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Monolithic Bi-Directional Switches — Opening New Horizons in Power Electronics

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Monolithic Bi-Directional Switches — Opening New Horizons in Power Electronics

Johann W. Kolar | **Jonas E. Huber** | **Daifei Zhang**

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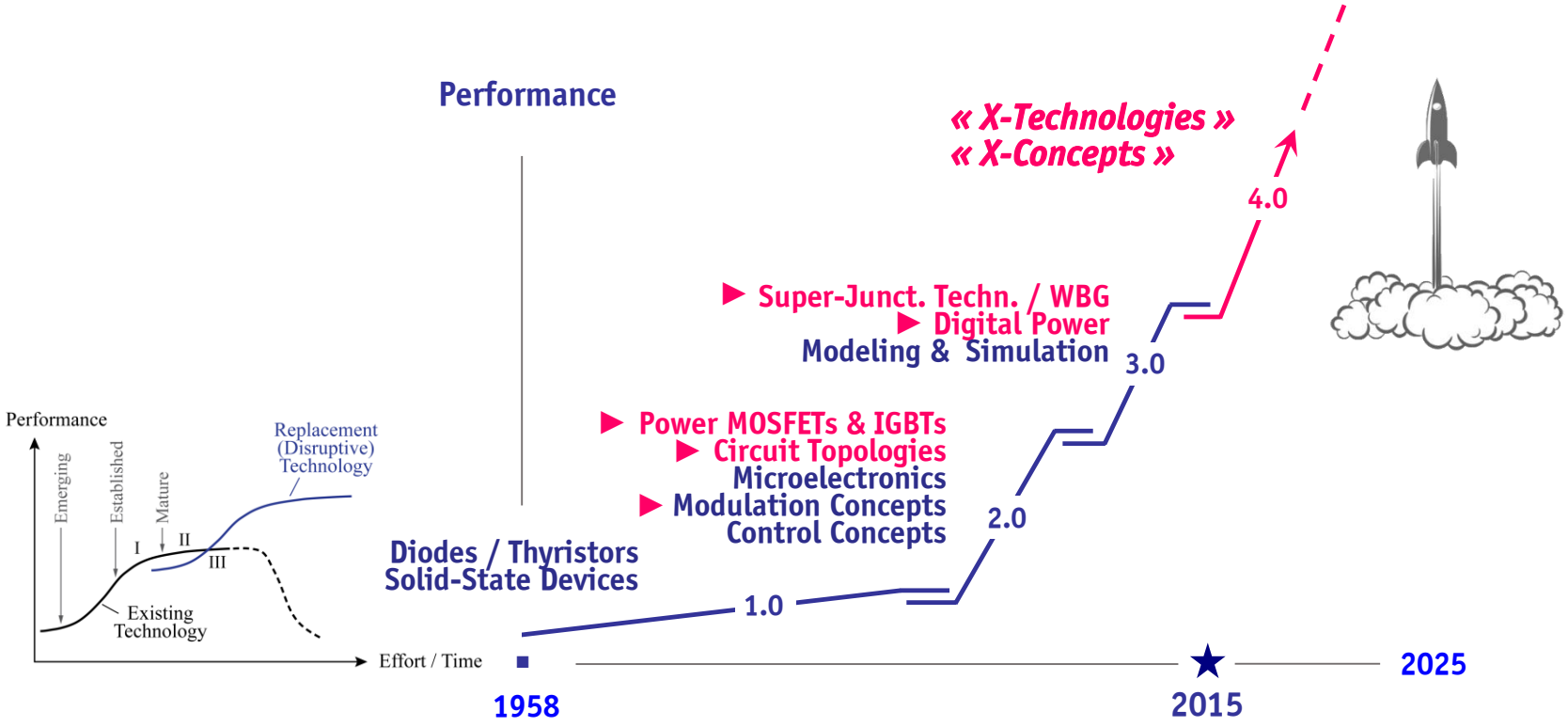
Outline

- *Introduction*
- *3-Φ AC/DC Grid Interfaces*
- *3-Φ AC/AC VSD Converter Systems*
- *GaN/SiC M-BDS R&D Activities*
- *Outlook*

M. Guacci
M. Haider
F. Krismer
J. Miniböck
N. Nain
L. Schrittwieser
F. Vollmaier
Acknowledgement G. Zulauf

S-Curve of Power Electronics

- *« X-Technologies » / "Moon-Shot" Technologies*
- *« X-Concepts » → Full Utilization of Basic Scaling Laws & X-Technologies*
- *Power Electronics 1.0 → Power Electronics 4.0*
- *2…5…10x Improvement NOT Only 10% !*



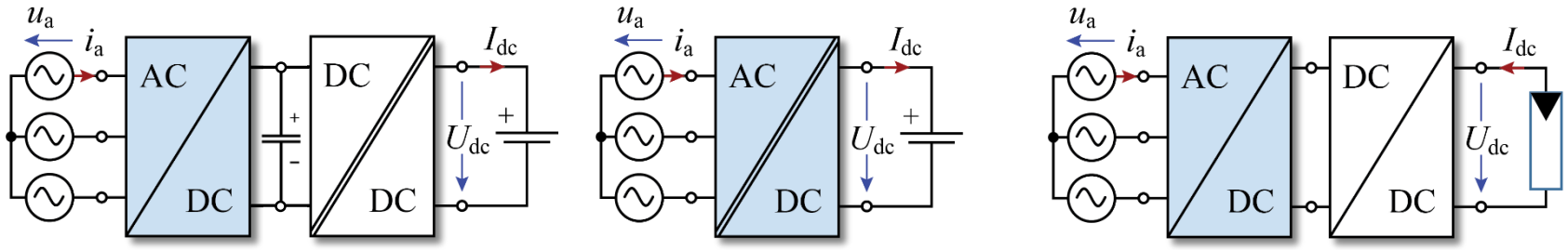
Global Megatrends

Digitalization →
Sustainable Mobility
Renewable Energy
Industry Automation
Etc.

3-Φ AC/DC Converter Application Areas

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

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



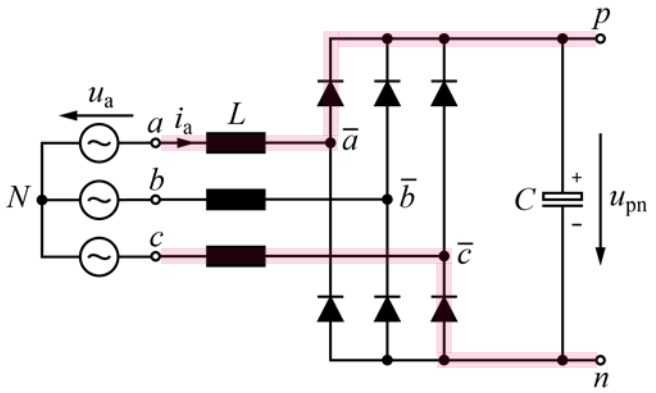
320...530V_{rms} Line-to-Line

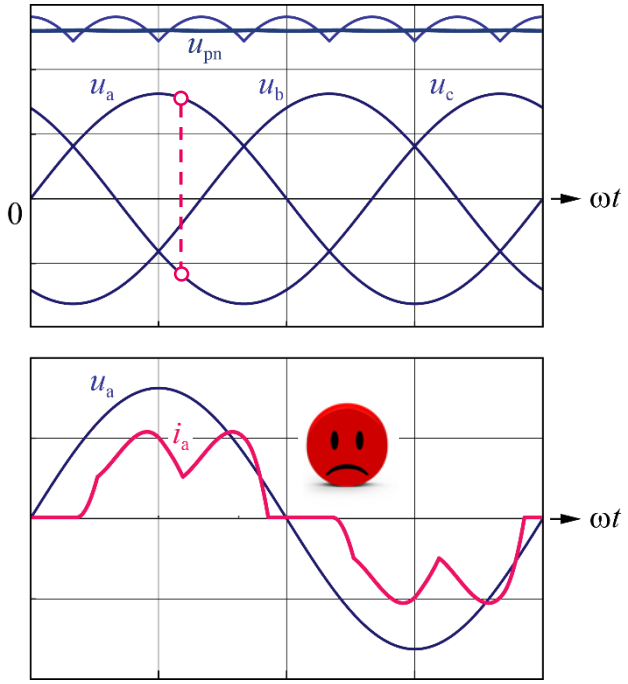
MPP Tracking in 60...90% of Max. Open Circuit Voltage

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

3-Φ Diode Bridge Rectifier

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



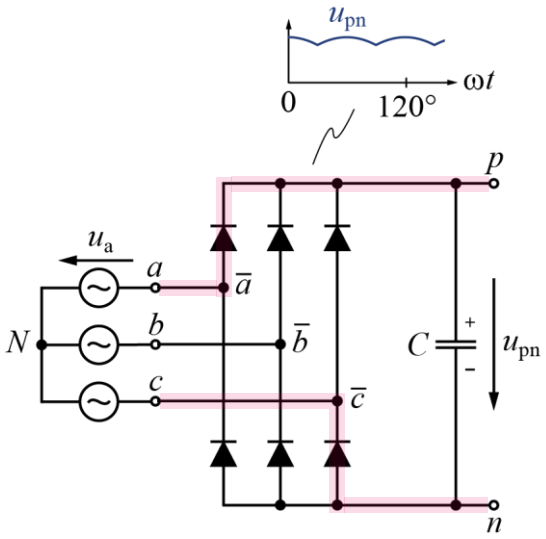


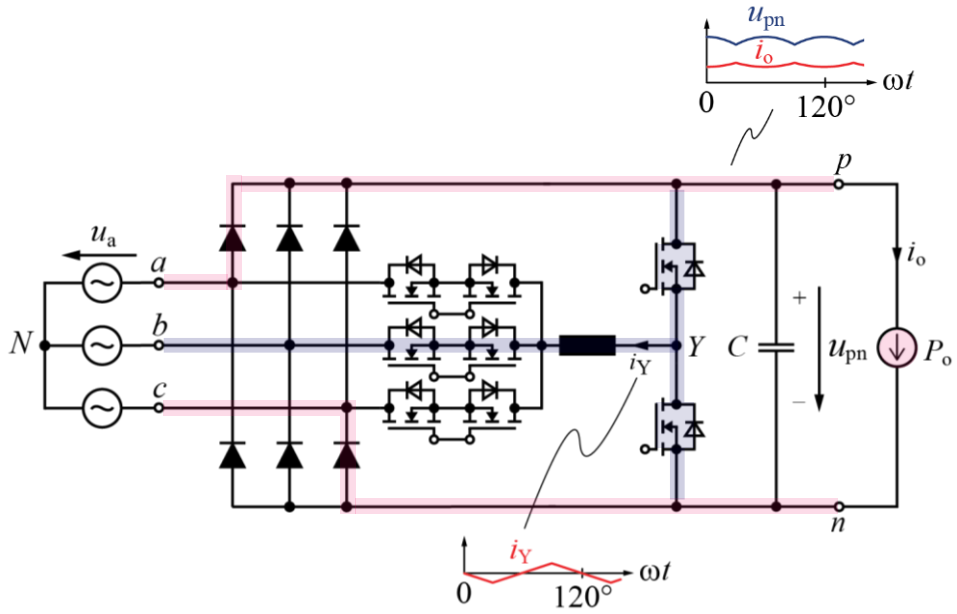
→ *Active Mains Current Shaping / Simultaneous Current Flow in All Phases*

3rd Harmonic Injection PFC Rectifier

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*



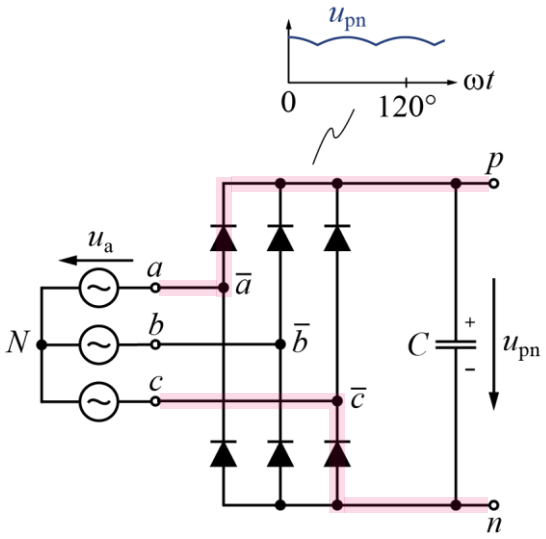


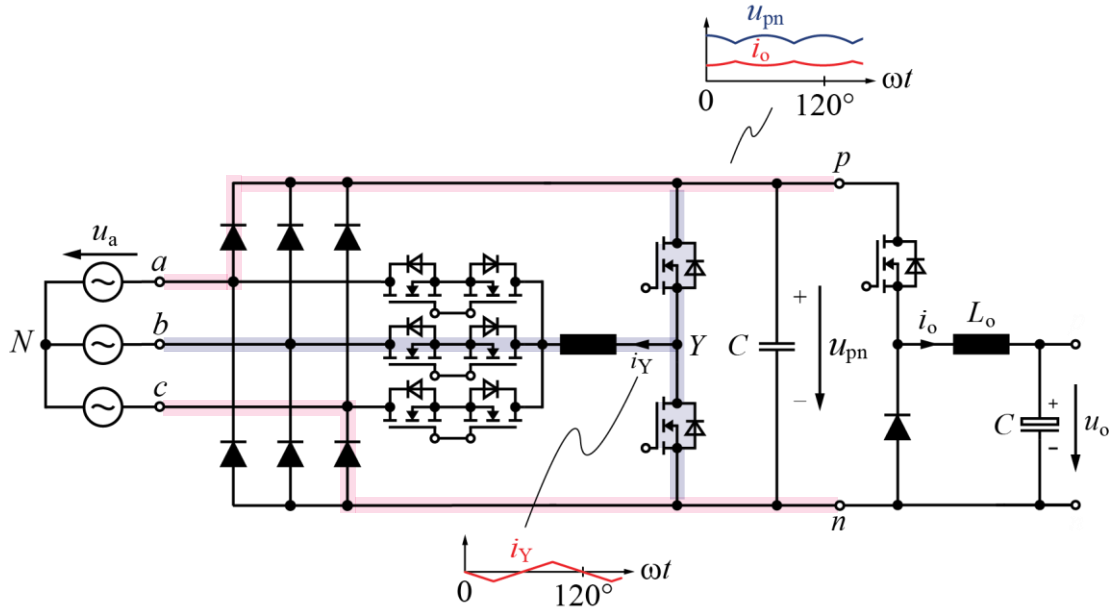
- *Non-Sinusoidal Mains Current*

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

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" Input Stage*





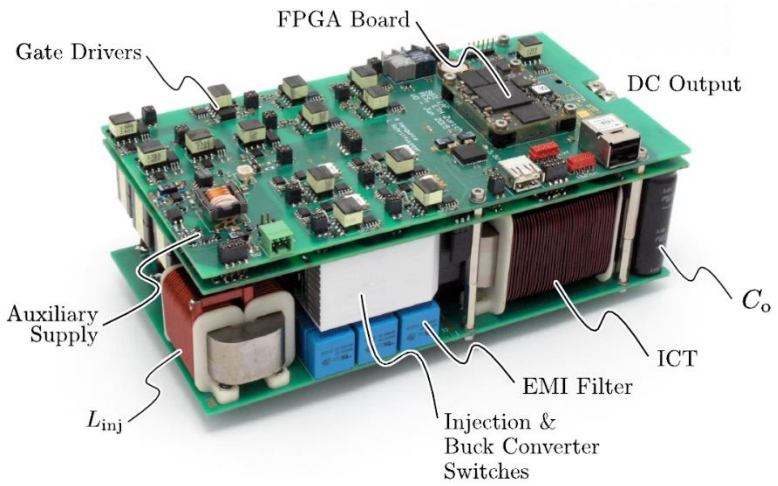
- *Non-Sinusoidal Mains Current*

→ *DC/DC Output Stage — P_0= const.*
→ *Sinusoidal Mains Current*
→ *Controlled Output Voltage*

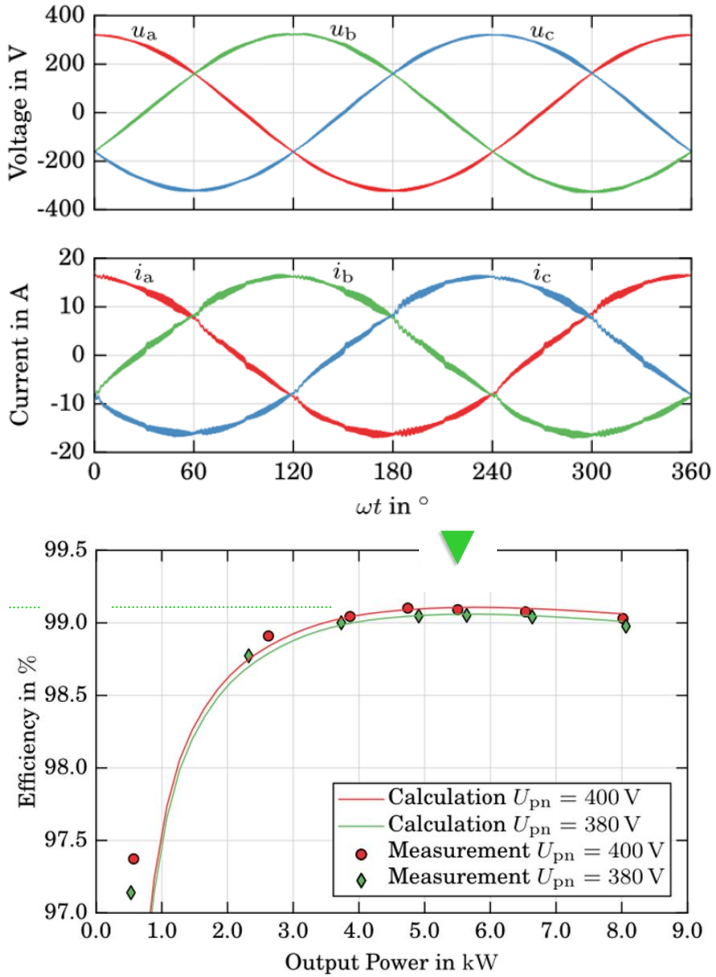
IAF Rectifier & Buck Output Stage

- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current THD_I ≈ 2% @ Rated Load*
- *Power Density ρ ≈ 4kW/dm³*

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



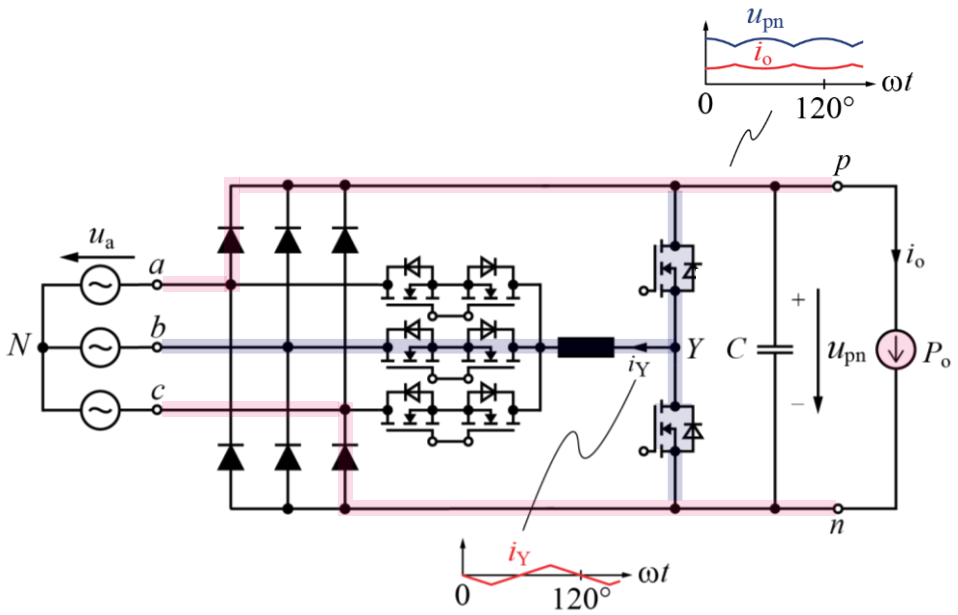
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck DC/DC Output Stages (!)*

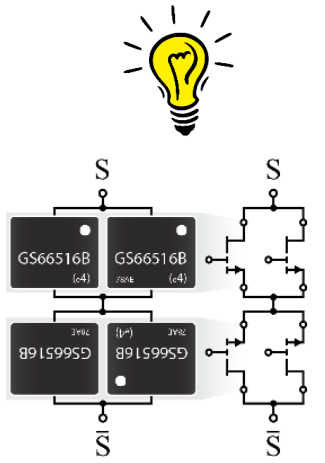


Remark Application of M-BDSs (1)

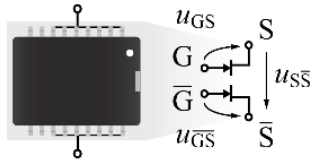
- M-BDS — *Monolithic Bidirectional / Bipolar Switch*
- *Realization of the Phase Selector Switches of 3rd Harmonic Inj. PFC Rectifiers*
- *Bipolar Voltage Blocking / Current Carrying Capability*

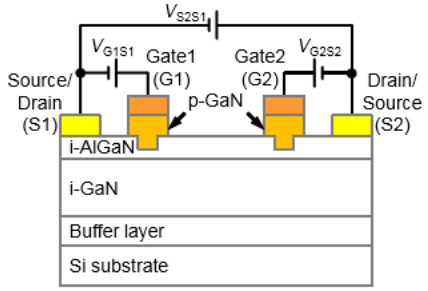
NEW ARRIVAL





Source: Panasonic ideas for life

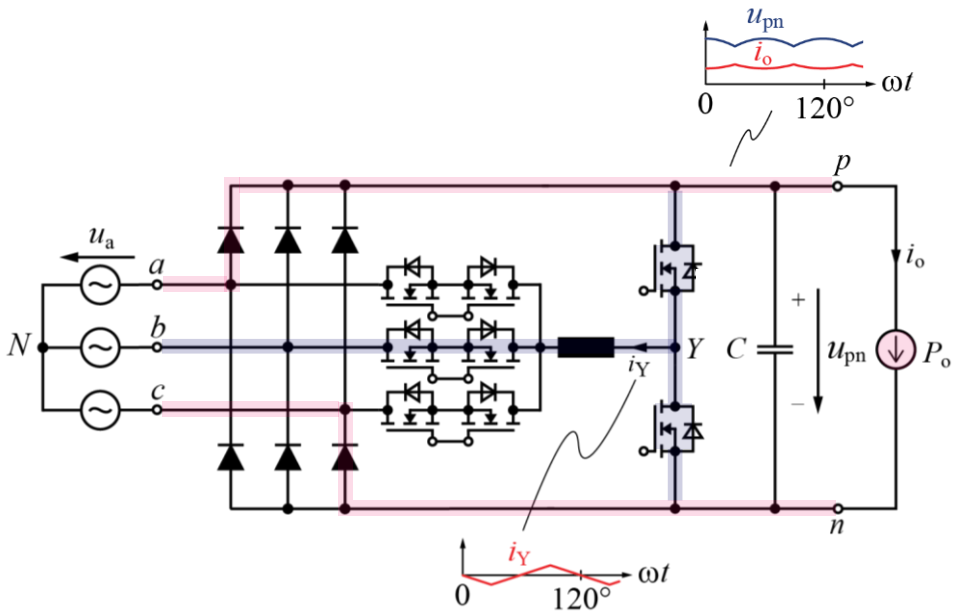


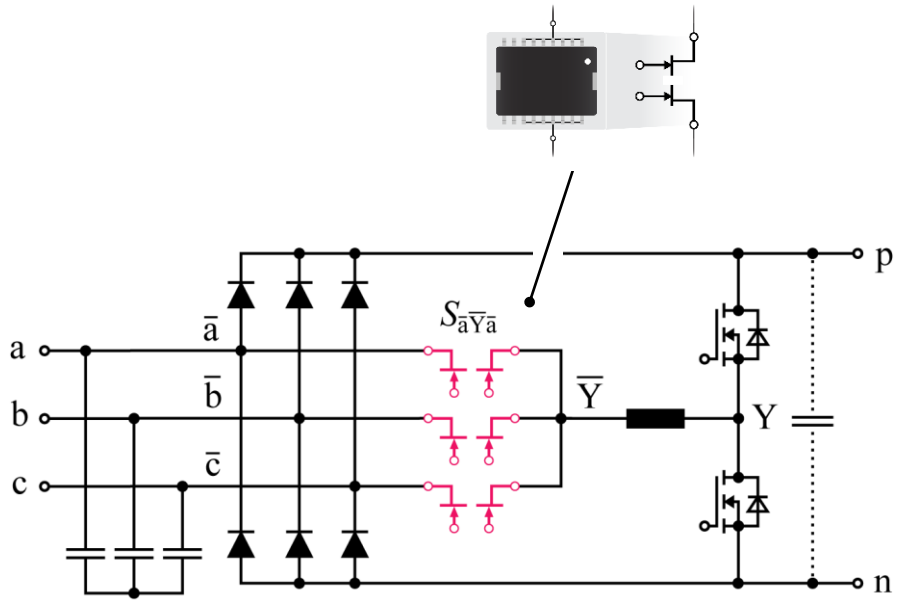


- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Remark Application of M-BDSs (2)

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

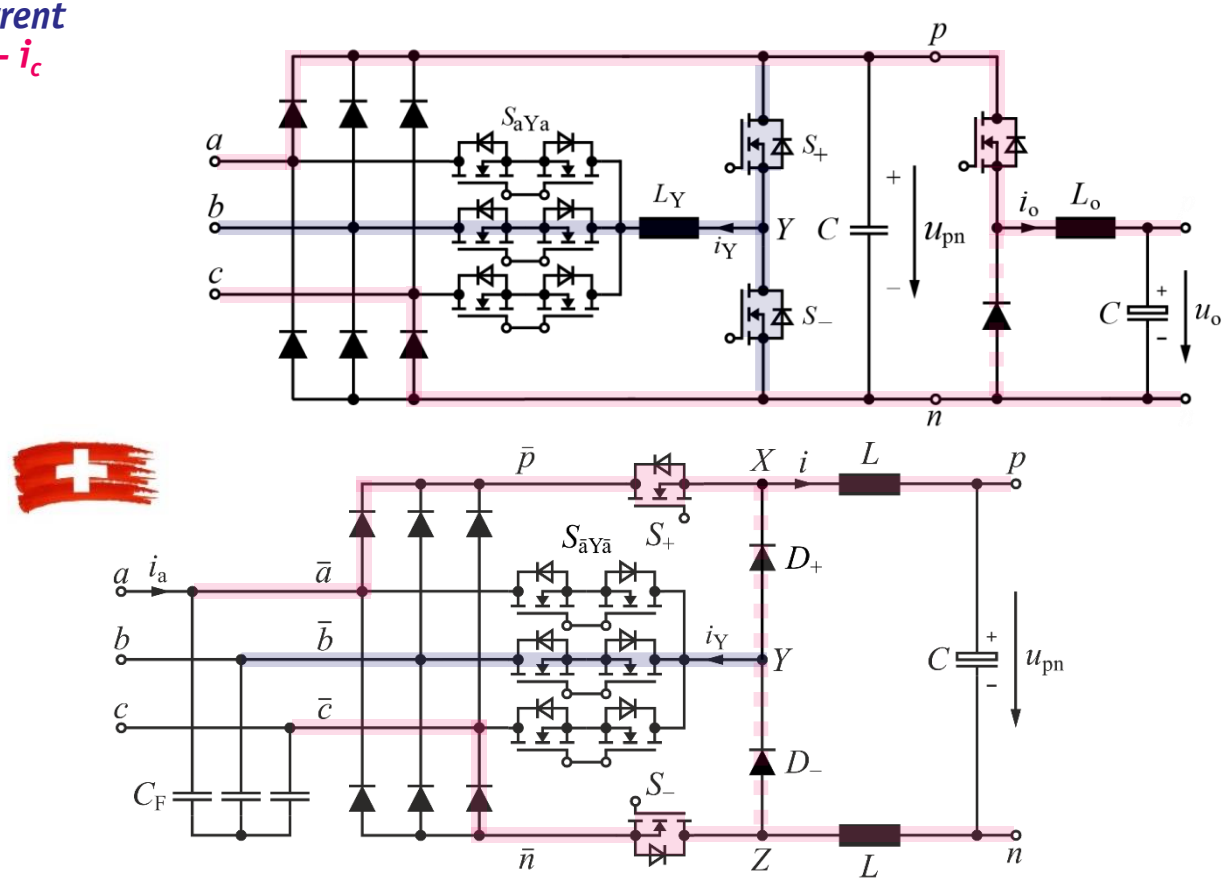




- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Swiss Rectifier

- *Integration of 3rd Harmonic Injector Switches & Buck Output Stage*
- *Controlled Output Voltage*
- *Sinusoidal Mains Current*
- *i_y Def. by KCL: E.g. i_a- i_c*

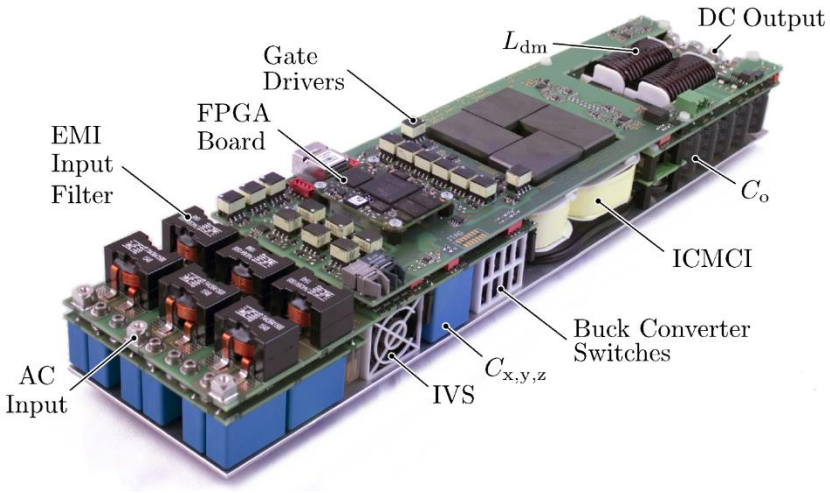


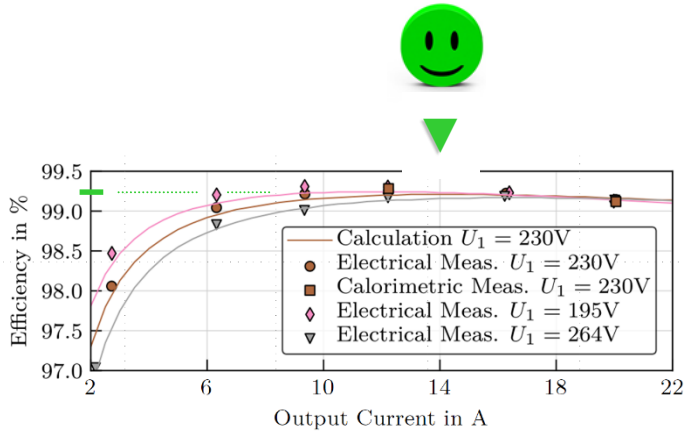
- *Low Complexity*

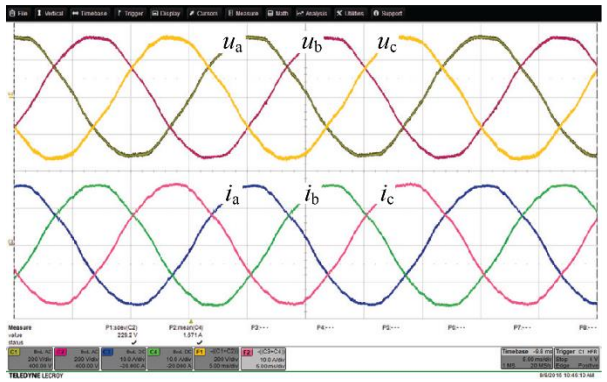
Swiss Rectifier Demonstrator

- *Efficiency η = 99.26% @ 60% Rated Load*
- *Mains Current THD_I ≈ 0.5% @ Rated Load*
- *Power Density ρ ≈ 4kW/dm³*

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



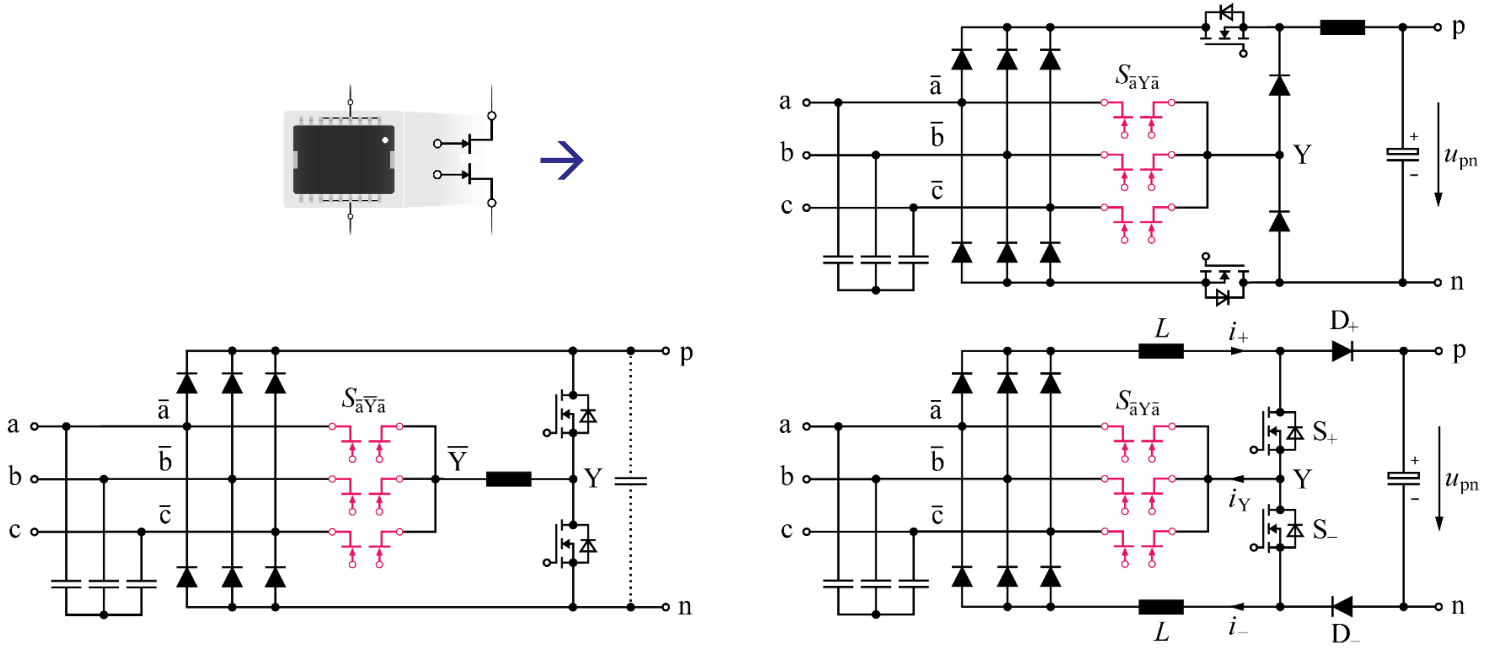




- *SiC Power MOSFETs & Diodes*
- *Integr. CM & Output Coupling Inductors (ICMCI)*

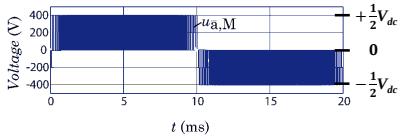
Remark M-BDS-Based 3rd Harm. Inj. Rectifiers

- *Bipolar Voltage Blocking / Current Carrying Capability*
- *Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$*



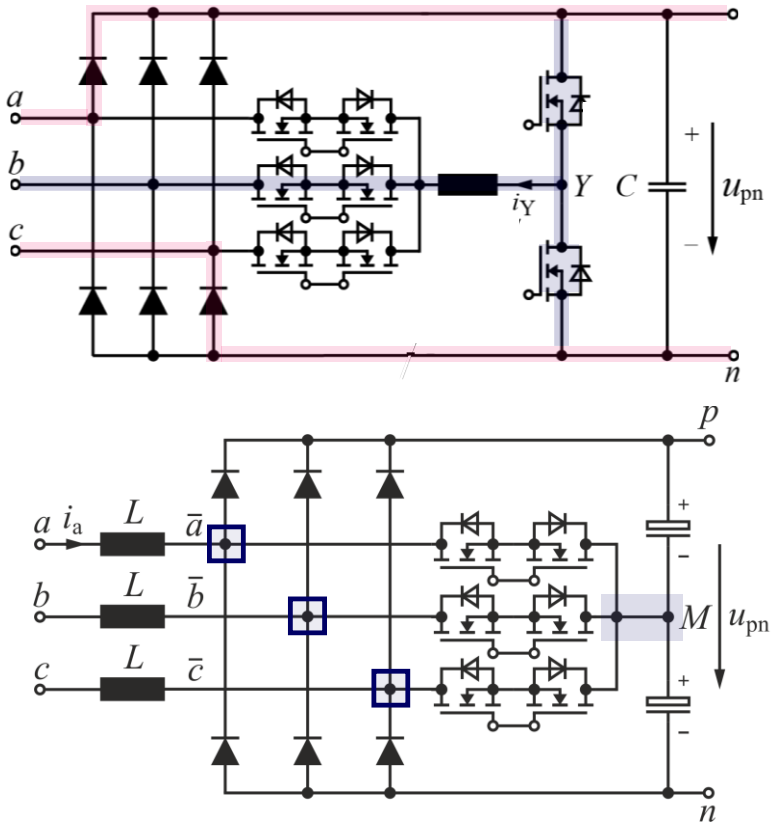
- *Mains Frequ. Operation of the Phase Selector Switches → Conduction Losses Only*

3-Level T-Type Boost PFC Rectifier



3-Level T-Type PFC (Vienna) Rectifier

- *3rd Harm. Inj. Inductor Shifted to AC-Side & PWM of DC-Midpoint Ref. Inj. Switches*
- *3-Level Diode Bridge Input Voltage*
- *Sinusoidal Input Current*
- *Controlled Output Voltage*



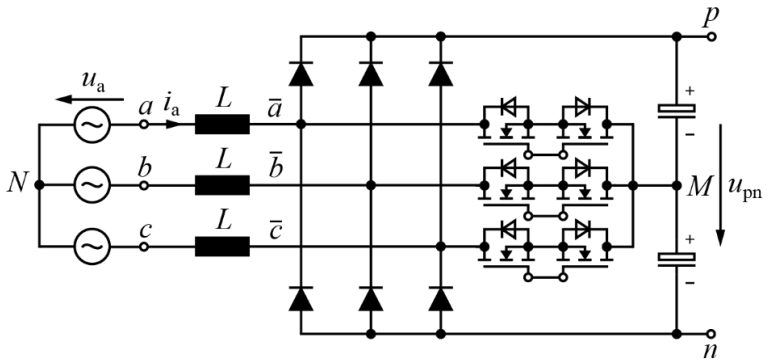
- *Low Sw. Voltage Stress*
- *Low AC-Side Inductance*
- *Low Conduction Losses*
- *Bridge-Leg & Phase Symmetry*

Vienna Rectifier Demonstrator (1)

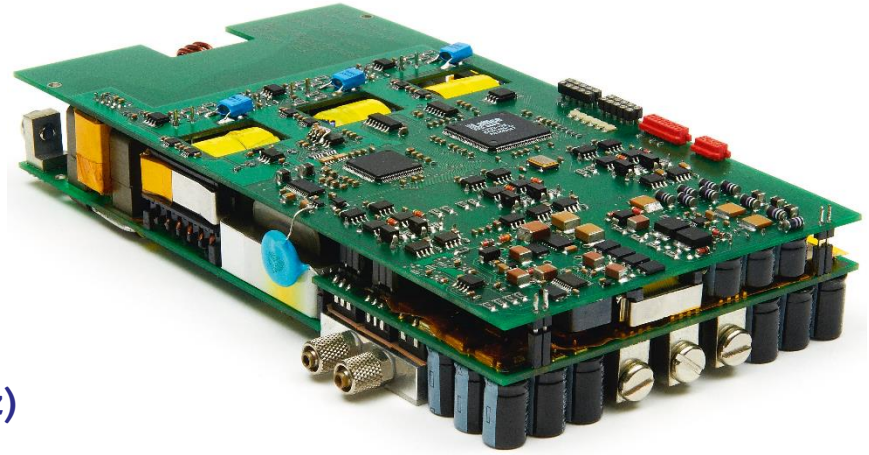
- *Design for More Electric Aircraft Application*
- *650V CoolMOS & 1200V SiC Diodes*
- *Coldplate Cooling*

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



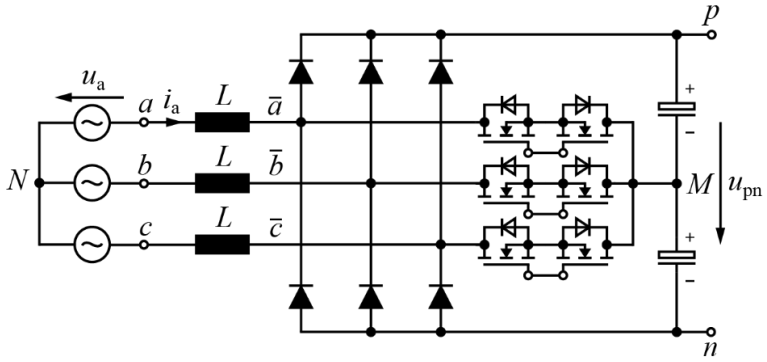
- THD_i = 1.6% @ f_N = 800Hz (f_P= 250kHz)

Vienna Rectifier Demonstrator (2)

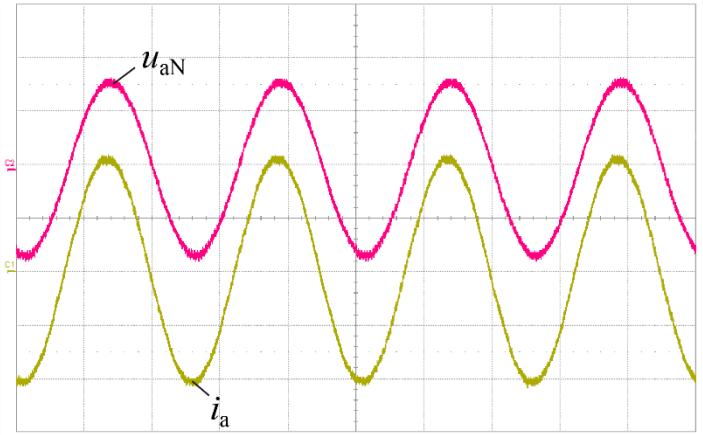
- *Design for More Electric Aircraft Application*
- *650V CoolMOS & 1200V SiC Diodes*
- *Coldplate Cooling*

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

η =96.8%
ρ =165 W/in³ (10 kW/dm³)
f_P = 250kHz



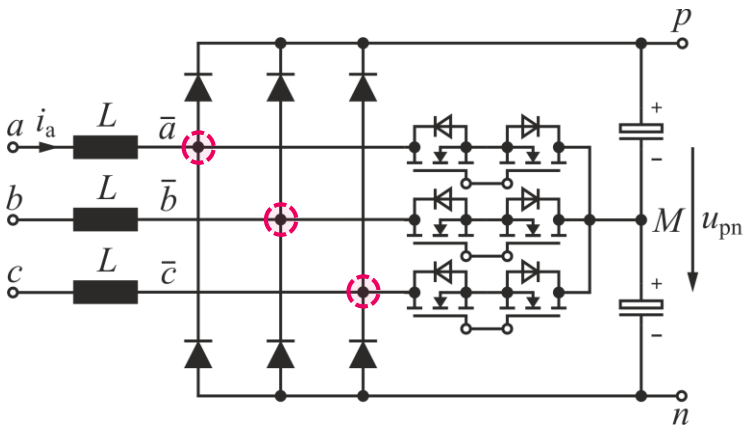
10A/Div
200V/Div
0.5ms/Div

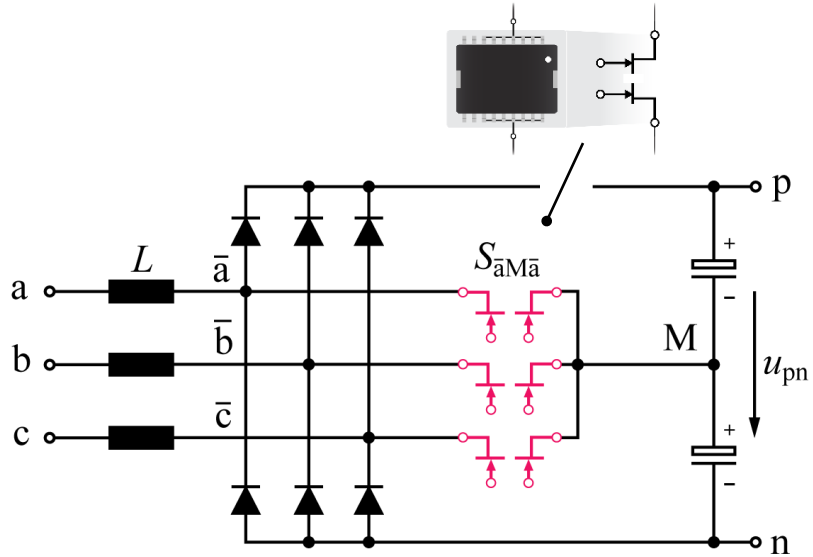


- THD_i = 1.6% @ f_N = 800Hz
- *System Allows 2-Φ Operation*

Remark Application of M-BDSs

- *M-BDS-Realization of the Midpoint-Switches*
- *Significant Reduction of Cond. Losses @ Given Chip Area*





- 600 V *M-BDSs @* U_{pn}= 800 V_{DC} *in Combination w/* 1200 V *SiC Diodes (MOSFETs for Bidir. Power Flow)*

Global Megatrends

Digitalization
Sustainable Mobility
Renewable Energy
Industry Automation
Etc.

Ultra-Fast / High-Power EV Charging

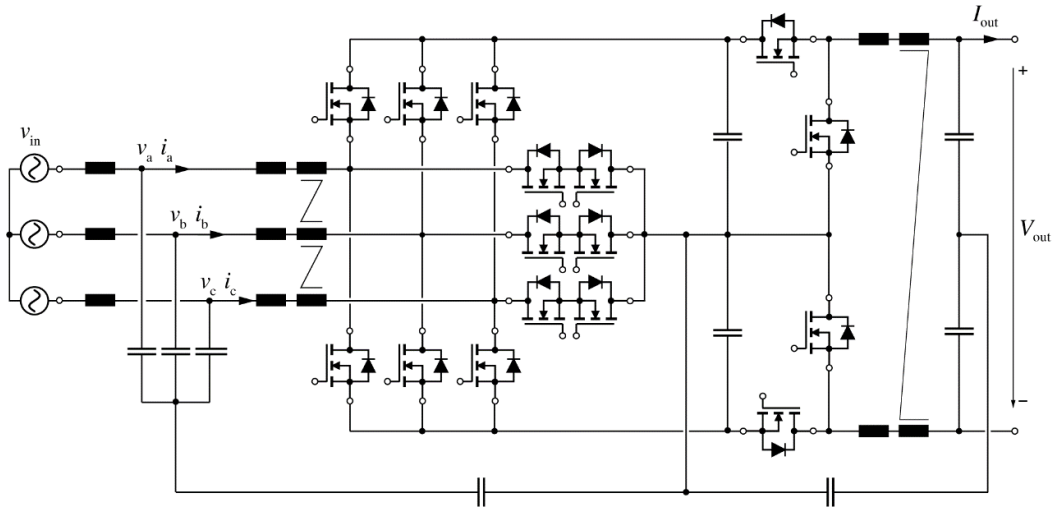
- *Modular Mains Interfaces | Future Non-Isolated Virtually Grounded Systems*
- *Very Wide Output Voltage Range (200...800V)*

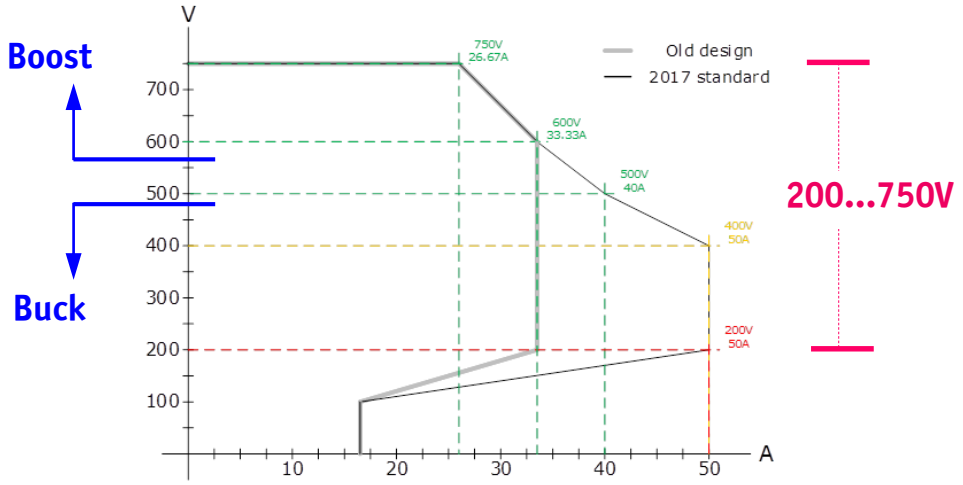
Source: www.autoevolution.com

- *Local Battery Buffer*
- *320kW → 400km Range in 20min*

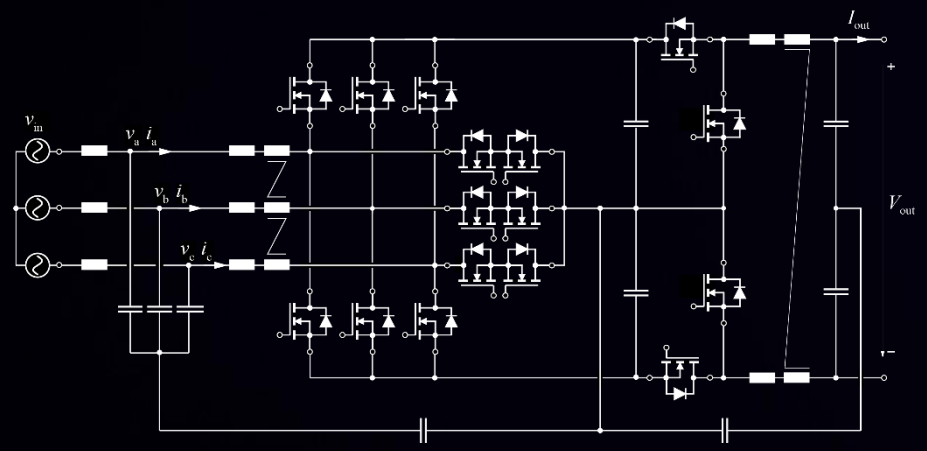
Bidirectional *Boost-Buck* PFC Rectifier Concepts

- *Vienna Rectifier Type Bidirectional Boost PFC AC/DC Front-End & DC/DC Buck Output Stage*
- *Coordinated "Synergetic Control" of AC/DC and DC/DC Converter Stage for Min. Sw. Losses*





- *Future Non-Isolated EV-Charging → Earth Leakage Curr. Limited Using "Virtual Ground Control"*



DUALITY

Boost-Buck

Buck-Boost

Source: www.reuts.com

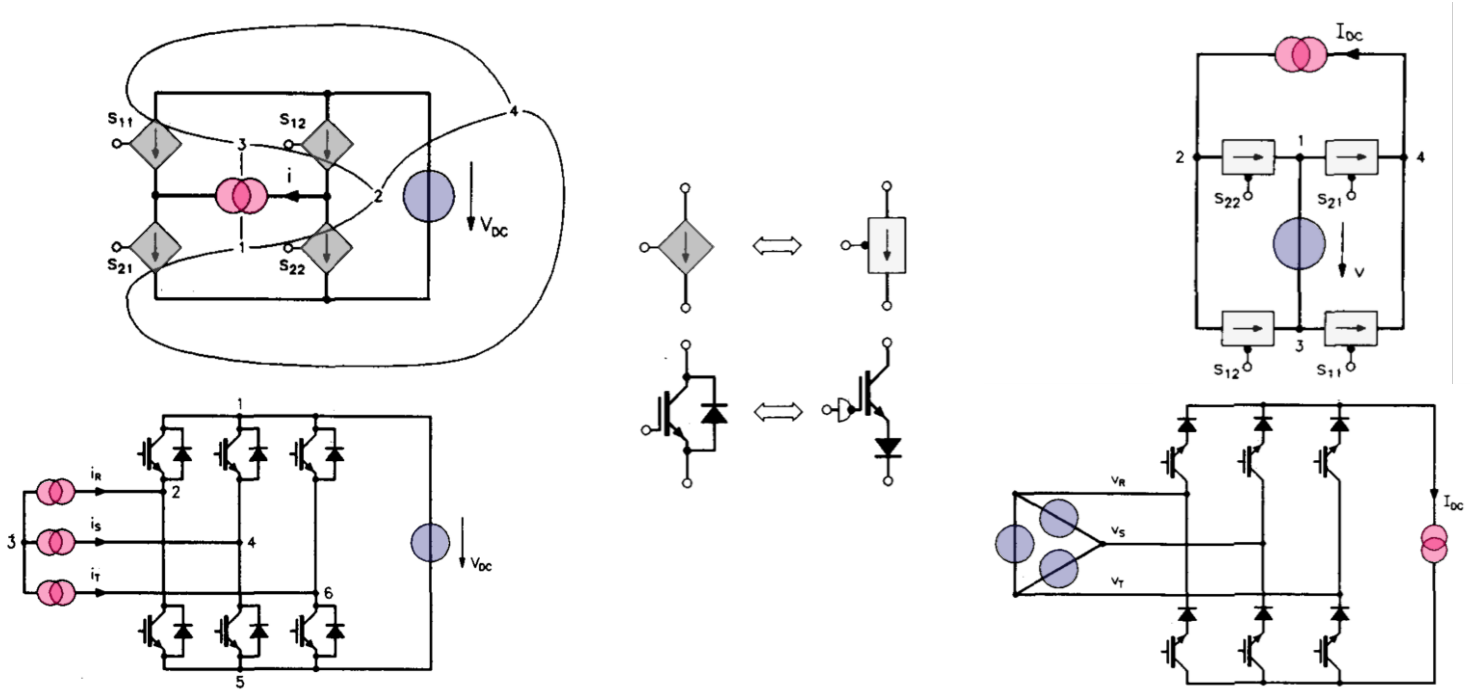
DUALITY

IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 29, NO. 2, MARCH/APRIL 1993

Quasi-Dual Modulation of Three-Phase PWM Converters

Johann W. Kolar, *Member, IEEE*, Hans Ertl, *Member, IEEE*, and Franz Zach, *Member, IEEE*

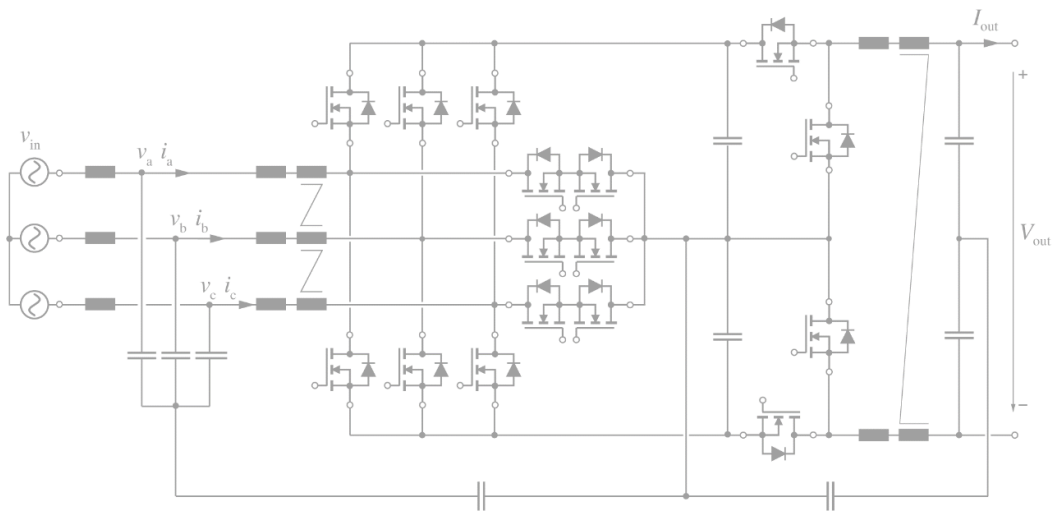
- *Duality of Voltage DC-Link & Current DC-Link Converter Circuits*
- *Unipolar Blocking / Bidir. Current → Bipolar Blocking Unidir. Switches → Appl. of M-BDSs (!)*

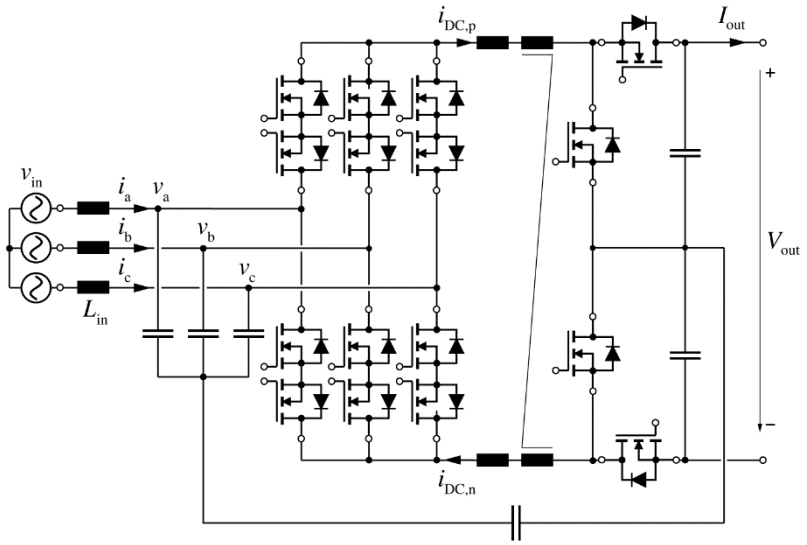


- *"Boost-Buck" Translated into "Buck-Boost" Functionality / Lower # of Ind. Components*

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*

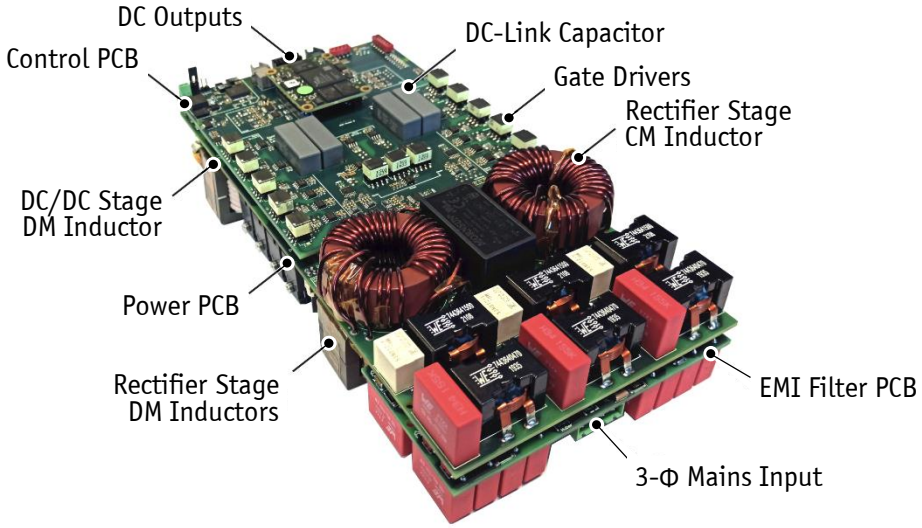




- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

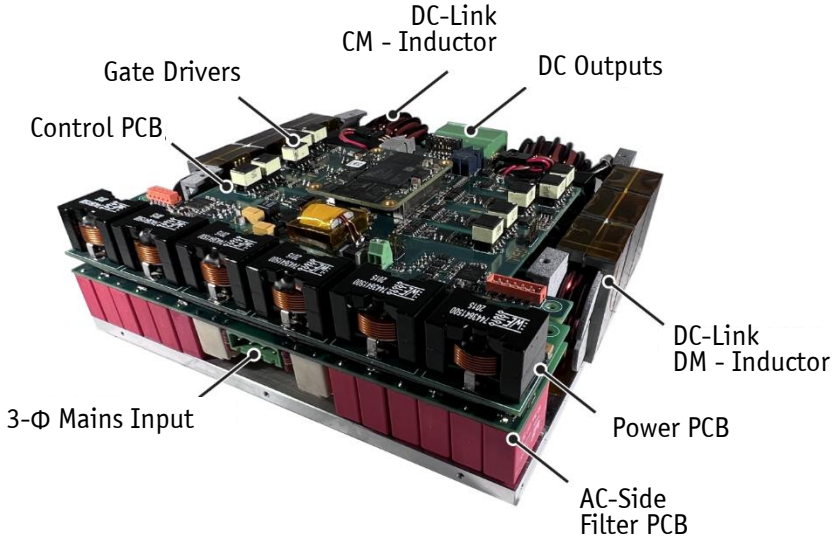
Boost-Buck | *Buck-Boost* Demonstrator Systems

- 10 kW @ 400...800 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 800 V_{DC}
- η = 98.8% @ 5.4 kW/dm³
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 100 kHz/200 kHz *eff.*



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

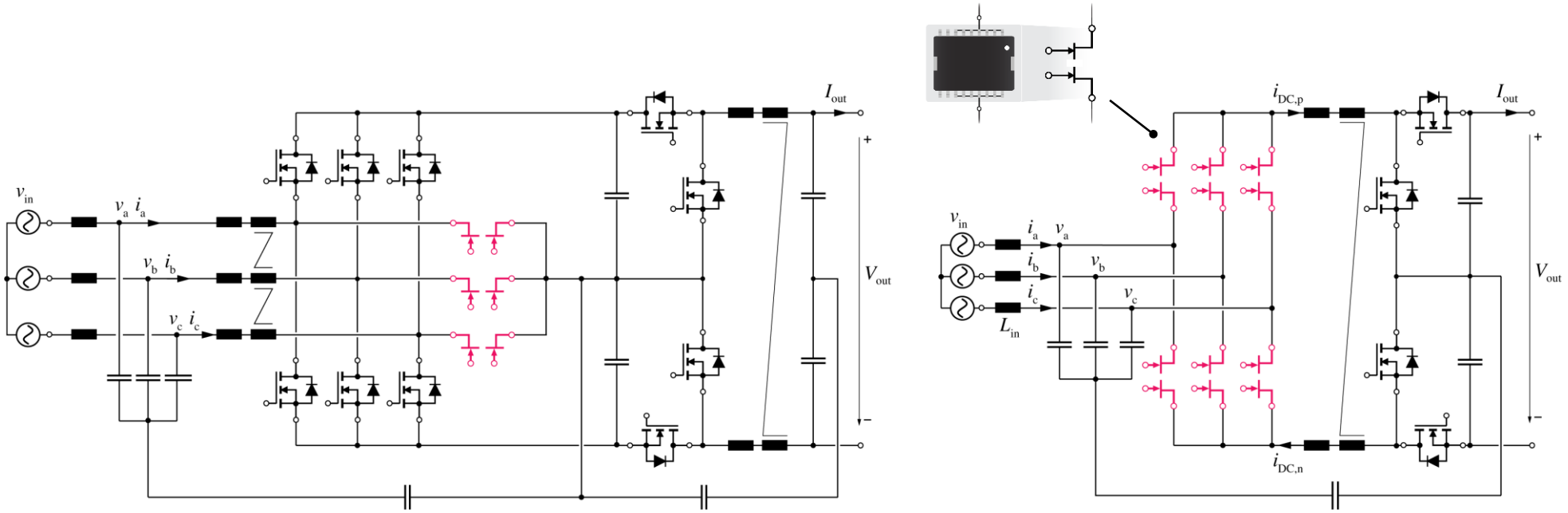
- 10 kW @ 400...1000 V_{DC} @ *3-Φ* 400 V_{rms} *Mains*
- U_{out} = 200 ... 1000 V_{DC}
- η = 98.6% @ 6.4 kW/dm³
- *AC/DC* — f_{sw} = 100 kHz
- *DC/DC* — f_{sw} = 2x 50 kHz/100 kHz *eff.*



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

Remark Application of M-BDSs

- *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*

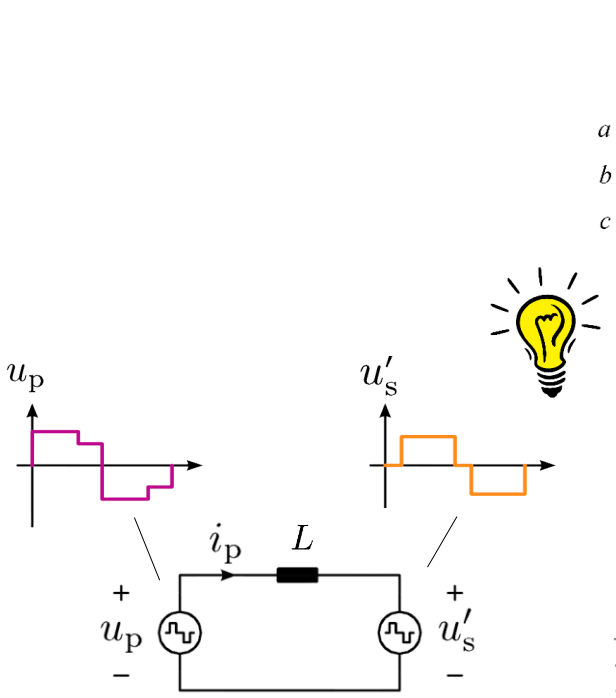


- **600 V *M-BDSs* *for Boost—Buck* & 1200 V *M-BDSs* *for Buck—Boost Combination* @ 400 V_{rms} *Mains***

3-Φ Isolated Matrix-Type Single-Stage 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*



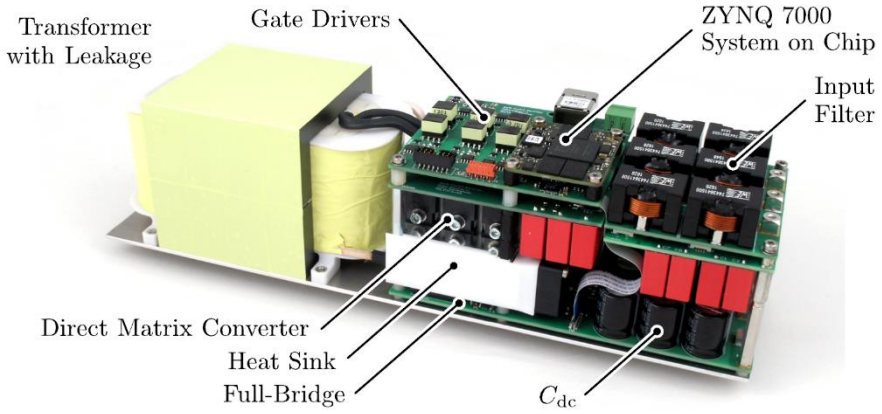
- *Equivalent Circuit*

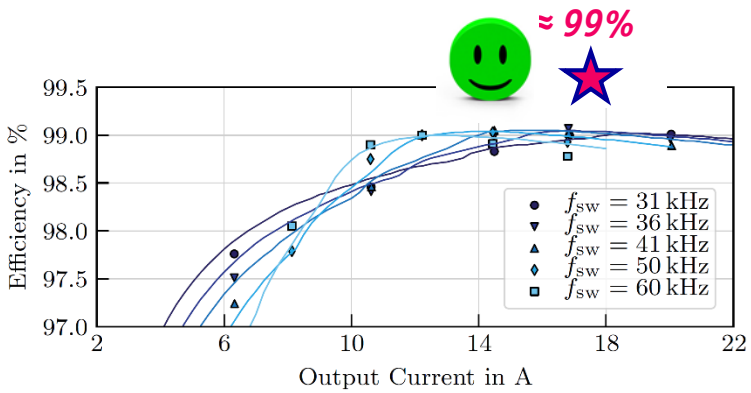
- *Transformer Voltages / Currents*

Isolated Matrix-Type PFC Rectifier (2)

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

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

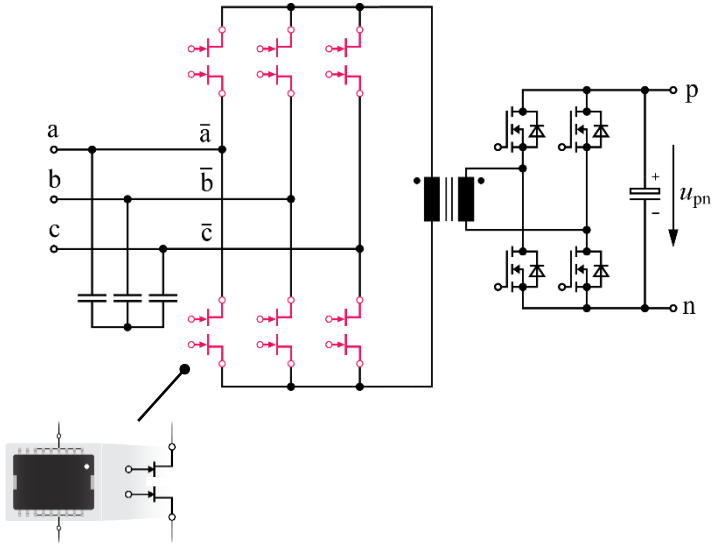


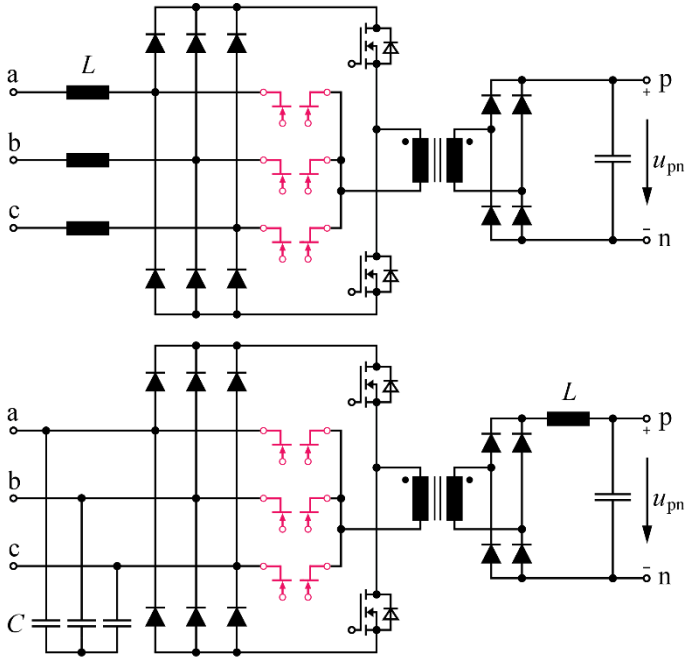


- **900V / 10mΩ SiC Power MOSFETs**
- **Opt. Modulation Based on 3D Look-Up Table**

Remark Application of M-BDSs

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





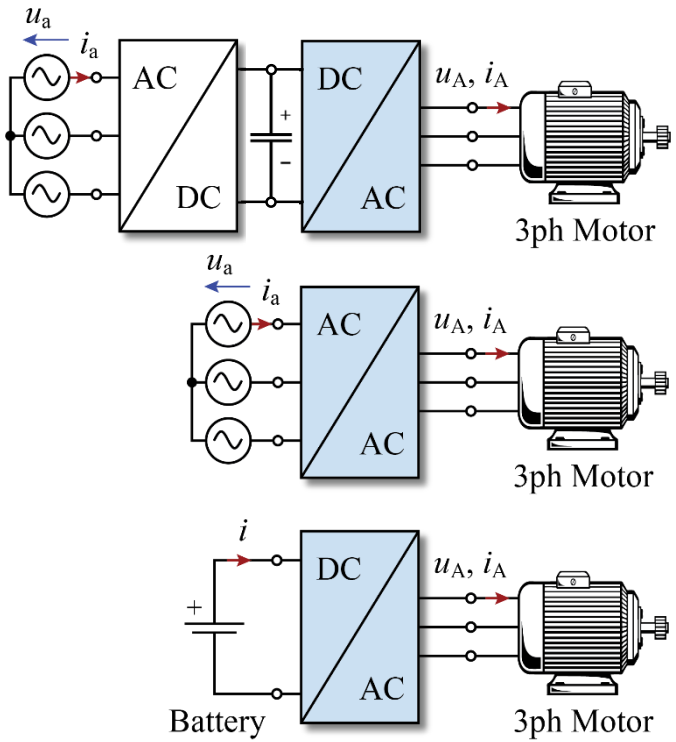
- *Functional Integration* → *Lower Complexity* BUT *Limited Controllability*

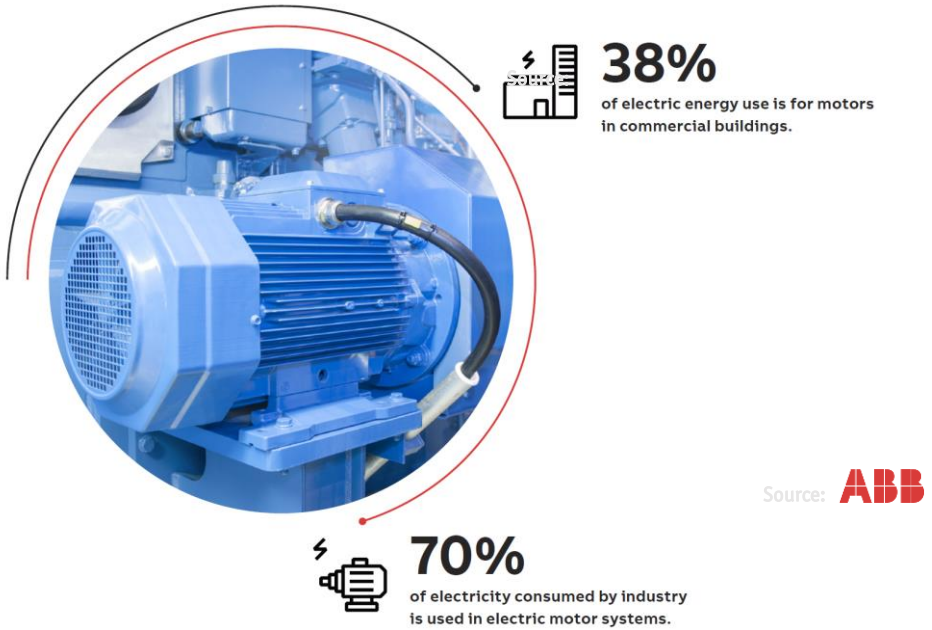
Global Megatrends

Digitalization
Sustainable Mobility
Renewable Energy
Industry Automation →
Etc.

Variable Speed Drive Concepts

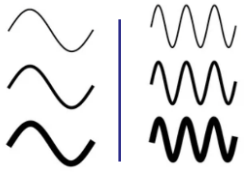
- *DC-Link Based AC/DC/AC OR Matrix-Type AC/AC Converters*
- *Battery OR Fuel-Cell Supply OR Common DC-Bus Concepts*





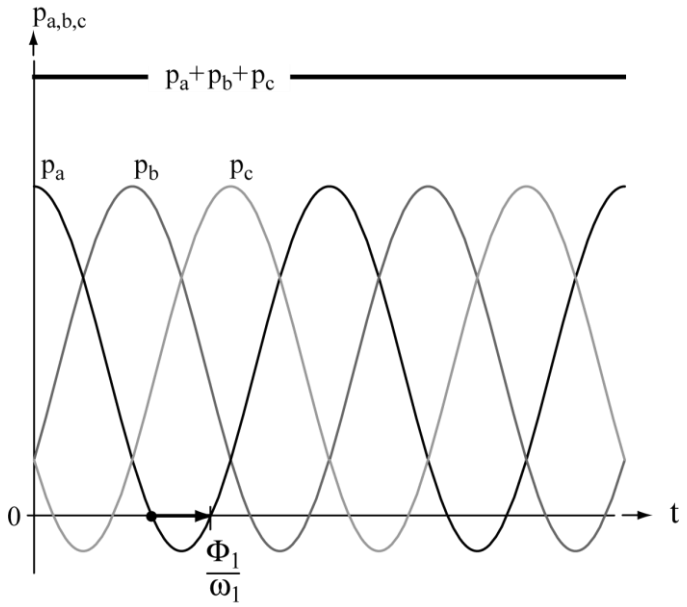
- *45% of World's Electricity Used for Motors in Buildings & Industrial Applications*

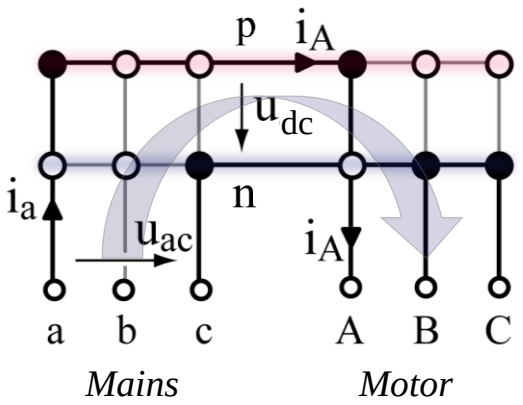
3-Φ AC/AC Matrix Converter

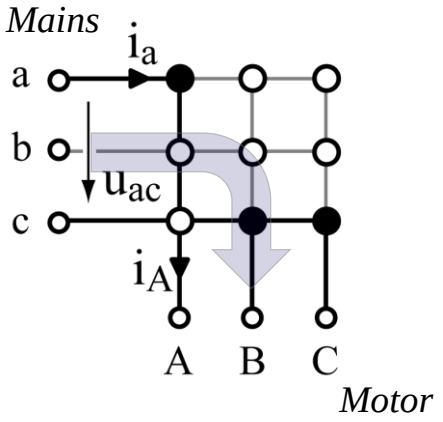


Indirect & Direct 3-Φ AC/AC Matrix Converter (1)

- *Constant 3-Φ Instantaneous Power Flow → No Low-Frequ. DC-Link Power Pulsation Buffer Requirement (!)*
- *Indirect AC/DC—DC/AC OR Direct AC/AC Power Conversion → IMC OR DMC*
- *Switch Matrix w/ Bipolar Voltage Blocking & Current Carrying Devices*



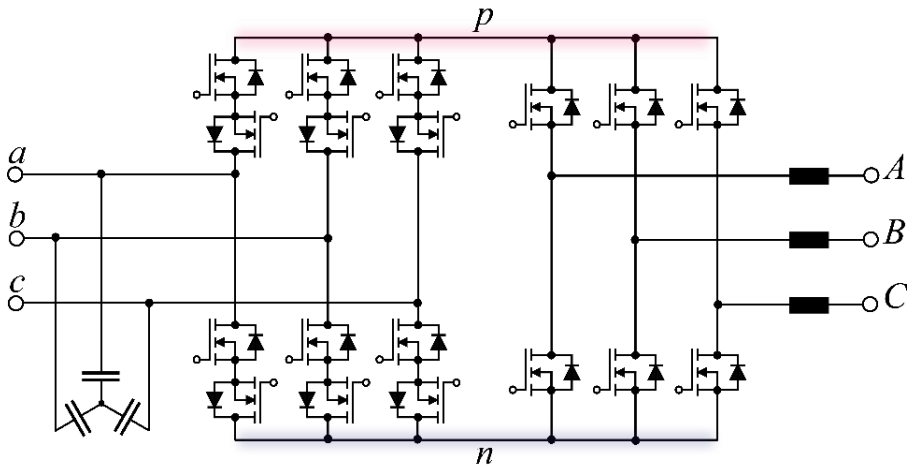


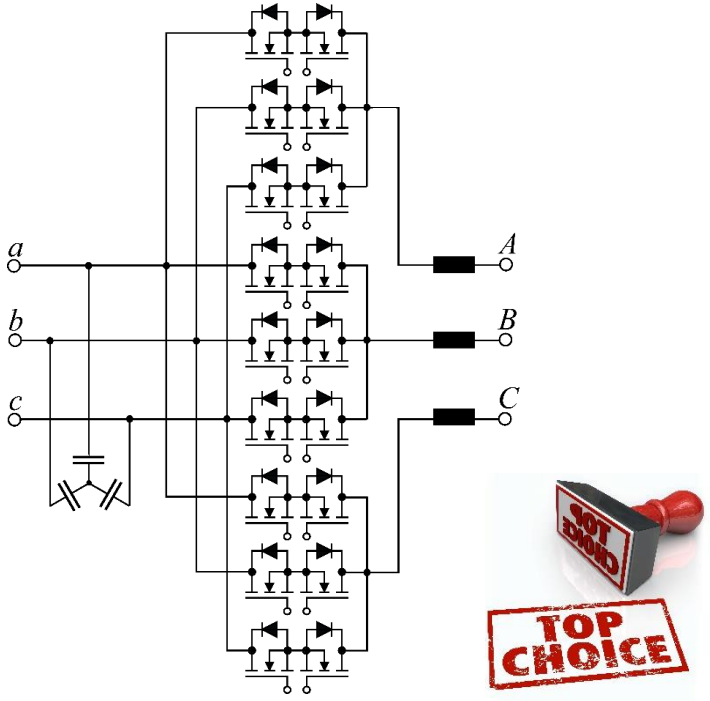


- *Output-Side Motor Inductor → Operation Limited to Buck-Type (Step-Down) Voltage Conversion*

Indirect & Direct 3-Φ AC/AC Matrix Converter (2)

- *Input Filter Capacitors | Sw. Stage | Motor Inductance*
- *Buck-Type Power Conversion Topology*



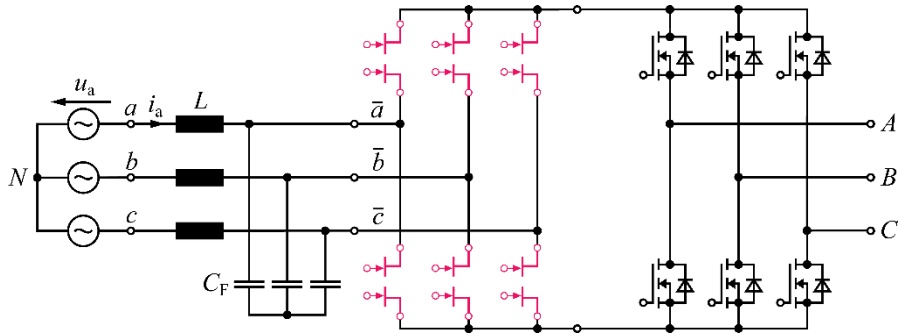


- *IMC Relies on Strictly Pos. DC-Link Voltage / i=0 Input Stage Commutation*
- *M-BDS-Based Realization of DMC Features Lower # of Switches / 4-Step Commutation Required*

Remark Application of M-BDSs

Indirect Matrix Converter (IMC)

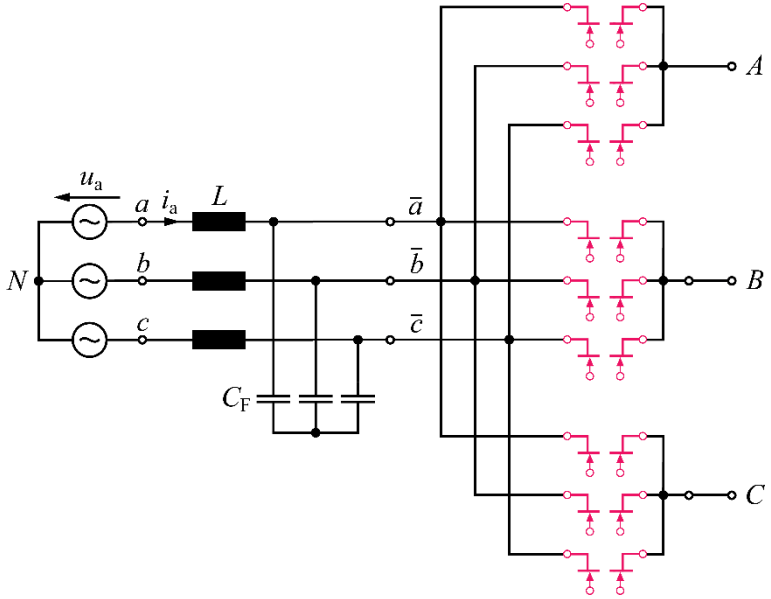
- M-BDS AC/DC Front-End
- ZCS Commutation of AC/DC Stage @ i_{DC}=0
- No 4-Step Commutation



- Higher # of Switches Compared to DMC
- Lower Cond. Losses @ Low Output Voltage
- Thermally Critical @ $f_{out} \rightarrow 0$

Direct Matrix Converter (DMC)

- 4-Step Commutation
- Exclusive Use of M-BDSs

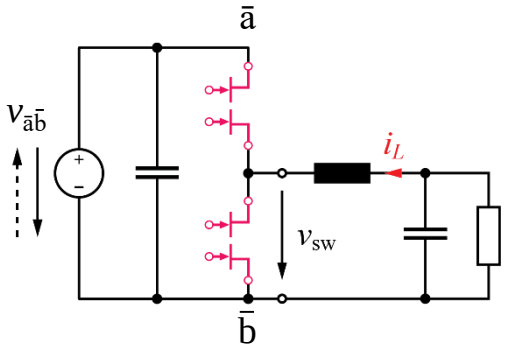


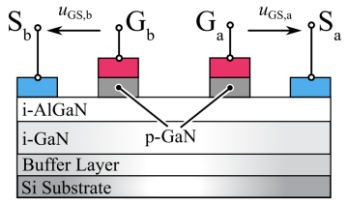
- Thermally Critical @ $f_{out} \approx f_{in}$

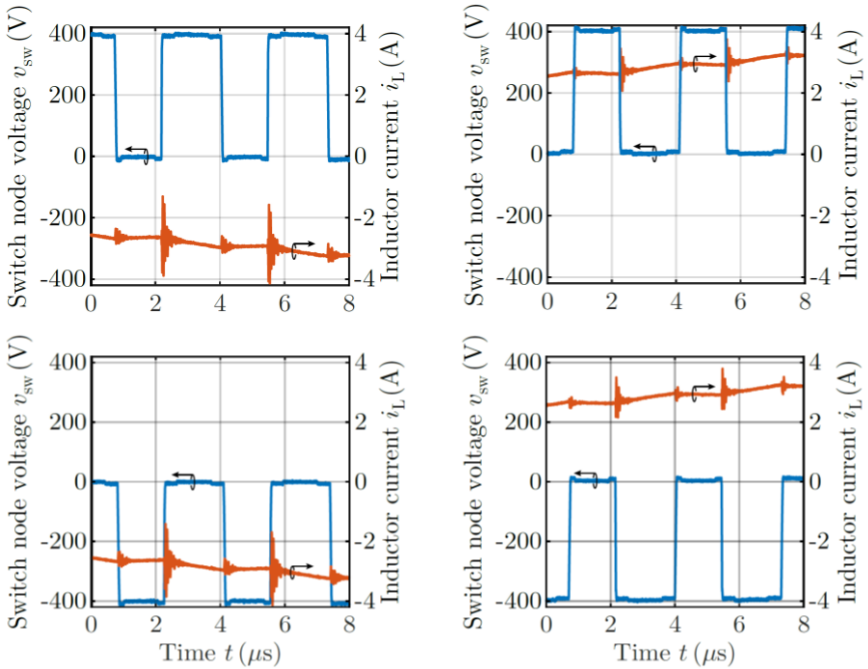
Selected GaN & SiC M-BDS R&D Activities

Experimental Analysis of 1st Gen. 600V GaN M-BDS

- PowerAmerica *Program — Based on Infineon's CoolGaN™ HEMT Technology*
- *Dual-Gate Device / Controllability of Currents in Both Directions*
- *Bipolar Voltage Blocking Capability | Normally-On or Normally-Off*



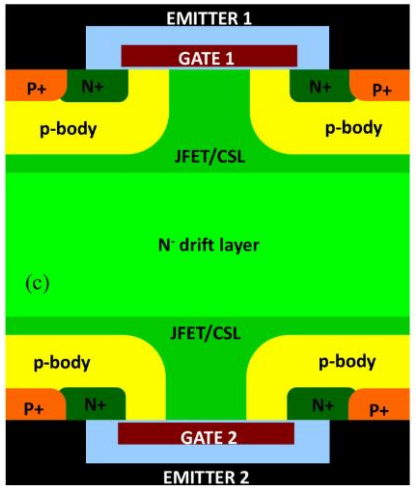


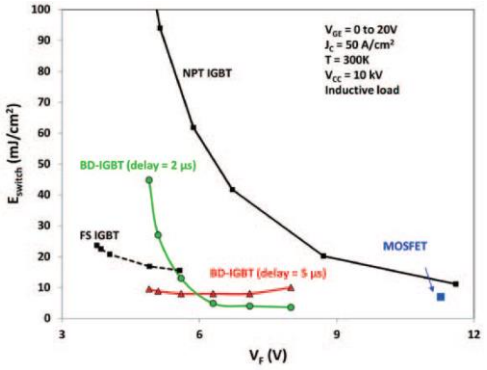


- *Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ | 600V Sample @ ± 400V*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

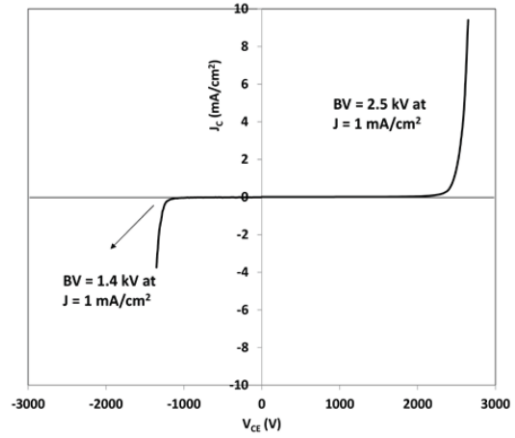
Monolithically Integrated Bi-Directional SiC IGBT

- *Planar-Gate Bi-Direct. IGBT Fabricated w/ Double-Sided Lithography Process on Free-Standing n⁻ Wafers*
- *MOS-Cells on Both Sides of Lightly Doped Drift Region / Cond. & Sw. Loss Infl. by Back-Side Gate Volt. Bias*
- *Challenging Packaging & Cooling*





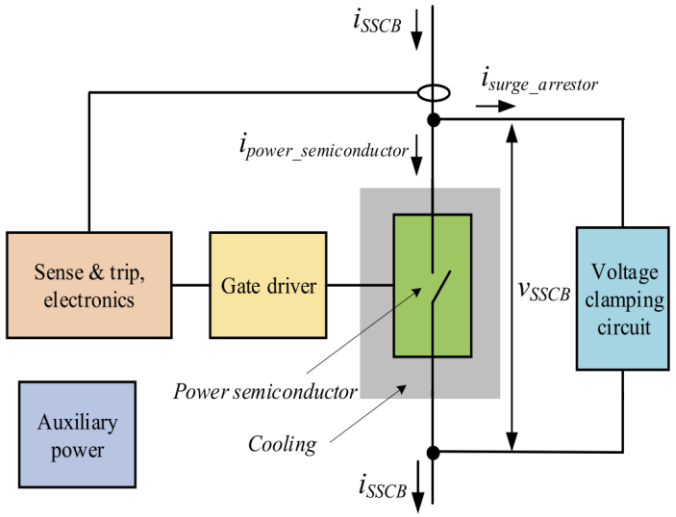
Chow et al., 2016



- *Simul. Performance of a 15kV BD-IGBT | Blocking Characteristic (max. 7.2 kV Meas.) – Epi Layer Defects etc.*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

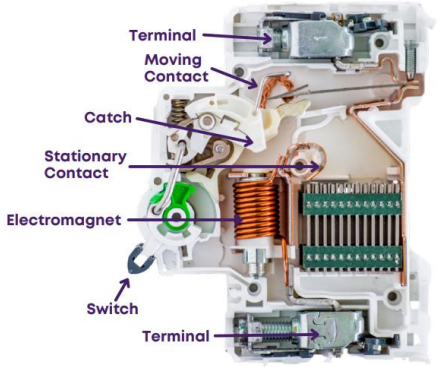
Remark Solid-State Circuit Breakers (SSCBs)

- *Ultra-Fast Fault Interruption | Reduced Fault Stress | Arc-Less | Low Surge Voltage | Long Lifetime*
- *Software / Remote Configurable Trip Behavior / Remote-Controlled Load Switch*

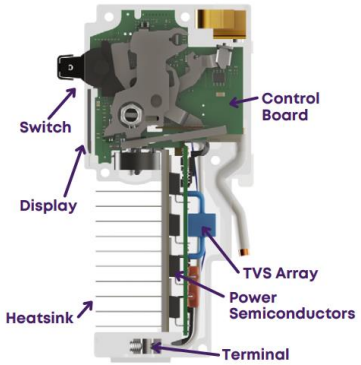


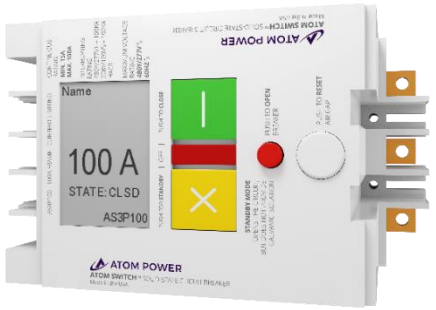
Rodrigues et al., 2021

Traditional Circuit Breaker



Solid-State Circuit Breaker





ATOM POWER

- *Recent LV Example w/ Custom SiC Modules / Max. 100A Cont. / UL-Certified*
- *M-BDSs — Low On-Resistance Mandatory (e.g. 1100V, 22mΩ GaN M-BDS) | Low Leakage Current*

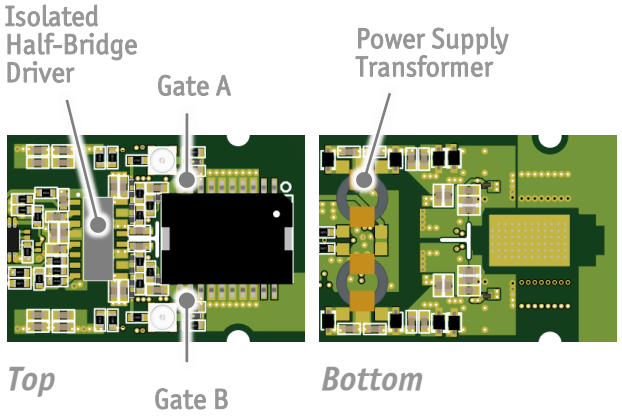
Outlook

Monolithic 3D-Integration

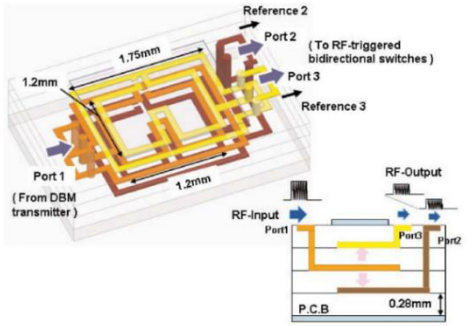
Source: Panasonic ISSCC 2014

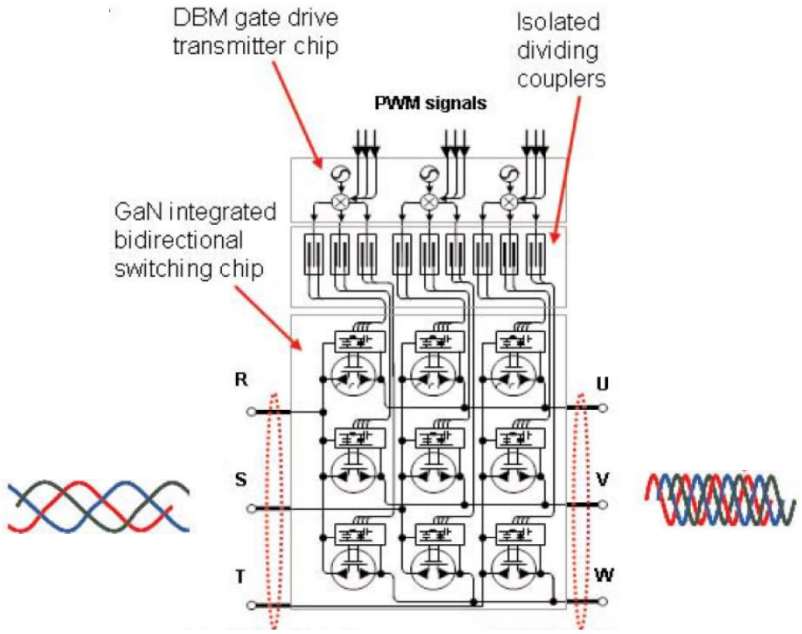
- *Example — M-BDS GaN 3x3 Matrix Converter with Drive-By-Microwave (DBM) Technology*

- *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)*



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





- *Massive Space Saving Compared to Discrete Realization*
- *Key for Future Super-Compact Power Electronics Converters (!)*

Thank you!