTPC), FW, $\mathrm{MC}_{(\mathrm{ext})}$ & MTPV (MTPF) based on [102, 105, 106, 131, 167] and [168, Chapt. 6.9]
  - **Sequential quadratic optimization problem** (online linearization, iteration, etc.),
  - Finding **intersection point** of two quadrics (ellipses, hyperbolas, etc.)
- **Novel** OFTC with **analytical but ANN-based** ORCC (no decision tree required) [24]
- **Performance aspects** for both approaches:
  - 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 or EESM)

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* [169]

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

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† 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 [105] (published 2017; doi: 10.1080/00207179.2017.1338359)

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

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

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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

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***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**

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

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

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Munich University of Applied Sciences (MUAS)
Munich, Germany
{andre.thommessen, christoph.hackl}@hm.edu

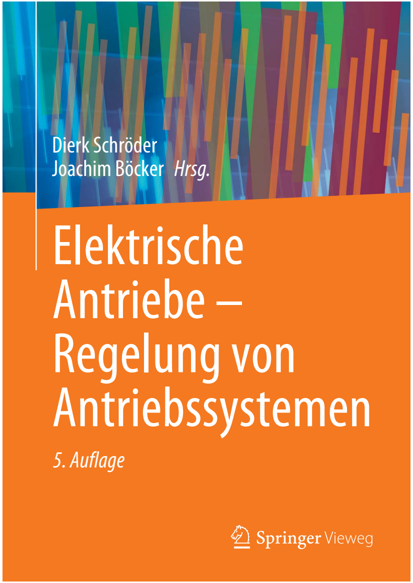
***Abstract*—In order to *analytically* solve the optimal feedforward torque control (OFTC) problem of induction machines (IMs), the unified theory for synchronous machine introduced in [1] is extended by considering relevant IM *nonlinearities* and incorporating stator *and* rotor copper losses. Instead of the well known *Maximum Torque per (stator) Current* (MTPC) operation strategy, *Maximum Torque per (copper) Losses* ($\mathrm{MTPL}_{\mathrm{Cu}}$) is realized and extended by the *Maximum (rotor) Current* ($\mathrm{MC}_{\mathrm{r,\,ext}}$) 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 [168] (published in 2020 in Schröder "Elektrische Antriebssysteme"; doi: 10.1007/978-3-662-62700-6)



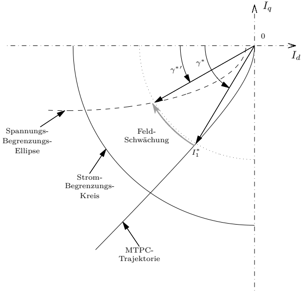


Abb. 6.101 Wirkungsweise der Feldschwächregelung mit Spannungsrückkopplung

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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