Comparisons of permanent magnet and field winding synchronous machines with inductions machines as traction drives for full electric vehicles

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut (ETI) – Professur für Hybridelektrische Fahrzeuge (HEV)

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Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Introduction
Karlsruhe Institute of Technology

KIT = Technical University of Karlsruhe
+ Research Center Karlsruhe

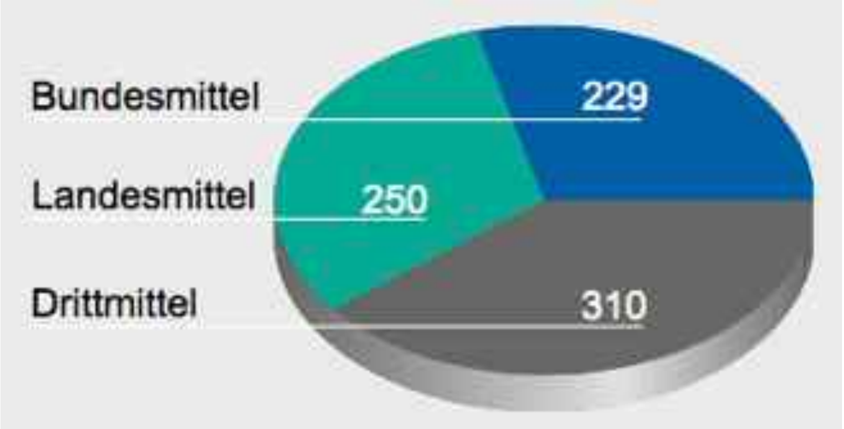
Teaching: 364 Professors

International attractiveness: 844 Foreign Researchers

Excellent education: 445 Apprentices

21.031 Students

Einnahmen in Mio. € (2011)	789
Bundesmittel	229
Landesmittel	250
Drittmittel	310



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Martin Doppelbauer
Univ.-Prof. Dr.-Ing.
Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Introduction

Institute of Electrical Engineering (ETI) at KIT

Engelbert Arnold
(Founder 1895)

Test hall around 1899

- App. 40 employees in total, 30 are scientific staff
- Cooperation with OEMs, industry and research cooperation
- Design and testing of power electronics up to 250 KW
- Design and testing of machines up to 200 kW / 30.000 /min

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Introduction

Institute of Electrical Engineering (ETI) at KIT

Prof. Dr.-Ing.

Michael Braun

Electric Drives and Power Electronics

Tel.: +49 (721) 608-42472

Michael.Braun@kit.edu

Campus Süd, Geb. 11.10

Raum 111

- Power converter design
- Modular multi level converter
- New converter topologies
- Machine control

Prof. Dr.-Ing.

Martin Doppelbauer

Professorship for Hybrid Electric Vehicles

Tel.: +49 (721) 608-46250

Martin.Doppelbauer@kit.edu

Campus Süd, Geb. 11.10

Raum 114

- Electromagnetic design
- Mechanical design and construction
- Industrial drive systems
- Electric vehicles

Motivation

Types of hybrid and electric vehicles

	Micro-Hybrid *MCHEV*	*Mild-Hybrid* *MHEV*	*Full-Hybrid* *FHEV*	*Plug-In Hybrid* *PHEV*	*Battery Elec. Vehicle* *BEV*	*Fuel-Cell Elec. Vehicle* *FCEV*
E-Maschine	< 2 kW	10 – 15 kW	15 – 60+ kW	30 – 120+ kW	30 – 120+ kW	30 – 120+ kW
Batterie	< 1 kWh	0,5 – 1,5 kWh	1,5 – 2,5 kWh	5 – 15 kWh	15 – 35 kWh	< 1 kWh
	Start/Stopp	Start/Stopp	Start/Stopp	Start/Stopp		
	Rekuperation < 2 kW	Rekuperation 10...15 kW	Rekuperation > 15 kW	Rekuperation > 15 kW		
		Lastpunkt-Verschiebung	Lastpunkt-Verschiebung	Lastpunkt-Verschiebung		
		Boosten < 15 kW	Boosten > 15 kW	Boosten > 30 kW		
			E-Fahren 1 – 3 km	E-Fahren 20 – 60 km	E-Fahren 80 – 160+ km	E-Fahren 400+ km

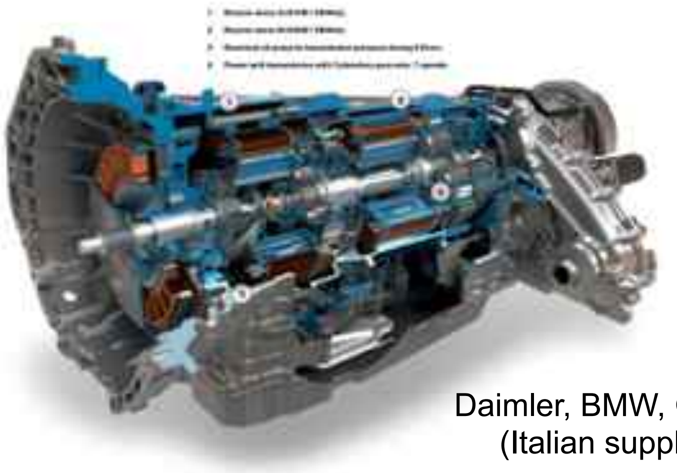
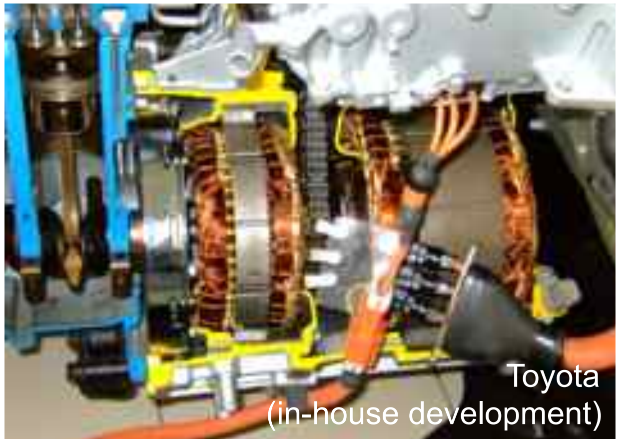
GEM – Gearbox integrated machines (Micro-Hybrid, Mild-Hybrid, Full-Hybrid)

TEM – Traction machines (Plug-In Hybrid, Battery Elec. Vehicle, Fuel-Cell Elec. Vehicle)

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.
Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Motivation

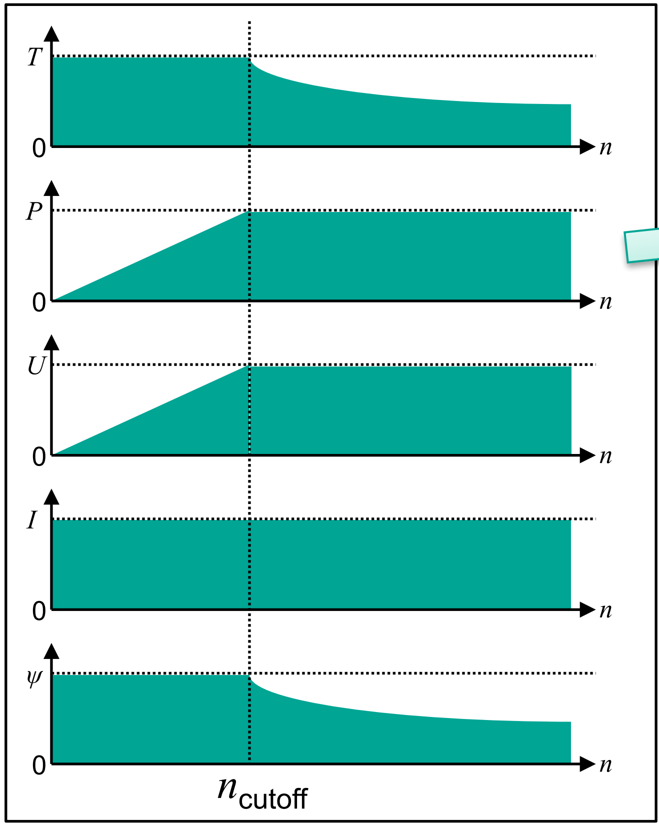
Examples of GEM and TEM machines

GEM Gearbox integrated machines	TEM Traction machines
 Daimler, BMW, GM (Italian supplier)	 Daimler et al (Brusa Switzerland)
 Toyota (in-house development)	 Renault (Conti and ZF)

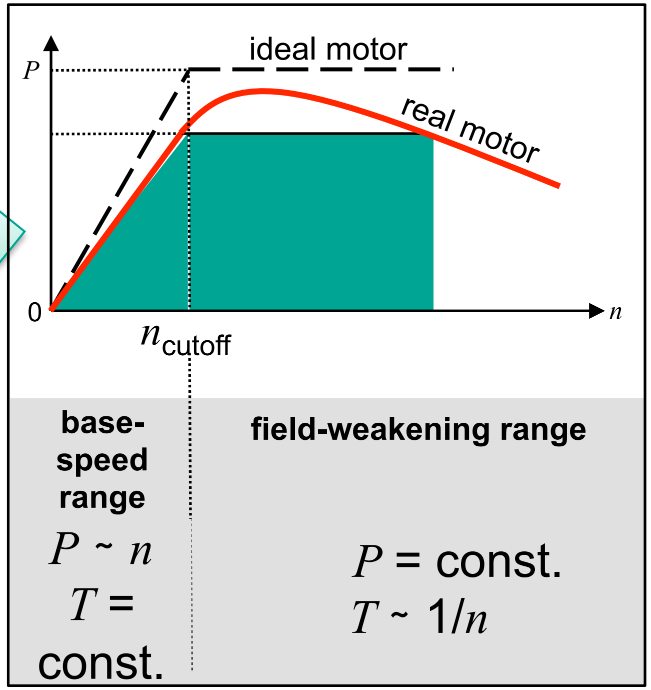
Motivation

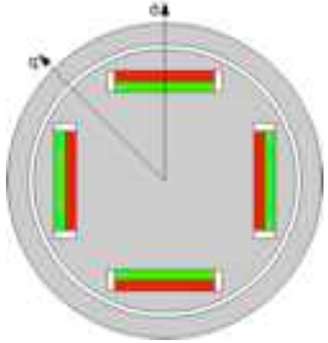
Base-speed and field-weakening range

Ideal machine



Actual machine with $L_q > L_d$





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Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

85 kW Drives (VW Golf class)
Technical Data

Fixed technical data:

- Inner housing diameter: 220 mm
- Inner housing length: 270 mm
  (iron length plus winding overhang)
- Inverter max. current: 425 A AC
- Battery max. current: 650 A DC
- Gearbox ratio (fixed): 9,7
  (12.000/min = 160 km/h)

Performance requirements:

Rated torque (S1-operation):		160Nm
Peak torque (short time):		270Nm
Rated power (S1 operation)	U_{DC}=216 / 320V:	50 / 65 kW
Peak power (short time)	U_{DC}=216 / 320V:	85 / 110 kW
Top Speed:		12.000/min

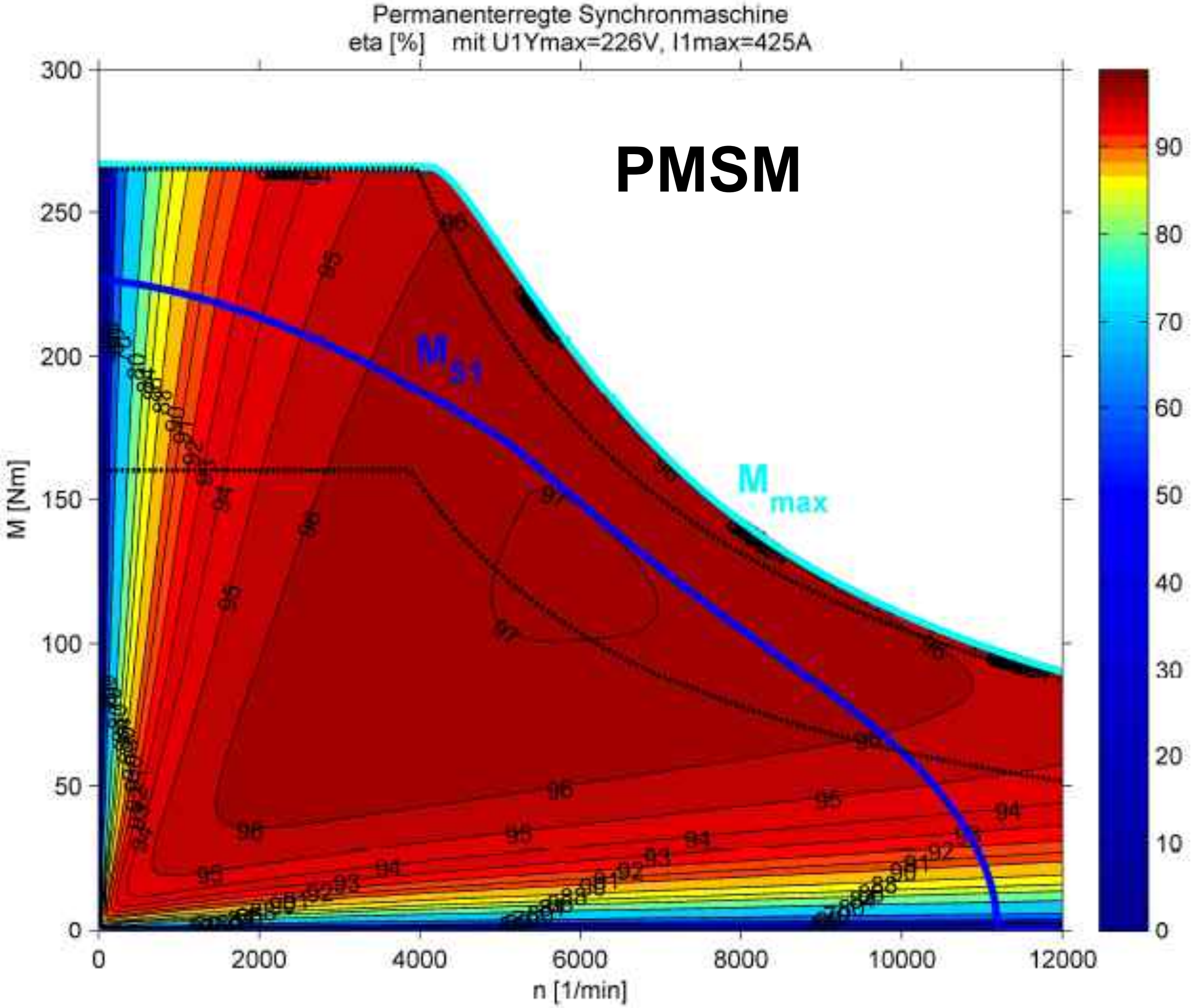
Image source: Volkswagen AG

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

85 kW Drives (VW Golf class)

All machines same housing diameter and length



Source: SEW Eurodrive

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Univ.-Prof. Dr.-Ing.

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85 kW Drives (VW Golf class)

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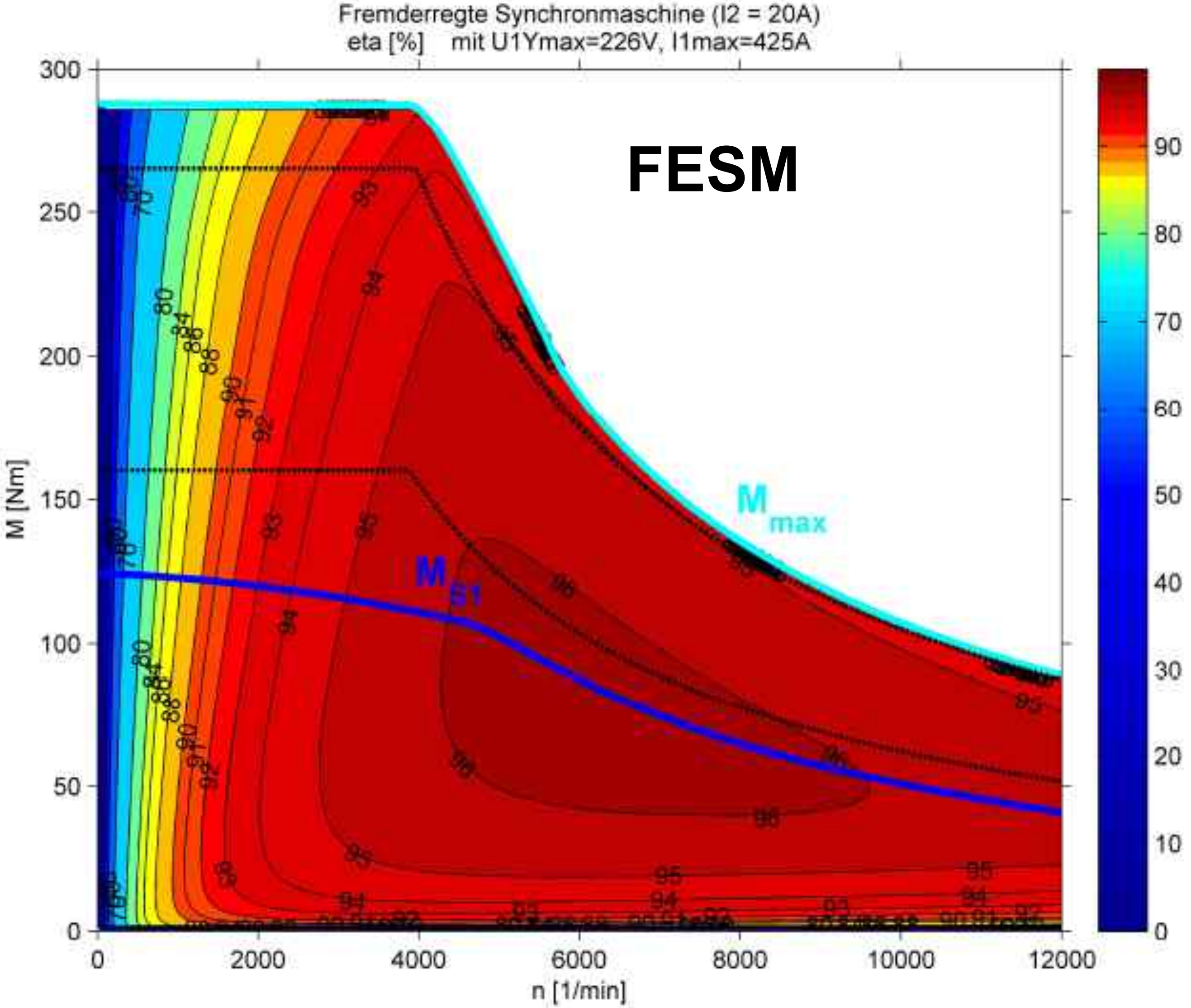

Source: SEW Eurodrive

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

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85 kW Drives (VW Golf class)

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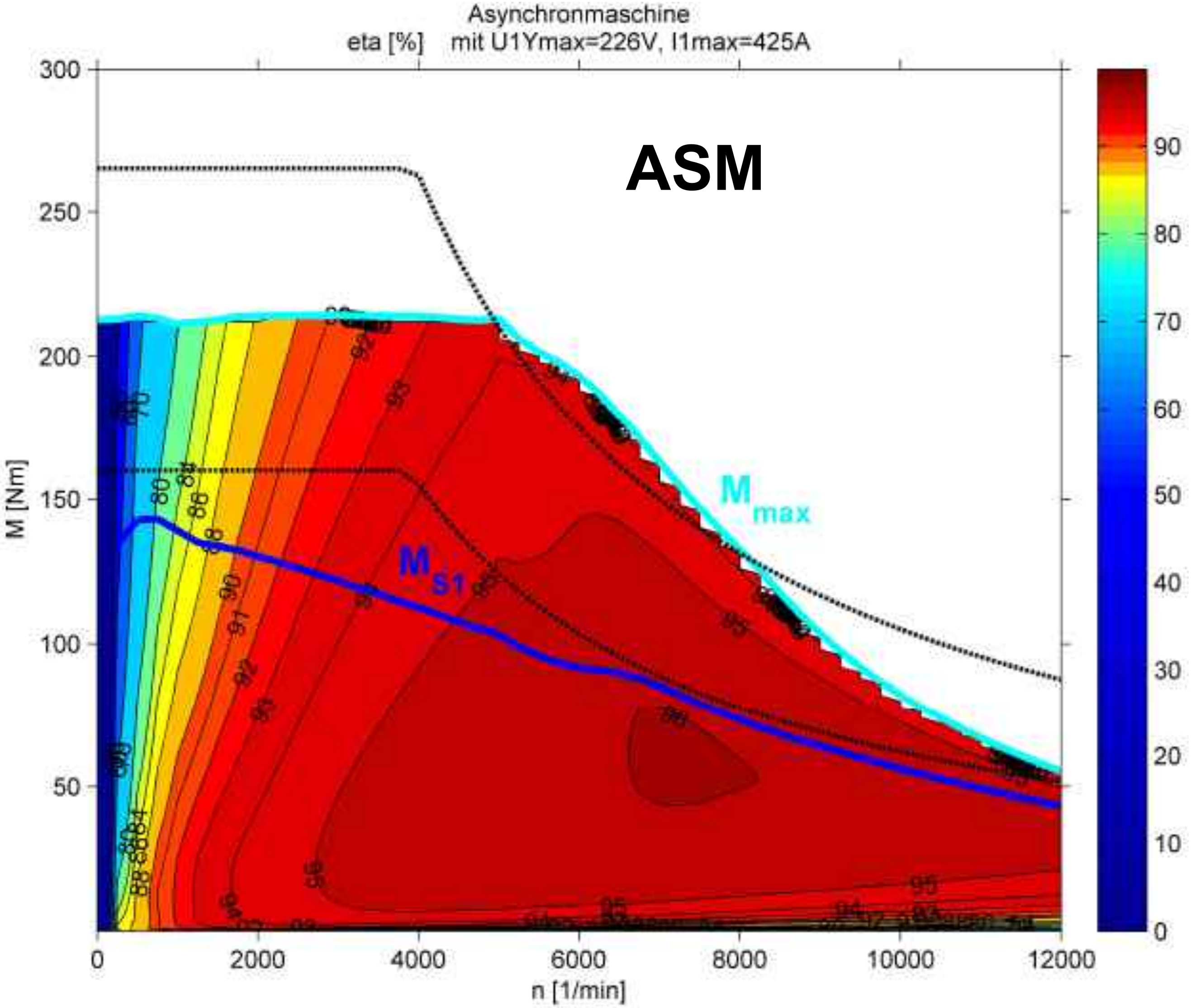

Source: SEW Eurodrive

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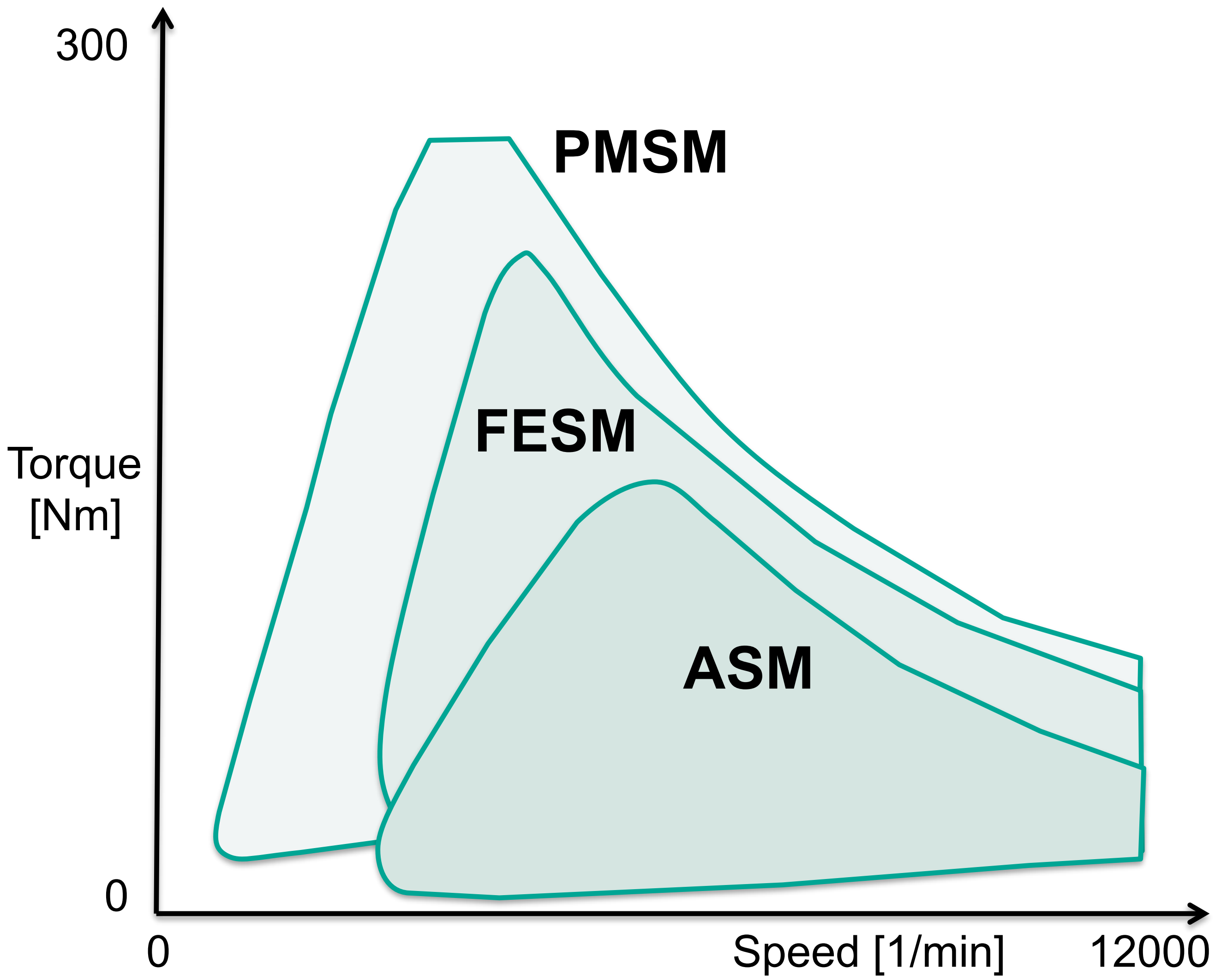
85 kW Drives (VW Golf class)
Area of highest efficiency (95%)



Martin Doppelbauer
Univ.-Prof. Dr.-Ing.
Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

85 kW Drives (VW Golf class)

All machines same housing diameter and length

	Required	PMSM	FESM	ASM
Iron length	-	175 mm	140 mm	160 mm
Motor mass	< 80 kg	78 kg	61 kg	73 kg
Cont. torque U_{DC}=320 V	160 Nm	180 Nm	115 Nm	110 Nm
Peak torque U_{DC}=320 V	270 Nm	270 Nm	290 Nm	215 Nm
Cont. power U_{DC}=216 V	50 kW	70 kW	38 kW	50 kW
Cont. power U_{DC}=320 V	65 kW	94 kW	48 kW	63 kW
Peak power U_{DC}=216 V	85 kW	84 kW	84 kW	81 kW
Peak power U_{DC}=320 V	110 kW	125 kW	125 kW	122 kW
Power density continuous	-	1,21 kW/kg	0,79 kW/kg	0,86 kW/kg
Best-point efficiency	-	97 %	96 %	96 %
FTP72 efficiency	-	80,2 %	86,2 %	86,6 %
Total losses FTP72	-	0,127 kWh	0,082 kWh	0,079 kWh

Source: SEW Eurodrive

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45 kW Drives (Subcompact category)
Technical Data

Fixed technical data:

- Iron stack diameter: 200 mm
- Iron stack length: 200 mm

- Battery max. Volt: 400 V DC
- Inverter (SVM) max. Volt: 282 V AC

- Gearbox ratio (fixed): 12

Performance requirements:

- Peak torque (short time): 130 Nm
- Rated power (S1 operation): 45 kW
- Rated torque (S1 operation): 86 Nm
- Top Speed: 12.000/min

Image source: Daimler AG

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Univ.-Prof. Dr.-Ing.

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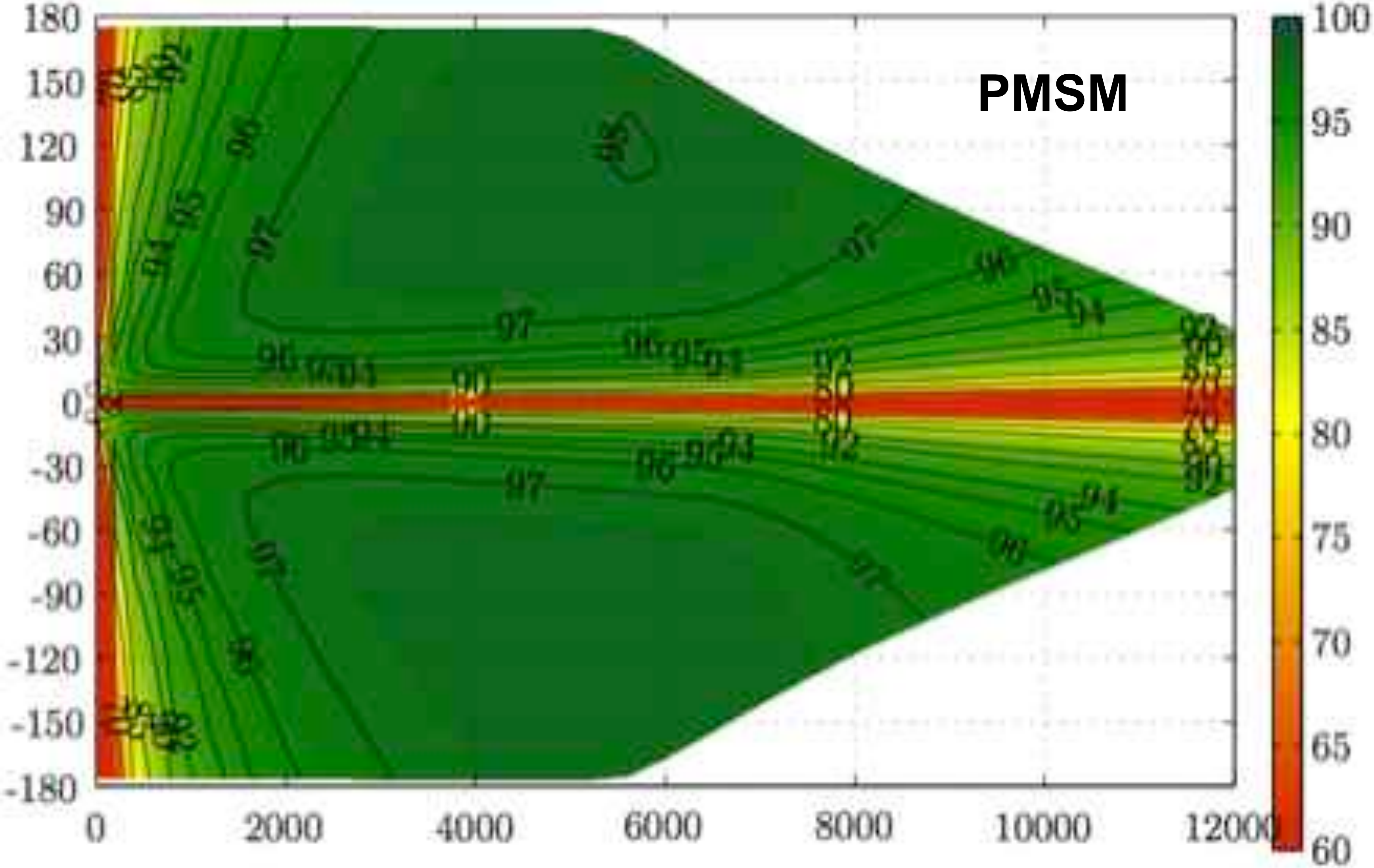
45 kW Drives (Subcompact category)

All machines identical stator and optimized rotor



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Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
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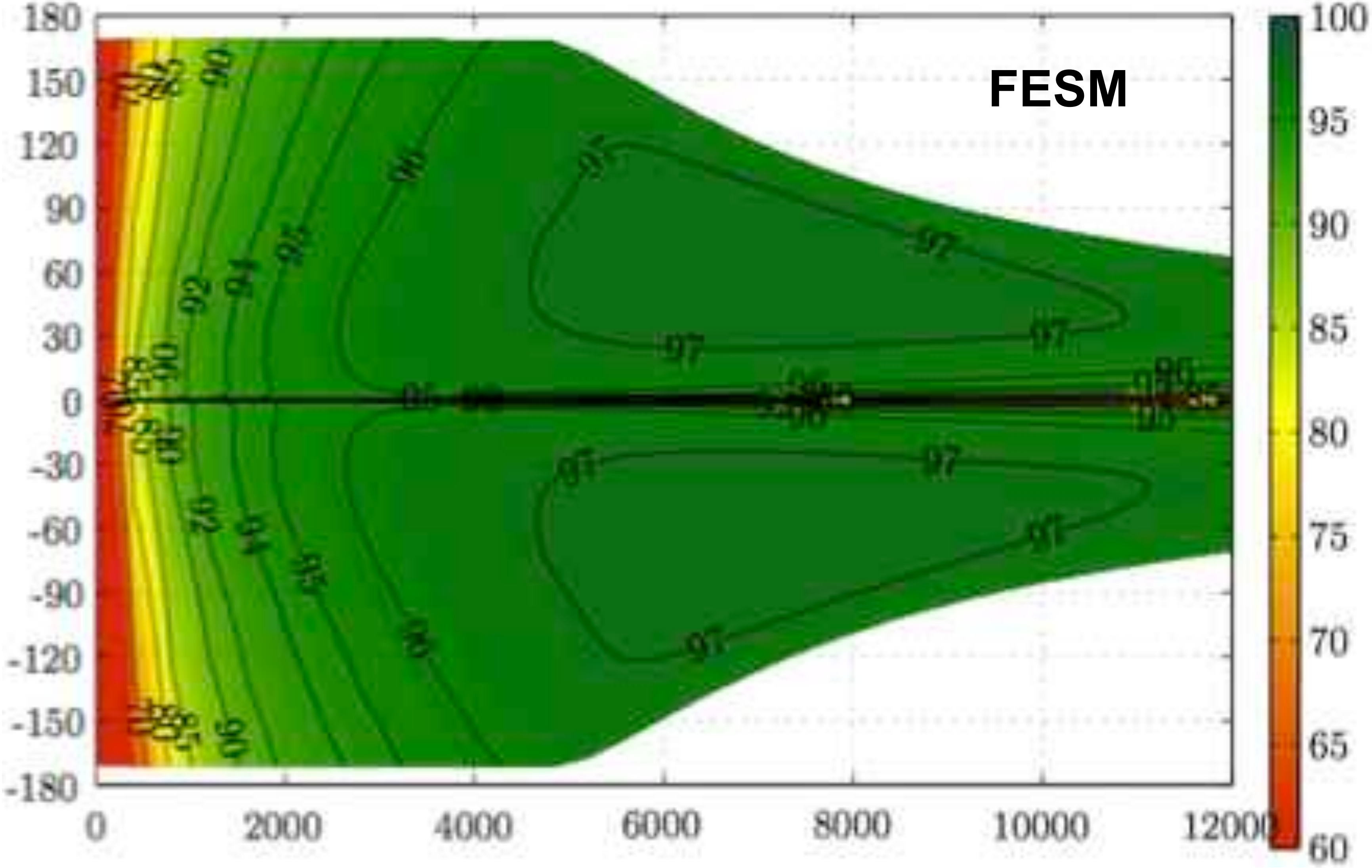
45 kW Drives (Subcompact category)

All machines identical stator and optimized rotor



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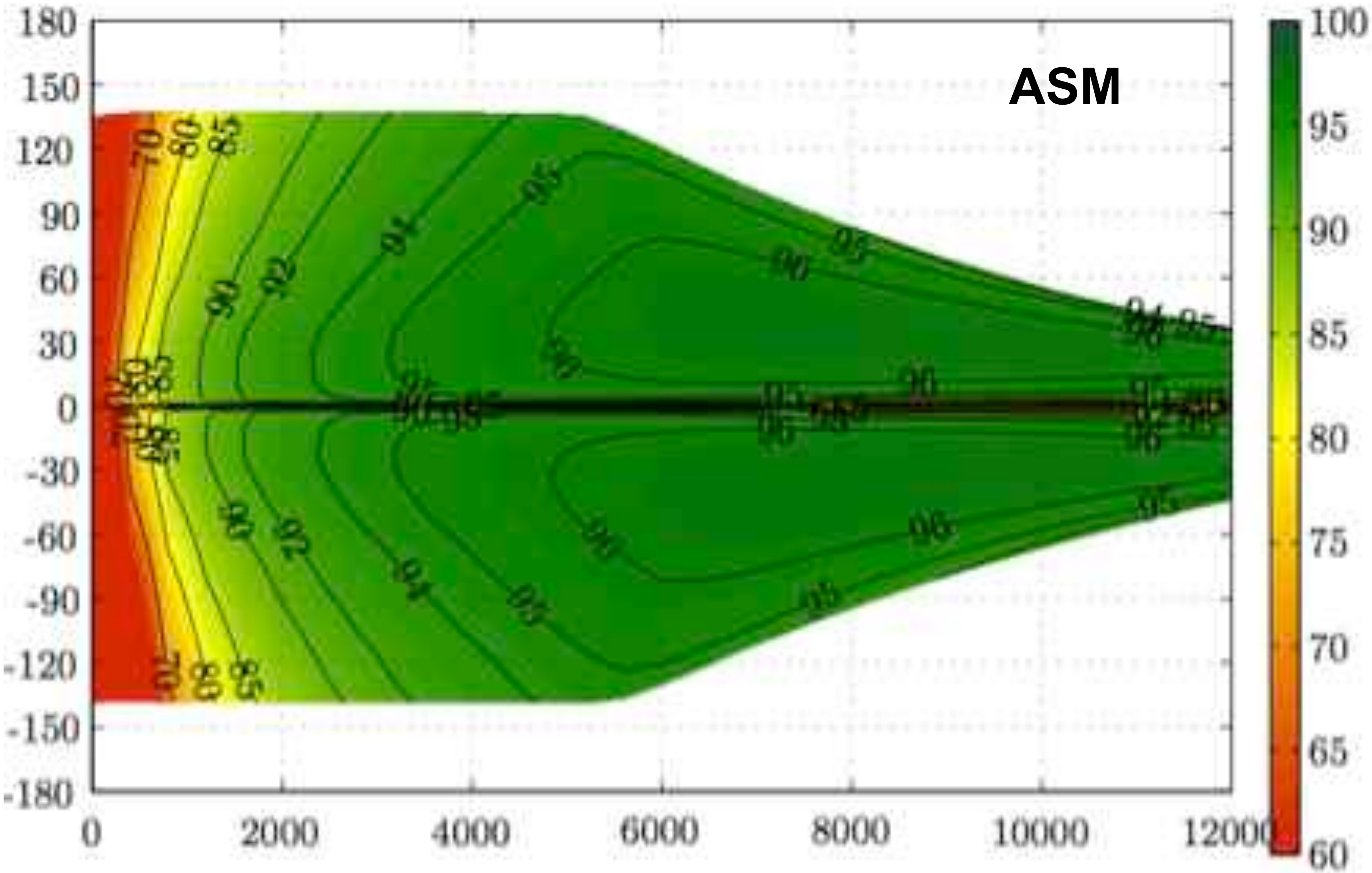
45 kW Drives (Subcompact category)

All machines identical stator and optimized rotor



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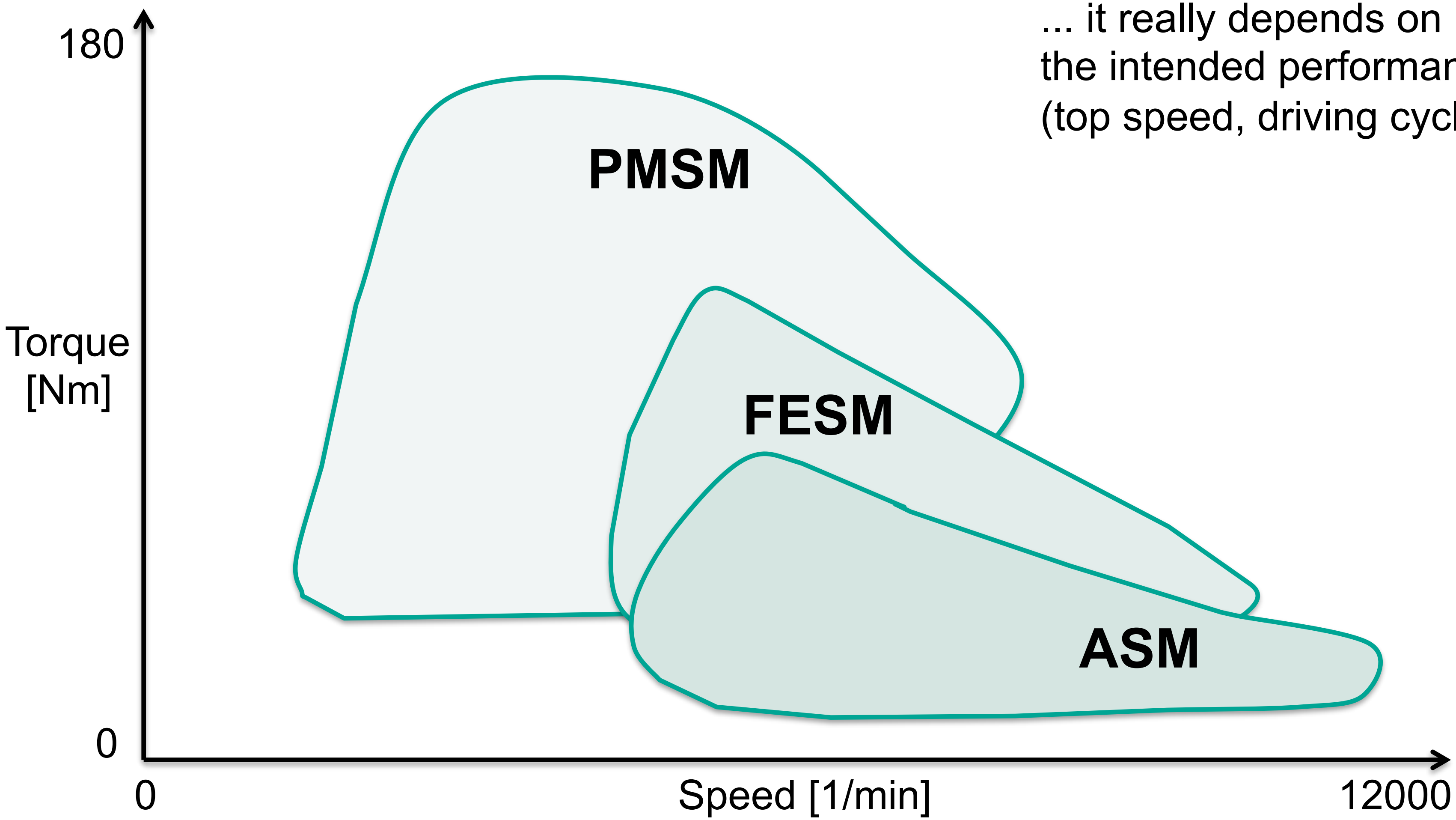
45 kW Drives (Subcompact category)

Area of highest efficiency (96…97%)



... it really depends on
the intended performance
(top speed, driving cycles)

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Driving Cycles

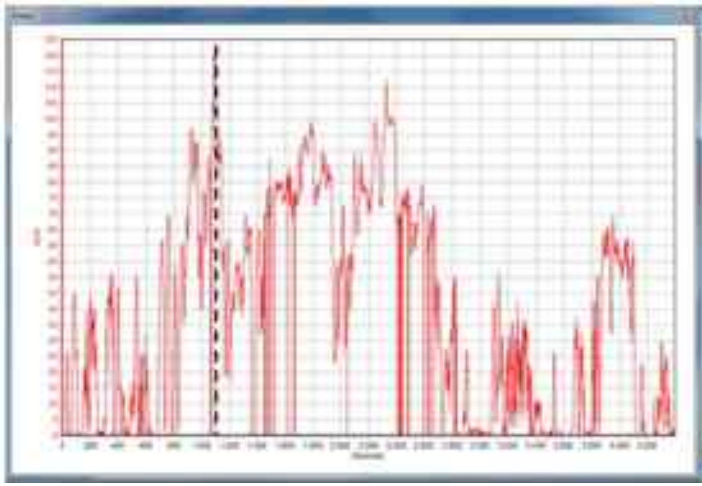
Synthetical and real-world road situations

Driving cycles:

- NEFZ (New European Driving Cycle)
- CADC (Common Artemis Driving Cycle: urban/road/motor130)
- HEV Karlsruhe Cycle

Typical driving situations
(Karlsruhe region with Opel Ampera test car):

- Traffic light stop
- Roundabout
- Entrance / exit of highway
- Traffic congestion



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Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
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45 kW Drives (Subcompact category)
Average motor efficiency

Fahrsituation	$\eta_{ges,\ PSM}$	$\eta_{ges,\ FESM}$	$\eta_{ges,\ ASM}$
Kreisverkehr	96.56	96.25	94.72
Ampel 30 $\frac{km}{h}$	96.26	93.4	89.95
Ampel 50 $\frac{km}{h}$	96.89	94.85	92.33
Ampel 60 $\frac{km}{h}$	97.03	95.59	93.17
Auffahrt auf Schnellstraßen	95.73	96.62	95.55
Abfahrt von Schnellstraßen	93.56	96.08	95.3
Überholvorgang	88.01	96.56	96.23
Parken	95.21	89.92	85.14
Stau	95.11	89.34	84.07
Testfahrt	93.22	96.07	94.94
NEFZ	91.73	95.94	94.73
CADC urban	96.04	94.78	92.19
CADC road	93.55	96.34	95.37
CADC motor 130	84.6	96.2	95.66

NEFZ=
Neuer Europäischer
Fahrzyklus

CADC=
Common Artemis
Driving Cycle

Production Aspects
Stator

Distributed winding

$q \geq 1$

- Wide variety of pole numbers
  ➥ Suited for all sizes of machines
  ➥ Suited for slow and high speed
- Very smooth air gap field
  ➥ Suited for all machine types (ASM, PMSM, FESM)
- Complex construction
  ➥ Manual work required

Single-tooth winding

$\frac{1}{4} \leq q \leq \frac{1}{2}$

- No. of poles app. equal to no. of teeth
  ➥ No. of poles grows with diameter
  ➥ Supply frequency grows with diam.
  ➥ Only for small or slow machines
- High amount of spatial air gap waves
  ➥ Additional losses, noise, vibration
  ➥ Not suited for induction machines
  ➥ Reduced efficiency
- Simple construction
  ➥ Fully automatable production

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.
Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Production Aspects
Rotor

PMSM	FESM	ASM
		
▪ Simple construction ➥ Fully automatable	▪ Complex construction ➥ Automization difficult	▪ Simple construction, much experience ➥ Fully automatable
▪ Rare earth magnets ➥ Very high material costs	▪ Lots of copper wire plus slip-rings/transformer ➥ High material and production costs	▪ Cheap material but copper die casting ➥ Medium costs

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

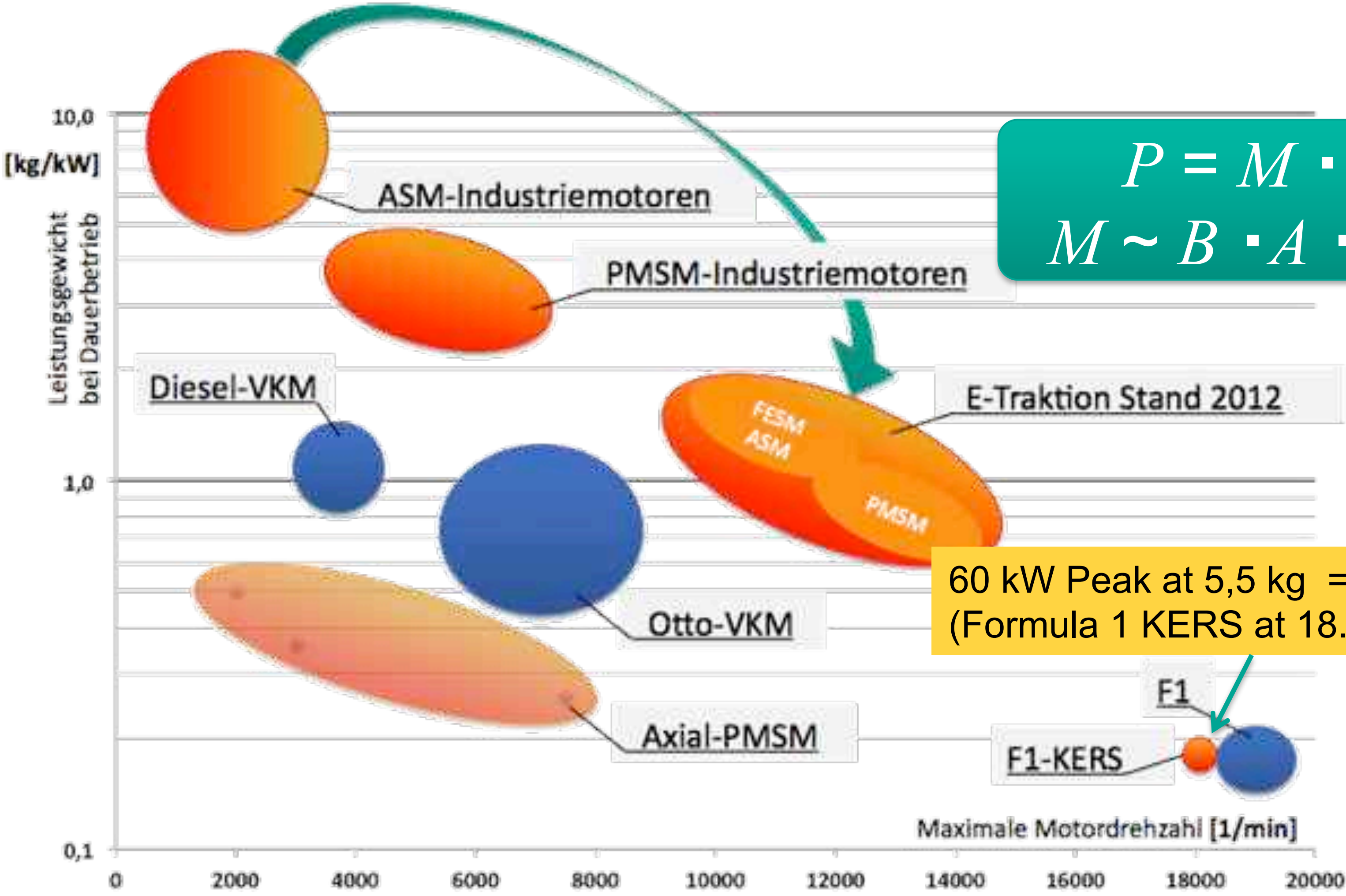
Safety Aspects

Functional Safety

	PMSM	FESM	ASM
Torque pulsation	⊖*	⊙	⊕
Torque build-up time	⊕	⊖	⊙
External short-circuit (back EMF)	⊖*	⊕	⊕⊕
External short-circuit (braking torque)	⊖*	⊕	⊕⊕

* depending on design

Machine Types
Development of power-density



$$P = M \cdot n$$
$$M \sim B \cdot A \cdot D^2 l$$

60 kW Peak at 5,5 kg = **0,1 kg/kW**
(Formula 1 KERS at 18.000/min)

Alle Angaben für Dauerbetrieb / Dauerleistung; Spitzenleistung je nach Leistungselektronik ca. 1,5 ... 3-fach höher

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
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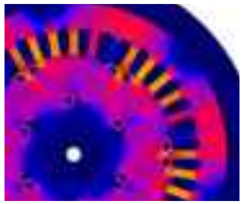
Machine Types

Summary of findings

	PMSM	FESM	ASM
Power density	⊕⊕	⊙	⊕
Best-point efficiency	⊕⊕	⊕	⊙
Driving-cycle efficiency	⊙	⊕⊕	⊕
Manufacturing cost	⊕*	⊖	⊙**
Material cost	⊖	⊙	⊕
Intrinsic safety	⊖	⊕	⊕⊕
Technical maturity	⊕	⊙	⊕⊕

⊕⊕ very good
⊕ good
⊙ neutral
⊖ bad
⊖⊖ very bad

* distributed winding
** die-cast copper rotor



BMW i3
Chevy Volt

Renault Kangoo
Renault Zoe

Tesla
Daimler B-class ED

Martin Doppelbauer
Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut
Professur Hybridelektrische Fahrzeuge

Karlsruher Institut für Technologie

Elektrotechnisches Institut

Hybrid Electric Vehicles

Thank you for your interest
Questions ?

Martin Doppelbauer

Univ.-Prof. Dr.-Ing.

Elektrotechnisches Institut (ETI) – Professur für Hybridelektrische Fahrzeuge (HEV)