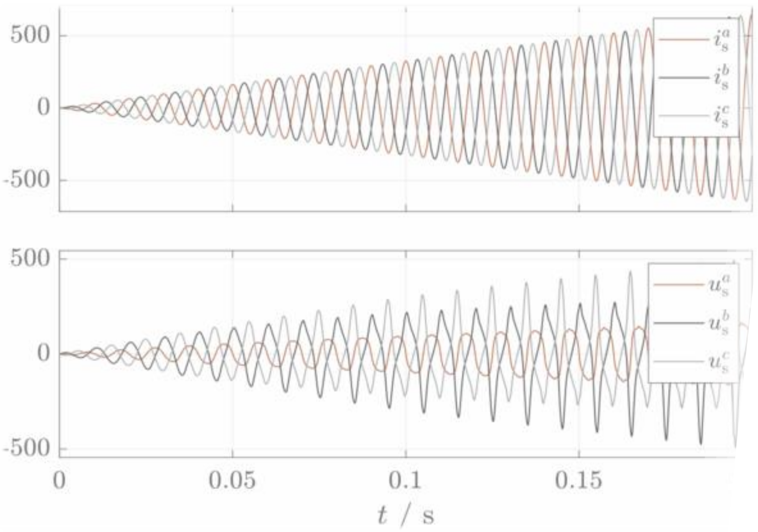
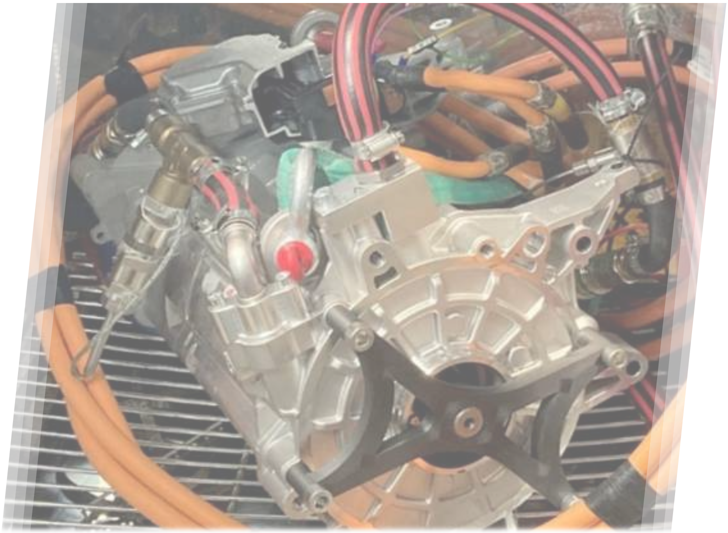


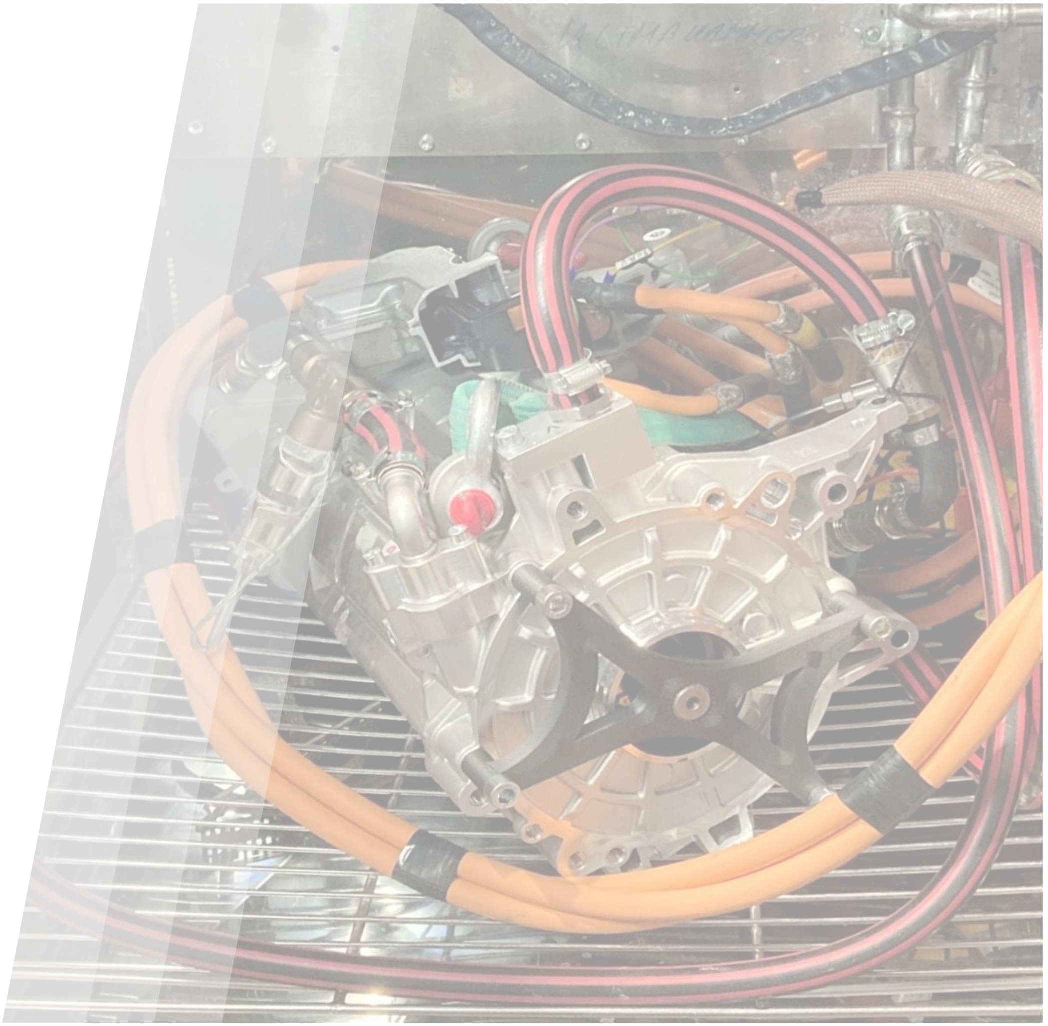

# E-Motor parameter identification: Possibilities from theory to vehicle

Johannes KÖLBL
Bernd PFEIFER
Christian SCHMIDT

We pioneer motion

# E-Motor parameter identification: Possibilities from theory to vehicle

1. **Personal introduction & motivation**
2. **Parameter identification**
   a. static on dyno test bench
   b. dynamic with ERA
3. **Evaluations**
   a. dyno vs. ERA
   b. on vehicle level
4. **Series identification with ERA**
5. **Summary & outlook**



ERA: E-machine Rapid Analyzer

1

# Personal introduction & motivation

# Personal introduction

**Christian SCHMIDT**
TPL / Test Engineer

**SCHAEFFLER @ Nürnberg**
Innovation System Concepts

christian.schmidt2@mail.schaeffler.com

**Johannes KÖLBL**
Expert PowerHIL / Test Engineer

**SCHAEFFLER @ Nürnberg**
E-powertrain testing

johannes.koelbl@mail.schaeffler.com

**Bernd PFEIFER**
PhD

**AVL SET GmbH @ Wangen im Allgäu**
**Hochschule München –**
**University of Applied Sciences**

bernd.pfeifer@avl.com

**SCHAEFFLER** Testcenter
Nürnberg

AVL inverter TS™ @ **AVL SET**
Wangen im Allgäu

Cooperation project:
**CE³ - Comparison of electric cars, electric drive dyno, and electric motor emulator**





# Motivation

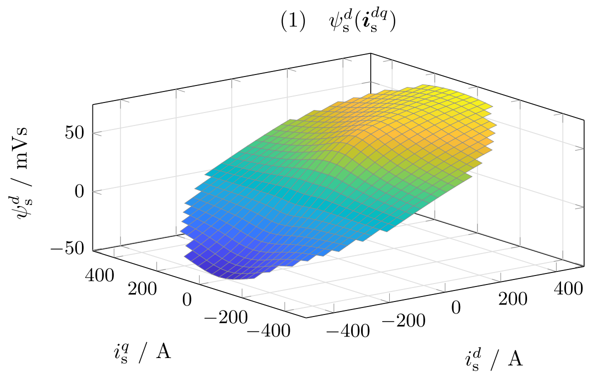
- Torque/speed control of electrical drives requires a parametrized machine model

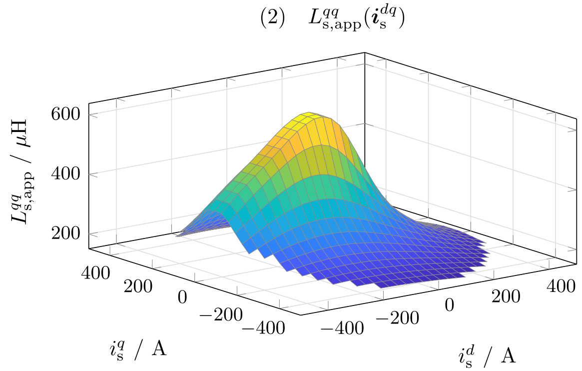
- Parameters vary per machine and per operating point

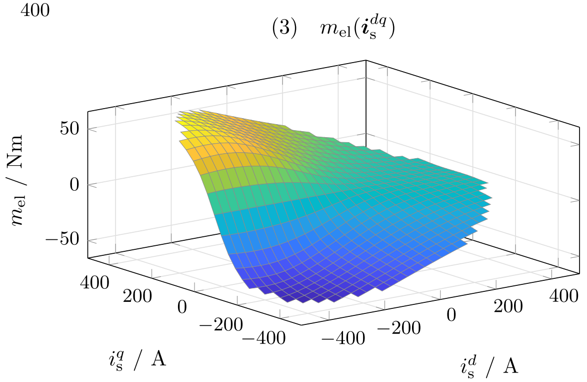
- More detailed and individual parameters

  → More robust, dynamic and efficient control

**Efficient electrical drive operation requires accurate machine parameters**




| Parameter name | Parameter |
|---|---|
| Stator resistance | $\boldsymbol{R}_s^{abc}(\vartheta_s)$ |
| Stator flux linkage maps (1) | $\boldsymbol{\psi}_s^{dq}(\boldsymbol{i}_s^{dq}, \vartheta_s)$ |
| ↪ Permanent magnet flux linkage | $\boldsymbol{\psi}_{pm}^{dq}(i_s^q, \vartheta_s)$ |
| ↪ Apparent inductance maps (2) | $\boldsymbol{L}_{s,app}^{dq}(\boldsymbol{i}_s^{dq}, \vartheta_s)$ |
| ↪ Differential inductance maps | $\boldsymbol{L}_{s,diff}^{dq}(\boldsymbol{i}_s^{dq}, \vartheta_s)$ |
| ↪ Torque maps (3) | $m_{el}(\boldsymbol{i}_s^{dq}, \vartheta_s)$ |

with stator currents $\boldsymbol{i}_s^{dq}$ and stator temperature $\vartheta_s$

$\boldsymbol{\psi}_s^{dq} = \boldsymbol{\psi}_{pm}^{dq} + \boldsymbol{L}_{s,app}^{dq}\,\boldsymbol{i}_s^{dq}$

$m_{el} = \frac{3n_p}{2}(\boldsymbol{i}_s^{dq})^\top \boldsymbol{J}\boldsymbol{\psi}_s^{dq}$

Fundamental and derived electromagnetic machine parameters as functions of stator currents and stator temperature.

# Static parameter identification on dyno test bench

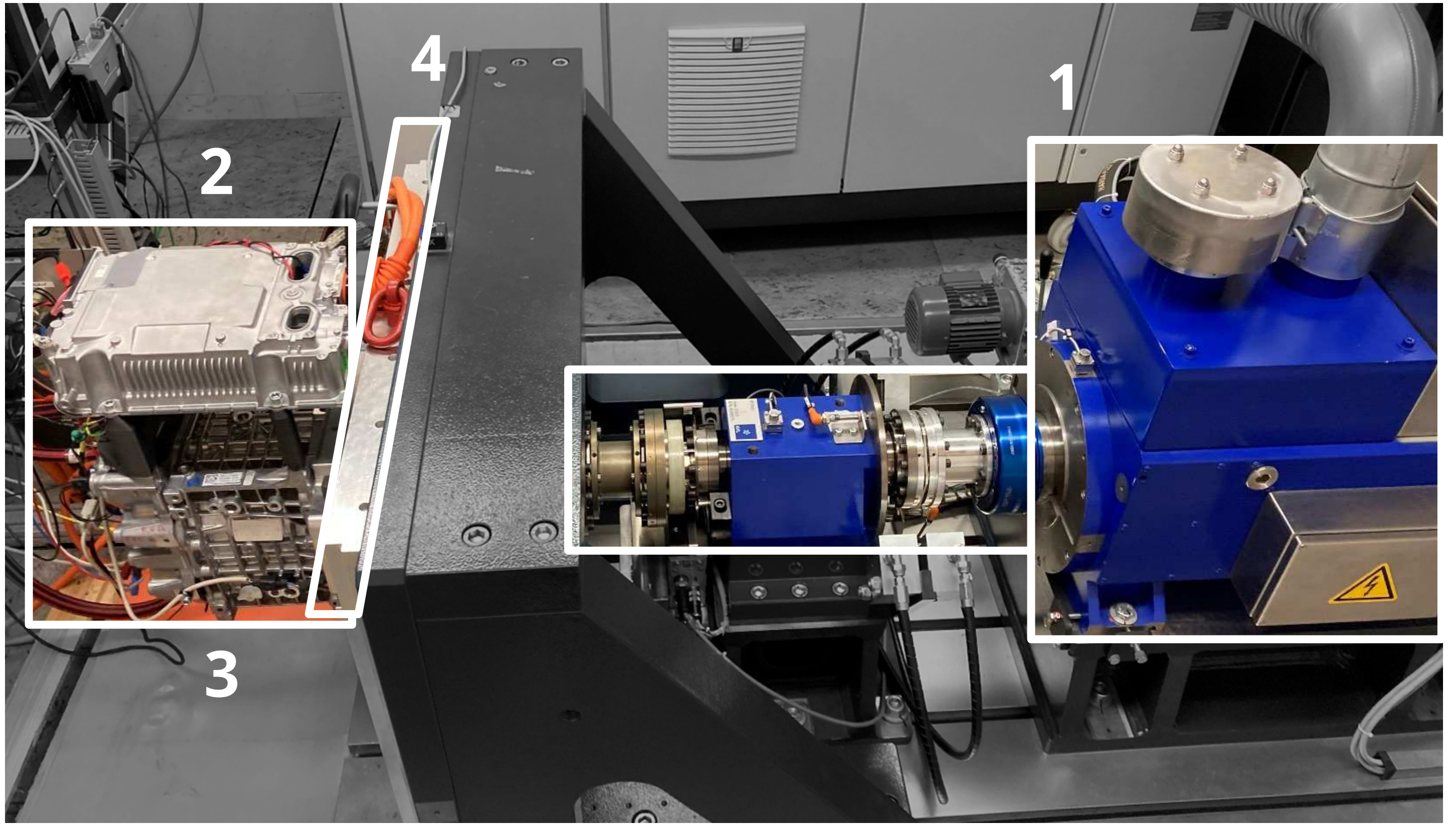
2.a

# Static parameter identification on dyno test bench

SCHAEFFLER HM AVL SET

## Test bench

1. Single-ended dyno test bench with external measurement system
2. High performance inverter → individual **Id / Iq controlling** necessary
3. Prepared electric machine **without** reducer
4. Test bench adaptation → **specific** adapter plate, shaft and coupling
5. Dyno booking, test execution and personnel




**Time and cost are primarily driven by manufacturing adaptation, test execution and personnel**

# Static parameter identification on dyno test bench

## Challenge

Stable steady-state working points

→ Identical conditions for

speed

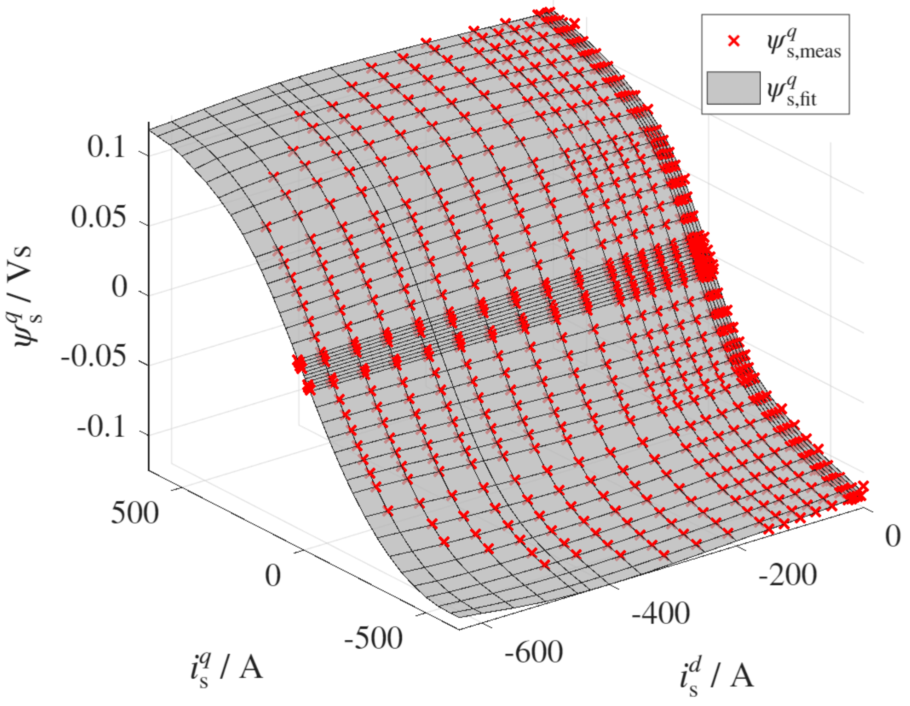
voltage

rotor temperature

over complete Id-Iq-current map

## Procedure

- Four-wire resistance measurement of stator
- Automatic test routine with
  - **BackEMF** measurement for PM flux linkage
  - **Id-Iq-current map** for stator flux linkage
- Parameter postprocessing offline with Schaeffler tool




**Accurate identification of d/q-axis stator flux-linkage maps under identical conditions**

EMF: electromotive force; PM: permanent magnet

# Dynamic parameter identification with ERA

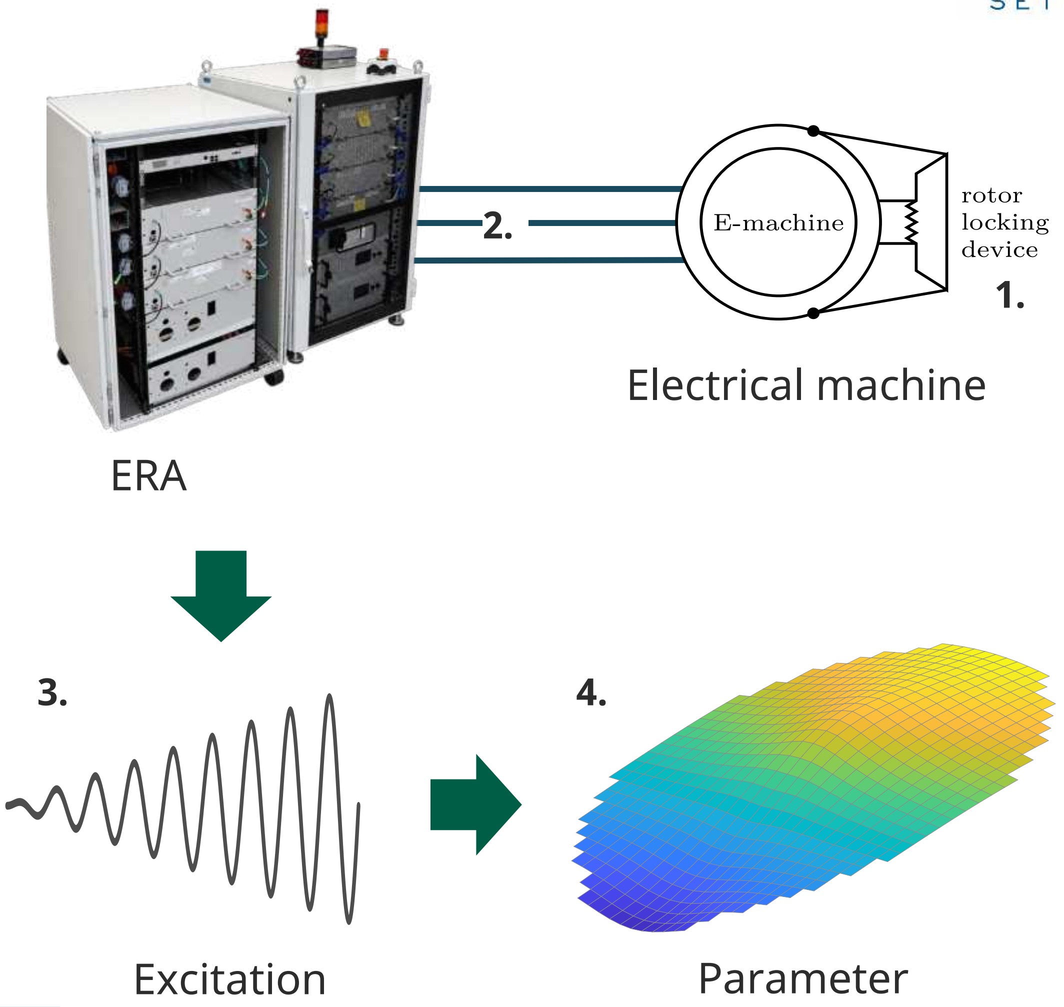
2.b

SCHAEFFLER HM AVL SET

# Basic idea – Electric machine Rapid Analyzer (ERA)

**Test bench (AVL Inverter TS™)**

- Robust current injection into unknown traction machines, enabled by high-performance multi-level topology
- Precise built-in voltage and current measurement, sampling rate up to 3.125 MHz (320 ns)
- The ERA is a hardware-reduced version of the AVL inverter TS™.




**Procedure**

1. Block rotor or connect rotor position sensor (RPS)
2. Connect the three-phase power cables
3. Inject highly dynamic current excitation
4. Identify machine parameters from the measured currents and voltages

**ERA used for machine parameter identification**

TS: test system; RPS: rotor position sensor

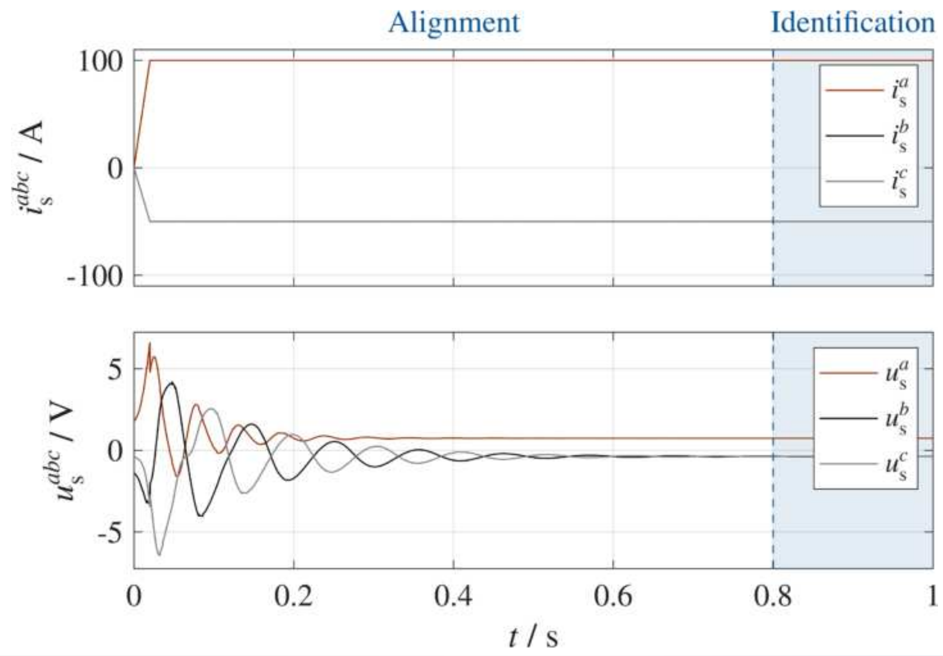


Public

# Identification scenario for resistance and permanent magnet (PM) flux linkage

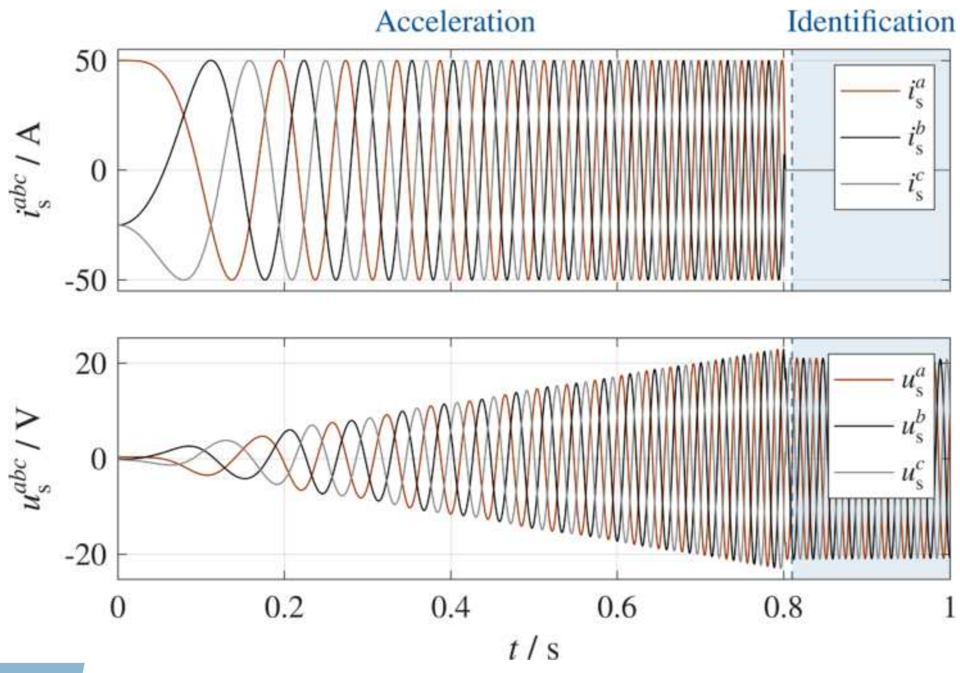
**Resistance:**

- **Alignment**: DC injection pulls the rotor d-axis onto the a-axis
- **Identification**: After alignment, resistance is identified from measured voltages and currents




**PM flux linkage:**

- **Acceleration**: AC injection accelerates the rotor from zero to reference speed
- **Identification**: After acceleration, switches are opened and PM flux linkage is identified from the back-EMF voltage

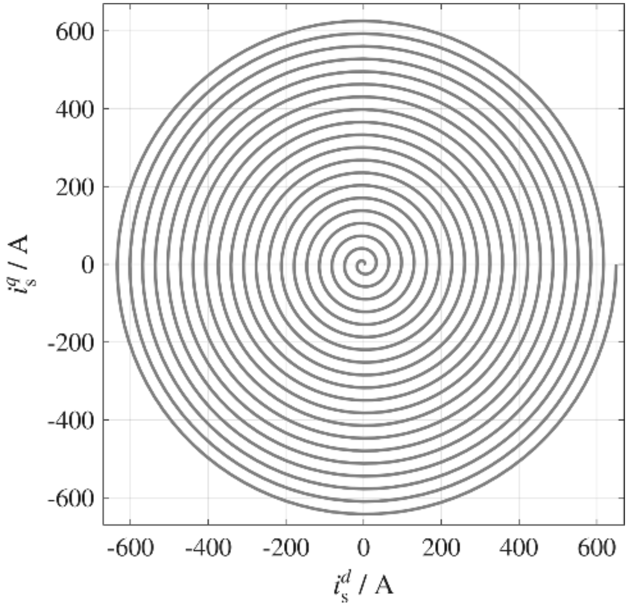


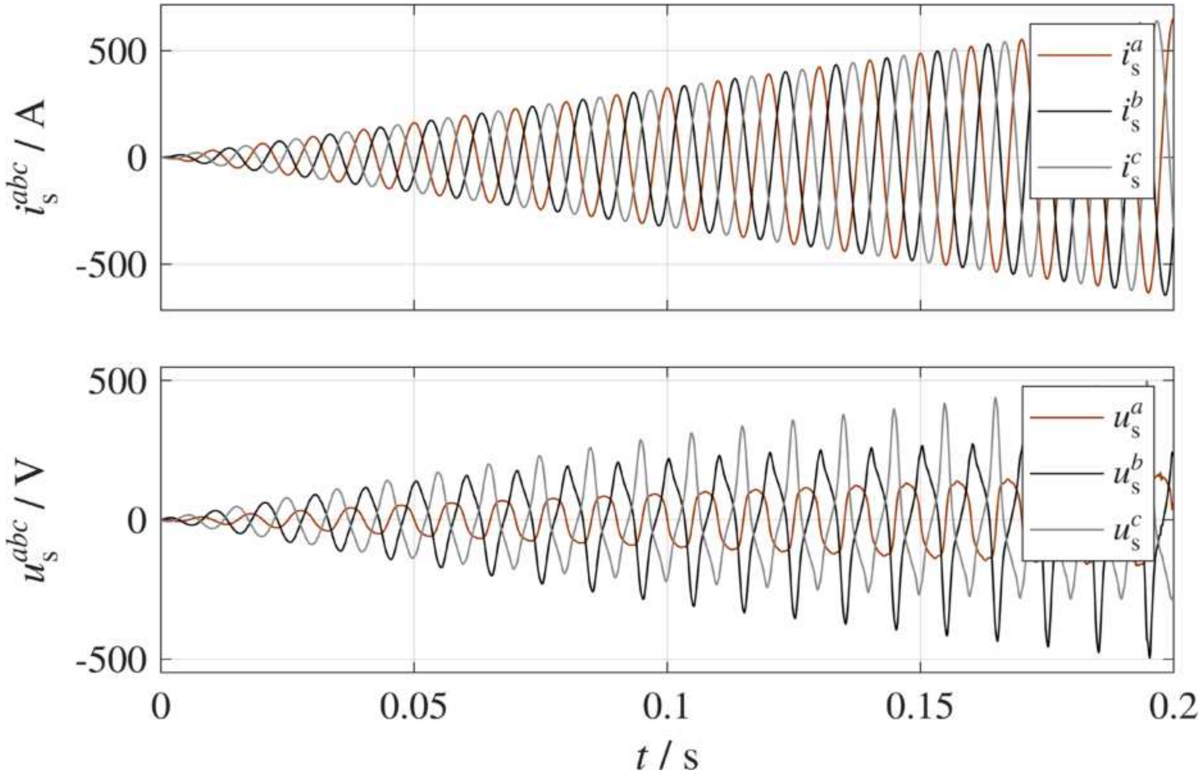

**Identification of resistance and PM flux done in advance**

EMF: electromotive force

# Identification scenario for inductances

- **Objective**: **cover all operating points of interest in minimum time, while accounting for**
- Hardware limits: maximum voltage, current, speed
- Physical effects: e.g. iron losses, excited by the current dynamics of the injection scenario




**Machine parameters are identified through dynamic current injection**

# Postprocessing – Measurements to parameter

## Signal preparation

- Signal filtering and compensation for sensor measurement errors
- Signal filtering to reduce measurement noise
- (Rotor position evaluation)

## Identification

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

## Parameter fitting

- Identification and compensation of flux linkage tilting due to physical iron effects
- Physical informed fitting of flux linkage maps
- Transfer of identified flux linkage maps to user environments
- (Compensation of cable)





# Comparison dyno vs. ERA identification

3.a

# Comparison dyno vs. ERA

| | Component | Dyno system | ERA system |
|---|---|---|---|
| **General** | Test bench | Single-ended dyno (1ED) | ERA |
| | AC inverter | 1x | integrated |
| | Test bench adaptation | Adapter-plate<br>Shaft<br>Coupling | Rotor locking device |
| | Testrun | Automated | Manual or automated |
| **Measurement** | Power Analyzer | External | External / integrated |
| | Current sensor | External | External / integrated |
| | Voltage sensor | External | External / integrated |
| | Temperature | (1x) | - |
| | Torque | (1x) | - |
| | Rotor position sensor (RPS) | 1x | (1x) |

costs

time

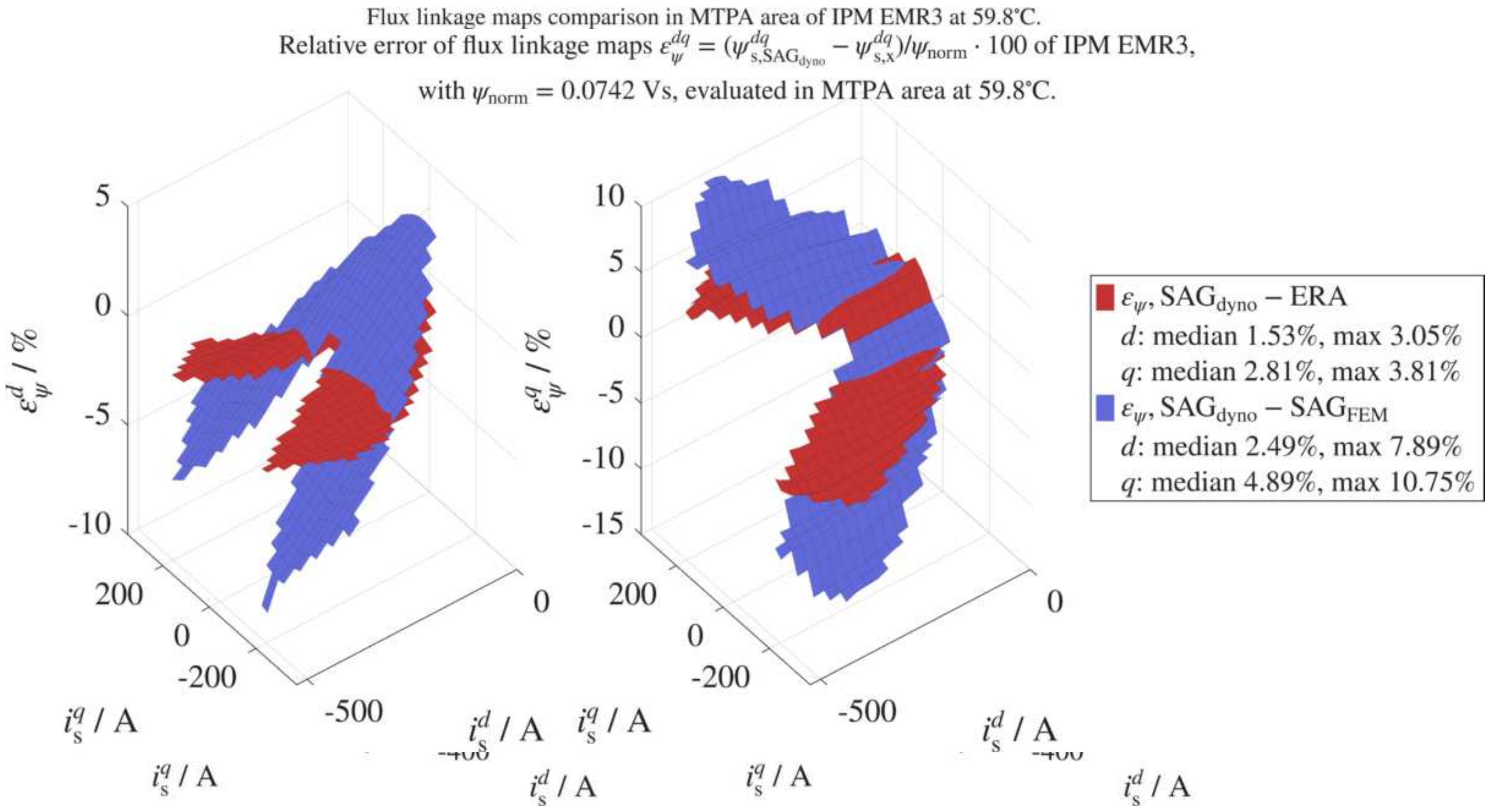
**Reduced effort with ERA-based parameter identification**

ERA: E-machine Rapid Analyzer; RPS: rotor position sensor

# Comparison dyno vs. ERA

| Parameter | Torque accuracy | System efficiency |
| --- | --- | --- |

- Stator flux linkage maps
- MTPA area
- Calculated LUTs from dyno
  - vs. ERA
  - vs. FEM

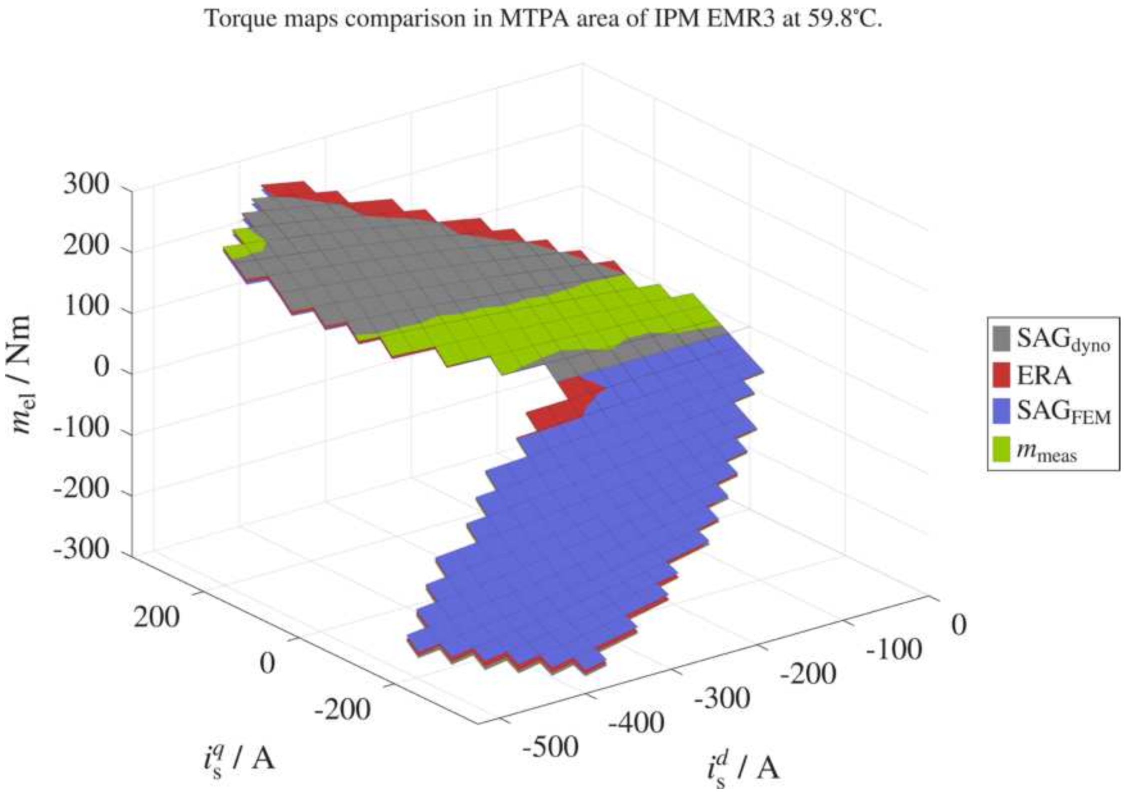



ERA: E-machine Rapid Analyzer; MTPA: maximum torque per ampere; FEM; finite element method

# Comparison dyno vs. ERA

Parameter | **Torque accuracy** | System efficiency

- Dyno torque (Id-/Iq-map)
- MTPA area
- Measured torque from dyno vs. inverter calculated with
  - dyno identification
  - ERA identification
  - FEM simulation

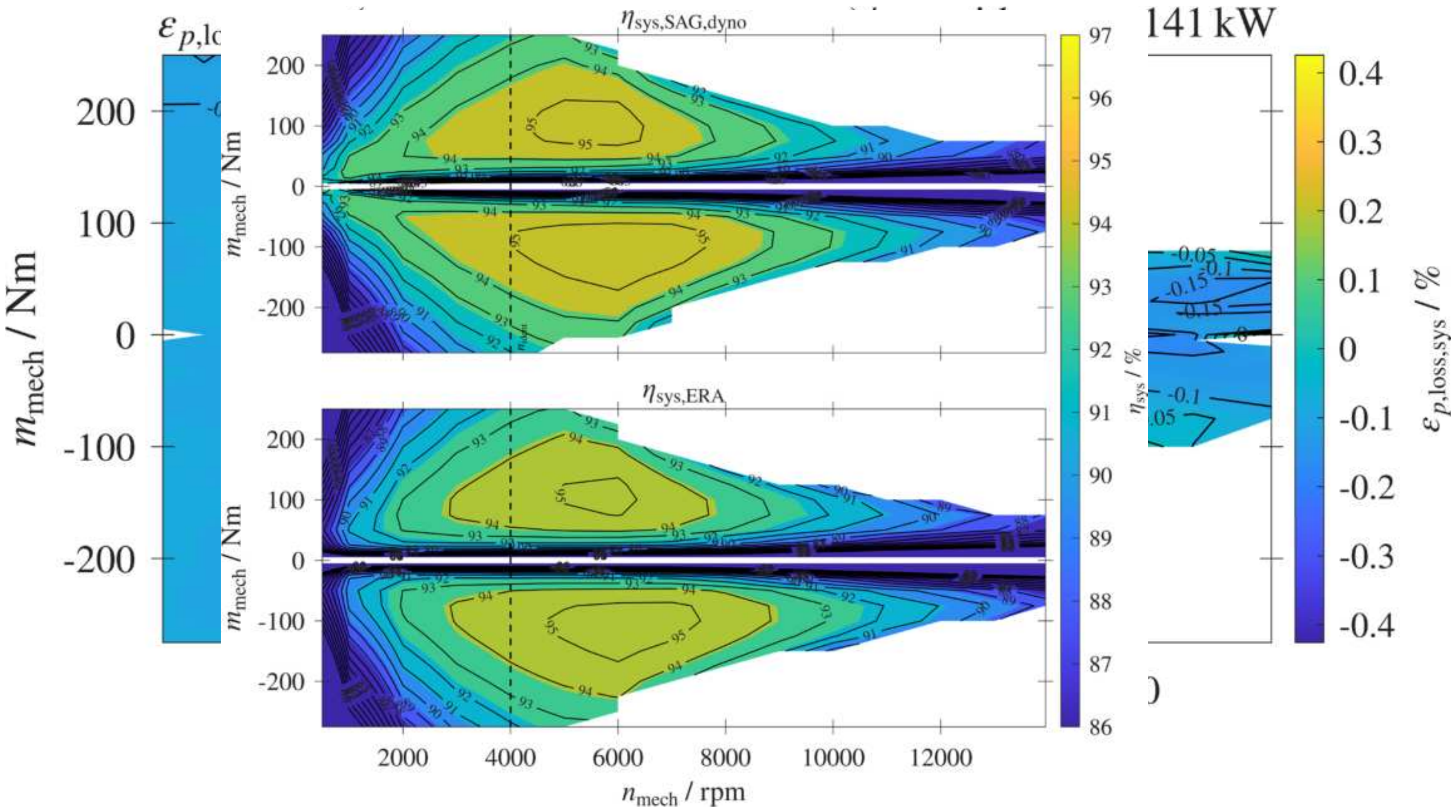



ERA: E-machine Rapid Analyzer; MTPA: maximum torque per ampere; FEM; finite element method

# Comparison dyno vs. ERA

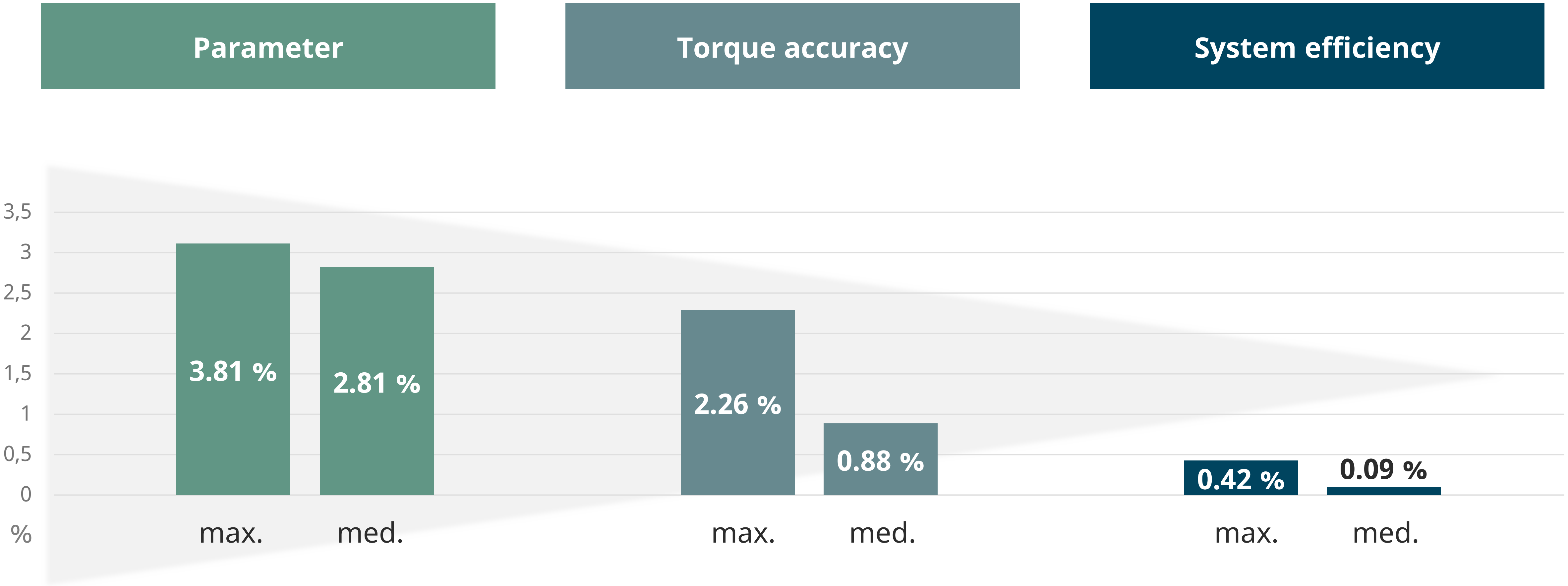
| Parameter | Torque accuracy | System efficiency |
|---|---|---|

- Torque-speed-map
- System efficiency
  - mot: $P_{mech} / P_{DC}$
  - gen: $P_{DC} / P_{mech}$
- Efficiency with
  - dyno identification
  - ERA identification




ERA: E-machine Rapid Analyzer; mot: motor mode; gen: generator mode

# Comparison dyno vs. ERA




**ERA-based identification delivers results comparable to dyno-based identification**

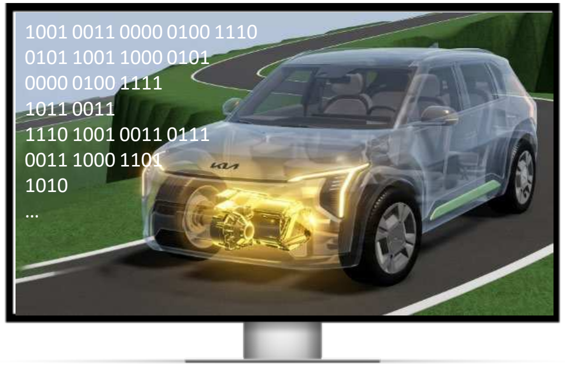
ERA: E-machine Rapid Analyzer; max: maximum; med: median

# Evaluations on vehicle level

3.b

# Evaluations on vehicle level with 400 V development vehicle – SC.EV32


**Data mining in cloud**




**Virtual development using "Digital Twin"**

## Vehicle

400 V Kia EV3 model year 2025

## Key components

EMR4 150 kW series with **ERA-based identification parameters**

## Set-up

Highlight: **"Rolling testbench"** in final vehicle environment

Full instrumentation for precise data acquisition:

- → HV voltage & current sensors
- → torque sensors in gearbox and drive shafts

## Focus

Live data transfer with LTE realtime cloud logging device

Generation of "Digital Twin" for 1-to-1 modelling of drive unit

EMR4: E-drivetrain 4th generation; ERA: E-machine Rapid Analyzer; LTE: long term evolution





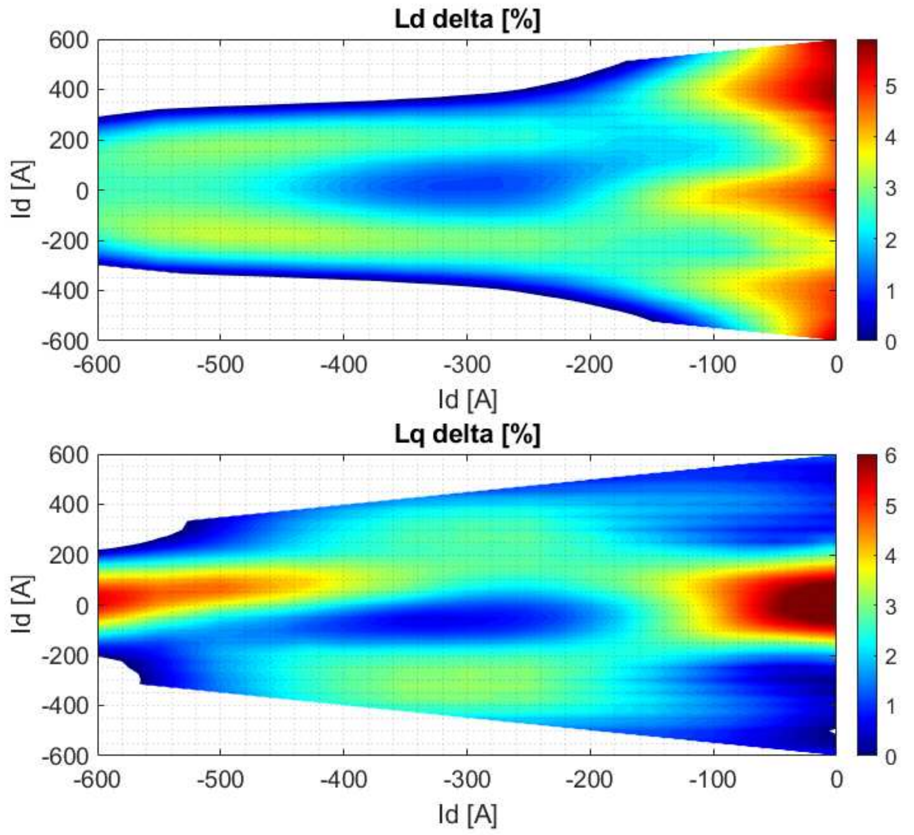
# Evaluations on vehicle level – Simulative assumptions

- Input data:
  Measured parameters with identical EMR3 series motor

- PsiD and PsiQ scaled with delta (ERA vs. test bench) over Id and Iq:

$$\psi_{\mathrm{s,scaled}}^{dq} = \psi_{\mathrm{s,orig}}^{dq} \left( 1 - \frac{L_{\mathrm{s,max}}}{L_{\mathrm{s,SAG}} - L_{\mathrm{s,ERA}}} \right)$$

- EDS simulation done with related motor model




EMR3: E-drivetrain 3th generation;
WLTC: worldwide harmonized light vehicles test cycle;
ERA: E-machine Rapid Analyzer; EDS: electric drive system

**Approx. 2 % differences in total vehicle consumption (rough estimation)**





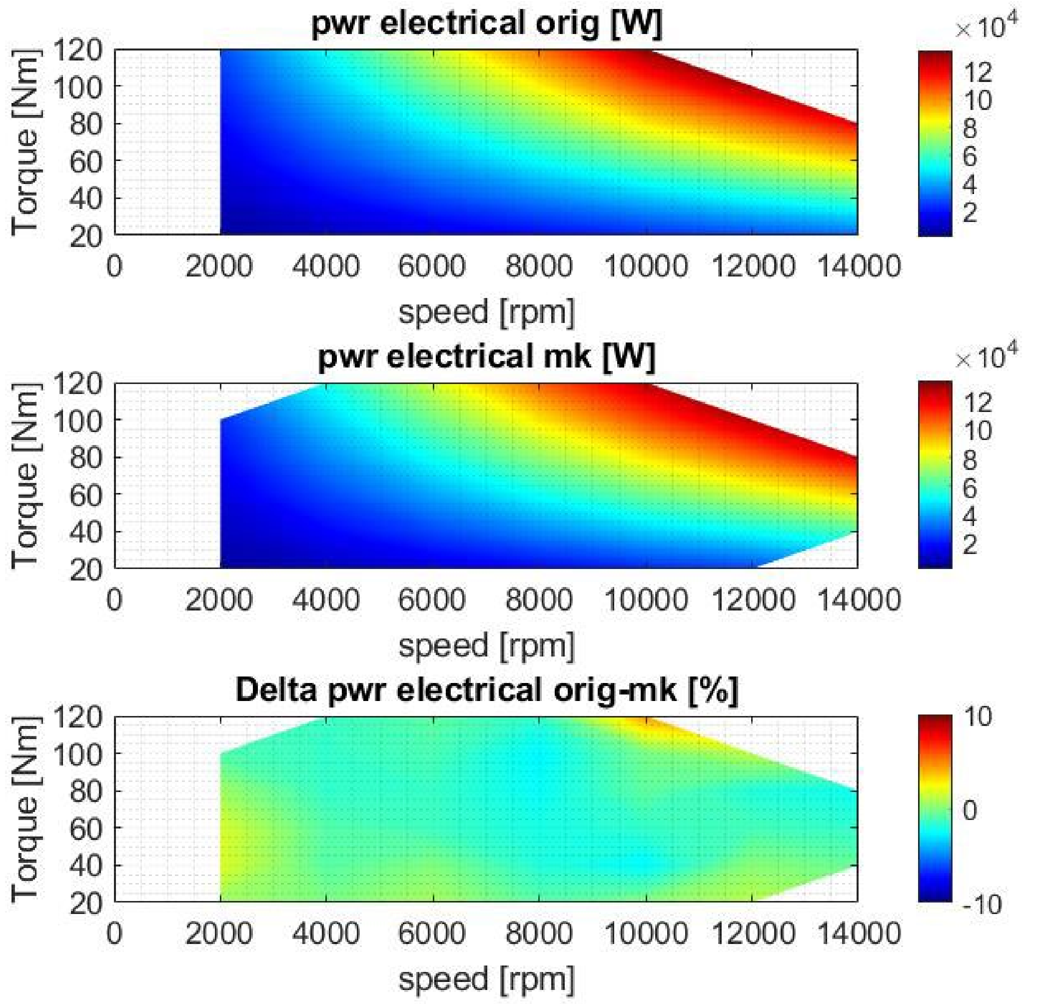
 

# Evaluations on vehicle level – Chassis dyno measurements

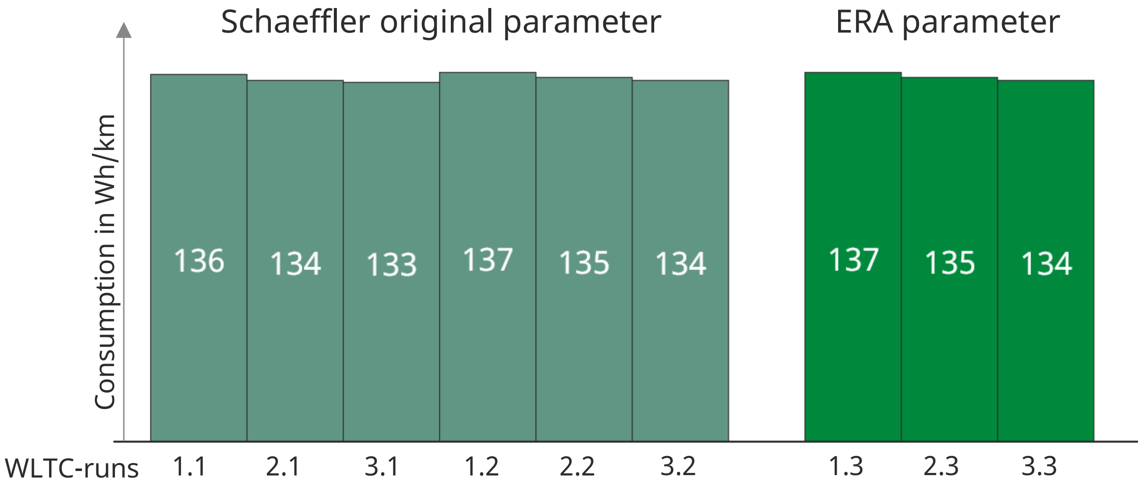
**Driving scenario #1** with SC.EV32:

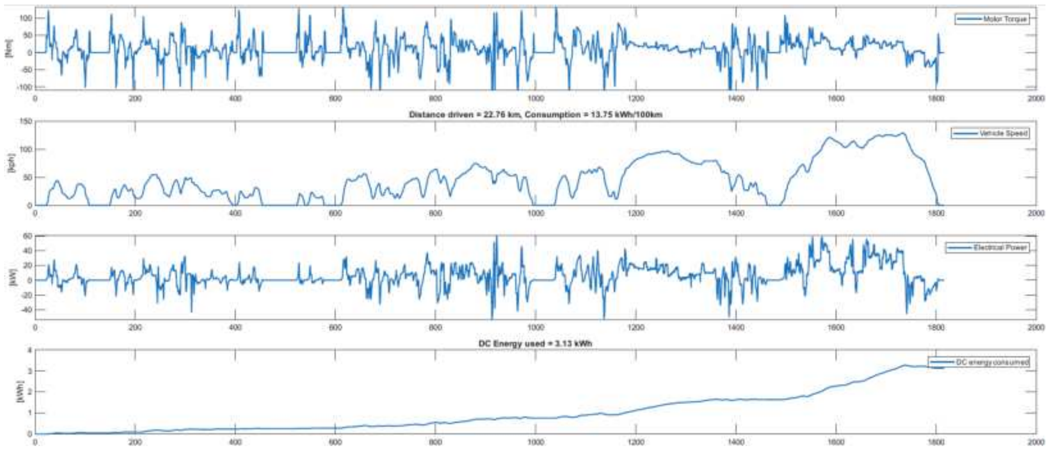
**Constant drive with single torque and speed plateaus**
(20 - 140 Nm and 2000 - 14000 rpm)

- Calculation on vehicle level
  → Averaging of plateaus
  → Integration into lookup tables
  → Calculation of electrical drivetrain power



# Evaluations on vehicle level – Chassis dyno measurements




**Driving scenario #2** with SC.EV32 :

**Repeatable WLTCs (3 cycles in one block)**

- 6x Schaeffler original parameter
- 3x ERA-based parameter

- Consumption decrease related to warming up reducer oil → less losses in reducer

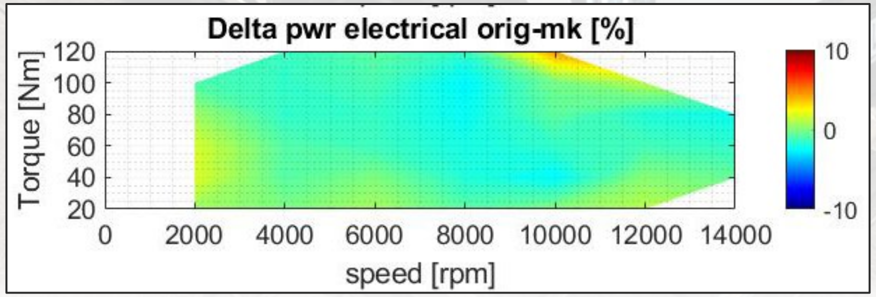
ERA: E-machine Rapid Analyzer; WLTC: worldwide harmonized light vehicles test cycle

# Evaluations on vehicle level – Chassis dyno measurements

**Driving scenario #1** with SC.EV32 :

**Constant drive with single torque and speed plateaus**
(20 - 140 Nm and 2000 - 14000 rpm)

- Calculation on vehicle level
  → Averaging of plateaus
  → Integration into lookup tables
  → Calculation of electrical drivetrain power



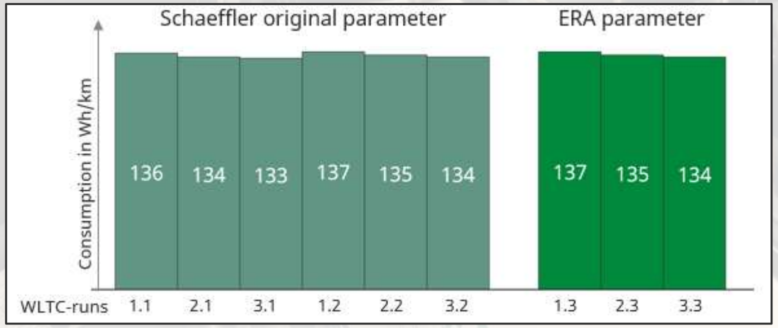

**Constant drive: < 0.5 % deviation in all relevant WLTC areas**

**Driving scenario #2** with SC.EV32 :

**Repeatable WLTCs (3 cycles in one block)**

- 6x Schaeffler original parameter
- 3x ERA-based parameter

- Consumption decrease related to warming up reducer oil
  → less losses in reducer



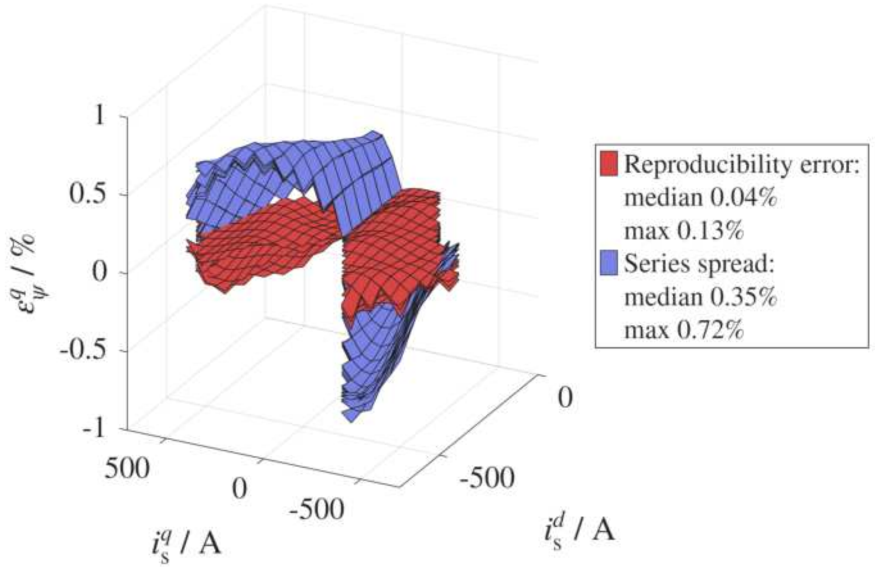

**Highly repeatable WLTC results: deviations < 0.5 % - less than test-bench measurement uncertainty**

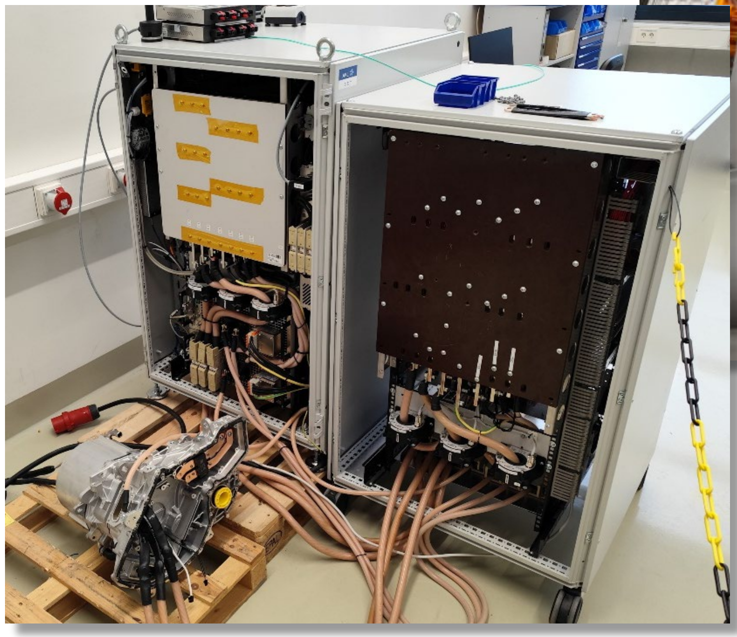
ERA: E-machine Rapid Analyzer; WLTC: worldwide harmonized light vehicles test cycle

# Series identification with ERA

# Series identification with ERA on EMR4 series

- 15 Schaeffler EMR4 machines from 9 months of series production
  → Each machine individually identified
- Figure shows 2 machines, identified 4 consecutive times each, evaluated in MTPA area



**High reproducibility of ERA-based identification:**
**Series-production variation clearly identifiable**

ERA: E-machine Rapid Analyzer; EoL: end of line; EMR4: E-drivetrain 4th generation; MTPA: maximum torque per ampere





5

# Summary & Outlook

# Summary and Outlook

## Summary

- High reproducibility (< 0,13 %)
- Cost dyno >> cost ERA (less hardware, fast procedure)
- Accuracy: < 2,26 % (dyno$_{torque}$), < 0,42 % (dyno$_{efficiency}$), < 0,5 % (vehicle$_{WLTC}$)

## Outlook

- Identification of parameter dependencies on angle, speed & iron losses
- Rotor-position-sensorless ERA
- Automated identification on ERA
- Use-cases: Failure analysis, EoL integration, new identification fields

SCHAEFFLER

HM

AVL

SET