Wide-Band-Gap-Antriebsumrichter
Aktuelle Trends und technische Lösungen

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VDE DACH-Fachtagung "Elektromechanische Antriebssysteme 2021"

November 10th, 2021

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Power Electronic Systems @ ETH Zurich

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AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
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Outline

- *Introduction*
- *WBG Trends and Challenges*
- *Full-Sinewave Filtering*
- *Multi-Level Inverter*
- *Filter-Integrated Converter Structures*
- *Conclusions*

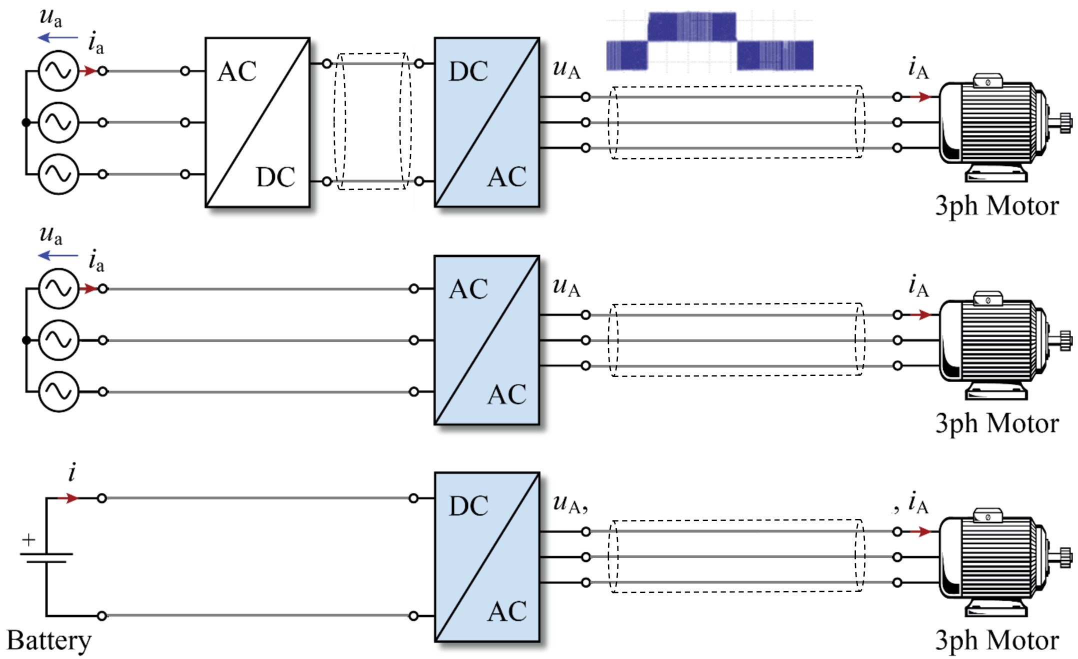
Acknowledgement:
M. Antivachis
J. Azurza
M. Haider
D. Menzi
S. Miric
J. Miniböck
M. Guacci
D. Zhang

3-Φ Variable Speed Drive Inverter Systems

State-of-the-Art Trends and Future Requirements

Variable Speed Drive Inverter Concepts

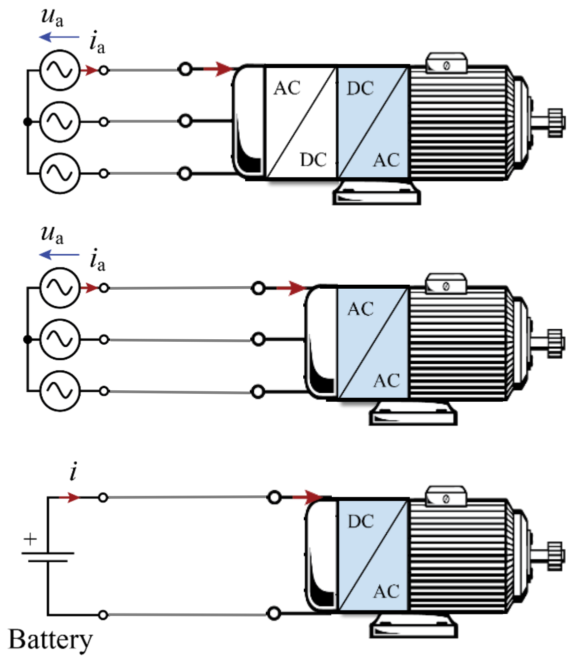
- DC-Link Based OR Matrix-Type AC/AC Converters
- Battery OR Fuel-Cell Supply OR Common DC-Bus Concepts

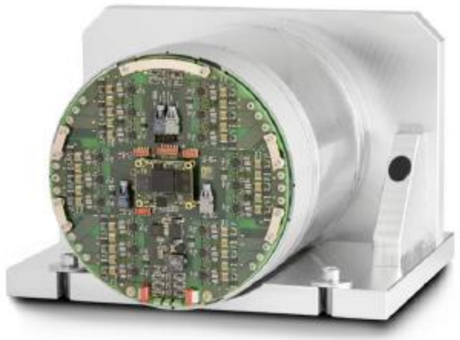


- High Performance @ High Level of Complexity / High Costs (!)
- All Separated → Large Installation Space / Complicated / Expert Installation

VSD Inverter - Future Requirements

- *"Non-Expert" Installation* → *Motor-Integrated Inverter OR "Sinus-Inverter"*
- *Low Losses & Low HF Motor Losses / Low Volume & Weight*
- *Wide Output Voltage Range / High Output Frequencies (High Speed Motors)*

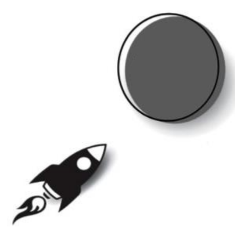




- *Main "Enablers"* → *SiC/GaN Power Semiconductors & Digitalization ("X-Technologies")*
  → *Adv. Inverter Topologies & Control Schemes ("X-Concepts")*

"X-Technologies"

WBG Semiconductors



Source:
www.terencemauri.com

Si vs. SiC

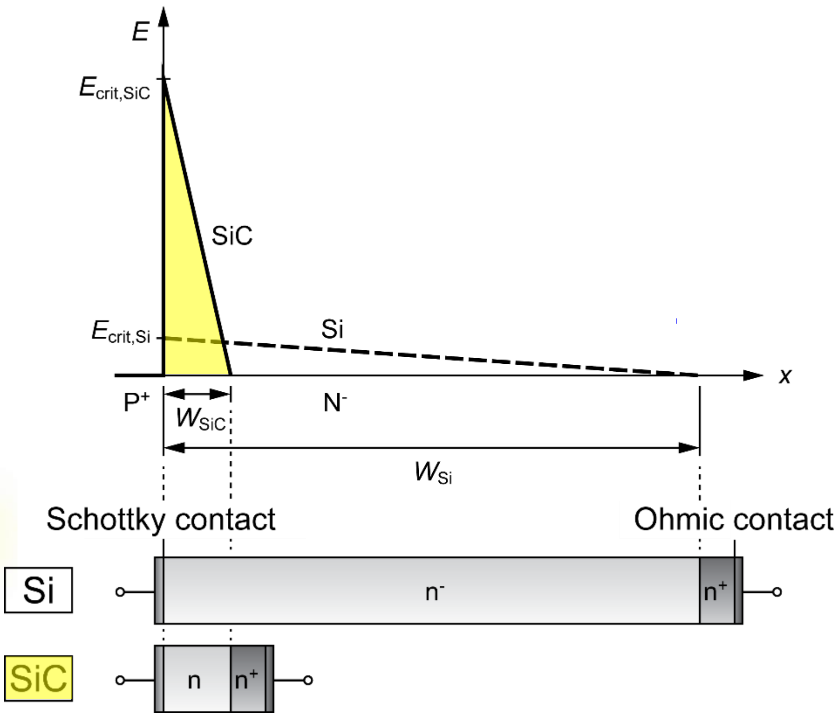
- *Higher Critical E-Field of SiC → Thinner Drift Layer*
- *Higher Maximum Junction Temperature $T_{j,max}$*

at 300 K	Si	GaAs	4H/6H-SiC	GaN
E_g (eV)	1.12	1.4	3.0-3.2	3.4
E_c (MV/cm)	0.25	0.3	2.2-2.5	3
μ_n (cm²/Vs)	1350	8500	100-1000	1000
ε_r	11.9	13	10	9.5
v_{sat} (cm/s)	1x10⁷	1x10⁷	2x10⁷	3x10⁷
λ (W/cmK)	1.5	0.5	3 - 5	1.3

$$R^*_{on} = \frac{4V_B^2}{\varepsilon \mu_n E_C^3} \leftarrow$$

For 1kV:	Si	SiC
W (µm)	100	10
N_D (cm^{-3})	10^{14}	10^{16}

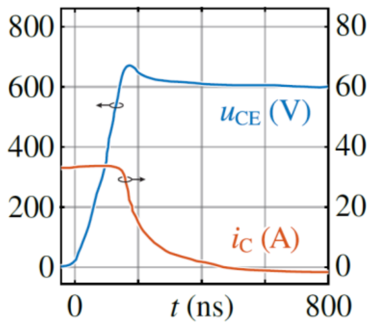
$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$



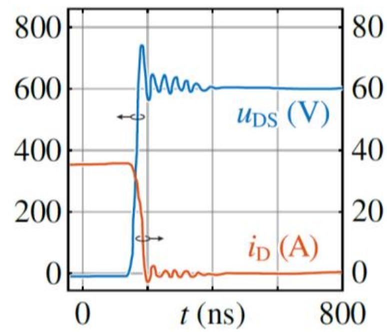
- *Massive Reduction of Relative On-Resistance → High Blocking Voltage Unipolar Devices*

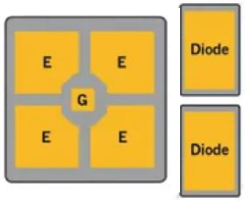
Si vs. SiC Switching Behavior

- *Si-IGBT* → *Const. On-State Voltage Drop / Rel. Low Switching Speed*
- *SiC-MOSFETs* → *Resistive On-State Behavior / Factor 10 Higher Sw. Speed*



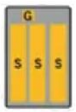
Source: Fuji Electric





Si 1200V 100A
Die Size: 98.8mm² + 39.4mm²

Source: Infineon



1200V 100A
Die Size: 25.6mm²

Source: Cree

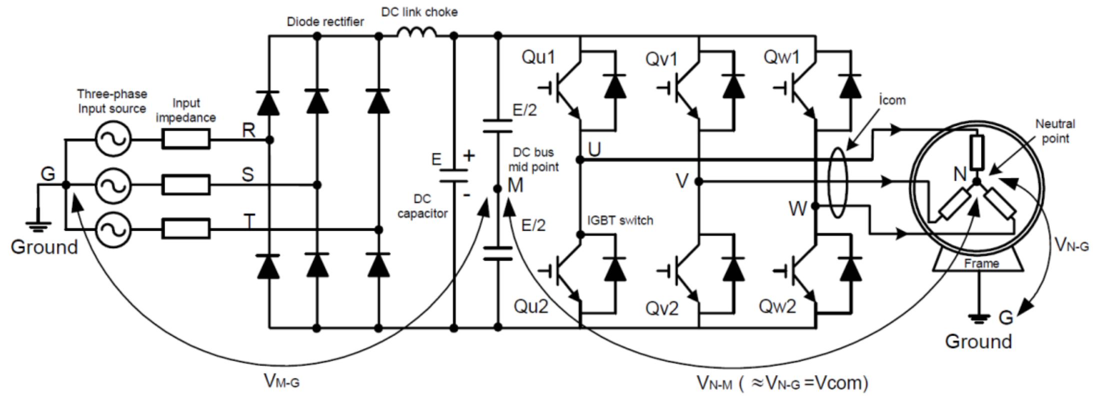
- *Extremely High di/dt & dv/dt* → *Challenges in Motor Insulation / Bearing Currents / EMI*
- *Small Chip Size & Integration* → *Challenges in Gate Drive & PCB / Packaging & Thermal Management*

Inverter Output Filters

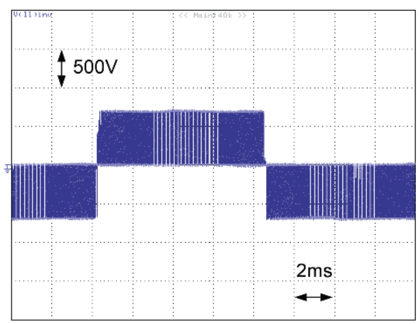
Full-Sinewave Filtering

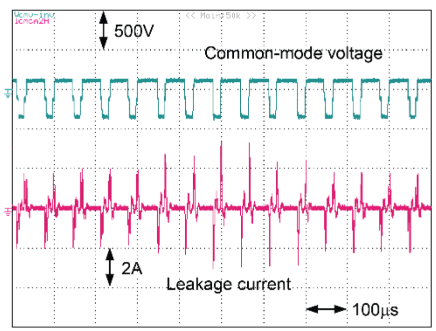
State-of-the-Art Drive System

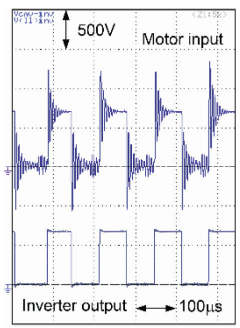
- *Standard 2-Level Inverter — Large Motor Inductance / Low Sw. Frequency*
- *Shielded Motor Cables / Limited Cable Length / Insulated Bearings / Acoustic Noise*

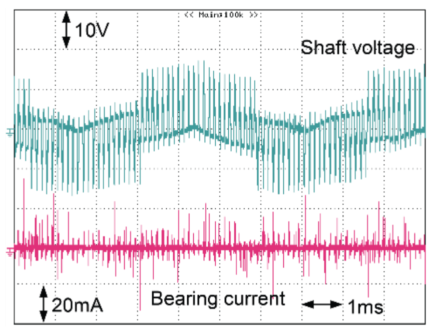


Source: YASKAWA







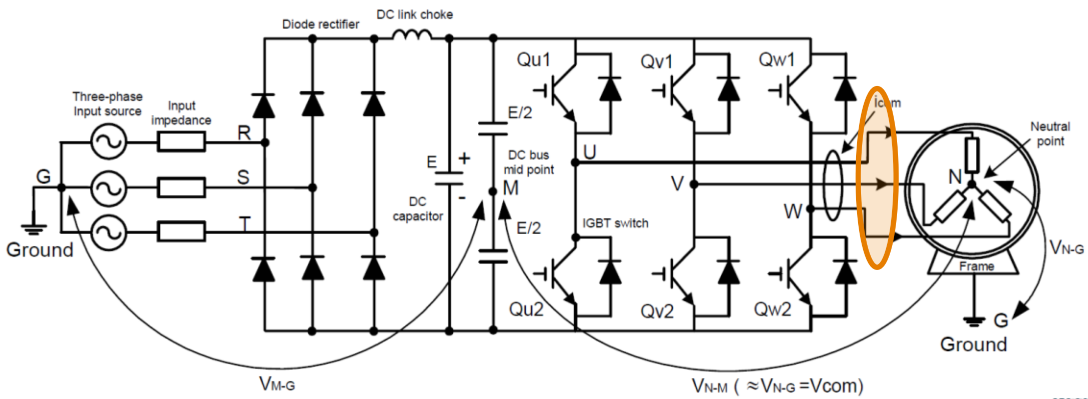


- *Line-to-Line Voltage* | *CM Leakage Current* | *Motor Surge Voltage* | *Bearing Current*

Output Voltage Filtering

- *Measures Ensuring EMI Compliance / Longevity of Motor Insulation & Bearings*
- *Motor Reactor | dv/dt Filters | DM-Sinus Filters | Full-Sinus Filters*

Source: YASKAWA



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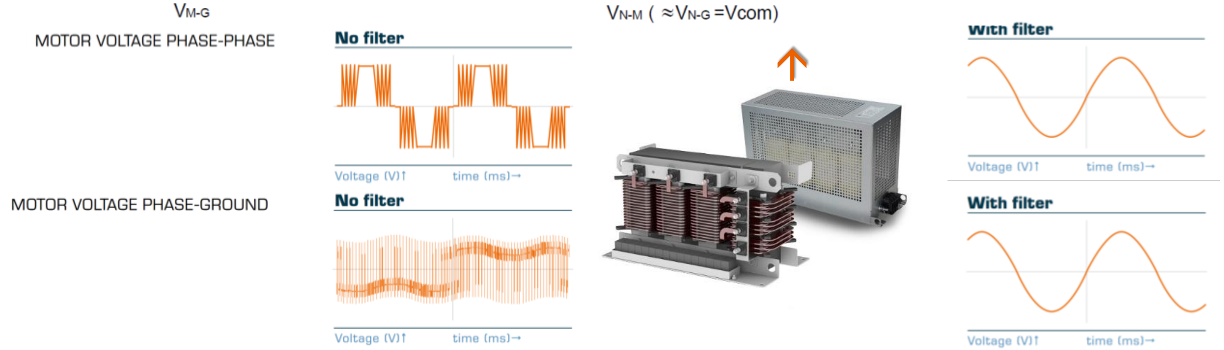
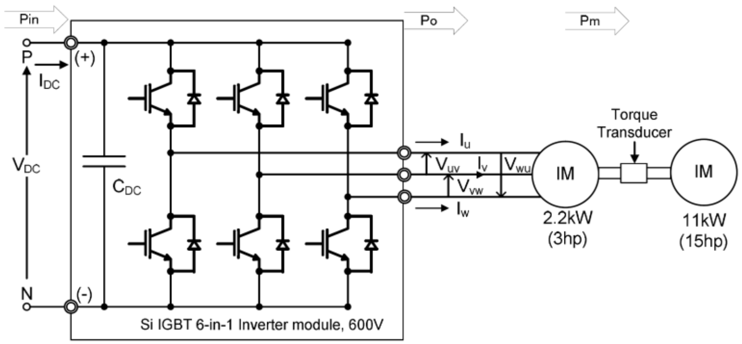


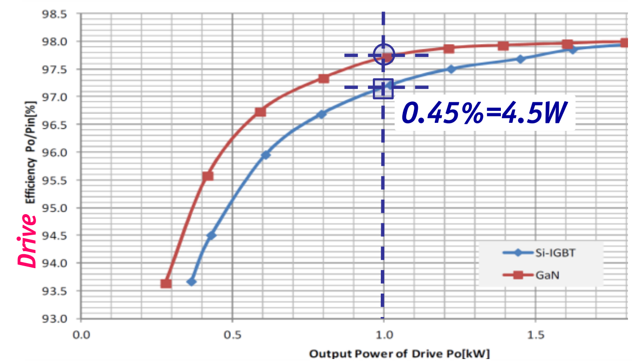
- *Small Filter Size → High Sw. Frequ. → SiC|GaN*

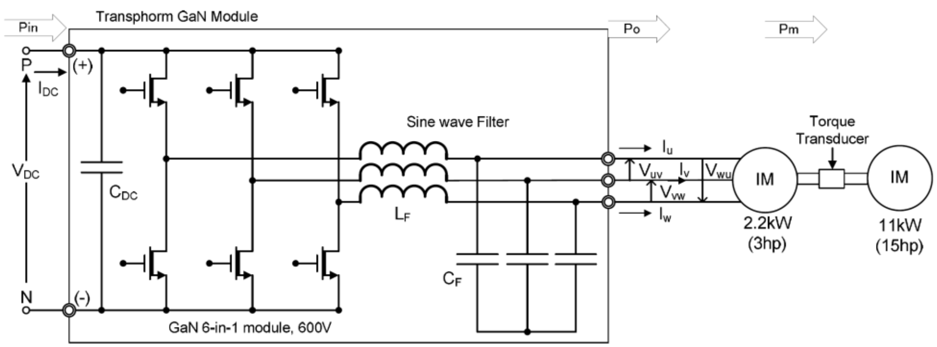
3-Φ 650V GaN Inverter System

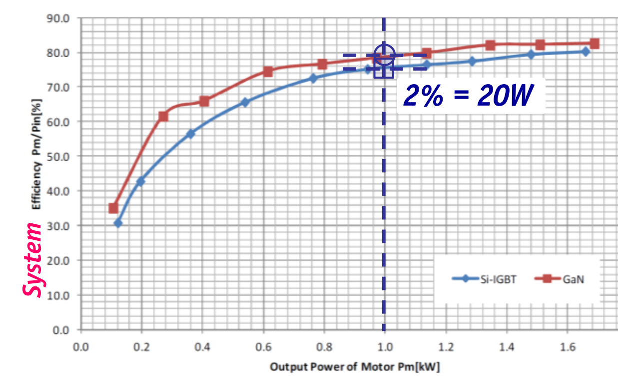
Source: YASKAWA

- *Comparison of Si-IGBT System (No Filter, f_S=15kHz) & GaN Inverter (LC-Filter, f_S= 100kHz)*
- *Measurement of Inverter Stage & Overall Drive Losses @ 60Hz*









- *Sinewave LC Output Filter → Corner Frequency f_C= 34kHz*
- *2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses) !*

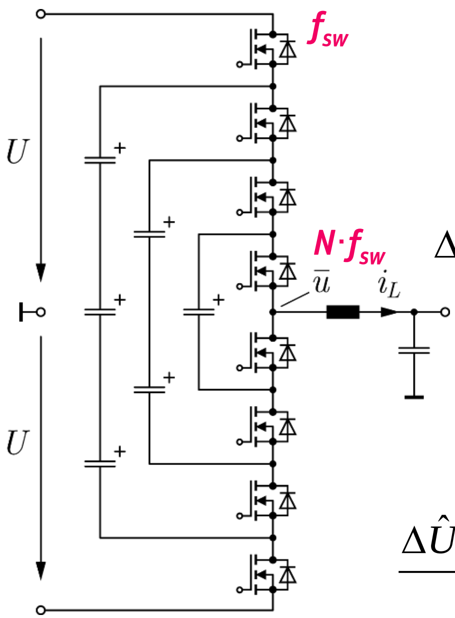
Multi-Level Inverters

Flying Capacitor Inverter

G. Rohner, S. Miric, D. Bortis, J. W. Kolar, M. Schweizer,
Comparative Evaluation of Overload Capability and Rated Power Efficiency of 200V Si/GaN 7-Level FC 3-Phase Variable Speed Drive Inverter Systems,
Proceedings of the 36th Applied Power Electronics Conference and Exposition (APEC 2021), June 14-17, 2021.

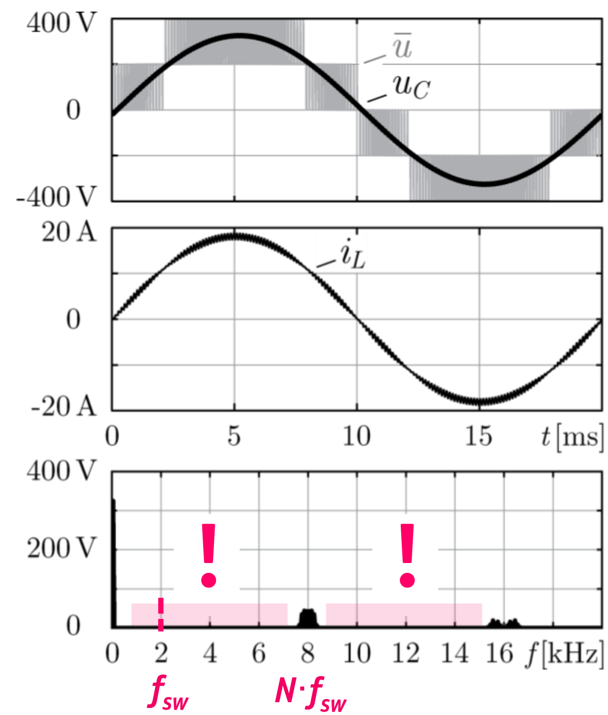
Scaling of Flying Cap. Multi-Level Concepts

- *Clear Partitioning of Overall Blocking Voltage* → *Lower Voltage Steps / Lower EMI / Reflections*
- *Higher Effective Switching Frequency @ Output* → $f_{sw,eff} = N \cdot f_{sw}$
- *Low Output Inductance & Application of LV Technology to HV*



$$\Delta\hat{I}_{\max,N} = \frac{1}{N^2}\,\Delta\hat{I}_{\max,N=1}, \qquad \Delta\hat{I}_{\max,N=1} = \frac{U}{8 f_s L}$$

$$\frac{\Delta\hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32}\left(\frac{f_O}{f_S}\right)^2\frac{1}{N^3}$$

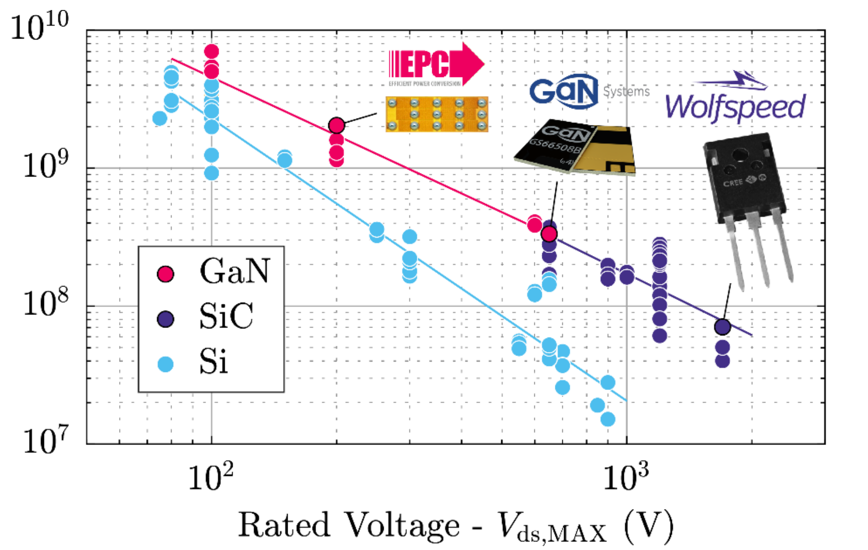


- *Scalability / Manufacturability / Standardization / Redundancy*

SiC/GaN Figure-of-Merit

- *Figure-of-Merit (FOM) Quantifies Conduction & Switching Properties*
- *FOM Identifies Max. Achievable Efficiency @ Given Sw. Frequ.*

$$FOM = \frac{1}{R_{ds,on} C_{oss}}$$



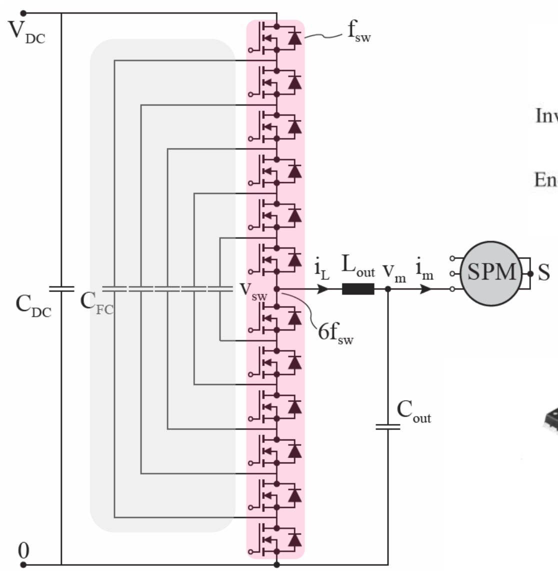
- *Advantage of LV over HV Power Semiconductors*
- *Advantage of Multi-Level over 2-Level Converter Topologies*

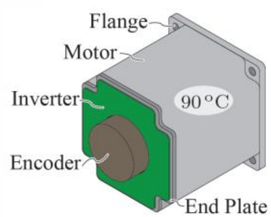
→ *Lower Overall On-Resistance @ Given Blocking Voltage*

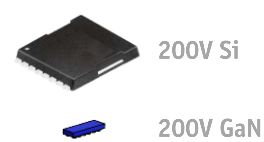
Motor Integrated 7-Level FC Inverter

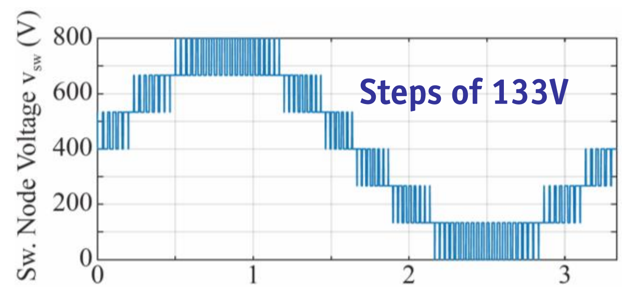
■ **Specifications**

- **DC Input Voltage:** 800V
- **Nominal Operation:** $15A_{peak}$, $350V_{peak}$ (7.5kW)
- **Overload Operation:** 45 A_{peak} for 3s
- **Temperature Aluminum (Flange):** 90°C









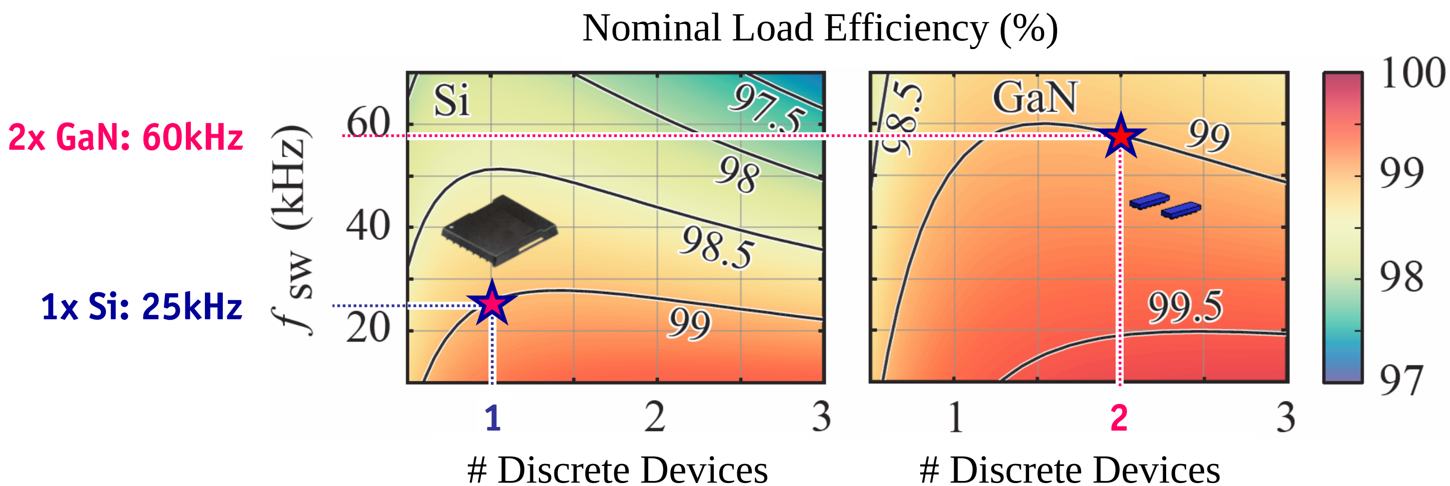
- *7-Level Flying Capacitor Inverter enables Usage of 200V Devices (Si or GaN)*

- *Nominal Efficiency Target 99% (only Semicond.)* → *# Semicond. Devices*
- *Max. Achievable Switching Freq.* → *Determines Flying Cap. Vol.*

Nominal Load Operation

- 99% at Nom. Load – 7.5 kW → *75W Total Semi. Losses (Only 2.1W per Switch)*
- Comparison of best 200V Si and GaN Devices available on the Market

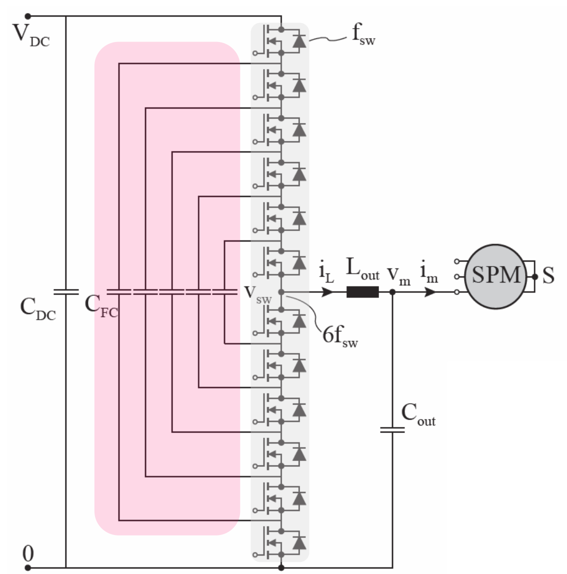
  - Si-MOSFET: IPT111N20NFD, Optimos 3 (11mOhm)
  - GaN: EPC2034C (8mOhm)

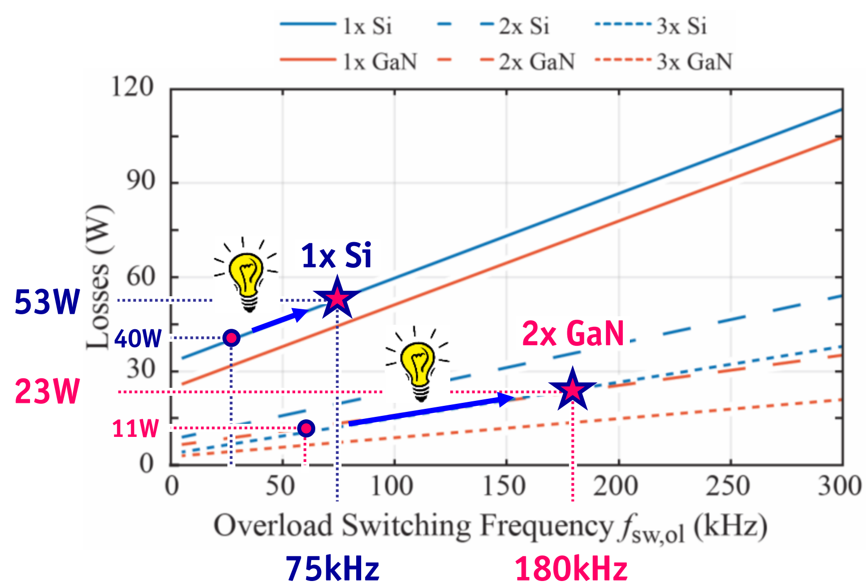


- *GaN achieves 2-3 times Higher Switch. Freq. compared to Si for 99% → 2-3x lower FC Volume*
- *Overload Capability → 3 x Nominal Load for 3 Seconds*

Overload Operation

- *Worst Case Overload Operation at Standstill*
- *3 x Torque/Current (45A$_{peak}$) for 3s* → *Strongly Increased Semicon. Losses*
  → *3 x Flying Cap. Vol. for same FC Voltage Ripple*





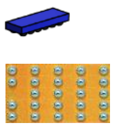
- *Conduction Losses dominate Overload Losses* → *Increase Switching Frequency at Overload*
- *3 x Switching Frequency* → *Flying Cap. designed for Nom. Load*
- *Max. Junction Temp. (Si: 175°C/ GaN: 150°C)* → *Proper Cooling Concept needed*

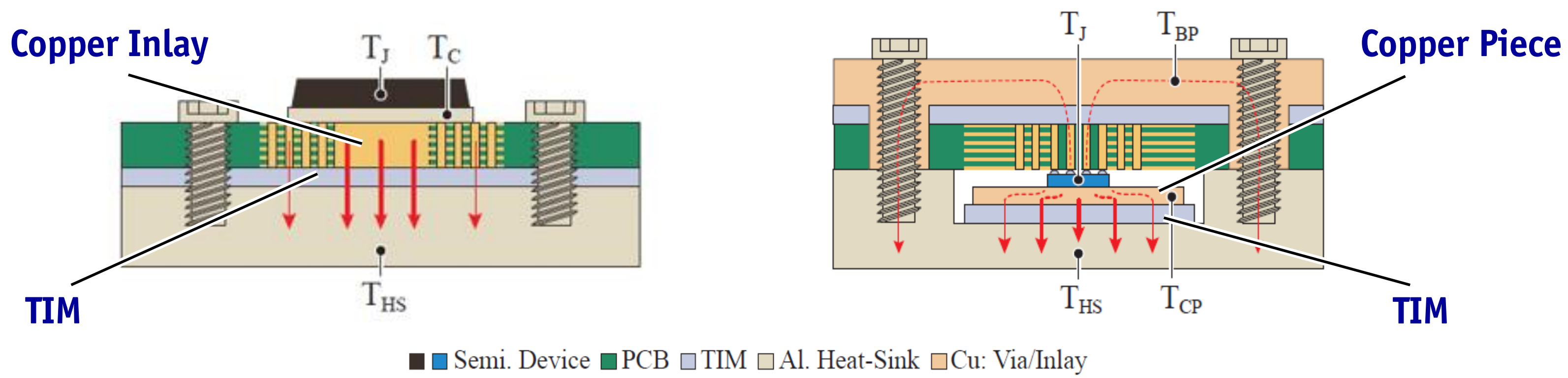
Cooling Concepts

- ***Si MOSFET*** → ***Cooling Through PCB with Copper Inlay***
- ***GaN (Bottom Side mounted)*** → ***Directly Attached Copper Piece & TIM to Heatsink***

Si: IPT111N20NFD
(Optimos 3 FD)
Bottom: $R_{\Theta JB} = 0.4$ K/W

GaN: EPC2034C
Top: $R_{\Theta JC} = 0.3$ K/W
Bottom: $R_{\Theta JB} = 4$ K/W





- ***Inlay for Si & Copper Plate for GaN*** → ***Thermal Capacitor & Heat Spreader***
- ***Minimize Th. Contact betw. GaN Device and Cu Plate*** → ***Heat Paste, Liquid Gap Filler, Solder Pad***
- ***Determine Thermal Performance*** → ***Realization & Dynamic Thermal Model***

Flying Capacitor Cell Realization

- ***Si MOSFET*** → ***Cooling Through PCB with Copper Inlay***
- ***GaN (Bottom Side mounted)*** → ***Directly Attached Copper Piece & TIM to Heatsink***

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GaN: EPC2034C

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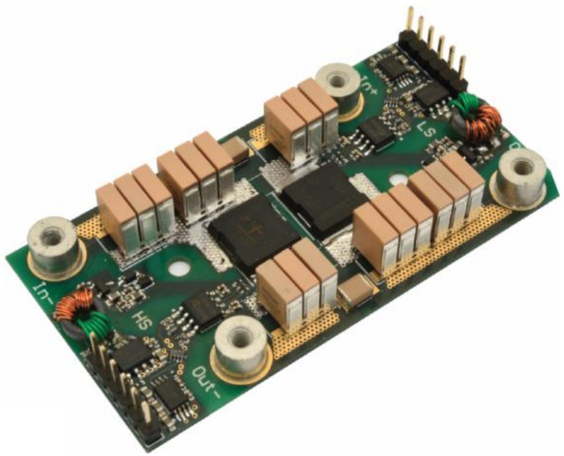

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- ***Determine Thermal Performance*** → ***Realization & Dynamic Thermal Model***

Dynamic Thermal Modeling

- *Si MOSFET* → *Cooling Through PCB with Copper Inlay*
- *GaN (Bottom Side mounted)* → *Directly Attached Copper Piece & TIM to Heatsink*

Si: IPT111N20NFD
(Optimos 3 FD)
Bottom: $R_{\Theta JB} = 0.4$ K/W

GaN: EPC2034C
Top: $R_{\Theta JC} = 0.3$ K/W
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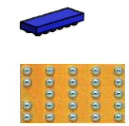
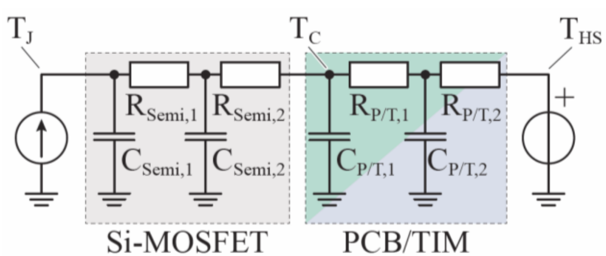
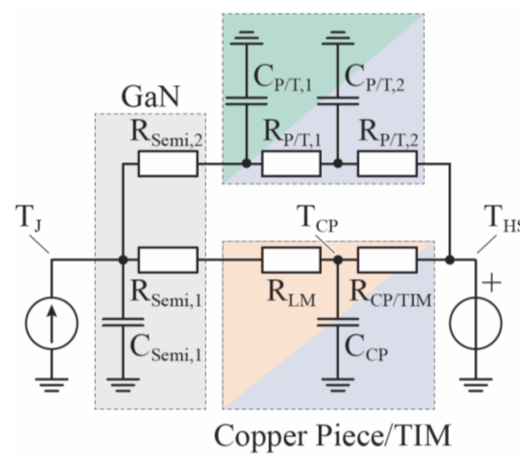


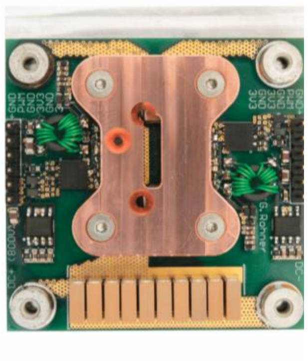


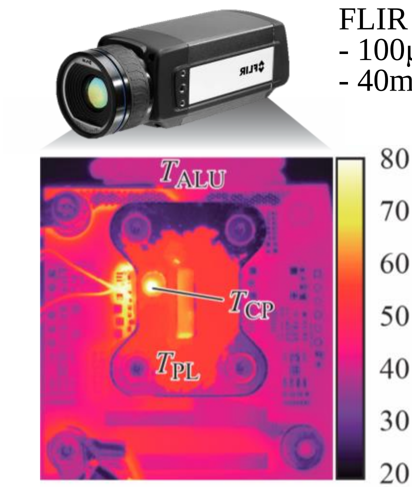


- *Inlay for Si & Copper Plate for GaN* → *Thermal Capacitor & Heat Spreader*
- *Minimize Th. Contact betw. GaN Device and Cu Plate* → *Heat Paste, Liquid Gap Filler, Solder Pad*
- *Determine Thermal Performance* → *Realization & Dynamic Thermal Model*

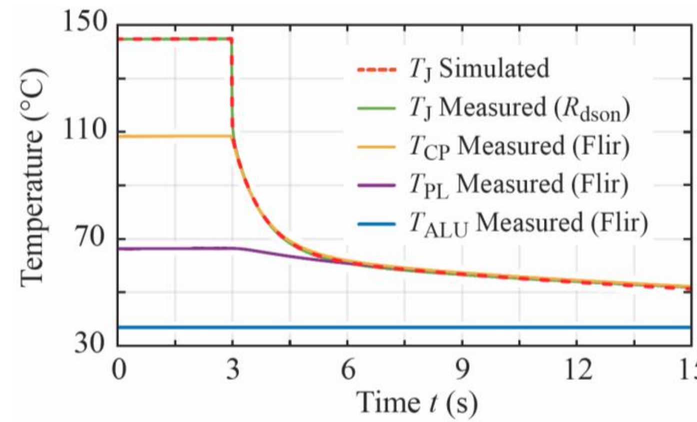
Dynamic Thermal Model Parametrization

- *Empirical Parametrization* → *Measure Temp. Profile for different Injected Power Profiles*
- *Junction Temp.* → *Electrically with temperature-dependent $R_{ds,on}$ (1ms Rate)*
- *Case, Cu-Plate & Heat Sink* → *Optically with Thermal Camera (40ms Rate)*





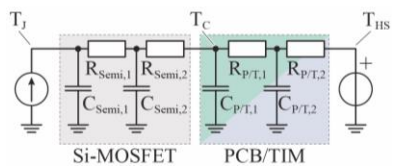
Thermal Camera View



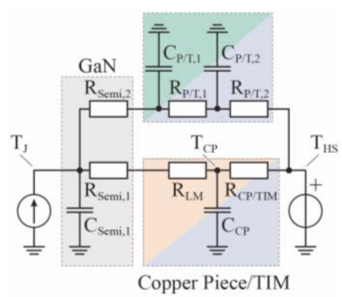
- *DC Power Injection* → *Relation betw. Junction Temp. and $R_{ds,on}$*
- *Pulsed Power Injection* → *Thermal Resitances* → *Thermal Capacitances*

Dynamic Thermal Model

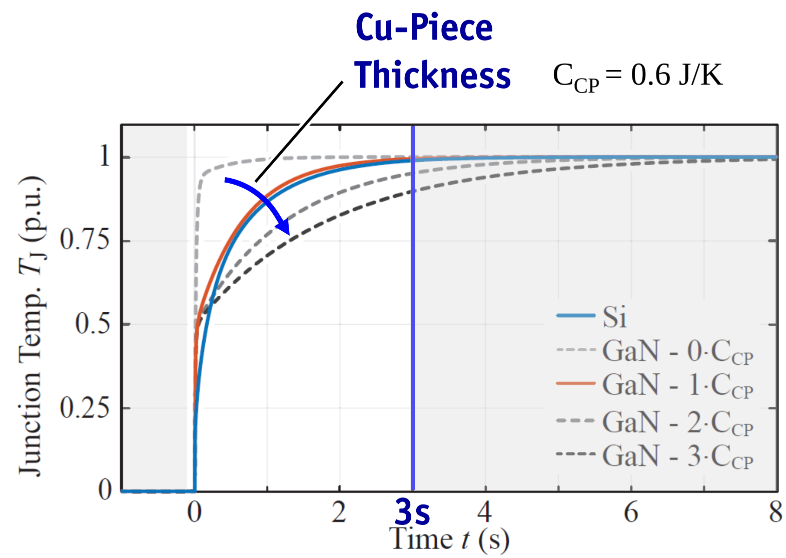
- *Normalized Thermal Step Response* → *Cu-Piece increases Time Constant drastically*
- *Similar Dyn. & Stat. Th. Behavior for 1xSi & 2xGaN if Cu-Piece same Dim. as Si-Exposed Pad*



Si: 0.91 K/W per Device



GaN: 1.81 K/W per Device



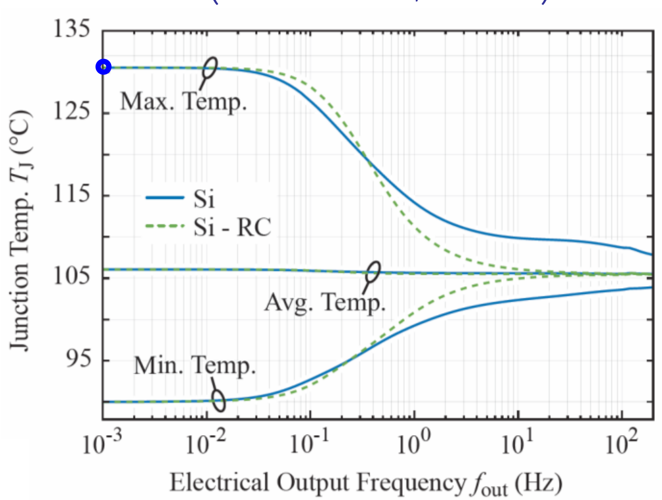
- *Initial Small Time Constant* → *Defined by Device Package* ($\tau < 10$ms)
- *Afterwards Large Time Constant* → *Defined by Cooling Concept* ($\tau_{\mathrm{Si}} = 0.4$ s, $\tau_{\mathrm{GaN}} = 0.65$ s)

- *Overload Duration >* $4 \cdot \tau_{\mathrm{Semi}}$ → *Equals Continuous Overload (Worst Case)*

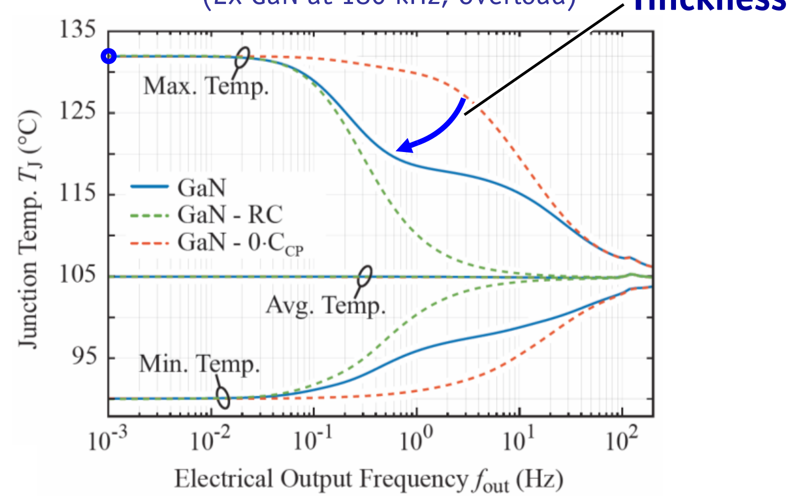
Thermal Cycling vs. Output Frequency (1)

- *Max. and Min. Junction Temperature within one Electric Period depending on f_{out}*
- *Maximum Overload Junction Temperature at Standstill → approx. 130°C for Si and GaN*

Si Temperature Profile
(1x Si at 75 kHz , Overload)



GaN Temperature Profile
(2x GaN at 180 kHz, Overload)

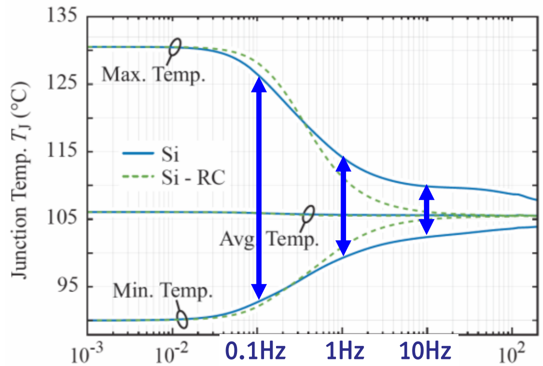


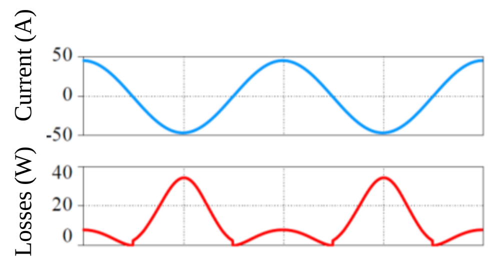
- *Immediate Reduction of Th. Cycling at Low Speeds → Th. Low-Pass Filter Behavior with τ_{Semi}*
- *Residual Th. Cycling at High Speeds due to thermal Behavior of Device Package*

- *Experimental Verification → AC Current & Switched 2L-Operation*

Thermal Cycling vs. Output Frequency (2)

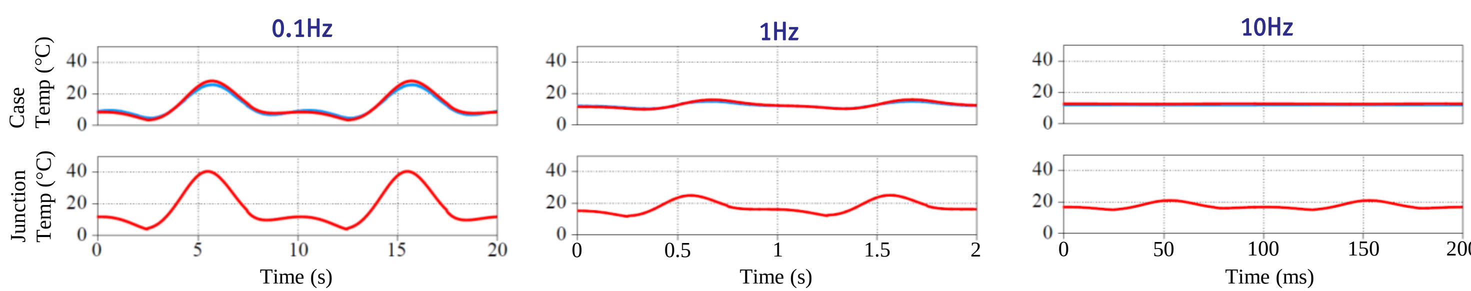
- *Switched 2L-Operation* → *Measurement and Simulation of Case Temperature*
- *Junction Temperature Profile* → *Determined from Thermal Model*
- *Injected Losses* → *Calculated from Semiconductor Loss Model*





Blue: Measured
Red: Simulated

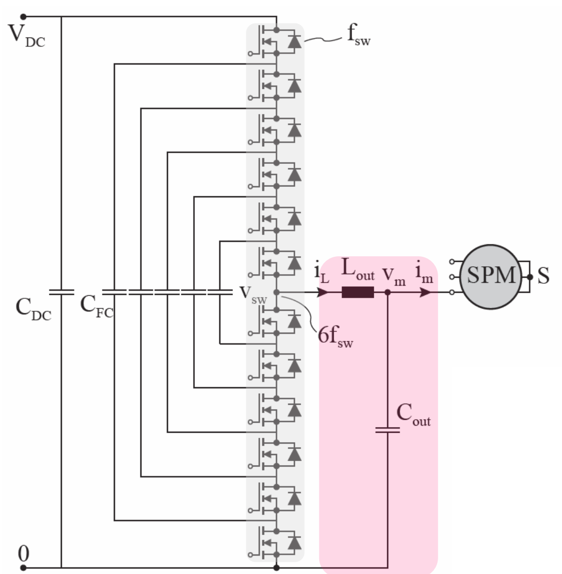
Temperatures referred to Heatsink Temp.

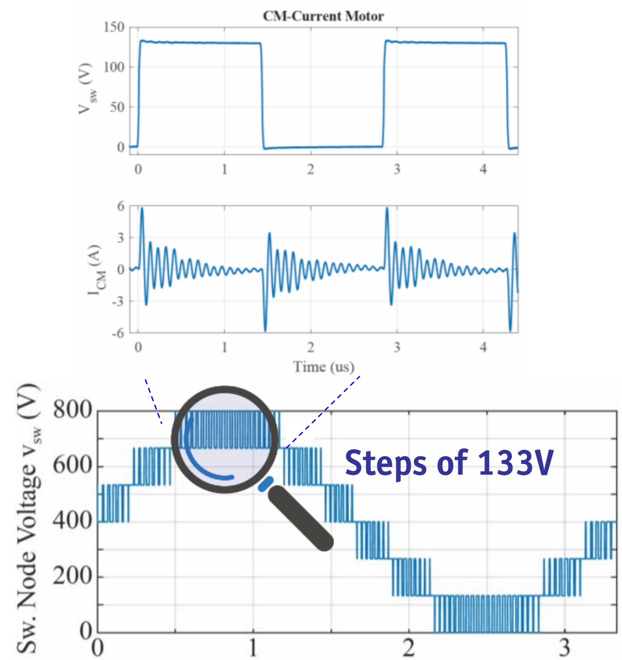


- *Very Good Agreement between Measured and Simulated Temperature Profiles*
- *Fast Decay of Thermal Cycling Magnitude with increasing Frequency*

LC Output Filter with Overload Capability

- *Multi-Level Converter* → *Small Voltage Steps but still high dv/dt*
- *LC Output Filter mitigate* → *CM & Bearing Currents*
  → *EMI Emissions & HF-Machine Losses*

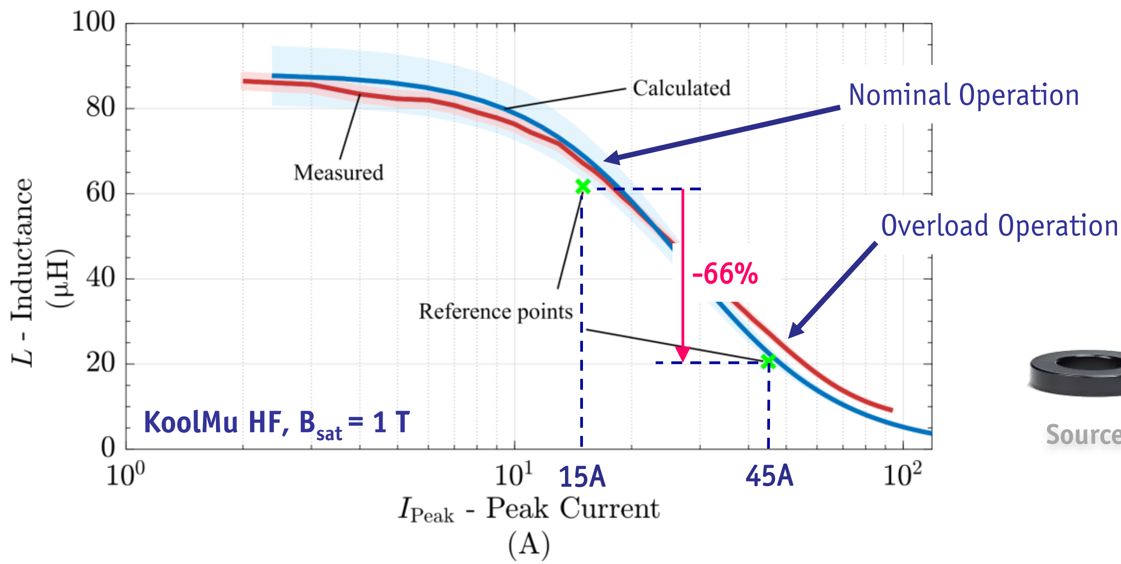




- *Multi-Level Converters enable* → *Small Filter Volume*
  → *Overload Capability (3 x I_{nom}) needed for Filter Inductor*

Output Inductor Design

- ***Ferrite Core Filter Inductor*** → ***Sudden Drop of Permeability around Saturation***
  → ***Magnetic Design for Overload needed***
- ***Powder Core Filter Inductor*** → ***Smooth Drop of Permeability till Saturation***

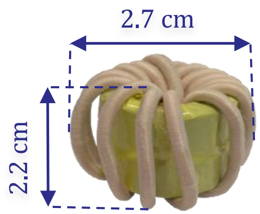


Source: mag-inc.com

- ***Max. FC Voltage Ripple*** → ***Inverter operated with 3x f_{sw} at Overload***
- ***Constant Inductor Current Ripple*** → ***Inductance can drop by x3 at Overload***
  → ***Powder Core Filter Inductor designed for Nominal Load (!)***

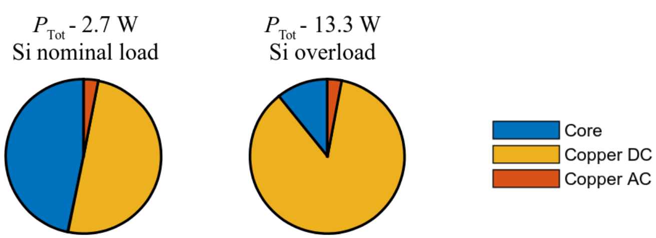
Output Inductor Design

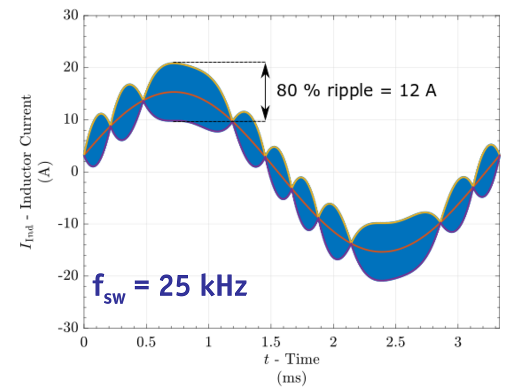
- *Filter Inductor Pareto Optimization for Si 7L FCi*

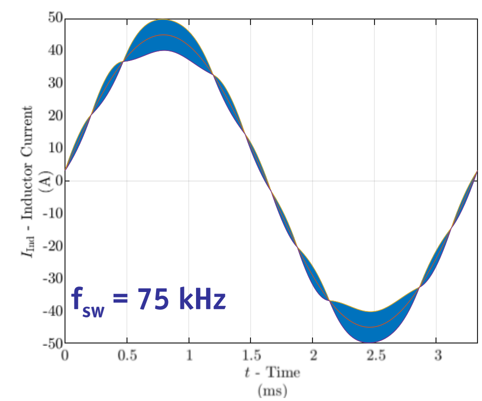


10.45 cm³

Nom. Ind.: 20.4 µH
OL Ind.: 7.6 µH
Ripple: 80%



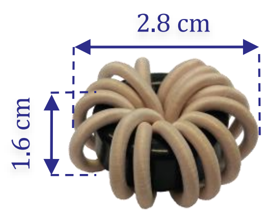




- *Tiny Filter Inductor for a Nominal 7.5kW Integrated Motor Drive → 3-4 x Smaller than Ferrite*
- *Temperature Increase of 5°C at Overload → based on Thermal Capacity*

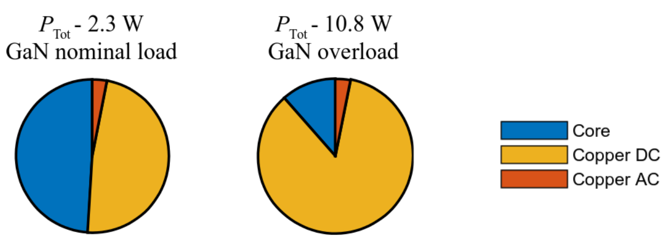
Output Inductor Design

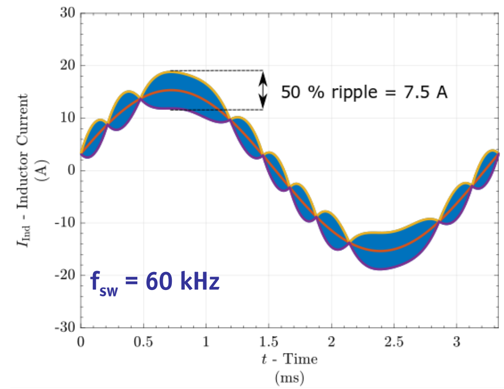
- *Filter Inductor Pareto Optimization for GaN 7L FCi*

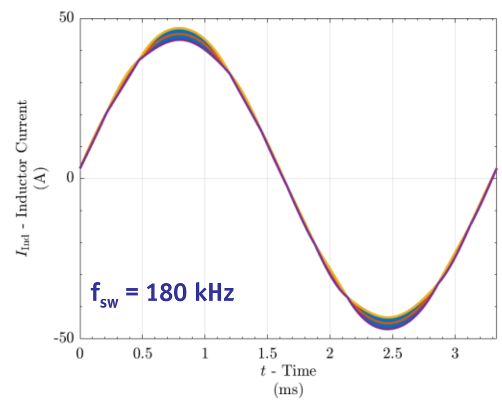


$8.2\ cm^3$

Nom. Ind.: 13.4 µH
OL Ind.: 4.9 µH
Ripple: 50%







- *Tiny Filter Inductor for a Nominal 7.5kW Integrated Motor Drive → 3-4 x Smaller than Ferrite*
- *Temperature Increase of 5°C at Overload → based on Thermal Capacity*

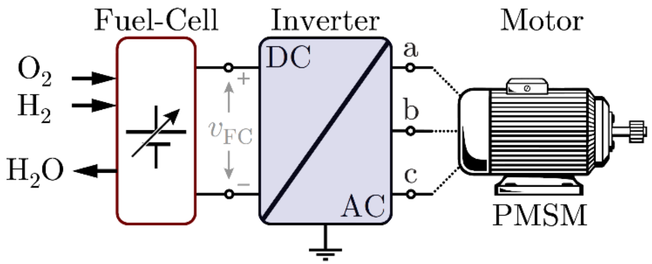
"X-Concepts"

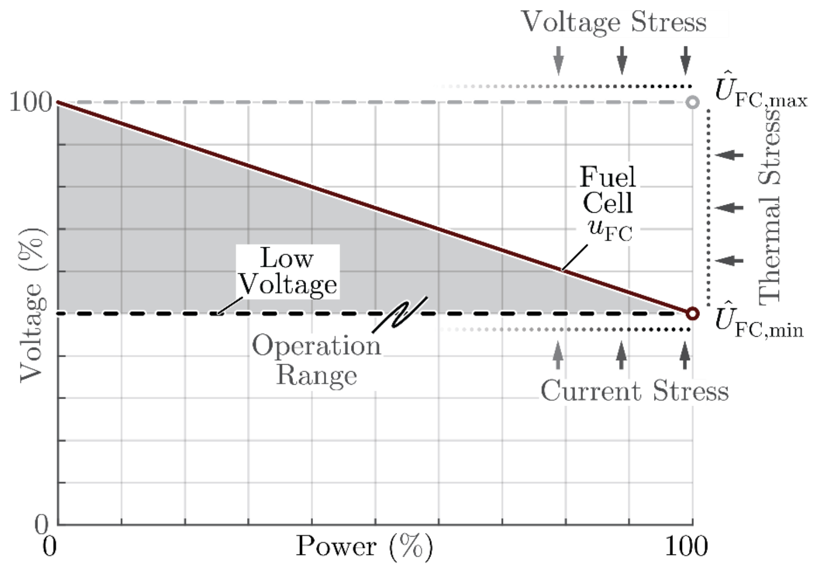
Phase-Modular Buck+Boost Inverter

Motivation

- *General / Wide Applicability*

— *Adaption to Load-Dependent Battery | Fuel Cell Supply Voltage*
— *VSDs → Wide Output Voltage & Speed Range*

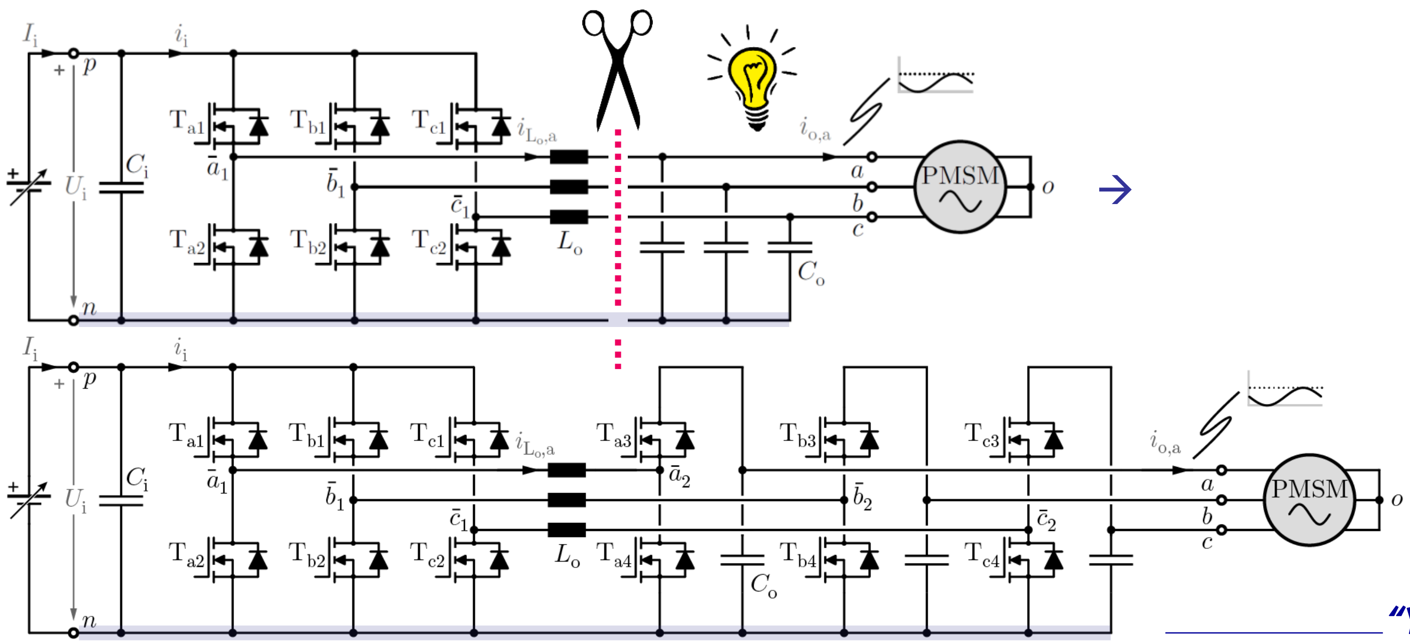




- *No Additional Converter for Voltage Adaption → Single-Stage Energy Conversion*

Buck-Boost Y–Inverter

■ ***Generation of AC-Voltages Using Unipolar Bridge-Legs***

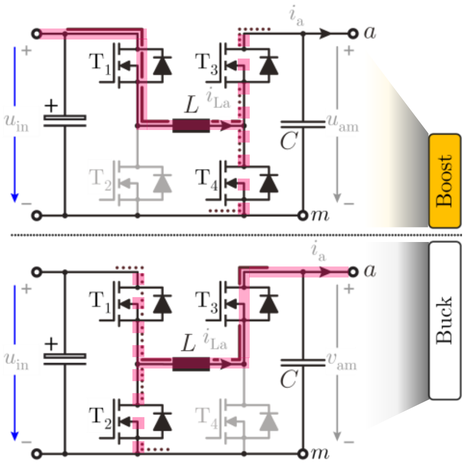


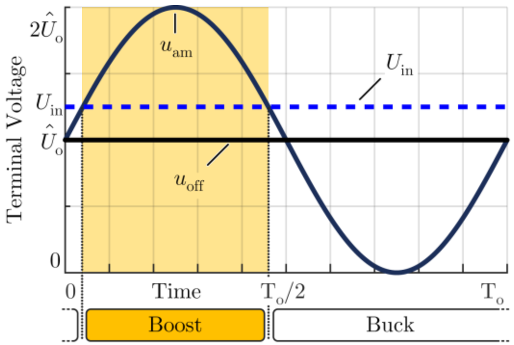
"Y-Inverter"

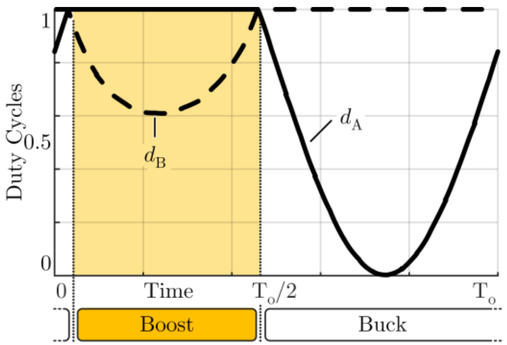
- ***Switch-Mode Operation of Buck OR Boost Stage*** → ***Single-Stage Energy Conversion (!)***
- **3-Φ Continuous Sinusoidal Output / Low EMI** → ***No Shielded Cables / No Motor Insul. Stress***

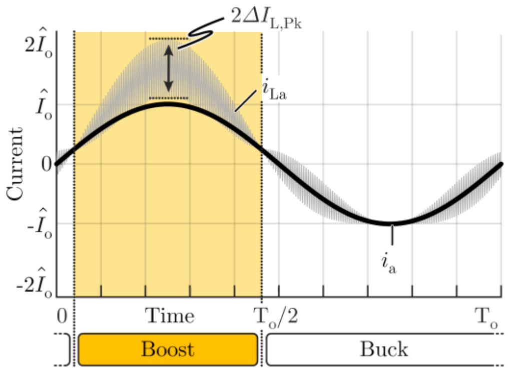
Buck-Boost Y–Inverter

- *Operating Behavior*







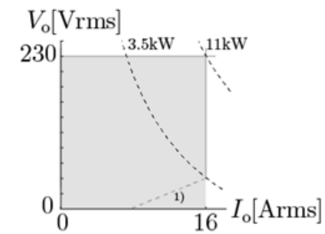


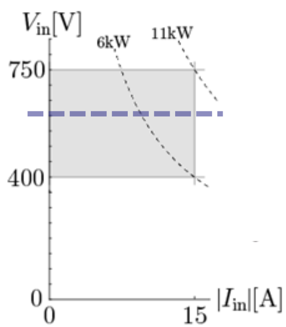
- $u_{am} < U_{in}$ → **Buck Operation**
- $u_{am} > U_{in}$ → **Boost Operation**
- Output Voltage Generation Referenced to DC Minus

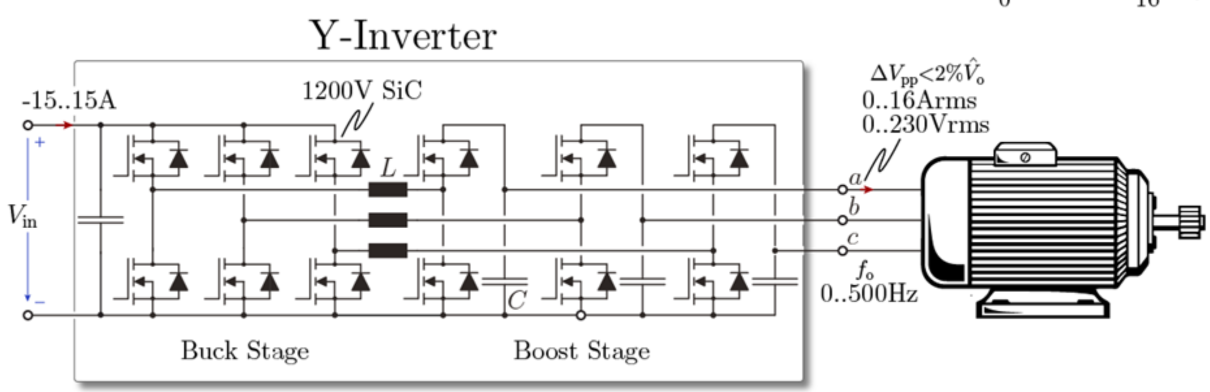
Y–Inverter VSD

- *Demonstrator Specifications*

- Wide DC Input Voltage Range → $400...750V_{DC}$
- Max. Input Current → ± 15A



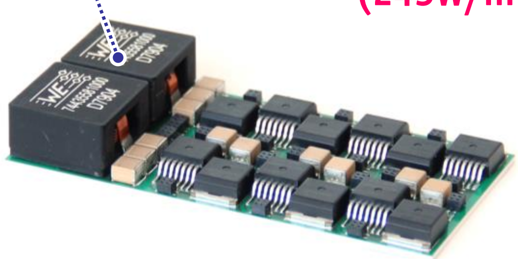




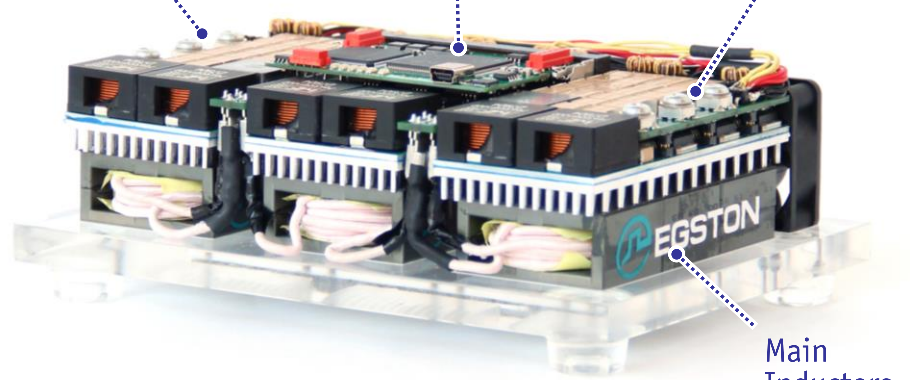
- Max. Output Power → 6...11 kW
- Output Frequency Range → 0...500Hz
- Output Voltage Ripple → 3.2V Peak @ Output of Add. LC-Filter

Y–Inverter Demonstrator

- 3x SiC (75mΩ)/1200V per Switch
- Sw. Frequency → 100kHz
- IMS Carrying Buck/Boost-Stage Transistors & Comm. Caps & 2nd Filter Ind.



★ 15kW/dm^3 (245W/in^3)



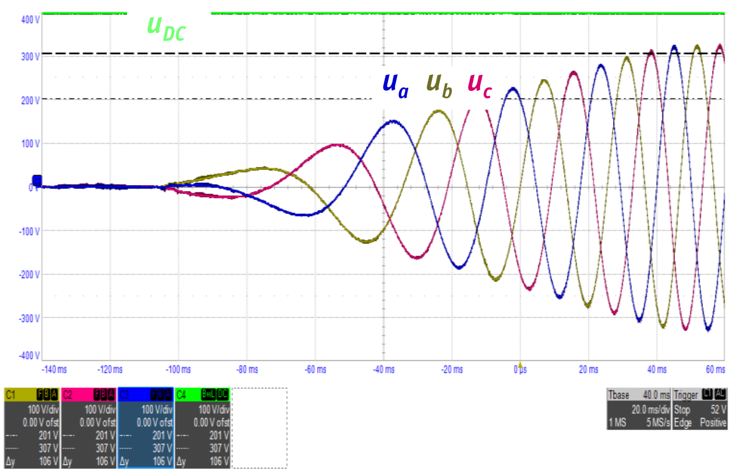
- Dimensions → 160 x 110 x 42 mm^3

Y–Inverter - Measurement Results

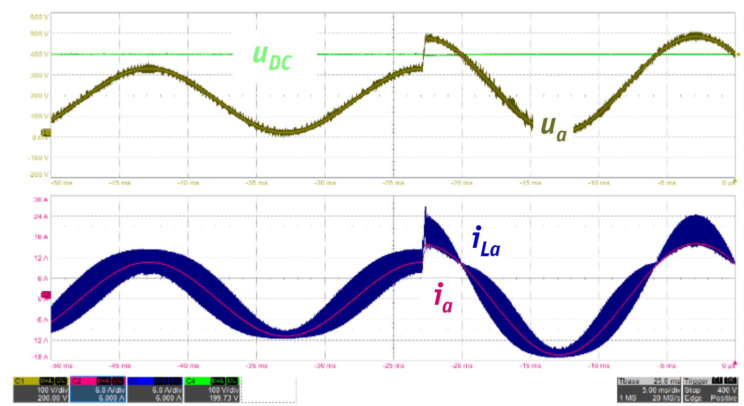
- *Transient Operation*

U_{DC} = 400V
U_{AC} = 400V_{rms} (Motor Line-to-Line Voltage)
f_0 = 50Hz
f_S = 100kHz / DPWM
P = 6.5kW

100V/div



100V/div
100V/div
6A/div
6A/div



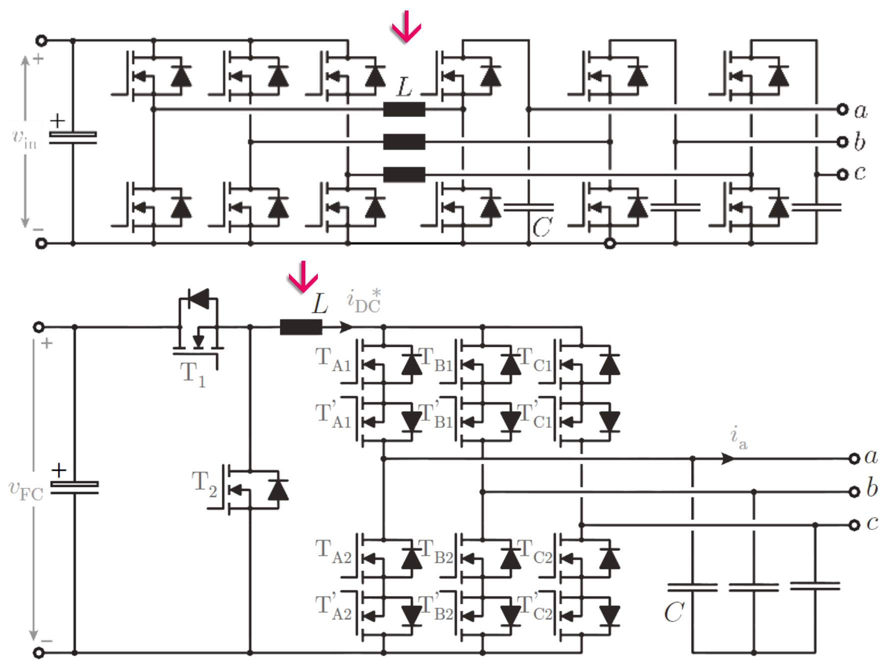
- *Dynamic Behavior V-f Control and Load-Step*
- *Smooth/Sinusoidal Voltage and Current Waveforms*

Three-Phase Integration

CSI & DC/DC Front-End

3-Φ Current Source Inverter Topology Derivation

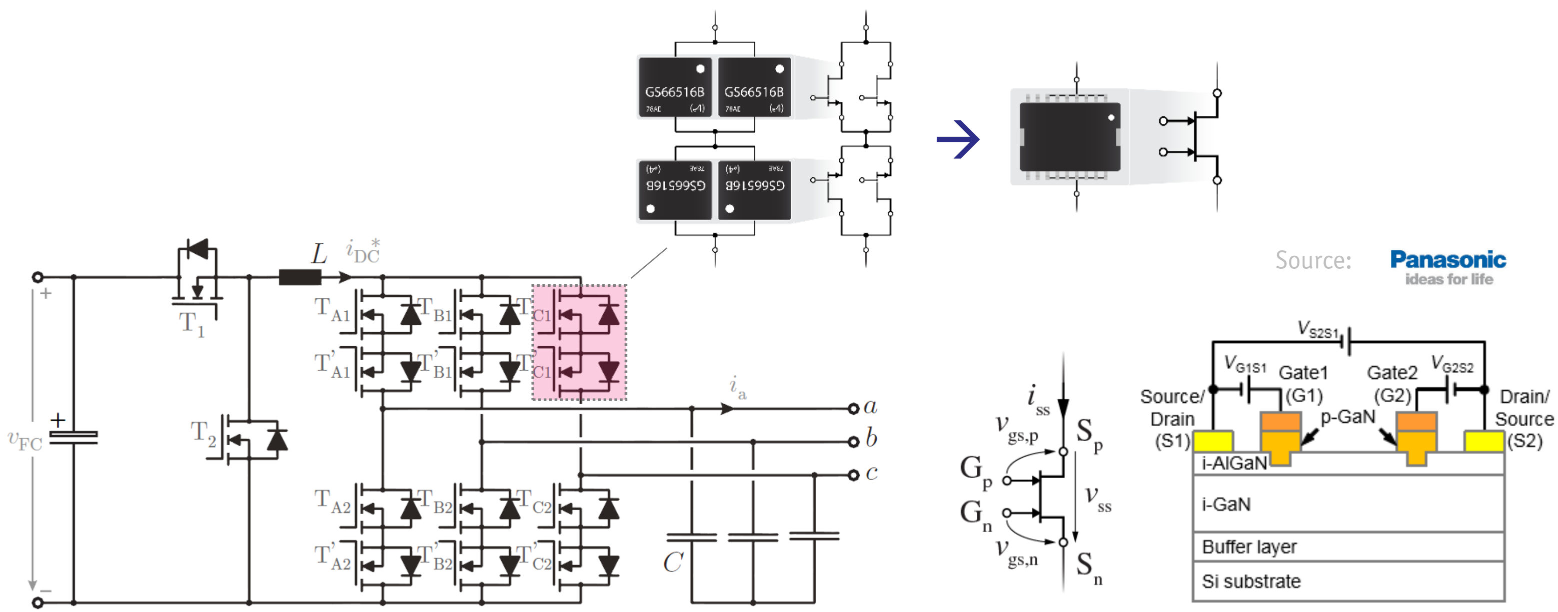
- *Y-Inverter* → *Phase Modules w/ Buck-Stage | Current Link | Boost-Stage*
- *3-Φ CSI* → *Buck-Stage V-I-Converter | Current DC-Link DC/AC-Stage*



→ *Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches*

3-Φ Current Source Inverter (CSI)

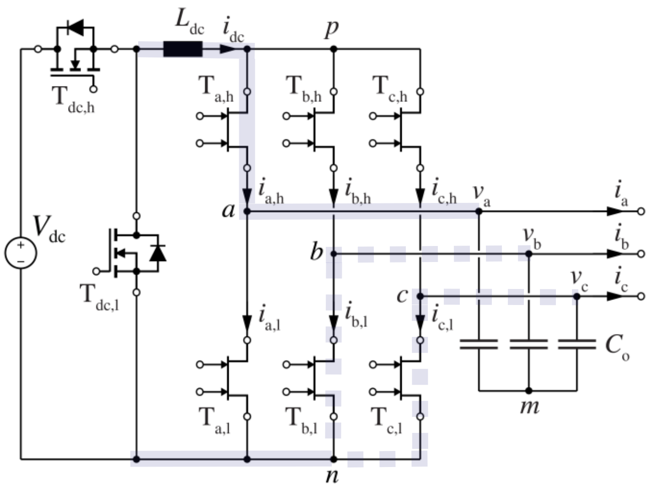
- *Bidirectional/Bipolar Switches → Positive DC-Side Voltage for Both Directions of Power Flow*

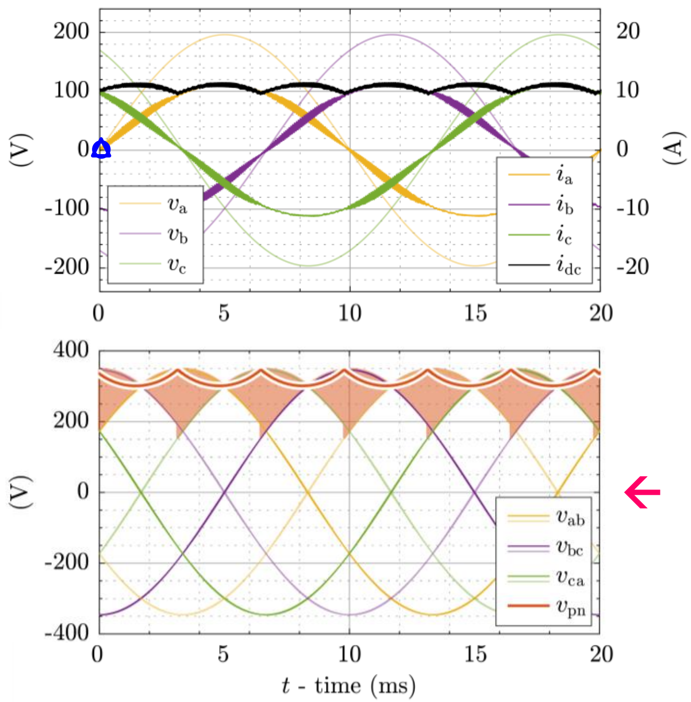


- *Monolithic Bidir. GaN Switches → Factor 4 (!) Red. of Chip Area Comp. to Disc. Realization*

3-Φ Buck-Boost CSI – Synergetic Control

- *"Synergetic" Control of Buck-Stage & CSI Stage*
- *6-Pulse-Shaping of DC Current by Buck-Stage → Allows Clamping of a CSI-Phase*





- *Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)*
- *Operation with Phase Shift of AC-Side Voltage & Current possible*

Conclusions

▶ Conclusions

- **"X-Technology": *SiC / GaN Enable Motor-integrated Drive Systems***

— *High dv/dt & Thermal Management are Major Challenges*
— *Continuous / Sinusoidal Output Voltage* → *Full-Sinewave Filters*

- **"X-Concepts": *Multi-Level Converters and Integrated Filters***

— *Low-Voltage Steps & Scaling of Inductor & FOM*
— *ALL SMD Realization* → *Automated Assembly*
— *Loss Distribution among many Devices* → *High Overload Capability*
— *Filtering Recommended* → *Powder Core*

— *Wide Input / Output Voltage Range*
— *Electromagnetically „Quiet"*
— *Synergetic Control & Monolithic Bidirectional GaN Switch*

- *System Level* → *Integration of Storage, Distributed DC Bus Systems / Industry 4.0 etc.*

Thank you!

Biography of the Presenter

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Dominik Bortis received the M.Sc. and Ph.D. degree in electrical engineering from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2005 and 2008, respectively. In May 2005, he joined the Power Electronic Systems Laboratory (PES), ETH Zurich, as a Ph.D. student. From 2008 to 2011, he has been a Postdoctoral Fellow and from 2011 to 2016 a Research Associate with PES.

Since January 2016 Dr. Bortis is heading the research group Advanced Mechatronic Systems at PES, which concentrates on ultra-high speed motors, bearingless drives, linear-rotary actuator and machine concepts with integrated power electronics. Targeted applications include e.g. highly dynamic positioning systems, medical systems, and future mobility concepts. Dr. Bortis has published 90+ scientific papers in international journals and conference proceedings. He has filed 30+ patents and has received 8 IEEE Conference Prize Paper Awards and 2 First Prize Transaction Paper Award.