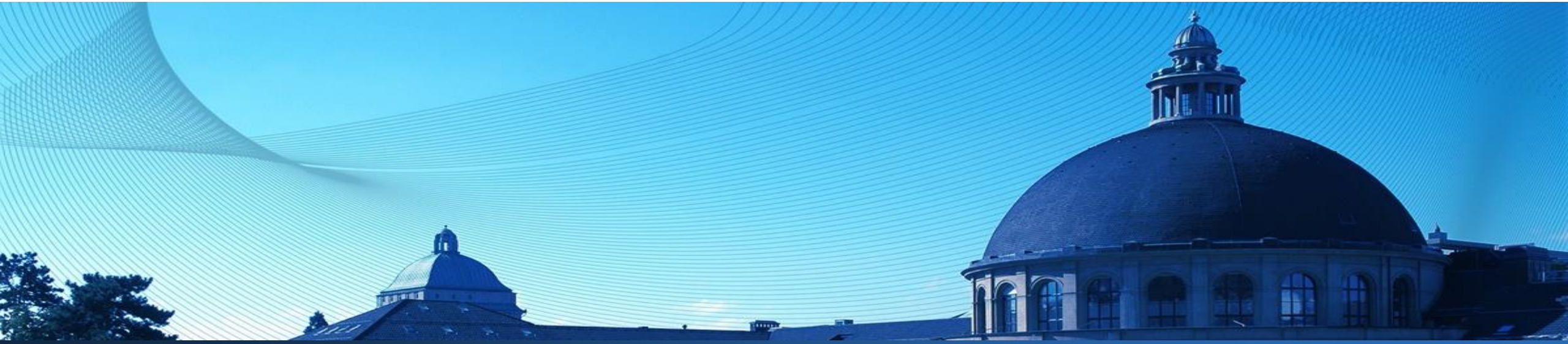
Future SiC/GaN Variable Speed Drive Inverter Topologies

"How to Handle a Double-Edged Sword"

Dominik Bortis, et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

2nd Wagner Automotive Symposium — Inverter Trends & Technology, November 7th, 2019



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Dominik Bortis, M.Guacci, M. Antivachis, J.W. Kolar

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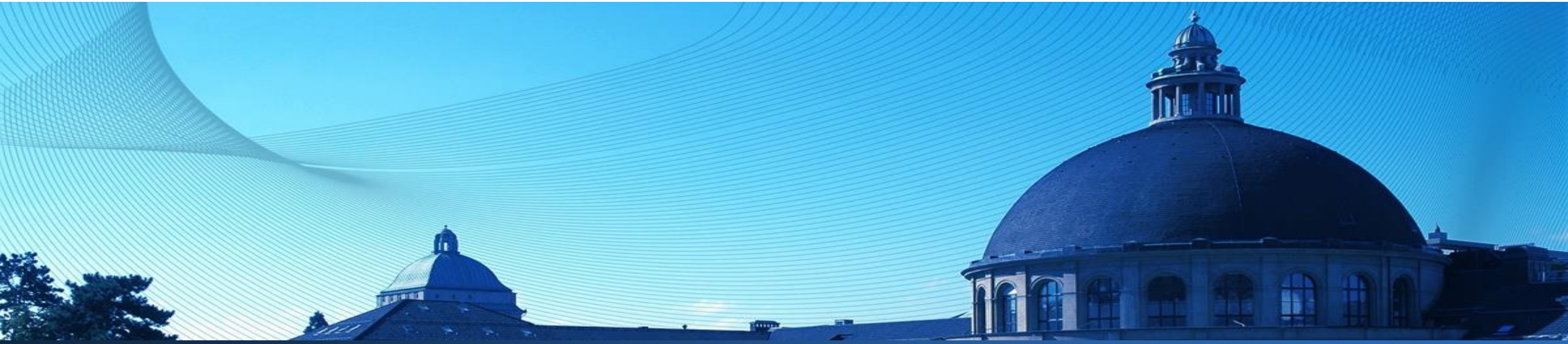


ETH Zurich

21	Nobel Prizes
509	Professors
5800	T&R Staff
2	Campuses
136	Labs
35%	Int. Students
90	Nationalities
36	Languages
150th	Anniv. in 2005

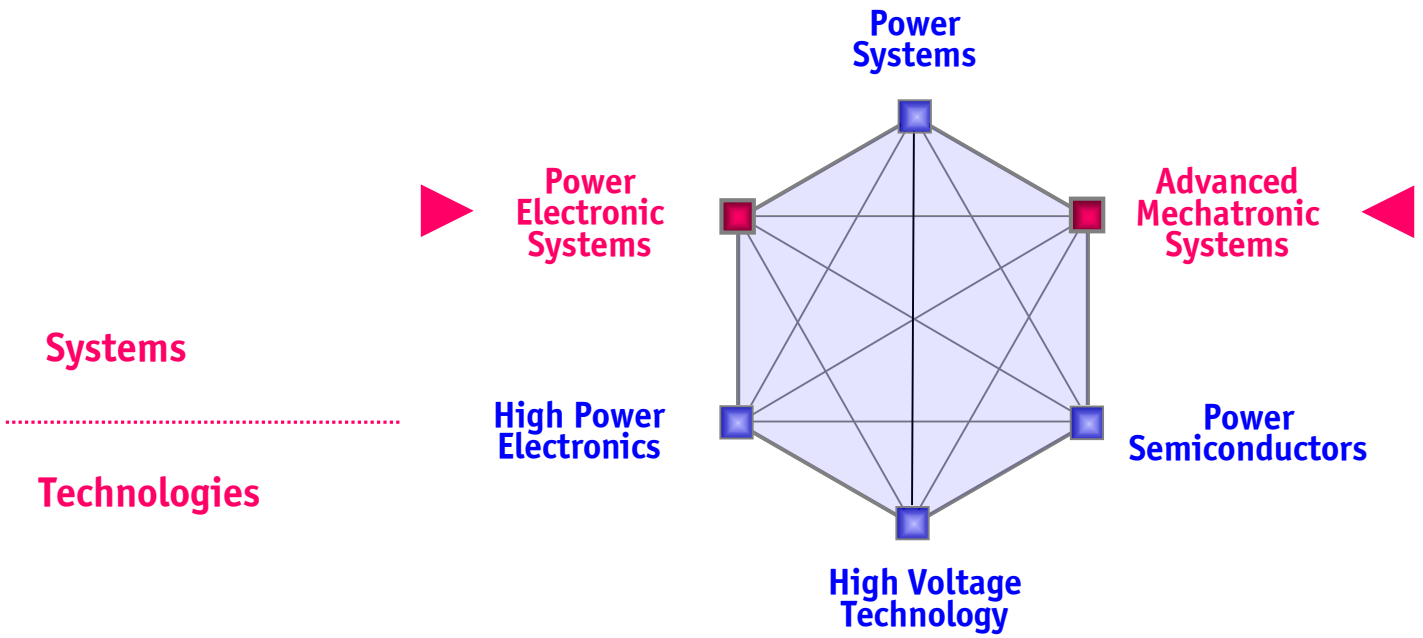
Departments

ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	**Information Technology and Electrical Eng.**
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

Students ETH in total

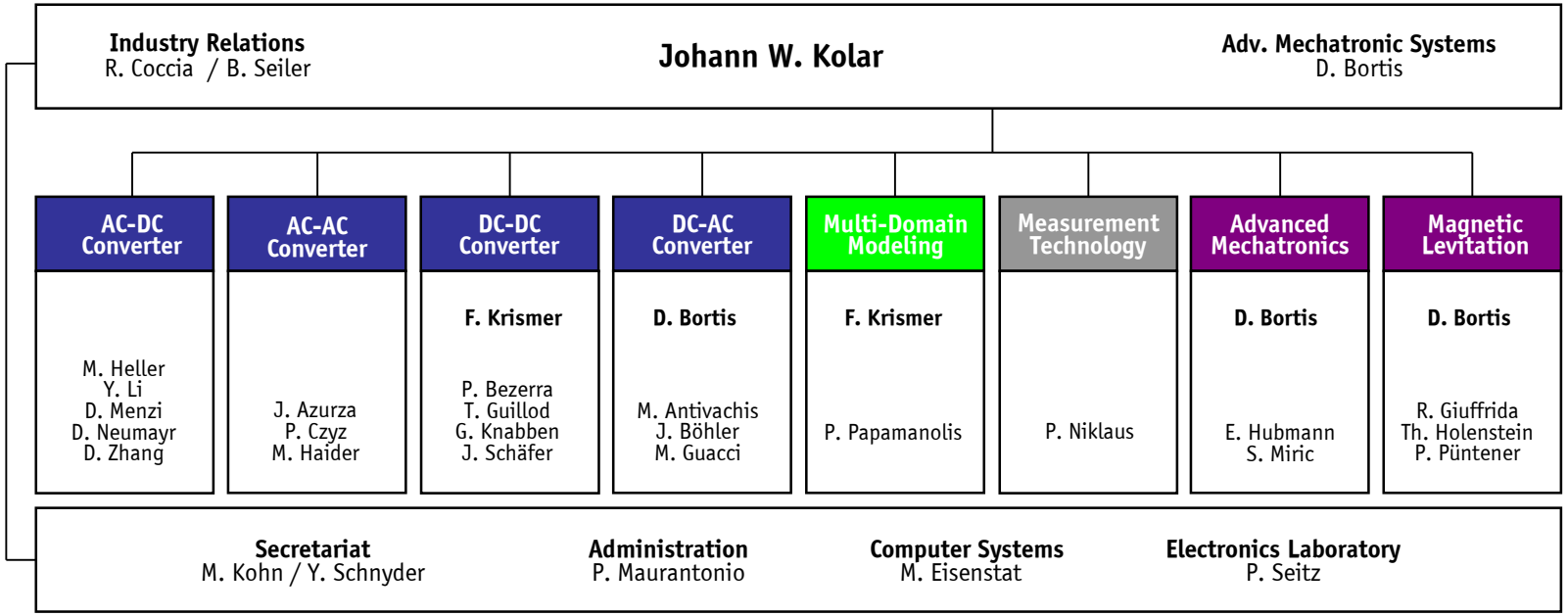
21'000	B.Sc.+M.Sc.-Students
4'300	Doctoral Students

ITET – Research in E-Energy



- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory



22 Ph.D. Students
1 PostDoc
2 Sen. Researchers

ECPE Competence Centre

EPSMA

Leading Univ. in Europe

Outline

- *Introduction*
- *SiC/GaN Application Challenges*
- *VSI with Output Filters*
- *Boost-Buck VSI*
- *Buck-Boost CSI*
- *Q3L & Modular Inverters*
- *Conclusions*

Acknowledgement: J. Azurza, T. Guillod, F. Krismer, D. Menzi, J. Miniböck, P. Niklaus, P. Papamanolis, D. Zhang

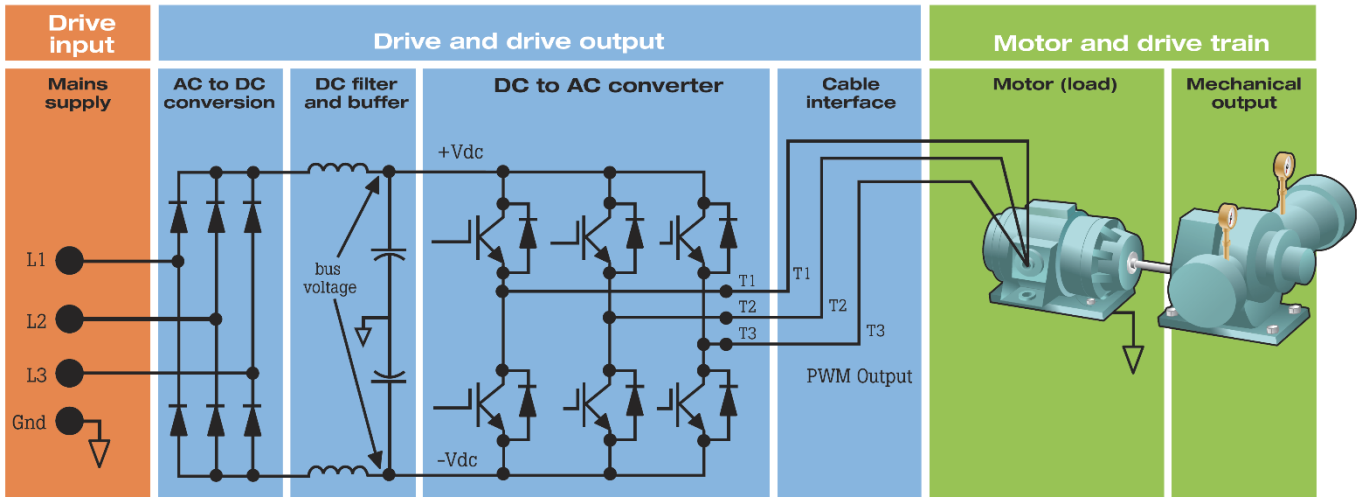
3-Φ Variable Speed Drive Inverter Systems

State-of-the-Art
Future Requirements

▶ VSD State-of-the-Art

- *Mains Interface / 3-Φ PWM Inverter / Motor — All Separated*
  - → *Large Installation Space / $$$*
  - → *Complicated / Expert Installation / $$$*
- *Conducted EMI / Radiated EMI / Bearing Currents / Reflections on Long Motor Cables*
  - → *Shielded Motor Cables / $$$*
  - → *Inverter Output Filters (Add. Vol.) / $$$*

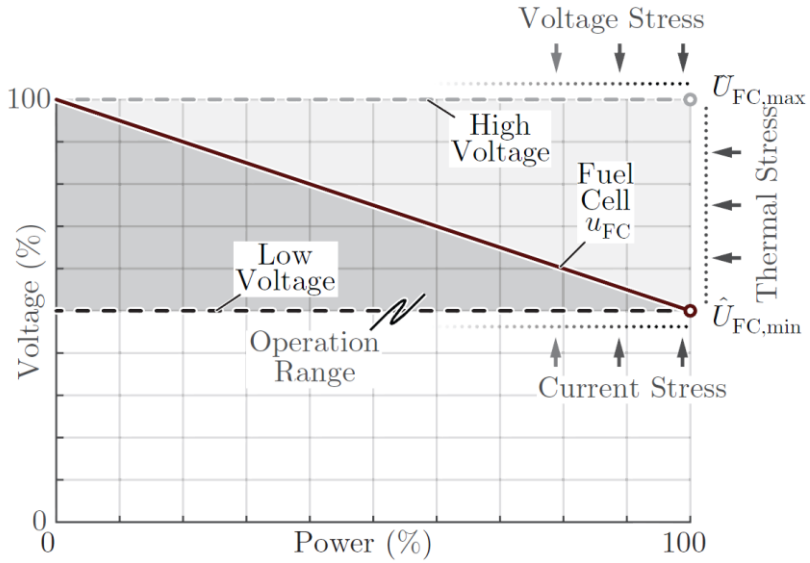
Source: FLUKE



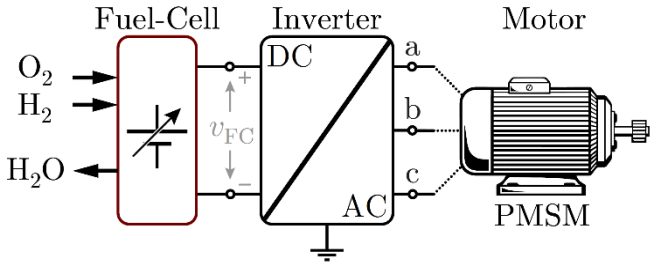
- *High Performance @ High Level of Complexity / High Costs (!)*

Future Requirements (1)

- *"Non-Expert" Install. / Low-Cost Motors* → *"Sinus-Inverter" OR Integrated Inv.*
- *Wide Applicability / Wide Voltage & Speed Range* → *Matching of Supply & Motor Voltage*
- *High Availability*



Source: magazine.fev.com

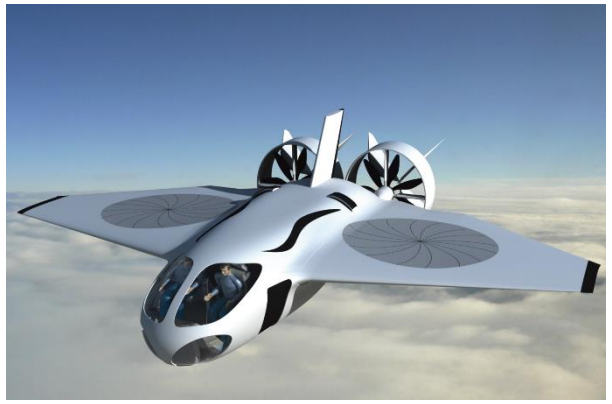


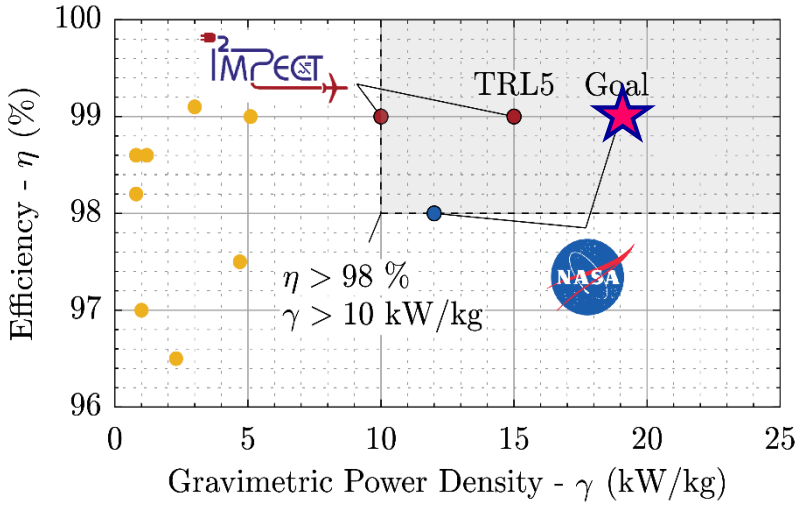
- *Single-Stage Energy Conversion* → *No Add. Converter for Voltage Adaption*

Future Requirements (2)

- Red. Inverter Volume / Weight → Matching of Low High-Speed Motor Volume
- Lower Cooling Requirement → Low Inverter Losses & Low HF Motor Losses
- High Speed Machines → High Output Frequency Range

Source: Georgia Tech

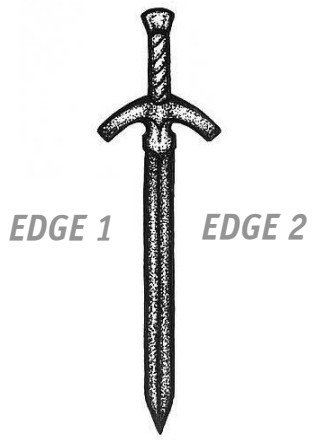




→ Main "Enablers" — SiC/GaN Power Semiconductors & Adv. Inverter Topologies

Enabling Technologies & Challenges

WBG Semiconductors
Advanced Inverter Topologies

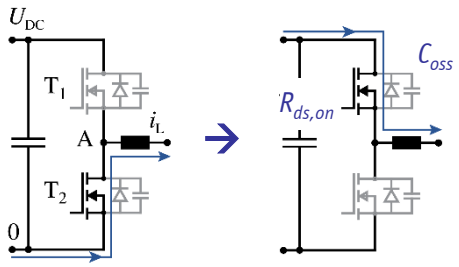


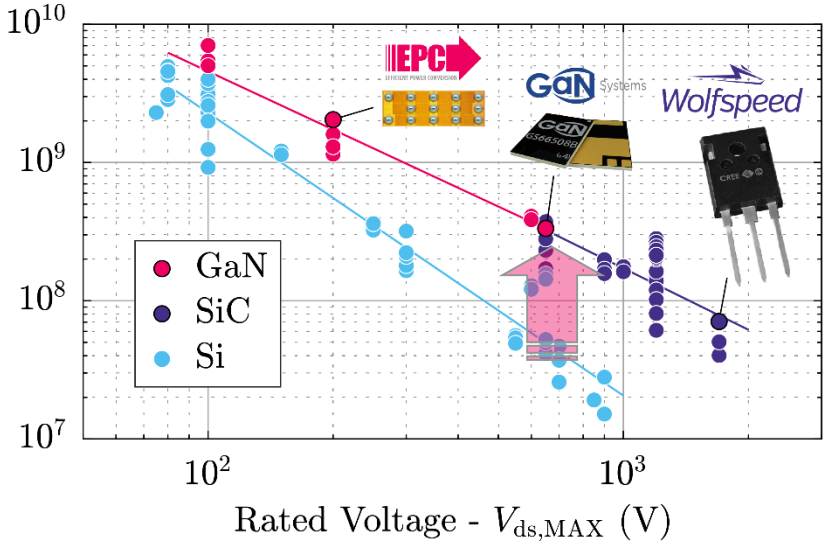
Idea: F.C. Lee

▶ SiC/GaN

- Very Low On-State Resistance → Low (Partial Load) Conduction Losses
- Very Low Switching Losses → High Switching Frequencies
- Small Chip Area → Compact Realization

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





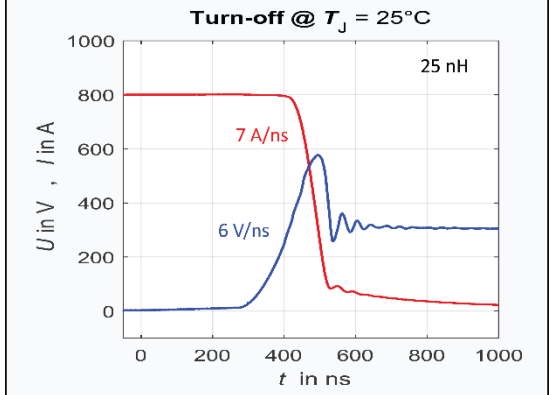
- Challenges → Packaging / Thermal Management / Gate Drive / PCB Layout

▶ Si vs. SiC

- *Extremely High dv/dt (Si-IGBT: dv/dt = 2…6kV/us vs. SiC-MOSFETs: dv/dt = 20…60kV/us)*
- *Very Low Switching Losses*
- *High Switching Frequencies*

Source: M. Bakran / ECPE 2019

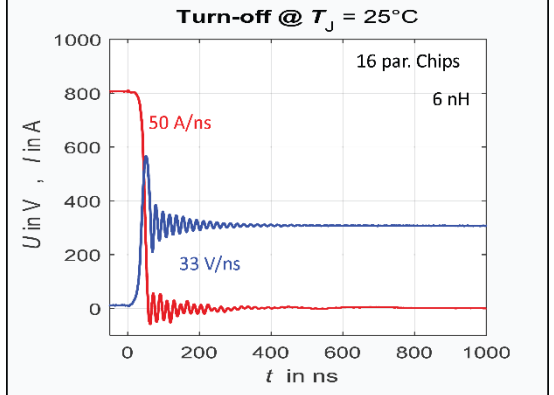
Si-IGBT / Hybrid-Pack 2



E_{off} = 45900 µJ

-> 8 kV/µs at 400V

SiC-MOSFET / (scaled for low inductance)



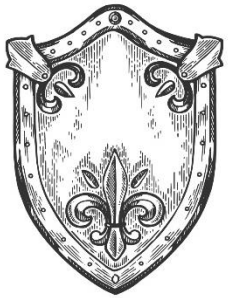
E_{off} = 4672 µJ

-> 44 kV/µs at 400 V

- *Challenges* → *Motor Insul. Stress (Volt. Peaks → Insul. Breakdown → Partial Discharge)*
  → *Reflections (Impedance Mismatch of long Cable & Motor)*
  → *Bearing Currents (Motor Shaft Volt. → Elect. Discharge in Bearing)*
  → *EMI (Conducted & Radiated)*

Inverter Output Filters

Full-Sinewave Filtering



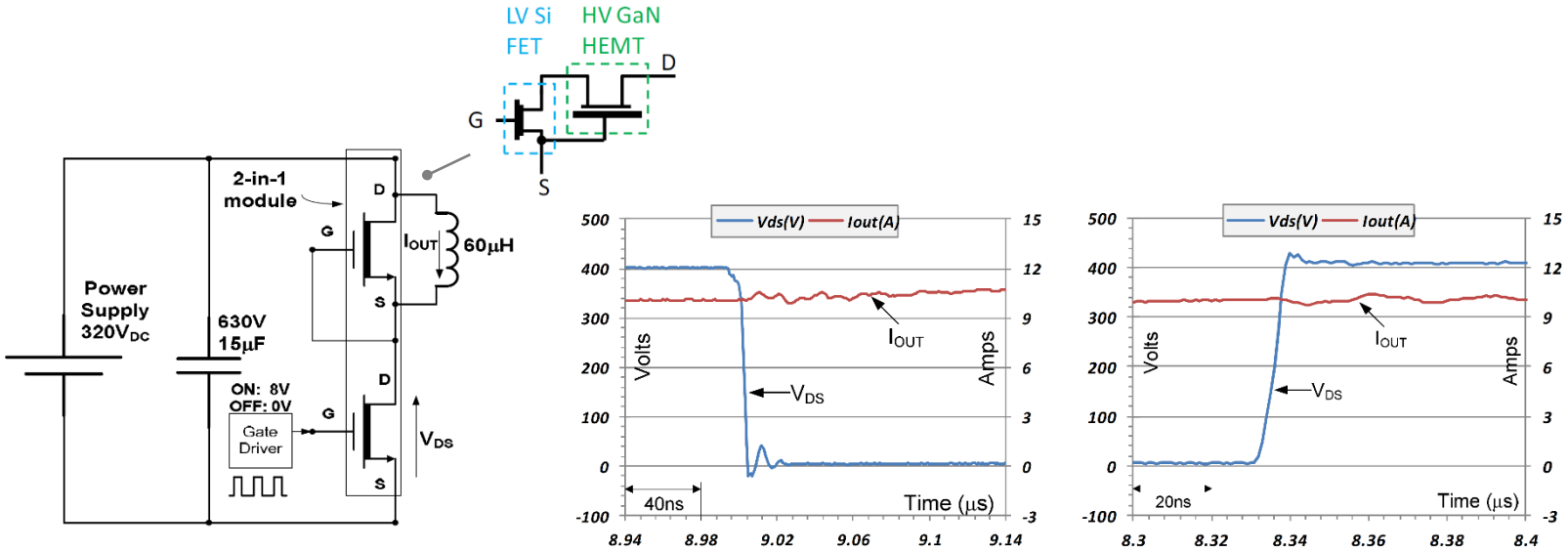
Full-Sinewave Filtering

YASKAWA

▶ 3-Φ 650V GaN Inverter System (1)

Source: YASKAWA

- *Transphorm 650V GaN HEMT/30V Si-MOSFET Cascode Switching Devices*
- *Measurement of Sw. Properties → Turn-On/Off 10A/400V*

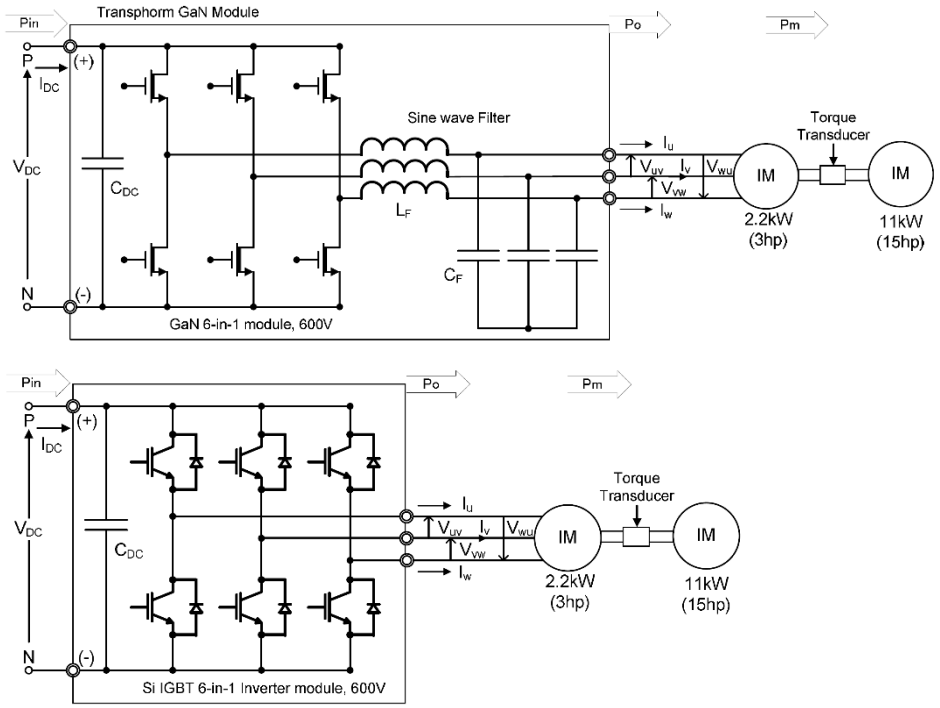


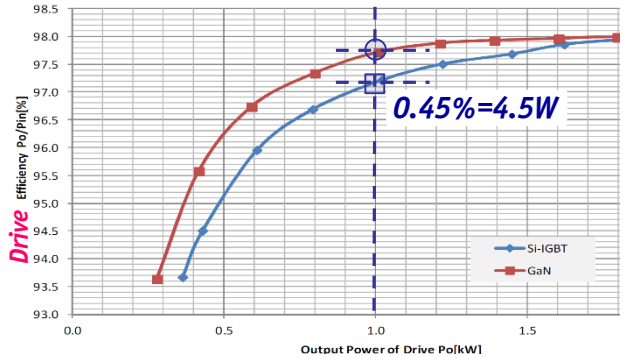
- *Factor 10 Lower On/Off Delay & Sw. Times Comp. to IGBTs*
- *Extremely Low Sw. Losses → Inverter Sw. Frequency f_S= 100kHz*
- *Sinewave LC Output Filter → Corner Frequency f_C= 34kHz (f_S= 100kHz)*

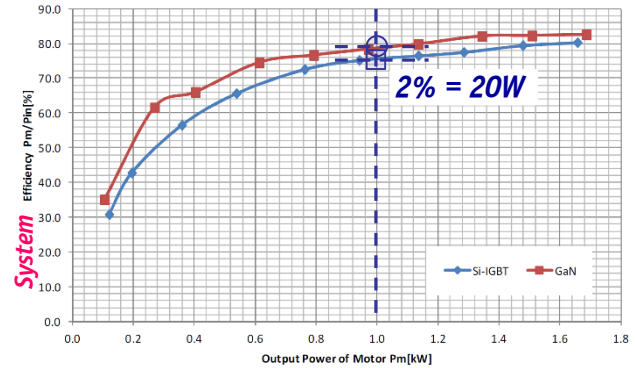
▶ 3-Φ 650V GaN Inverter System (2)

Source: YASKAWA

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





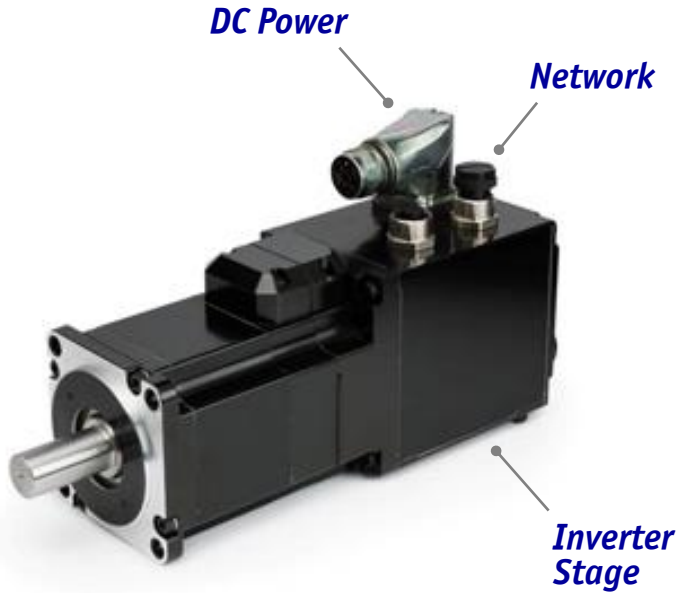


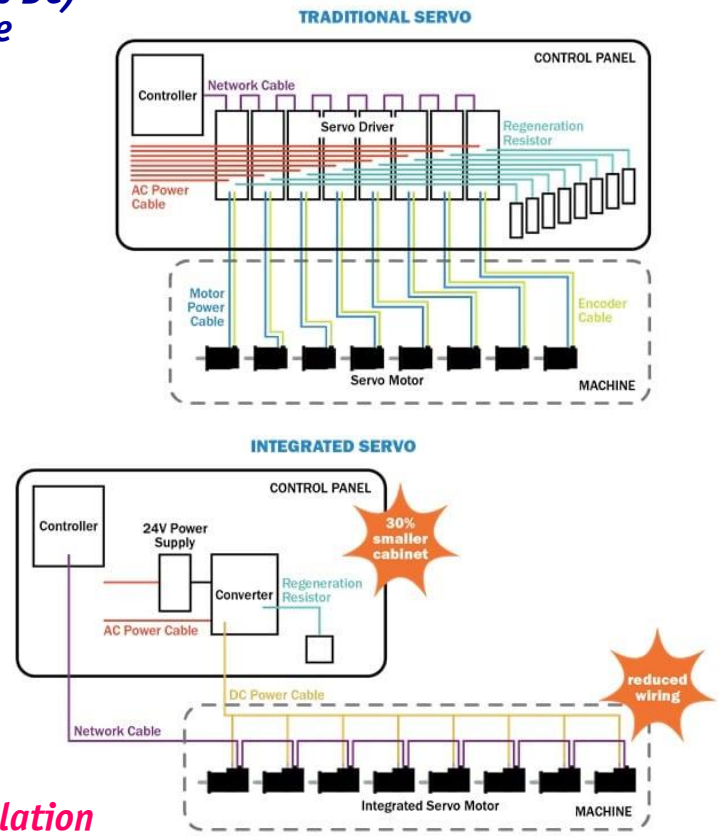
→ 2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses) !

▶ 3-Φ 650V GaN Inverter System (3)

Source: YASKAWA

- *Sigma-7F Servo Drive — Integration of Inverter (TO-220 GaN) Into Motor Housing*
- *Distributed DC-Link System ("Converter" generates DC)*
- *0.1 – 0.4kW / 270...324V Nominal DC Link Voltage*





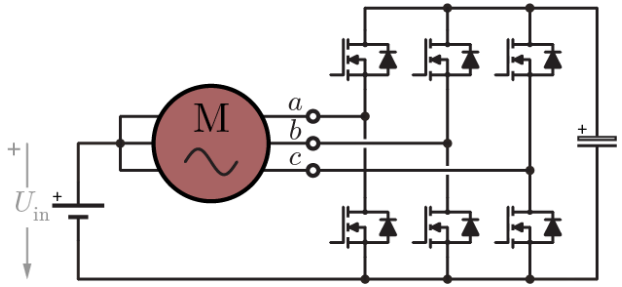
- *Small Size (0.4 kW @ 70 x 70x 170mm)*
- *Massive Saving in Cabling Effort / Simplified Installation*

Buck-Boost Inverter

VSI & DC/DC Front-End
Phase-Modular Buck-Boost Inverter
CSI & DC/DC Front-End

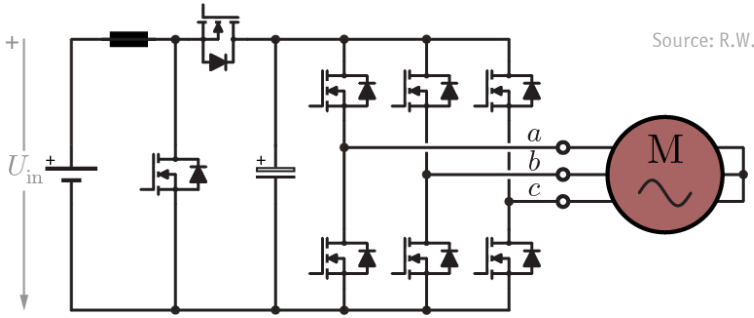
▶ Boost Converter DC-Link Voltage Adaption

- *Inverter-Integr. DC/DC Boost Conv. → Higher DC-Link Voltage / Lower Motor Current*
- *Access to Motor Star Point & Specific Motor Design Required*
- *No Add. Components*



Source: J. Pforr et al. / 2009

- *Explicit Front-End DC/DC Boost Stage*

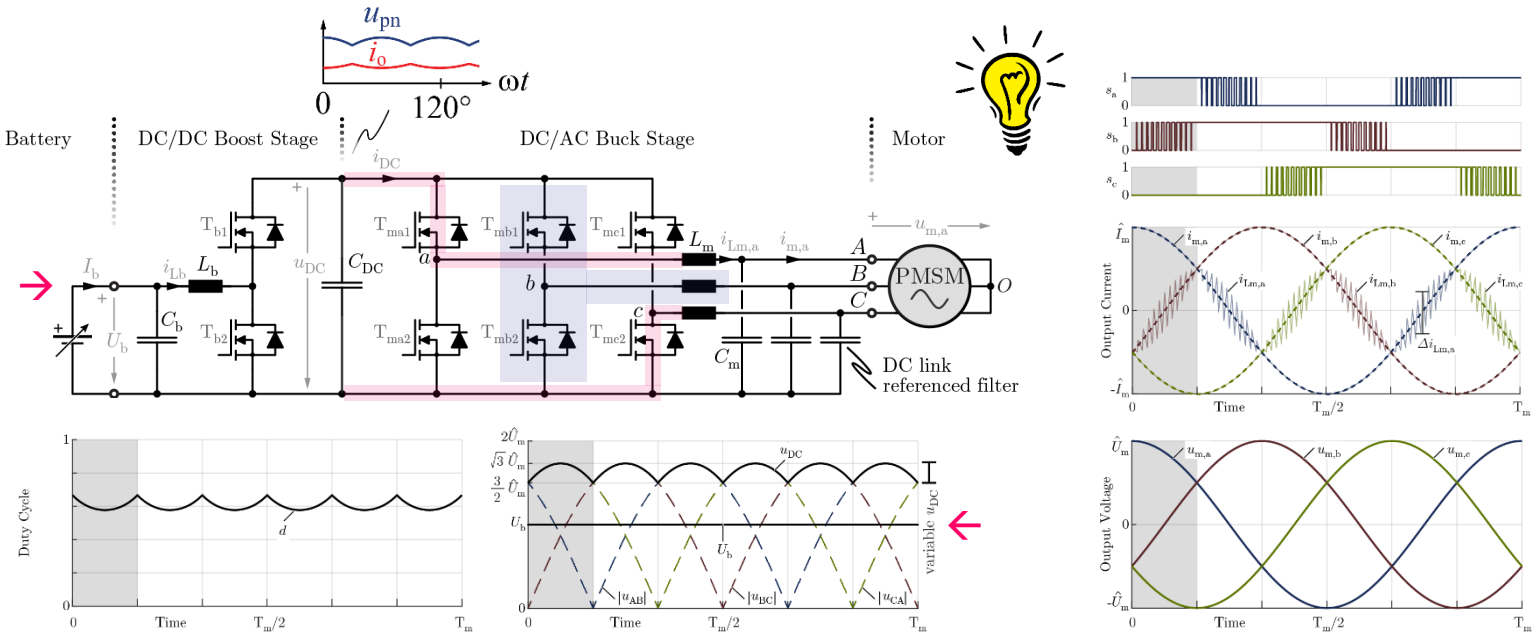


Source: R.W. Erickson et al. / 1986

→ *Analyze Coupling of the Control of Both Converter Stages → "Synergetic Control"*

▶ "Synergetic Control" of Boost-Buck Inverter (1)

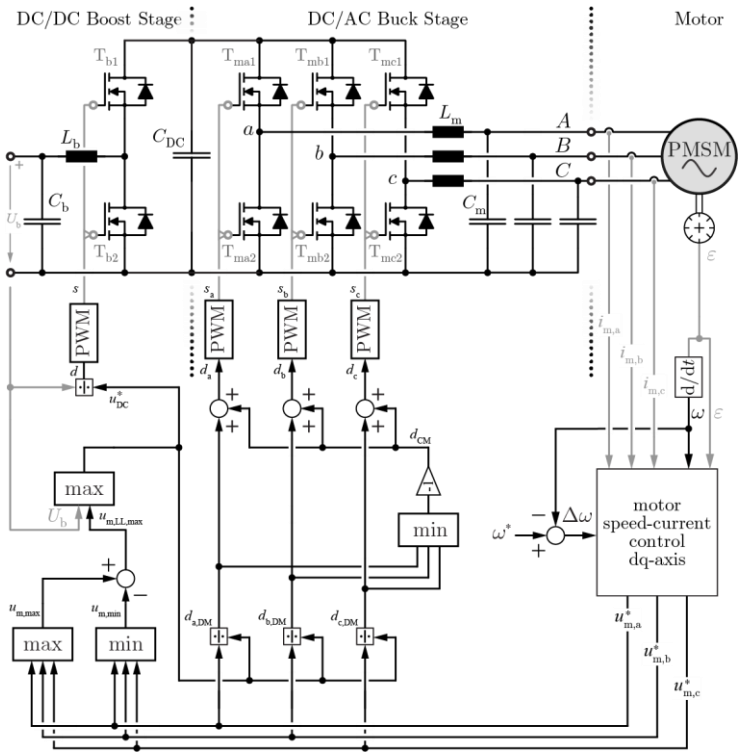
- DC/DC Boost Converter Used for 6-Pulse Shaping of DC-Link Voltage
- 2 (!) Inverter Phases Clamped (1/3 PWM) → Low Switching Losses / High Efficiency
- Conv. PWM Inverter / Clamped Boost-Stage Operation @ Low Speed

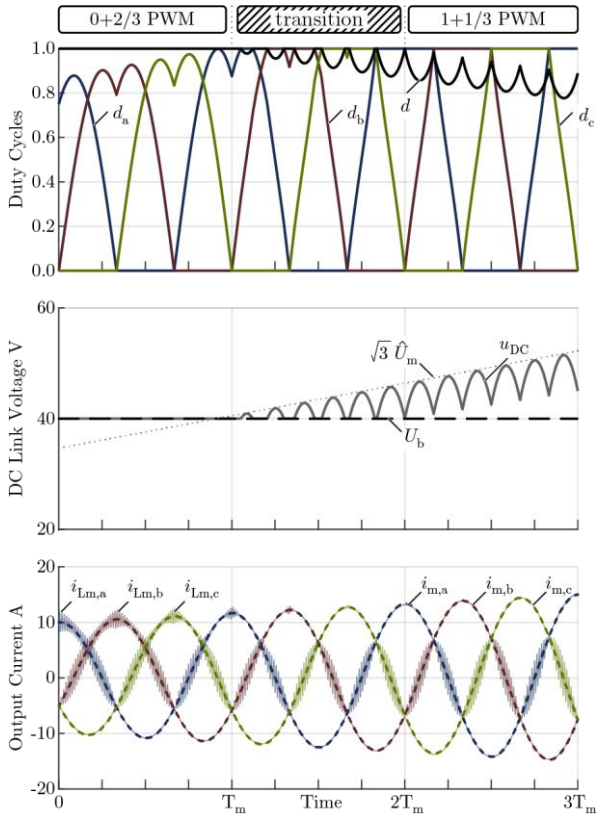


- Preferable for Low-Dynamics Drive Systems

▶ "Synergetic Control" of Boost-Buck Inverter (2)

■ Control Structure and Simulation Results





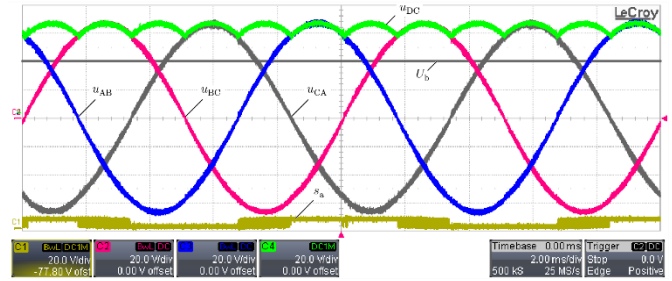
- **Seamless Transition** — Clamped Boost-Stage → Temporary → Full Boost-Stage Operation

▶ "Synergetic Control" of Boost-Buck Inverter (3)

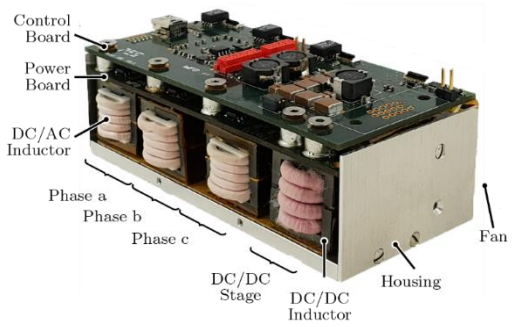
■ Experimental Verification

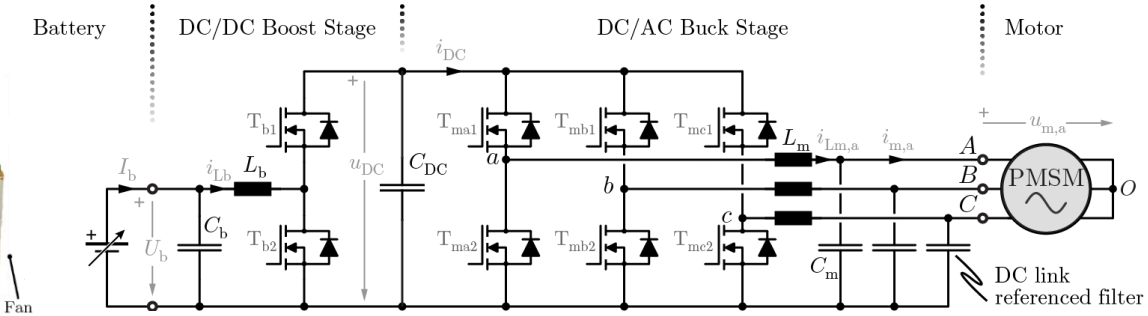
U_b = 40...60V
P = 500W
f_S = 300kHz (200V EPC GaN, 2 per Switch)
f_0 = 5kHz (max.)
M = 0...2 (for U_b=40V)

$$M = \frac{\hat{U}_\mathrm{m}}{\frac{1}{2}U_\mathrm{b}}$$



185cm³ / 11.3in³

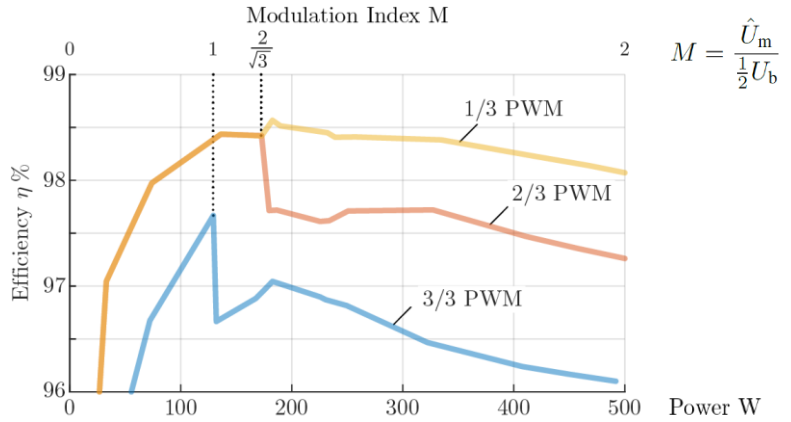


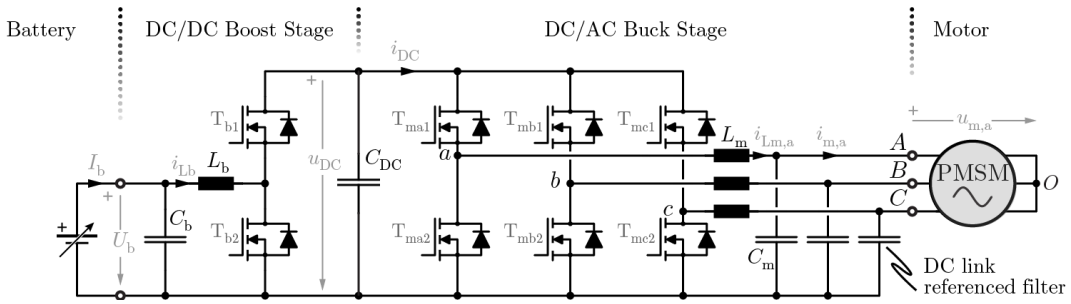


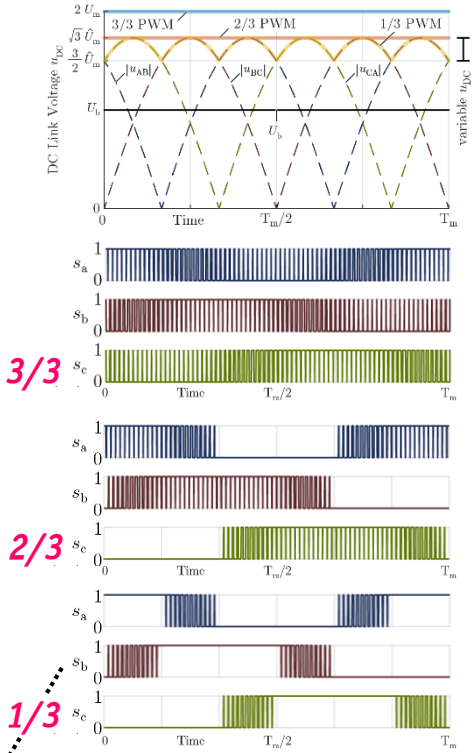
→ Comparison to Conv. U_{DC}=const. Operation (PWM of 2/3 Phases or 3/3 Phases)

▶ "Synergetic Control" of Boost-Buck Inverter (4)

- **Experimental Verification**
  - Const. DC-Link Voltage & PWM of 3/3 Phases or 2/3 Phases
  - Synergetic Control = PWM of 1/3 Phases → Substantial Loss Saving (!)





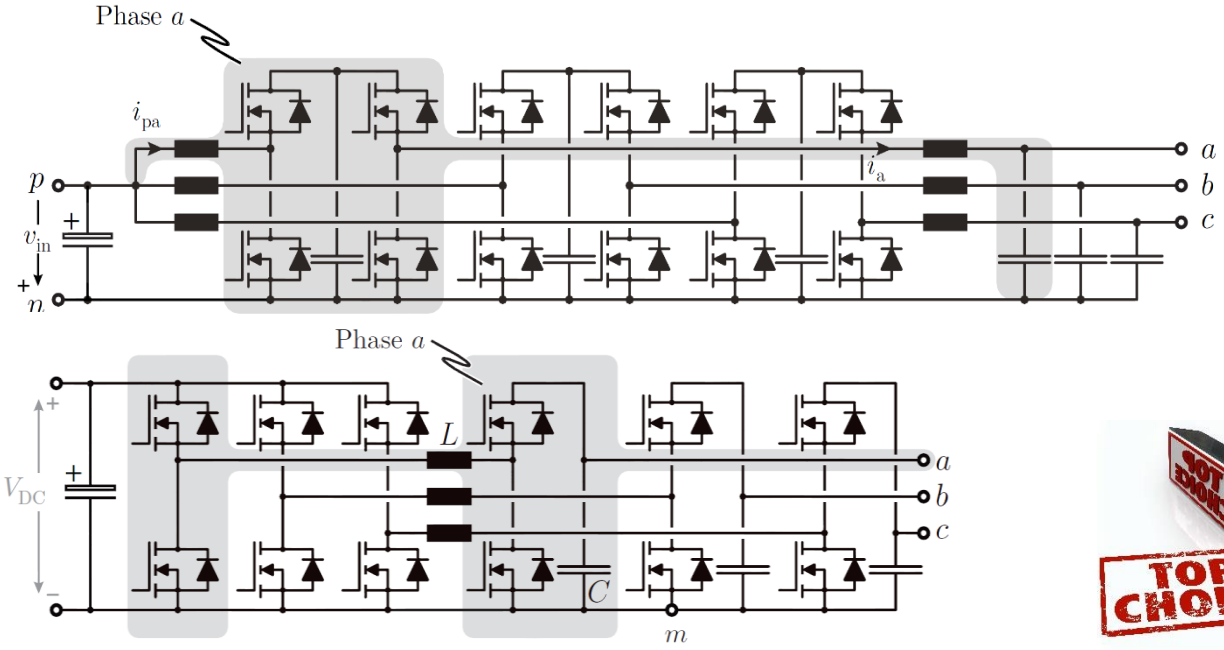


Phase-Modular Topologies

Boost-Buck Modules
Buck-Boost Modules

▶ Phase-Modular Boost-Buck / Buck-Boost Inverter

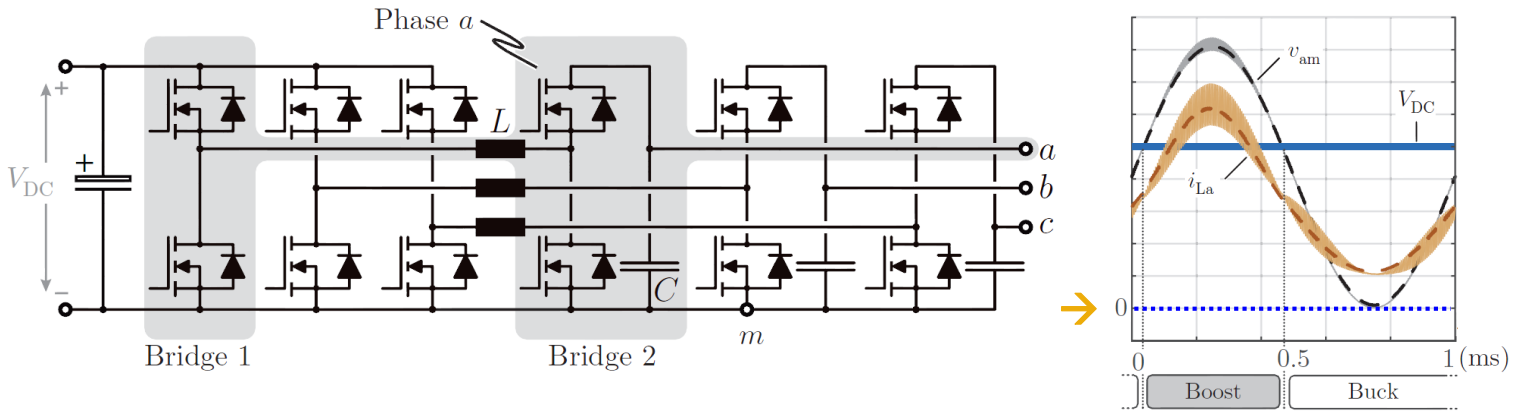
- *Realization of 3-Φ Inverter Using 3 DC/DC Converter (Phase) Modules — S. Cuk/1982*
- *Wide Voltage Conv. Range → Battery or Fuel-Cell Supply & Adaption to Motor Voltage*
- *Continuous Output Voltage → Explicit or Integrated LC Output Filter*



→ *Preference for Low Number of Ind. Components → Buck-Boost Concept — "Y-Inverter"*

Y-Inverter Lighthouse Project

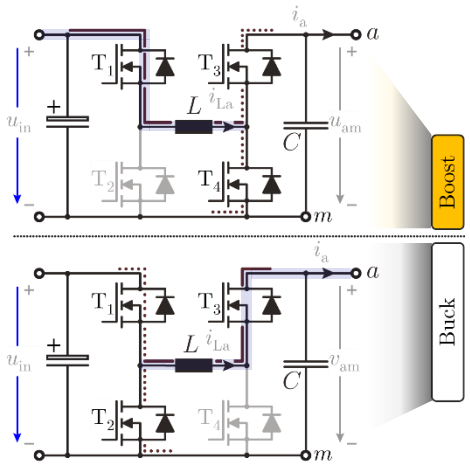
- 3-Φ Continuous Output / Low EMI ! - No Shielded Cables / No Insul. Stress
- Buck-Boost Operation / Wide Input &/or Output Range - Industrial Drive
- Standard Bridge Legs / Building Blocks - 1.2kV SiC MOSFETs
- High Power Density

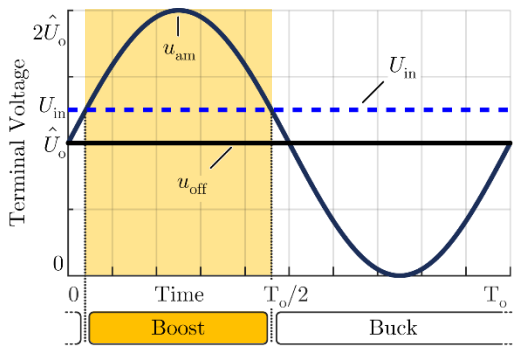


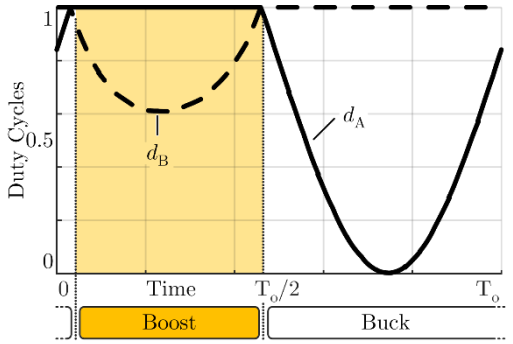
- Project Scope → Hardware Demonstrator / Exp. Analysis / Comparative Evaluation

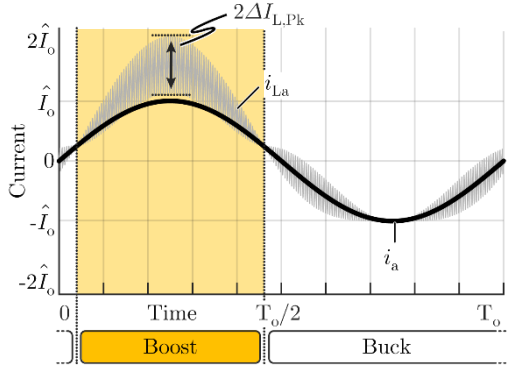
▶ Y-Inverter (1)

- *Operating Behavior*





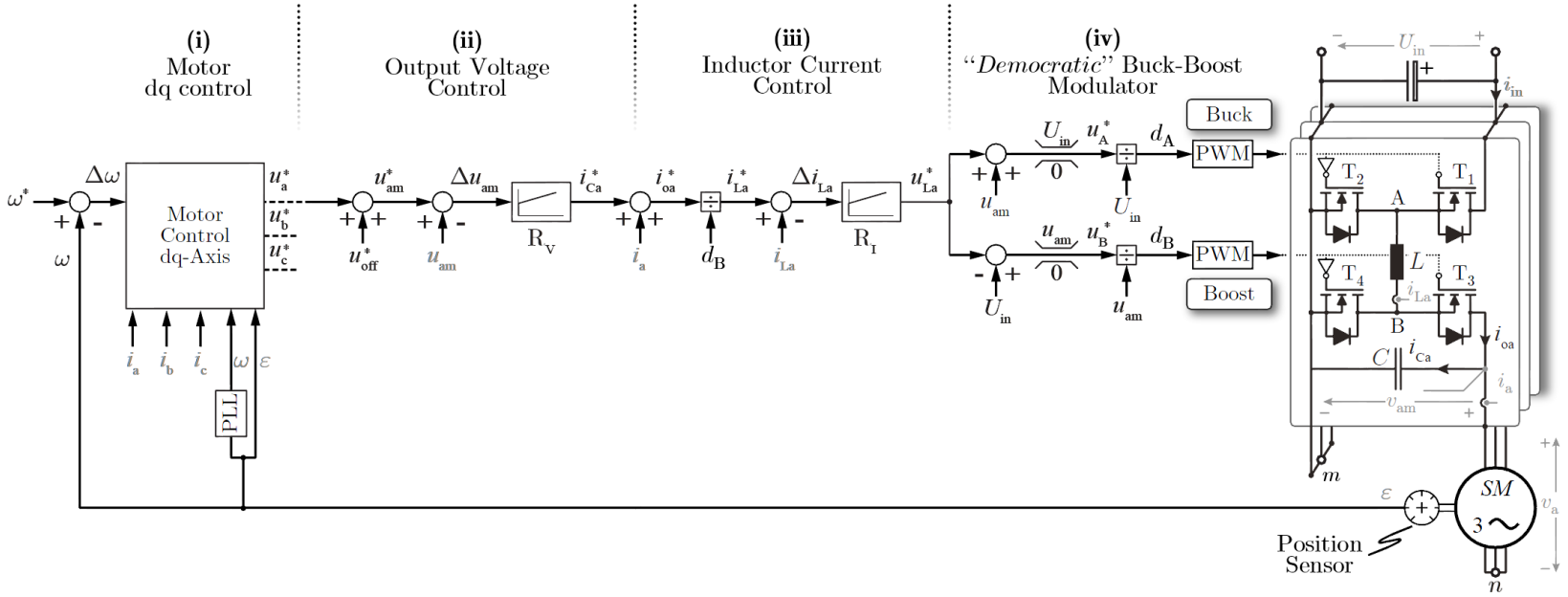




- $u_{am} < U_{in}$ → Buck Operation
- $u_{am} > U_{in}$ → Boost Operation
- Output Voltage Generation Referenced to DC Minus

▶ Y-Inverter (2)

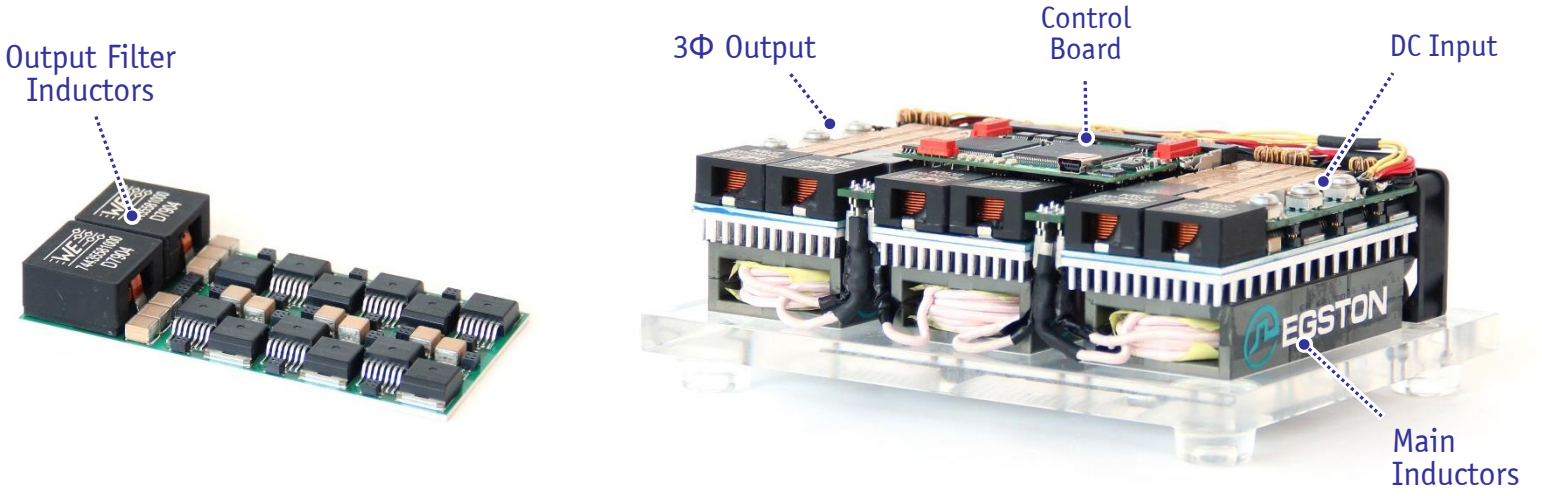
• Control Structure



■ *"Democratic Control"* → **Seamless Transition Between Buck & Boost Operation**

▶ *Y-Inverter Prototype*

- DC Voltage Range 400...750V_{DC}
- Max. Input Current ± 15A
- Output Voltage 0...230V_{rms} (Phase)
- Output Frequency 0...500Hz
- Sw. Frequency 100kHz
- 3x SiC (75mΩ)/1200V per Switch
- IMS Carrying Buck/Boost-Stage Semicond. & Comm. Caps & 2nd Filter Ind.



- Dimensions → 160 x 110 x 42 mm^3 (15kW/dm^3, 245W/in^3)

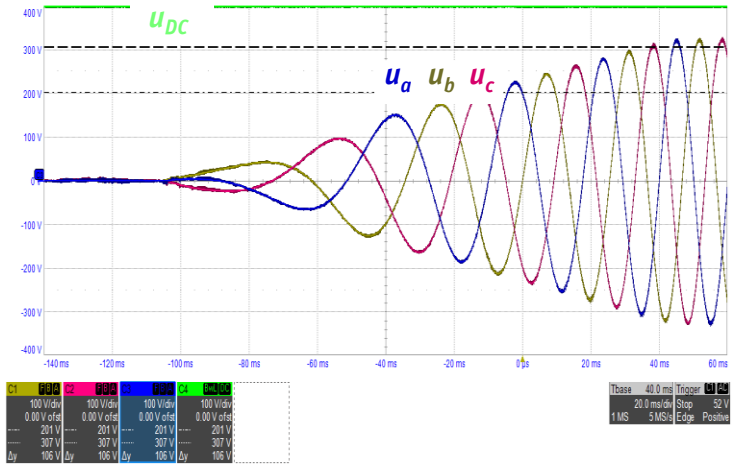
▶ Experimental Results - Dynamic Behavior

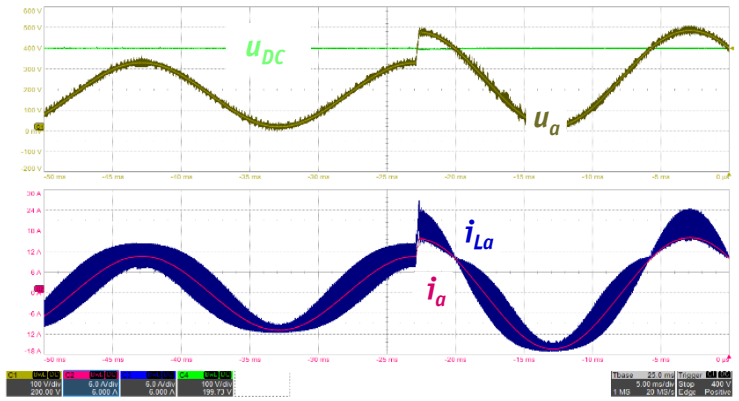
- *Transient Operation*

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

P = 6.5kW

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

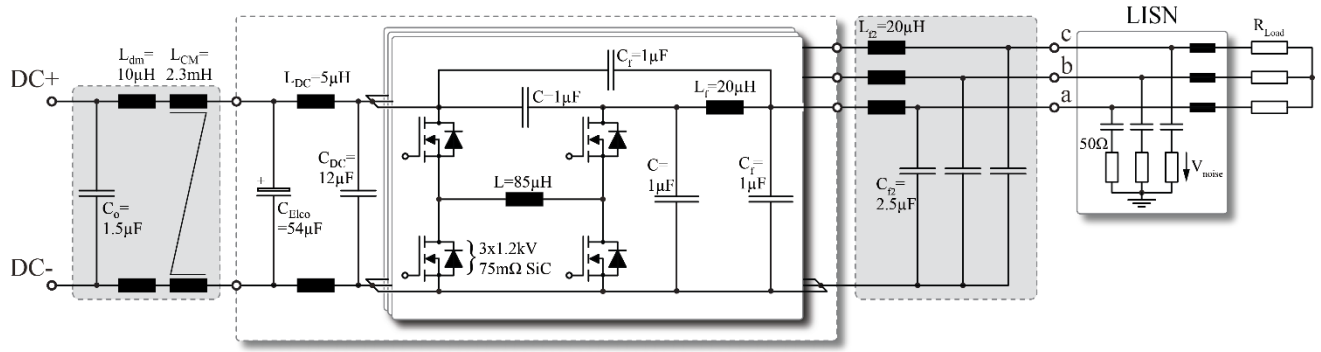


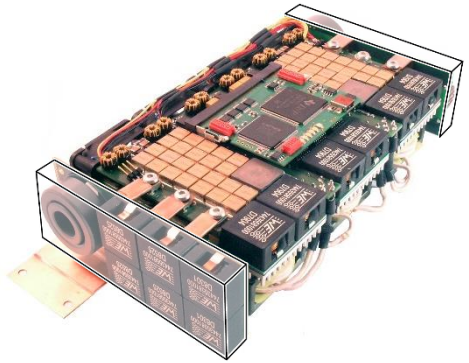


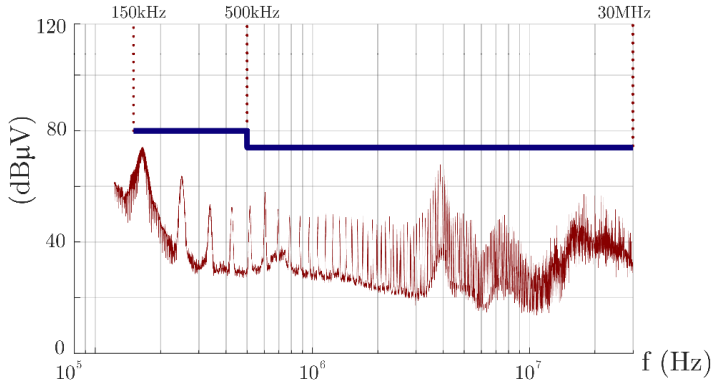
- *Dynamic Behavior V-f Control and Load-Step*

▶ Experimental Results - Conducted EMI

- Measurements of the Cond. EMI Noise on the AC-Side (QP, with AC-LISN)



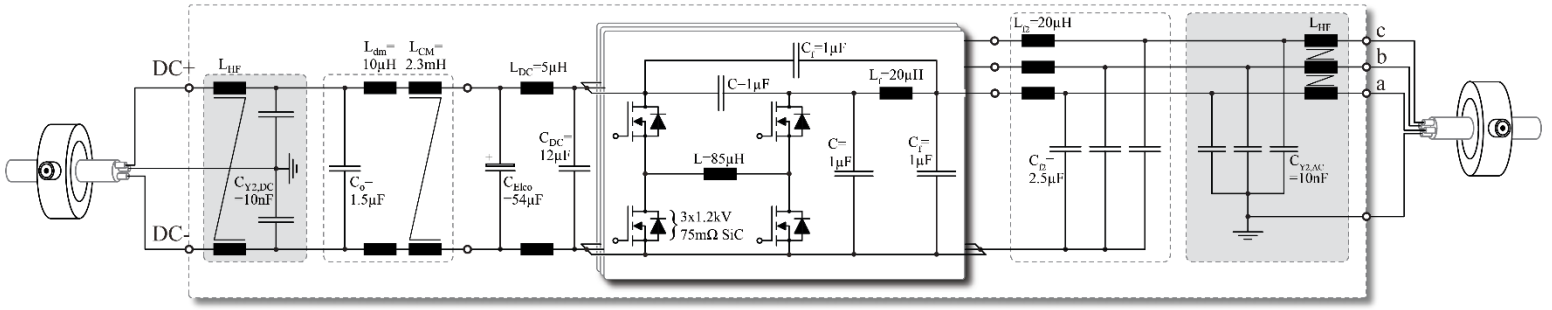


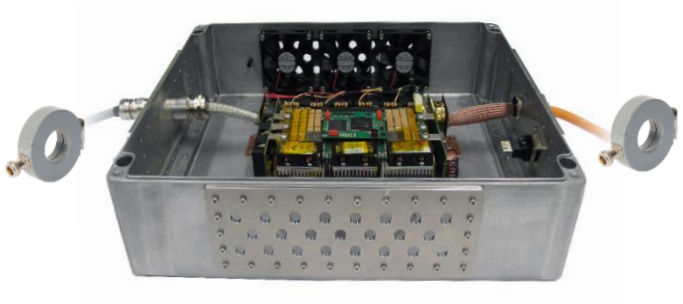


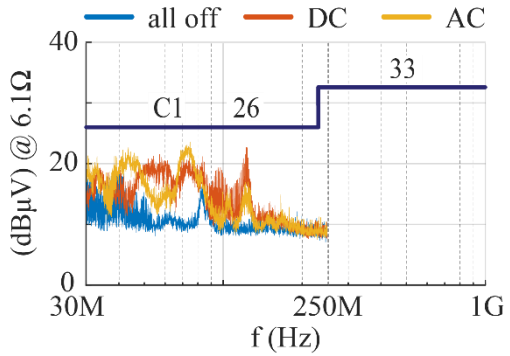
→ *Low Add. EMI Filter Volume — 74cm³ for Each Filter (incl. Radiated EMI Filter)*
→ *Total Power Density Reduces — 15kW/dm³ (740cm³) → 12kW/dm³ (890cm³)*
→ *Conducted EMI with Unshielded Motor Cable Fulfilled*

▶ Experimental Results - Radiated EMI

- Y-Inverter Placed in Metallic Enclosure → Emulate Housing, but UNshielded Cables (!)
- Measurement Setup → According IEC 61800-3
- Alternative Measurement Principle → Conducted CM-Current Instead of Radiation





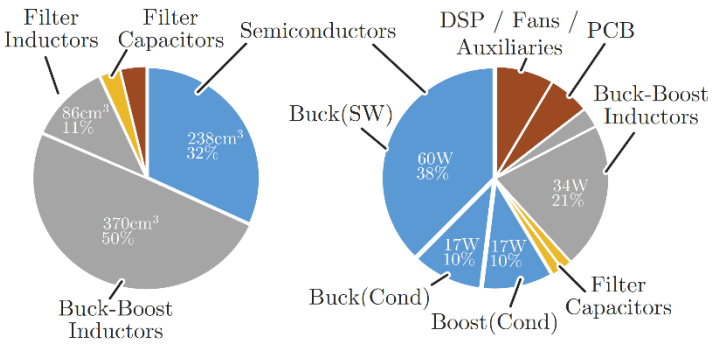


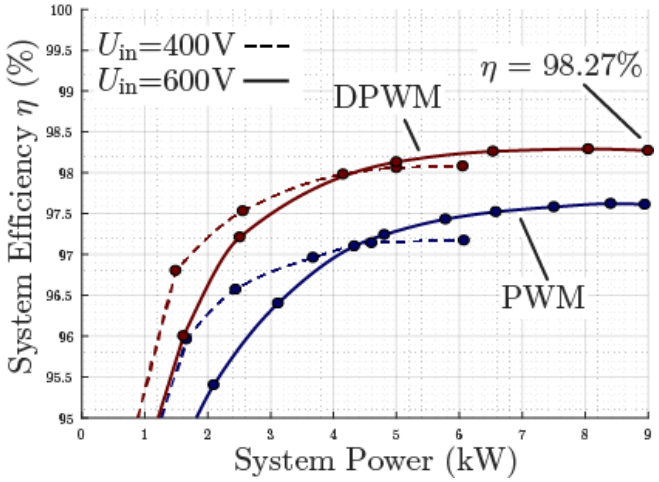
→ *Already Noticeable Noise Floor*
→ *HF-Emissions Well Below Equivalent EMI-Limit* → Verification Using Antenna

▶ Efficiency Measurements

- *Dependency on Input Voltage & Output Power Level*

U_{DC}= 400V / 600V
U_{AC}= 230V_{rms} (Motor Phase-Voltage)
f_S = 100kHz





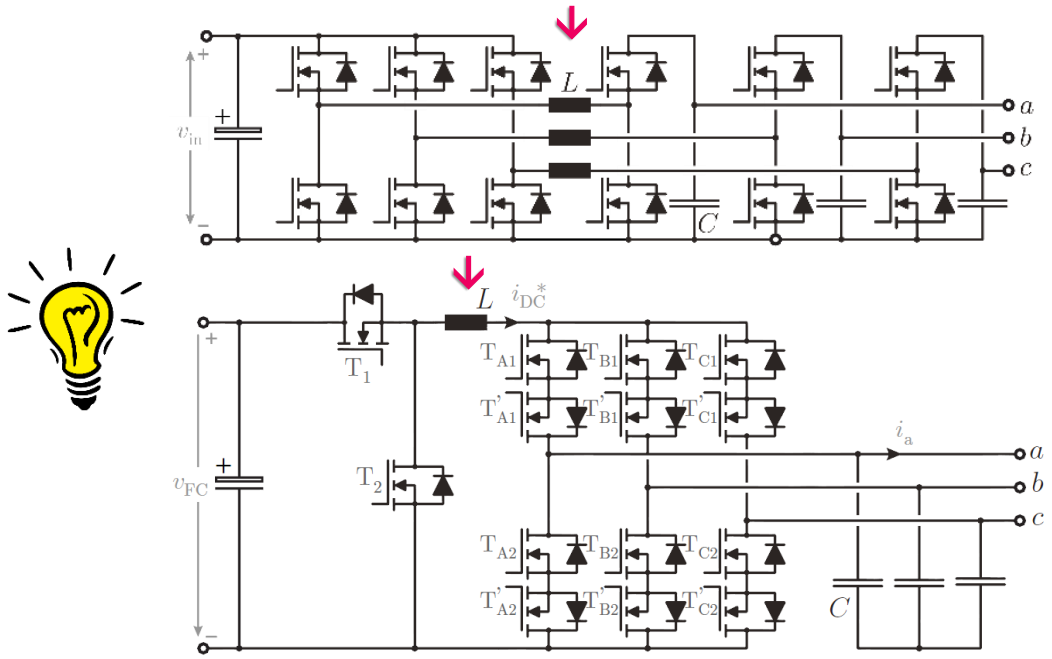
→ *Multi-Level Bridge-Leg Structure for Increase of Power Density @ Same Efficiency*

DC/DC Buck Stage & Current Source Inverter

Monolithic Bidir. GaN Switches
Synergetic Control

▶ Current Source Inverter (CSI) Topologies

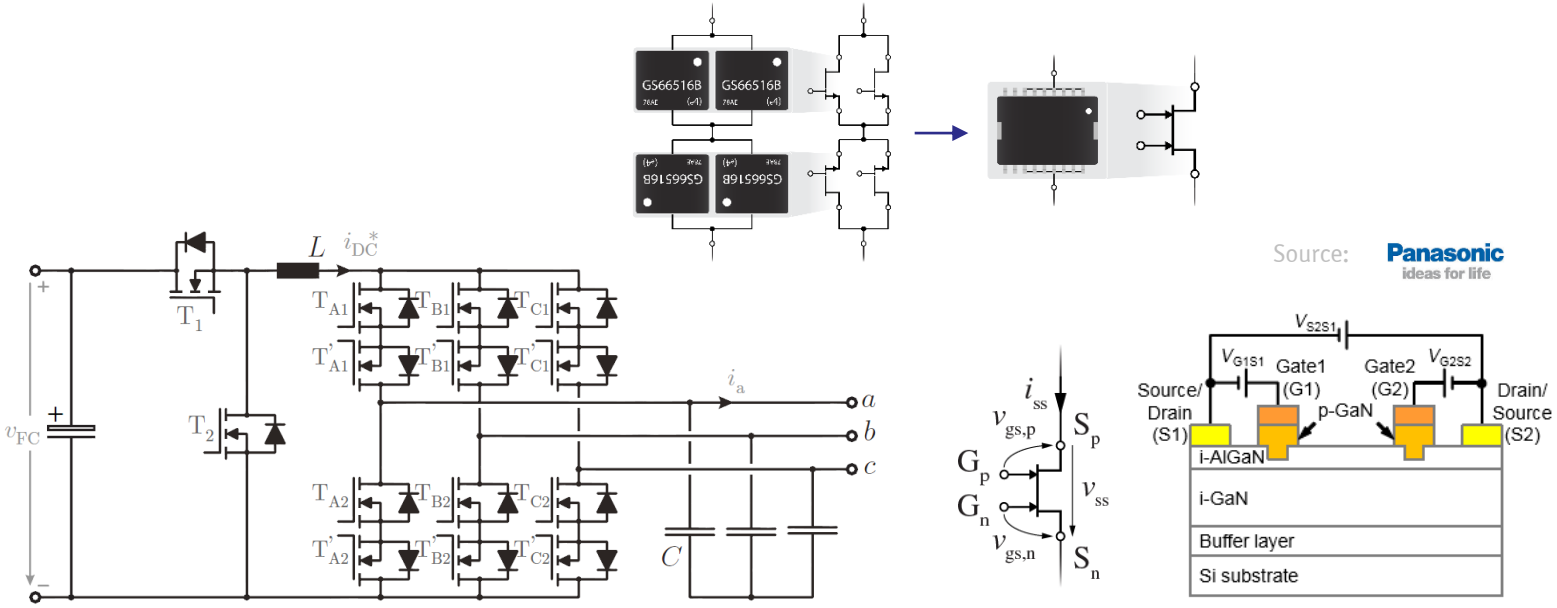
- *Phase Modular Concept → Y-Inverter (Buck-Stage / Current Link / Boost-Stage)*
- *3-Φ Integrated Concept → Buck-Stage & Current DC Link Inverter*



→ *Low Number of Ind. Components & Utilization of Bidir. GaN Semicond. Technology*

▶ 3-Φ Integrated Buck-Boost CSI (1)

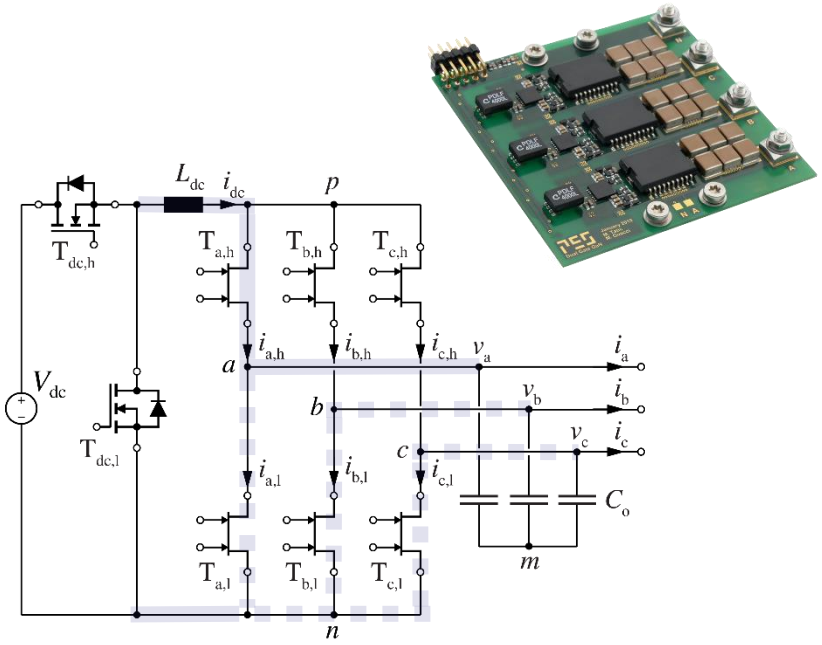
- Basic Topology Proposed in 1984 (Ph.D. Thesis of K.D.T. Ngo/CPES)
- Monolithic Bidirectional 650V GaN e-FETs

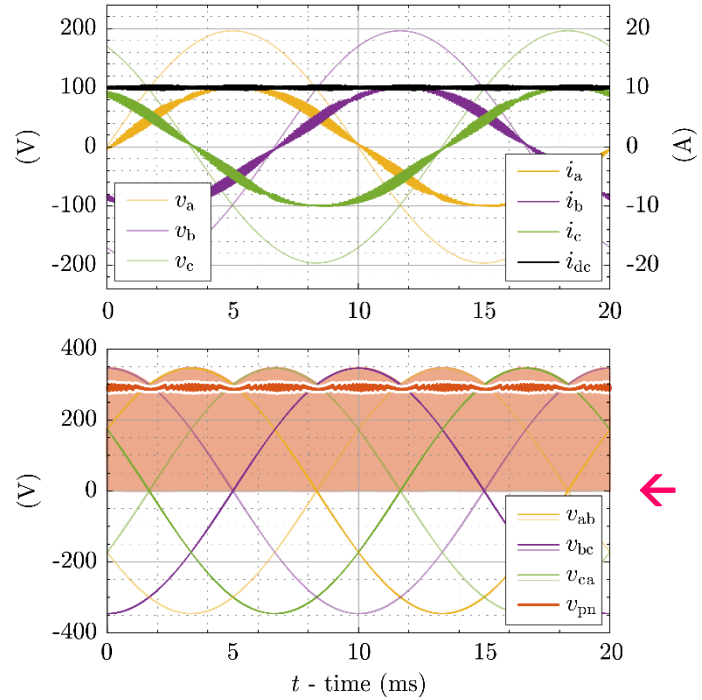


→ Factor 4 Improvement in Chip Area Comp. to Discrete Realization
→ Also Beneficial for Matrix Converter Topologies or Back-to-Back Configurations

▶ 3-Φ Integrated Buck-Boost CSI (2)

- Monolithic Bidir. GaN Switches Featuring 2 Gates / Full Controllability
- Buck-Stage for Impressing Const. DC Current / PWM of CSI for Output Voltage Control

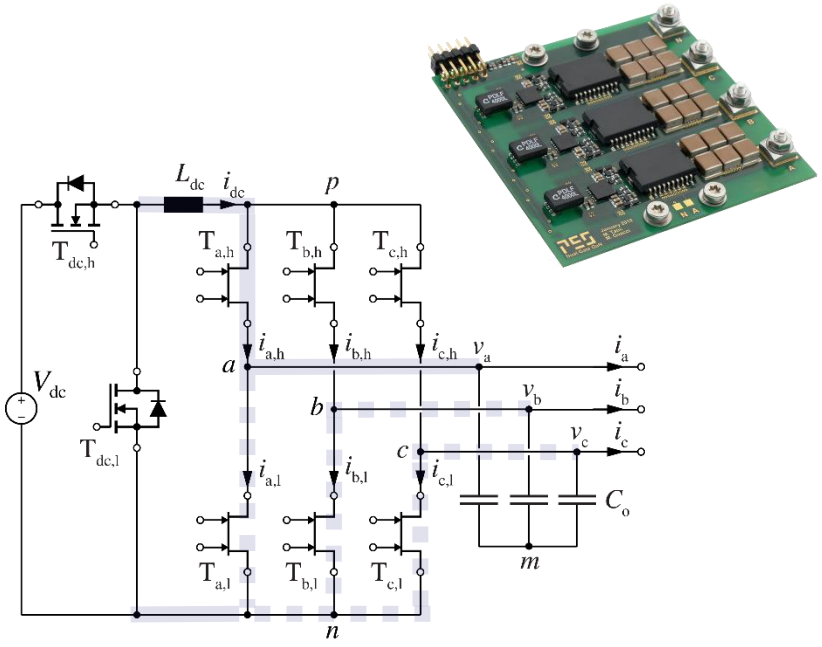


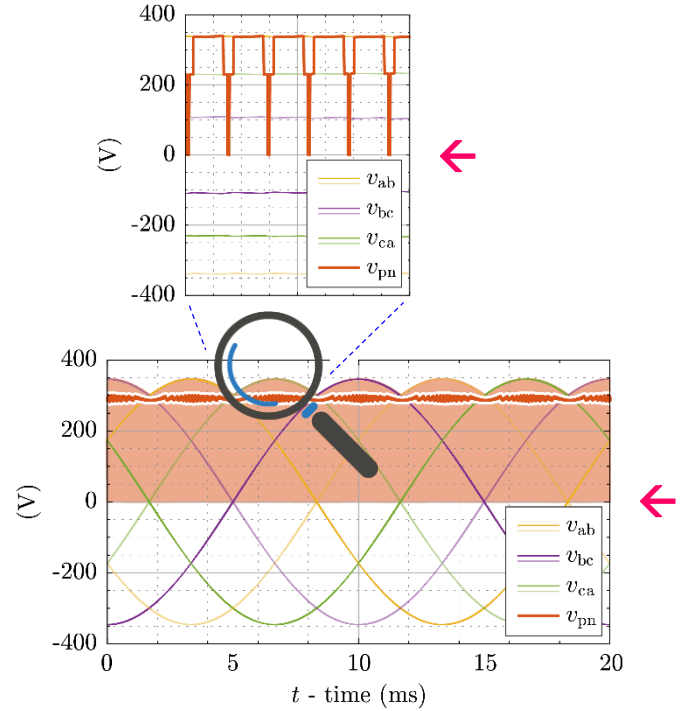


- Conventional Control of Inverter Stage → Switching of All 3 Phase Legs (3/3)

▶ 3-Φ Integrated Buck-Boost CSI (3)

- Monolithic Bidir. GaN Switches Featuring 2 Gates / Full Controllability
- Buck-Stage for Impressing Const. DC Current / PWM of CSI for Output Voltage Control

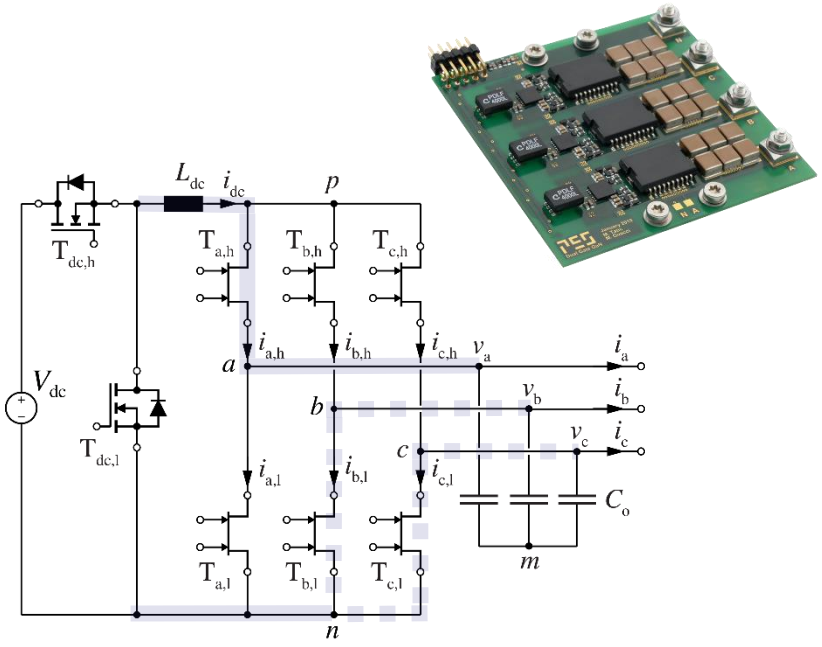


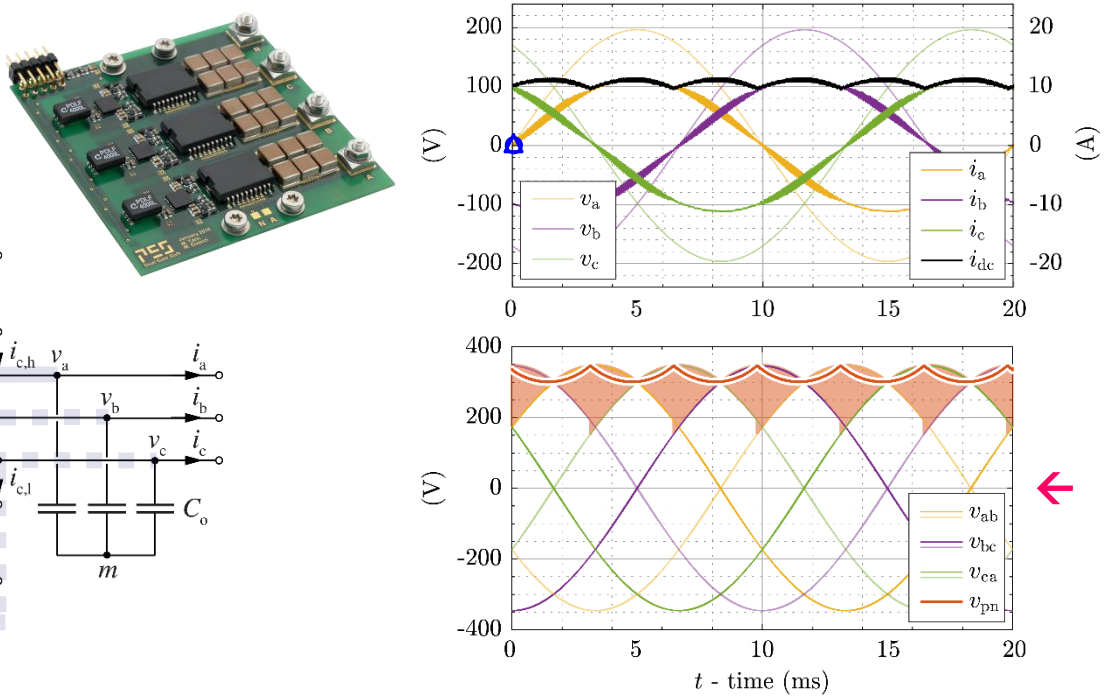


- Conventional Control of Inverter Stage → Rel. High CSI-Stage Sw. Losses

▶ 3-Φ Integrated Buck-Boost CSI (4)

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

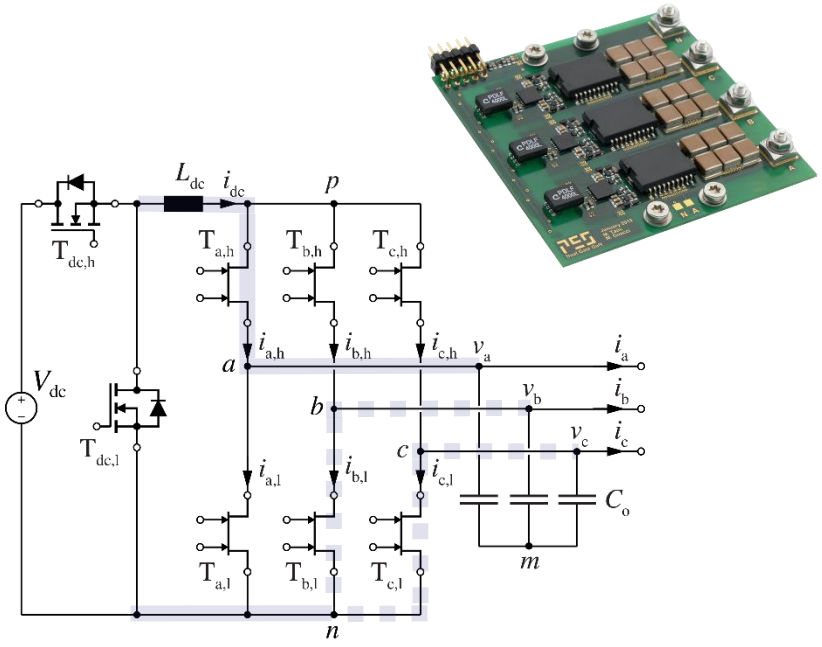


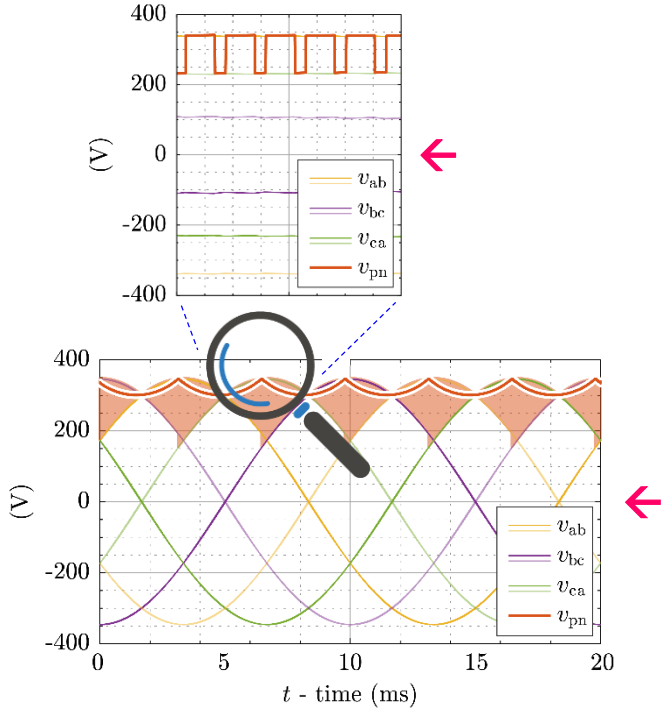


- *Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)*

▶ 3-Φ Integrated Buck-Boost CSI (5)

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

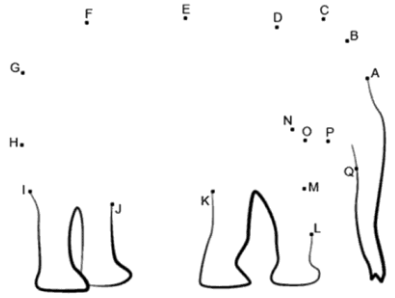




- *Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)*

Further Concepts

Quasi-2-Level FC Inverter
Integrated Filter Power Module



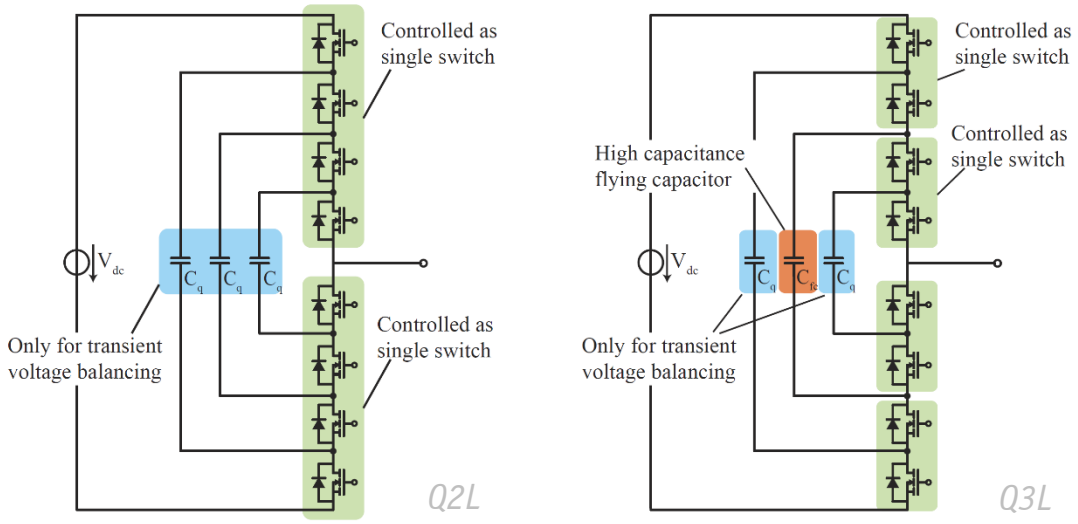
Quasi-2L/3L Flying Capacitor Inverter

▶ Quasi-2L & Quasi-3L Inverters (1)

- *Operation of N-Level Topology in 2-Level or 3-Level Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

- *Schweizer (2017)*

ABB



- *Reduced Average dv/dt → Lower EMI / Lower Reflection Overvoltages*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

▶ Quasi-2L & Quasi-3L Inverters (2)

- Operation of 5L Bridge-Leg Topology in Quasi-3L Mode
- Intermediate Voltage Levels Only Used During Sw. Transients
- Applicability to All Types of Multi-Level Converters

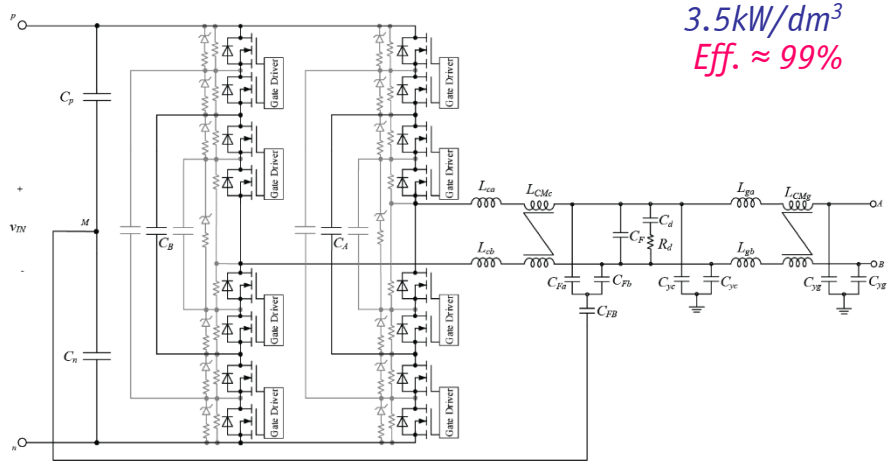
3.3kW @ 230V_{rms}/50Hz
Equiv. f_S= 48kHz

3.5kW/dm³
Eff. ≈ 99%

- Schweizer (2017)

ABB

SMD
150V Si-MOSFETs



- Reduced Average dv/dt → Lower EMI / Reflection Overvoltages
- Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors
- Low Voltage/$R_{DS(on)}$/$ MOSFETs → High Efficiency / No Heatsinks / SMD Packages

▶ Quasi-2L & Quasi-3L Inverters (3)

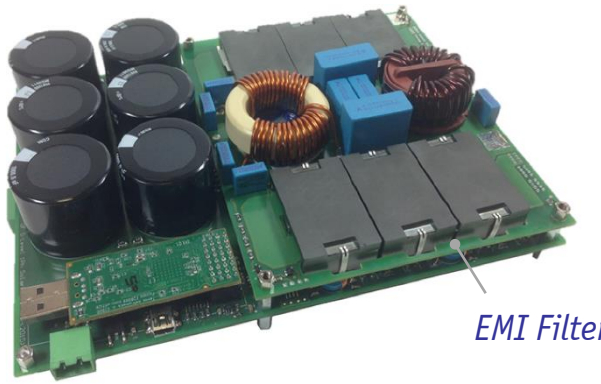
- Operation of 5L Bridge-Leg Topology in Quasi-3L Mode
- Intermediate Voltage Levels Only Used During Sw. Transients
- Applicability to All Types of Multi-Level Converters

3.3kW @ 230V_{rms}/50Hz
Equiv. f_S= 48kHz

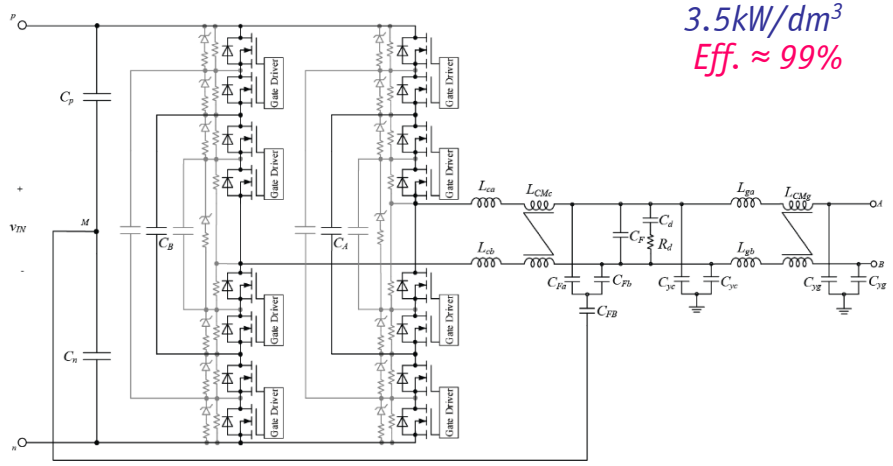
3.5kW/dm³
Eff. ≈ 99%

- Schweizer (2017)

ABB



EMI Filter



- Reduced Average dv/dt → Lower EMI / Reflection Overvoltages
- Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors
- Low Voltage/$R_{DS(on)}$/$ MOSFETs → High Efficiency / No Heatsinks / SMD Packages

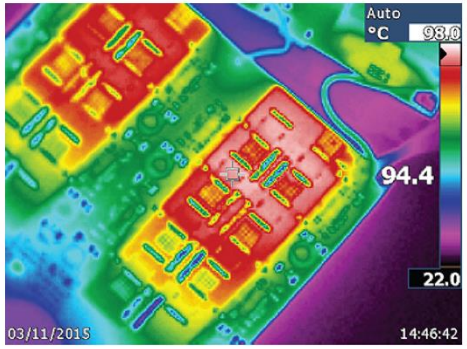
▶ Quasi-2L & Quasi-3L Inverters (4)

- Schweizer (2017)

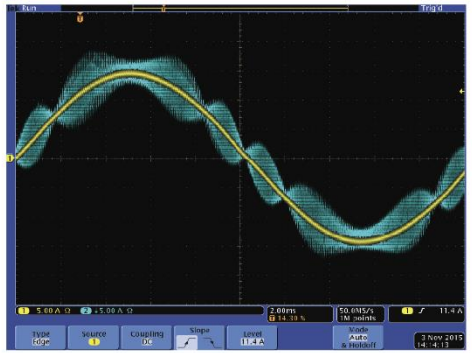
ABB

- Operation of 5L Bridge-Leg Topology in Quasi-3L Mode
- Intermediate Voltage Levels Only Used During Sw. Transients
- Applicability to All Types of Multi-Level Converters

Operation @ 3.2kW



- Conv. Output Voltage
- Sw. Stage Output Voltage
- Flying Cap. (FC) Voltage
- Q-FC Voltage (Uncntrl.)



- Output Current
- Conv. Side Current

- Reduced Average dv/dt → Lower EMI / Reflection Overvoltages
- Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors
- Low Voltage/$R_{DS(on)}$/$ MOSFETs → High Efficiency / No Heatsinks / SMD Packages

Ultra-Compact Integrated Filter Power Module

650V GaN E-HEMT Technology

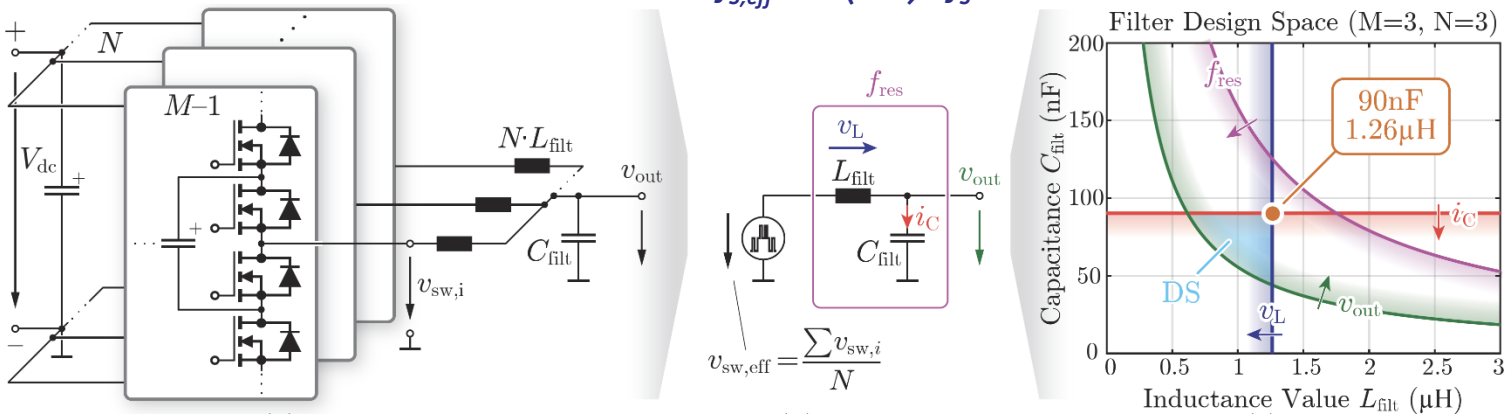
$f_{S,eff}$ = 4.8MHz

f_{out} = 100kHz

▶ Integrated Filter GaN Half-Bridge Module (1)

- Minimization of Filter Volume by Series & Parallel Interleaving & Extreme Sw. Frequency
- Selection of M=3 / N=3 Considering Efficiency / Filter Volume Trade-Off
- 650V GaN E-HEMT Technology
- U_{DC}=800V, P=10kW, $\Delta u_{out,pp}$= 1%, $f_{S,eff}$= 4.8MHz

V_L < 15%
I_C <30%



$N \cdot L_{filt}$=3.3uH
C_{filt}=90nF

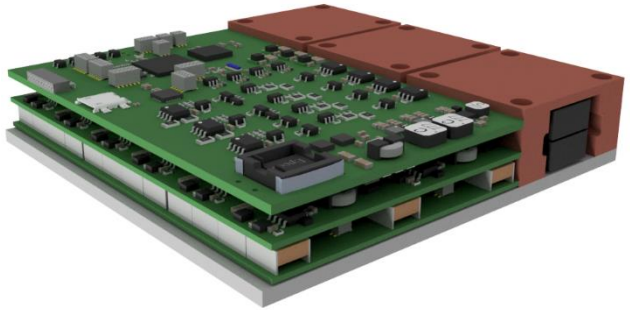
- Design for Max. Output Frequency of f_{out} = 100kHz (!) @ Full-Scale Voltage Swing

▶ Integrated Filter GaN Half-Bridge Module (2)

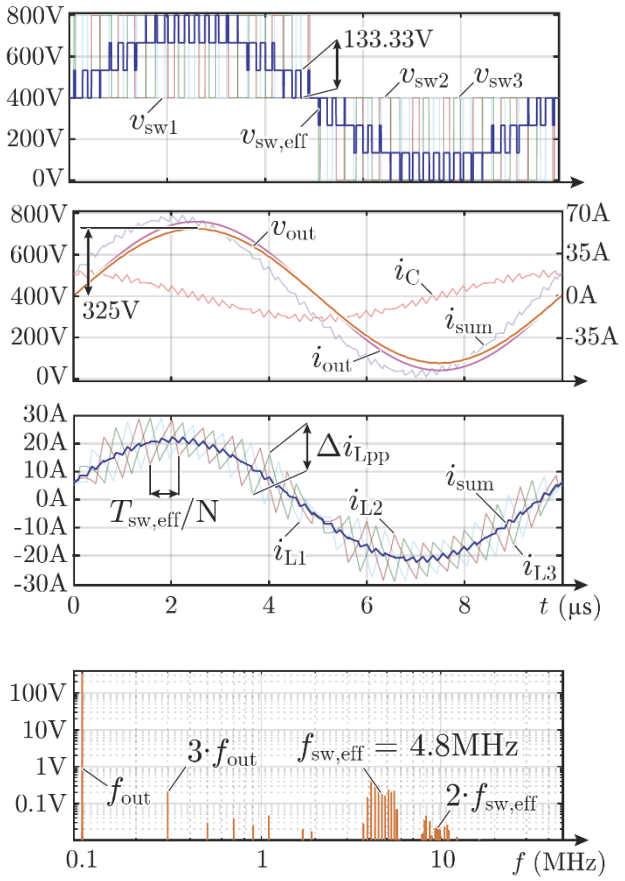
- *10kW Demonstrator System*

— *650V GaN Power Semiconductors*
— *Volume of ≈180cm³ (incl. Control etc.)*
— *H_2O Cooling Through Baseplate*

★ *≈ 50kW/dm³*



- *Operation @ f_{out}=100kHz ($f_{S,eff}$= 4.8MHz)*
- *95% calc. Efficiency*

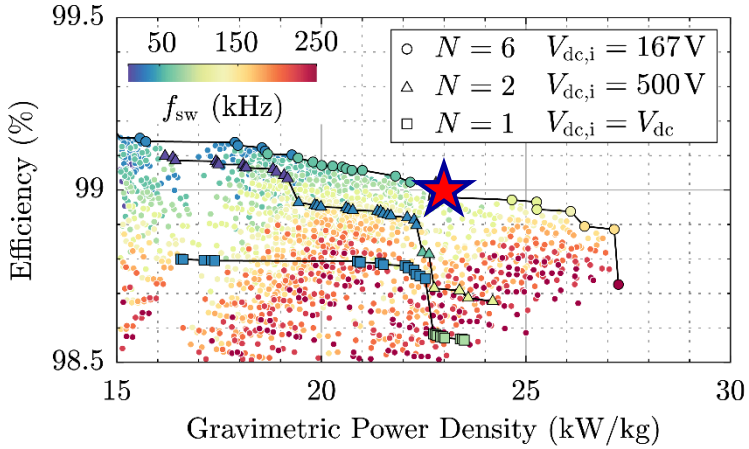


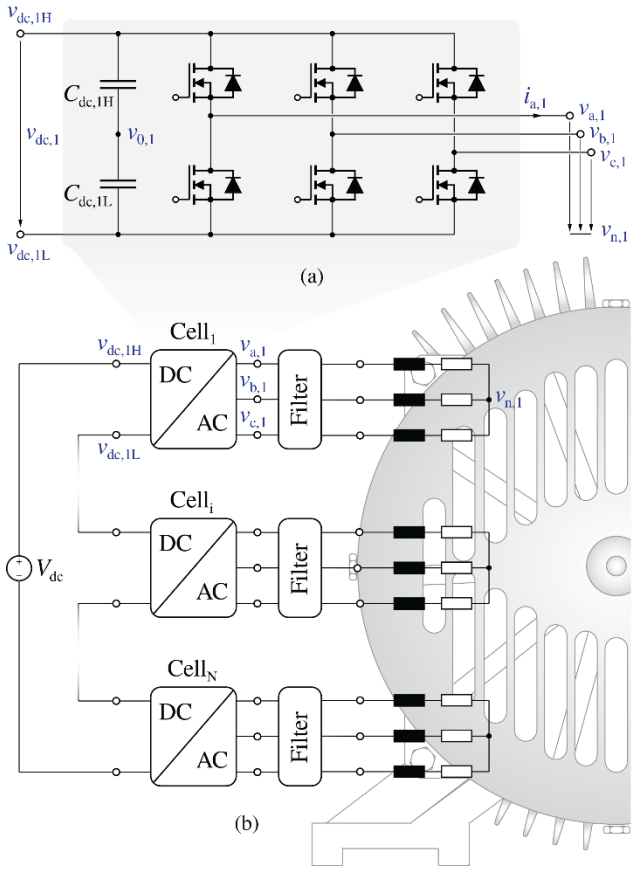
Motor-Integrated Modular Inverter

▶ Motor-Integrated Modular Inverter

- *Machine/Inverter Fault-Tolerant VSD*
- *Motor-Integr. Low-Voltage Inverter Modules*
- *Very-High Power Density / Efficiency*
- *Supply of 3-Φ Winding Sets / Low C Buffer Cap.*

- *Rated Power 45kW / f_{out} = 2kHz*
- *DC-Link Voltage 1 kV*

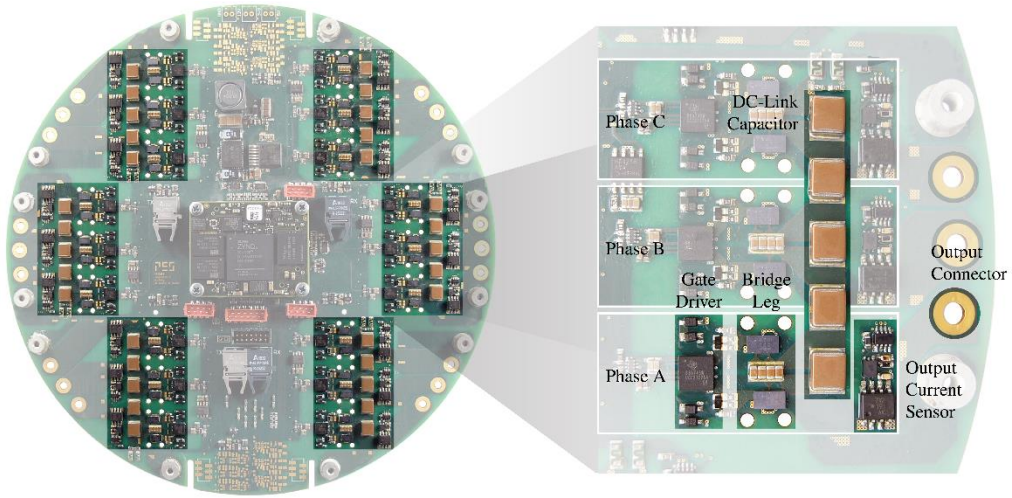


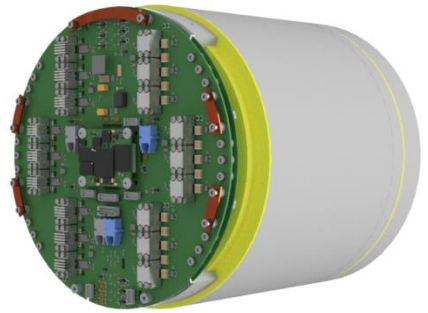


→ *Evaluate Machine Concept (PMSM vs. SRM etc.) / Wdg Topologies / Filter Requ. / etc.*

▶ Motor-Integrated Inverter Demonstrator

- *Rated Power* *9kW @ 3700rpm*
- *DC-Link Voltage* *650V...720V*
- *3-Φ Power Cells* *5+1*
- *Outer Diameter* *220mm*





- *Axial Stator Mount*
- *200V GaN e-FETs*
- *Low-Capacitance DC-Links*
- *45mm x 58mm / Cell*

→ *Main Challenge — Thermal Coupling/Decoupling of Motor & Inverter*

Conclusions

▶ Conclusions

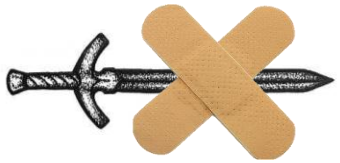
- *Future Need for Single-Edged „SWISS Knife“-Type Systems feat. Multiple Tools*

— *Wide Input / Output Voltage Range*
— *Continuous / Sinusoidal Output Voltage*
— *Electromagnetically „Quiet“ - No Shielded Cables*
— *On-Line Monitoring / Industry 4.0*
— *“Plug & Play“ / Non-Expert Installation*
— *SMART Motors*

Source: UK Outdoor Store

- *Enabling Technologies*

— *SiC / GaN*
— *Adv. (Multi-Level) Topologies incl. PFC Rectifier*
— *“Synergetic” Control*
— *Monolithic Bidirectional GaN*
— *Intelligent Power Modules*
— *Integration of Switch / Gate Drive / Sensing / Monitoring*
— *Adv. Modeling / Simulation / Optimization*



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

Thank you!

Biography of the Presenter

bortis@lem.ee.ethz.ch

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, co-supervising Ph.D. students and leading industry research projects.

Since January 2016 he is heading the research group Advanced Mechatronic Systems at PES, which concentrates on ultra-high speed motors, magnetic bearings and bearingless drives, new linear-rotary actuator and machine concepts with integrated power electronics. Targeted applications include e.g. highly dynamic and precise positioning systems, medical and pharmaceutical systems, and future mobility concepts. Dr. Bortis has published 90+ scientific papers in international journals and conference proceedings. He has filed 32 patents and has received 6 IEEE Conference Prize Paper Awards.