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Latest Findings in Three-Phase AC/DC Converter Research

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June 7, 2018

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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, D. Rothmund

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Outline

- *Introduction*
- *High-Power EV Battery Charging*
- *Advanced Inverter Systems*
- *Conclusions*

Source: Porsche Mission-E Project

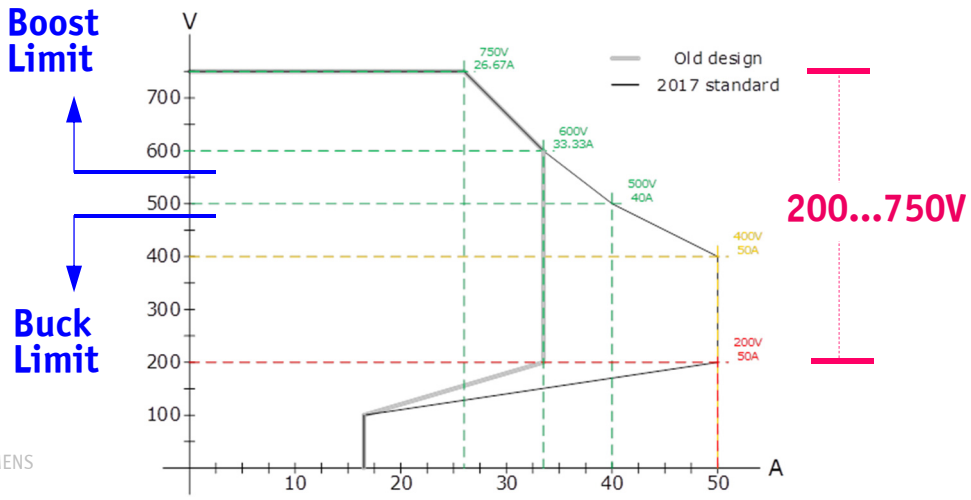
Buck-Boost PFC Rectifier

SWISS Rectifier

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*

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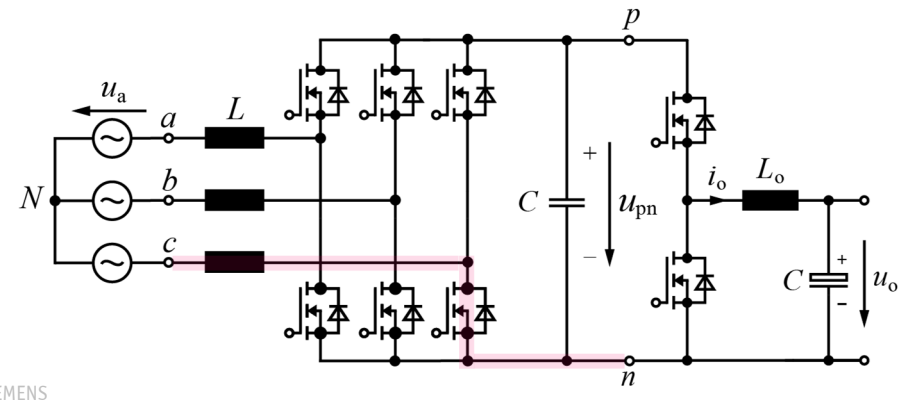

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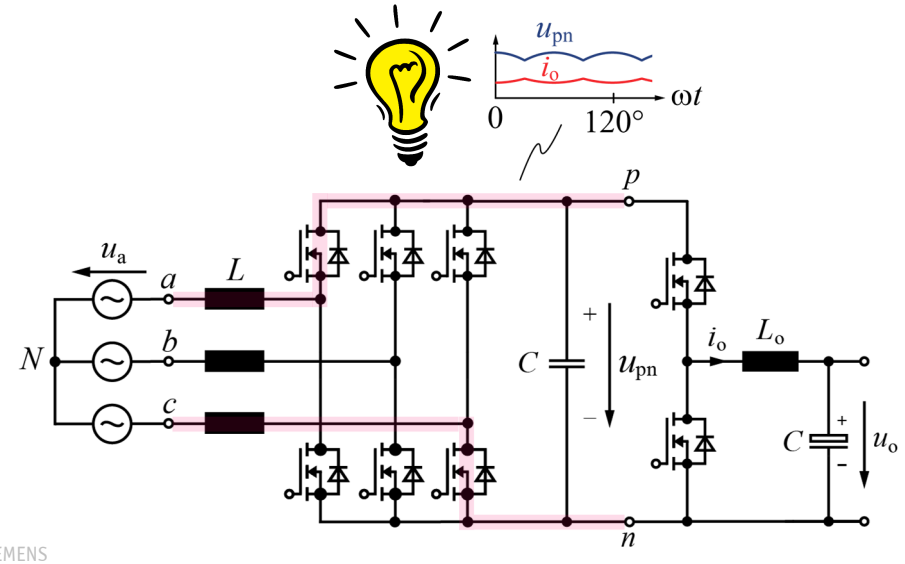
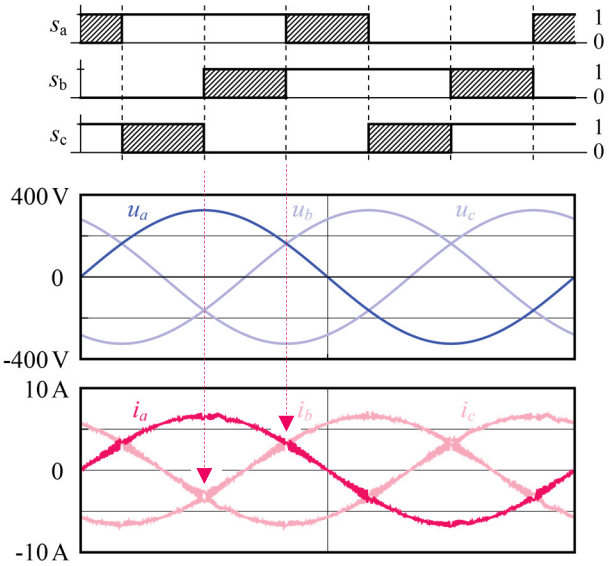
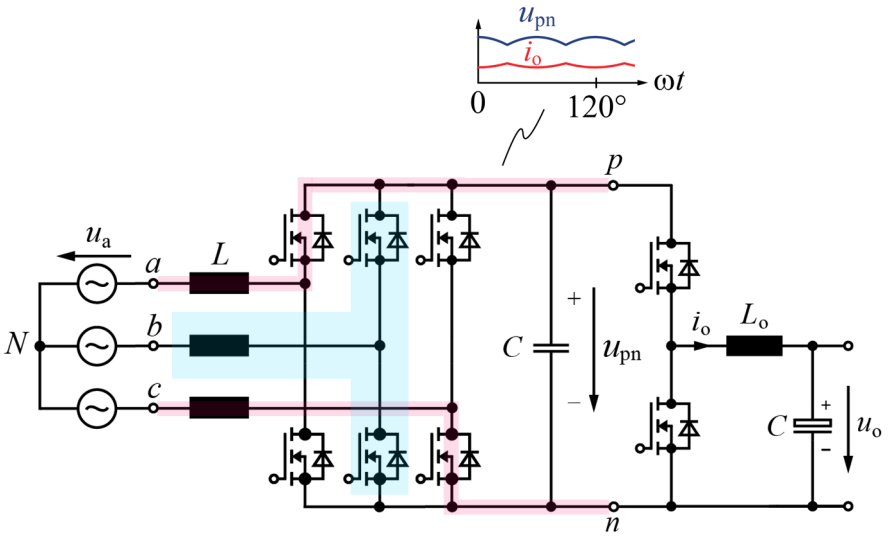


► *Buck-Stage Utilized for DC Link Voltage Shaping / Switching of Single Mains Phase*

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

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





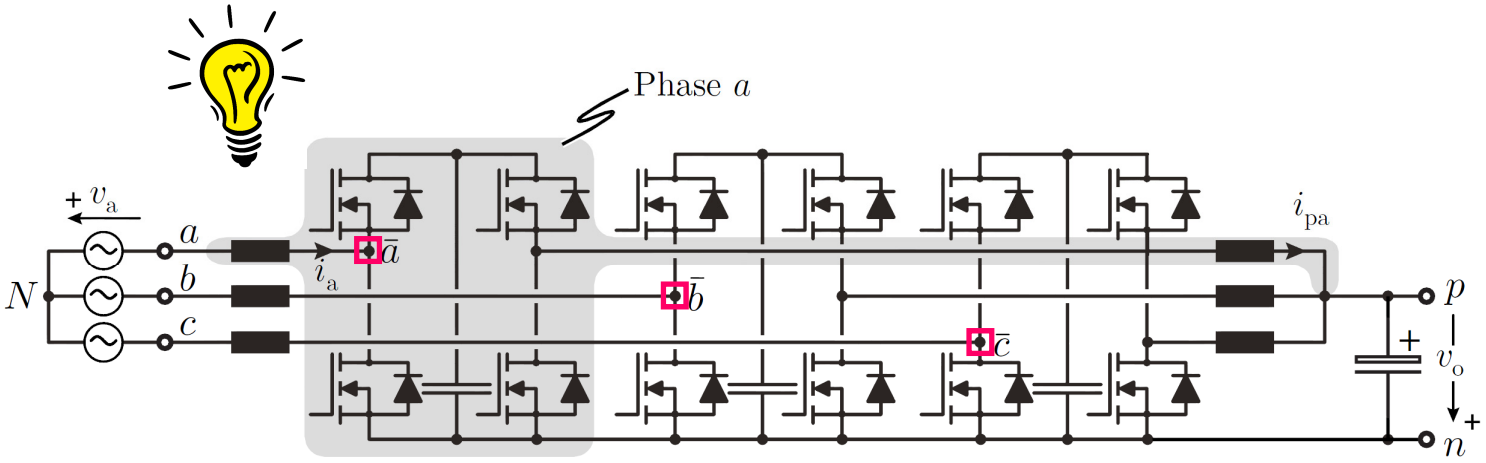
- **High Output Voltage → Operation as *Conv. Boost-Type* PWM Rectifier / Clamped Buck-Stage**

Alternative #1

Trident Rectifier

Phase-Modular Approach #1 → Trident Rectifier

- *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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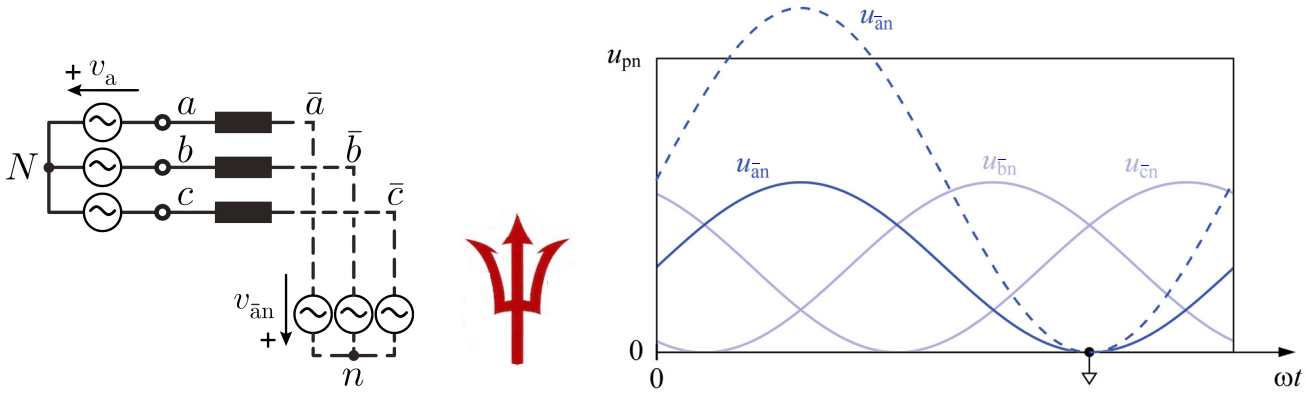
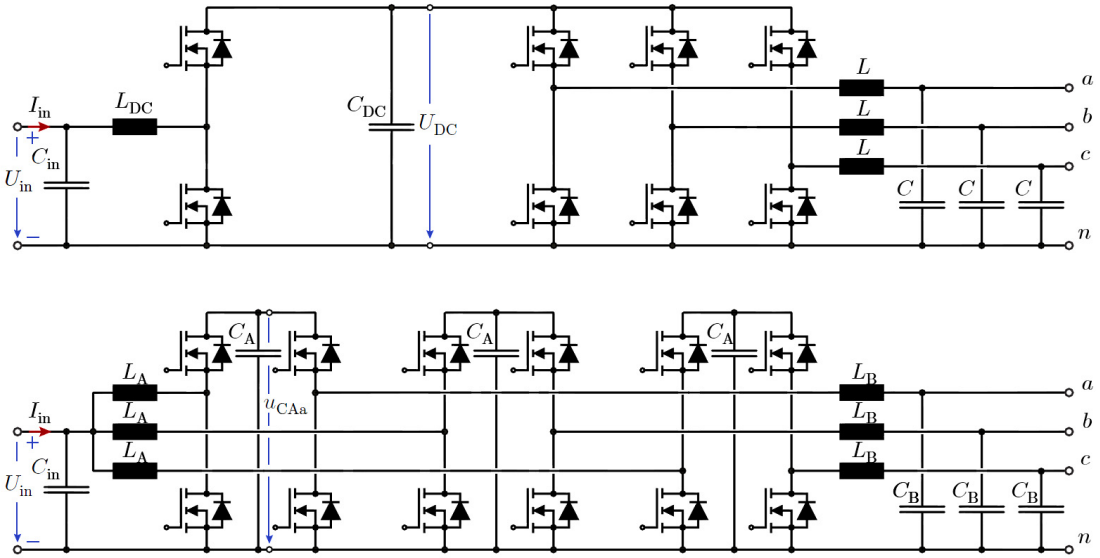
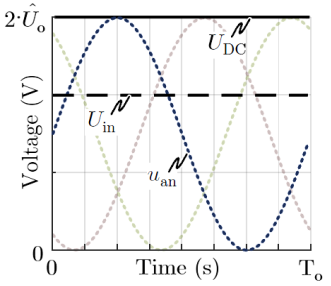


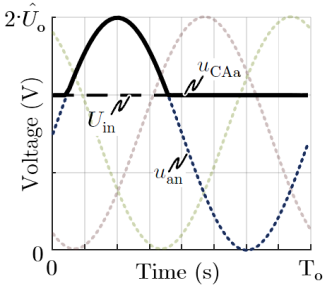
- Continuous Input and Output Currents
- Clamping of Boost or Buck Bridge Leg of Phase Module → Low Switching Losses

Comparative Evaluation (1)

- *Example of DC/AC Converter*
- *400...750V DC Input Voltage Range → 230V$_{rms}$ AC Output / Phase*



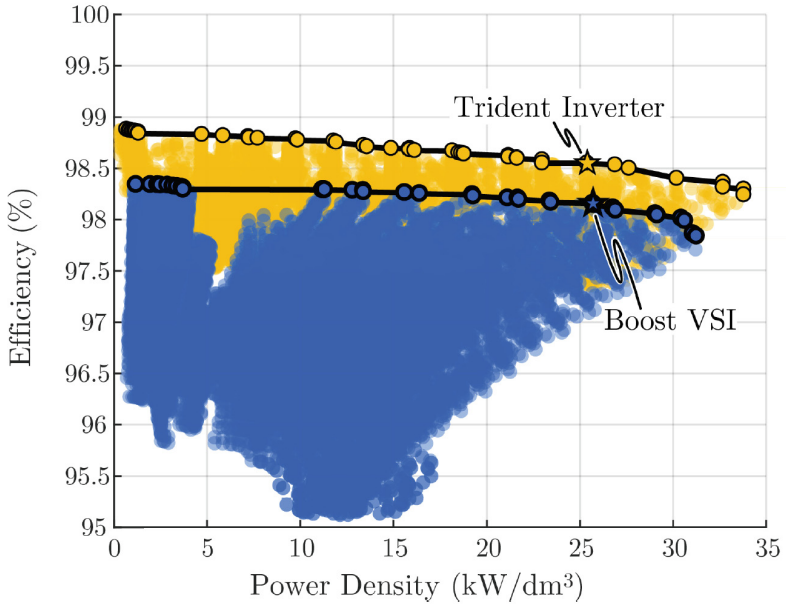




- **Continuous Input and Output Currents**
- **Clamping of Boost or Buck Bridge Leg of Phase Module → Low Switching Losses**

Comparative Evaluation (2)

- *Example of DC/AC Converter*
- *400...750V DC Input Voltage Range → 230V$_{rms}$ AC Output / Phase*



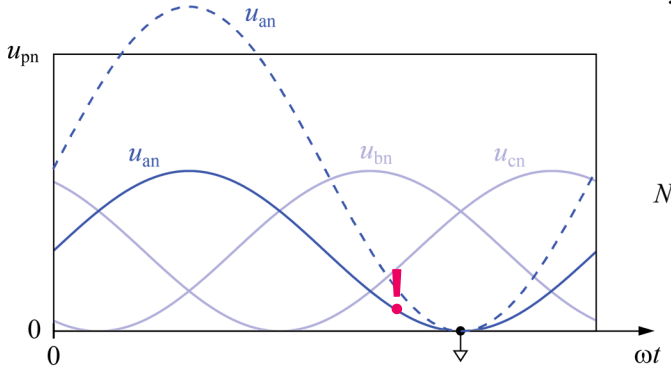
- **Continuous Input and Output Currents**
- **Clamping of Boost or Buck Bridge Leg of Phase Module → Low Switching Losses**

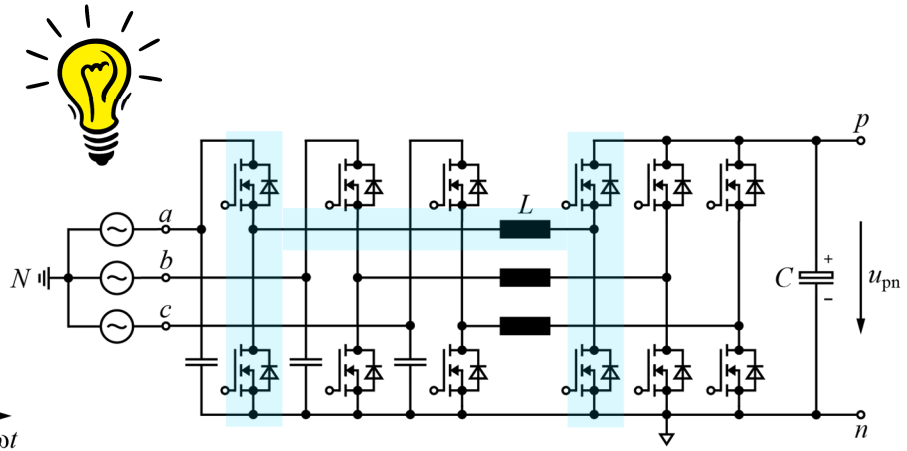
Alternative #2

X-Rectifier

Phase-Modular Approach #2 → X-Rectifier

- *"Buck-Boost" Instead of "Boost-Buck" Phase Modules*
- *Coupling of Electronic 3-Φ VARIAC and Boost-Type Rectifier*
- *AC Input Phase Voltages Generated with Reference to DC-Minus*

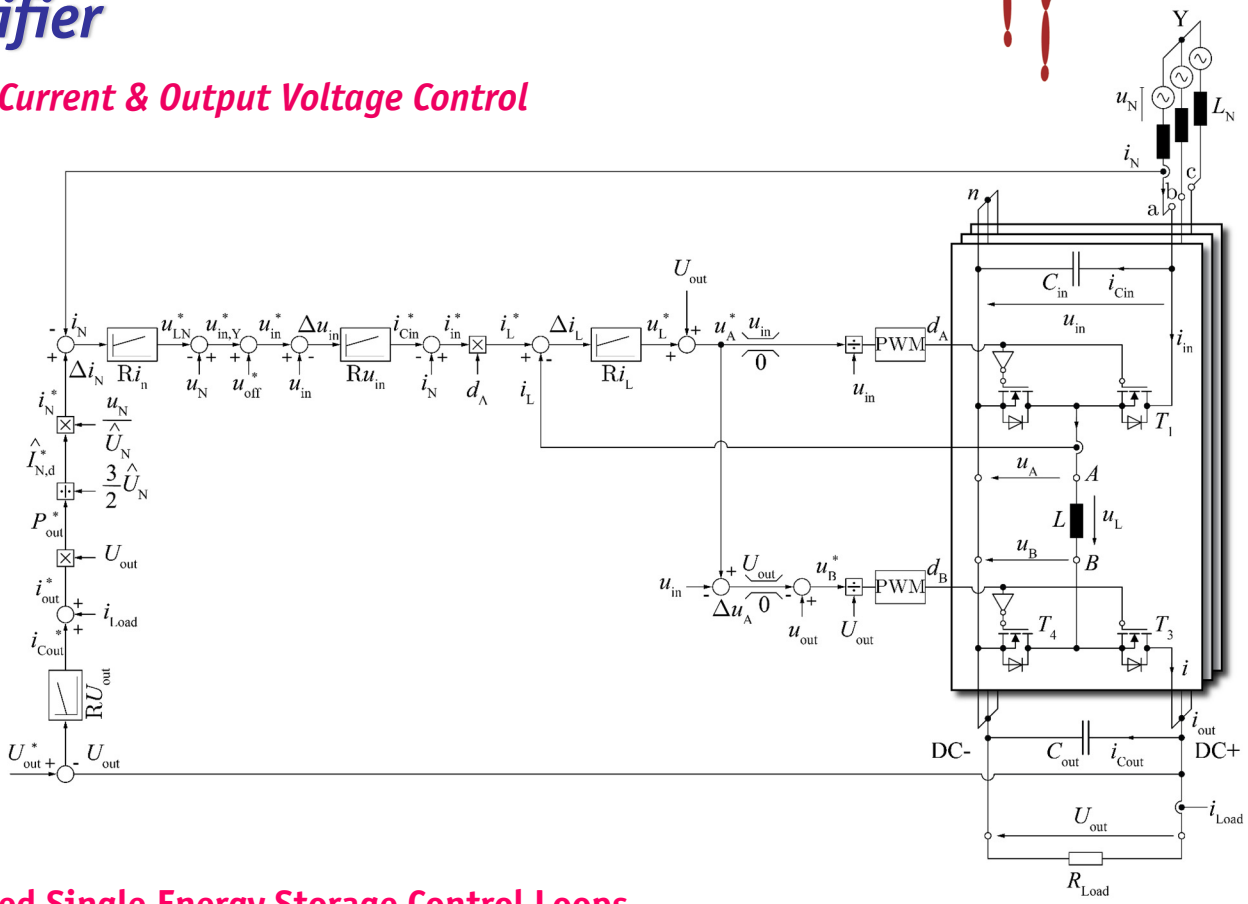




- **No Intermediate DC Link Voltages**
- **Converter Integrated Filter Inductors → High Power Density**
- **Clamping of Boost or Buck Bridge Leg → Low Switching Losses**

X-Rectifier

- *Input Current & Output Voltage Control*

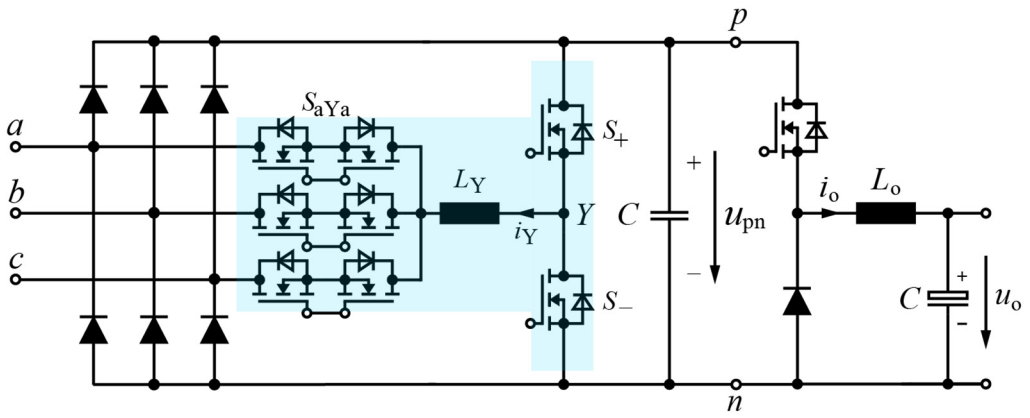


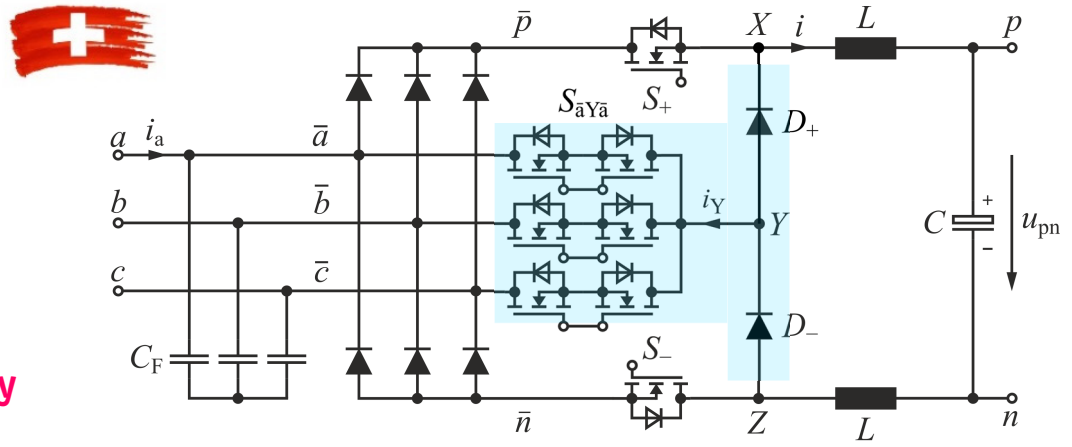
- **Cascaded Single Energy Storage Control Loops**
- **Seamless Transition between Boost- & Buck-Mode** → *"Democratic" Control*

SWISS Rectifier

Swiss Rectifier

- Controlled Output Voltage
- Sinusoidal Mains Current
- i_y Def. by KCL: E.g. i_a- i_c



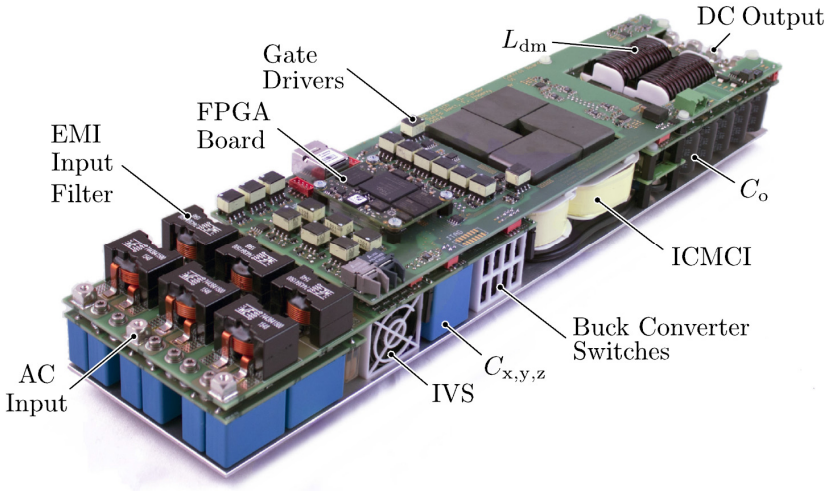


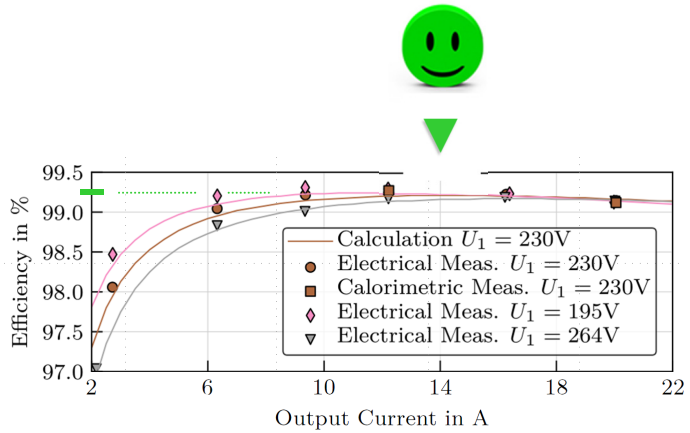
- Low Complexity

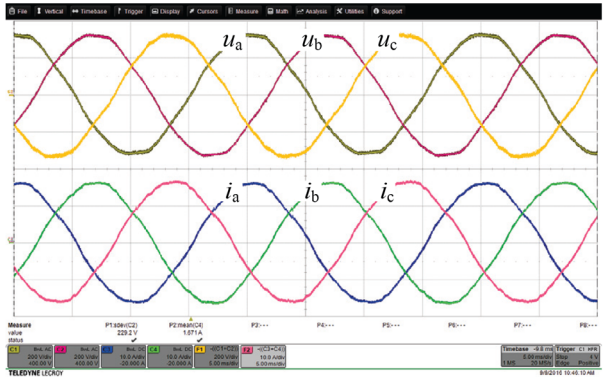
Swiss Rectifier Demonstrator

- Efficiency η = 99.26% @ 60% Rated Load
- Mains Current $THD_I \approx 0.5\%$ @ Rated Load
- Power Density $\rho \approx 4 kW/dm^3$

P_O= 8 kW
U_N= 400V_{AC} → U_O= 400V_{DC}
f_S = 27kHz







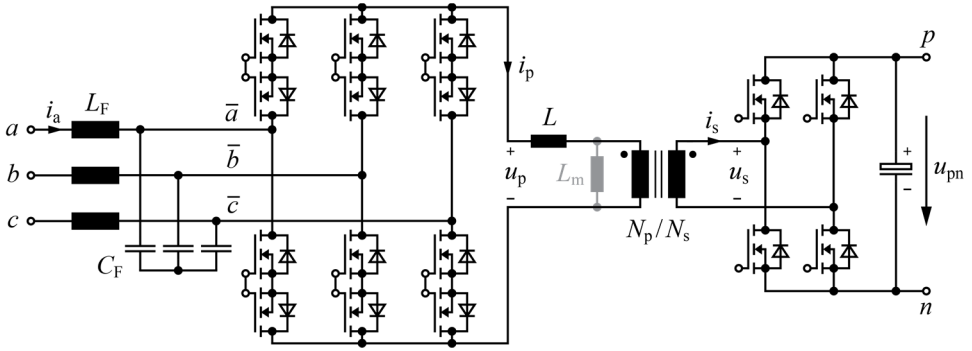
- SiC Power MOSFETs & Diodes
- Integr. CM Coupled Output Inductors (ICMCI)

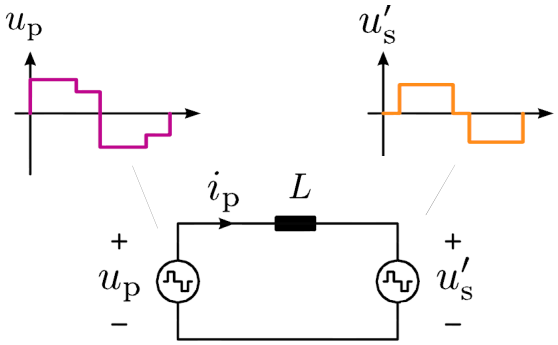
Isolated Single-Stage PFC Rectifiers

Matrix-Type Rectifier
D3AB-Rectifier

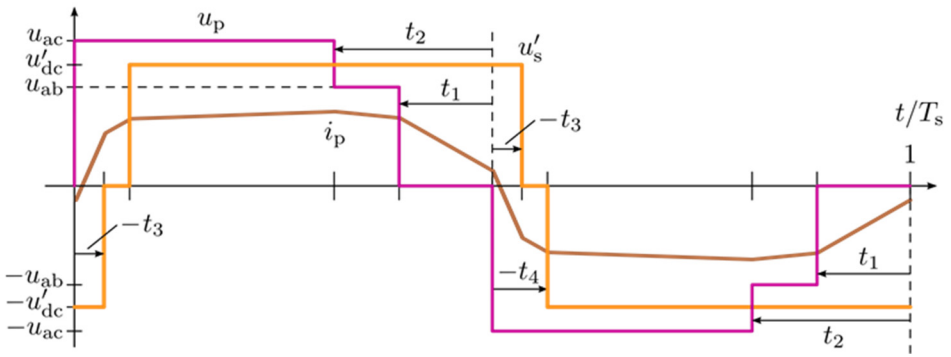
Isolated *Matrix-Type* PFC Rectifier

- *Based on Dual Active Bridge* (DAB) Concept
- Opt. Modulation ($t_1 \ldots t_4$) for Min. Transformer RMS Curr. & ZVS or ZCS
- Allows Buck-Boost Operation





▶ Equivalent Circuit

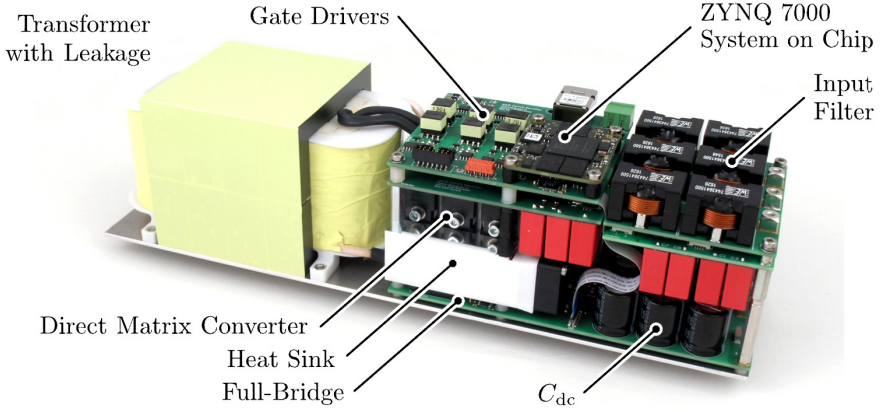


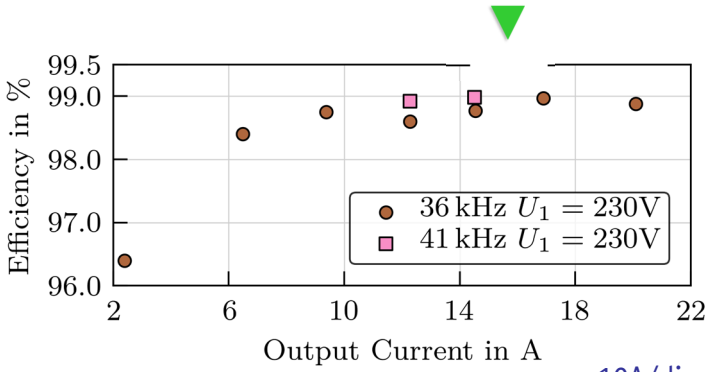
▶ Transformer Voltages / Currents

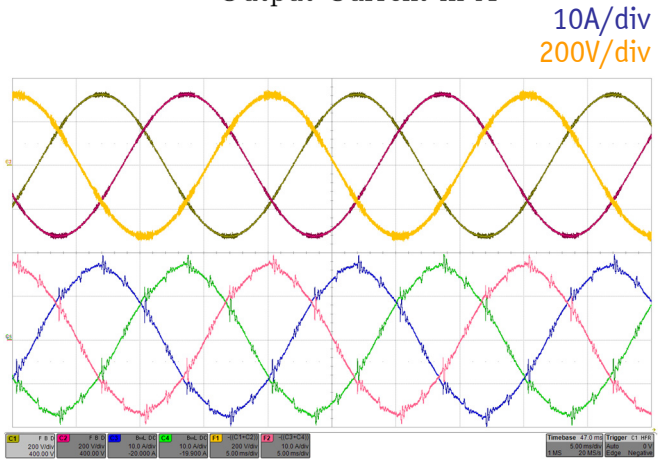
Isolated *Matrix-Type* PFC Rectifier

- Efficiency η = 98.9% @ 60% Rated Load (ZVS)
- Mains Current $THD_I \approx 4\%$ @ Rated Load
- Power Density $\rho \approx 4\text{kW/dm}^3$

P_0= 8 kW
U_N= 400V_{AC} → U_0= 400V_{DC}
f_S = 36kHz





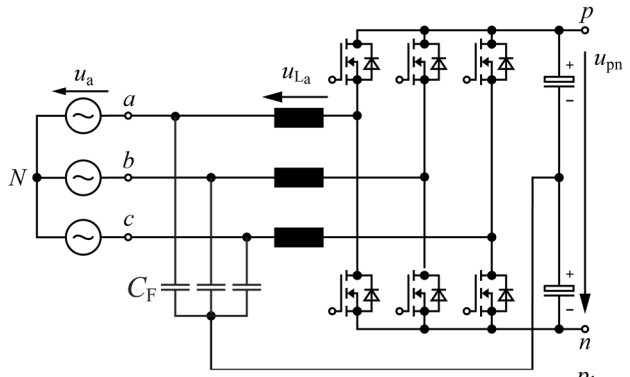


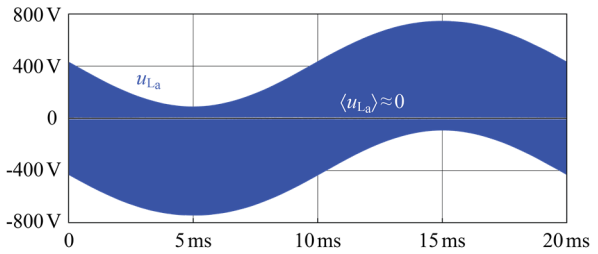
- 900V / 10mΩ SiC Power MOSFETs
- Opt. Modulation Based on 3D Look-Up Table

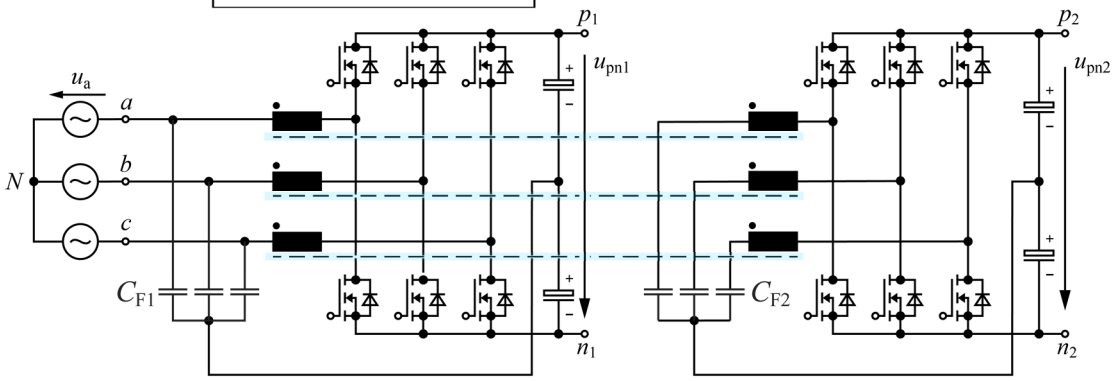
Isolated Dual 3-Φ Active Bridge Rectifier

Dual 3-Φ Active Bridge Converter

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



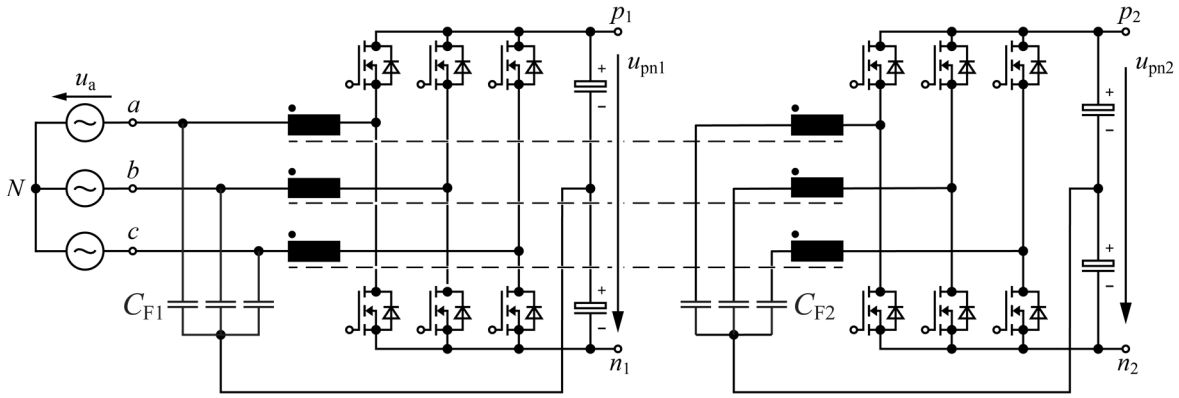


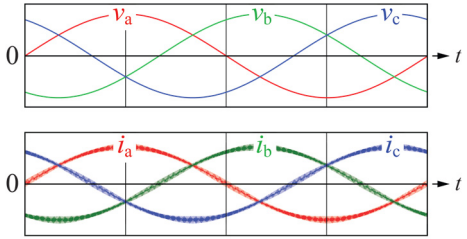


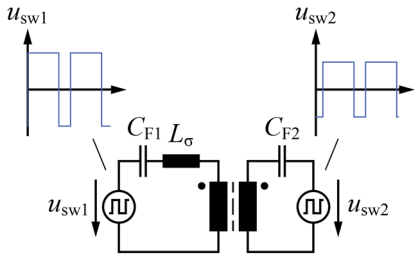
▶ *Three-Port System* - AC Input / Isol. DC Output / Non-Isol. DC Output

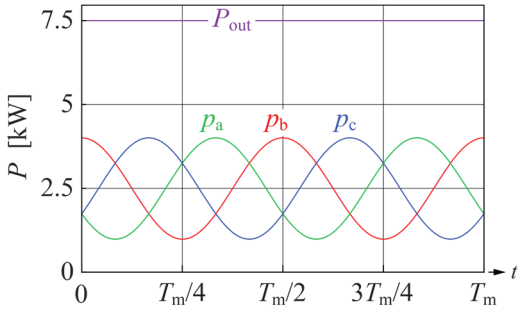
Dual 3-Φ Active Bridge Converter

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





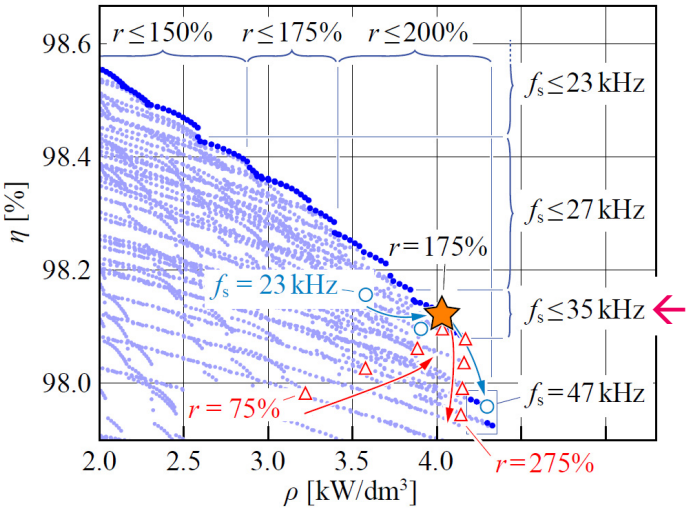


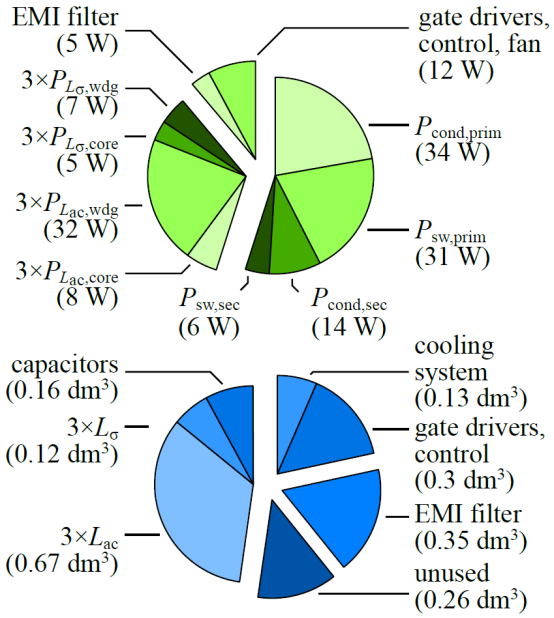


► *Three-Port System* - AC Input / Isol. DC Output / Non-Isol. DC Output

Dual 3-Φ Active Bridge Converter

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





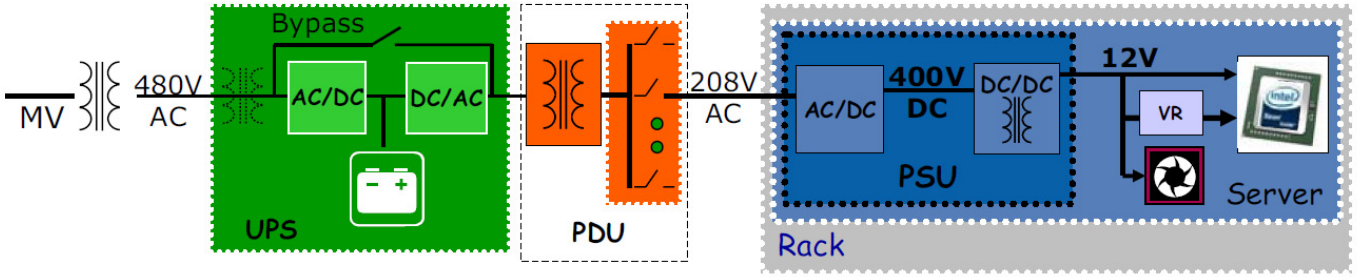
► *Efficiency* > 98% in Wide Output Power Range @ 4kW/dm³ Power Density (65W/in³)


Remark

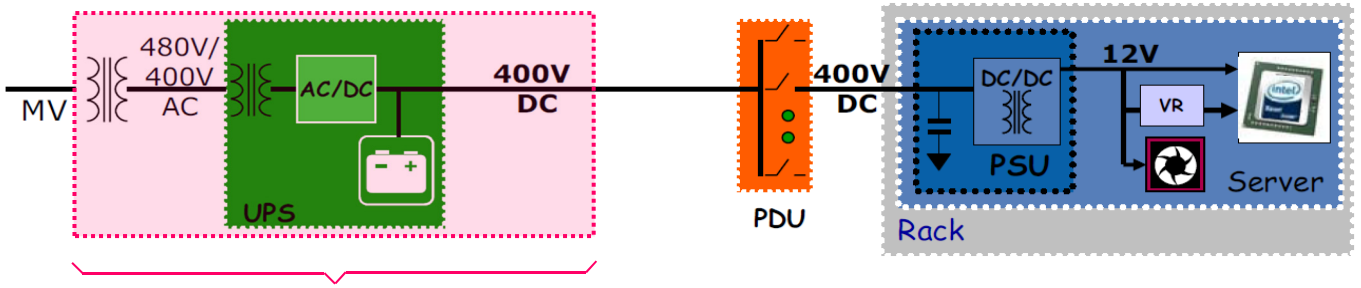
SST-Based Datacenter 400V DC Distribution System

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US 480V_{AC} Distribution



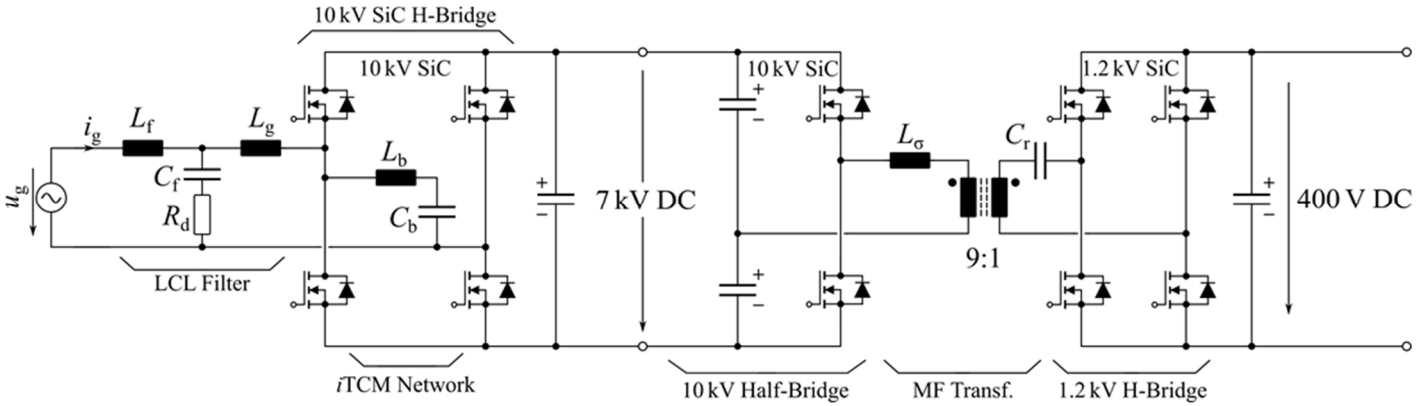
— Facility-Level 400 V_{DC} Distribution → Gain in Efficiency / Complexity



- Direct 3-Φ 6.6kV AC → 400V DC Conversion / Unidirectional SST

25kW SwiSS-Transformer

- *Bidirectional 1-Φ 3.8 kV_{rms} AC → 400V DC Power Conversion*
- *Based on 10kV SiC MOSFETs*
- *Full Soft-Switching*



► *35...75kHz iTCM Input Stage*

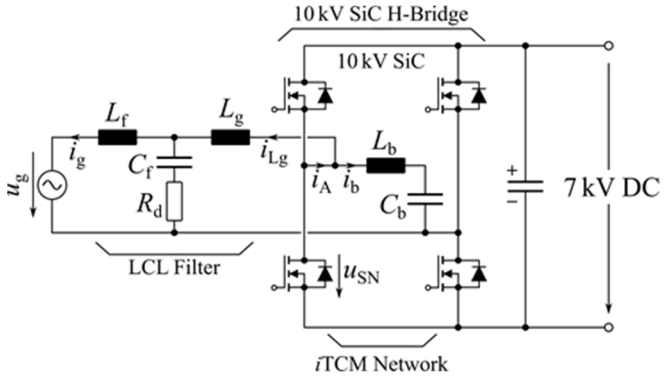
► *48kHz DC-Transformer Output Stage*

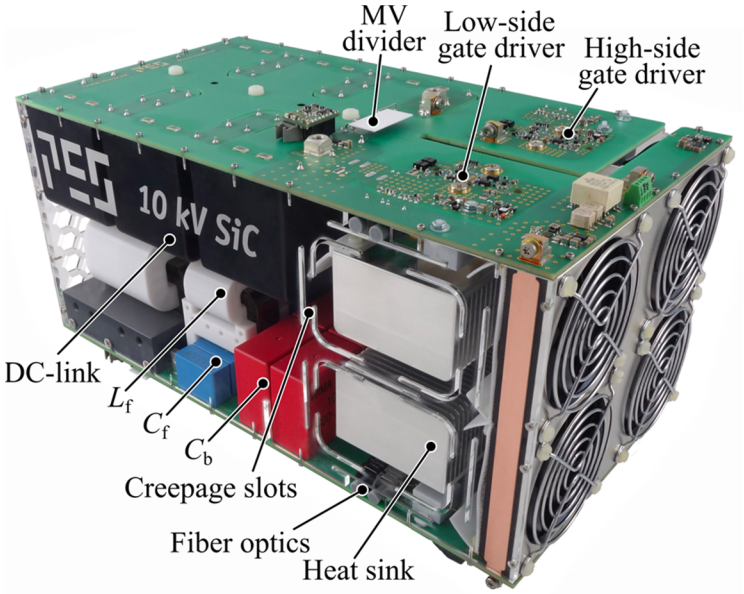
AC/DC Converter

1-Φ 3.8 kV_{rms} AC → 7kV DC Input Stage

- Based on 10kV / 10A SiC MOSFETs
- Integrated Triangular Current Mode Operation (iTCM) → Full Soft Switching
- Sine-Shaped Triangular Current due to Sw. Frequ. Variation

★ 3.3kW / dm^3





► Air-Cooling / Heat Sinks on Potential

1-Φ 3.8 kV_{rms} AC → 7kV DC Input Stage

- Based on 10kV / 10A SiC MOSFETs
- Integrated Triangular Current Mode Operation (iTCM) → Full Soft Switching
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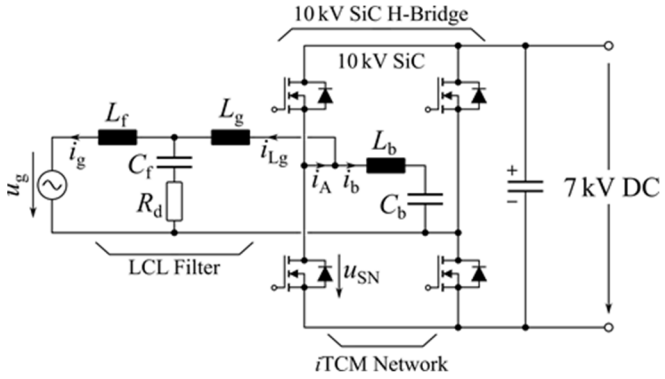
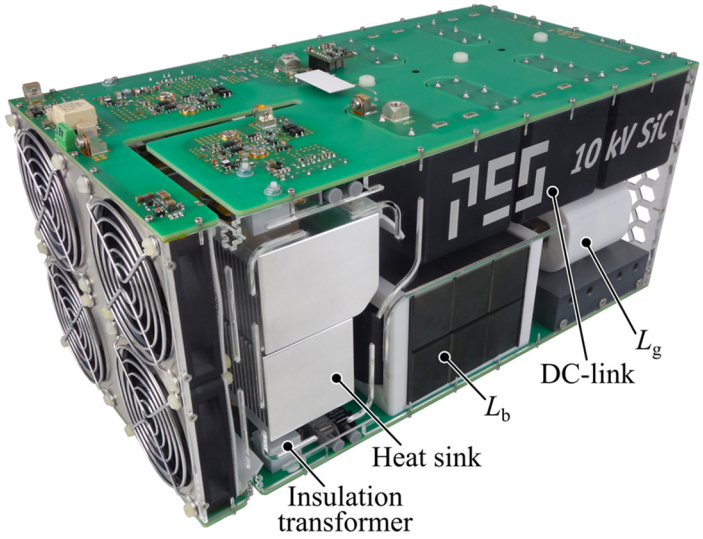
★ 3.3kW / dm^3





► Air-Cooling / Heat Sinks on Potential

1-Φ 3.8 kV_{rms} AC → 7kV DC Input Stage

- Based on 10kV / 10A SiC MOSFETs
- Integrated Triangular Current Mode Operation (iTCM) → Full Soft Switching
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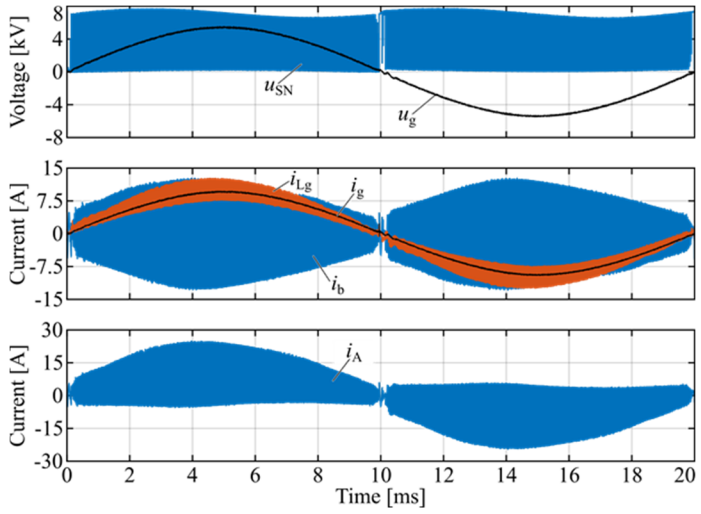
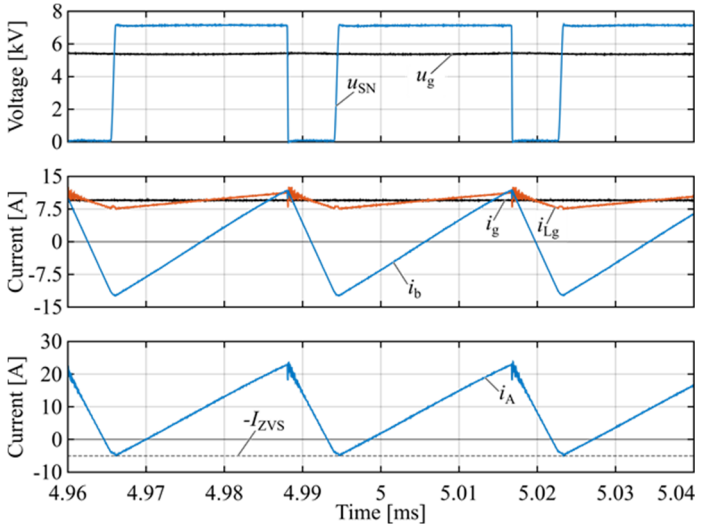


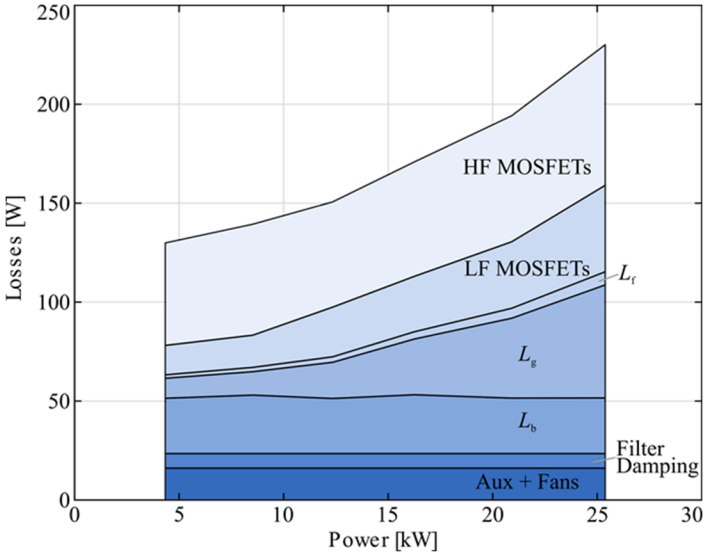
► Low-Ripple / Continuous Input Current



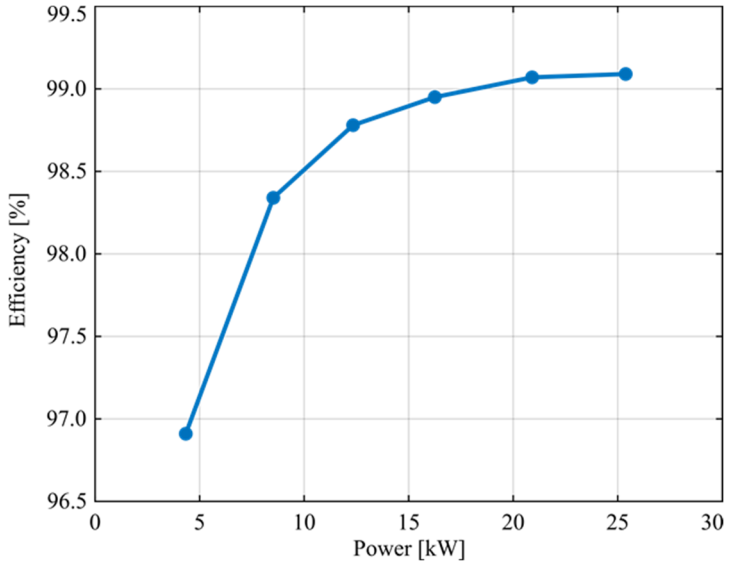
► Triangular Switching Node Current

1-Φ 3.8 kV_{rms} AC → 7kV DC Input Stage

- 99.1% Peak Efficiency @ 25kW
- Low Switching Losses Despite 35...75kHz Sw. Frequency
- Low Losses in iTCM Inductor



► Loss Distribution

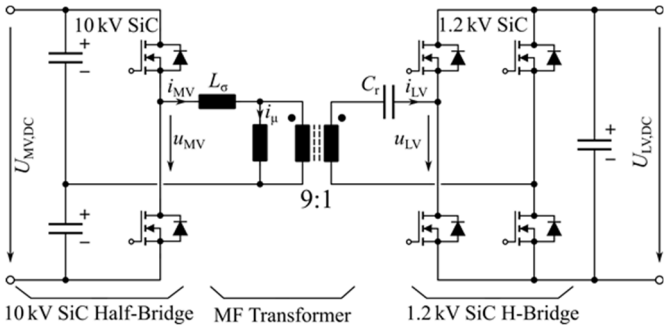


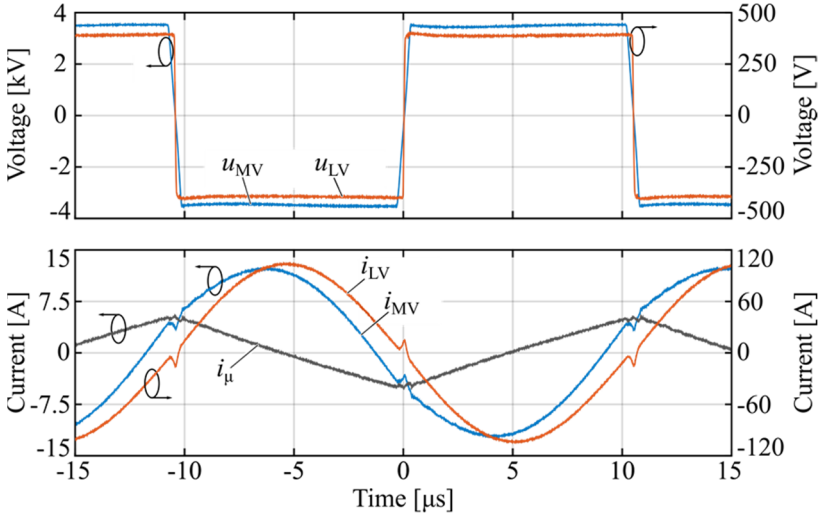
► Efficiency

DC/DC Converter

7kV → 400V DC/DC Converter

- *Operation as 48kHz DC-Transformer*
- *ZVS Over Full Power Range*

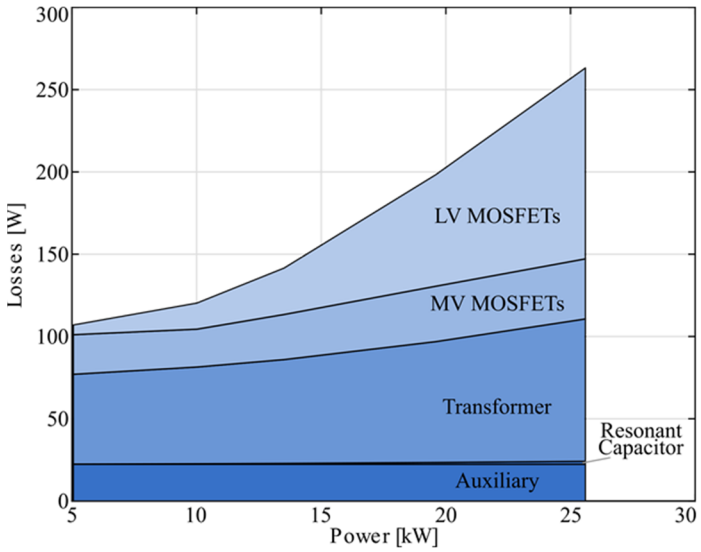




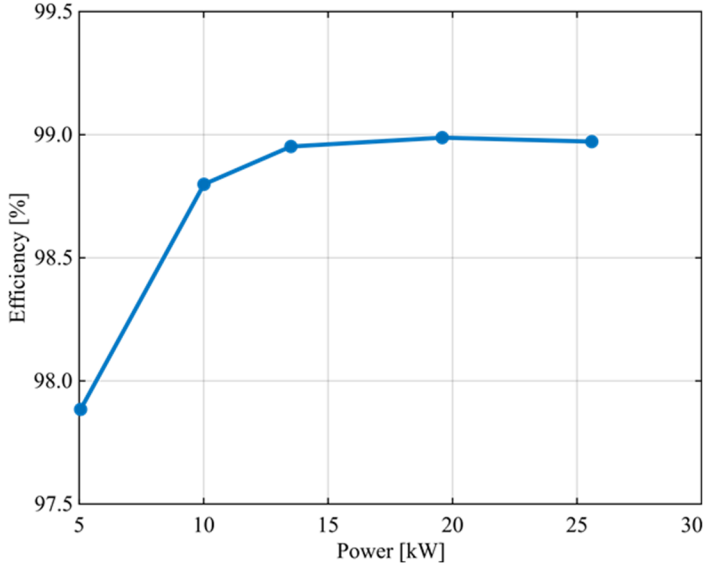
- ▶ *Very Robust to Changes in Sw. Frequency & Comp. Values*

7kV → 400V DC/DC Converter

- *99.0% Peak Efficiency @ 20kW*
- *High Share of Losses of LV Side MOSFETs & Transformer*
- *Possible Efficiency Improvement by Changing to Latest SiC Generation*



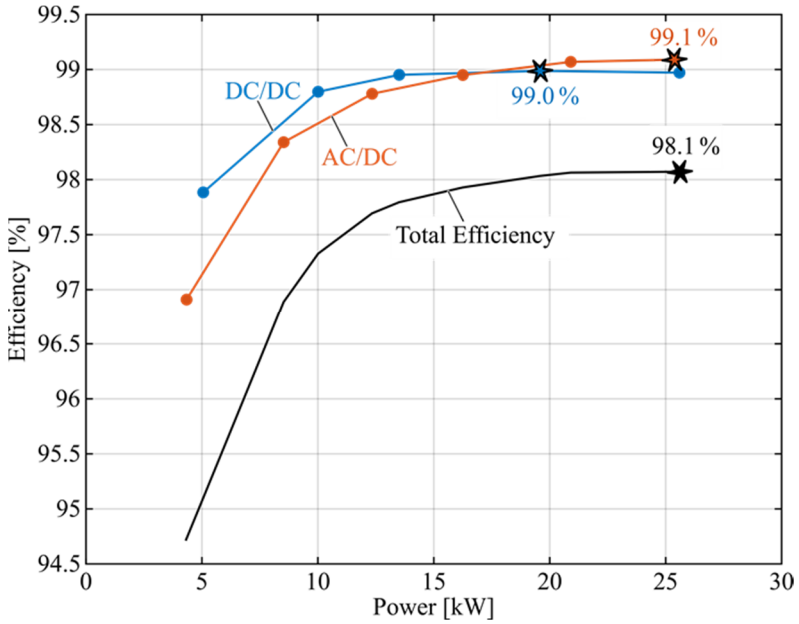
► *Loss Distribution*



► *Efficiency*

1-Φ 3.8 kV_{rms} AC → 400 V DC Efficiency

- 98.1% Overall Efficiency @ 25kW



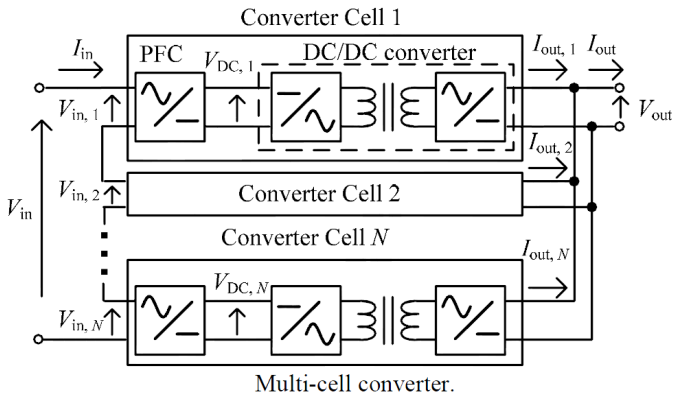
- Significantly Simpler System Structure Compared to Multi-Module SST Approach

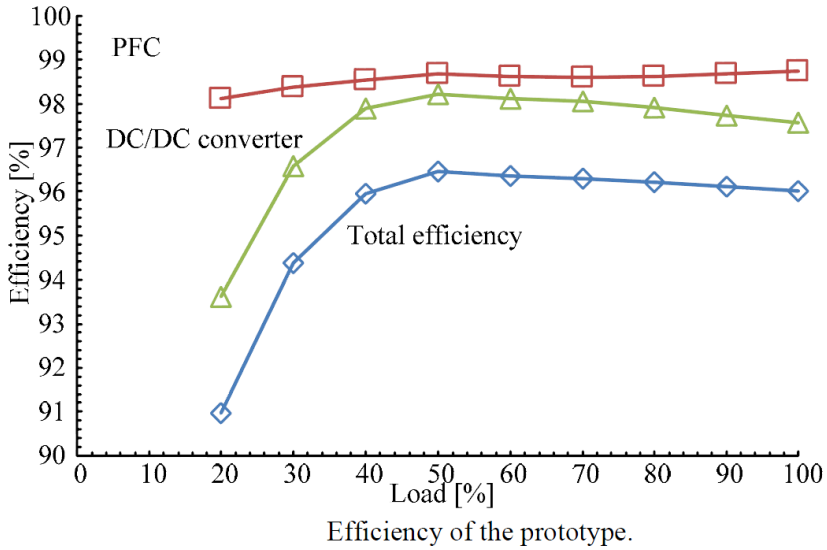
Remark: 1-Φ 2.4 kV_{rms} AC → 54V DC

Fuji Electric

- Published @ IEEE APEC 2017
- N=5 Series-Connected Cells at MV-Side / Cost Optimum

- Module Input Stage → Boost PFC Half Contr. Thyr. Rect. / 1.2kV IGBTs & SiC Diodes
- Module Output Stage → 3-Level DC/DC Conv. - 600V SJ & 100V MOSFETs





Efficiency of the prototype.

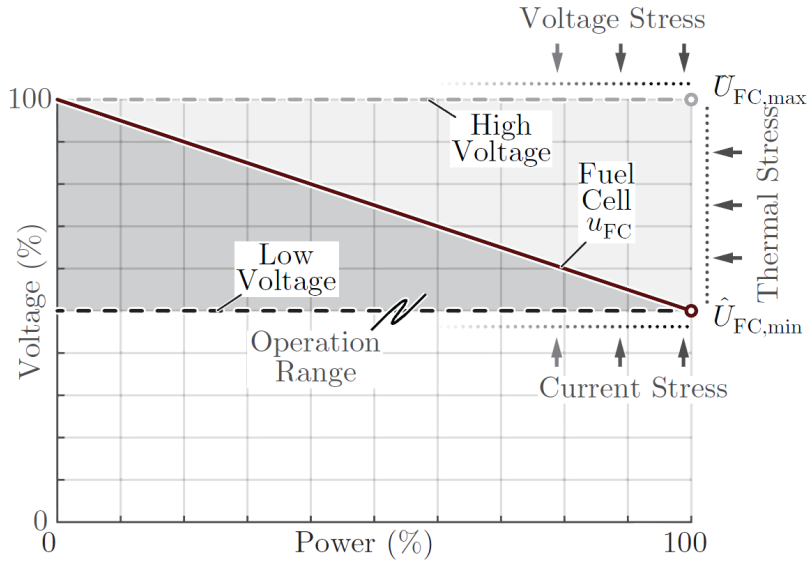
- Power Density of 0.4kW/dm³

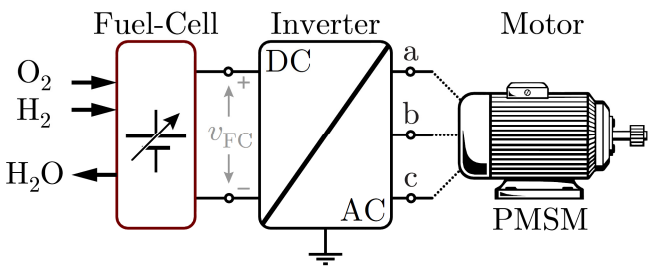
Source: ABB

Advanced Variable Speed Drive Systems

Inverter / Drive Applications

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

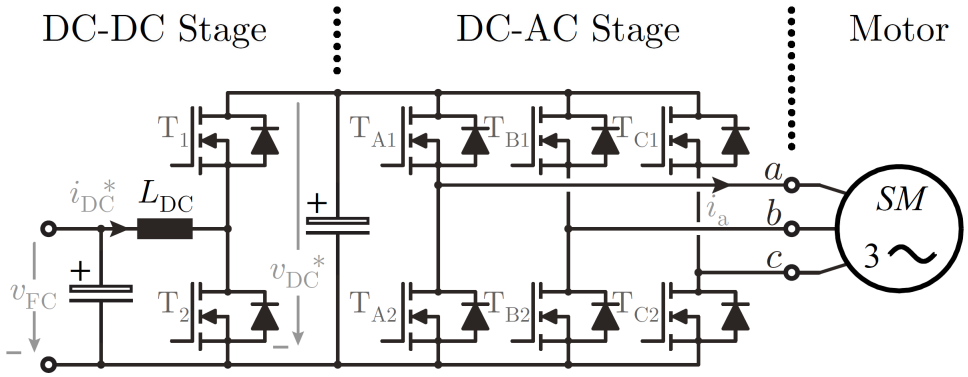




- *Inverter Input Voltage Adaption by DC/DC Boost Converter*

Inverter / Drive Applications

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

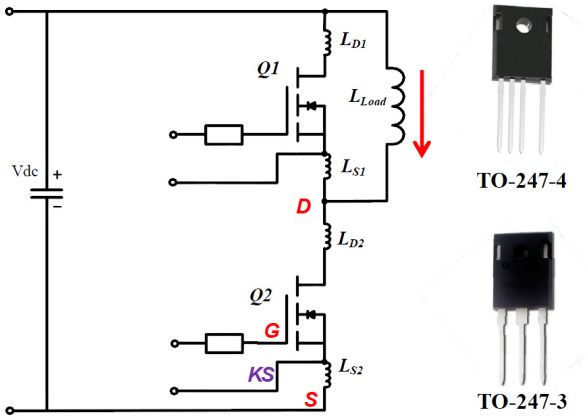


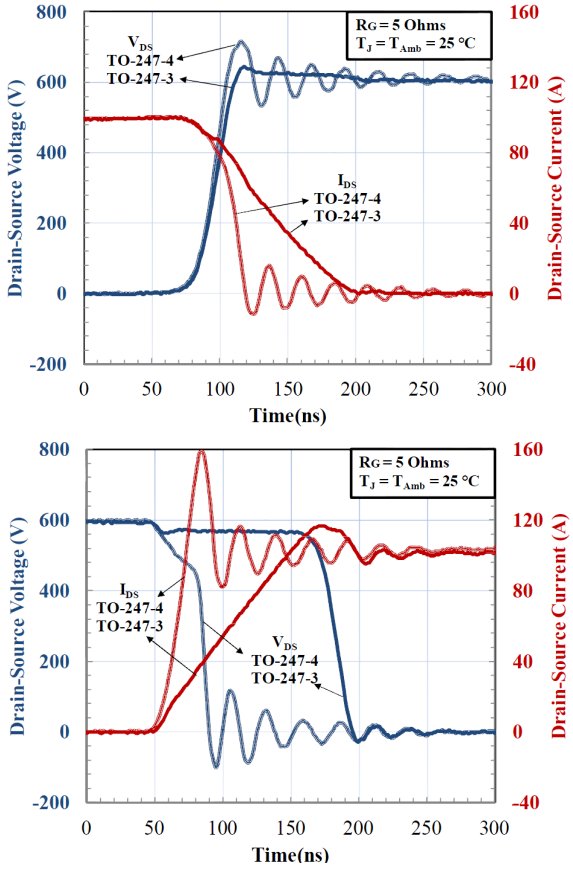
- *Motor Winding Insulation Stress* / Reflections on Long Motor Cables / Bearing Currents

Output Filter Requirement (1)

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

Source: CREE

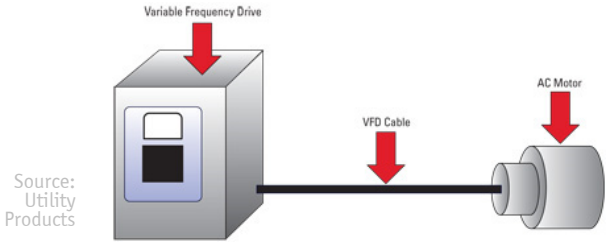




- *Motor Winding Insulation Stress* / Reflections on Long Motor Cables / Bearing Currents

Output Filter Requirement (2)

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

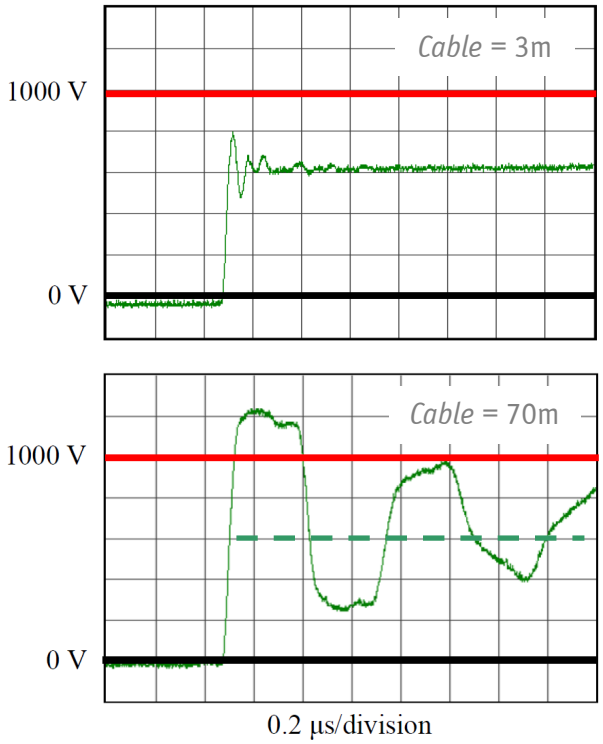


Source: Utility Products

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

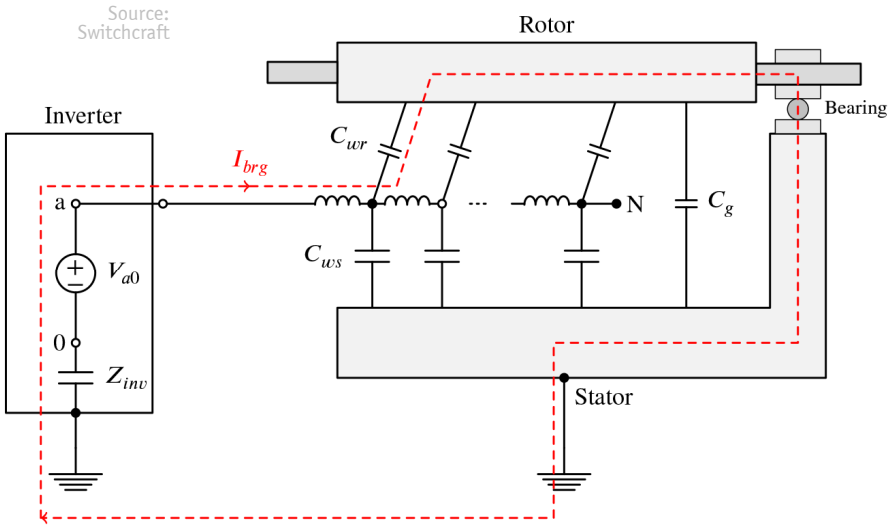


- *Imped. Matching @ Motor Terminals / Double Transition PWM / dv/dt- or Sine Wave Filters*

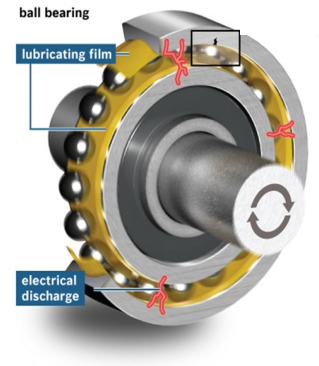
Output Filter Requirement (3)

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

Source: Switchcraft



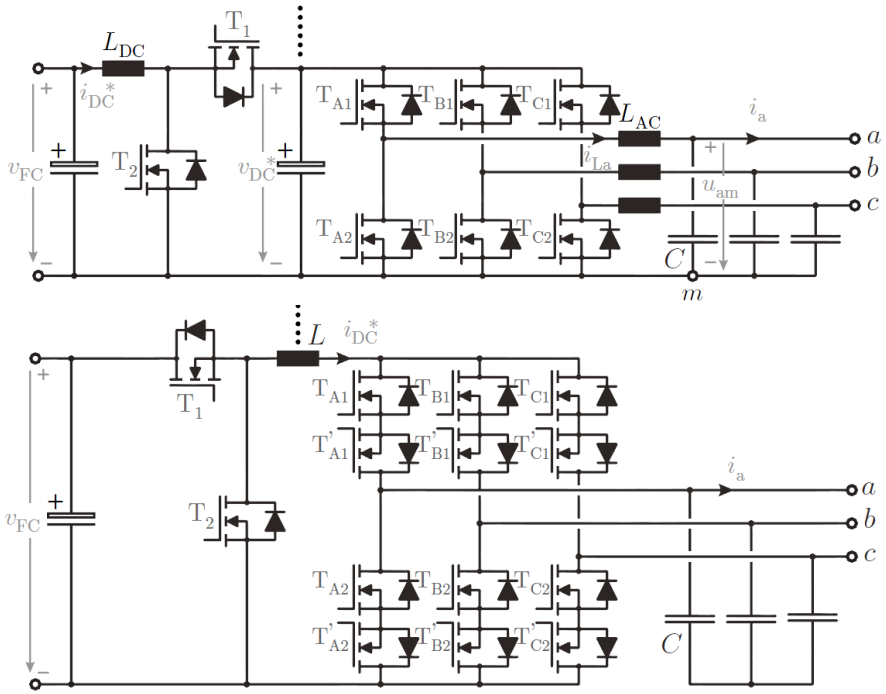
Source: BOSCH



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

Buck-Boost Inverters with Output Filter

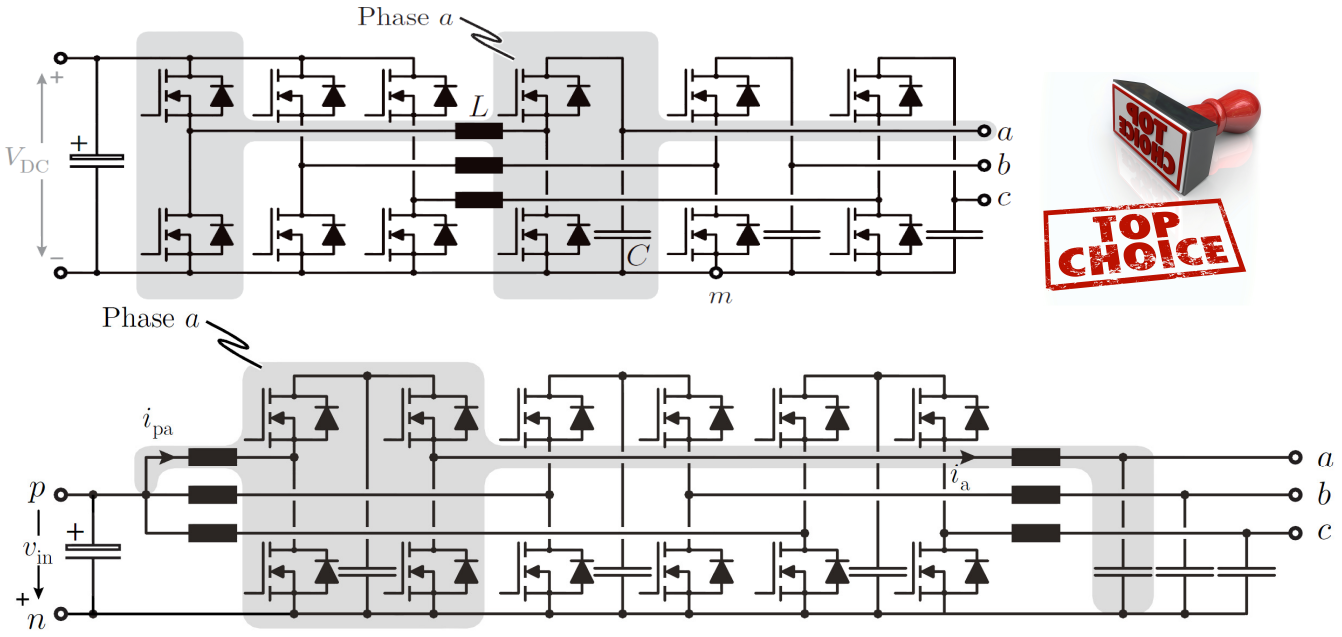
- Boost Converter & *Voltage DC Link Inverter* with LC Output Filter
- Buck Converter & *Current DC Link Inverter* ("Integrated Filter")



▶ *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*

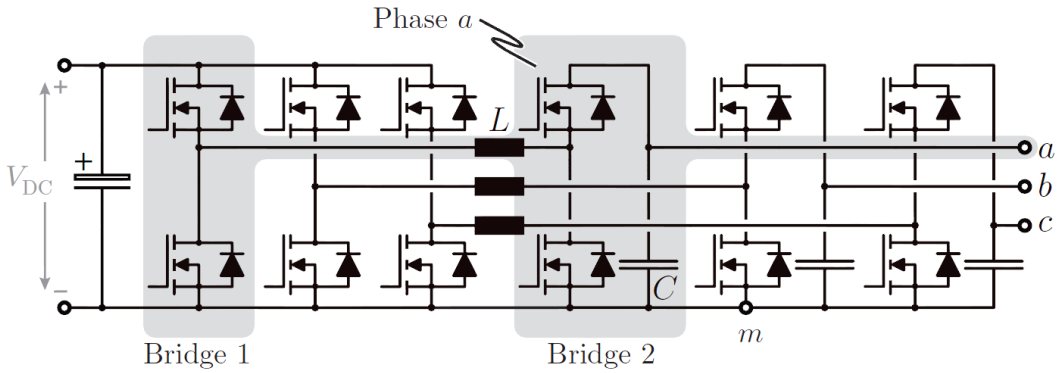


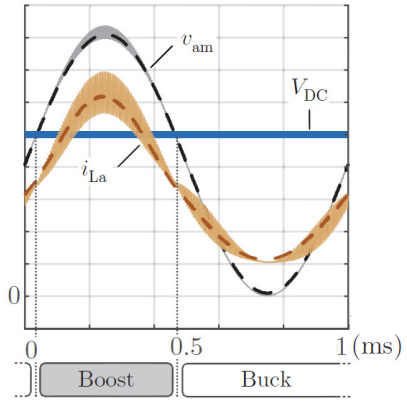
- *Motor Winding Insulation Stress* / Reflections on Long Motor Cables / Bearing Currents

X-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

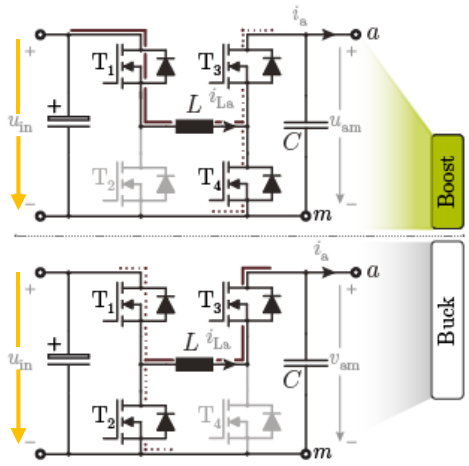


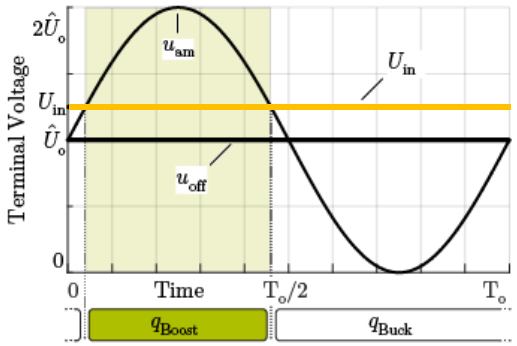


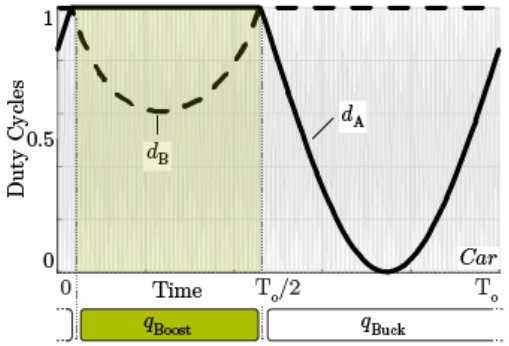
- Project Scope → Hardware Demonstrator / Exp. Analysis / Comparative Evaluation

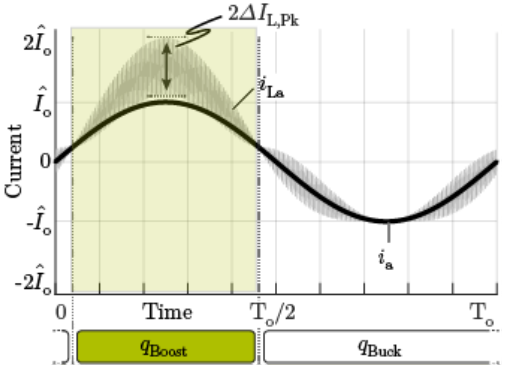
X-Inverter

- *Operating Behavior*







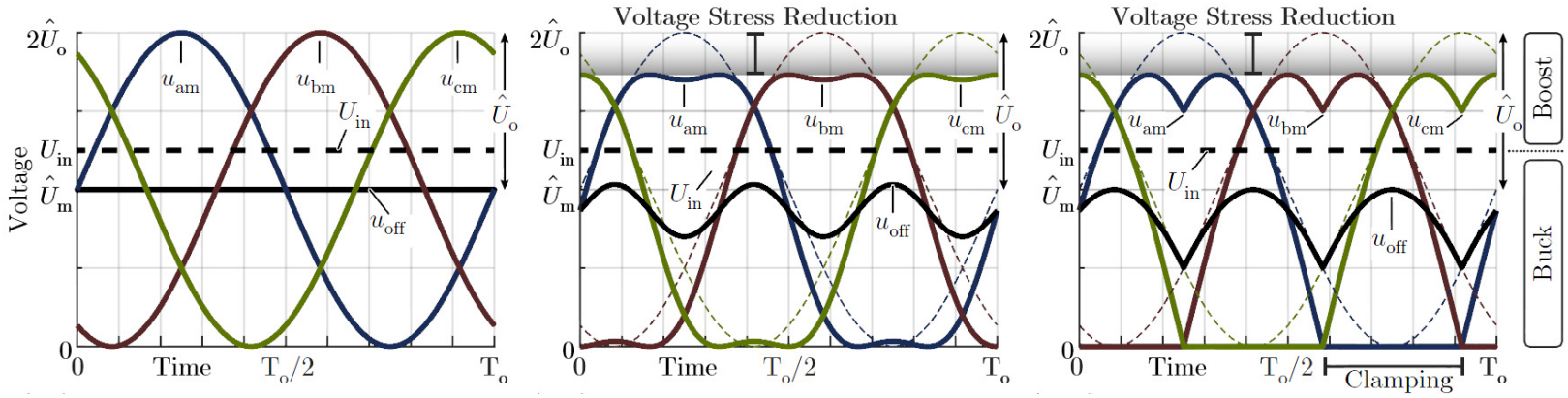


- $u_{am} < U_{in}$ → Buck Operation
- $u_{am} > U_{in}$ → Boost Operation
- Output Voltage Generation Referenced to DC Minus

X-Inverter

- *Modulation Schemes*

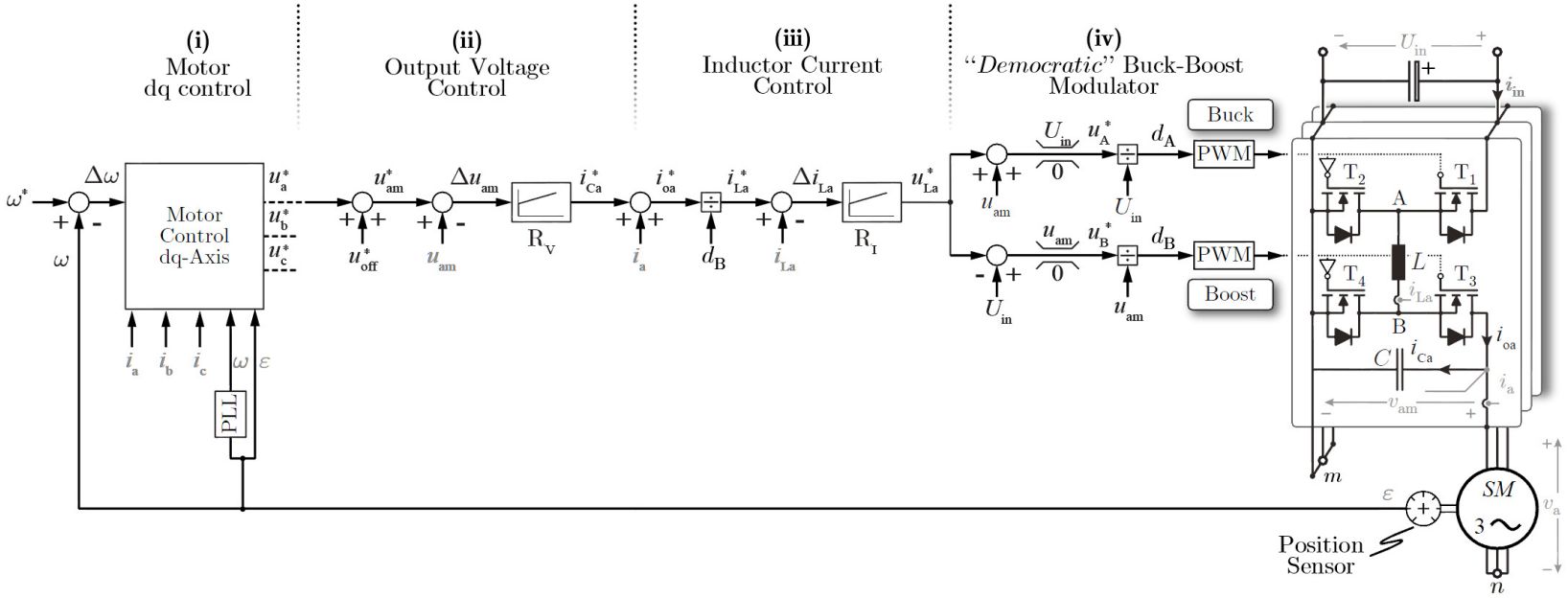
- **Output Voltage DC Offset for Low Modulation Index**
- ***Third Harmonic Injection*** **OR** ***Phase Clamping***



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

X-Inverter

- *Control Structure*

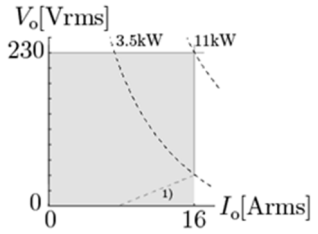


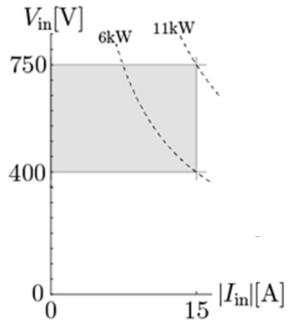
- *"Democratic Control"* → **Seamless Transition Between Buck & Boost Operation**

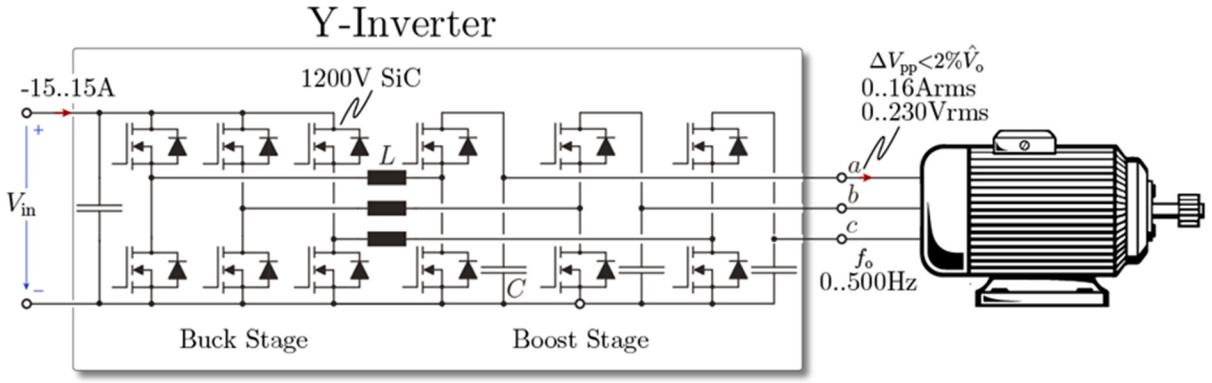
X-Inverter

- *Demonstrator Specifications*

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





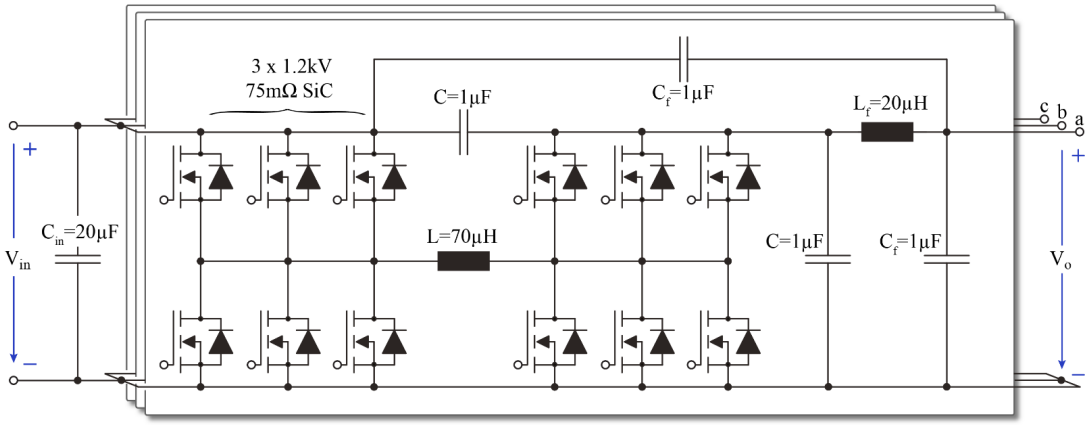


- Max. Output Power → 6...11 kW
- Output Frequency Range → 0...500Hz
- Output Voltage Ripple → 3.2V Peak-to-Peak (incl. Add. Output Filter)

X-Inverter

- *Demonstrator Power Circuit*

f_S = 100kHz

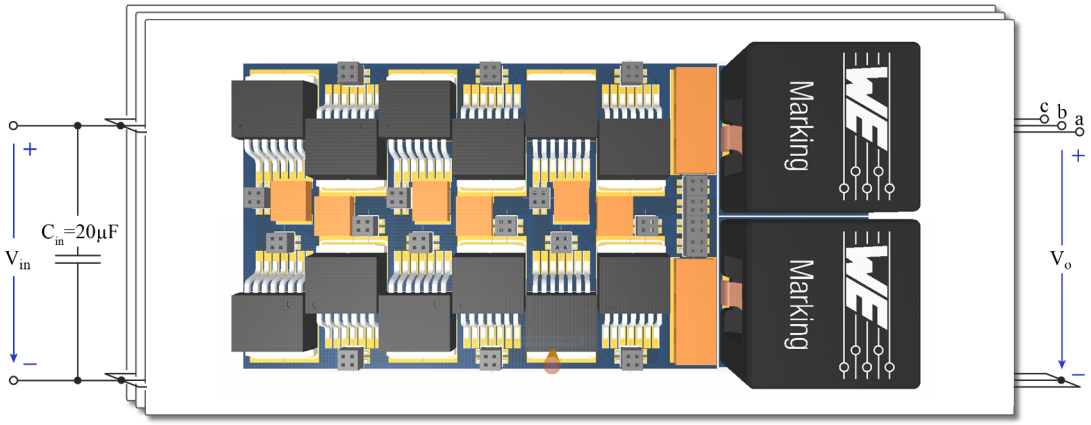


- Inductors → 2 x EELP 43 Ferrite Cores / N97 per Phase
- Add. Output Filter → 3.2V Peak-to-Peak Output Voltage Ripple
- Power Semiconductors → 3 x Cree 1200V/75mΩ SiC MOSFETs per Switch Mounted on IMS

X-Inverter

- *Demonstrator Power Circuit*

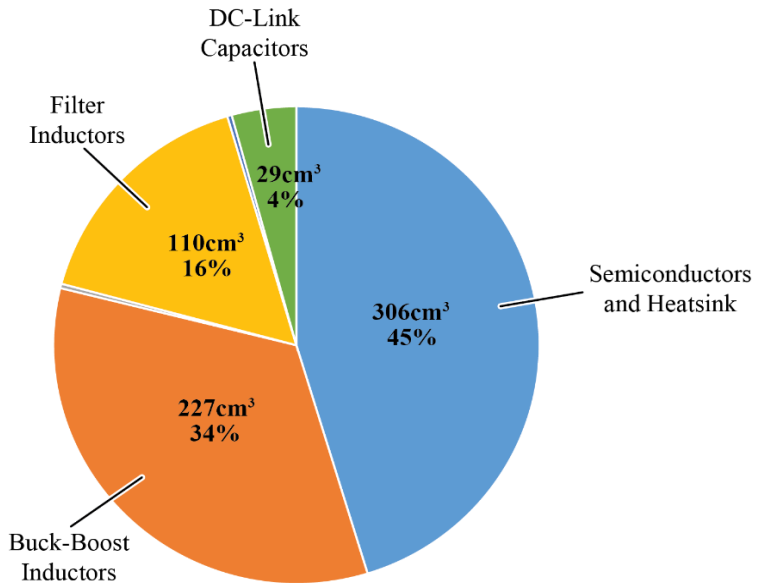
f_S = 100kHz



- 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

X-Inverter

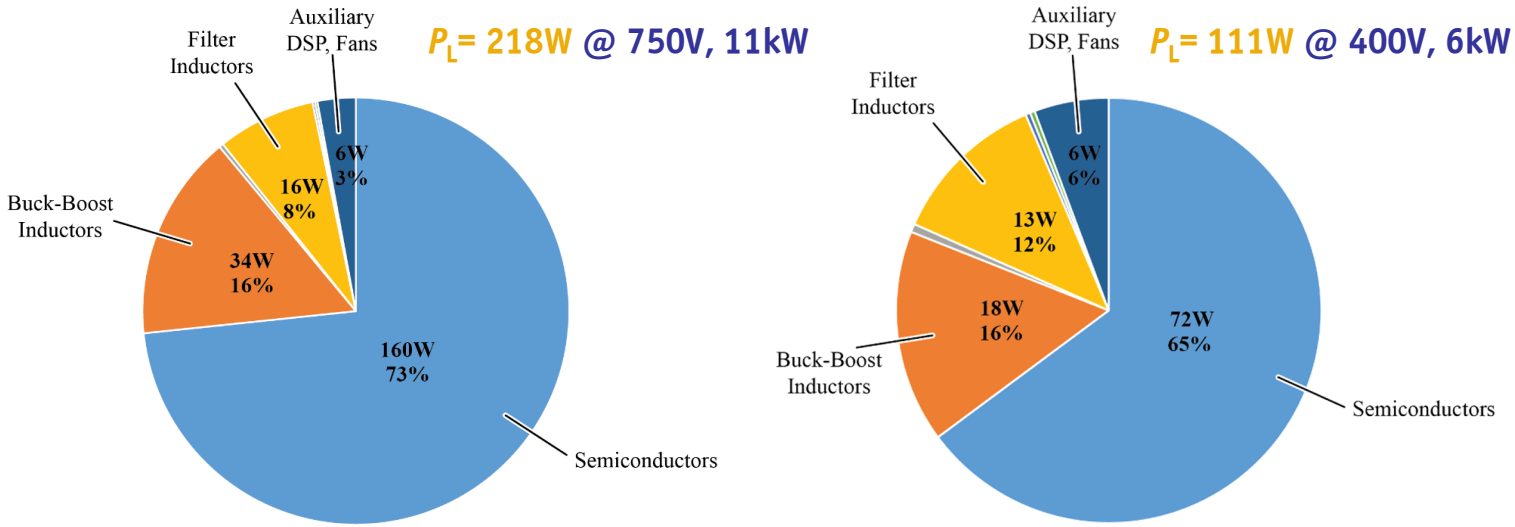
- *Demonstrator Performance – Volume Distribution*



- **Power Density → 15kW/dm³ (0.73dm³)**

X-Inverter

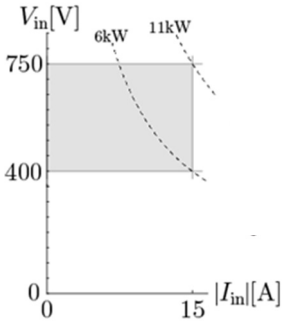
- *Demonstrator Performance* – *Loss Distribution* (Design Margin Considered)

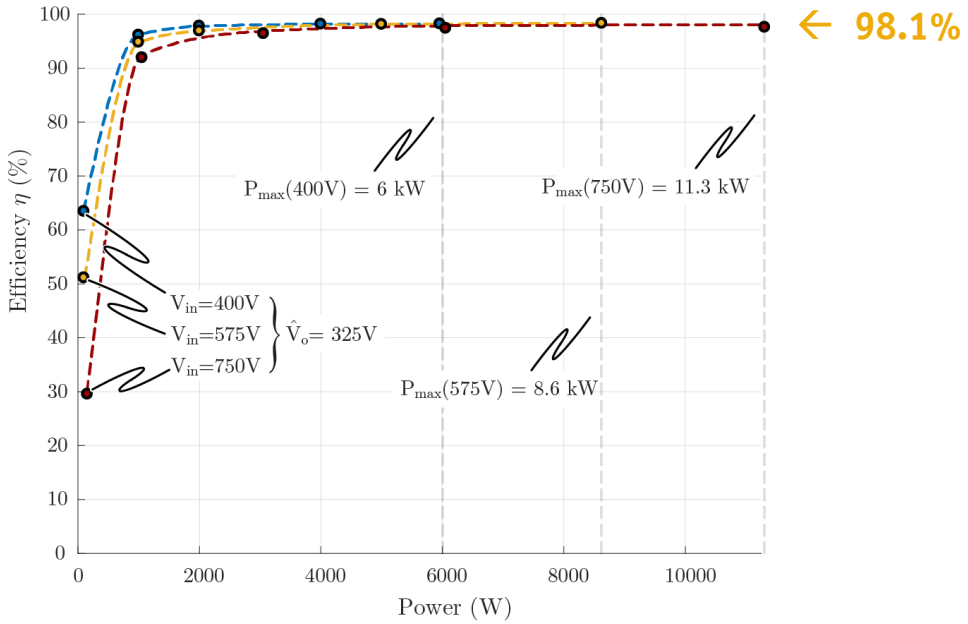


- 98% Efficiency Target @ Rated Power & Input/Output Voltage

X-Inverter

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



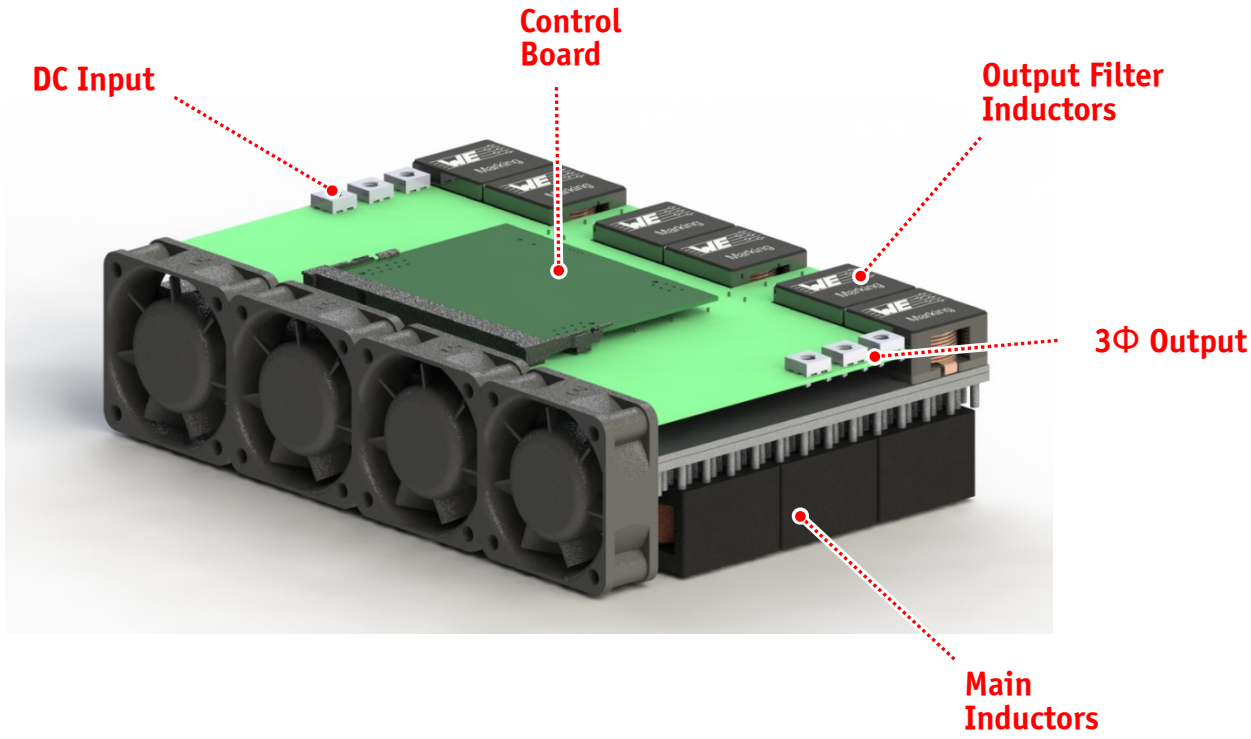


← 98.1%

- Higher Efficiency for *Phase Clamping Modulation*

X-Inverter

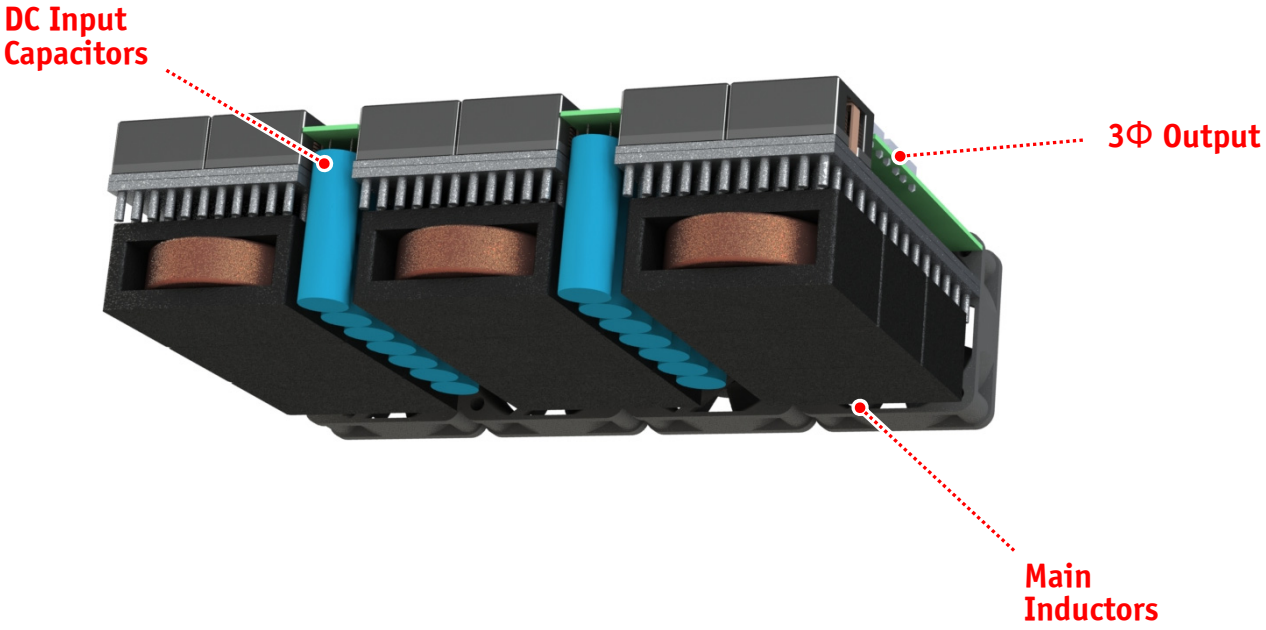
- *Demonstrator – Virtual Prototype (1)*



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

X-Inverter

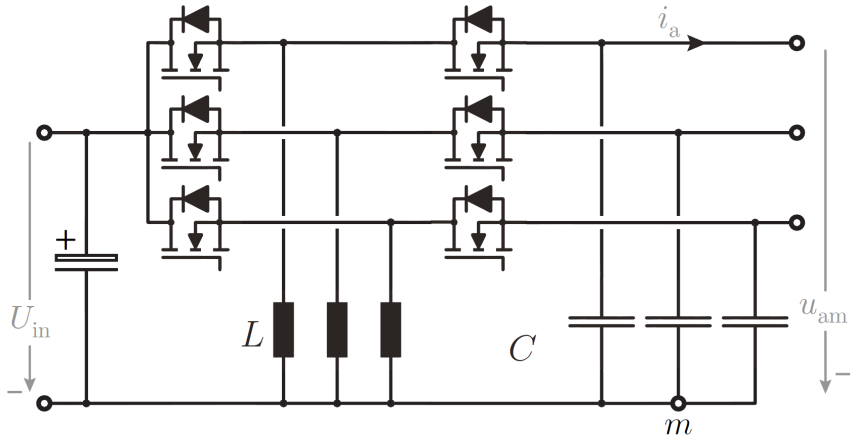
- *Demonstrator – Virtual Prototype (2)*



- **Dimensions → 160 x 110 x 42 mm³**

X-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*
- *X-Rectifier & 1/3-Rectifier*
  - *Next Generation PMW Rectifiers*
  - *Next Generation Integrated Motor Drives*

Source: UK Outdoor Store

Thank You !