International Forum on
Recent Trends in Power Electronics

Latest Findings in Three-Phase AC/DC Converter Research

Johann W. Kolar et al.

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

May 18, 2018

ETH zürich

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Latest Findings in Three-Phase AC/DC Converter Research

J.W. Kolar, M. Antivachis, D. Bortis, D. Menzi, J. Miniböck, F. Krismer

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Outline

- Energy Research @ ETH Zurich

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

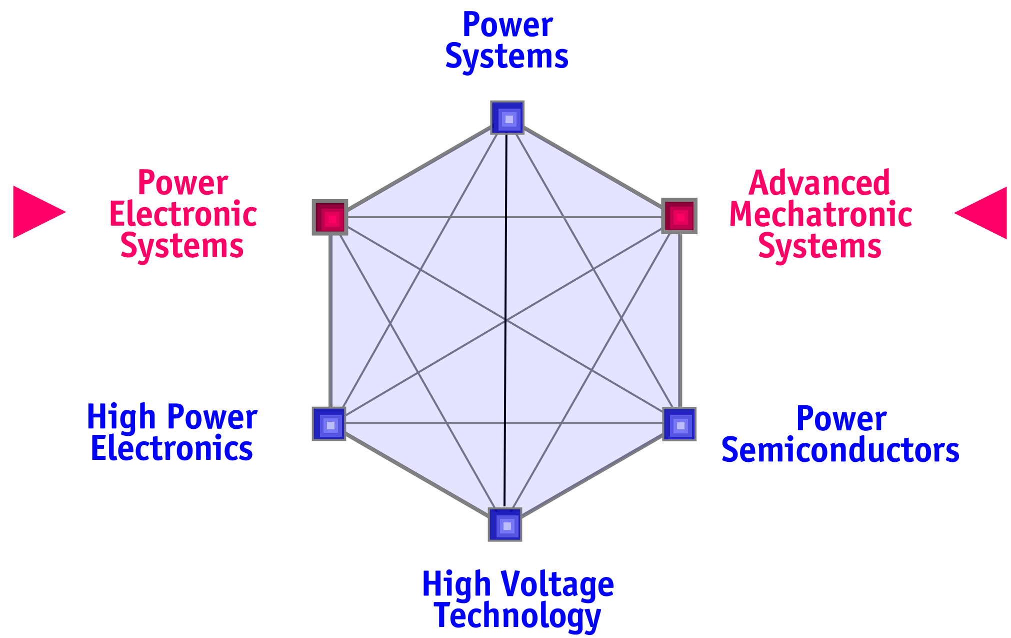
Students ETH in total

14’500	B.Sc.+M.Sc.-Students
4’000	Doctoral Students

ITET - Power Electronic Systems Laboratory

Systems

Technologies



- 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**
C. Gammeter D. Menzi D. Neumayr D. Rothmund J. Schäfer L. Schrittwieser	J. Azurza P. Czyz	P. Bezerra T. Guillod G. Knabben O. Knecht	M. Antivachis J. Böhler M. Guacci	P. Papamanolis	P. Niklaus	M. Flankl M. Mauerer	Th. Holenstein P. Püntener S. Miric M. Schuck

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

23 Ph.D. Students
2 Sen. Level Researchers

Leading Univ. in Europe

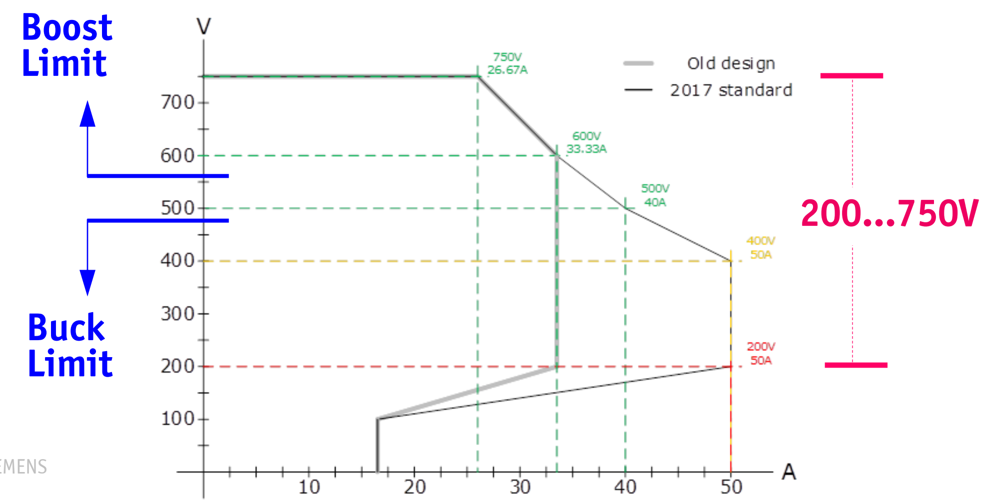
Source: Porsche
Mission-E Project

High-Power EV Battery Charging

High-Power EV Battery Charging

- *China -* EV Charging Equipment Supplier Qualification Standard
- *Extremely Wide DC Output Voltage Range*

Source: SIEMENS



▶ *Buck-Boost Functionality → Boost-Type PFC Rectifier & Back-End Buck Converter*

High-Power EV Battery Charging

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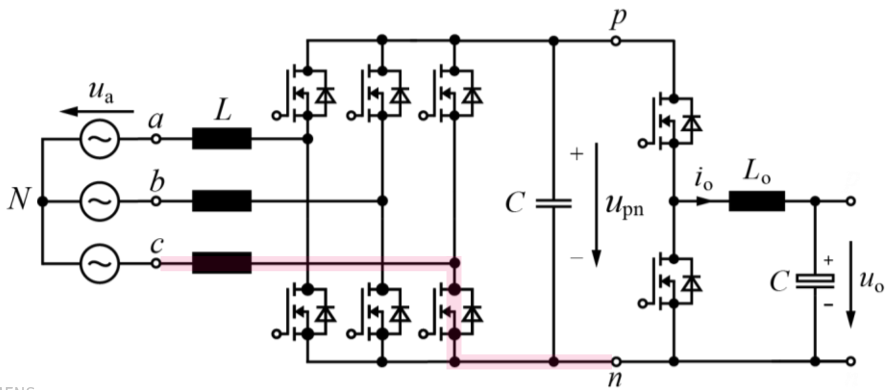
Source: SIEMENS



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High-Power EV Battery Charging

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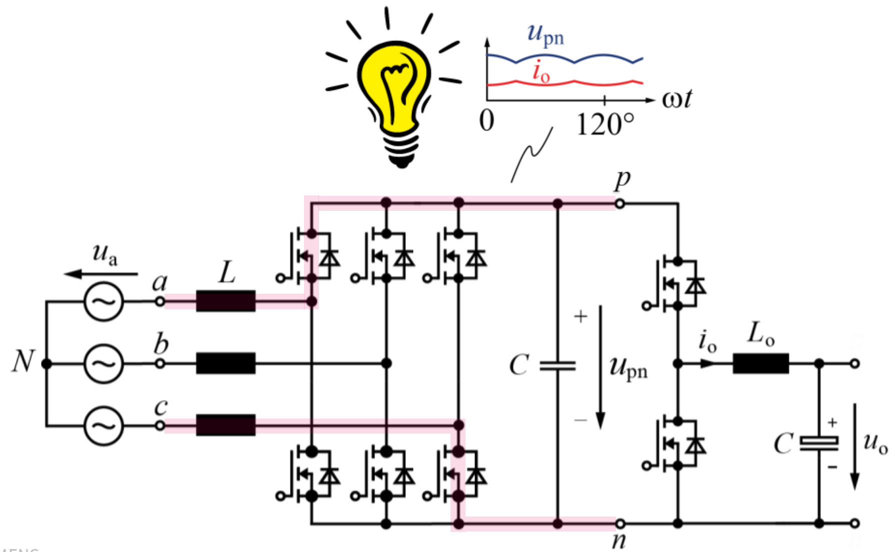
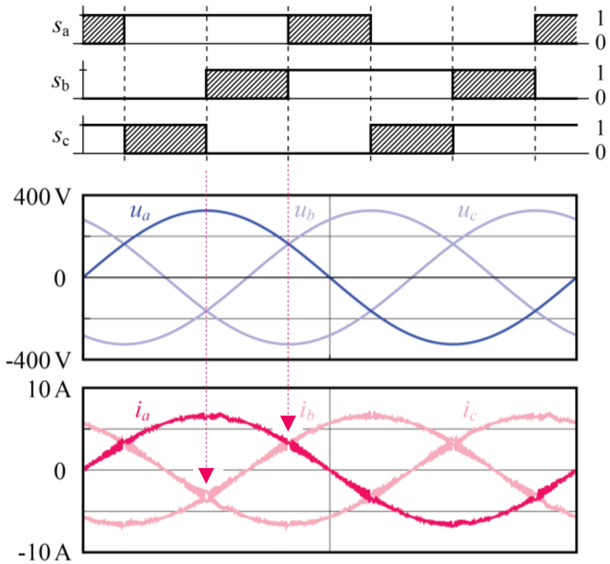
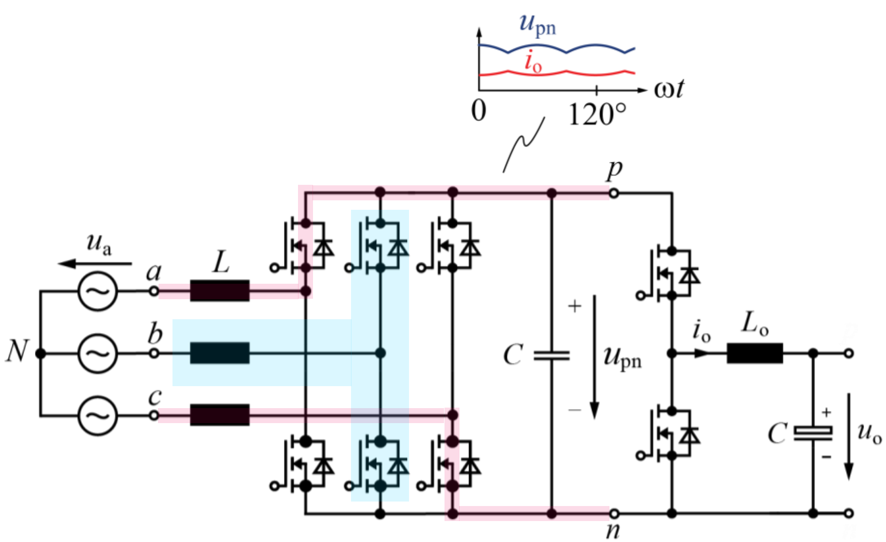


► *Buck-Stage Utilized for DC Link Voltage Shaping / Switching of Single Mains Phase*

1-out-of-3 *Boost+Buck* AC/DC Converter

- *Single Phase PWM Operation → Low Switching Losses / High Efficiency*
- Cont. Input & Output Currents

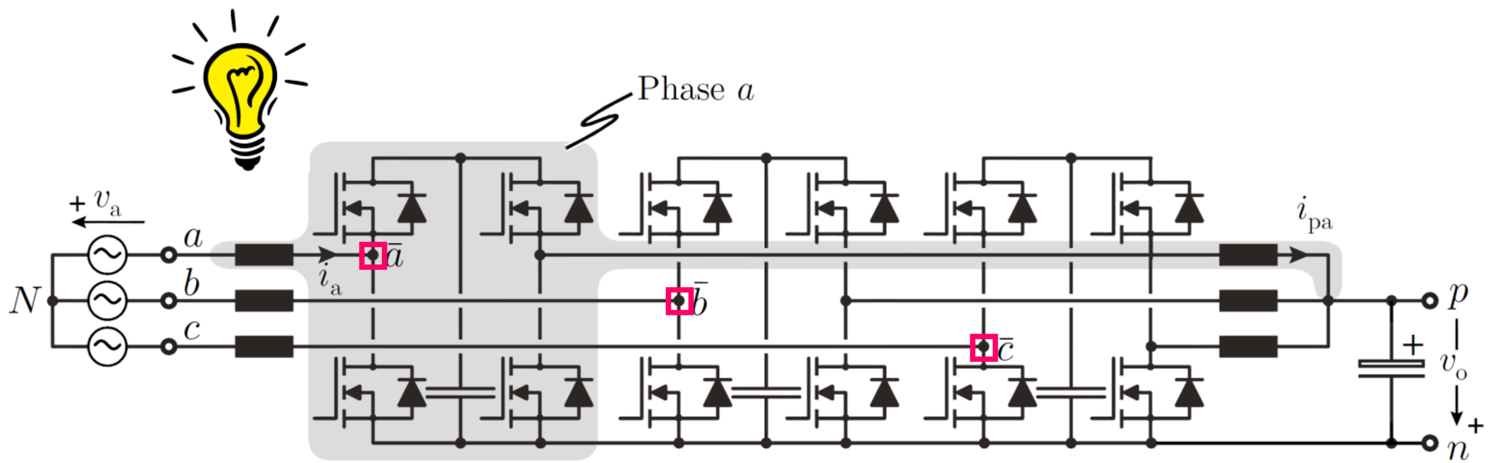




▶ High Output Voltage → Operation as *Conv. Boost-Type* PWM Rectifier / Clamped Buck-Stage

Alternative Phase-Modular Approach #1

- *Individual DC Link Voltages of the Phases*
- *AC Input Phase Voltages Generated with Reference to DC-Minus*
- DC Link Voltages Adapted to Required AC Input Phase Voltage



- ▶ Continuous Input and Output Currents
- ▶ Clamping of Boost or Buck Bridge Leg of Phase Module → Low Switching Losses

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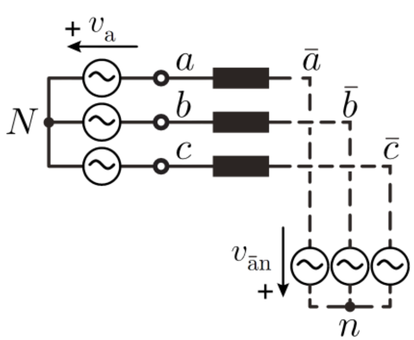
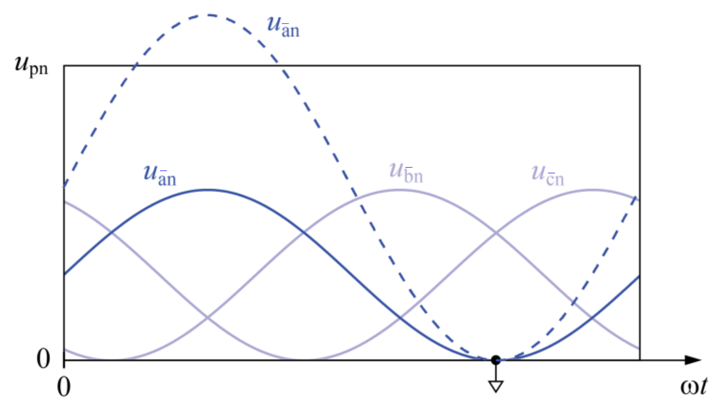
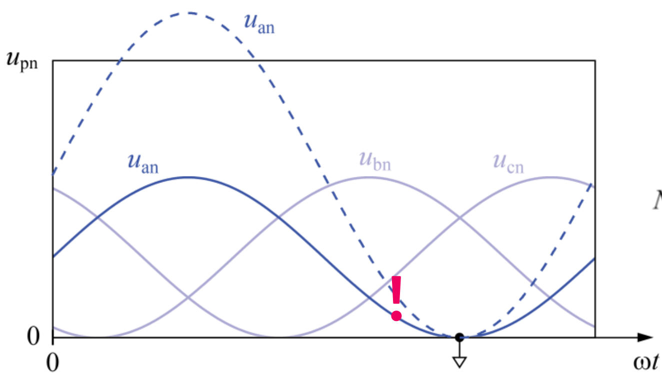


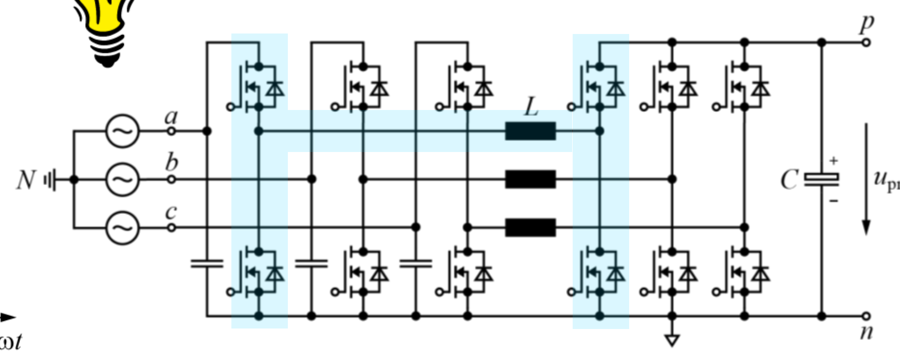


- Continuous Input and Output Currents
- Clamping of Boost or Buck Bridge Leg of Phase Module → Low Switching Losses

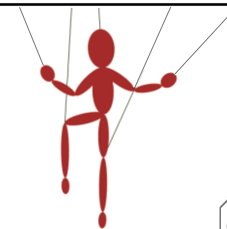
Alternative Phase-Modular Approach #2

- *"Buck-Boost" Instead of "Boost-Buck" Phase Modules*
- *AC Input Phase Voltages Generated with Reference to DC-Minus*



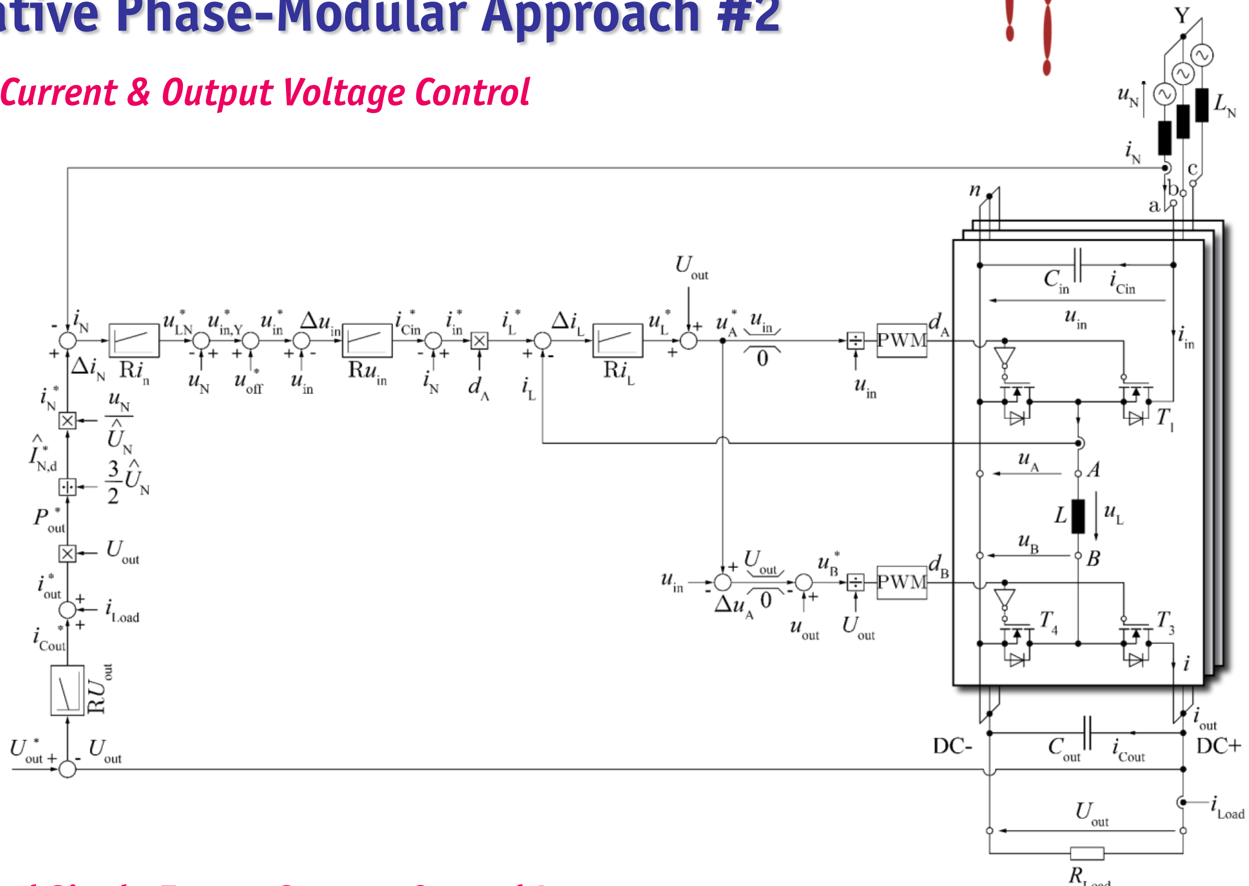


- **No Intermediate DC Link Voltages**
- **Converter Integrated Filter Inductors → High Power Density**
- **Clamping of Boost or Buck Bridge Leg → Low Switching Losses**



Alternative Phase-Modular Approach #2

- *Input Current & Output Voltage Control*

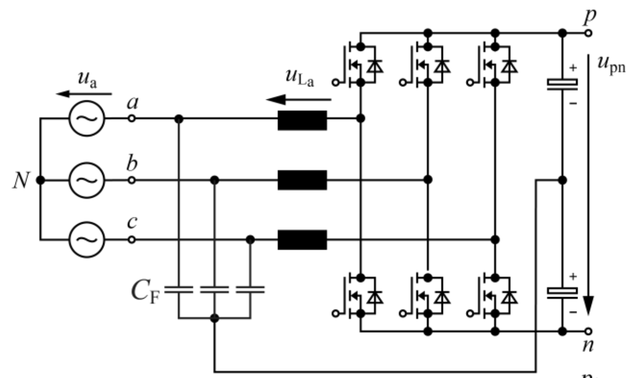


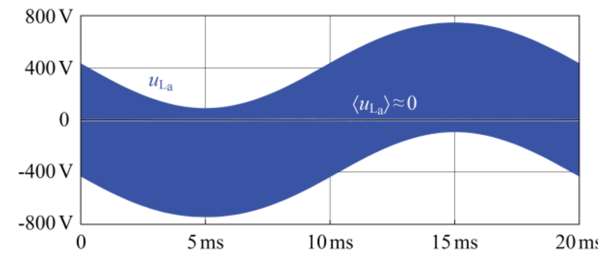
- **Cascaded Single Energy Storage Control Loops**
- **Seamless Transition between Boost- & Buck-Mode → *"Democratic" Control***

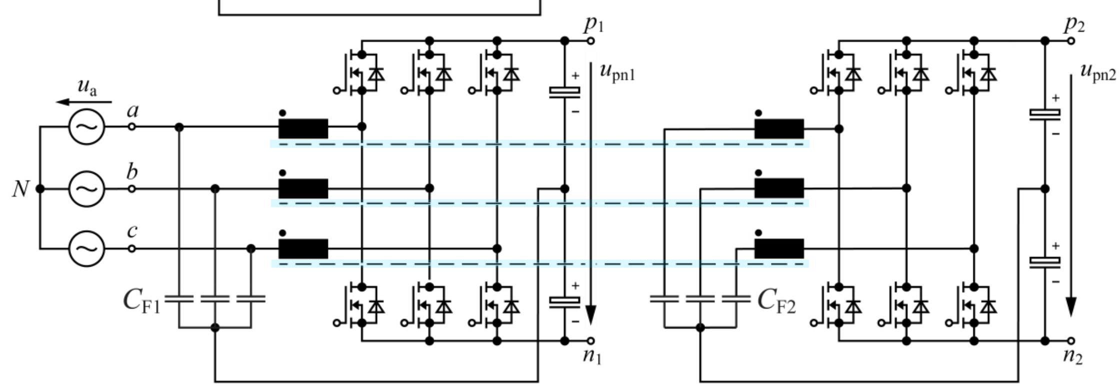
Isolated Single-Stage AC/DC Converter

Dual 3-Φ Active Bridge Converter

- *HF-Components of Boost Ind. Voltages* ***Utilized for Power Transfer***
- *Dual Active Bridge Concept*
- *ZVS*



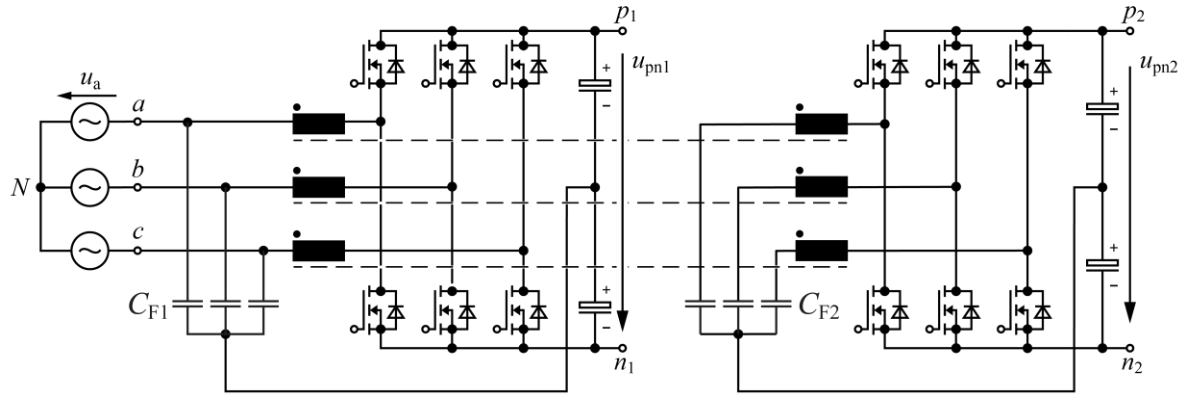


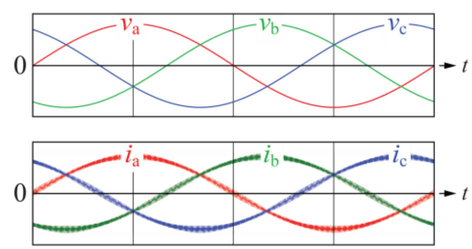


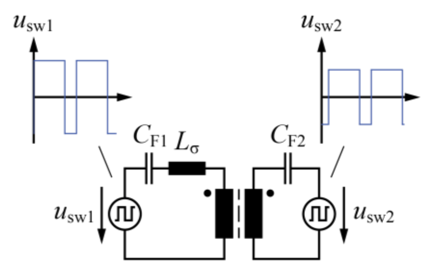
► *Three-Port System* - **AC Input / Isol. DC Output / Non-Isol. DC Output**

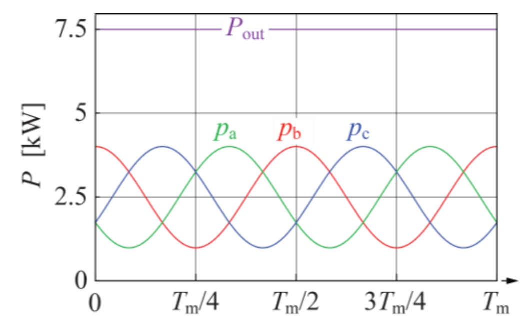
Dual 3-Φ Active Bridge Converter

- *HF-Components of Boost Ind. Voltages Utilized for Power Transfer*
- *Dual Active Bridge Concept*
- *ZVS*





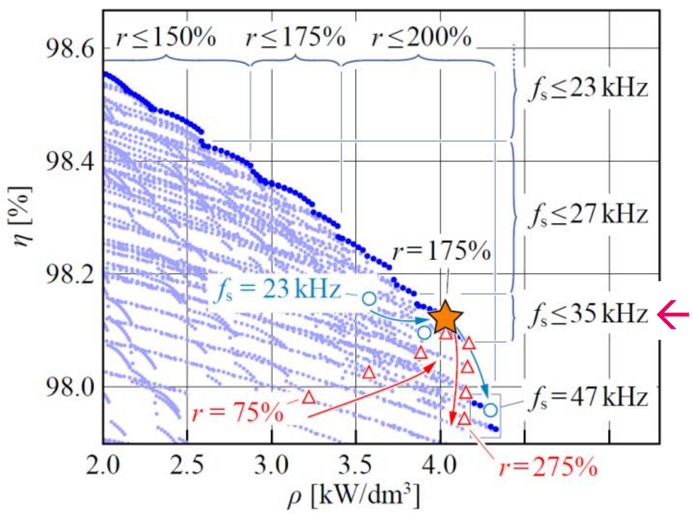


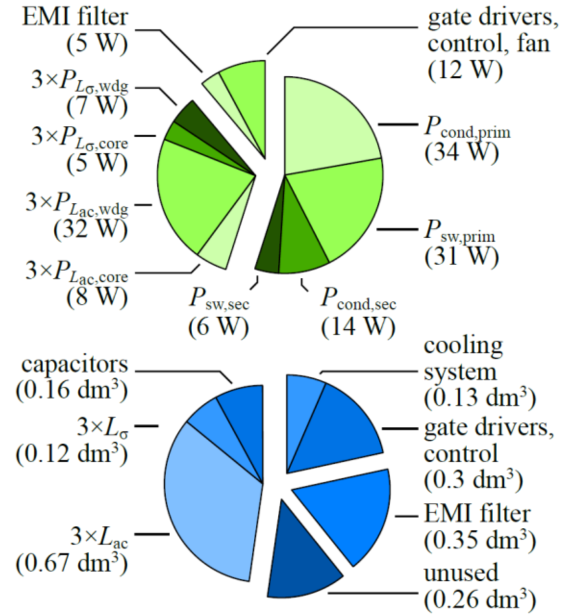


▶ *Three-Port System* - AC Input / Isol. DC Output / Non-Isol. DC Output

Dual 3-Φ Active Bridge Converter

- Multi-Objective Optimization → *Efficiency / Power Density Pareto Front*
- Volume and Loss Distribution
- P= 8kW, 400V$_{AC}$ / 400V$_{DC}$





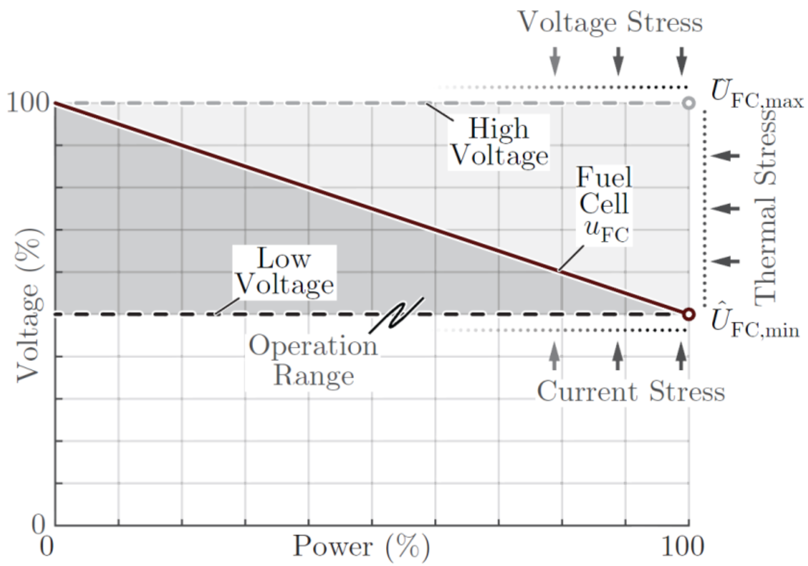
▶ *Efficiency* > 98% in Wide Output Power Range @ 4kW/dm³ Power Density (65W/in³)

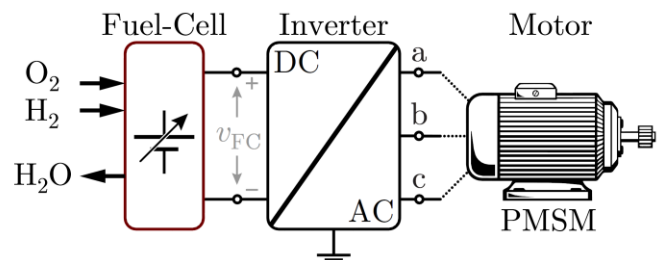
Source: ABB

Advanced Variable Speed Drive Systems

Inverter / Drive Applications

- *Battery or Fuel-Cell Supply → Wide DC Input Voltage Range*
- *Matching of Supply & Rated Motor Voltage*

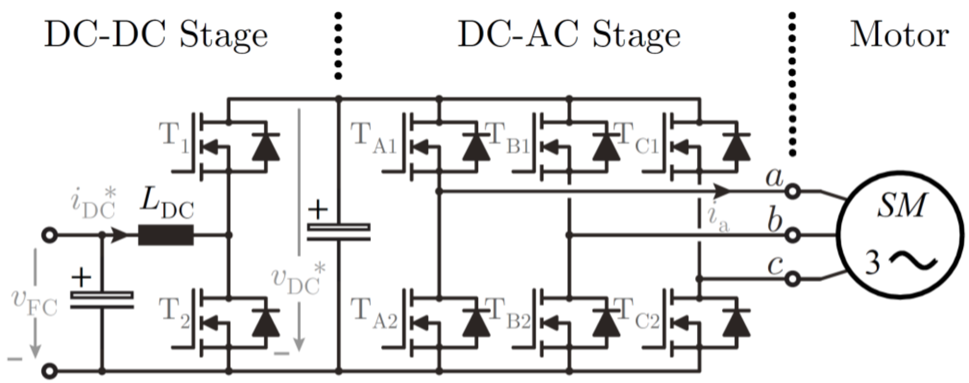




▶ *Inverter Input Voltage Adaption by DC/DC Boost Converter*

Inverter / Drive Applications

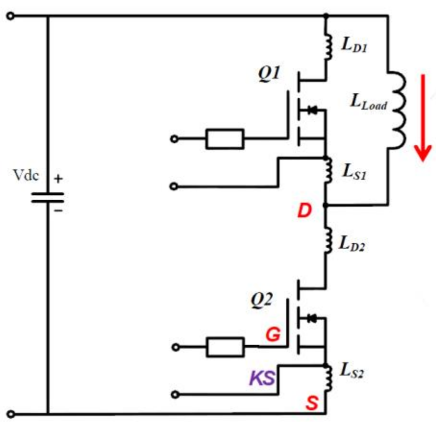
- **Front-End DC/DC Boost Converter** ***DC Link Voltage Adaption***
- ***SiC Power Semiconductors*** → ***Low Switching (& Conduction) Losses***



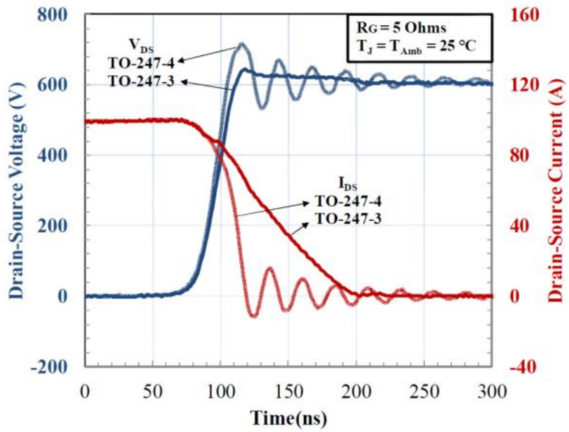
▶ ***Motor Winding Insulation Stress*** / **Reflections on Long Motor Cables / Bearing Currents**

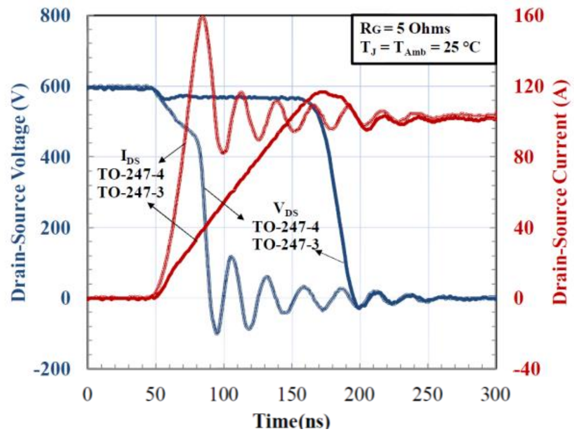
Output Filter Requirement (1)

- *Ultra-Fast Switching of WBG Power MOSFETs*
- *Typical dv/dt of 30...50kV/us*



Source: CREE

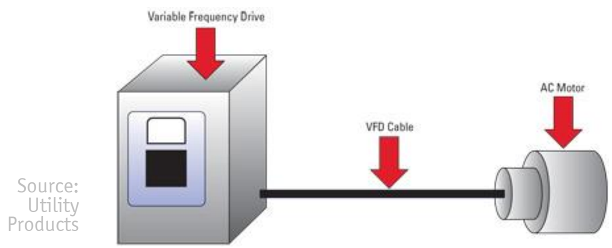




► *Motor Winding Insulation Stress* / **Reflections on Long Motor Cables / Bearing Currents**

Output Filter Requirement (2)

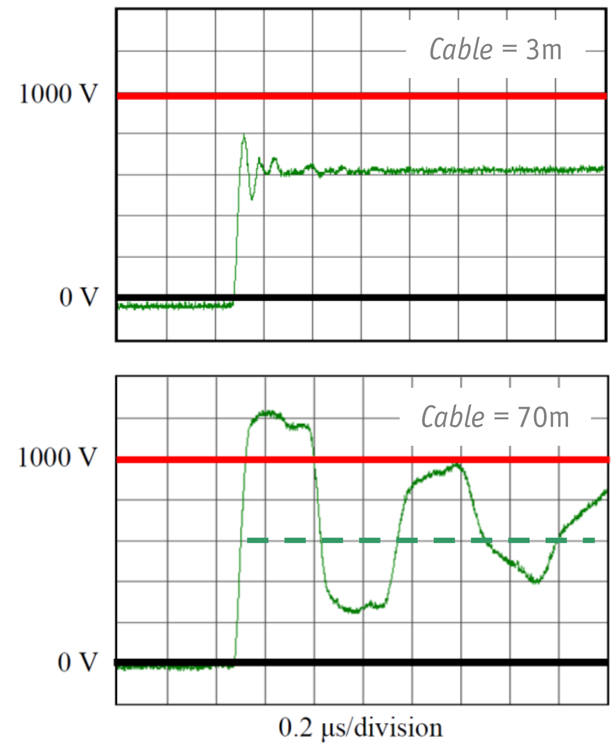
- *Long Motor Cables → $2 \times U_{DC}$ Overvoltage / Insul. Stress*
- *Application Restrictions (NEMA Standard)*



Power Line Voltage	Motor Cable Length[1] up to 75 ft	up to 100 ft	up to the max. length in the "Motor Connection Spec."	longer
208 – 240 V AC	General Purpose Motor (NEMA MG 1, Part 30)			(3)
480 V AC	General Purpose Motor (NEMA MG 1, Part 30)		Inverter Duty Motor (NEMA MG 1, Part 31)[2]	(3)
575 – 600 V AC	General Purpose Motor (NEMA MG 1, Part 30)	Inverter Duty Motor (NEMA MG 1, Part 31)[2]		(3)

1. These maximum motor cable lengths are rules of thumb based on the motor's stator insulation and the VFD's maximum motor cable length capability. RFI/EMC concerns are not taken into account. All lengths are based on the ACH550 VFD. Competitive VFDs may need a significantly shorter motor cable length.
2. Follow the maximum cable length recommendations of the motor manufacturer, if they are more restrictive.
3. For motor cable lengths longer than the VFD's recommendation, a sine wave filter and/or other considerations may be required. Contact ABB.

Source: ABB

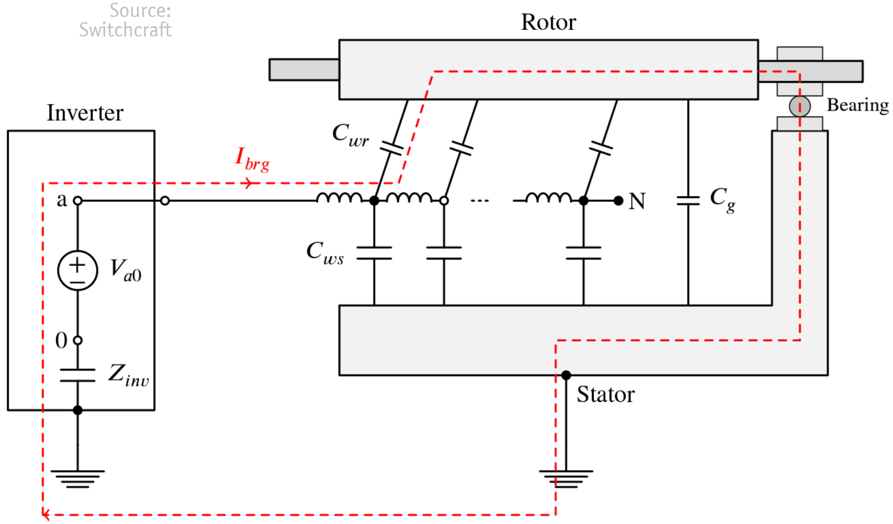


▶ *Imped. Matching @ Motor Terminals / Double Transition PWM / dv/dt- or Sine Wave Filters*

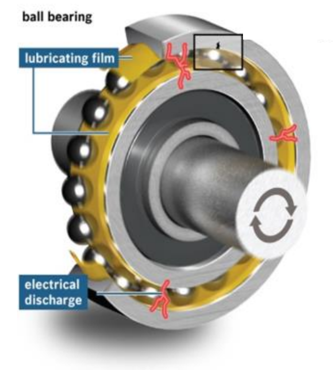
Output Filter Requirement (3)

- *CM Inverter Output Voltage → Shaft Voltage → Electrical Discharge in Bearing ("EDM")*
- *CM Conducted EMI → Expensive Shielded Motor Cables*

Source: Switchcraft



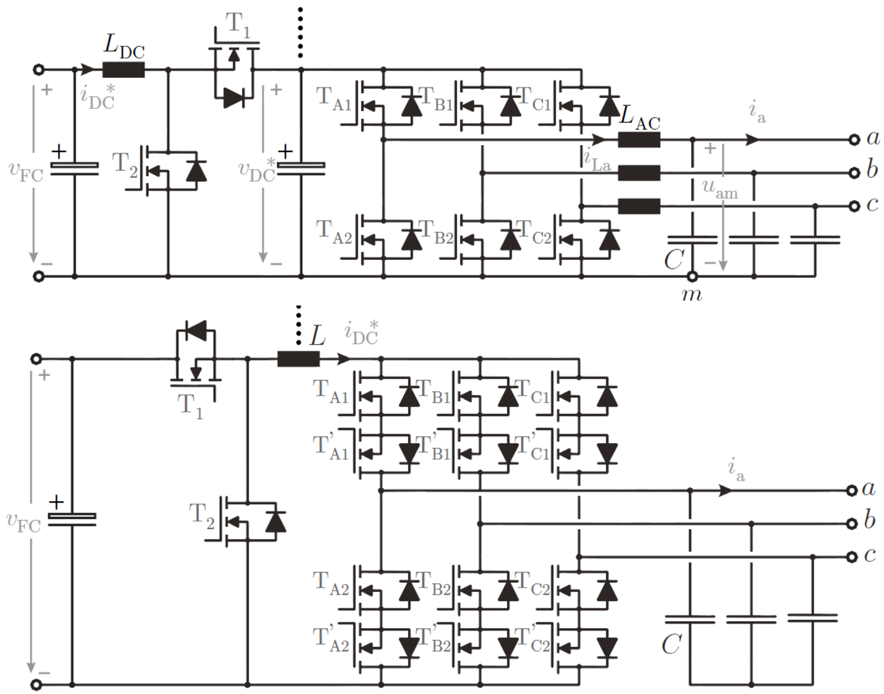
Source: BOSCH



► *Cond. Grease / Ceram. Bearings / Shaft Grndg Brushes / dv/dt- or Sine Wave Filters*

Buck-Boost Inverters with Output Filter

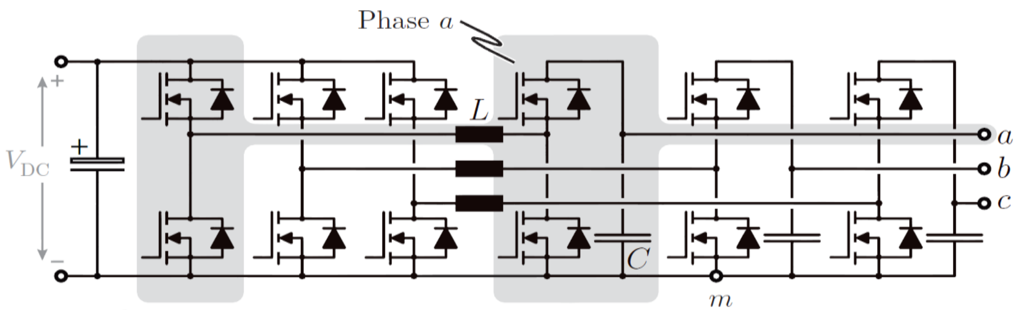
- Boost Converter & *Voltage DC Link Inverter* with LC Output Filter
- Buck Converter & *Current DC Link Inverter* ("Integrated Filter")

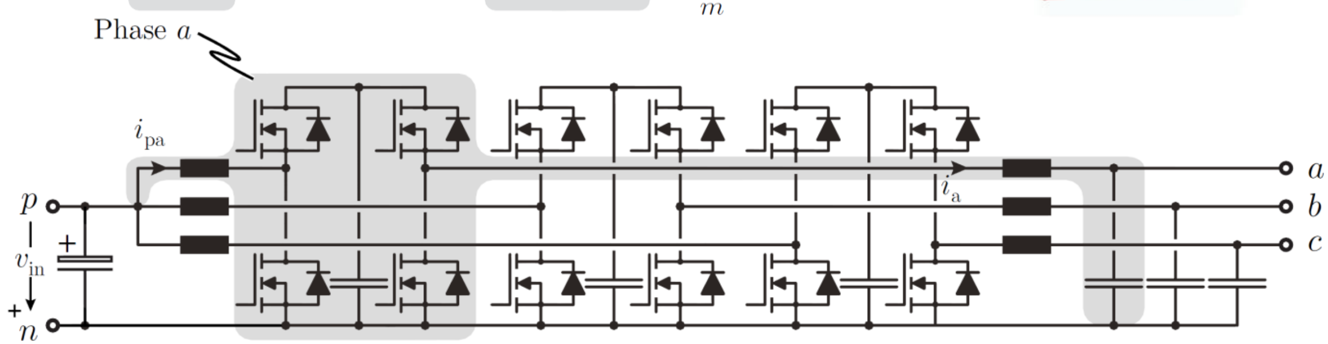


▶ *Large Number of Ind. Components OR Large Number of Power Semiconductors*

Buck-Boost Inverter with Output Filter

- *Battery or Fuel-Cell Supply → Wide DC Input Voltage Range*
- *Matching of Supply & Rated Motor Voltage*



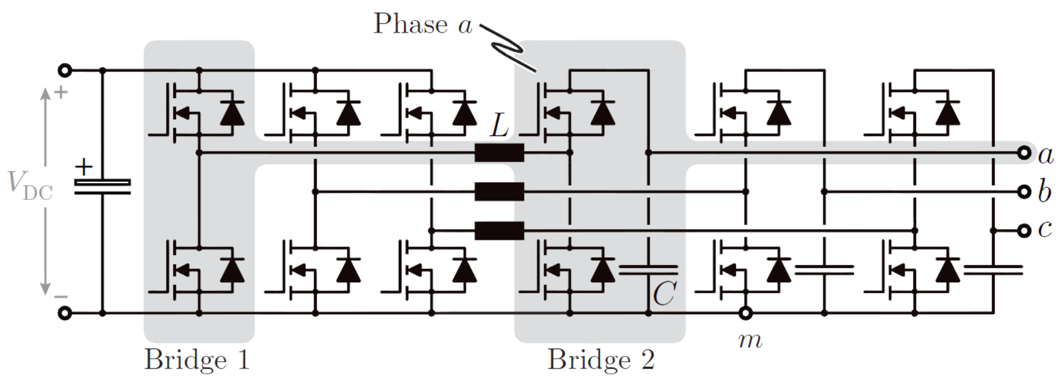


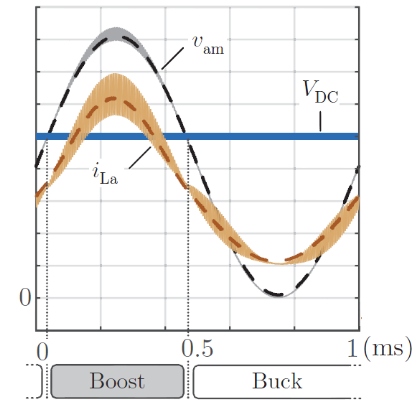
▶ *Motor Winding Insulation Stress* / **Reflections on Long Motor Cables / Bearing Currents**

Y-Inverter Lighthouse Project

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

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

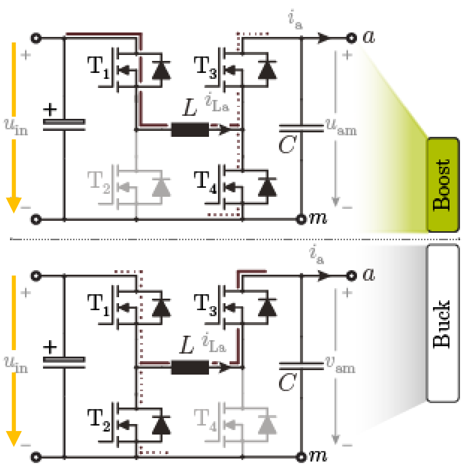


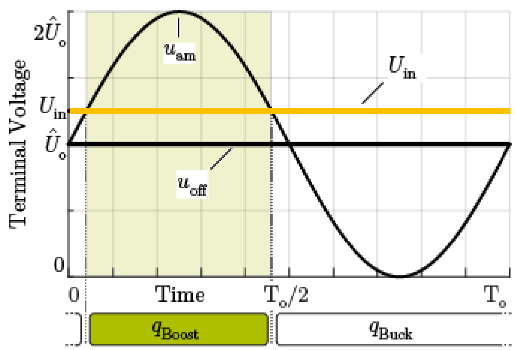


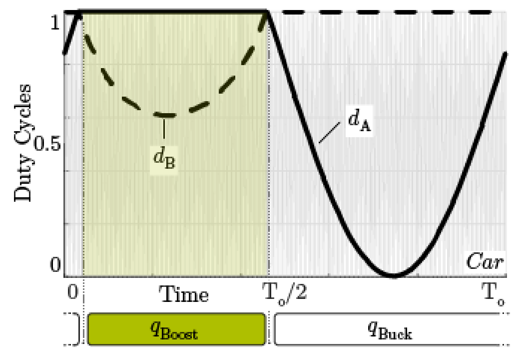
■ Project Scope → Hardware Demonstrator / Exp. Analysis / Comparative Evaluation

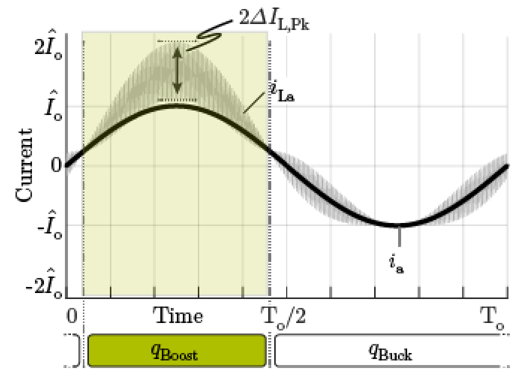
Y-Inverter

- *Operating Behavior*







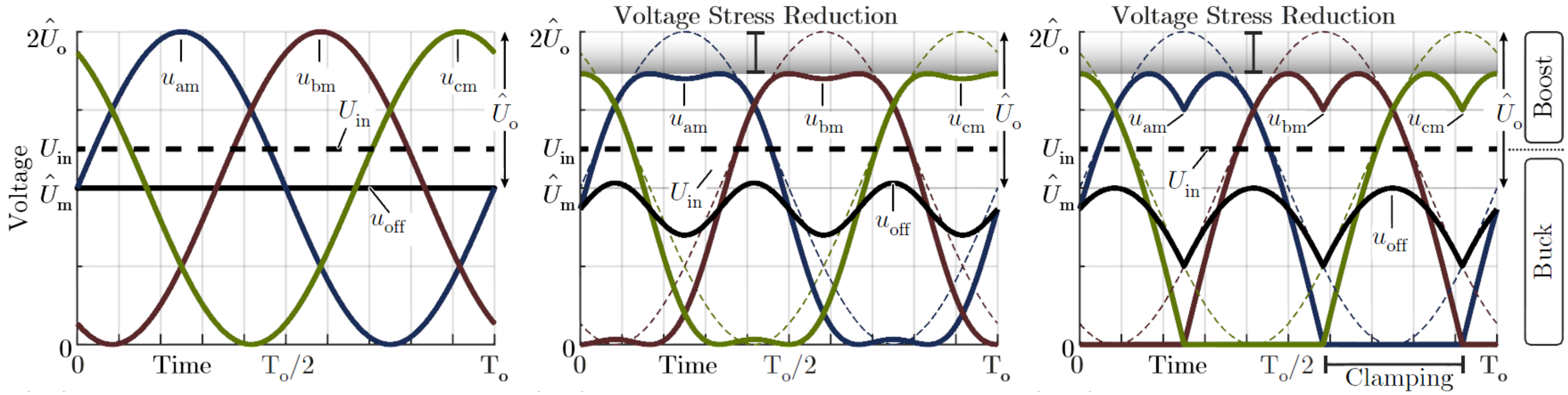


- $u_{am} < U_{in}$ → Buck Operation
- $u_{am} > U_{in}$ → Boost Operation
- Output Voltage Generation Referenced to DC Minus

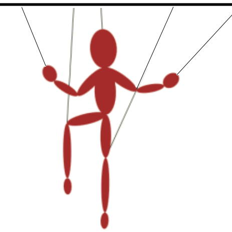
Y-Inverter

- *Modulation Schemes*

- **Output Voltage DC Offset for Low Modulation Index**
- *Third Harmonic Injection* **OR** *Phase Clamping*

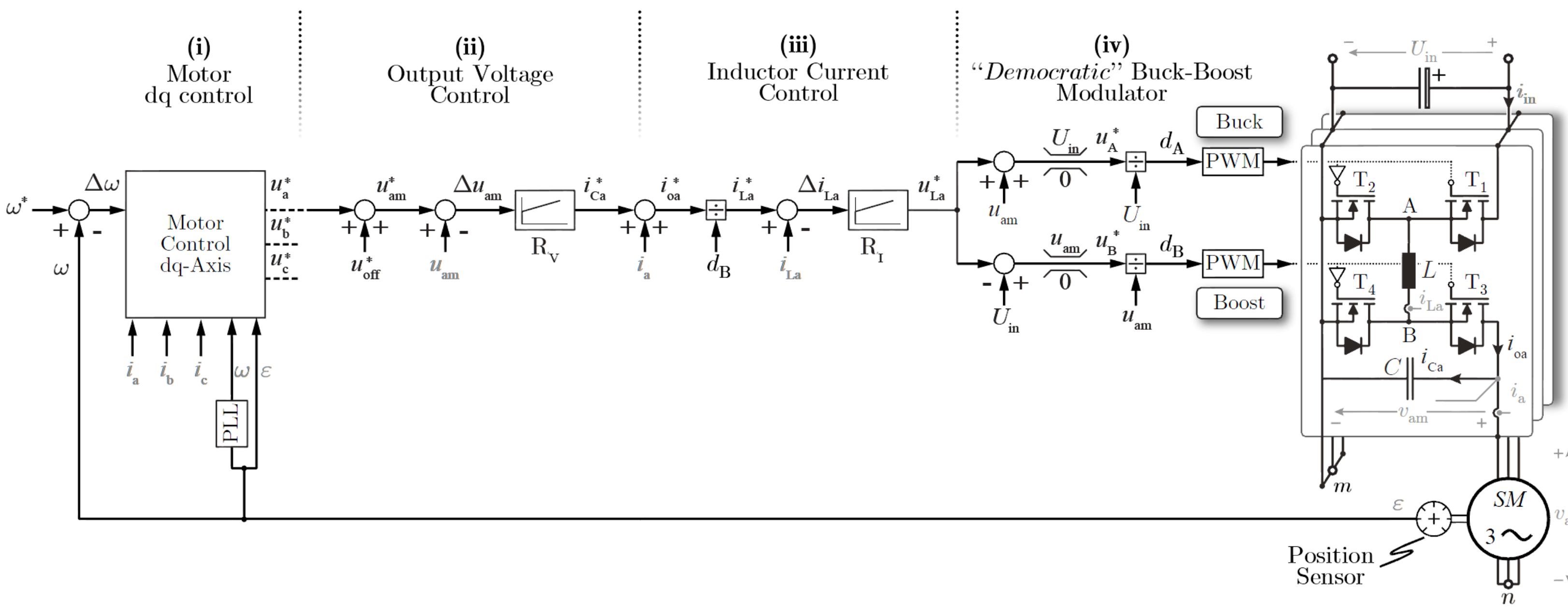


- *Reduced Output Voltage Amplitude* / *Reduction of Sw. Losses*



Y-Inverter

- *Control Structure*

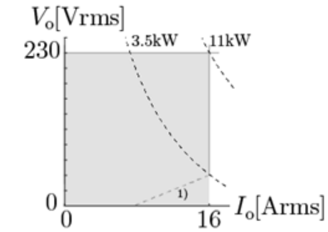


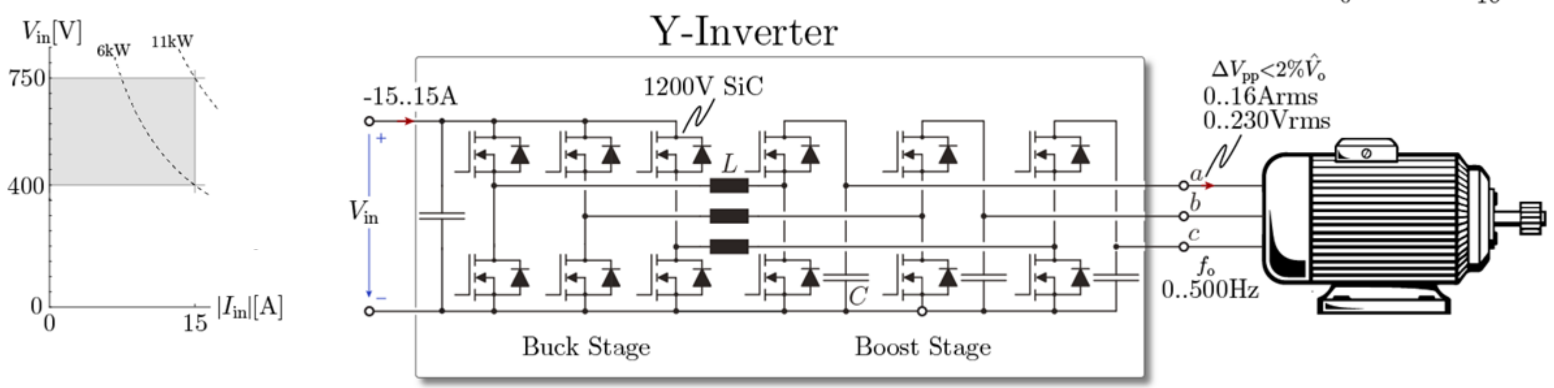
- *"Democratic Control"* → **Seamless Transition Between Buck & Boost Operation**

Y-Inverter

- *Demonstrator Specifications*

- **Wide Input Voltage Range → 400…750V$_{DC}$**
- **Max. Input Current → ± 15A**



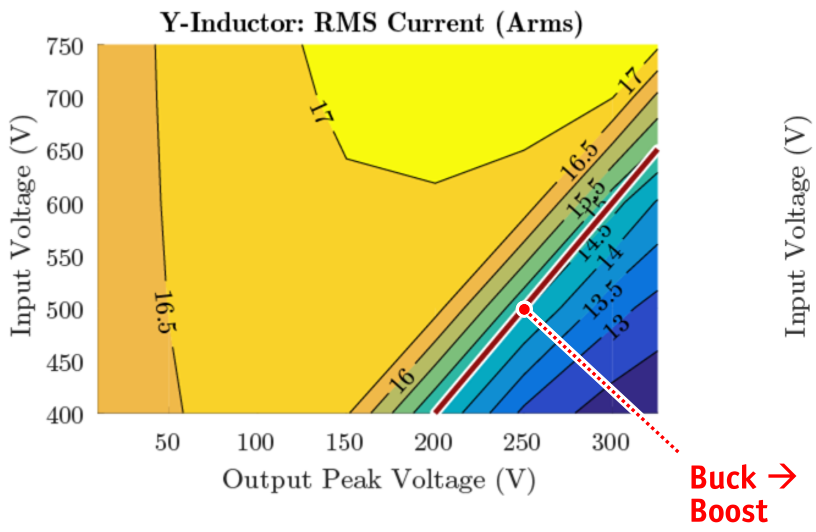


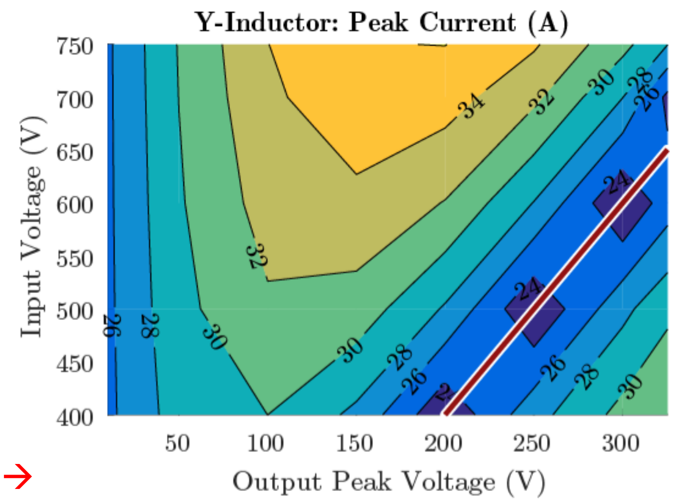
- **Max. Output Power → 6…11 kW**
- **Output Frequency Range → 0…500Hz**
- **Output Voltage Ripple → 3.2V Peak-to-Peak (incl. Add. Output Filter)**

Y-Inverter

- *System Design*

- Identification of Worst Case Component Stresses
- Analysis in Input Voltage / Output Voltage / Output Power 3D-Design Space



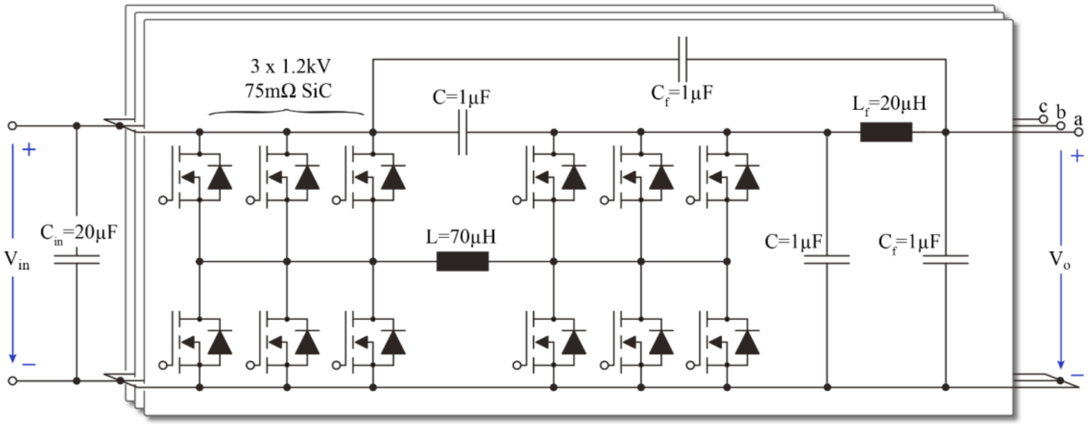


- Example of Inductor Current Stress Analysis → $I_{L,rms}$ and $I_{L,pk}$

Y-Inverter

- *Demonstrator Power Circuit*

f_S = 100kHz

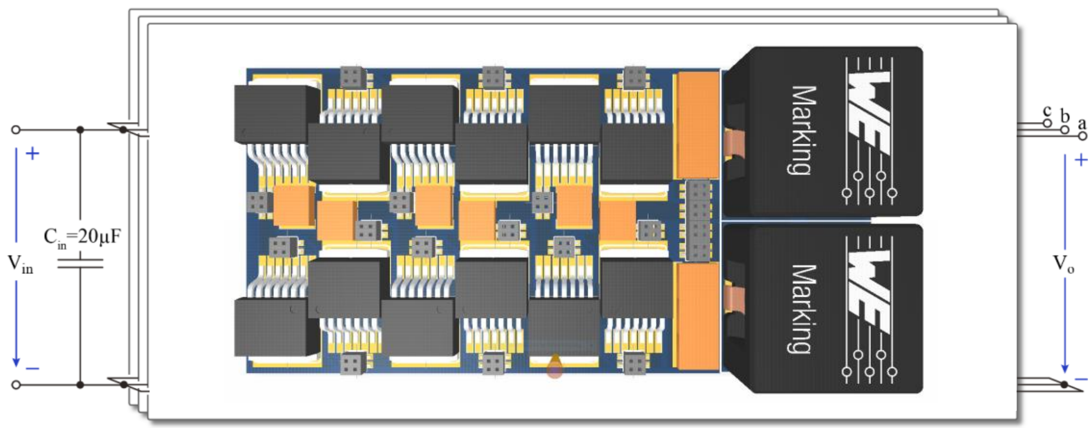


- Inductors → 2 x EELP 43 Ferrite Cores / N97 per Phase
- Add. Output Filter → 3.2V Peak-to-Peak Output Voltage Ripple
- Power Semiconductors → 3 x Cree 1200V/75mΩ SiC MOSFETs per Switch Mounted on IMS

Y-Inverter

- *Demonstrator Power Circuit*

f_S = 100kHz



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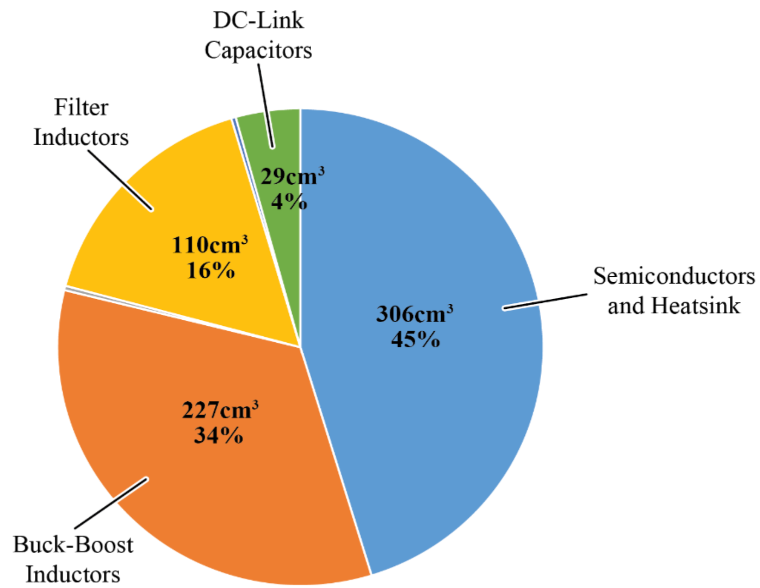
Y-Inverter

- *Demonstrator Performance – Volume Distribution*

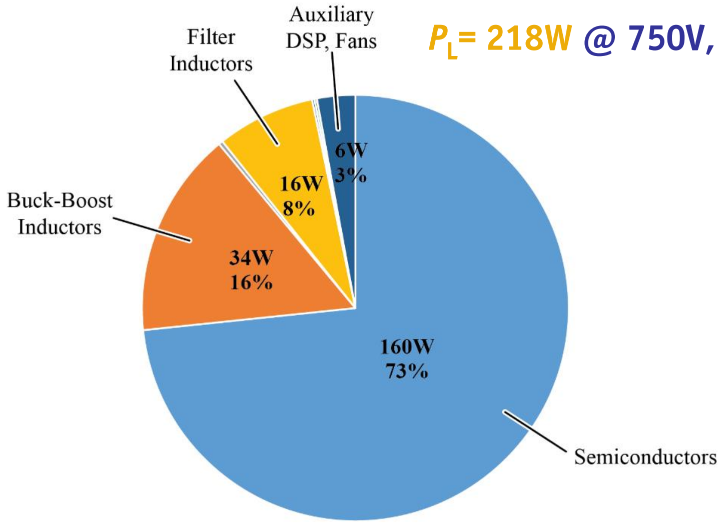


- **Power Density** → 15kW/dm^3 (0.73dm^3)

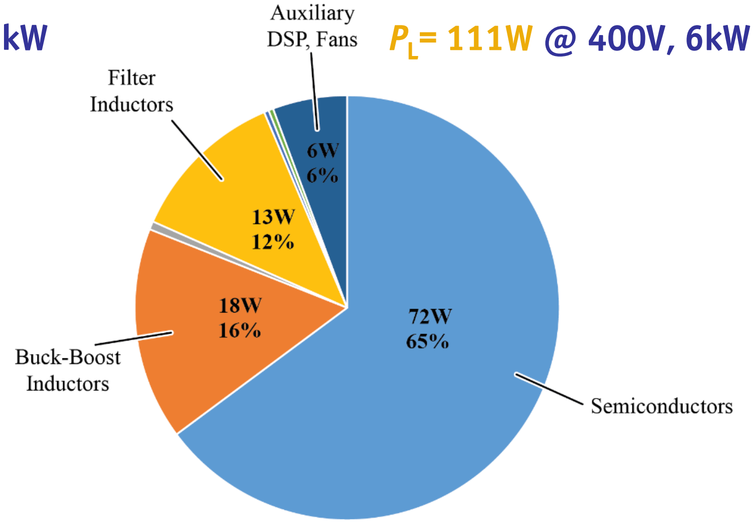
Y-Inverter

- *Demonstrator Performance* – *Loss Distribution* (Design Margin Considered)

P_L= 218W @ 750V, 11kW



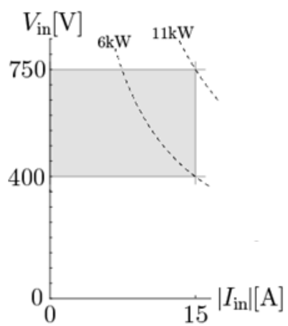
P_L= 111W @ 400V, 6kW

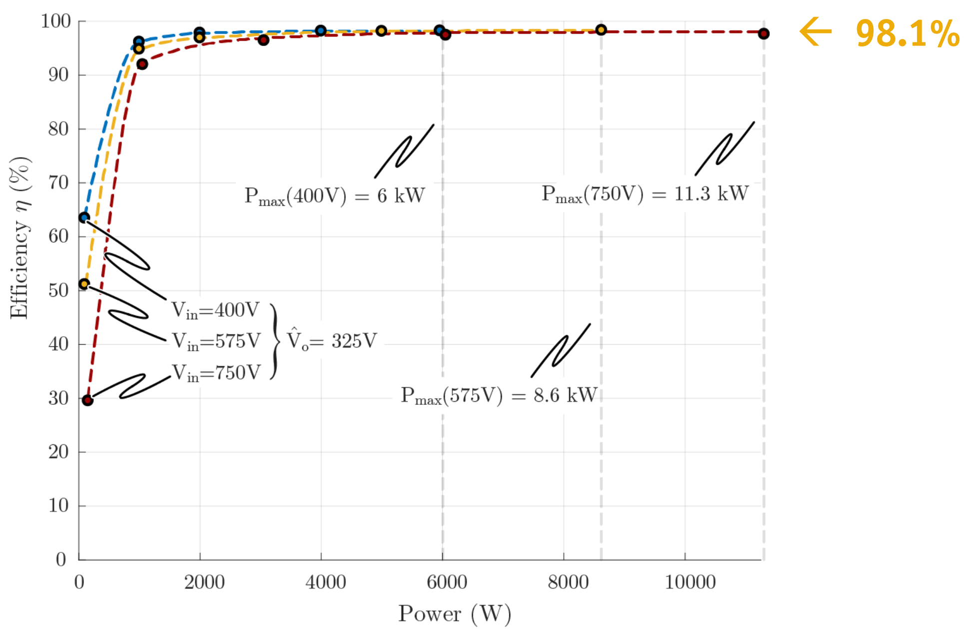


- 98% Efficiency Target @ Rated Power & Input/Output Voltage

Y-Inverter

- *Demonstrator Performance – Efficiency over Output Power @ Given Input Voltage*

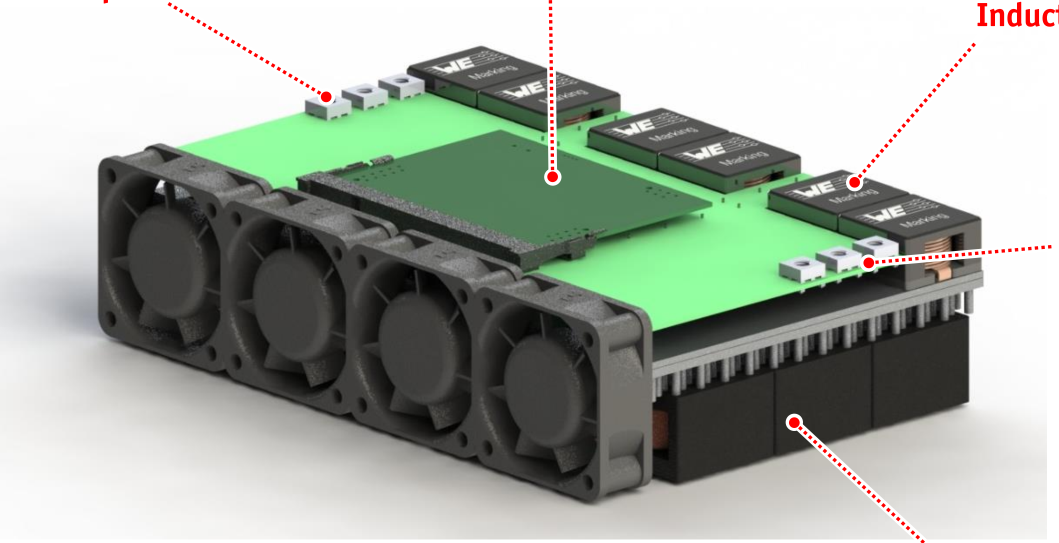




- **Higher Efficiency for *Phase Clamping Modulation***

Y-Inverter

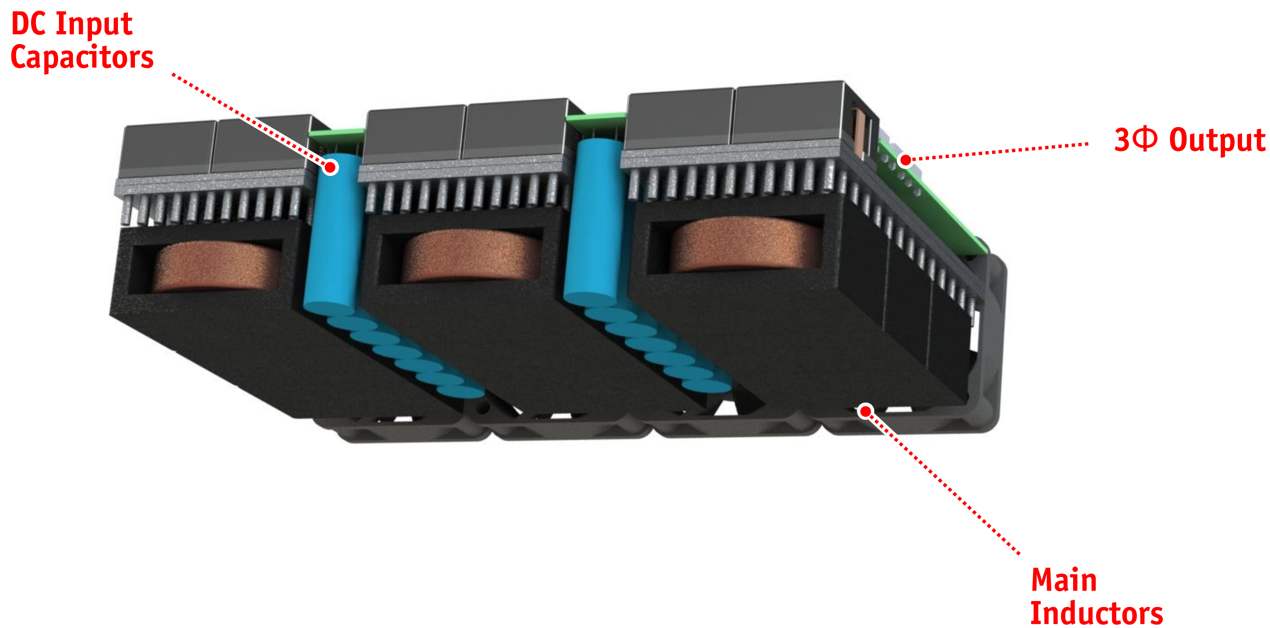
- *Demonstrator – Virtual Prototype (1)*



- **Dimensions →** 160 x 110 x 42 mm^3

Y-Inverter

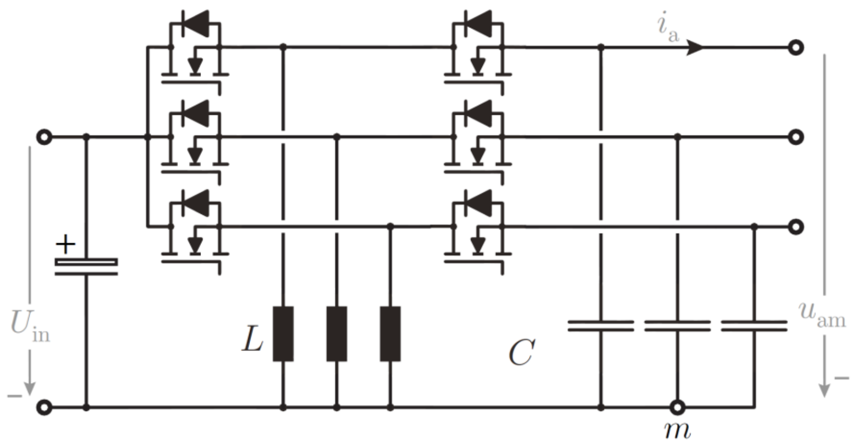
- *Demonstrator – Virtual Prototype (2)*



- **Dimensions →** 160 x 110 x 42 mm^3

Y-Inverter

- *Alternative Power Circuit Topology*



- **Lower Number of Switches / Higher Component Stresses** → *Low Power Applications*

Conclusions

► *Future Need for „SWISS Knife“-Type Power Converters*

* Wide Input / Load Voltage Range
* Standard Building Blocks / Modular
* Bidirectional Power Transfer
* Electromagnetically „Quiet“
* 10kW/dm^3 Power Density incl. EMI Filter @ Air Cooling
* 98% Efficiency

► *Y-Inverter / Rectifier*

* Next Generation Integrated Motor Drives
* Next Generation PMW Rectifiers

Source: UK Outdoor Store

Thank You !