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

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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

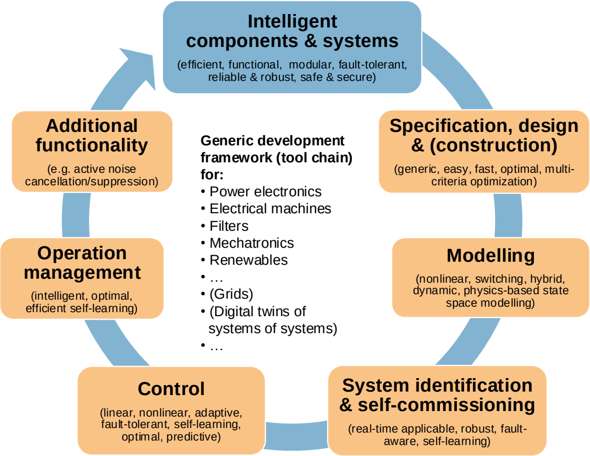
LMRES – Laboratory for Mechatronic and Renewable Energy Systems

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

Outline

Introduction

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



Outline

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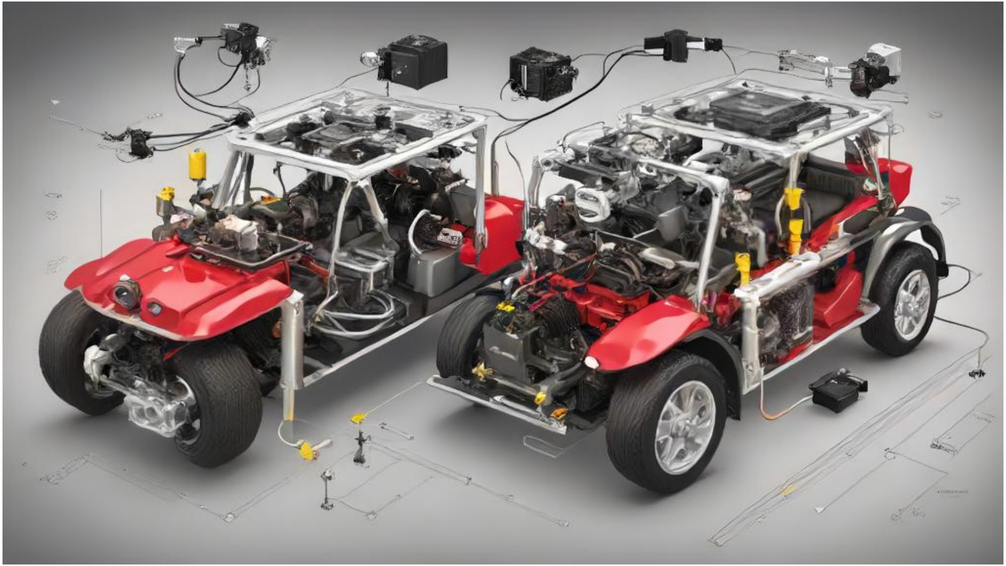
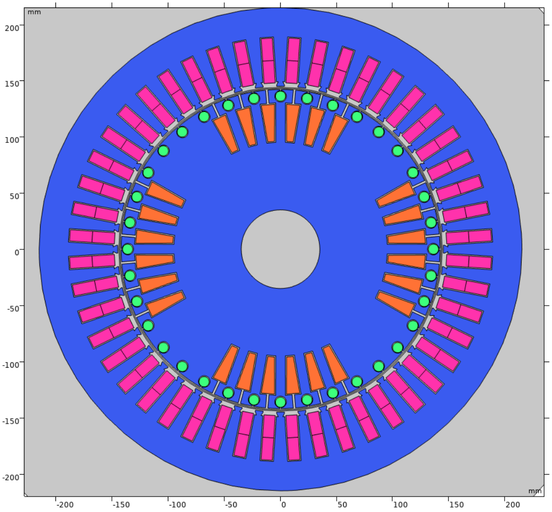
Modelling

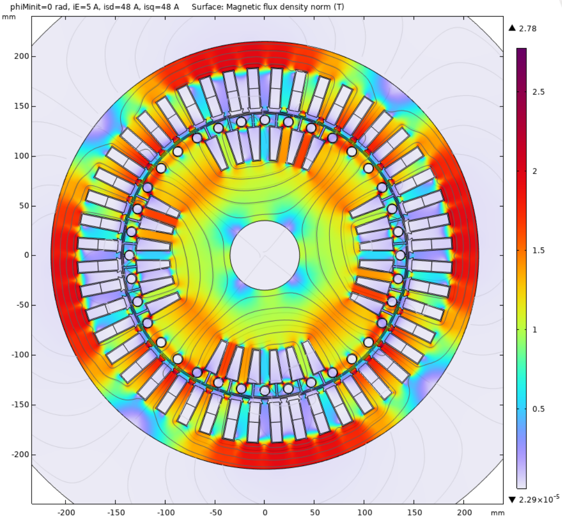
Motivation: Output of DeepAI Figure Generator (prompted with “Electric vehicle with motor, power electronics & battery”)



Modelling

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





Outline

Modelling

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

Kirchhoff's voltage equation:

- single-phase: $u = R\,i + \frac{\mathrm{d}}{\mathrm{d}t}\psi \quad \Longleftrightarrow \quad \frac{\mathrm{d}}{\mathrm{d}t}\psi = u - R\,i$
- three-phase: $\boldsymbol{u}_{\mathrm{z}}^{abc} = \boldsymbol{R}_{\mathrm{z}}^{abc}\boldsymbol{i}_{\mathrm{z}}^{abc} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{z}}^{abc} \quad \Longleftrightarrow \quad \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{z}}^{abc} = \boldsymbol{u}_{\mathrm{z}}^{abc} - \boldsymbol{R}_{\mathrm{z}}^{abc}\boldsymbol{i}_{\mathrm{z}}^{abc}, \quad \mathrm{z} \in \{\mathrm{s}, \mathrm{Fe}, \mathrm{r}, \mathrm{e}, \dots\}$

where

- applied winding voltage u (arbitrary shape) or $\boldsymbol{u}_{\mathrm{z}}^{abc} := (u_{\mathrm{z}}^{a}, u_{\mathrm{z}}^{b}, u_{\mathrm{z}}^{c})^{\top} \in \mathbb{R}^3$
- winding current i (arbitrary shape) or $\boldsymbol{i}_{\mathrm{z}}^{abc} := (i_{\mathrm{z}}^{a}, i_{\mathrm{z}}^{b}, i_{\mathrm{z}}^{c})^{\top} \in \mathbb{R}^3$
- winding resistance $R := R(i, \phi, \omega, \vartheta, \dots)$ or $\boldsymbol{R}_{\mathrm{z}}^{abc} := \boldsymbol{R}_{\mathrm{z}}^{abc}(\boldsymbol{i}_{\mathrm{z}}^{abc}, \phi, \omega, \boldsymbol{\vartheta}_{\mathrm{z}}^{abc}, \dots) \in \mathbb{R}^{3\times 3}$
- flux linkage $\psi := \psi(i, \phi, \omega, \vartheta, \dots)$ or $\boldsymbol{\psi}_{\mathrm{z}}^{abc} := (\psi_{\mathrm{z}}^{a}, \psi_{\mathrm{z}}^{b}, \psi_{\mathrm{z}}^{c})^{\top} = \boldsymbol{\psi}_{\mathrm{z}}^{abc}(\boldsymbol{i}_{\mathrm{z}}^{abc}, \phi, \omega, \boldsymbol{\vartheta}_{\mathrm{z}}^{abc}, \dots) \in \mathbb{R}^3$

***Remark**: Resistance R and flux linkage ψ may depend on states $\boldsymbol{x} := (i, \phi, \omega, \vartheta, \dots)^{\top} \in \mathbb{R}^{N_{\boldsymbol{x}}}$ 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.*

Outline

Modelling

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

$$
\left.
\begin{array}{llcll}
\text{Stator:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} & -\omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}, \\
\text{Stator iron:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq\gamma} & = & - \boldsymbol{R}_{\mathrm{s,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma} & -\omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s,Fe}}^{dq\gamma}, \\
\text{Rotor:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{r}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{r}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{r}}^{dq\gamma}\boldsymbol{i}_{\mathrm{r}}^{dq\gamma} & -(\omega_{\mathrm{p}}-\omega_{\mathrm{r}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{r}}^{dq\gamma}, \\
\text{Rotor iron:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{r,Fe}}^{dq\gamma} & = & - \boldsymbol{R}_{\mathrm{r,Fe}}^{dq\gamma}\boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma} & -(\omega_{\mathrm{p}}-\omega_{\mathrm{r}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{r,Fe}}^{dq\gamma}, \\
\text{Excitor:} & \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{e}}^{dq\gamma} & = & \boldsymbol{u}_{\mathrm{e}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{e}}^{dq\gamma}\boldsymbol{i}_{\mathrm{e}}^{dq\gamma} & -(\omega_{\mathrm{p}}-\omega_{\mathrm{e}})\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{e}}^{dq\gamma}, \\
\text{Mechanical subsystem:} & \frac{\mathrm{d}}{\mathrm{d}t}\omega_{\mathrm{m}} & = & \frac{1}{\Theta_{\mathrm{m}}}\Big(m_{\mathrm{m}} - \mathfrak{F}\omega_{\mathrm{m}} + m_{\mathrm{l}}\Big) & \\
 & \frac{\mathrm{d}}{\mathrm{d}t}\phi_{\mathrm{m}} & = & \omega_{\mathrm{m}} &
\end{array}
\right\} \tag{1}
$$

with machine torque $m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{s,Fe}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{r}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{r,Fe}}^{dq\gamma}, \boldsymbol{i}_{\mathrm{e}}^{dq\gamma}, \boldsymbol{\psi}_{\mathrm{pm}}^{dq\gamma}, \phi_{\mathrm{m}}, \dots)$ and rotation matrix (by $\pi/2$)

$$
\boldsymbol{J}_0 := \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
$$

***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 $\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{f}_{\psi}^{-1}(\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}, \ldots)$ (**FLD+II**):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} = \boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} \tag{2}$$

- Current Dynamics with Differential Inductances $\boldsymbol{L}_{\mathrm{s}}^{dq\gamma}$ and Flux Linkages $\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}$ (**CD+DI&FL**):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = (\boldsymbol{L}_{\mathrm{s}}^{dq\gamma})^{-1}\Big(\boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma} + \underbrace{\frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial\phi_{\mathrm{m}}}\omega_{\mathrm{m}} + \frac{\partial\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial\vartheta}\frac{\mathrm{d}}{\mathrm{d}t}\vartheta + \ldots}_{=:\boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma}}\Big) \tag{3}$$

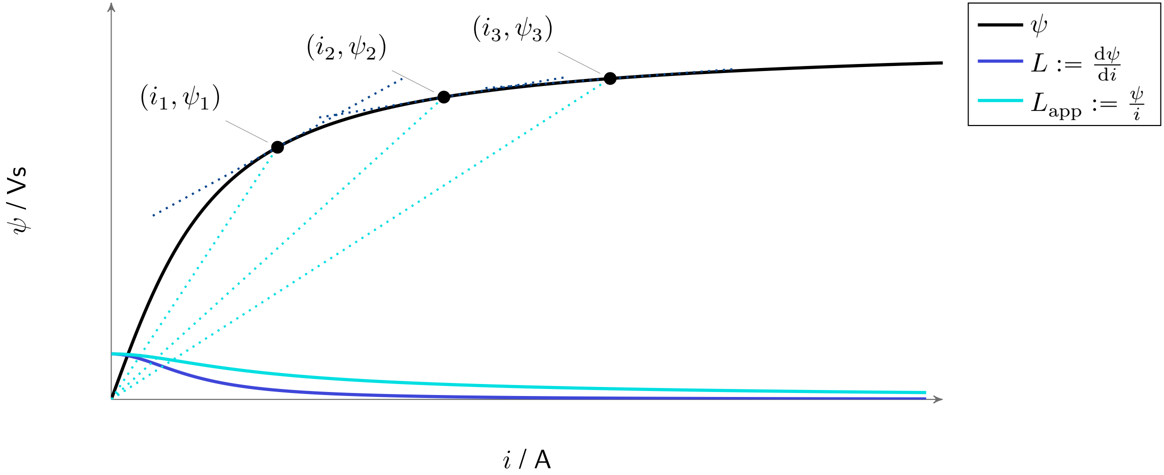
- Current Dynamics with Differential $\boldsymbol{L}_{\mathrm{s}}^{dq\gamma}$ & Apparent $\boldsymbol{L}_{\mathrm{s,app}}^{dq\gamma}$ Inductances and Permanent-Magnet Flux Linkages $\boldsymbol{\psi}_{\mathrm{pm}}^{dq\gamma}$ (**CD+DAI&PMFL**):

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} = (\boldsymbol{L}_{\mathrm{s}}^{dq\gamma})^{-1}\Big(\boldsymbol{u}_{\mathrm{s}}^{dq\gamma} - \boldsymbol{R}_{\mathrm{s}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} - \omega_{\mathrm{p}}\boldsymbol{J}_0(\boldsymbol{L}_{\mathrm{s,app}}^{dq\gamma}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma} + \boldsymbol{\psi}_{\mathrm{pm}}^{dq\gamma}) + \boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma}\Big) \tag{4}$$

***Remark**: Important to note that* $\boldsymbol{L}_{\mathrm{s}}^{dq\gamma} := \frac{\mathrm{d}\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\mathrm{d}\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}} \neq \boldsymbol{L}_{\mathrm{s,app}}^{dq\gamma} := \frac{\boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}(\boldsymbol{i}_{\mathrm{s}}^{dq\gamma},\ldots) - \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}(\boldsymbol{0}_3,\ldots)}{\boldsymbol{i}_{\mathrm{s}}^{dq\gamma}}$

Identification and simulation

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



Outline

Identification and simulation

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

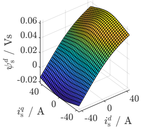
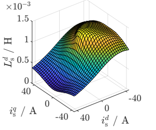
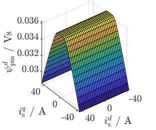
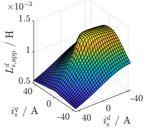
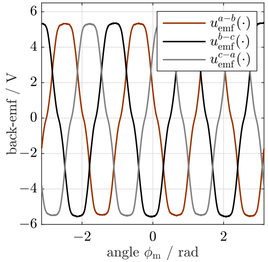
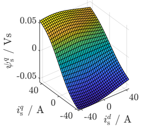
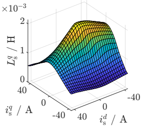
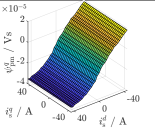
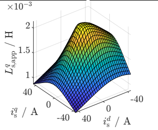
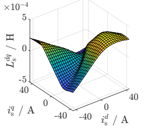
	FLD+II	CD+DI&FL	CD+DAI&PMFL
$\boldsymbol{R}_{\mathrm{s}}^{dq(\gamma)}(\boldsymbol{x})$	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+0) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{L}_{\mathrm{s}}^{dq(\gamma)}(\boldsymbol{x})$	–	$3\ (+3) \times N_{\boldsymbol{x}}$-D–LUTs	$3\ (+3) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{L}_{\mathrm{s,app}}^{dq(\gamma)}(\boldsymbol{x})$	–	–	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{\psi}_{\mathrm{pm}}^{dq(\gamma)}(\boldsymbol{x})$	–	–	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs
$\boldsymbol{\psi}_{\mathrm{s}}^{dq(\gamma)}$	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs	$2\ (+1) \times N_{\boldsymbol{x}}$-D–LUTs	–
$\boldsymbol{f}_{\psi}(\cdot)^{-1}$	yes	no	no
t_{exec} (in p.u.)	$1.00^{\star}$ / $1.07^{\dagger}$ / $2.55^{\ddagger}$	1.55	1.83

Remark*: The states* $\boldsymbol{x} := (\boldsymbol{i}_{\mathrm{x}}^{abc}, \phi_{\mathrm{m}}, \phi_{\mathrm{p}}, \omega_{\mathrm{m}}, \omega_{\mathrm{p}}, \boldsymbol{\vartheta}_{\mathrm{x}}^{abc}, \ldots)^{\top} \in \mathbb{R}^{N_{\boldsymbol{x}}}$ *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.;* $N_{\boldsymbol{x}}$ *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

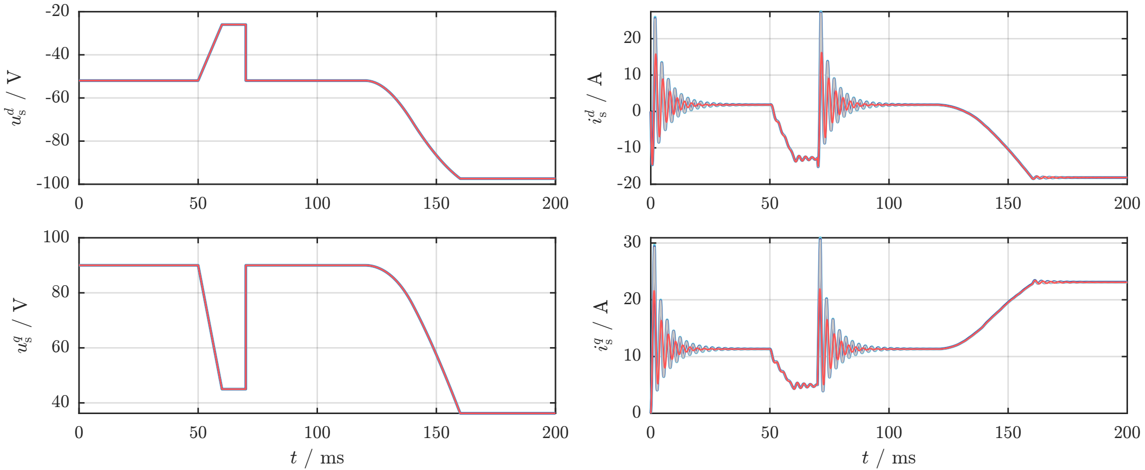
	$\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq})$	$\boldsymbol{L}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq})$	$\boldsymbol{\psi}_{\mathrm{pm}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq})$	$\boldsymbol{L}_{\mathrm{s,app}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq})$	$\boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma} = \frac{\partial \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial \phi_{\mathrm{m}}}\omega_{\mathrm{m}}$
d					
q					
dq/qd	—		—	—	

Remark: *For simplicity, only the dependencies on* $\boldsymbol{i}_{\mathrm{s}}^{dq} := (i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})^{\top}$ *are shown, i.e.* $\boldsymbol{x} := (i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})^{\top}$ *with* $N_{\boldsymbol{x}} = 2$.

Outline

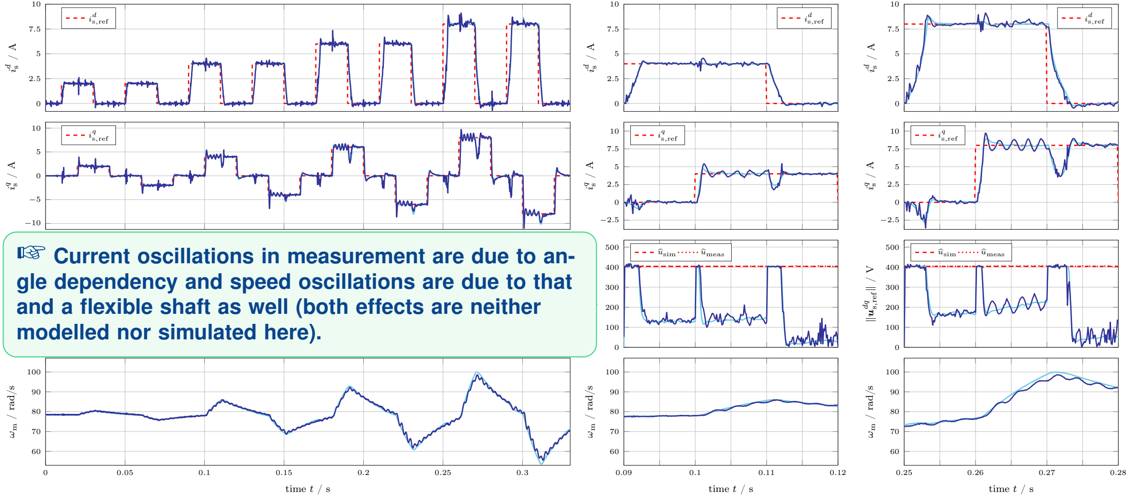
Identification and simulation

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



Identification and simulation

Exemplary results: Comparison of closed-loop nonlinear electrical drive system ($4.0\,$kW RSM @ $\omega_\mathrm{m} \approx 80\,\frac{\mathrm{rad}}{\mathrm{s}}$):
[——] simulation (CD+DI&FL), [——] measurement

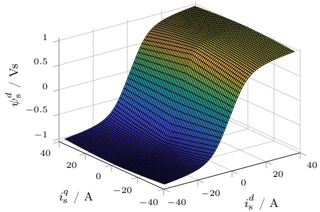


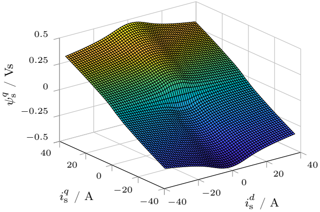
☞ **Current oscillations in measurement are due to angle dependency and speed oscillations are due to that and a flexible shaft as well (both effects are neither modelled nor simulated here).**

Identification and simulation

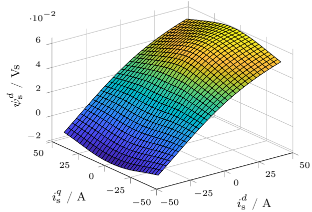
Exemplary results: Flux Linkage Prototype Functions (**FLPFs**) [2] – Analytic functions for flux linkage representation

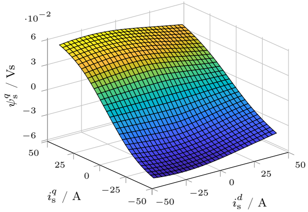
$\psi_{\mathrm{s}}^{d/q}$ of typical RSM





$\psi_{\mathrm{s}}^{d/q}$ of typical IPMSM





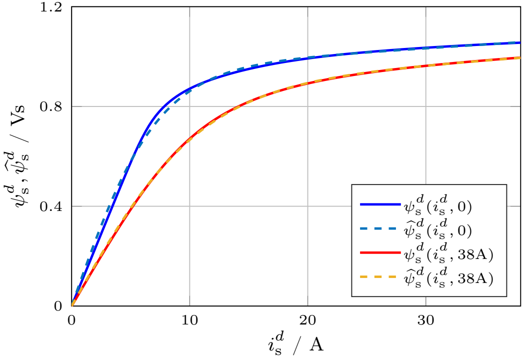
General FLPF idea

$$\widehat{\psi}_{\mathrm{s}}^{d}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}) = \widehat{\psi}_{\mathrm{s,self}}^{d}(i_{\mathrm{s}}^{d}) - \widehat{\psi}_{\mathrm{s,cross}}^{d}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})$$

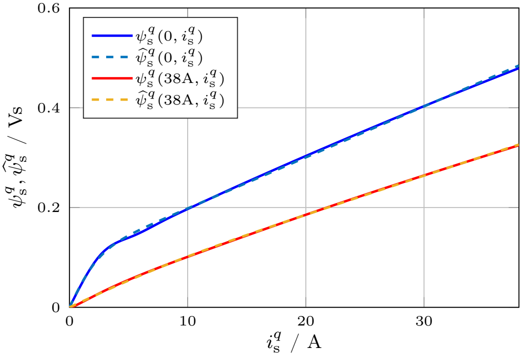
$$\widehat{\psi}_{\mathrm{s}}^{q}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q}) = \widehat{\psi}_{\mathrm{s,self}}^{q}(i_{\mathrm{s}}^{d}) - \widehat{\psi}_{\mathrm{s,cross}}^{q}(i_{\mathrm{s}}^{d}, i_{\mathrm{s}}^{q})$$

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

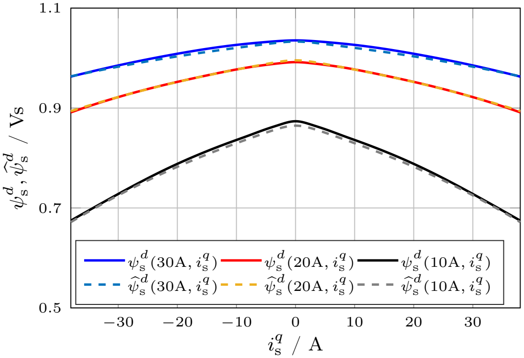


(b) q-axis flux linkage ψ_s^q v.s. q-axis current i_s^q

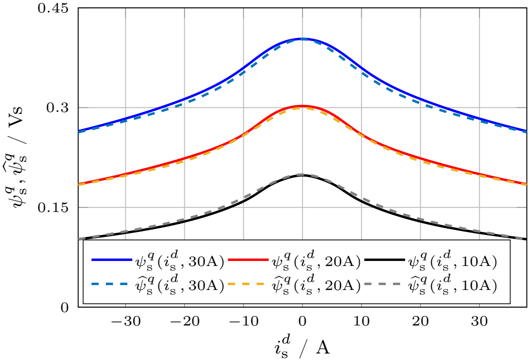
e.g., $\widehat{\psi}_{s,\text{self}}^{d,q}(i_s^d) \propto \tanh(i_s^{d/q}) + i_s^{d/q}$

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

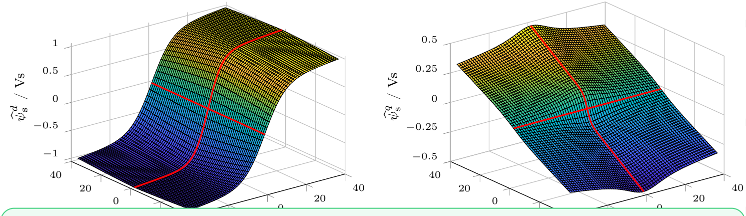


(b) q-axis flux linkage ψ_s^q v.s. d-axis current i_s^d

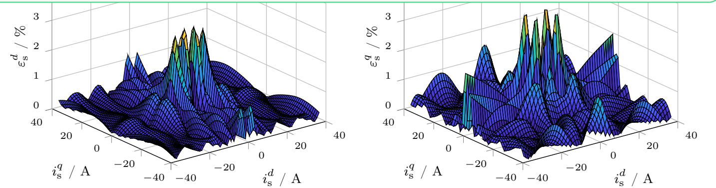
e.g., $\widehat{\psi}_{s,\mathrm{cross}}^{d/q} \propto -\ln\big(\cosh(i_s^{d/q})\big)$ or $\widehat{\psi}_{s,\mathrm{cross}}^{d/q} \propto \exp\big(-(i_s^{d/q})^2\big)$

Identification and simulation

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



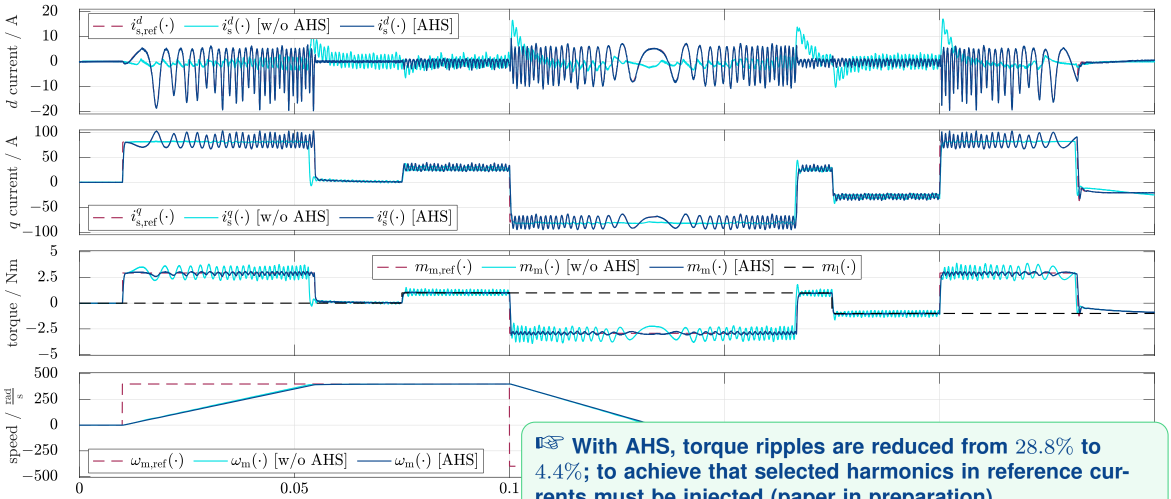
☞ **Flux linkage prototype functions (FLPFs) can also be used for self-commissioning [3] or in the framework of Artificial Neuronal Networks (ANNs) to identify inverter and machine simultaneously [4].**



- **Flux linkages** approximated by FLPFs $\widehat{\psi}_s^d(i_s^d, i_s^q)$ & $\widehat{\psi}_s^q(i_s^d, i_s^q)$ with high accuracy (usually $\geqslant 95\%$)
- **Energy conservation** assured, i.e. $\frac{\partial \widehat{\psi}_s^d(i_s^d, i_s^q)}{\partial i_s^q} = \frac{\partial \widehat{\psi}_s^q(i_s^d, i_s^q)}{\partial i_s^d}$ (reciprocity)
- **Few parameters** to be fitted (only $10 \sim 20$ 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 $2.6\,\mathrm{kW}$ BLDC machine (compensating for $\boldsymbol{\delta}_{\mathrm{s}}^{dq\gamma} = \frac{\partial \boldsymbol{\psi}_{\mathrm{s}}^{dq\gamma}}{\partial \phi_{\mathrm{m}}} \omega_{\mathrm{m}}$)



☞ **With AHS, torque ripples are reduced from 28.8% to 4.4%; to achieve that selected harmonics in reference currents must be injected (paper in preparation).**

Outline

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)

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