Reluctance Synchronous Motors for ESP Systems

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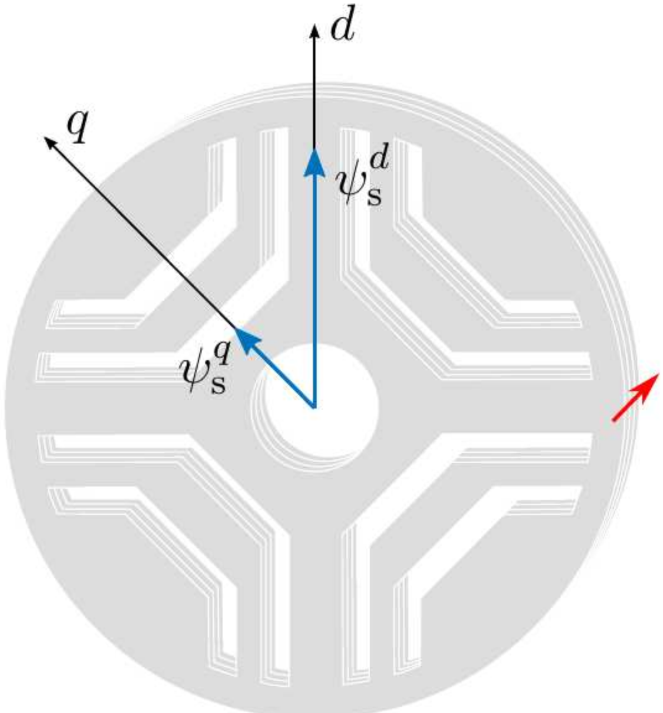
Munich

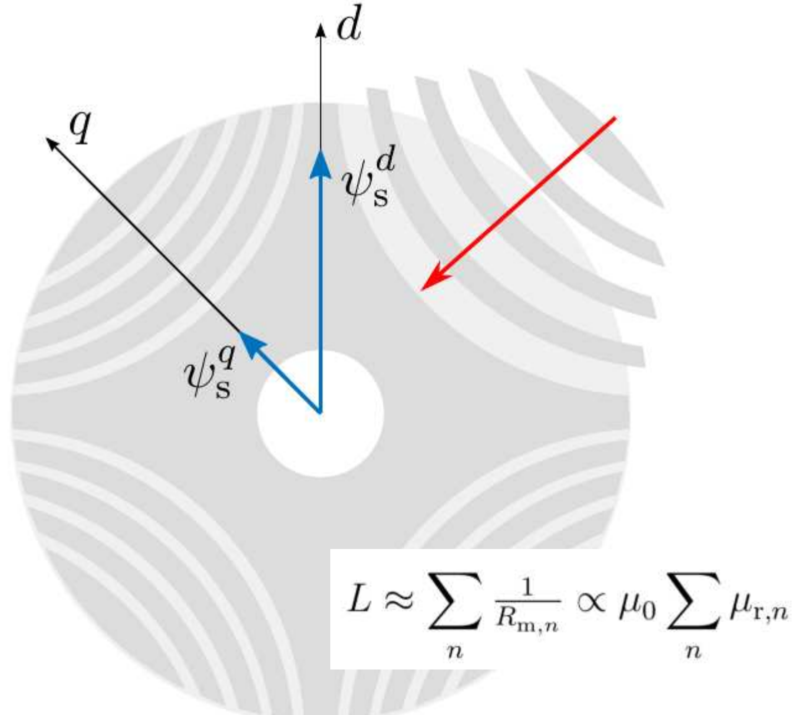
Outline

- **RSM working principle**
  - Rotor design(s) and torque
  - Rotor, stator and casing
- **RSM capabilities**
  - Torque
  - ABB uses RSMs (to improve efficiency or decrease size)
  - Efficiency comparison (not much out there!)
- **RSM modeling and control**
  - Flux linkages, torque and differential inductances
  - FOC-based current control system
  - Measurement results (control performance & efficiency map)

RSM working principle:
Examplary rotor designs and torque



(a) *Transversal laminierter Rotor.*

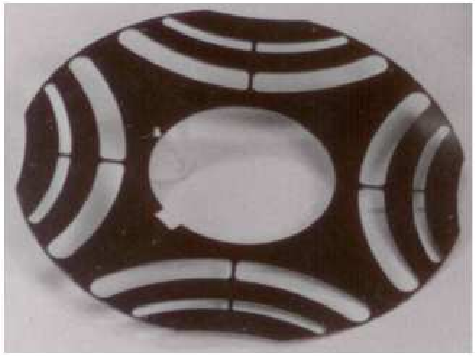


(b) *Axial laminierter Rotor.*

$$m_m(\boldsymbol{i}_s^{dq}) = \underbrace{\frac{2}{3\kappa^2} n_p \left(L_s^d - L_s^q\right) i_s^d i_s^q}_{=: m_{m,rm}} + \underbrace{\frac{2}{3\kappa^2} n_p L_{s,m}\left((i_s^q)^2 - (i_s^d)^2\right)}_{=: m_{m,km}}$$

RSM working principle: Different designs for different powers

9 kW



42 kW

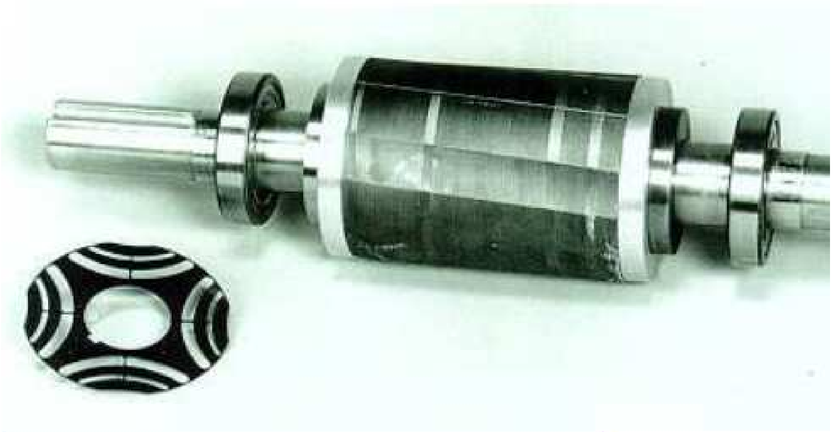
110 kW

42 kW

* Courtesy of M. Kamper, University of Stellenbosch

RSM working principle: Rotor comparison

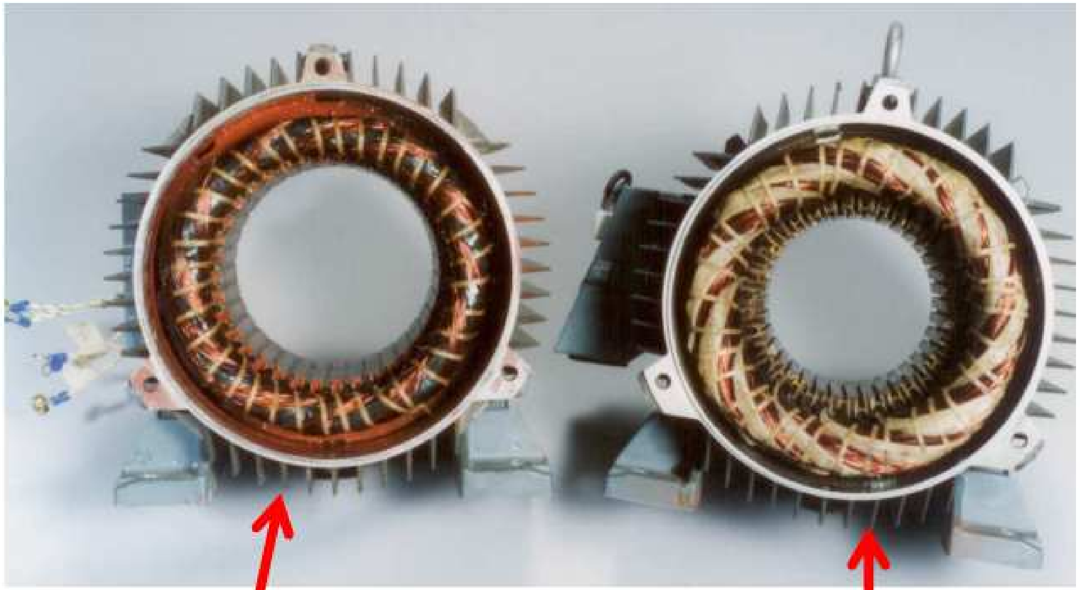
2.8 kW DC
2.2 kW IM
9 kW RSM

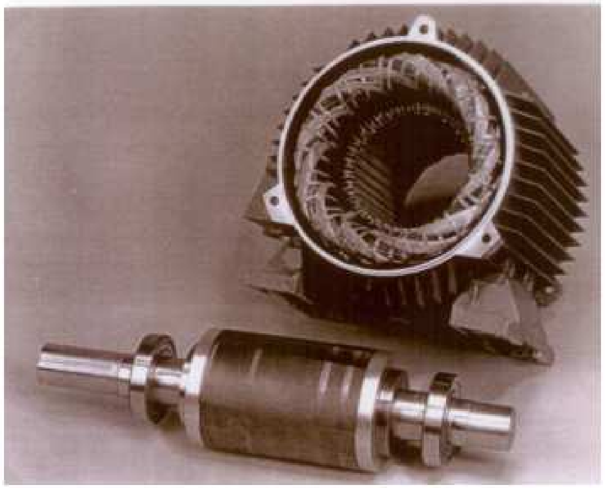


9 kW @ 1500 r/min RSM rotor - skewed

* Courtesy of M. Kamper, University of Stellenbosch

RSM working principle: Stator and Casing



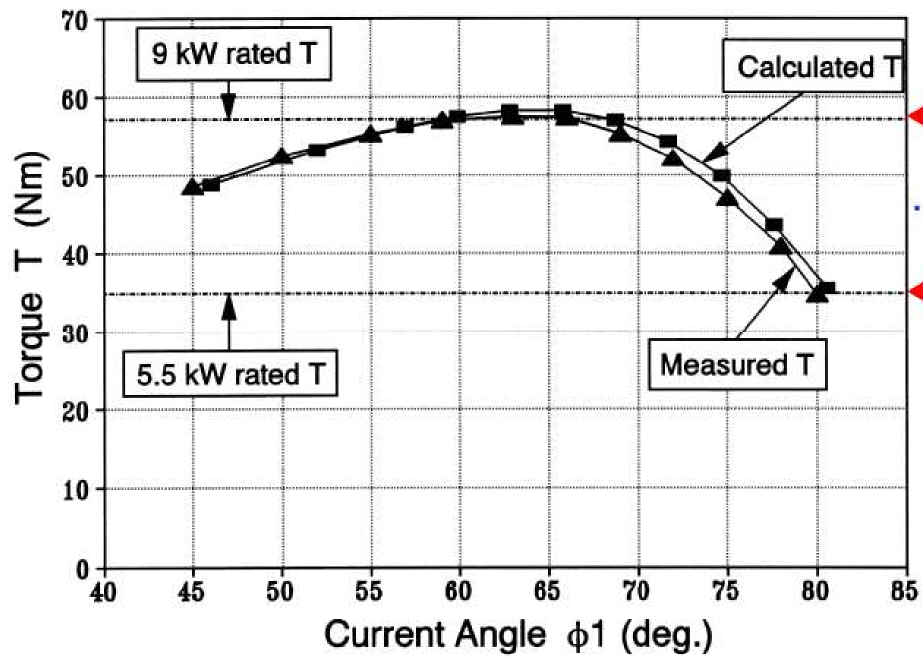


5.5 kW standard line started Induction Machine – stator and casing

9 kW Converter-fed RSM – stator in 5.5 kW IM casing

* Courtesy of M. Kamper, University of Stellenbosch

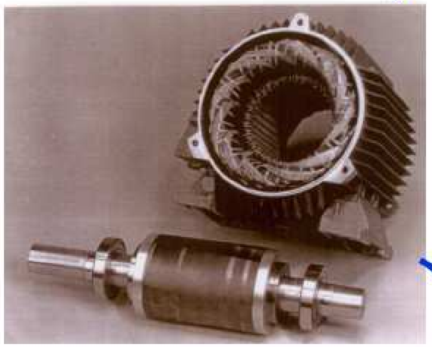
RSM capabilities: Torque



9 kW RSM

… in same casing!

5.5 kW Induction Machine



Kamper M.J., Van der Merwe F.S. and Williamson S.: "Direct finite element design optimisation of the cageless reluctance synchronous machine", IEEE Trans. on Energy Conversion, Vol. 11, No. 3, September **1996**, pp. 547-553.

* Courtesy of M. Kamper, University of Stellenbosch

RSM capabilities:
ABB uses RSMs (17 – 350 kW)

Package highlights	
Super efficiency	Meets the IE4 super premium efficiency and offers excellent partial load efficiency performance
Reliability	IE4 SynRM motors run uniquely cool keeping the motor bearing temperature very low which increases bearing system reliability
Easy retrofit	Can replace standard induction motors – same power and size combinations

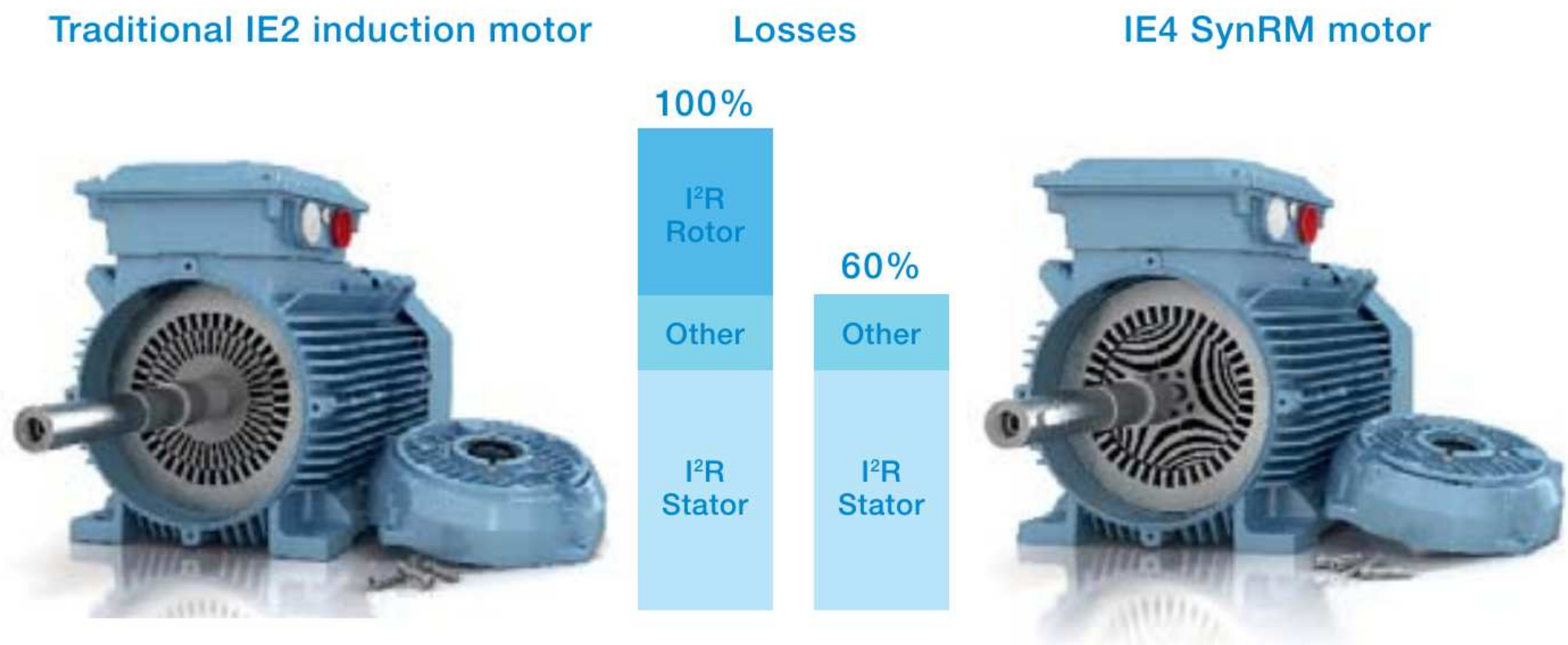
Package highlights	
Small size	Same output with a motor that's up to two frame sizes smaller – enables smaller, lighter and more cost-efficient machine designs.
High output	Up to double output power at higher speed without increasing motor size
Good efficiency	Good efficiency from IE2 to IE3

* ABB „Synchronous reluctance motor-drive package for machine builders", Brochure 2014

Super premium efficiency from same frame size

Same power from smaller size

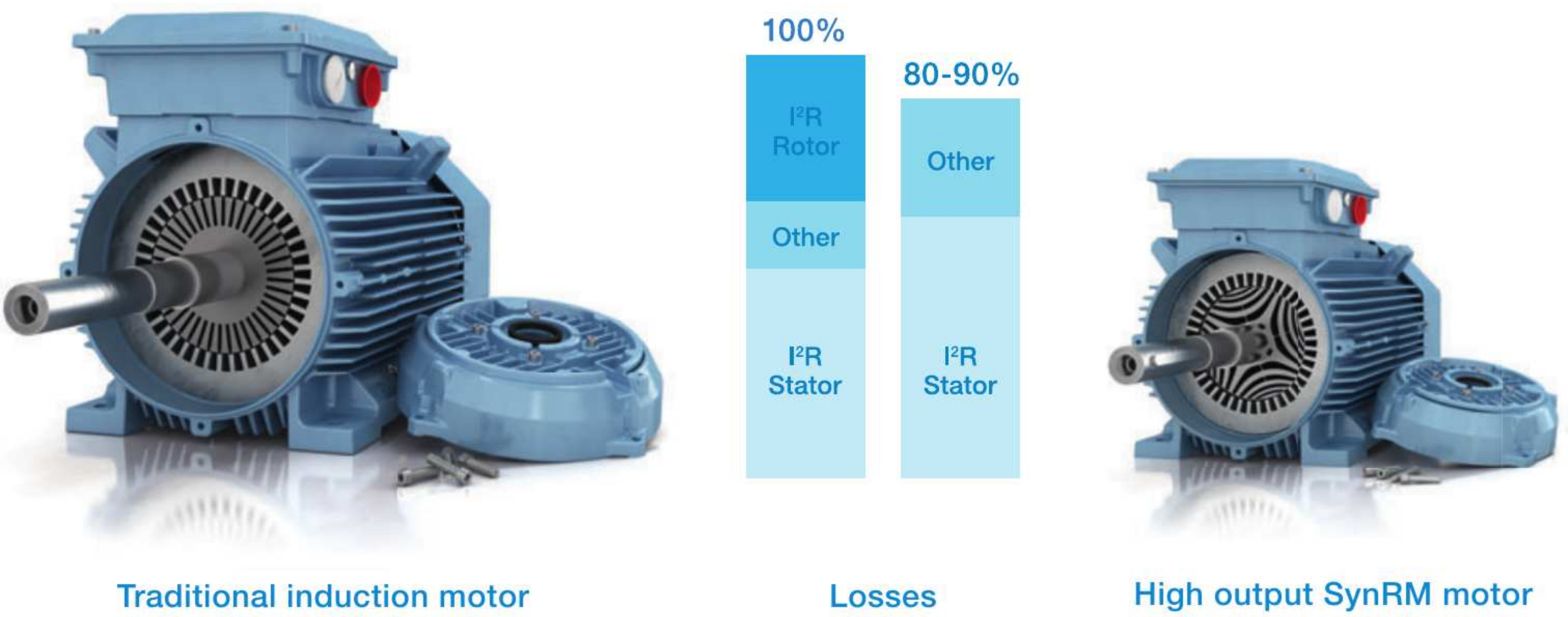
RSM capabilities:
ABB uses RSMs (… to improve efficiency)



IE4 SynRM motor reduces losses up to 40 %

* ABB „Synchronous reluctance motor-drive package for machine builders“, Brochure 2014

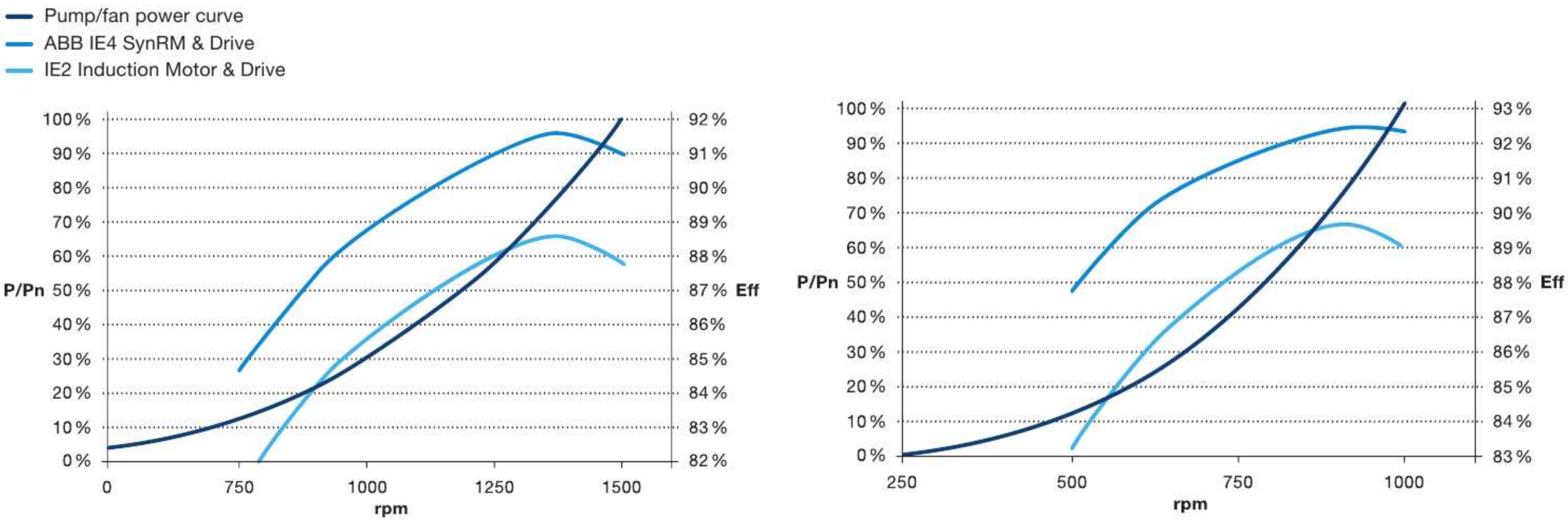
RSM capabilities:
ABB uses RSMs (… or to decrease size)



* ABB „High output synchronous reluctance motor and drive package“, Brochure 2012

RSM capabilities:
Efficiency comparison IM vs. RSM (#1)

Motor-drive package efficiency curves



15 kW, 1500 rpm, drive system in pump/fan duty

37 kW, 1000 rpm, drive system in pump/fan duty

* ABB „Low voltage - IE4 synchronous reluctance motors“, Brochure 2016

RSM capabilities: Efficiency comparison IM vs. RSM (#2)

TABLE III
Induction motor and TLSyRM tests
Induction motor nameplate: $V_{nom} = 400$ V, $P_{nom} = 4$ kW
Comparison at constant speed and torque.
Comparison at constant speed and winding temperature.

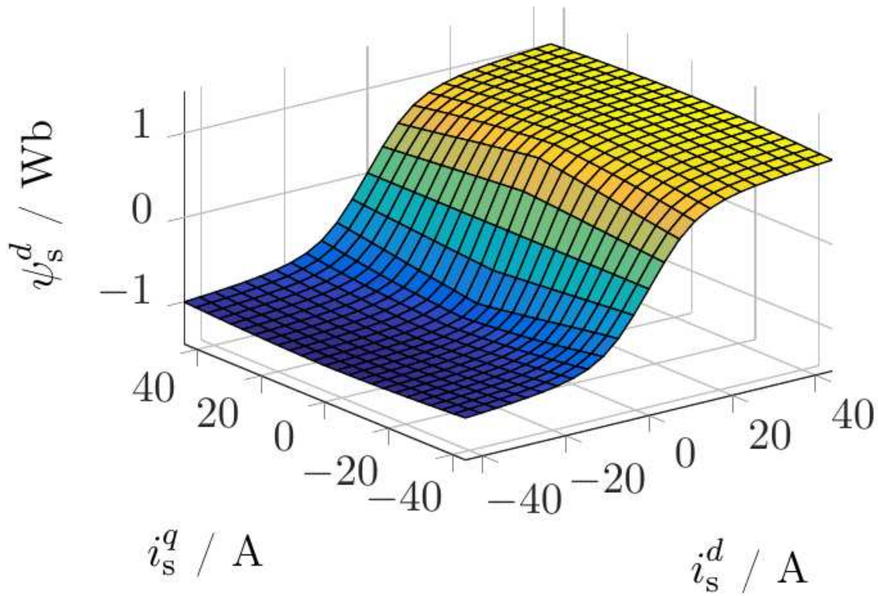
	I.M. (1)	TLSyRM (eq. torque) (2)	TLSyRM (eq. temp.) (3)
T [Nm]	27.1	27.1	31.7
n_0 [rpm]	1202	1100	1100
N [rpm]	1101	1100	1100
Average windings overtemperature [°C]	104	80	108
V_{rms} [[V]	323	305	317
I_{rms} [A]	8.63	9.56	10.8
P_{in} [W]	4050	3750	4480
P_{out} [W]	3125	3122	3652
Efficiency	0.772	0.832	0.815
Fundamental power factor	0.839	0.743	0.756
P_{jstat} [W]	442	508	705
P_{jrot} [W]	295	0	0
[illegible]	[illegible]	[illegible]	[illegible]

TABLE IV
Induction motor and TLSyRM tests
Induction motor nameplate: $V_{nom} = 400$ V, $P_{nom} = 2.2$ kW
Comparison at constant speed and torque.
Comparison at constant speed and winding temperature.

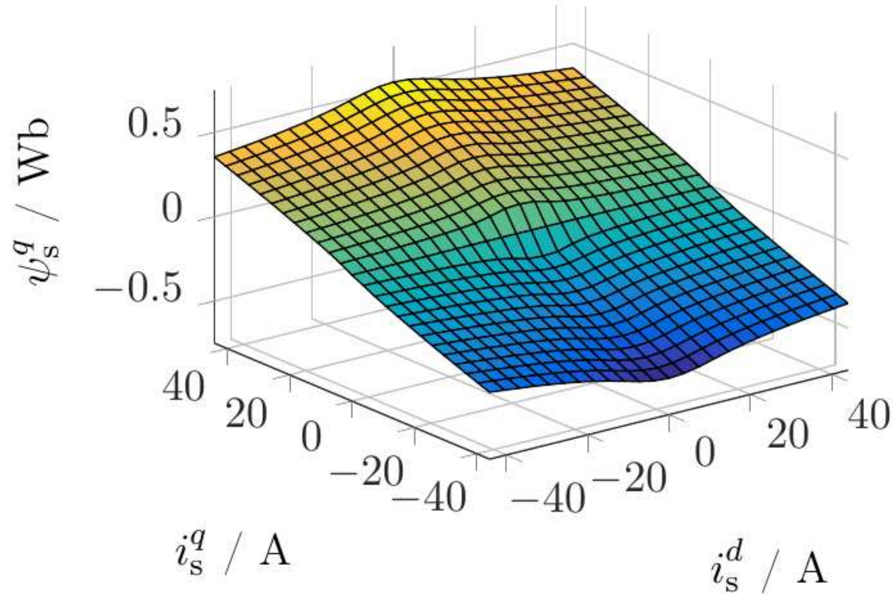
	I.M. (1)	TLSyRM (eq. torque) (2)	TLSyRM (eq. temp.) (3)
T [Nm]	15.2	15.1	16.6
n_0 [rpm]	1300	1200	1200
N [rpm]	1190	1200	1200
Average windings overtemperature [°C]	102	85	103
V_{rms} [[V]	350	336	346
I_{rms} [A]	5.32	5.45	5.92
P_{in} [W]	2673	2390	2690
P_{out} [W]	1894	1897	2086
Efficiency	0.709	0.794	0.775
Fundamental power factor	0.830	0.754	0.757
P_{jstat} [W]	394	392	489
P_{jrot} [W]	184	0	0
[illegible]	[illegible]	[illegible]	[illegible]

* A. Bogletti,.„Experimental Comparison of Induction and Synchronous Reluctance Motors Performance“, 2005

RSM modeling and control: Nonlinear flux linkage and torque



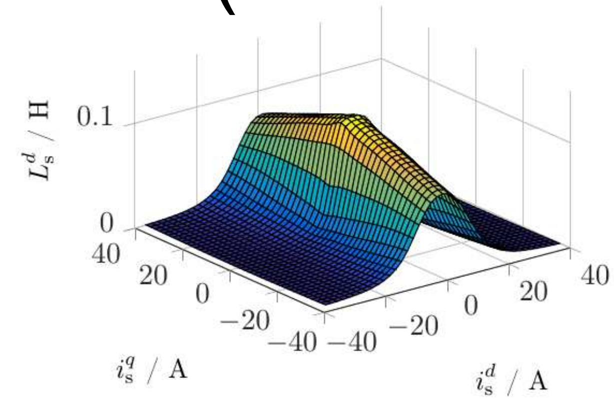
(a) *d-Statorflussverkettung* ψ_{s}^{d}.



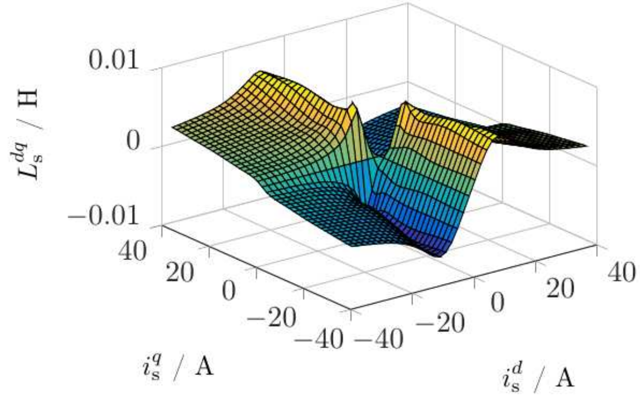
(b) *q-Statorflussverkettung* ψ_{s}^{q}.

$$\boxed{m_{\mathrm{m}}(\boldsymbol{i}_{\mathrm{s}}^{dq}) = \frac{2}{3\kappa^2} n_{\mathrm{p}} \, (\boldsymbol{i}_{\mathrm{s}}^{dq})^{\top} \boldsymbol{J} \boldsymbol{\psi}_{\mathrm{s}}^{dq}(\boldsymbol{i}_{\mathrm{s}}^{dq}) = \frac{2}{3\kappa^2} n_{\mathrm{p}} \left(\psi_{\mathrm{s}}^{d}(\boldsymbol{i}_{\mathrm{s}}^{dq}) \, i_{\mathrm{s}}^{q} - \psi_{\mathrm{s}}^{q}(\boldsymbol{i}_{\mathrm{s}}^{dq}) \, i_{\mathrm{s}}^{d} \right)}$$

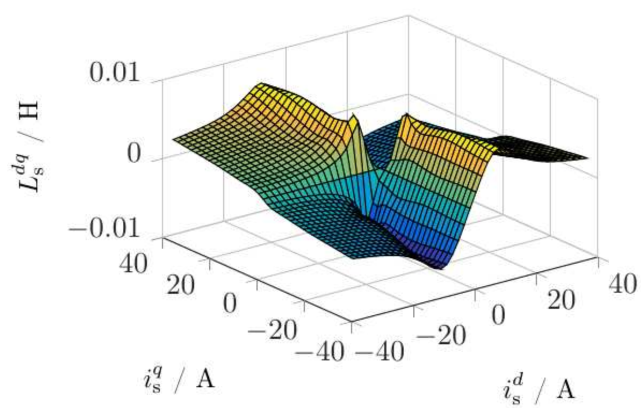
RSM modeling and control: Nonlinear (differential) inductances



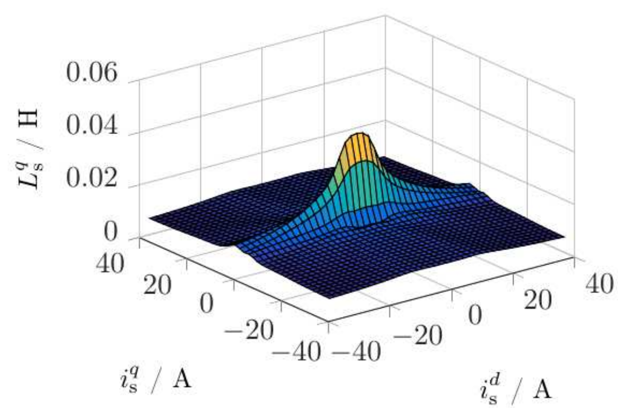
(a) *d-Induktivität* $L_s^d := \partial\psi_s^d / \partial i_s^d$.



(b) *Koppelinduktivität* $L_s^{dq} := \partial\psi_s^d / \partial i_s^q$.

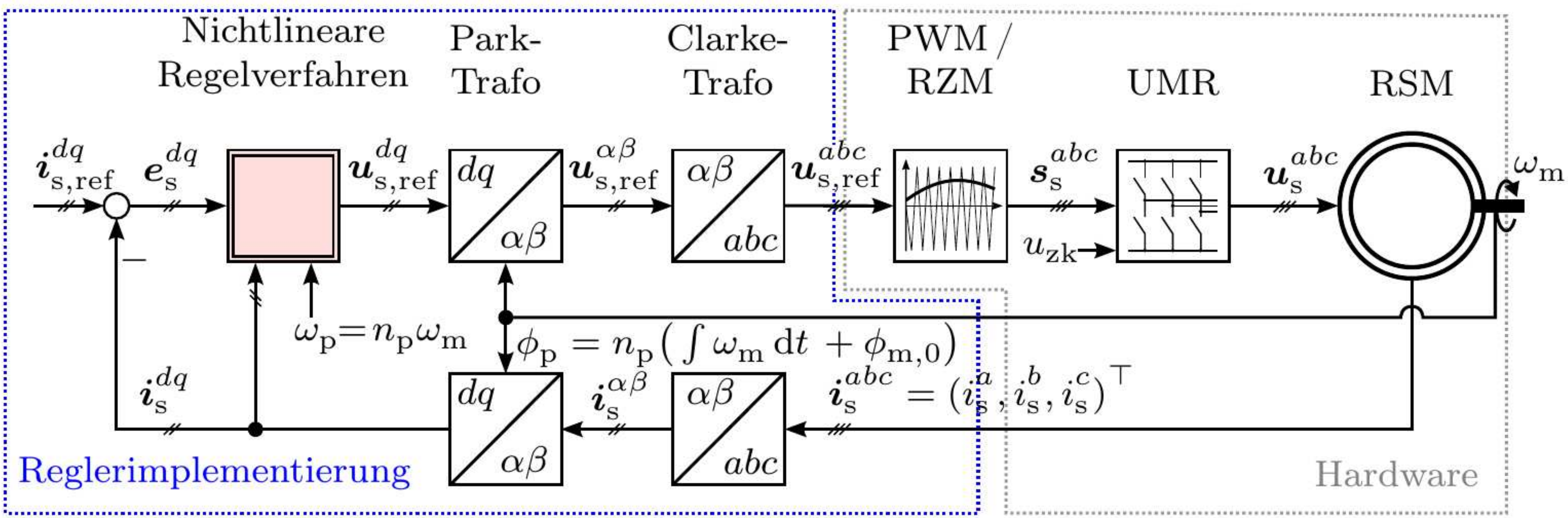


(c) *Koppelinduktivität* $L_s^{qd} := \partial\psi_s^q / \partial i_s^d$.

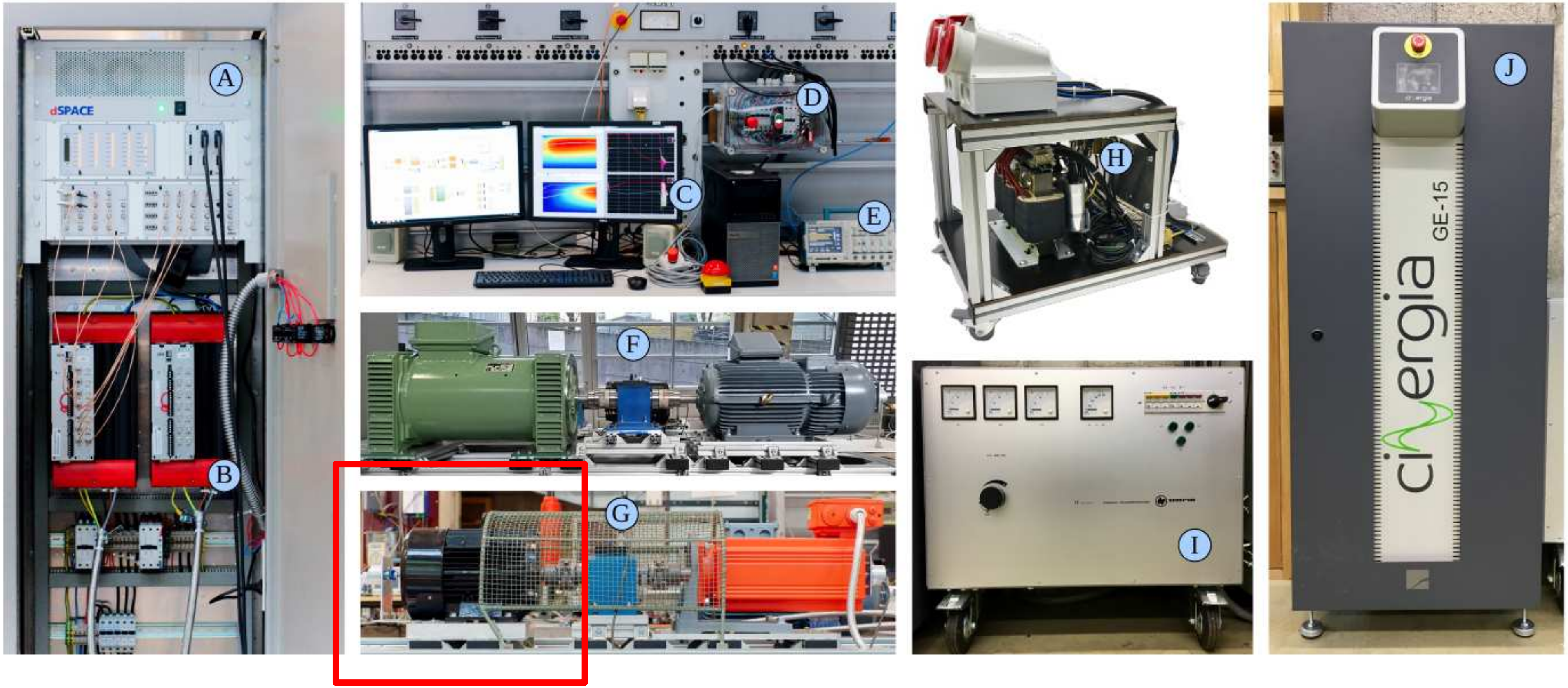


(d) *q-Induktivität* $L_s^q := \partial\psi_s^q / \partial i_s^q$.

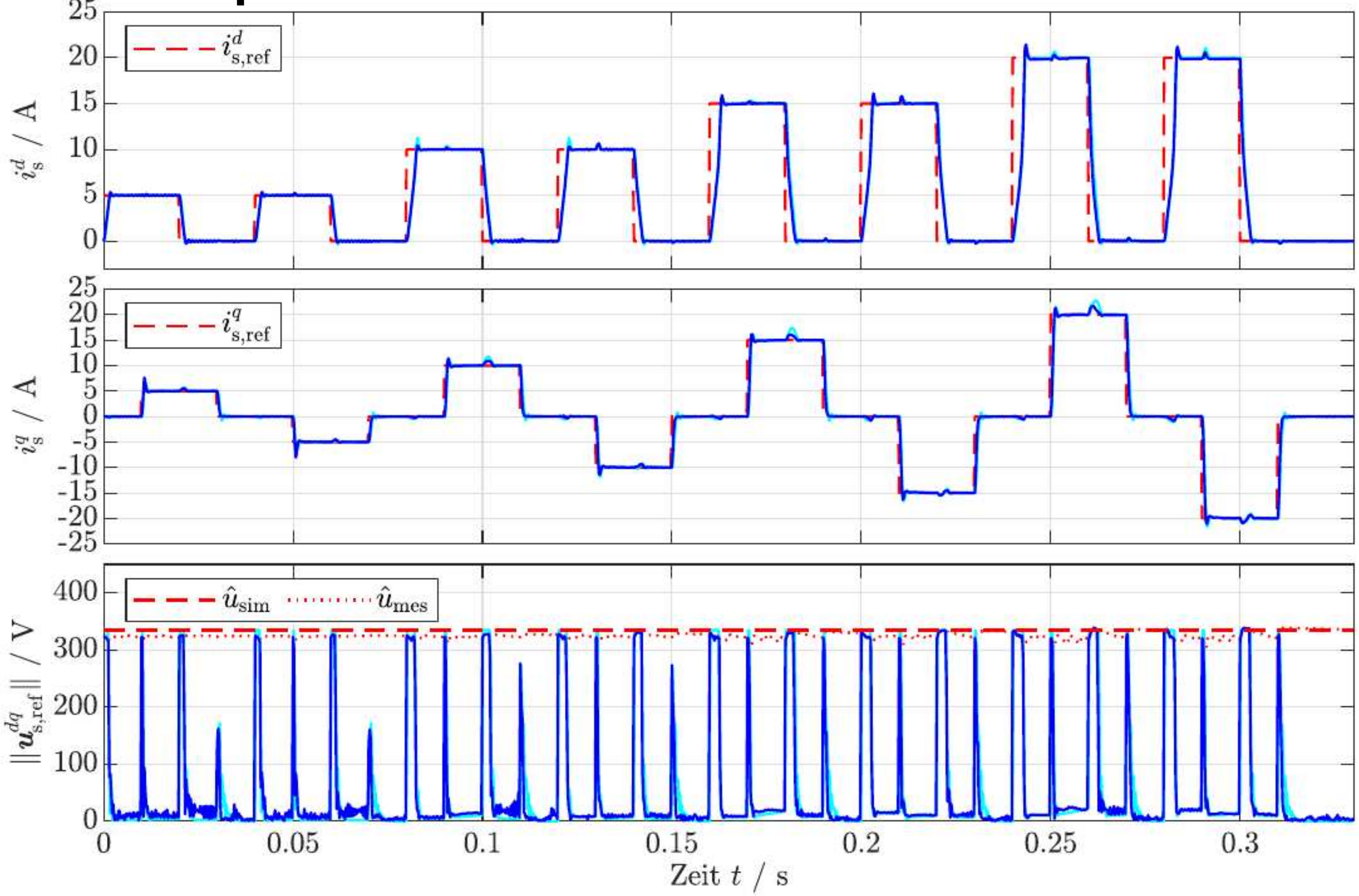
RSM modeling and control: Nonlinear control system



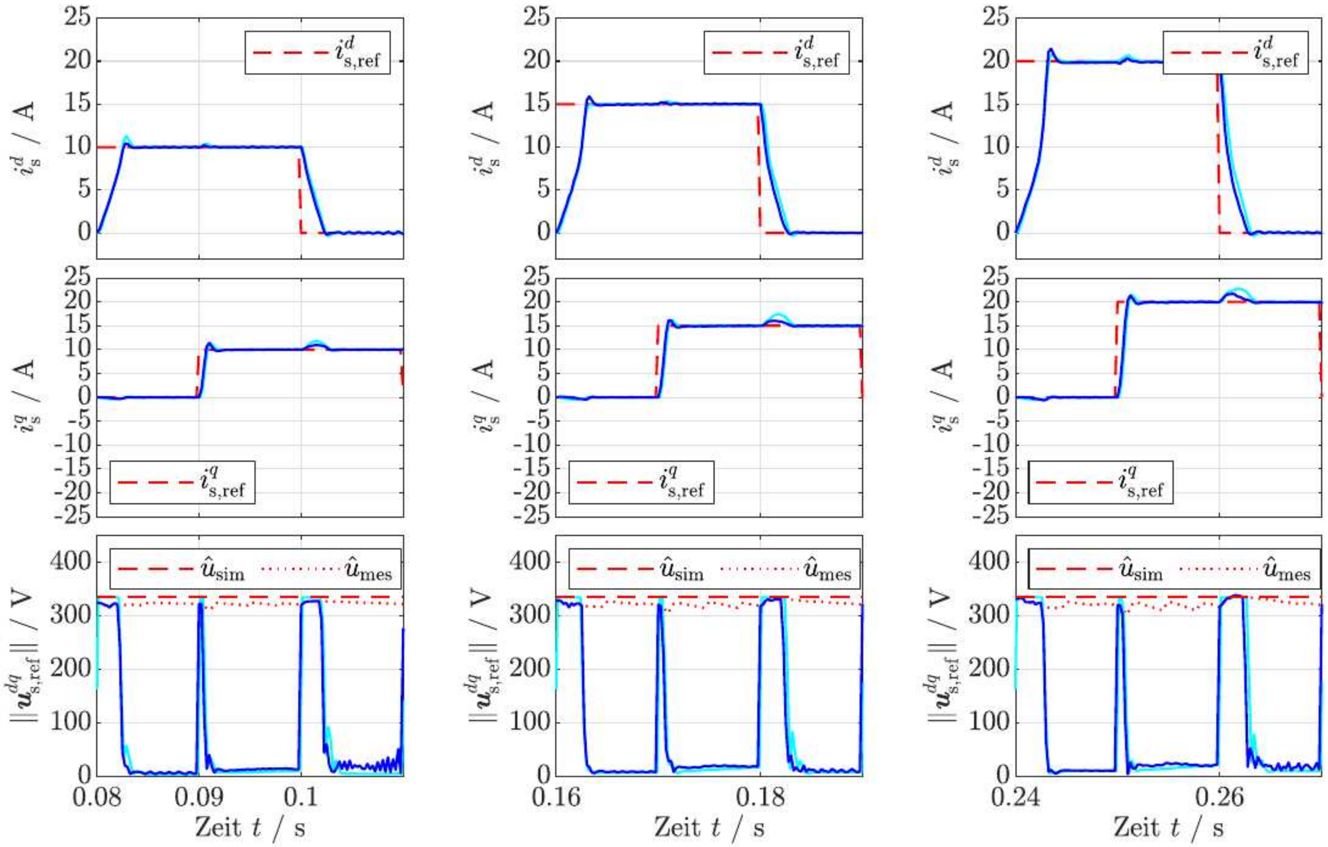
RSM modeling and control: Some laboratory setups @MUAS



RSM modeling and control: Control performance



RSM modeling and control: Control performance (zoomed-in plots)



(b) *Zoom 1.* (c) *Zoom 2.* (d) *Zoom 3.*

RSM modeling and control: Efficiency map (as generator)