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Monolithic Bi-Directional Switches —
X-Technology of 3-Φ AC/DC Mains Interfaces

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Part #3
Special Session

New Developments in
WBG Bidirectional Switches
and Applications

Oct. 11, 2022

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M-BDS — X-Technology of 3-Φ AC/DC Mains Interfaces

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Outline

- ▶ *Introduction*

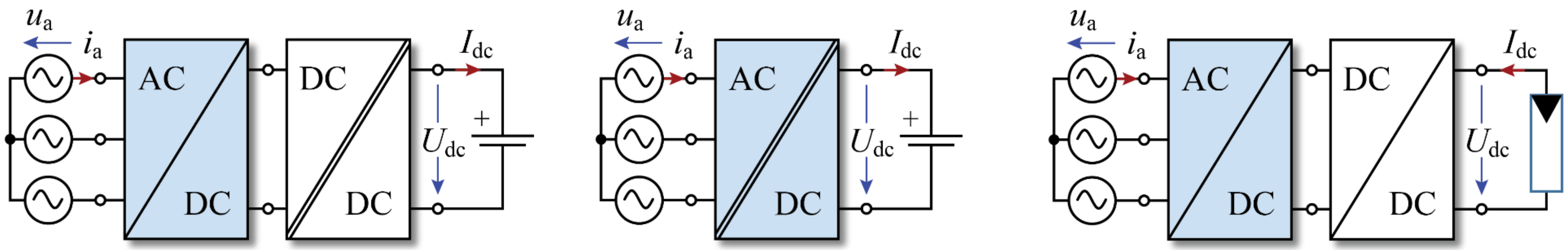
- ▶ *Diode-Bridge & Active Filter*
- ▶ *Boost-Type / VIENNA Rectifier*
- ▶ *Buck-Boost Type Converters*

- ▶ *Conclusions*

3-Φ AC/DC Converter Application Areas

- *Electric Vehicle Battery Charging*
- *Datacenter Power Supply*
- *Renewable Energy Applications*

Typ. 200…1000 V_{DC} EV Battery
Voltage Range



320…530 V_{rms}
Line-to-Line

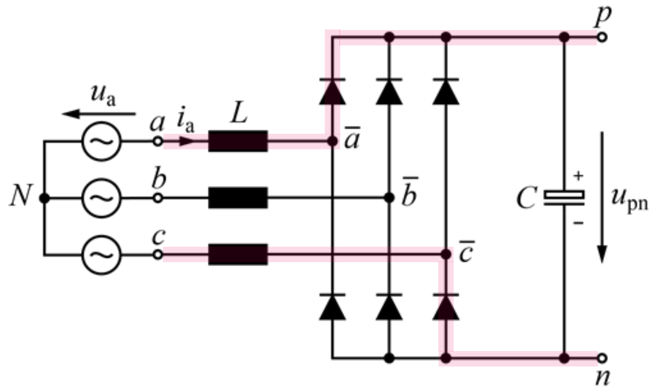
MPP Tracking in 60…90 % of
Max. Open Circuit Voltage

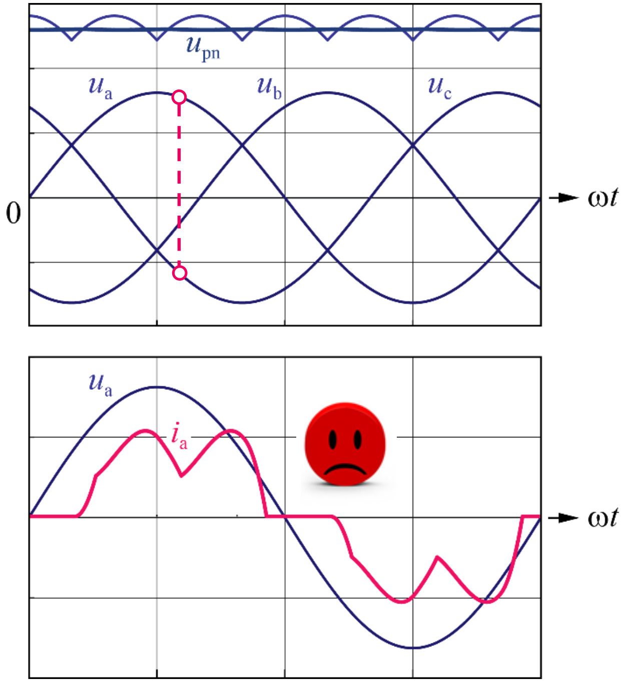
- *Non-Isolated* OR *Isolated Output*
- *Wide AC Input* &/OR *DC Output Voltage Range*
- *Unidirectional* OR *Bidirectional Power Transfer*

3^{rd} Harmonic Inj. Diode-Bridge Rectifier
3-Level Boost-Type VIENNA Rectifier

3-Φ Diode Bridge Rectifier

- *Conduction States Defined by Line-to-Line Mains Voltages*
- *Intervals with Zero Current / LF Harmonics*
- *No Output Voltage Control*

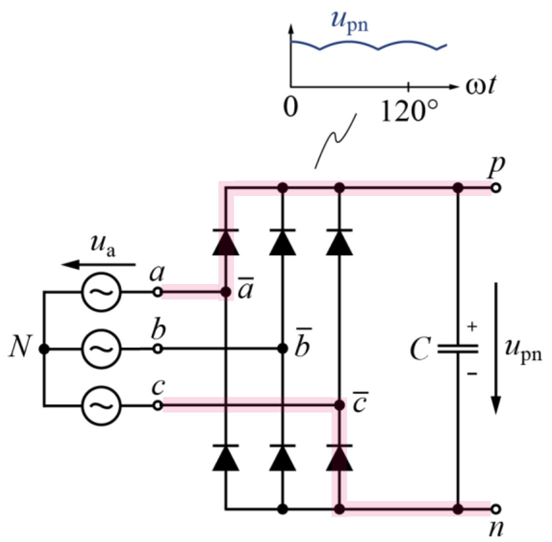


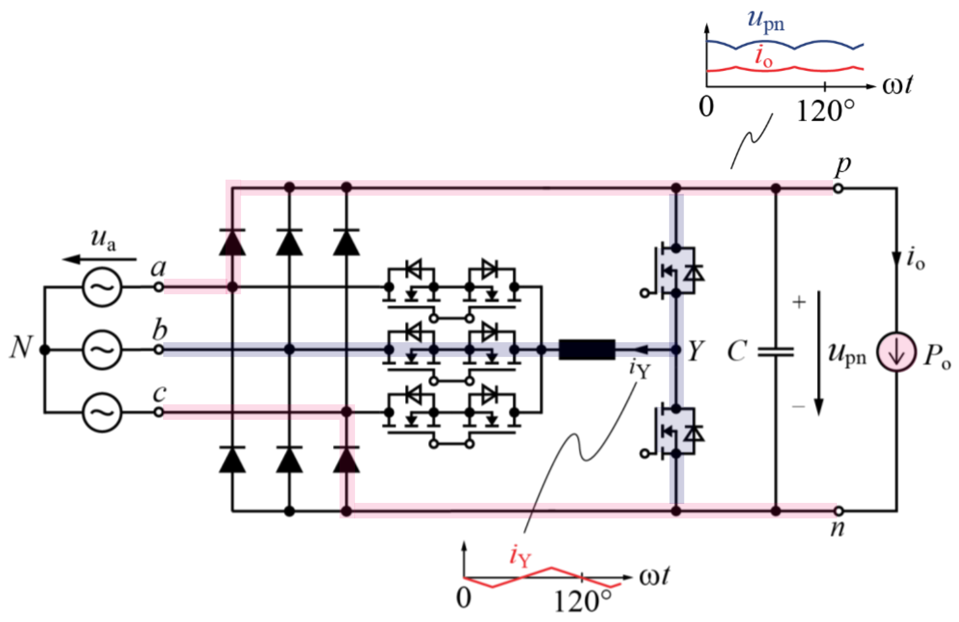


→ *Active Mains Current Shaping / Simultaneous Current Flow in All Phases*

Integrated Active Filter (IAF) PFC Rectifier

- 3rd Harmonic Current Injection into Phase with Lowest Voltage
- Phase Selector AC Switches Operated @ Mains Frequency — "3-Φ Unfolder"



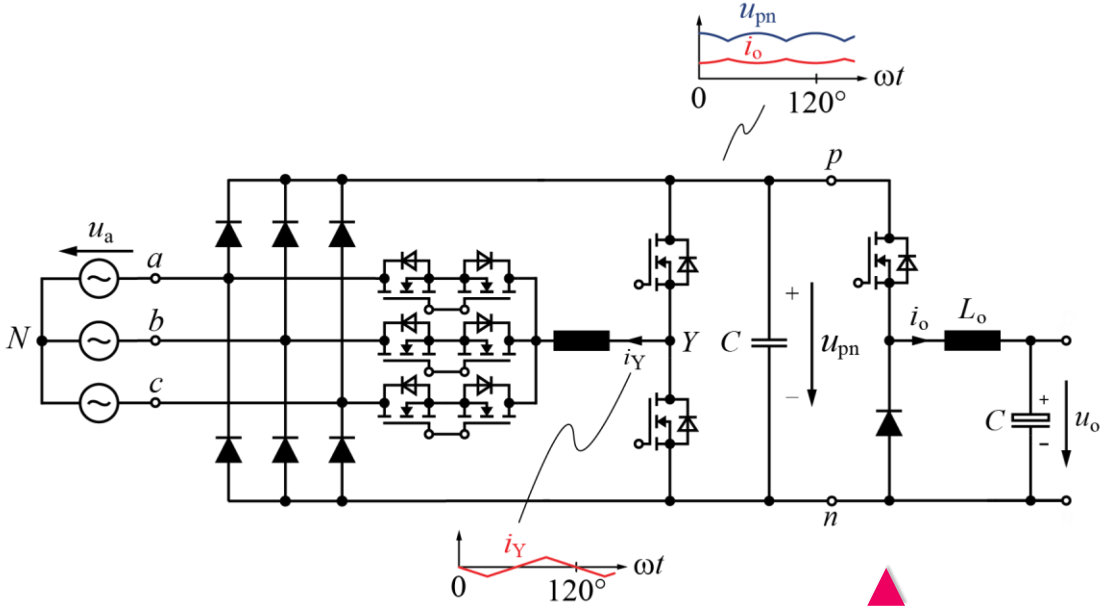


- Non-Sinusoidal Mains Current

→ P_0= const. Required
→ Sinusoidal Mains Current
→ NO (!) DC Voltage Control

IAF Rectifier & Buck Output Stage

- *Buck-Output Stage* → *P_0= const. & Output Voltage Control*
- *Sinusoidal Mains Current*

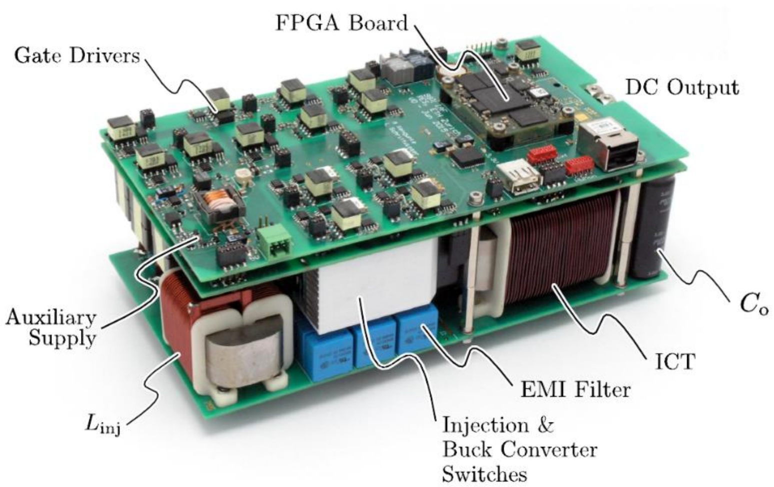


- *Buck-Stage Could be Replaced by Isolated DC/DC Conv. or Inverter*

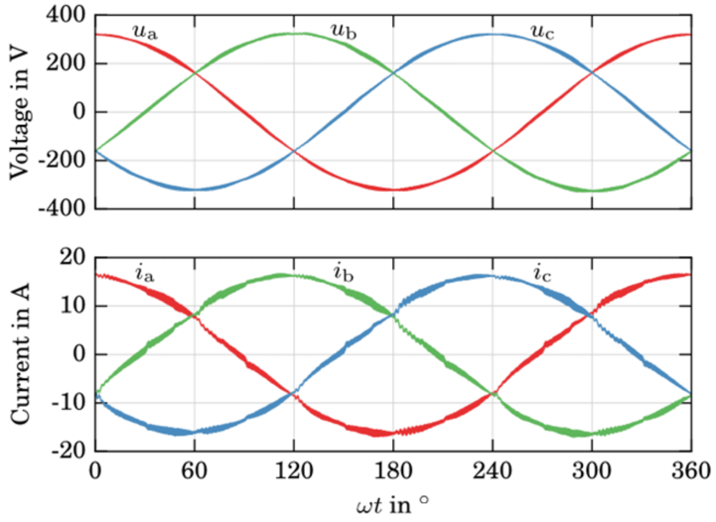
IAF Rectifier & Buck Output Stage

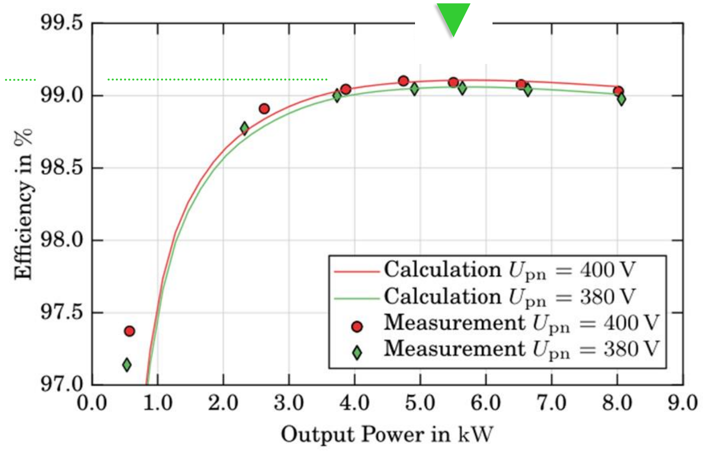
- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current $THD_I \approx$ 2% @ Rated Load*
- *Power Density $\rho \approx$ 4kW/dm^3*

P_0= 8 kW
U_N= 400V$_{AC}$ → U_0= 400V$_{DC}$ const. / Controlled
f_S = 27kHz



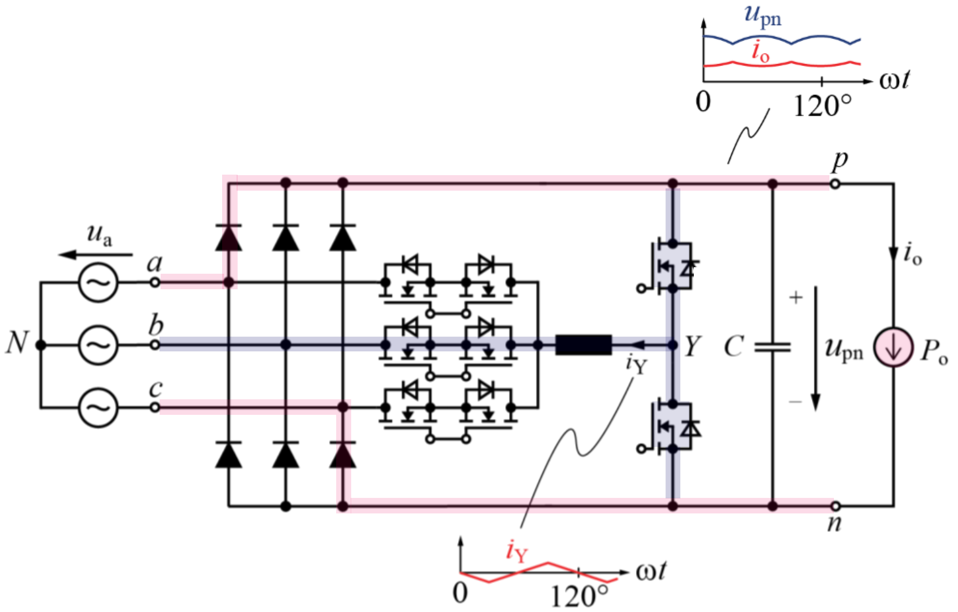
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck DC/DC Output Stages (!)*

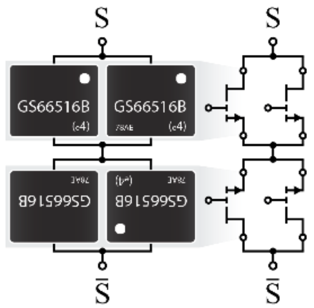


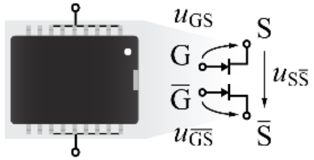


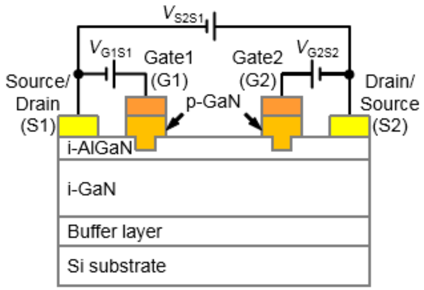
Remark Application of M-BDS

- M-BDS — Monolithic Bidirectional / Bipolar Switch
- Realization of the Phase Selector Switches of 3rd Harmonic Inj. PFC Rectifiers
- Bipolar Voltage Blocking / Current Carrying Capability







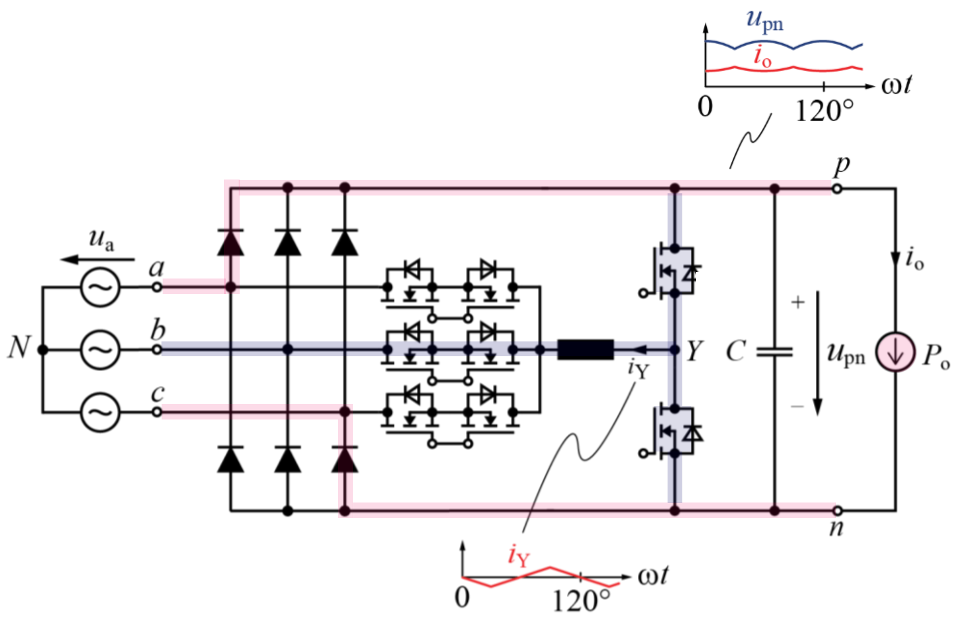


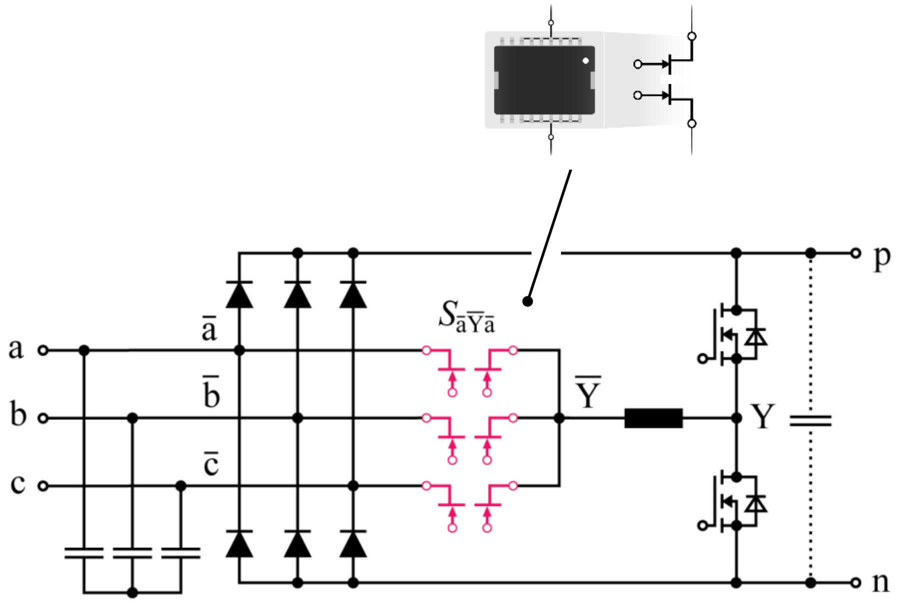
Source: Panasonic ideas for life

- M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization w/ Same $R_{(on)}$ (!)

Remark Application of M-BDS

- *Realization of the Phase Selector Switches of 3rd Harmonic Inj. PFC Rectifiers*
- *Bipolar Voltage Blocking / Current Carrying Capability*

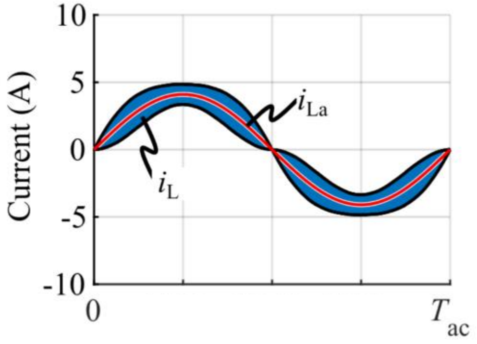


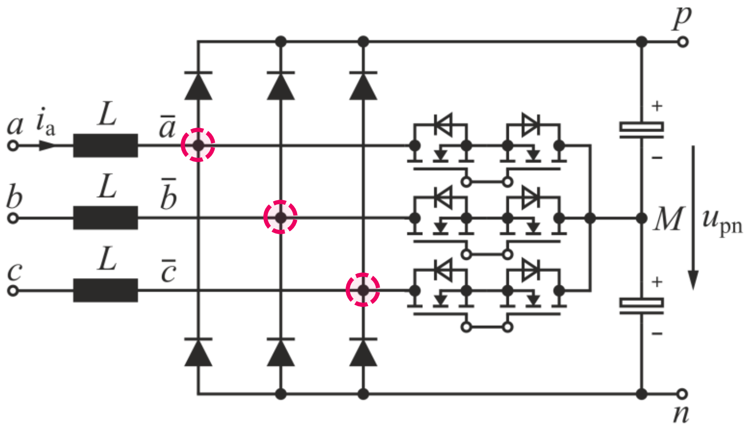


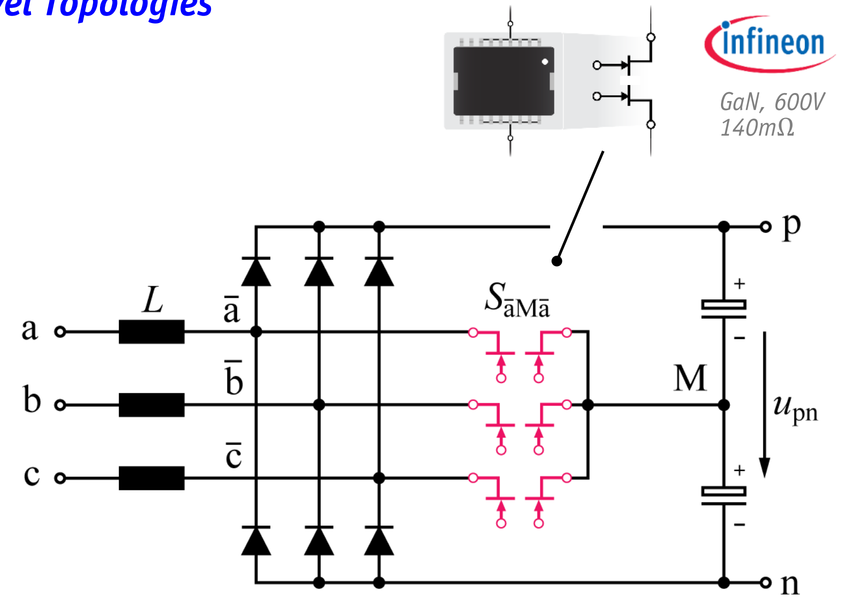
- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization w/ Same $R_{(on)}$ (!)*

Remark 3-Level T-Type PFC (Vienna) Rectifier

- Control of Diode Bridge Input Voltage → Sinusoidal Input Current Shaping
- Controlled Output Voltage > Mains Line-to-Line Voltage Amplitude → Boost-Type
- Low Conduction Losses Compared to Alternative 3-Level Topologies







- Voltage Stress of T-Type Switches Defined by Half (!) the DC-Link Voltage
- Utilization of 600 V GaN M-BDSs @ U_{pn}= 800 V_{DC} in Combination w/ 1200 V SiC Diodes

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Buck-Boost Voltage | Current DC-Link PFC Rectifier

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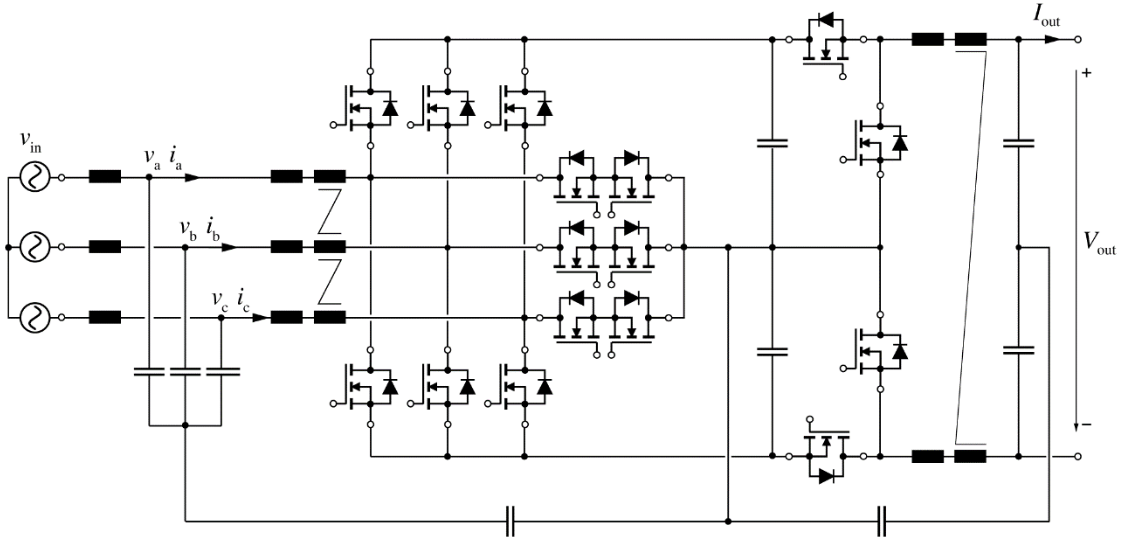
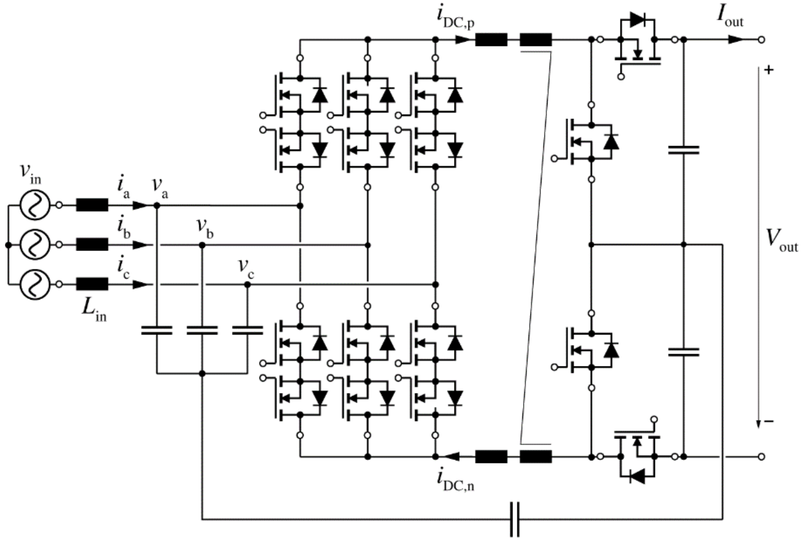
Bidirectional *Buck-Boost* PFC Rectifier Concepts

- *Boost—Buck OR Buck—Boost Combination*
- *Closed Loop vs. Open Loop Mains Current Control & Active Input Filter Damping*
- *"Synergetic Control" of AC/DC and DC/DC Converter Stage*

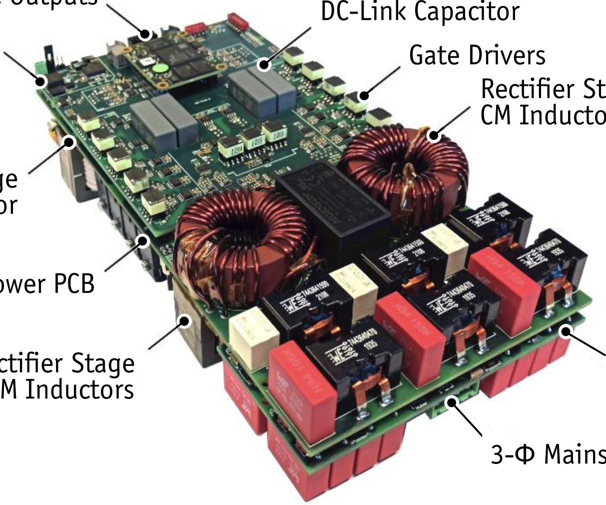




- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

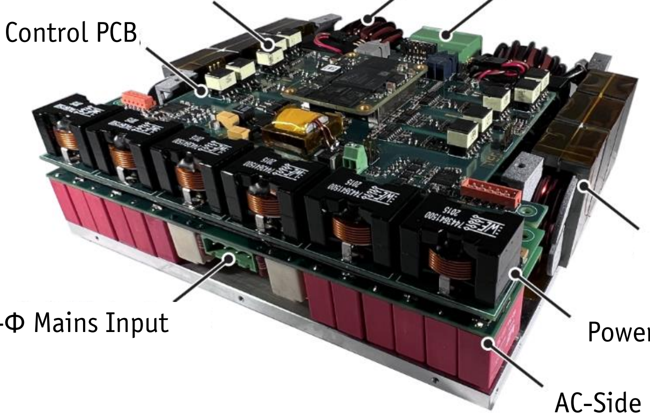
Boost-Buck | *Buck-Boost* Demonstrator Systems

- 10 kW @ 400...800 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 800 V_{DC}
- η = 98.8% @ 5.4 kW/dm^3
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 100 kHz/200 kHz *eff.*



- *Boost-Buck Voltage DC-Link PFC Rectifier*

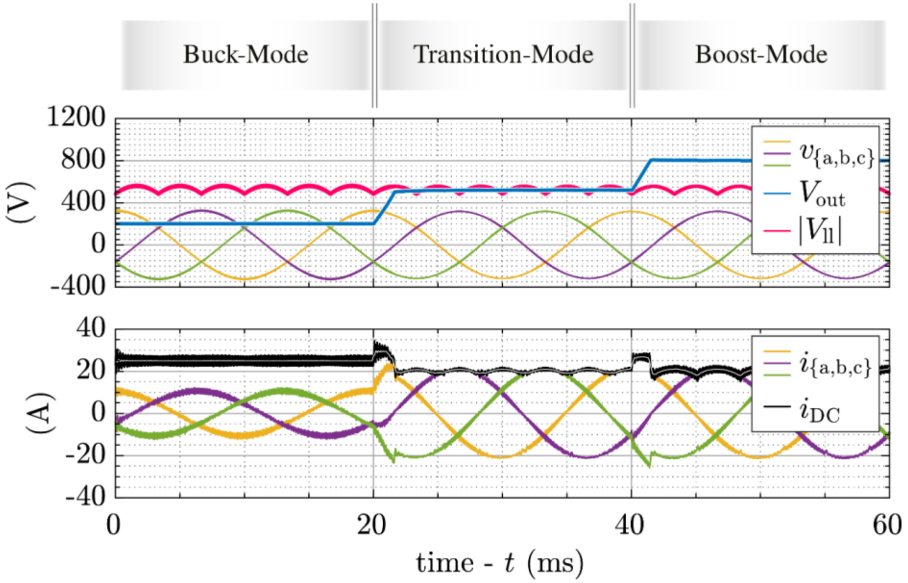
- 10 kW @ 400...1000 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 1000 V_{DC}
- η = 98.6% @ 6.4 kW/dm^3
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 50 kHz/100 kHz *eff.*

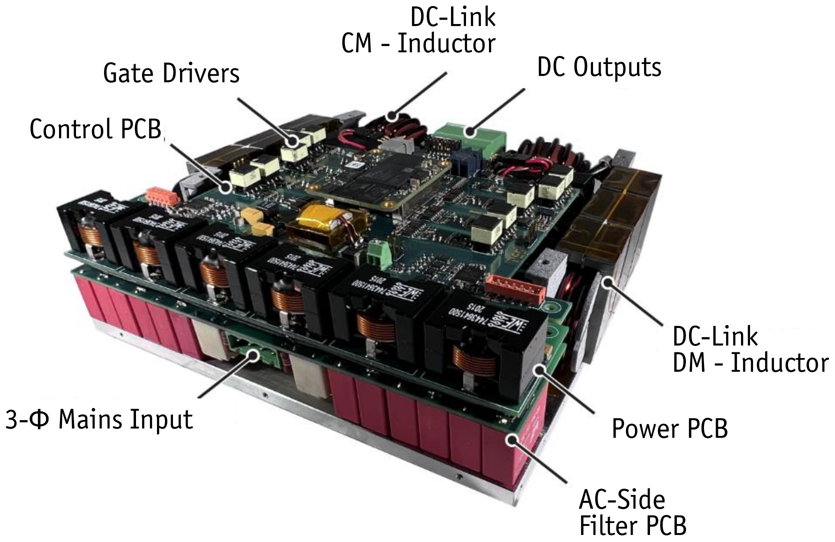


- *Buck-Boost Current DC-Link PFC Rectifier*

Buck-Boost Demonstrator System

- *"Synergetic" Control of CSR-Stage & Boost-Stage → 6-Pulse i_{DC} / Significant Red. of Sw. Losses*
- *Seamless Transition from Full Boost Operation @ 6-Pulse i_{DC} to Buck Operation @ i_{DC}=const.*

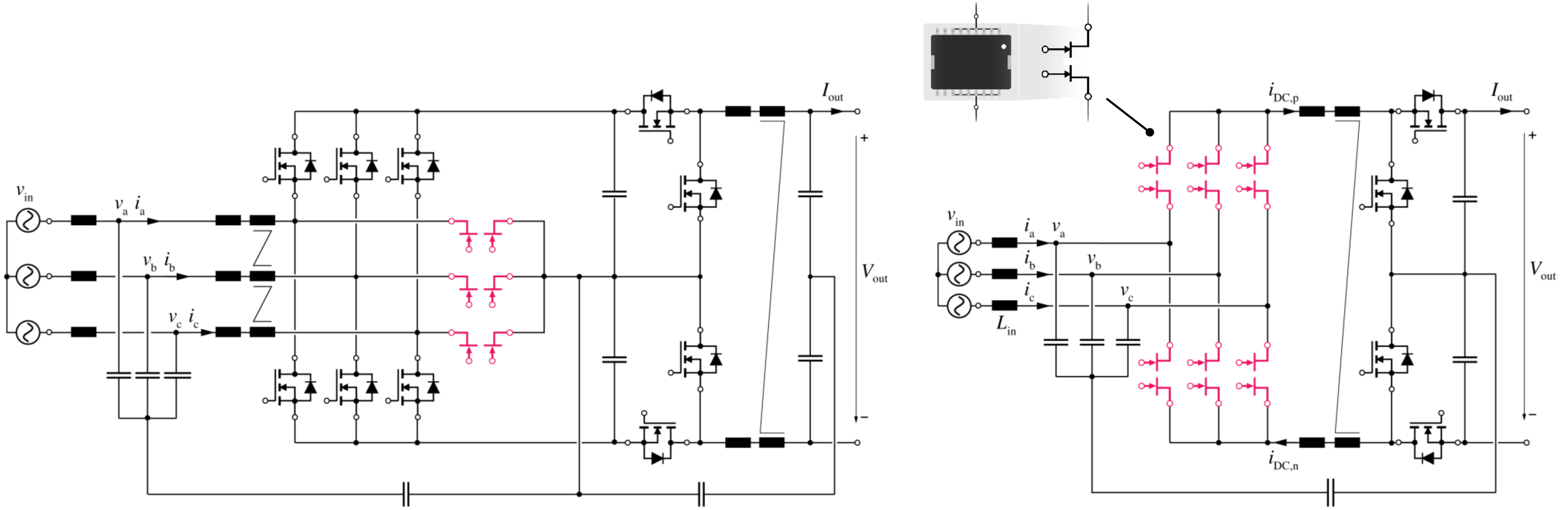




- *"Virtual Ground" Control of Output Voltage Midpoint → Non-Isolated EV Charger (!)*

Remark Application of M-BDS

- *Boost—Buck OR Buck—Boost Combination*
- *Closed Loop vs. Open Loop Mains Current Control & Active Input Filter Damping*
- *"Synergetic Control" of AC/DC and DC/DC Converter Stage*

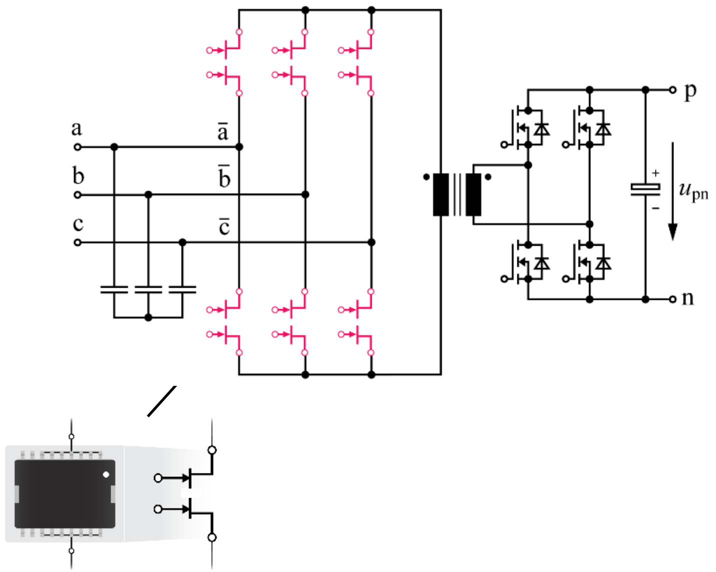


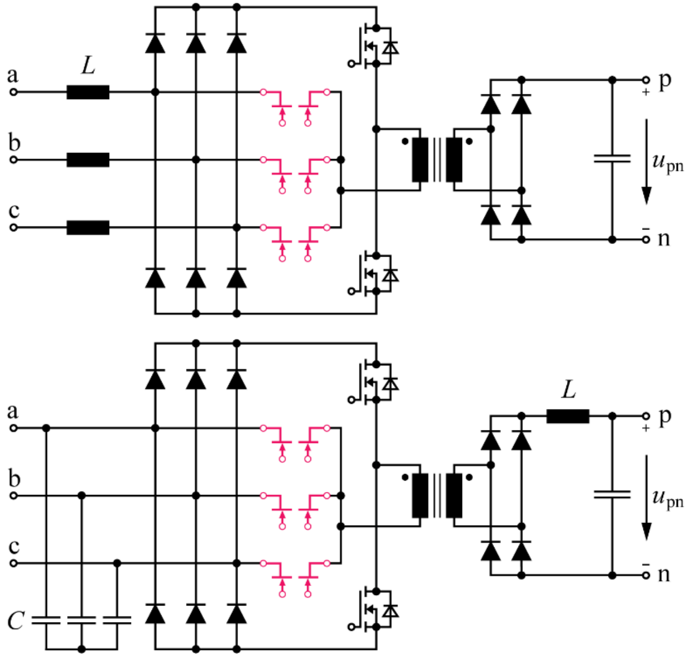
- 600 V *M-BDSs for Boost—Buck* & 1200 V *M-BDSs for Buck—Boost Combination* @ 400 V_{rms} *Mains*

Outlook

Isolated Single-Stage PFC Rectifier Systems

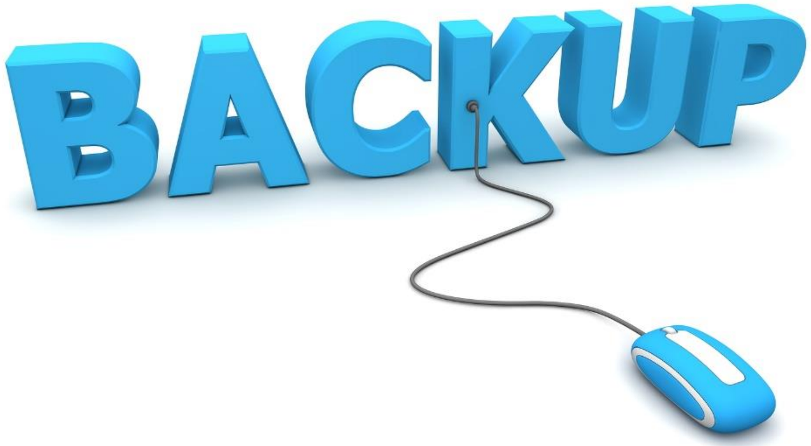
- Matrix-Type Bidirectional DAB-Based Topology
- *Vienna Rectifier II (Boost-Type / Unidirectional)*
- *Vienna Rectifier III (Buck-Type / Unidirectional)*





- *Functional Integration* → *Lower Complexity* BUT *Limited Controllability*

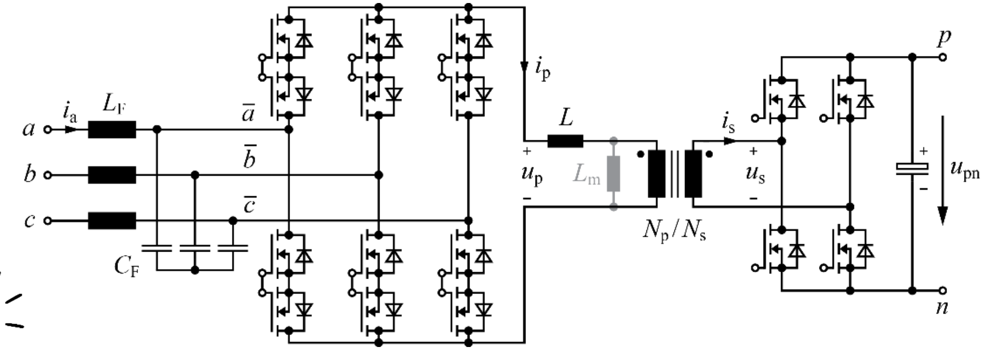
Thank you!

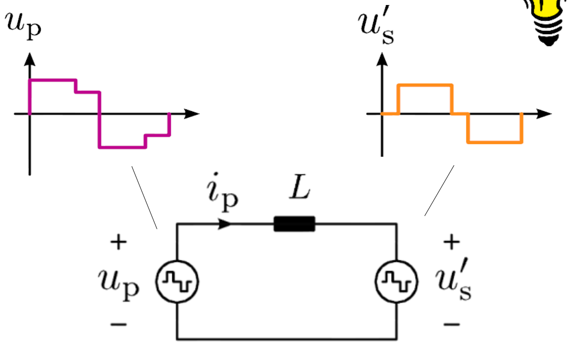

BACKUP

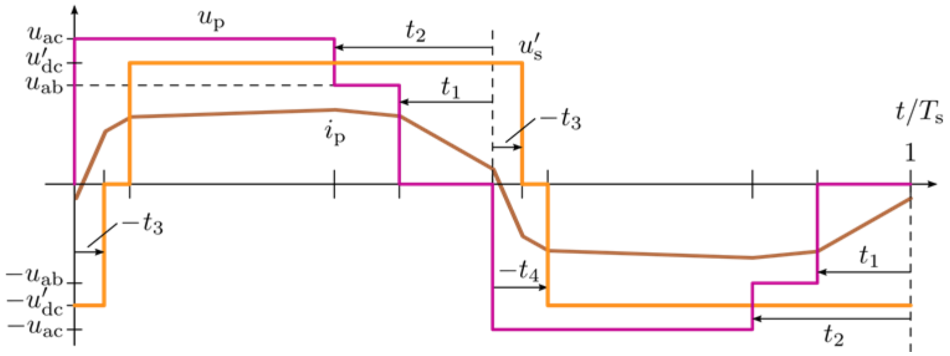
3-Φ Isolated Matrix-Type PFC Rectifier

Isolated Matrix-Type PFC Rectifier (1)

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





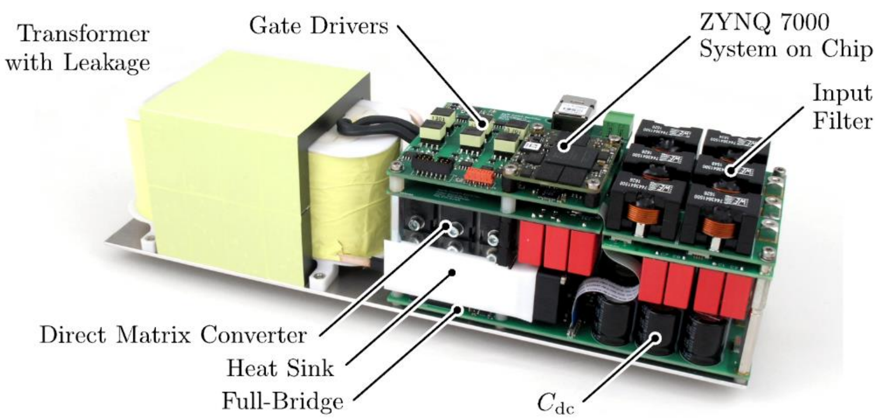


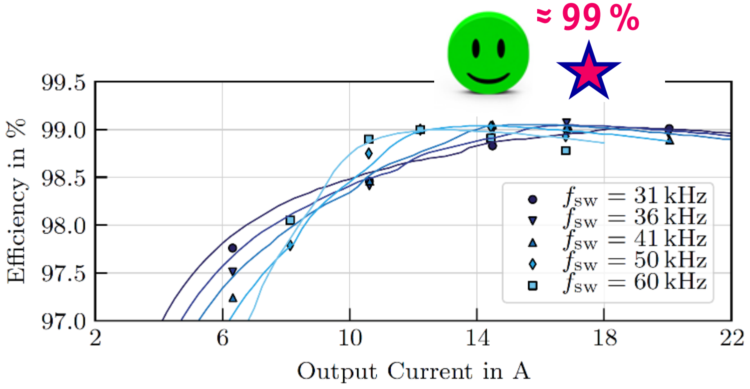
- *Equivalent Circuit*
- *Transformer Voltages / Currents*

Isolated Matrix-Type PFC Rectifier (2)

- Efficiency η = 98.9 % @ 60% Rated Load (ZVS)
- Mains Current $THD_I \approx$ 4 % @ Rated Load
- Power Density $\rho \approx$ 4 kW/dm³

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



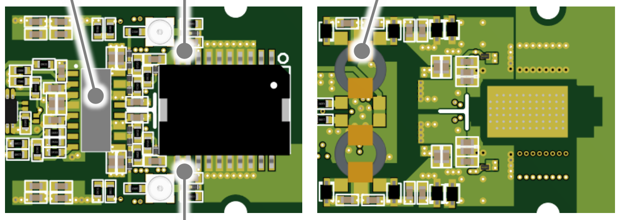


- ▶ 900 V / 10mΩ SiC Power MOSFETs
- ▶ Opt. Modulation Based on 3D Look-Up Table

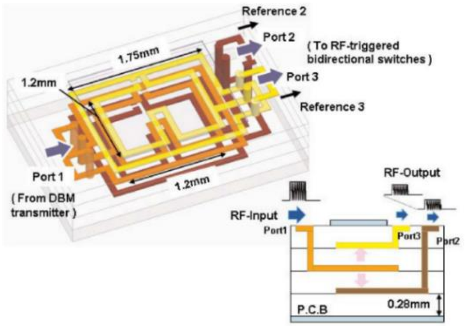
Monolithic 3D-Integration

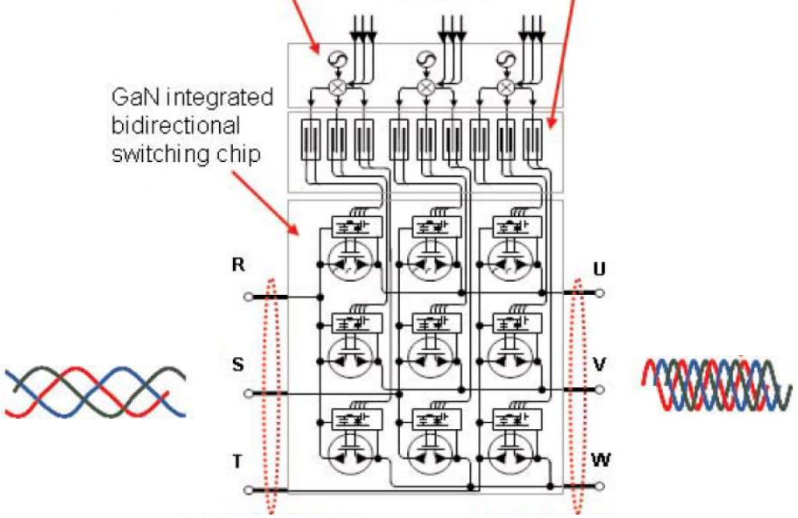
Source: Panasonic ISSCC 2014

- M-BDS GaN 3x3 Matrix Converter with Drive-By-Microwave (DBM) Technology
  - 9 Dual-Gate GaN AC-Switches / 4-Step Commutation
  - DBM Gate Drive Transmitter Chip & Isolating Couplers
  - Ultra Compact → 25 x 18 mm^2 (600 V, 10 A – 5 kW Motor)



5.0GHz Isolated (5 kV$_{DC}$) Dividing Coupler





- Massive Space Saving Compared to Discrete Realization (!)

End