ETH zürich

ECCE 2021 Vancouver, Canada Oct. 10-14

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

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Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Special Session

Wide-Bandgap Bidirectional Switches and the Applications They Enable

Oct. 10, 2021

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

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Outline

- *Introduction*

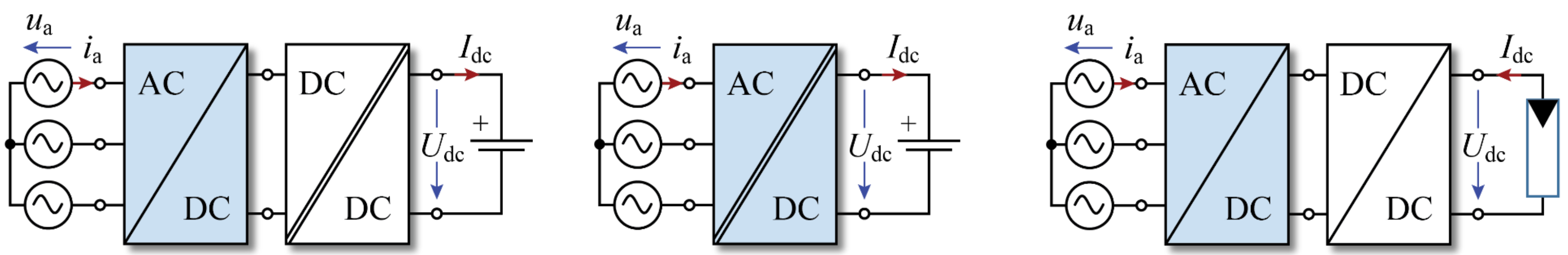
- *Integrated Active Filter PFC Concepts*
- *3-Level T-Type Boost Converters*
- *Current Source Buck-Boost Converters*
- *Isolated Matrix-Type Converters*

- *Conclusions*

3-Φ AC/DC Converter Application Areas

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

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



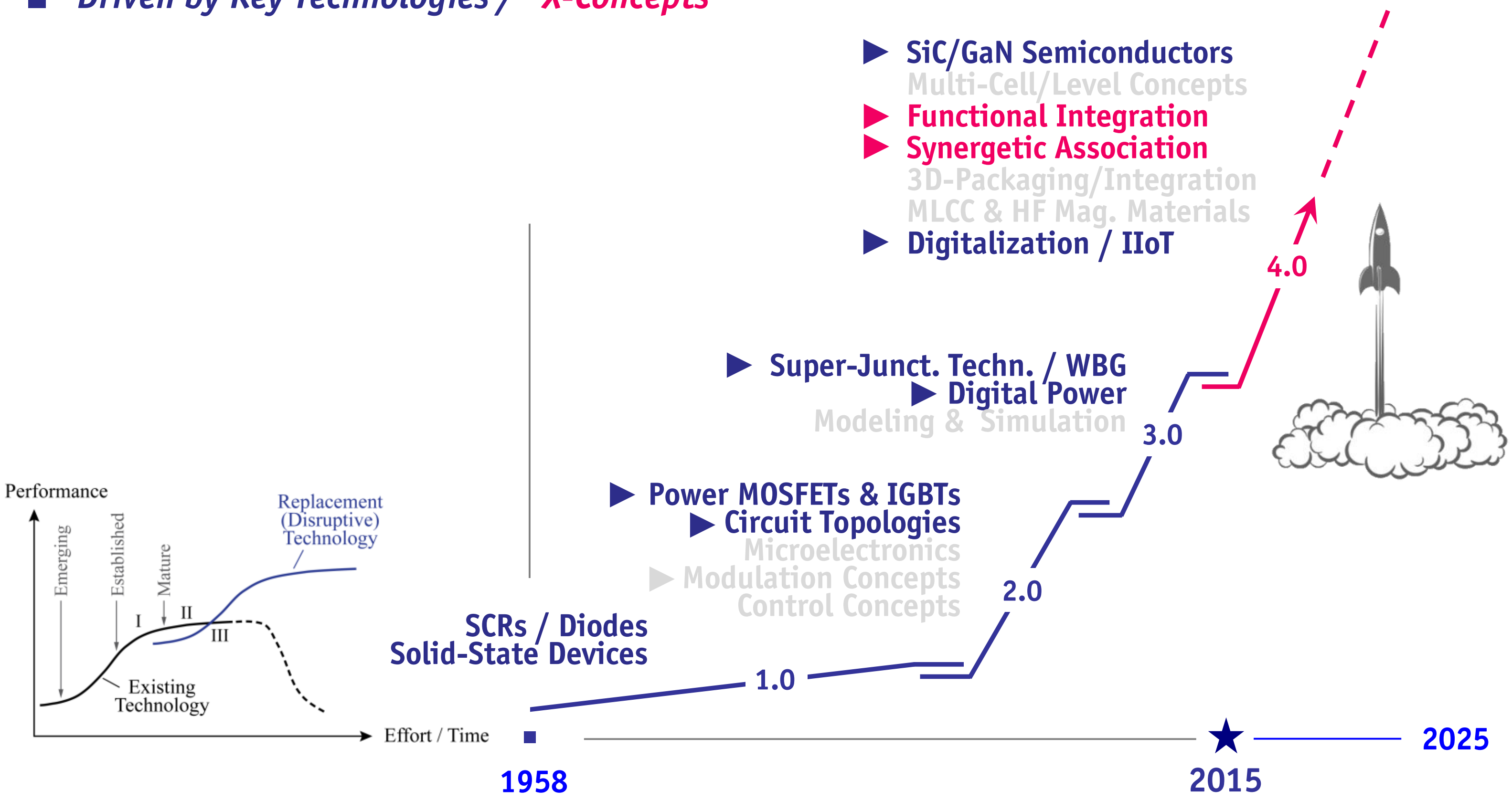
320...530V_{rms} Line-to-Line

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*

S-Curve of Power Electronics

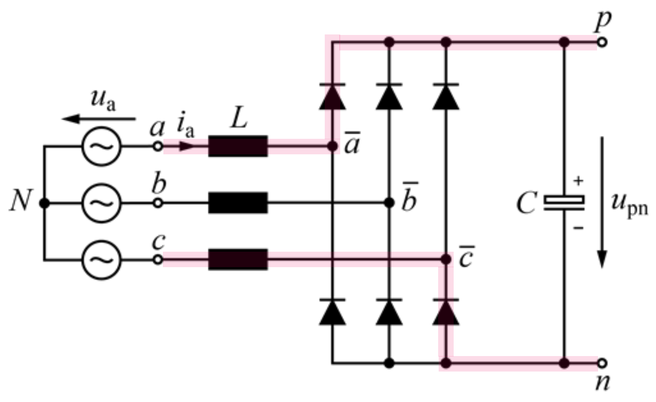
- *Power Electronics 1.0 → Power Electronics 4.0*
- *Driven by Key Technologies / "X-Concepts"*

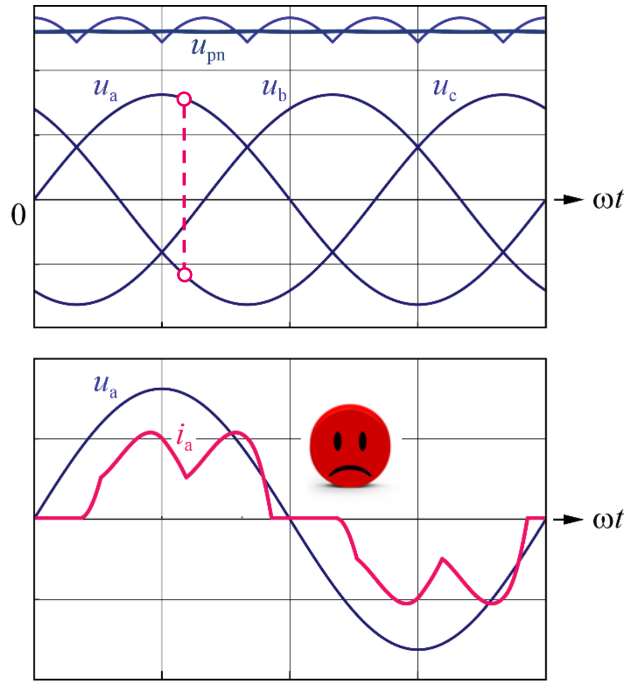


3rd Harmonic Injection PFC Rectifier

3-Φ Diode Bridge Rectifier

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

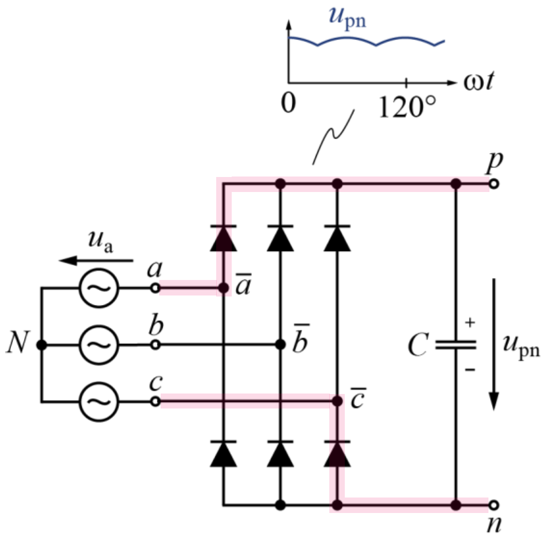




→ *Active Mains Current Shaping / Simultaneous Current Flow in All Phases*

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*



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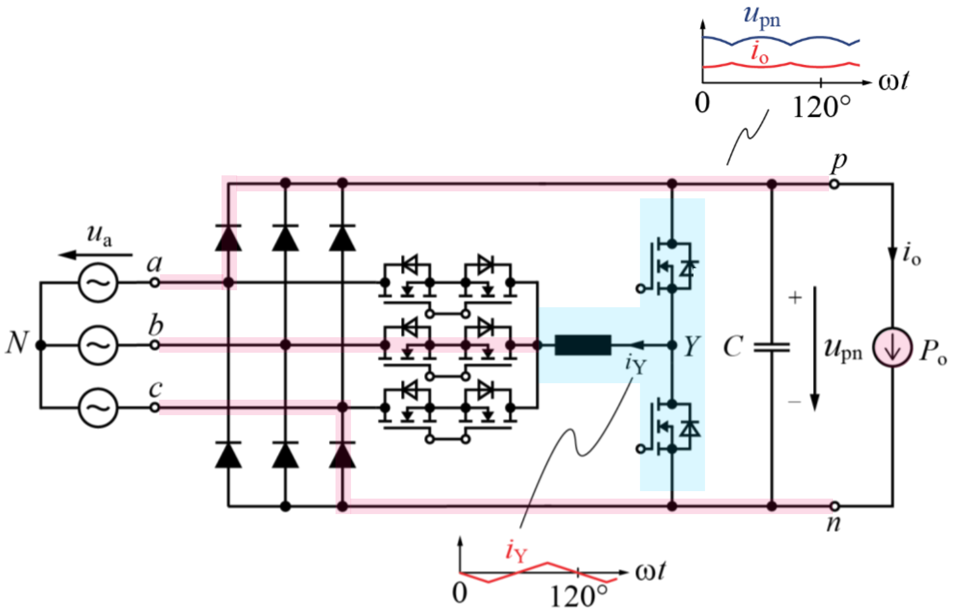


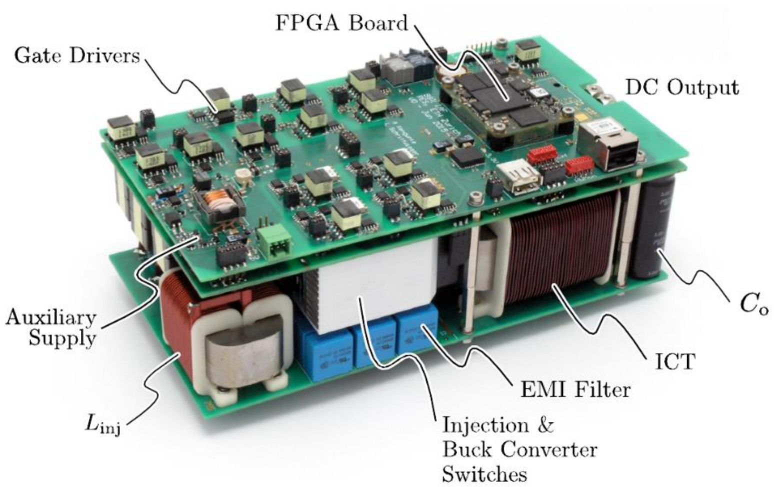
- *Non-Sinusoidal Mains Current*

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

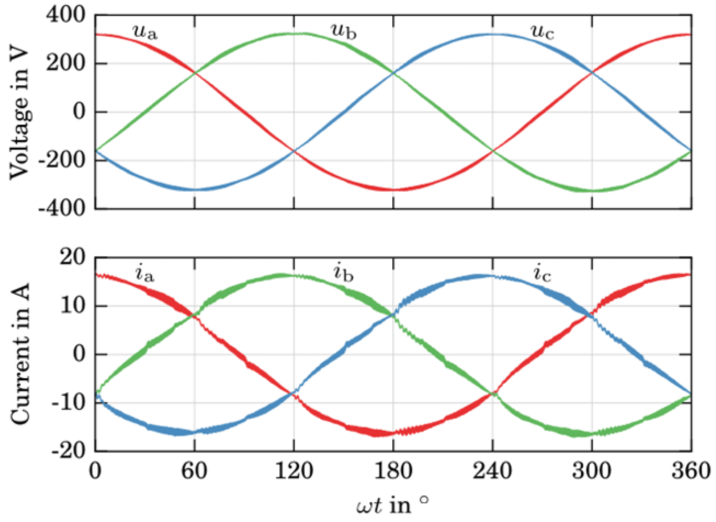
IAF Rectifier Demonstrator

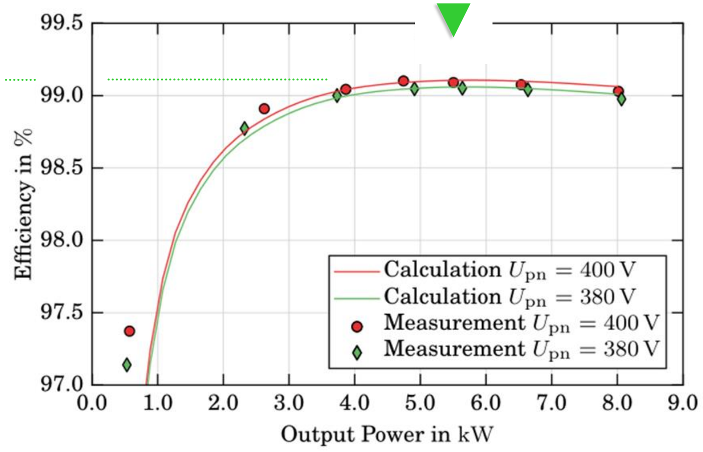
- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current $THD_I \approx$ 2% @ Rated Load*
- *Power Density $\rho \approx$ 4kW/dm³*

P_0 = 8 kW
U_N = 400V_{AC} → U_0 = 400V_{DC}
f_S = 27kHz



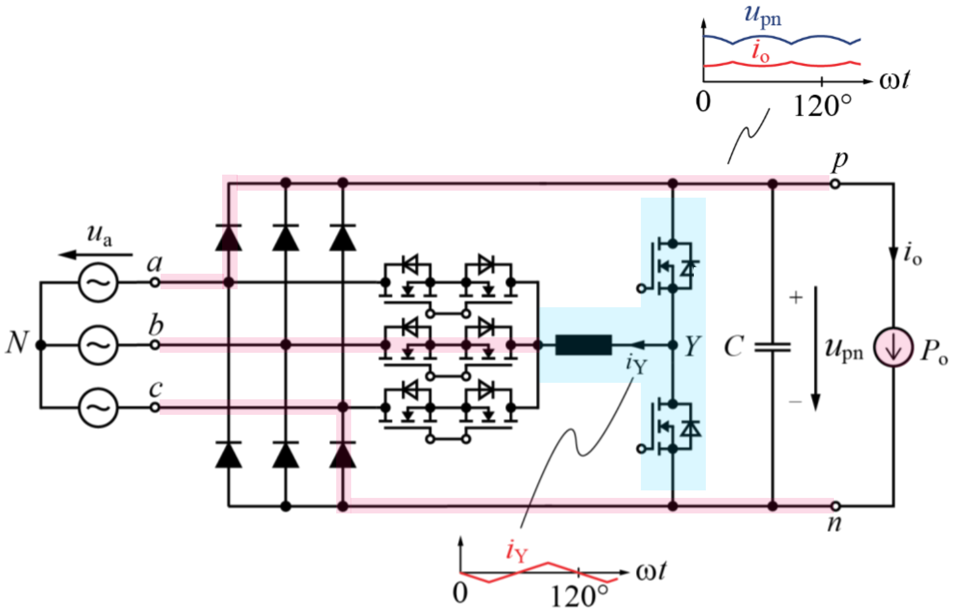
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck Output Stages*

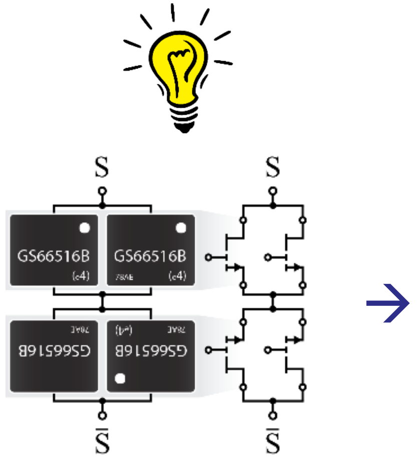




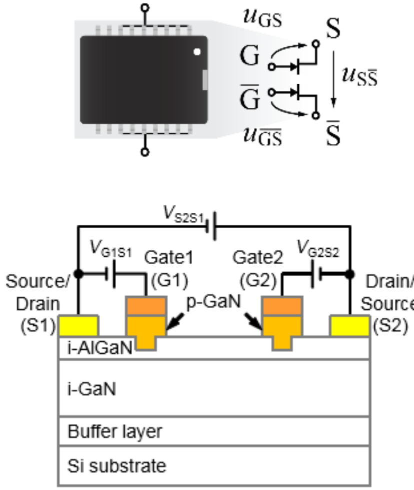
Remark Application of GaN M-BDS (1)

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





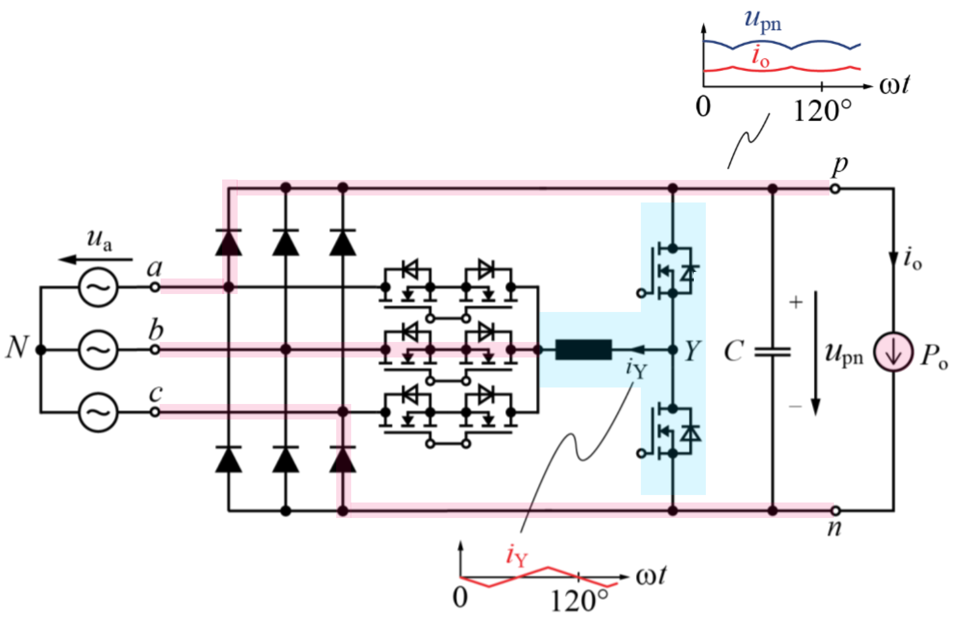
Source: Panasonic ideas for life

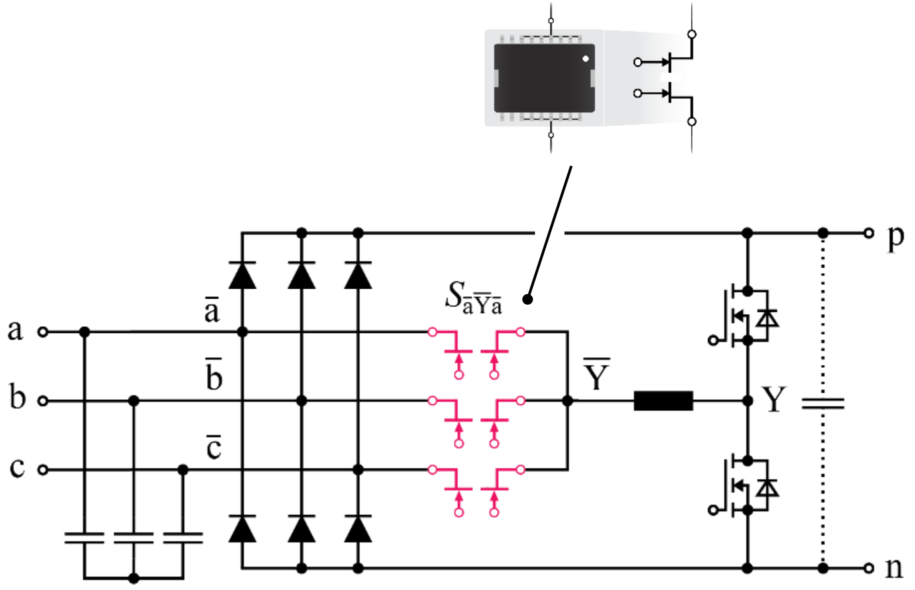


- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Remark — Application of GaN M-BDS (2)

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



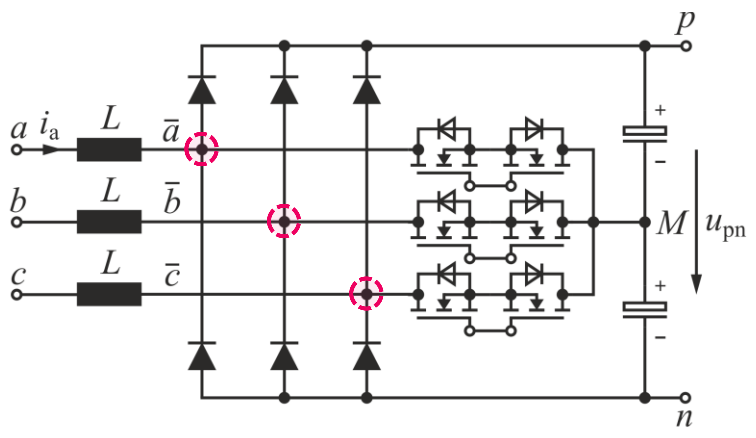


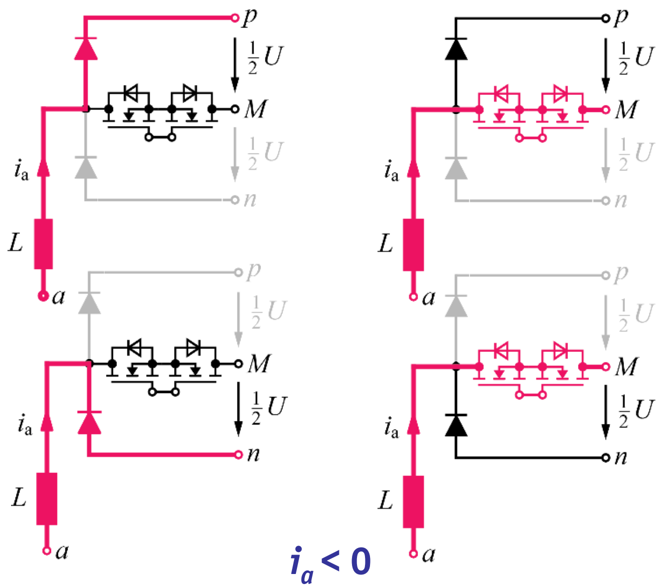
- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

3-Level T-Type
PFC Rectifier

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*





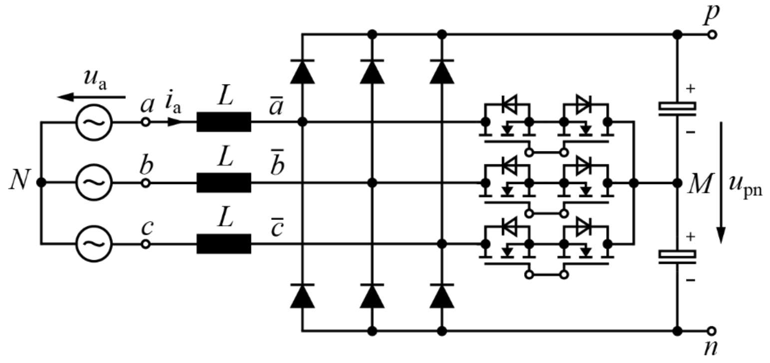
- *Voltage Stress of T-Type Switches Defined by Half (!) the DC-Link Voltage*

Vienna Rectifier Demonstrator

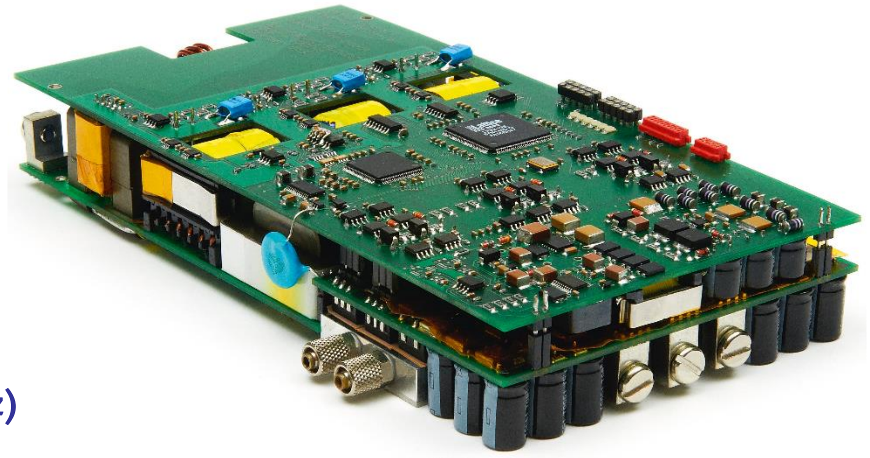
- *Design for More Electric Aircraft Application*
- *650V CoolMOS & 1200V SiC Diodes*
- *Coldplate Cooling*

P_O= 10 kW
U_N= 400V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_O= 800V_{DC}

η =96.8%



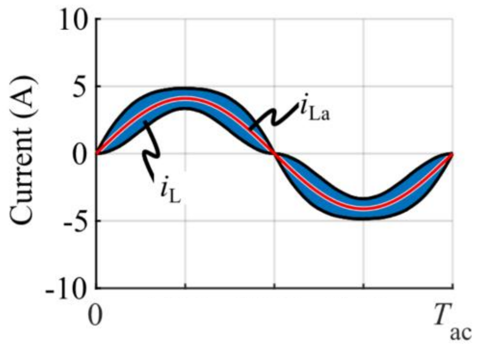
★ ρ =10 kW/dm³

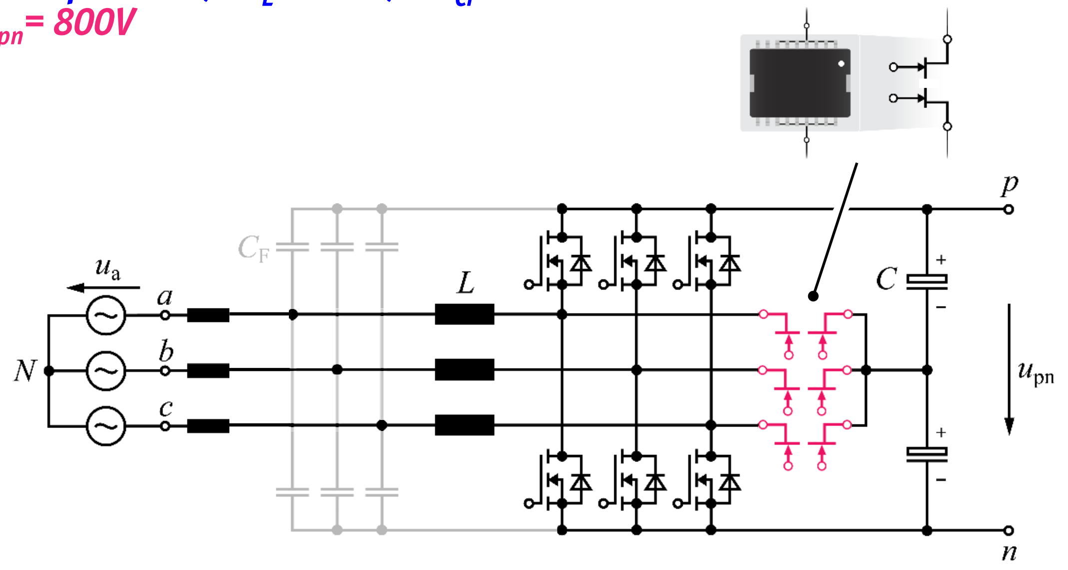


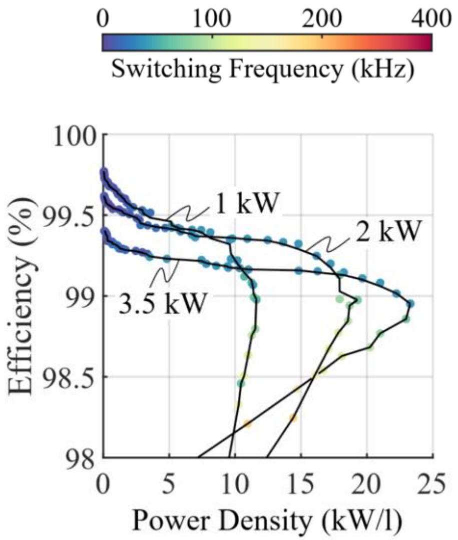
- THD_i = 1.6% @ f_N = 800Hz (f_P= 250kHz)

Remark — Application of GaN M-BDS

- *600V GaN M-BDSs, $R_{(on)}$=140mΩ*
- *1200V SiC MOSFETs, $R_{(on)}$=140mΩ*
- *Heatsink Design for T_j=120°C, CSPI= 15W/dm³K*
- *CCM Operation, Δi_L=±30%, Δu_{CF}=±1%*
- *U_{pn}= 800V*





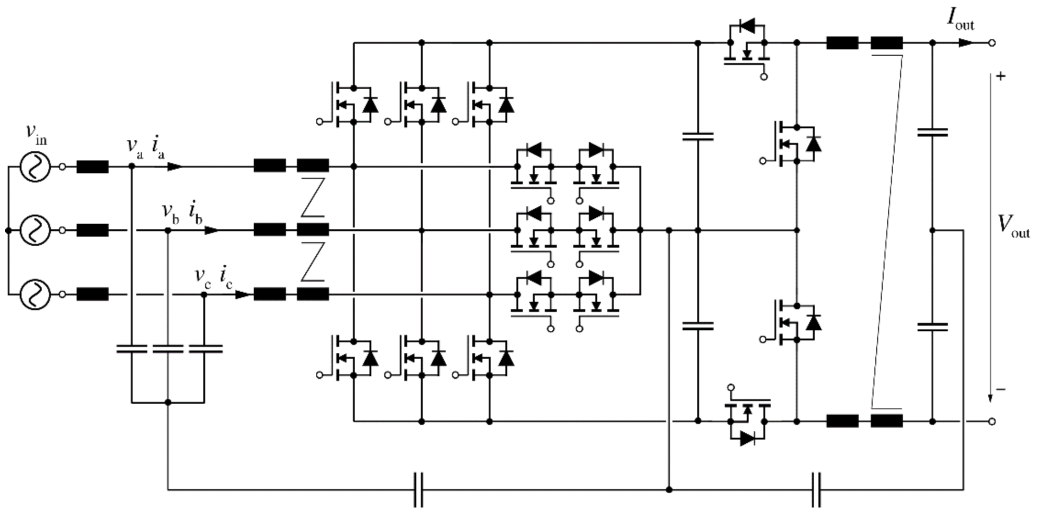


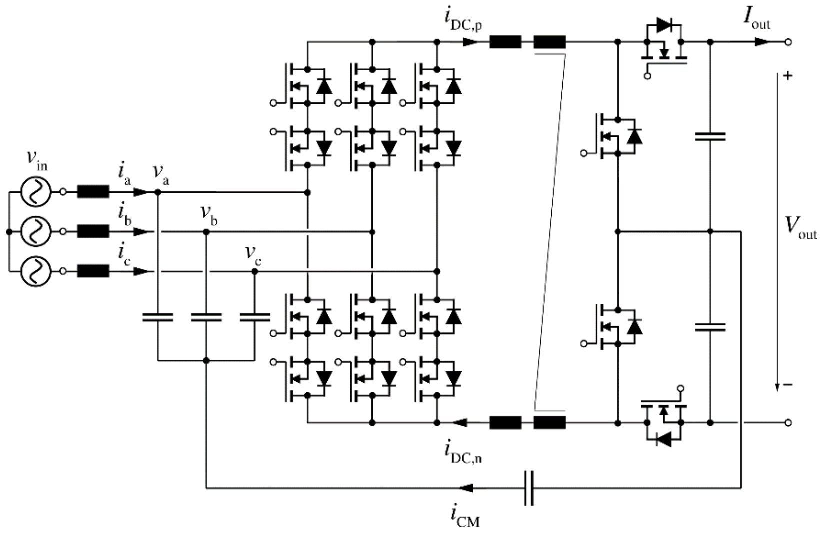
- *Bidirectional Power Flow*
- *Max. Power Density of 20kW/dm³ (w/o Full EMI-Filter) @ 99% Efficiency*

Buck-Boost
Current DC-Link
PFC Rectifier

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*

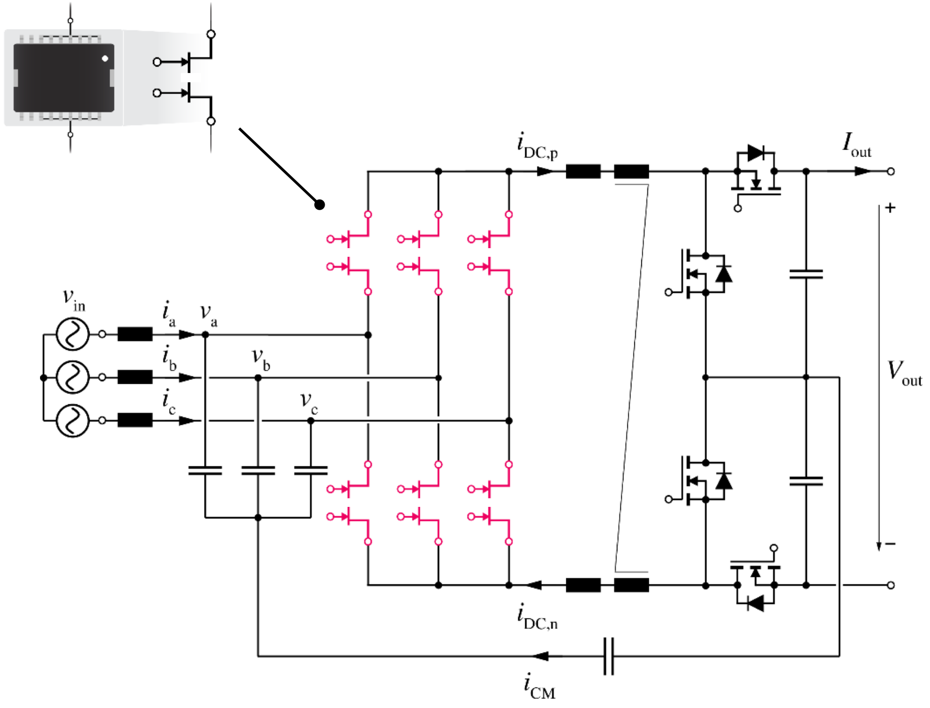


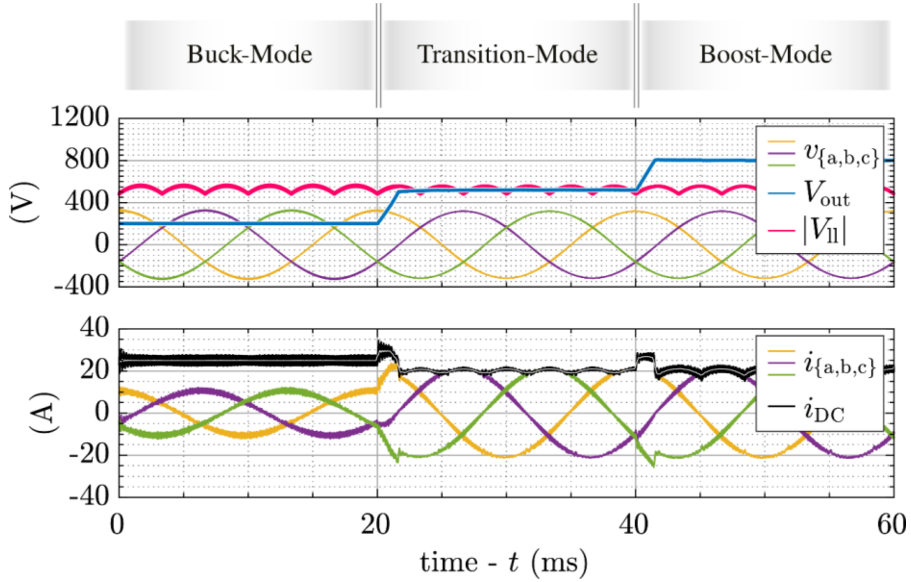


- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

Remark Application of GaN M-BDS

- "Synergetic" Control of CSR-Stage & Boost-Stage
- 6-Pulse-Shaping of i_{DC} by Boost-Stage → Allows Clamping of a CSR-Phase (2/3 Modulation)



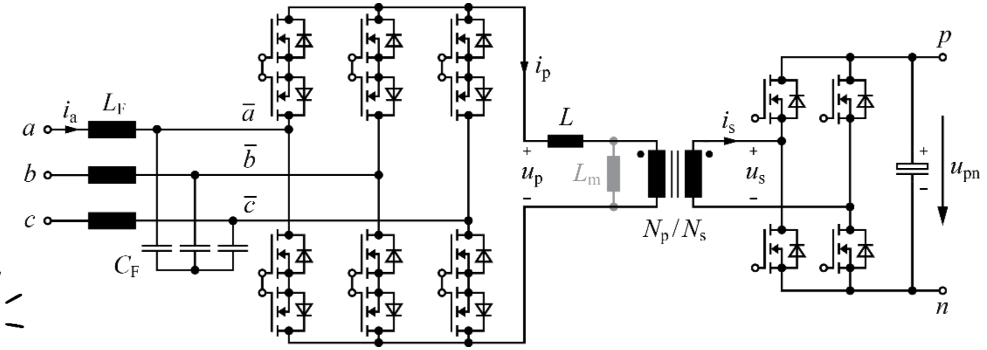


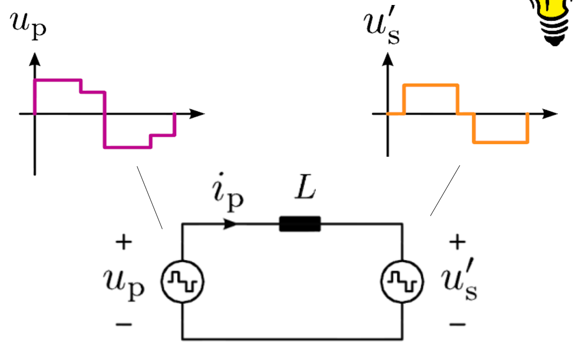
- Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses
- Seamless Transition from Buck @ i_{DC}=const. to Full Boost Operation @ 6-Pulse i_{DC}

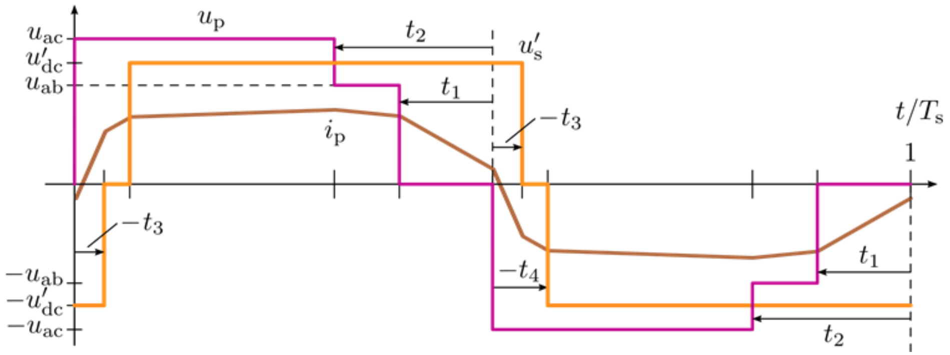
3-Φ Isolated Matrix-Type PFC Rectifier

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*





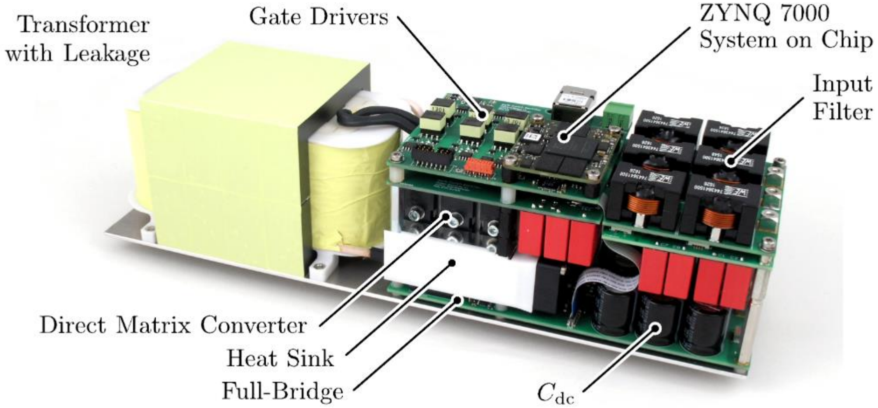


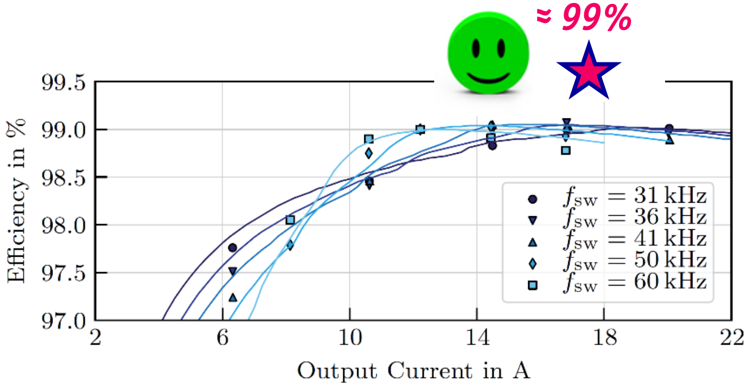
- *Equivalent Circuit*
- *Transformer Voltages / Currents*

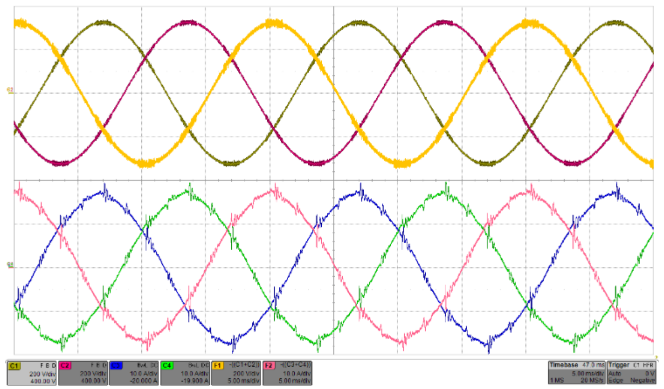
Isolated Matrix-Type PFC Rectifier (2)

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

P_O= 8 kW
U_N= 400V_{AC} → U_O= 400V_{DC}
f_S = 36kHz



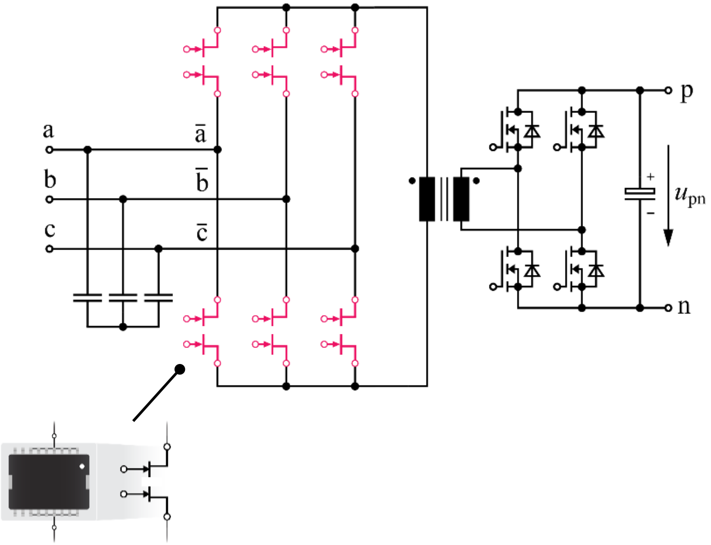


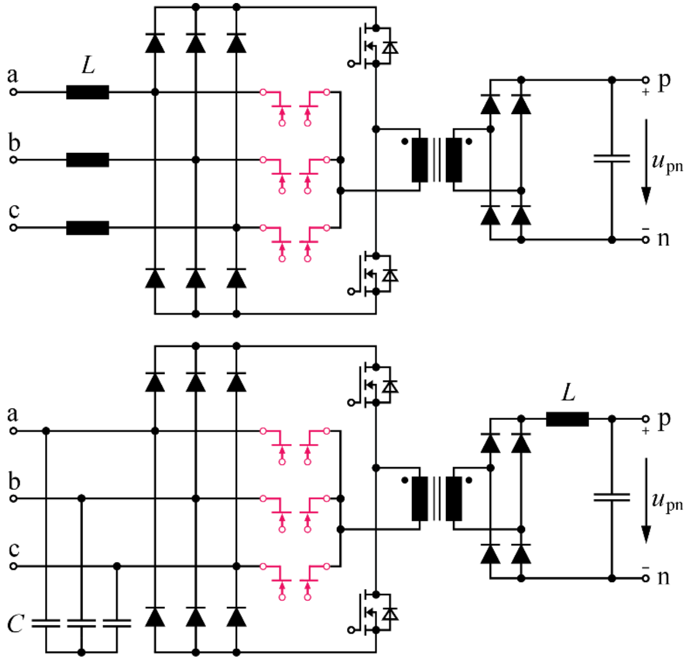


- ▶ 900V / 10mΩ SiC Power MOSFETs
- ▶ Opt. Modulation Based on 3D Look-Up Table

Remark Application of GaN M-BDS

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





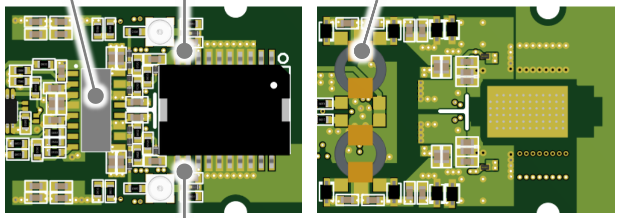
- *Functional Integration* → *Lower Complexity* **BUT** *Limited Controllability*

Outlook

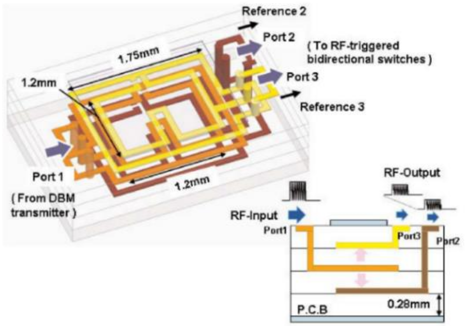
Monolithic 3D-Integration

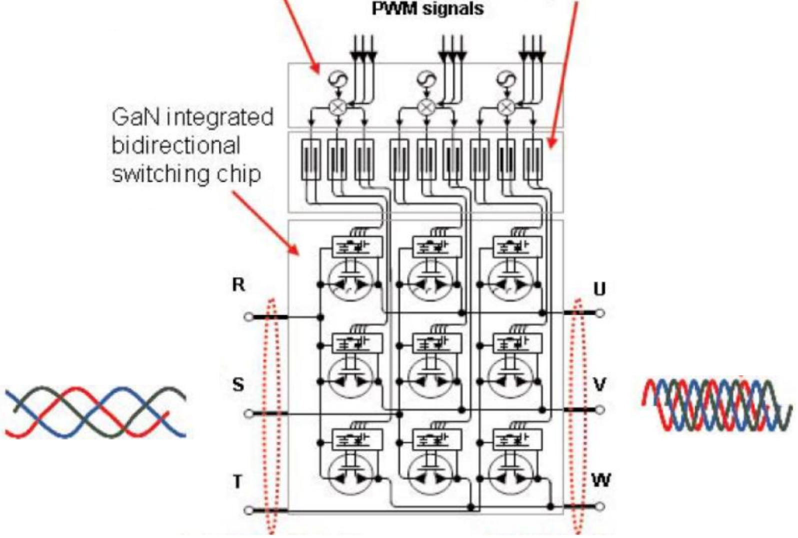
Source: Panasonic ISSCC 2014

- *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 mm² (600V, 10A – 5kW Motor)*



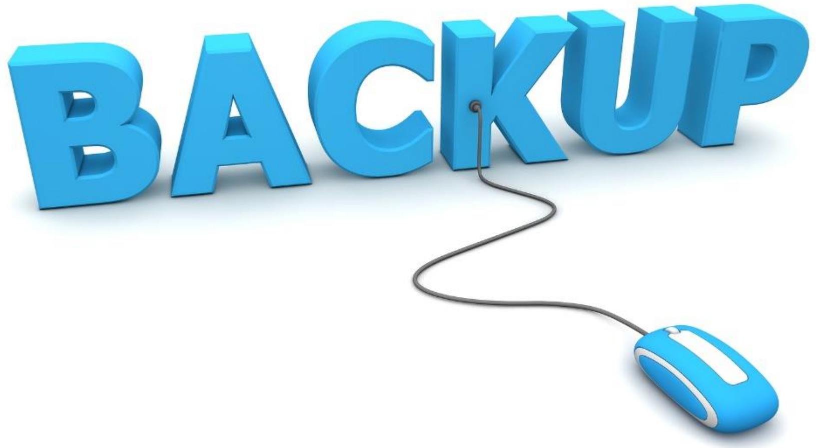
5.0GHz Isolated (5 kV_{DC}) Dividing Coupler





- *Massive Space Saving Compared to Discrete Realization (!)*

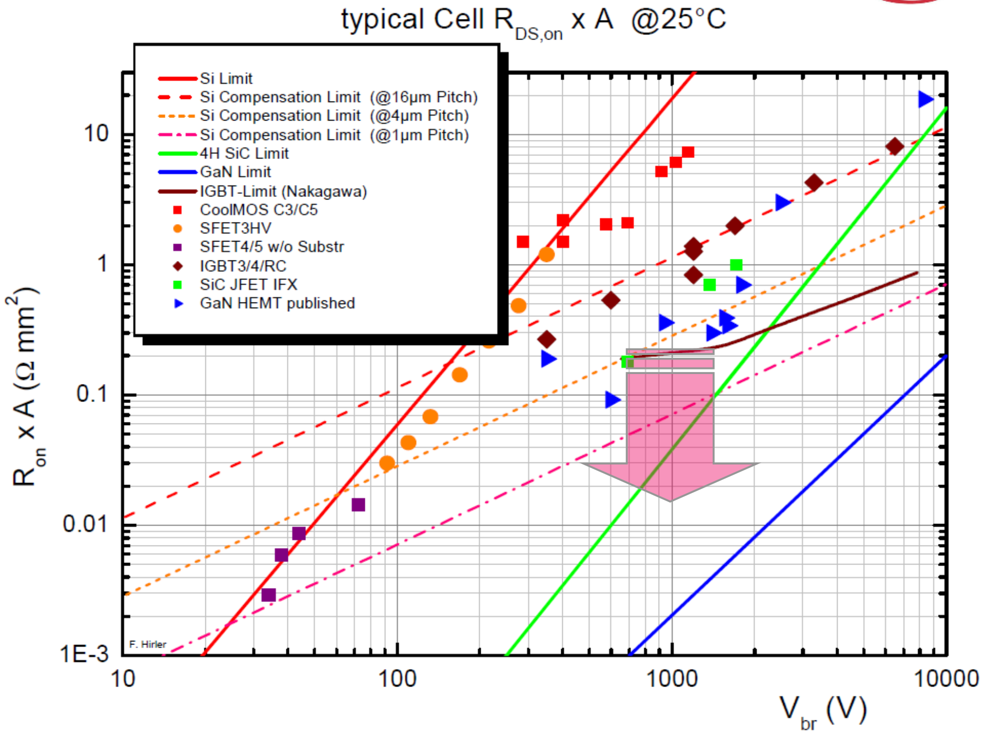
Thank you!


BACKUP

Technology Push — *WBG Power Semiconductors*

- *Higher Critical E-Field Compared to Si → Thinner Drift Layer*
- *Low $R_{DS(on)}$ High-Voltage Unipolar Devices / Small Chip Size*
- *Higher Max. Junction Temperature $T_{j,max}$*
- *Excellent Switching Performance*

Source: Infineon

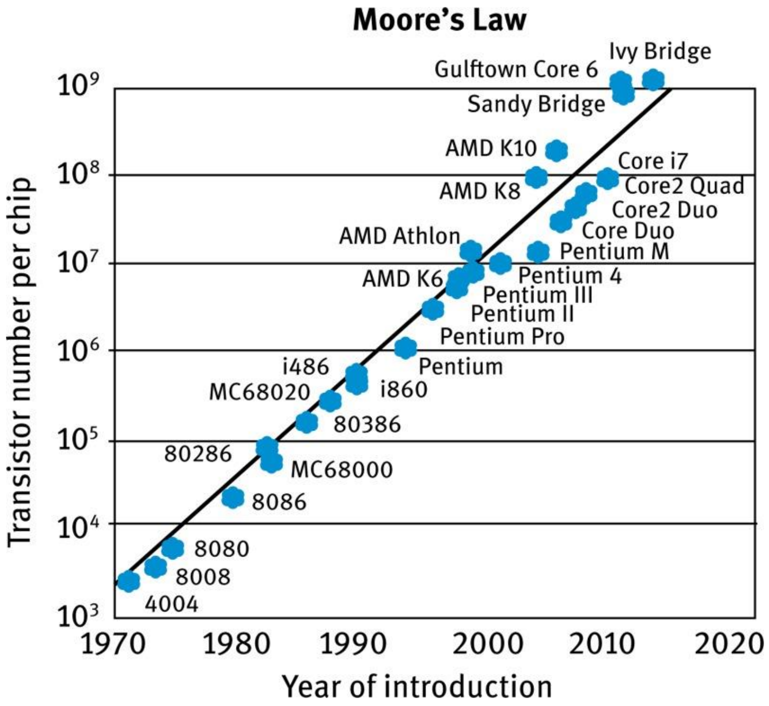


- *Advanced Packaging Mandatory (!)*

Technology Push — *Digitalization*

- *Exponentially Improving uC / Storage Technology (!)*

— *Extreme Levels of Density / Processing Speed*
— *Software Defined Functions / Flexibility*
— *Cont. Relative Cost Reduction*



Source: Ostendorf & König / DeGruyter

- *Fully Digital Control of Complex Multi-Switch Systems*
- *Massive Computational Power → Fully Automated Design & Manufacturing / Industrial IoT (IIoT)*

End