



Hochschule
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Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

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

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07.06.2022 – University of Bremen, Germany



Outline

- 1 Introduction
- 2 ANN-based OFTC of synchronous machines
- 3 Conclusion

Outline

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Introduction

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

Outline

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

Introduction

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



HM – Munich University of Applied Sciences

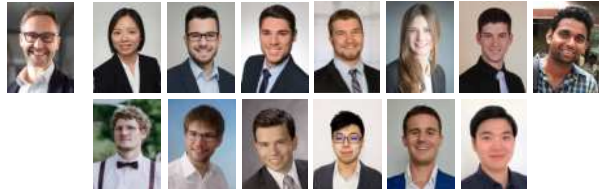
- 14 departments
- >18.000 students
- ~480 professors
- 3 campuses

ISES – Institute for Sustainable Energy Systems

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

LMRES – Laboratory for Mechatronics and Renewable Energy Systems

- International team
- 13 PhD candidates (status 2022)
- >150 publications / >4.3 Mio. € raised



Outline

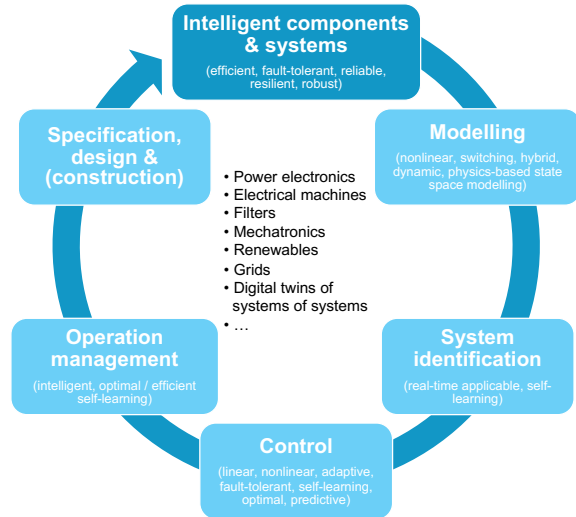
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Introduction

- Research environment
- **Research projects and expertise**
- Selected research results

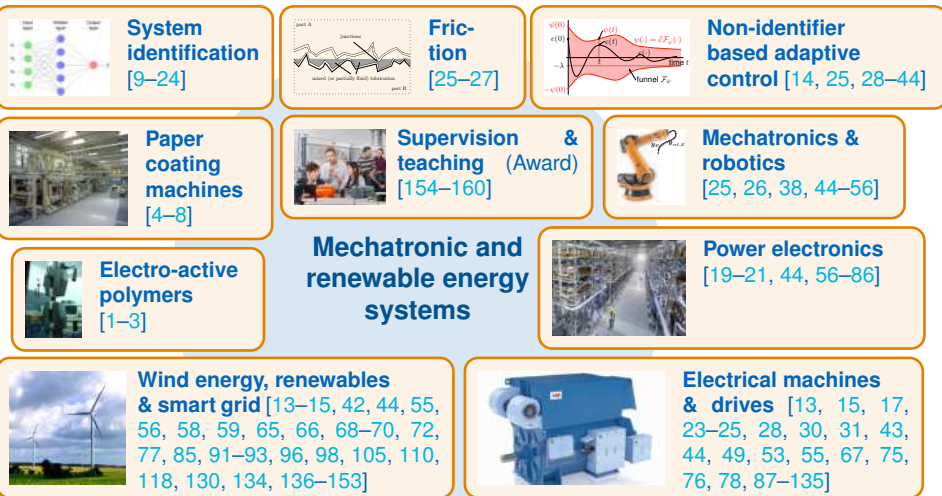
Introduction

LMRES – Research projects and research goals (funding: > 4.3 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)



Introduction

LMRES – Interdisciplinary expertise & publications (1 monograph, 14 book chapters, 53 articles & 91 conference papers)



Outline

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Introduction

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Introduction

LMRES – Selected research results: Electrical/industrial/traction drives (reliability) [113]

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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 isolated (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), post-fault 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.
 $\zeta \in \mathbb{R}^n$ Real vector (bold), expressed as $\zeta = (\zeta_1, \zeta_2, \dots, \zeta_n)^T$.
 $\|\zeta\|$ Euclidean norm of ζ .
 $\|\zeta\|_1$ The maximum sum of ζ_i is $\|\zeta\|_1$.

Subscripts and superscripts

$\square^T$ Transpose operator applied to vector or matrix.
 $\square_s$ Phasor description of a variable at *steady state*.
 $\square_\lambda$ Subscript “s” denotes referencing to the stator.
 $\square_\Lambda$ 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

$T_{VSD} \in \mathbb{R}^{6 \times 6}$ Vector space decomposition matrix.
 $T_1(\phi) \in \mathbb{R}^{2 \times 2}$ Park’s transformation with angle $\phi \in \mathbb{R}$.
 $T_k \in \mathbb{R}^{3 \times 2}$ Optimization matrix.
 k_1^*, k_2^* Scalar optimization parameters in T_k of the $\Gamma \in \{X, Y\}$ coordinate.
 $J \in \mathbb{R}^{2 \times 2}$ Rotation matrix.
 u Electrical voltage (V).
 i Electrical current (A).
 ψ Flux linkage (Wb).
 $\zeta_{a1}^{a1} \dots \zeta_{a6}^{a6} \in \mathbb{R}^6$ Stator space vector expressed in the $(a_1 b_1 c_1 - a_2 b_2 c_2)$ frame, where $\zeta \in \{u, \psi, i\}$.
 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).
 λ Arbitrary variable.

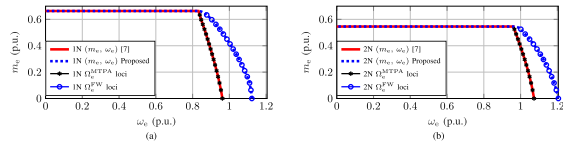


Fig. 1. Postfault comparison of the permissible (m_e, ω_e) characteristics between the presented algorithm in [7] and proposed optimum C with respect to the (a) 1N and (b) 2N neutral configurations, showing the enhancement in terms of extending the permissible

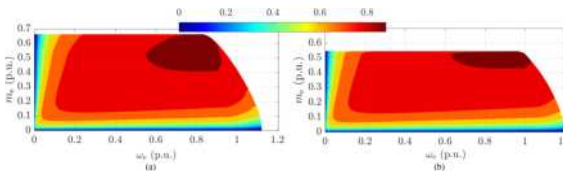


Fig. 2. Postfault efficiency maps of (a) 1N and (b) 2N connections within the (m_e, ω_e) range of the proposed optimization in Section III-C

Introduction

LMRES – Selected research results: Wind energy systems & power electronics (reliability; VDE Award) [76]

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IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 34, NO. 3, MARCH 2019

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. $x := (x_1, \dots, x_n)^T \in \mathbb{R}^n$: column vector, $n \in \mathbb{N}$ where $n^T :=$ “transposed” and “is defined as.” $I_n := \text{diag}(1, \dots, 1) \in \mathbb{R}^{n \times n}$: identity matrix. $O_{n \times p} \in \mathbb{R}^{n \times p}$: zero matrix, $n, p \in \mathbb{N}$. $x \in \mathbb{R}^n$ (in X): physical quantity x where each of the n elements has SI unit X . $\text{mod}(x, y)$: remainder of the division x/y , $x \in \mathbb{R}$, $y \in \mathbb{R} \setminus \{0\}$. $\text{atan2}: \mathbb{R}^2 \rightarrow [-\pi, \pi)$, $(x, y) \rightarrow \text{atan2}(y, x)$: extension of the inverse tangent function to whole circle. $T_{\phi} := \frac{1}{2} \begin{bmatrix} 1 & -j \\ j & 1 \end{bmatrix}$ and $T_{\phi}^{-1} :=$

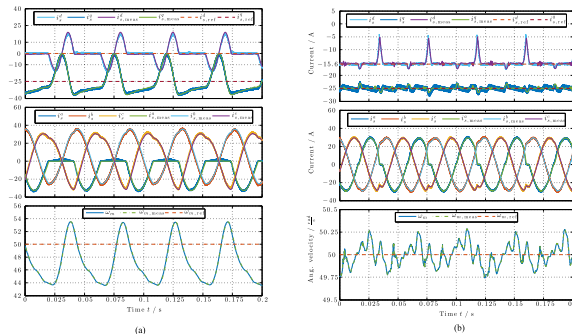
$T_{\phi}(\phi) := \begin{bmatrix} \cos(\phi) & -\sin(\phi) \\ \sin(\phi) & \cos(\phi) \end{bmatrix} =: T_{\phi}(-\phi)^{-1}$: Park transformation matrix. $J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$: rotation matrix.

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, modified flat-top modulation, and optimally injected d -current. (a) Experiment (E₁): Comparison of simulation and measurement results for standard control; $\text{THD}_{i_d} = 41.8\%$ (simulation) versus $\text{THD}_{i_d,\max} = 45.4\%$ (measurement). (b) Experiment (E₂): Comparison of simulation and measurement results for fault-tolerant control system.

Introduction

LMRES – Selected research results: Traction drives & power electronics (efficiency; Cooperation with BMW) [126]

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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

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

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-

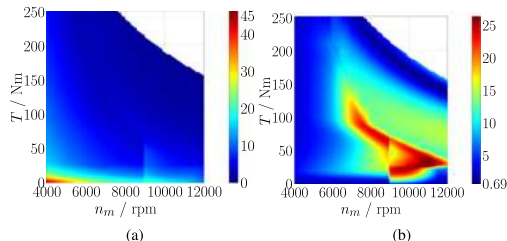


Fig. 9. Numerical performance evaluation of the optimization results. (a) $I_{s,THD}(\alpha_{aniso})/\%$. (b) $I_{s,THD,dev}/\%$.

Introduction

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

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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 (i) 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 & reproducible (d, q) -reference frame; (ii) 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 e.g. flux linkages, torque, iron resistance and efficiency; and (iii) 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 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 (MTPL) minimizing copper and iron losses.

Index Terms—machine identification, flux linkages, iron resistance, induction machine, efficiency, MTPL, MTPC, MTPL.

NOTATION

$\mathbb{N}, \mathbb{R}$: natural, real numbers; $\mathbf{x} := (x_1, \dots, x_n)^\top \in \mathbb{R}^n$: col-

ϕ_p & $\omega_p := \frac{d}{dt}\phi_p$: Park transformation angle and angular velocity; $\mathbf{J} := \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$: rotation matrix (by $\frac{\pi}{2}$).

1. MOTIVATION AND CONTRIBUTIONS

Maximum efficiency operation (or *loss minimizing control*) of induction machines has been subject to extensive research in the past. In contrast to LUT-based direct torque control (see e.g. [1]), for vector control, two main approaches are typically distinguished: (i) Offline calculation of optimal references (e.g. [2–4]) or (ii) search-based online techniques (e.g. [5–8]).

The objective is to compute *optimal* reference currents (set points) for a given reference torque while complying with physical constraints (e.g. current & voltage limits) and minimizing losses. This problem is known as the optimal feedforward torque control (OFTC) problem [9, 10]. Depending on the optimization objective, different OFTC strategies are obtained; e.g. *Maximum Torque Per Current* (MTPC), minimizing the copper losses in the machine, or *Maximum Torque Per Voltage* (MTPV), minimizing the stator voltage magnitude. As an extension to these ‘classical’ OFTC strategies (for IMs see e.g. [2, 5, 11]), *Maximum Torque Per Losses* (MTPL) [or *Maximum Efficiency Per Torque* (MEPT)] considers and minimizes copper and iron losses to maximize the overall machine efficiency (for IMs see e.g. [4, 7, 8, 12, 13]).

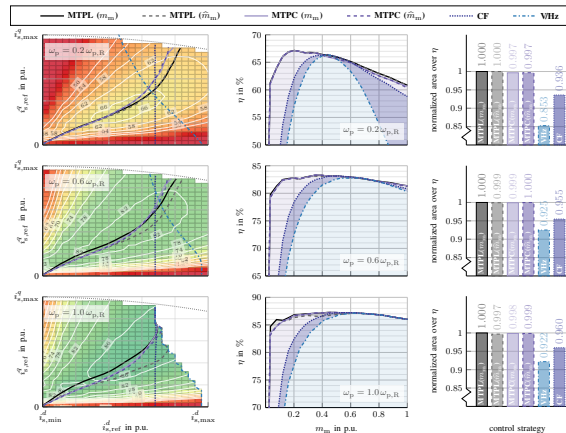


Figure 12: Efficiency comparison for $\omega_p \in [0.2, 0.6, 1] \cdot \omega_{p,R}$ (from top to bottom), with efficiency contour plots in current locus (left column), efficiency-over-torque plots (middle column) and overall performance bar plots (right column).

Introduction

LMRES – Selected research results: Electrical/industrial/traction drives (self-commissioning) [135]



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Analytical Prototype Functions for Flux Linkage Approximation in Synchronous Machines

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AND RALPH KENNEL¹ (Senior Member, IEEE)

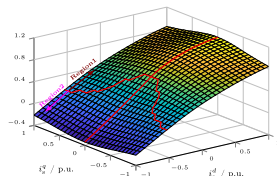
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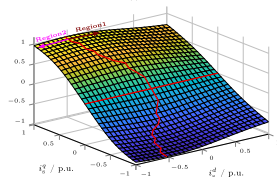
CORRESPONDING AUTHOR: SHIH-WEI SU (e-mail: shihwei.su@tum.de).

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 linkage prototype functions are continuously differentiable, obey the energy conservation rule and, as fitting results show, achieve a (very) high approximation accuracy over the whole operation range.

INDEX TERMS Analytical flux linkage prototype functions, interior permanent magnet synchronous ma-

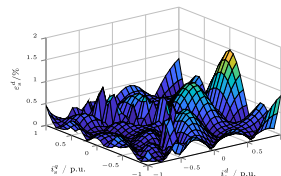


(a)

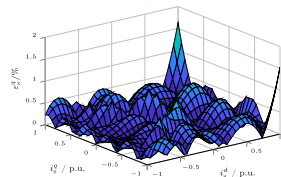


(b)

FIGURE 10. Approximation results of the proposed analytical flux linkage prototype functions (40), (41), (46) and (47): (a) fitted d -axis flux linkages [b] fitted q -axis flux linkages $\hat{\psi}_i^q$; zero locus $\pm \frac{d\psi}{dt}(L=0)$ [—] is



(a)



(b)

FIGURE 11. Approximation errors of the proposed analytical flux linkage prototype functions (40), (41), (46) and (47) compared to the real flux maps: (a) normalized d -axis error e_d^d ; (b) normalized q -axis error e_q^q .

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. Hackl¹, 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 antipwindup, 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 $n, m \in \mathbb{N}$. $\mathbf{x} := (x_1, \dots, x_n)^T \in \mathbb{R}^n$: column vector (where $\cdot$ means “is defined as” and T means “transposed”). $\mathbf{0}_n := (0, \dots, 0)^T \in \mathbb{R}^n$: zero vector. $\|\mathbf{x}\| := \sqrt{\mathbf{x}^T \mathbf{x}}$: Euclidean norm of $\mathbf{x}$. $\mathbf{A} \in \mathbb{R}^{n \times m}$: real (non-square) matrix. $\text{diag}(\mathbf{a}) \in \mathbb{R}^{n \times n}$: diagonal matrix with

IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 35, NO. 3, MARCH 2020

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

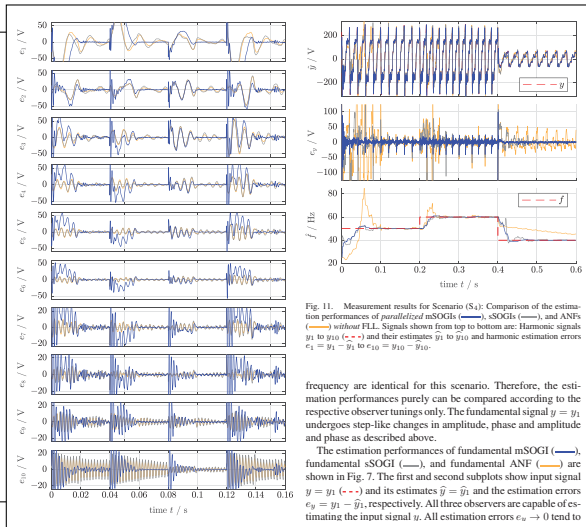


Fig. 11. Measurement results for Scenario (S4): Comparison of the estimation performances of parallelized mSOGIs (—), sSOGIs (---), and ANFs (— · —) without FLL. Signals shown from top to bottom are: Harmonic signals y_1 to y_{10} (— · —) and their estimates $\hat{y}_1$ to $\hat{y}_{10}$ and harmonic estimation errors $e_u = y_u - \hat{y}_u$ 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 $e_u \rightarrow 0$ tend to

2 ANN-based OFTC of synchronous machines

- Motivation
- Problem statement and proposed solution
- OFTC with analytical ORCC
 - Considered machines
 - Analytical computation
 - Operation strategies
 - 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.farmwood.co.uk



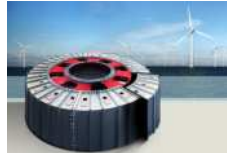
www.abb.com (from video)



www.bmw.de



www.siemens.com



www.siemens.com

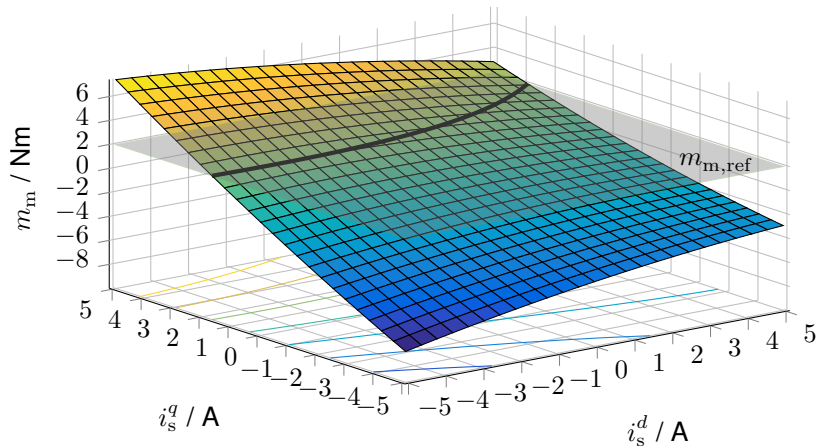


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- buildings (e.g. air conditioning or fans)
- industrial applications (e.g. pumps)
- traction drives (e.g. electric vehicles, trains, etc.)
- power generation (e.g. conventional power plants or wind turbine systems)
- (more) electric aircrafts
- ...

Motivation

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

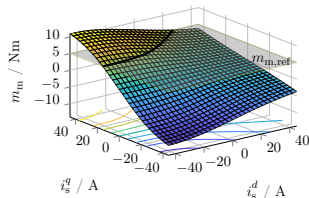


$$m_{m,\text{ref}} \stackrel{!}{=} m_m(\mathbf{i}_s^{dq}) = \frac{2n_p}{3\kappa^2} (\mathbf{i}_s^{dq})^\top \mathbf{J} \psi_s^{dq} \implies \boxed{\mathbf{i}_{s,\text{ref}}^{dq} := (\mathbf{i}_{s,\text{ref}}^d, \mathbf{i}_{s,\text{ref}}^q)^\top = (\textcolor{red}{?}, \textcolor{red}{?})^\top}$$

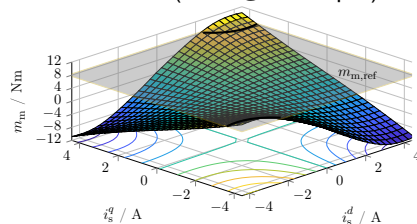
Motivation

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

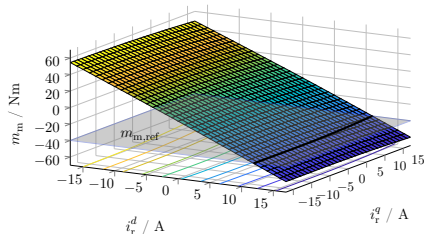
Nonlinear IPMSM (3.9 kW@5 500 rpm)



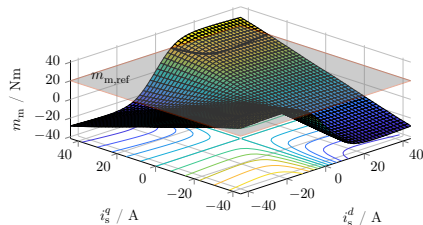
Nonlinear IM (3 kW@1 445 rpm)



Nonlinear DFIM (10 kW@1 500 rpm)



Nonlinear RSM (9.6 kW@1 500 rpm)



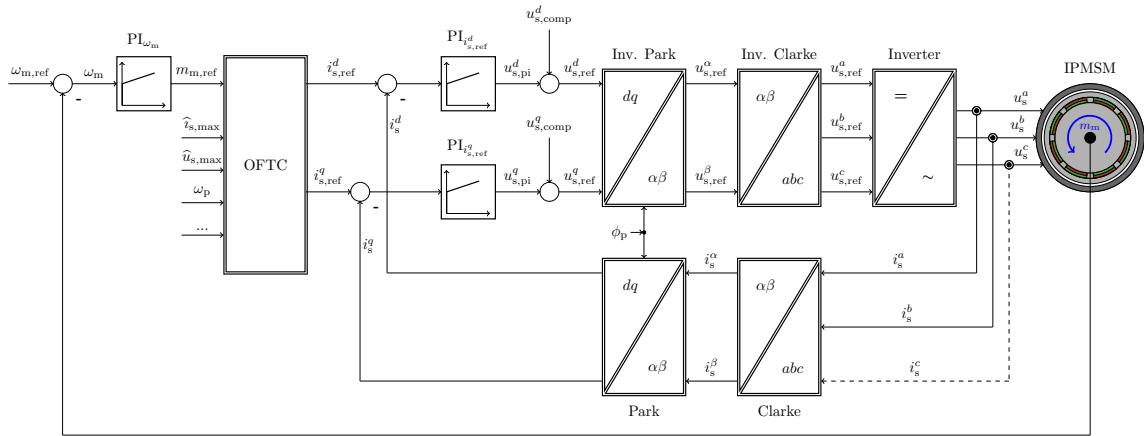
Outline

2 ANN-based OFTC of synchronous machines

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 - Implementation results

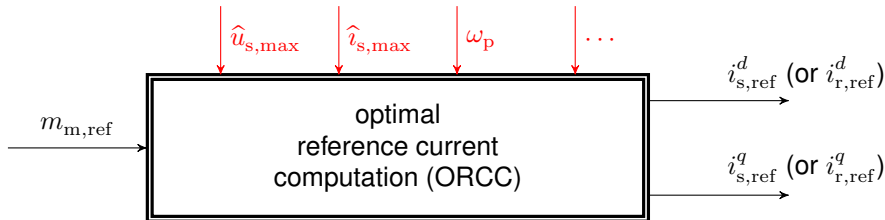
Problem statement and proposed solution

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)



$$\mathbf{i}_{s,ref}^{dq}(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) = \begin{pmatrix} i_{s,ref}^d(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) \\ i_{s,ref}^q(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) \end{pmatrix}$$

- ✓ Numerical solutions and/or look-up tables
(but: limited storage, accuracy, real-time applicability)
- ? Analytical solutions

(some do exist but impose simplifying assumptions such as $R_s = 0$, $R_{s,Fe} = 0$ and/or $L_{s,m} = 0$, etc.)

⇒ For more details, see invited IEEE IES Webinar from April 2021

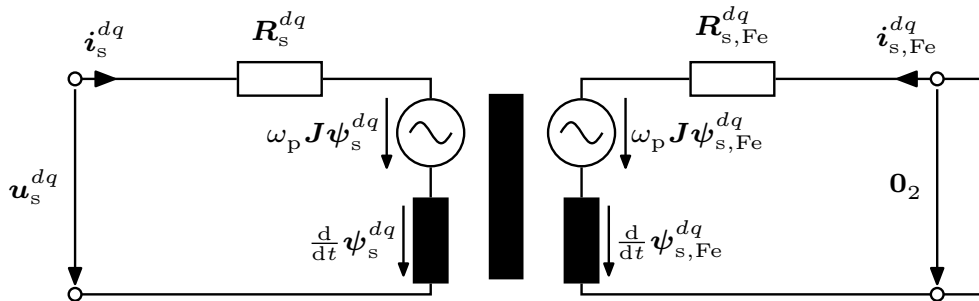
(<https://resourcecenter.ies.ieee.org/education/webinars/IESWEB0080.html>)

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OFTC with analytical ORCC

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

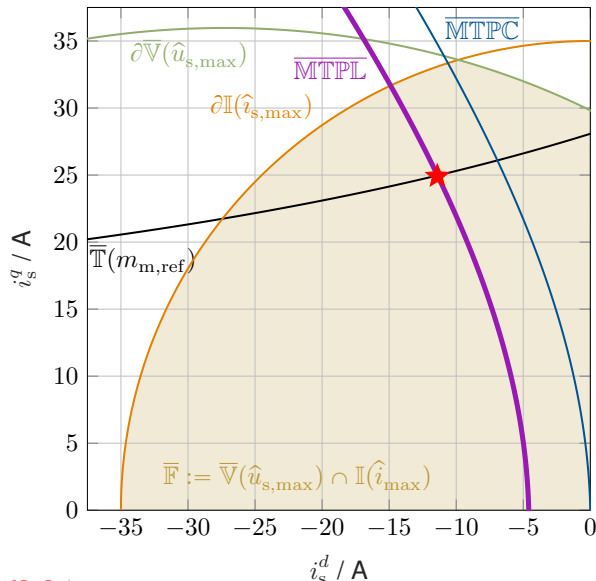


with $\psi_s^{dq} = \psi_{s,Fe}^{dq}$ (single assumption!) and *nonlinear*

- *current, angle, speed and temperature dependent stator resistance, i.e.* $R_s^{dq} := R_s^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$
- *current, angle, speed and temperature dependent iron resistance, i.e.* $R_{s,Fe}^{dq} := R_{s,Fe}^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$
- *current, angle, speed and temperature dependent flux linkages, i.e.* $\psi_s^{dq} := \psi_s^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$

OFTC with analytical ORCC

Analytical computation: Sequential quadratic optimization problem with multiple constraints (**intersection point problem**)



$$\max_{\mathbf{i}_s^{dq} \in \bar{\mathbb{F}}} -f(\mathbf{i}_s^{dq}) \quad \text{subject to}$$

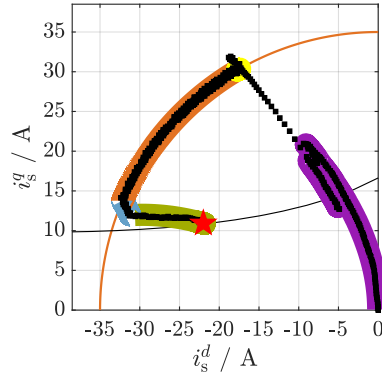
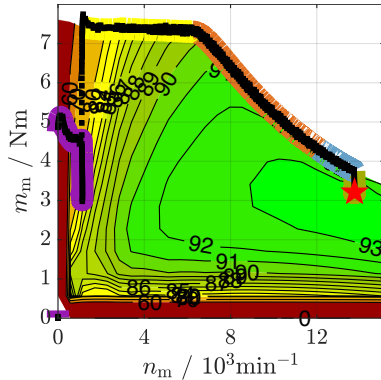
$$\begin{cases} \|\mathbf{i}_s^{dq}\|^2 \leq \hat{i}_{s,\max}^2, \\ \text{(current circular area)} \\ \|\mathbf{u}_s^{dq}(\mathbf{i}_s^{dq}, \omega_p, \dots)\|^2 \leq \hat{u}_{s,\max}^2, \\ \text{(voltage elliptical area)} \\ |m_m(\mathbf{i}_s^{dq}, \omega_p, \dots)| \leq |m_{m,\text{ref}}|, \\ \text{and } \text{sign}(m_{m,\text{ref}}) = \\ \text{sign}(m_m(\mathbf{i}_s^{dq})). \end{cases}$$

$\Rightarrow$ e.g. minimize copper,
i.e., $-f(\mathbf{i}_s^{dq}) = -\|\mathbf{i}_s^{dq}\|^2 - f(\mathbf{i}_s^{dq}) =$
 $-R_s \|\mathbf{i}_s^{dq}\|^2 - R_{s,\text{Fe}} \|\mathbf{i}_{s,\text{Fe}}^{dq}\|^2.$

$\Rightarrow \mathbf{i}_{s,\text{ref}}^{dq} = \mathbf{i}_{s,\text{MTPL}}^{dq}$ at $\star$, i.e., MTPL
with $m_{m,\text{ref}} = m_m(\mathbf{i}_{s,\text{ref}}^{dq})$ feasible.

OFTC with analytical ORCC

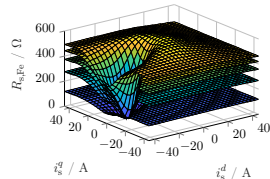
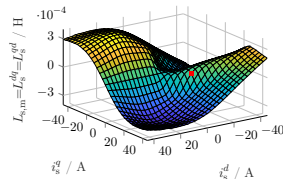
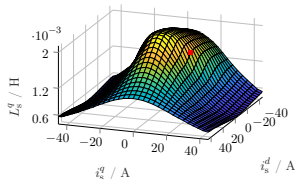
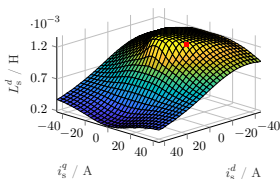
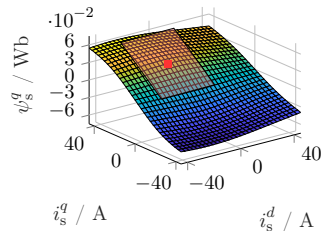
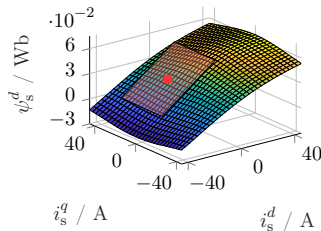
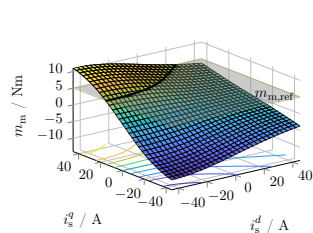
Operation strategies: Overview



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

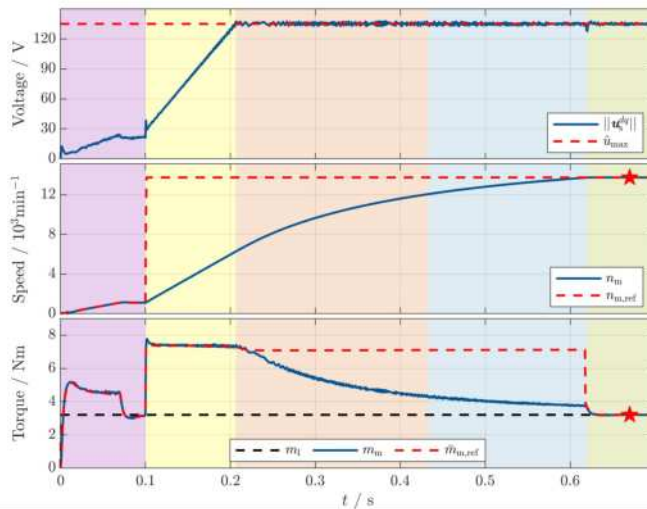
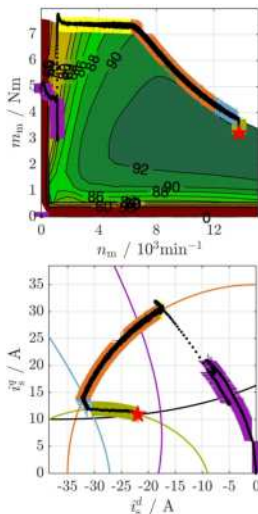
OFTC with analytical ORCC

Implementation results for IPMSM (3.9 kW@5 500 rpm): Torque, flux linkages, differential inductances & iron resistance



OFTC with analytical ORCC

Implementation results for IPMSM (3.9 kW@5 500 rpm): Animation



MTPL [purple]

MC_{ext} [yellow]

MC [orange]

MTPV [blue]

FW [green]

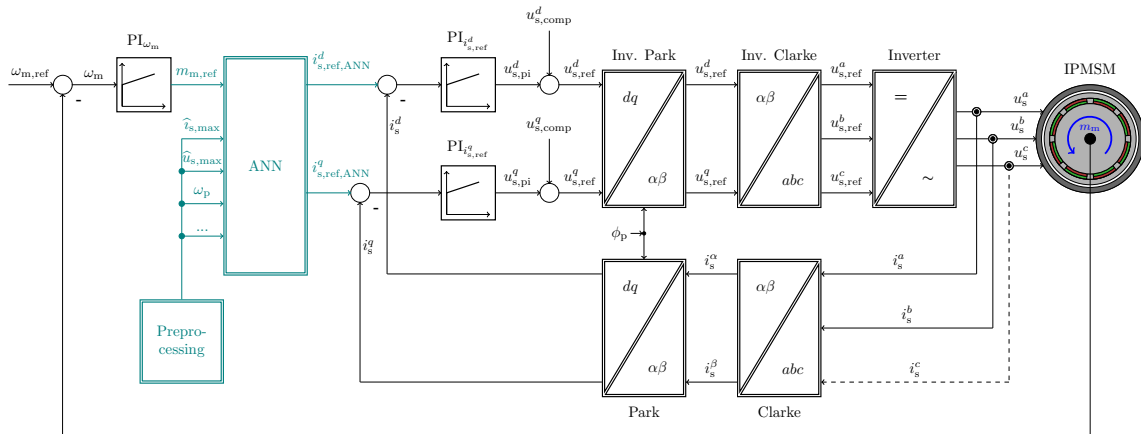
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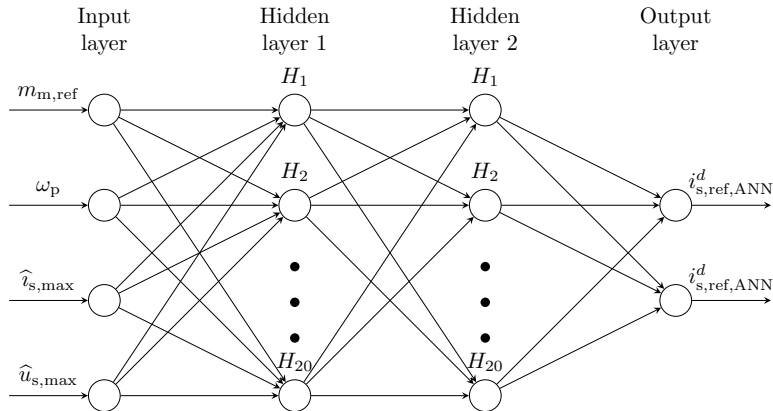
OFTC with ANN-based ORCC

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



OFTC with ANN-based ORCC

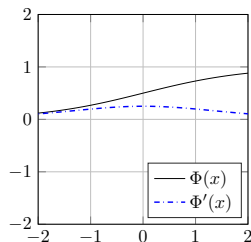
Artificial Neural Network Design: Used ANN topology



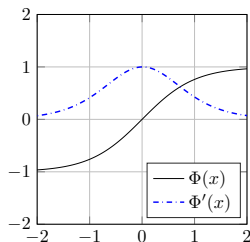
$$\hat{\mathbf{y}} = \begin{pmatrix} i_{\text{ref,ANN}}^d \\ i_{\text{ref,ANN}}^q \end{pmatrix} = \Phi_4 \left(\mathbf{W}_4 \Phi_3 \left(\mathbf{W}_3 \Phi_2 \left(\mathbf{W}_2 \Phi_1 \left(\mathbf{W}_1 \begin{pmatrix} m_{\text{m,ref}} \\ \omega_{\text{p}} \\ \hat{i}_{\text{s,max}} \\ \hat{u}_{\text{s,max}} \end{pmatrix} + \mathbf{b}_1 \right) + \mathbf{b}_2 \right) \right) + \mathbf{b}_3 \right) + \mathbf{b}_4 \Bigg).$$

OFTC with ANN-based ORCC

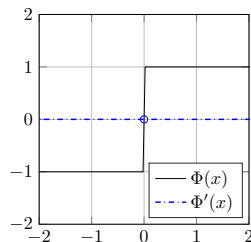
Artificial Neural Network Design: Possible and used ANN activation function



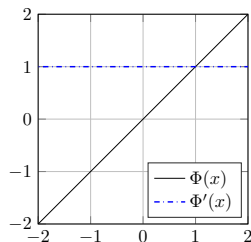
(a) Sigmoid.



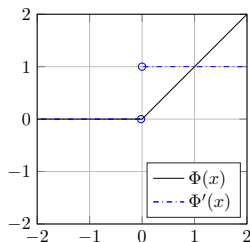
(b) Tangens hyperbolicus.



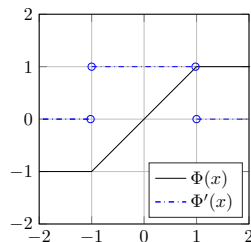
(c) Signum (sign).



(d) Identity.



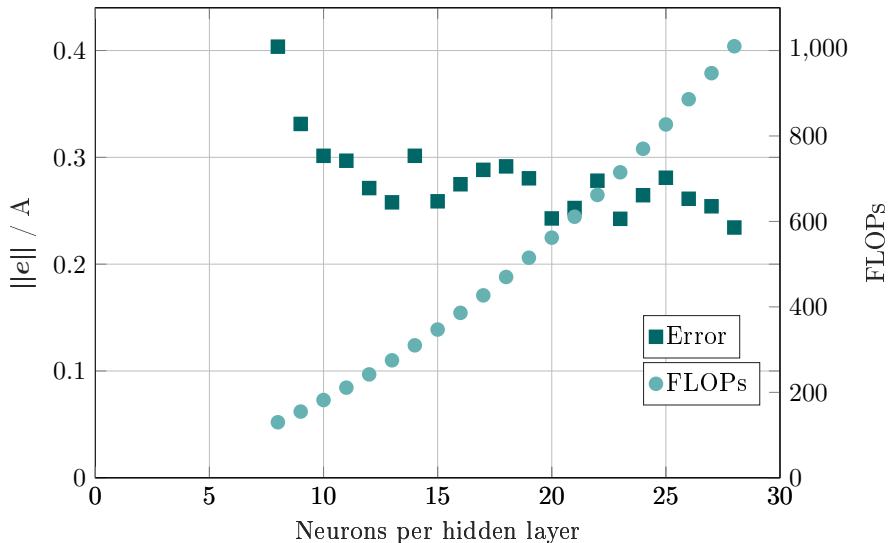
(e) Rectified Linear Unit (ReLU).



(f) Saturation.

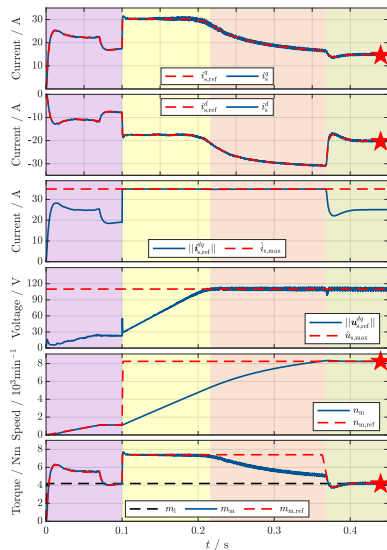
OFTC with ANN-based ORCC

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

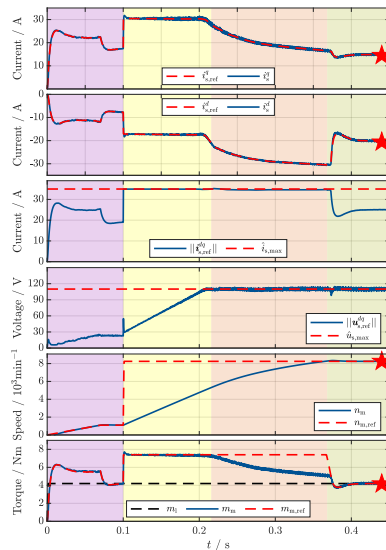


OFTC with ANN-based ORCC

Implementation results: Time series



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



(b) ANN-based OFTC (OFTC_{ANN}).

OFTC with ANN-based ORCC

Implementation results: Performance comparison and execution times

Performance measure	$\mathbf{X=OFTC}_{\text{LUT}}$	$\mathbf{X=OFTC}_{\text{NUM}}$	$\mathbf{X=OFTC}_{\text{ANA}}$	$\mathbf{X=OFTC}_{\text{ANN}}$
$\int i_{s,\text{ref},\text{OFTC}_{\text{NLP}}}^d - i_{s,\text{ref},\text{X}}^d dt$	0.176 As	0.186 As	0.384 As	0.227 As
$\int i_{s,\text{ref},\text{OFTC}_{\text{NLP}}}^q - i_{s,\text{ref},\text{X}}^q dt$	0.195 As	0.207 As	0.256 As	0.213 As
$\int m_{\text{ref},\text{X}} - m_{\text{m}} dt$	0.018 Nms	0.017 Nms	0.026 Nms	0.020 Nms
$\int \hat{u}_{s,\text{max}} - \ \mathbf{u}_{s,\text{ref},\text{X}}^{dq}\ dt$	0.445 Vs	0.446 Vs	0.454 Vs	0.459 Vs
$\int \hat{i}_{s,\text{max}} - \ \mathbf{i}_{s,\text{ref},\text{X}}^{dq}\ dt$	0.010 As	0.000 As	0.000 As	0.059 As
$\int n_{\text{m},\text{ref}} - n_{\text{m},\text{X}} dt$	$752.4 \frac{\text{s}}{\text{min}}$	$750.9 \frac{\text{s}}{\text{min}}$	$752.6 \frac{\text{s}}{\text{min}}$	$757.8 \frac{\text{s}}{\text{min}}$
$\bar{t}_{\text{exec},\text{X}}$	2 734.782 μs	448.745 μs	439.671 μs	5.855 μs

Outline

3 Conclusion

Conclusion

Summary and future work

To take home

- **Unified** framework for OFTC with analytical ORCC for MTPL (MTPC), FW, MC_(ext) & MTPV (MTPF) based on [100, 103, 104, 129, 161] and [162, 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 $R_s \neq 0$, $R_{s,Fe} \neq 0$ and $L_{s,m} \neq 0$ 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* [163]

References

Journal article (published 2022; see doi: [10.3390/en15051838](https://doi.org/10.3390/en15051838))



energies



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.; Hackl, C.M. 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. *Energies* 2022, 15, 1838. <https://doi.org/10.3390/en15051838>

Artificial Neural Network based Optimal Feedforward Torque Control of Synchronous Machines
Prof. Dr.-Ing. habil. Christoph M. Hackl

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Journal article [103] (published 2017; doi: [10.1080/00207179.2017.1338359](https://doi.org/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 *quadratics* 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

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KEYWORDS

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

References

Conference publication (published in ICIT 2021 proceedings; see doi: [10.1109/icit46573.2021.9453497](https://doi.org/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 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 RSMs (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

Artificial Neural Network based Optimal Feedforward Torque Control of Synchronous Machines

Prof. Dr.-Ing. habil. Christoph M. Hackl

References

Conference publication (published in ISIE 2021 proceedings; see doi: [10.1109/ISIE45552.2021.9576186](https://doi.org/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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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* (MTPL_{Cu}) is realized and extended by the *Maximum (rotor) Current* (MC_{r,ext}) strategy due to stator and rotor current limitations. Modeling magnetic saturation and cross-coupling effects leads to a constrained *nonlinear* optimization problem which is solved based on the idea of *sequential quadratic programming* (SQP). The second order Taylor approximations are formulated in implicit

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

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

Artificial Neural Network based Optimal Feedforward Torque Control of Synchronous Machines

Prof. Dr.-Ing. habil. Christoph M. Hackl

References

Chapter 6.9 in [162] (published in 2020 in Schröder “Elektrische Antriebssysteme”; doi: [10.1007/978-3-662-62700-6](https://doi.org/10.1007/978-3-662-62700-6))

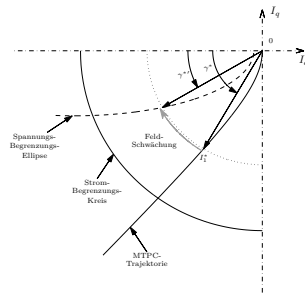
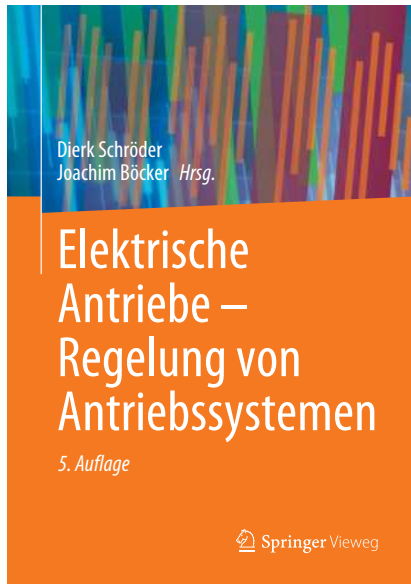


Abb. 6.101 Wirkungsweise der Feldschwächregelung mit Spannungsrückkopplung

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 vereinfachten 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

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Motivation

Electrical machines: Widely-used, compact and efficient actuators



www.farmwood.co.uk



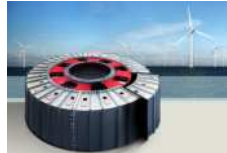
www.abb.com (from video)



www.bmw.de



www.siemens.com



www.siemens.com

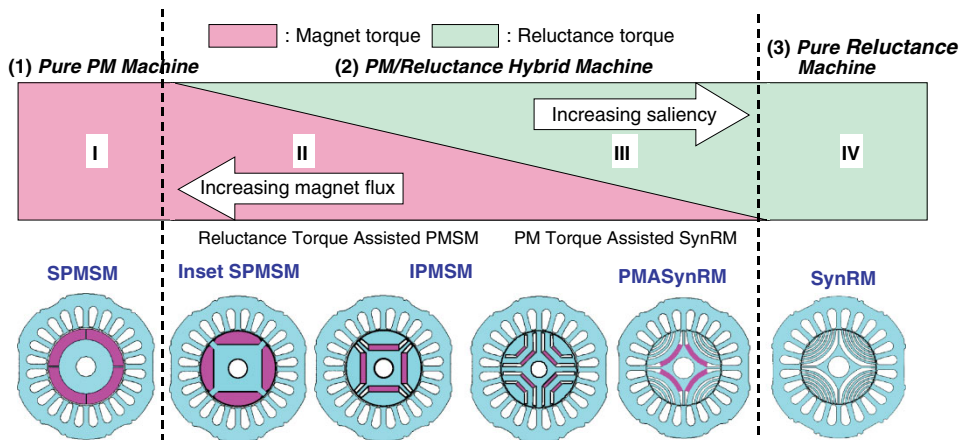


www.lilium.com

- 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

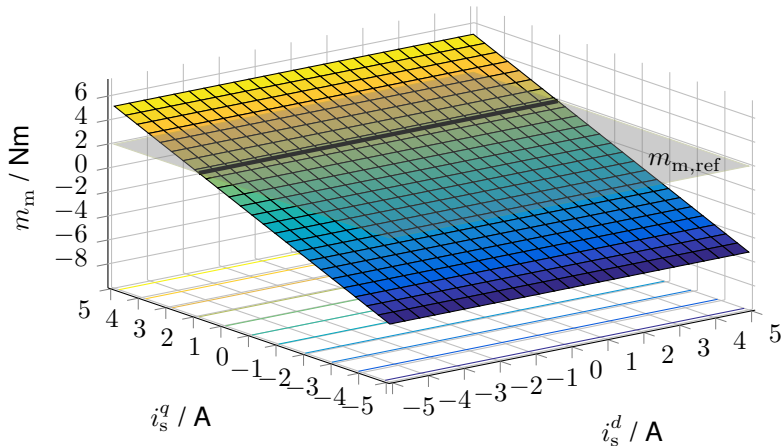
Examples of anisotropic synchronous machines [164] with “saliency ratio” $L_s^d/L_s^q \neq 1$



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

Motivation

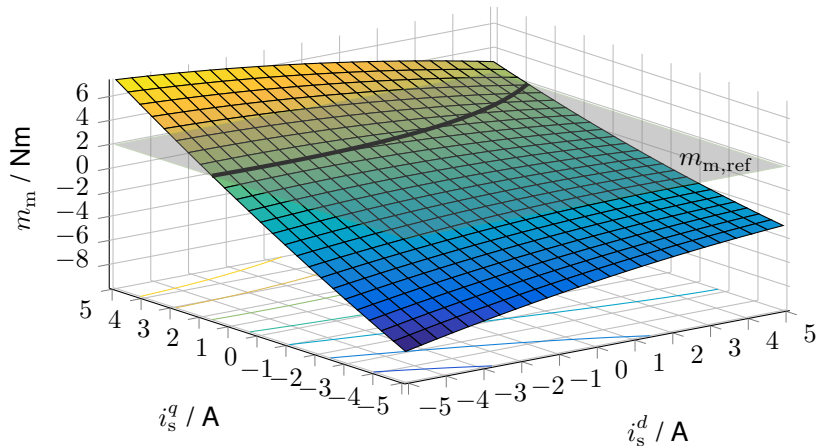
Optimal feedforward torque control problem: **Isotropic, linear PMSM** (without iron losses)



$$m_{m,\text{ref}} \stackrel{!}{=} m_m(i_s^d, i_s^q) = \frac{2n_p}{3\kappa^2} \psi_{\text{pm}} i_s^q \implies \mathbf{i}_{s,\text{ref}}^{dq} := (i_{s,\text{ref}}^d, i_{s,\text{ref}}^q)^\top = \left(0, \frac{3\kappa^2 m_{m,\text{ref}}}{2n_p \psi_{\text{pm}}}\right)^\top$$

Motivation

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

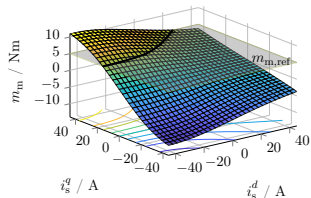


$$m_{m,\text{ref}} \stackrel{!}{=} m_m(i_s^{dq}) = \frac{2n_p}{3\kappa^2} \left[\tilde{\psi}_{\text{pm}} i_s^q + (\tilde{L}_s^d - \tilde{L}_s^q) i_s^d i_s^q + \tilde{L}_{s,m} ((i_s^q)^2 - (i_s^d)^2) \right] \implies \boxed{i_{s,\text{ref}}^{dq} := (\textcolor{red}{?}, \textcolor{red}{?})^\top}$$

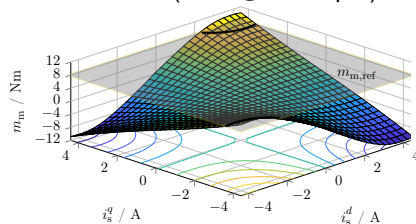
Motivation

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

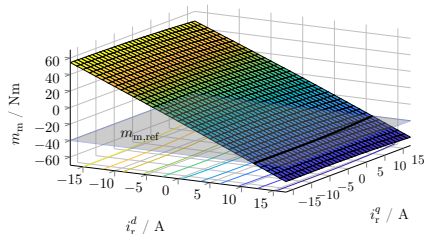
Nonlinear IPMSM (3.9 kW@5 500 rpm)



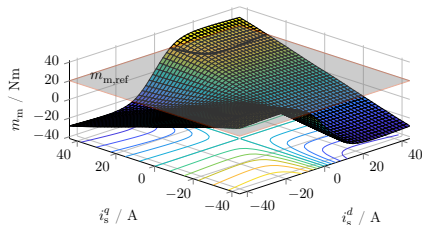
Nonlinear IM (3 kW@1 445 rpm)



Nonlinear DFIM (10 kW@1 500 rpm)



Nonlinear RSM (9.6 kW@1 500 rpm)



Outline

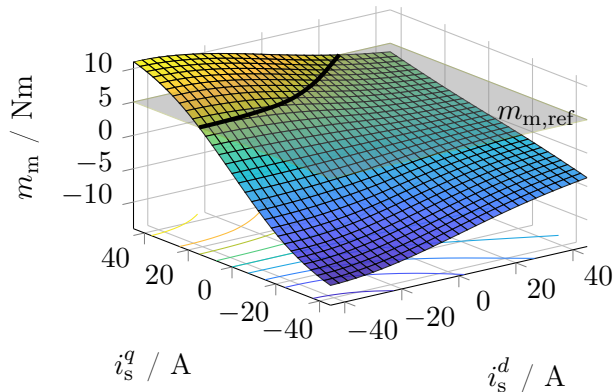
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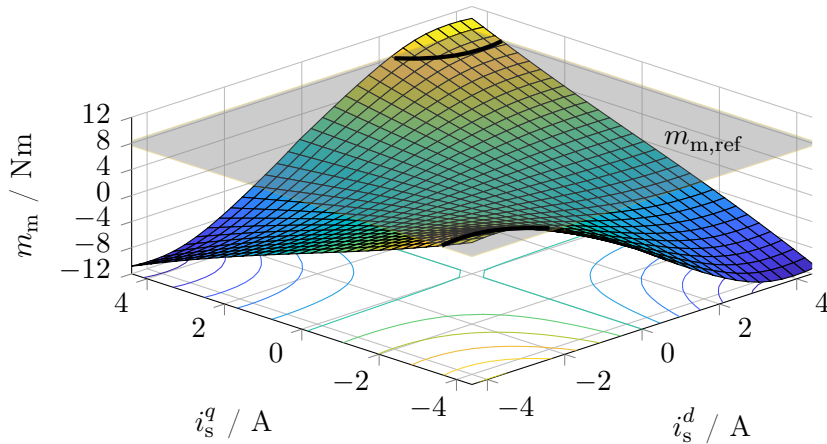
Optimal feedforward torque control problem: **Nonlinear anisotropic IPMSM** (3.9 kW@5 500 rpm)



$$m_{m,\text{ref}} \stackrel{!}{=} m_m(\mathbf{i}_s^{dq}, \omega_p) = \frac{2n_p}{3\kappa^2} \left(\mathbf{i}_s^{dq} + \mathbf{i}_{s,\text{Fe}}^{dq}(\mathbf{i}_s^{dq}, \omega_p) \right)^\top \mathbf{J} \boldsymbol{\psi}_s^{dq} \quad \Rightarrow \quad \boxed{\mathbf{i}_{s,\text{ref}}^{dq} := (\mathbf{i}_{s,\text{ref}}^d, \mathbf{i}_{s,\text{ref}}^q)^\top = (\textcolor{red}{?}, \textcolor{red}{?})^\top}$$

Motivation

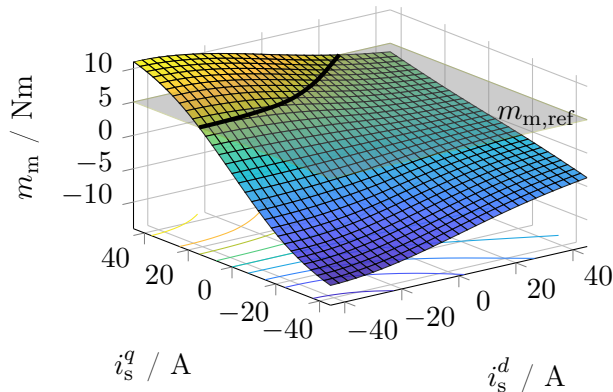
Optimal feedforward torque control problem: **Nonlinear induction machine** (IM; 3 kW@1 445 rpm)



$$m_{m,\text{ref}} \stackrel{!}{=} m_m(\mathbf{i}_s^{dq}, \omega_p) = \frac{2n_p}{3\kappa^2} \left(\mathbf{i}_s^{dq} + \mathbf{i}_{s,\text{Fe}}^{dq}(\mathbf{i}_s^{dq}, \omega_p) \right)^\top \mathbf{J} \boldsymbol{\psi}_s^{dq} \implies \boxed{\mathbf{i}_{s,\text{ref}}^{dq} := (\mathbf{i}_{s,\text{ref}}^d, \mathbf{i}_{s,\text{ref}}^q)^\top = (\textcolor{red}{?}, \textcolor{red}{?})^\top}$$

Motivation

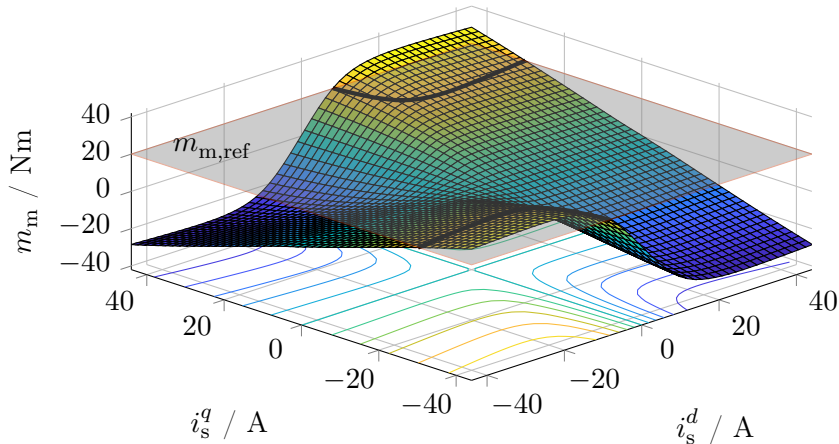
Optimal feedforward torque control problem: **Nonlinear doubly-fed induction machine** (DFIM; 10 kW@1 500 rpm)



$$m_{m,ref} \stackrel{!}{=} m_m(\mathbf{i}_r^{dq}, \omega_p) = -\frac{2n_p}{3\kappa^2} \left(\mathbf{i}_r^{dq} + \mathbf{i}_{r,Fe}^{dq}(\mathbf{i}_r^{dq}, \omega_p, \dots) \right)^\top \mathbf{J} \boldsymbol{\psi}_r^{dq} \Rightarrow \boxed{\mathbf{i}_{r,ref}^{dq} := (\mathbf{i}_{r,ref}^d, \mathbf{i}_{r,ref}^q)^\top = (? , ?)^\top}$$

Motivation

Optimal feedforward torque control problem: **Nonlinear reluctance synchronous machine** (RSM; 9.6 kW@1 500 rpm)



$$m_{m,\text{ref}} \stackrel{!}{=} m_m(\mathbf{i}_s^{dq}, \omega_p) = \frac{2n_p}{3\kappa^2} \left(\mathbf{i}_s^{dq} + \mathbf{i}_{s,\text{Fe}}^{dq}(\mathbf{i}_s^{dq}, \omega_p) \right)^\top \mathbf{J} \boldsymbol{\psi}_s^{dq} \implies \boxed{\mathbf{i}_{s,\text{ref}}^{dq} := (\mathbf{i}_{s,\text{ref}}^d, \mathbf{i}_{s,\text{ref}}^q)^\top = (\textcolor{red}{?}, \textcolor{red}{?})^\top}$$

Outline

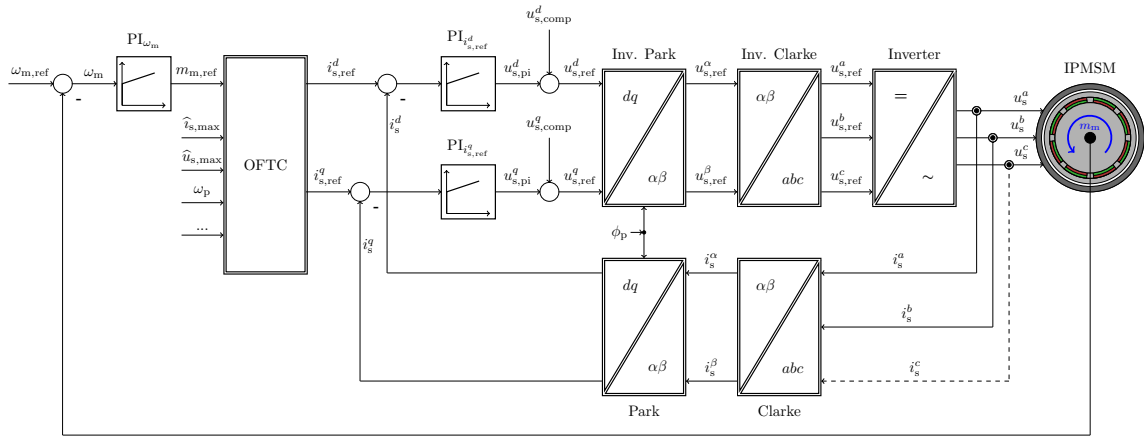
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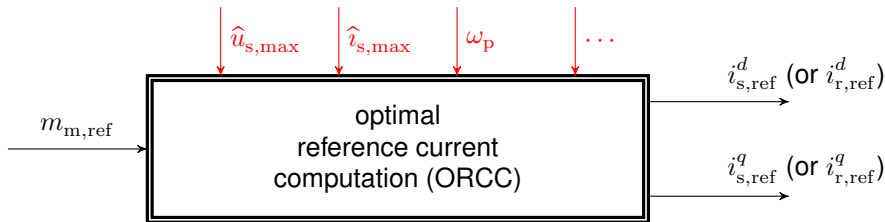
Problem statement and proposed solution

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)



$$\mathbf{i}_{s,ref}^{dq}(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) = \begin{pmatrix} i_{s,ref}^d(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) \\ i_{s,ref}^q(m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}, \omega_p, \dots) \end{pmatrix}$$

✓ Numerical solutions and/or look-up tables
(but: limited storage, accuracy, real-time applicability)

? Analytical solutions

(some do exist but impose simplifying assumptions such as $R_s = 0$, $R_{s,Fe} = 0$ and/or $L_{s,m} = 0$, etc.)

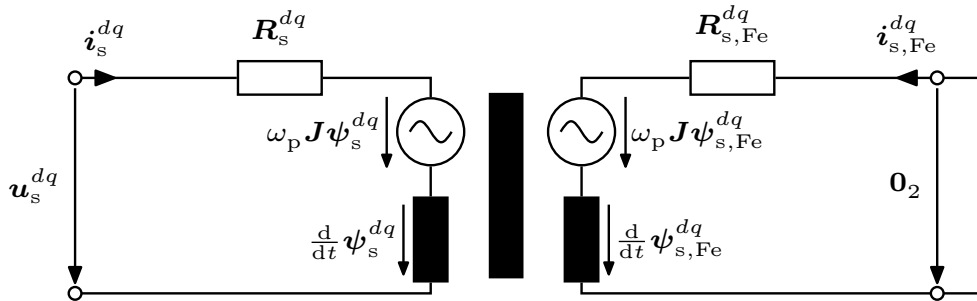
Problem statement and proposed solution

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

$$\begin{aligned}
 \text{Stator:} \quad & \underbrace{\begin{pmatrix} u_s^d \\ u_s^q \end{pmatrix}}_{=: \mathbf{u}_s^{dq}} = \underbrace{\begin{bmatrix} R_s^d & R_s^{dq} \\ R_s^{qd} & R_s^q \end{bmatrix}}_{=: \mathbf{R}_s^{dq}} \underbrace{\begin{pmatrix} i_s^d \\ i_s^q \end{pmatrix}}_{=: \mathbf{i}_s^{dq}} + \omega_p \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{=: \mathbf{J}} \underbrace{\begin{pmatrix} \psi_s^d \\ \psi_s^q \end{pmatrix}}_{=: \mathbf{\psi}_s^{dq}} + \cancel{\frac{d}{dt} \psi_s^{dq}} \\
 \text{Iron:} \quad & \underbrace{\begin{pmatrix} 0 \\ 0 \end{pmatrix}}_{=: \mathbf{0}_2} = \underbrace{\begin{bmatrix} R_{s,Fe}^d & R_{s,Fe}^{dq} \\ R_{s,Fe}^{qd} & R_{s,Fe}^q \end{bmatrix}}_{=: \mathbf{R}_{s,Fe}^{dq}} \underbrace{\begin{pmatrix} i_{s,Fe}^d \\ i_{s,Fe}^q \end{pmatrix}}_{=: \mathbf{i}_{s,Fe}^{dq}} + \omega_p \mathbf{J} \mathbf{\psi}_s^{dq} + \cancel{\frac{d}{dt} \psi_s^{dq}} \\
 & \mathbf{i}_{s,Fe}^{dq} = -(\mathbf{R}_{s,Fe}^{dq})^{-1} \left[\omega_p \mathbf{J} \mathbf{\psi}_s^{dq} + \cancel{\frac{d}{dt} \psi_s^{dq}} \right] \\
 \text{Mech.:} \quad & \frac{d}{dt} \omega_m = \frac{1}{\Theta_m} (m_m + m_l) \quad \text{with} \quad \omega_p = n_p \omega_m \\
 & m_m = \frac{2}{3\kappa^2} (\mathbf{i}_s^{dq} + \mathbf{i}_{s,Fe}^{dq})^\top \mathbf{J} \mathbf{\psi}_s^{dq} \\
 \text{Losses:} \quad & p_{s,L} = \underbrace{\frac{2}{3\kappa^2} (\mathbf{i}_s^{dq})^\top \mathbf{R}_s^{dq} \mathbf{i}_s^{dq}}_{=: p_{s,Cu}} + \underbrace{\frac{2}{3\kappa^2} (\mathbf{i}_{s,Fe}^{dq})^\top \mathbf{R}_{s,Fe}^{dq} \mathbf{i}_{s,Fe}^{dq}}_{=: p_{s,Fe}}
 \end{aligned}$$

Problem statement and proposed solution

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

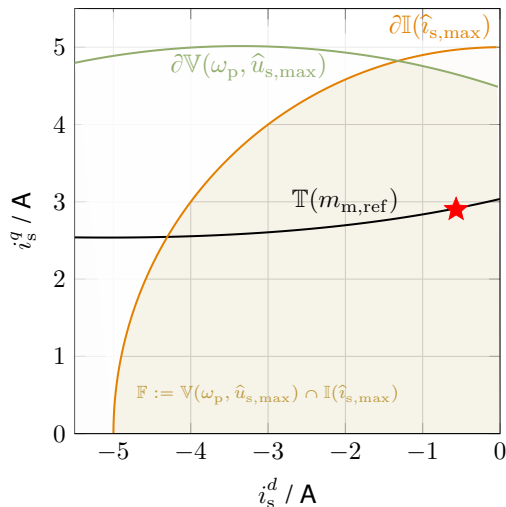


with $\psi_s^{dq} = \psi_{s,Fe}^{dq}$ (single assumption!) and (possibly) *nonlinear*

- *current, angle, speed and temperature dependent stator resistance, i.e.* $R_s^{dq} := R_s^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$
- *current, angle, speed and temperature dependent iron resistance, i.e.* $R_{s,Fe}^{dq} := R_{s,Fe}^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$
- *current, angle, speed and temperature dependent flux linkages, i.e.* $\psi_s^{dq} := \psi_s^{dq}(i_s^{dq}, \phi_p, \omega_p, \vartheta_s)$

Problem statement and proposed solution

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



$$\max_{\mathbf{i}_s^{dq} \in \mathbb{F}} -f(\mathbf{i}_s^{dq}) \quad \text{subject to}$$

$$\left\{ \begin{array}{l} \|\mathbf{i}_s^{dq}\|^2 \leq \hat{i}_{s,max}^2, \\ \text{(current circular area)} \\ \|\mathbf{u}_s^{dq}(\mathbf{i}_s^{dq}, \omega_p, \dots)\|^2 \leq \hat{u}_{s,max}^2, \\ \text{(voltage elliptical area)} \\ |m_m(\mathbf{i}_s^{dq}, \omega_p, \dots)| \leq |m_{m,ref}|, \\ \text{and } \text{sign}(m_{m,ref}) = \\ \text{sign}(m_m(\mathbf{i}_s^{dq})). \end{array} \right.$$

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

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

Outline

4

Appendix

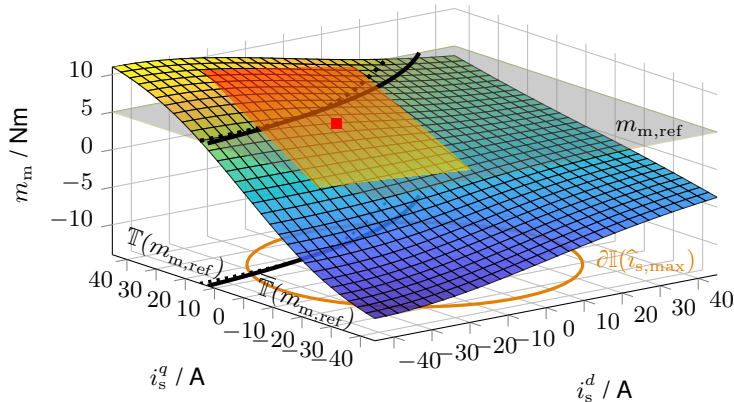
- Motivation
- Optimal feedforward torque control problem: Identical for all machines (examples)
- Problem statement and proposed solution
- **OFTC with analytical ORCC**
 - Analytical computation
 - Operation strategies
 - Operation management and decision tree
 - Implementation results
- OFTC with ANN-based ORCC
 - Overview
 - Artificial Neural Network Design
 - Implementation results
- Analytical solution
 - Analytical solution for optimization problem with quadrics
 - Analytical solution for intersection points of two quadrics
 - Roots of a fourth-order polynomial
- Optimal operation strategies and operation management
 - Maximum Torque per Flux (MTPF)
 - Illustration of MTPC, FW and MTPV
 - Neglecting stator resistance and/or mutual inductance

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



■ ...

OFTC with analytical ORCC: Analytical computation

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

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

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

$$\implies \mathbb{I}(\hat{i}_{s,\max}) := \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid (\mathbf{i}_s^{dq})^\top \mathbf{I}_2 \mathbf{i}_s^{dq} - \hat{i}_{s,\max}^2 \leq 0 \}$$

- (Linearized) Voltage elliptical area: $(u_s^d)^2 + (u_s^q)^2 \leq \hat{u}_{s,\max}^2 \iff \|\mathbf{u}_s^{dq}(\mathbf{i}_s^{dq}, \omega_p, \dots)\|^2 = \dots \leq \hat{u}_{s,\max}^2$

$$\implies \overline{\mathbb{V}}(\hat{u}_{s,\max}) := \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid (\mathbf{i}_s^{dq})^\top \overline{\mathbf{V}}(\overline{\omega}_p) \mathbf{i}_s^{dq} + 2\overline{\mathbf{v}}(\overline{\omega}_p)^\top \mathbf{i}_s^{dq} + \overline{\nu}(\overline{\omega}_p, \hat{u}_{s,\max}) \leq 0 \}$$

- (Linearized) Reference torque hyperbola: $m_m(\mathbf{i}_s^{dq}, \omega_p, \dots) = \frac{3}{2}n_p(\mathbf{i}_s^{dq} + \mathbf{i}_{s,\text{Fe}}^{dq})^\top \mathbf{J}\psi_s^{dq} \stackrel{!}{=} m_{m,\text{ref}} \iff \dots$

$$\implies \overline{\mathbb{T}}(m_{m,\text{ref}}) := \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid (\mathbf{i}_s^{dq})^\top \overline{\mathbf{T}} \mathbf{i}_s^{dq} + 2\overline{\mathbf{t}}^\top \mathbf{i}_s^{dq} - m_{m,\text{ref}} = 0 \}$$

■ ...

OFTC with analytical ORCC: Analytical computation

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

Step 3: Optimization problem with equality constraint

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

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

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

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

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

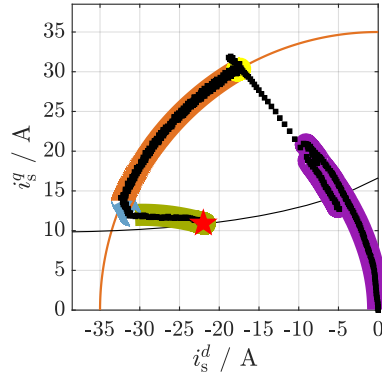
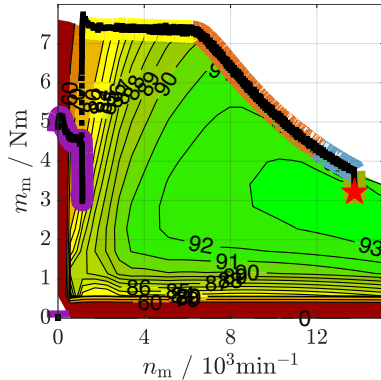
Both lead to subproblem of solving a fourth-order (quartic) polynomial

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

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

OFTC with analytical ORCC: Operation strategies

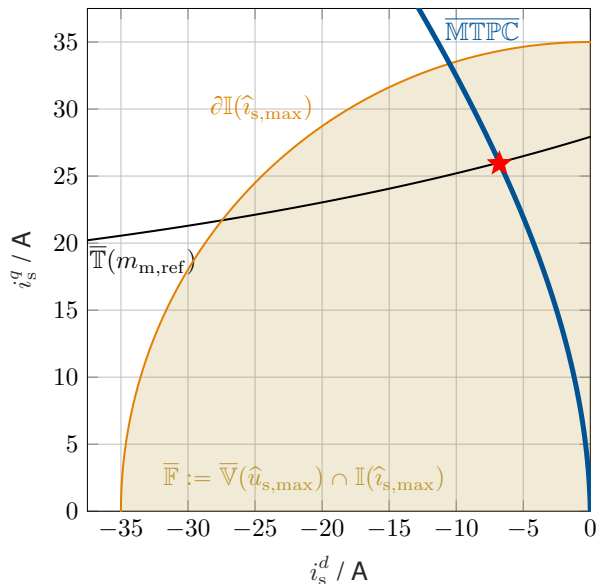
Overview



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

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

$$\begin{aligned} \max_{\mathbf{i}_s^{dq} \in \bar{\mathbb{F}}} -p_{s,Cu}(\mathbf{i}_s^{dq}) \quad \text{s.t.} \\ \underbrace{(\mathbf{i}_s^{dq})^\top \bar{\mathbf{T}} \mathbf{i}_s^{dq} + 2 \bar{\mathbf{t}}^\top \mathbf{i}_s^{dq}}_{\approx m_m(\mathbf{i}_s^{dq})} - m_{m,\text{ref}} = 0 \end{aligned}$$

Solution set

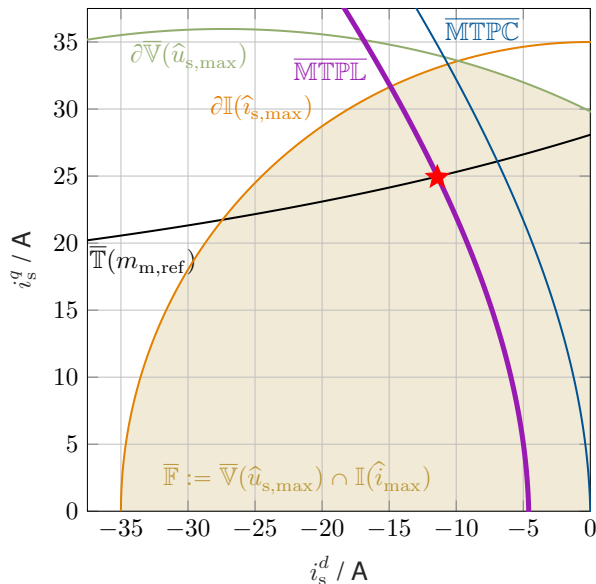
$$\begin{aligned} \overline{\text{MTPC}}(\bar{\mathbf{i}}_s^{dq}, \bar{\omega}_p, \dots) &:= \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid \\ &(\mathbf{i}_s^{dq})^\top \bar{\mathbf{M}}_C \mathbf{i}_s^{dq} + 2 \bar{\mathbf{m}}_C^\top \mathbf{i}_s^{dq} = 0 \} \end{aligned}$$

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

$$\begin{aligned} \max_{\mathbf{i}_s^{dq} \in \bar{\mathbb{F}}} & -p_{s,Cu}(\mathbf{i}_s^{dq}) - p_{s,Fe}(\mathbf{i}_s^{dq}) \quad \text{s.t.} \\ & \underbrace{(\mathbf{i}_s^{dq})^\top \mathbf{T} \mathbf{i}_s^{dq} + 2 \bar{\mathbf{t}}^\top \mathbf{i}_s^{dq}}_{\approx m_m(\mathbf{i}_s^{dq})} - m_{m,ref} = 0 \end{aligned}$$

Solution set

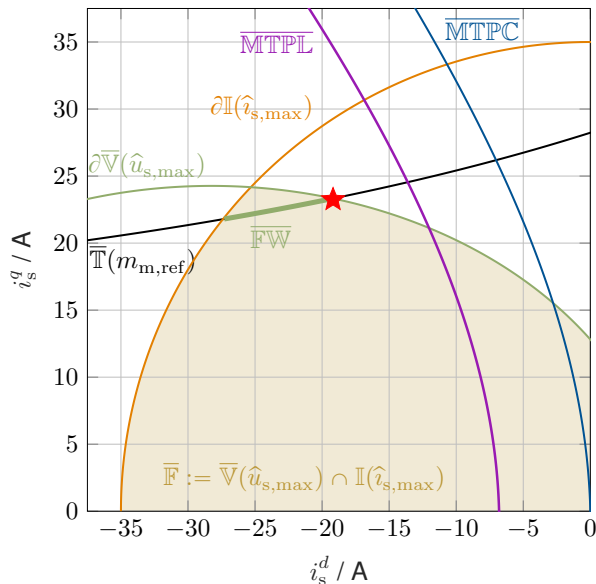
$$\begin{aligned} \overline{\text{MTPL}}(\bar{\mathbf{i}}_s^{dq}, \bar{\omega}_p, \dots) &:= \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid \\ & (\mathbf{i}_s^{dq})^\top \overline{\mathbf{M}}_L \mathbf{i}_s^{dq} + 2 \bar{\mathbf{m}}_L^\top \mathbf{i}_s^{dq} + \bar{\mu}_L = 0 \} \end{aligned}$$

Optimal reference currents (★)

$$\mathbf{i}_{s,MTPL}^{dq} = \overline{\text{MTPL}} \cap \bar{\mathbf{T}}(m_{m,ref})$$

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

$$\begin{aligned} \max_{\mathbf{i}_s^{dq} \in \bar{\mathbb{F}}} & -p_{s,Cu}(\mathbf{i}_s^{dq}) - p_{s,Fe}(\mathbf{i}_s^{dq}) \quad \text{s.t.} \\ & \underbrace{(\mathbf{i}_s^{dq})^\top \mathbf{T} \mathbf{i}_s^{dq} + 2 \mathbf{t}^\top \mathbf{i}_s^{dq}}_{=m_m(\mathbf{i}_s^{dq})} - m_{m,ref} = 0 \end{aligned}$$

Feasible set

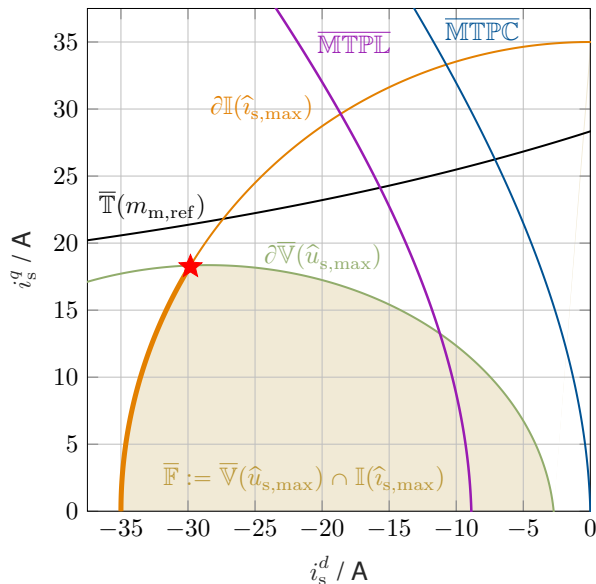
$$\begin{aligned} \bar{\mathbb{F}}\bar{\mathbb{W}}(\bar{\mathbf{i}}_s^{dq}, \bar{\omega}_p, \dots, m_{m,ref}, \hat{u}_{s,max}, \hat{i}_{s,max}) := \\ \bar{\mathbb{F}}(\hat{u}_{s,max}, \hat{i}_{s,max}) \cap \bar{\mathbb{T}}(m_{m,ref}) \end{aligned}$$

Optimal reference currents (★)

$$\mathbf{i}_{s,FW}^{dq} = \partial \bar{\mathbb{V}}(\hat{u}_{s,max}) \cap \bar{\mathbb{T}}(m_{m,ref})$$

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

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

Feasible set

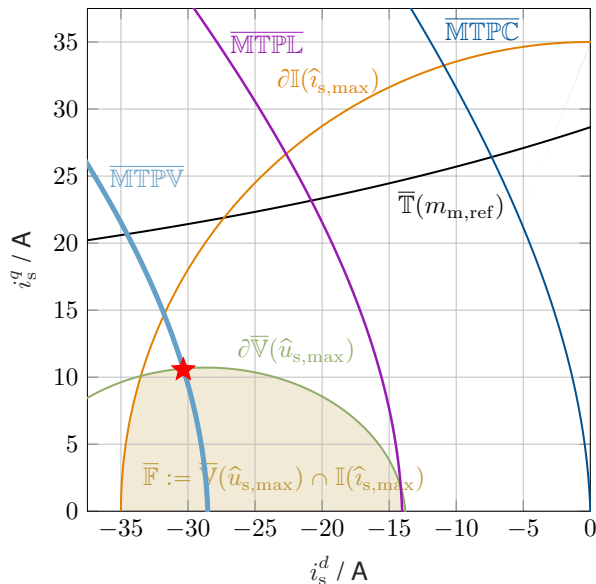
$$\overline{\text{MC}}(\bar{\mathbf{i}}_s^{dq}, \bar{\omega}_p, \dots, \hat{u}_{s,\text{max}}, \hat{i}_{s,\text{max}}) := \\ \bar{\mathbb{V}}(\hat{u}_{s,\text{max}}) \cap \partial \mathbb{I}(\hat{i}_{s,\text{max}})$$

Optimal current reference (★)

$$\mathbf{i}_{s,\text{MC}}^{dq} = \partial \bar{\mathbb{V}}(\hat{u}_{s,\text{max}}) \cap \partial \mathbb{I}(\hat{i}_{s,\text{max}})$$

OFTC with analytical ORCC: Operation strategies

Maximum Torque per Voltage (**MTPV** @ $3.50 \cdot \omega_{m,R}$): Reference torque **not feasible**



Optimization problem

$$\begin{aligned} \max_{\mathbf{i}_s^{dq} \in \overline{F}} & -\|\mathbf{u}_s^{dq}(\mathbf{i}_s^{dq})\|^2 \quad \text{s.t.} \\ & \underbrace{(\mathbf{i}_s^{dq})^\top \overline{\mathbf{T}} \mathbf{i}_s^{dq} + 2 \overline{\mathbf{t}}^\top \mathbf{i}_s^{dq}}_{=m_m(\mathbf{i}_s^{dq})} - m_{m,\text{ref}} = 0 \end{aligned}$$

Solution set

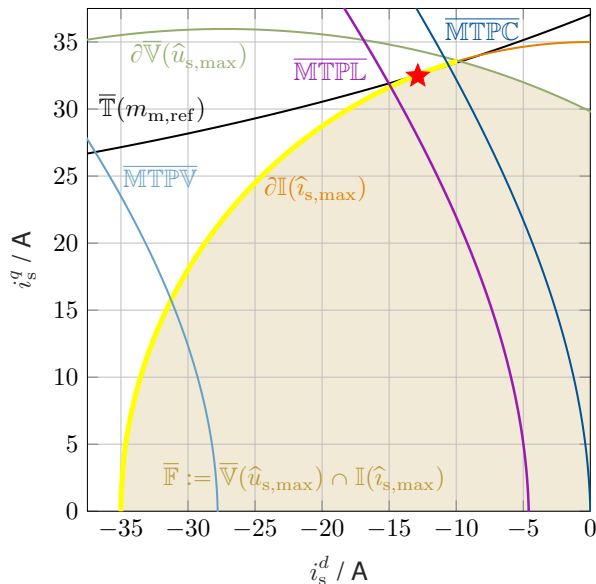
$$\overline{\text{MTPV}}(\mathbf{i}_s^{dq}, \overline{\omega}_p, \dots) := \left\{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid (\mathbf{i}_s^{dq})^\top \overline{\mathbf{M}}_V \mathbf{i}_s^{dq} + 2 \overline{\mathbf{m}}_V^\top \mathbf{i}_s^{dq} + \overline{\mu}_V = 0 \right\}$$

Optimal reference currents (★)

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

OFTC with analytical ORCC: Operation strategies

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



Optimization problem

$$\max_{i_s^{dq} \in \overline{F}} |(m_m(i_s^{dq}))| \quad \text{s.t.}$$

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

Solution set

$$\overline{MC}_{\text{ext}}(\bar{i}_s^{dq}, \bar{\omega}_p, \dots, \hat{u}_{s,\text{max}}, \hat{i}_{s,\text{max}}) := \overline{V}(\hat{u}_{s,\text{max}}) \cap \partial I(\hat{i}_{s,\text{max}})$$

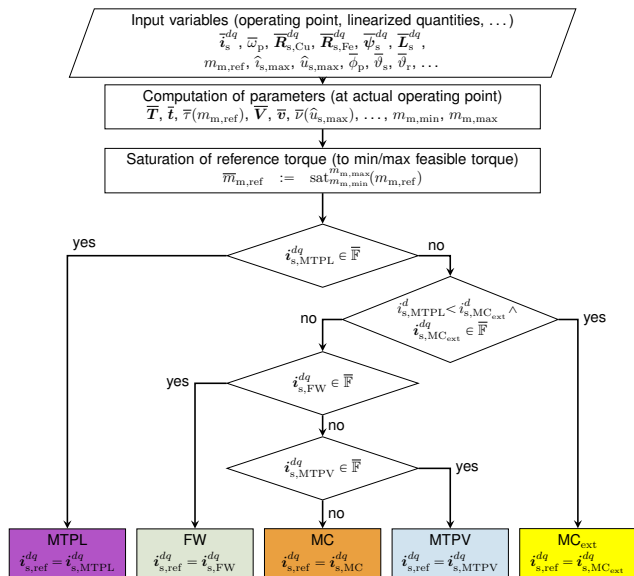
Optimal current reference (★)

$$i_{s,\text{MC}_{\text{ext}}}^{dq} = \overline{T}(m_{m,\text{ref}}) \cap \partial I(\hat{i}_{s,\text{max}})$$

$$\text{with } i_{s,\text{MTPL}}^d < i_{s,\text{MC}_{\text{ext}}}^d$$

OFTC with analytical ORCC: Operation management

Decision tree



OFTC with analytical ORCC: Implementation results

Exemplary laboratory setup

Reluctance SM (RSM) and Permanent-magnet SM



Real-time system and VSIs

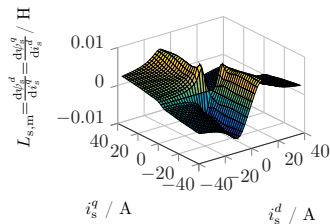
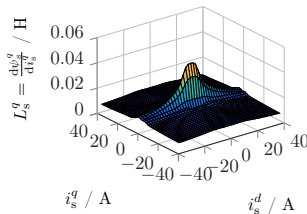
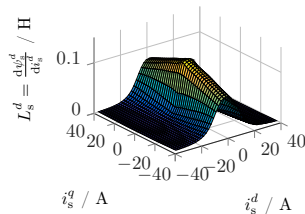
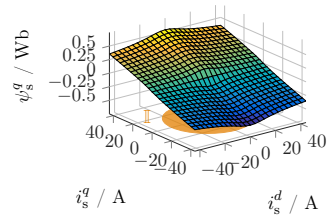
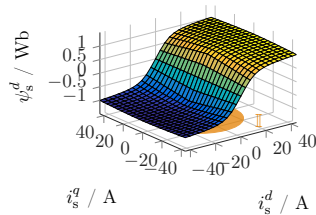
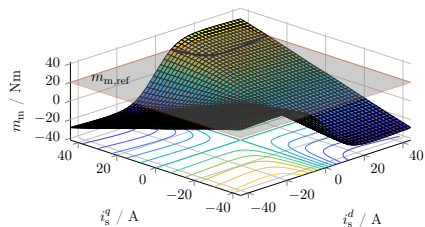


Host PC (rapid prototyping)



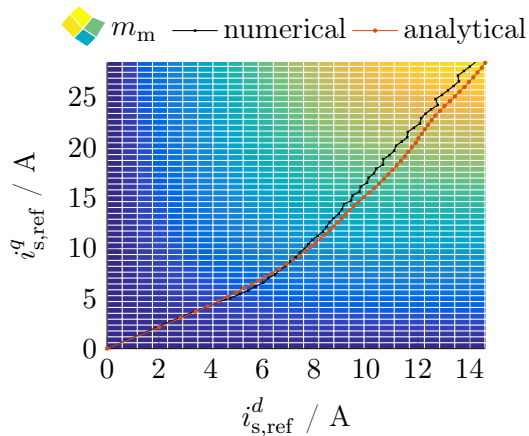
OFTC with analytical ORCC: Implementation results

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

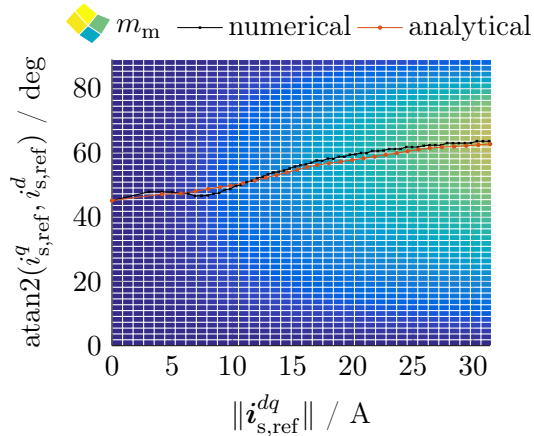


OFTC with analytical ORCC: Implementation results

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



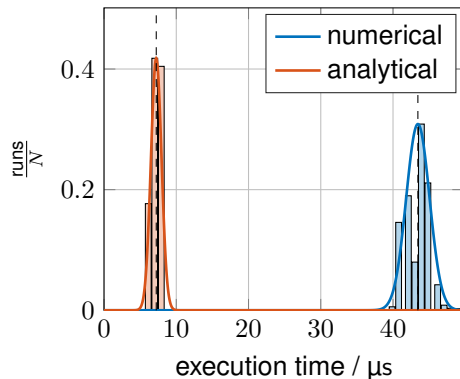
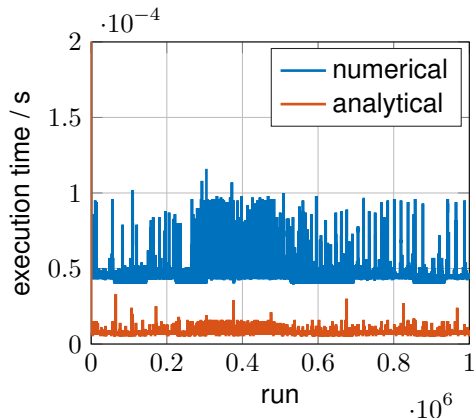
Cartesian coordinates



polar coordinates

OFTC with analytical ORCC: Implementation results

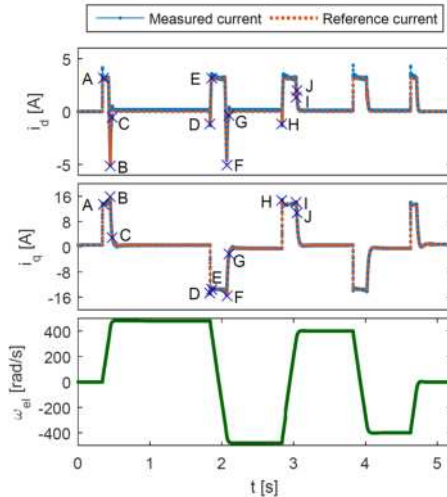
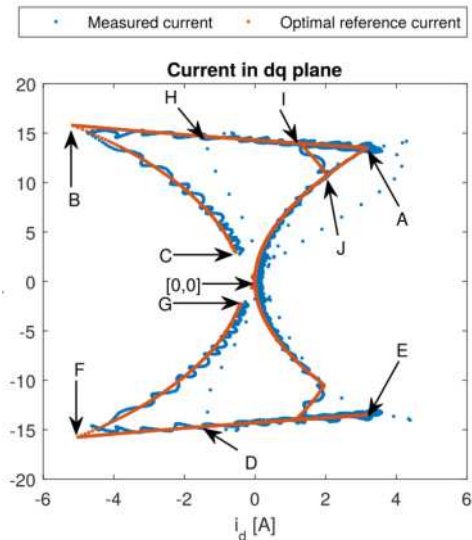
RSM (9.6 kW@1 500 rpm): Comparison of computational load



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

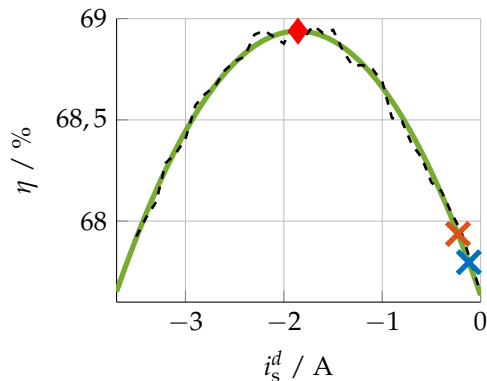
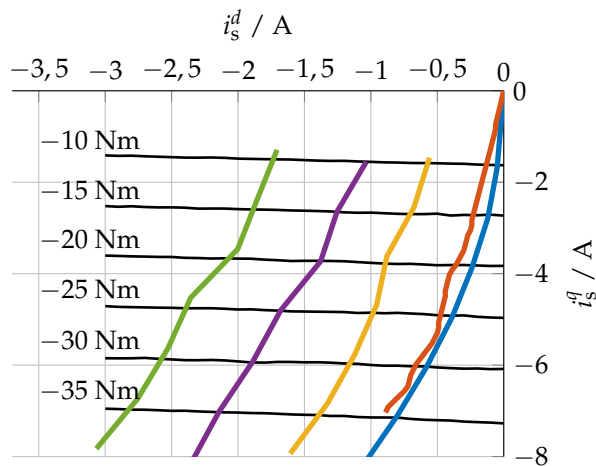
OFTC with analytical ORCC: Implementation results

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



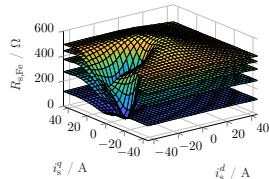
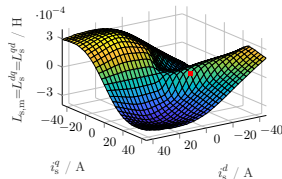
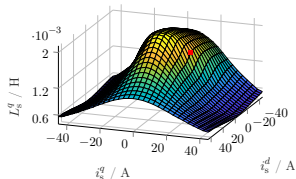
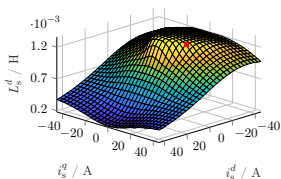
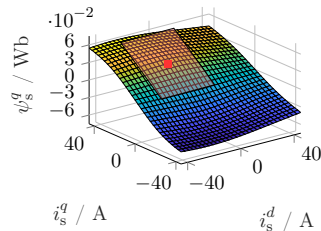
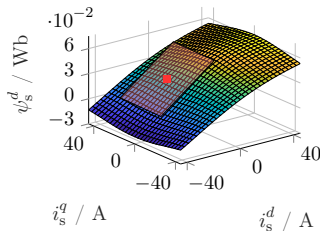
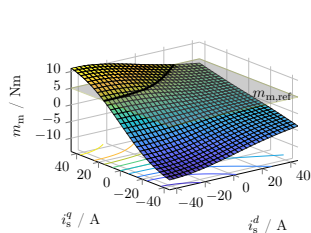
OFTC with analytical ORCC: Implementation results

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



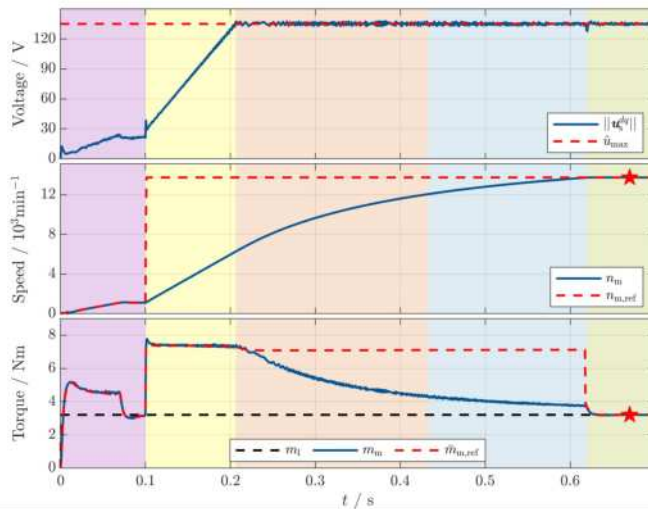
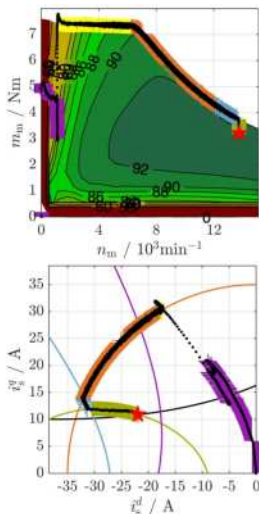
OFTC with analytical ORCC: Implementation results

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 [purple]

MC_{ext} [yellow]

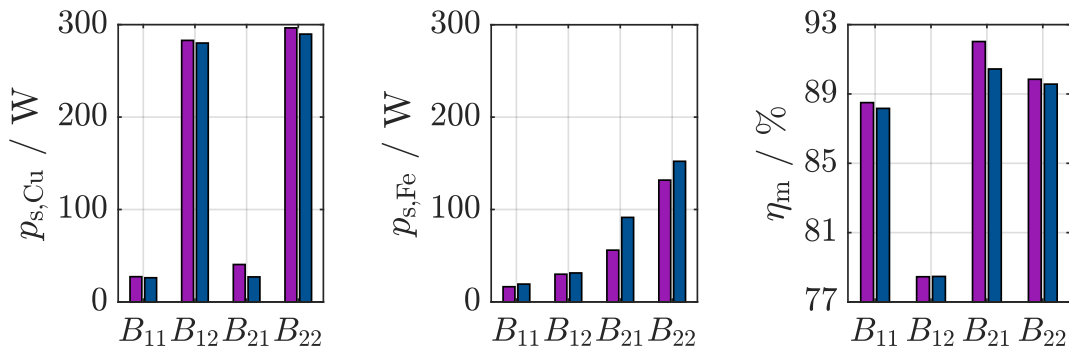
MC [orange]

MTPV [blue]

FW [green]

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

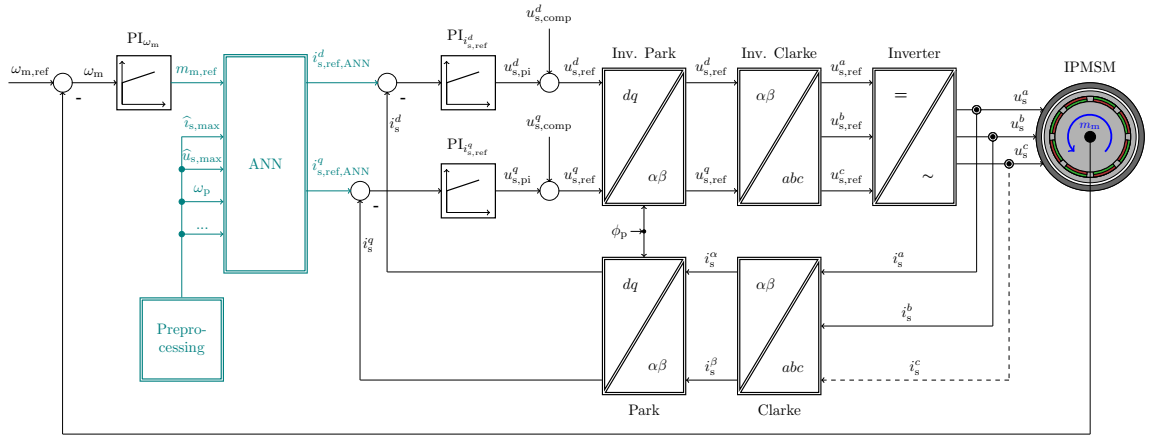
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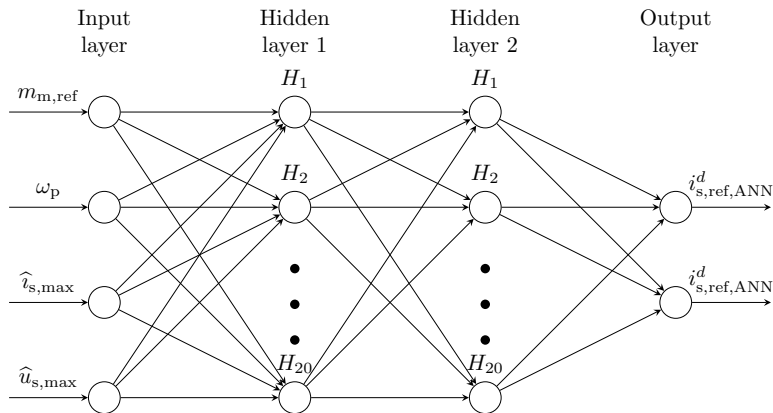
OFTC with ANN-based ORCC: Overview

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



OFTC with ANN-based ORCC: Artificial Neural Network Design

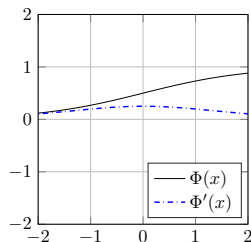
Used ANN topology



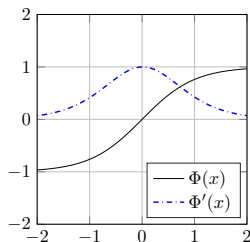
$$\hat{\mathbf{y}} = \begin{pmatrix} i_{\text{ref,ANN}}^d \\ i_{\text{ref,ANN}}^q \end{pmatrix} = \Phi_4 \left(\mathbf{W}_4 \Phi_3 \left(\mathbf{W}_3 \Phi_2 \left(\mathbf{W}_2 \Phi_1 \left(\underbrace{\mathbf{W}_1 \begin{pmatrix} m_{\text{m,ref}} \\ \omega_p \\ \hat{i}_{\text{s,max}} \\ \hat{u}_{\text{s,max}} \end{pmatrix}}_{=\mathbf{x}} \right) + \mathbf{b}_1 \right) + \mathbf{b}_2 \right) \right) + \mathbf{b}_3 \right) + \mathbf{b}_4 \right).$$

OFTC with ANN-based ORCC: Artificial Neural Network Design

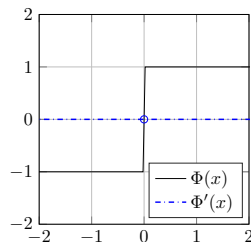
Possible and used ANN activation function



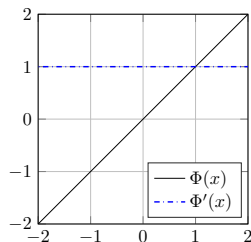
(a) Sigmoid.



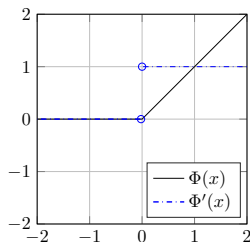
(b) Tangens hyperbolicus.



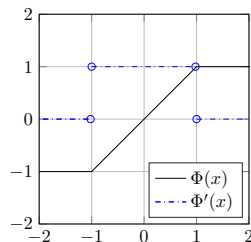
(c) Signum (sign).



(d) Identity.



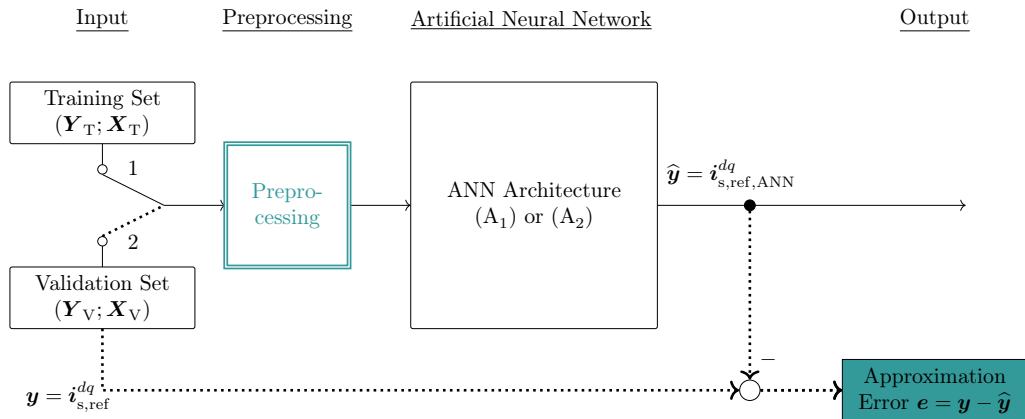
(e) Rectified Linear Unit (ReLU).



(f) Saturation.

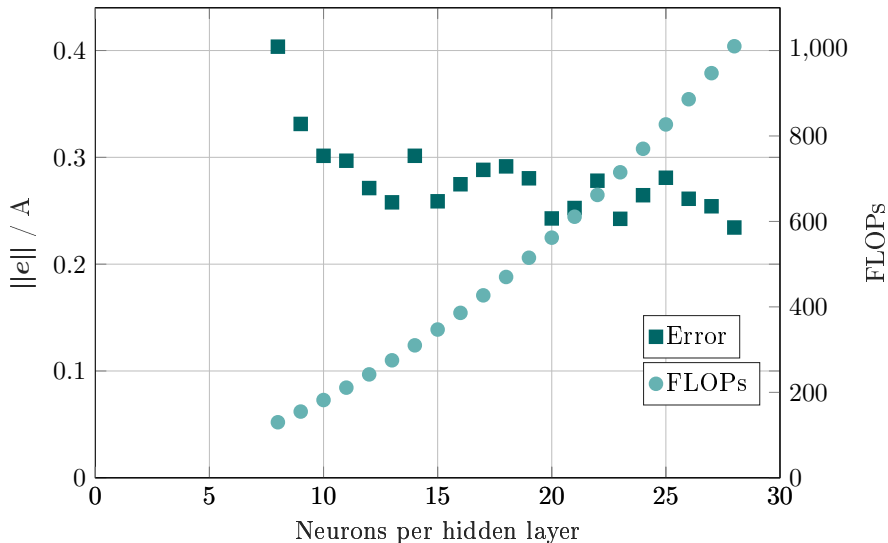
OFTC with ANN-based ORCC: Artificial Neural Network Design

ANN training and validation



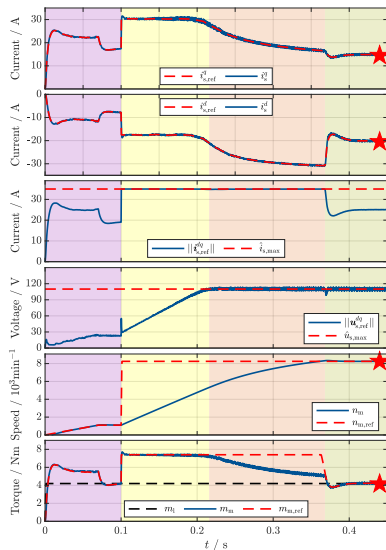
OFTC with ANN-based ORCC: Artificial Neural Network Design

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

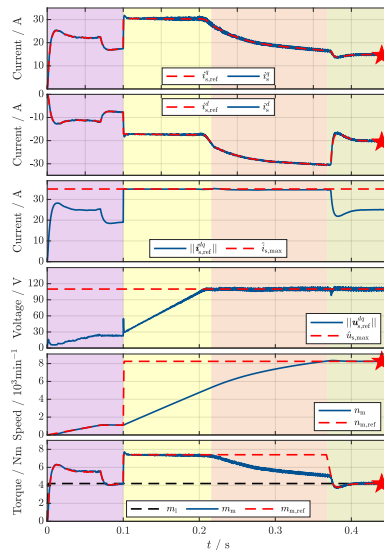


OFTC with ANN-based ORCC: Implementation results

Time series



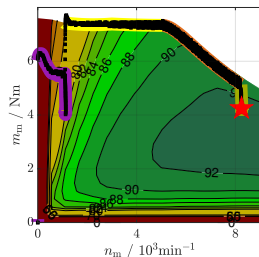
(a) OFTC with analytical ORCC (OFTC_{ANA}).



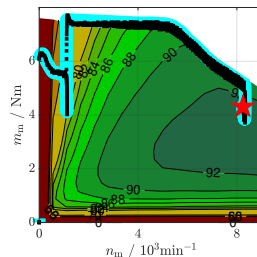
(b) ANN-based OFTC (OFTC_{ANN}).

OFTC with ANN-based ORCC: Implementation results

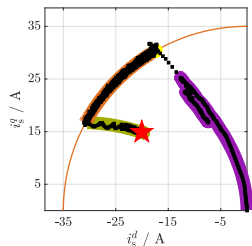
Speed-torque map



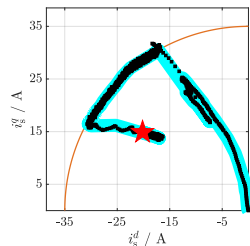
(a) Speed-torque map (OFTC_{ANA}).



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



(c) Current locus (OFTC_{ANA}).



(d) Current locus (OFTC_{ANN}).

OFTC with ANN-based ORCC: Implementation results

Performance comparison and execution times

Performance measure	$\mathbf{X=OFTC}_{\text{LUT}}$	$\mathbf{X=OFTC}_{\text{NUM}}$	$\mathbf{X=OFTC}_{\text{ANA}}$	$\mathbf{X=OFTC}_{\text{ANN}}$
$\int i_{s,\text{ref},\text{OFTC}_{\text{NLP}}}^d - i_{s,\text{ref},\text{X}}^d dt$	0.176 As	0.186 As	0.384 As	0.227 As
$\int i_{s,\text{ref},\text{OFTC}_{\text{NLP}}}^q - i_{s,\text{ref},\text{X}}^q dt$	0.195 As	0.207 As	0.256 As	0.213 As
$\int m_{\text{ref},\text{X}} - m_{\text{m}} dt$	0.018 Nms	0.017 Nms	0.026 Nms	0.020 Nms
$\int \hat{u}_{s,\text{max}} - \ \mathbf{u}_{s,\text{ref},\text{X}}^{dq}\ dt$	0.445 Vs	0.446 Vs	0.454 Vs	0.459 Vs
$\int \hat{i}_{s,\text{max}} - \ \mathbf{i}_{s,\text{ref},\text{X}}^{dq}\ dt$	0.010 As	0.000 As	0.000 As	0.059 As
$\int n_{\text{m},\text{ref}} - n_{\text{m},\text{X}} dt$	$752.4 \frac{\text{s}}{\text{min}}$	$750.9 \frac{\text{s}}{\text{min}}$	$752.6 \frac{\text{s}}{\text{min}}$	$757.8 \frac{\text{s}}{\text{min}}$
$\bar{t}_{\text{exec},\text{X}}$	2 734.782 μs	448.745 μs	439.671 μs	5.855 μs

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Analytical solution

Analytical solution for optimization problem with quadrics

Problem

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

$\implies$ Hyperbolas for MTPC, MTPV and MPTF (with $R_s \neq 0$ & $L_{s,m} \neq 0$!)

Lagrangian with Lagrangian multiplier $\lambda \in \mathbb{C}$

$$\mathcal{L}(\mathbf{i}_s^{dq}, \lambda) := -Q_A(\mathbf{i}_s^{dq}) + \lambda Q_B(\mathbf{i}_s^{dq})$$

Gradient (necessary conditions)

$$\mathbf{g}_{\mathcal{L}}(\mathbf{i}_s^{dq}, \lambda) := \begin{pmatrix} \left(\frac{\frac{d\mathcal{L}(\mathbf{i}_s^{dq}, \lambda)}{d\mathbf{i}_s^{dq}}}{\frac{d\mathcal{L}(\mathbf{i}_s^{dq}, \lambda)}{d\lambda}} \right)^\top \\ \frac{d\mathcal{L}(\mathbf{i}_s^{dq}, \lambda)}{d\lambda} \end{pmatrix} \stackrel{!}{=} \mathbf{0}_3 \Leftrightarrow \begin{pmatrix} -2\mathbf{A}\mathbf{i}_s^{dq} - 2\mathbf{a} + \lambda(2\mathbf{B}\mathbf{i}_s^{dq} + 2\mathbf{b}) \\ (\mathbf{i}_s^{dq})^\top \mathbf{B} \mathbf{i}_s^{dq} + 2\mathbf{b}^\top \mathbf{i}_s^{dq} + \beta \end{pmatrix} \stackrel{!}{=} \mathbf{0}_3.$$

Analytical solution

Example: Analytical solution for optimization problem with quadrics (cont'd)

Hessian (sufficient conditions)

$$\begin{aligned} \mathbf{H}_{\mathcal{L}}(\mathbf{i}_s^{dq}, \lambda) &:= \frac{d}{d(\mathbf{i}_s^{dq}, \lambda)} \left(\frac{d \mathcal{L}(\mathbf{i}_s^{dq}, \lambda)}{d(\mathbf{i}_s^{dq}, \lambda) \mathcal{L}(\mathbf{i}_s^{dq}, \lambda)} \right)^{\top} \\ &= \begin{bmatrix} 2\mathbf{M}(\lambda) & 2\mathbf{B}\mathbf{i}_s^{dq} + 2\mathbf{b} \\ (2\mathbf{B}\mathbf{i}_s^{dq} + 2\mathbf{b})^{\top} & 0 \end{bmatrix} = \mathbf{H}_{\mathcal{L}}(\mathbf{i}_s^{dq}, \lambda)^{\top} \stackrel{!}{<} \mathbf{0} \end{aligned}$$

Analytical solution

Analytical solution for intersection points of two quadrics

Problem

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

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

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

and note that

$$Q_D(\mathbf{x}) := \mathbf{x}^\top \underbrace{\left(\mathbf{D} \mathbf{x} + 2\mathbf{d} \right)}_{\stackrel{!}{=} \lambda \mathbf{J} \mathbf{x}} \stackrel{!}{=} 0 \iff \mathbf{x}^\star(\lambda) = -2(\mathbf{D} - \lambda \mathbf{J})^{-1} \mathbf{d}$$

Analytical solution

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

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

$$Q_A(\mathbf{x}^*(\lambda)) = 4\mathbf{d}^\top (\mathbf{D} - \lambda \mathbf{J})^{-\top} \mathbf{A} (\mathbf{D} - \lambda \mathbf{J})^{-1} \mathbf{d} - 4\mathbf{a}^\top (\mathbf{D} - \lambda \mathbf{J})^{-1} \mathbf{d} + \alpha = 0 \quad \left| \cdot \underbrace{[\det(\mathbf{D} - \lambda \mathbf{J})]^2}_{\propto \lambda^2} \right.$$

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

$\Rightarrow$ Analytical (real) solutions $\lambda^* \in \{\lambda_1, \dots, \lambda_4\}$ can be computed [?]:

$$\Rightarrow \boxed{\mathbf{x}^*(\lambda^*) = -2(\mathbf{D} - \lambda^* \mathbf{J})^{-1} \mathbf{d}}$$

Analytical solution

Roots of a fourth-order polynomial (Euler's solution [165])

Problem: Find roots of

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

Solution:

Step 1: Transform $\chi(\lambda)$ to *depressed* polynomial $\chi_{\text{dep}}(y)$

$$\chi_{\text{dep}}(y) := y^4 + p y^2 + q y + r \stackrel{!}{=} 0 \quad (\text{where } \lambda := y - \frac{c_3}{4c_4})$$

with coefficients

$$\begin{aligned} p &:= \frac{1}{c_4} \left(c_2 c_4 - \frac{3c_3^2}{8} \right), & q &:= \frac{1}{c_4} \left(\frac{c_3^3}{8} - \frac{c_2 c_3 c_4}{2} + c_1 c_4^2 \right) & \text{and} \\ r &:= \frac{1}{c_4} \left(-\frac{3c_3^4}{256} + c_4^3 c_0 - \frac{c_4^2 c_3 c_2}{4} + \frac{c_4 c_3^2 c_2}{16} \right). \end{aligned}$$

Analytical solution

Roots of a fourth-order polynomial (Euler's solution [165]; cont'd)

Step 2: Find roots $z_1^*, z_2^*, z_3^* \in \mathbb{C}$ of Euler's resolvent cubic polynomial

$$\chi_{\text{res}}(z) := z^3 + \underbrace{2p}_{=:d_2} z^2 + \underbrace{(p^2 - 4r)}_{=:d_1} z - \underbrace{q^2}_{=:d_0} \stackrel{!}{=} 0$$

by defining

$$\begin{aligned} \tilde{q} &:= \frac{d_1}{3} - \frac{d_2^2}{9} & \text{and} & & \tilde{r} &:= \frac{d_1 d_2 - 3d_0}{6} - \frac{d_2^3}{27} & \text{and} \\ s_1 &:= \sqrt[3]{\tilde{r} + \sqrt{\tilde{q}^3 + \tilde{r}^2}} & \text{and} & & s_2 &:= \sqrt[3]{\tilde{r} - \sqrt{\tilde{q}^3 + \tilde{r}^2}}. \end{aligned}$$

Roots of resolvent are then given by

$$z_1^* = (s_1 + s_2) - \frac{d_2}{3} \quad \text{and} \quad z_{2,3}^* = -\frac{1}{2}(s_1 + s_2) - \frac{d_2}{3} \pm j\frac{\sqrt{3}}{2}(s_1 - s_2).$$

Analytical solution

Roots of a fourth-order polynomial (Euler's solution [165]; cont'd)

Step 3: With the roots $z_1^*, z_2^*, z_3^* \in \mathbb{C}$ of $\chi_{\text{res}}(z)$, the roots $\lambda_1^*, \dots, \lambda_4^* \in \mathbb{C}$ of the fourth-order polynomial $\chi(\lambda)$ are given by

$$\begin{aligned}\lambda_1^* &= \frac{(-1)^l}{2} \left(\sqrt{z_1^*} + \sqrt{z_2^*} + \sqrt{z_3^*} \right) - \frac{c_3}{4c_4}, \\ \lambda_2^* &= \frac{(-1)^l}{2} \left(\sqrt{z_1^*} - \sqrt{z_2^*} - \sqrt{z_3^*} \right) - \frac{c_3}{4c_4}, \\ \lambda_3^* &= \frac{(-1)^l}{2} \left(-\sqrt{z_1^*} + \sqrt{z_2^*} - \sqrt{z_3^*} \right) - \frac{c_3}{4c_4}, \quad \text{and} \\ \lambda_4^* &= \frac{(-1)^l}{2} \left(-\sqrt{z_1^*} - \sqrt{z_2^*} + \sqrt{z_3^*} \right) - \frac{c_3}{4c_4},\end{aligned}$$

where $l \in \{0, 1\}$ must be chosen such that [165]

$$(-1)^l (\lambda_1^* \lambda_2^* \lambda_3^* + \lambda_1^* \lambda_2^* \lambda_4^* + \lambda_1^* \lambda_3^* \lambda_4^* + \lambda_2^* \lambda_3^* \lambda_4^*) = -q.$$

Outline

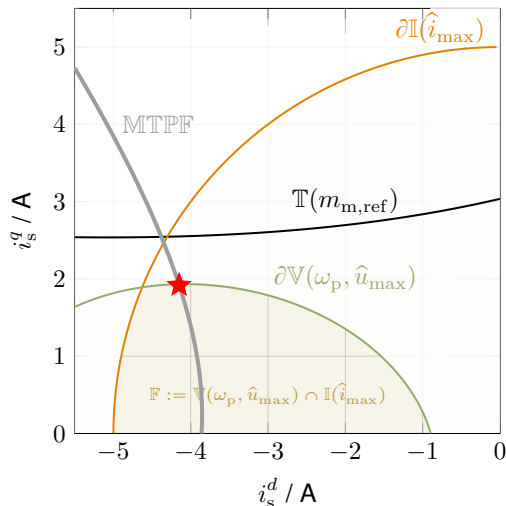
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Optimal operation strategies and operation management

Maximum Torque per Flux (**MTPF**): Reference torque **not** feasible



Optimization problem

$$\begin{aligned} \max_{\mathbf{i}_s^{dq} \in \mathbb{F}} & -\|\boldsymbol{\psi}_s^{dq}(\mathbf{i}_s^{dq})\|^2 \quad \text{s.t.} \\ & \underbrace{(\mathbf{i}_s^{dq})^\top \mathbf{T} \mathbf{i}_s^{dq} + 2 \mathbf{t}^\top \mathbf{i}_s^{dq}}_{=m_m(\mathbf{i}_s^{dq})} - m_{m,\text{ref}} = 0 \end{aligned}$$

Solution set

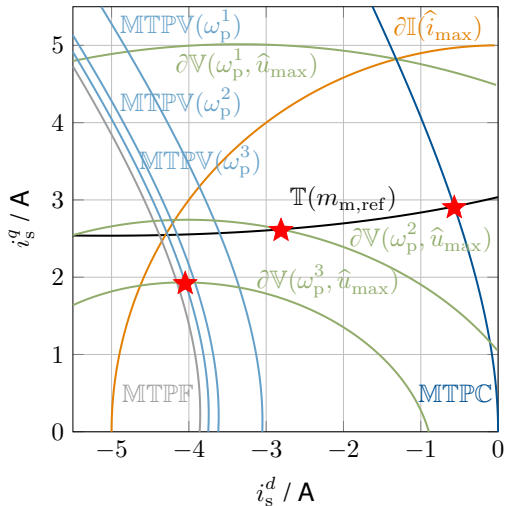
$$\begin{aligned} \text{MTPF} &:= \{ \mathbf{i}_s^{dq} \in \mathbb{R}^2 \mid \\ & (\mathbf{i}_s^{dq})^\top \mathbf{M}_F \mathbf{i}_s^{dq} + 2 \mathbf{m}_F^\top \mathbf{i}_s^{dq} + \mu_F = 0 \} \end{aligned}$$

Optimal current reference (★)

$$\mathbf{i}_{s,\text{ref}}^{dq} = \text{MTPF} \cap \partial V(\omega_p, \hat{u}_{\max})$$

Optimal operation strategies and operation management

Illustration of MTPC ($\omega_p^1 = \omega_{p,R}$), FW ($\omega_p^2 = 2\omega_{p,R}$) and MTPV ($\omega_p^3 = 3\omega_{p,R}$)



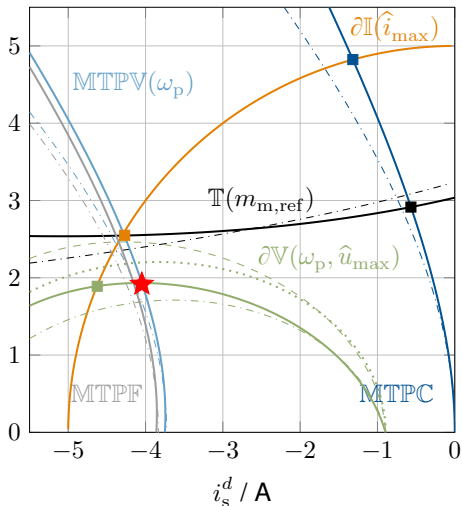
- reference torque (hyperbola)
- current constraint (circle)
- voltage constraint (ellipse)
- MTPC hyperbola
- MTPV hyperbola
- MTPF hyperbola
- ★ optimal operation point $i_{s,ref}^{dq}$

Remark:

$\lim_{\omega_p \rightarrow \infty} MTPV(\omega_p) = MTPF$
or $MTPV(\omega_p)|_{R_s=0} = MTPF$

Optimal operation strategies and operation management

Illustration of the effect of neglecting R_s and/or $L_{s,m}$



--- $R_s = 0$ (and $L_{s,m} \neq 0$)

----- $L_{s,m} = 0$ (and $R_s \neq 0$)

..... $R_s = 0$ and $L_{s,m} = 0$

⇒ **Reduced efficiency!**
(and wrong torque and/or possibly wrong operation strategies)