Trends for Automotive Traction Inverters driven by the HV-Battery and the eMotor

Wangener Automotive Symposium
Inverter Trends and Technology

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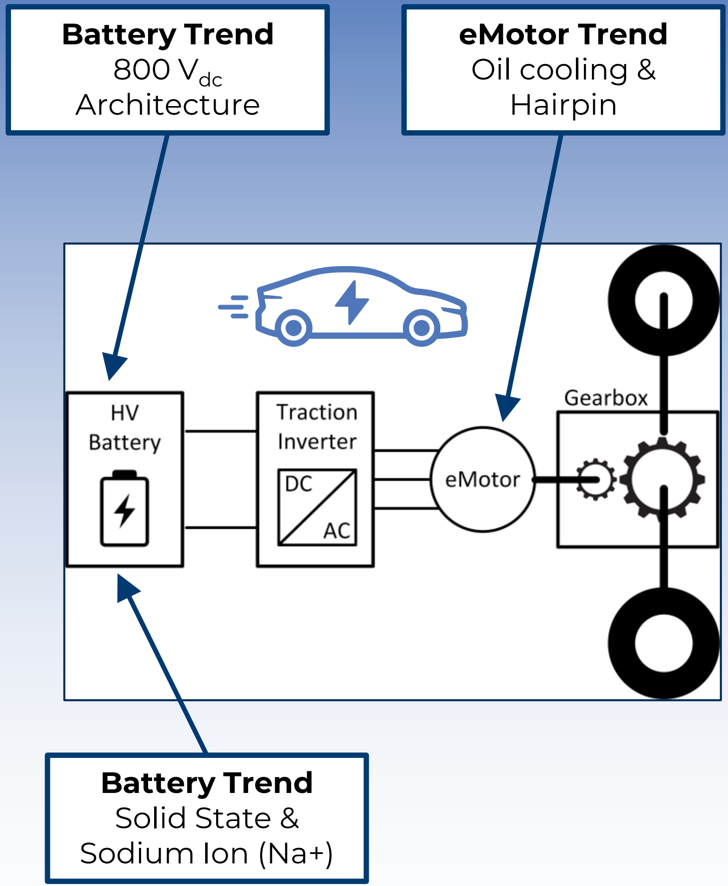
Introduction

Main Electric Interfaces of the Inverter

- HV-Battery
- eMotor

Many Inverter Trends are driven or impacted by the Electric Inverter Interfaces

- **800 V battery** architecture results in higher Inverter DC voltages
- Next gen batteries (Na+ & Solid State) feature a higher **SoC-dependency** of the voltage
- Oil cooling & Hairpin technology result in **increased continuous power** and **harmonic motor losses**



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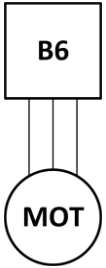
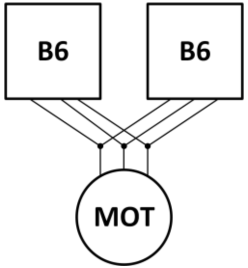
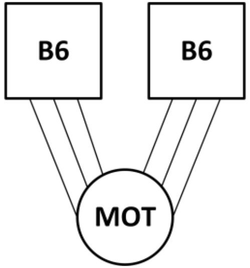
800 V Battery Architecture

Benefits

- Charging Speed
- Cable/busbar cross section & DC-cap reduced
- Beneficial High Power Implementation INV

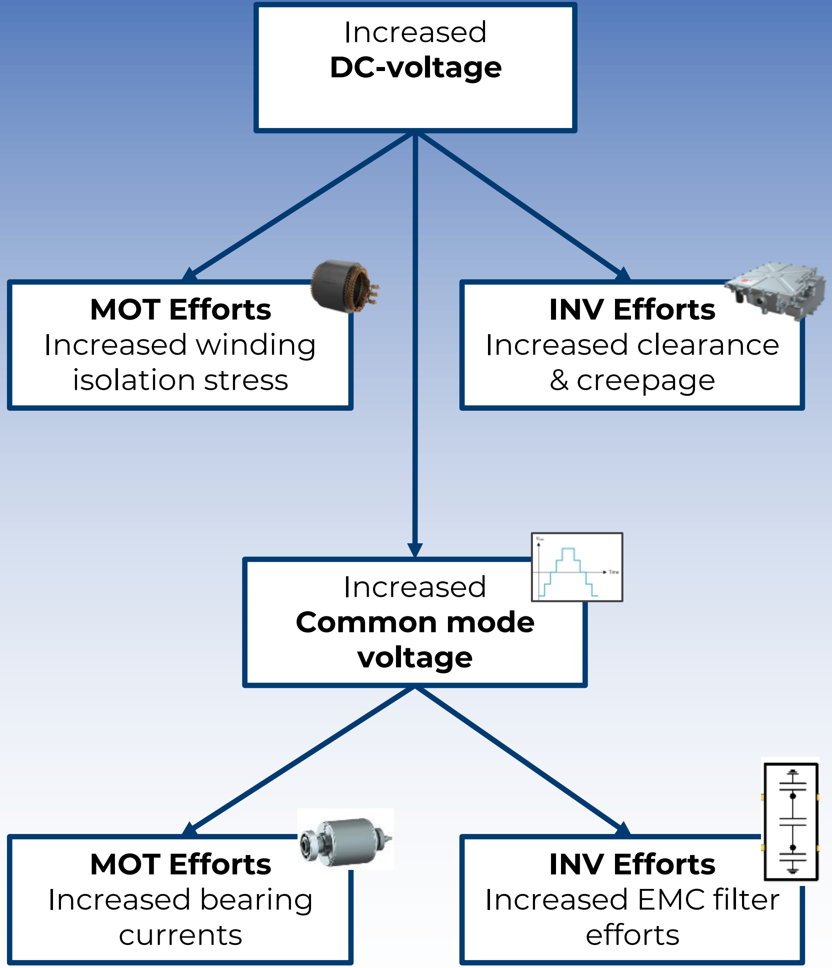
 400 kW High Power eDrive F-Segment		
800 V Battery	**400 V Battery**	
3 phase	3 phase	2x 3 phase (6 Phase)
~650 Arms	~1300 Arms	2x 650 Arms
1x B6	2x B6 hard parallel	2x separate B6
Classic Architecture	AC-Current Imbalance	SW Control Efforts
		

800 V Battery Architecture

Increased Efforts

- Increased Inverter Efforts
- Increased Motor Efforts
- Increased Efforts Charging Compatibility

Efficiency!?



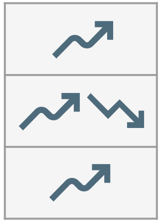
800 V Battery Architecture

Inverter Losses 400 V ⇒ 800 V

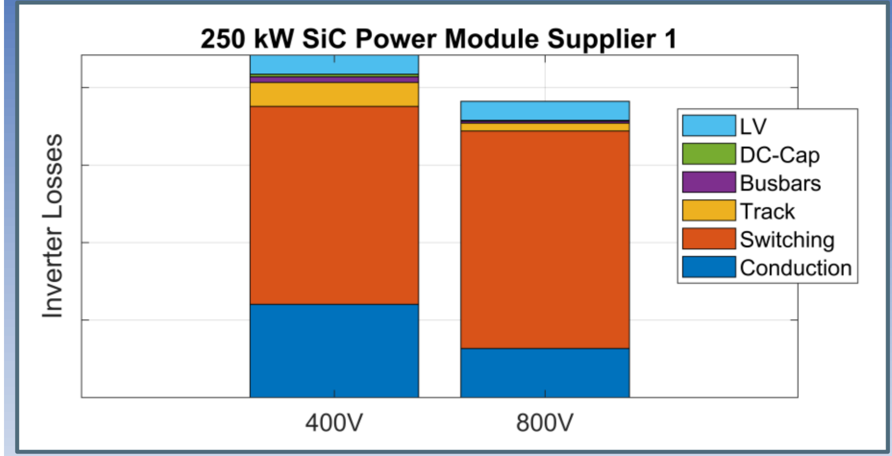
- Conduction losses
- Switching losses
- **Overall Inverter losses (typ.)**

Motor Losses 400 V ⇒ 800 V

- Copper losses
- Harmonic Motor losses
- **Overall Motor losses (typ.)**

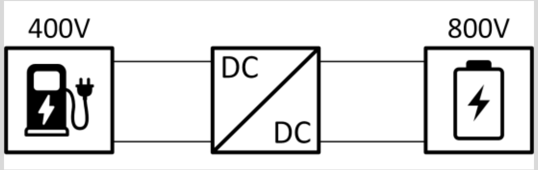
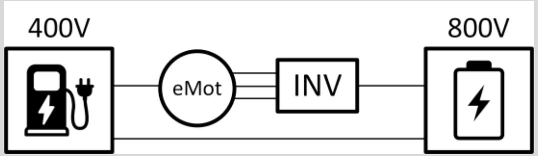
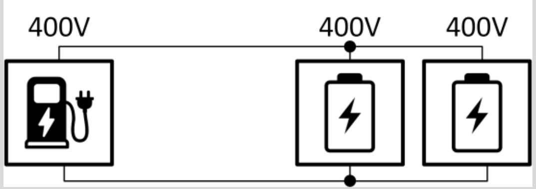


Is a 800 V eDrive more efficient than a 400 V eDrive? **Potentially yes, but it depends!**



210 kW EESM		
	400 V Battery	**800 V Battery**
Isolation thickness	100 %	170 %
Copper cross section	100 %	91 %

Charging Compatibility

	Separate DC/DC	Boost Charge via Mot+Inv	Split Battery
Tech.			
Power	Limited by DC/DC	Typ. limited by Motor	Unlimited
Eff.	+++	+	+++
Costs	High Cost	Low Cost	
Chall.	Packaging & Cost	NVH, Torque Safety, eDrive lifetime, active load for charging station	HV-Safety, Balancing

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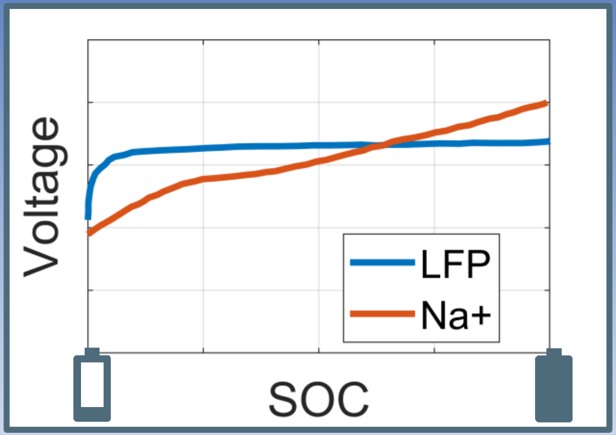
Voltage Dependency on SoC

Available DC-voltage depends on SoC

- High DC voltage for full battery
- Low DC voltage for empty battery
- Strong SOC dependency for next gen. Batteries if full SOC range is used



Increasing Peak Power at low voltage

- Via Motor Technology, e.g. **E**lectrically **E**xcited **S**ynch. **M**achine (**EESM**) improving the power factor
- Via Inverter SW, e.g. Overmodulation & 6-Step increasing the achievable modulation index
- Via Inverter HW, e.g. DC/DC-boost converter increasing the available DC voltage

DC/DC

EESM

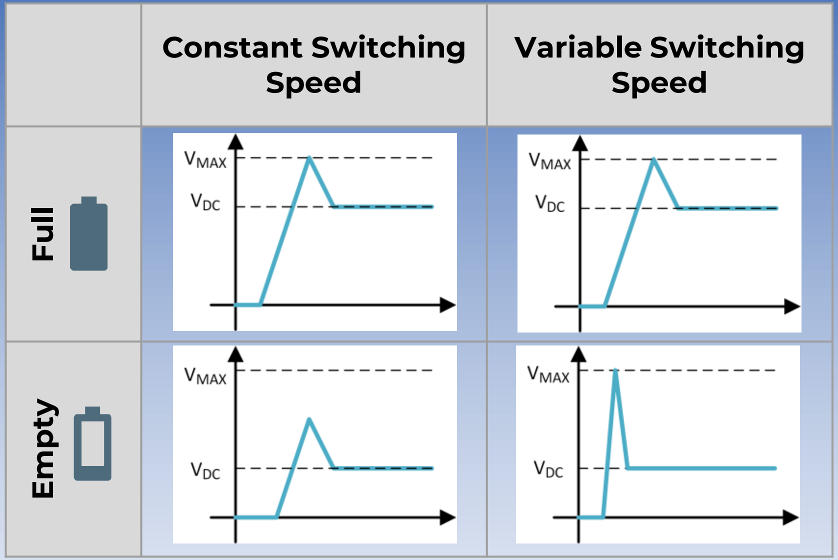
$$P_{AC,avail} = 3 * I_{AC} * \underbrace{M * \frac{V_{DC}}{\sqrt{2} * \sqrt{3}}}_{V_{AC,avail}} * \cos(\varphi)$$

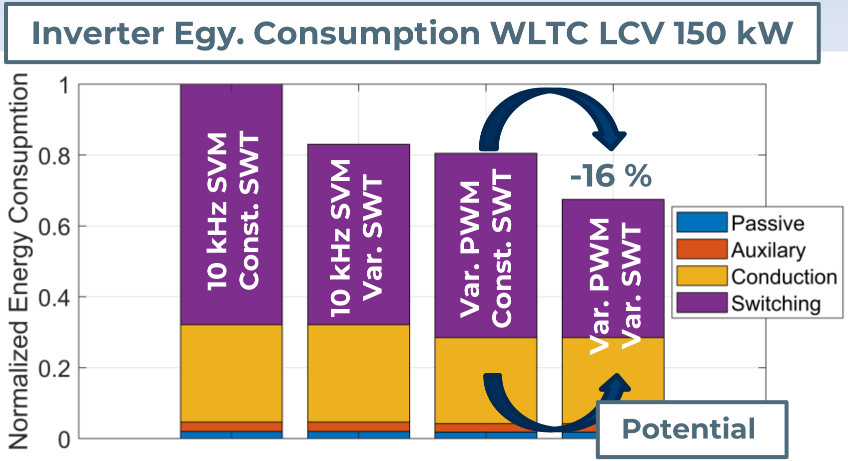
6-step

Voltage Dependency on SoC

Variable switching speed (Var. SWT)

- Increased SoC-dependency of the DC voltage increases usable range of var. SWT
- Increased switching speed for low DC voltage and low AC currents increases efficiency
- Efficiency benefits impacted by variable switching frequency (Var. PWM)
- Efficiency benefits increased if harmonic motor losses are dominant and decrease if inverter switching losses are dominant
- Additional efforts regarding motor isolation (and potentially EMC-filter)





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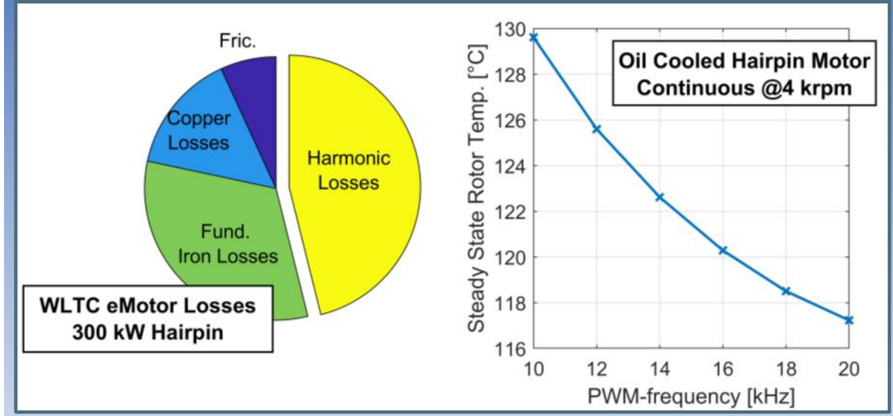
Minimizing Harmonic Losses

Harmonic Motor losses

- Dominant eDrive losses in WLTC
- Potentially limiting continuous rotor performance
- Reduction by thin motor laminations and magnet segmentation

Alternative Reduction of Harmonic Motor Losses via Inverter

- Increased switching frequency (SiC/GaN)
- Increased number of voltage levels (Multilevel Inverter or Switched Battery Architecture)
- Variable DC-voltage (DC/DC between Bat & Inv)
- Alternative Modulation & Optimized Pulse Patterns



Variable DC-voltage

Multilevel Inverter

SiC/GaN

OPP

$$\Delta i \sim \frac{V_{Mot}}{\boxed{l_{Mot,Diff}}} * \Delta T_{Switch}$$

Increased power density of eMotor increases magnetic saturation

Minimizing Harmonic Losses

3-Level Inverter (3 Lvl)

- Reduced Harmonic Motor Losses improve efficiency
- Significant increase of Inverter BOM
- Investigation of the 3 Lvl converter topologies via HPC parallel computing simulation to compare
  - Required semiconductor area
  - DC-link capacitor voltage ripple (time domain)
  - Modulation & operation strategy
  - Thermal performance (Junction temperature)
  - Harmonic Motor Losses (quantified by WTHD)

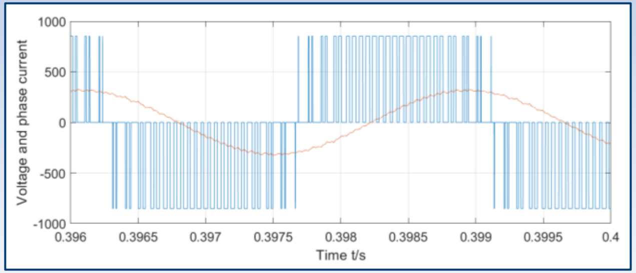
Refer to **Valeo‘s latest Publication** on 3 Lvl (SIA 2024): **No overall inverter benefit** (efficiency, volume, cost) of **investigated full SiC 3-Lvl-topologies** compared to 2-Lvl-SiC-Inverters.

HPC parallel computing

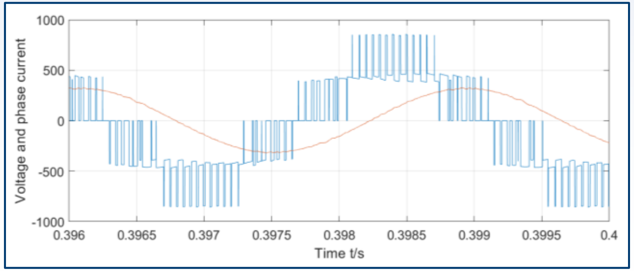
Inverter Model
- Thermo Electric
- Control
- DC-link ripple

Motor Model
- Voltage equations
- Inductance based
- AC-ripple

2-Level



3-Level



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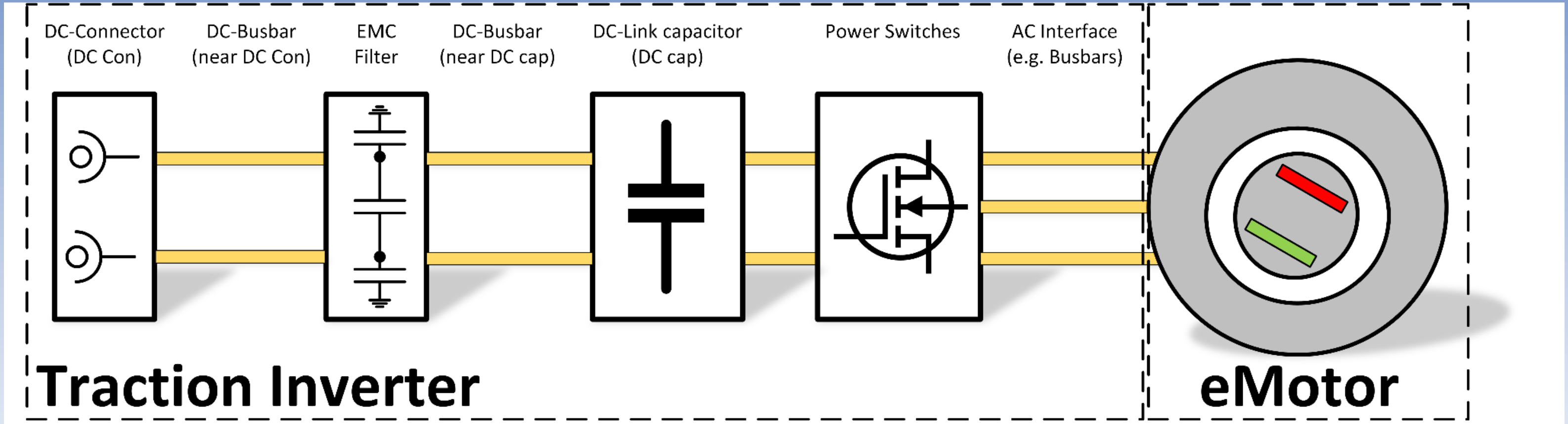
Inverter Operation at the Thermal Limit



Traditional eDrive

- Peak performance thermally limited by Power Switches
- Continuous performance thermally limited by eMotor

Modern eDrive

- High power density of Inverters results in compact Passives
- Well cooled eMotor w/ Oil
- Inverter Passives may become continuous performance limit

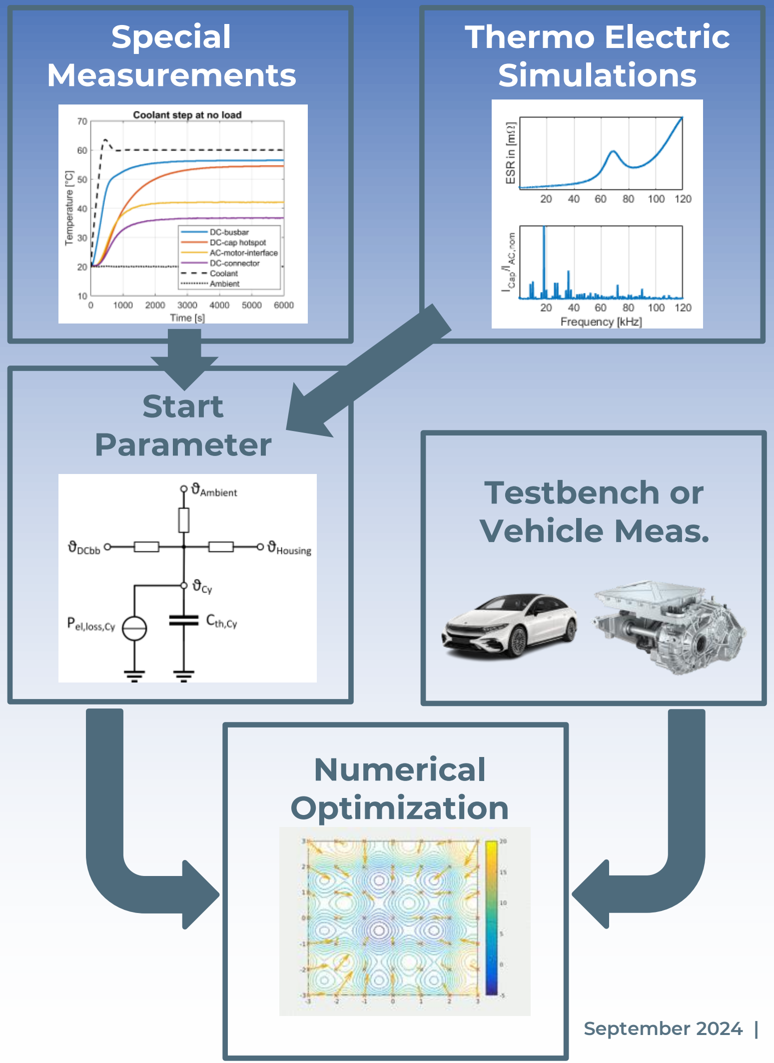
Trend

- Cost efficient “sensorless” thermal protection via real-time thermal models
- Efficiency trends need to be considered

Inverter Thermal Limit

Calibration of “virtual sensors” for Passives:

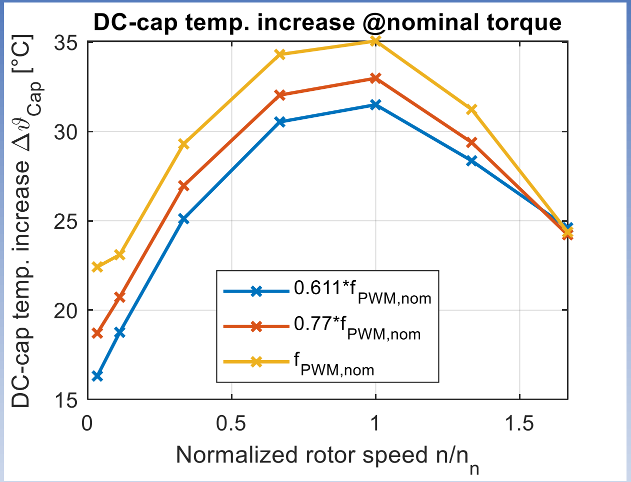
- Setting start parameters and boundaries via
    - Simulations (3D simulation, thermo electric)
    - Special measurements (Inlet step response, loss-less operation)
- Training & validation measurement data on eAxle level or vehicle level to account for
    - Thermal interaction between inverter, motor and gearbox
    - Vehicle related effects
- Final calibration via optimization algorithms to reach highest accuracies

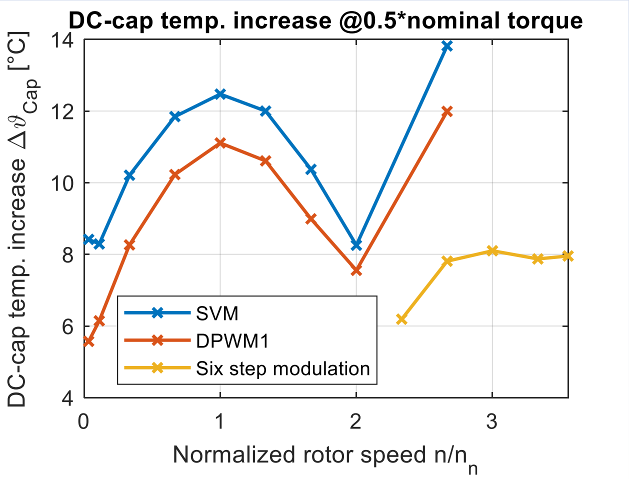


Inverter Thermal Limit

Impact of Efficiency Trends on Passives Temp.

- Variable Switching Frequency
- Variable Switching Speed
- Variable Modulation Method
- Variable Flow Rate



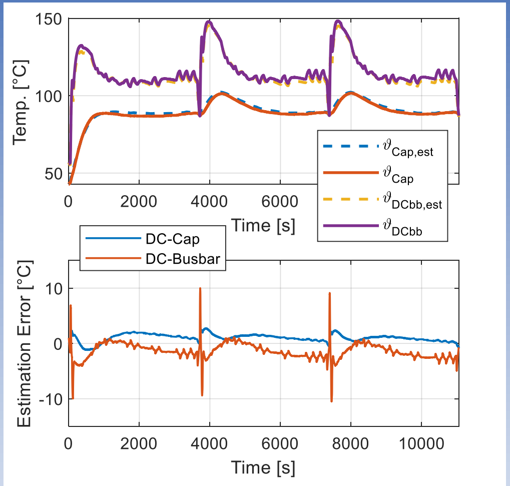


Inverter Thermal Limit

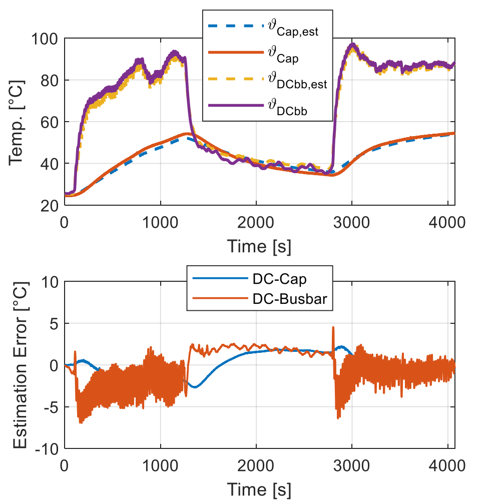
Cross Validation with Driving Cycles

- **High accuracies** for overload and dynamic driving cycles (e.g. DC-cap estimation error < 3 K)
- **Increased Performance** (+43 % AC RMS current in a high load high temperature driving cycle compared to conventional thermal protection)

Overload Driving Cycle near thermal limit



Dynamic vehicle Measurements



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Conclusion

Battery Trends
- 800 V_{dc} Architecture
- Next Gen Batteries

Changing INV Boundaries
- DC voltage & CM voltage ⇑
- SoC dependency ⇑

Inverter Impact & Trends
- Additional Efforts Mot & Inv
- Simplified High Power Arch.
- 400/800V Charging
- Variable Switching Speed

Motor Trends
- Oil Cooling
- Hairpin

Changing INV Boundaries
- Continuous Motor Perf. ⇑
- Harmonic Motor Losses ⇑

Inverter Impact & Trends
- ”Virtual Temp Sensors” INV
- New INV architectures
- Optimized Pulse Patterns
- PWM frequency ⇑ (GaN/SIC)

Optimized Inverter solutions require a deep understanding on system level including the electric interfaces of the Inverter like HV-battery and eMotor.

SMART TECHNOLOGY
FOR SMARTER MOBILITY