



Hochschule
München (HM)
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

Modern modelling, identification and simulation of electrical drive systems

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Outline

- 1 Introduction
- 2 Modern modelling, identification and simulation of electrical drive systems
- 3 Conclusion

Outline

1 Introduction

- Research environment
- Research projects and expertise

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Introduction

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



HM – Munich University of Applied Sciences

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

 **ISES is part of the Promotionszentrum “Energietechnik” with the right to award doctorates (since July 16th)!**

ISES – Institute for Sustainable Energy Systems

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

LMRES – Laboratory for Mechatronic and Renewable Energy Systems

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



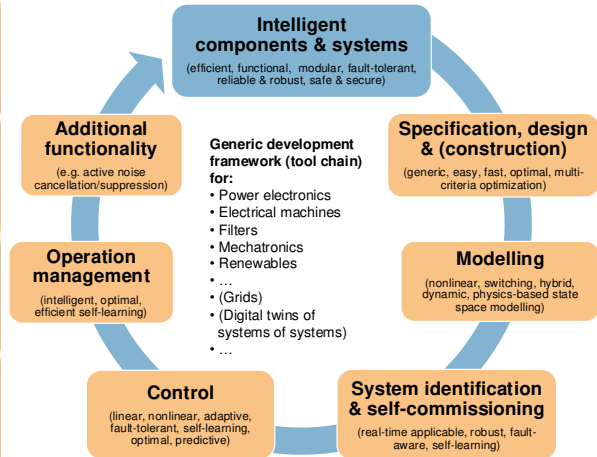
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Introduction

LMRES – Research projects and research goals (for more details, see lmres.ee.hm.edu)



2 Modern modelling, identification and simulation of electrical drive systems

- Modelling
 - Motivation
 - Key equations
 - Generic machine model
- Identification and simulation
 - Electrical machine dynamics
 - Required data
 - Exemplary results

2 Modern modelling, identification and simulation of electrical drive systems

■ Modelling

- Motivation
- Key equations
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■ Identification and simulation

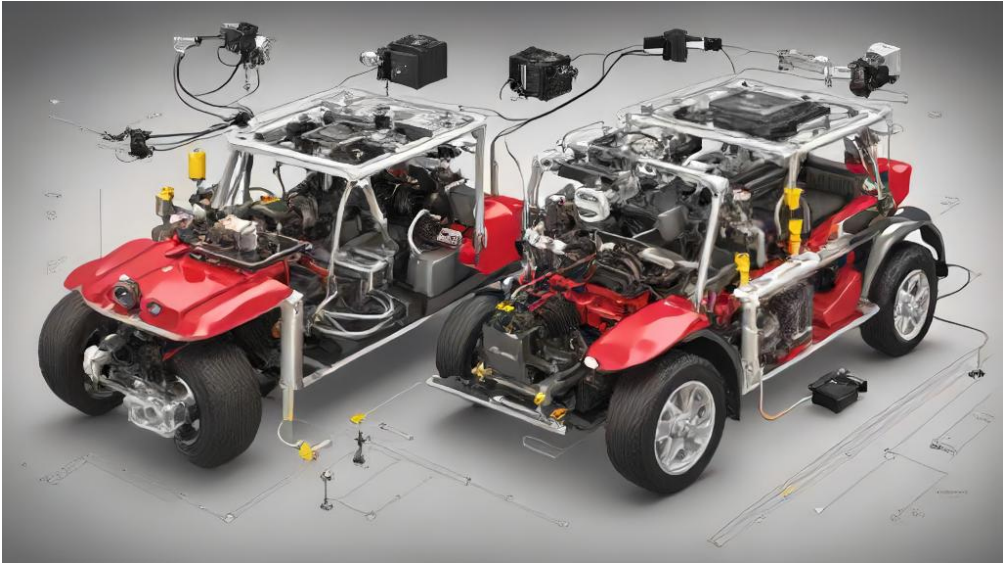
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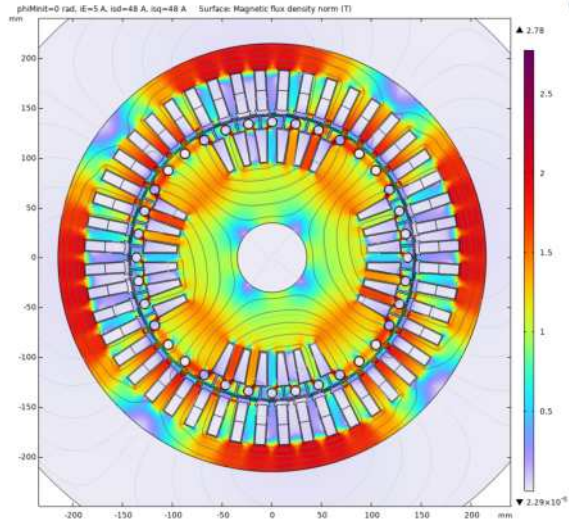
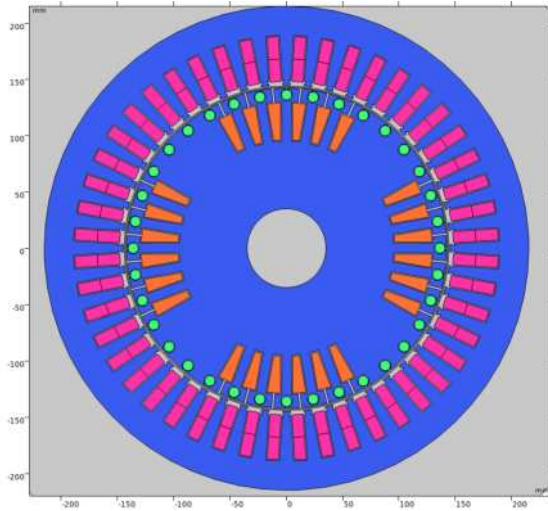
Modelling

Motivation: Output of [DeepAI Figure Generator](#) (prompted with “Electric vehicle with motor, power electronics & battery”)



Modelling

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



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Modelling

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

Kirchhoff's voltage equation:

- single-phase: $u = R i + \frac{d}{dt} \psi \iff \frac{d}{dt} \psi = u - R i$

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

where

- applied winding voltage u (arbitrary shape) or $\mathbf{u}_z^{abc} := (u_z^a, u_z^b, u_z^c)^\top \in \mathbb{R}^3$

- winding current i (arbitrary shape) or $\mathbf{i}_z^{abc} := (i_z^a, i_z^b, i_z^c)^\top \in \mathbb{R}^3$

- winding resistance $R := R(i, \phi, \omega, \vartheta, \dots)$ or $\mathbf{R}_z^{abc} := \mathbf{R}_z^{abc}(\mathbf{i}_z^{abc}, \phi, \omega, \boldsymbol{\vartheta}_z^{abc}, \dots) \in \mathbb{R}^{3 \times 3}$

- flux linkage $\psi := \psi(i, \phi, \omega, \vartheta, \dots)$ or $\boldsymbol{\psi}_z^{abc} := (\psi_z^a, \psi_z^b, \psi_z^c)^\top = \boldsymbol{\psi}_z^{abc}(\mathbf{i}_z^{abc}, \phi, \omega, \boldsymbol{\vartheta}_z^{abc}, \dots) \in \mathbb{R}^3$

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

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Modelling

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

$$\left. \begin{array}{ll}
 \text{Stator:} & \frac{d}{dt} \psi_s^{dq\gamma} = u_s^{dq\gamma} - R_s^{dq\gamma} i_s^{dq\gamma} - \omega_p J_0 \psi_s^{dq\gamma}, \\
 \text{Stator iron:} & \frac{d}{dt} \psi_{s,Fe}^{dq\gamma} = -R_{s,Fe}^{dq\gamma} i_{s,Fe}^{dq\gamma} - \omega_p J_0 \psi_{s,Fe}^{dq\gamma}, \\
 \text{Rotor:} & \frac{d}{dt} \psi_r^{dq\gamma} = u_r^{dq\gamma} - R_r^{dq\gamma} i_r^{dq\gamma} - (\omega_p - \omega_r) J_0 \psi_r^{dq\gamma}, \\
 \text{Rotor iron:} & \frac{d}{dt} \psi_{r,Fe}^{dq\gamma} = -R_{r,Fe}^{dq\gamma} i_{r,Fe}^{dq\gamma} - (\omega_p - \omega_r) J_0 \psi_{r,Fe}^{dq\gamma}, \\
 \text{Excitor:} & \frac{d}{dt} \psi_e^{dq\gamma} = u_e^{dq\gamma} - R_e^{dq\gamma} i_e^{dq\gamma} - (\omega_p - \omega_e) J_0 \psi_e^{dq\gamma}, \\
 \text{Mechanical subsystem:} & \frac{d}{dt} \omega_m = \frac{1}{\Theta_m} (m_m - \mathfrak{F} \omega_m + m_l) \\
 & \frac{d}{dt} \phi_m = \omega_m
 \end{array} \right\} \quad (1)$$

with machine torque $m_m(i_s^{dq\gamma}, i_{s,Fe}^{dq\gamma}, i_r^{dq\gamma}, i_{r,Fe}^{dq\gamma}, i_e^{dq\gamma}, \psi_{pm}^{dq\gamma}, \phi_m, \dots)$ and rotation matrix (by $\pi/2$)

$$J_0 := \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Remark: Please note that consideration of γ -component might be crucial to allow for e.g. currents including third-order harmonics as possibly present in delta-connected or grounded star-point configurations [1].

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Identification and simulation

Electrical machine dynamics in (d, q, γ) -reference frame [for simplicity: only considering stator currents]

- Flux Linkage Dynamics with Inverse Interpolation $\mathbf{i}_s^{dq\gamma} = \mathbf{f}_\psi^{-1}(\psi_s^{dq\gamma}, \dots)$ (FLD+II):

$$\frac{d}{dt} \psi_s^{dq\gamma} = \mathbf{u}_s^{dq\gamma} - \mathbf{R}_s^{dq\gamma} \mathbf{i}_s^{dq\gamma} - \omega_p \mathbf{J}_0 \psi_s^{dq\gamma} \quad (2)$$

- Current Dynamics with Differential Inductances $\mathbf{L}_s^{dq\gamma}$ and Flux Linkages $\psi_s^{dq\gamma}$ (CD+DI&FL):

$$\frac{d}{dt} \mathbf{i}_s^{dq\gamma} = (\mathbf{L}_s^{dq\gamma})^{-1} \left(\mathbf{u}_s^{dq\gamma} - \mathbf{R}_s^{dq\gamma} \mathbf{i}_s^{dq\gamma} - \omega_p \mathbf{J}_0 \psi_s^{dq\gamma} + \underbrace{\frac{\partial \psi_s^{dq\gamma}}{\partial \phi_m} \omega_m + \frac{\partial \psi_s^{dq\gamma}}{\partial \vartheta} \frac{d}{dt} \vartheta + \dots}_{=: \delta_s^{dq\gamma}} \right) \quad (3)$$

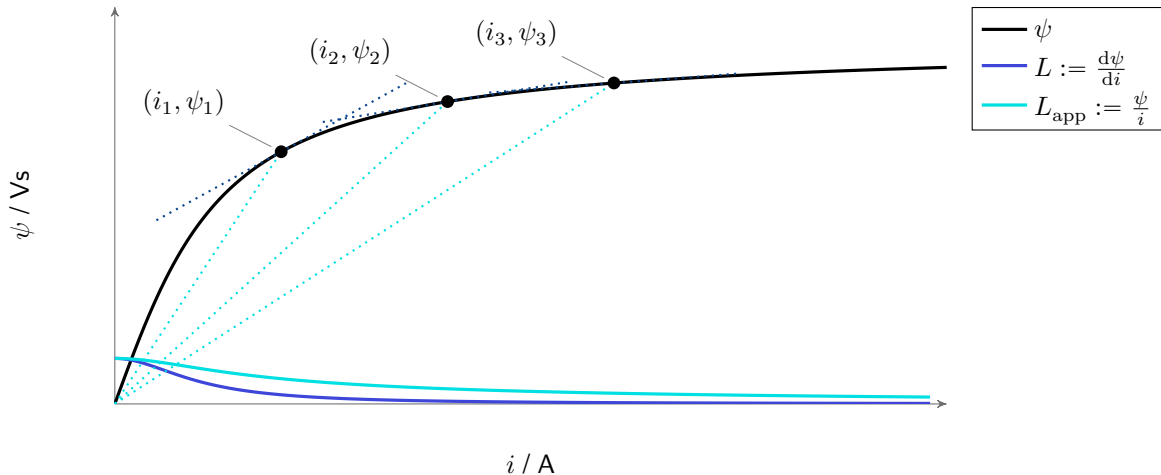
- Current Dynamics with Differential $\mathbf{L}_s^{dq\gamma}$ & Apparent $\mathbf{L}_{s,app}^{dq\gamma}$ Inductances and Permanent-Magnet Flux Linkages $\psi_{pm}^{dq\gamma}$ (CD+DAI&PMFL):

$$\frac{d}{dt} \mathbf{i}_s^{dq\gamma} = (\mathbf{L}_s^{dq\gamma})^{-1} \left(\mathbf{u}_s^{dq\gamma} - \mathbf{R}_s^{dq\gamma} \mathbf{i}_s^{dq\gamma} - \omega_p \mathbf{J}_0 (\mathbf{L}_{s,app}^{dq\gamma} \mathbf{i}_s^{dq\gamma} + \psi_{pm}^{dq\gamma}) + \delta_s^{dq\gamma} \right) \quad (4)$$

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

Identification and simulation

Electrical machine dynamics: Illustration of differential inductance L (tangent) and apparent inductance L_{app} (secant)



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Identification and simulation

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

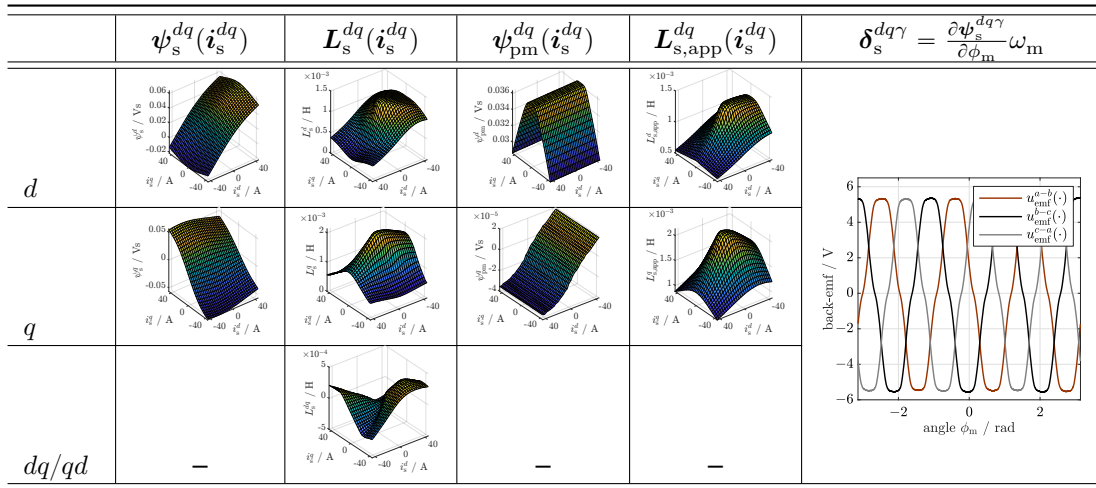
	FLD+II	CD+DI&FL	CD+DAI&PMFL
$R_s^{dq(\gamma)}(x)$	$3 (+0) \times N_x$ -D-LUTs	$3 (+0) \times N_x$ -D-LUTs	$3 (+0) \times N_x$ -D-LUTs
$L_s^{dq(\gamma)}(x)$	–	$3 (+3) \times N_x$ -D-LUTs	$3 (+3) \times N_x$ -D-LUTs
$L_{s,app}^{dq(\gamma)}(x)$	–	–	$2 (+1) \times N_x$ -D-LUTs
$\psi_{pm}^{dq(\gamma)}(x)$	–	–	$2 (+1) \times N_x$ -D-LUTs
$\psi_s^{dq(\gamma)}$	$2 (+1) \times N_x$ -D-LUTs	$2 (+1) \times N_x$ -D-LUTs	–
$f_\psi(\cdot)^{-1}$	yes	no	no
t_{exec} (in p.u.)	$1.00^* / 1.07^\dagger / 2.55^\ddagger$	1.55	1.83

Remark: The states $x := (i_x^{abc}, \phi_m, \phi_p, \omega_m, \omega_p, \vartheta_x^{abc}, \dots)^\top \in \mathbb{R}^{N_x}$ comprise currents, machine and/or transformation angles, machine and/or transformation angular frequencies and temperatures to allow for proper simulation/emulation of iron losses, magnetic saturation and cross-coupling, anisotropy, proximity and/or skin effect, slip rings or winding asymmetries, etc.; N_x represents the dimension of the considered

 **AVL-SET GmbH and LMRES (HM) work together on fast, accurate and overall machine identification approaches (joint research project) in order to allow for even more sophisticated machine emulation.**

Identification and simulation

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



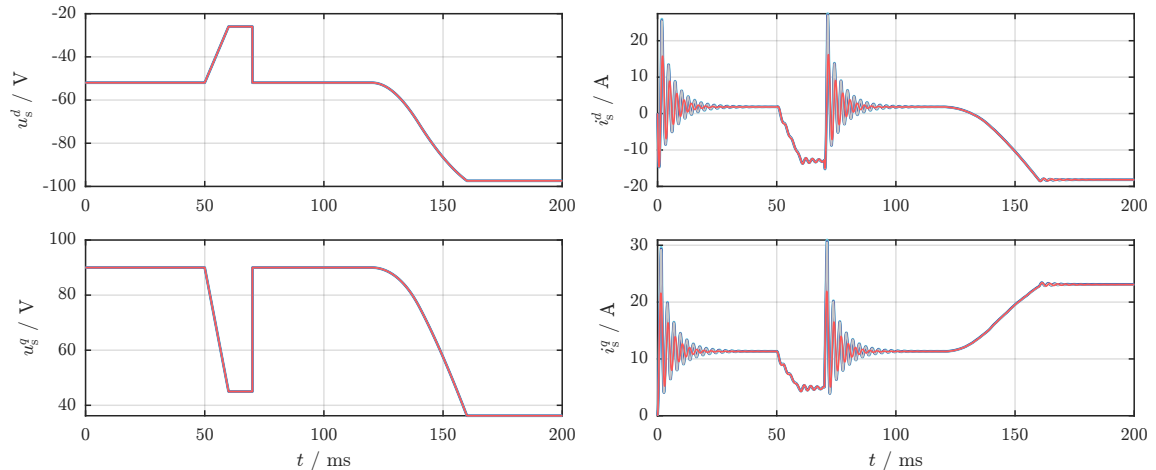
Remark: For simplicity, only the dependencies on $i_s^{dq} := (i_s^d, i_s^q)^\top$ are shown, i.e. $x := (i_s^d, i_s^q)^\top$ with $N_x = 2$.

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Identification and simulation

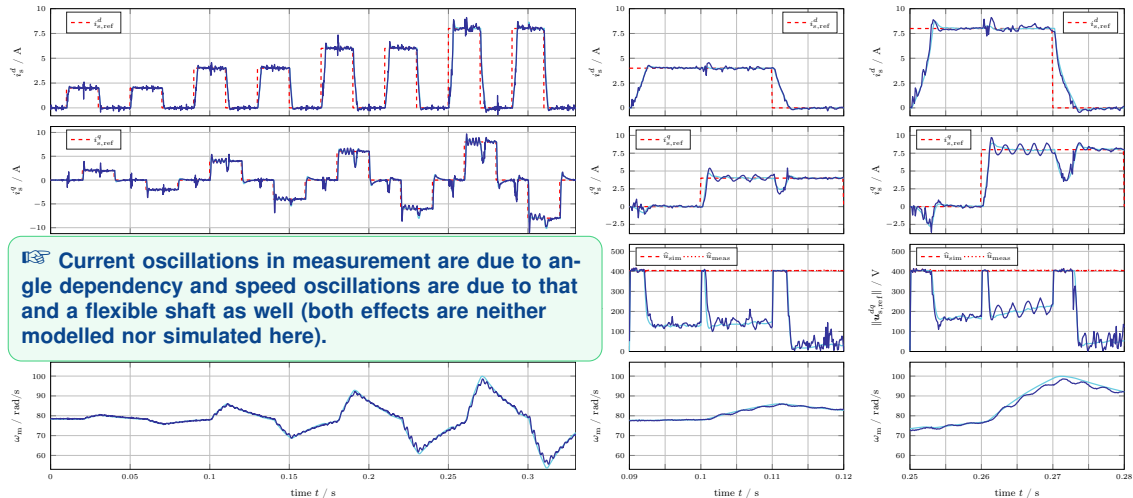
Exemplary results: Open-loop current responses for diff. dynamics implementations (3.8 kW IPMSM @ $\omega_{m,R} = 576 \frac{\text{rad}}{\text{s}}$):
 [—] FLD+II (bil. Inv.), [—] CD+DI&FL, [—] CD+DAI&FL, [—] CD+DAI&FL ($\mathbf{L}_s^{dq} = \mathbf{L}_{s,\text{app}}^{dq}$; wrong implement.!).



Identification and simulation

Exemplary results: Comparison of closed-loop nonlinear electrical drive system (4.0 kW RSM @ $\omega_m \approx 80 \frac{\text{rad}}{\text{s}}$):

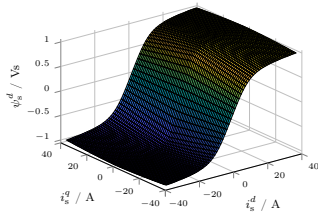
[—] simulation (CD+DI&FL), [—] measurement



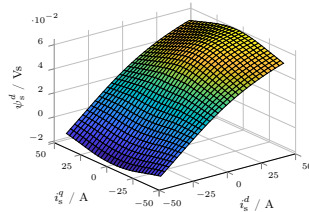
Identification and simulation

Exemplary results: Flux Linkage Prototype Functions (**FLPFs**) [2] – Analytic functions for flux linkage representation

$\psi_s^{d/q}$ of typical RSM

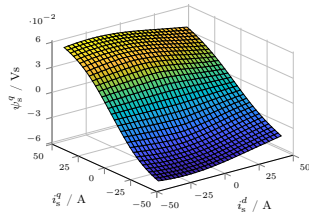
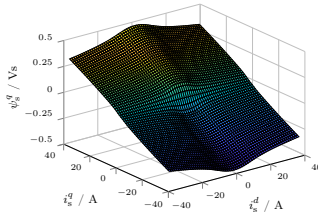


$\psi_s^{d/q}$ of typical IPMSM



General FLPF idea

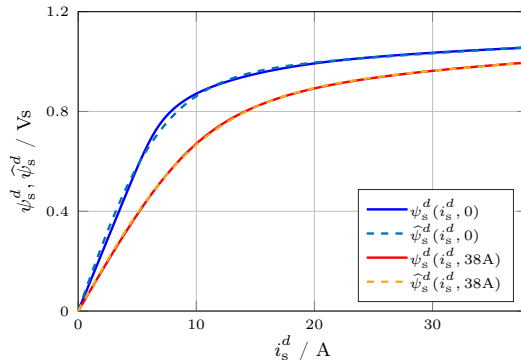
$$\hat{\psi}_s^d(i_s^d, i_s^q) = \hat{\psi}_{s,\text{self}}^d(i_s^d) - \hat{\psi}_{s,\text{cross}}^d(i_s^d, i_s^q)$$



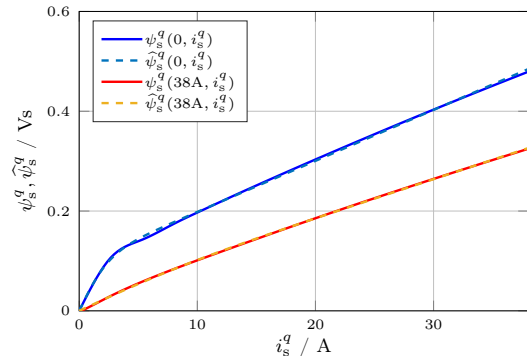
$$\hat{\psi}_s^q(i_s^d, i_s^q) = \hat{\psi}_{s,\text{self}}^q(i_s^q) - \hat{\psi}_{s,\text{cross}}^q(i_s^d, i_s^q)$$

Identification and simulation

Exemplary results: Flux Linkage Prototype Functions (**FLPFs**) [2] – Observation for self-axis effects (9.6 kW RSM)



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

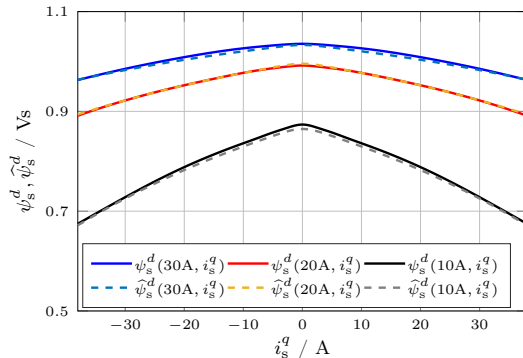


(b) q -axis flux linkage ψ_s^q v.s. q -axis current i_s^q

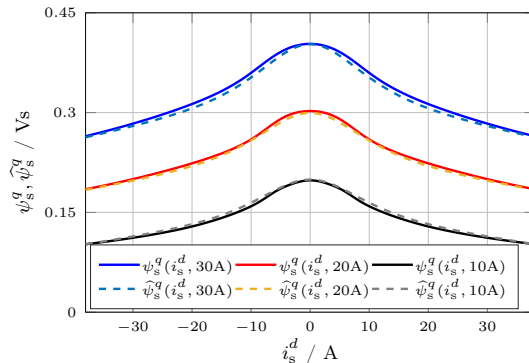
$$\text{e.g., } \hat{\psi}_{s,\text{self}}^{d,q}(i_s^d) \propto \tanh(i_s^{d/q}) + i_s^{d/q}$$

Identification and simulation

Exemplary results: Flux Linkage Prototype Functions (**FLPFs**) [2] – Observation for cross-coupling effects (9.6 kW RSM)



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

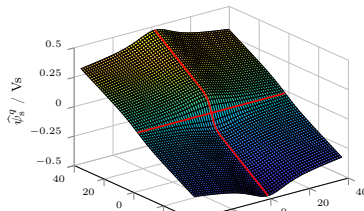
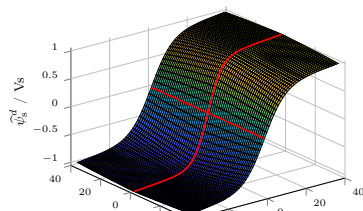


(b) q -axis flux linkage ψ_s^q v.s. d -axis current i_s^d

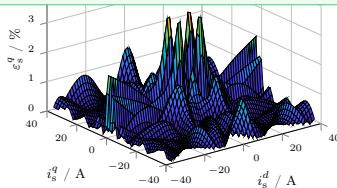
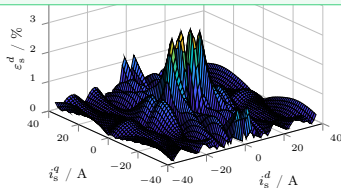
$$\text{e.g., } \hat{\psi}_{s,\text{cross}}^{d/q} \propto -\ln(\cosh(i_s^{d/q})) \quad \text{or} \quad \hat{\psi}_{s,\text{cross}}^{d/q} \propto \exp(-(i_s^{d/q})^2)$$

Identification and simulation

Exemplary results: Flux Linkage Prototype Functions (**FLPFs**) [2] – Estimation accuracy & properties (9.6 kW RSM)



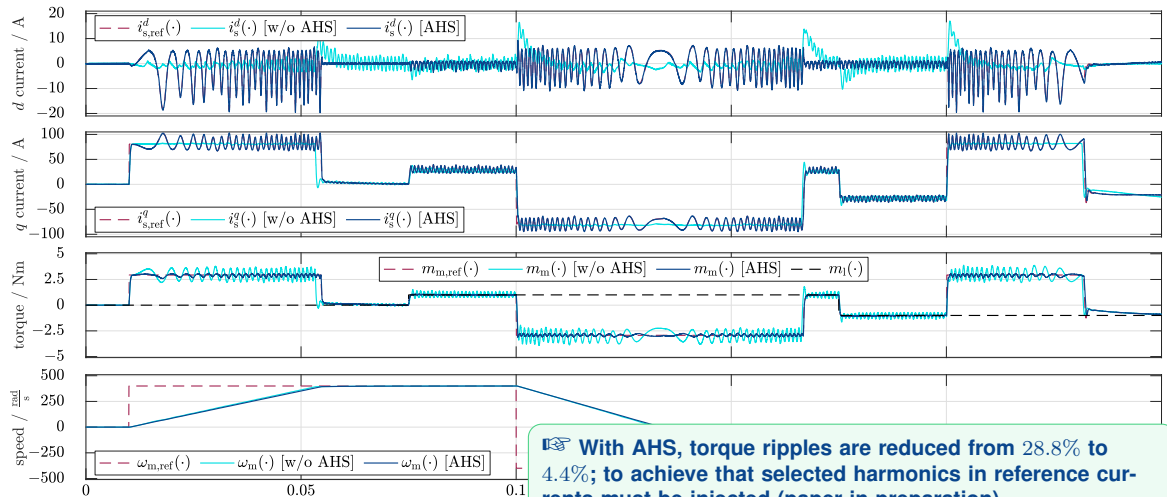
✋ Flux linkage prototype functions (FLPFs) can also be used for self-commissioning [3] or in the framework of Artificial Neuronal Networks (ANNs) to identify inverter and machine simultaneously [4].



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

Identification and simulation

Exemplary results: Active Harmonics Suppression (**AHS**) in 2.6 kW BLDC machine (compensating for $\delta_s^{dq\gamma} = \frac{\partial \psi_s^{dq\gamma}}{\partial \phi_m} \omega_m$)



3 Conclusion

Conclusion

Summary and future work

To take home

- **Generic modeling approach** for **any electrical machine** covering **all physical effects**, e.g.
 - iron losses,
 - anisotropy, magnetic saturation and cross-coupling,
 - harmonics (in e.g. back-emf),
 - proximity and/or skin effect, or
 - slip rings or winding asymmetries.
- **Generic identification approach** is work in progress (with AVL-SET GmbH)
- **Generic control approach** for **any electrical machine** covering **all physical effects**, i.e.
 - High-performance current & torque control
 - Optimal operation management (efficiency maximization) considering all (machine) losses
 - Additional functionality (e.g., Active Harmonics Suppression (AHC) or Active Noise Cancellation (ANC))

Future work

- more comprehensive experimental validation (e.g., validation for *multi-phase* machines)
- impact of (parameter/modelling/alignment) uncertainties on simulation/emulation/control
- new book series “**Moderne elektrische Antriebe**” with **Springer** in preparation
(first volume to appear in 2025)

References I

- [1] Johannes Rossmann, Niklas Monzen, Maarten J. Kamper, and Christoph M. Hackl. Nonlinear three-phase reluctance synchronous machine modeling with extended torque equation. In *2023 IEEE 32nd International Symposium on Industrial Electronics (ISIE)*. IEEE, 2023.
- [2] Shih-Wei Su, Christoph M. Hackl, and Ralph Kennel. Analytical prototype functions for flux linkage approximation in synchronous machines. *IEEE Open Journal of the Industrial Electronics Society*, 3:265–282, 2022.
- [3] Shih-Wei Su, Niklas Monzen, Ralph Kennel, and Christoph M. Hackl. Self-identification of reluctance synchronous machines with analytical flux linkage prototype functions. In *2023 11th International Conference on Power Electronics and ECCE Asia (ICPE 2023 - ECCE Asia)*. IEEE, 2023.
- [4] Simon Wiedemann and Christoph M. Hackl. Simultaneous identification of inverter and machine nonlinearities for self-commissioning of electrical synchronous machine drives. *IEEE Transactions on Energy Conversion*, pages 1–14, 2023.