

Analytische Berechnung der optimalen Sollströme für beliebige Synchronmaschinen zur Minimierung der Kupfer- & Eisenverluste in allen Betriebsbereichen

Eine umfassende Theorie zur Minimierung der Maschinenverluste

Christoph Hackl

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Hochschule München

Outline

- 1 Laboratory for Mechatronic and Renewable Energy Systems (LMRES)
- 2 Generic loss minimization in synchronous machines



Outline

1 Laboratory for Mechatronic and Renewable Energy Systems (LMRES)

- Research group
- Research projects
- Interdisciplinary expertise and publications



LMRES

Research group: 9 PhD candidates, 1 Post-Doc, several PhD collaborations@EAL&NES



H. Eldeeb, M.Sc.
(CRES, 09/2015)



C. Dirscherl, M.Sc.
(CRES, 01/2014)



C. Hackl, Dr.-Ing.
(CRES, 01/2014)



J. Kullick, M.Sc.
(CRES, 10/2015)



K. Schechner, M.Sc.
(CRES, 01/2014)



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

External PhD students



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



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



K. Bär, M.Sc.
(THI, 07/2017)



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



S. Krüner, M.Sc.
(SINNPower,11/2015)

...

LMRES

Research projects with focus on **modeling, simulation, control, efficiency** and **reliability**
(funding: > 2.3 million €; e.g. DAAD, Bavaria, BMBF, BMWi, DFG, EU)

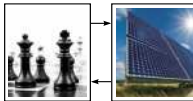
Large-scale WTS



Small-scale WTS



MPC for RES



AWE systems



Geothermal energy



Wave energy (SinnPower)



Electric vehicles (BMW)



Power systems



Biogas power plants



Multi-level converters



Electrical drives



Motion control

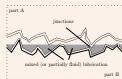


LMRES

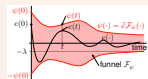
Interdisciplinary expertise and >100 publications (since 2014 > 80; all peer-reviewed)



System identification
[9–13]



Friction
[14, 15]



Non-identifier based adaptive control
[14, 16–27], [28–31]



Paper coating machines
[4–8]



Teaching [115, 116], [31, 117–122, 122, 123]



Robotics & Mechatronics [14, 32–41], [15, 31, 42]



Electro-active polymers
[1–3]

Mechatronic & renewable energy systems



Power electronics
[43, 44], [45–53], [54–60], [31, 61–66], [67–72], [73]



Renewable energy systems [44], [13, 28, 30, 31, 45, 48, 52, 53, 55–57, 59, 61, 67, 72, 73, 78–80, 83, 85, 92, 97–114]



Electrical drives (motors/generators)
[14, 16, 18, 19, 37, 41, 74–77], [13, 29, 31, 54, 62, 67, 69, 72, 78–97]

Outline

2 Generic loss minimization in synchronous machines

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



Motivation

Synchronous machines: Widely-used, compact and efficient actuators



www.bmw.de



www.farmwood.co.uk

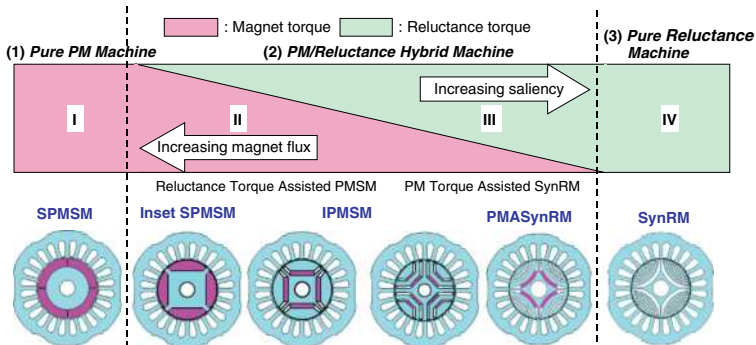


www.abb.com (from video)

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

Motivation

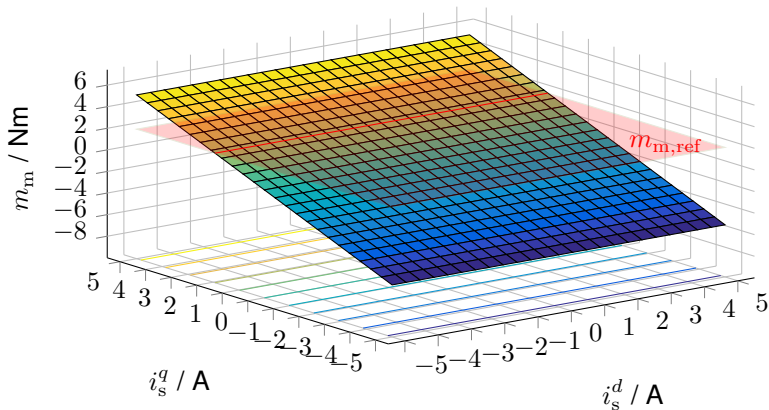
Examples of anisotropic synchronous machines [124] with “saliency ratio” $L_s^d/L_s^q \neq 1$



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

Motivation

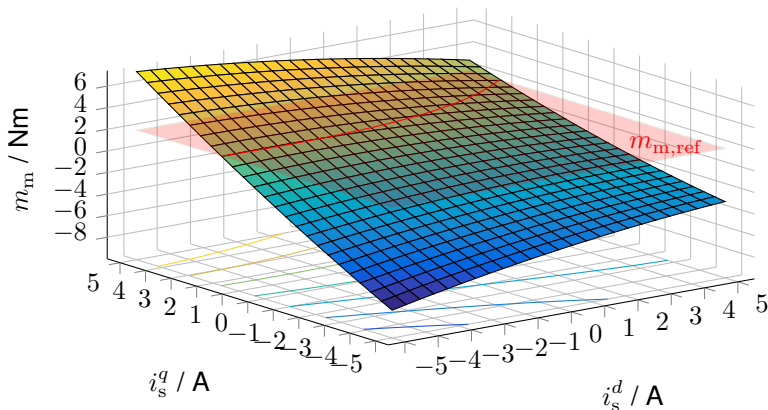
Optimal feedforward torque control problem: **Isotropic machine**



$$m_{m,ref} \stackrel{!}{=} m_m(i_s^d, i_s^q) = \frac{3}{2} n_p \psi_{pm} i_s^q \quad (\Rightarrow i_{s,ref}^q = \frac{2 m_{m,ref}}{3 n_p \psi_{pm}})$$

Motivation

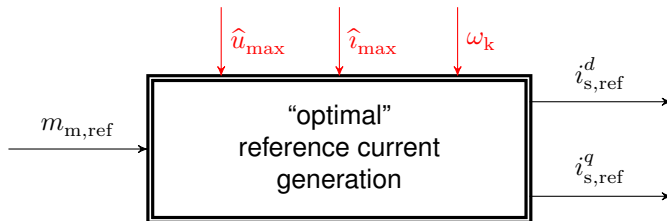
Optimal feedforward torque control problem: **Anisotropic machine** (with cross-coupling)



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

Problem statement and proposed solution

Optimal feedforward torque control problem: Optimal reference current generation

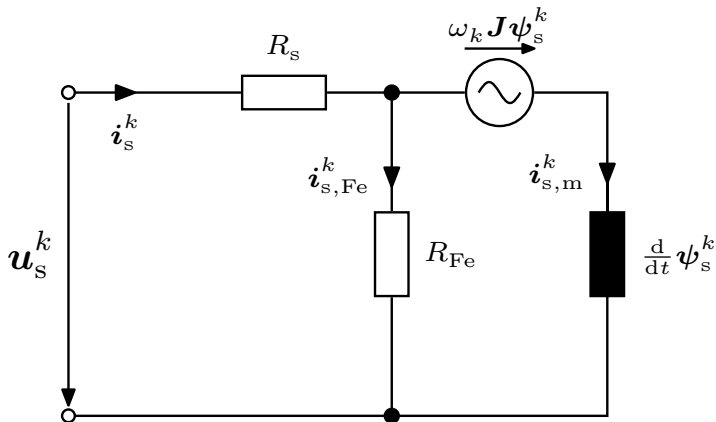


$$\dot{i}_{s,\text{ref}}^k(m_{m,\text{ref}}, \hat{u}_{\max}, \hat{i}_{\max}, \omega_k) = \begin{pmatrix} i_{s,\text{ref}}^d(m_{m,\text{ref}}, \hat{u}_{\max}, \hat{i}_{\max}, \omega_k) \\ i_{s,\text{ref}}^q(m_{m,\text{ref}}, \hat{u}_{\max}, \hat{i}_{\max}, \omega_k) \end{pmatrix}$$

- ✓ Numerical solutions and/or look-up tables
(but: limited storage, accuracy, real-time applicability)
- ? Analytical solutions (some do exist but impose simplifying assumptions
such as $R_s = 0$, $R_{Fe} = 0$ and/or $L_m = 0$)

Problem statement and proposed solution

Considered anisotropic synchronous machines with iron losses [125]: Electrical circuit



Problem statement and proposed solution

Considered anisotropic synchronous machines with iron losses [125]: Modeling

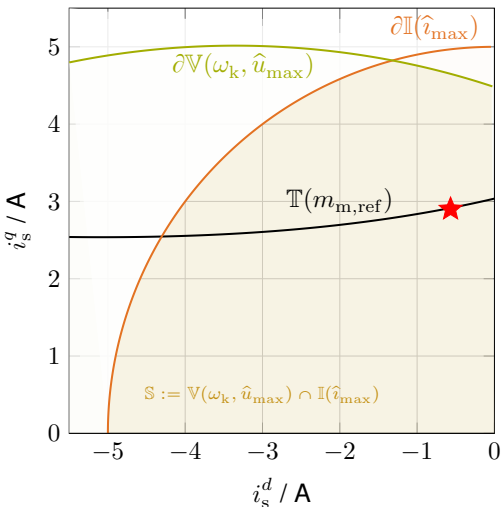
$$\begin{aligned}
 \overbrace{\begin{pmatrix} u_s^d \\ u_s^q \end{pmatrix}}^{=: \mathbf{u}_s^k} &= R_s(\vartheta) \overbrace{\begin{pmatrix} i_s^d \\ i_s^q \end{pmatrix}}^{=: \mathbf{i}_s^k} + \omega_k \overbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}^{=: \mathbf{J}} \overbrace{\begin{pmatrix} \psi_s^d(\mathbf{i}_{s,m}^k) \\ \psi_s^q(\mathbf{i}_{s,m}^k) \end{pmatrix}}^{=: \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k)} + \cancel{\frac{d}{dt} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k)} \\
 \mathbf{i}_s^k &= \mathbf{i}_{s,m}^k + \mathbf{i}_{s,Fe}^k = \mathbf{i}_{s,m}^k + \frac{\omega_k \mathbf{J} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k) + \cancel{\frac{d}{dt} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k)}}{R_{Fe}(\omega_k)} \\
 p_{\text{loss}} &= p_{Cu}(\mathbf{i}_s^k) + p_{Fe}(\boldsymbol{\psi}_s^k, \omega_k) = \frac{3}{2} R_s \|\mathbf{i}_s^k\|^2 + \frac{3}{2} \frac{\|\omega_k \mathbf{J} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k) + \cancel{\frac{d}{dt} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k)}\|^2}{R_{Fe}(\omega_k)} \\
 m_m(\mathbf{i}_{s,m}^k) &= \frac{3}{2} n_p (\mathbf{i}_{s,m}^k)^\top \mathbf{J} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k)
 \end{aligned}$$

Assumption (Affine flux linkage (at least locally))

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

Problem statement and proposed solution

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



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

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

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

Problem statement and proposed solution

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

Step 1: Derivation of quadrics $Q_A(\mathbf{i}_s^k) := (\mathbf{i}_s^k)^\top \mathbf{A} \mathbf{i}_s^k + 2\mathbf{a}^\top \mathbf{i}_s^k + \alpha$:

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

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

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

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

- Reference torque hyperbola:

$$m_m(\mathbf{i}_{s,m}^k) = \frac{3}{2} n_p (\mathbf{i}_{s,m}^k)^\top \mathbf{J} \boldsymbol{\psi}_s^k(\mathbf{i}_{s,m}^k) \stackrel{!}{=} m_{m,\text{ref}} \iff \dots$$

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

- ...

Problem statement and proposed solution

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

Step 2: Optimization problem with equality constraint

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

$\implies$ Hyperbolas for e.g. MTPC, MTPL or MTPV (with $R_s, R_{Fe} \neq 0$ & $L_m \neq 0$)

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

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

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

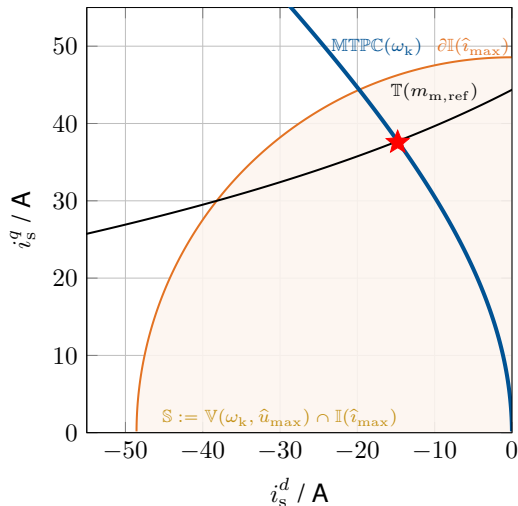
Both lead to subproblem of solving a fourth-order (quartic) polynomial

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

$\implies$ Analytical solutions exist (e.g. Euler's solution, see [126])

Optimal operation strategies

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



Optimization problem

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

Solution set

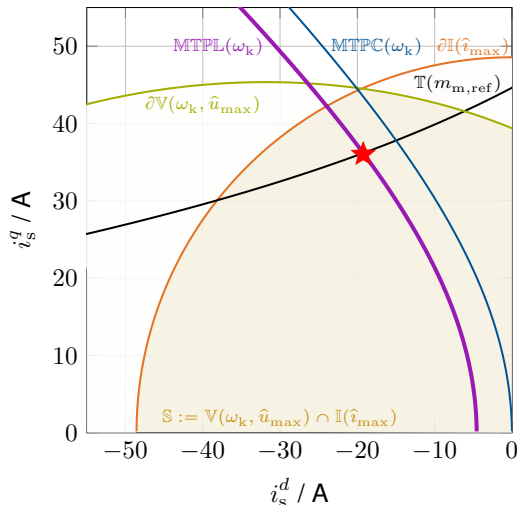
$$\begin{aligned} \text{MTPC}(\omega_k) := \{ & \mathbf{i}_s^k \in \mathbb{R}^2 \mid \\ & (\mathbf{i}_s^k)^\top \mathbf{M}_C \mathbf{i}_s^k + 2 \mathbf{m}_C^\top \mathbf{i}_s^k = 0 \} \end{aligned}$$

Optimal reference currents (★)

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

Optimal operation strategies

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



Optimization problem

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

Solution set

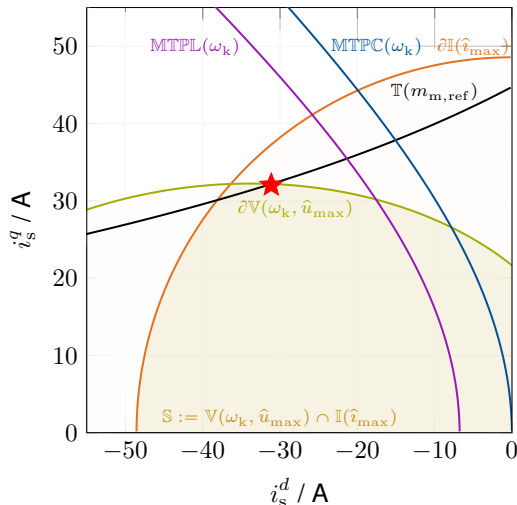
$$\begin{aligned} \text{MTPL}(\omega_k) &:= \{ \mathbf{i}_s^k \in \mathbb{R}^2 \mid \\ & (\mathbf{i}_s^k)^\top \mathbf{M}_L \mathbf{i}_s^k + 2 \mathbf{m}_L^\top \mathbf{i}_s^k + \mu_L = 0 \} \end{aligned}$$

Optimal reference currents (★)

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

Optimal operation strategies

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



Optimization problem

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

Feasible set

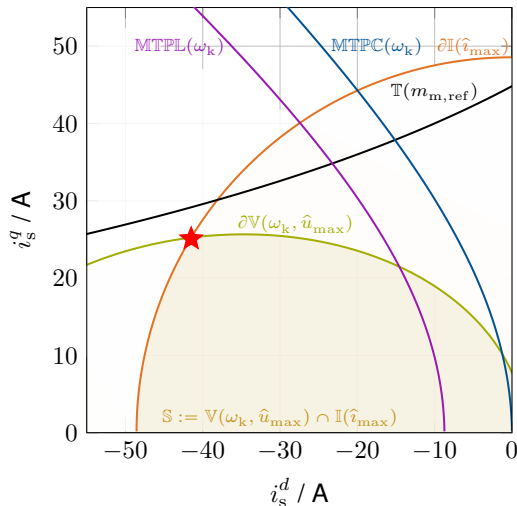
$$\text{FW}(m_{m, \text{ref}}, \omega_k, \hat{u}_{\max}) := \mathbb{S}(\omega_k, \hat{u}_{\max}, \hat{i}_{\max}) \cap \mathbb{T}(m_{m, \text{ref}})$$

Optimal reference currents (★)

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

Optimal operation strategies

Maximum Current (**MC** @ $1.75 \cdot \omega_{m, \text{rat}}$): Reference torque **not** feasible



Optimization problem

$$\max_{\dot{i}_s^k \in \mathbb{S}} m_m(\dot{i}_s^k)$$

Feasible set

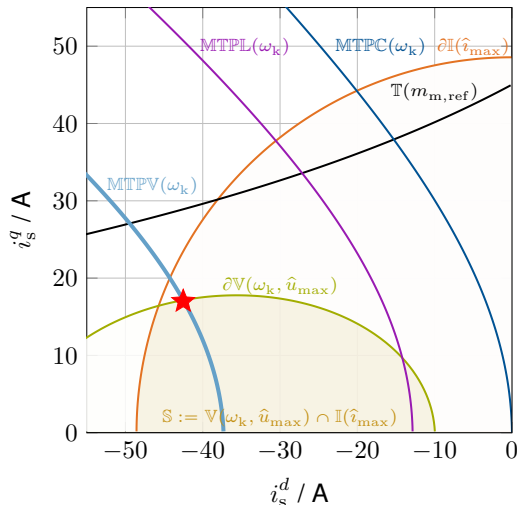
$$\text{MC}(\omega_k, \hat{u}_{\max}, \hat{i}_{\max}) := \mathbb{V}(\omega_k, \hat{u}_{\max}) \cap \partial \mathbb{I}(\hat{i}_{\max})$$

Optimal current reference (★)

$$\dot{i}_{s, \text{ref}}^k = \partial \mathbb{V}(\omega_k, \hat{u}_{\max}) \cap \partial \mathbb{I}(\hat{i}_{\max})$$

Optimal operation strategies

Maximum Torque per Voltage (MTPV @ $2.50 \cdot \omega_{m, \text{rat}}$): Reference torque **not** feasible



Optimization problem

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

Solution set

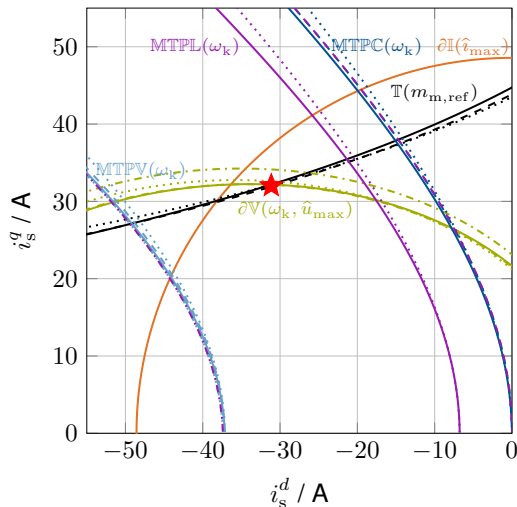
$$\text{MTPV}(\omega_k) := \left\{ \mathbf{i}_s^k \in \mathbb{R}^2 \mid (\mathbf{i}_s^k)^\top \mathbf{M}_V \mathbf{i}_s^k + 2 \mathbf{m}_V^\top \mathbf{i}_s^k + \mu_V = 0 \right\}$$

Optimal reference currents (★)

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

Optimal operation strategies

Field Weakening (FW @ $1.40 \cdot \omega_{m, \text{rat}}$): Illustration of the effect of neglecting R_s , R_{Fe} and/or L_m



- $R_s = 0$
- $L_m = 0$
- - - - $R_{Fe} = \infty$

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

Analytical solution

Example: 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

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

Analytical solution

Example: 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.

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

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

$\implies$ Analytical (real) solutions $\lambda^* \in \{\lambda_1, \dots, \lambda_4\}$ can be computed [126]:

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

Implementation results

Laboratory setup

Reluctance SM (RSM) and Permanent-magnet SM



Host PC (rapid prototyping)

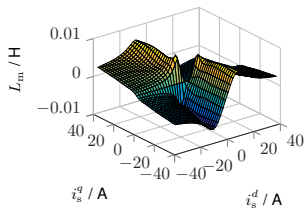
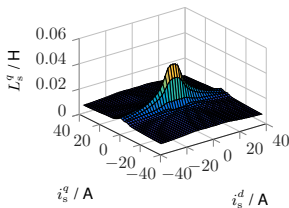
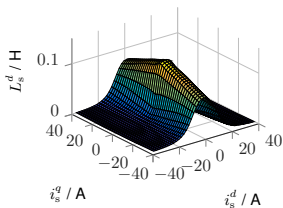
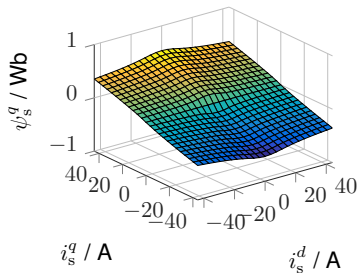
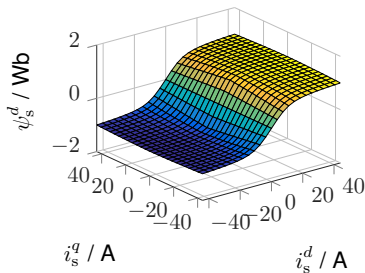


Real-time system and VSIs



Implementation results

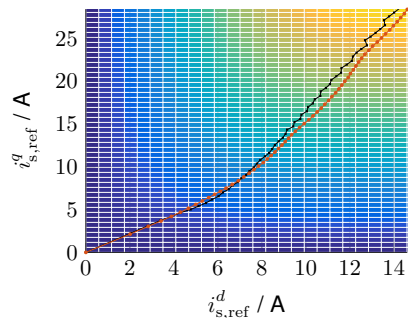
RSM: Nonlinear flux linkages and differential inductances



Implementation results

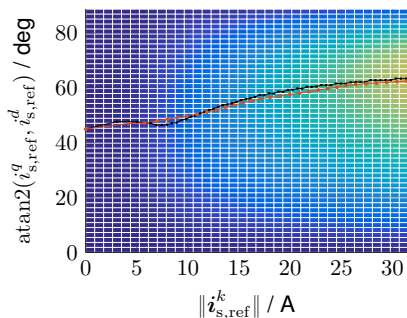
RSM: Comparison of numerical and analytical solutions for MTPC

m_m — numerical — analytical



Cartesian coordinates

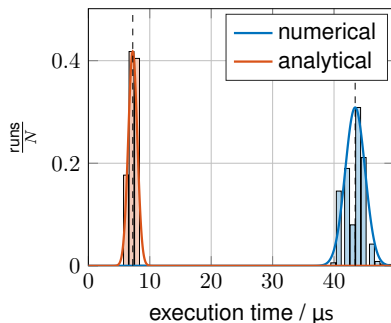
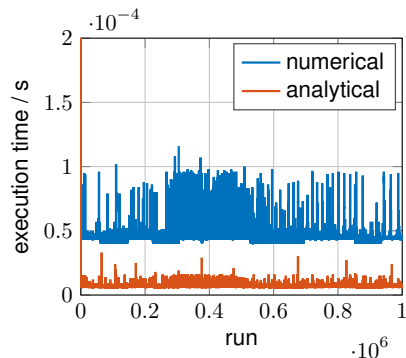
m_m — numerical — analytical



polar coordinates

Implementation results

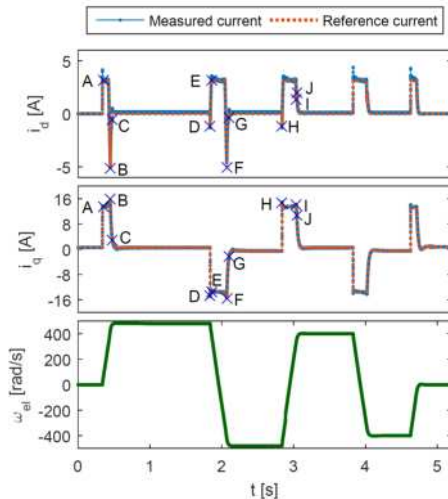
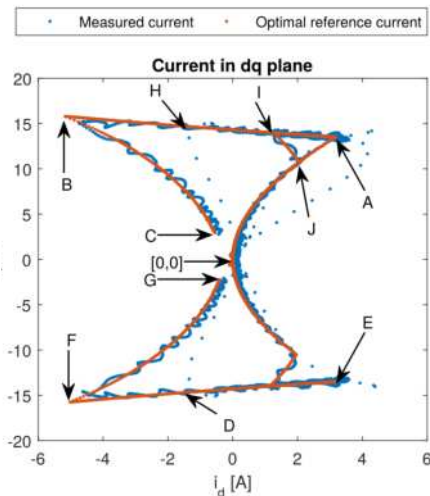
RSM: Comparison of computational load



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

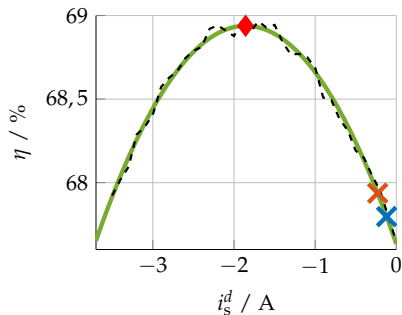
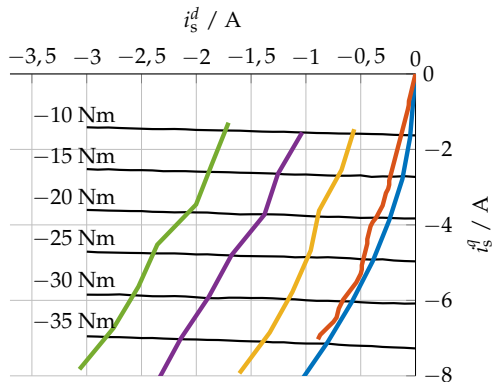
Implementation results

PME-RSM: Implementation by colleagues ($p_{m, \text{rat}} = 4,5 \text{ kW}$ & $L_s^d/L_s^q = 1.43$) [127]



Implementation results

IPMSM (generator mode): Efficiency enhancements considering iron losses [97]



Conclusion

Summary and future work

To take home

- **unified** theory for MTPC, **MTPL**, FW, MC and MTPV based on [90]
 - **quadrics** (implicit formulation),
 - **optimization problems** with **equality constraint**, and
 - **intersection** of two quadrics
- **analytical** solution for reference currents (& transition points)
- $R_s \neq 0$, $R_{Fe} \neq 0$ and $L_m \neq 0$ (can all be considered **simultaneously**)
- **fast(er)** and **more accurate** computation
- **applicable** in real-world (e.g. nonlinear RSM, PME-RSM or IPMSM; also IMs)

Future work

- convergence (mathematical proof for nonlinear flux linkages)
- more extensive experimental validation
- impact of (parameter) uncertainties
- consideration of *rotor* iron losses (e.g. for induction machines)
- combination with minimization of *conduction and switching losses*

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

Hisham Eldeeb^a, Christoph M. Hackl^{a,*}, Lorenz Horlbeck^b and Julian Kullick^a

^aResearch Group 'Control of Renewable Energy Systems (CRES)', Munich School of Engineering (MSE), Technical University of Munich (TUM), Munich, Germany; ^bInstitute of Automotive Technology (FTM), Technical University of Munich (TUM), Munich, Germany

ABSTRACT

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

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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

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