Machine copier - Fast, easy and precise identification of electrical machines

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Agenda

1 Introduction

Introduction

AVL SET GmbH

2012

SET Power Systems is founded as a joint venture between SET & AVL List

5 employees

2019

SET Power Systems becomes AVL SET

Technology leader in e-motor emulation (P-HiL)

90 employees

2025

AVL SET

- Modular Gen5 approach
- Installed Base: 170+ Test channels

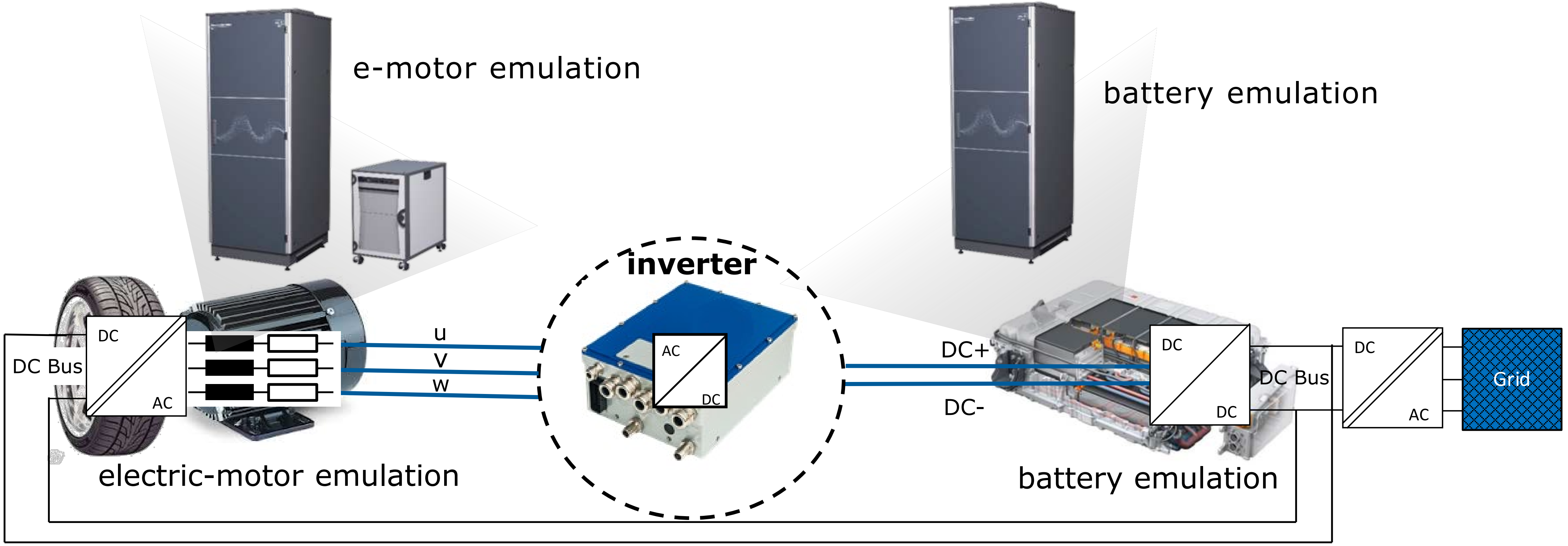
170 employees

Installed Base: 174 Test Channels

In Total: **48 MEGAWATT INSTALLED POWER-HIL** (by end of year 2024)

Introduction

AVL inverter TS™



- AVL inverter TS™ tests inverter, which must be parametrized using (electrical) machine parameters
- Machine parameters may be unknown or only approximately/linearly known

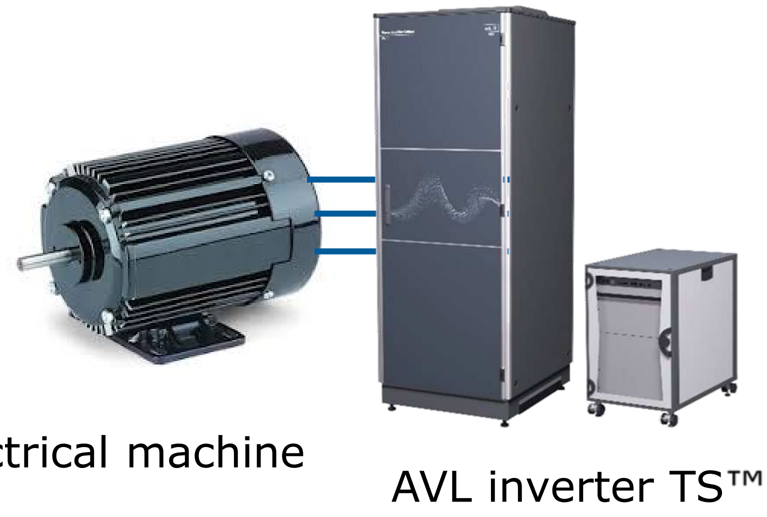
Introduction

Motivation

- **Can the AVL inverter TS™ be used to identify electrical machine parameters?**

  - AVL inverter TS™ is a high-performance 3-phase current source inverter, including multilevel topology, high-precision voltage and current sensors, sample period of 320 ns, and a power capability of up to 960 kW [8]

  - These features enable precise, dynamic, and robust injection of currents into unknown electrical machines



→ Our objective is to identify electrical machine parameters using the AVL inverter TS™

Introduction

Motivation

How is machine identification currently done? How do we want to do it?

Steady-state identification	Dynamic identification (machine copier)
Requires a complete dynamometer setup, including torque sensors, a load machine, shaft coupling, and precise machine alignment ➔ Extensive hardware preparation	No dynometer setup, no torque sensor, no load machine, no machine alignment necessary Only a rotor locking device and 3-phase power cables are needed. ➔ Less hardware preparation
Long measurement durations	Very short measurement durations

➔ Costly and time-consuming

➔ Slows down development and validation and processes [6]

➔ Lowers costs/time of machine identification drastically

Is it that simple? How does it work?

What are the challenges?

2 Identification method

Identification method

Basic equations

General stator voltage equation of electrical machines in (d,q)-reference system in scalar notation

$$\begin{pmatrix} u_\mathrm{s}^d \\ u_\mathrm{s}^q \end{pmatrix} = \begin{bmatrix} R_\mathrm{s}^d & 0 \\ 0 & R_\mathrm{s}^q \end{bmatrix} \begin{pmatrix} i_\mathrm{s}^d \\ i_\mathrm{s}^q \end{pmatrix} + \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \psi_\mathrm{s}^d \\ \psi_\mathrm{s}^q \end{pmatrix} + \omega_\mathrm{p} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} \psi_\mathrm{s}^d \\ \psi_\mathrm{s}^q \end{pmatrix}$$

and in vector-matrix notation

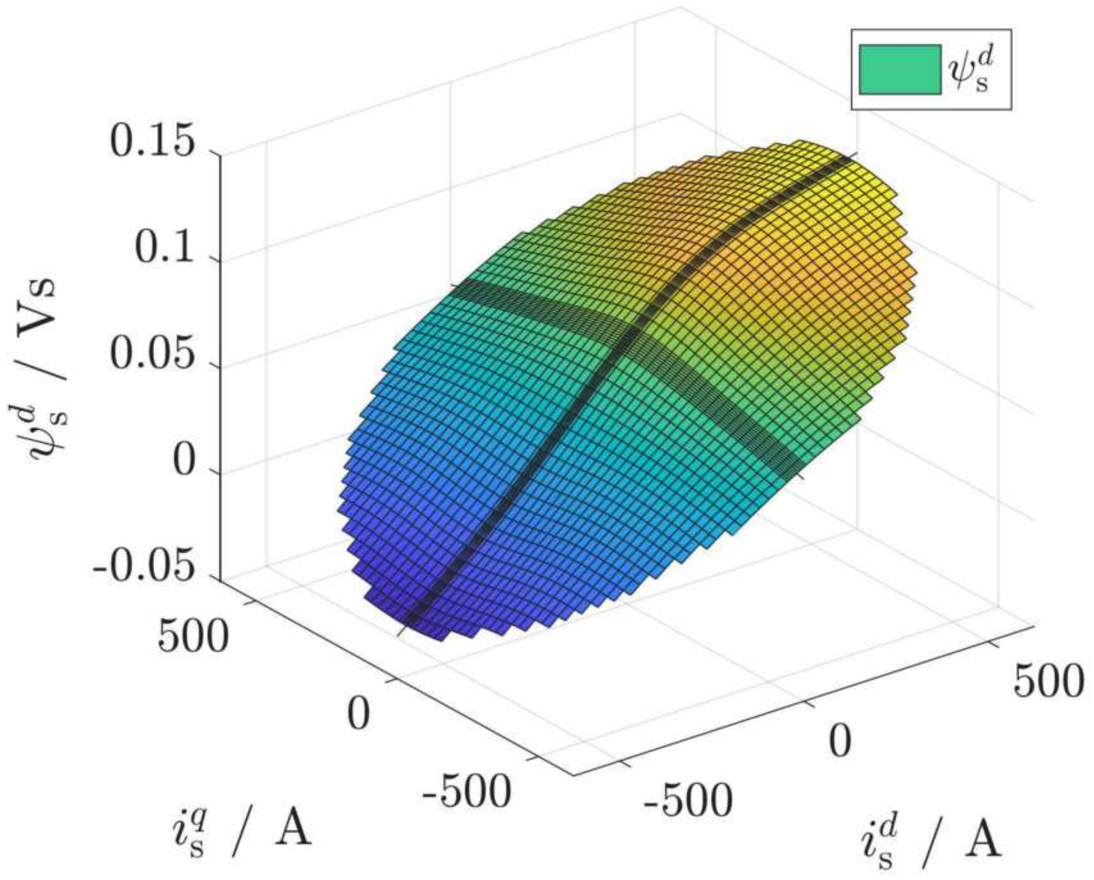
$$\boldsymbol{u}_\mathrm{s}^{dq} \quad = \quad R_\mathrm{s} \boldsymbol{i}_\mathrm{s}^{dq} + \tfrac{\mathrm{d}}{\mathrm{d}t} \boldsymbol{\psi}_\mathrm{s}^{dq} + \omega_\mathrm{p} \boldsymbol{J} \boldsymbol{\psi}_\mathrm{s}^{dq}$$

with stator flux linkages in dependency on stator currents and rotor temperature

$$\boldsymbol{\psi}_\mathrm{s}^{dq}(\boldsymbol{i}_\mathrm{s}^{dq}, \vartheta_\mathrm{r}) := \boldsymbol{\psi}_\mathrm{s}^{dq}$$

Identification method

Basic equations



Due to the physical characteristics, such as

- cross-coupling effects
- magnetic saturation, or
- temperature-dependent resistances,

the stator flux linkage $\boldsymbol{\psi}_\mathrm{s}^{dq}(\mathbf{i}_\mathrm{s}^{dq}, \vartheta_\mathrm{r})$ can <u>not</u> be decomposed into individual functions by applying the superposition principle

$$\boldsymbol{\psi}_\mathrm{s}^{dq}(\boldsymbol{i}_\mathrm{s}^{dq}, \vartheta_\mathrm{r}) \quad \neq \quad f(i_\mathrm{s}^d) + f(i_\mathrm{s}^q) + f(\vartheta_\mathrm{r})$$

➔ This leads to an exponentially increasing measurement effort for every new dimension

$$n_\mathrm{breakpoints} \quad = \quad \mathrm{len}|\boldsymbol{i}_\mathrm{s}^d| \cdot \mathrm{len}|\boldsymbol{i}_\mathrm{s}^q| \cdot \mathrm{len}|\boldsymbol{\vartheta}_\mathrm{r}|$$

Identification method

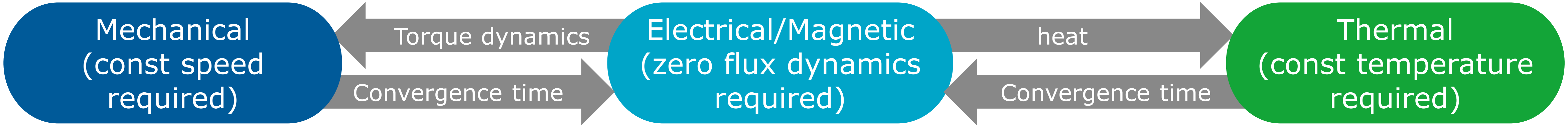
Steady-state identification

Steady-state identification is the most used method for parameter identification of electrical machines.

$$\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{r}}) \;=\; \frac{1}{\omega_{\mathrm{p}}}\boldsymbol{J}^{-1}\left(\boldsymbol{u}_{\mathrm{s}}^{dq} - R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{s}}^{dq} - \underbrace{\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{r}})}_{\approx \boldsymbol{0}_2}\right) = \boldsymbol{L}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{r}})\boldsymbol{i}_{\mathrm{s}}^{dq} + \boldsymbol{\psi}_{\mathrm{pm}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{r}})$$

Necessary conditions:

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}, \vartheta_{\mathrm{r}}) \;=\; \boldsymbol{0}_2, \quad \omega_{\mathrm{p}} \neq 0, \quad \omega = const., \quad \vartheta_{\mathrm{r}} = const.$$



Fulfilling this conditions is time-consuming, as it is constrained by the comparatively slow mechanical and thermal time constants of the system.

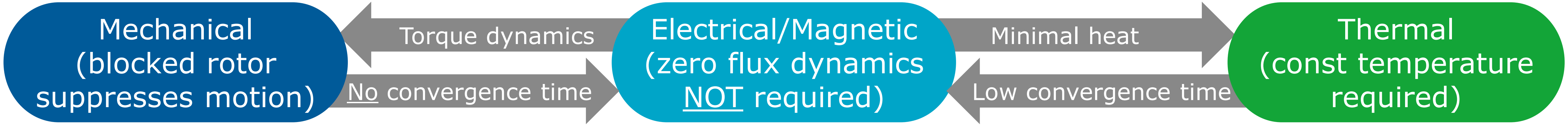
Identification method

Dynamic identification

The stator voltage equation is reformulated to

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq},\vartheta_{\mathrm{r}}) \quad = \quad \boldsymbol{u}_{\mathrm{s}}^{dq} - R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{s}}^{dq} - \omega_{\mathrm{p}}\boldsymbol{J}\boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq},\vartheta_{\mathrm{r}})$$

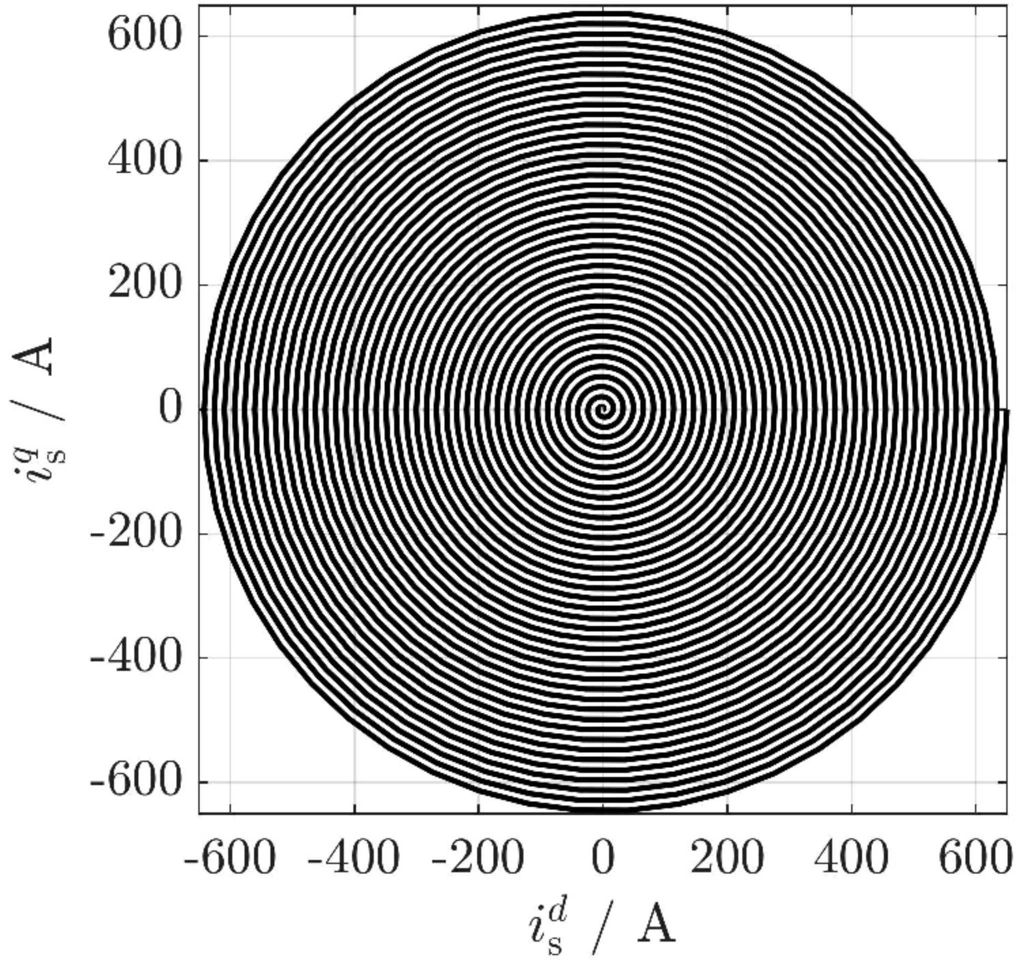
- Flux dynamics are not neglected
- Speed can be zero



➔ Identification time decreases drastically

Identification method

Scenario



What should the identification scenario look like?

Objective: Achieve all operating points of interest in the shortest possible time.

The identification duration of this method is constrained by

- the maximum stator voltage, which is limited either by the machine's voltage capability or by the supply voltage of the power inverter, and
- the sampling period of the analog-to-digital conversion, which determines the number of measurable data points

Identification method

Preprocessing/Identification/Postprocessing

Preprocessing

- Compensation for sensor measurement errors
- Signal filtering to reduce measurement noise

Identification

- Identification of resistance
- Identification of permanent magnet flux linkage [10]
- Identification of stator flux linkage maps based on differential flux linkage equation

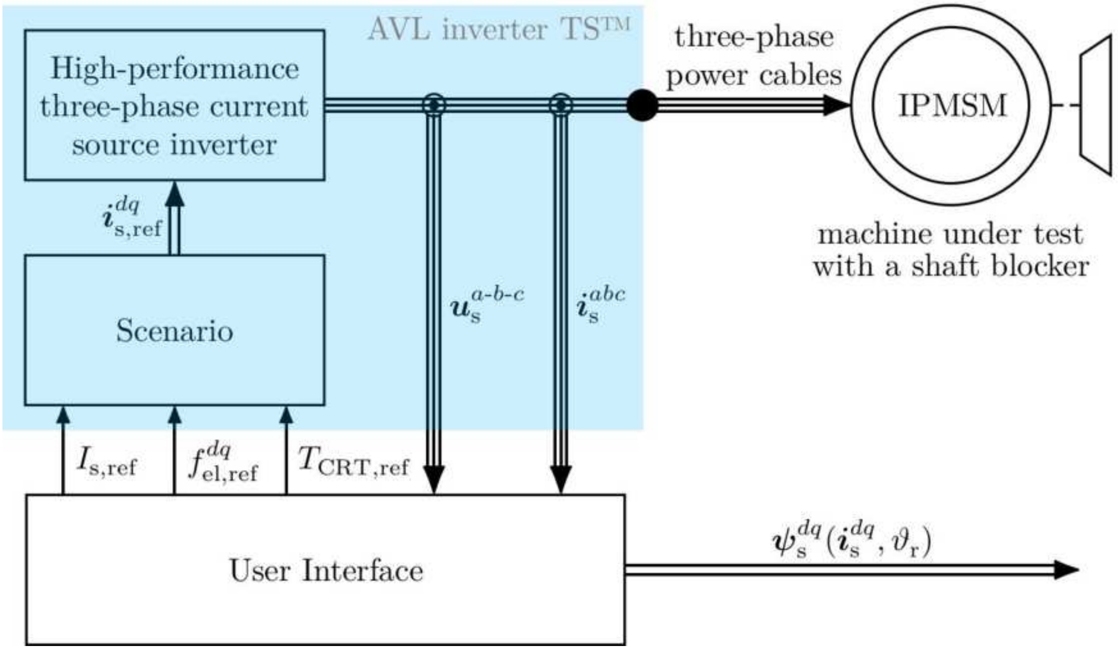
Postprocessing

- Physical-based fitting of flux linkage maps
- Transfer of identified flux linkage maps to user environments

3 Experimental validation

Experimental validation

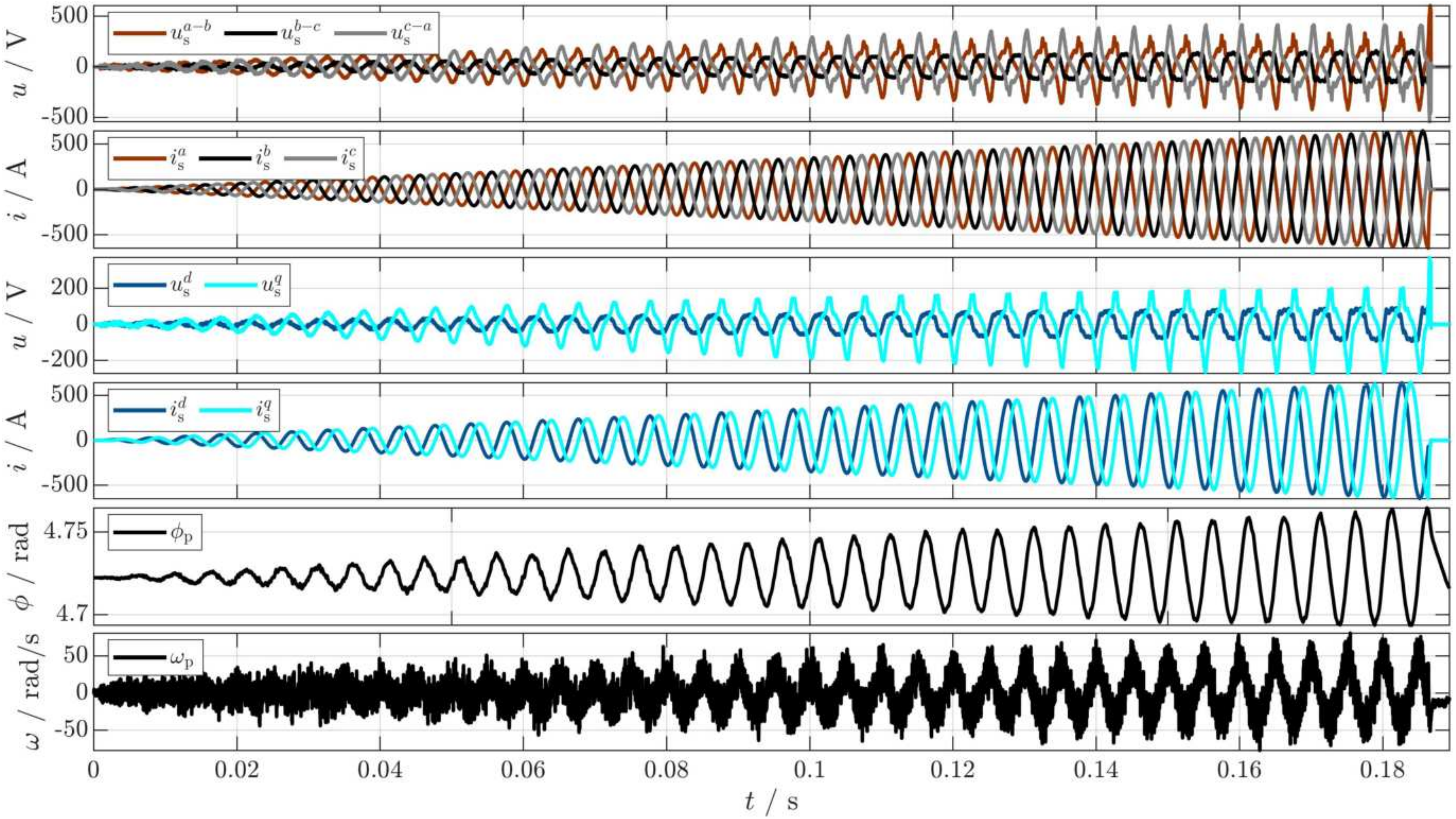
Hardware setup



- Machine under test:
  - Interior Permanent Magnet Synchronous Machine (IPMSM) of the EMR3 series by Schaeffler with a maximum stator RMS current of $I_{s,max,RMS} = 450$ A
- Sensors:
  - Integrated current and voltage sensors of the AVL inverter TS™
  - Additional external current and voltage sensors combined with a high-speed power analyzer provided by Schaeffler
  - Machine's built-in rotor position sensor (not required for the identification procedure)
  - NTC temperature sensor

Experimental validation

Measurement scenario of machine copier



User-defined inputs:

- Current amplitude:
  - $I_{s,ref} = 650$ A
- Rise Time:
  - $T_{CRT,ref} = 0.2$ s
- Frequency:
  - $f_{el,ref}^{dq} = 200$ Hz

Experimental validation

Comparison conditions - Machine copier vs conventional steady-state identification

Identical machine used

- Identical machine sample used -> moved from AVL inverter TS™ to Schaeffler’s dynamometer test bench

Identical measurement setups used

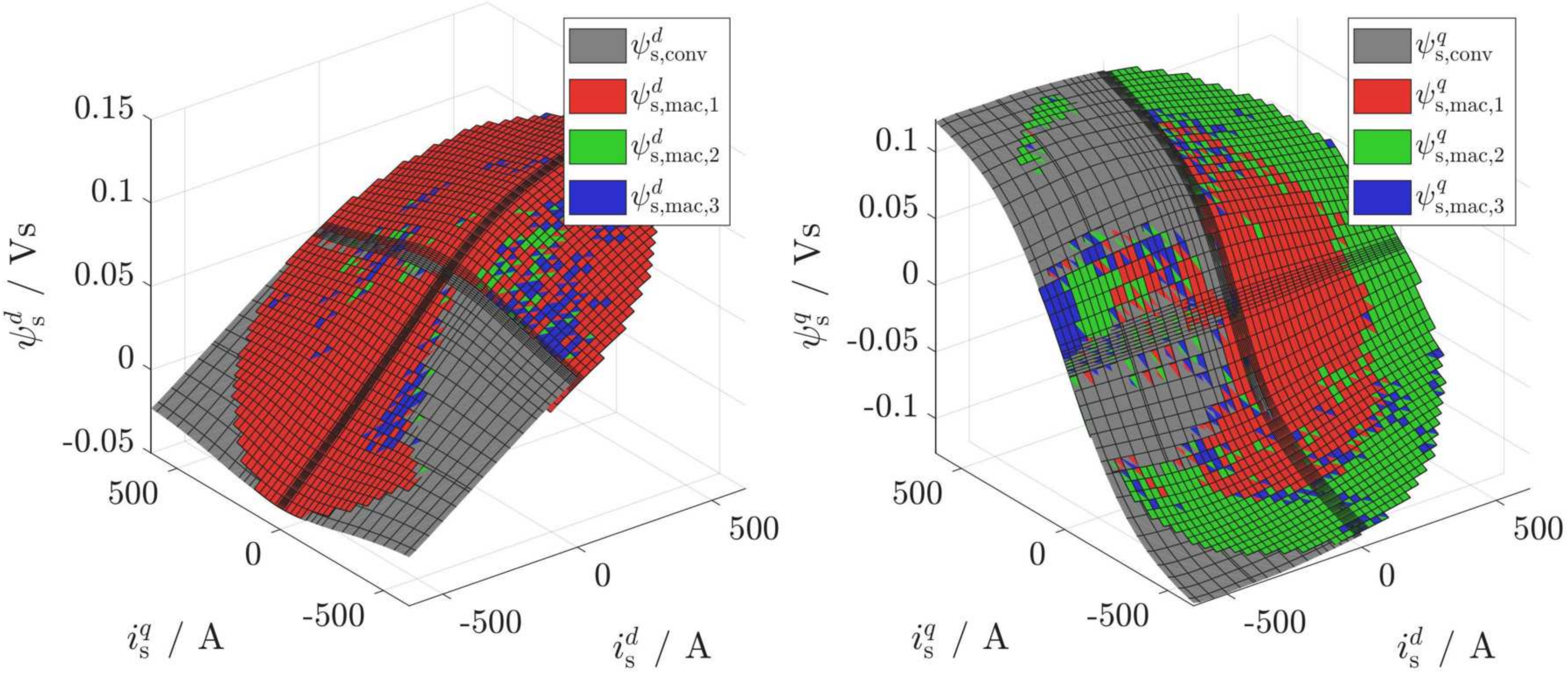
- Current and voltage sensors combined with a high-speed power analyzer provided by Schaeffler

Measurements performed under constant speed, frequency and temperature conditions

➔ Maximal comparability and measurement validity

Experimental validation

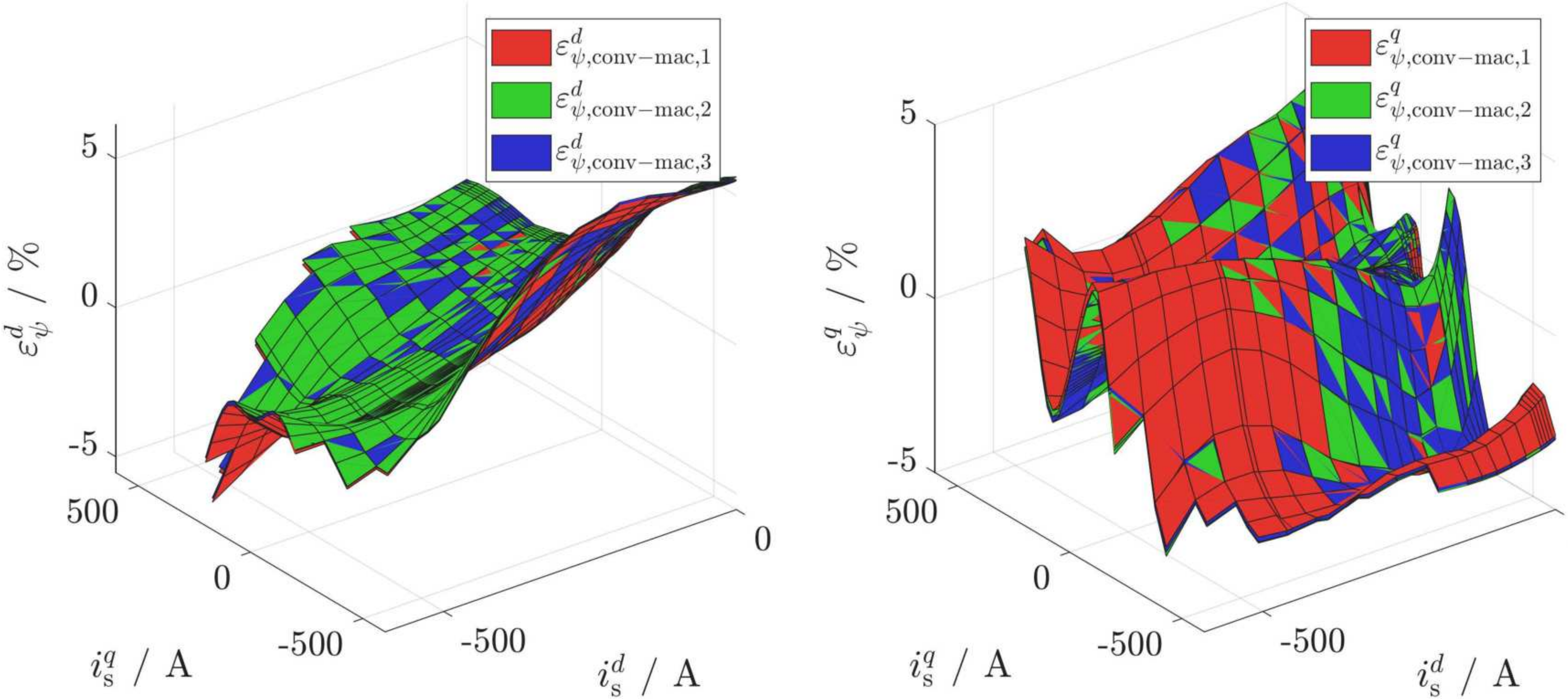
Comparison – Stator flux linkage maps



Experimental validation

$$(\max|\varepsilon_\psi^d|, \max|\varepsilon_\psi^q|)^\top = (5.87\,\%, 4.64\,\%)^\top$$
$$(\mathrm{mean}|\varepsilon_\psi^d|, \mathrm{mean}|\varepsilon_\psi^q|)^\top = (1.52\,\%, 1.36\,\%)^\top$$

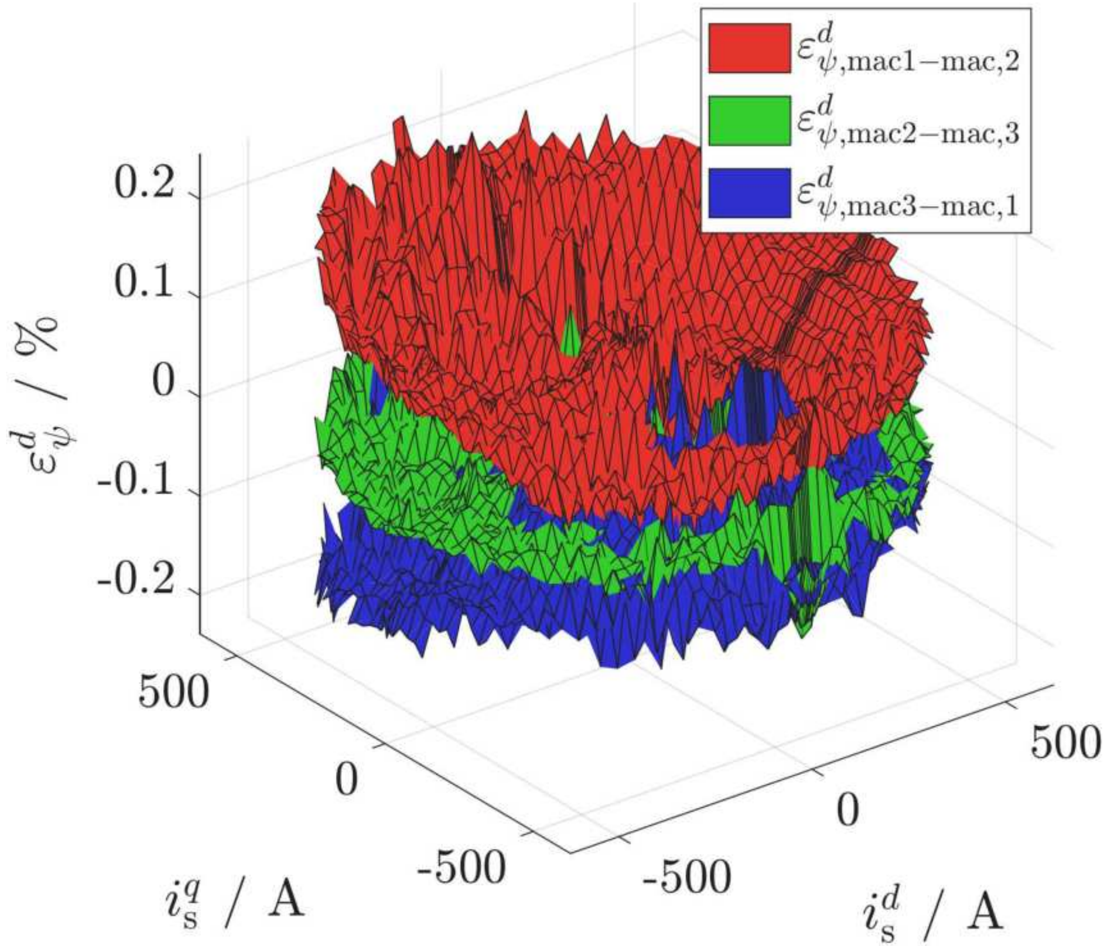
Comparison – Relative error of stator flux linkage maps

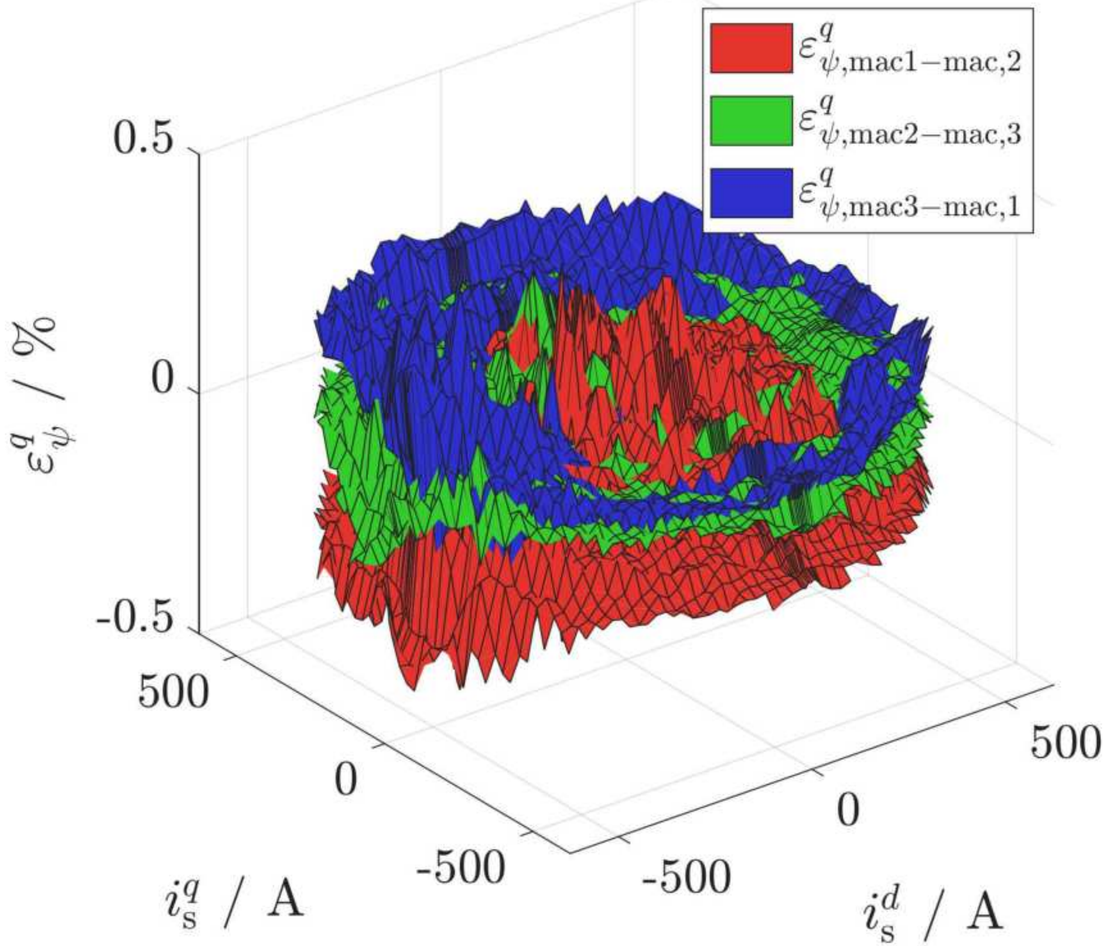


Experimental validation

$$(\max|\varepsilon_{\psi}^{d}|, \max|\varepsilon_{\psi}^{q}|)^{\top} = (0.24\,\%, 0.43\,\%)^{\top}$$
$$(\mathrm{mean}|\varepsilon_{\psi}^{d}|, \mathrm{mean}|\varepsilon_{\psi}^{q}|)^{\top} = (0.07\,\%, 0.09\,\%)^{\top}$$

Comparison – Reproducibility of stator flux linkage maps identified by machine copier

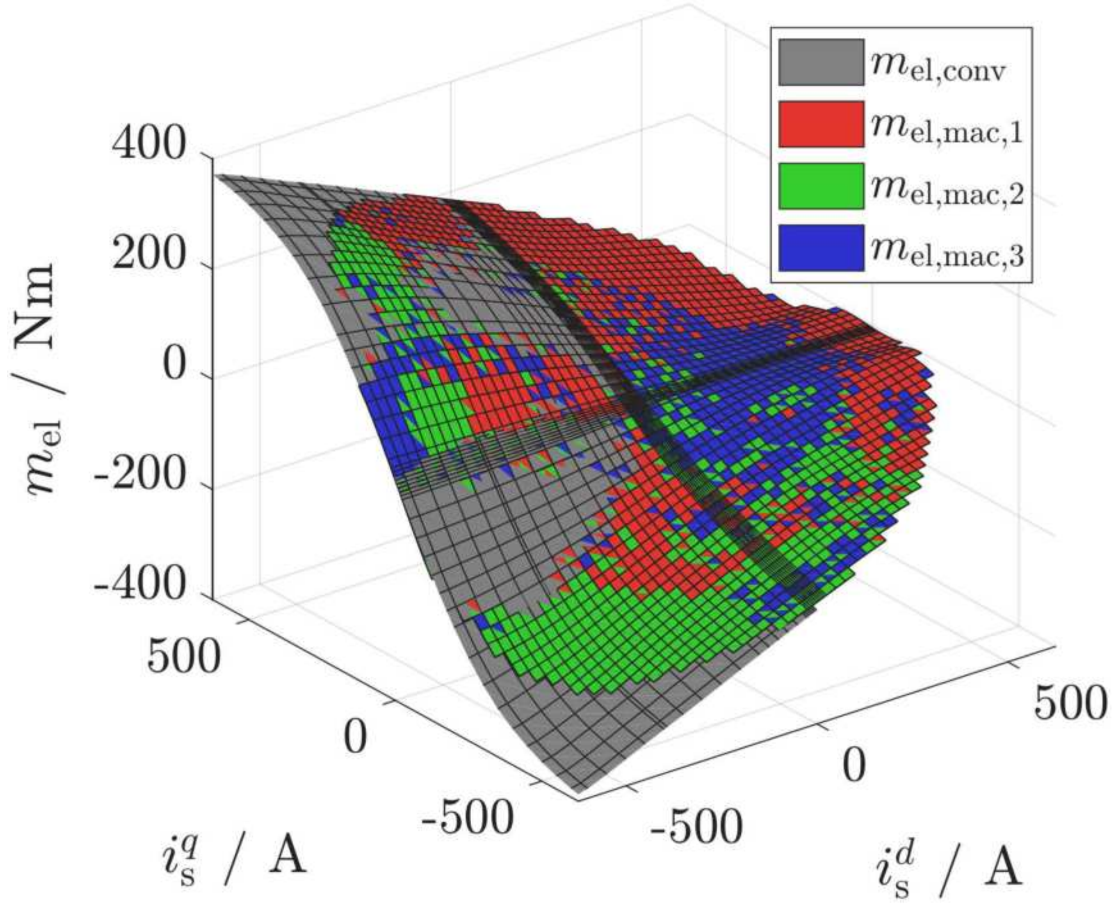


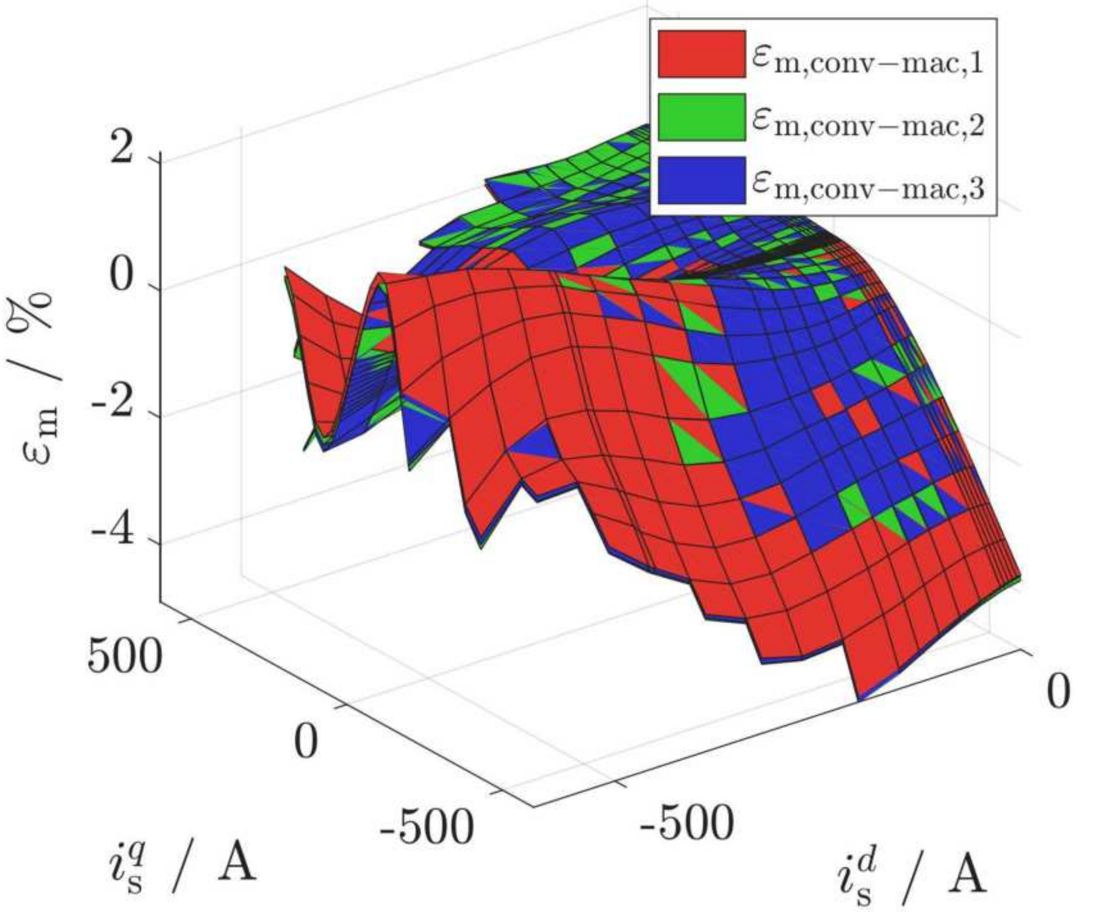


Experimental validation

$$\max|\varepsilon_m| = 4.52\,\%$$
$$\mathrm{mean}|\varepsilon_m| = 0.57\,\%$$

Comparison – Torque maps and relative error of torque maps





Experimental validation

Discussion of the results

- Maximum relative error of stator flux linkage maps is 5.87%
- Maximum relative stochastic error of three identical identified stator flux linkage maps of machine copier method is 0.43%
- This indicates systematic errors such as:
  - Sensor errors
  - Voltage drops
  - Inverter nonlinearities
  - Physical effects
  - …

Future work

- Analyze systematic errors
- Finding: Iron losses significantly affect stator flux linkage maps identified by the machine copier method due to the highly dynamic identification scenario
  - Compensation for iron losses required
  - Achieve similar iron losses as in steady-state identification
- Validation with torque and efficiency maps
- Analyze and compare inverter used in steady-state identification with AVL inverter TS™

4 Conclusion

Conclusion

Summary

- Novel method for (highly) dynamic parameter identification with AVL inverter TS™
- Experimental validation in cooperation Schaeffler
- Comparison of stator flux linkage maps between the conventional and the machine copier method

Outlook

- Enhance accuracy across multiple operating states
- Enable automated dynamic identification
- Reduce sensor requirements

Application potential

- End-of-Line testing and individual machine parametrization
- Production spread evaluation and component tolerance definition
- Prototype identification, benchmarking, or inverter parametrization

5 References

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Thank you

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