AVL SET GmbH

High performance e-motor emulation on the example of a six-phase synchronous motor

Inverter Trends & Technology – 2nd Wangener Automotive Symposium
November 7th 2019, Dr.-Ing. Patrick Winzer

Why 6~ motors?

System level
- Fault tolerance through redundancy (autonomous driving)

Performance level
- Improved magnetics (torque ripple, utilization)
- Twice the power with the same PE parts

System level
- More parts required

Performance level
- Control strategies more challenging

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Performance level
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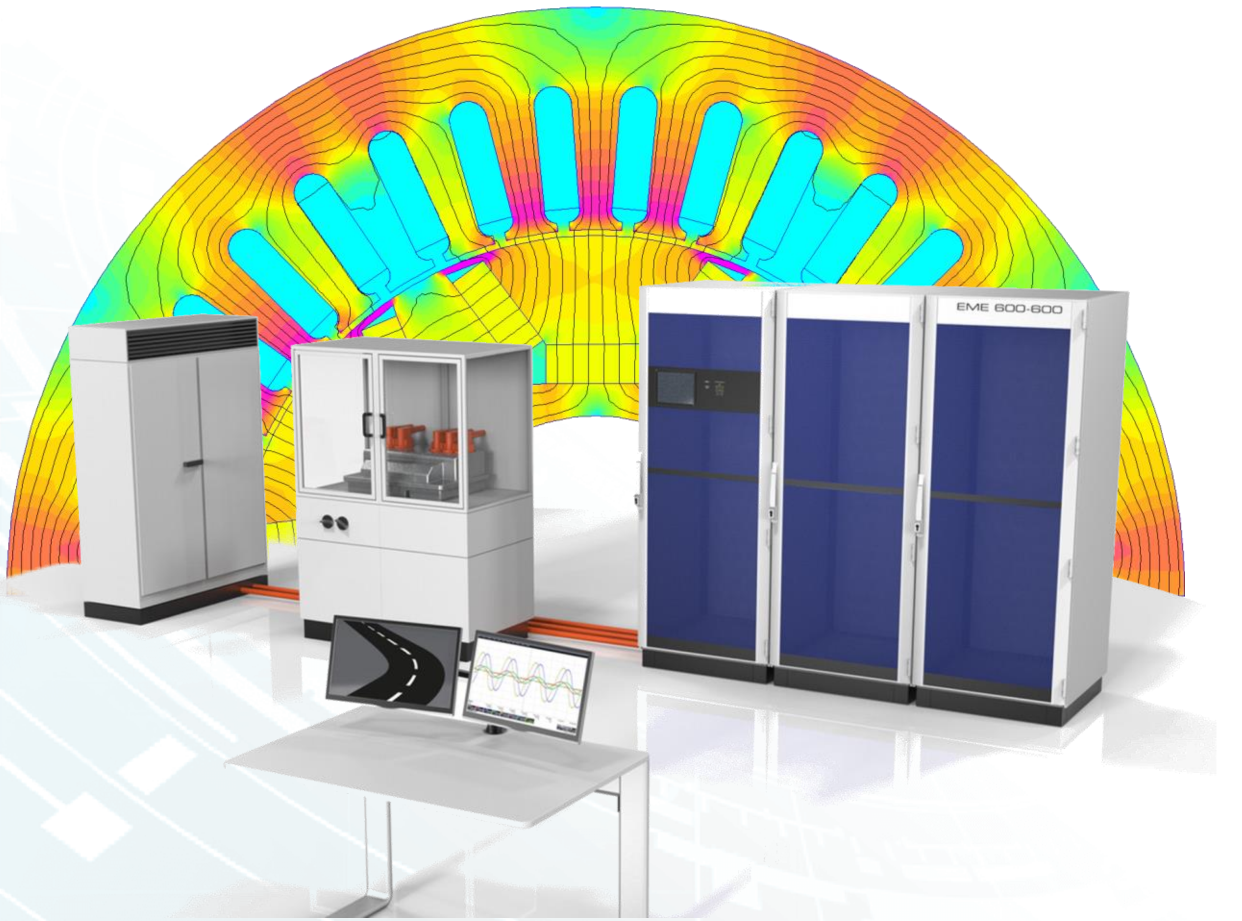
System level
- More parts requ

Performance level
- Control strategies more challenging

Emulator use-case
- Choosing the right model and modeling depth
- Generating motor data
- Understanding the effects
- Optimizing the inverter using an E-Motor Emulator

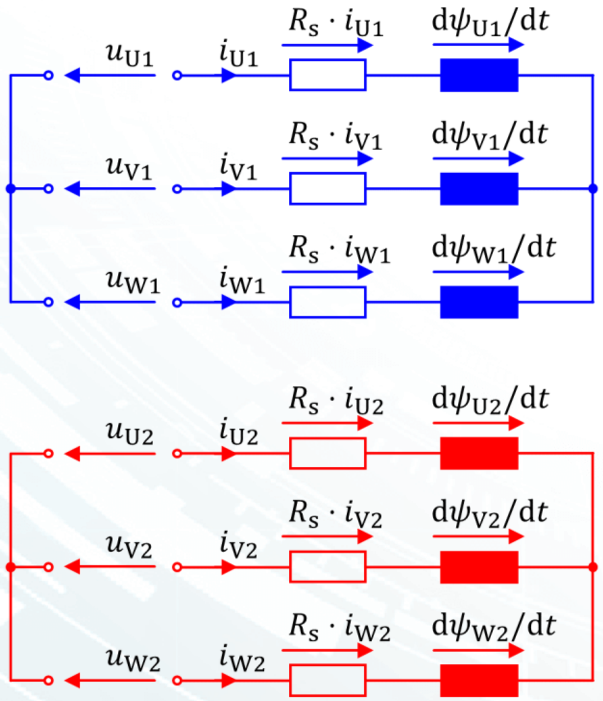
Agenda

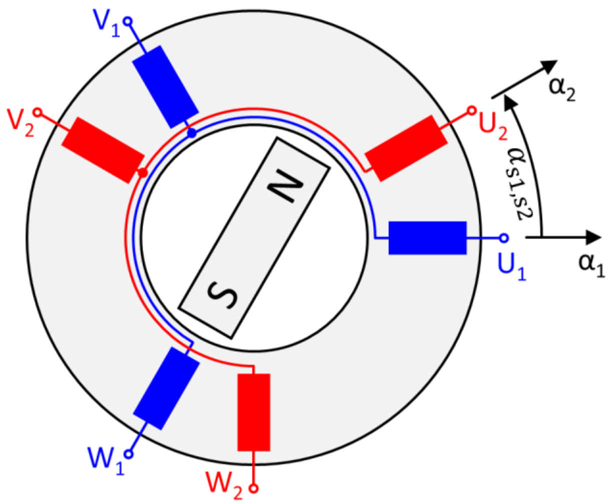


1. Modeling of the 6~ PMSM
    1. 6~ theory
    2. 6~ PMSM model depths
2. Magnetical effects
3. Dynamic behavior of the 6~ PMSM
4. Live Test Cases with the Emulator

Modeling of the 6~ PMSM
6~ theory

The 6~ motor in U/V/W representation





$$u_{U1} = R_s \cdot i_{U1} + \frac{d\psi_{U1}}{dt}$$

$$u_{V1} = R_s \cdot i_{V1} + \frac{d\psi_{V1}}{dt}$$

$$u_{W1} = R_s \cdot i_{W1} + \frac{d\psi_{W1}}{dt}$$

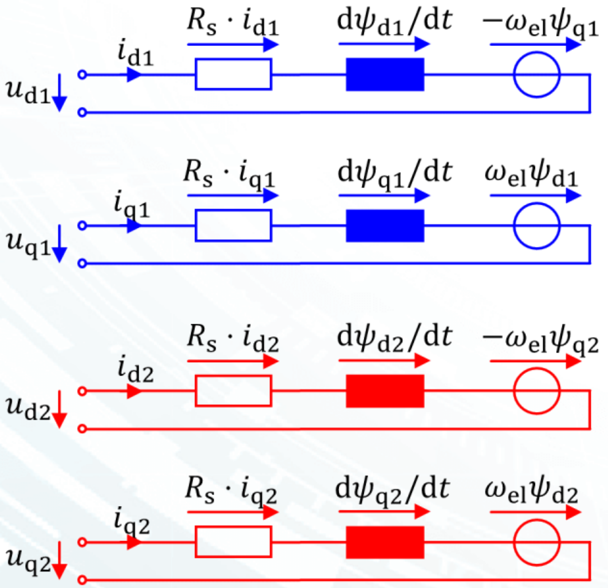
$$u_{U2} = R_s \cdot i_{U2} + \frac{d\psi_{U2}}{dt}$$

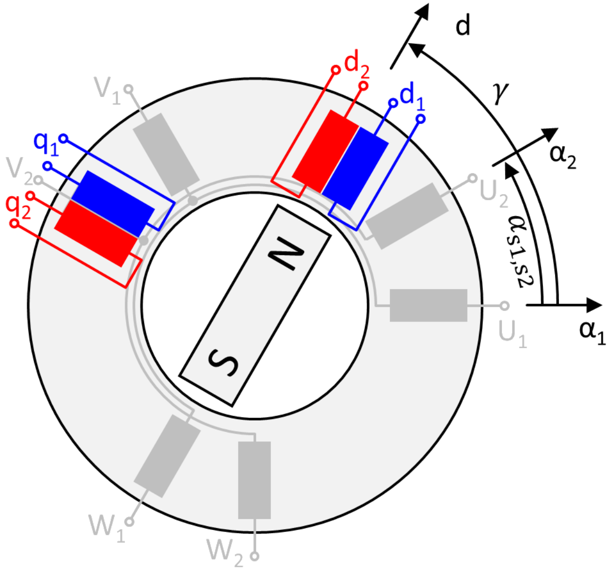
$$u_{V2} = R_s \cdot i_{V2} + \frac{d\psi_{V2}}{dt}$$

$$u_{W2} = R_s \cdot i_{W2} + \frac{d\psi_{W2}}{dt}$$

Modeling of the 6~ PMSM
6~ theory

The 6~ motor in d/q representation



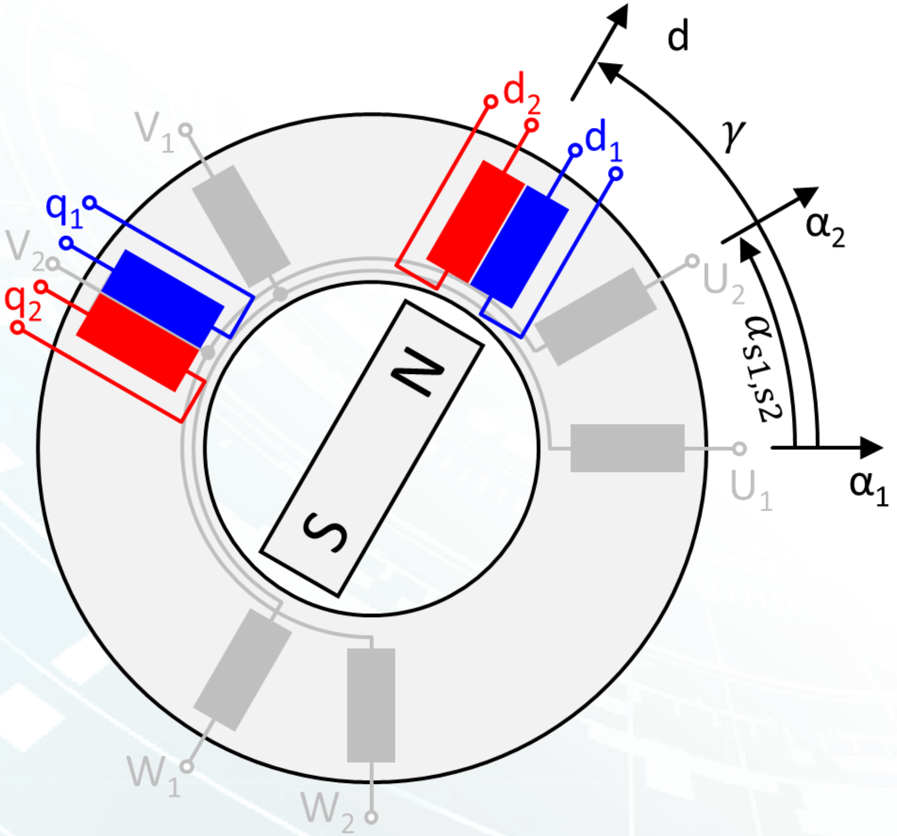


$$u_{d1} = R_s \cdot i_{d1} + \frac{d\psi_{d1}}{dt} - \omega_{el} \cdot \psi_{q1}$$
$$u_{q1} = R_s \cdot i_{q1} + \frac{d\psi_{q1}}{dt} + \omega_{el} \cdot \psi_{d1}$$
$$u_{d2} = R_s \cdot i_{d2} + \frac{d\psi_{d2}}{dt} - \omega_{el} \cdot \psi_{q2}$$
$$u_{q2} = R_s \cdot i_{q2} + \frac{d\psi_{q2}}{dt} + \omega_{el} \cdot \psi_{d2}$$

$$M_i = \frac{3}{2} p \cdot \left(\psi_{d1} \cdot i_{q1} - \psi_{q1} \cdot i_{d1} + \psi_{d2} \cdot i_{q2} - \psi_{q2} \cdot i_{d2}\right)$$

Modeling of the 6~ PMSM
6~ PMSM model depths

The 6~ PMSM as linear model (L)



$$u_{d1} = R_s \cdot i_{d1} + \frac{d\psi_{d1}}{dt} - \omega_{el} \cdot \psi_{q1}$$

$$u_{q1} = R_s \cdot i_{q1} + \frac{d\psi_{q1}}{dt} + \omega_{el} \cdot \psi_{d1}$$

$$u_{d2} = R_s \cdot i_{d2} + \frac{d\psi_{d2}}{dt} - \omega_{el} \cdot \psi_{q2}$$

$$u_{q2} = R_s \cdot i_{q2} + \frac{d\psi_{q2}}{dt} + \omega_{el} \cdot \psi_{d2}$$

$$\psi_{d1} = L_{d1,d1} \cdot i_{d1} + L_{d1,d2} \cdot i_{d2} + \psi_{PM}$$

$$\psi_{q1} = L_{q1,q1} \cdot i_{q1} + L_{q1,q2} \cdot i_{q2}$$

$$\psi_{d2} = L_{d2,d1} \cdot i_{d1} + L_{d2,d2} \cdot i_{d2} + \psi_{PM}$$

$$\psi_{q2} = L_{q2,q1} \cdot i_{q1} + L_{q2,q2} \cdot i_{q2}$$

Data origin

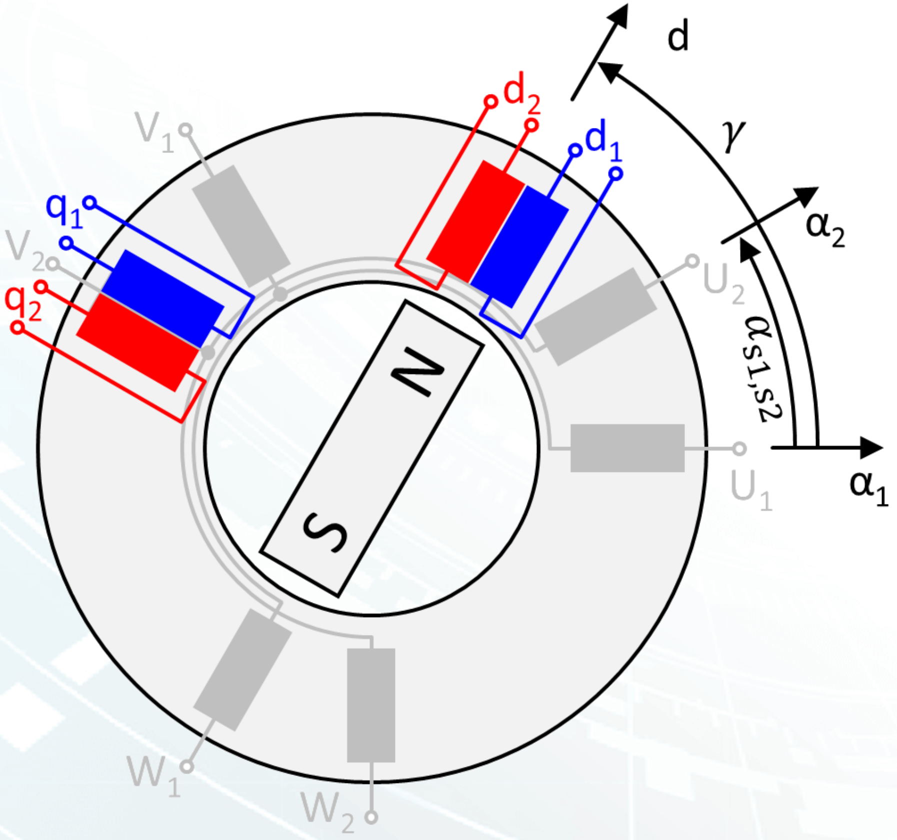
- Analytical calculation

Useful for

- Quick proof of concept for new designs
- Debugging of functions
- Parameter studies

Modeling of the 6~ PMSM
6~ PMSM model depths

The 6~ PMSM as nonlinear model (NL)



$$u_{d1} = R_s \cdot i_{d1} + \frac{d\psi_{d1}}{dt} - \omega_{el} \cdot \psi_{q1}$$
$$u_{q1} = R_s \cdot i_{q1} + \frac{d\psi_{q1}}{dt} + \omega_{el} \cdot \psi_{d1}$$
$$u_{d2} = R_s \cdot i_{d2} + \frac{d\psi_{d2}}{dt} - \omega_{el} \cdot \psi_{q2}$$
$$u_{q2} = R_s \cdot i_{q2} + \frac{d\psi_{q2}}{dt} + \omega_{el} \cdot \psi_{d2}$$

$$\psi_{d1} = \mathrm{LUT}\left(i_{d1}, i_{q1}, i_{d2}, i_{q2}\right)$$
$$\psi_{q1} = \mathrm{LUT}\left(i_{d1}, i_{q1}, i_{d2}, i_{q2}\right)$$

Data origin

- Finite Elements Analysis (FEA)
- Dyno measurements

Useful for

- Controller tuning
- Operational strategies

Modeling of the 6~ PMSM
6~ PMSM model depths

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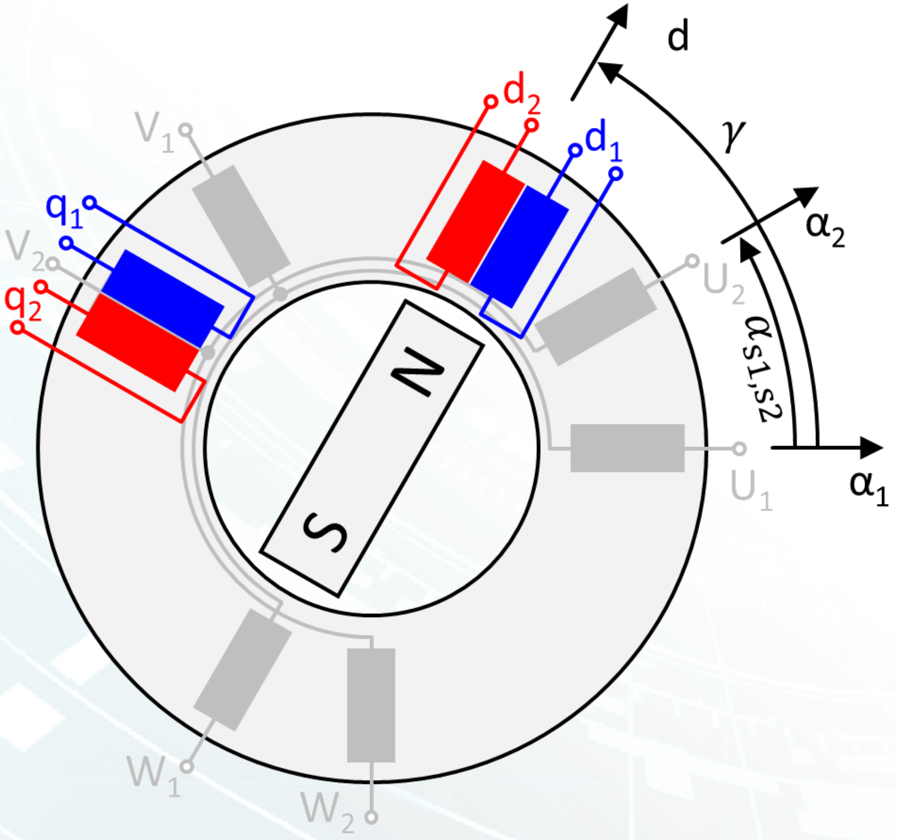
The 6~ PMSM as nonlinear model with harmonics (NLH)



$$u_{d1} = R_s \cdot i_{d1} + \frac{d\psi_{d1}}{dt} - \omega_{el} \cdot \psi_{q1}$$

$$u_{q1} = R_s \cdot i_{q1} + \frac{d\psi_{q1}}{dt} + \omega_{el} \cdot \psi_{d1}$$

$$u_{d2} = R_s \cdot i_{d2} + \frac{d\psi_{d2}}{dt} - \omega_{el} \cdot \psi_{q2}$$

$$u_{q2} = R_s \cdot i_{q2} + \frac{d\psi_{q2}}{dt} + \omega_{el} \cdot \psi_{d2}$$

$$\psi_{d1} = \mathrm{LUT}\left(i_{d1}, i_{q1}, i_{d2}, i_{q2}, \gamma\right)$$

$$\psi_{q1} = \mathrm{LUT}\left(i_{d1}, i_{q1}, i_{d2}, i_{q2}, \gamma\right)$$

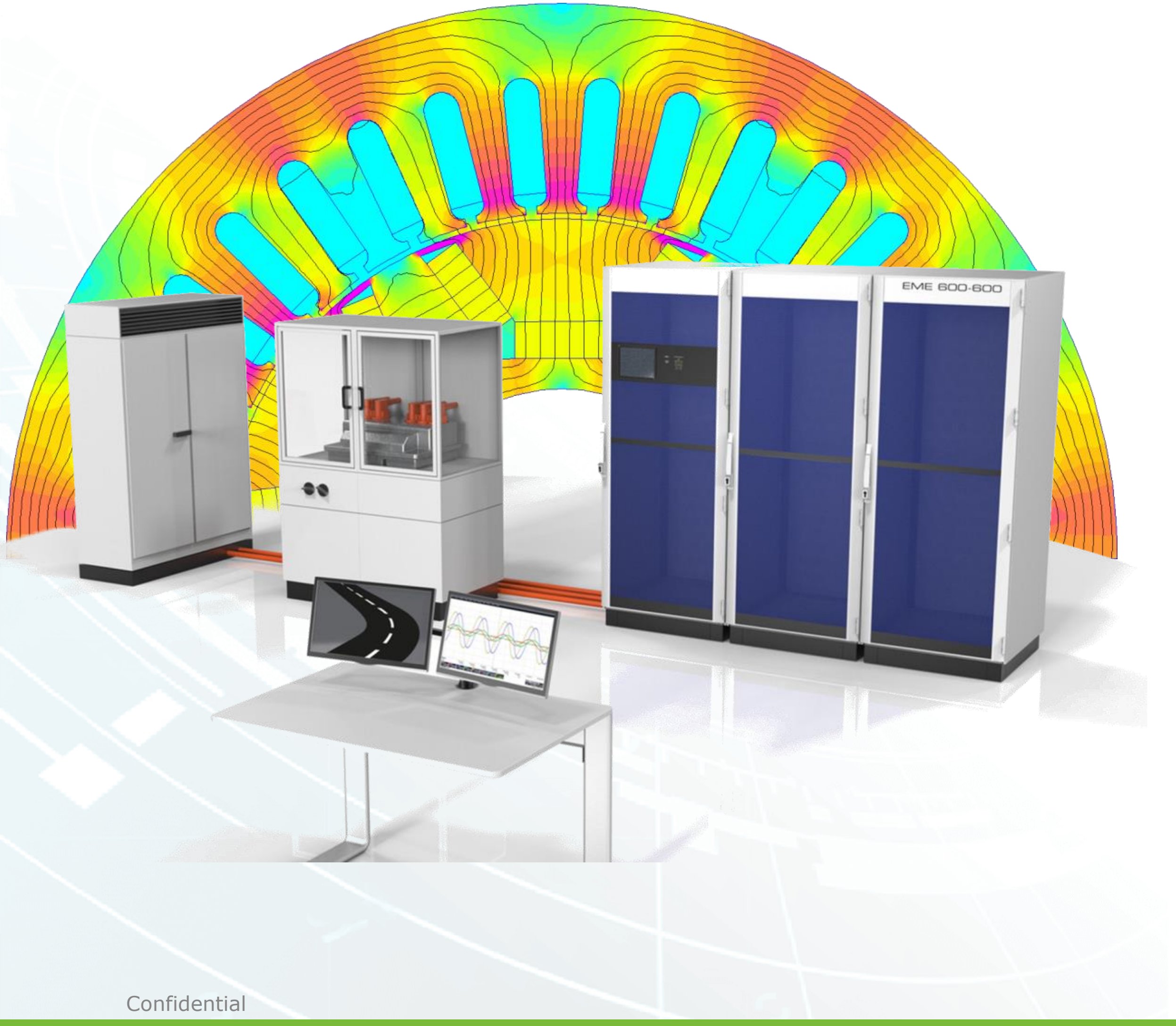
Data origin

- Finite Elements Analysis (FEA)
- Dyno measurements + analytical models

Useful for

- Controller robustness test
- Fine-tuning of harmonic effects

Agenda



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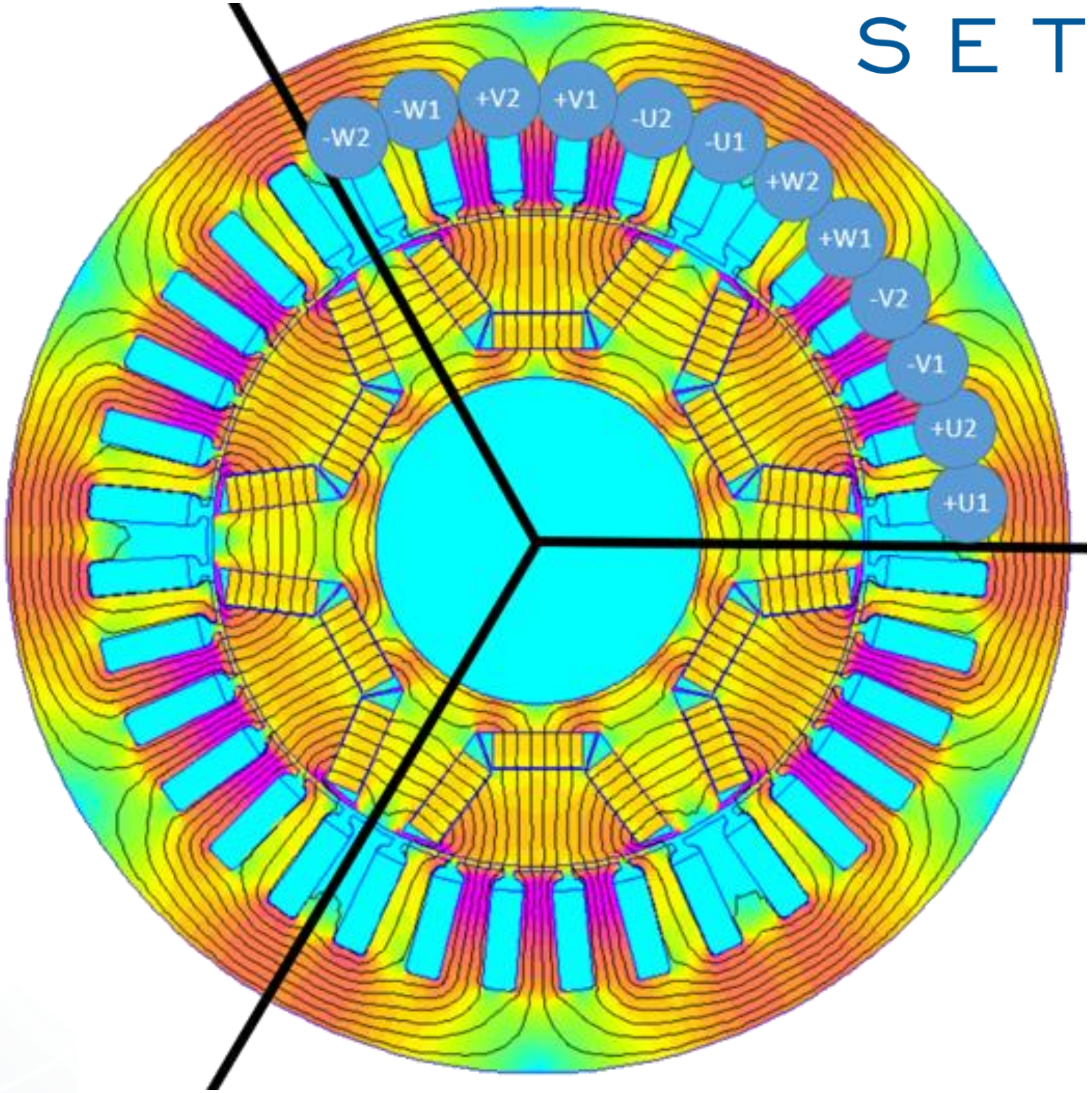
2. **Magnetical effects**
3. Dynamic behavior of the 6~ PMSM
4. Live Test Cases with the Emulator

Magnetical Effects
FEA Model

Geometry

- Derived from a 3ph motor geometry
- Number of pole pairs $p = 3$
- Magnetics
  - Neodymium magnets
  - buried in U-Shape: $L_\mathrm{q} > L_\mathrm{d}$
  - Saturating iron curve
- Winding
  - distributed
  - 1 coil per phase and pole pair
  - Stator offset $\alpha_{s1,s2} = 30°$



Magnetical Effects
FEA result discussion

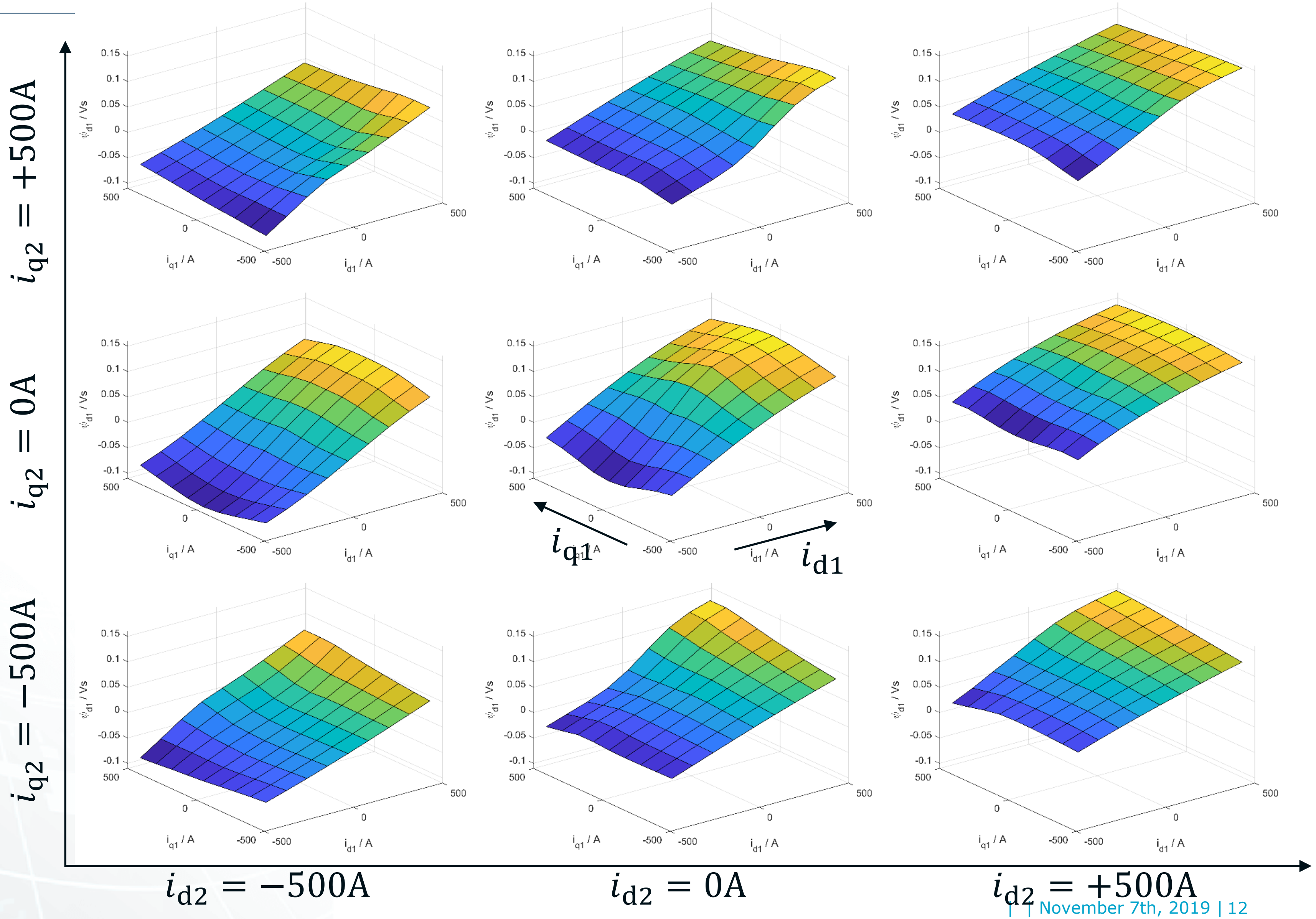
Nonlinear model

Graphs are representing flux linkage in d1-axis

$$\psi_{d1} = f(i_{d1}, i_{q1}, i_{d2}, i_{q2})$$

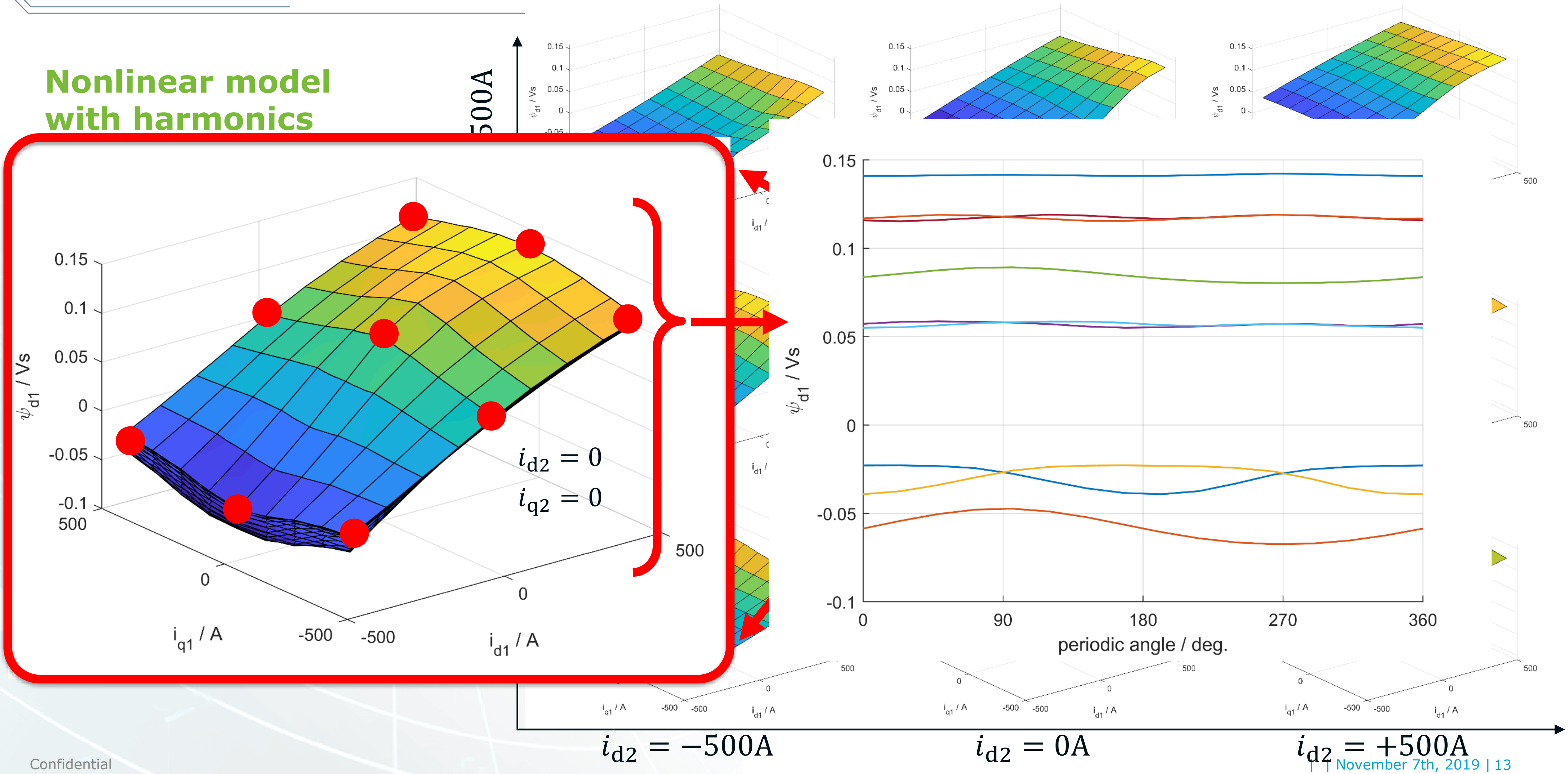
The motor exhibits various magnetic effects such as:

- Saturation
- d/q-cross coupling
- Inter-stator coupling
- Inter-stator d/q-cross coupling
- Rotor position dependent flux linkage (see next slide)

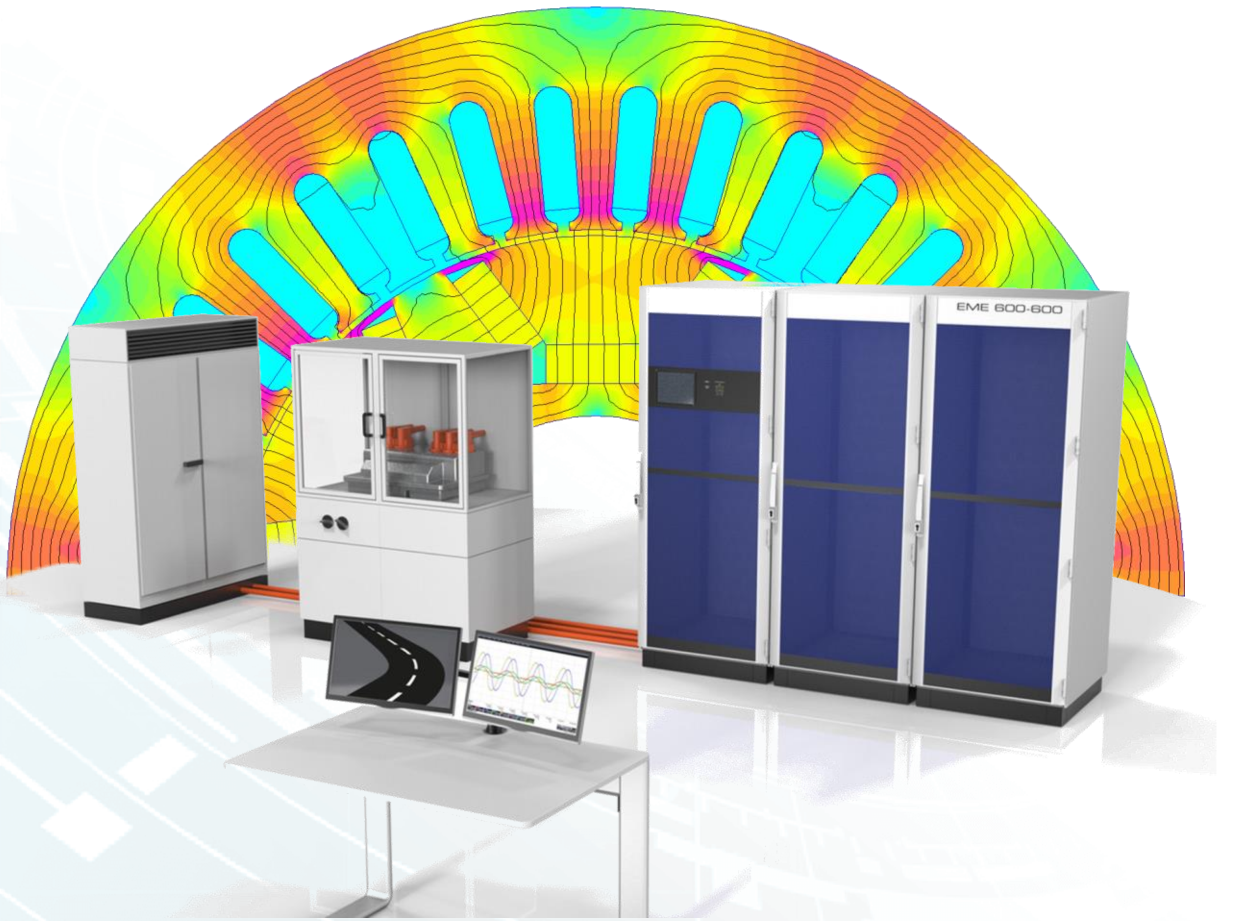


Magnetical Effects
FEA result discussion

Nonlinear model with harmonics



Agenda



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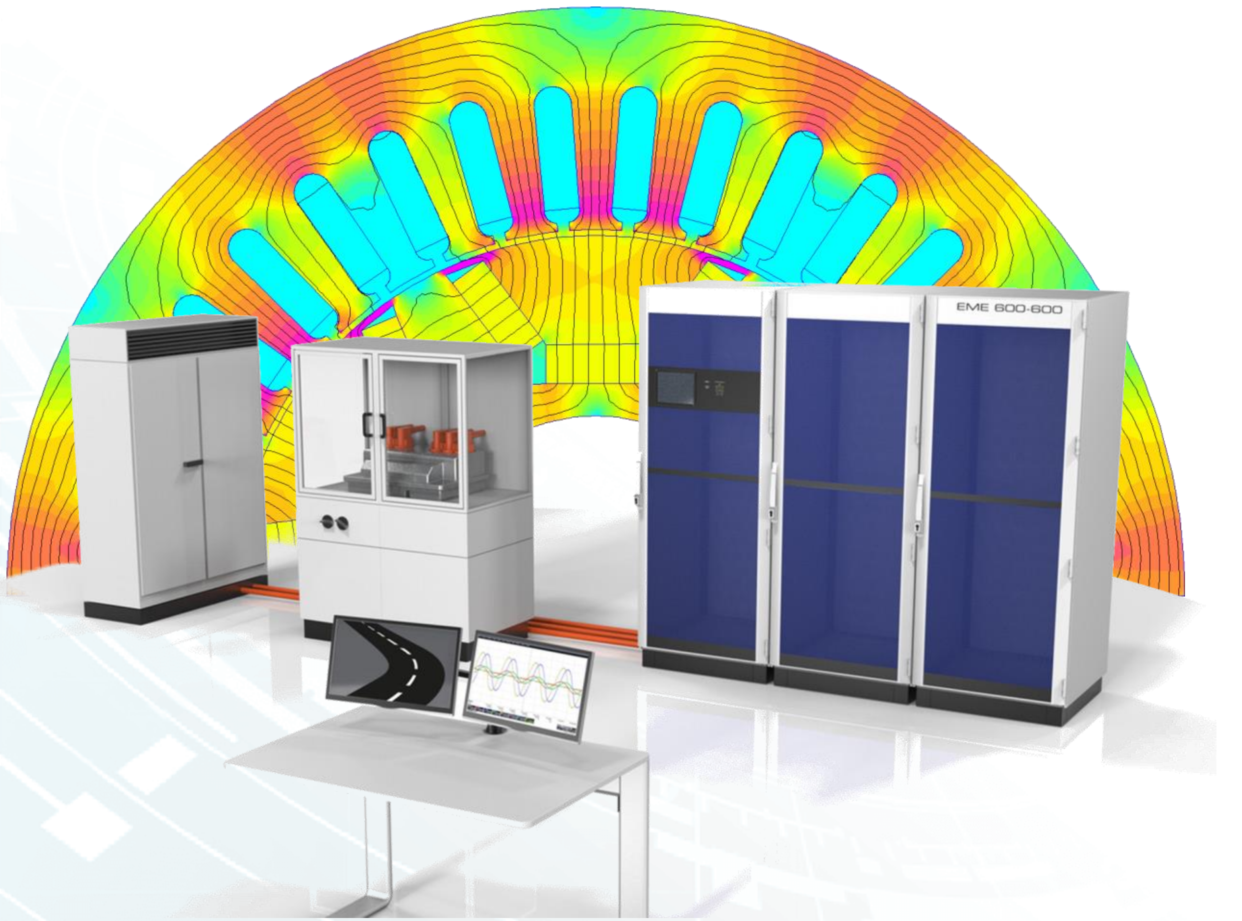

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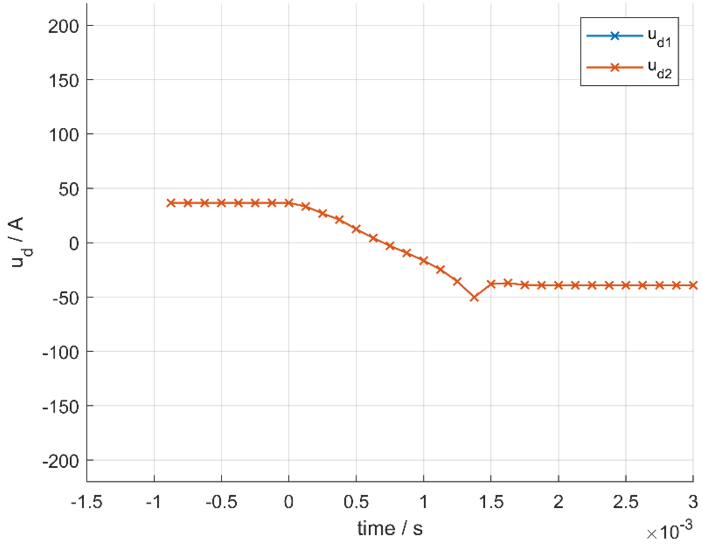
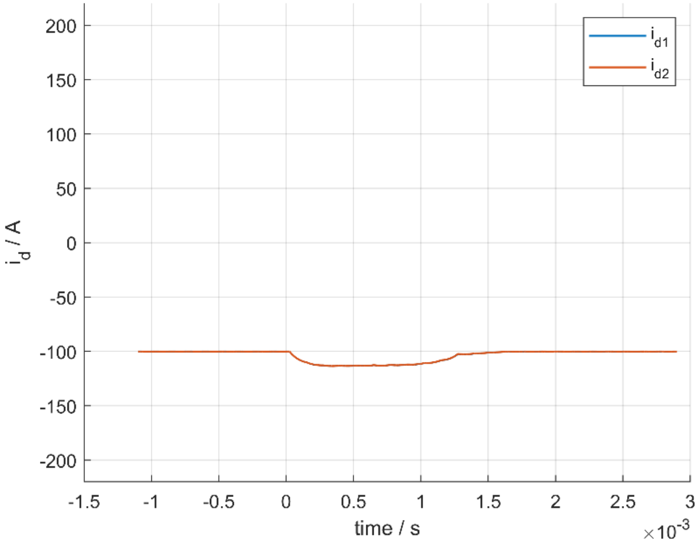
4. **Live Test Cases with the Emulator**

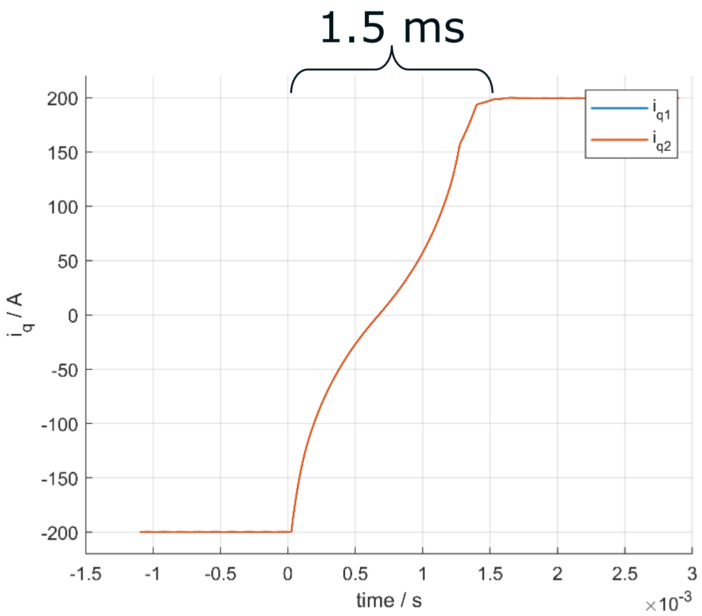
Live Test Cases with the Emulator

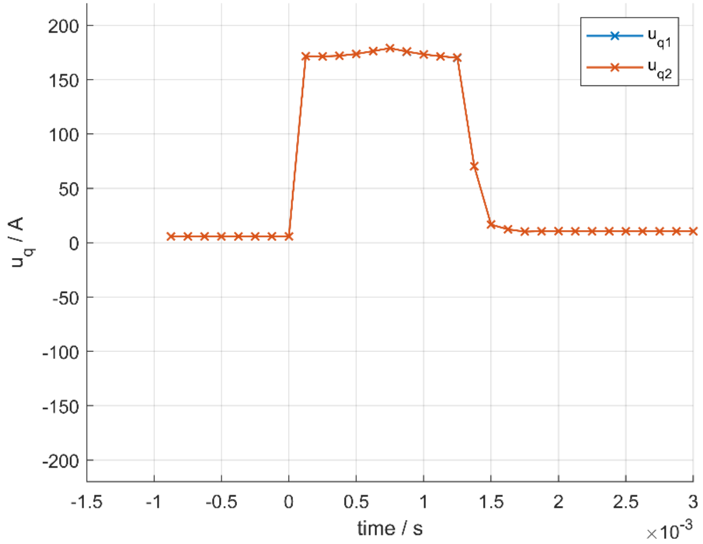
Test #1: Tuning the controller parameters in NL mode

- Motor runs in steady state (1000 rpm, $i_{d1,2} = -100\text{A}$, $i_{q1,2} = -200\text{A}$
- Set currents of $i_{q1,2}$ will be inverted instantly (generator -> motor)
- UUT uses model predictive current control
- **Test Case:** Adjusting dynamic gain factor and integral part to optimize dynamics and stationary accuracy





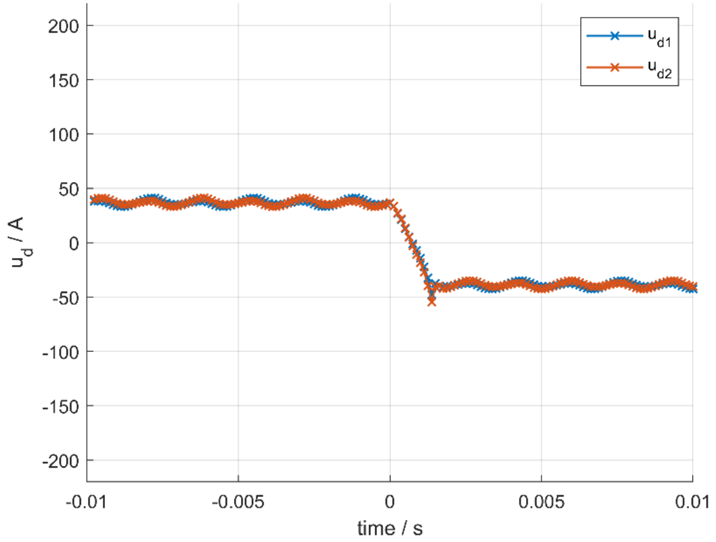


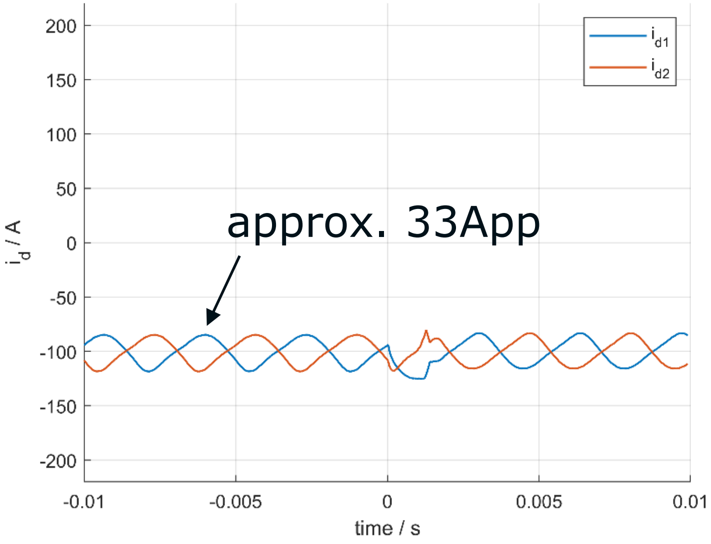


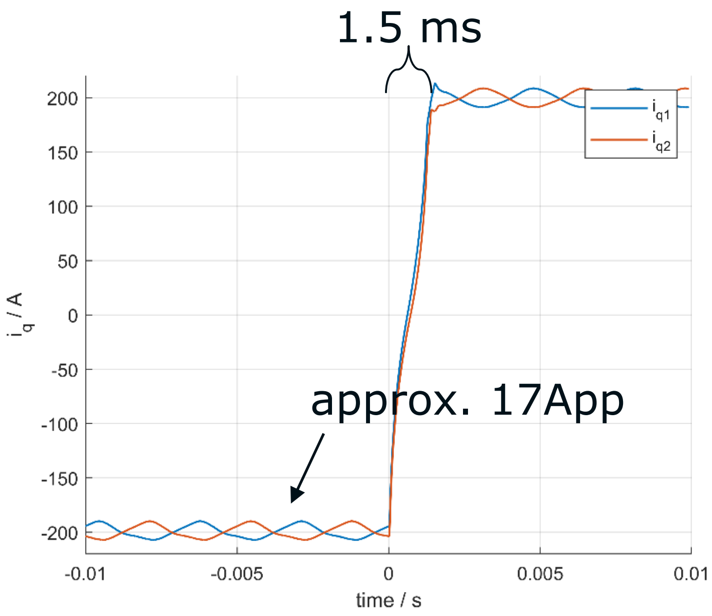
Live Test Cases with the Emulator

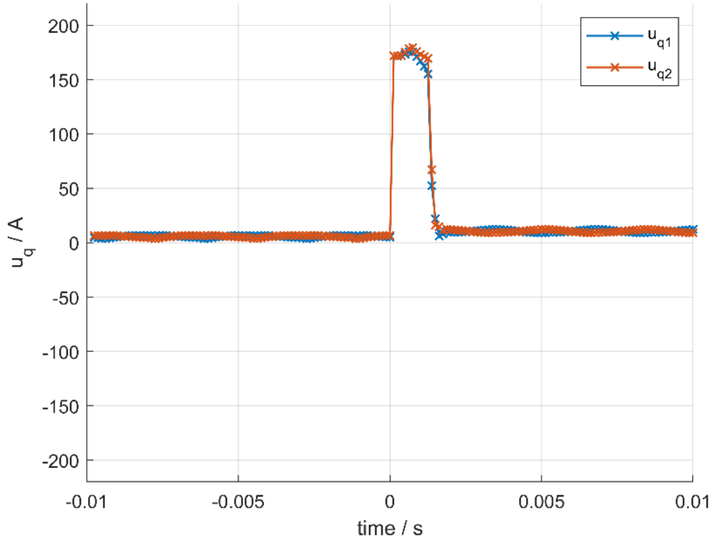
Test #2: Validating the controller parameters in NLH mode

- Same test as #1, but now with harmonics model
- **Test Case:** see if optimized controller of fundamental wave model also works with „real" motor behavior, i.e. magnetic and winding harmonics





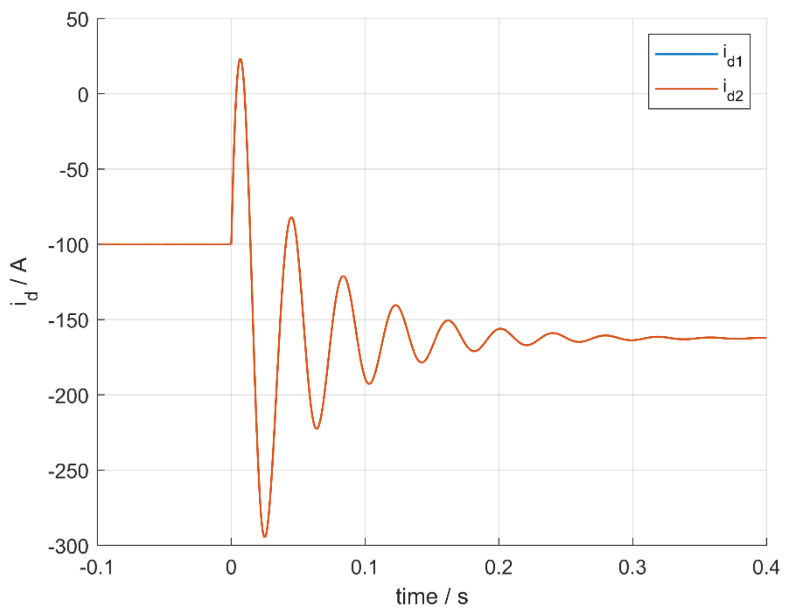


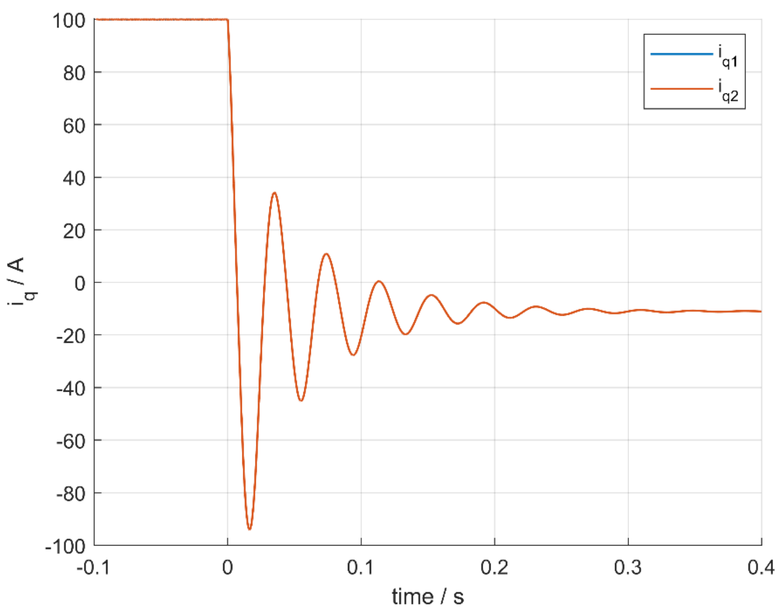


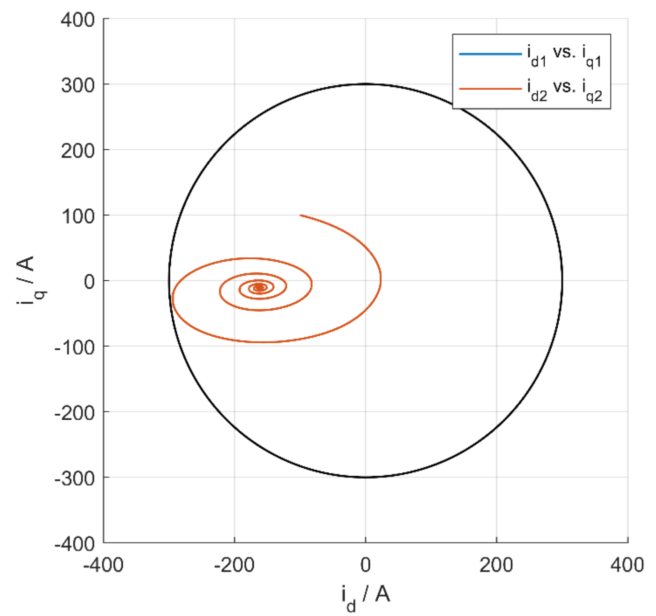
Live Test Cases with the Emulator

Test #3: short-curcuiting in NL mode

- Motor runs in steady state (500 rpm, $i_{\mathrm{d}1,2} = -100\mathrm{A}$, $i_{\mathrm{q}1,2} = -100\mathrm{A}$)
- **Test Case:** Check if UUT enters safe state (ASC) when an error occurs.



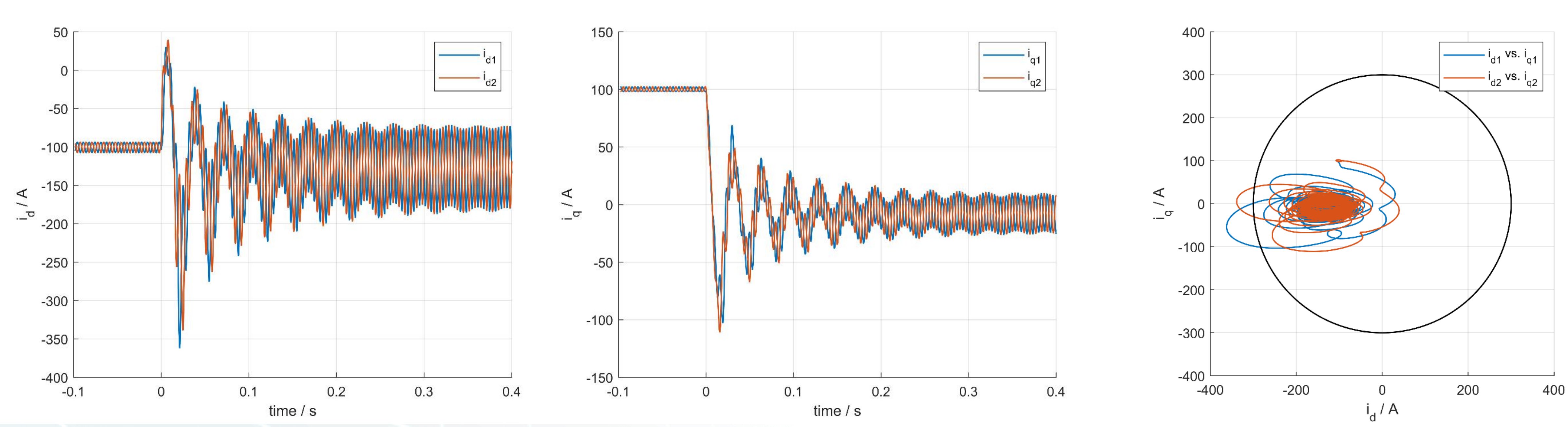




Live Test Cases with the Emulator

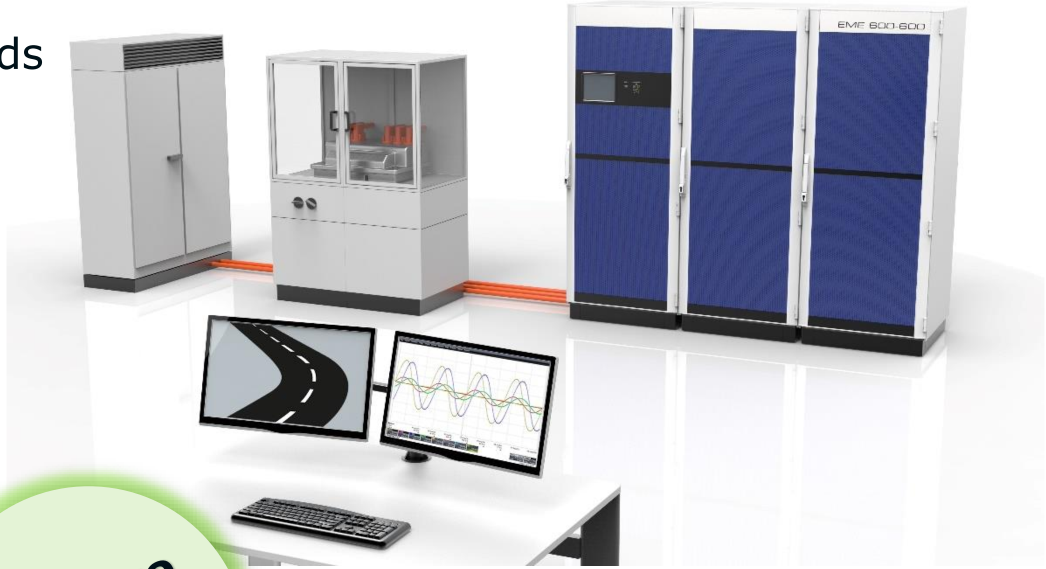
Test #4: short-curcuiting in NLH mode

- Same test as #3, but now with harmonics model
- **Test Case:** Check if UUT enters safe state (ASC) when an error occurs.
  Check if harmonics lead to overcurrents.



Summary

- **Fast**
  - Motor type and parameters can be changed within seconds
  - No mechanical adaption necessary
- **Flexible**
  - Arbitrary electrical faults
    (short circuits, wire breaks, etc.)
  - Arbitrary mechanical faults
    (blocking rotor, cracking shaft)
  - Extreme drive situations
    (curbstone test, Aquaplaning)
  - No functional limitations
- **Safe**
  - Protection of UUT
  - No rotating parts
- **Reproducible**
  - No manufacturing tolerances
  - Worldwide identical test results



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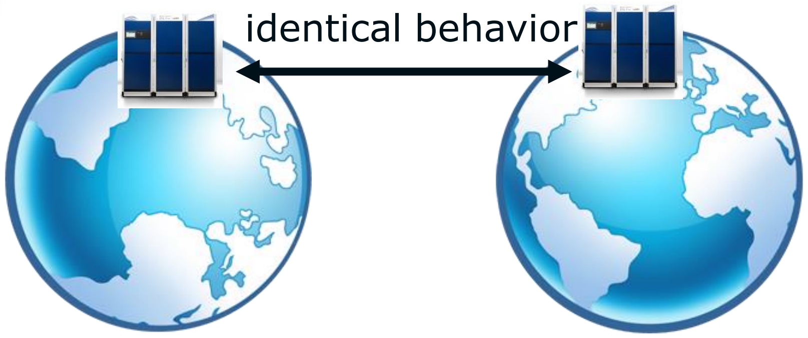
TIME
SAVINGS

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