ETH zürich

20th Ee 2019

Source: next-gen-forum.com

NEXT GENERATION

3-Φ Variable-Speed Drive PWM Inverter Concepts

J.W. Kolar, et al.

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

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3-Φ Variable-Speed Drive PWM Inverter Concepts

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

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Oct. 26, 2019

ETH Zurich

21 Nobel Prizes
530 Professors
6100 T&R Staff

2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages

150th Anniv. in 2005

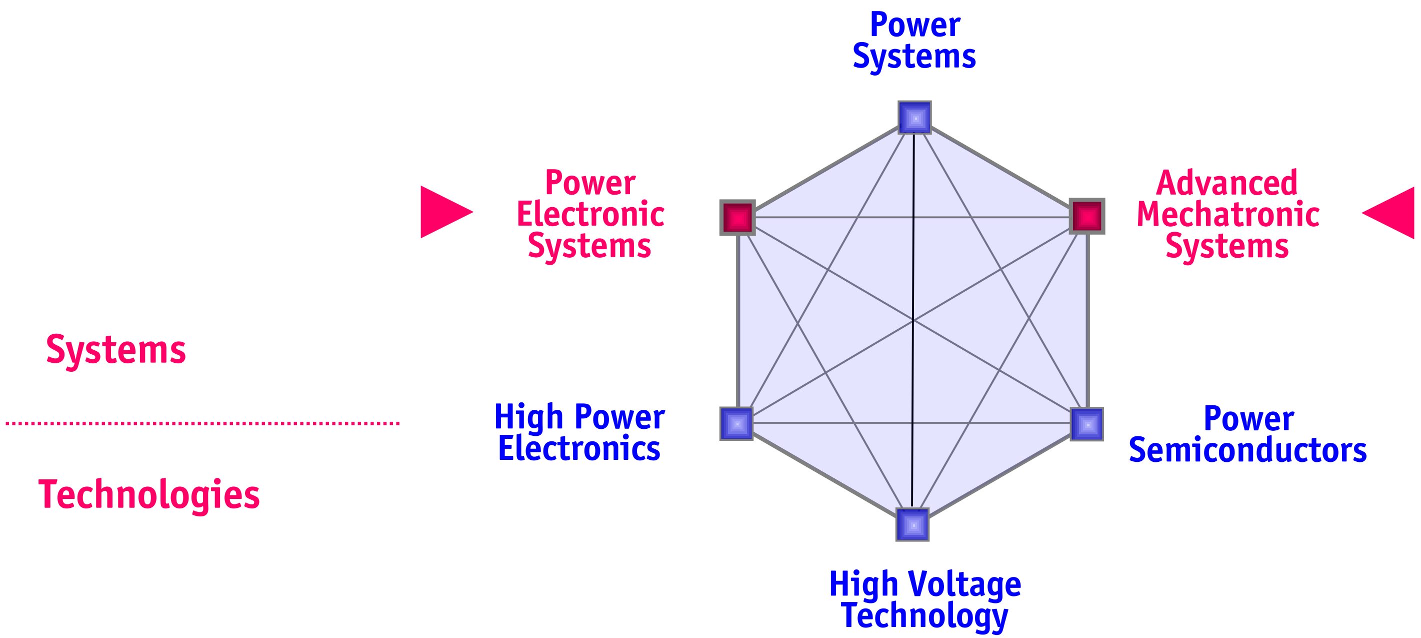
Departments

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

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	**D. Bortis**	**F. Krismer**		**D. Bortis**	**D. Bortis**
M. Heller Y. Li D. Menzi D. Neumayr D. Zhang	J. Azurza P. Czyz M. Haider	P. Bezerra T. Guillod G. Knabben J. Schäfer	M. Antivachis J. Böhler M. Guacci	P. Papamanolis	P. Niklaus	E. Hubmann R. Giuffrida	Th. Holenstein P. Püntener S. Miric

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

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 Filter
- Boost-Buck VSI
- Buck-Boost CSI
- Q3L & Modular Inverter

- Conclusions

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

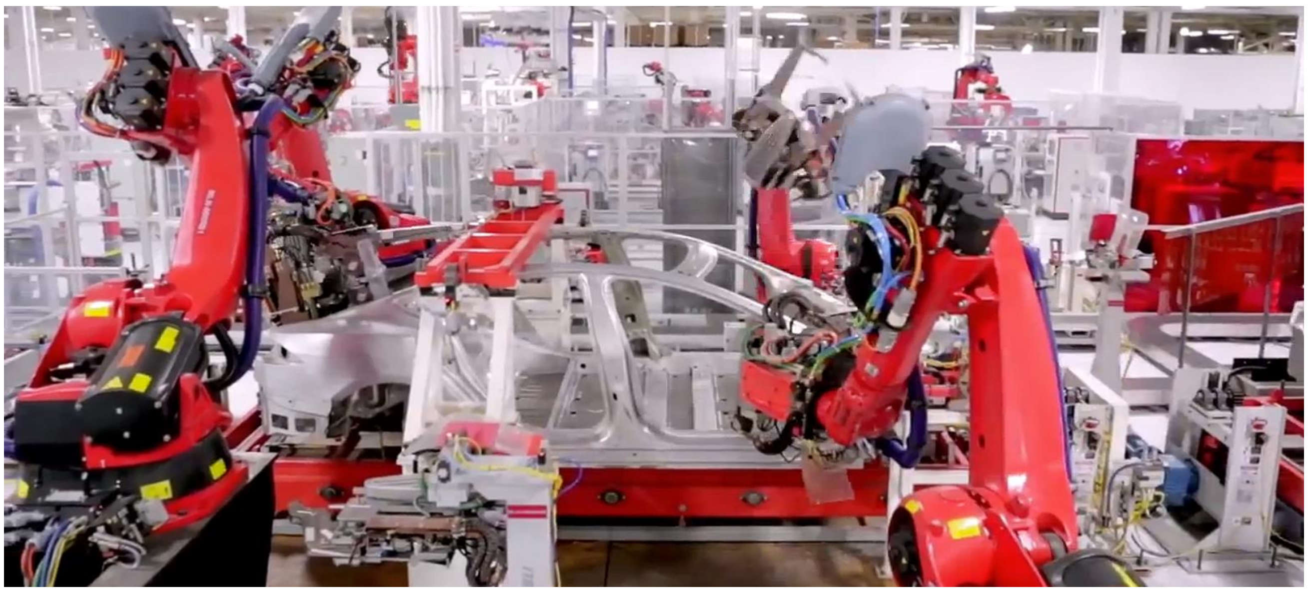
3-Φ Variable Speed Drive Inverter Systems

State-of-the-Art
Future Requirements

Applications of Drive Systems

- Industry Automation / Robotics
- Material Machining / Processing – Drilling, Milling, etc.
- Pumps / Fans / Compressors
- Transportation
- etc., etc. .... Everywhere !

Source: TESLA MOTORS

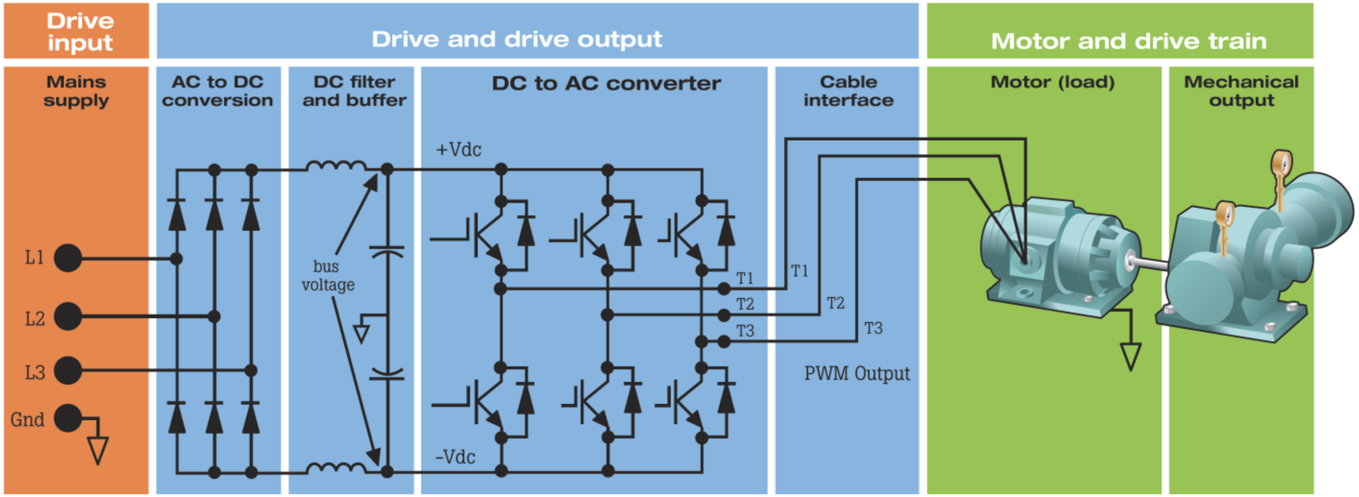


- *60% of El. Energy Used in Industry Consumed by VSDs*

► VSD State-of-the-Art

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

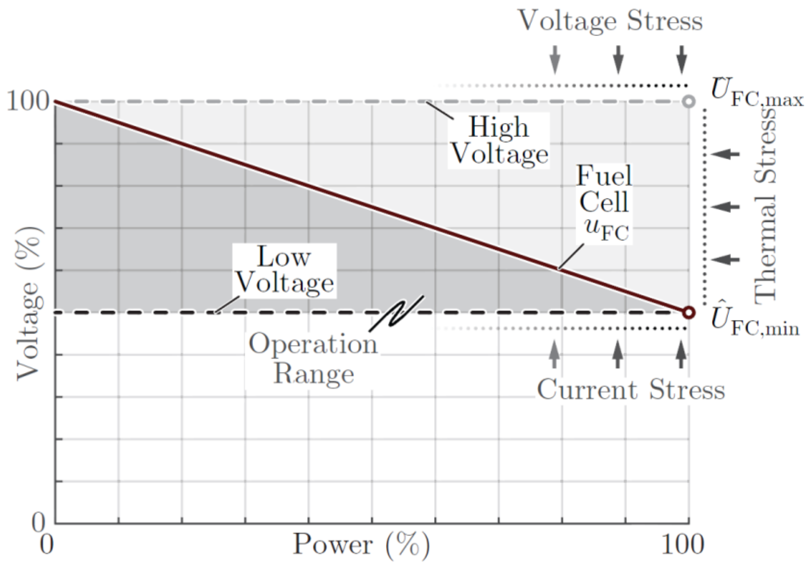
Source: FLUKE



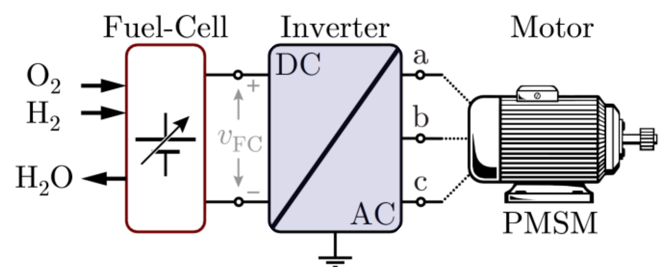
- High Performance @ High Level of Complexity / High Costs (!)

▶ 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

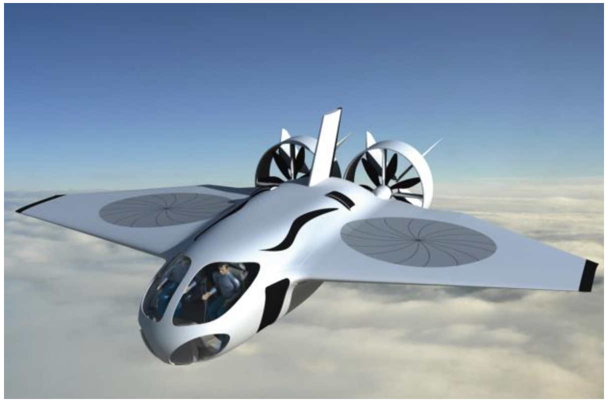


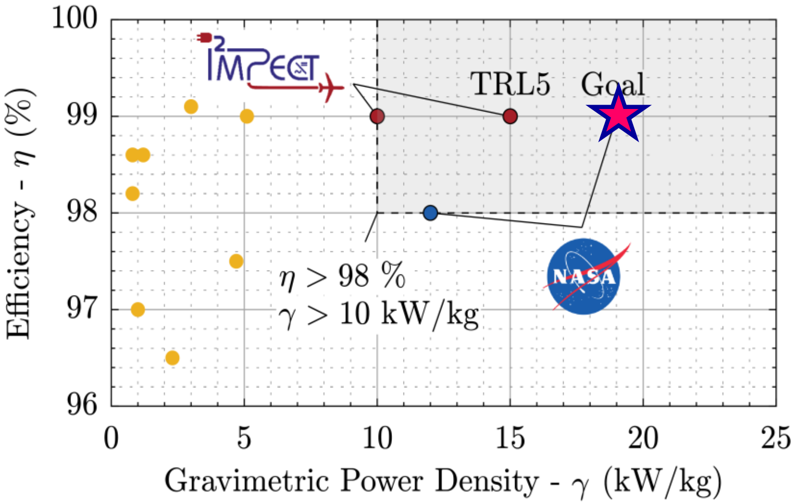
- *Single-Stage Energy Conversion* → *No Add. Converter for Voltage Adaption*

► Future Requirements (2)

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

Source: Georgia Tech





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

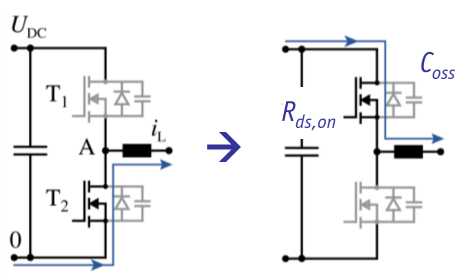
Enabling Technologies & Challenges

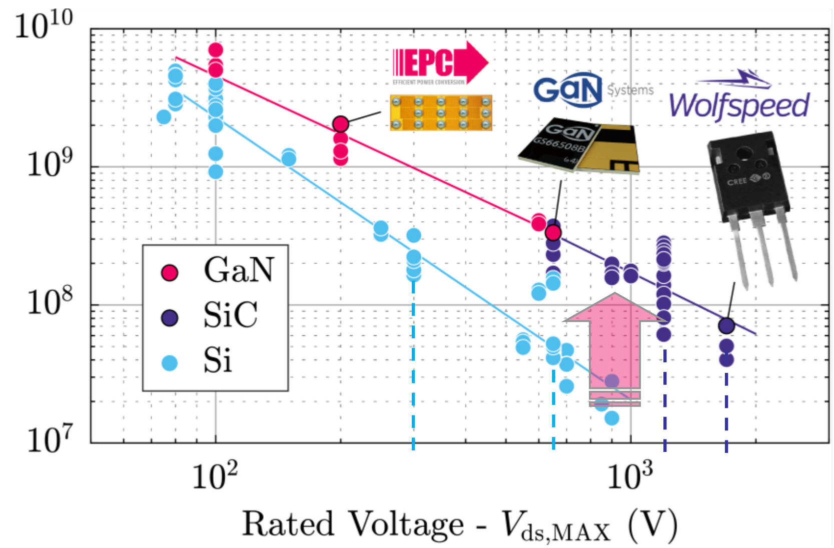
WBG Semiconductors
Advanced Inverter Topologies

▶ SiC/GaN

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

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



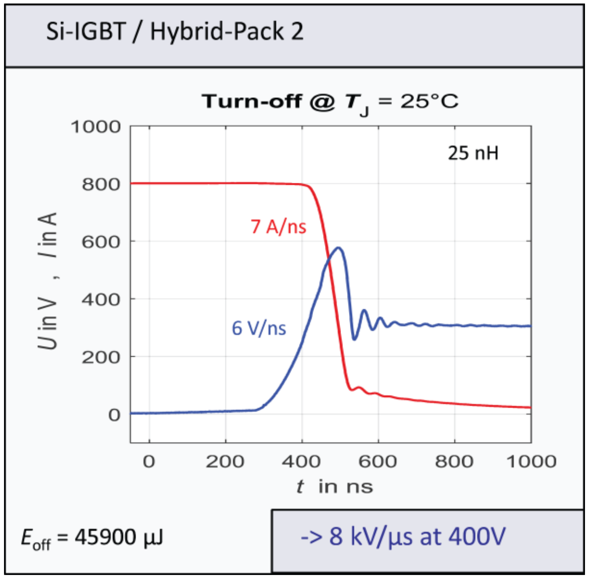


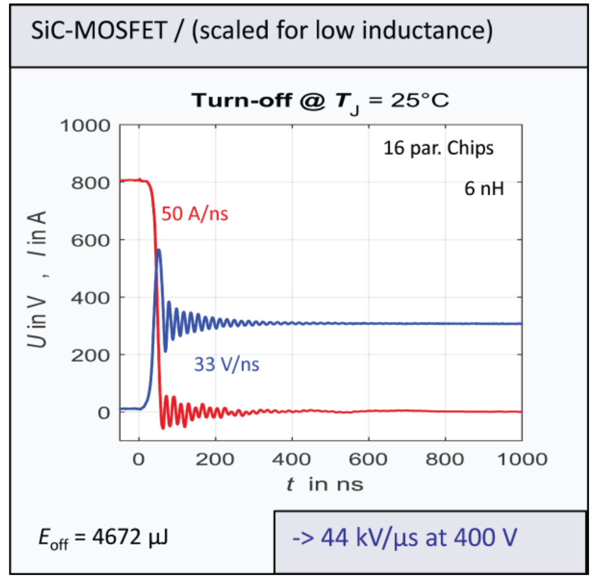
→ *Challenges in Packaging / Thermal Management / Gate Drive / PCB Layout*
→ *Extremely High Sw. Speed (dv/dt)* → *Motor Insul. Stress / Reflections / Bearing Curr. / EMI*

Si vs. SiC

- Si-IGBT → dv/dt = 2…6 kV/us (Inverters for Var. Speed Drives / IEC 61800-3)
- SiC-MOSFETs → dv/dt = 20…60 kV/us

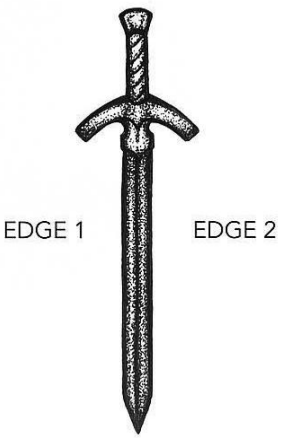
Source: M. Bakran / ECPE 2019





→ Extremely High dv/dt → Motor Insul. Stress / Reflections / Bearing Curr. / EMI

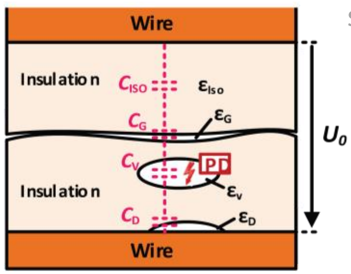
GaN/SiC VSD Application Challenges



Idea: F.C. Lee

► PD Motor Insulation Destruction (1)

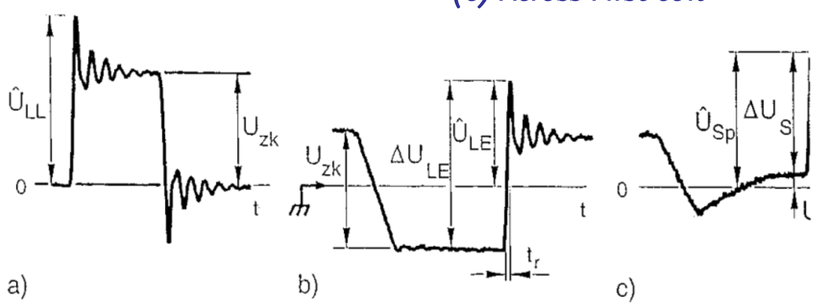
- *High dv/dt* → *Uneven Wdg. Voltage Distribution / Reflections — High Voltage Peaks*
- *Voltage Peaks* → *Local Insul. Breakdown e.g. in Air-Filled Voids = Partial Discharge (PD)*
- *PD* → *Grad. Destroys Insul. (Impinging Electrons, Ozone Chem. Attack)*



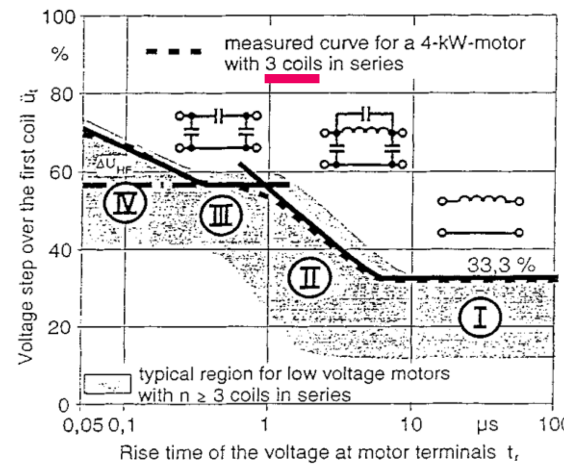
Source: Bakran / ECPE 2019

Inverter Motor Voltages

(a) Line-to-Line
(b) Line-to-Earth
(c) Across First Coil



Source: Kaufhold et al. 2000

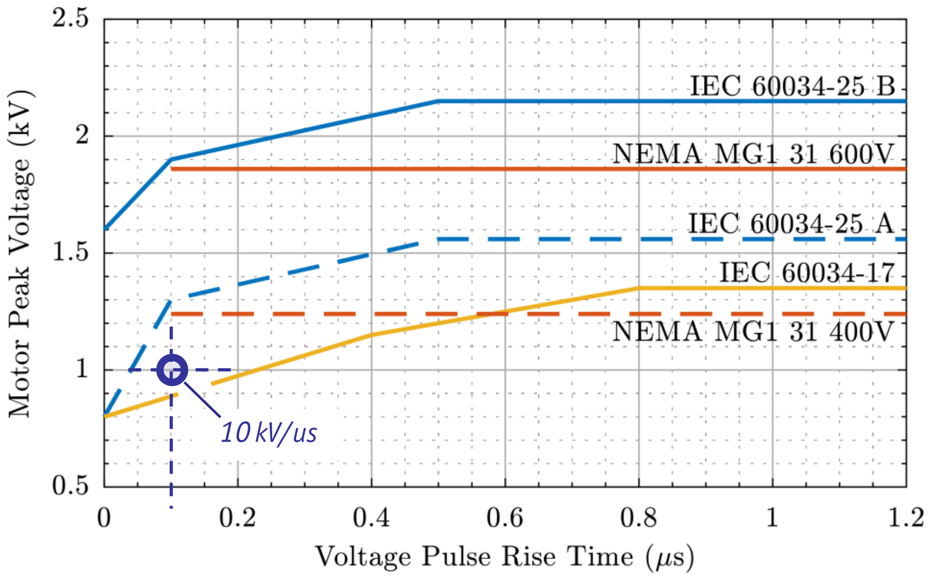


- *Preventing PD* → *Ampl. of Voltage Peaks < PD Inception Voltage (PDIV)*
- *PDIV Parameters* → *Temp. / Humidity / Pressure / Insul. Thick. / Type / Wire Diameter etc.*

PD Motor Insulation Destruction (2)

- dv/dt-Limits Specified by Standards

- National Electrical Manufact. Association (NEMA, Motors Manufact. in USA)
- Intern. Electrotechn. Commission (IEC)



NEMA MG1 Part 31 - 400V & 600V

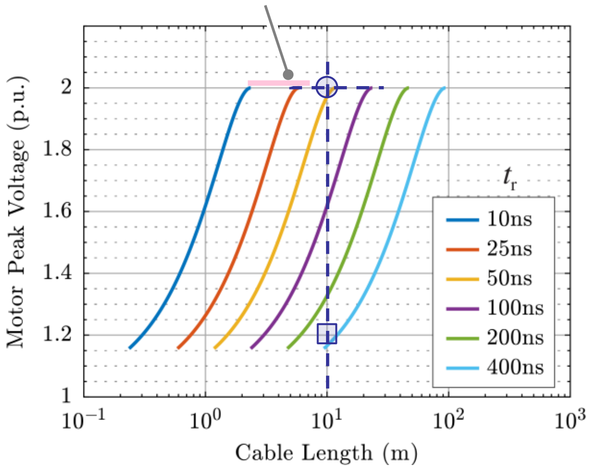
IEC 60034-17 - Cage Induction Motors
IEC 60034-25 - 500V (A) & 690V (B)
IEC 60034-27 - PD Measurements
...

- Ensuring the Limits → dv/dt-Filtering OR Full-Sinewave Filtering
- Relevance of dv/dt-Limits, e.g. for Single-Tooth Windings Under Discussion

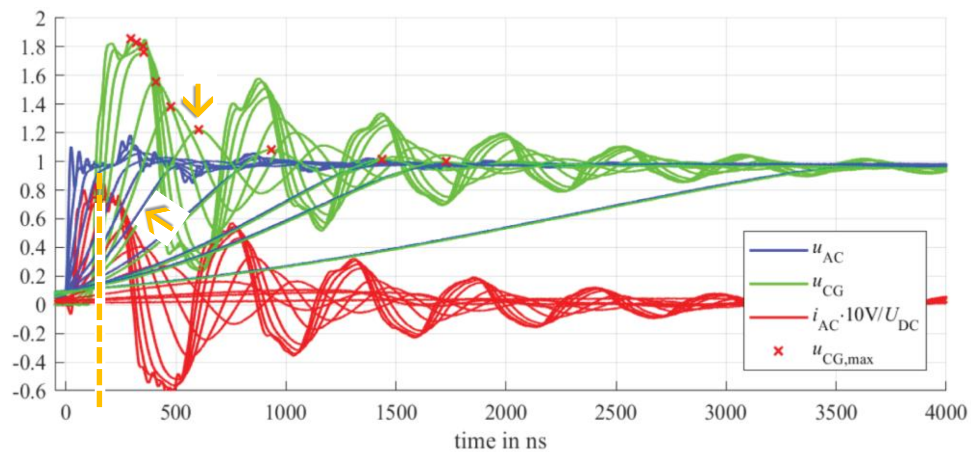
▶ Surge Voltage Reflections

- *Short Rise Time of Inverter Output Voltage*
- *Impedance Mismatch of Cable & Motor* → *Reflect. @ Motor Terminals / High Insul. Stress*
- *Long Motor Cable* $l_c \geq \frac{1}{2} t_r v$

SiC



Source: Bakran / ECPE 2019

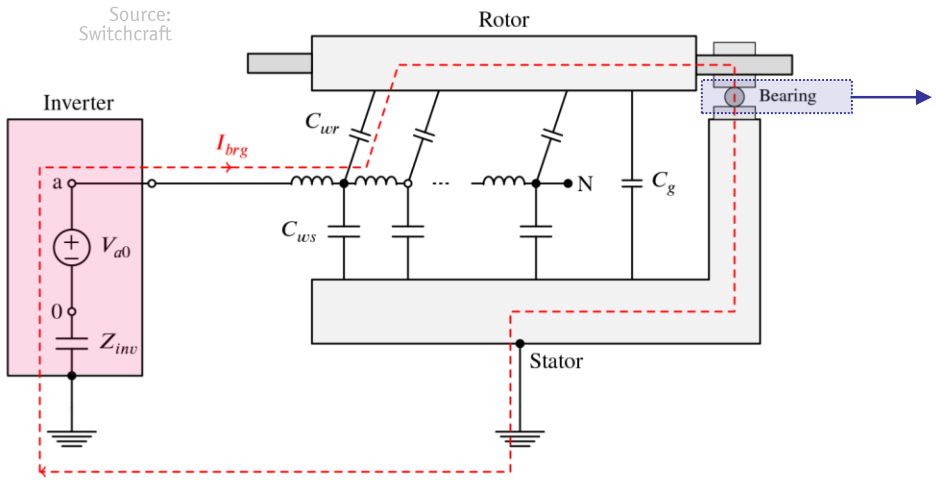


→ *dv/dt-Filtering OR Sinewave Filtering / Termination & Matching Networks etc.*

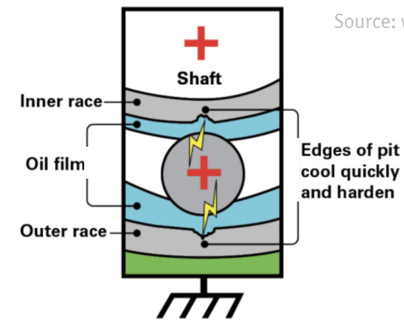
► Motor Bearing Currents

- *Switching Frequency CM Inverter Output Voltage → Motor Shaft Voltage*
- *Electrical Discharge in the Bearing ("EDM")*

Source: Switchcraft



Source: www.est-aegis.com



Source: BOSCH

→ *Cond. Grease / Ceram. Bearings / Shaft Grndg Brushes / dv/dt- OR Full-Sinewave Filters*

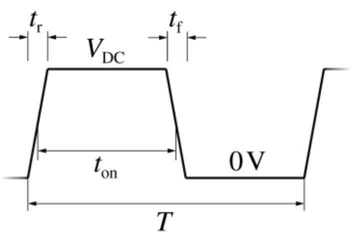
▶ SiC vs. Si Inverter EMI Spectrum

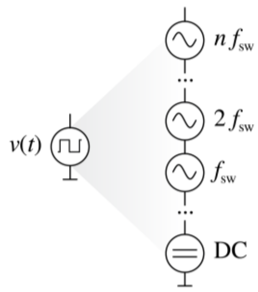
- SiC Enables Higher dv/dt → Factor 10
- SiC Enables Higher Switching Frequencies → Factor 10
- EMI Envelope Shifted to Higher Frequencies

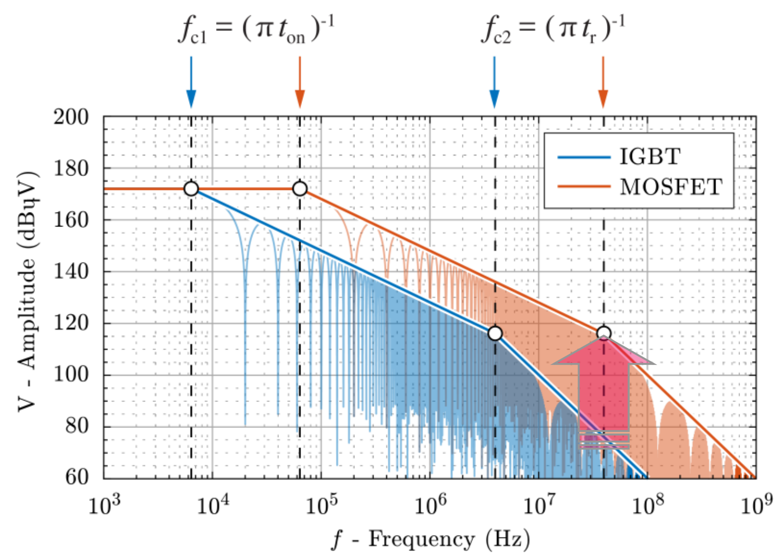
Source/Idea: M. Schutten / GE

f_S= 10kHz & 5 kV/us for (Si IGBT)
f_S= 100kHz & 50 kV/us for (SiC MOSFET)

V_{DC} = 800V
DC/DC @ D= 50%







→ Higher Influence of Filter Component Parasitics and Couplings
→ dv/dt-Filtering OR Full Sinewave Filtering, Shielded Motor Cables

Inverters with LC-Output Filter

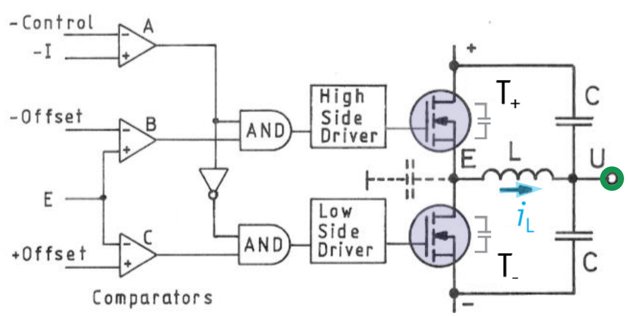
Full-Sinewave Filtering

Full-Sinewave Filtering

NFO®
Sinus

▶ Full-Sinewave Filtering @ ZVS/TCM Operation

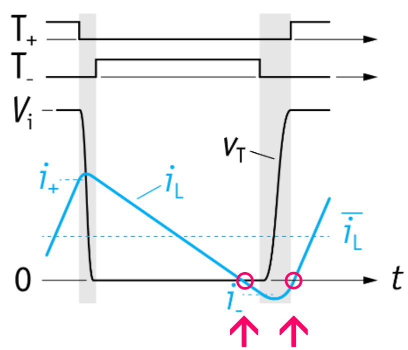
- *ZVS of Inverter Bridge-Legs (No Use of the Intrinsic Diodes of Si MOSFETs)*
- *High Sw. Frequency & TCM → Low Filter Inductor Volume*



Source: Joensson

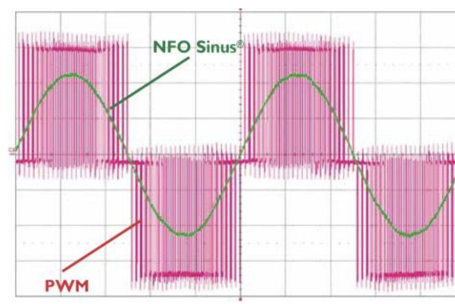
PCIM'88
(POWER CONVERSION)
CONFERENCE
DECEMBER 8-10, 1988
TOKYO, JAPAN

← **1988 !**



Source: NFO Sinus

NFO Sinus® is available in size 0,37 kW up to 22 kW



- *Widely Varying Switching Frequency → Voltage Headroom and/or Multiple Bridge-Legs*
- *Rel. High Current Stress on the Power Transistors*

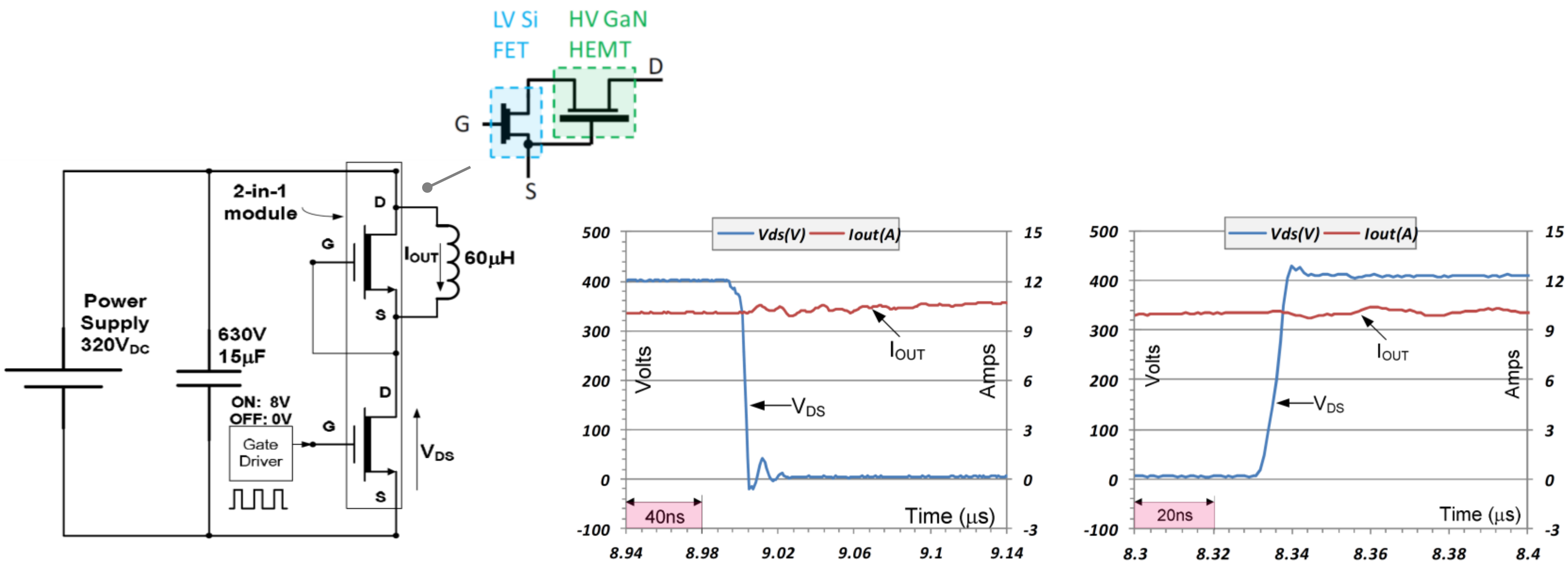
Full-Sinewave Filtering

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*

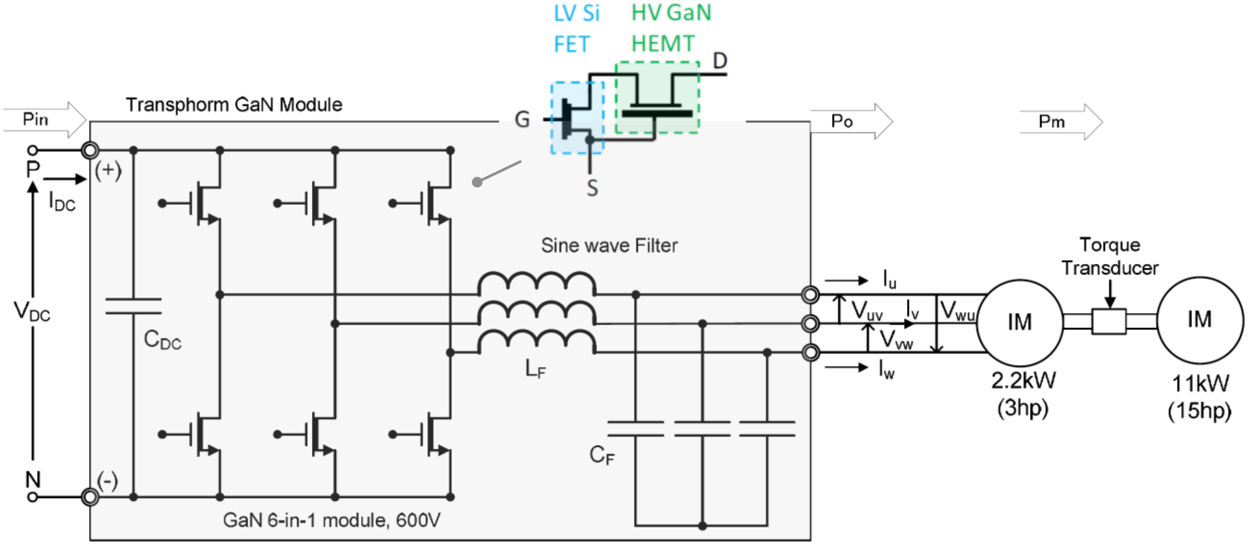


- *Factor 10 Lower On/Off Delay & Sw. Times Comp. to IGBTs*
- *Extremely Low Sw. Losses → Inverter Sw. Frequency f_S= 100kHz*

▶ 3-Φ 650V GaN Inverter System (2)

Source: YASKAWA

- *Transphorm 650V Normally-On GaN HEMT/30V Si-MOSFET Cascode 6-in-1 Power Module*
- *Sinewave LC Output Filter — Corner Frequency f_C= 34kHz (f_S= 100kHz)*
- *No Freewheeling Diodes*



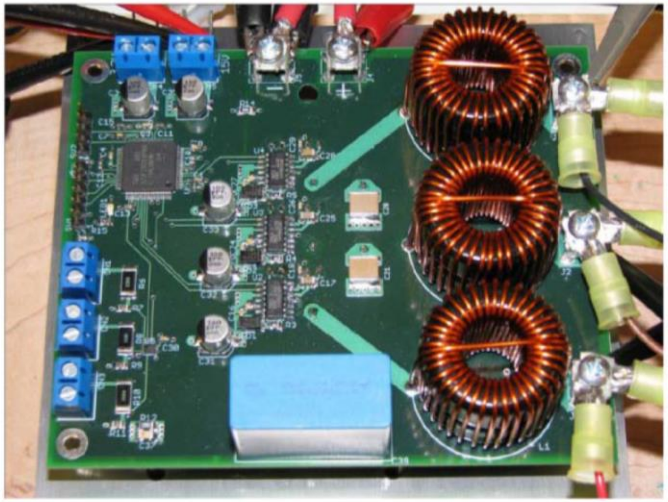
600V/14A

→ *Very Low Filter Volume Compared to Si-IGBT Drive Systems (f_C= 0.8kHz @ $f_S \approx$ 3kHz)*

► 3-Φ 650V GaN Inverter System (3)

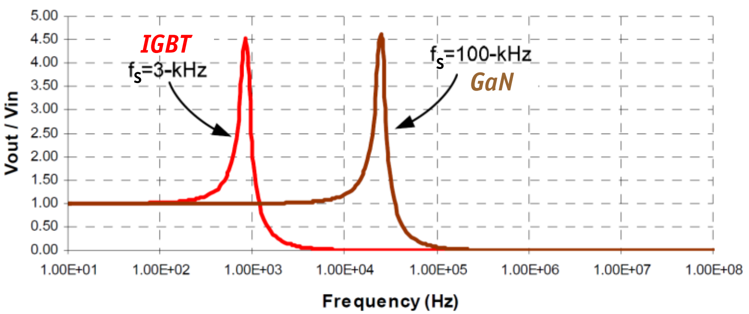
Source: YASKAWA

- *Transphorm 650V Normally-On GaN HEMT/30V Si-MOSFET Cascode 6-in-1 Power Module*
- *Sinewave LC Output Filter — Corner Frequency f_C= 34kHz (f_S= 100kHz)*
- *No Freewheeling Diodes*



L_F=220uH Iron Powder Core Filter Inductors, C_F=0.1uF

$f_C \approx 1/5\, f_S$

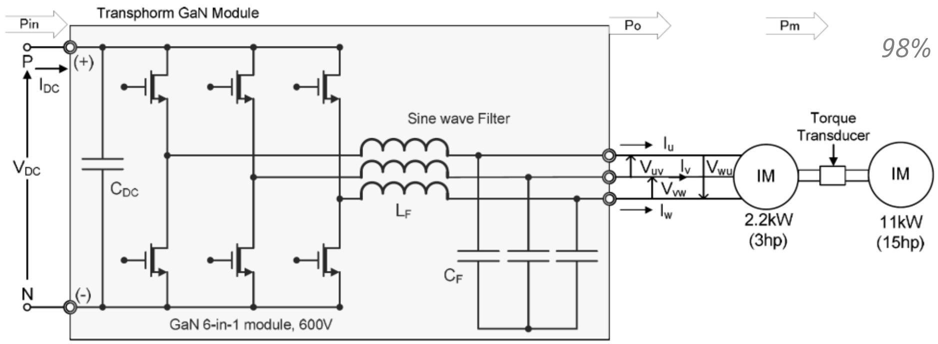


→ *Very Low Filter Volume Compared to Si-IGBT Drive Systems (f_C= 0.8kHz @ $f_S \approx$ 3kHz)*
→ *Lower Size of DC Input Capacitor (-75% vs. IGBT) & -8dB Audible Noise @ 6krpm*

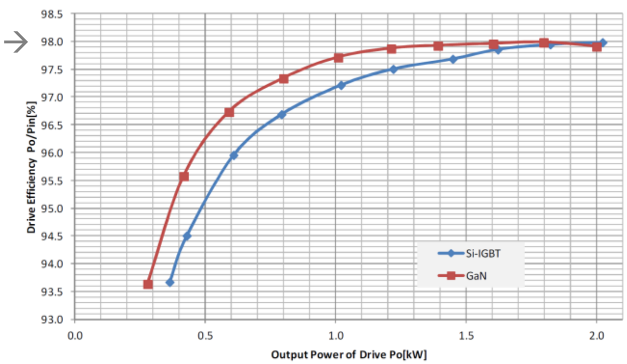
▶ 3-Φ 650V GaN Inverter System (4)

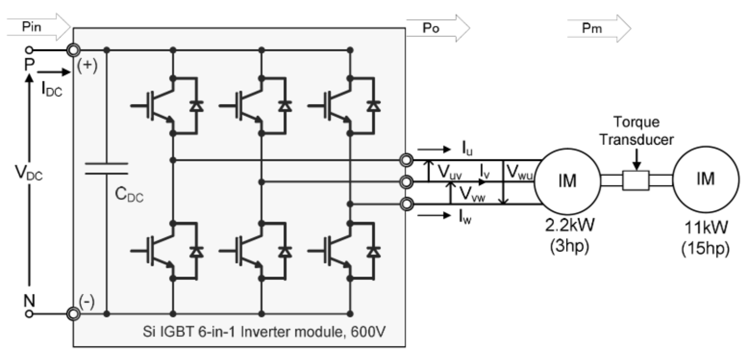
Source: YASKAWA

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

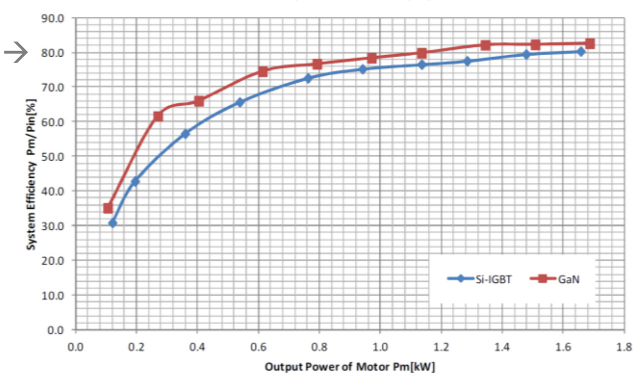


98% →





80% →

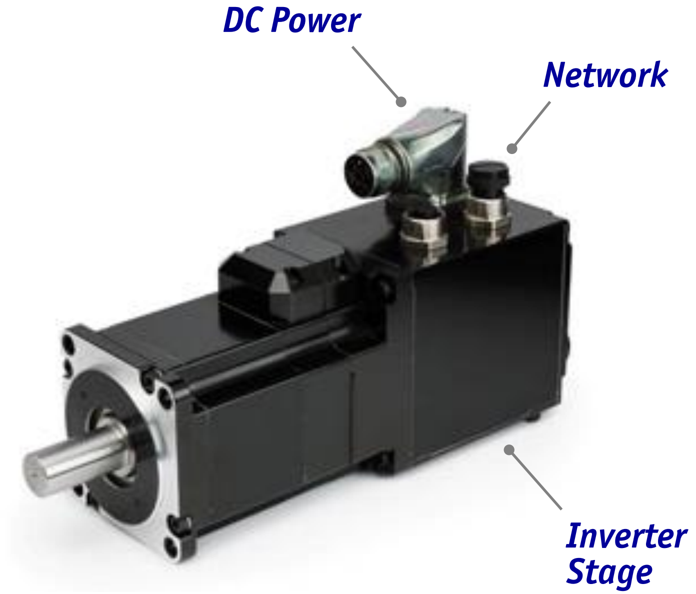


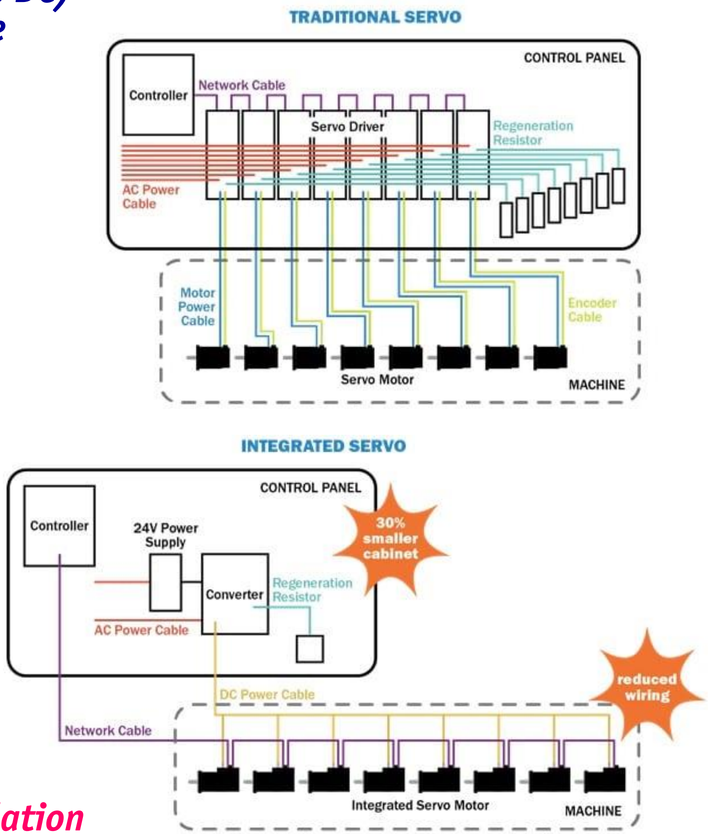
→ *2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses) !*

▶ 3-Φ 650V GaN Inverter System (5)

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*





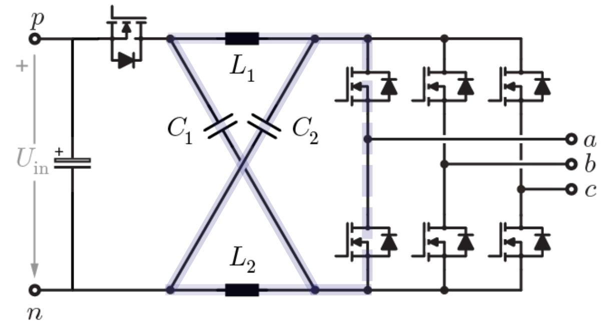
- *Small Size (0.4 kW @ 70 x 70x 170mm)*
- *Massive Saving in Cabling Effort / Simplified Installation*

Buck-Boost Inverters

Z-Source Inverter etc.
VSI & DC/DC Front-End
Phase-Modular Buck-Boost Inverter
CSI & DC/DC Front-End

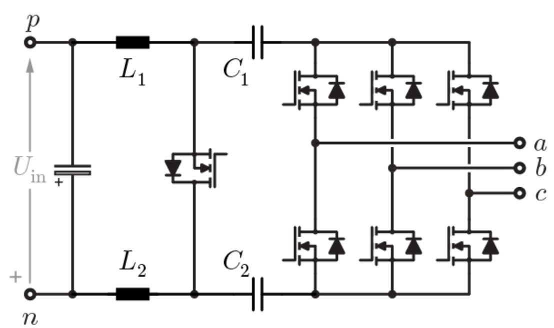
▶ "Outside-the-Box" Topologies

- *Z-Source Inverter → Shoot-Through States Utilized for Boost Function*
- *Higher Component Stress Eff. Limits Boost Operation to ≈120% U_{in}*



Source: F.Z. Peng / 2003
J. Rabkowski / 2007

- *3-Φ Back-End DC/AC Cuk-Converter*

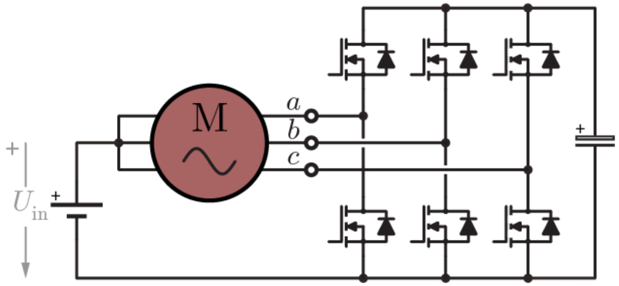


Source: T.A. Lipo et al. /2002 & K.D.T Ngo / 1984

- *Integration Typ. Results in Higher Comp. Stresses & Complexity / Lower Performance*

▶ Boost Converter DC-Link Voltage Adaption

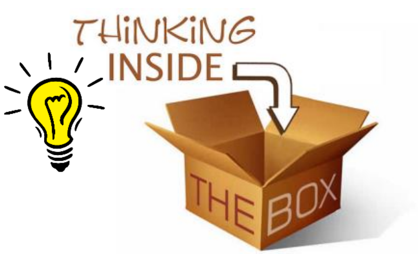
- *Inverter-Integr. DC/DC Boost Conv. → Higher DC-Link Voltage / Lower Motor Current*
- *Access to Motor Star-Point & Specific Motor Design Required*
- *No Add. Components*

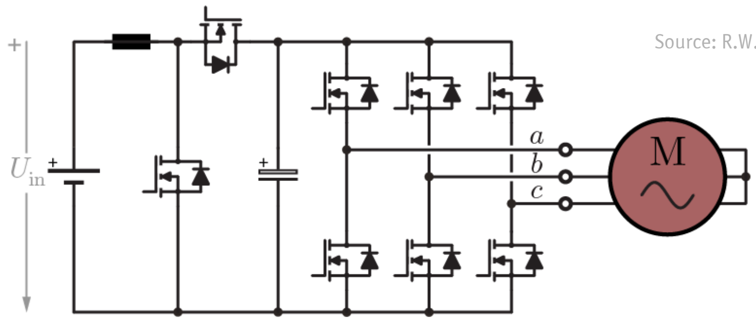


Source: J. Pforr et al. / 2009

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

Source: www.rick-gerber.com



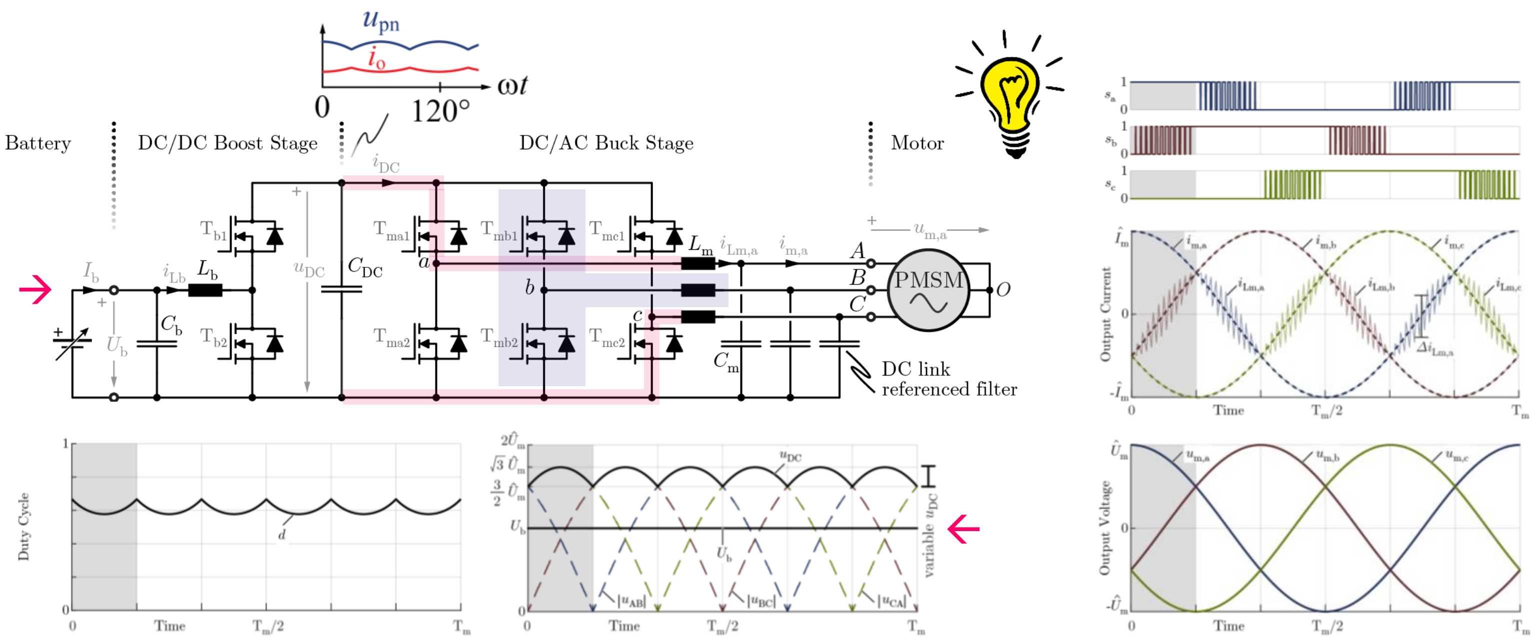


Source: R.W. Erickson et al. / 1986

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

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

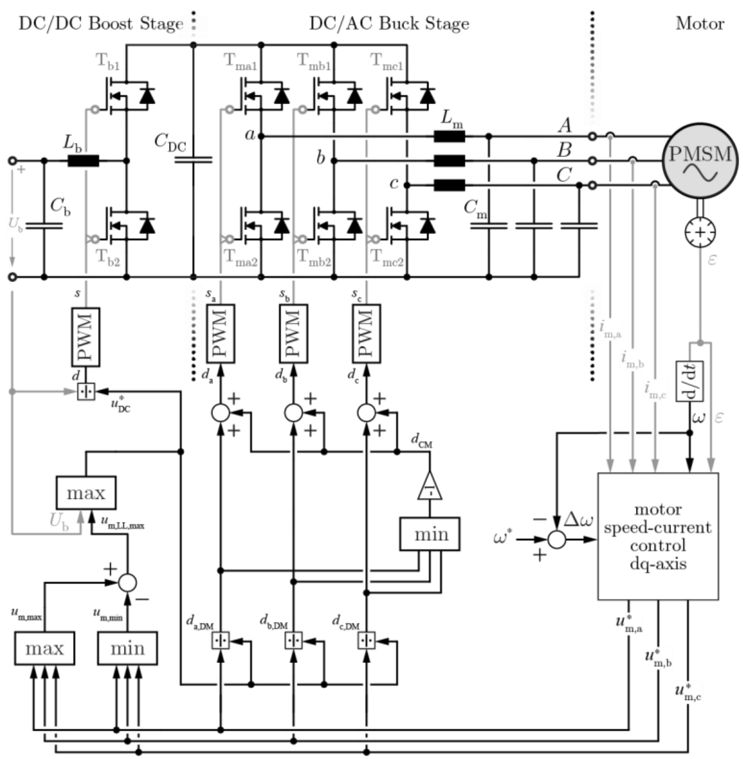
- *DC/DC Boost Converter Used for 6-Pulse Shaping of DC-Link Voltage*
- *2 (!) Inverter Phases Clamped (1/3 PWM) → Low Switching Losses / High Efficiency*
- *Conv. PWM Inverter / Clamped Boost-Stage Operation @ Low Speed*

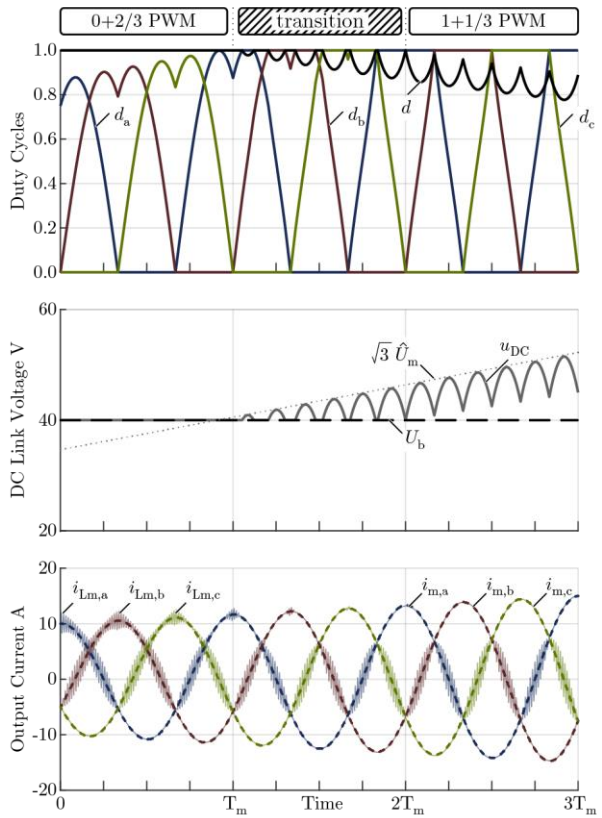


- *Preferable for Low-Dynamics Drive Systems*

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

■ Control Structure & Simulation Results





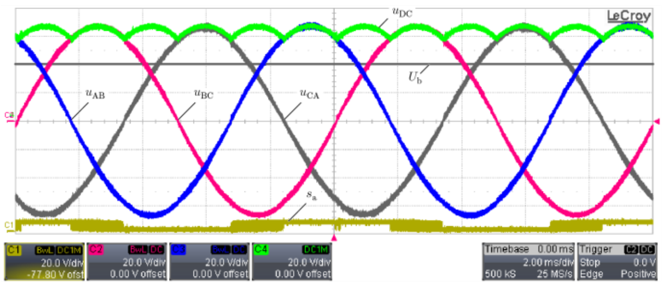
- *Seamless Transition — Clamped Boost-Stage → Temporary → Full Boost-Stage Operation*

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

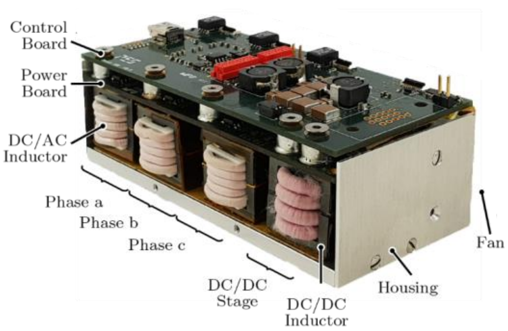
■ Experimental Verification

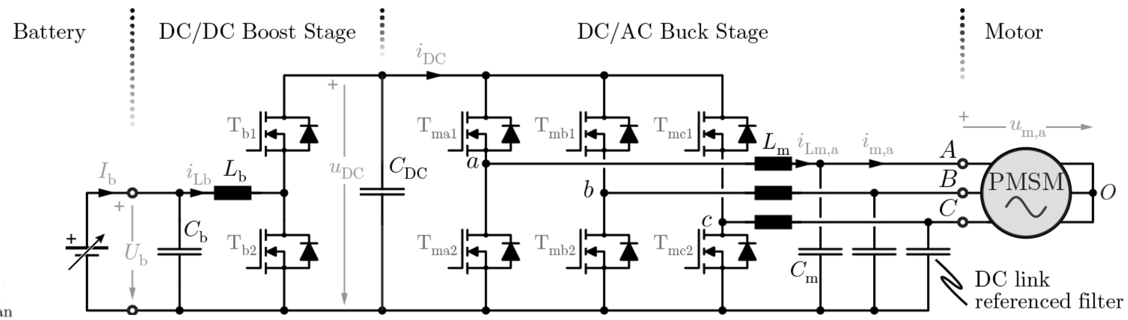
U_b = 40…60V
P = 500W
f_S = 300kHz (200V EPC GaN, 2 per Switch)
f_0 = 5kHz (max.)
M = 0…2 (for U_b=40V)

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



185cm³ / 11.3in³



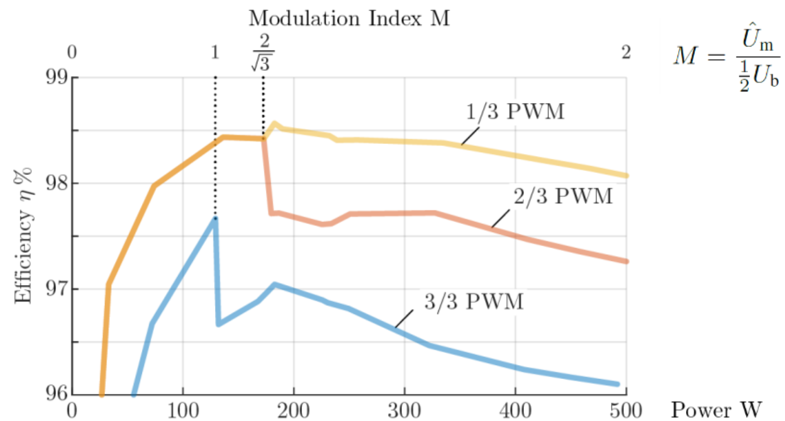


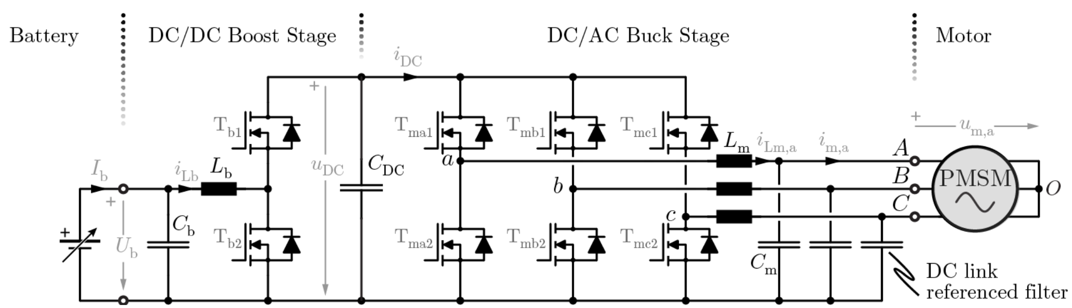
→ Comparison to Conv. U_{DC}=const. Operation (PWM of 2/3 Phases or 3/3 Phases)

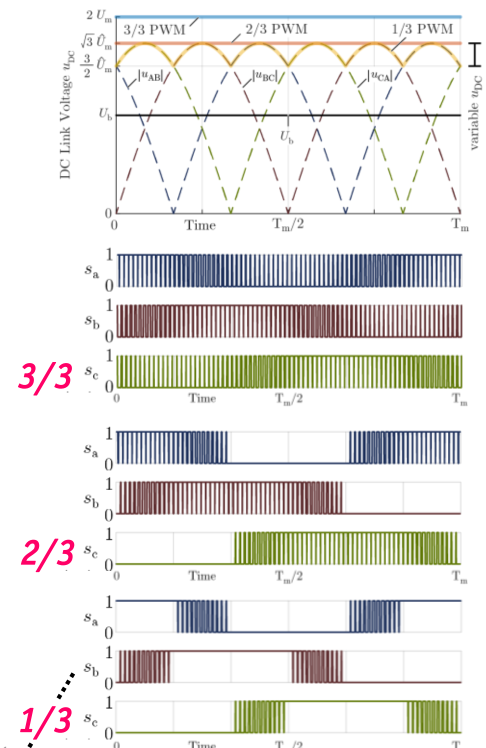
▶ "Synergetic Control" of Boost-Buck Inverter (4)

■ *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

General Remarks

- Usually DC-Link Voltage Midpoint Considered as AC Output Ref. Point
- Open Machine Starpoint → Introduce CM Voltage Shift → Neg. DC-Rail as Reference

Source: Cuk (1982)

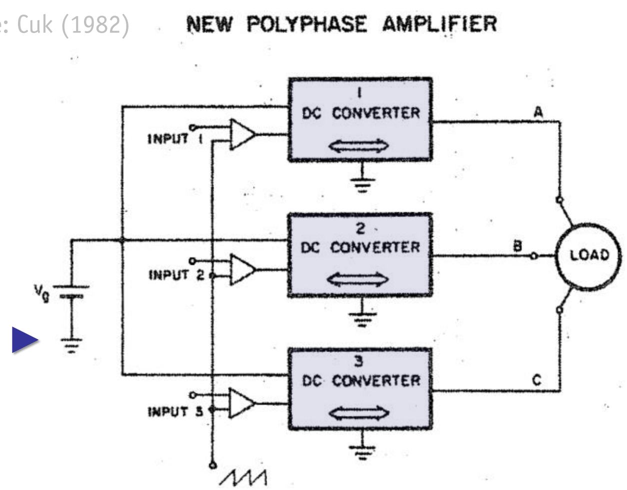


Fig. 7. New three-phase switching amplifier. Three bidirectional dc-dc converters, with their own modulators, driven by a set of three-phase sine waves, constitute three phase voltages around the differential load.

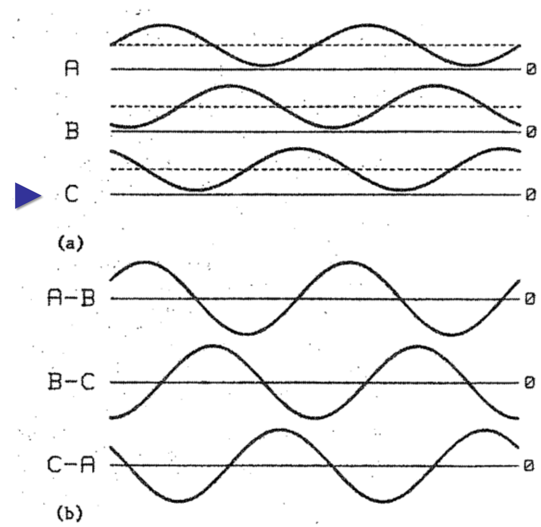
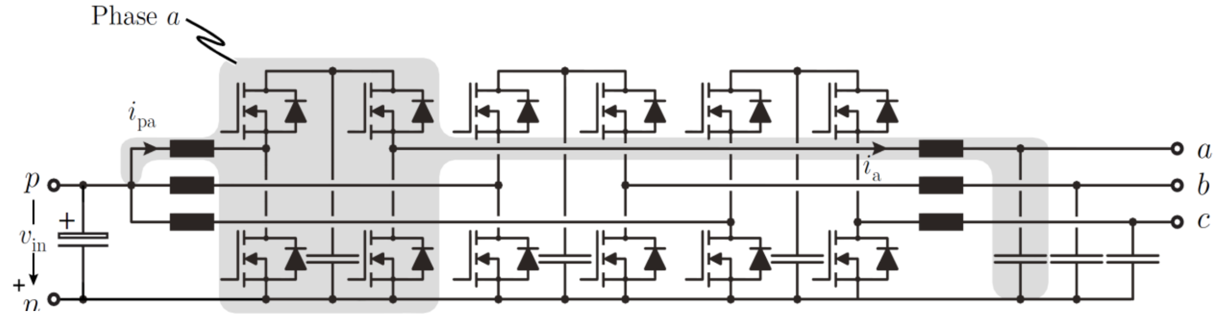


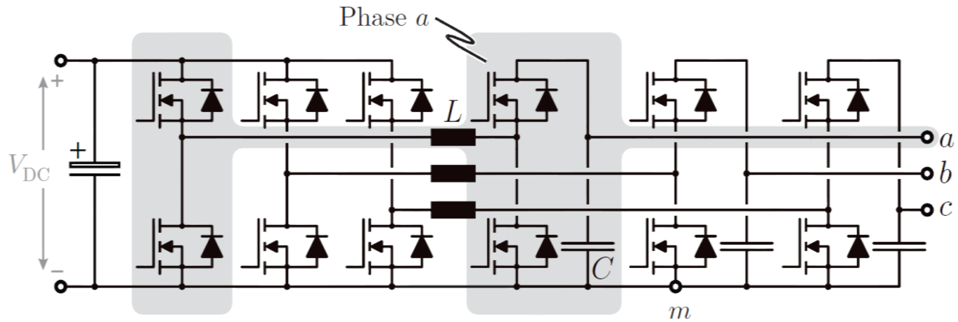
Fig. 8. (a) Line-to-ground and (b) line-to-line voltages generated by the new three phase power amplifier. The dc component of the line-to-ground voltages automatically disappears in line-to-line voltages which are pure ac.

→ Realization of 3-Φ Inverter Using 3 x DC/DC Converter (Phase) Modules — S. Cuk/1982

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

- Wide Voltage Conv. Range → Battery or Fuel-Cell Supply & Adaption to Motor Voltage
- Continuous Output Voltage → Explicit or Integr. LC Output Filter



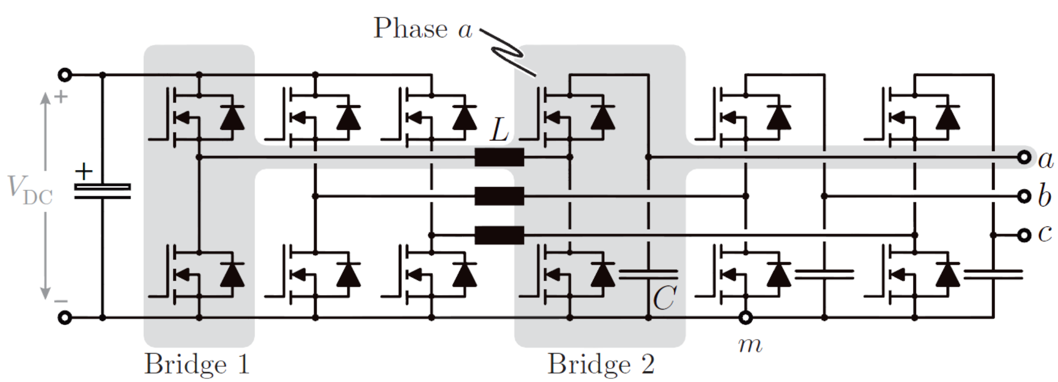


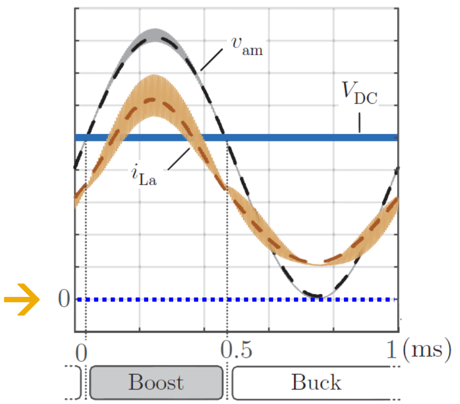
→ Preference for Low Number of Ind. Components → Buck-Boost Concept — "Y-Inverter"

Y-Inverter Lighthouse Project

- 3-Φ Continuous Output / Low EMI !
- Buck+Boost Operation / Wide Input &/or Output Range
- Standard Bridge-Legs / Building Blocks
- ZVS Operation / High Power Density

- No Shielded Cables / No Insul. Stress
- Industrial Drive
- 1.2kV SiC MOSFETs

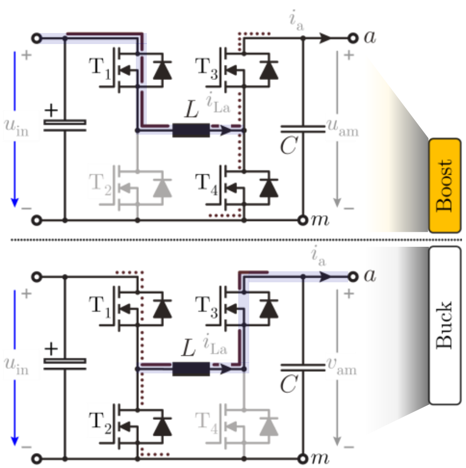


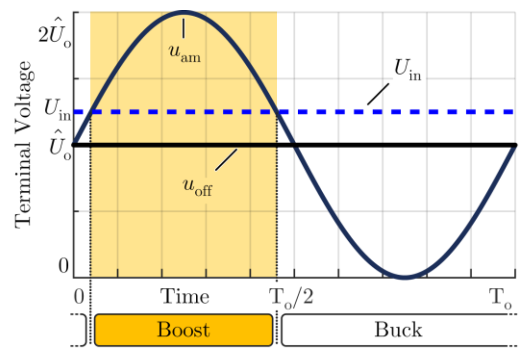


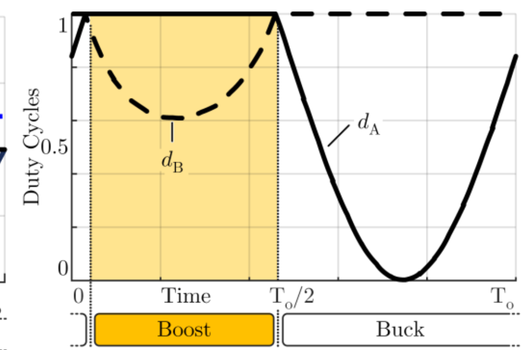
■ *Project Scope →* Hardware Demonstrator / Exp. Analysis / Comparative Evaluation

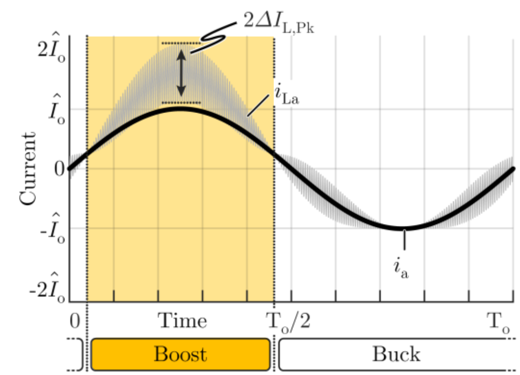
▶ Y-Inverter (1)

- *Operating Behavior*







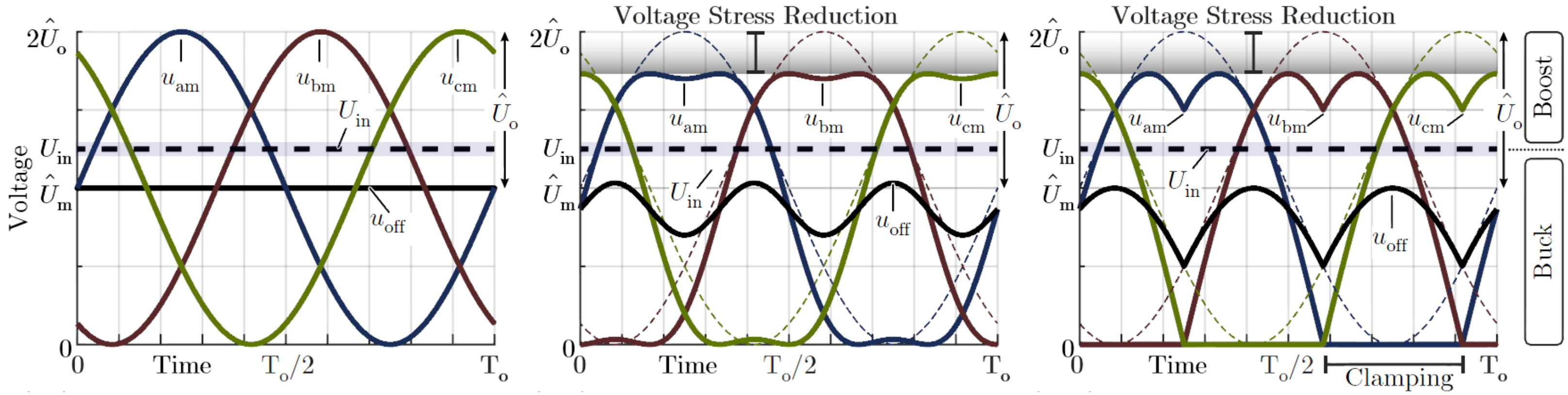


- $u_{am} < U_{in}$ → Buck Operation
- $u_{am} > U_{in}$ → Boost Operation
- Output Voltage Generation Referenced to DC Minus
- *Switch-Mode Operation of Only Buck OR Boost Stage*

▶ Y-Inverter (2)

- Modulation Scheme

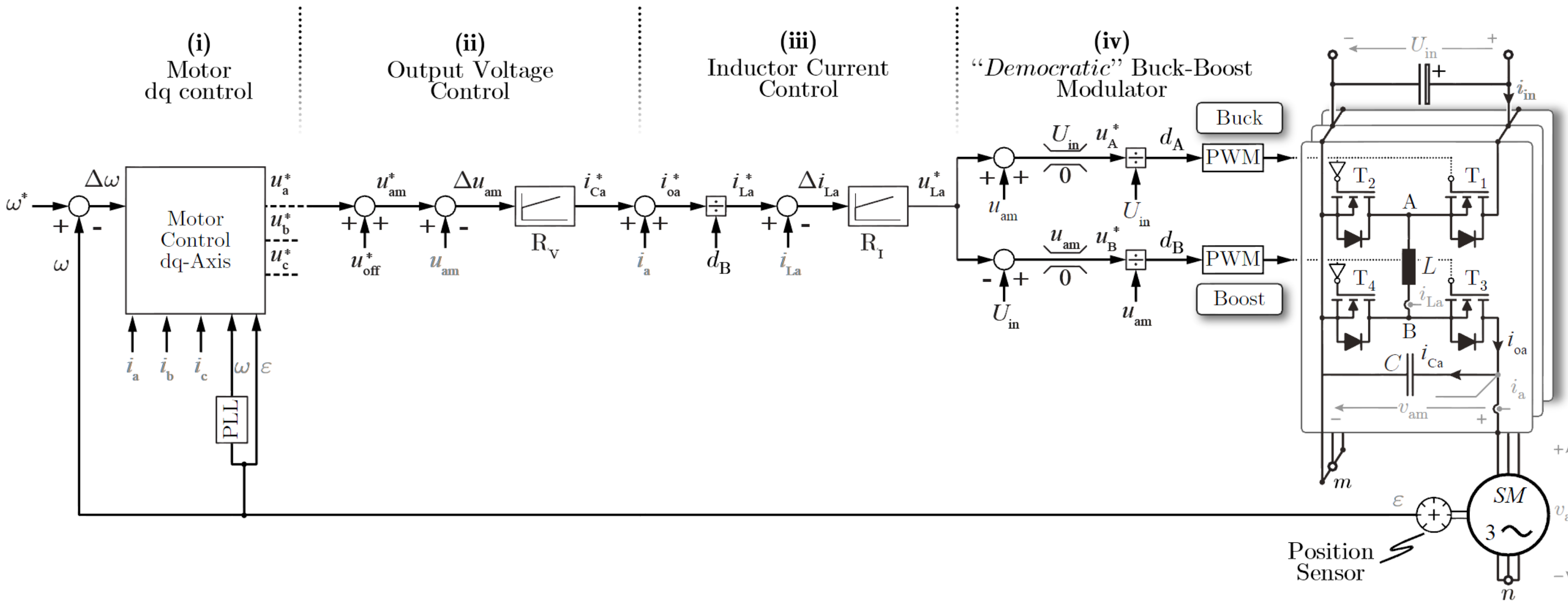
- Continuous Modulation → Opt. DC-Offset of Output Phase Voltages for Low Mod. Index
- Sin. Mod. w/o 3rd Harm. Inj. OR Phase Clamping (DPWM)



- DPWM → Min. DC-Link Voltage & Low Sw. Losses BUT Unsymm. Curr. Stress on Transistors

▶ Y-Inverter (3)

- *Control Structure*

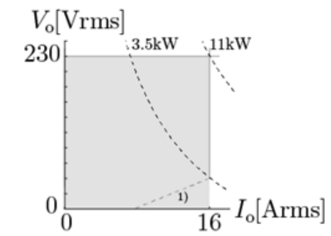


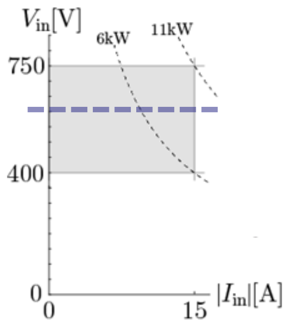
■ *"Democratic Control"* → ***Seamless Transition Between Buck & Boost Operation***

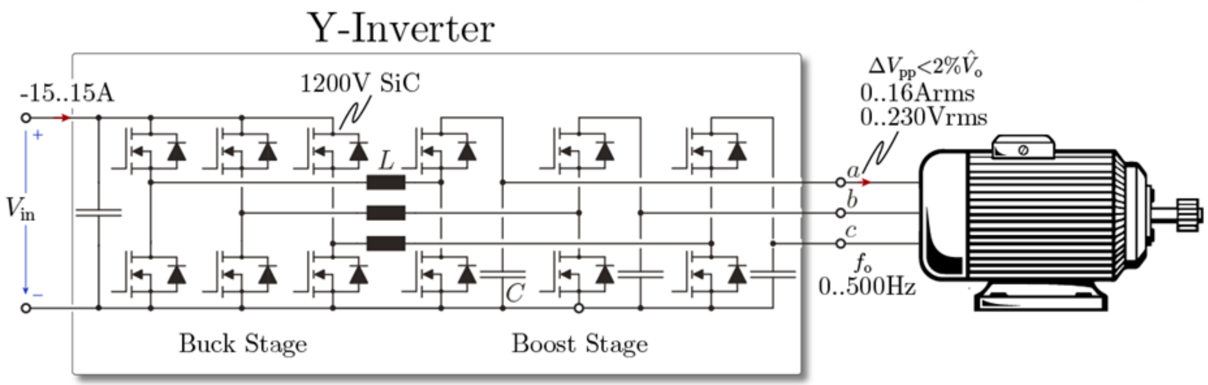
▶ Y-Inverter Prototype (1)

- *Demonstrator Specifications*

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



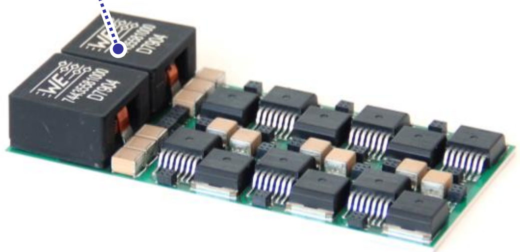


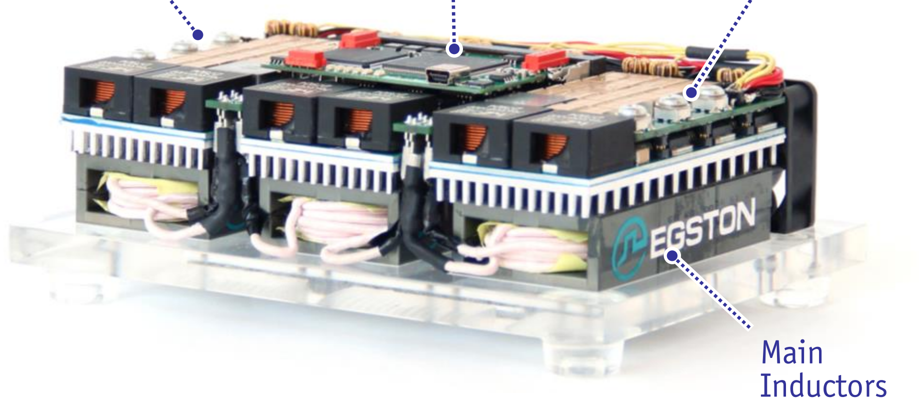


- Max. Output Power → 6...11 kW
- Output Frequency Range → 0...500Hz
- Output Voltage Ripple → 3.2V Peak @ Output of Add. LC-Filter

► Y-Inverter Prototype (2)

- 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 Transistors & Comm. Caps & 2nd Filter Ind.





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

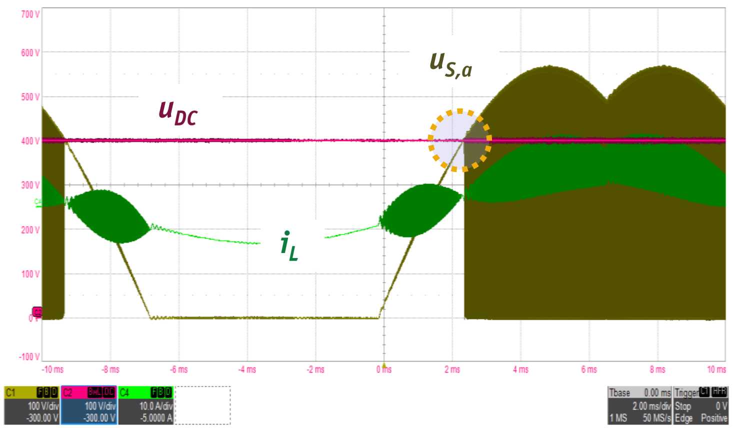
▶ *Measurement Results (1)*

- ***Stationary Operation***

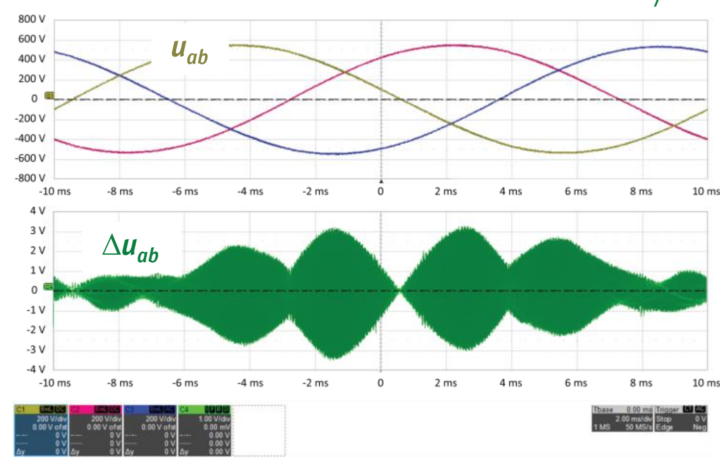
U_{DC}= 400V
U_{AC}= 400V_{rms} (Motor Line-to-Line Voltage)
f_0 = 50Hz
f_S = 100kHz / DPWM

P = 6.5kW

100V/div
10A/div



200V/div
1V/div



→ ***Line-to-Line Output Voltage Ripple < 3.2V***

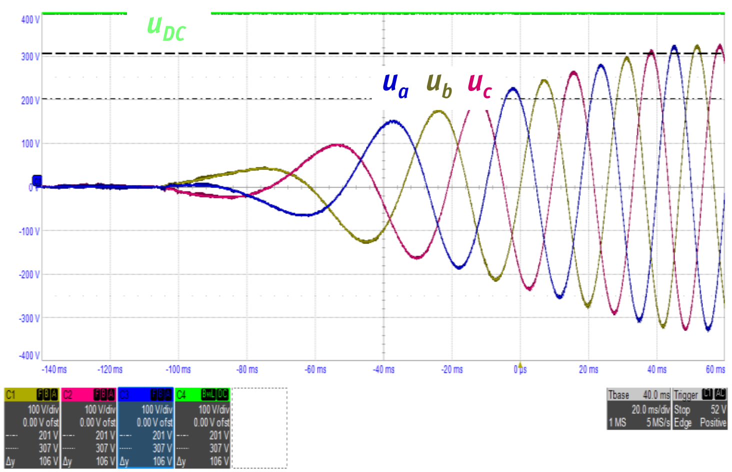
▶ Measurement Results (2)

- *Transient Operation*

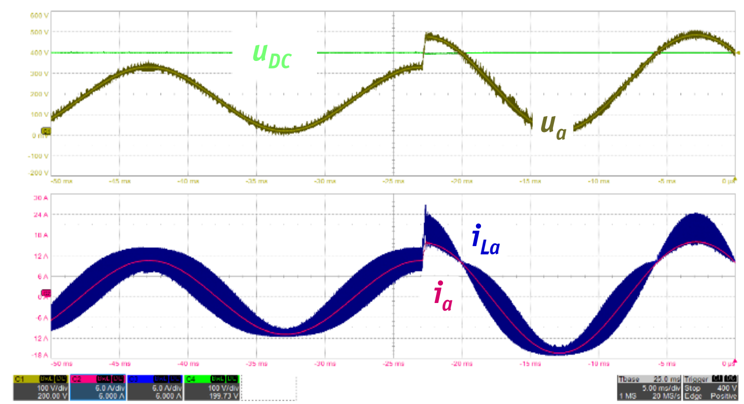
U_{DC} = 400V
U_{AC} = $400V_{rms}$ (Motor Line-to-Line Voltage)
f_0 = 50Hz
f_S = 100kHz / DPWM

P = 6.5kW

100V/div



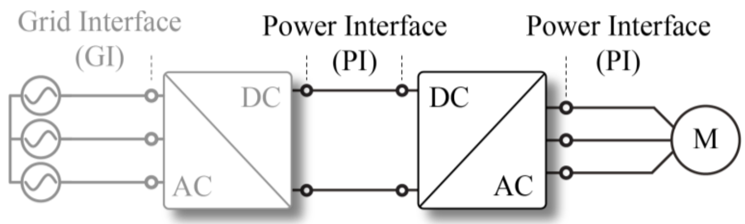
100V/div
100V/div
6A/div
6A/div

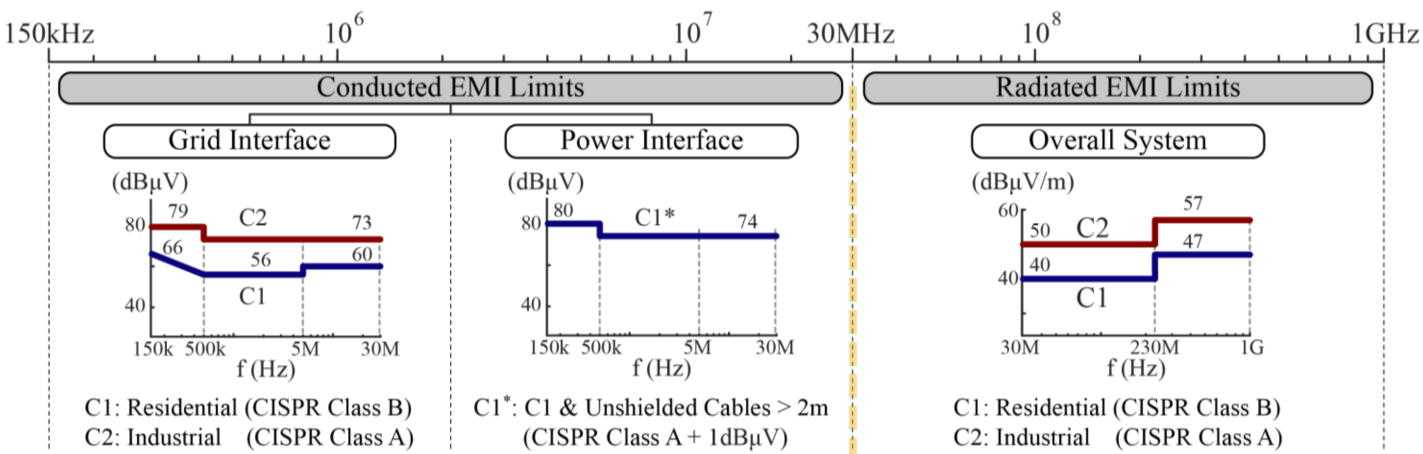


■ *Dynamic Behavior V-f Control and Load-Step*

▶ EMI-Limits (VSD Product Standard)

- IEC 61800-3 → Product Standard for Variable-Speed Motor Drives
- EMI Emission Limits → Grid Interface (GI) and Power Interface (PI)
- Application → Residential (C1) or Industrial (C2)

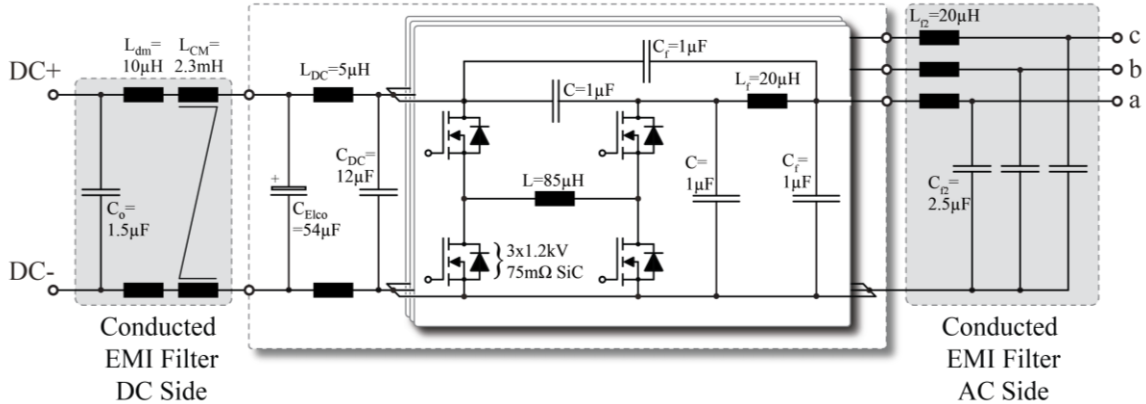


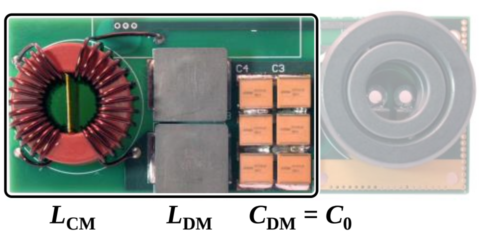


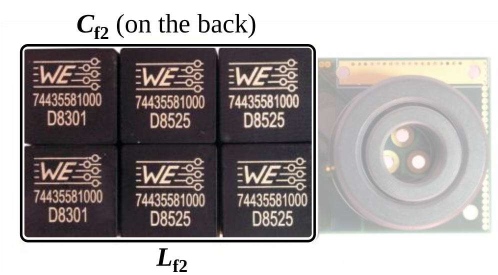
■ *EMI-Filter Design for Unshielded Cables > 2m and Resid. Applications (Cond. & Rad.)*

▶ Conducted EMI-Filter

- Separate Cond. DM & CM EMI-Filter on DC-Side & DC-Minus Ref. EMI-Filter on AC-Side



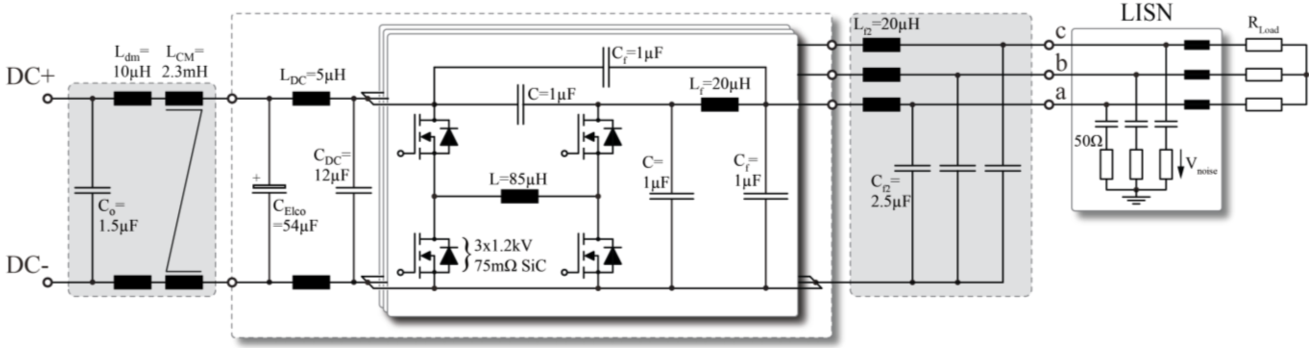


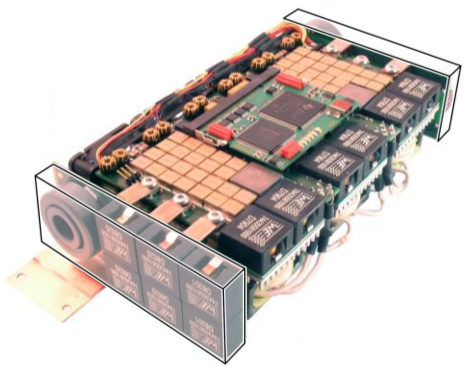


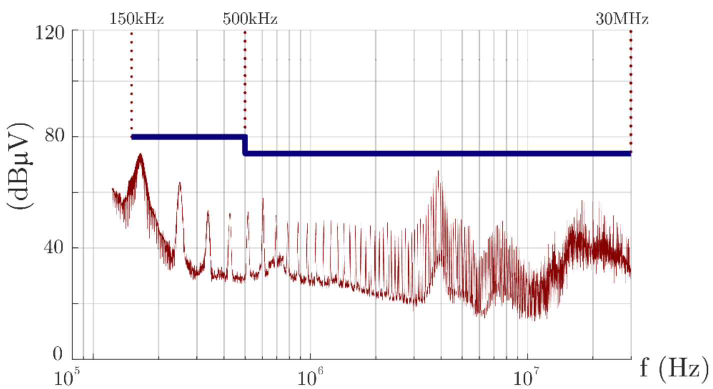
→ *Low Add. EMI Filter Volume — 74cm³ for Each Filter (incl. Toroid. Rad. EMI Filter)*
→ *Total Power Density Reduces — 15kW/dm³ (740cm³) → 12kW/dm³ (890cm³)*

▶ Experimental Results - Conducted EMI

- Measurements of the Cond. EMI Noise on the AC-Side (QP, with 50Hz AC-LISN)



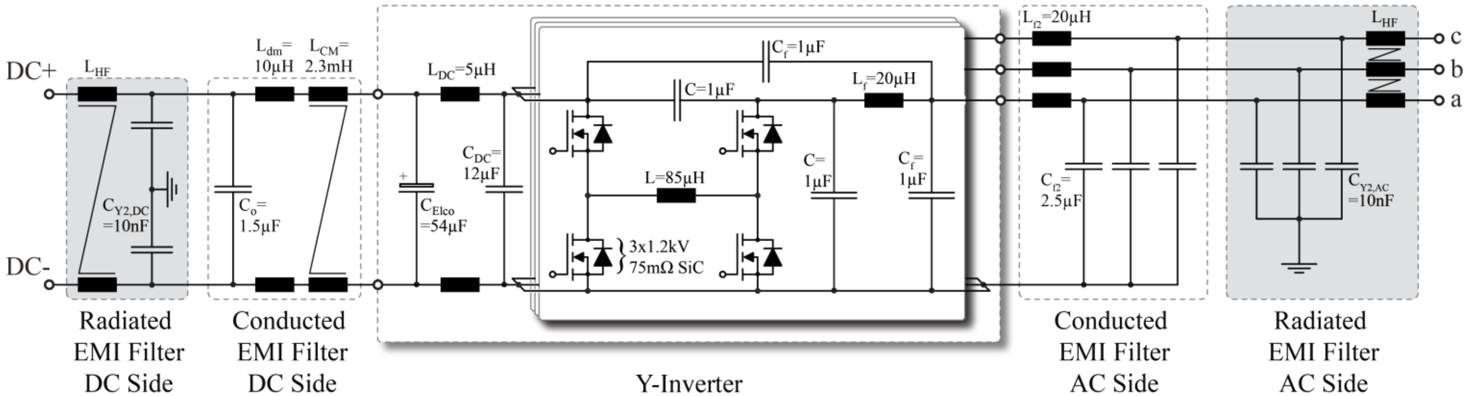


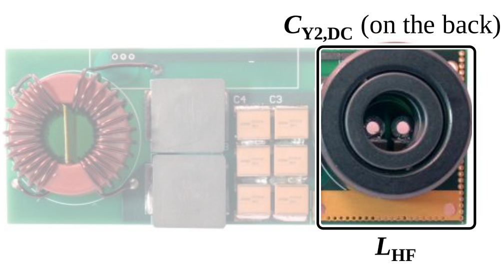


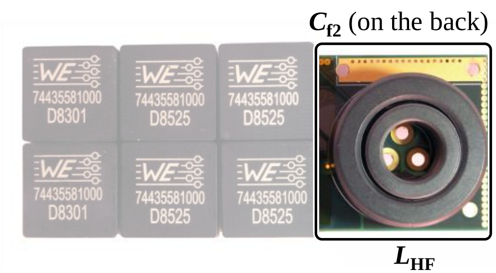
→ Small 80uH CM-Ind. Added on AC-Side - (3cm³ of Add. Volume = 0.5% of Converter Vol.)
→ Conducted EMI with Unshielded Motor Cable Fulfilled

▶ Radiated EMI-Filter

- Single-Stage HF CM-Filter on DC-Side and AC-Side
- Plug-On CM-Cores (NiZn-Ferrites) → Low Parasitics & Good HF-Att. up to 1GHz



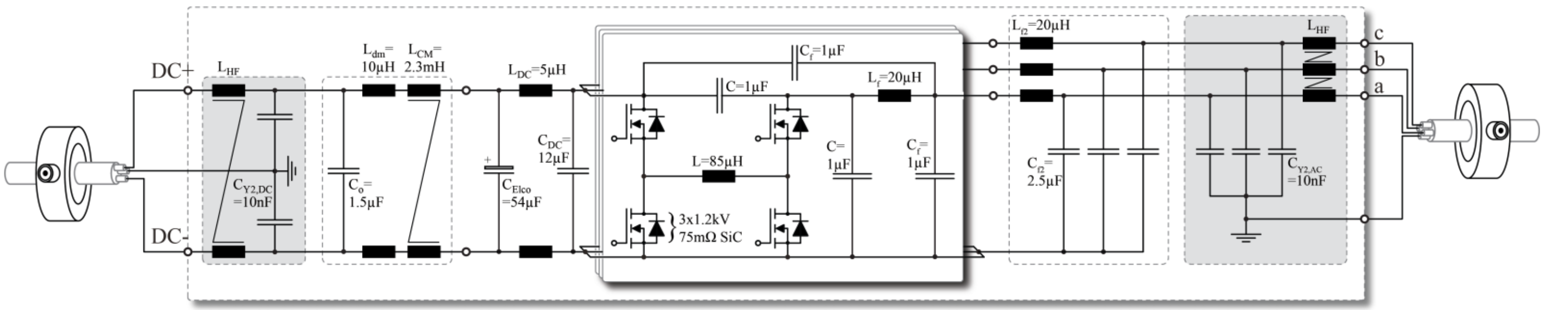


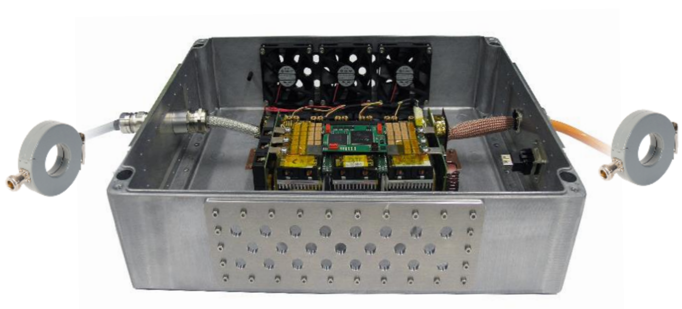


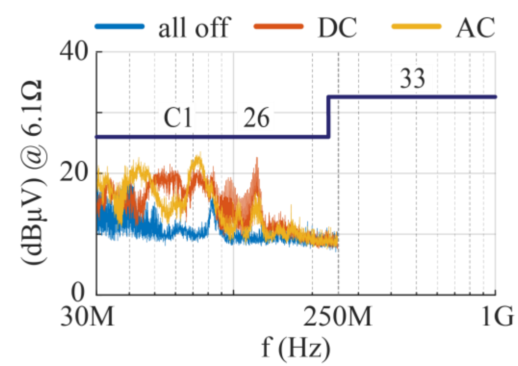
→ *Additional EMI Filter Volume Already Considered with Conducted EMI Filter*
→ *Total Power Density Slightly Reduces — 15kW/dm³ → 12kW/dm³*

▶ Experimental Results - Radiated EMI

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





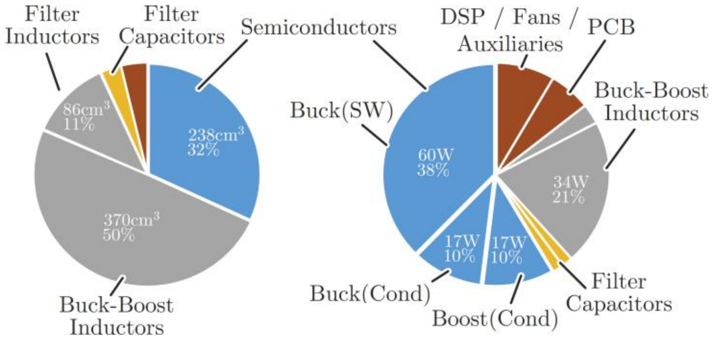


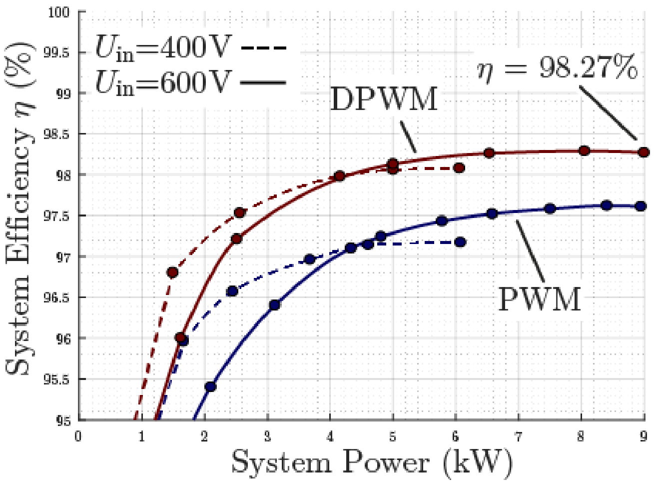
→ *Already Noticeable Noise Floor*
→ *HF-Emissions Well Below Equivalent EMI-Limit* → *Next Step: Verification Using Antenna*

► Efficiency Measurements

- *Dependency on Input Voltage & Output Power Level*

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





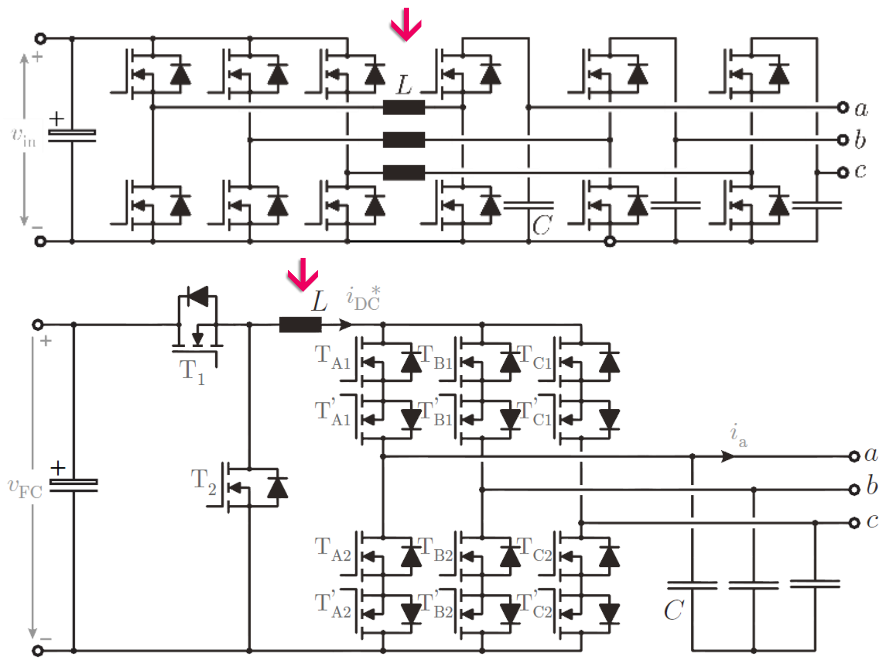
→ *Multi-Level Bridge-Leg Structure for Increase of Power Density @ Same Efficiency*

DC/DC Buck-Stage & Current Source Inverter

Monolithic Bidir. GaN Switches
Synergetic Control

► Current Source Inverter (CSI) Topologies

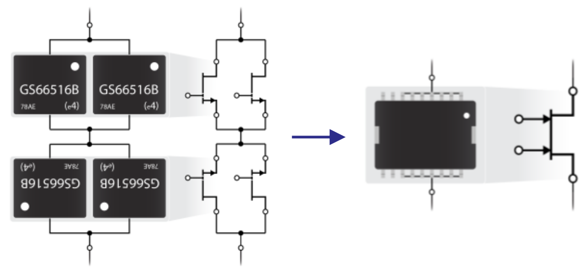
- *Phase Modular Concept → Y-Inverter (Buck-Stage / Current Link / Boost-Stage)*
- *3-Φ Integrated Concept → Buck-Stage & Current DC-Link Inverter*

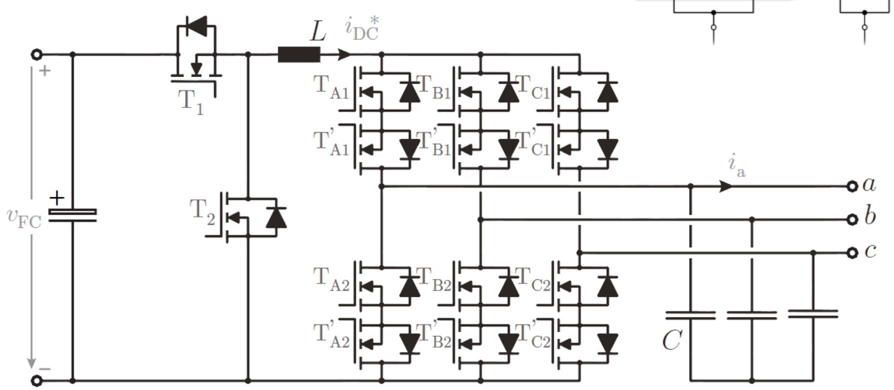


→ Low Number of Ind. Components & Utilization of Bidir. GaN Semicond. Technology

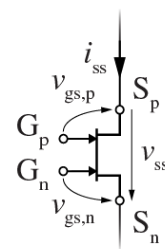
▶ 3-Φ Integrated Buck-Boost CSI (1)

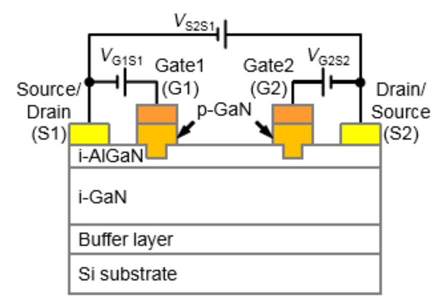
- Basic Topology Proposed in 1984 (Ph.D. Thesis of K.D.T. Ngo/CPES)
- Bidir./Bipolar Switches → Positive DC-Side Voltage for Both Directions of Power Flow





Source: Panasonic ideas for life

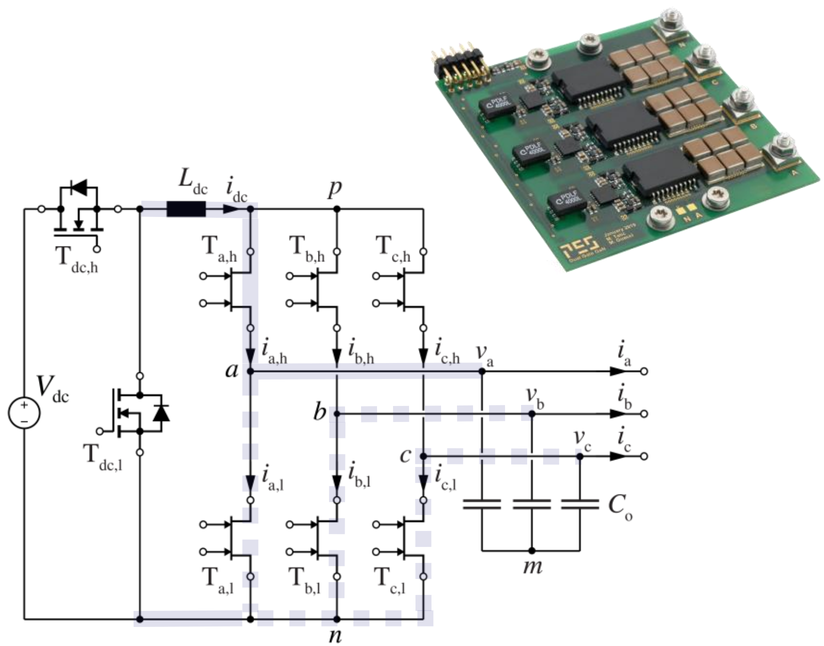


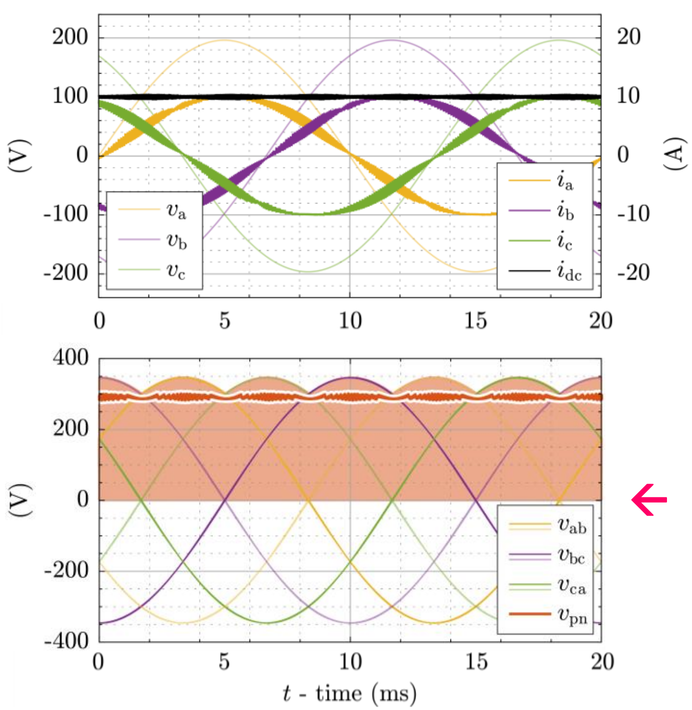


→ Monol. GaN Switches → Factor 4 Improvement in Chip Area Comp. to Discrete Realiz.
→ Also Beneficial for Matrix Converter Topologies

▶ 3-Φ Integrated Buck-Boost CSI (2)

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

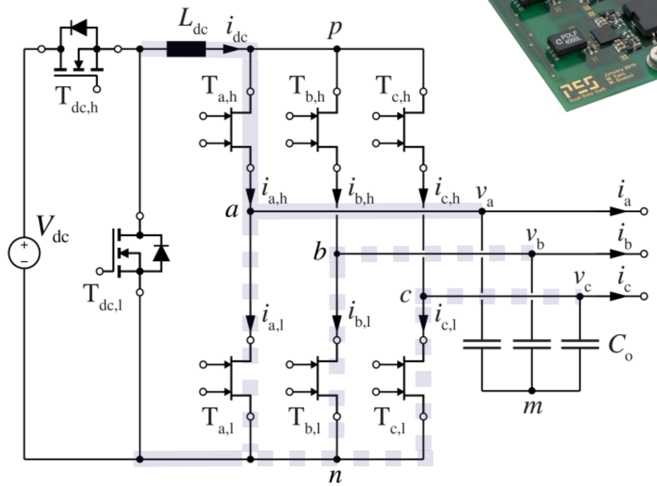


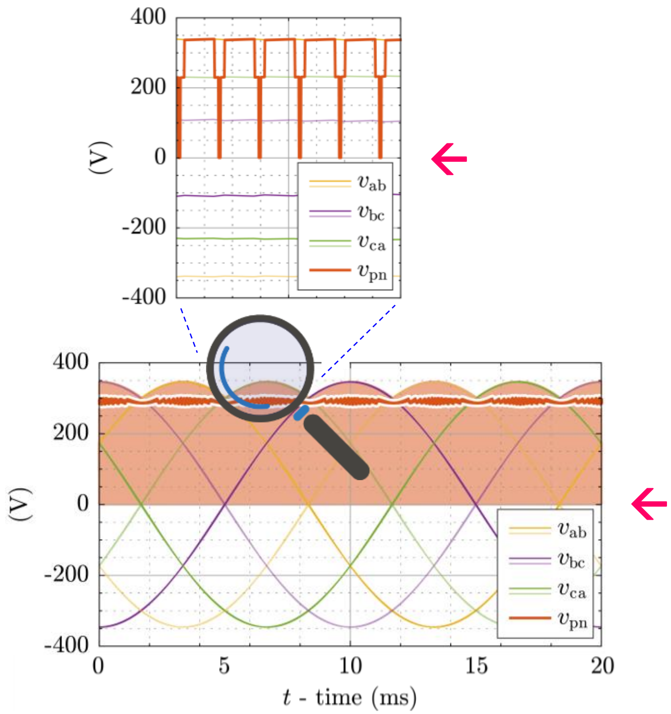


- Conventional Control of Inverter Stage → Switching of All 3 Phase Legs (3/3)

▶ 3-Φ Integrated Buck-Boost CSI (3)

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

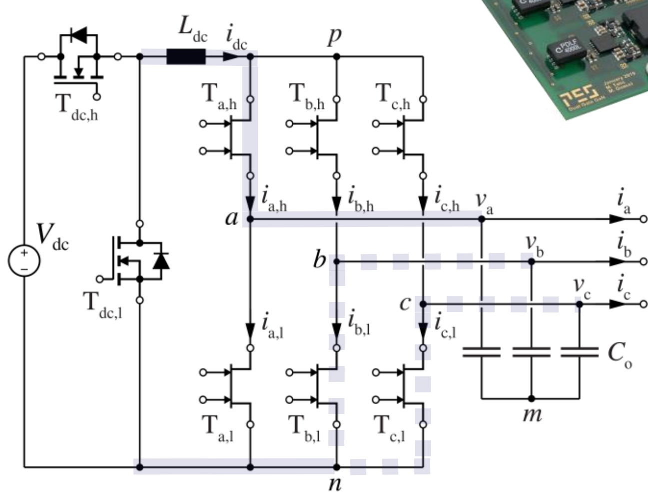


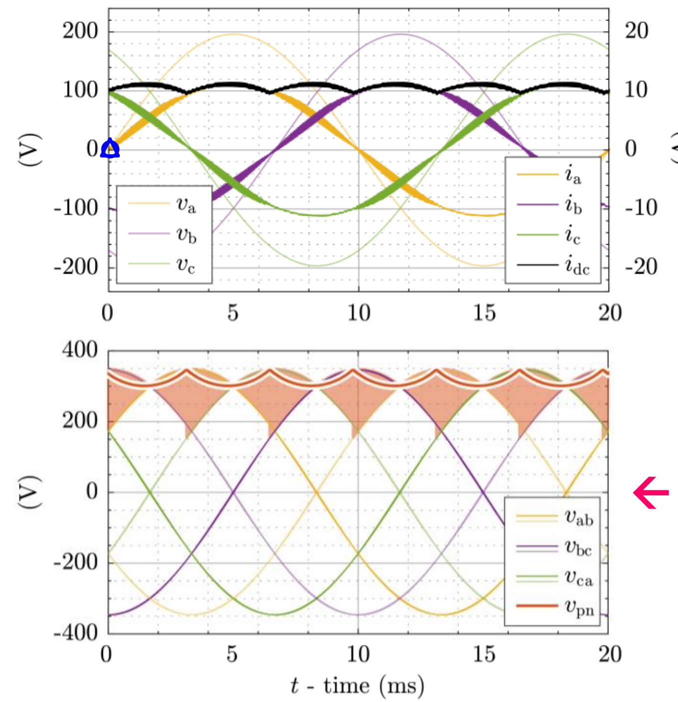


- *Conventional Control of Inverter Stage → Rel. High CSI-Stage Sw. Losses*

▶ 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*

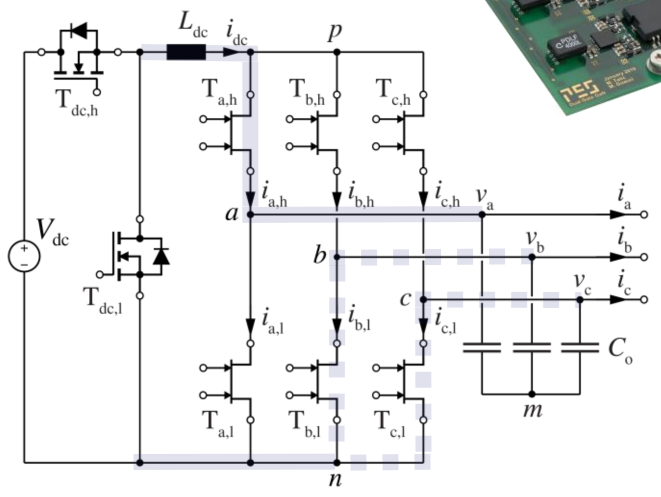


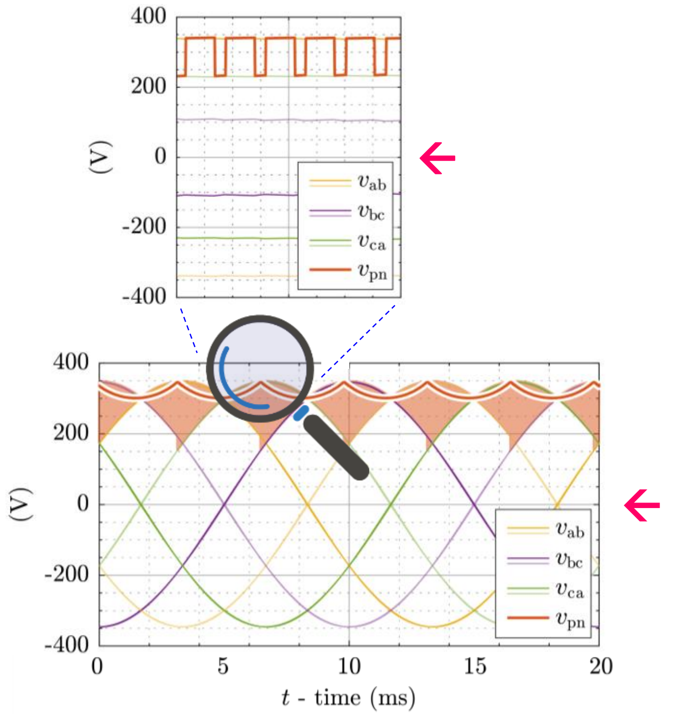


- *Switching of Only 2 of 3 Phase Legs → Significant Reduction of Sw. Losses*

► 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

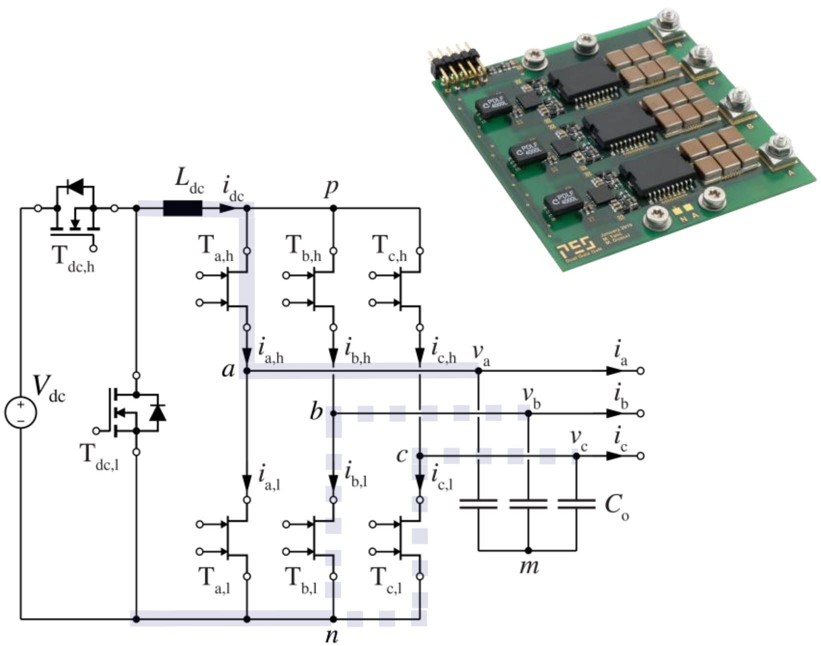


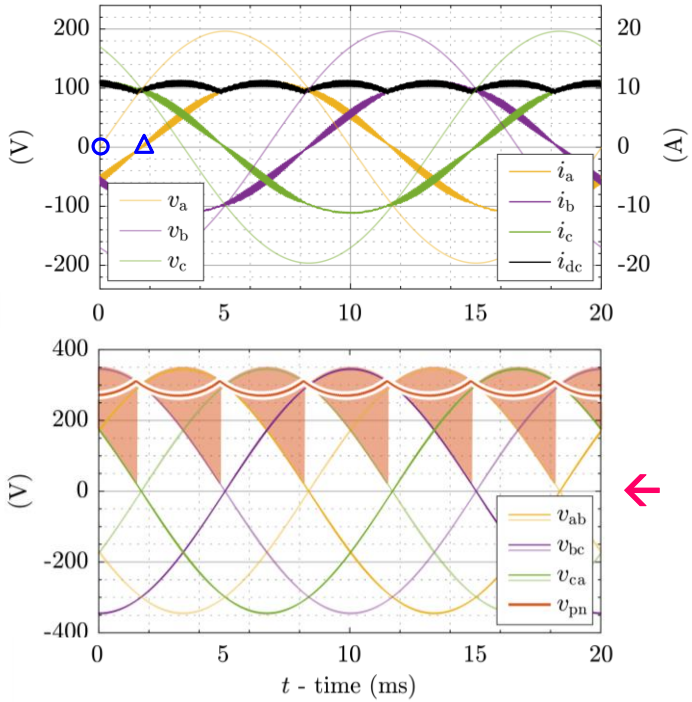


- Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)

► 3-Φ Integrated Buck-Boost CSI (6)

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

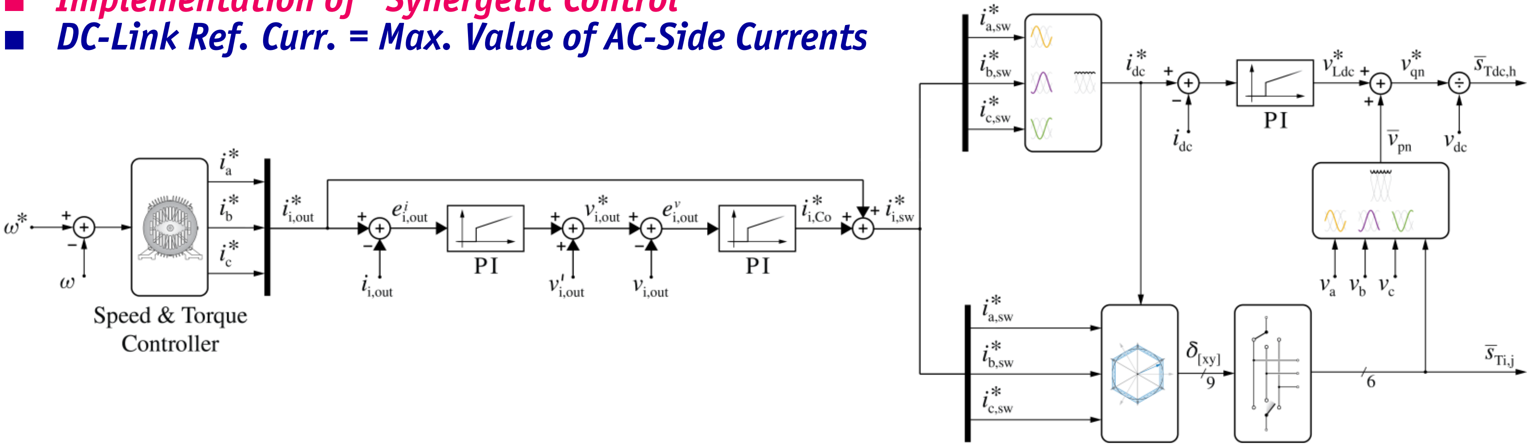




- *Operation for 30° Phase Shift of AC-Side Voltage & Current*

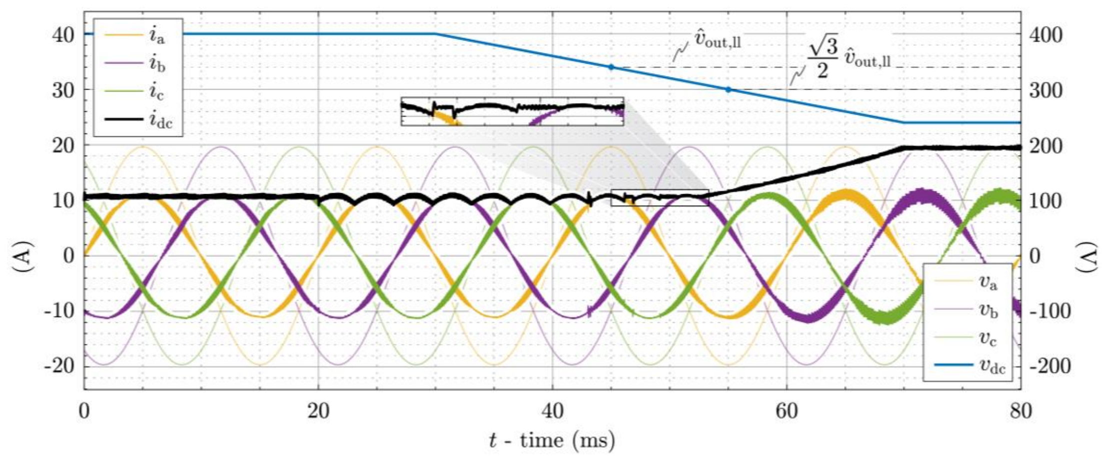
▶ 3-Φ Integrated Buck-Boost CSI (7)

- *Implementation of "Synergetic Control"*
- *DC-Link Ref. Curr. = Max. Value of AC-Side Currents*



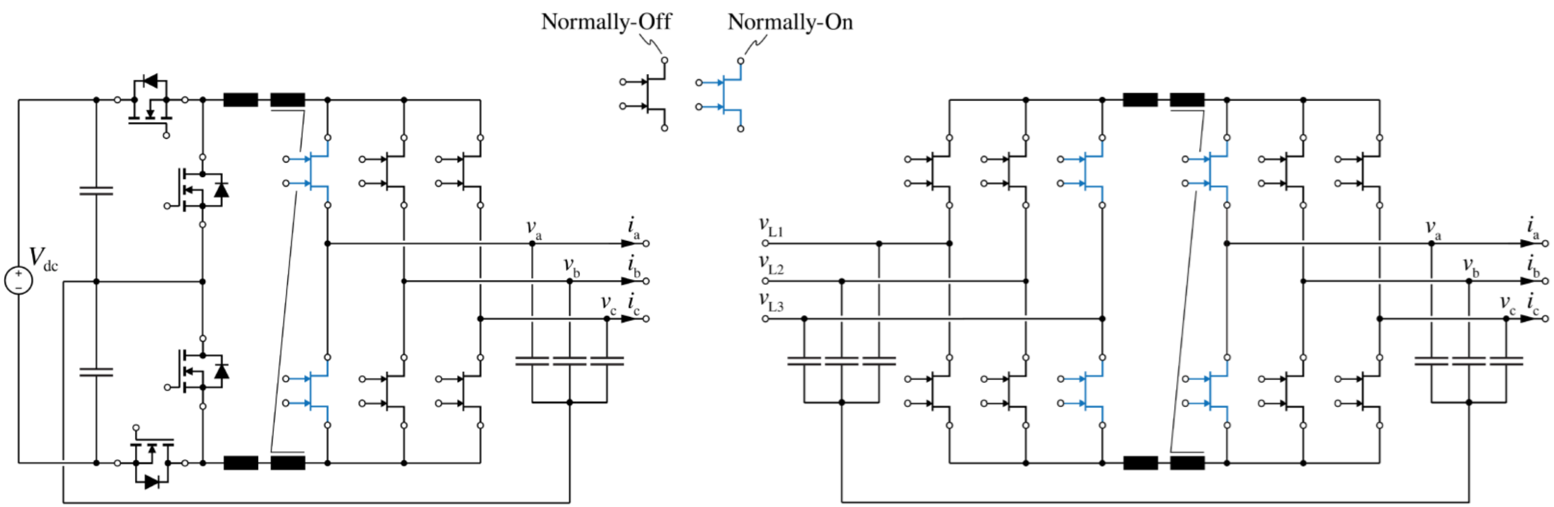
3/3 Mod. (i_{DC}=const.) →
2/3 Mod. (6-Pulse i_{DC}) →
Partial 2/3 Mod. →
Full-Boost Operation

- *Seamless Transition from Buck to Boost Operation*



► Future Research

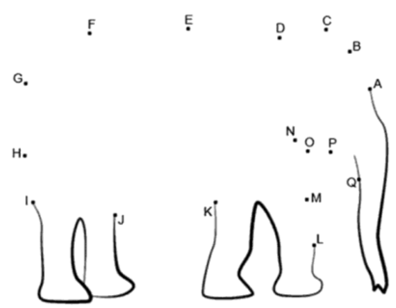
- *Advanced DC/AC Topologies incl. CM-Filtering*
- *Extension of 2/3-PWM to Bipolar DC-Link Voltage 3-Φ AC/AC Converter*
- *Multi-Objective Design & Comparative Evaluation*



- *Partial Use of "Normally-On" Switches for Freewheeling in Case of Auxiliary Power Loss*

Further Concepts

Quasi-2-Level FC Inverter
Power Module with Integrated Filter



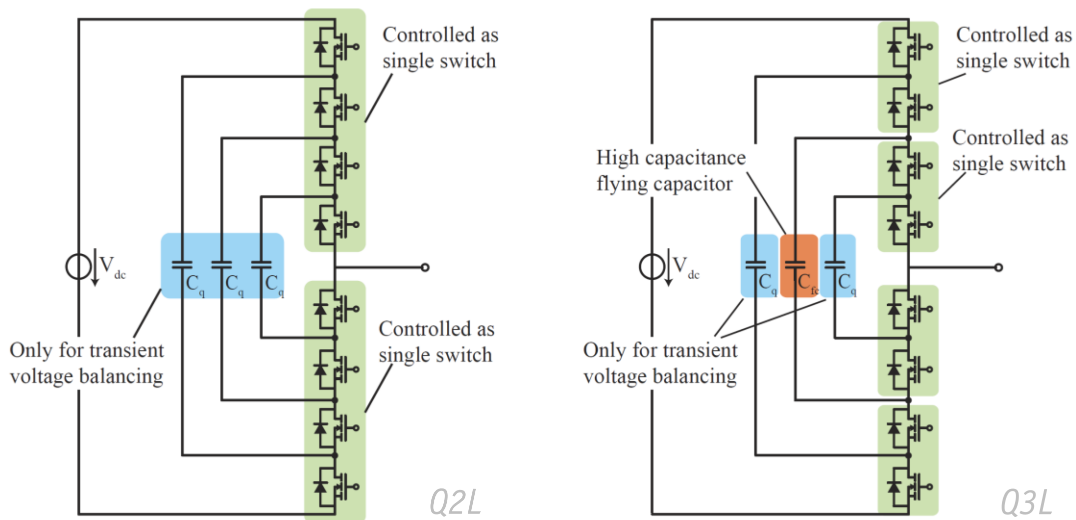
Quasi-2L/3L Flying Capacitor Inverter

▶ 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

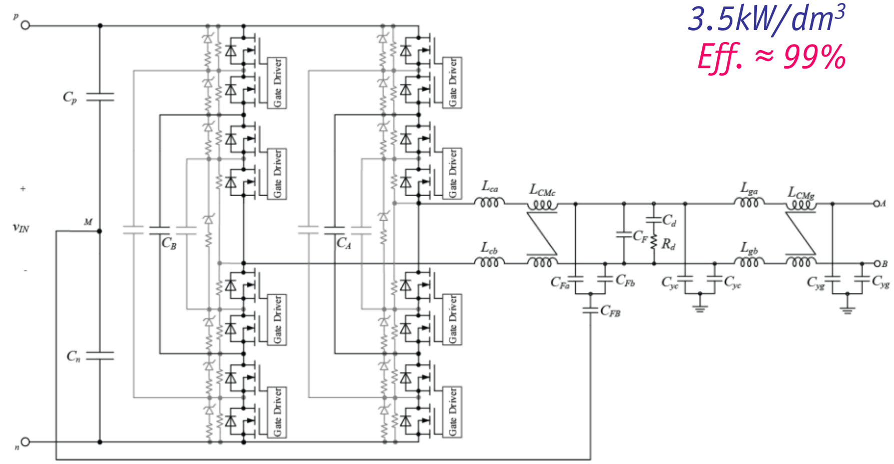
- Schweizer (2017)

ABB

SMD
150V Si-MOSFETs

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

3.5kW/dm^3
Eff. ≈ 99%



- Reduced Average dv/dt → Lower EMI / Refection 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)

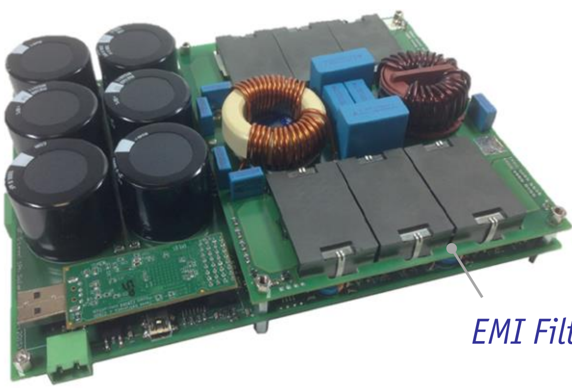
- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

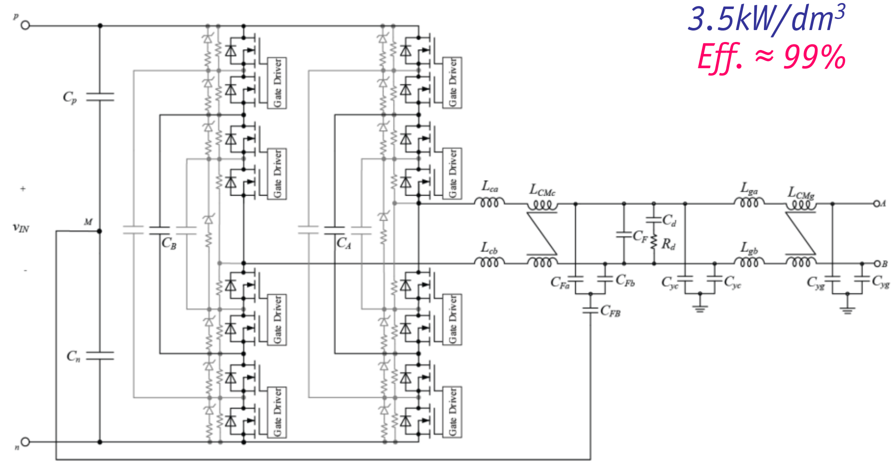
- Schweizer (2017)

ABB

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

3.5kW/dm^3
Eff. ≈ 99%





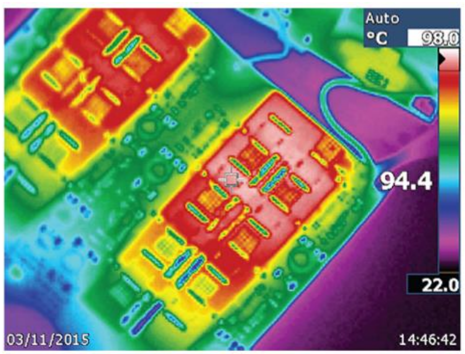
- *Reduced Average dv/dt → Lower EMI / Refection Overvoltages*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/$R_{DS(on)}$/$ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

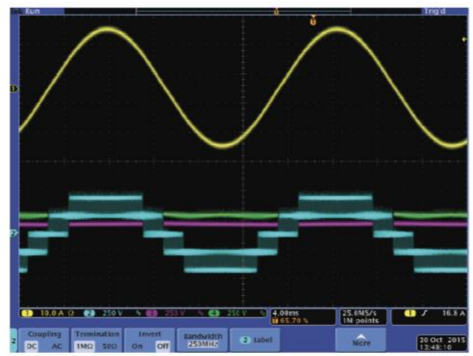
▶ Quasi-2L & Quasi-3L Inverters (4)

- Schweizer (2017)
ABB

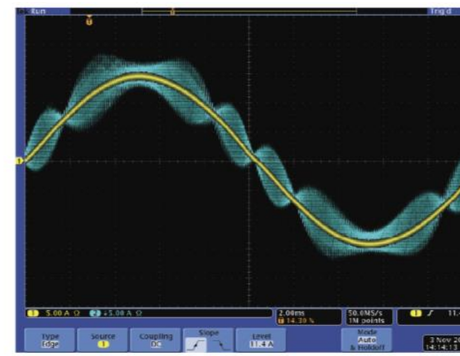
- Operation of 5L Bridge-Leg Topology in Quasi-3L Mode
- Intermediate Voltage Levels Only Used During Sw. Transients
- Applicability to All Types of Multi-Level Converters

Operation @ 3.2kW





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



— Output Current
— Conv. Side Current

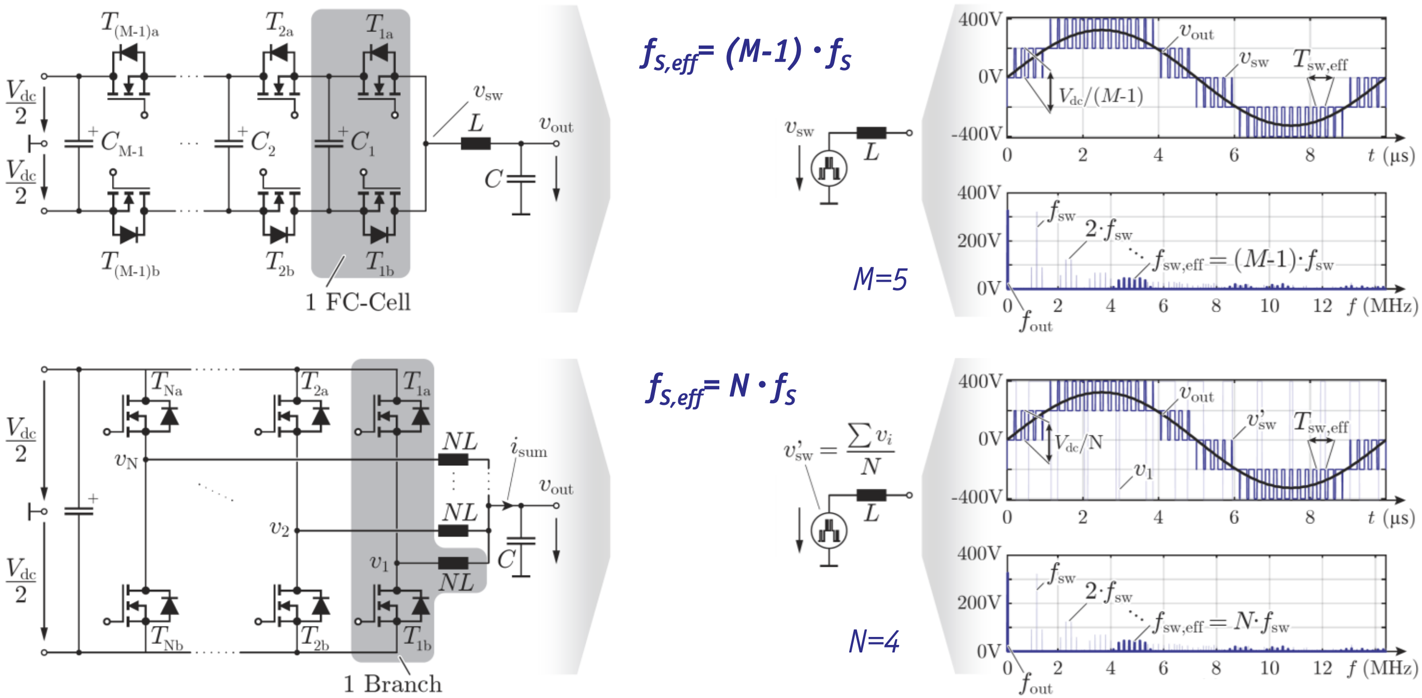
- Reduced Average dv/dt → Lower EMI / Refection Overvoltages
- Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors
- Low Voltage/$R_{DS(on)}$/$ MOSFETs → High Efficiency / No Heatsinks / SMD Packages

Ultra-Compact Power Module with Integrated Filter

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
- Handling of DC Output Requires Flying Capacitor Approach for Series Interleaving

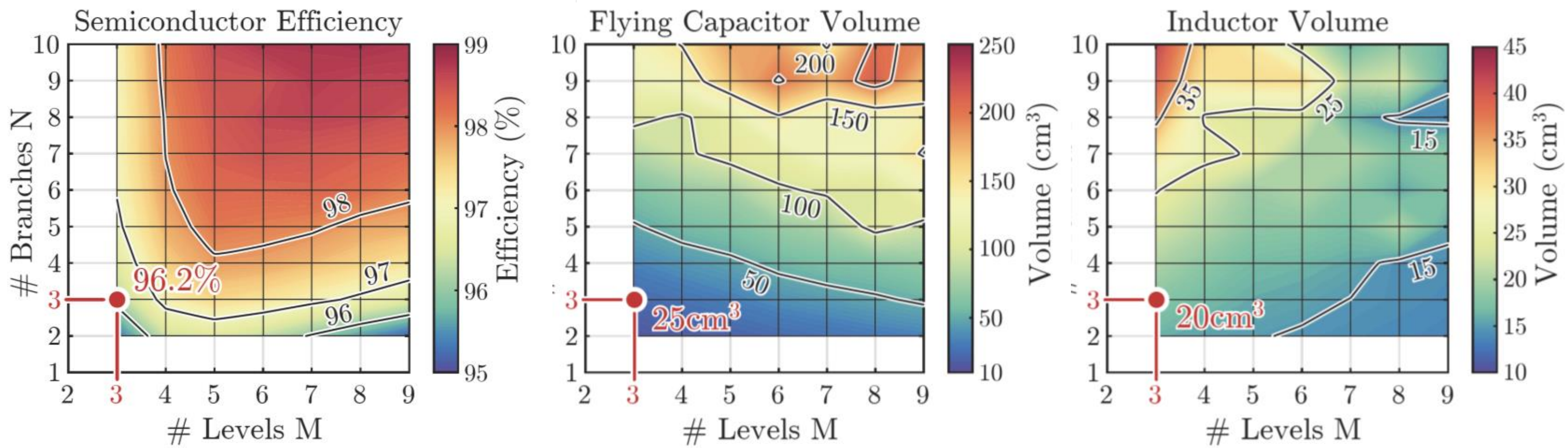


→ Target: Best Combination of Multiple Levels (M) & Parallel Branches (N)

► Integrated Filter GaN Half-Bridge Module (2)

- *Analysis of Best Combination of Levels (M) & Parallel Branches (N)*
- *Application of GaN Semiconductor Technology*
- U_{DC}=800V, P=10kW, $\Delta u_{out,pp}$= 1%, $f_{S,eff}$= 4.8MHz

@ C_{filt}= 90nF =const.



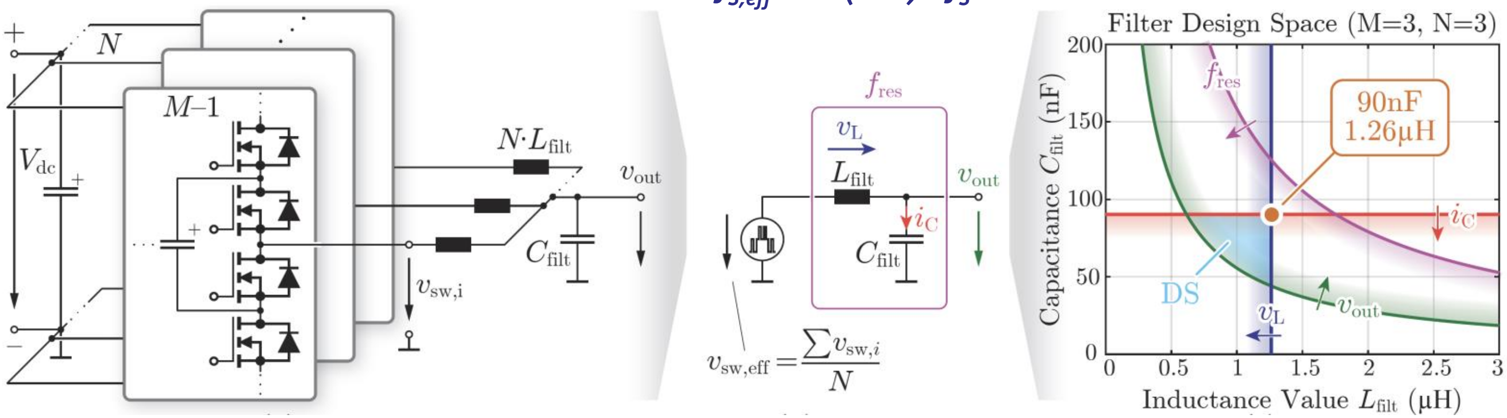
→ L_{filt}= 1.26uH Fixed in Order to Limit Branch Current Ripple for High N
→ Selection of M=3 / N=3 Considering Efficiency / Filter Volume Trade-Off

► Integrated Filter GaN Half-Bridge Module (3)

- Selection of M=3 / N=3 Considering Efficiency / Filter Volume Trade-Off
- $N \cdot L_{filt}$=3.3uH of Branch Inductance / C_{filt} = 90nF
- 650V GaN E-HEMT Technology
- $f_{S,eff}$= 4.8MHz

V_L < 15%
I_C <30%

$f_{S,eff} = N \cdot (M-1) \cdot f_S$



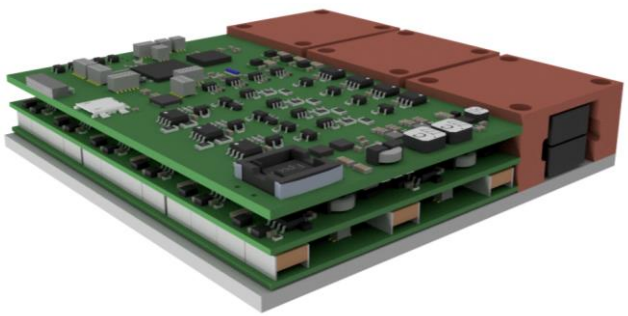
- Design for Max. Output Frequency of f_{out} = 100kHz (!) @ Full-Scale Voltage Swing

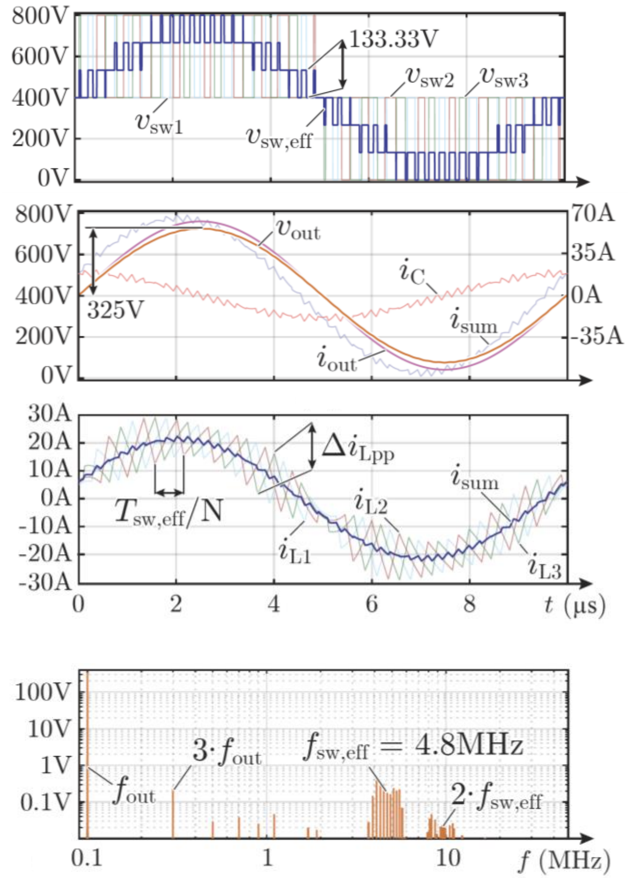
► Integrated Filter GaN Half-Bridge Module (4)

■ **Demonstrator System**

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

★ ≈ 50kW/dm³





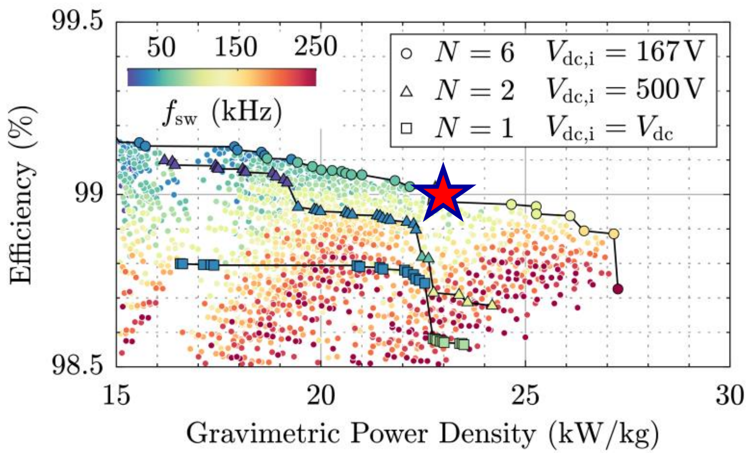
● Operation @ f_{out}=100kHz ($f_{S,eff}$= 4.8MHz)

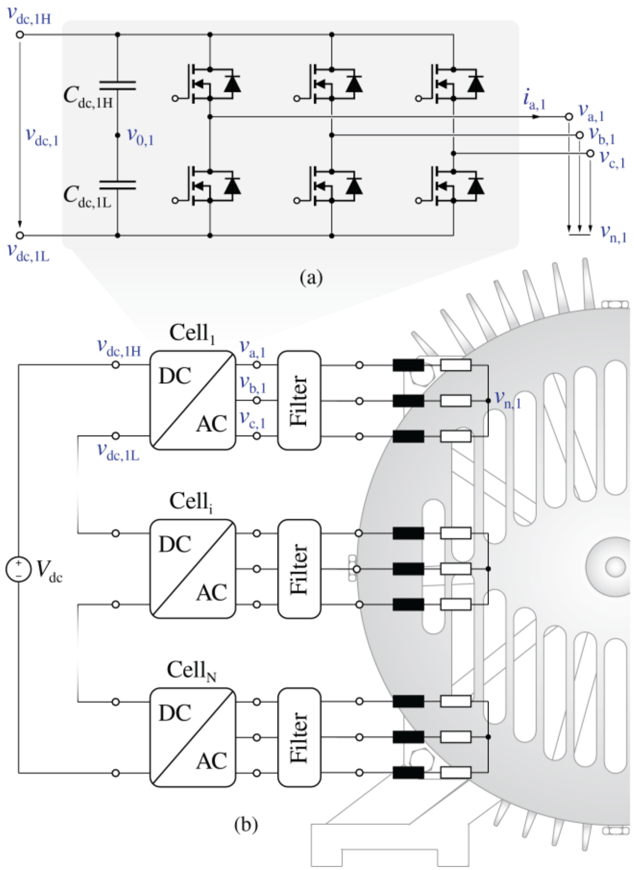
Motor-Integrated Modular Inverter

▶ 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

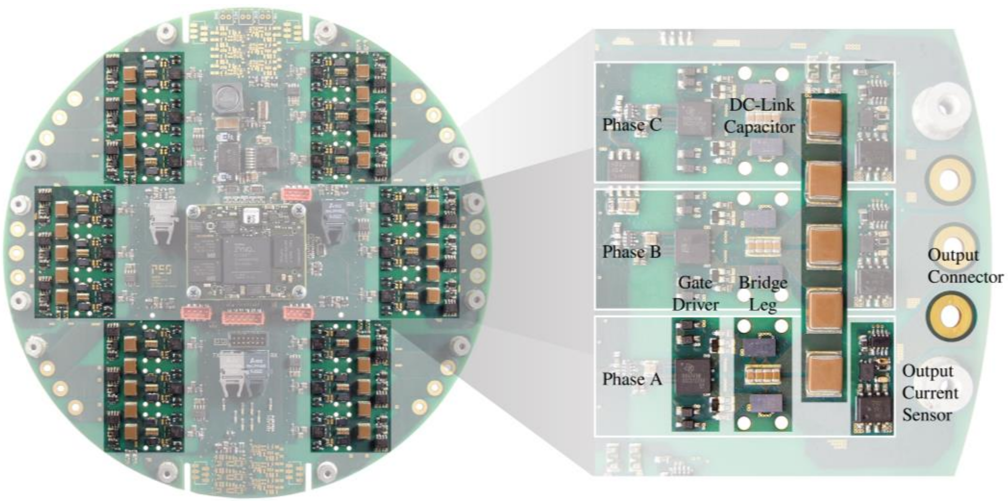




→ **Evaluate Machine Concept (PMSM vs. SRM etc.)** / Wdg Topologies / Filter Requ. / etc.

▶ Motor-Integrated Inverter Demonstrator

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



Source: Oak Ridge Nat. Lab

— 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 „SWISS Knife"-Type Systems**

— 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!