Planning and application of electrical drives (PAED) - Drives for electric vehicles

TU DARMSTADT – Basics of Drive Calculations

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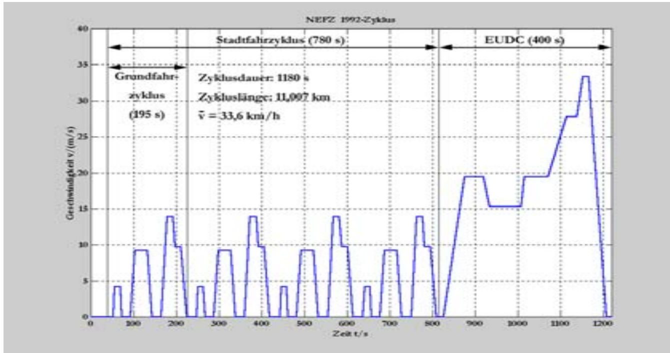

Source: Daimler

Based on literature by M. Ade, S. Dewenter, M. Brüggemann and P. Morrison

Contents

- Hybrid vehicles - Overview
- Electric vehicles – Overview
- Electric vehicles – Drive components
- Electric vehicles – Simulation vehicle - track
- Electric vehicles – Simulation of the drive components
- Electric vehicles – Examples of simulation

TESLA Roadster

Hybrid vehicles - Overview

Motivation for hybrid drives

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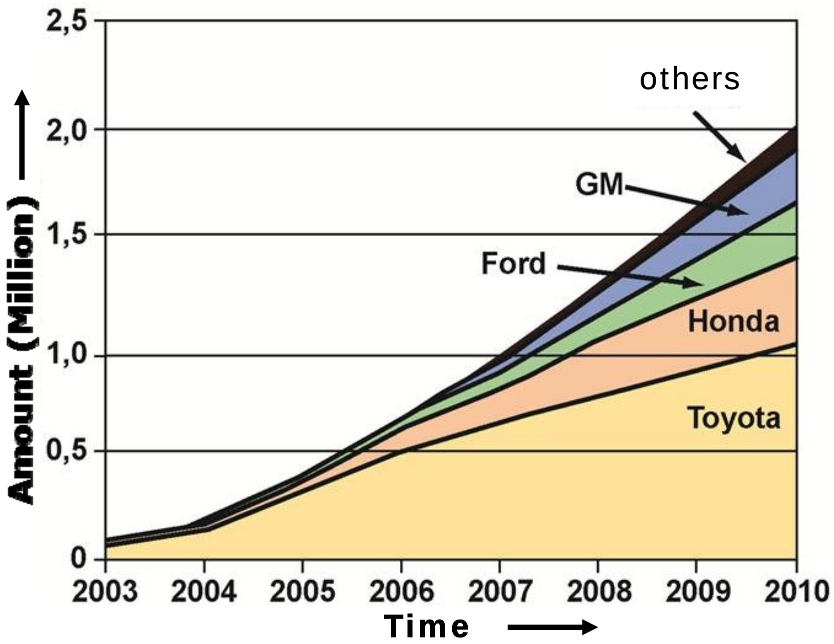
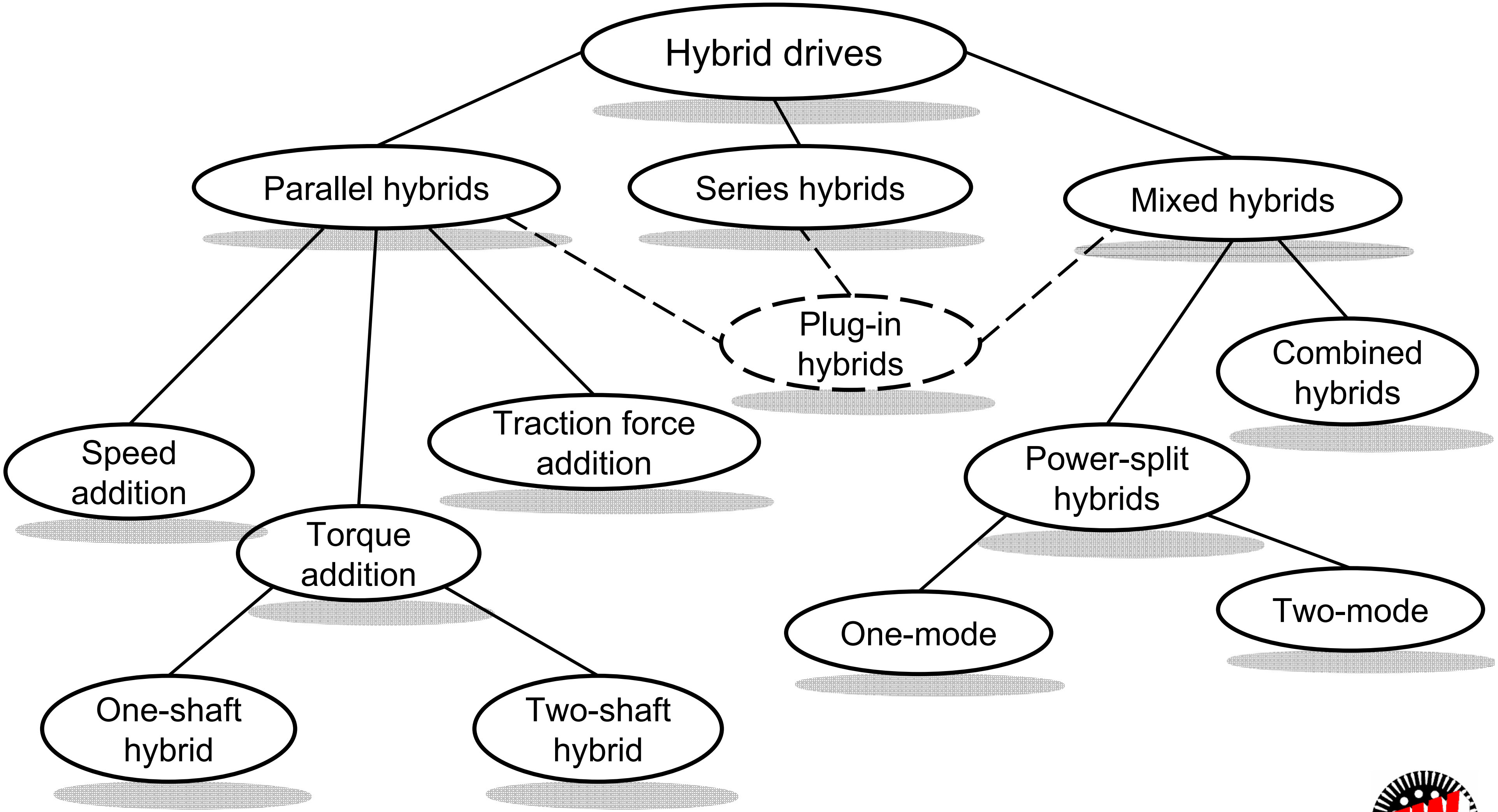
- **Market prognosis 2010**
  - **Global production approx. 65 Mio. cars**
  - **Market share HEV approx. 3 % (market segment Mini in FRG 2006 approx. 3 %)**
  - **Share of European brands small**
    - → **Demand for catch up production / sale**
    - → **Further development e.g. by the use of simulation programs**



- **Advantages of simulation models**
  - **Build-up of know how / development tools**
  - **Design / tuning / dimensioning of drive train components before manufacturing of prototype**

  → **Contribution to reduction of development costs**

Possible hybrid topologies

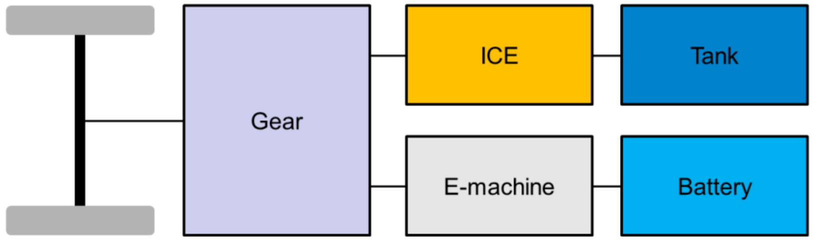


Overview hybrid vehicles

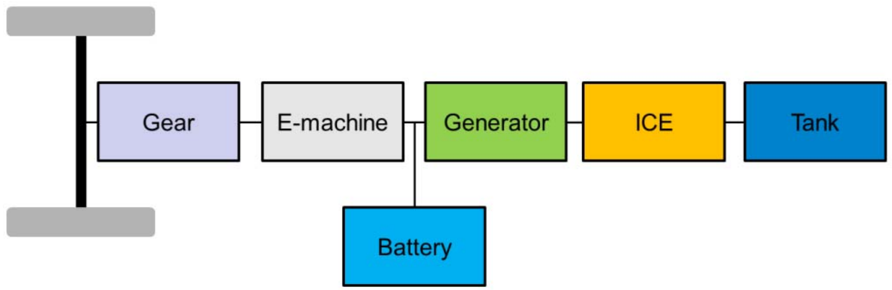
	Micro hybrid	Mild hybrid	Full hybrid
Power range in kW Voltage in V	2-3 12	10-15 42	> 15 > 100
Motor start/stop	X	X	X
Recuperation		X	X
Boost			X
Purely electric driving			X

Overview hybrid vehicles

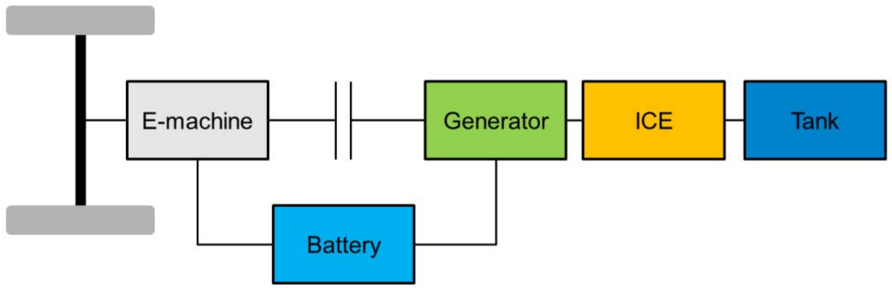
Parallel hybrid



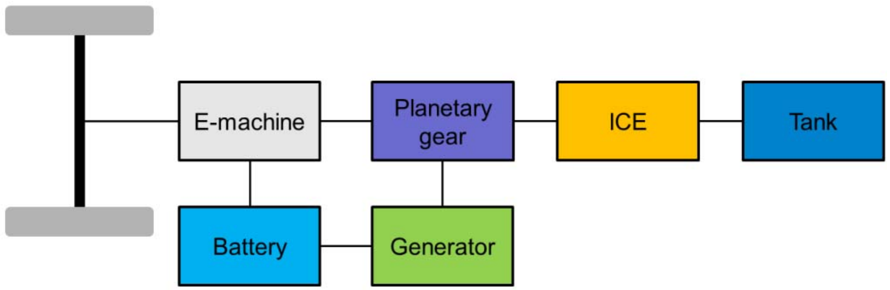
Series hybrid



Combined hybrid

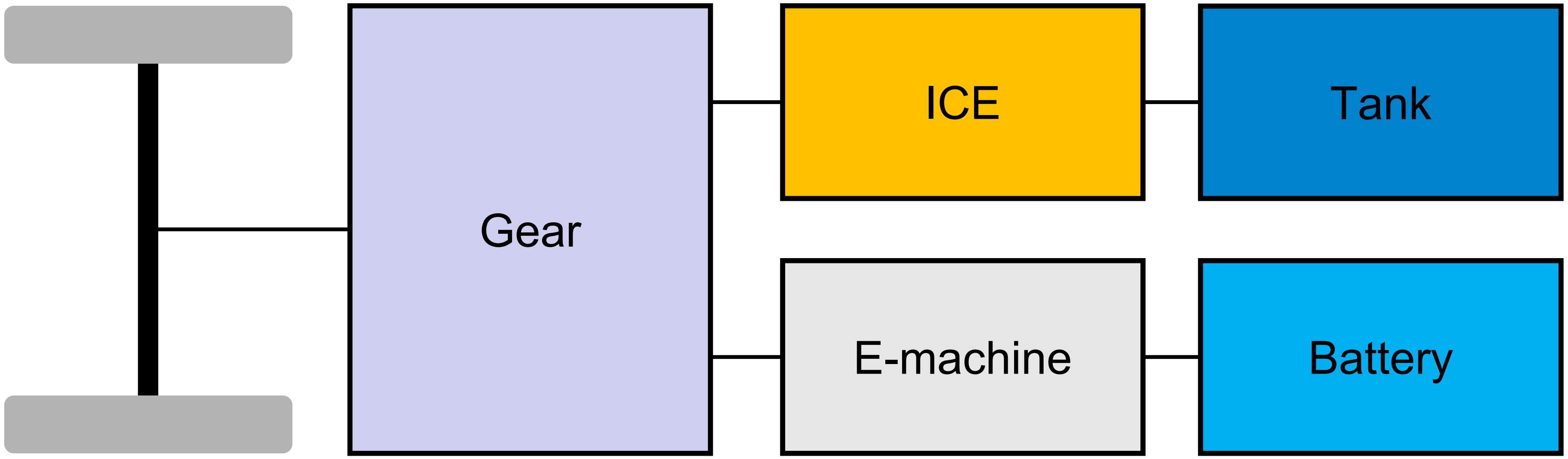


Power split hybrid



Parallel hybrid

Parallel hybrid drive



Parallel hybrid

Different variants of parallel hybrid

- Torque addition:
  - Fixed connection of both drive types (e.g. by chain or spur gear)
  - Distinction between one- and two shaft hybrid
- Tractive force addition („*Through-the-road hybrid*“):
  - Special case of torque addition
  - Coupling of both drive types over track
- Rotational speed addition:
  - Connection by planetary gear
  - Fixed torque ratio between drives, therefore free choice of rotational speed

Parallel hybrid

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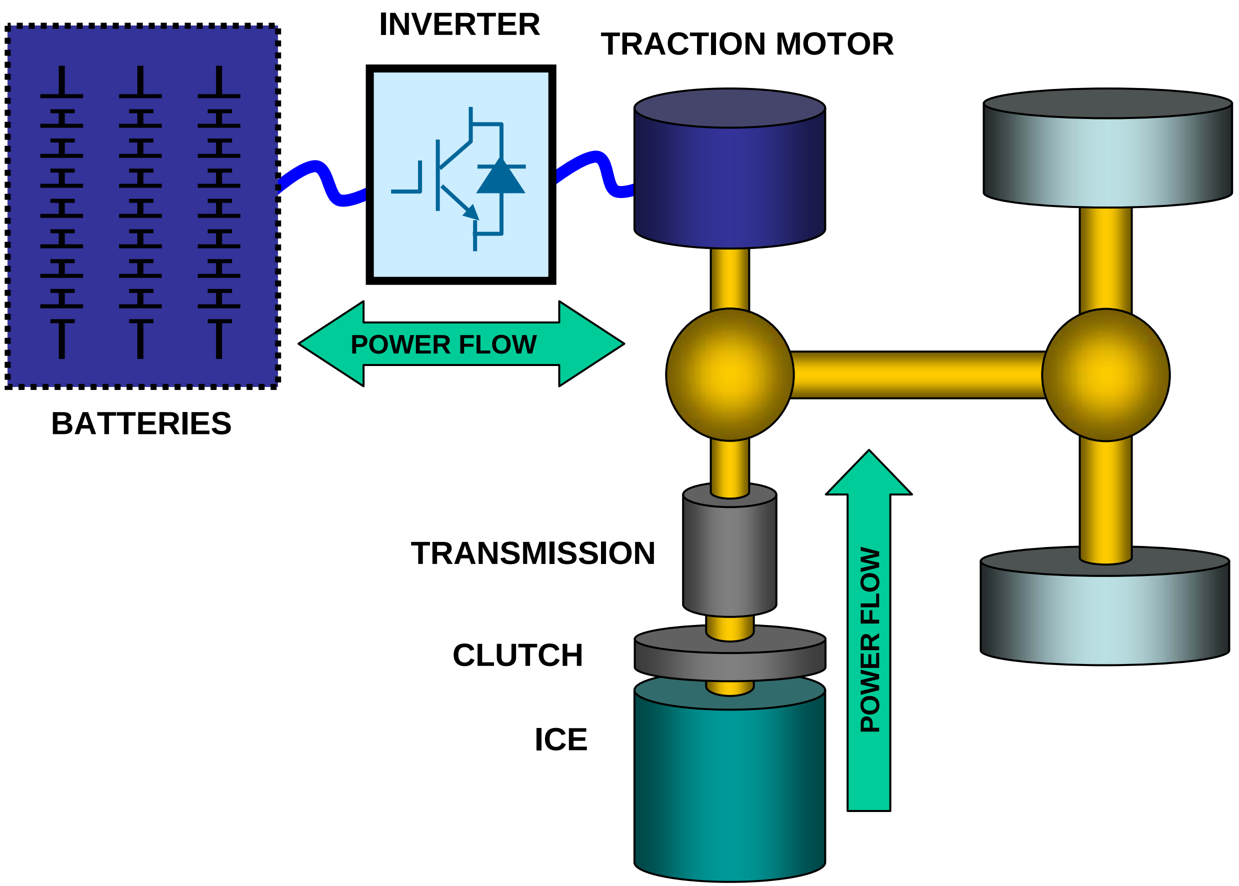


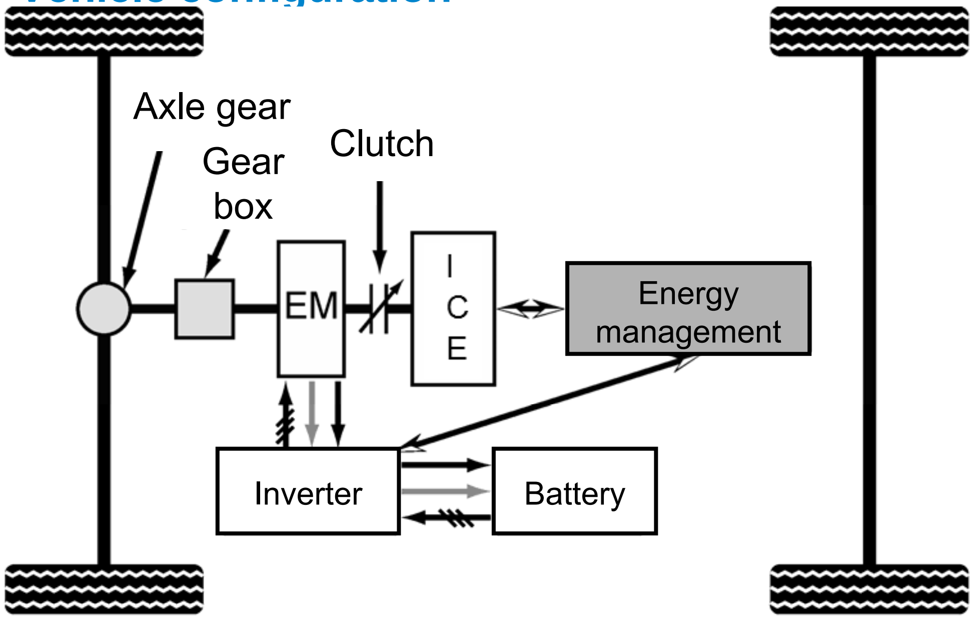
Source:

Parker Hannifin

- - - - - Mechanical load sharing - - - - -

Parallel hybrid

- ***Mercedes Benz* (MB) *E-Class 220 CDI***
  - **Vehicle: fictive**
  - **Electrically supplied ancillary units**
  - **Max. additional power consumption**
- **Vehicle configuration**



ICE: Internal combustion engine
EM: Electric machine

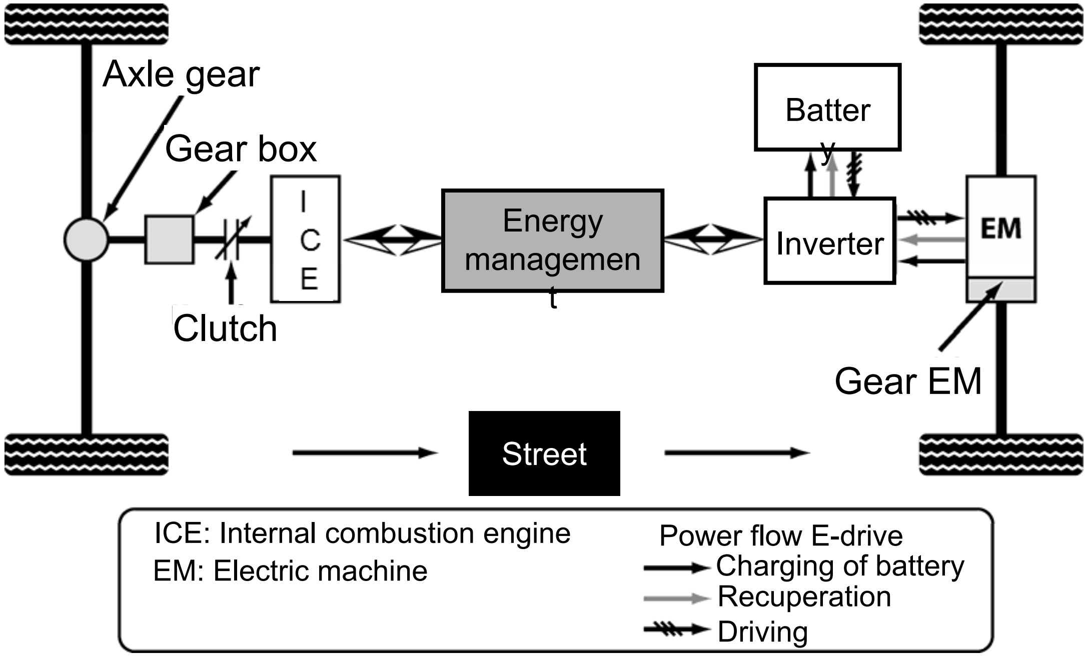
Power flow E-drive
→ Charging of battery
→ Recuperation
→ Driving

***Example:* Vehicle data P-HEV1**

ICE	2,2 l CDI
Cylinders	4
M_N / P_N	300 Nm / 105 kW
Gear	Automatic
Transmission ratios gear 1 … 5	3.95 / 2.42 / 1.49 / 1.00 / 0.83
Axle gear	2,87
Vehicle	MB E Class
c_W-value	0,27
Reference area	~ 2.25 m^2
Wheels	r = 0,299 m
Empty mass Battery E-Machine Inverter DC/DC-converter Board battery Alternator **Total weight** **→Additional weight**	1640 kg 40 kg 60 kg 10 kg 5 kg -10 kg -5kg **1740 kg** **approx. 100 kg**

Parallel hybrid „Through the road“

- *Mercedes Benz* (MB) *B-Class*
  - Vehicle: fictive
  - Electrically supplied ancillary units
  - Max. additional power consumption
- Vehicle configuration

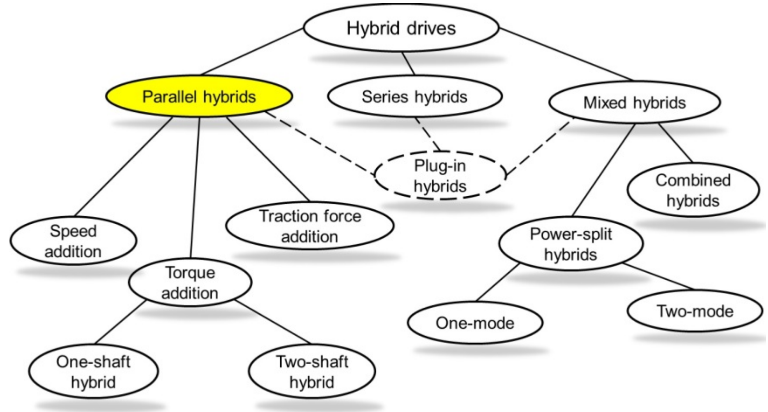


Example: **Vehicle data P-HEV2**

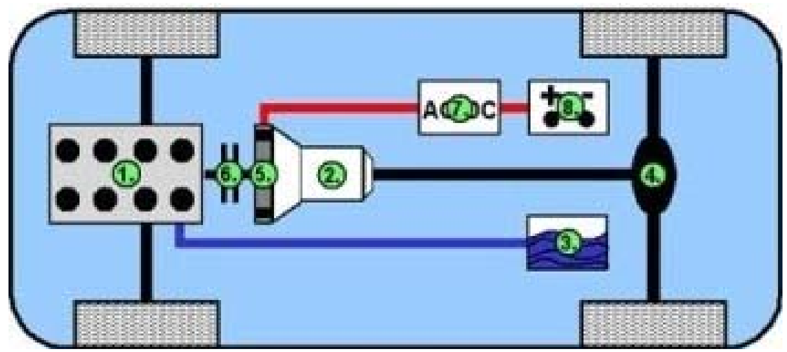
ICE	1,7 l CDI
Zylinders	4
M_N / P_N	180 Nm / 67 kW
Gear	Automatic
Transmission ratios gear 1 … 5	2.72 / 1.69 / 1.12 / 0.79 / 0.65
Axle gear	3,95
Vehicle	MB B Class
c_W-value	0,3
Reference area	~ 2.42 m^2
Wheels	r = 0,3205 m
Empty mass Battery E-Machine Inverter DC/DC-converter Board battery Alternator **Total weight** **→Additional weight**	1435 kg 40 kg 42 kg 8.5 kg 5 kg -10 kg -5kg **1515 kg** **ca. 80 kg**

Parallel hybrid

- ICE and E-Machine can both drive
- Advantage:
  - Only two machines
  - Part of traction directly by ICE (no „unnecessary“ energy conversion)
  - Further saving potentials by „downsizing“
- Draw backs:
  - ICE - operating points depend on cruise environment
  - More complex energy management



Parallel hybrid

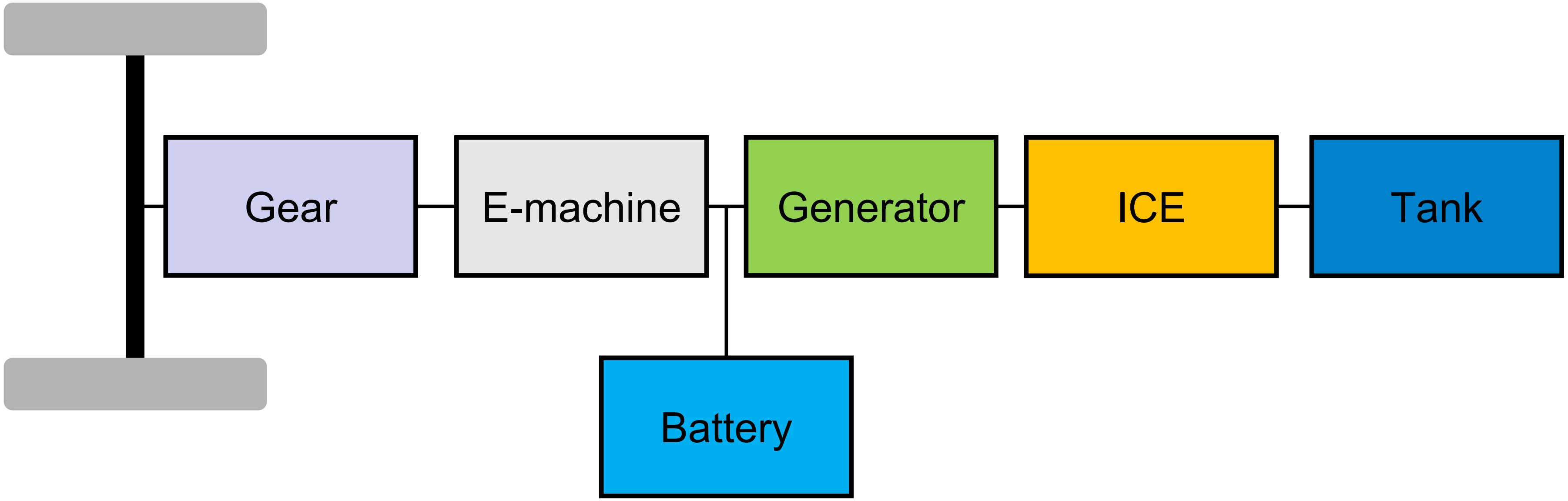


1. ICE; 2. Gear; 3. Tank; 4. Differential gear; 5. E-Machine; 6. Clutch; 7. Converter; 8. Battery

(Source: Hybrid-Autos.info)

Series hybrid

Series hybrid drive



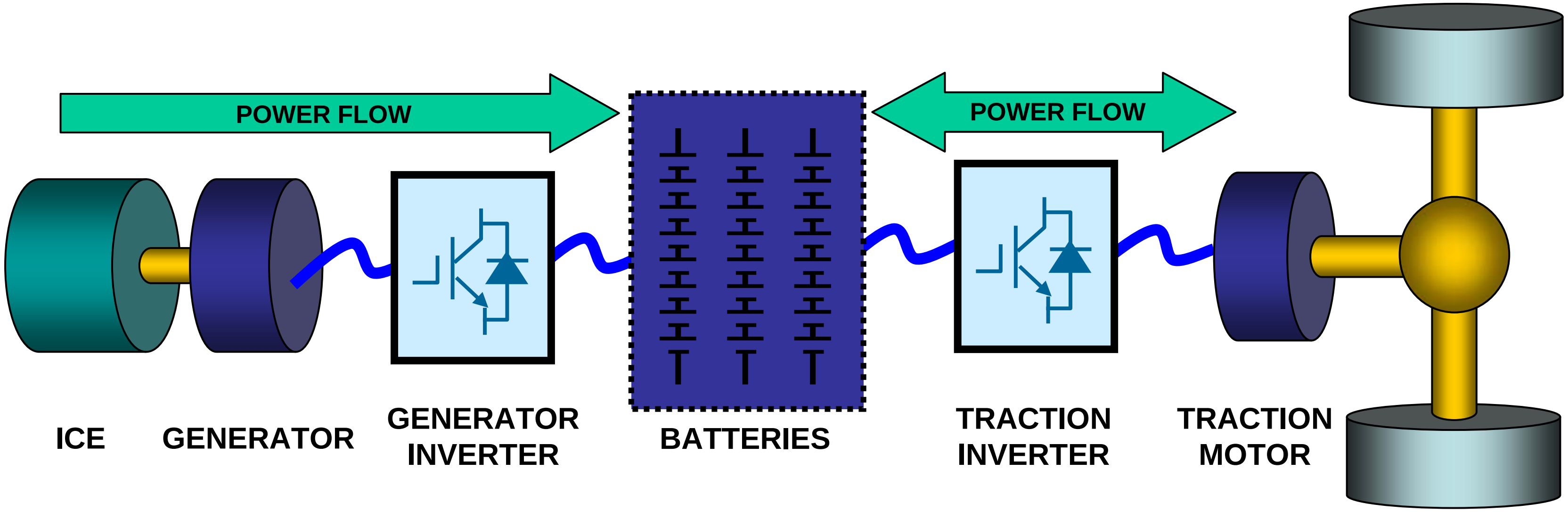
Example: Diesel-electric city busses: Diesel engine runs in optimal operating point = max. efficiency (e. g. 43%)

E-machines + converter → speed variable!

Series hybrid

Source:

Parker Hannifin



- - - - - No mechanical connection - - - - -

Series hybrid busses

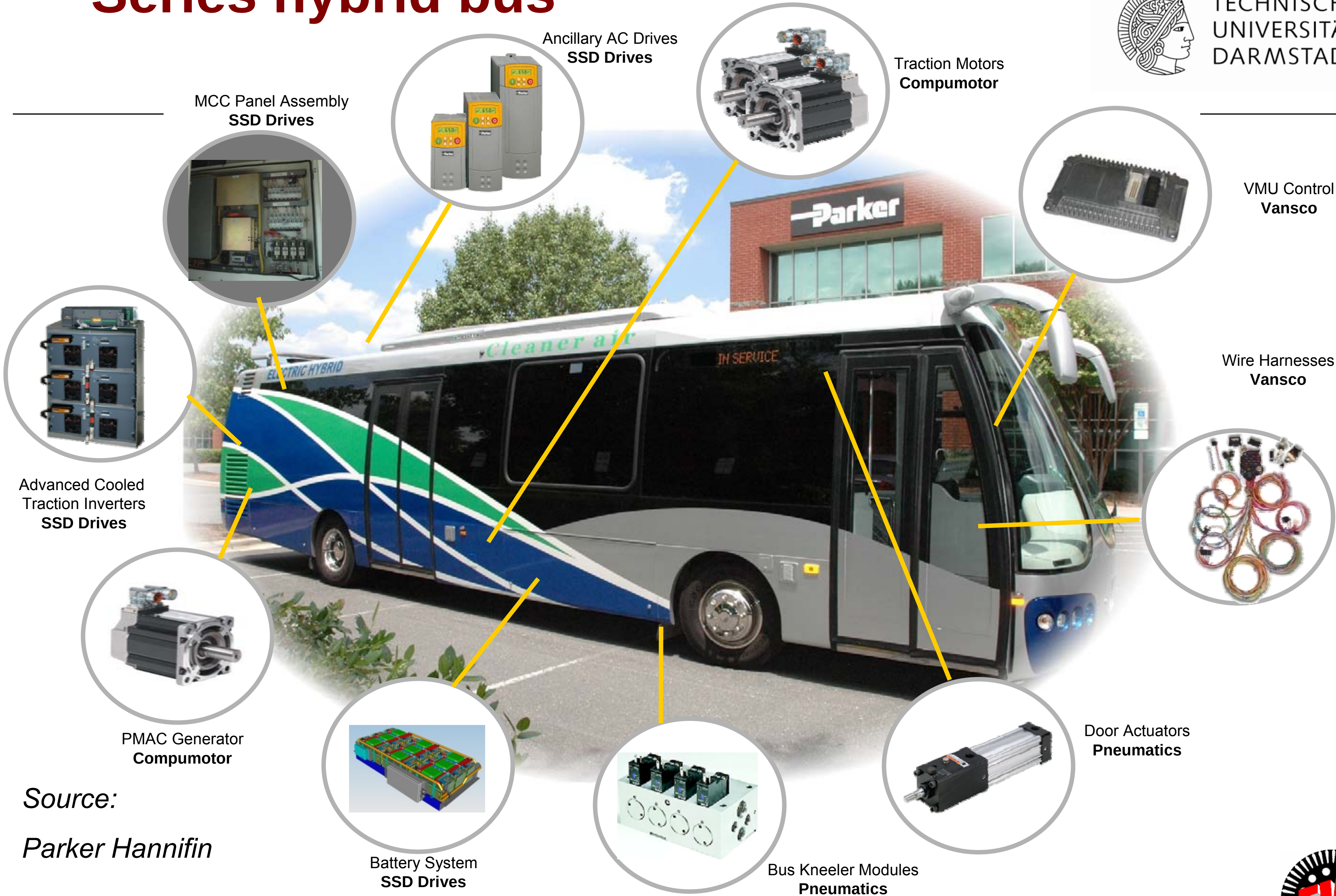
Electric components:

- Control panels
- Traction inverters
- Advanced battery system
- Traction motors
- Generators (PM AC)
- Charging inverters

Source:

Parker Hannifin

Series hybrid bus



Source:

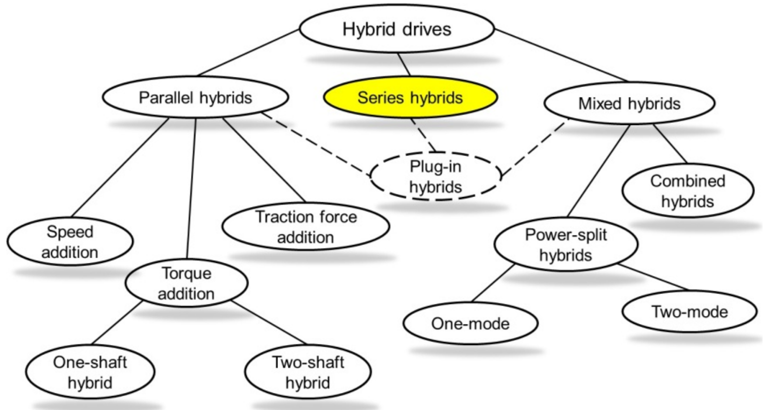
Parker Hannifin

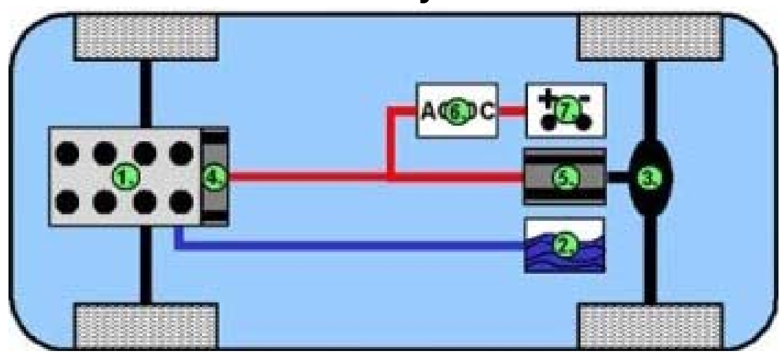
Series hybrid

- ICE only for electricity generation
- No mechanic connection of IEC and track

- Advantages:
  - Degrees of freedom in vehicle design
  - IEC operates in point of best efficiency
  - No gear needed

- Draw backs:
  - Additional, double energy conversion
  - Three full-valued machines
    (→ Full hybrid!)

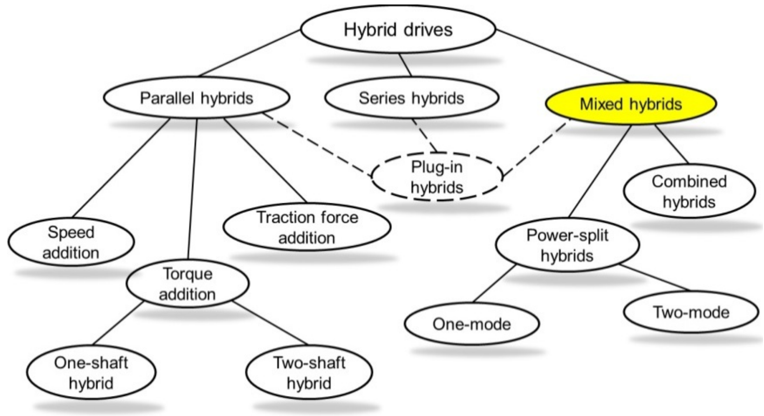




(Source: Hybrid-Autos.info)

Mixed hybrid

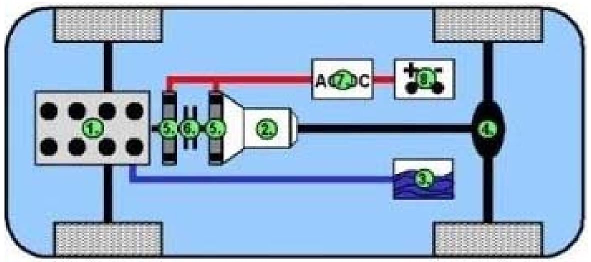
- <u>Different variants of mixed hybrid</u>



- Combined Hybrid:
  - Elective drive either as series or parallel hybrid

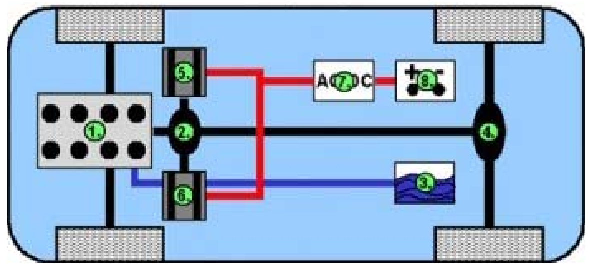
- Power-split Hybrid
  - One-Mode: one fixed range of operating
  - Dual-Mode: two ranges of operating and four fixed gears

Combined hybrid



1. ICE; 2. Gear; 3. Tank; 4. Differential gear; 5. E-Gen. (left), E-mot. (right); 6. Clutch; 7. Converter; 8. Battery

Power-Split (One-mode) hybrid



1. ICE; 2. Planetary gear; 3. Tank; 4. Differential gear; 5. EM 1; 6. EM 2; 6. Converter; 7. Battery

(Source: Hybrid-Autos.info)

Combined hybrid

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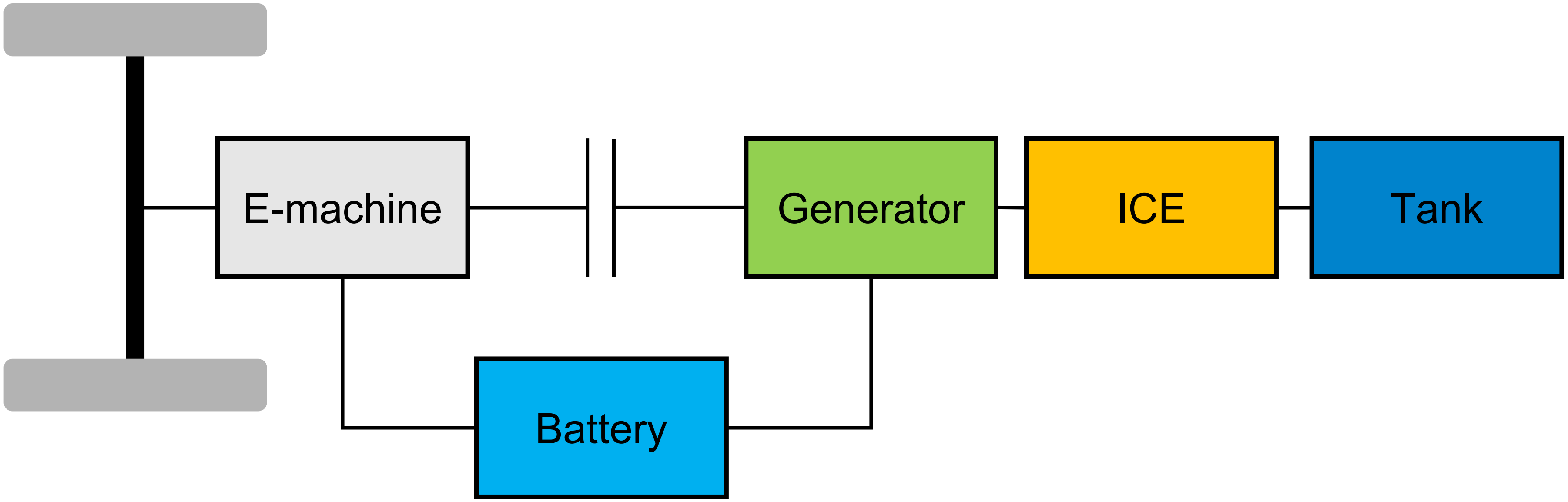
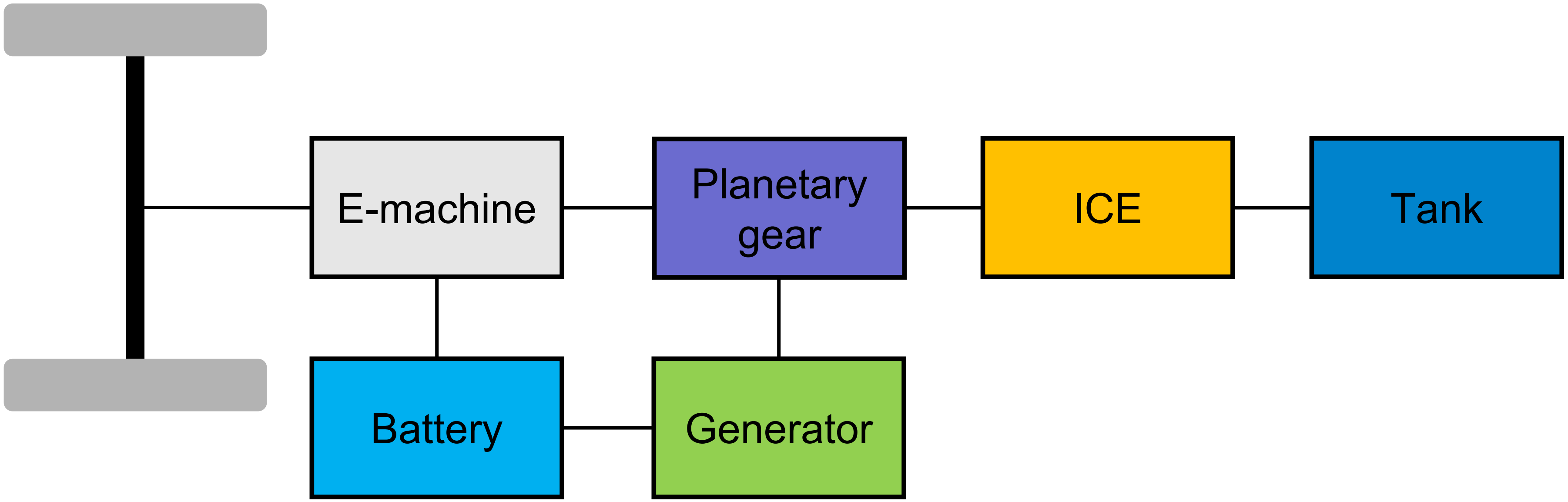
Combined hybrid drive



Power-split hybrid

Power-split hybrid drive



Example: *Toyota Prius*: power splitting gear,

Ni-MH-battery

Hybridization classes

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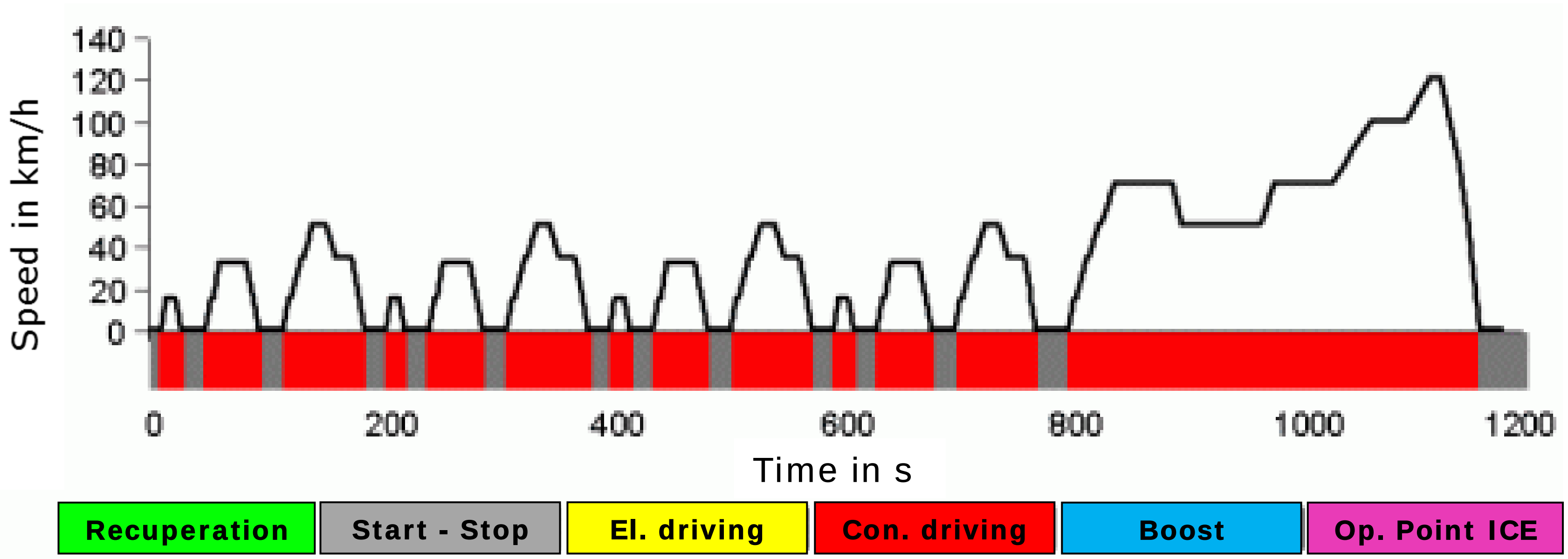
Class	Micro hybrid	Mild hybrid	Full hybrid
Power range	2 – 3 kW	10 – 15 kW	>15 kW
Operating voltage	12 V	42 – 144 V (with DC – DC - converter)	>> 100 V (with DC – DC - converter)
Characteristics	• hardly any difference to a conventional vehicle • starter-generator instead of an alternator	• traction- instead of board battery • use of crankshaft-stator-generators • „downsizing“ – option	• sufficiently big dimensioned traction batteries and electric machines for purely electric drive
Components of one operating strategy	• no „real“ recuperation, but optimized charging of board battery • start – stop - function	• “real” recuperation • start - stop – function • „boost“ - option • load-point shift	• real recuperation • start – stop - function • „boost“ – option • load-point shift • purely electric driving possible
Saving potentials *	2 – 10 %	10 – 20 %	20 – 50 %

(* C. C. Chan: „Electric, Hybrid, and Fuel-Cell Vehicles: Architectures and Modeling“)

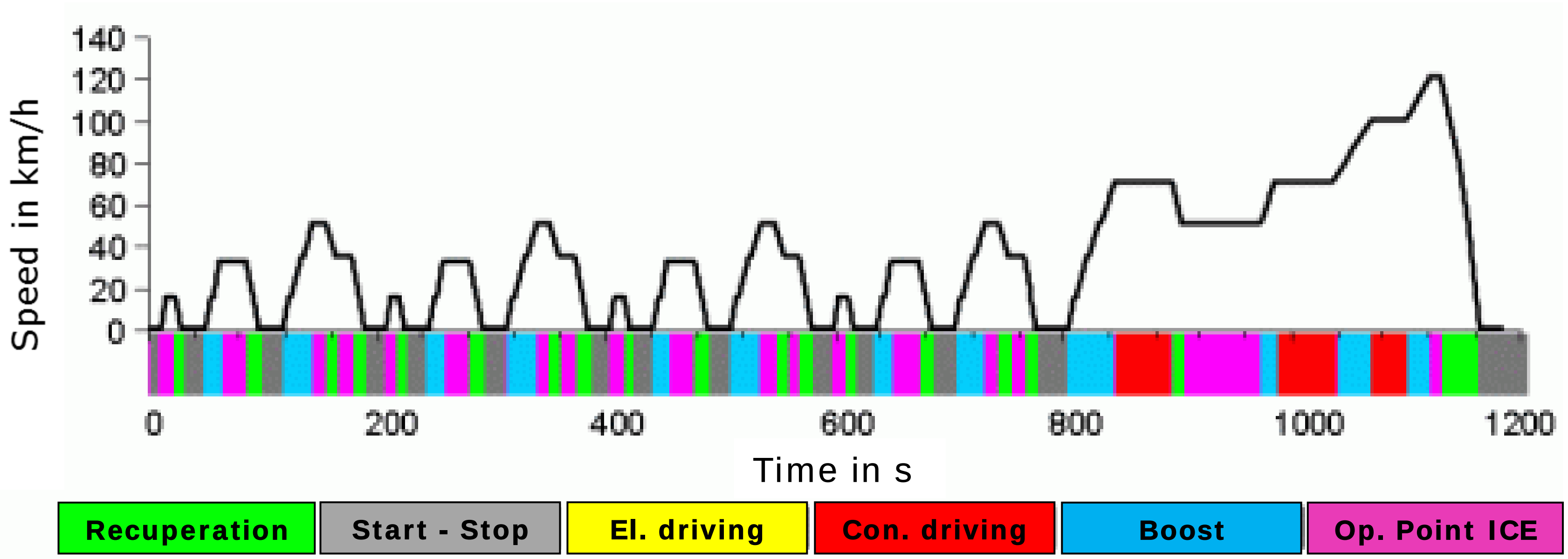
Micro hybrid



(Source: Hybrid-Autos.info)

- Start – stop
- conventional driving

Mild hybrid

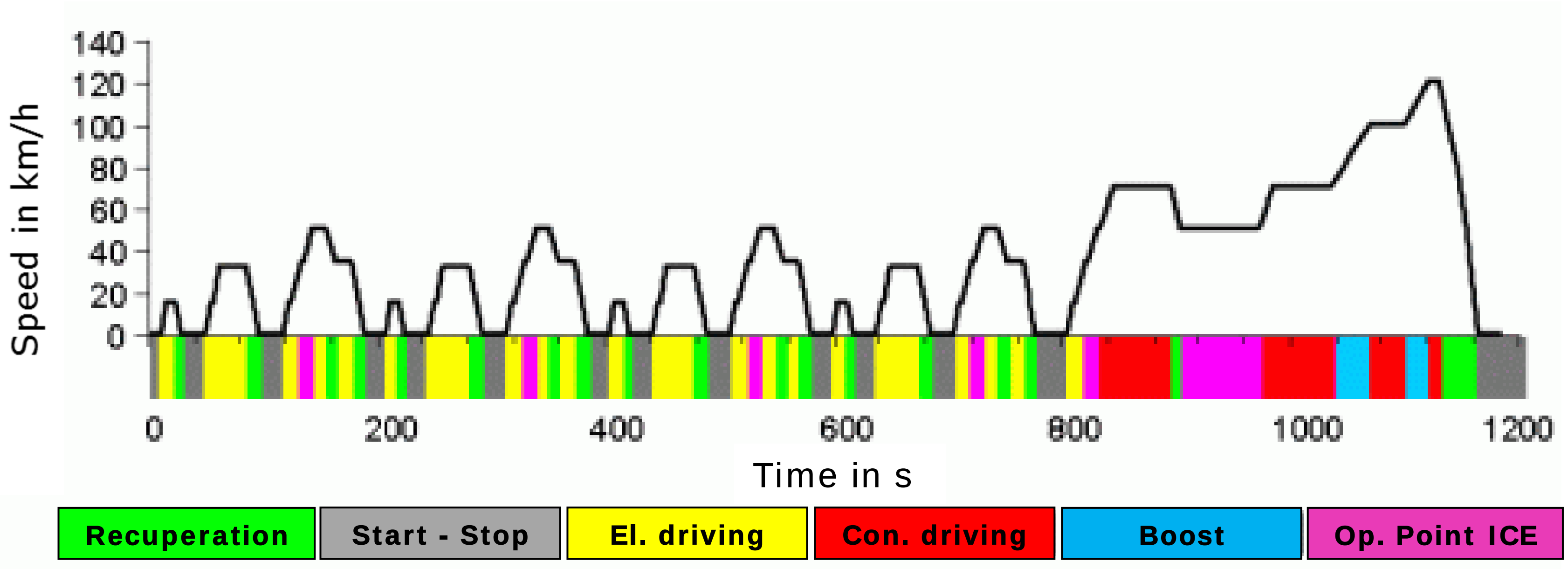


(Source: Hybrid-Autos.info)

<u>Additionally to micro hybrid:</u>

- Recuperation
- Boost
- Load point shift

Full hybrid



(Source: Hybrid-Autos.info)

<u>Additionally to mild hybrid:</u>

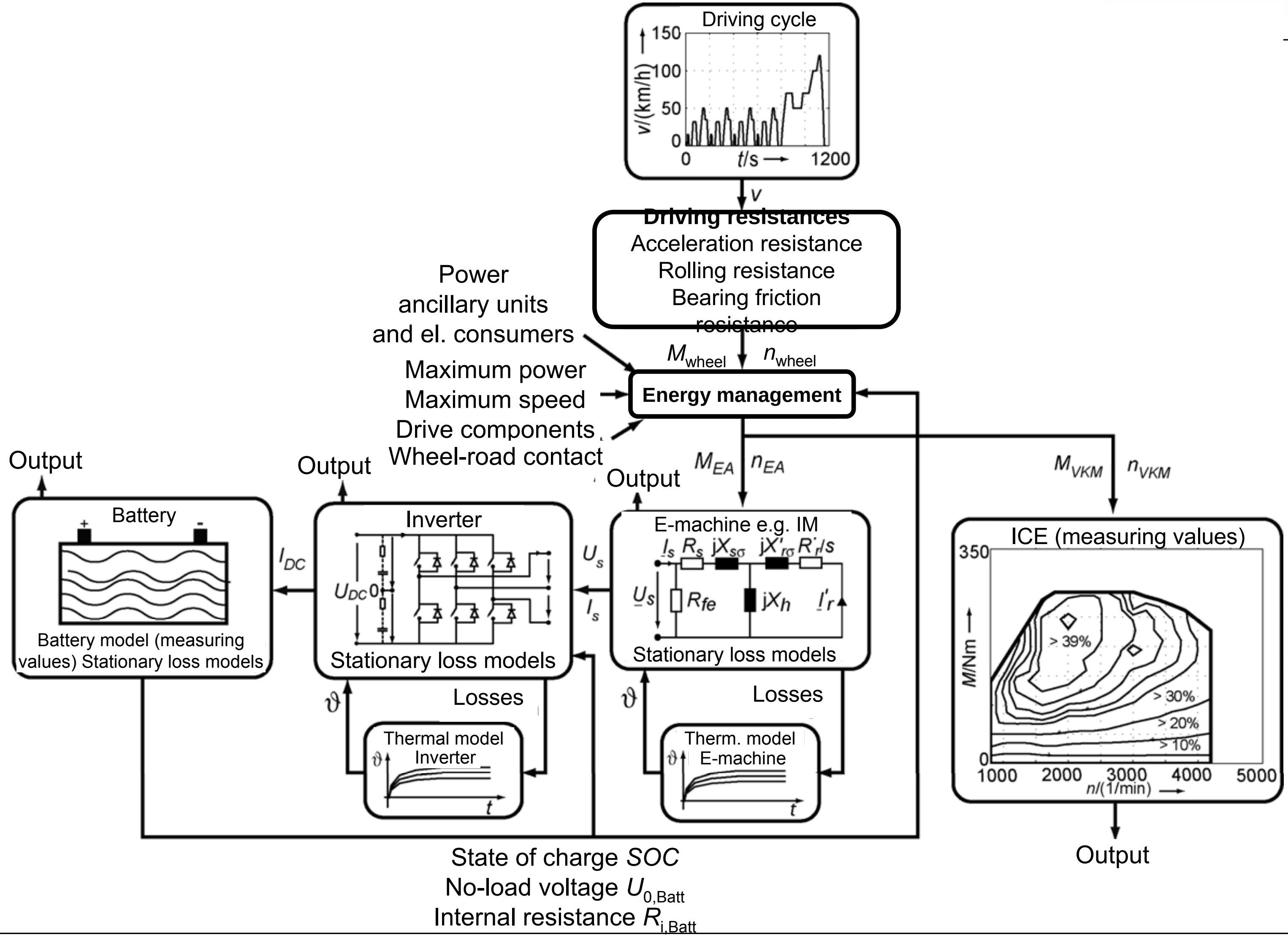
• Pure electric driving

Current and future hybrid vehicles (selection)

	Series hybrid	Parallel hybrid: Torque-addition	Parallel hybrid: Tractive force-addition	Mixed hybrid: Combined	Mixed hybrid: Power-split (One-Mode)	Mixed hybrid: Power-split (Two-Mode)
Mild hybrid	(does not make sense)	*Honda* („*IMA*“): • *Jazz* • Insight • CR-Z *BMW*: •**ActiveHybrid 7** Mercedes-Benz: • **S400 BlueHYBRID**	(unknown)	(does not make sense)	(does not make sense)	(does not make sense)
Full hybrid	*Audi*: • *A1 e-tron (2013)* *BMW*: • *Megacity Vehicle (2013)*	*Audi*: • **Q5 Hybrid (2011)** • **A8 Hybrid (2011)** *VW*: • **Touareg Hybrid** (2011) *Porsche*: • **Cayenne S Hybrid**	*Peugeot* („*Hybrid4*“): • 3008 (2011)	*Opel*: • Ampera (2011) *Chevrolet*: • Volt (2011)	*Toyota* („*HSD*“): • Prius 3 • *Auris HSD* *Lexus* („*HSD*“): • CT 200h • *HS 240h* • *GS 450h* • **LS 600h** • RX 450h	*BMW*: • **X6 ActiveHybrid** *Mercedes*: • **ML 450 Hybrid**

Vehicle classes: *compact class* middle class *upper middle class* **upper class** **off-road vehicle**

Simulation models for hybrid drives



Hybrid operation: Energy management

Aim of an energy management strategy:

→ Reaching the destination with…

- Minimal consumption
  (Criterion for performed Matlab-Simulation)
- Minimal emission
- Etc.

Challenge: (partly) missing previous knowledge of…

- Traffic density
- Driving behavior of driver
- Topography of route
- Weather (→ Use of headlight, air conditioning, etc.)
- Charging possibilities at grid (→ Plug-In hybrid)
- ...

Conclusion:

→ THE optimal operating strategy does not exist, but

→ Many different, more or less good approximations

Hybrid operation: Energy management

- Task:
  - Generating set values for drives with consideration of a desired aim
  - General validity
- Aim: Minimizing of fuel consumption
- Method: Use of hybrid functions
  - ICE - start/stop
  - ICE – load-point shift
  - Electric driving
  - Electric boost
- Boundary conditions:
  - Limit of starting processes ICE
    - Follow up time / minimum duty cycle
  - SOC within band SOC_{min} … SOC_{max}
  - Max. torque of rotating drive parts (ICE, electric machine, gear)
  - Max. power of static drive components (battery, inverter)
  - Max. temperature of active parts inverter and electric machine

Hybrid operation: Energy management

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Towards a good energy management strategy:

→ Tactical separation of total power and distribution on the single machines

→ Considering characteristics of electric machine and ICE and variable parameters (e. g. in battery)

Two basic optimizing approaches:

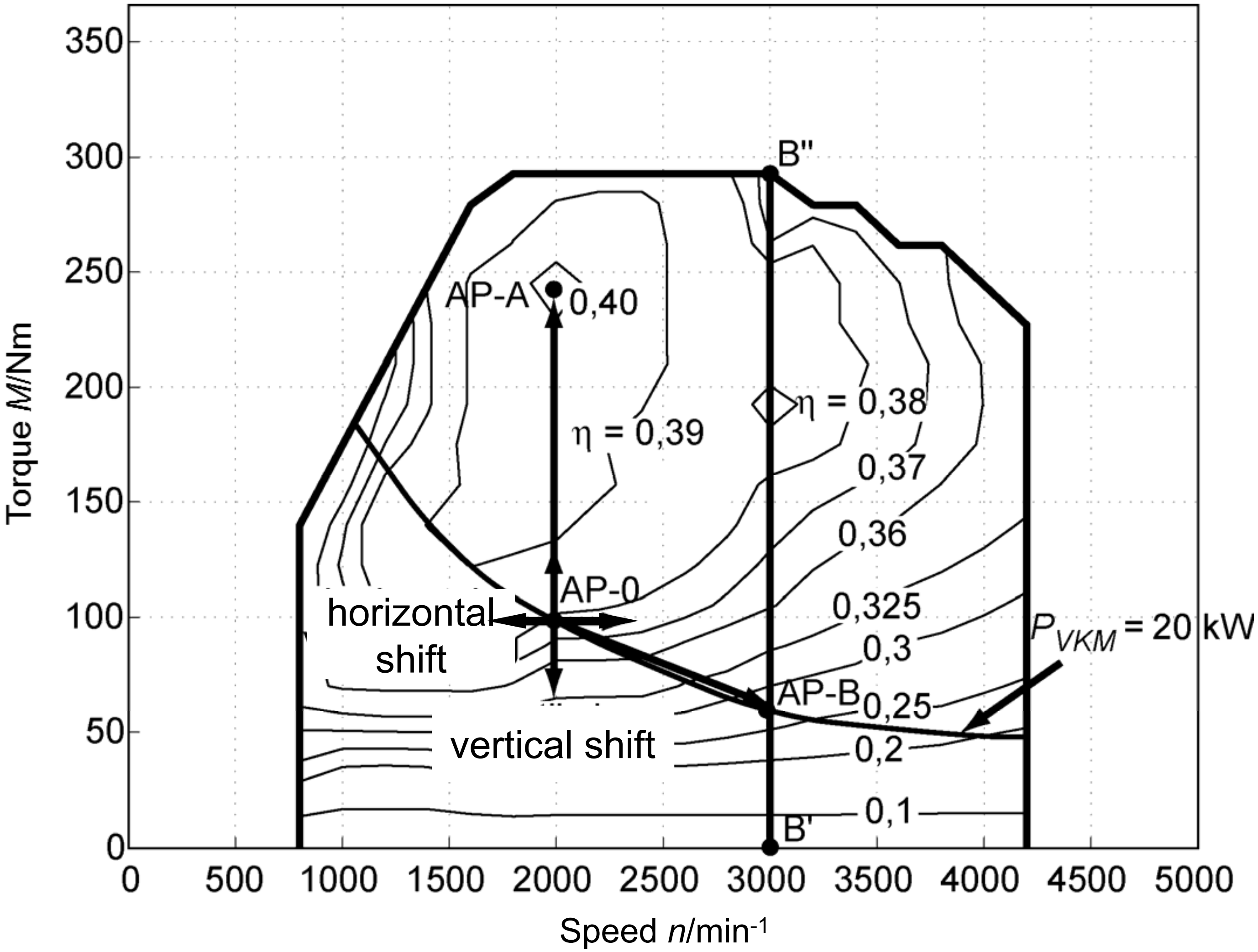
Foreseeing energy management

→ Approximation of demanded power based on past power demand

Operating state management of ICE

- Consideration of boundary conditions e. g. ICE temperature
- → Load-point shift

Example: ICE-load point shift



ICE – Load-point shift – Battery charge

- Battery effective power equals the charging resp. discharging power reduced by the battery losses

- Charging of the battery is done (except for regenerative braking) by load-point shift of ICE under expense of fuel.

- While discharging of battery this fuel consumption is converted into drive power. This amount of charge is to be replaced at a later time by the ICE.

- The loading of the drive train (resulting drive train losses) due to the battery charging is considered.

- Charging: $P_{B,eff}$ added to the losses, discharging: losses subtracted from $P_{B,eff}$.

- Influence of this load-point shift weighted with factor k_{Batt} =1, 2, or 3:

- $k_{Batt} \cdot P_{B,eff}$ added to resp. subtracted from losses: allows analysis of sensitivity during simulation for minimal total losses.

Example: Calculation of fuel consumption HEV

Results P-HEV1

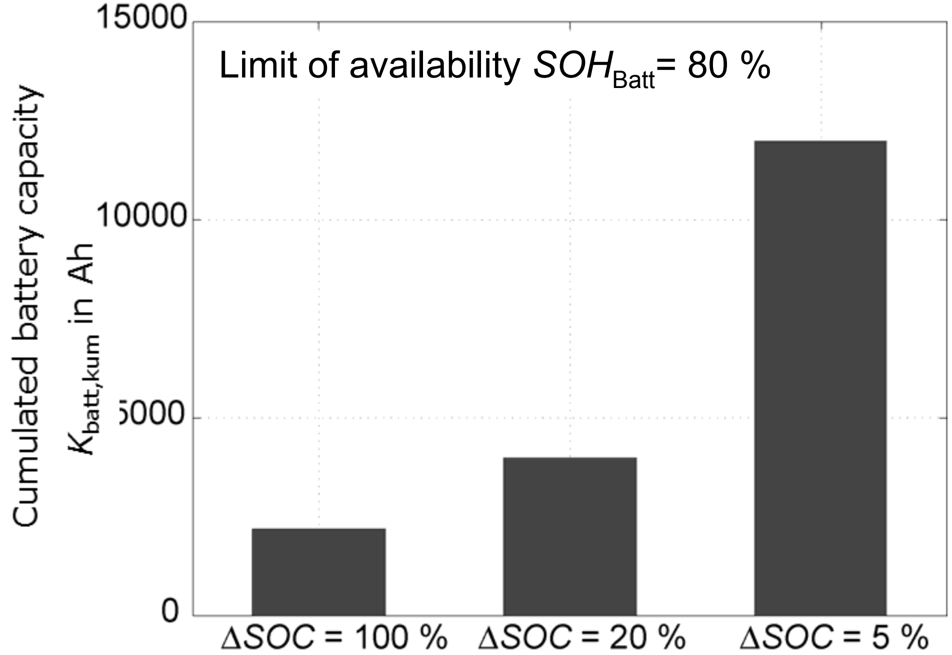
Cycle	k_{Batt}	$P_{E\text{-}Drive,max}$ kW	ΔSOC %	Min. consumption l/(100 km) P-HEV1	Min. consumption l/(100 km) ICE-vehicle	Fuel savings
NEDC	1	10	5	8,1	10,2	**20 %**
UDDS	2	10	10	8,4	10,6	**21 %**
Japan-10-15	2	10	10	9,6	12,9	**25 %**
Highway-FET	1	15	5	6,2	6,5	**5 %**

Results P-HEV2

Cycle	k_{Batt}	$P_{E\text{-}Drive,max}$ kW	ΔSOC %	Min. consumption l/(100 km) P-HEV2	Min. consumption l/(100 km) ICE-vehicle	Fuel savings
NEFZ	1	15	5	8,1	9,3	**13 %**
UDDS	1	10	5	8,5	9,8	**13 %**
Japan-10-15	1	10	5	9,5	11,7	**19 %**
Highway-FET	1	10	5	6,1	6,1	**0 %**

Example: Calculation of fuel consumption HEV

- **Results depend on driving cycle and configuration of HEV**
- **k_{Batt}: battery charging not / only slightly artificially forced**
- **$P_{E\text{-}Drive,\ max}$: electric starting is limited to small power**
- **ΔSOC: Battery usage limited on a small window ΔSOC**
  $\rightarrow$ cumulated battery capacity high



Energy management

<u>Specific aspects of energy management for different topologies</u>

- Series hybrid:
  - 2-dimensional (torque- and speed-) load-point shift
  - Only one driving motor → simple energy management
  - „One-point-operation“ vs. „trajectory operation“

- Parallel hybrid:
  - Torque addition: torque-load-point shift
  - Speed addition: speed-load-point shift

- Power-split hybrid:
  - E-machine 1 at driving shaft: torque-load-point shift
  - ICE and E-machine 2: 2-dim. Load-point shift

(<u>as long as</u> gear equations are fulfilled)

Electric vehicles - Overview

Zero emission vehicle – Definition

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- Definition zero emission vehicle:

  Zero emission of any kind of pollutant in operation and standstill, no evaporation emission, no indirect emission

- Based on the environment legislation of *California Air Resources Board* (CARB)

- Exhaust gas legislation der CARB valid in *California* and also 12 other states of the USA

- By law subsidized ZEV-share is rising
  - From 10% in 2003 to
  - 16% in 2018

California – Classification of vehicles

- **TLEV: Transitional low emission vehicle**

  This is the weakest emission standard in *California*. TLEVs expire in 2004 and are being removed from the market.

- **LEV: Low emission vehicle**

  All vehicles which were sold after 2004 in *California* match at least this standard.

- **ULEV: Ultra low emission vehicle**

  ULEVs are 50% cleaner than the average vehicle of the current build year.

- **SULEV: Super ultra low emission vehicle**

  SULEVs are 90% cleaner than the average vehicle of the current build year.

California – Classification of vehicles

- **ZEV – Zero emission vehicles**

  ZEVs have no exhaust gas emission. This includes battery powered fuel cell based electric vehicles. The category ZEV includes two additional classes [18]:

  - PZEV: Partial zero emission vehicle

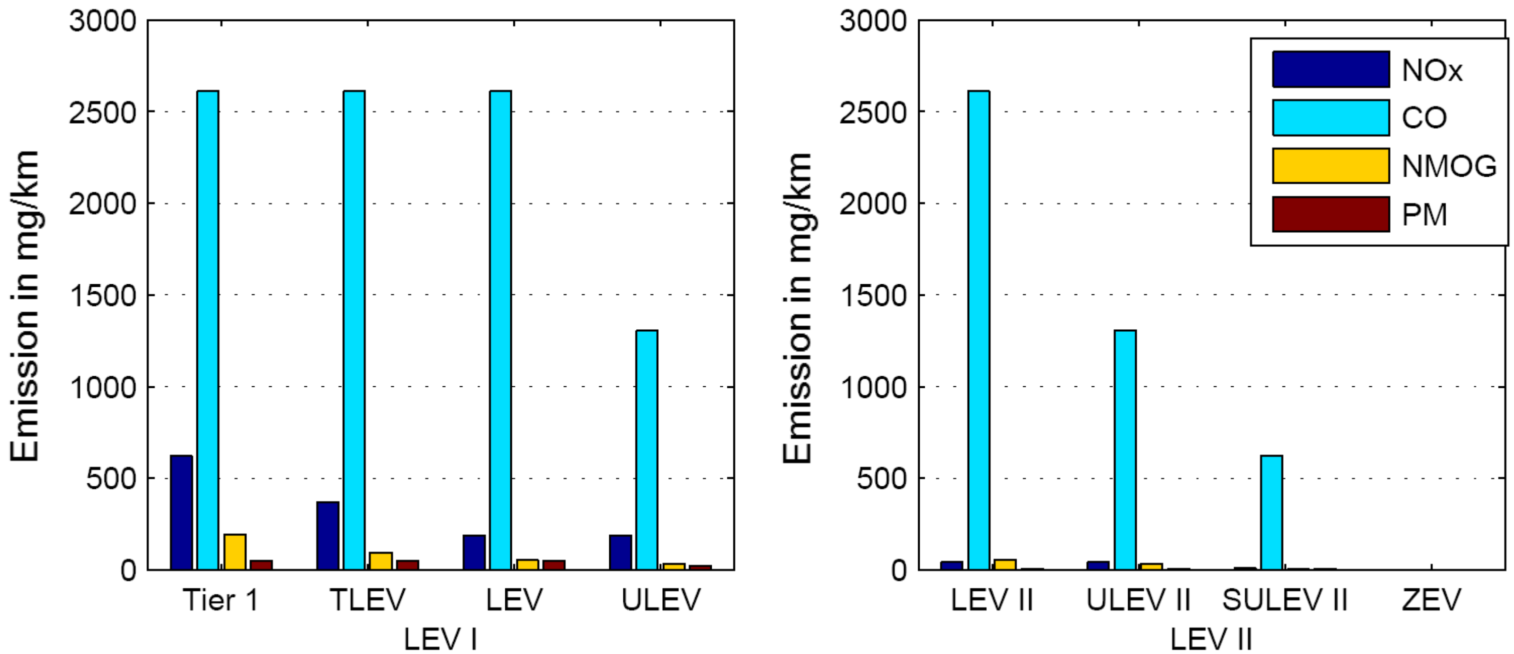
    PZEVs fulfill the SULEV exhaust gas emission standards, have no evaporation emission and a 15 years / 150.000 miles warranty. No evaporation emission means, that vehicles have less emission, while driving than typical vehicles with ICE in turn-off state.

  - AT PZEV: Advanced technology PZEVs

    AT PZEVs fulfill the PZEV requirements and have additionally ZEV- similar properties. A CNG-vehicle (compressed natural gas) or a hybrid vehicle with engine emission, which fulfill the PZEV standards, would be classified as AT PZEV.

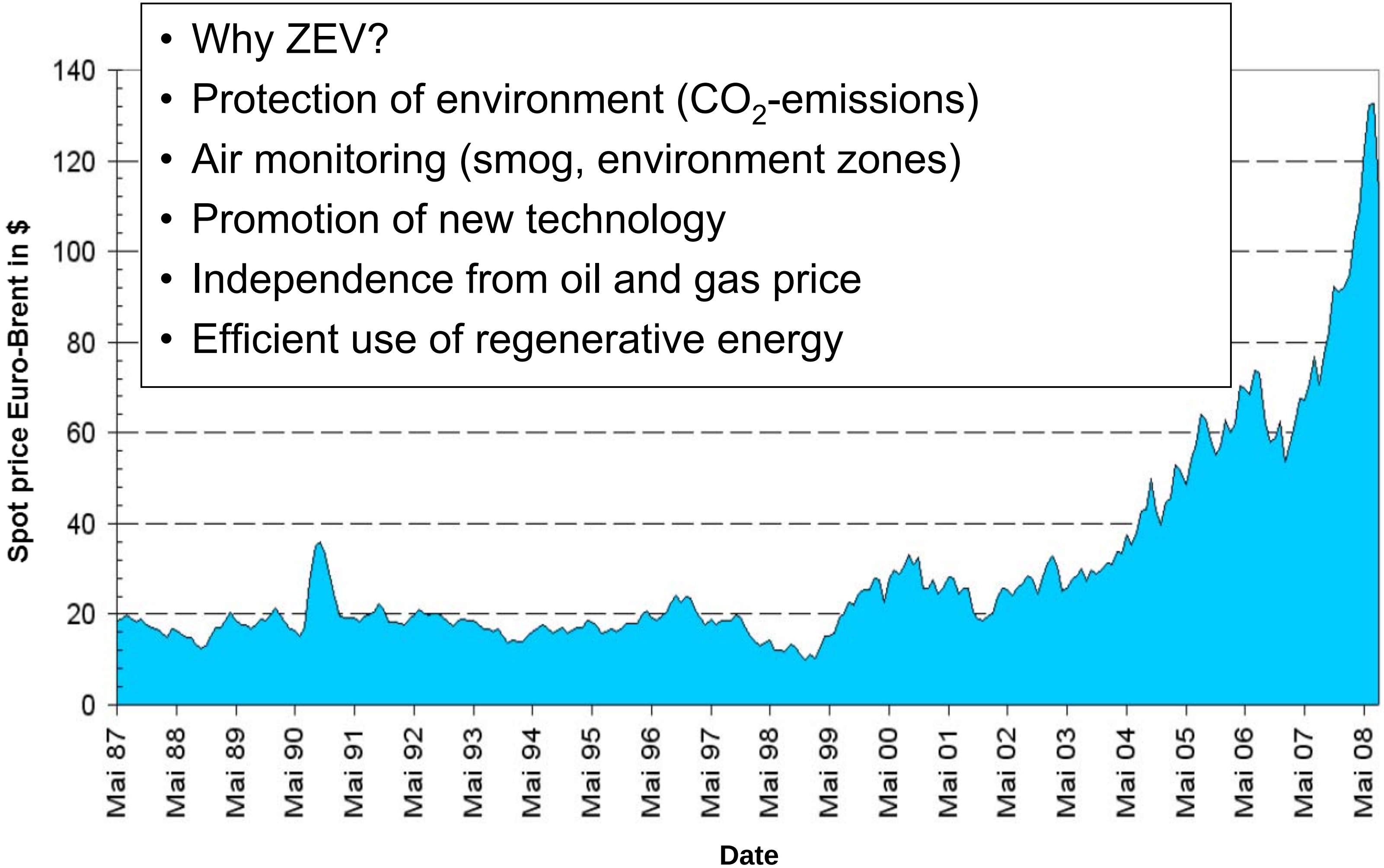
Zero emission vehicle – Legislation

- ZEV with conventional drive / exhaust gas treatment unfeasible
- Possibility of allowance of partial-zero-emission-vehicle-credits
  - Share can also be fulfilled by SULEV II+ certified



Zero emission vehicle – Motivation

- Why ZEV?
- Protection of environment (CO_2-emissions)
- Air monitoring (smog, environment zones)
- Promotion of new technology
- Independence from oil and gas price
- Efficient use of regenerative energy



Battery powered vehicles

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System:

a) Battery

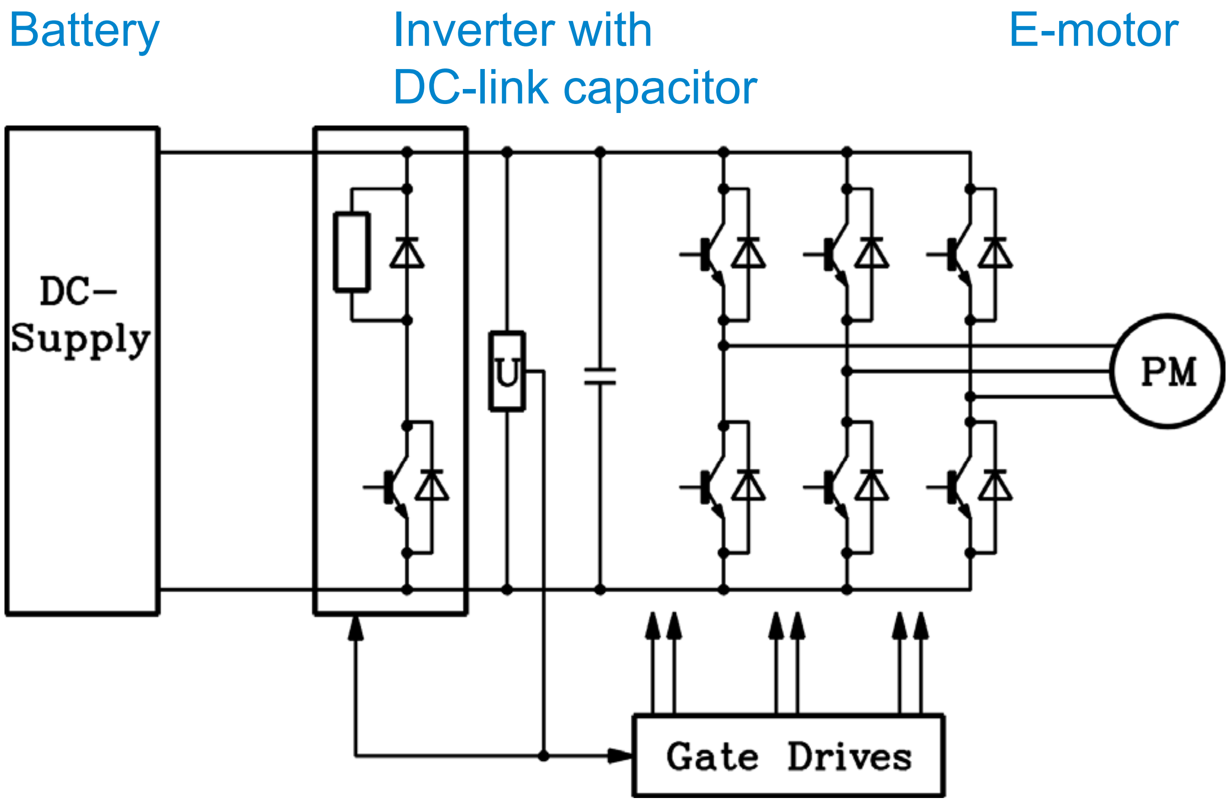
b) Inverter

c) E-motor

d) Gear

e) Wheel

f) Track



Drive variants for ZEV target and aim quantities

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- *Example*-requirements for a zero emission vehicle:
- **By law** requested range in FTP-72 driving cycle 100 miles
  → **110 miles** (177 km) **range** as desired value during FTP-72 driving cycle
- Target in example:
  - **Sprint from zero to 100 km/h in 7 seconds**
  - **Feature for sportive driving**
    → compare *VW Golf GTI, Tesla Roadster*
  - Temporary **max. speed 150 km/h**
    - No long range - limousine for highway journeys,
    - Rather commuter vehicle for city traffic
- Assumption **empty weight of vehicle 900kg**
  - Comparable to *Smart Fortwo*
  - Air resistance $c_w A = 0.5$ (comparable to *Smart Roadster*)

TESLA Roadster (USA)

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- Lithium-ion-battery:
6381 cells = 11 series modules
1 module = 9 series component
1 component = 69 parallel cells

- Max. torque 271 Nm

- Max. power 185 kW

- Sports vehicle

- 1.2 tons empty weight

- 0 … 100 km/h in 4 seconds

- max. 200 km/h (125 mph)

- max. motor speed: 13000/min

- Squirrel cage induction machine

- Price: 110.000 USD

- Range: 392 km in combined EPA-test cycle with 45 kWh battery energy

- 3.5 h charging time

- Lifespan 500 cycles: 500 x 392 = 200000 km

Tesla Roadster (Source: http://www.teslamotors.com/)

Lightning GT (UK)

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- Lithium-ion-batteries: (*AltairNano*: „NanoSafe“) Nano-titanat-technology instead of graphite
- Max. power 552 kW
- Sports vehicle
- Carbon fiber-Kevlar-composite chassis
- 0 … 100 km/h in 4 seconds
- Max. 210 km/h
- 4 PM-synchronous motors as brushless-DC hub motors (P_N = 120 kW each Motor), *PML Flightlink Ltd.*

- Range: 415 km with fully charged battery
- 10 min. quick-charge: 155 km range
- Lifespan: after 15000 cycles: 85% of new-capacity

Source: Lightning Car Company, UK

Electric vehicles –

Drive components

Drive variants for ZEV
Simulation – Simulation model

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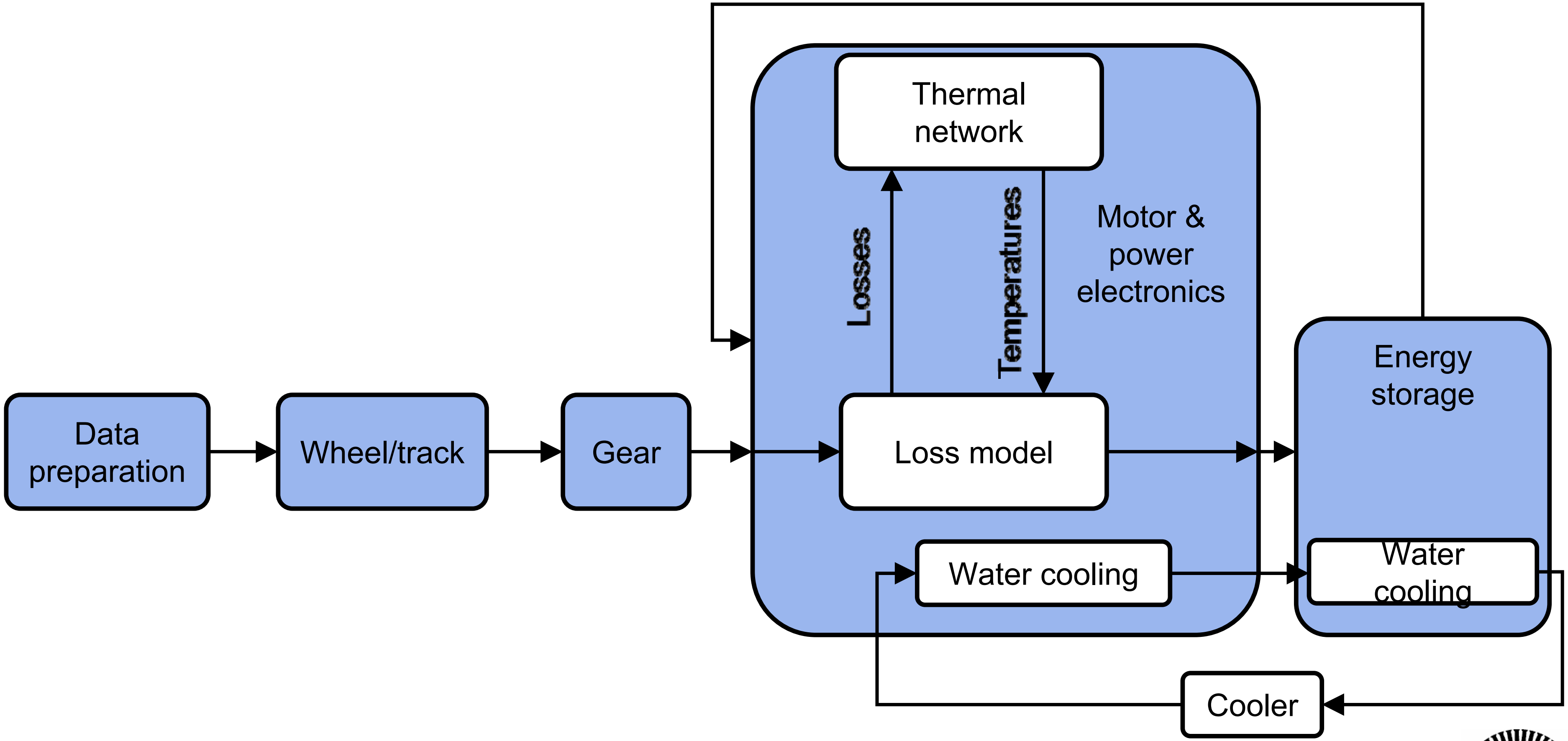
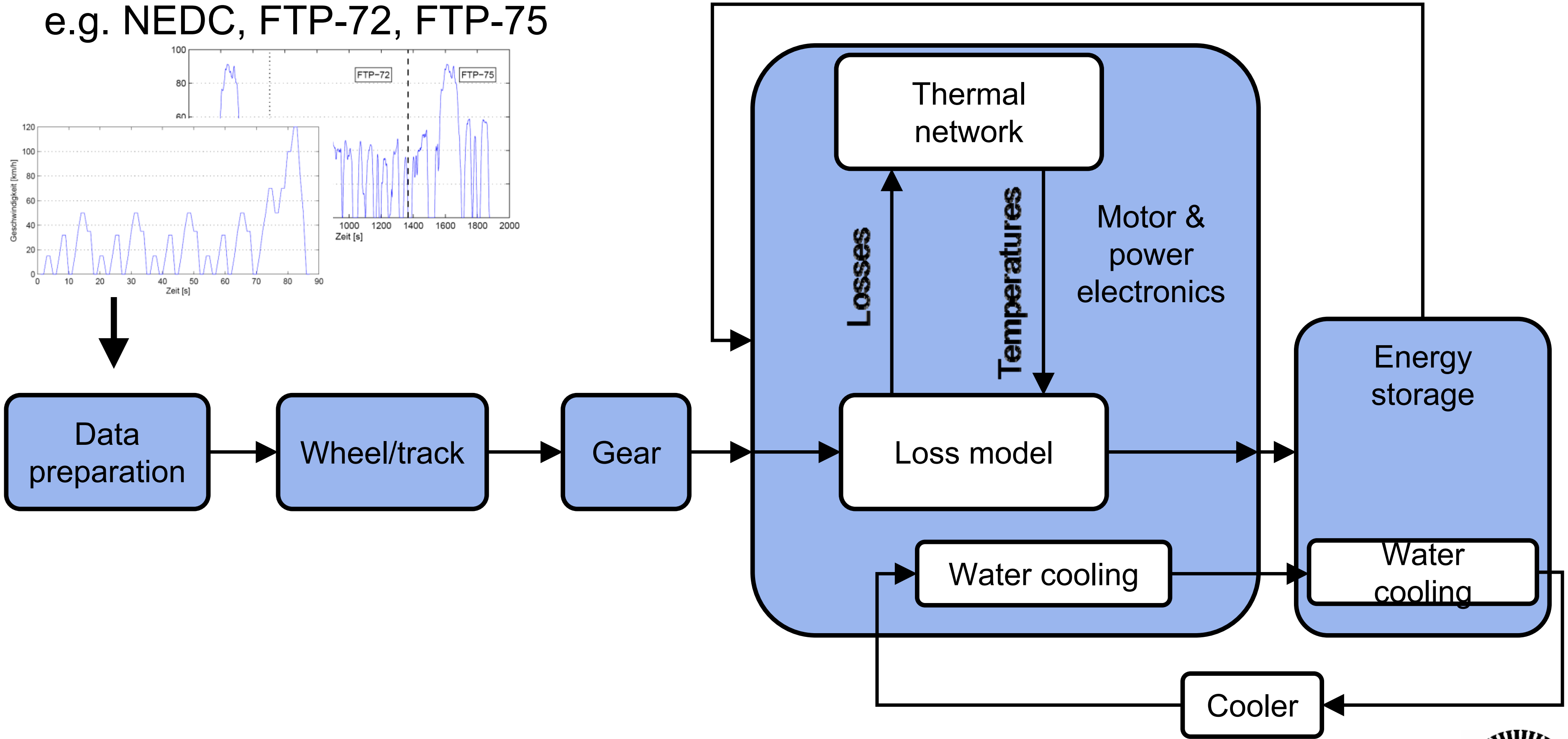
- Simulation model implementation in *Matlab Simulink*



Driving cycles for ZEV
Simulation – Simulation model

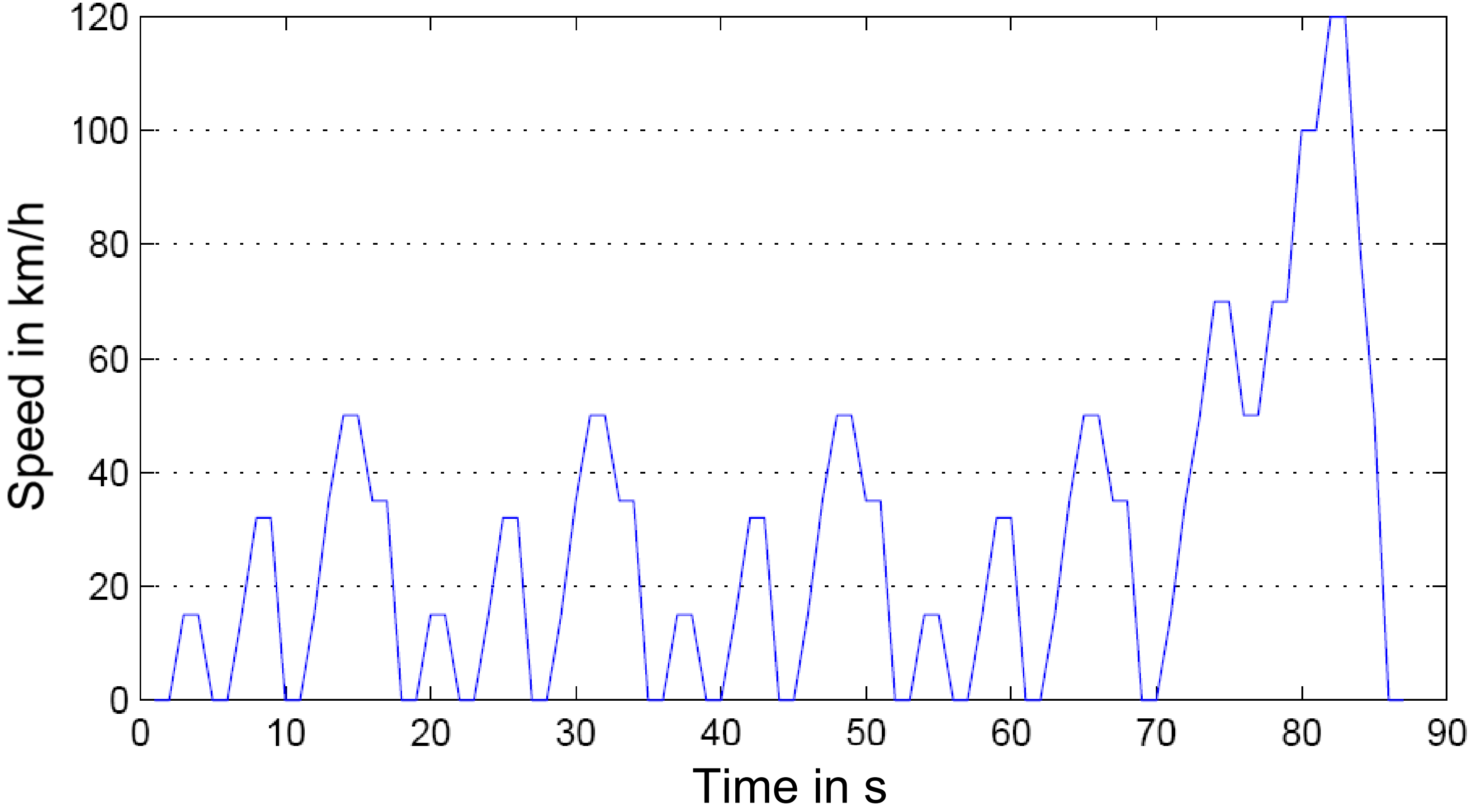
Driving cycles

e.g. NEDC, FTP-72, FTP-75

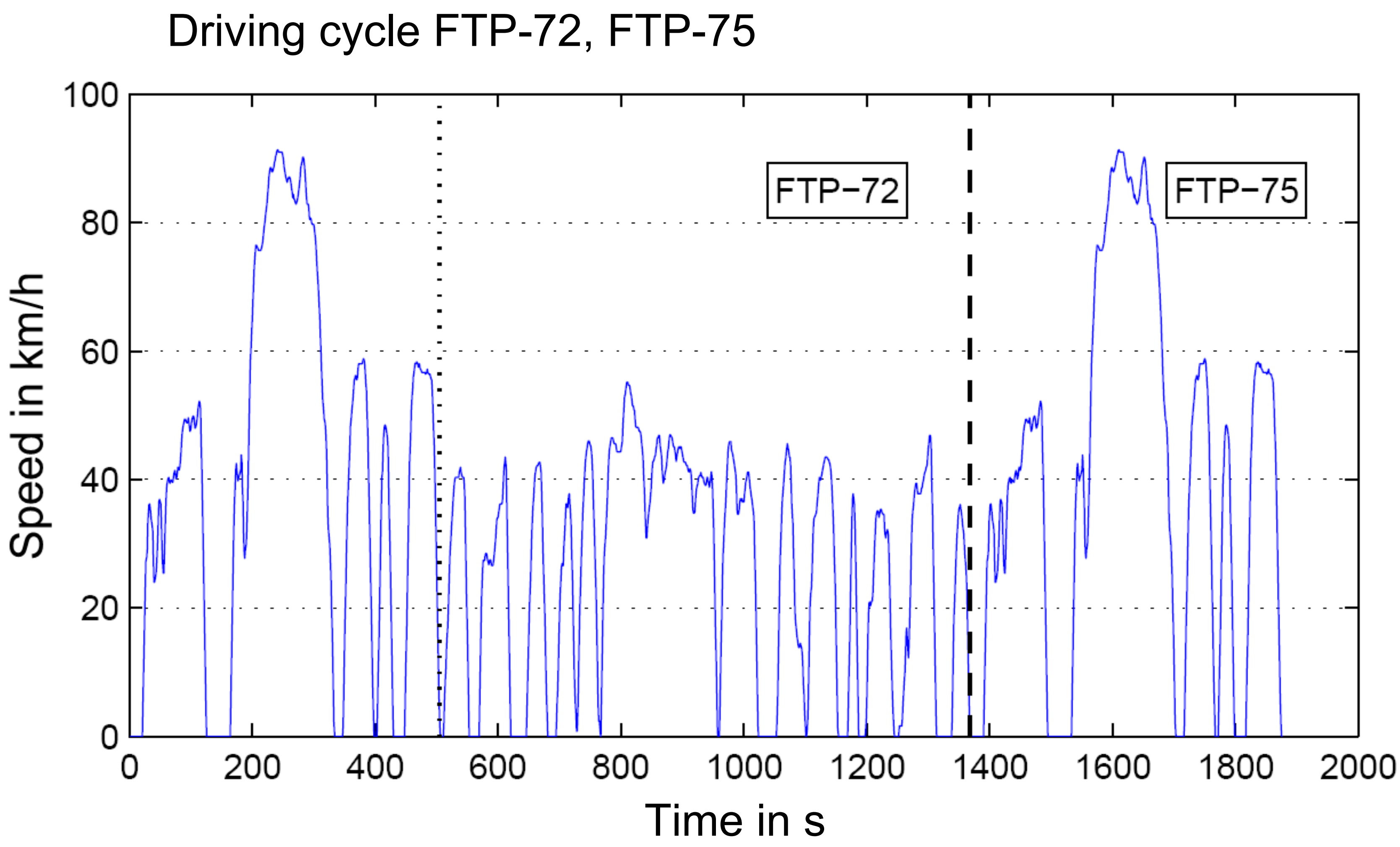


Driving cycle NEDC

Driving cycle: NEDC: New European driving cycle

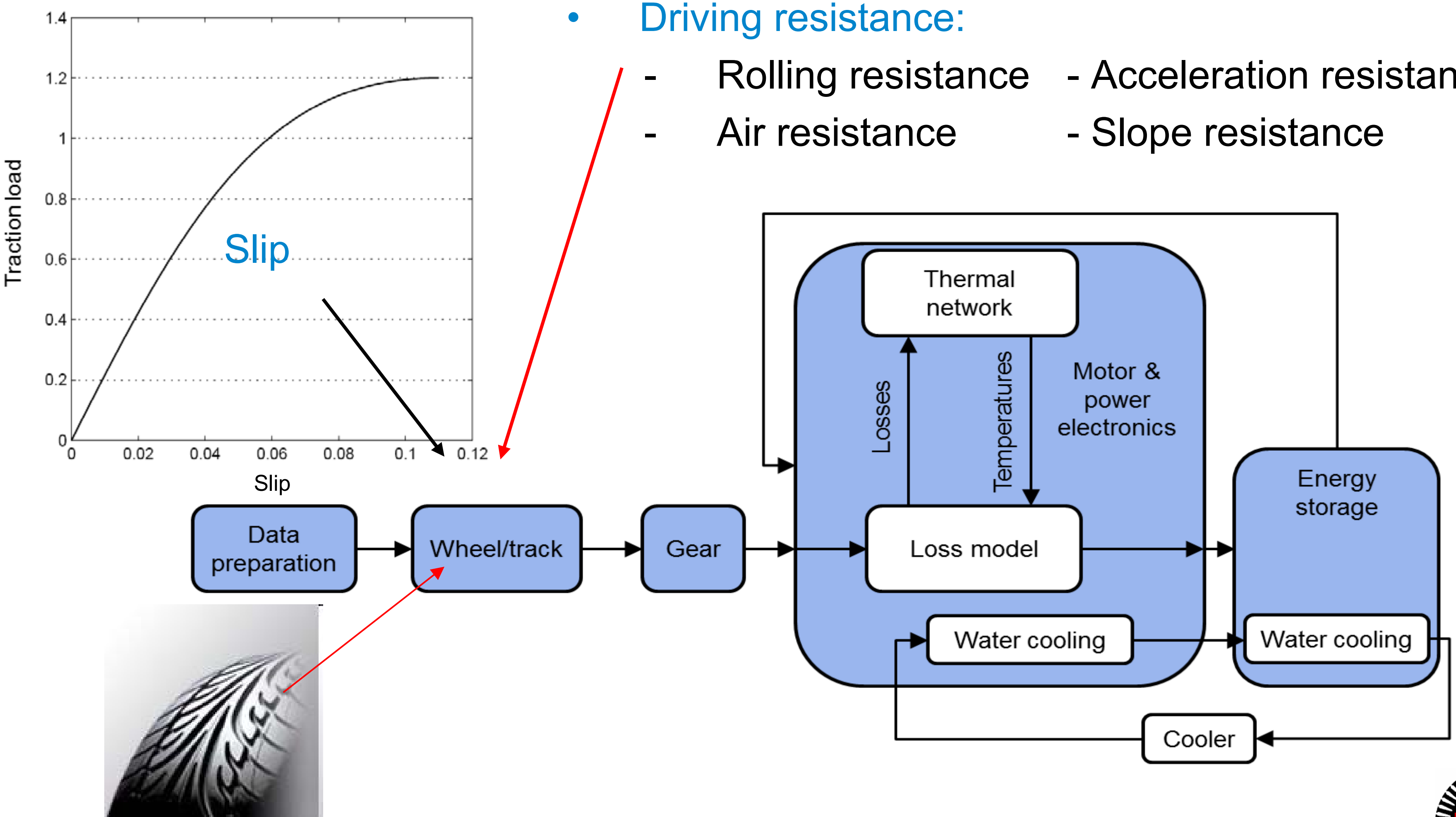


Driving cycle FTP-72, FTP-75



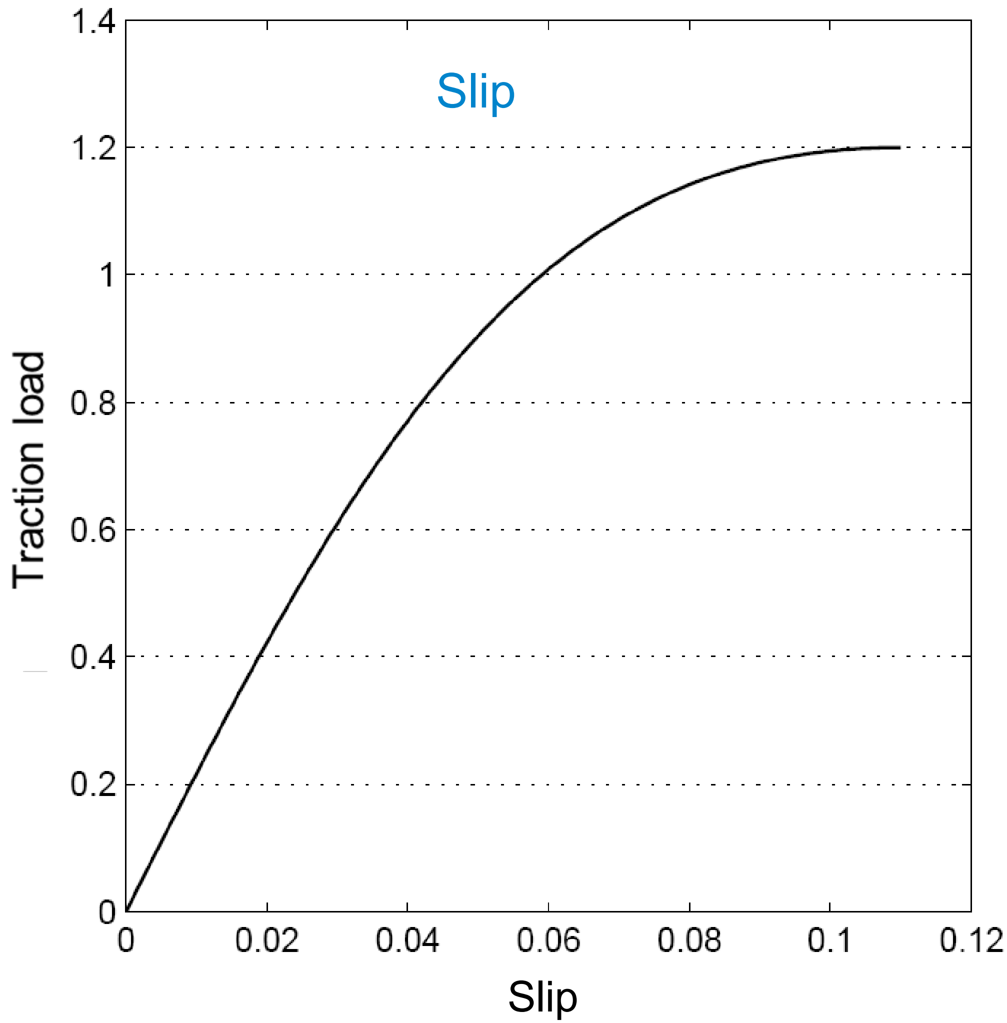
Driving resistances
Simulation – Wheel / track

- Driving resistance:
  - Rolling resistance - Acceleration resistance
  - Air resistance - Slope resistance



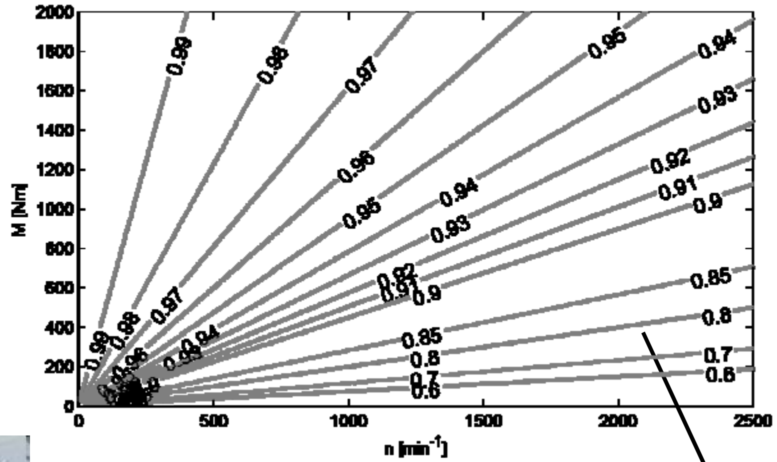
Slip between wheel and track
Simulation – Wheel / track

- Without slip, there is no tractive force transmission to the track, but only „pure“ rolling!



Single-stage gear between wheel and E-motor

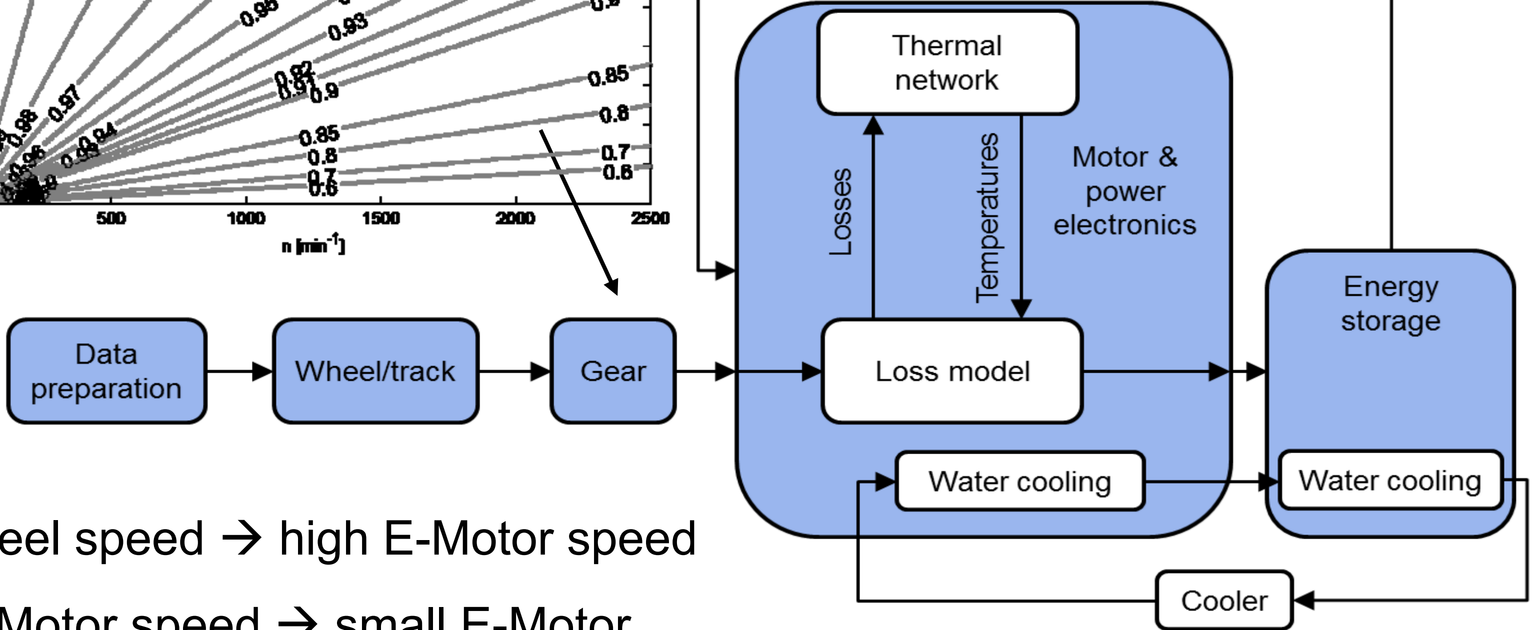
- Efficiency of gear



Single stage reduction gear

i = 8

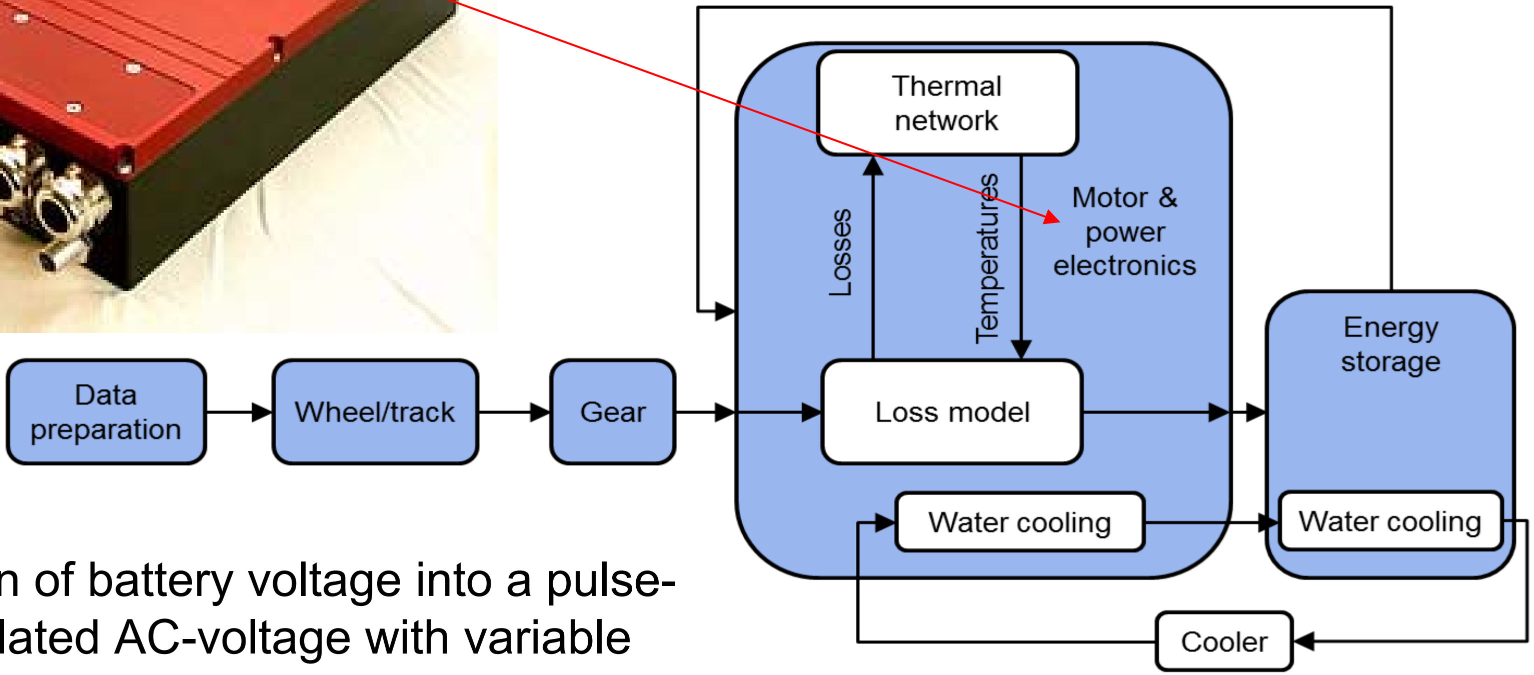
Above approx. i = 10 double-stage gear necessary!



- Low wheel speed → high E-Motor speed

- High E-Motor speed → small E-Motor

Power electronic chopper (Inverter)



- Conversion of battery voltage into a pulse-width-modulated AC-voltage with variable frequency

- Variable frequency = variable motor speed

Example: Inverter *Brusa*

- *Brusa DMC524* 3-phase-inverter for automobile applications

  - 480 V DC-link voltage
  - 600 V IGBTs
  - 80kW continuous power

- Model for calculation of switching- and conduction losses for diodes and transistors

- For Simulation: e. g.
  board grid power = 150 W constant power

Example: Inverter ***Brusa***

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Electric properties	
Minimal supply voltage for full output current in V	200
Maximum operating supply voltage in V	480
Over voltage cutoff in V	500
Maximum permitted over voltage in V	520
Continuous current, RMS in A	225
Repetitive maximum current, RMS, 30s 100%, 90s 50% in A	300
Continuous power in kW	80
Maximum power in kW	106
PWM frequency symmetric modulation in kHz	24
Mechanic properties	
Height in mm	88
Width mm	240
Length in mm	360
Volume in cm²	7600
Weight (without cooling water) in kg	9.5
Ambient operating temperature in °C	-40…+85

Example: Inverter – *Conti Temic*

- **Technical data IGBT-Inverter**

Maximum current I_{max}	250 A
DC-link voltage U_{DC}	110 - 370 V
Switching frequency $f_{switching}$	8 kHz
Weight $m_{inverter}$	10 kg
Coolant flow $\dot{V}$	8 l/min
Coolant-supply temperature ϑ_{CS}	85 °C
DC-link capacitance $C_{DC\text{-}link}$	2 mF
DC-link resistance $R_{DC\text{-}link}$	1 mΩ

- **Loss groups**

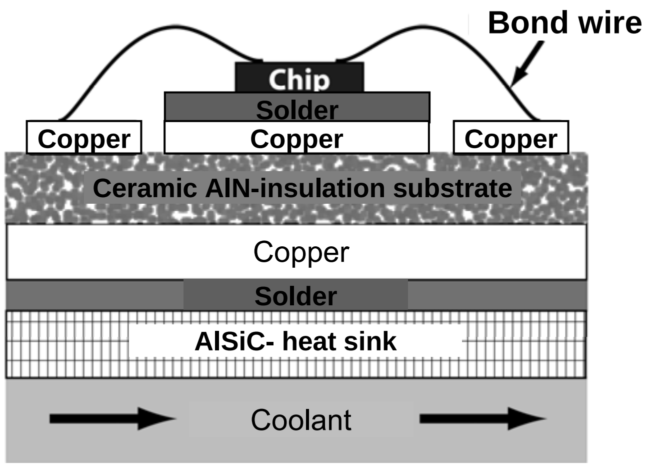
Losses	**IGBT**	**Diode**
Static losses Conduction losses P_C Blocking losses P_{block}	 x (X)	 x (X)
Switching losses Switch-on losses P_{ON} Switch-off losses P_{OFF}	 x x	 (x) X
Trigger losses $P_{trigger}$	x	x

Inverter – Heating

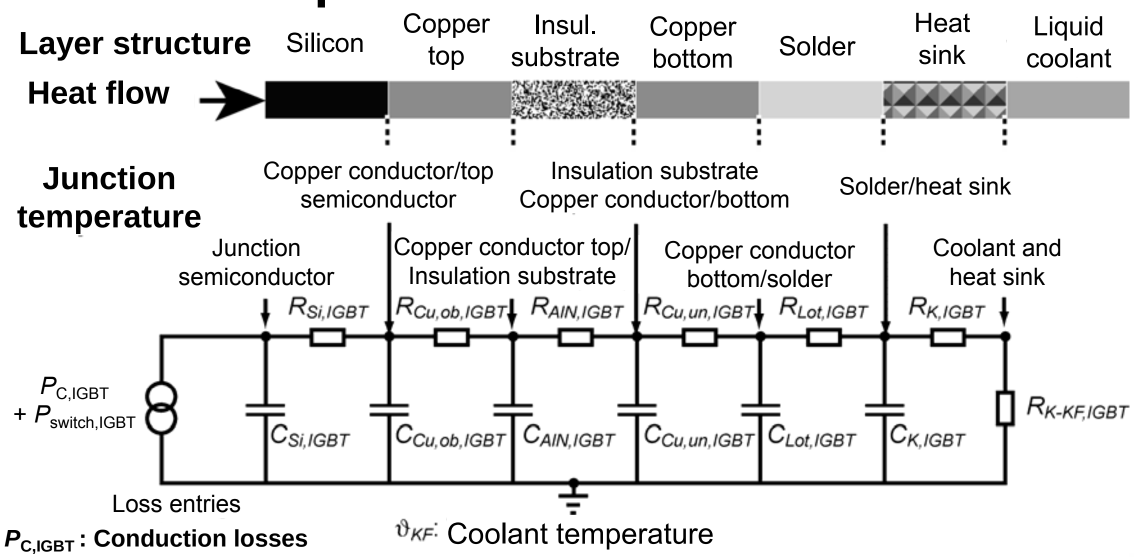
- **Modeling**
  - *RC*-network (*R*: heat resistance, *C*: heat capacity)
    → Dynamic calculation temperatures
  - 6-body-model
  - Analytic calculation *R*, *C* on the basis of structure geometry
  - No thermal coupling to neighboring power electronic semi conductors

- **Structure technology**

Structure of power modules



- **Thermal equivalent circuit IGBT**



$P_{C,IGBT}$: **Conduction losses**
$P_{switch,IGBT}$: **Switching losses**

Example: PM-synchronous machine *Brusa*

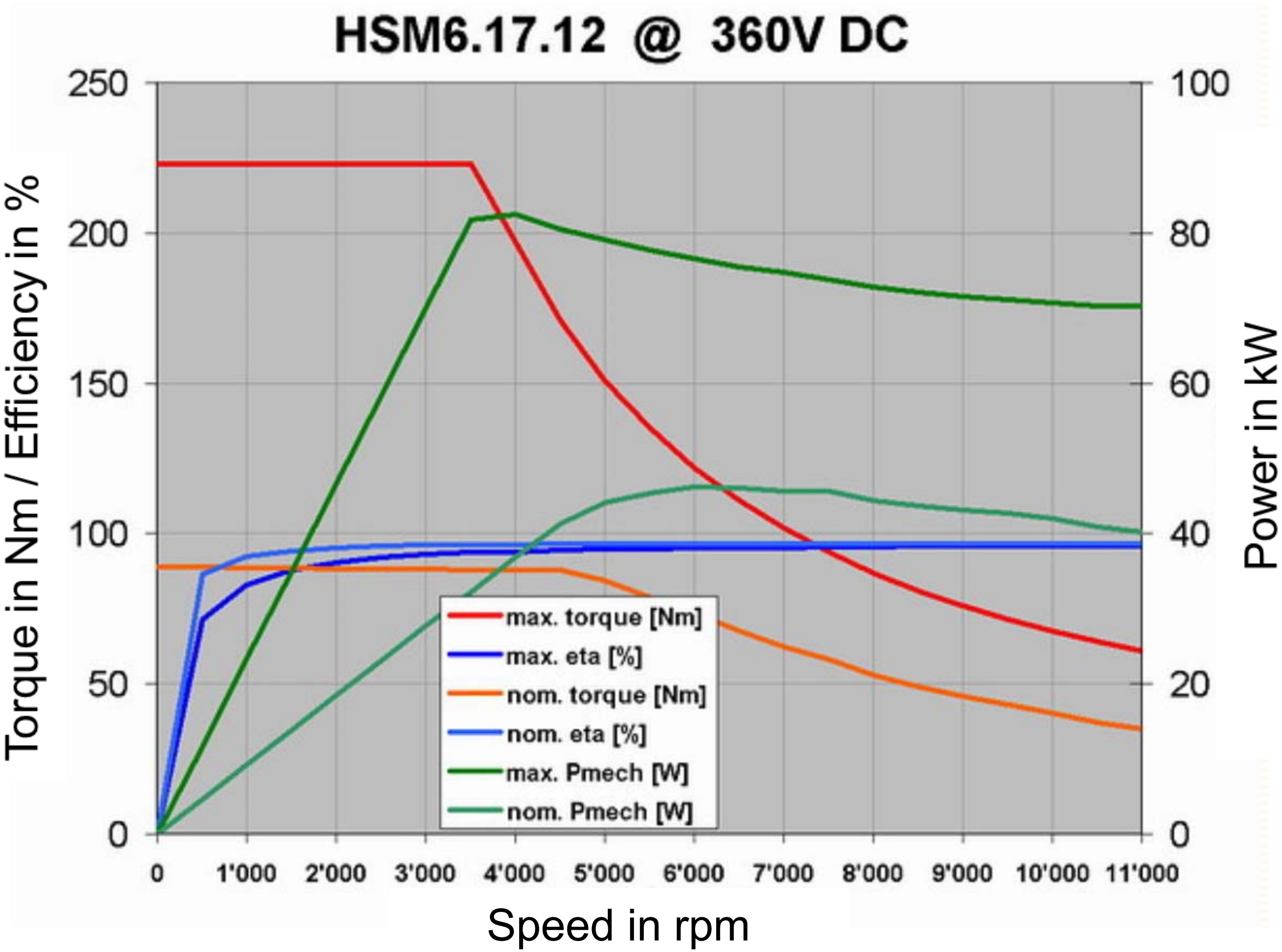
- *Brusa Hybrid Synchronous Machine 6.17.12*
  - 40 kW rated power, 85 Nm rated torque
  - Available on the market
  - Used in E-cars by hobbyists

Example: PM-synchronous machine *Brusa* - Data

Mechanic properties	
Number of slots *Q*	36
Pole count	6
Number of turns per pole and phase *q*	2

Electric properties	
Rated power in kW	40
Rated speed in1/min	4500
Rated torque in Nm	85
Rated current in A, phase	96
Rated voltage in V, phase	164
$\cos\varphi$	0,885
Efficiency in %	95,7
Losses in W	1800

Example: PM-synchronous machine *Brusa* - Torque-power curves



Example: PM-synchronous machine *Brusa* – Main dimensions (recalculated)

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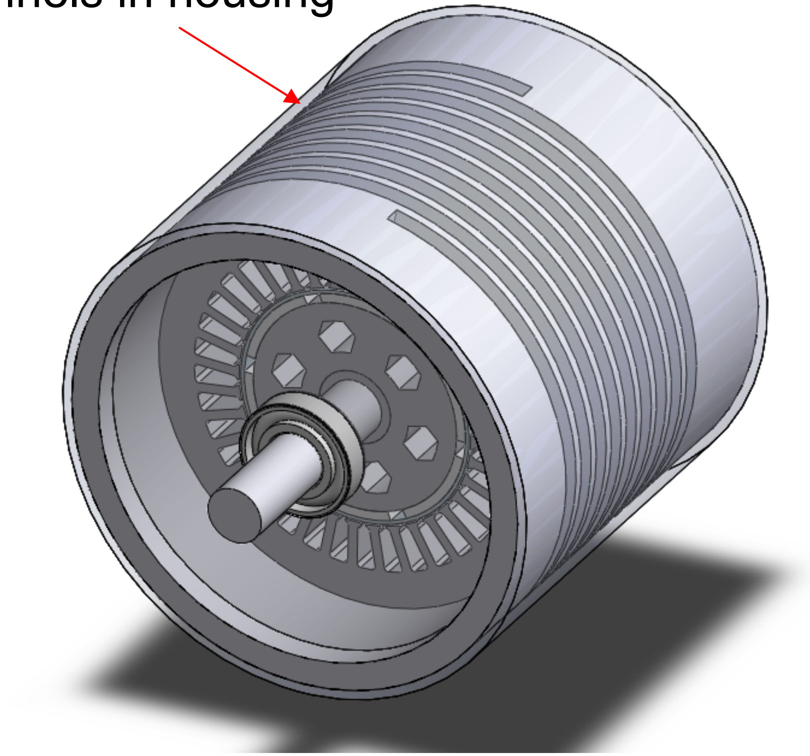
Geometric properties	
Outer length in mm	240
Diameter in mm	260
Rotor diameter in mm	114
Iron length in mm	120
Air gap length in mm	1
Bandage height mm	2
Magnet height in mm	5
Pole coverage ratio in %	0,85

Water jacket cooling in spiral channels in housing



Example: Efficiency of drive train – E-Motor + Inverter + Gear, *Brusa*

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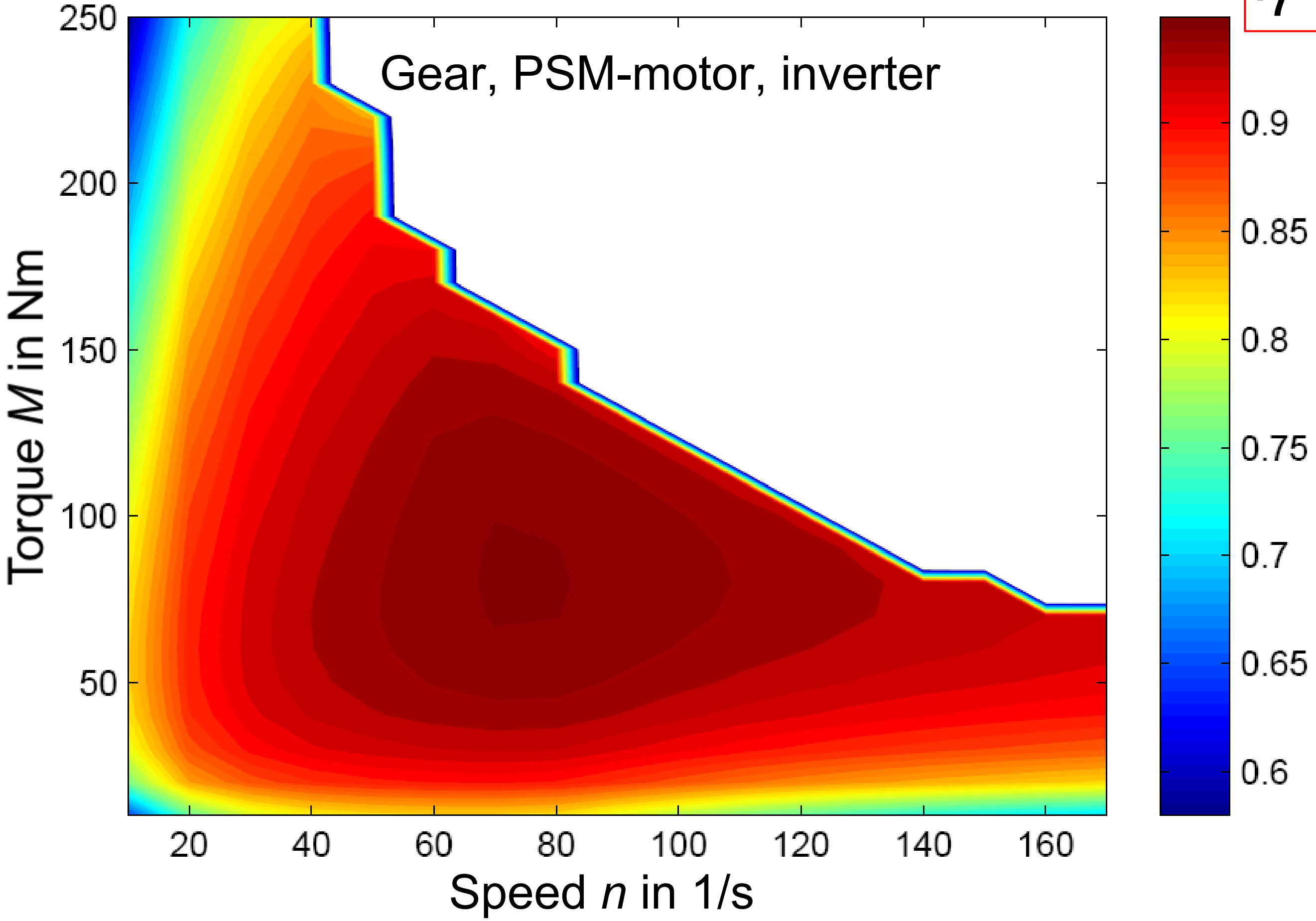
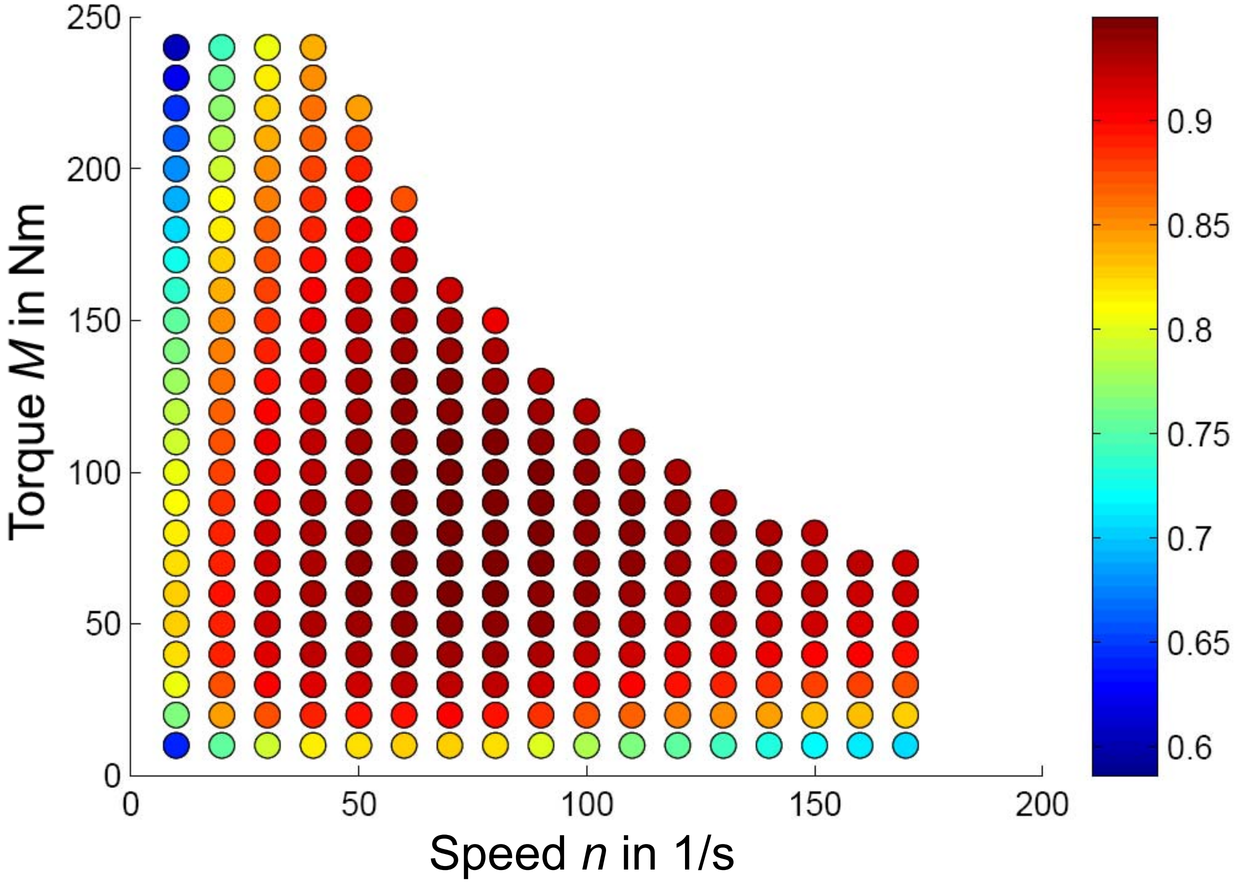
Calculated efficiency map

$$\eta = M_R \Omega_R / P_B$$



Example: Efficiency of drive train – E-Motor + Inverter + Gear, *Brusa*

- Screened efficiency map
- Steps of in 10 Nm and 10 1/s distances



Efficiency

Gear, PSM-motor, inverter

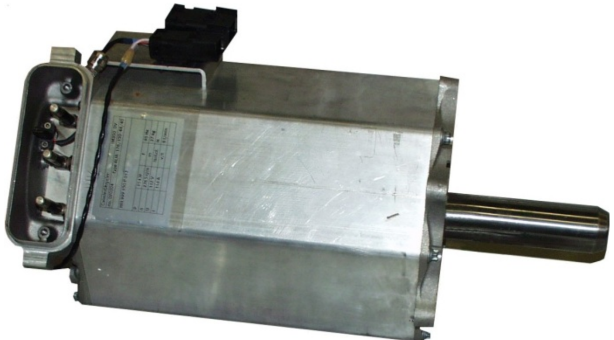
Example: PM-synchronous- and squirrel cage induction machines (*Daimler*)

PM-synchronous machine

- Technical data electric machines

	PSM	ASM
Rated power P_N Maximum power P_{max}	20,5 kW 42 kW	15 kW 35 kW
Rated speed n_N Maximum speed n_{max}	1500 min^{-1} 6000 min^{-1}	2765 min^{-1} 12500 min^{-1}
Rated torque M_N Maximum torque M_{max}	130 Nm 270 Nm	52 Nm 120 Nm
Outer diameter d_{sa}	286 mm	150 mm
Iron length l_{Fe}	95 mm	180 mm
Coolant flow	8 l/min	8 l/min
Coolant supply temperature	85 °C	85 °C
Thermal class	H	H

Squirrel cage induction machine



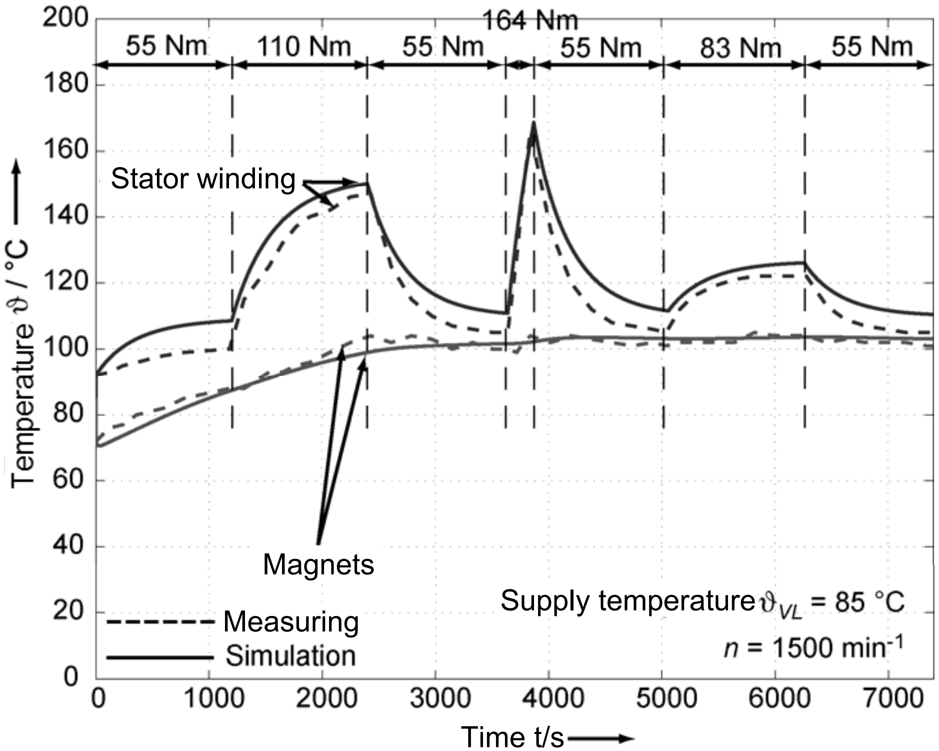
Loss groups for PM-synchronous - and squirrel cage induction machines

PM-synchronous machine	Squirrel cage induction machine
Stator ohmic losses	Stator ohmic losses
Iron losses	Iron losses
Losses in magnets and rotor	Rotor ohmic losses
	Additional losses for sinusoidal current operation
Ventilation- and bearing- friction losses	Ventilation- and bearing- friction losses
Additional losses in inverter	Additional losses in inverter

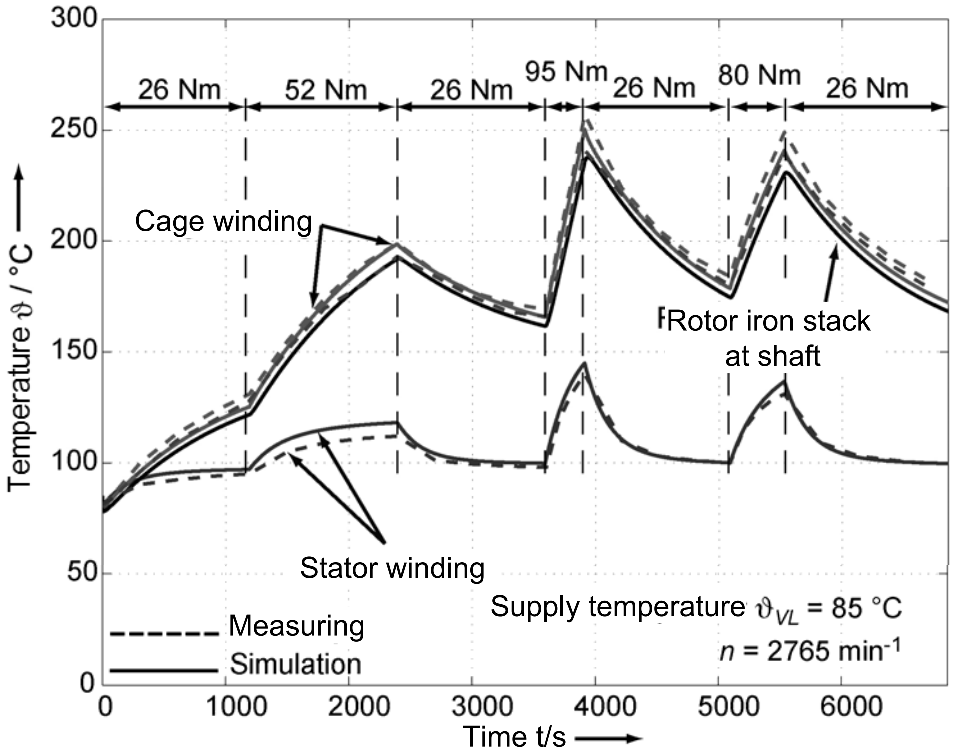
Heating of PM-synchronous- and squirrel cage induction machines

- **Comparison calculation – Measuring (test rig) for driving example: constant speed, variable load**

PM-synchronous motor



Squirrel cage induction machine



Battery variants: *Ragone*-diagram

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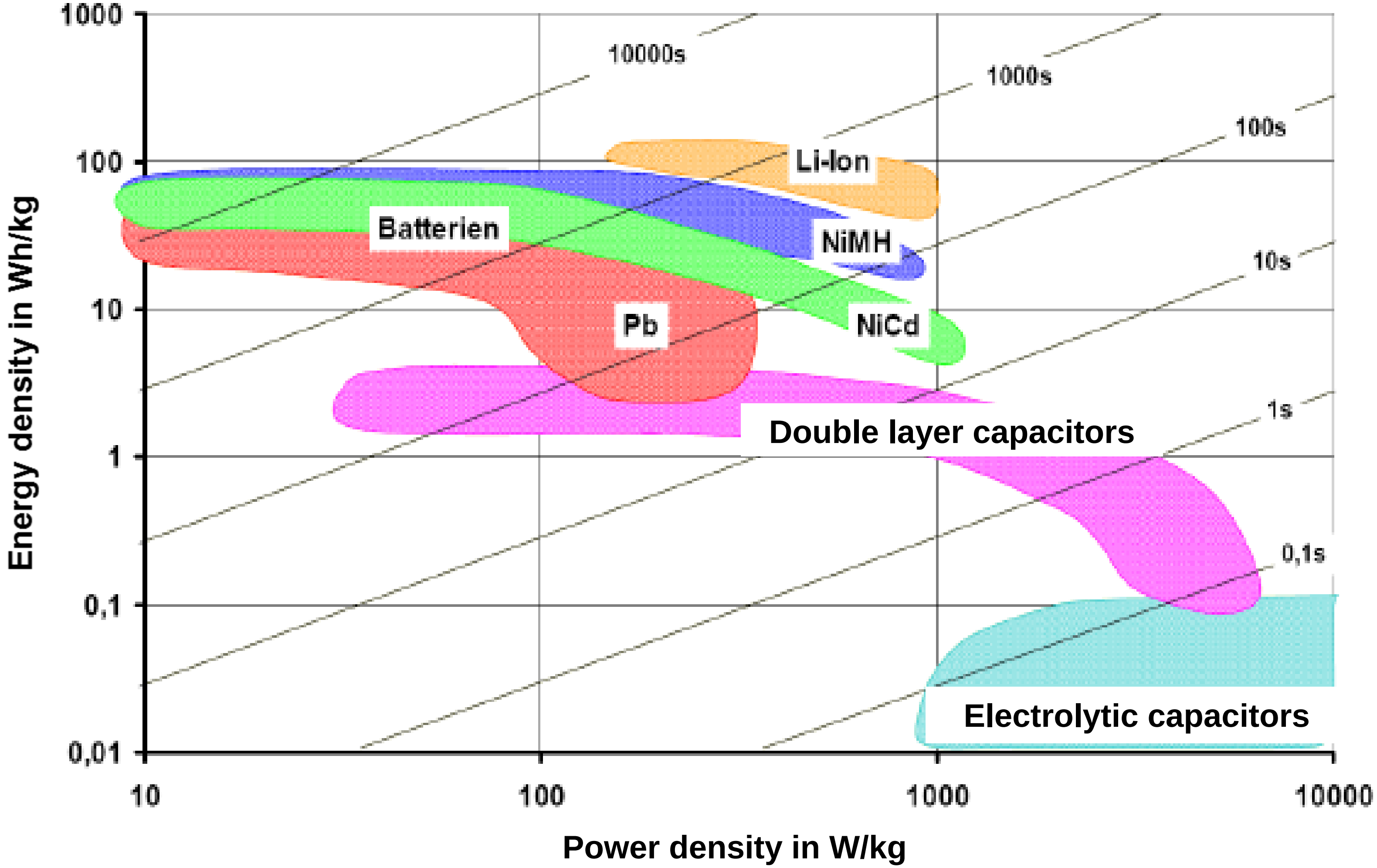

Battery variants: Energy & power density

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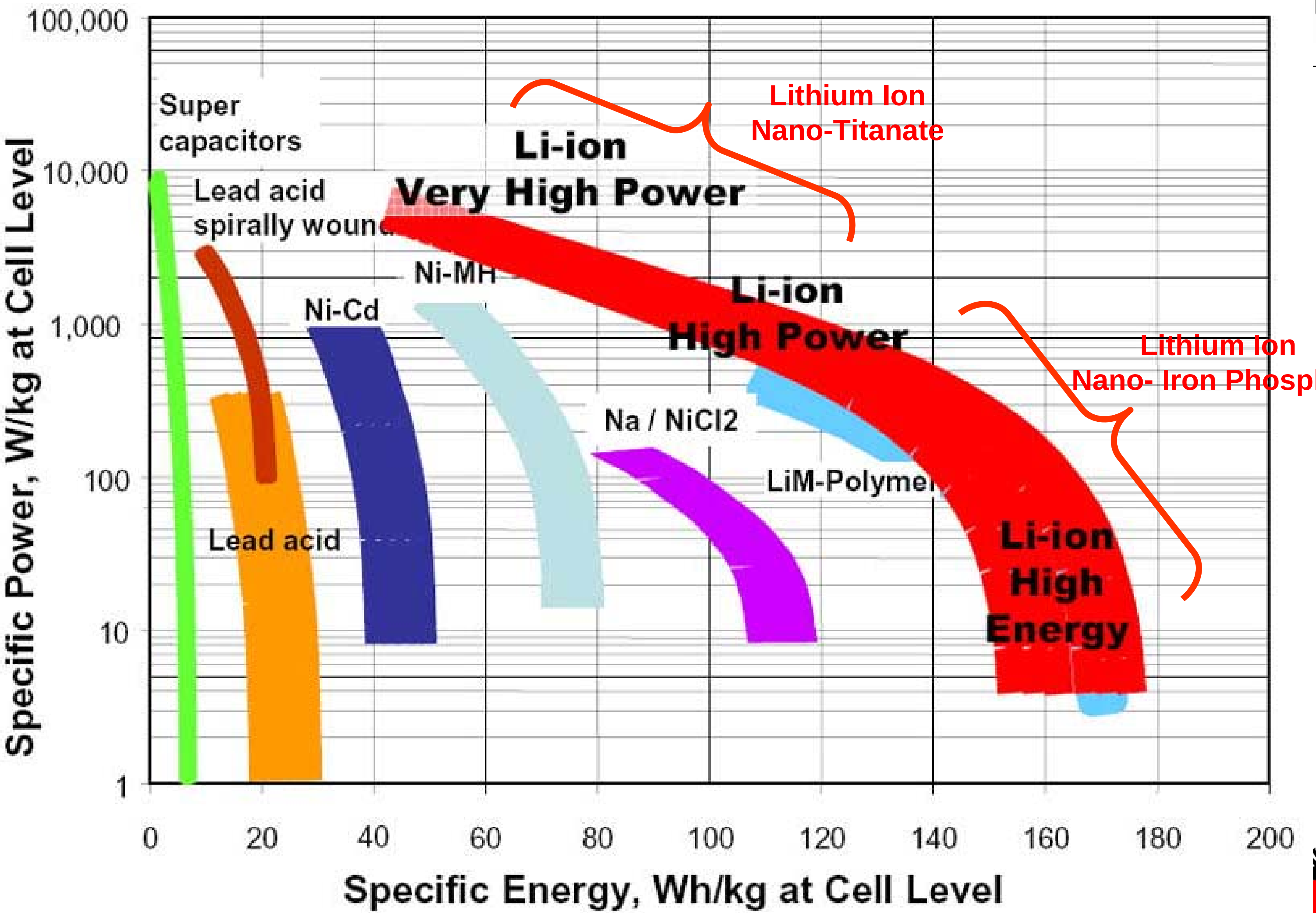


Lead batteries: VRLA (Valve-regulated lead acid)

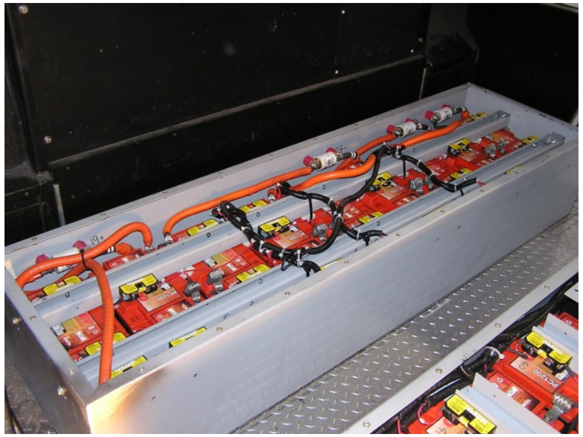
- designation for 'maintenance-free lead-acid batteries'
- not really "sealed", but vented for overpressure
- 2 types: Absorbed Glass Mat (AGM) or Gel battery
- use less electrolyte, less space than flooded designs
- high-rate power capacity (short duration)
- cost-effective, deep discharge, used in UPS systems
- 3-5 year life in heavy-duty vehicle service

Traditional choice for hybrid Electric transit vehicle designs

Low cost, rugged and field-proven

Can be combined with UltraCaps for greater power cycling capacity

Typical VRLA batteries



VRLA Vehicle battery pack string

Lithium-ion (Li-ion)-batteries

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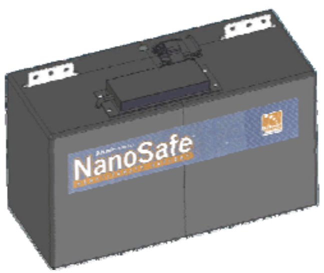
- compact, light weight, highest power density
- safety issues with older tech: cell phone/laptop types
- new nano-titanate cells handle 20,000 recharging cycles
- fast charge – up to 80% in one minute
- long life claims – 10+ years;
- new technology – cost is 4-to-5 x VRLA cost, for same power
- price will decrease as technology matures

High power, mid-energy density



Li-ion nano-titanate battery

“flat” wound cell
2.3 V 11 A-h

High energy, mid-power cycling

Spiral-wound cell
3.3 V 2.3 A-h

Li-ion nano-iron phosphate battery

Data of Li-ion-batteries

Properties	Lithium-ion	Lithium-polymer	*Kokam*
Conductance (20 °C) in mS/cm	2 – 5	0.05 – 0.5	0.05 – 0.5
No-load voltage in V	4.2	4.2	4.2
Rated voltage in V	3.7	3.7	3.7
Discharge lower limit voltage in V	2.5	2.7	2.7
Energy density (weight) in Wh/kg	90 – 160	130 – 144	136
Energy density (volume) in Wh/l	200 – 300	230 – 410	276
Power density in W/kg		300 – 1500	2700
Self discharge at 20 °C in %/month	5 – 10	2 – 8	2 – 8
Possible cycles	500 – 1200	500 – 1000	500 – 1000
Storage capability in a	5 – 10	5 – 10	5 – 10

Example: Lithium-polymer-cells *Kokam SLPB 98188216*

	1 cell	116-pack
Rated voltage in V	3.7	429.2
Rated discharge capacity in Ah	30	30
Rated charge current in A	30	30
Maximum discharge current in A	600	600
Cut-off voltage in V	2.7	313
Weight in kg	~ 0.82	~ 95

- 116-pack: 116 cells in series for height DC-link voltage
- Limitation of recuperation power to maximum 14,6 kW
- Weight is being increased by packaging, cooling, sensors and control devices

Li-ion-batteries: Discharge characteristics

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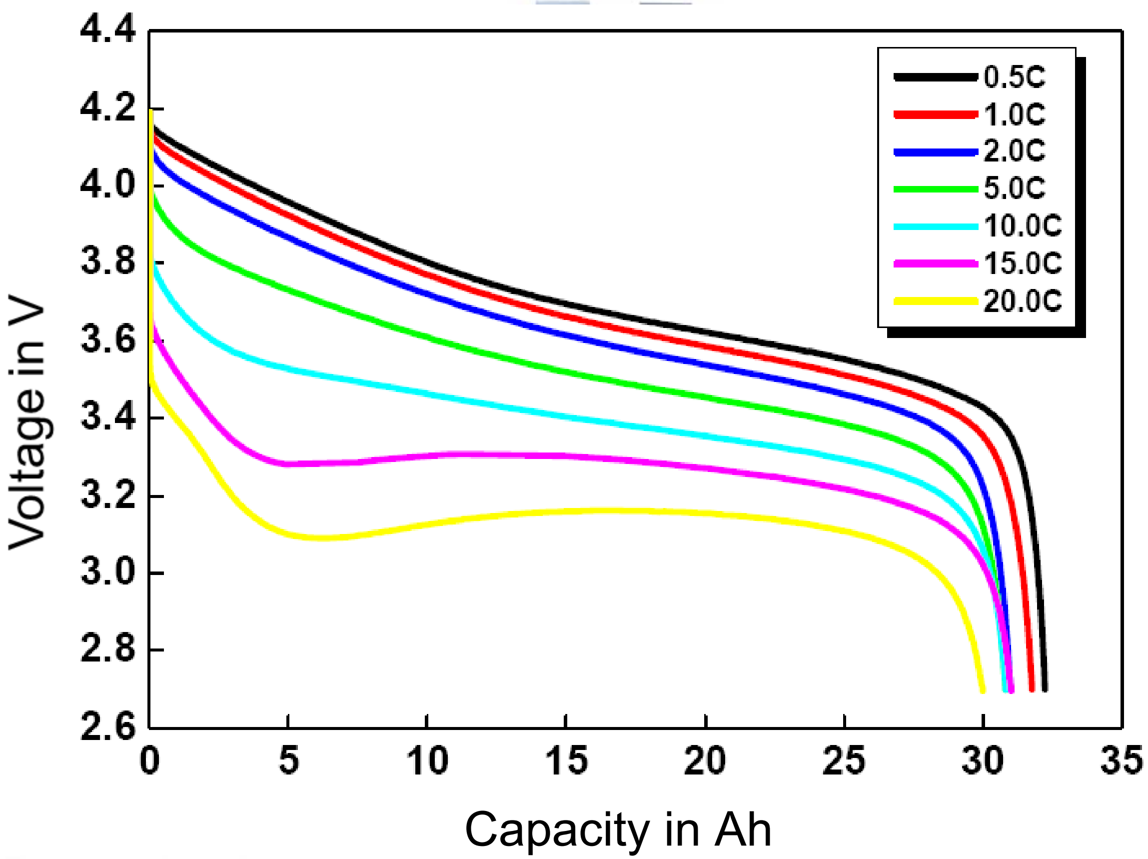
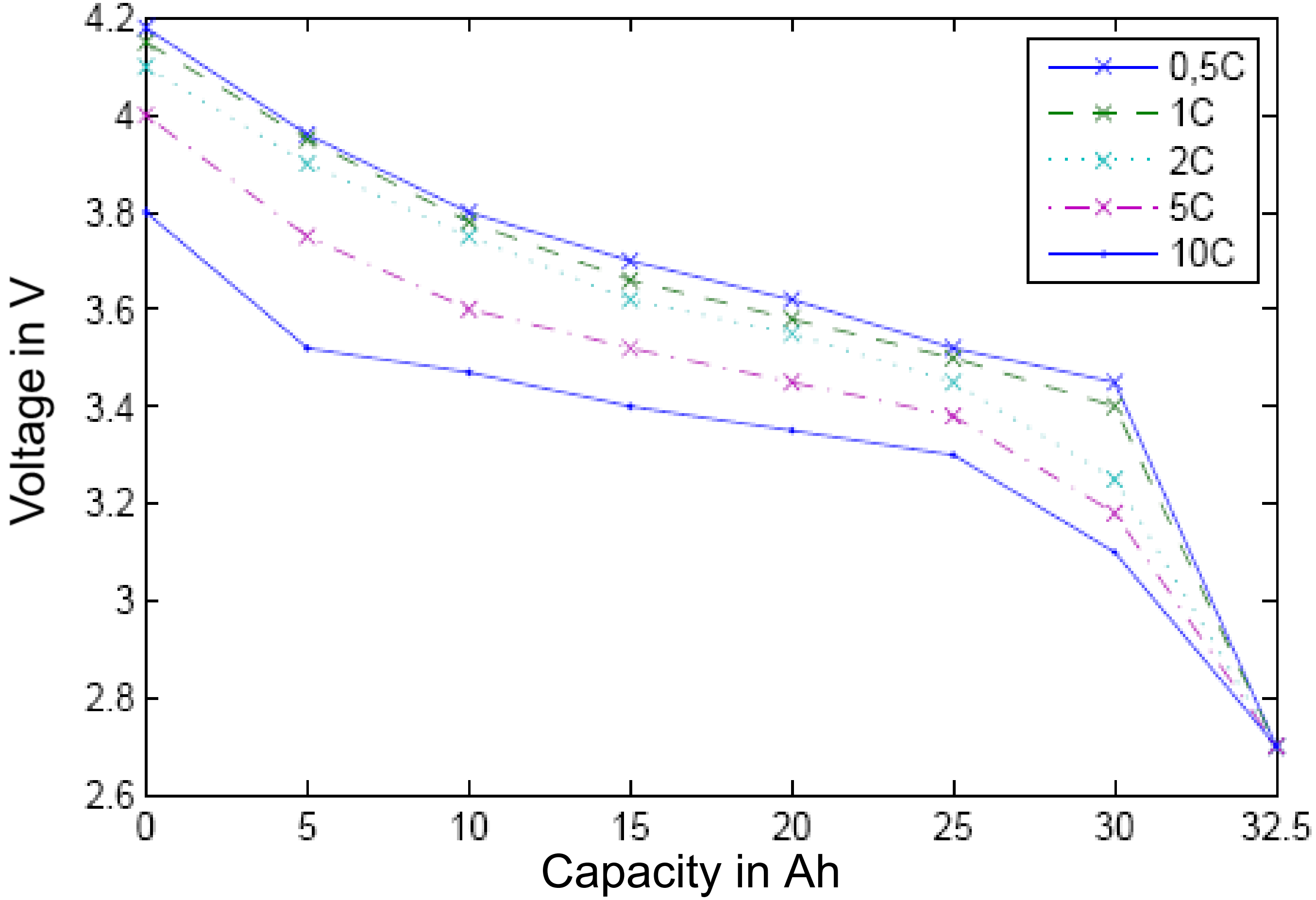
Calculation approach:

1. Determination of battery voltage and battery current
2. Calculation of losses
3. Change of *SOC*
4. Feed-back of DC-link voltage to power electronics



- Discharging rate of 1.0C equals to 30 A

Li-ion-batteries *Kokam SLPB 98188216*: Discharge characteristics

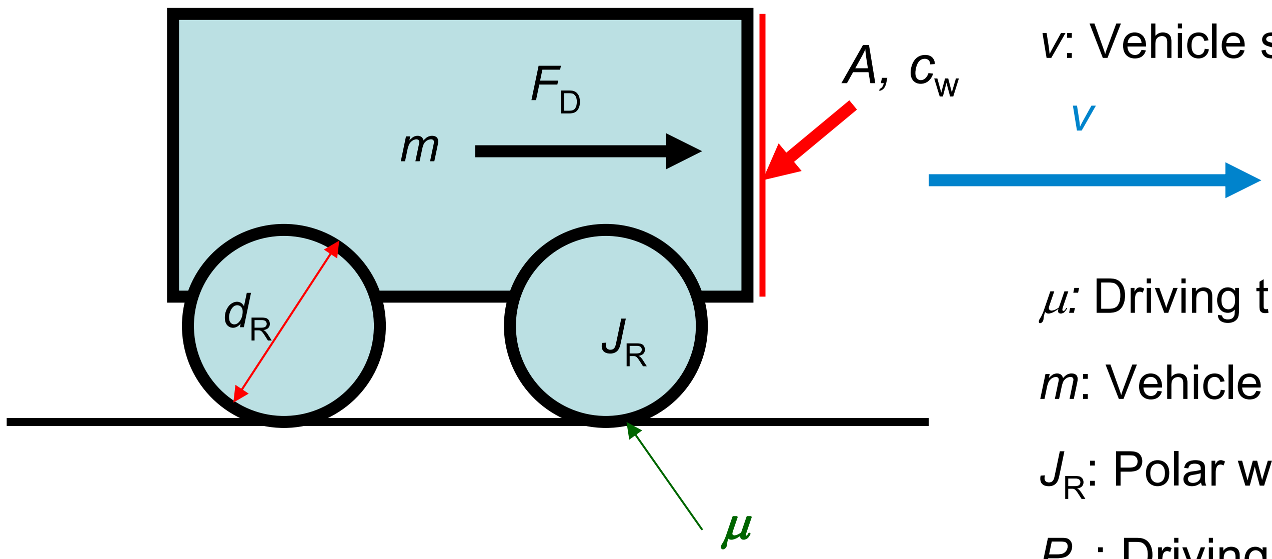


- Discharge rate of 1.0C equals to 30 A

Electric vehicles – Simulation

Vehicle - Track

Modeling of the vehicle



$$P_D = F_D \cdot v$$

A: Reference area

c_w: Drag coefficient

d_R: Wheel diameter

v: Vehicle speed

μ: Driving traction coefficient

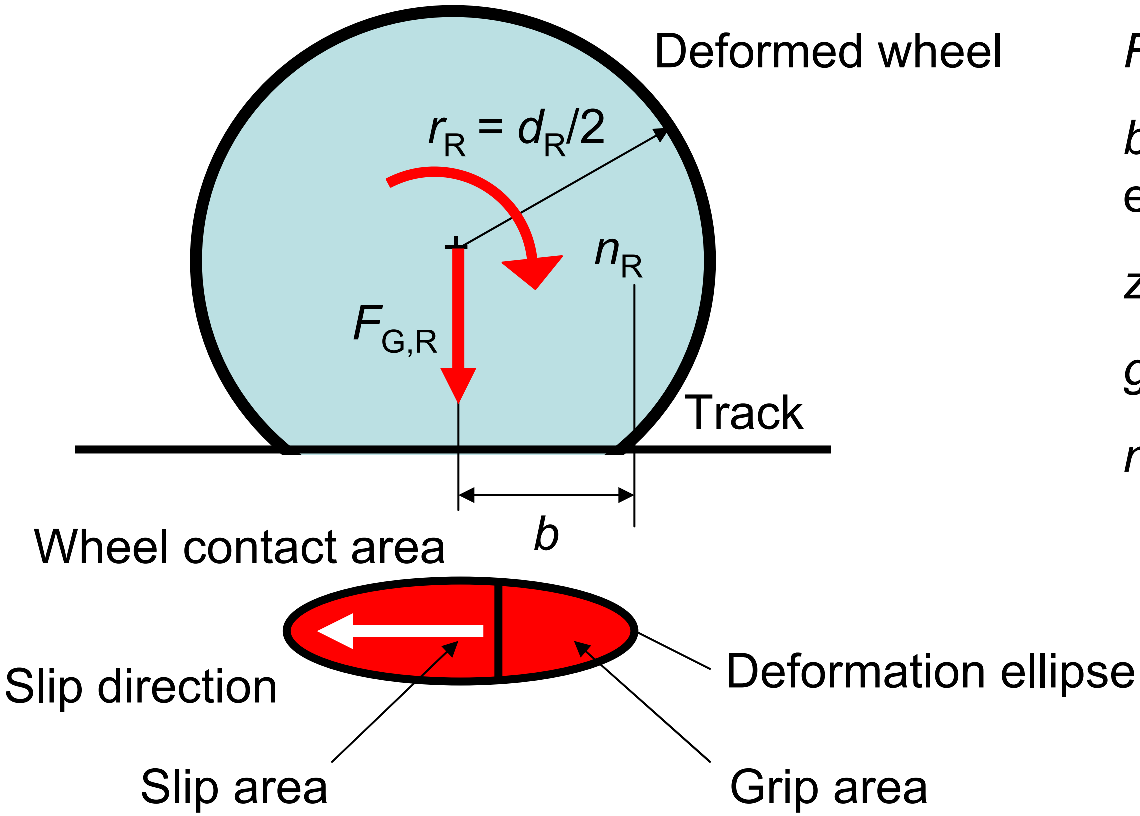
m: Vehicle weight

J_R: Polar wheel moment of inertia

P_D: Driving power

F_D: Driving force in centroid of vehicle

Wheel-track-contact



$F_{G,R}$: Normal force per wheel

b: Big radius of deformation ellipse

z_R: Number of wheels

g: Gravitational acceleration

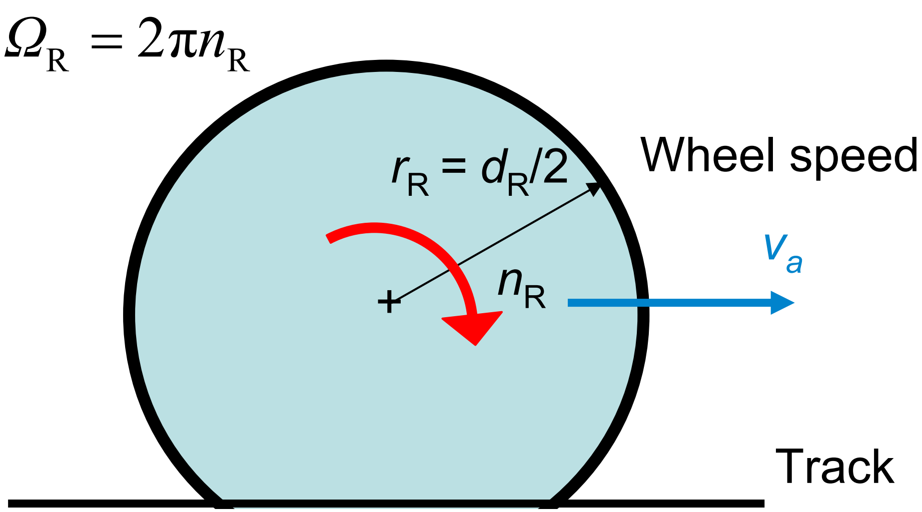
n_R: Wheel speed

$$F_{G,R} = m \cdot g / z_R$$

Wheel slip *s*

Wheel WITH force transmission

slip *s* between wheel and track



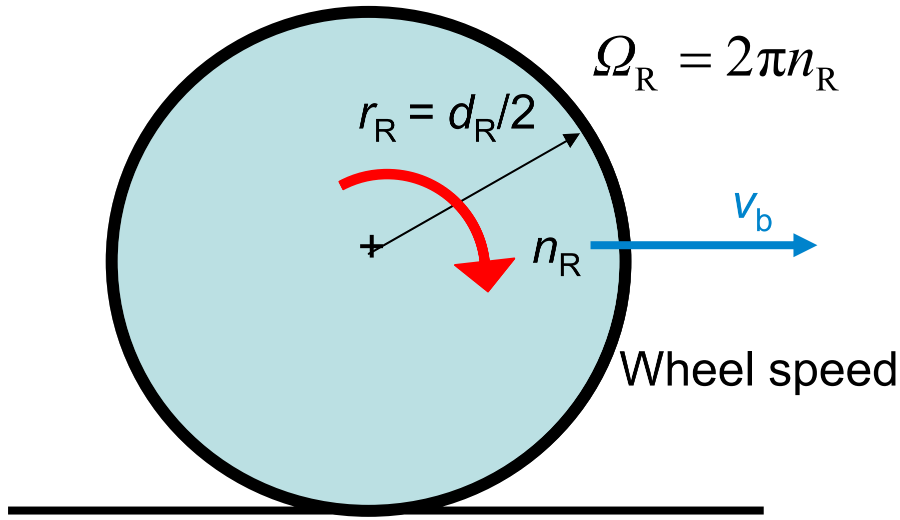
$\Omega = v_a / r_R$ $\quad$ $s = (\Omega_R - \Omega) / \Omega_R$

Wheel speed v_a is SMALLER than the circumferential speed of wheel v_U

$$v_a < v_U = d_R \pi n_R$$

Wheel WITHOUT force transmission

„purely rolling“ wheel, slip *s* = 0



Wheel speed v_b = circumferential speed of wheel v_U

$$v_b = v_U = d_R \pi n_R$$

Transmittable Force F_D from wheel to track

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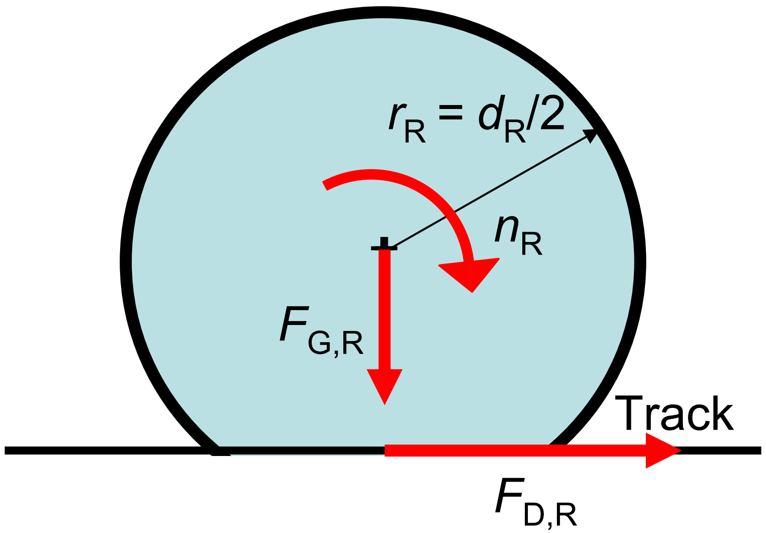


Slope $\tan\alpha$:

$$F_{N,R} = F_{G,R} \cdot \cos\alpha$$

Maximum transmittable driving force per wheel:

$$F_{D,R,max} = \mu(s) \cdot F_{N,R}$$

μ: Traction force coefficient

So that the wheels do not spin („wheelspin“):

$$F_{D,R} \leq F_{A,R,max}$$

$z_{R,D}$: Number of driven wheels

Maximum transmittable driving force to the track: $$F_{D,max} = z_{R,D} \cdot F_{D,R,max}$$

Condition against wheel spin: $$F_D \leq F_{D,max}$$

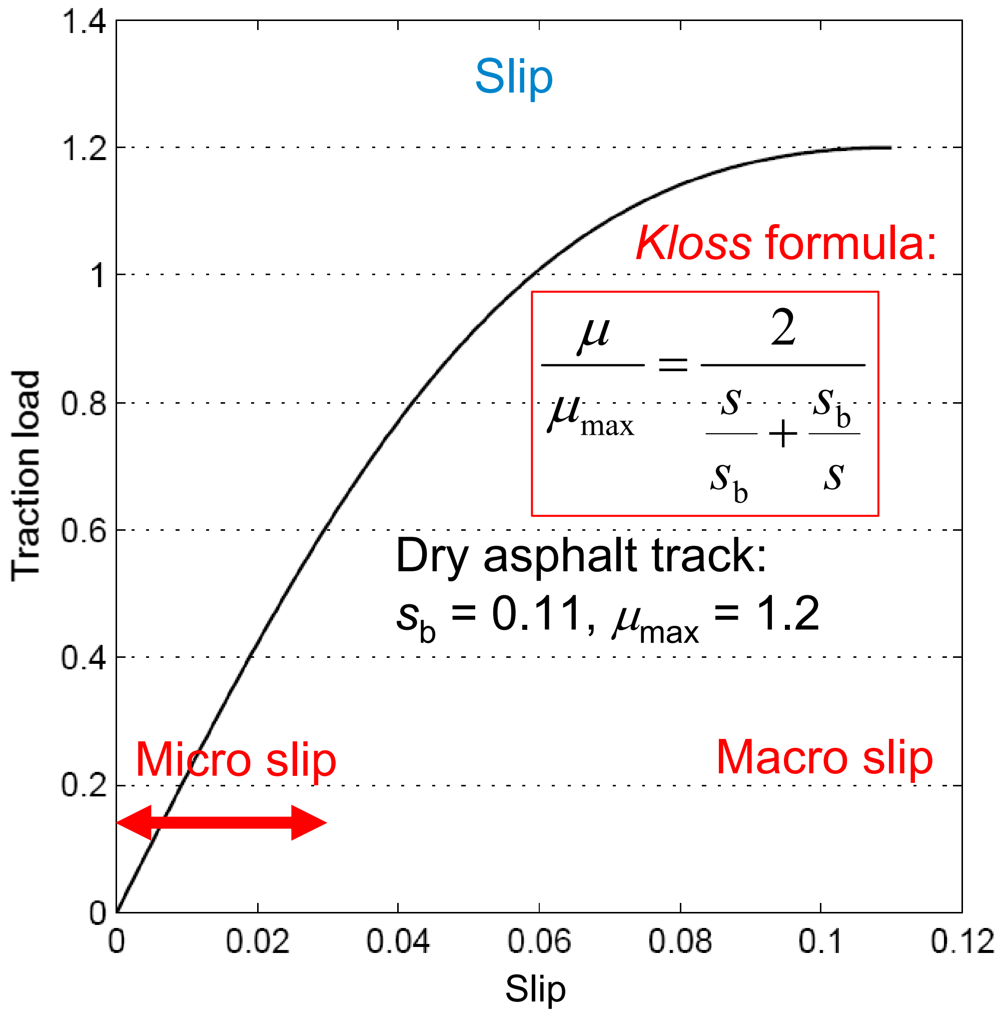
Slip between wheel and track
Simulation – Wheel / Track

-Without slip → no transmission of force to track, only „pure“ rolling!

- With dry asphalt and good traction (summer wheels) at a slip of approx. 0.1 the maximum of traction force coefficient μ of approx. 1.2 is reached.

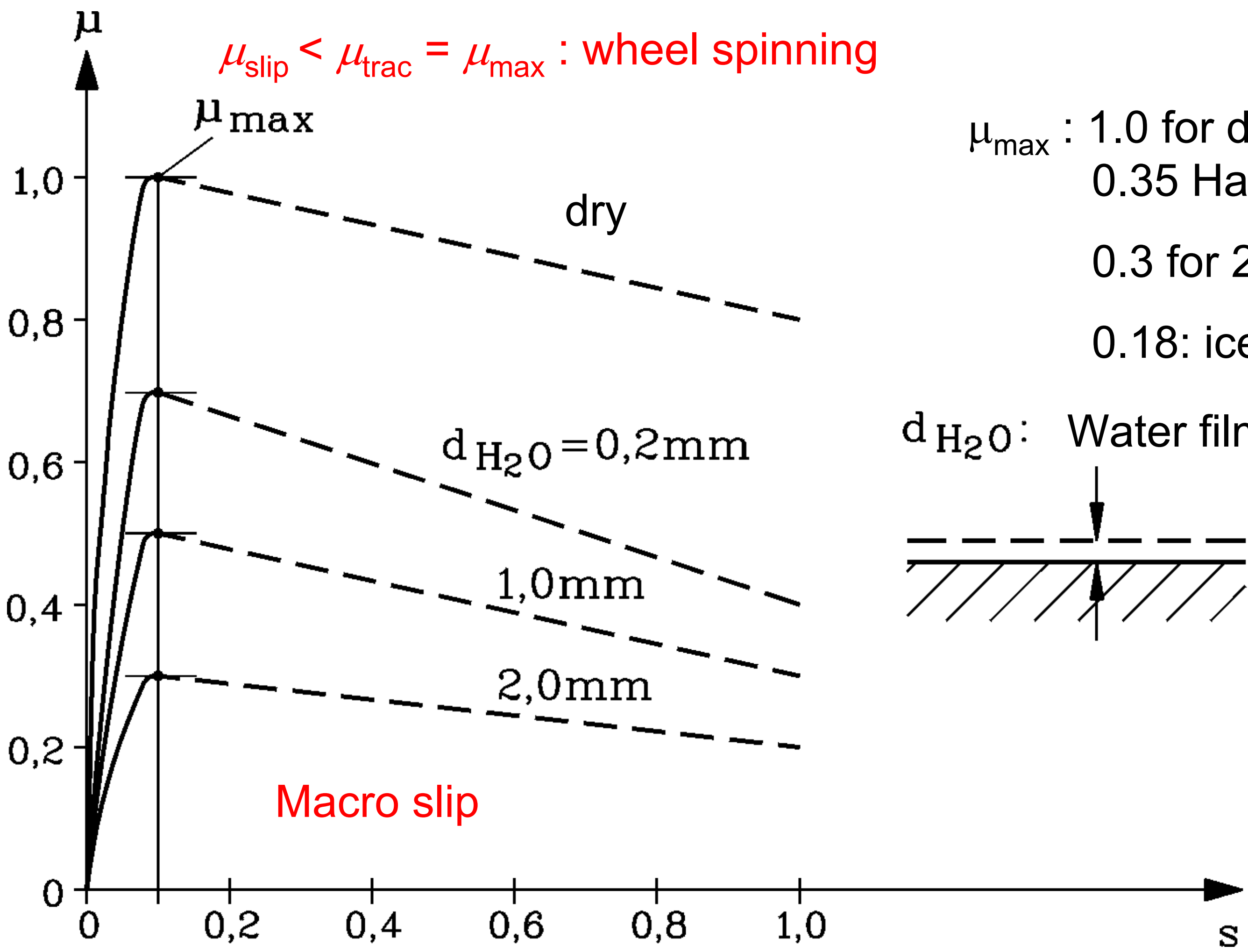
- Micro slip up to approx. 3%: driving with constant speed

- Macro slip: > 10%: acceleration



Traction coefficient μ and wheel slip *s*

$\mu_{slip} < \mu_{trac} = \mu_{max}$: wheel spinning



μ_{max} : 1.0 for dry track
0.35 Hard snow
0.3 for 2mm water film
0.18: ice on the track

d_{H_2O}: Water film thickness

Track

Traction coefficient vs. slip

Kloss formula

$$\frac{\mu}{\mu_{\max}} = \frac{2}{\frac{s}{s_\mathrm{b}} + \frac{s_\mathrm{b}}{s}}$$

Dry asphalt track:
$s_\mathrm{b} = 0.11$, $\mu_{max} = 1.2$

Empiric, more exact formula:

$$\mu = \mu_{\max} \cdot \left(1 - e^{-S_\mathrm{t} \cdot s}\right) - \frac{A_\mathrm{b} \cdot e^{W \cdot s}}{100 A_\mathrm{b} + e^{W \cdot s} - 1} + 0.01 \qquad 0 \le s \le 1$$

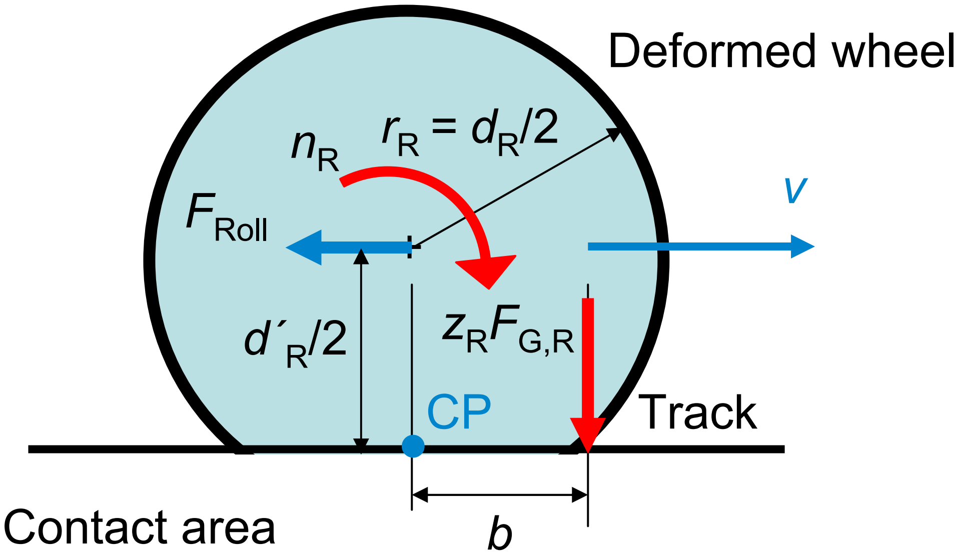
S_t: slope of $\mu(s)$-curve for $s = 0$ (Value range: 10 … 50)

A_b: depression of $\mu(s)$-curve for $s = 1$ (Value range : 0 … μ_{max})

W: inflection point (Value range : 10 … 100)

Dry asphalt track: $S_t = 30$, $A_b = 0.3$, $W = 10$

Rolling resistance F_{Roll} of all wheels



F_G: Normal force on all wheels

b: Big radius of deformed ellipsis

g: Gravitational acceleration

n_R: Wheel speed

CP: Contact point

α: Slope angle of track

$$F_G = m \cdot g \qquad F_N = F_G \cdot \cos\alpha$$

Torque balance: $\quad d'_R < d_R$

$$F_{Roll} \cdot d'_R / 2 = z_R F_{G,R} \cdot b_R$$

$d'_R \approx d_R$:

$$\boxed{F_{Roll} = (2b / d_R) \cdot F_N = f_R \cdot F_N}$$

Rolling resistance coefficient $f_R = f_R(v)$ due to deformation work of wheels :

Depends on vehicle speed and wheel property

Rolling resistance coefficient of tyres

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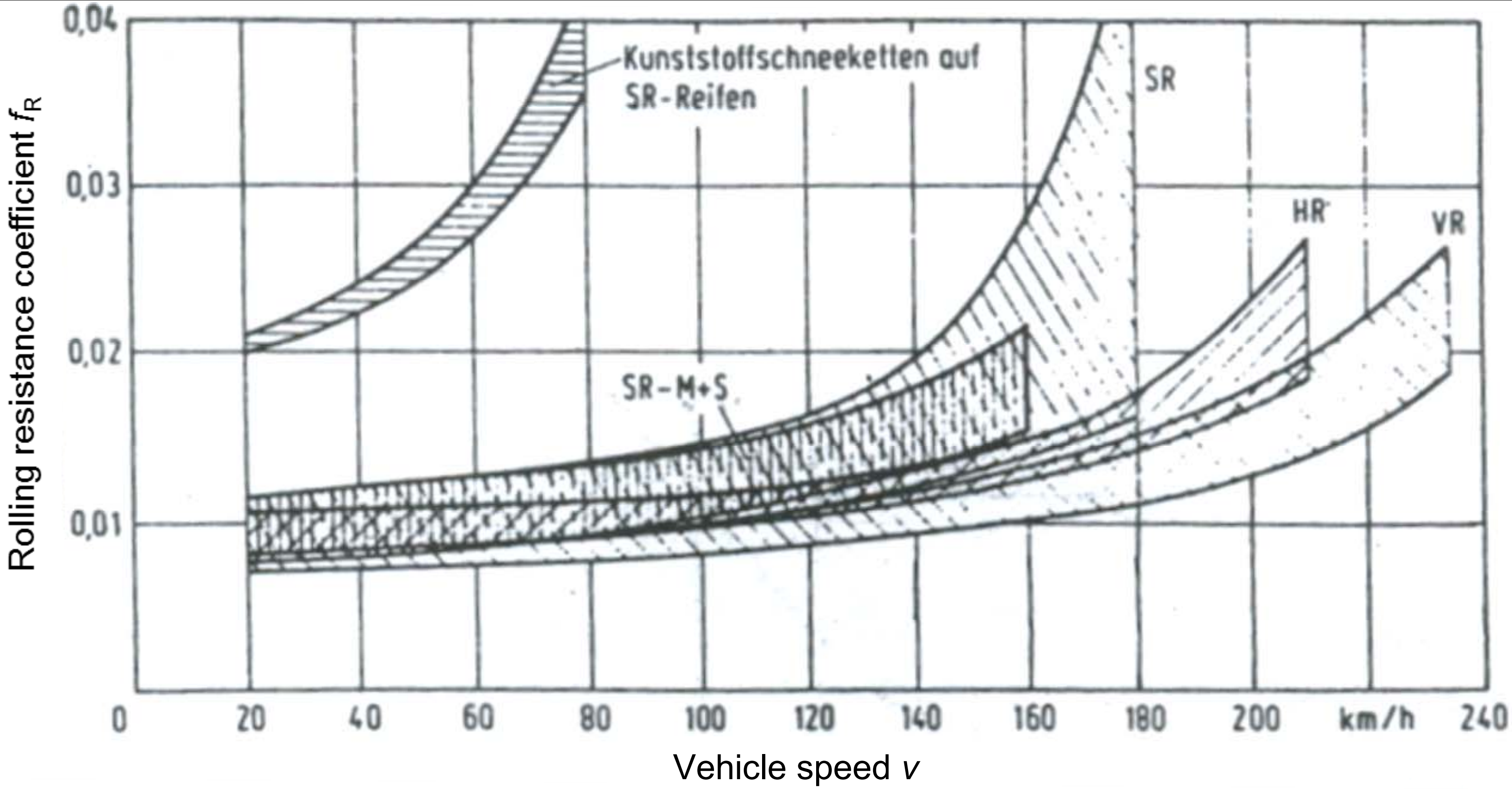


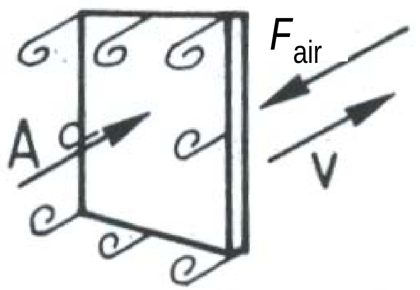
Example: no slope: F_G = 8000 N (weight: 800 kg), $f_R = b/r_R = 0.01$, F_{Roll} = 80 N

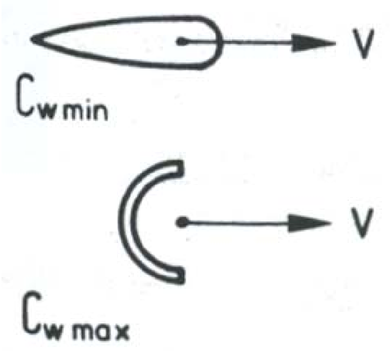
$$f_R = f_{R0} + f_{R1} \cdot (v/v_0) + f_{R4} \cdot (v/v_0)^4$$

v_0 = 27.8 m/s = 100 km/h

$f_{R0} = 0.009$, $f_{R1} = 0.0015$, $f_{R4} = 0.0012$

Air resistance F_{air}





Vehicle speed *v* equals the negative air speed for non-moving air

Ram pressure: $p_{\mathrm{Ram}} = \rho_{\mathrm{Air}} v^2 / 2$

Air resistance force:

$$F_{\mathrm{Air}} = (c_{\mathrm{w}} A) \rho_{\mathrm{Air}} v^2 / 2$$

Example: VW-Golf: $c_w A = 0.56$ m², $c_w = 0.4$

A: Reference area

ρ_{Air}: Density of air

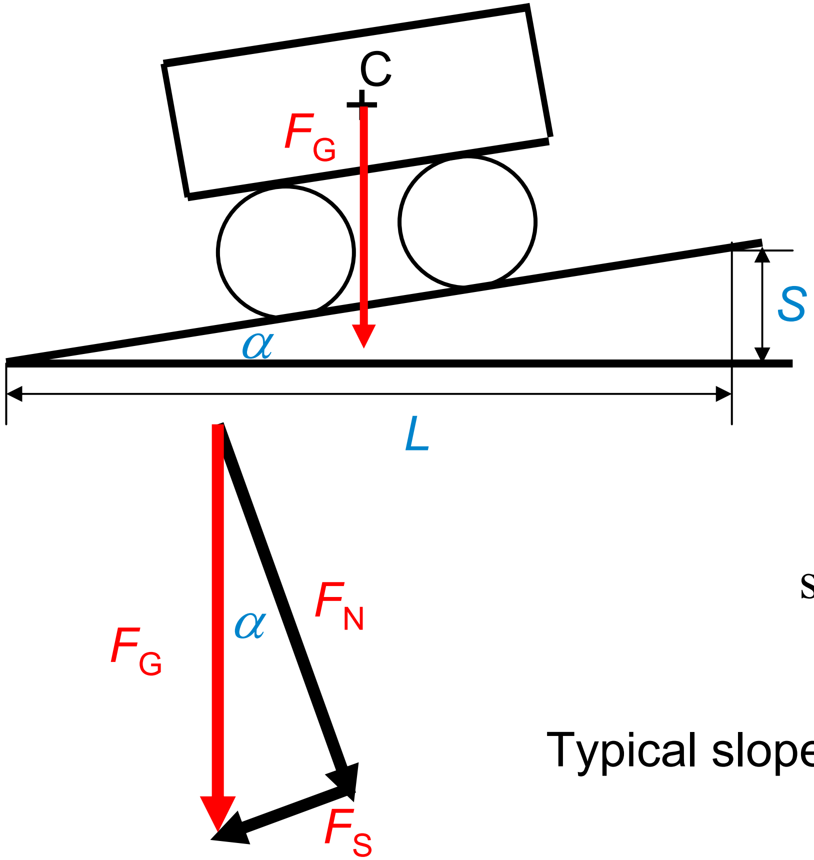
v: Vehicle speed

c_w: Drag coefficient

c_w-values person cars: 0.2 … 0.5

$$\rho_{\mathrm{Air},20°C} = 1.202\,\mathrm{kg/m^3}$$

Slope resistance F_S



Slope: $\tan\alpha = S/L$

C: Centroid

F_N: Normal force $F_N = F_G \cdot \cos\alpha$

F_S: Downhill force = slope resistance:

$$F_S = F_G \cdot \sin\alpha$$

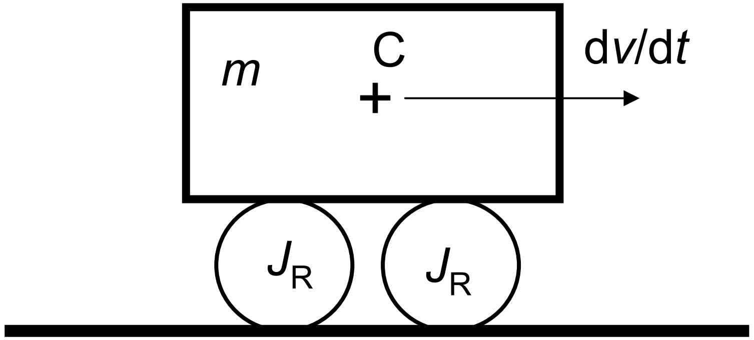
$$\sin\alpha = \frac{S}{\sqrt{S^2 + L^2}} \approx \frac{S}{L} = \tan\alpha, \quad S << L$$

Typical slope of track: S/L = 0 … 25%

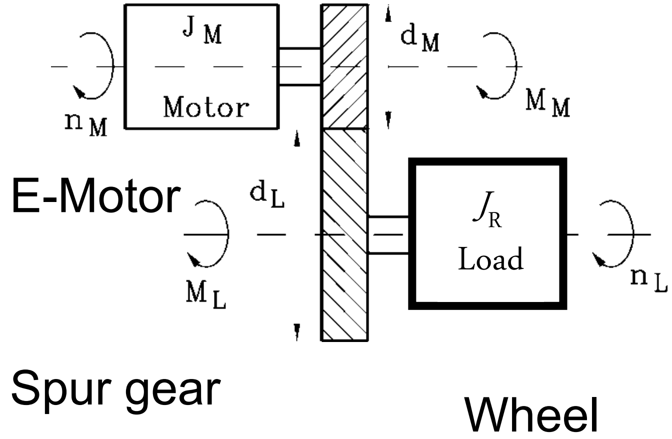
Example: Slope *Turracher Höhe* (*Carinthia, Austria*): $\tan\alpha$ = 0.22 = 22%

Vehicle acceleration force d*v*/d*t*

Vehicle:



Drive:



Vehicle acceleration: d*v*/d*t*

Acceleration of linearly moved masses: $F_a = m \cdot dv/dt$

Acceleration of rotating masses (wheels, gear, E-motor): $M_a = J \cdot d\Omega/dt$
(torque *M* necessary)

Maximum permitted acceleration („comfort“): $(dv/dt)_{max} = 2 m/s^2 \approx 0.2\, g$

Rotating mass adding factor Δ

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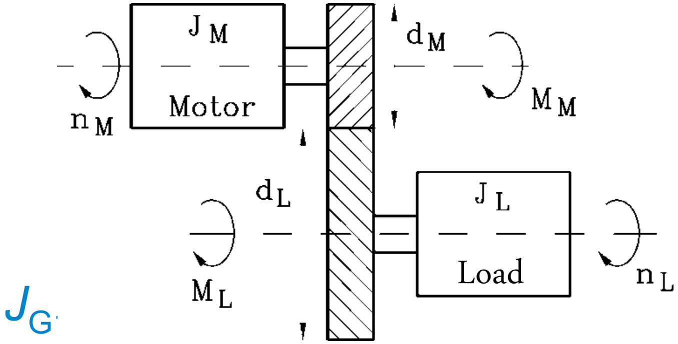
Total kinetic energy:

$$W_{\mathrm{kin}} = \frac{mv^2}{2} + \frac{(z_{\mathrm{R}} J_{\mathrm{R}} + J_{\mathrm{G1}})\Omega_{\mathrm{R}}^2}{2} + \frac{(J_{\mathrm{M}} + J_{\mathrm{G2}})\Omega_{\mathrm{M}}^2}{2} = \frac{m' \cdot v^2}{2}$$



$n_{\mathrm{L}} = n_{\mathrm{R}}$, „load“ = driven wheels of driven axle

Equivalent linear accelerated mass *m´*: $m' = m \cdot (1 + \Delta)$

Typical value for the share of the rotating masses to be accelerated by kinetic energy: $\Delta = 0.2$

Acceleration force F_{a}: $F_{\mathrm{a}} = m' \cdot (\mathrm{d}v / \mathrm{d}t)$

Bearing friction F_{Bg}

Per wheel: $F_{\mathrm{Bg,R}} = F_{\mathrm{G,R}} \cdot k_{\mathrm{Bg}}$

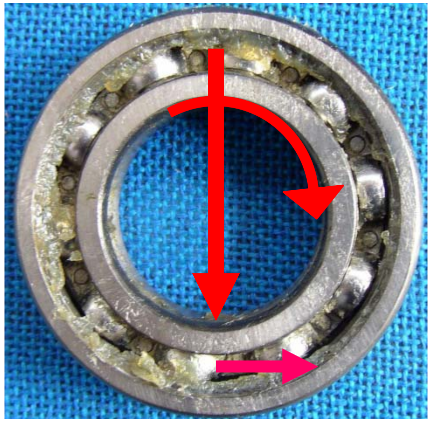
Per vehicle: $F_{\mathrm{Bg}} = z_{\mathrm{R}} F_{\mathrm{G,R}} \cdot k_{\mathrm{Bg}} = m \cdot g \cdot k_{\mathrm{Bg}}$

Example:

m = 1500 kg
F_{Bg} = 73. 5 N

Per wheel: Bearing force $F_{G,R}$

Braking bearing friction force $F_{Bg,R}$



Wheel speed n_R

Example:
Ball bearing

Friction coefficient k_{Bg} = 0.005 as an estimation !
Depending on type of bearing, state of lubrication, age, bearing load, and wheel speed this value is varying and can be calculated according to exact formulas!

Demanded driving force F_D and power P_D

1) Steady state operation: $dv/dt = 0$: $F_{D,steady} = F_{Roll} + F_{Air} + F_S + F_{Bg}$

2) Non-steady-state: $dv/dt \neq 0$: $F_{D,non\text{-}steady} = m' \cdot (dv/dt) + F_{Roll} + F_{Air} + F_S + F_{Bg}$

Accelerating: $dv/dt > 0$

Braking: $dv/dt < 0$

3) Driving power $P_D = F_D v$: steady state: $P_{D,steady} = F_{D,stat} v = (F_{Roll} + F_{Air} + F_S + F_{Bg}) \cdot v$

$$P_{D,stat} = \left[(f_R + \tan\alpha) \cdot F_N + F_{Bg}\right] \cdot v + c_w A \frac{\rho_L}{2} v^3$$

Dominating at:

low speed (first term) — high speed (second term)

4) Driving energy in driving example (time period $t_2 - t_1$):

$$W_D = \int_{t_1}^{t_2} P_D(t) \cdot dt$$

Example: Driving force F_A

Data: m = 1500 kg, v = 80 km/h, f_R = 0.01, $c_w A$ = 0.56m^2

a) Rain-wet asphalt: μ_{max} = 0.5 at s_b = 0.11,
Acceleration: dv/dt = 1 m/s^2, Δ = 0.2,
Slope 10%

b) Dry asphalt: μ_{max} = 1.2 at s_b = 0.11,
No acceleration: dv/dt = 0
No slope

$$F_G = 14700\,\text{N}, F_{Bg} = 73.5\,\text{N}, F_{Air} = 166\,\text{N}$$

a) $F_N = 14627\,\text{N}, F_{Roll} = 146\,\text{N}, F_S = 1463\,\text{N}, F_B = 1800\,\text{N}$

$$F_D = F_B + F_S + F_{Roll} + F_{Air} + F_{Bg} = \boxed{3648\,\text{N}}$$

b) $F_N = 14700\,\text{N}, F_{Roll} = 147\,\text{N}, F_S = 0, F_B = 0$

$$F_D = F_{Roll} + F_{Air} + F_{Bg} = \boxed{386.5\,\text{N}}$$

Slip losses

- μ_{max} at s_b result for a given state of track.

- For demanded driving force and vehicle weight resp. slope a needed traction force coefficient μ concludes. For sym. Centroid location and two axles:

$$F_{N,axle} = m \cdot g \cdot \cos\alpha / 2$$

1 driven axle: $\mu = F_D / F_{N,axle}$

- From above the wheel slip is determined with the aid of $\mu(s)$-curve or from der *Kloss* function:

$$\frac{s}{s_b} = \frac{\mu_{max}}{\mu} - \sqrt{\left(\frac{\mu_{max}}{\mu}\right)^2 - 1}$$

- Due to the wheel slip the friction power occurs as slip power P_{sl}. Hence the driving power equals the mechanic power P_m at the driving wheels reduced by this slip power P_{sl}.

$$P_{sl} = s \cdot P_m \qquad P_D = (1 - s) \cdot P_m$$

Slip losses = friction heat = slip power P_{sl}:

$$P_{sl} = \frac{s}{1 - s} \cdot P_D$$

Braking slip force: $F_{sl} = P_{sl} / v$

Example: Slip losses

Data: m = 1500 kg, v = 80 km/h, f_R = 0.01, $c_w A$ = 0.56m^2

a) Rain-wet asphalt: μ_{max} = 0.5 at s_b = 0.11, acceleration: dv/dt = 1 m/s^2, Δ = 0.2, slope 10%, F_D = 3648 N

b) Dry asphalt: μ_{max} = 1.2 at s_b = 0.11, no acceleration: dv/dt = 0 no slope,

F_D = 386.5 N

a) $F_{N,axle}$ = 14641 N, μ = 3648/14641 = 0.249, s = 0.0292,

$P_D = F_D v$ = 81067 W, P_{sl} = 2438 W, braking force: F_{sl} = 109.7 N = 3% v. F_D

b) $F_{N,axle}$ = 14700 N, μ = 386.5/14700 = 0.0263, s = 0.011,

$P_D = F_D v$ = 8589 W, P_{sl} = 94 W, braking force: F_{sl} = 4.2 N = 1.1% von F_D

Conclusion:

Slip losses can be neglected for normal driving conditions in the range of micro slip!

Electric vehicles –

Simulation of the drive components

Single-stage gear

$$v_{\mathrm{U,Gr}} = d_{\mathrm{M}} \pi n_{\mathrm{M}} = d_{\mathrm{R}} \pi n_{\mathrm{R}}$$

$$i = n_{\mathrm{M}} / n_{\mathrm{R}} = d_{\mathrm{R}} / d_{\mathrm{M}}$$

$$F_{\mathrm{Gt}} = 2M_{\mathrm{M}} / d_{\mathrm{M}} = 2M_{\mathrm{R}} / d_{\mathrm{R}}$$

$$i = M_{\mathrm{R}} / M_{\mathrm{M}} \qquad M_{\mathrm{M}} = M_{\mathrm{R}} / i$$

Speed-dependent loss torque due to oil viscosity: $M_{\mathrm{d0}} = p_0 M_{\mathrm{N}}$

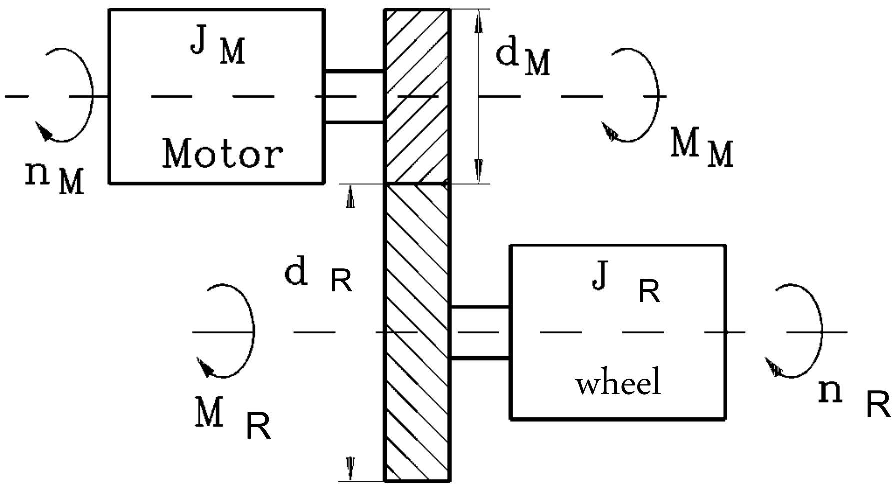
Load-dependent loss torque due to tooth meshing: $M_{d1} = p_1 M_N$

m = torque/rated torque = M/M_{N}

ν = speed/rated speed = n/n_{N}

Single-stage reduction gear (spur gear)

$i = n_{\mathrm{M}} / n_{\mathrm{R}}$: transmission ratio



$$\eta_{\mathrm{G}} = \frac{P_{out}}{P_{\mathrm{in}}} = \frac{M_{out} 2\pi n_{\mathrm{M}}}{M_{\mathrm{in}} 2\pi n_{\mathrm{M}}} = \frac{M}{M + \nu \cdot M_{\mathrm{d0}} + m \cdot M_{\mathrm{d1}}} = \frac{m}{m + \nu \cdot p_0 + m \cdot p_1}$$

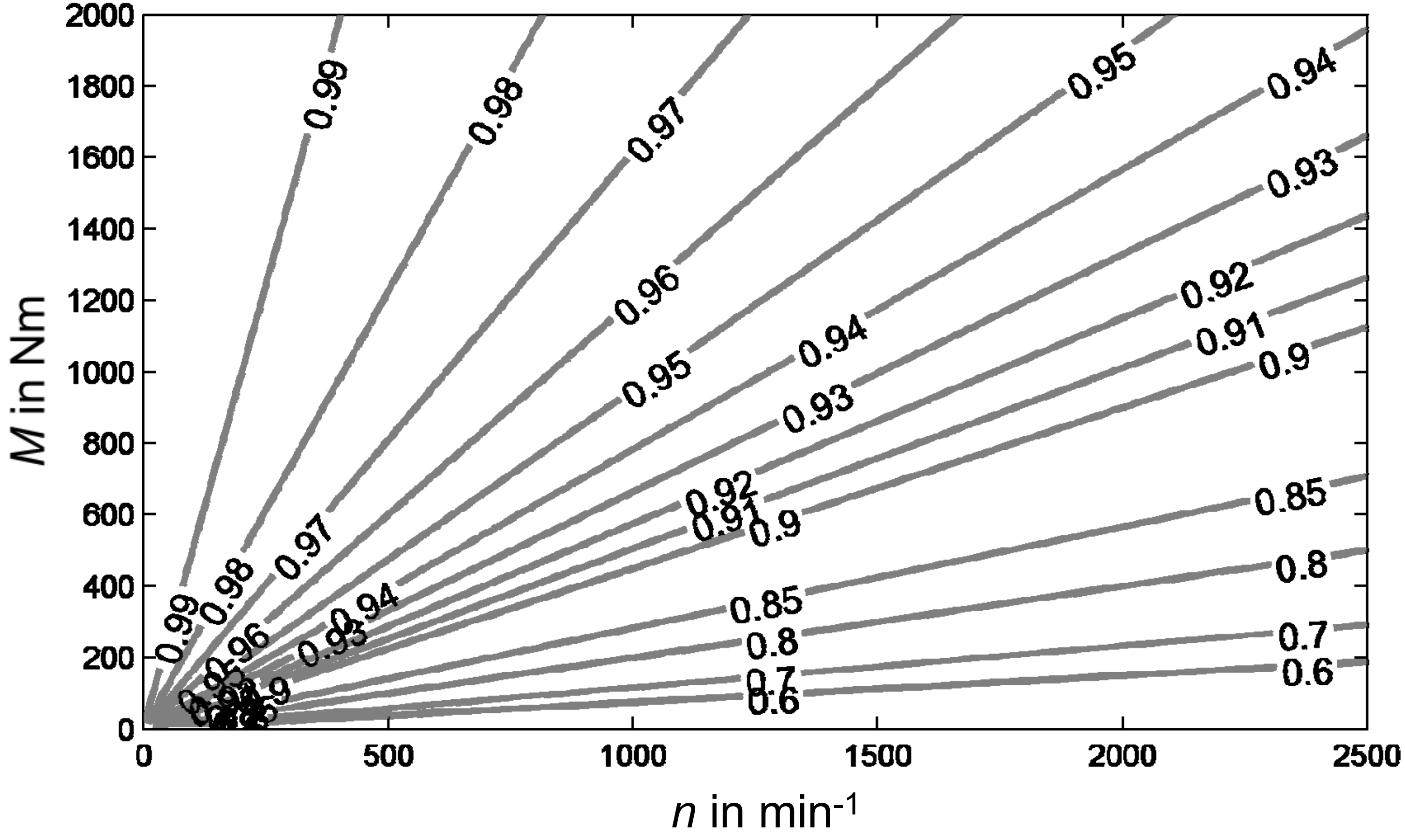
Example: p_0 = 0.011, p_1 = 0.0043, η_{GN} = 0.9849

Gear efficiency

- Gear efficiency

Single-stage reduction gear

i = 1/8, spur gear (helical gear)



Power requirement to the driving motor

Wheel torque from driving force: $F_{\mathrm{D}} = M_{\mathrm{R}} /(d_{\mathrm{R}} / 2)$

Wheel speed from vehicle speed an wheel slip: $n_{\mathrm{R}} = \dfrac{v}{d_{\mathrm{R}} \pi \cdot (1 - s)}$

Motor torque over gear and its loss torque: $M_{\mathrm{M}} = M_{\mathrm{R}} /(i \cdot \eta_{\mathrm{G}})$

Motor speed over gear: $n_{\mathrm{M}} = n_{\mathrm{R}} \cdot i$

PM-synchronous motor – Field oriented operation

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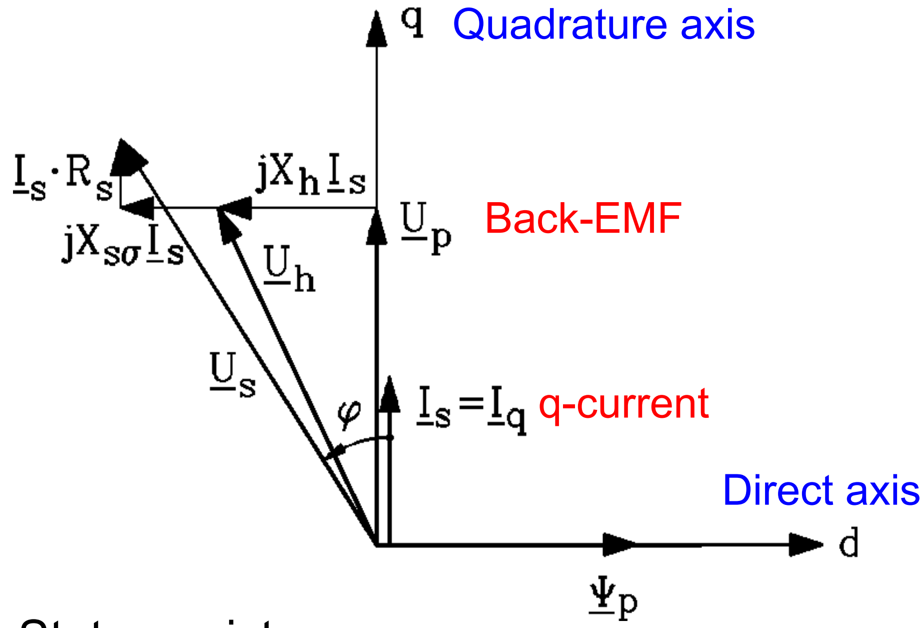

$$M_e = \frac{P_\delta}{\Omega_{syn}} = m \cdot p \cdot \frac{\Psi_p}{\sqrt{2}} \cdot I_s$$

M_e: El. torque

P_δ: Internal power

Ω_{syn}: Synchronous speed

$m = 3$: Number of phases

p: Number of pole pairs

Ψ_p: Flux linkage (peak)

$I_s = I_{s1}$: Stator phase current (RMS)

U_p : back-EMF (RMS)

R_s: Stator resistance

X_h, $X_{s\sigma}$: Reactance (main- and stray- (h + σ))

$U_s = U_{s1}$: Phase voltage (RMS, fundamental)

- Stator current is DIRECTLY proportional to torque M_e
- Speed is proportional to stator frequency $n = f_s / p$

PM-synchronous motor – Operation at full flux

Torque constant: Nm/A

$$M_e = \frac{P_\delta}{\Omega_{syn}} = m \cdot p \cdot \frac{\Psi_p}{\sqrt{2}} \cdot I_s = k_T I_s \qquad k_T = m \cdot p \cdot \frac{\Psi_p}{\sqrt{2}}$$

$$\boxed{k_T = m \cdot p \cdot \frac{\Psi_p}{\sqrt{2}}}$$

Field oriented operation: PM-synchronous motor with I_q impressing:

a) Thermal continuous torque: Rated torque M_N at n_N
- Ohmic losses P_{Cu}
- Iron losses $P_{Fe,s+r}$,
- Magnet- and friction losses P_M, P_R

b) Demagnetization/inverter current limit:
- Stator field influences magnets: Inverter current limit has to be beneath demagnetization limit.

c) Short time operation:
- Maximum torque at inverter current limit
- Motor operated at short time, utilization of thermal time constant of motors.

d) Maximum operating speed: $n_{max} = n_{sl}/1.2$

e) Voltage limit: Maximum inverter output voltage.

Field weakening for PM-synchronous machines

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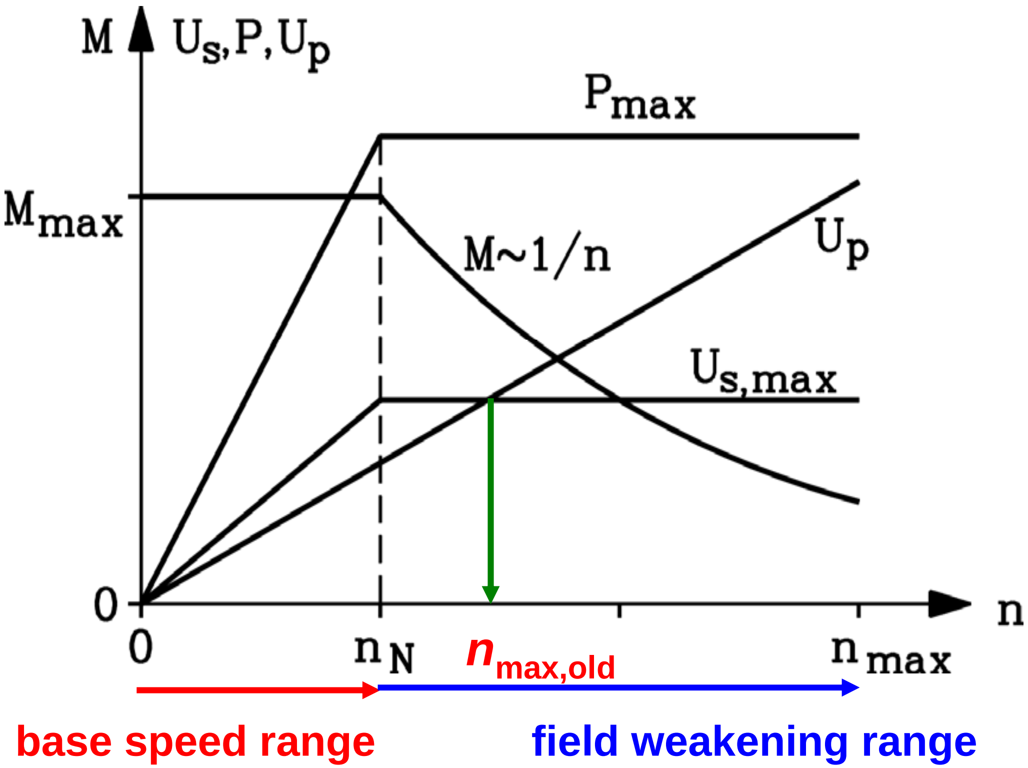


- From rated speed n_N on voltage limit $U_{s,max}$ is reached.

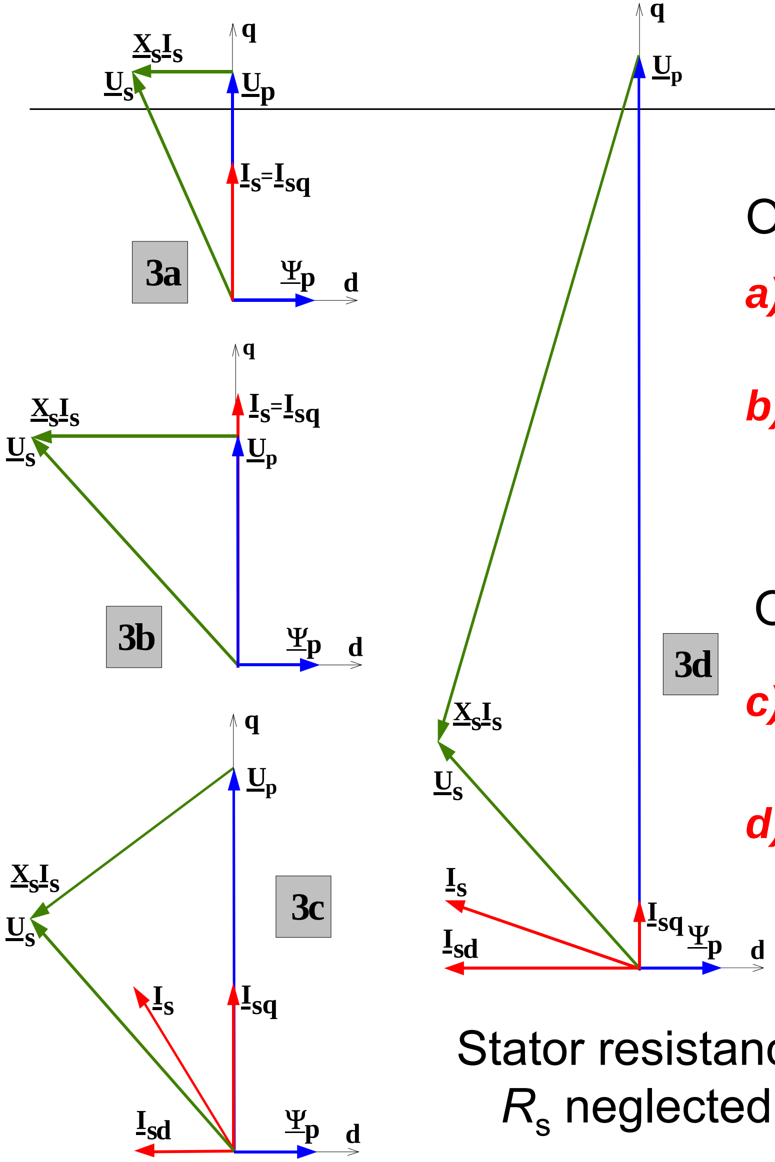
- By impressing a negative *d*-current a voltage opposing U_p is induced into the stator winding, so that U_s remains constant.

- *d*-current generates with rotor flux no torque!

- At constant total current q-current has to be reduced due to the required *d*-current, so that torque *M* is also being reduced! („Field weakening range“)

Instead of $n_{max,old}$ (at $U_s = U_p$) a higher n_{max} is reached, but with reduced torque, which is not proportional to I_s anymore.

Field weakening for PM-machines with negative d-current



Operation with full flux:

a) $n = n_N$: Rated current, rated torque, I_q-control, $M \sim I_s$

b) $n = n_N$: 2x rated current, 2x rated torque, I_q-control, $M \sim I_s$

Operation at field weakening:

c) $n = 1.7n_N$: 1.5x rated current, 1.3x rated torque

d) $n = 4n_N$: 1.7x rated current, 0.5x rated torque

Stator resistance R_s neglected

Current pilot control: ***I_s is in front of U_p, M is proportional to I_s, but higher speed than n_{max} (at $U_s = U_p$) possible!***

Condition for good capability of field weakening

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	Voltage u_s	Current i_s	d-axis i_{sd}	q-axis i_{sq}	Power	Speed n	$\cos\varphi$
a)	0.8	1.0	0	1.0	P_N	n_N	0.89 ind
b)	1.0	2.0	0	2.0	$2P_N$	n_N	0.7 ind
c)	1.0	1.5	**-0.8**	1.27	$2P_N$	$1.7n_N$	0.98 ind
d)	1.0	1.7	**-1.6**	0.5	$2P_N$	$4n_N$	0.89 **cap**

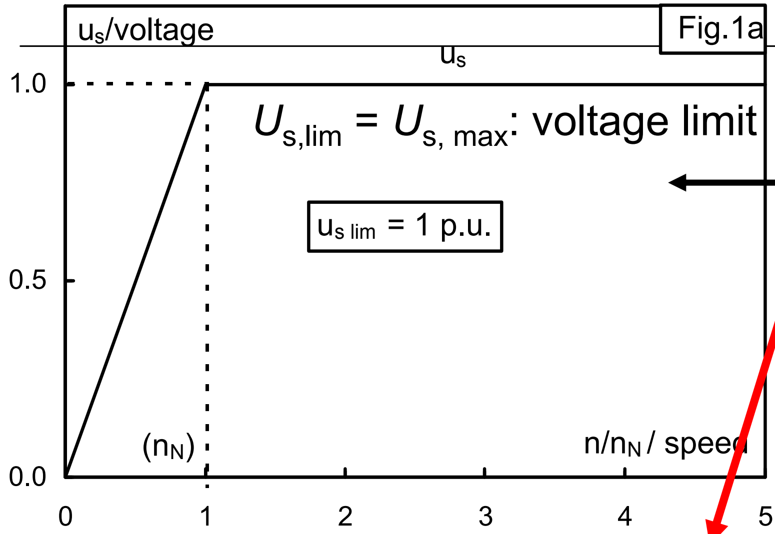
High field weakening range: $U_p >> U_{s,max}$, $U_{s,max}$ and R_s neglected

$$I_{s,d} \cong U_p / X_s = \Psi_p / L_s = \Psi_p / L_d$$

The required field weakening current I_d is approximately the generator short circuit current. The short circuit current has to be smaller than the inverter current limit for infinite field weakening!

$$I_{s,d,max} < I_{s,max}$$

Comparison of a well (A) and a badly (B) field weakable PM-synchronous motor

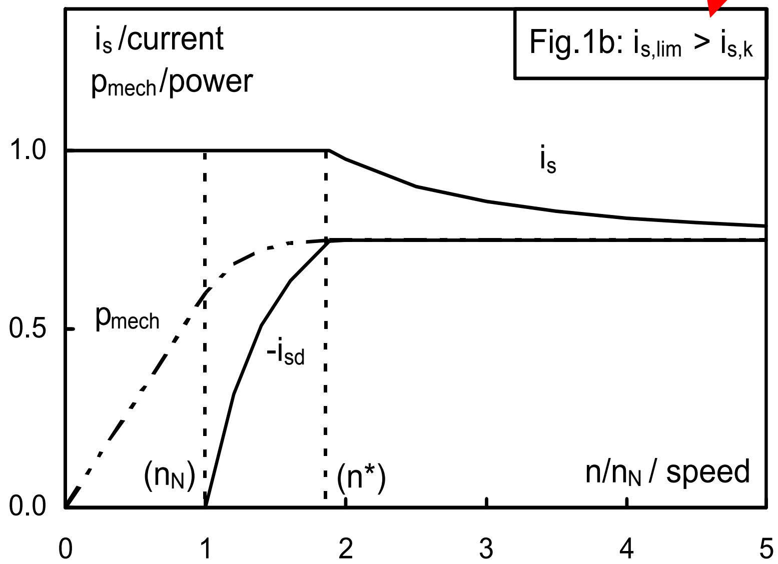


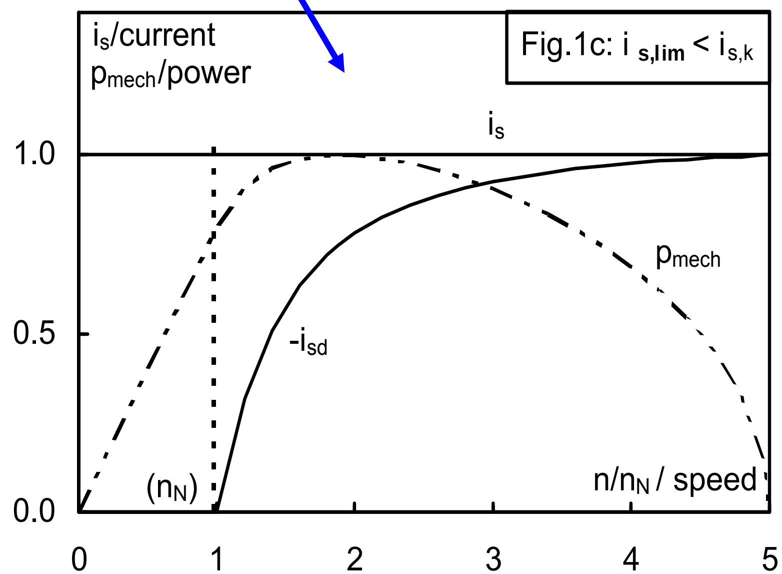
$I_{s,lim} = I_{s,\,max}$: Current limit

a) Inverter output voltage for maximum motor power

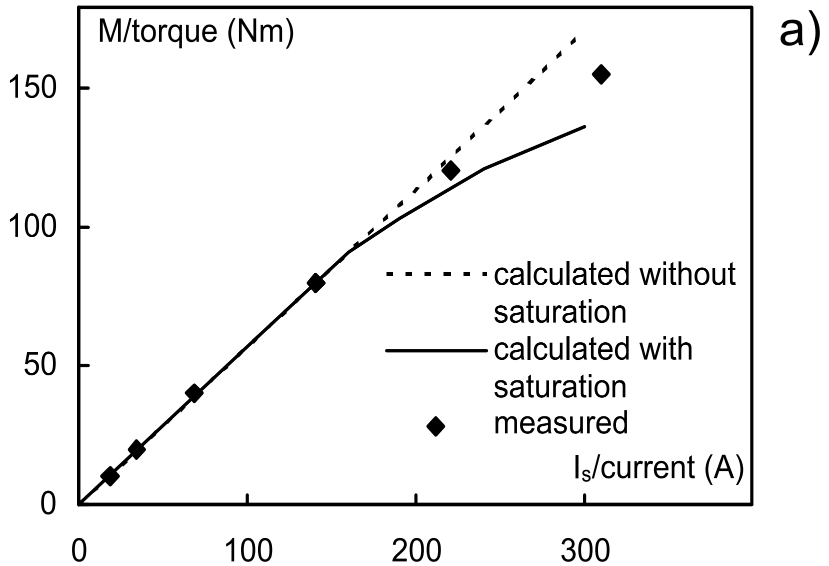
b) Motor A: Inverter current limit high $i_{s,lim} > i_{s,k}$

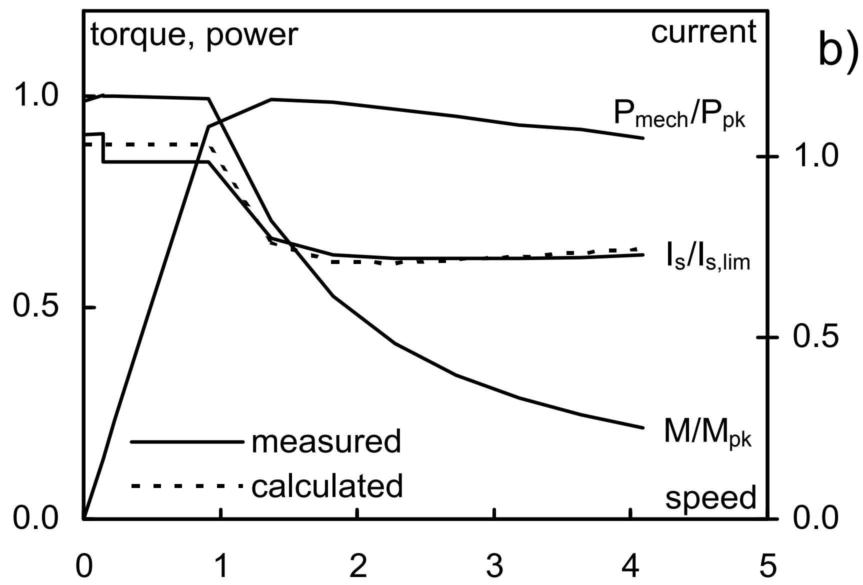
c) Motor B: Inverter current limit small $i_{s,lim} < i_{s,k}$





Example: PM-synchronous motor for E-car drive





a) Torque-current-curve at low speed (full flux)

b) Measured Torque-speed characteristic at 132V DC-link voltage = battery voltage,

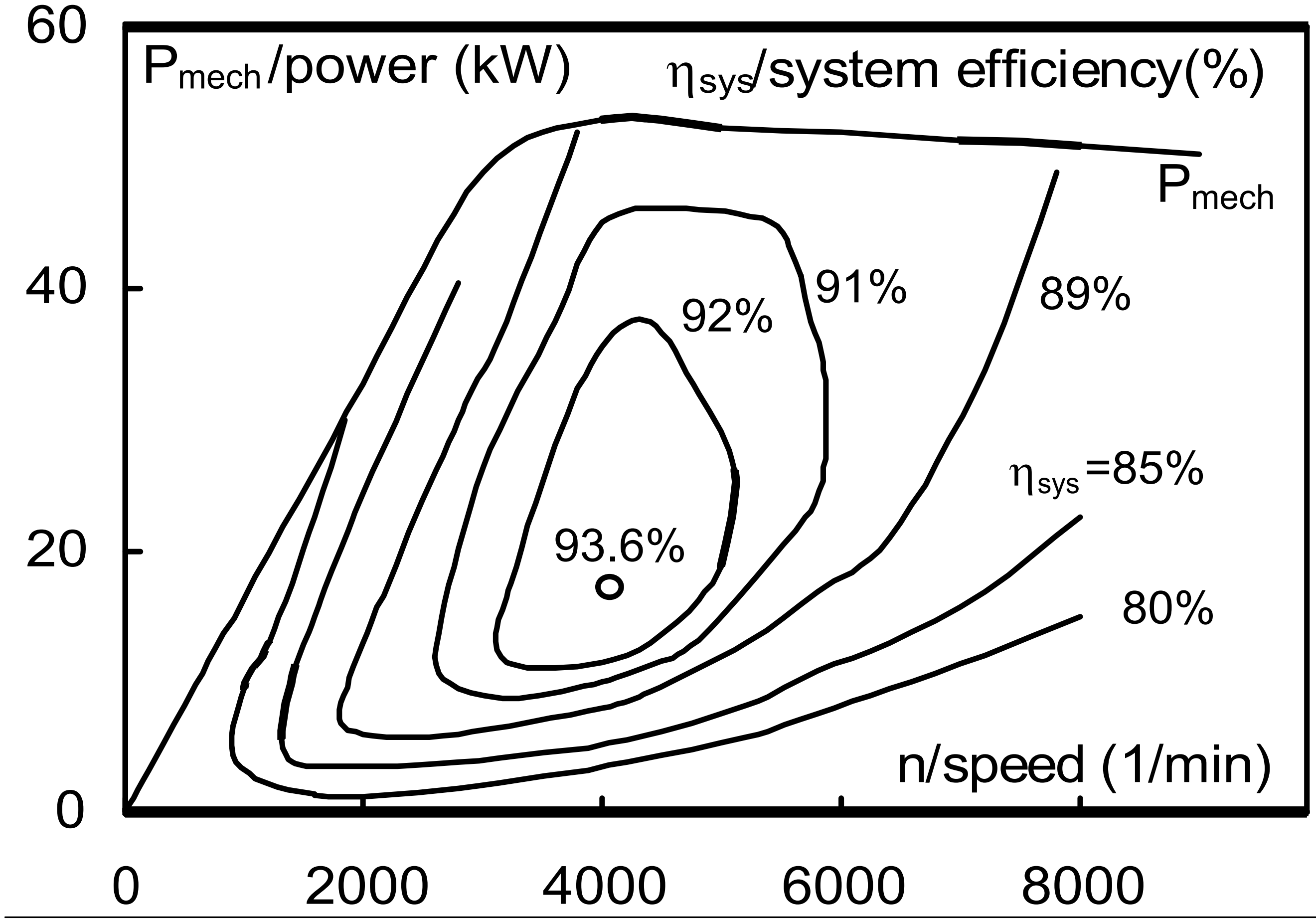
Source: Ackva, A. et al.: EPE 1997, Trondheim

$$M_{pk} = 156\text{Nm}, P_{pk} = 35\text{kW}, I_{s,lim} = 315\text{A}$$

($I_{s,lim} = I_{s,\,max}$: Current limit)

Example: PM-synchronous motor + inverter: Efficiency map

Measured motor output power and system efficiency (PM-synchronous motor + inverter) at 190V DC-link voltage = battery voltage



Source: Ackva, A. et al.: EPE 1997, Trondheim

Example: PM-Synchronous motor efficiency

Measured operating parameters in continuous operation at
a) 132V , b) 160 V DC-link voltage = battery voltage

Speed in 1/min	n	2200	9000
Motor output power in kW	P_M	26	15
Battery voltage in V	U_B	132	160
Battery current in A	I_B	227.5	119
Shaft torque in Nm	M	113	16
Motor fundam. voltage in V	U_{s1} (rms)	52	68.5
Motor fundam. current in A	I_{s1} (rms)	213	164
Power factor	$\cos\varphi_s$	0.87	0.52
Motor ohmic losses in W	P_{Cu}	2180	1260
Winding temperature in °C	ϑ_{Cu}	148	142
Motor efficiency in %	η_M	90.2	85.9
System efficiency in %	η_{sys}	86.6	78.9

Source: Ackva, A. et al.: EPE 1997, Trondheim

Example: Characteristics of a PM-synchronous motor *(Brusa)*

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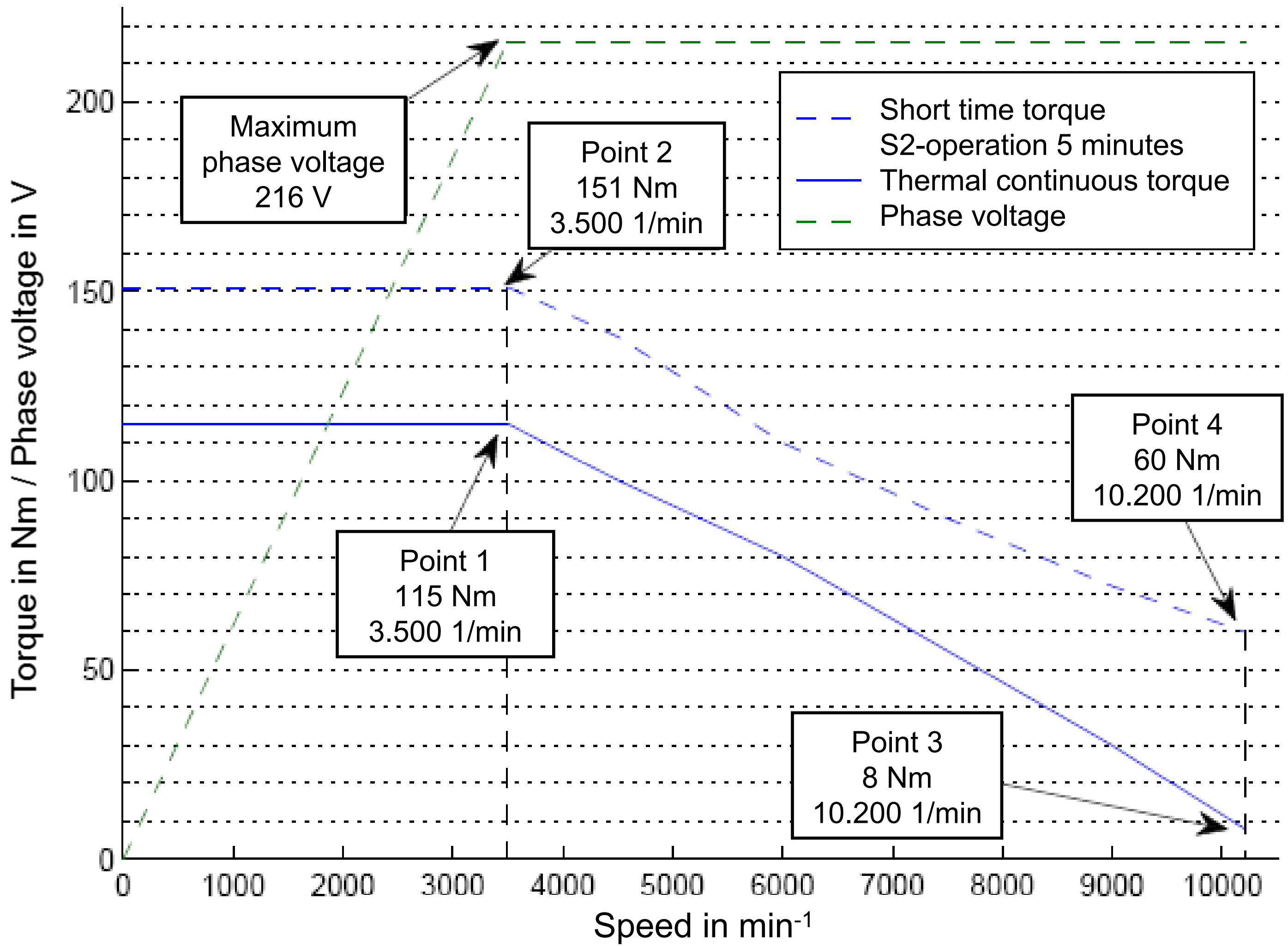

Loss groups of the PM-machine

1.Stator:

1.a) Ohmic losses inclusive current harmonics $P_{Cu,s}$

1.b) Iron losses in stator iron stack (teeth and yoke)

$$P_{Fe,s} = P_{Fe,d} + P_{Fe,ys}$$

2. Rotor:

2.a) Eddy current losses in magnets P_M due to stator current ripple (of inverter supply) and flux pulsation due to slot openings

2.b) Iron losses in rotor iron stack $P_{Fe,r}$ due to stator current ripple

2.c) Friction losses: Bearing- and air friction P_{bg+fr}

Determination of the motor operating values for the required torque M_M and speed n_M

Motor shaft torque approx. as big as air gap torque: $M_M \approx M_e$

Required q-current: $$I_q = \frac{M_M}{3p\Psi_p/\sqrt{2}} < I_{s,max}$$

at $f_s = n_M \cdot p$, $\omega_s = 2\pi f_s$

$$P_M = 2\pi n_M M_M$$

Required voltage without field weakening:

$$U_{s1} = \sqrt{(\omega_s \Psi_p/\sqrt{2} + R_s I_q)^2 + (\omega_s L_q I_q)^2} \le U_{s,max}$$

In case $U_{s1} > U_{s,max}$: Required field weakening current I_d (negative):
(R_s neglected!)

$$I_d = \frac{\sqrt{U_{s,max}^2 - (\omega_s L_q I_q)^2} - \omega_s \Psi_p/\sqrt{2}}{\omega_s L_d} \le \sqrt{I_{s,max}^2 - I_q^2}$$

Motor current: $I_{s1} = \sqrt{I_d^2 + I_q^2} \le I_{s,max}$

In case I_d is too big → I_q and therefore torque has to be reduced!

Loss calculation in the PM-synchronous motor

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Ohmic losses (stator): $P_{\mathrm{Cu,s}} = 3R_{\mathrm{s}}(\vartheta)\cdot I_{\mathrm{s1}}^2$

Iron losses: $$P_{\mathrm{Fe}} = P_{\mathrm{Fe0}}\cdot\left(\frac{\omega_{\mathrm{s}}}{\omega_{\mathrm{N}}}\right)^{1.8}\cdot\left(\frac{U_{\mathrm{s1}}}{\omega_{\mathrm{s}}\Psi_{\mathrm{p}}/\sqrt{2}}\right)^2$$

Friction losses: $P_{\mathrm{fr}} = 2\pi n_{\mathrm{M}} M_{\mathrm{fr}}(n_{\mathrm{M}})$

Additional losses (eddy current losses in magnets, rotor parts, winding) at sinusoidal current:

$$P_{\mathrm{ad}} = P_{\mathrm{ad,N}}\cdot\left(\frac{\omega_{\mathrm{s}}}{\omega_{\mathrm{N}}}\right)^{1.5}\cdot\left(\frac{I_{\mathrm{s1}}}{I_{\mathrm{sN}}}\right)^2$$

Additional losses due to current ripple with switching frequency (about constant value, a. o. depending on modulation degree *m*): $P_{\mathrm{ad,inv}}$

Total losses of motor: $P_{\mathrm{d,M}} = P_{\mathrm{Cu,s}} + P_{\mathrm{Fe}} + P_{\mathrm{ad}} + P_{\mathrm{fr}} + P_{\mathrm{ad,inv}}$

Motor efficiency: $\eta_{\mathrm{M}} = P_{\mathrm{M}}/(P_{\mathrm{M}} + P_{\mathrm{d,M}}) = P_{\mathrm{M}}/P_{\mathrm{e}}$ $\qquad \cos\varphi_{\mathrm{s}} = P_{\mathrm{e}}/(3U_{\mathrm{s1}}I_{\mathrm{s1}})$

Example: Motor losses

Rated data:

6-pole PM-synchronous motor, M_N = 95.5 Nm, n_N = 2200/min, P_N = 22 kW
f_N = 110 Hz, L_d = 0.186 mH, L_q = 0.219 mH, $R_{s,\,20°C}$/ $R_{s,\,155°C}$ = 10.5/16.0 mOhm
Ψ_p = 98 mVs (20°C), P_{Fe0} = 248 W, P_{adN} = 110 W, $P_{ad,inv}$ = 56 W, M_{fr} = 0.05 Nm
I_{sN} = 174 A, U_{sN} = 50 V, motor weight 45 kg, water jacket cooling

Ohmic losses, 155°C: 1453 W

Iron losses: 270 W

Friction losses: 11.5 W

Additional losses: 110 W

Additional losses due to current ripple: 56 W

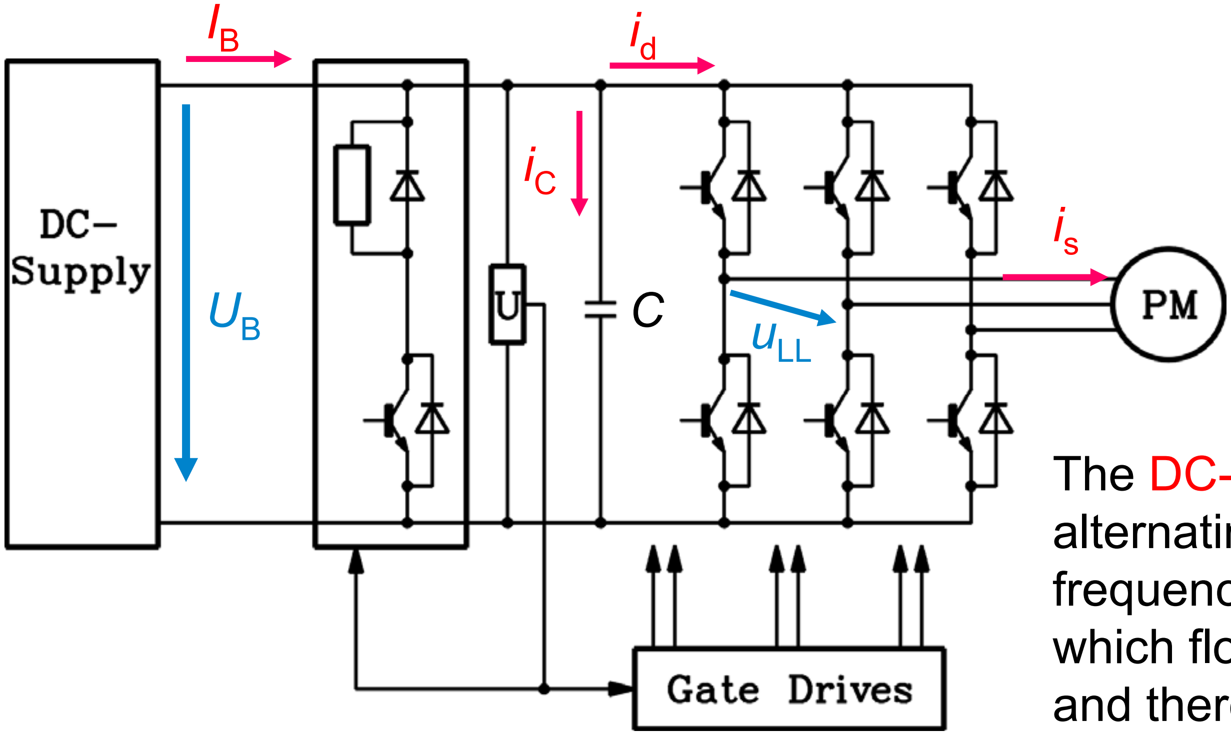
Source: Ackva, A. et al.: EPE 1997, Trondheim

Total losses: 1900 W

$\cos\varphi_s$ = 0.916

Motor efficiency: 92.05%

Modeling of the inverter



I_B: Battery current

i_d: DC-link current

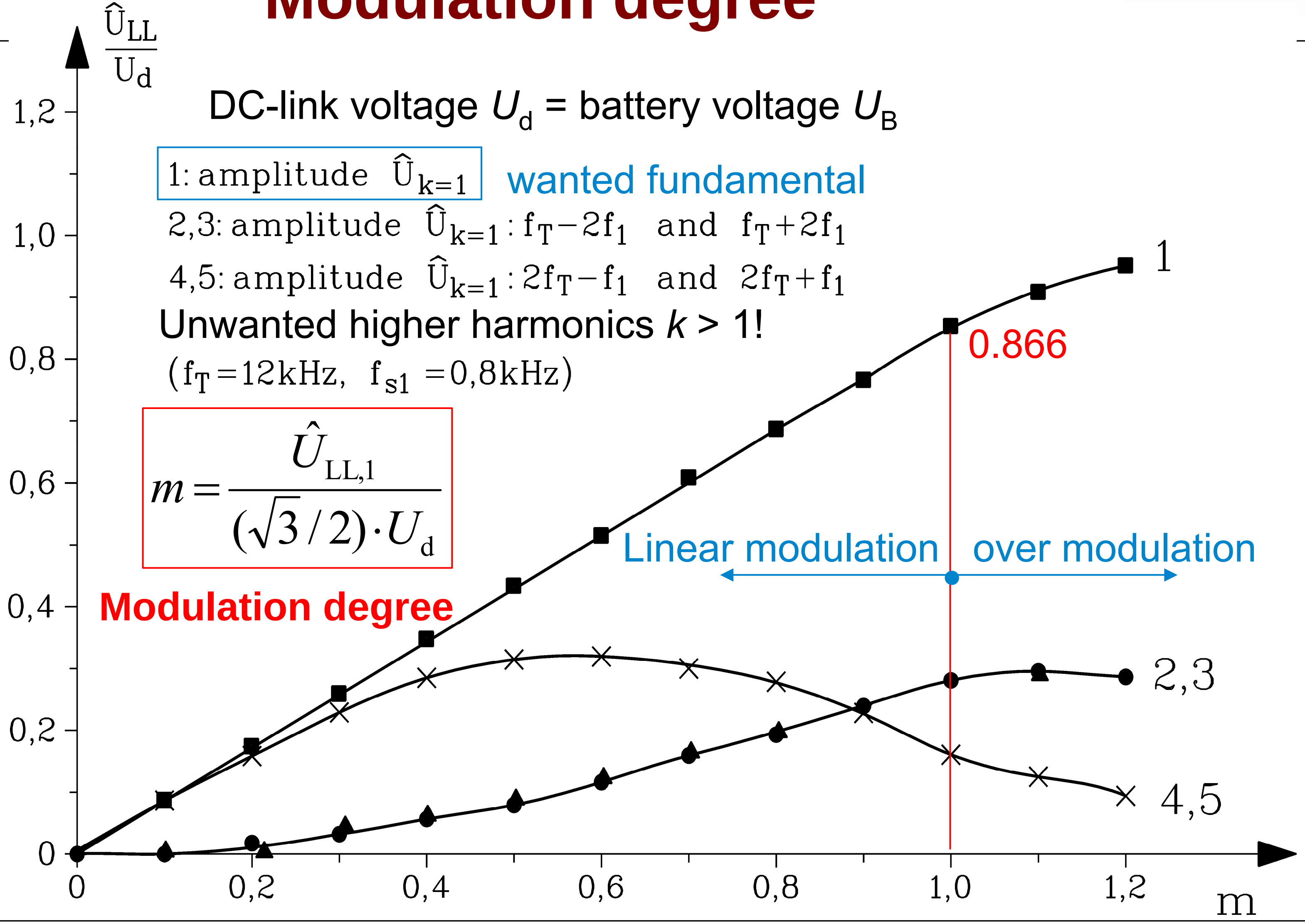
i_C: capacitor current

C: DC-link capacity

The lint-to-line pulsed stator voltage u_{LL} has a fundamental U_{LL1} with f_s. Its rectification is mainly the battery voltage U_B.

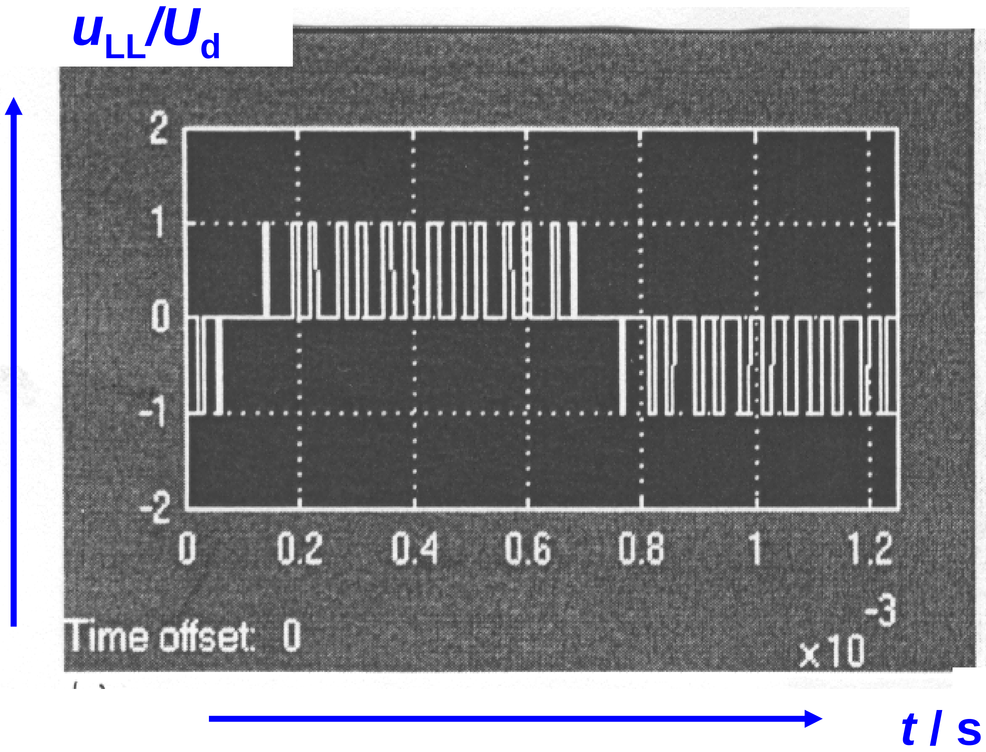
The DC-link current i_d contains the alternating part from the switching frequency f_T of the transistors, which flows as capacitor current i_C and therefore hardly loading the battery. The DC-part is the battery current, which is being distributed on the three phases with the fundamental frequency f_s as stator frequency.

Pulse width modulation – Modulation degree

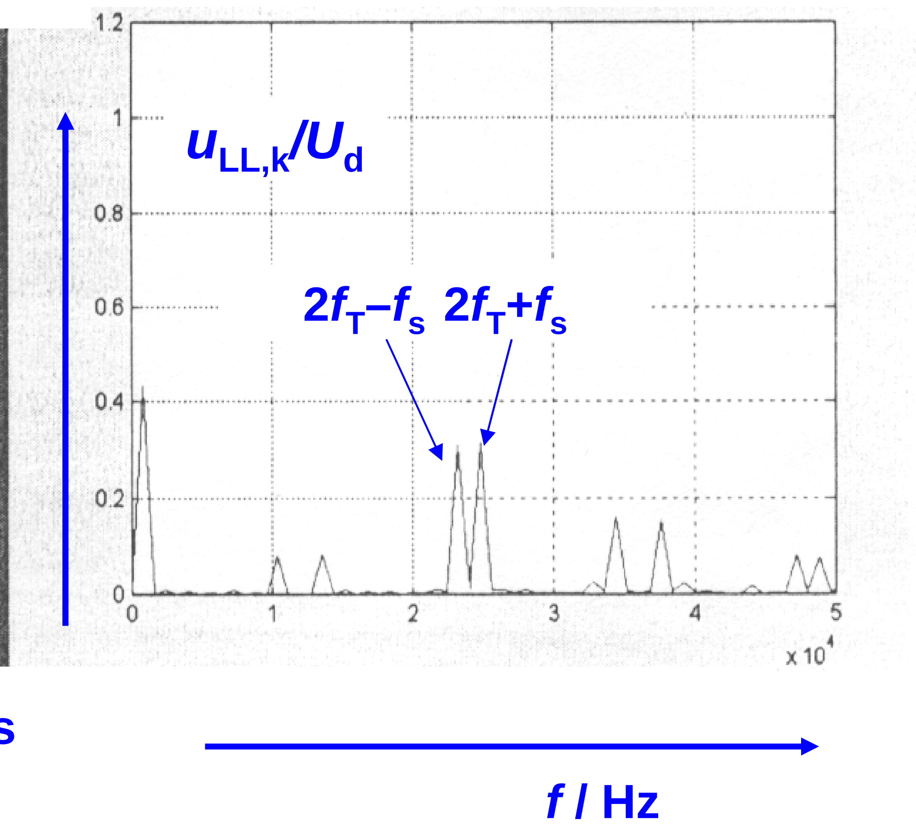


Line-to-line inverter output voltage: *m* = 0.5

Pulse width modulated output voltage



***Fourier*-spectrum of *U*-harmonics**



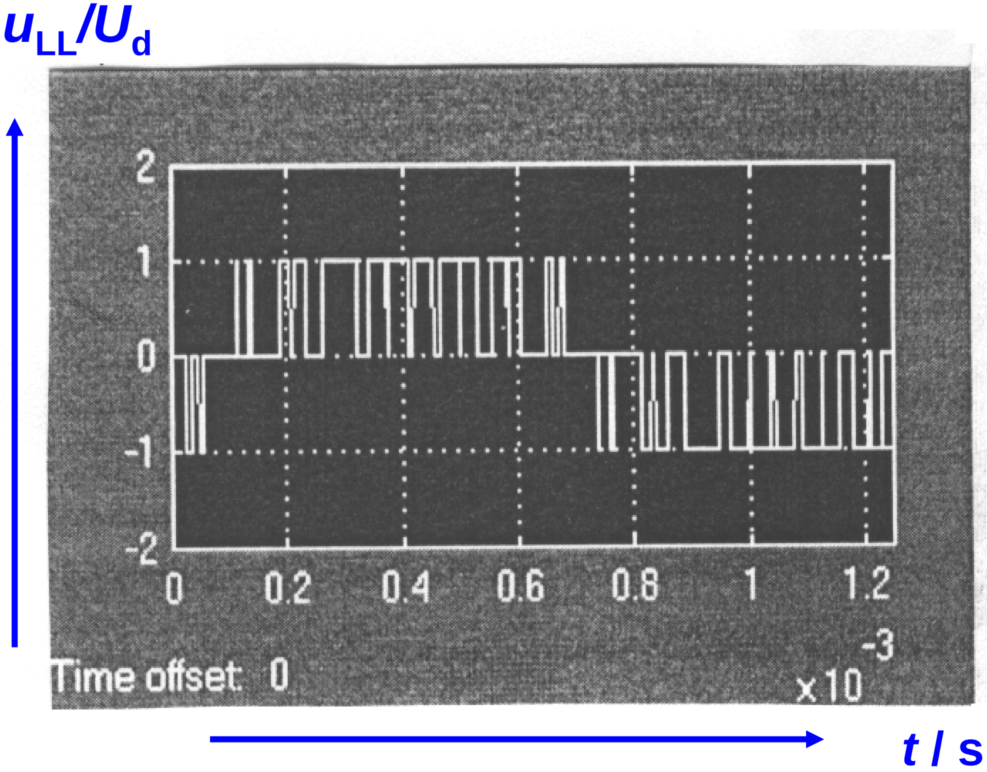
Example: **Fundamental f_s = 800 Hz**

Switching frequency f_T = 12000 Hz = 15f_s

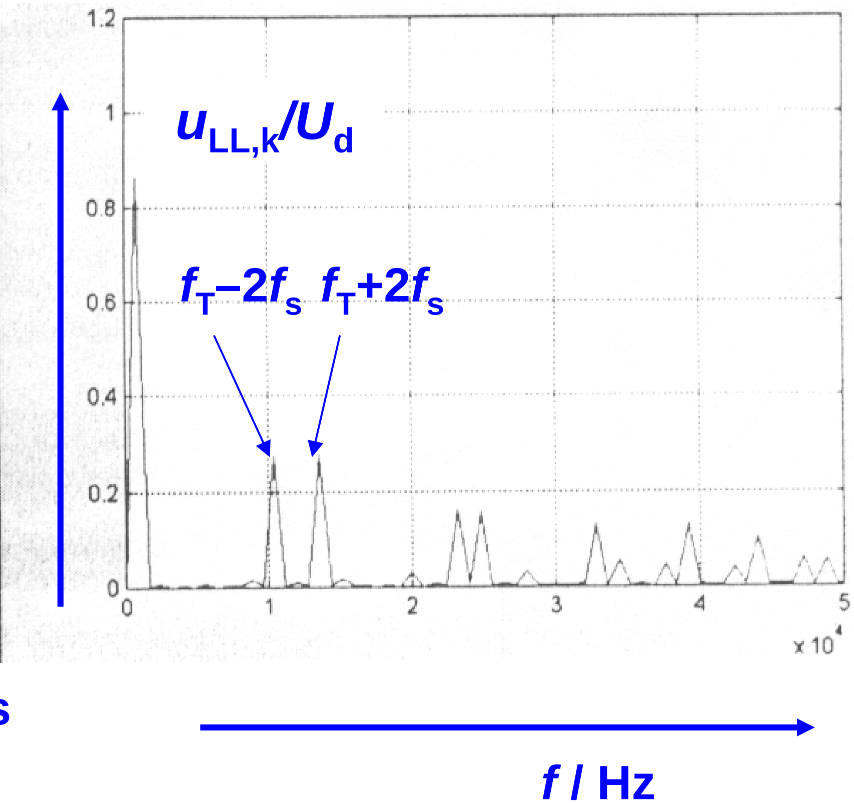
Voltage fundamental: amplitude 0.43U_d

Line-to-line inverter output voltage: m = 1.0

Pulse width modulated output voltage



Fourier-spectrum of _U_-harmonics



Example: Fundamental f_s = 800 Hz

Switching frequency f_T = 12000 Hz = 15f_s

Voltage fundamental:
amplitude 0.86U_d

Square wave operation: Over modulation $m = \infty$

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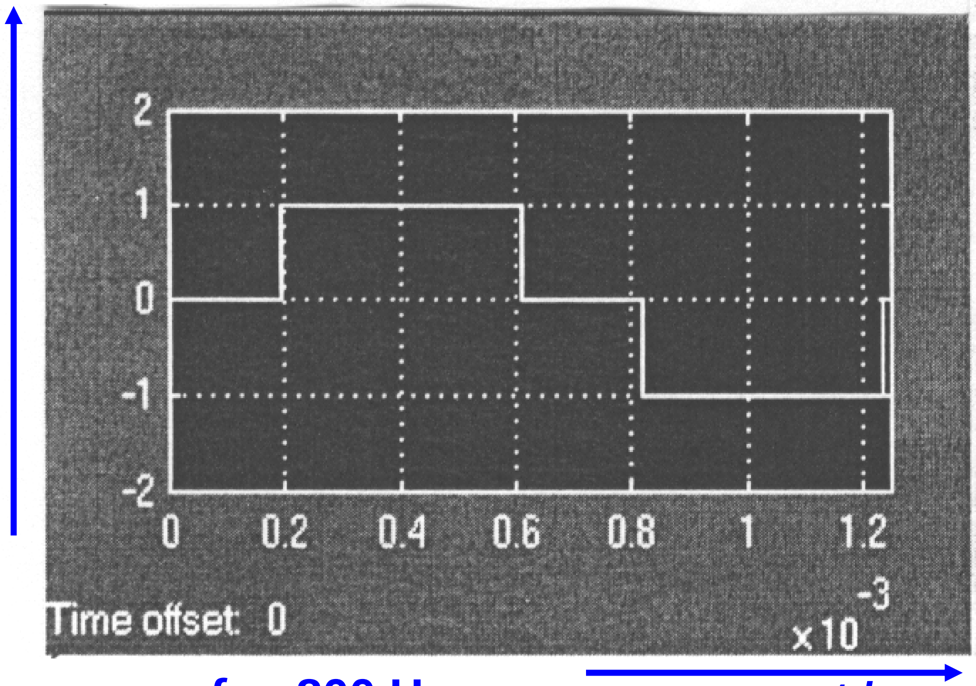
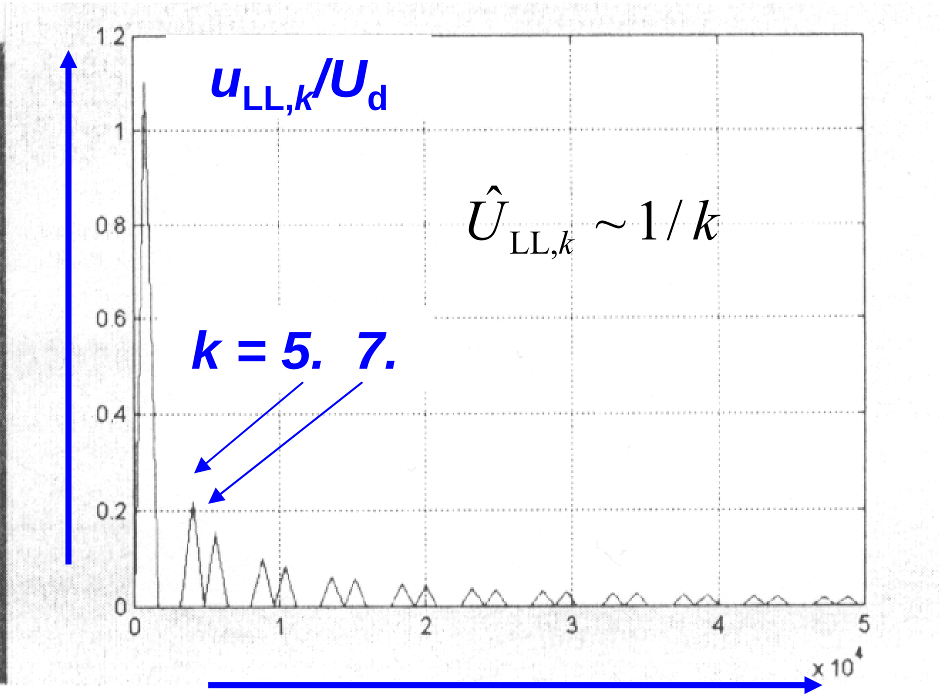
Pulse width modulated output voltage



f_s = 800 Hz

Fourier-spectrum of U-harmonics



Example: **Fundamental frequency f_s = 800 Hz**

Switching frequency $f_T = f_s$ "six step operation"

Voltage fundamental: amplitude $1.1U_d$

Estimation of max. inverter output voltage

Maximum inverter fundamental output voltage at:
a) Square wave operation:

Line-to-line voltage peak value:

$$\hat{U}_{\mathrm{LL1}} = \frac{4}{\pi} \cdot \sin\left(\frac{2}{3} \cdot \frac{\pi}{2}\right) \cdot U_{\mathrm{d}} = \frac{2\sqrt{3}}{\pi} \cdot U_{\mathrm{d}}$$

Phase voltage, RMS-value: $U_{\mathrm{s1}} = \hat{U}_{\mathrm{LL1}} / (\sqrt{2} \cdot \sqrt{3}) = \frac{\sqrt{2}}{\pi} \cdot U_{\mathrm{d}}$

b) At linear limit of modulation *m* = 1: $\hat{U}_{\mathrm{LL1}} = \frac{\sqrt{3}}{2} \cdot U_{\mathrm{d}}$ $U_{\mathrm{s1}} = \frac{U_{\mathrm{d}}}{2\sqrt{2}}$

Example:

Battery voltage $U_B = U_d = 480$ V:

a) $\hat{U}_{\mathrm{LL1}} = 529\mathrm{V}$ $U_{\mathrm{s1}} = 216\mathrm{V}$

b) $\hat{U}_{\mathrm{LL1}} = 415\mathrm{V}$ $U_{\mathrm{s1}} = 170\mathrm{V}$

Modeling of the inverter

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I_{s1}: Fundamental of stator phase current

U_{s1}: Fundamental of stator phase voltage $\quad U_{s1} = U_{LL1} / \sqrt{3}$

φ_{s1}: Phase angle between I_{s1} and U_{s1}

$P_{d,inv}$: Inverter losses

Power balance

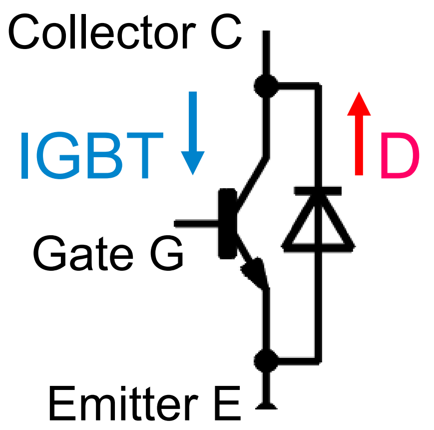
$$P_B = 3U_{s1} I_{s1} \cos\varphi_{s1} + P_{d,inv}$$

Inverter losses:

- Conduction losses $P_{inv,C}$
- Switching losses $P_{inv,S}$
- Base supply $P_{inv,0}$ = approx. 50 W

} $P_{d,inv}$

Modeling of the inverter



IGBT: **I**nsulated **G**ate **B**ipolar **T**ransistor = switching transistor

D: Free wheeling diode (antiparallel): Conducts current during voltage brake

Example: IGBT a. Diode *FS200 R06KE3, Fa. Infineon*

Blocking voltage: $U_{CE,sperr}$ = 600 V, battery voltage should not exceed 500 V

IGBT:

Collector continuous-/peak current: $I_{C,N}$ = 200 A, $I_{C,pk}$ 400 A (1 ms), $U_{CE,N}$ = 300 V
Continuous junction temperature 125°C: $U_{CE,sat}$ = 1.6 V at 200 A
Conducting voltage U_{CE0} = 0.8 V, conducting resistance R_{TD} = 4 mΩ
Switch-on-/-off losses at $U_{CE,N}$, $I_{C,N}$: 1.7 mJ/6.7 mJ per switching process

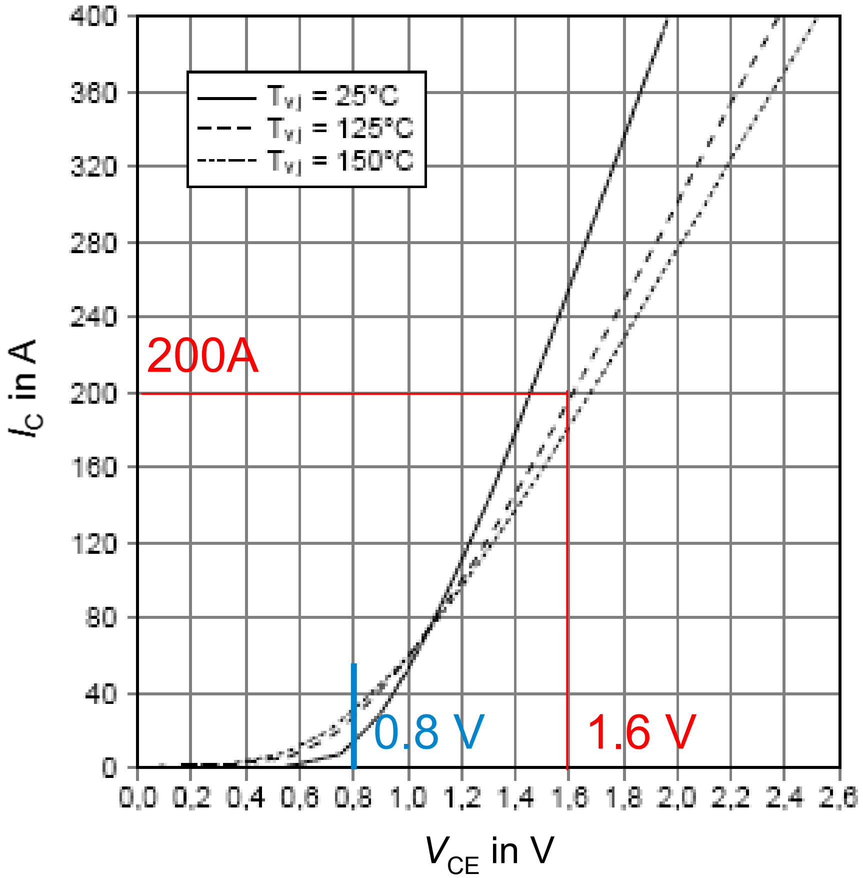
Free wheeling diode:

Continuous-/peak current: $I_{F,N}$ = 200 A, $I_{F,pk}$ 400 A (1 ms), $U_{F,N}$ = 300 V
Continuous junction temperature 125°C: conducting voltage U_{F0} = 0.8 V, Conducting resistance R_{FD} = 2.5 mΩ
Cut-off losses at $U_{F,N}$, $I_{F,N}$: 5.2 mJ per switching process

Power switch IGBT (inverter)

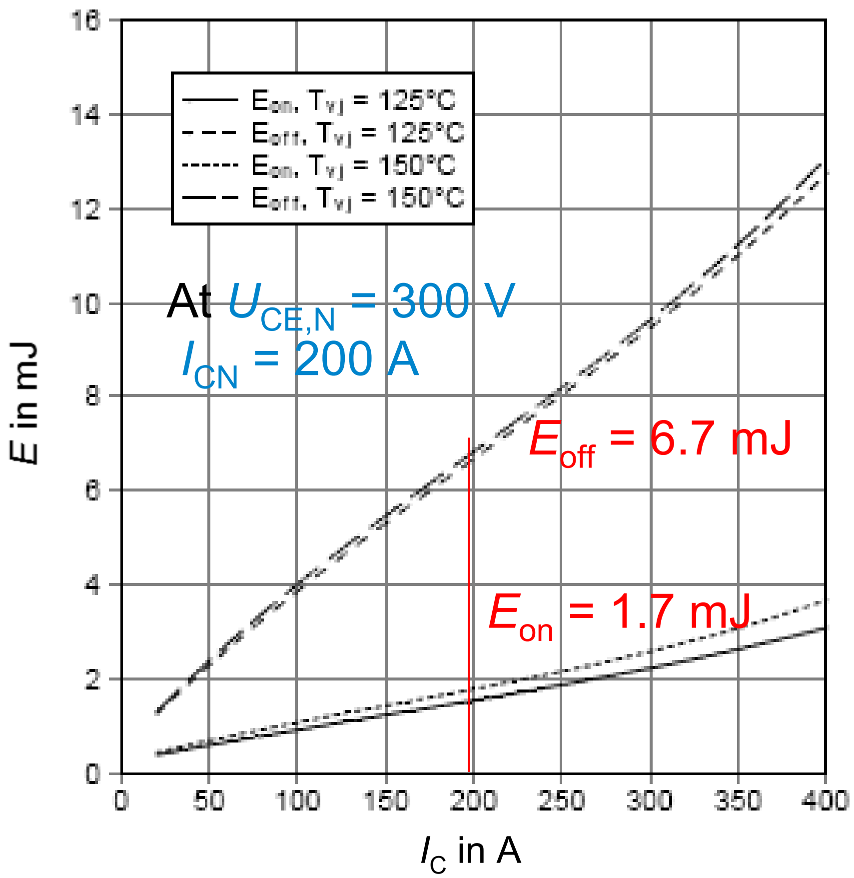
FS200 R06KE3, Fa. Infineon

Conduction characteristics



$$R_{TD} = (2.4 - 0.8)/400 = 4\,\mathrm{m\Omega}$$

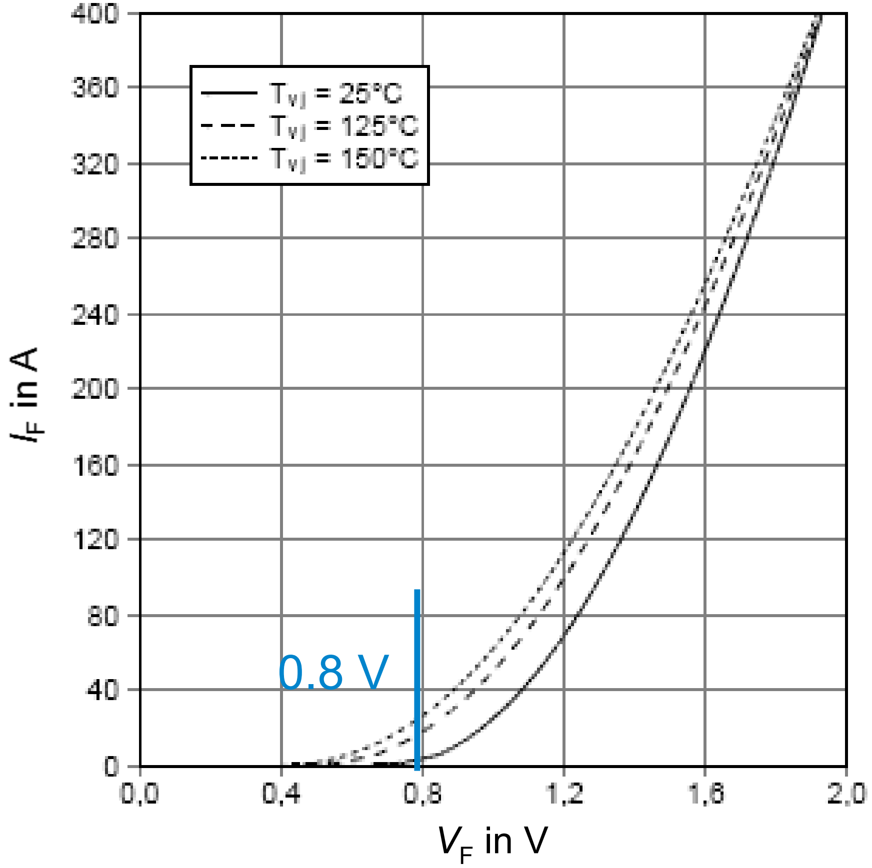
Switching losses (t_{on} = 40 ns, t_{off} = 70 ns)



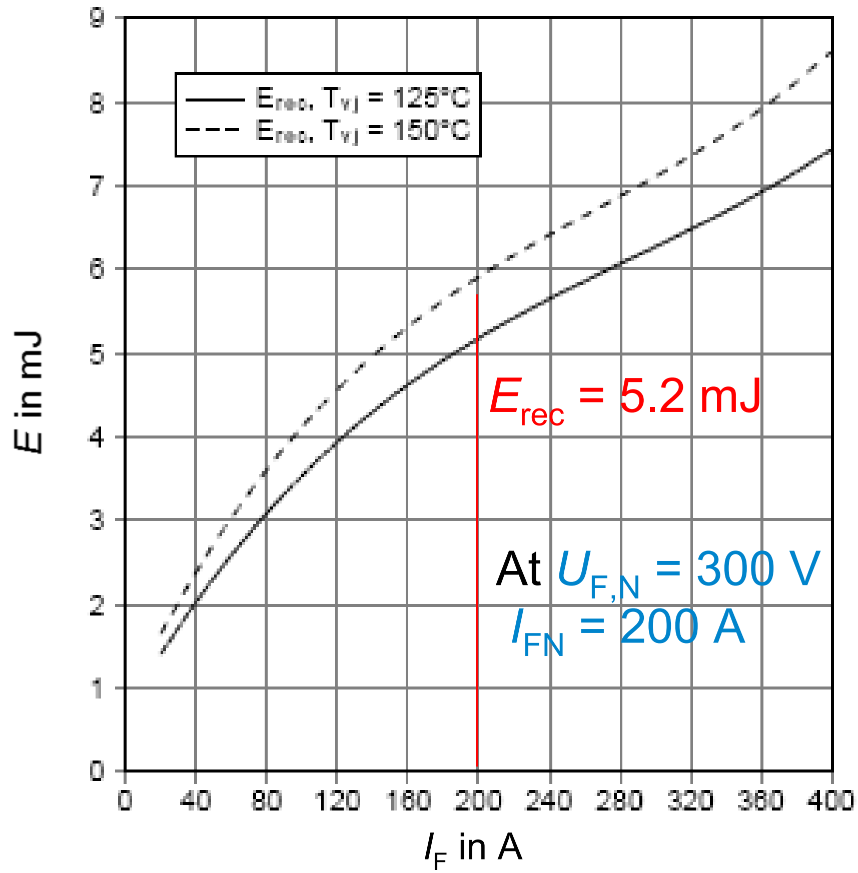
Free wheeling diode (inverter)

FS200 R06KE3, Fa. Infineon

Conduction characteristics



Switching losses E_{rec} (very small)



$$R_{FD} = (1.8 - 0.8) / 400 = 2.5\,\text{m}\Omega$$

Estimation of losses of the inverter

for modulation degree $0 \le m \le 1$

- Conduction losses per IGBT:

$$P_{\mathrm{T,D}} = U_{\mathrm{CE0}}\hat{I}_{\mathrm{s}} \cdot \left(\frac{1}{2\pi} + \frac{m \cdot \cos\varphi_{\mathrm{s}}}{8}\right) + R_{\mathrm{TD}}\hat{I}_{\mathrm{s}}^2 \cdot \left(\frac{1}{8} + \frac{m \cdot \cos\varphi_{\mathrm{s}}}{3\pi}\right)$$

- Switching losses per IGBT:

$$P_{\mathrm{T,S}} = \frac{f_{\mathrm{T}}}{\pi} \cdot \frac{\hat{I}_s}{I_{\mathrm{C,N}}} \cdot \frac{U_{\mathrm{d}}}{U_{\mathrm{CE,N}}} \cdot \left(E_{\mathrm{on}} + E_{\mathrm{off}}\right)$$

- Conduction losses per Diode:

$$P_{\mathrm{D,D}} = U_{\mathrm{F0}}\hat{I}_{\mathrm{s}} \cdot \left(\frac{1}{2\pi} - \frac{m \cdot \cos\varphi_{\mathrm{s}}}{8}\right) + R_{\mathrm{FD}}\hat{I}_{\mathrm{s}}^2 \cdot \left(\frac{1}{8} - \frac{m \cdot \cos\varphi_{\mathrm{s}}}{3\pi}\right)$$

- Cut-off losses per Diode:

$$P_{\mathrm{D,S}} = \frac{f_{\mathrm{T}}}{\pi} \cdot \left(0.55 + 0.45 \cdot \frac{\hat{I}_{\mathrm{s}}}{I_{\mathrm{F,N}}}\right) \cdot \frac{U_{\mathrm{d}}}{U_{\mathrm{F,N}}} \cdot E_{\mathrm{rec}}$$

For higher modulation degree *m* the IGBTs conduct more often and the diodes less, hence the IGBT losses increase with increasing *m*!

- Conduction- and switching losses for 6 IGBTs and Diodes:

$$P_{\mathrm{inv,S+D}} = 6 \cdot \left(P_{\mathrm{T,D}} + P_{\mathrm{T,S}} + P_{\mathrm{D,D}} + P_{\mathrm{D,S}}\right)$$

Example: Losses of the inverter

m = 1, $\cos\varphi_s$ = 0.8, U_d = 480 V, f_T = 12 kHz, I_{s1} = 100 A, U_{s1} = 170 V

Output fundamental power: $$P_e = 3U_{s1}I_{s1}\cos\varphi_{s1} = 40.8\,\mathrm{kW}$$

Loss component	Losses in W
Transistor conduction losses	38.8 W
Transistor switching losses	36.3 W
Diode conduction losses	8.7 W
Diode switching losses	27.6 W
Sum per transistor-diode pair	111.4 W
Sum aver all 6 pairs	668.4 W
Efficiency in %	98.27

Inverter efficiency: $$\eta_{inv} = P_e/(P_e + P_{d,inv})$$

Board grid energy demand
(is added as additional losses of the inverter)

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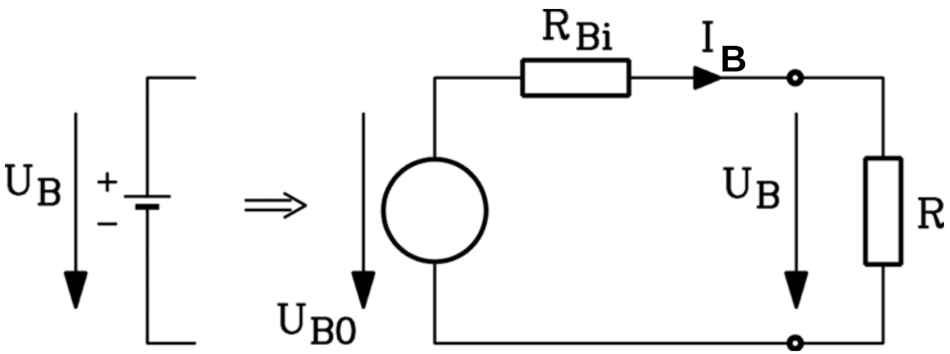
Component	Power consumption in W
Control devices	60
Headlight	90
Vehicle reg. light a. rear light	25
Instrument light	20
Ventilation	50
Power steering	25
Sum	270

Average demand:
(day/night)
(warm/cold)
(rain/dry)
in minimum 150 W

More electric consumers:
Wiper motor, compressor for air conditioning, radio + DVD-player, navigation, heatable windows and mirrors, electric adjustable chassis (suspension), electric heating

12 V supply: From battery (e. g. 400 V DC) by DC-DC-converter to 12 V DC step-down

Modeling of the battery



$$U_B = U_{B0} - I_B \cdot R_{Bi}$$

$$Q = I_B \cdot t_B$$

$$W_B = Q \cdot U_B$$

$$Q_{Rest} = y \cdot Q_N$$

Discharging: $I_B > 0$

Charging: $I_B < 0$

Consumer reference system

U_{B0}: No-load voltage

R_{Bi}: Internal battery resistance

Q: Obtained amount of el. charge

t_B: Discharge time for Q at current I = const.

W_B: Obtained energy from battery

Q_N: Rated charge (Ah), often also denoted as C

$y = 1-Q/Q_N$: State of Charge SOC

Example:

Pb-battery: U_{B0} = 144 V, R_{Bi} = 0.055 Ω, Q_N = 100 Ah

Battery current *I* at obtained power P_B

$$U_B = U_{B0} - I_B \cdot R_{Bi}$$

$$P_B = (U_{B0} - I_B \cdot R_{Bi}) I_B$$

For a fixed power the batteries can be charged/discharged with
a) low current and high voltage

b) High current and low voltage (unfavorable).

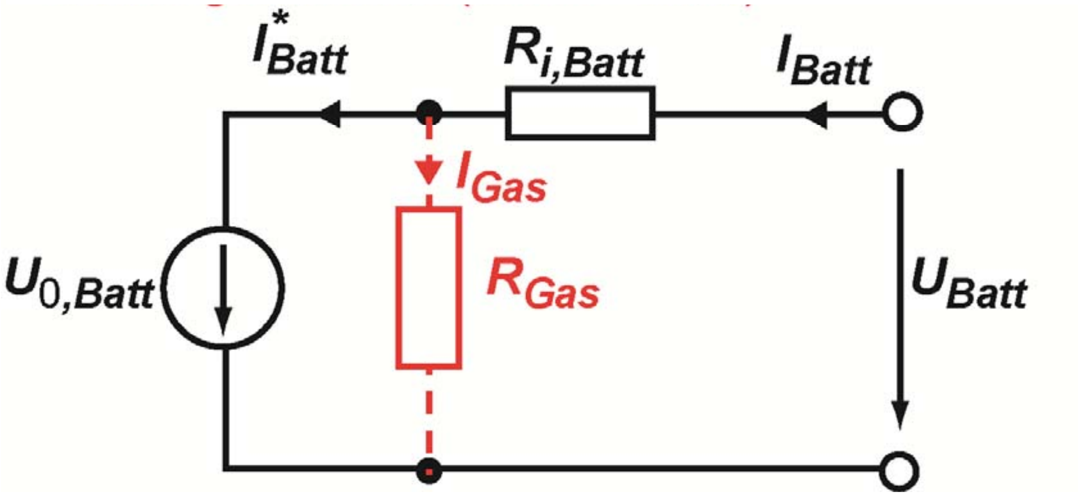
a) $$I_B = \frac{U_{B0}}{2R_{Bi}} - \sqrt{\left(\frac{U_{B0}}{2R_{Bi}}\right)^2 - \frac{P_B}{R_{Bi}}} \le I_{B,max}$$

b) $$I_B = \frac{U_{B0}}{2R_{Bi}} + \sqrt{\left(\frac{U_{B0}}{2R_{Bi}}\right)^2 - \frac{P_B}{R_{Bi}}} \le I_{B,max}$$

Modeling: Traction battery

▪ Equivalent circuit

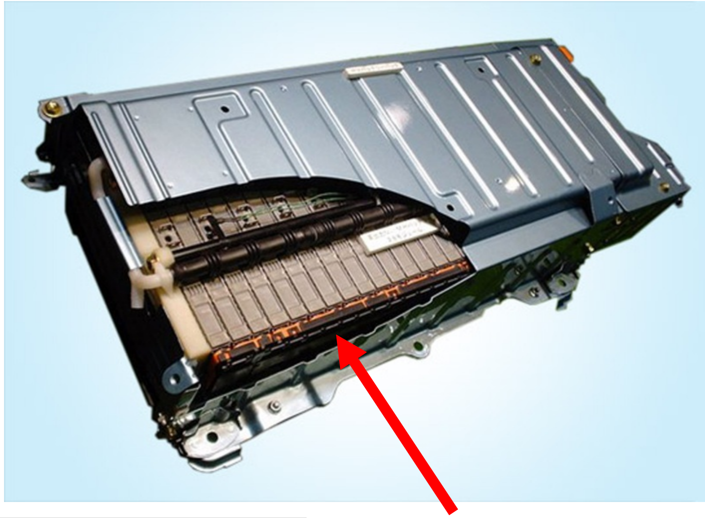
- Discharging of battery and charging without gassing reaction (SOC ≤ 80 %)
- For charging of battery with gassing reaction > 80 %



▪ **Modeling**

- **EC-parameters: characteristics**
- $U_{0,Batt}$ **= f(*SOC*)**
- $R_{i,Batt}$ **= f(*SOC*)**
- R_{Gas} **= f(*SOC*)**
- ***SOC*: Ah-balance**

Example: Modeling of the Ni-metal-hydride-battery



NiMH-Battery
Toyota Prius II

- **Technical data**

Battery parameter	**Data**
Number of cells in series	$n_{cell} = 228$
min./max. cells voltage	$U_{cell,min/Max} = 0,9$ V / 1,6 V
Min./max. battery-no-load voltage	$U_{batt,min/max} = 273$ V / 330 V
Battery rated capacity	$Q_{batt,N} = 6,5$ Ah
Number of parallel battery branches	$a_{batt} = 1$
Internal resistance $R_{Bi} = f(SOC)$	$R_{Bi} = 0.85 \dots 1.2\ \Omega$

Batteries for hybrid- vs. E - car

Ni-Me-hydride-battery (Comp. *Ovonics*) for hybrid vehicle

- Battery voltage (no-load): 160 V
- 10.5 Ah
- Battery internal resistance: at -5°C: 0.05 Ohm, at 40°C: 0.01 Ohm
- Battery maximum current: For 10 s: 292 A; for 1 s: 365 A

Lead-gel-battery for E-car:

- Battery voltage (no-load): 144 V = 12 x 12 V-cells
- 100 Ah
- Battery internal resistance: 0.055 Ohm
- Battery maximum current: 300 A

In hybrid vehicles the necessary amount of energy storage is much smaller then in E-cars (range!), but the power peaks due to recuperation during braking or due to high power consumption during „boosting" are much higher. Hence a protection of the batteries with an additional super cap-storage is recommended, as they have high power densities.

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Battery cells in comparison

	Lead-gel	Ni-metal-hydride	Li-ion
Cell voltage	2 V	1.2 V	3.5 V
Energy density	30 Wh/kg	80 Wh/kg	100 Wh/kg
Efficiency	70 … 85 %	85 %	90%
Operating temp.	0 … 55°C	-20 … 55°C	-20…60°C

Electric vehicles

– Simulation examples

a) *Example:*

Constant speed – Range calculation

Example: Range calculation for v = const.

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Tasks:

No slope: $\alpha = 0$, v = const. = 120 km/h, m = 1437 kg, $c_w A = 0.56\ \text{m}^2$, d_R = 0.6 m
$f_R = 0.01$, $\eta_G = 0.9$, $i = 8.02$, Q = 100 Ah, U_{B0} = 192 V, $R_{Bi} = 0.055\ \Omega$ (Pb-Gel)
SOC: start: 100%, end: 25%, PM-synchronous motor 6-poles and IGBT-inverter (efficiency field for U_B = 190 V), board grid: 400 W

Results:

1) Driving resistances: $F_{Bg} \cong 0$, F_{Roll} = 141 N, F_L = 375 N, F_D = 515 N, P_D = 17.17 kW
2) Wheel speed and gear: n_W = 1061/min, n_M = 8509/min, P_M = 19.078 kW
3) Motor data: M_M = 21.4 Nm, driving system efficiency: 80% (inverter: 93%, PM-syn. motor 86%)
4) Battery power: 19.078/0.8 + 400 = 24248 W = P_B, $I_B = \frac{U_{B0}}{2R_{Bi}} - \sqrt{\left(\frac{U_{B0}}{2R_{Bi}}\right)^2 - \frac{P_B}{R_{Bi}}} = 131.2\,\text{A}$
5) Range: $y = 1 - SOC_{end} = 0.75$, $t = Q \cdot y / I_B$ = 2058 s = 34.3 min, $s = v \cdot t$ = 68.6 km

Example: PM-synchronous drive

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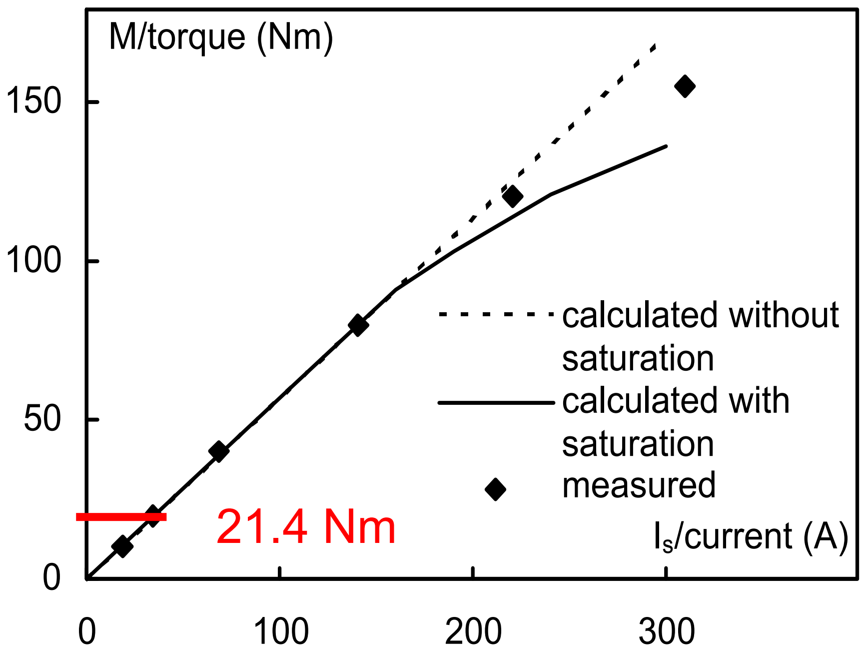
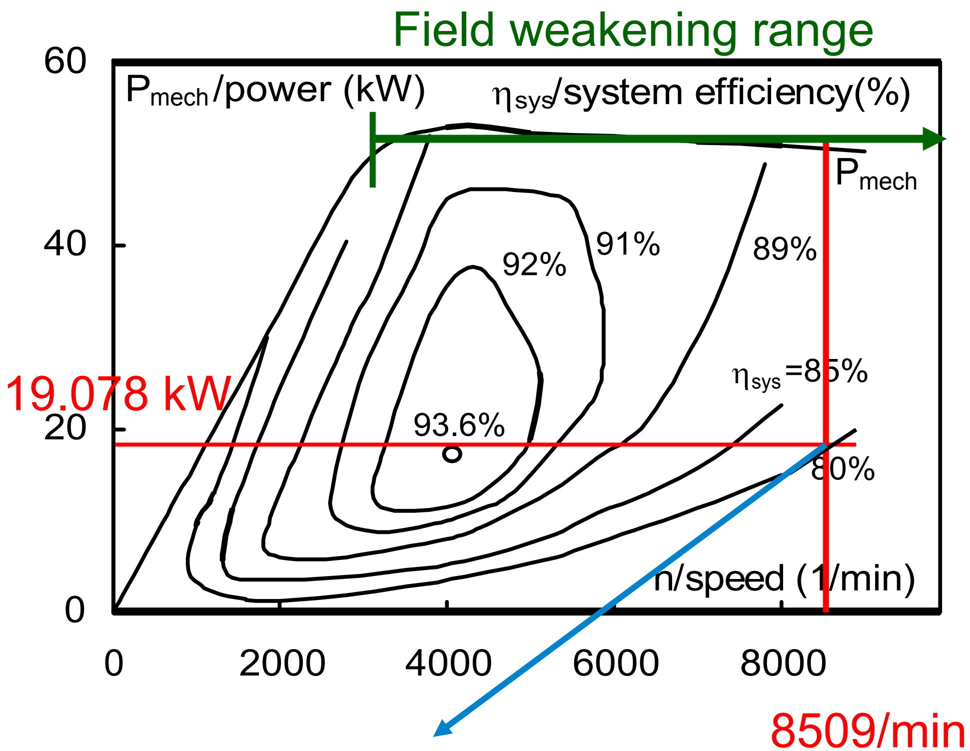
Torque- quadrature current-curve



Source: Ackva, A. et al.: EPE 1997, Trondheim

Power+ efficiency (motor + inverter)



System efficiency in high field weakening range and partial load: 80%

b) *Example:*

Speed cycles – Range calculation and capability of acceleration

Example: Specification for a fictive E-car – during cycle and at max. acceleration

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Specification:

m = 900 kg (empty) $c_w A$ = 0.5 m^2, d_R = 0.623 m, Δ = 0.2 rotating mass adding factor,

f_R = 0.008, η_G accord. Efficiency field, i = 8, Q = 30 Ah, U_{B0} = 480 V, R_{Bi} = 0.0696 Ω (Li-Ion, *comp. Kokam*), PM-synchronous motor 6-poles (*comp.. Brusa,* 6.17.12): 4500/min, 85 Nm, max. 11000/min, IGBT-inverter: *comp.. Brusa*, DMC524, 80 kW (106 kW short time), 600 V blocking voltage, board grid: 150 W

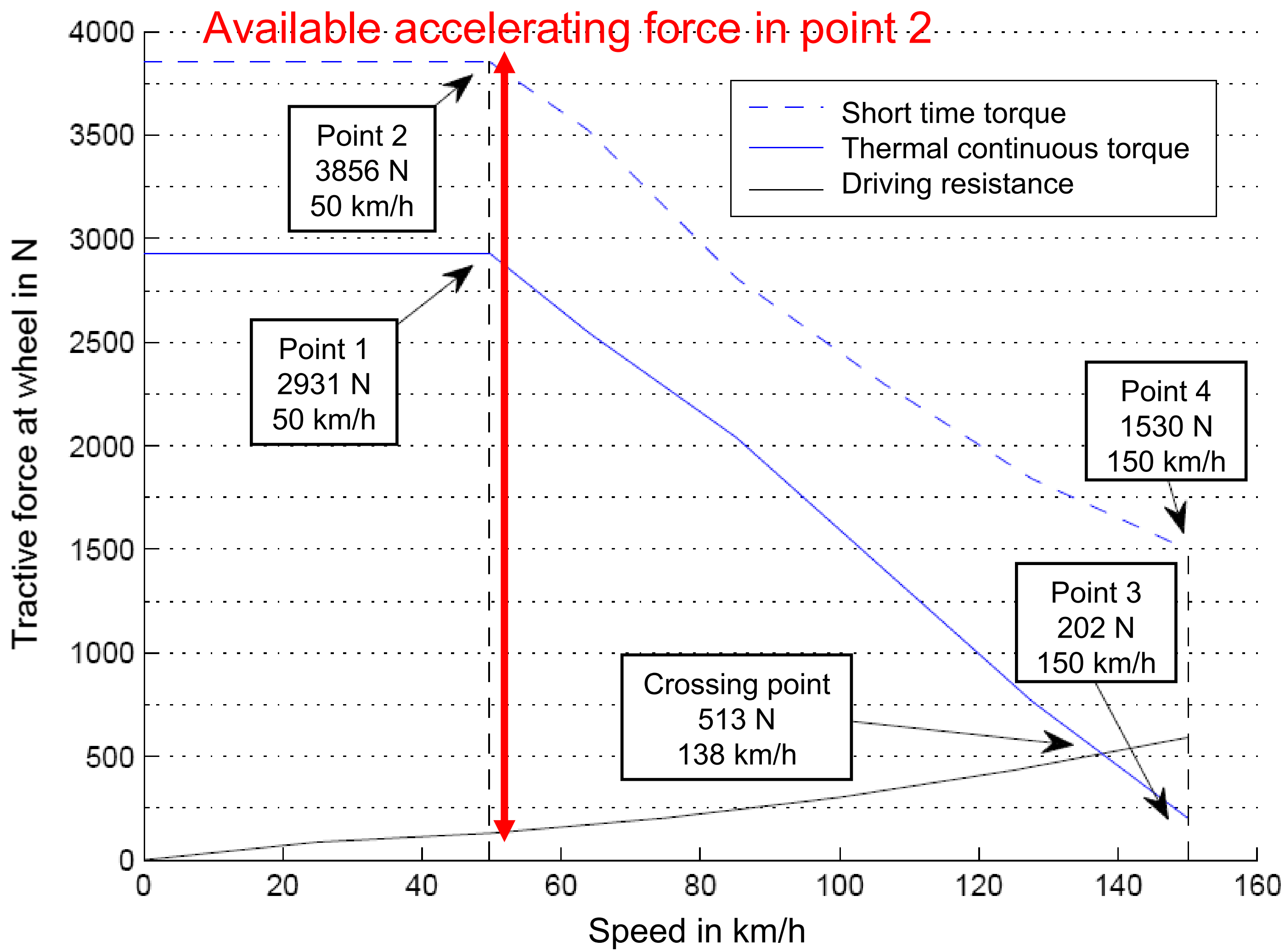
The vehicle is designed for v_{max} = 150 km/h : motor speed = 10200/min.

Example: Driving resistances

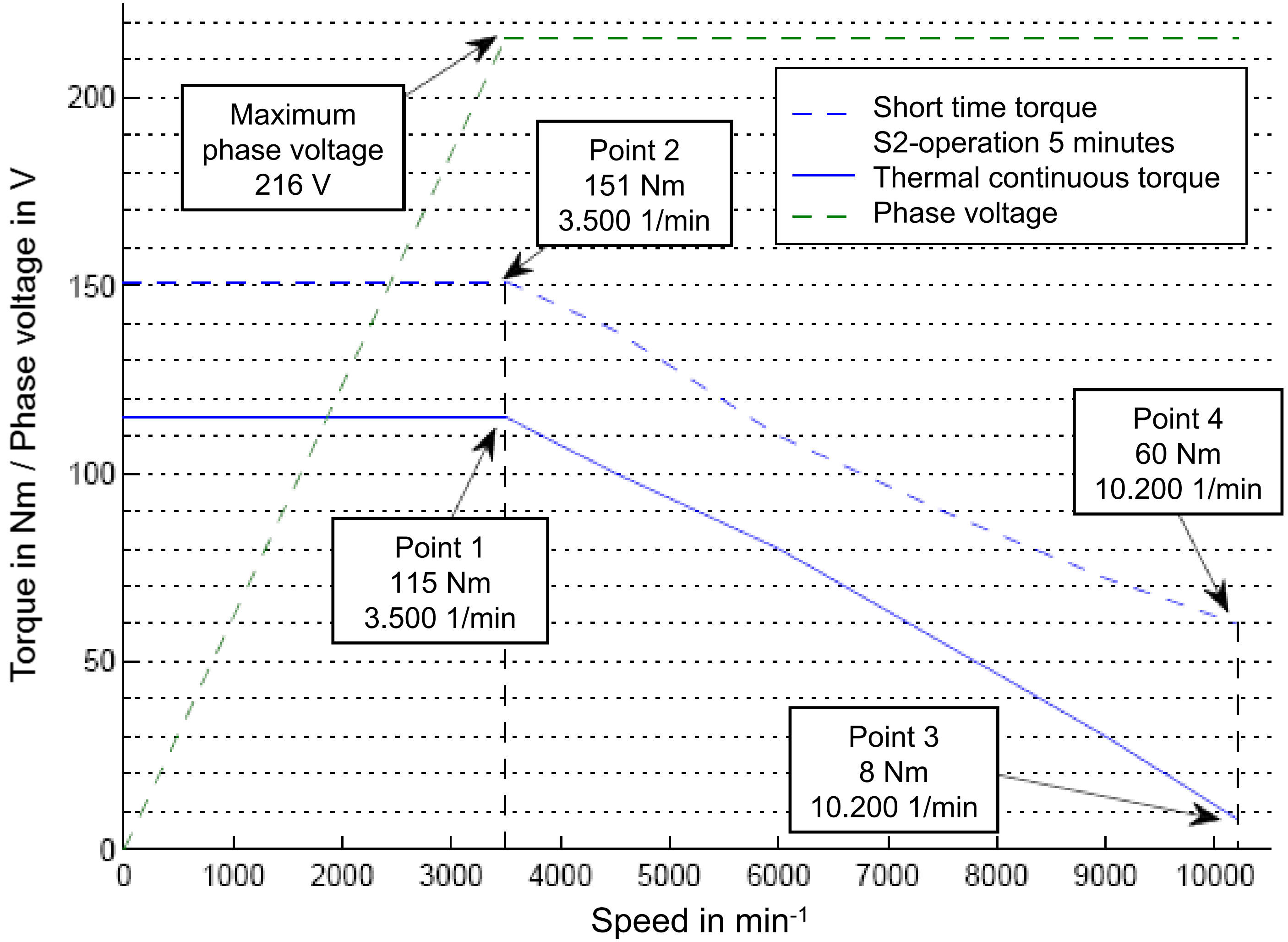
Speed in km/h	Driving resistance in N
0	0
25	85.2
50	128.5
75	201.5
100	302
125	432
138	513
150	591

$\alpha = 0$

Example: E-car solutions in motor characteristic field



Example: Border lines of a PM-synchronous-motor *(Brusa)*



Example: E-car: PM-motor and vehicle-load data

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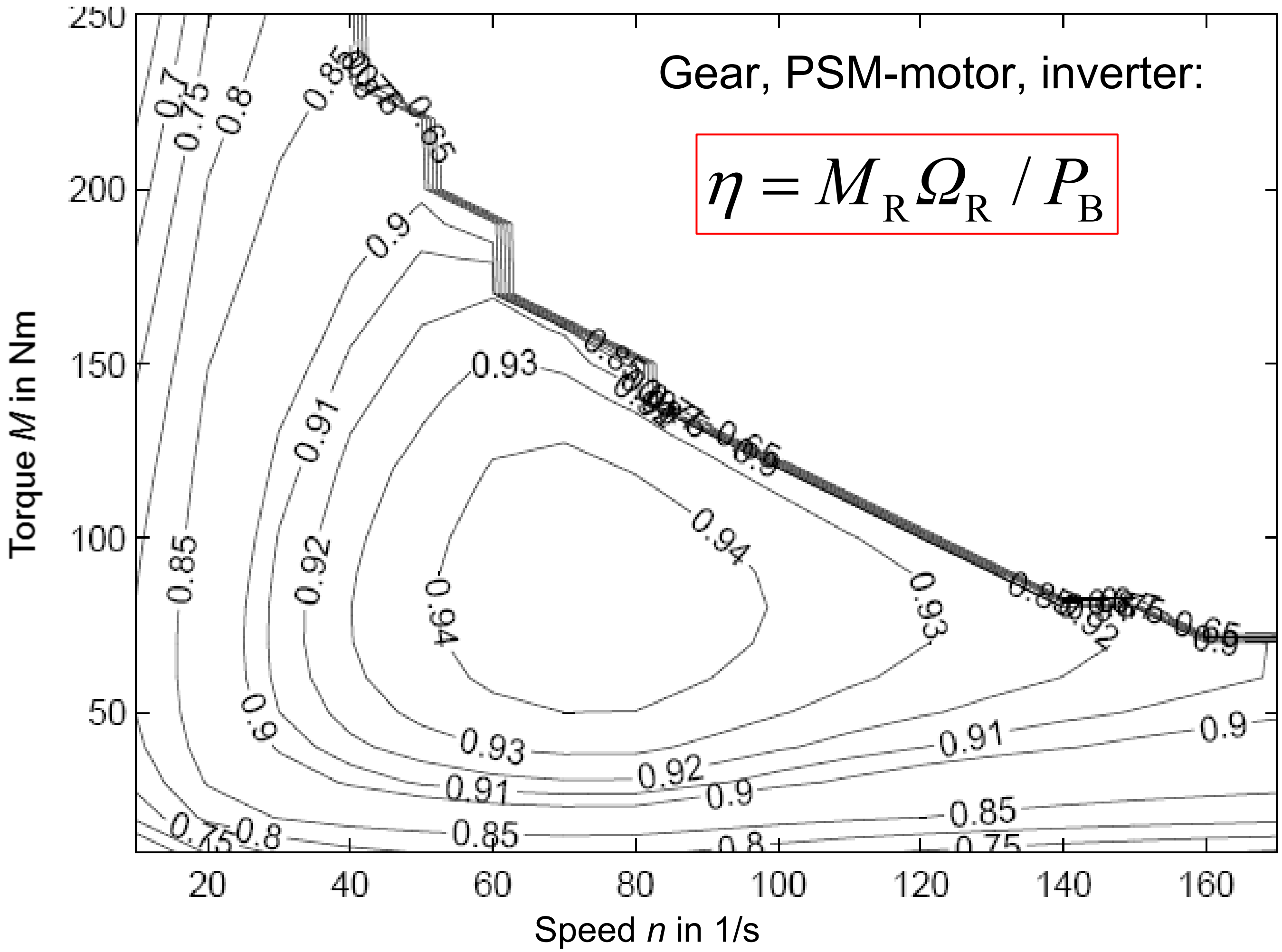
Point in characteristic	Speed in m/s resp. km/h	I_d in A	I_q in A
1 (n_N / M_d)	13.8 / 49.7	0	102
2 (n_N / M_{S2})	13.62 / 49	0	139
3 (n_{max} / M_d)	41.55 / 149.6	84	7
4 (n_{max} / M_{S2})	41.05 / 147.78	109.5	52.5

Speed	Thermal continuous torque in Nm	Maximum short time torque (S2-5 min operation)
n_N = 58.1 /s	115 / point 1	151 / point 2
n_{max} = 170.1 /s	8 / point 3	60 / point 4

Example: E-car (*Brusa*-drive) calculated efficiency field



Example: Losses in four operation points

Due to high accelerating force slip losses also occur!

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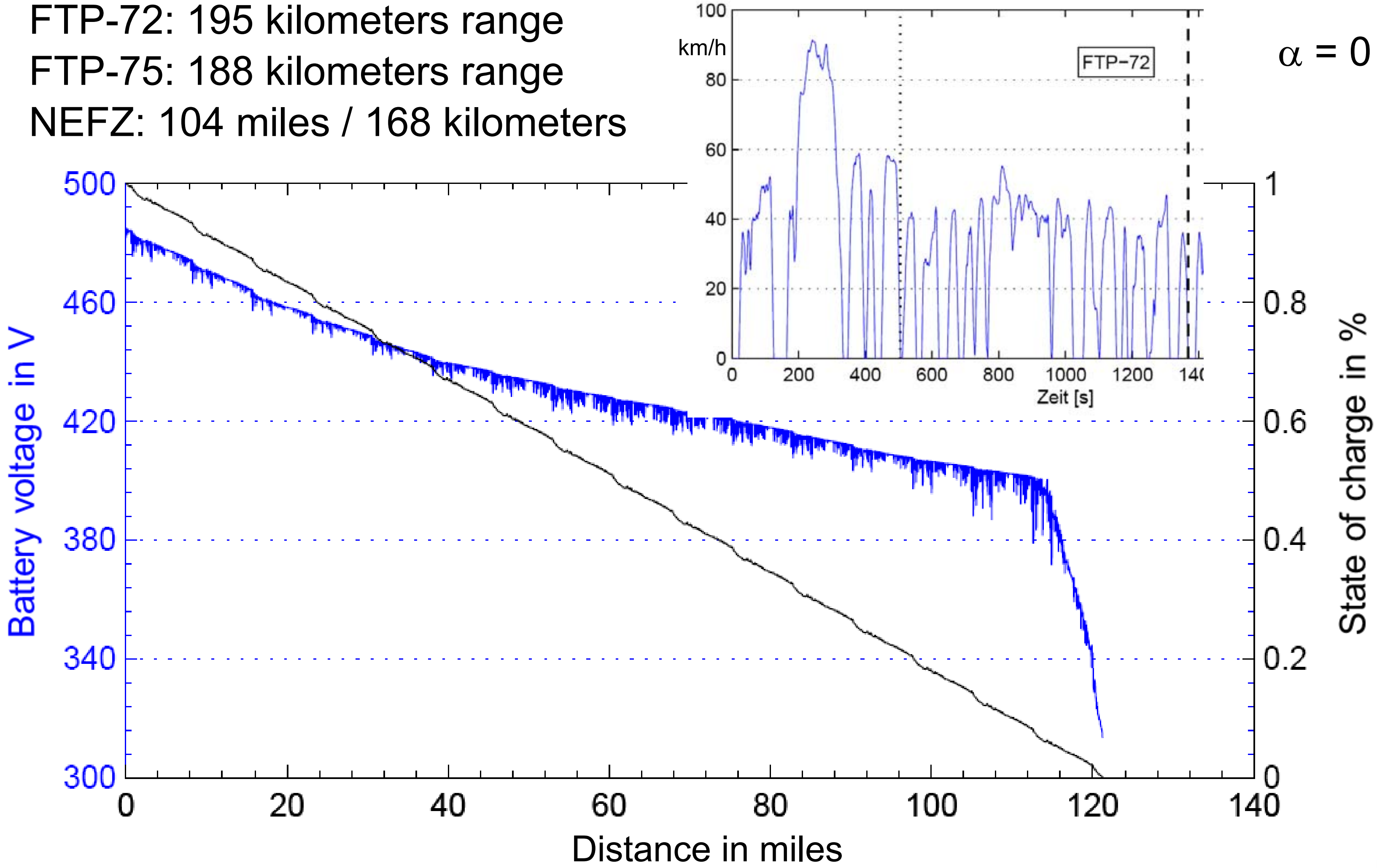
Losses in W	Point 1 (n_N / M_d)	Point 2 (n_N / M_{S2})	Point 3 (n_{max} / M_d)	Point 4 (n_{max} / M_{S2})
Wheel slip losses	1237	2280	16	936
Gear	190	247	127	365
Power electronics	794	916	736	985
Board grid	150	150	150	150
Motor	1944	3245	3700	5190
Battery	623	1135	51	1605
Sum of losses	4838	7973	4780	9231
Driving power in kW	40.5	52.5	8.4	62.8
Efficiency in %				
Total vehicle	89.3	86.8	63.7	87.2
Motor	95.6	94.4	70.0	92.5
Power electronics	98.4	98.4	94.3	98.5

$\alpha = 0$

Example: Range E-car in FTP-72 cycle

- FTP-72: 195 kilometers range
- FTP-75: 188 kilometers range
- NEFZ: 104 miles / 168 kilometers



Example: E-car in FTP-72 cycle – Recuperation

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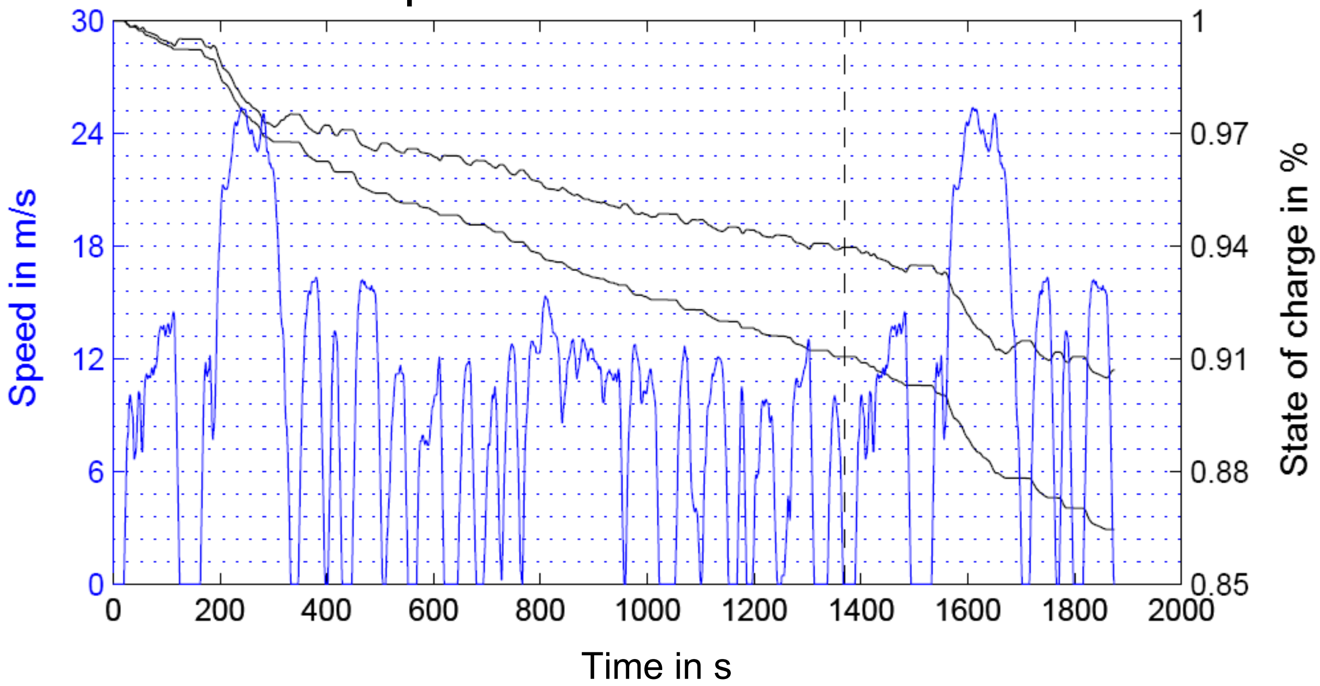
- Difference due to recuperation in FTP-72 and FTP-75

$\alpha = 0$



	FTP-72	FTP-75
State of charge with recuperation	94%	91%
State of charge without recuperation	90,9%	86,5%
Savings	34%	33,3%

Example: E-car in FTP-72 cycle – Battery loading

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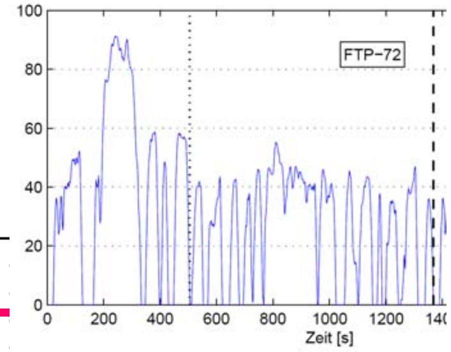
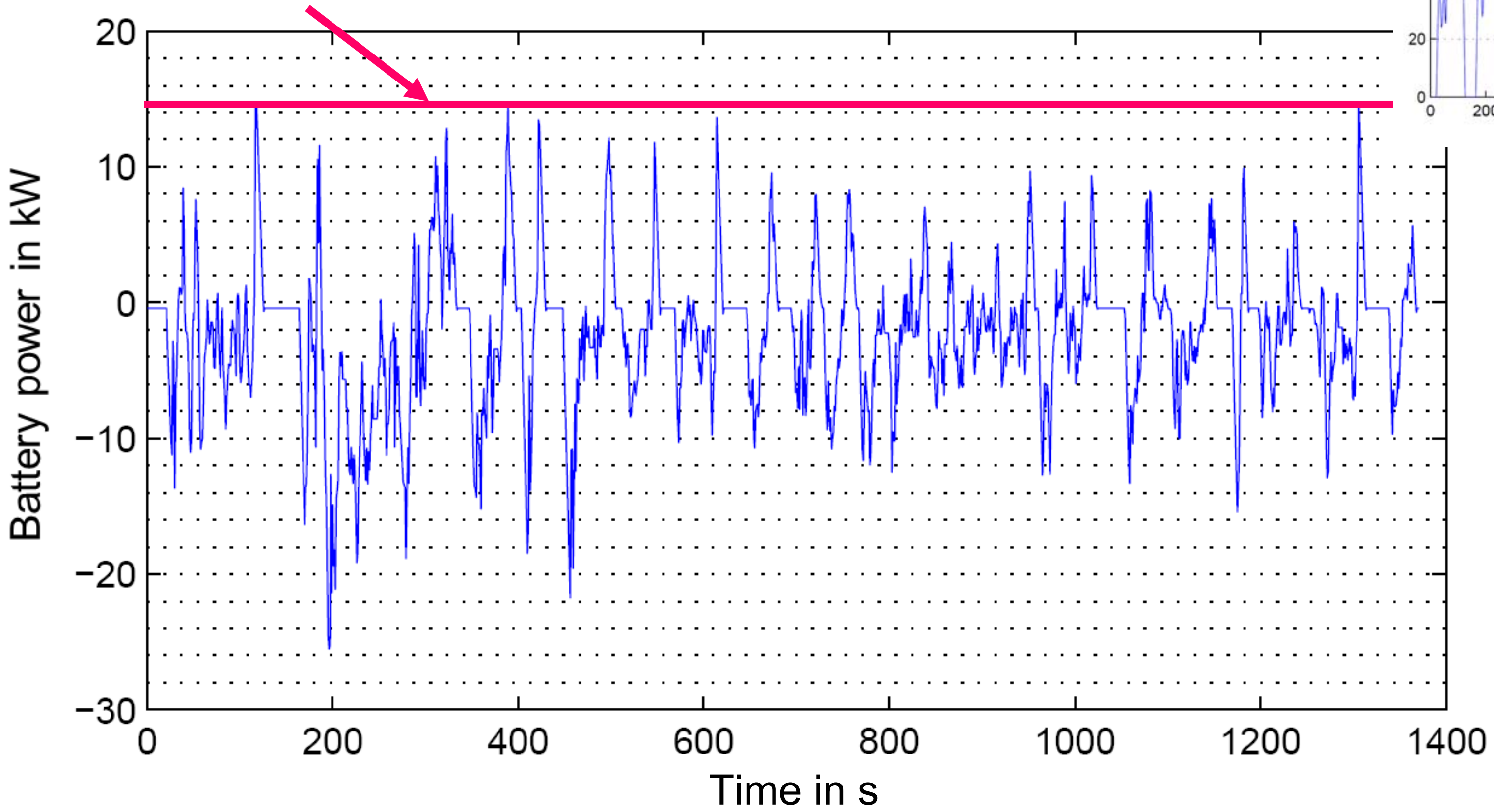


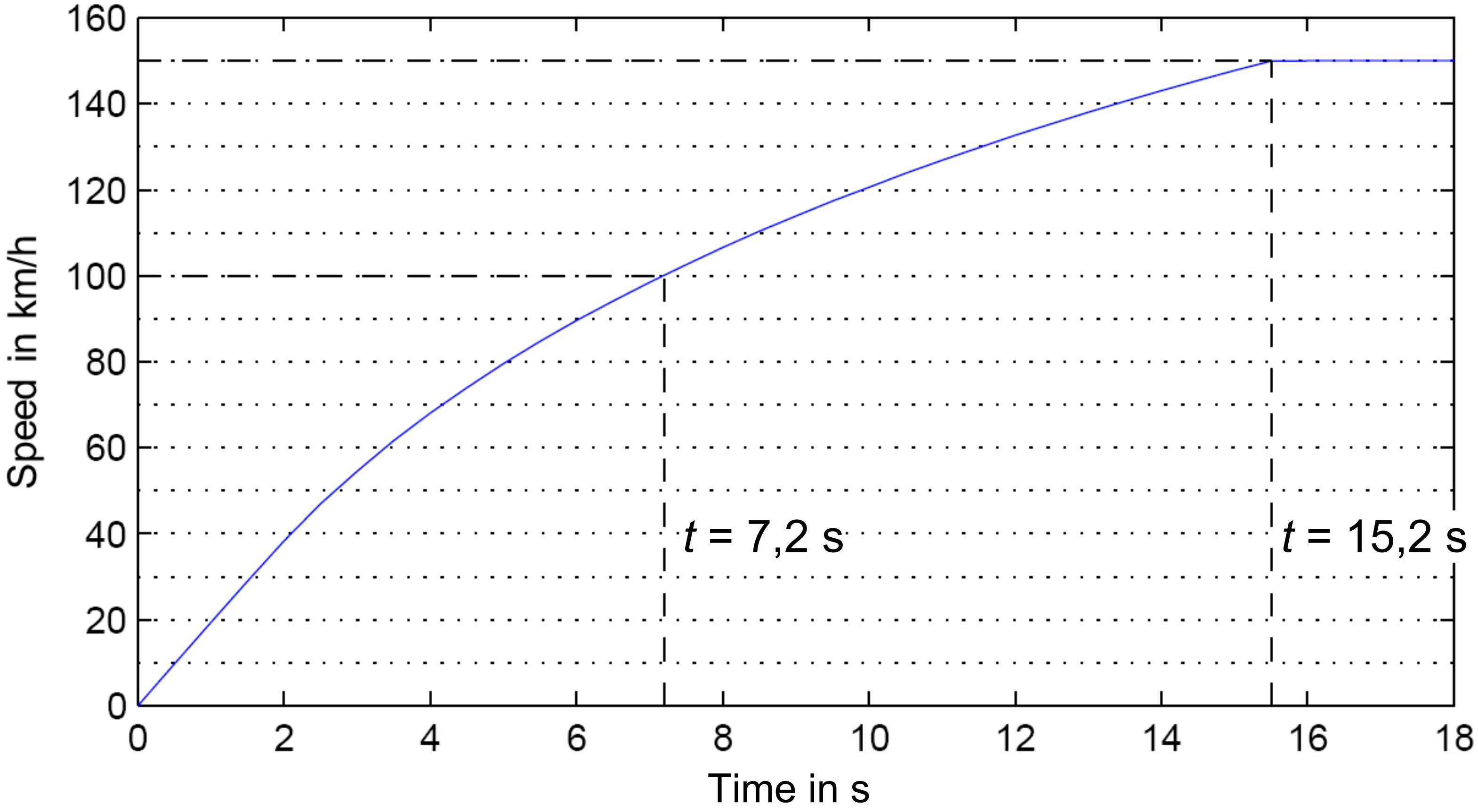
- Battery power during FTP-72 cycle
- Limit for feed-back at 14.6 kW



Example: E-car results in sprint

- 7,2 seconds from zero to 100 km/h
- 15,2 seconds from zero to 150 km/h

Empty car mass 900 kg, $\alpha = 0$



Sample: E-car operating time in % in the motor operation map

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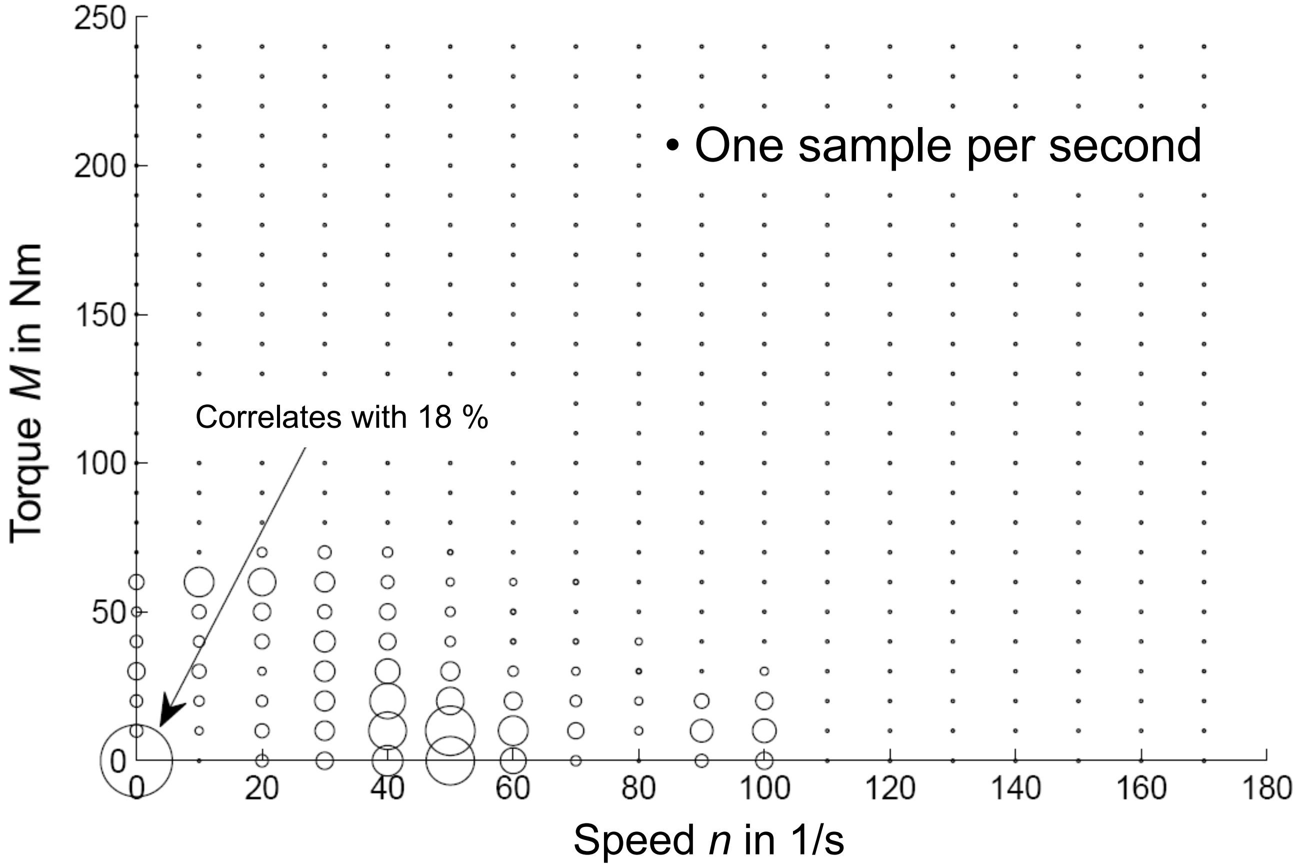
- Evenly screened occurrence of operation points during the FTP-72 cycle
- Torque-speed-combinations at gear input in steps of 10 Nm and 10 1/s



Example: E-car: Occurrence of different operation points and correlating efficiency during FTP-72 cycle

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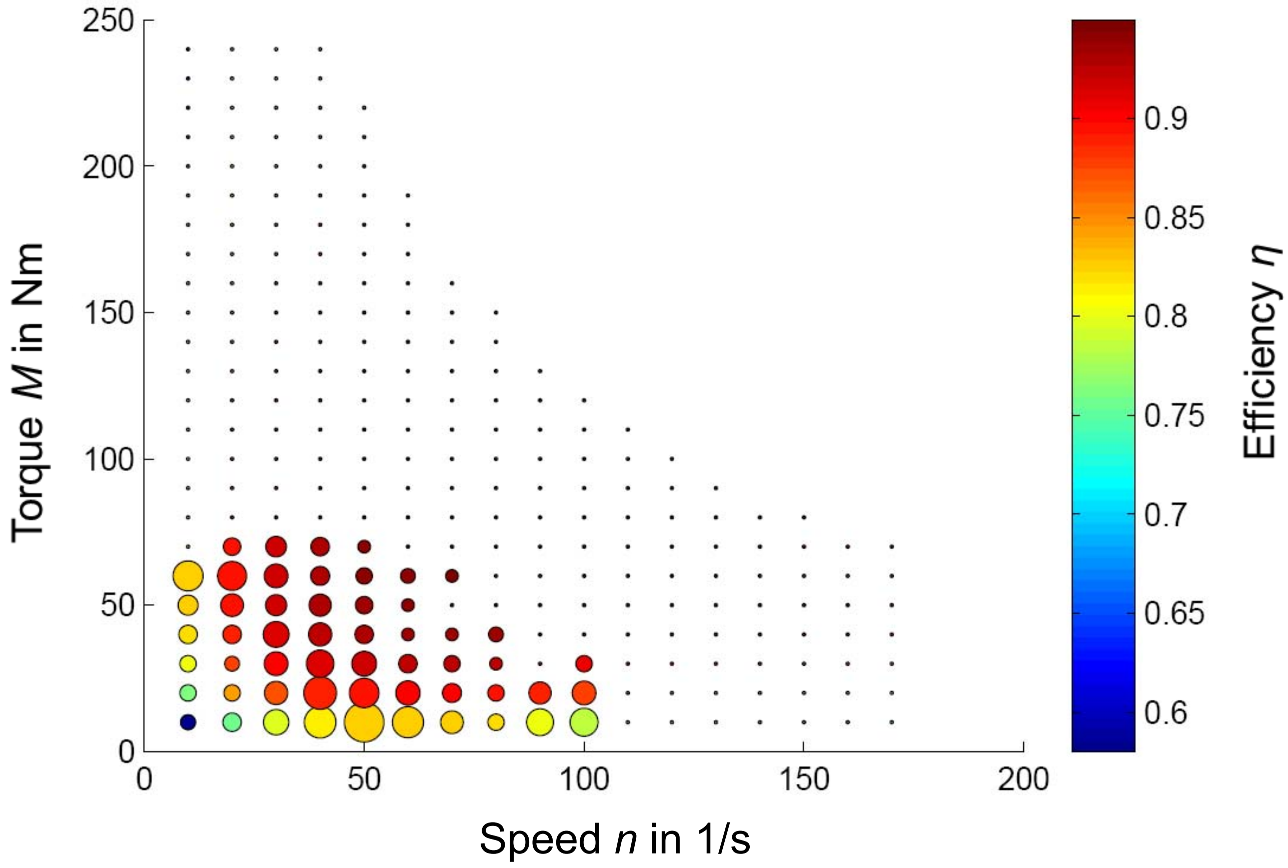
- Area size of points = duration of this operation point
- Color = efficiency



gear, PSM-motor, inverter

TECHNISCHE UNIVERSITÄT DARMSTADT

Have fun while self-designing an E-car-drive !

Source: Tesla roadster