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GaN/SiC Monolithic Bidirectional Switches – Drivers of a Next Wave of Power Electronics Innovations

Johann W. Kolar et al.

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

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… Let's Catch the Wave!

J. W. Kolar | J. Huber | D. Zhang | D. Menzi | N. Nain | S. Weihe

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
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GaN/SiC Monolithic Bidirectional Switches – Drivers of a Next Wave of Power Electronics Innovations

Abstract — Power Electronics is a key technology for all forms of generation and utilization of electric power in modern societies, ranging from renewable energy systems and highly diverse power supply applications including fast-charging of EVs and hyper-scale datacenters to variable frequency drives for industrial automation.

The progress in the area has been driven over the past 40 years by new power semiconductor device concepts and corresponding circuit topologies with a focus on voltage-source converter (VSC) structures and/or the application of switching elements limited to unipolar voltage-blocking capability. With reference to recently intensifying R&D activities on two-gate monolithic bi-directional switches (M-BDSs) featuring bipolar voltage blocking and bidirectional current control capability, the talk highlights the potential advantages of M-BDSs for the realization of ultra-compact non-isolated and isolated three-phase PFC rectifier systems and next generation inverter systems with low motor insulation stress. In this context, the performance gains achievable utilizing three-level T-type VSC topologies, new Solid-State-Transformer structures, and the unique features of current-source converter approaches – today solely employed in thyristor-based high-power medium-voltage motor drives – and AC/AC matrix converter concepts over state-of-the-art VSC systems are emphasized. Final considerations are on the paramount importance of minimization of life-cycle environmental impacts and/or ensuring circular economy compatibility of future power electronics systems for the next disruptive performance improvement towards Power Electronics 5.0.

Outline

- Introduction

- 3-Φ PFC Rectifiers
- 3-Φ Variable Speed Motor Drives
- M-BDS R&D Activities

- Outlook

Acknowledgement
M. Guacci
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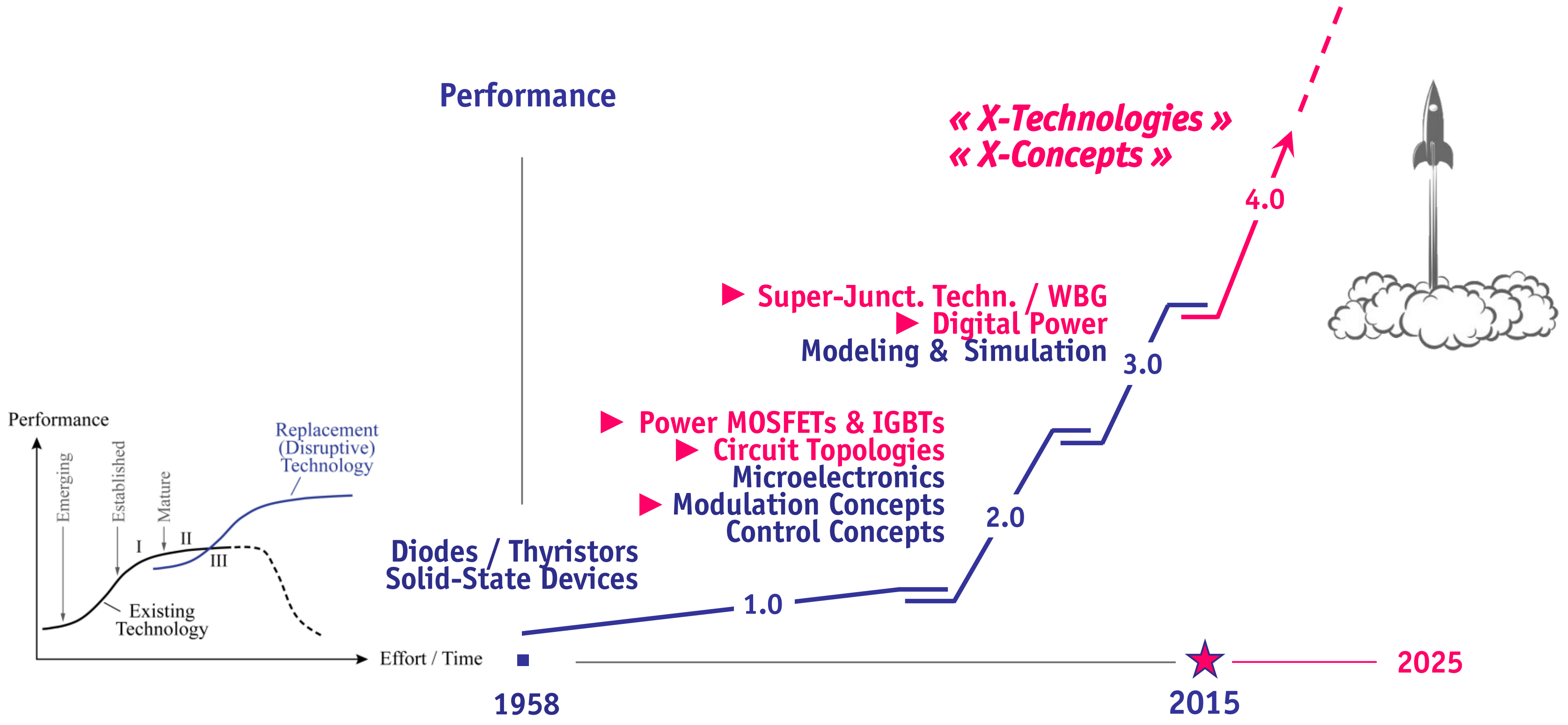
S-Curve of Power Electronics

- *« 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

Renewable Energy
Digitalization →
Sustainable Mobility
Industry Automation
Etc.

Renewable Energy — Photovoltaics

- 3-Φ DC/AC Mains Interface
- Lower Costs / Higher Efficiency / Lower Weight
- 20 Years Lifetime / Life-Cycle Assessment

Source: REUTERS/Stringer

- Globally Installed PV Capacity Forecasted to 2.8 Terawatt by 2030 (IEA)

Digitalization — Datacenters

- *Medium-Voltage → Power-Supplies-on-Chip (0.6 ... 0.8V) Power Conversion*
- *Trend Towards 380V_{DC} Power Distribution*
- *Short Innovation Cycles*
- *Modularity / Scalability*

Server-Farms
up to **450 MW**
99.9999%/<30s/a
$1.0 Mio./Outage

Since 2006
Running Costs >
Initial Costs

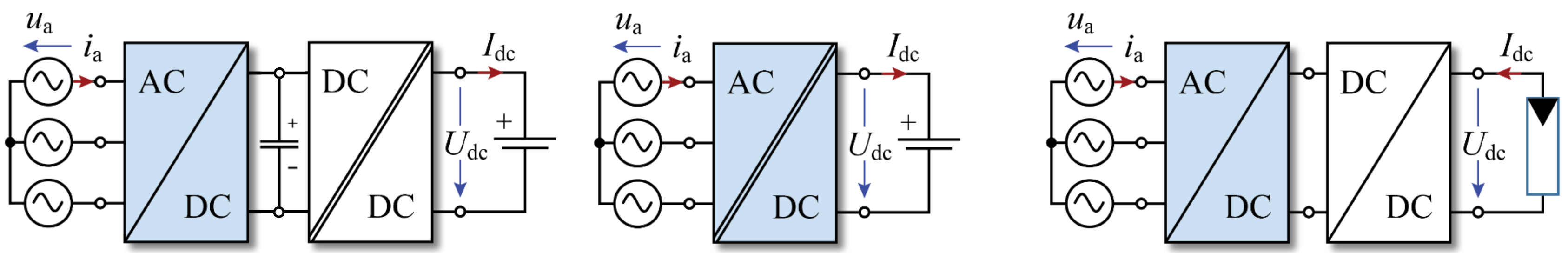
Source: Facebook

— *Higher Availability*
— *Higher Efficiency*
— *Higher Power Density*
— *Lower Costs*

3-Φ AC/DC Converter Application Areas

- Datacenter Power Supply
- Renewable Energy Applications
- El. Vehicle Battery Charging — Full Rated Output for 3-Φ OR 1-Φ Grid

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



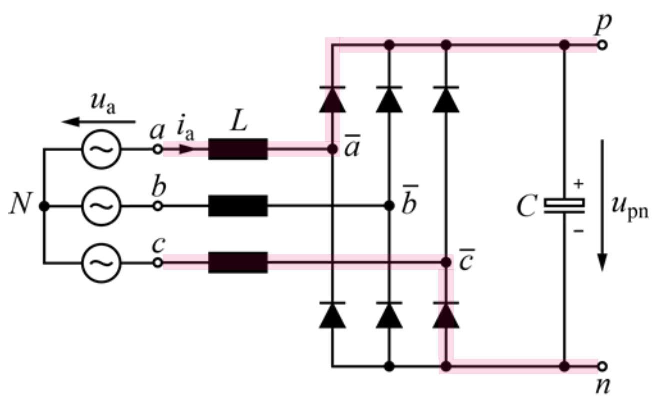
320...530V_{rms} Line-to-Line

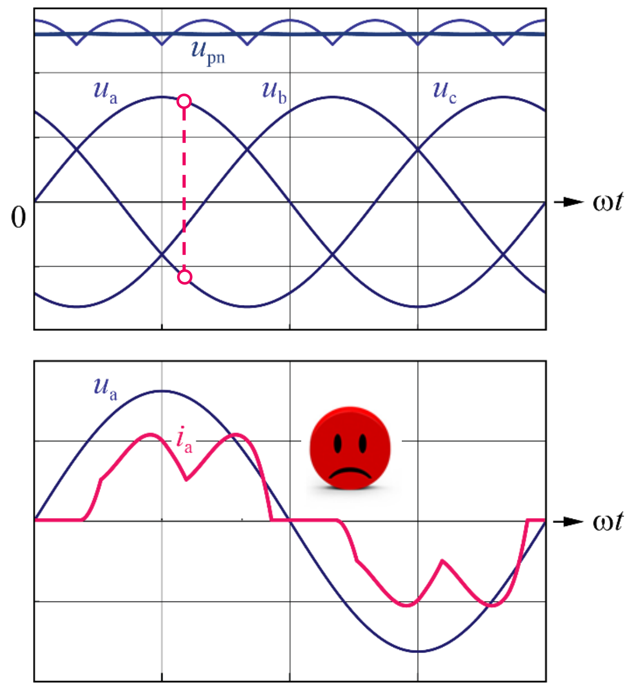
MPP Tracking in 60...90% of Max. Open Circuit Voltage

- 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*

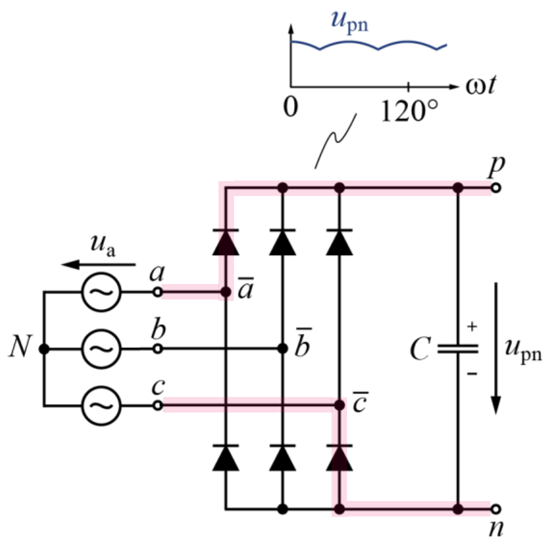




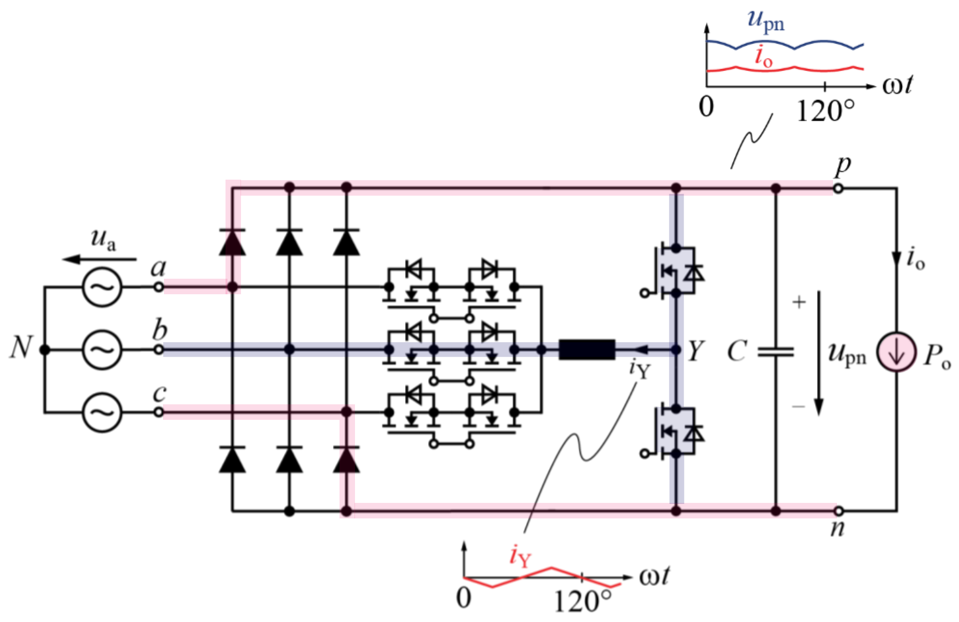
→ *Active Mains Current Shaping / Simultaneous Current Flow in All Phases*

Integrated Active Filter (IAF) PFC Rectifier (1)

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



→

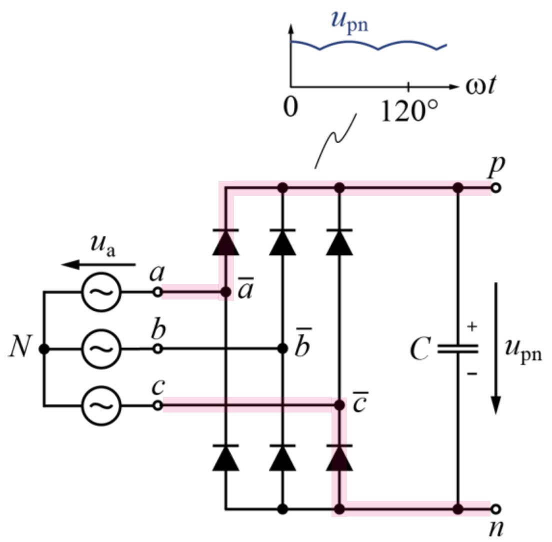


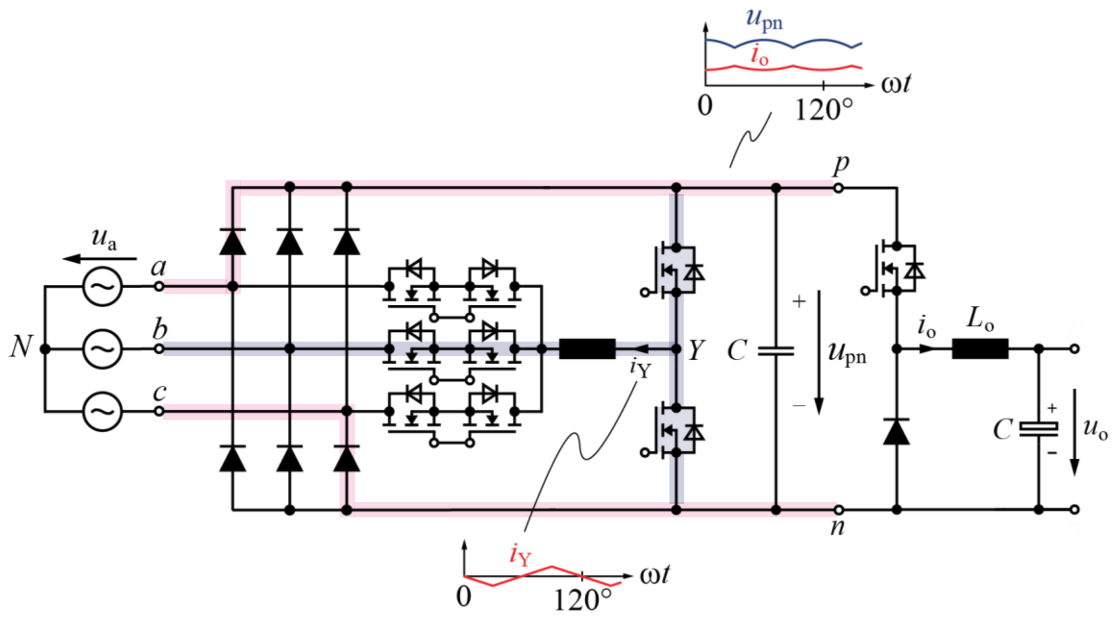
- Non-Sinusoidal Mains Current

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

Integrated Active Filter (IAF) PFC Rectifier (2)

- 3^{rd} *Harmonic Current Injection into Phase with Lowest Voltage*
- *Phase Selector AC Switches Operated @ Mains Frequency — "3-Φ Unfolder" Input Stage*





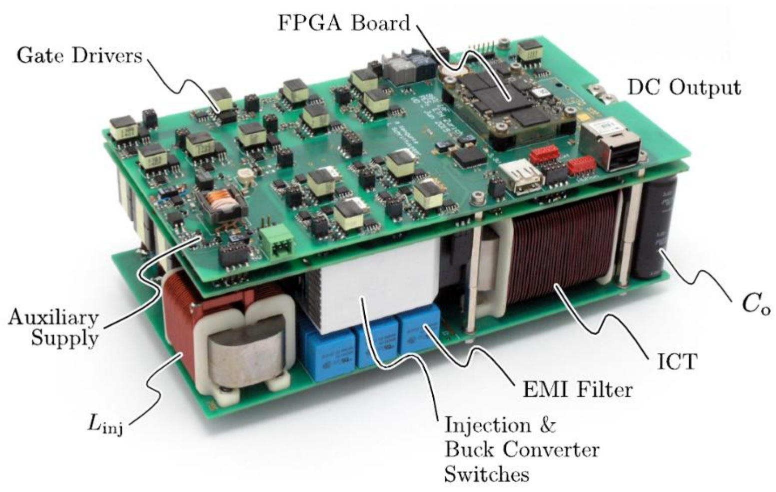
- *Non-Sinusoidal Mains Current*

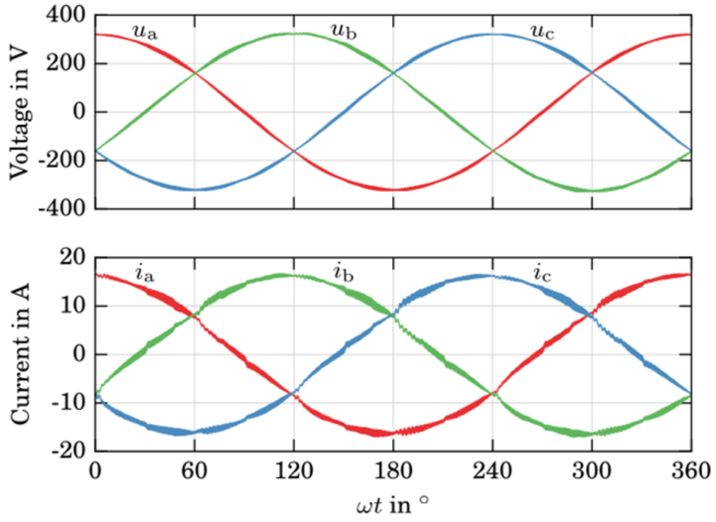
→ *DC/DC Output Stage — P_0= const.*
→ *Sinusoidal Mains Current*
→ *Controlled Output Voltage*

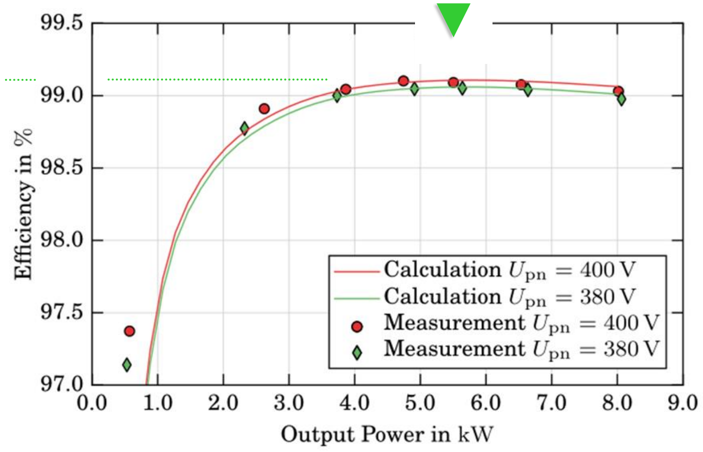
IAF Rectifier & Buck Output Stage

- *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



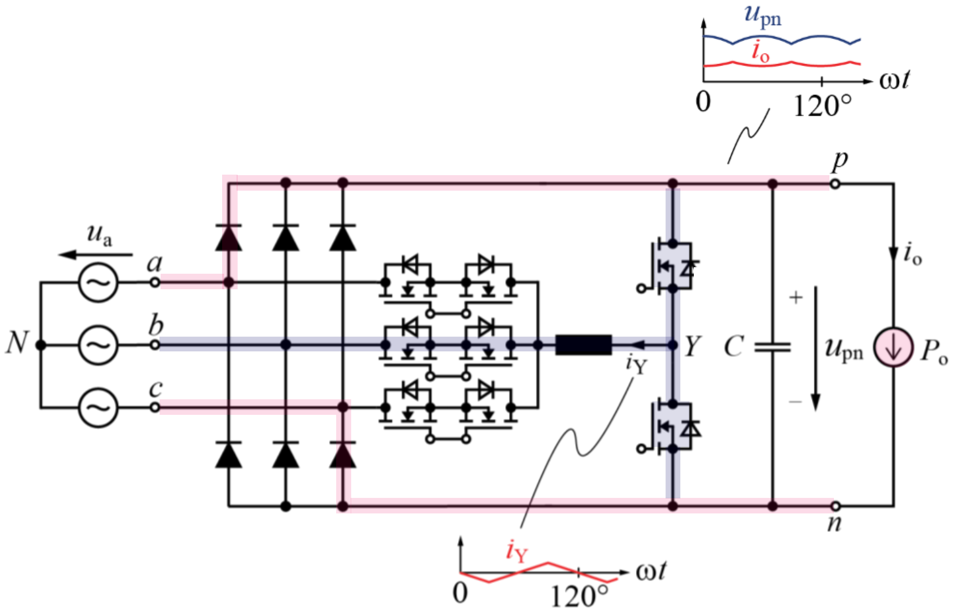


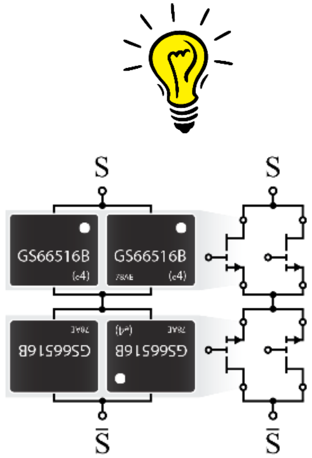


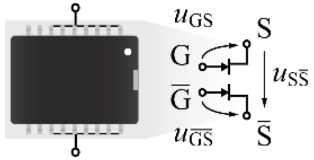
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck DC/DC Output Stages (!)*

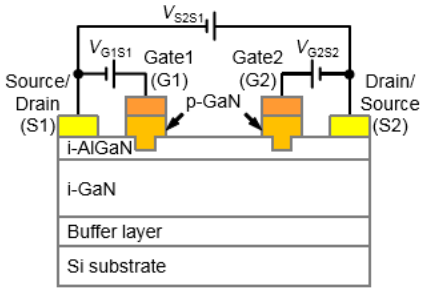
Remark Application of M-BDSs (1)

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







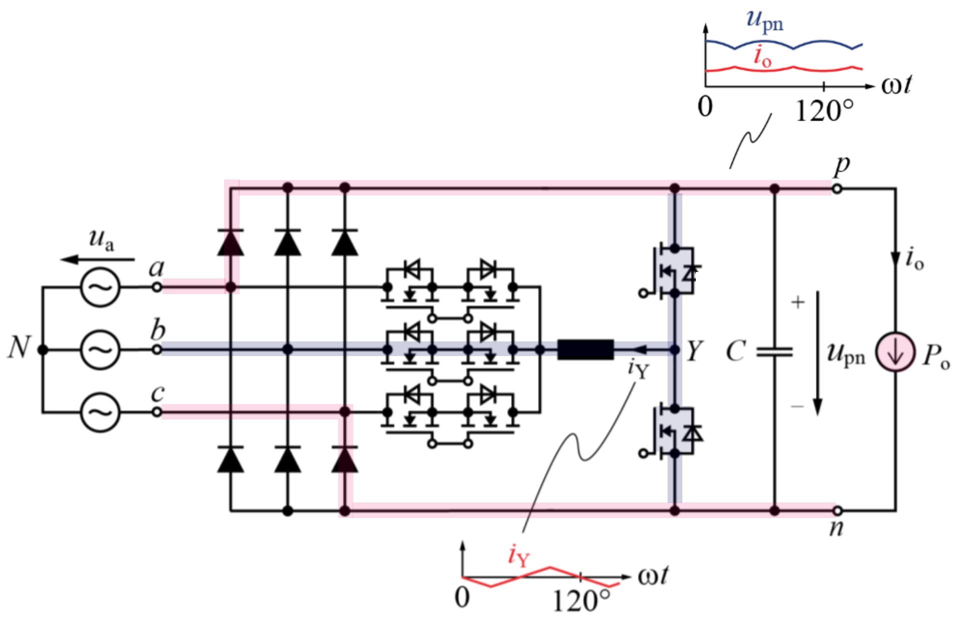


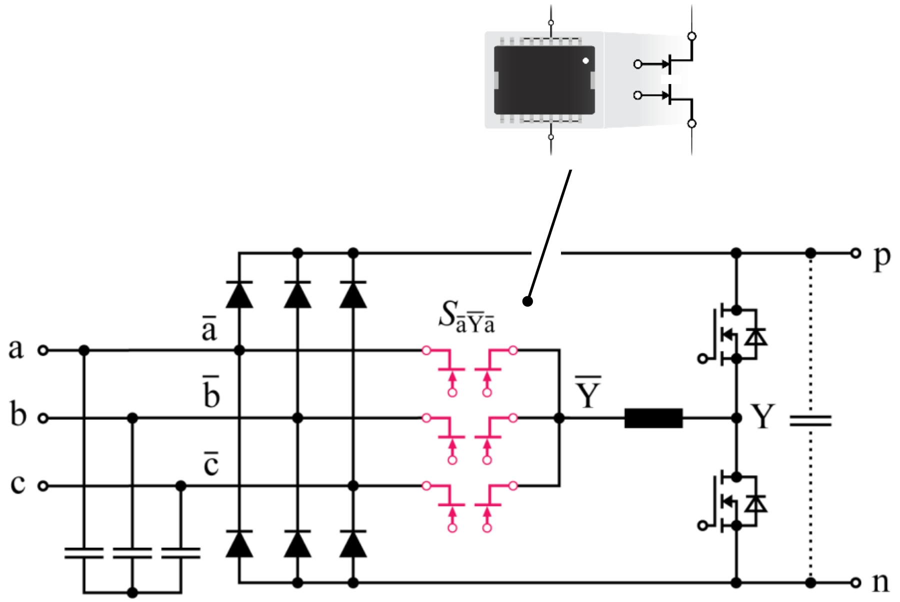
Source: Panasonic

- ***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*

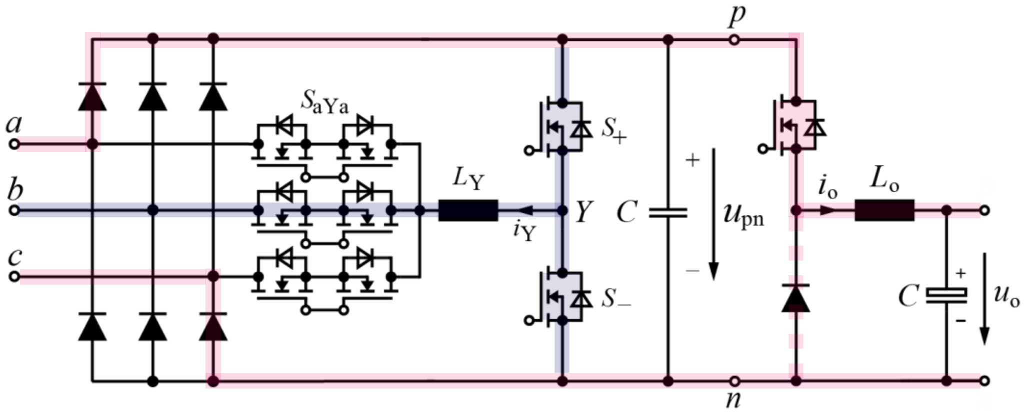


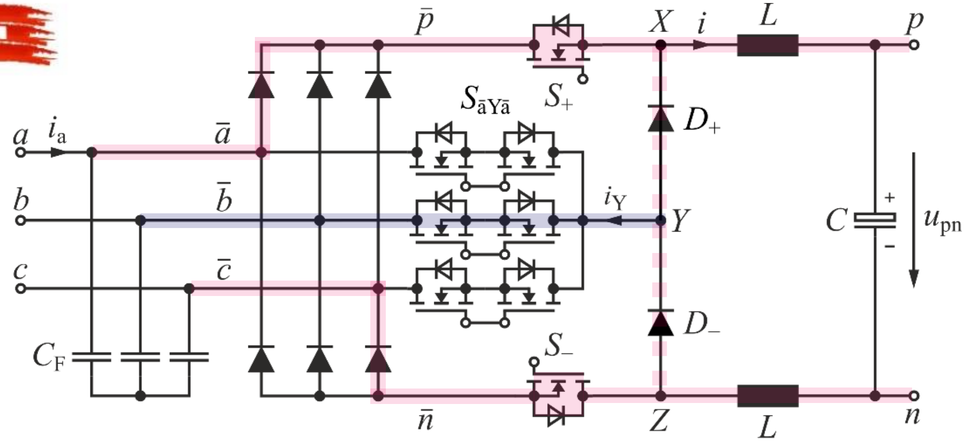


- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Swiss Rectifier

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



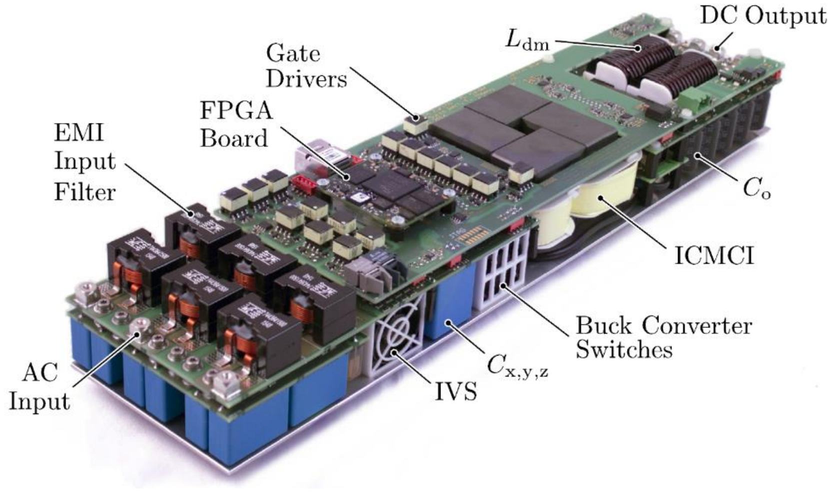


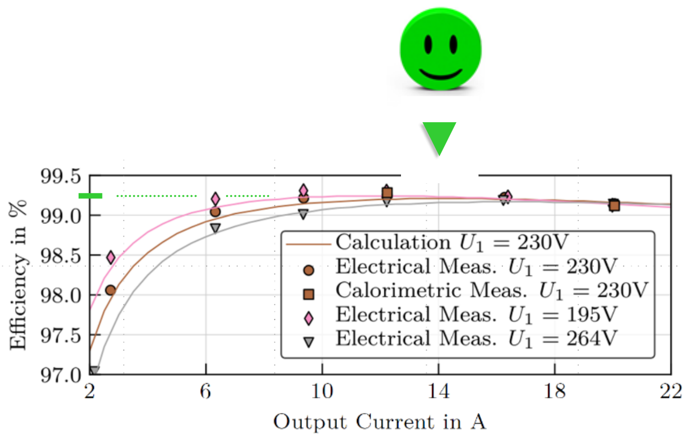
- *Low Complexity*

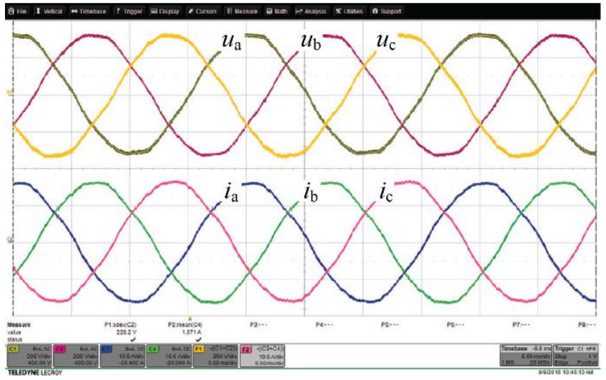
Swiss Rectifier Demonstrator

- *Efficiency η = 99.26% @ 60% Rated Load*
- *Mains Current $THD_I \approx 0.5\%$ @ 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 = 27kHz



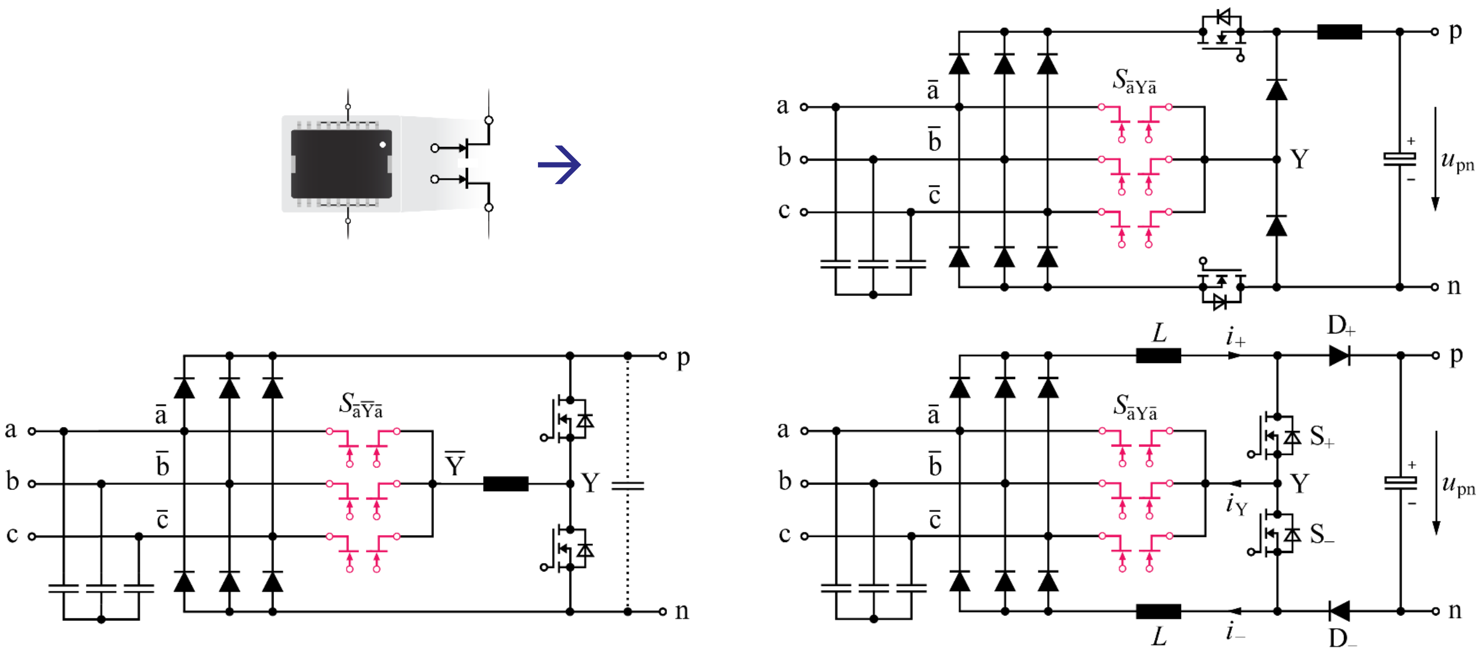




- *SiC Power MOSFETs & Diodes*
- *Integr. CM & Output Coupling Inductors (ICMCI)*

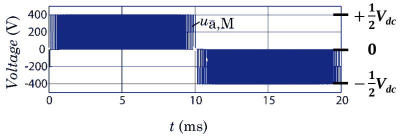
Remark M-BDS-Based 3rd Harm. Inj. Rectifiers

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



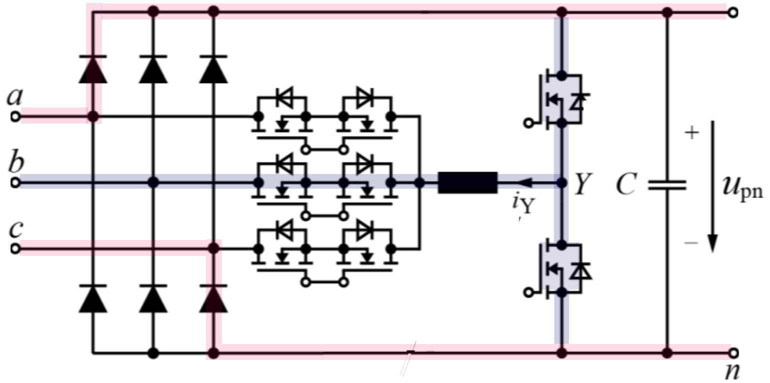
- *Mains Frequ. Operation of the Phase Selector Switches → Conduction Losses Only*

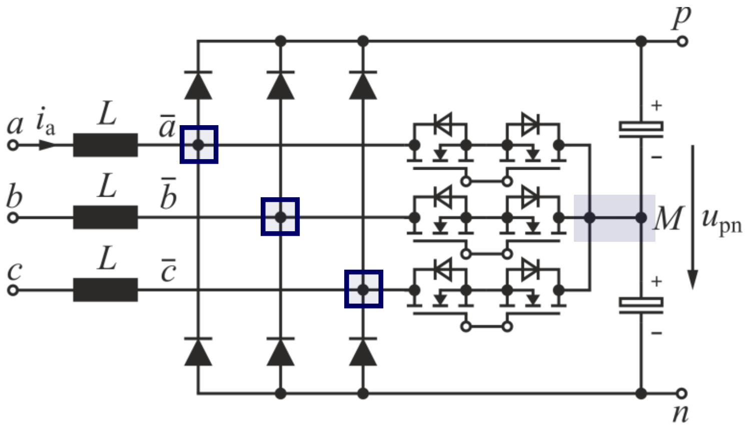
3-Level T-Type Boost PFC Rectifier



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





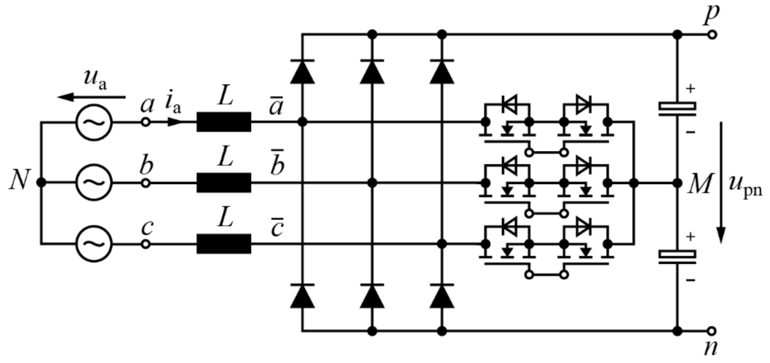
- Low Sw. Voltage Stress
- Low AC-Side Inductance
- Low Conduction Losses
- Bridge-Leg Symmetry & Phase Symmetry

Vienna Rectifier Demonstrator (1)

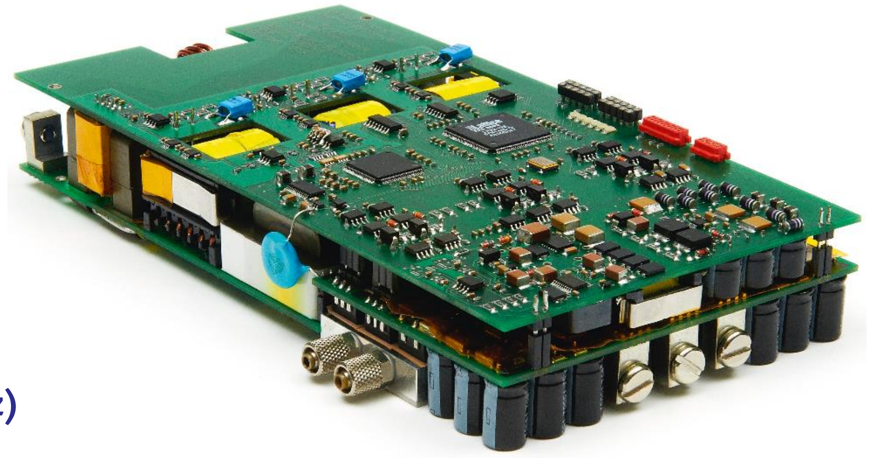
- *Design for More Electric Aircraft Application*
- *650V CoolMOS & 1200V SiC Diodes*
- *Coldplate Cooling*

P_0= 10 kW
U_N= 400V_{AC}±10%
f_N = 50Hz or 360…800Hz
U_0= 800V_{DC}

η =96.8%



★ *ρ = 10 kW/dm³*



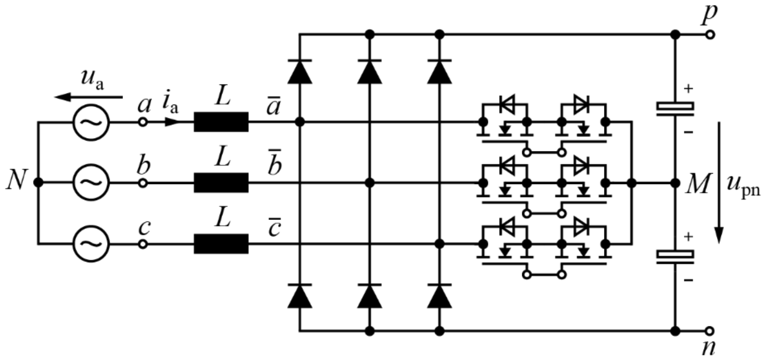
- *THD_i = 1.6%* @ f_N = 800Hz (f_P= 250kHz)

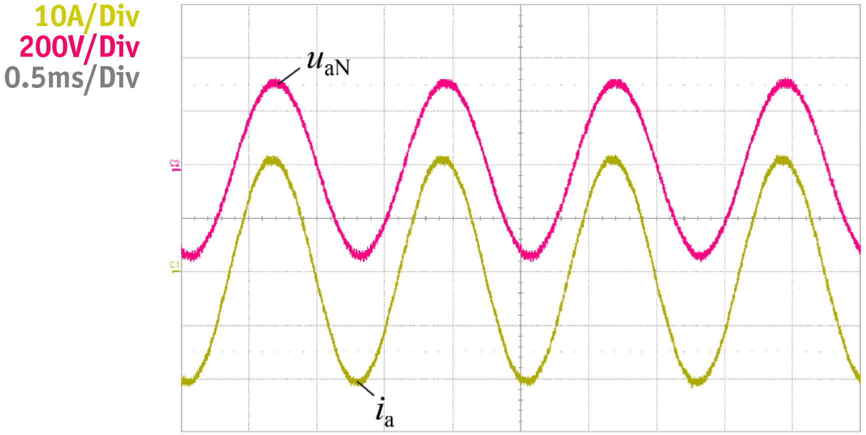
Vienna Rectifier Demonstrator (2)

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

P_0= 10 kW
U_N= 400V$_{AC}$±10%
f_N = 50Hz or 360…800Hz
U_0= 800V$_{DC}$

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

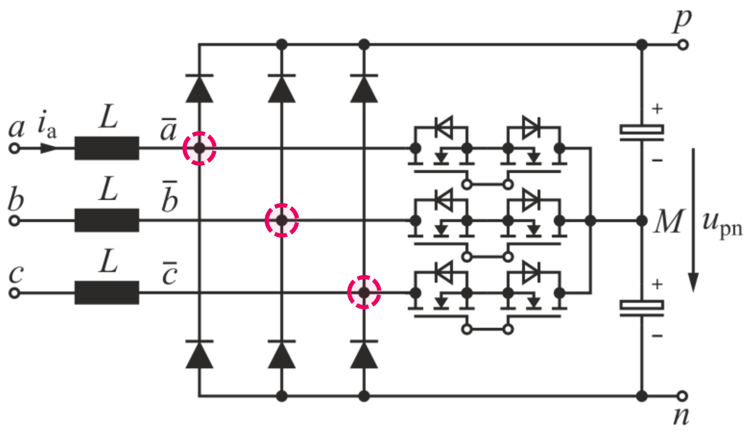


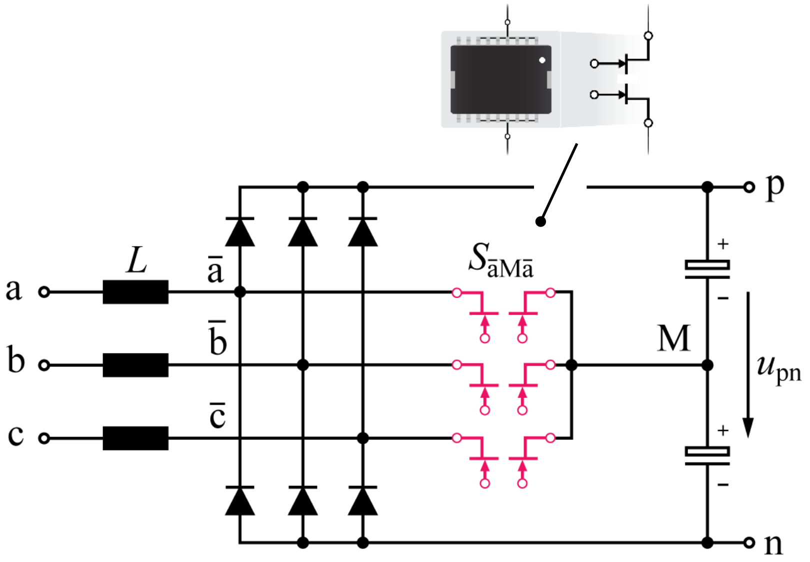


- *THD$_i$ = 1.6% @ f_N = 800Hz*
- *System Allows 2-Φ Operation*

Remark Application of M-BDSs

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





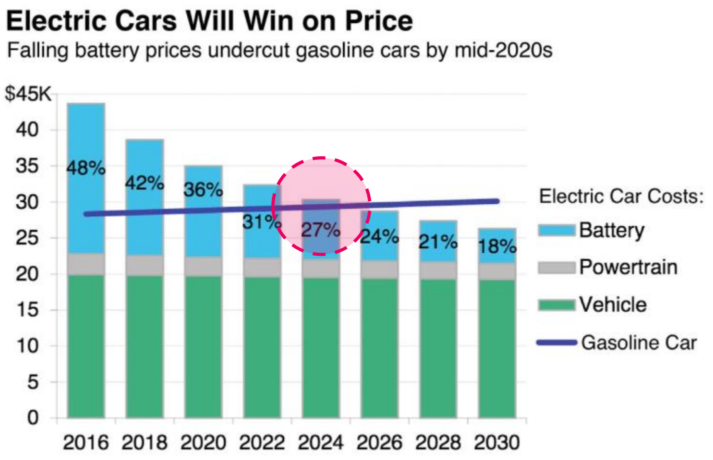
- 600 V *M-BDSs @ U_{pn}*= 800 V_{DC} *in Combination w/* 1200 V *SiC Diodes (MOSFETs for Bidir. Power Flow)*

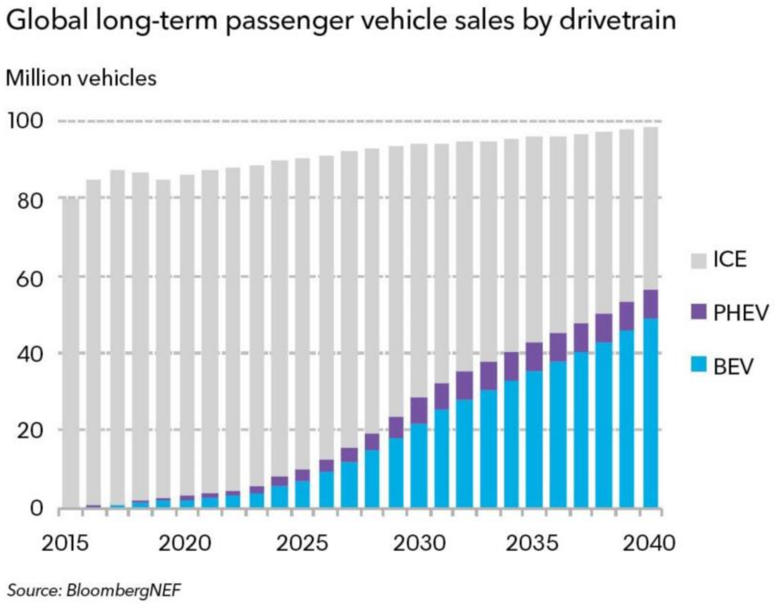
Global
Megatrends

Digitalization
Renewable Energy
Sustainable Mobility →
Industry Automation
Etc.

Electric Vehicle Outlook 2019

- *Bloomberg NEF — By 2040 — 57% of All Passenger Vehicle Sales*
  30% of Global Passenger Vehicle Fleet





- *Falling Battery Costs → Price Parity of EVs & ICE-V by Mid-2020s → Tipping Point for EV Industry*

Disruptive Innovations

- *Example — Rapid Change of Transportation Enabled by New Technology (ICE) & Business Model*
  Tony Seba: "All New Vehicles, Globally, will be Electric by 2030"

— NY City, 5th Av., Easter Parade → *Year 1900: One Motor Cycle / Year 1913: One Horse & Carriage (!)*

Source: Tony Seba

- *Further Examples — Digital / Analogue Photography, VHS Cassette Tape System / DVD etc.*
- *«The Stone Age Didn´t End for the Lack of Stones» (Disrupted by Bronze Tools)*

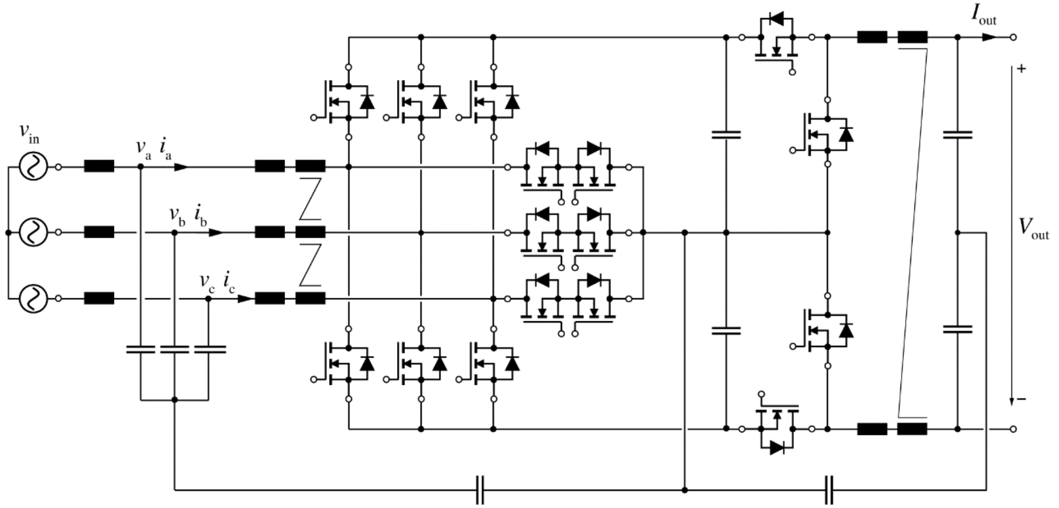
Ultra-Fast / High-Power EV Charging

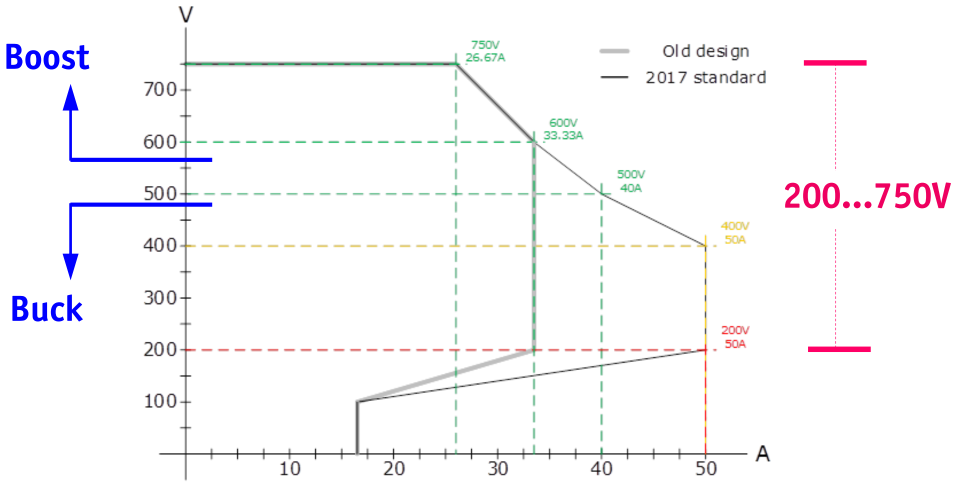
- *Modular Mains Interfaces | Future Non-Isolated Virtually Grounded Systems*
- *Very Wide Output Voltage Range (200...1000V)*

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

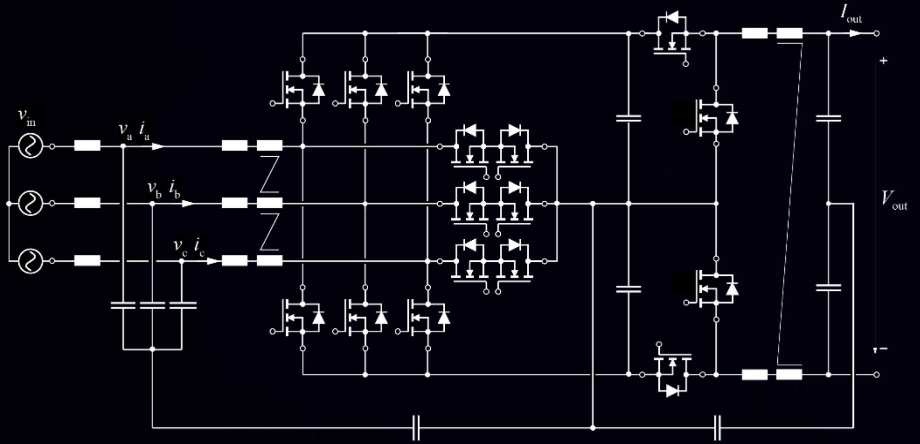
Bidir. *Boost-Buck* PFC Rectifier Concepts

- *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

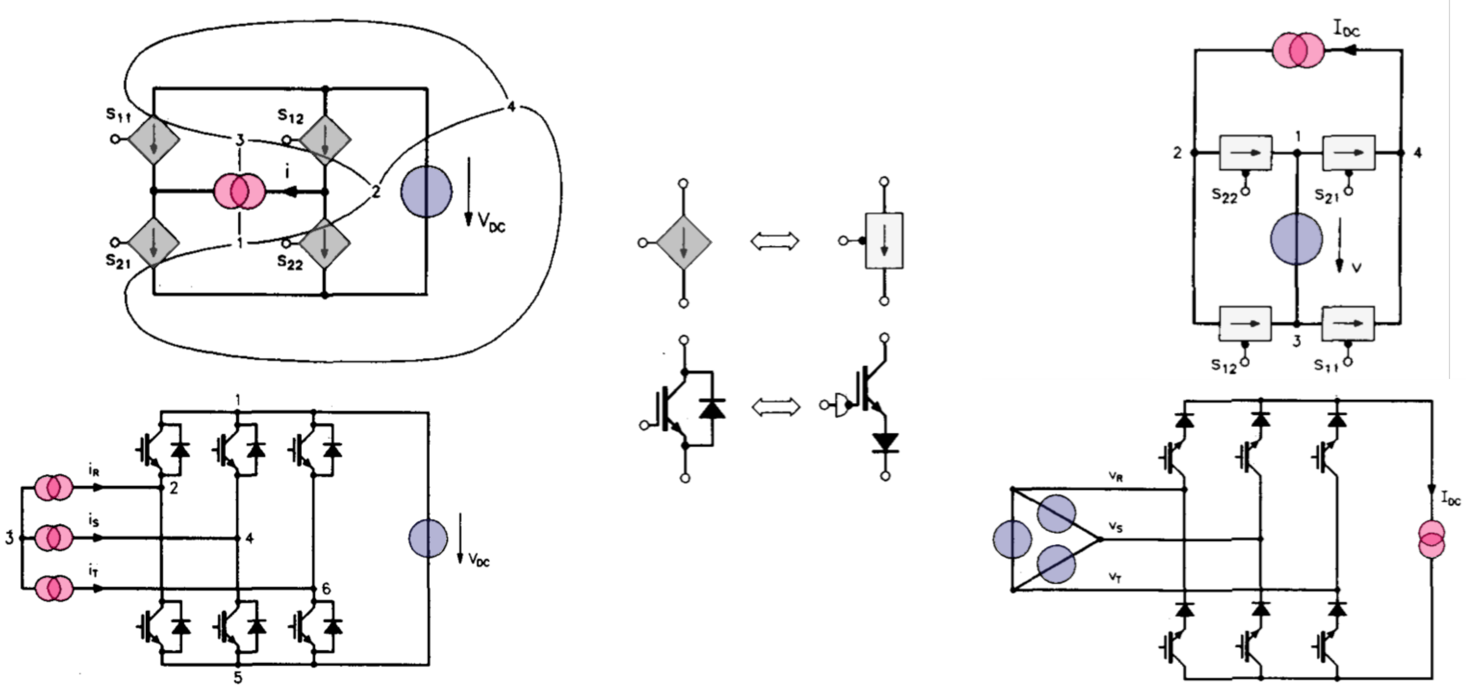
DUALITY

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*

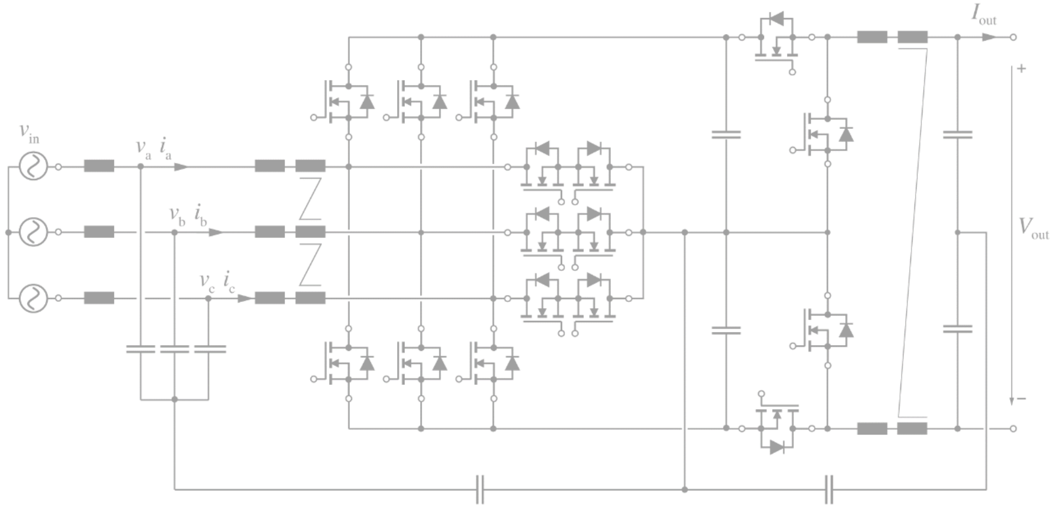
- *Duality of Voltage DC-Link & Current DC-Link Converter Circuits*
- *Unipolar Blocking / Bidir. Current → Bipolar Blocking Unidir. Switches → Appl. of M-BDSs (!)*

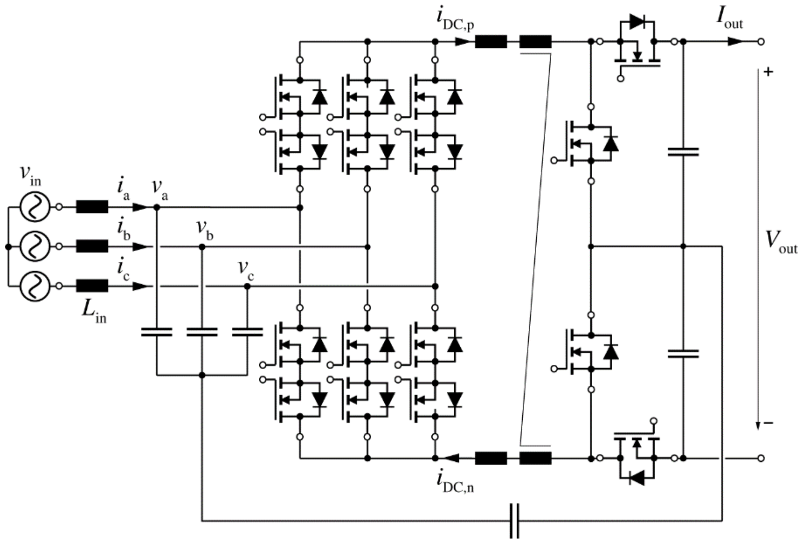


- *"Boost-Buck" Translated into "Buck-Boost" Functionality / Lower # of Ind. Components*

Bidir. *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*



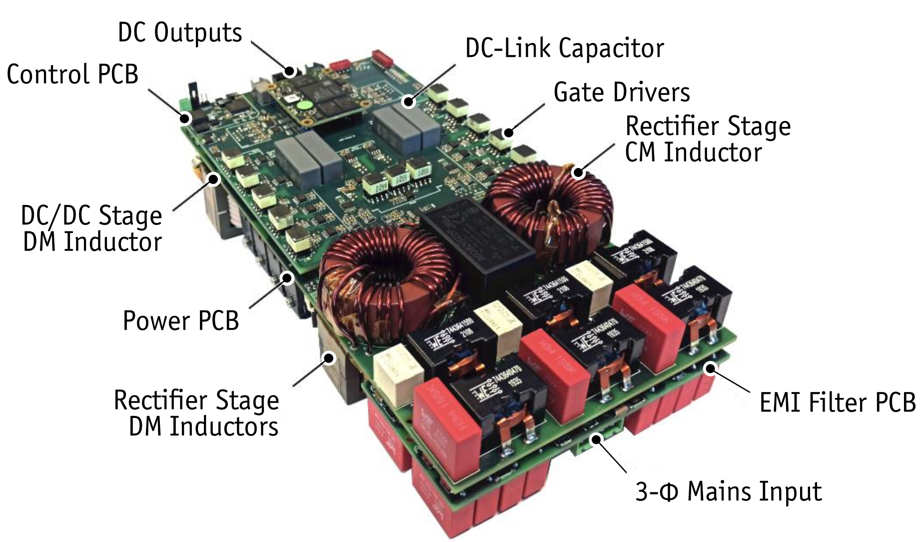


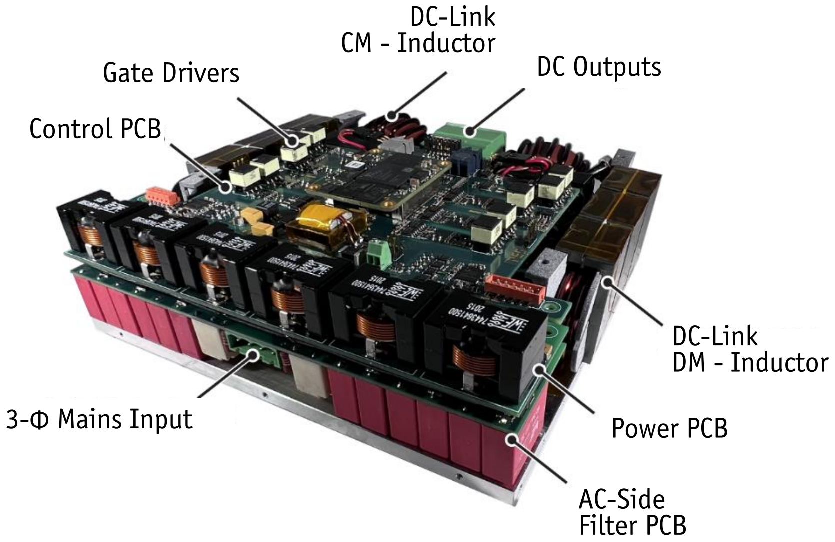
- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

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.*

- 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.*



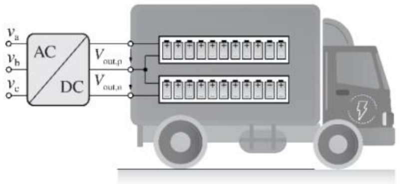


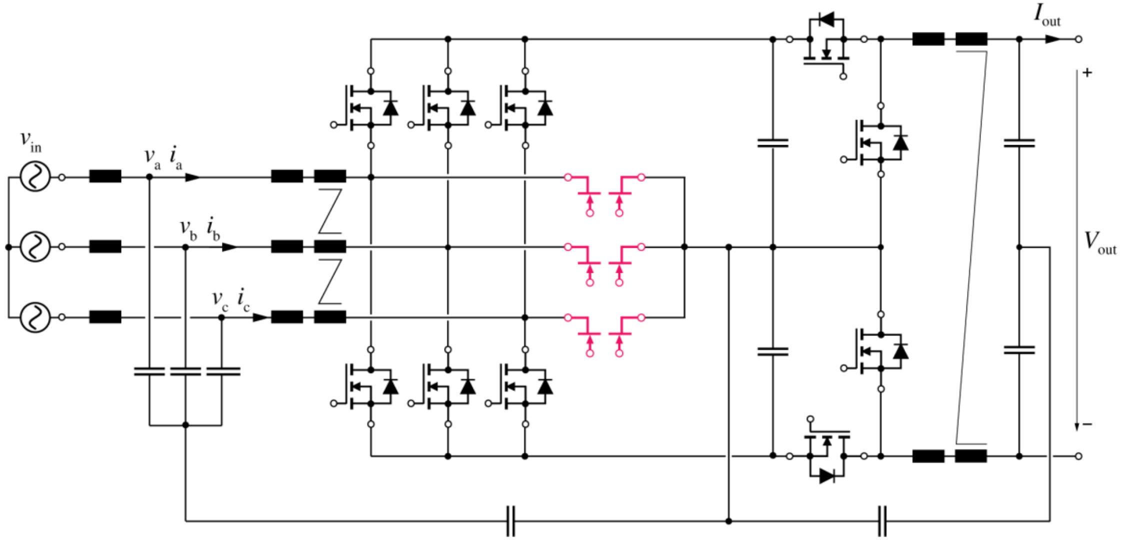
- *Boost-Buck Voltage DC-Link PFC Rectifier*

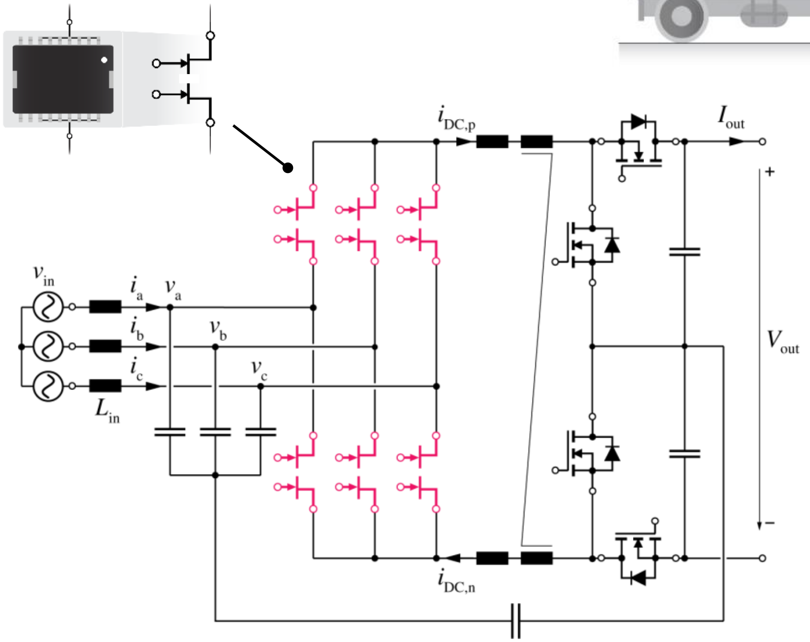
- *Buck-Boost Current DC-Link PFC Rectifier*

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*

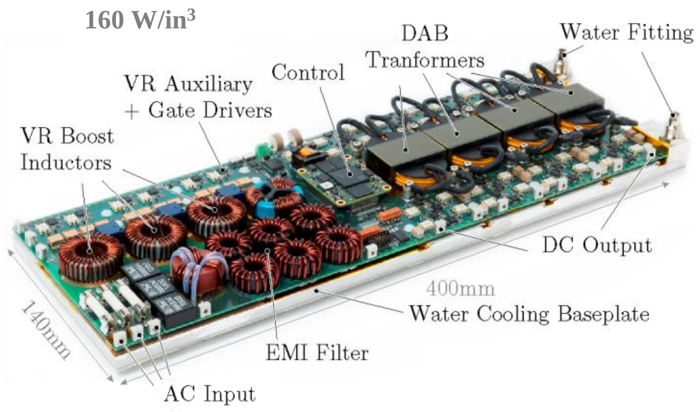
3-Φ Isolated Matrix-Type Single-Stage PFC Rectifier

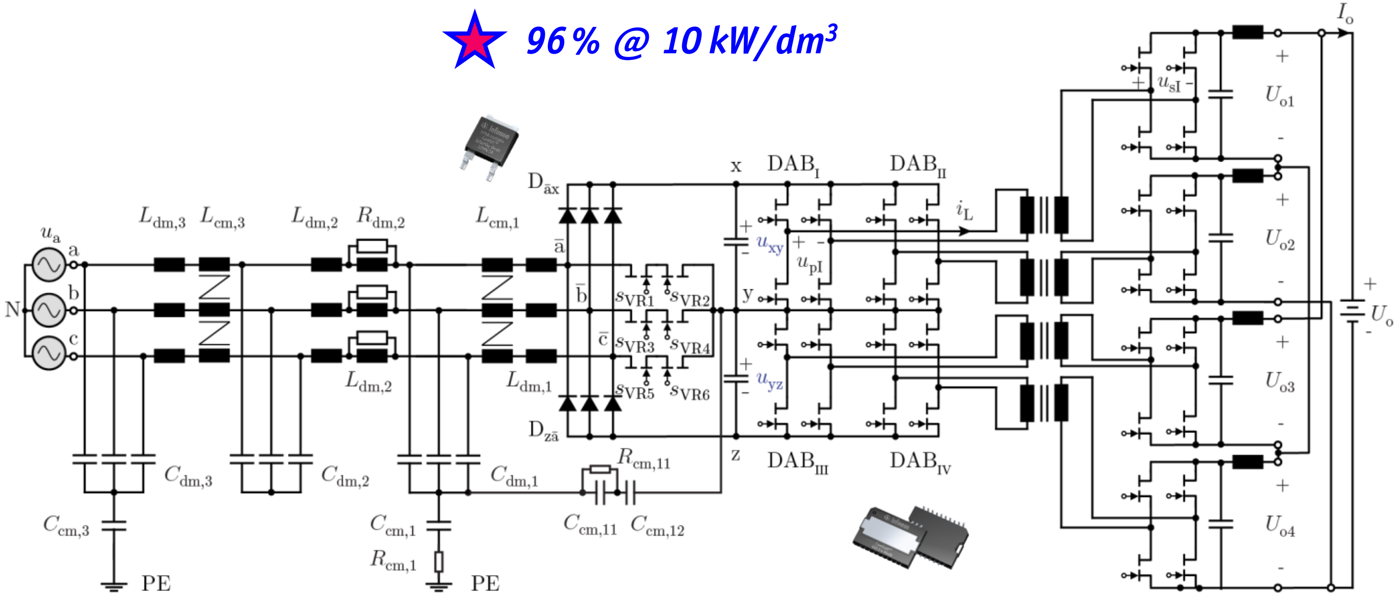
Isolated Two-Stage 3-Φ AC/DC Converter

- 3-Φ AC/DC Converter Front-End — Vienna Rectifier / Split DC-Link | f_{sw}=560 kHz
- 2x 2 Dual Active Bridge DC/DC Converter Isolation Stages | f_{sw} = 180…330 kHz

— P = 10kW
— U_{in} = 400 V_{AC} line-to-line
— U_{out} = 250 … 800 V_{DC}
— CISPR 11/ Class A

96 % @ 10 kW/dm³

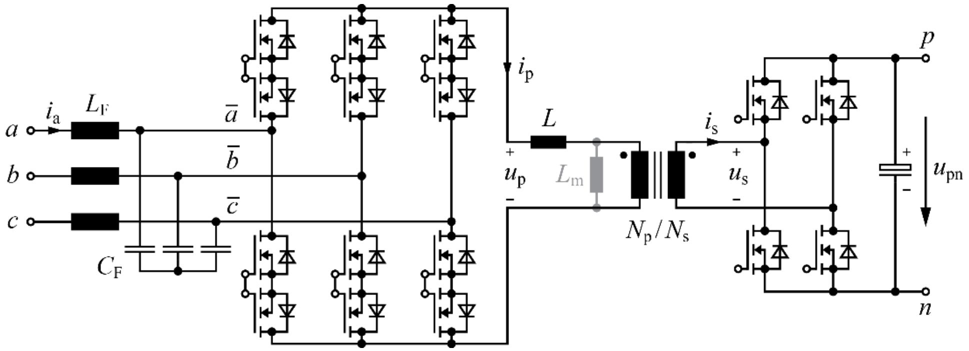


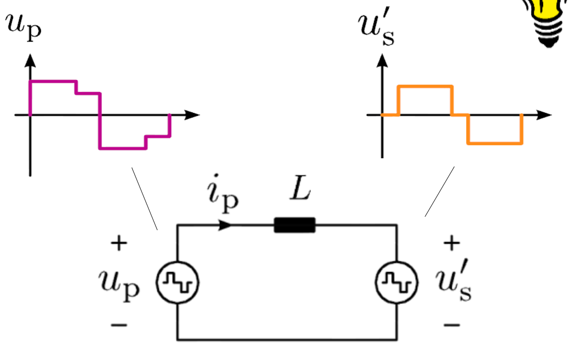


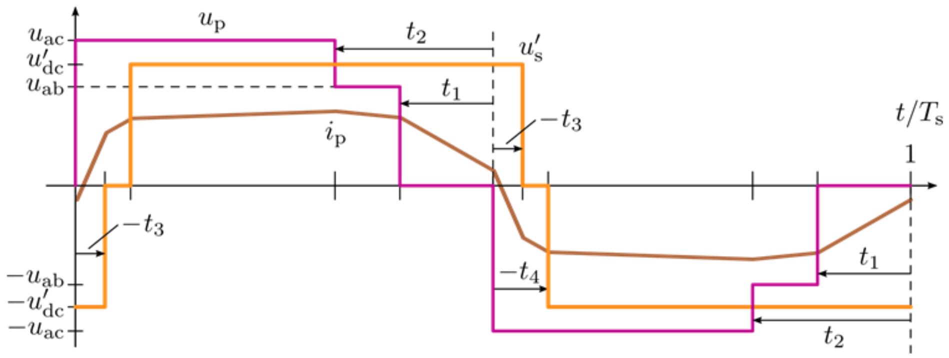
- 600V CoolGaN GIT HEMTs / 1200V CoolSiC Schottky Diodes
- Low Sw. Loss Synergetic Control of Input & Output Stage — Six-Pulse-Shaped DC-Link Voltage

Isolated Single-Stage 3-Φ AC/DC Converter

- Low-Frequ. 3-Φ AC / High-Frequ. 1-Φ AC Matrix Converter Input Stage
- Converter Operation Based on the Dual Active Bridge (DAB) Concept
- Bidirectional Buck-Boost Operation





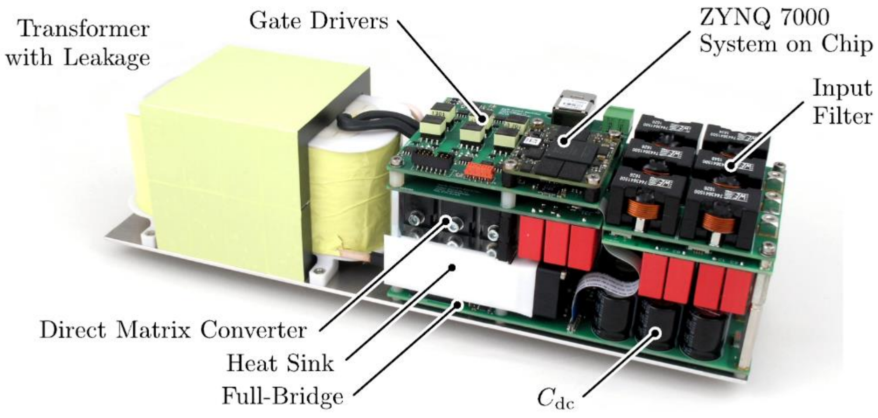


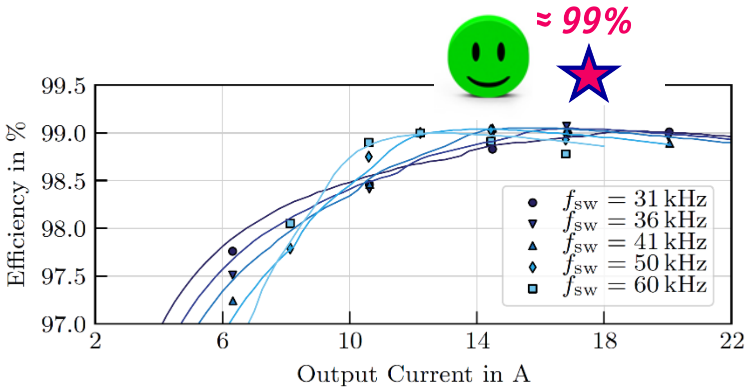
- Equivalent Circuit
- Transformer Voltages / Currents

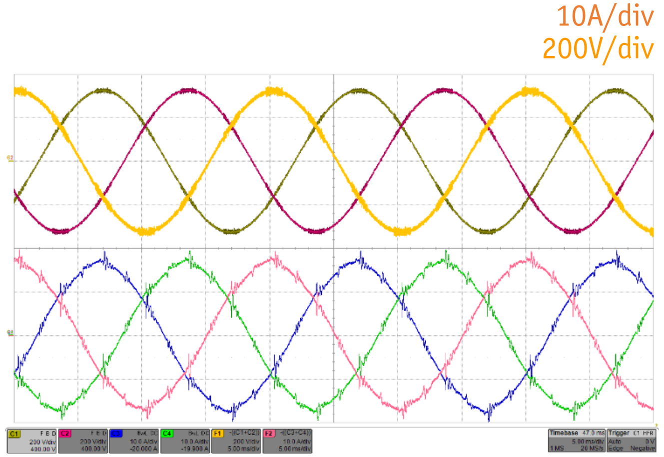
Isolated Matrix-Type 3-Φ PFC Rectifier Demonstrator

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

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



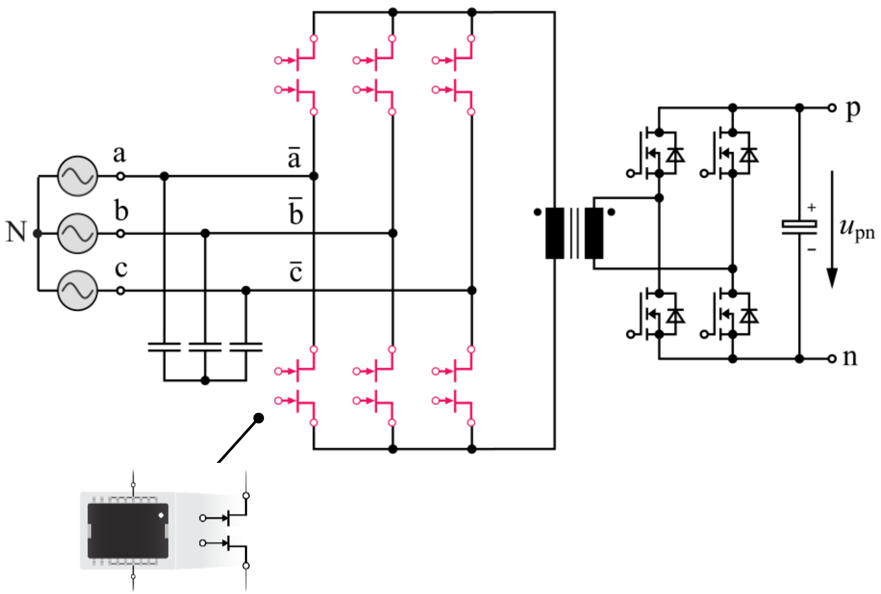


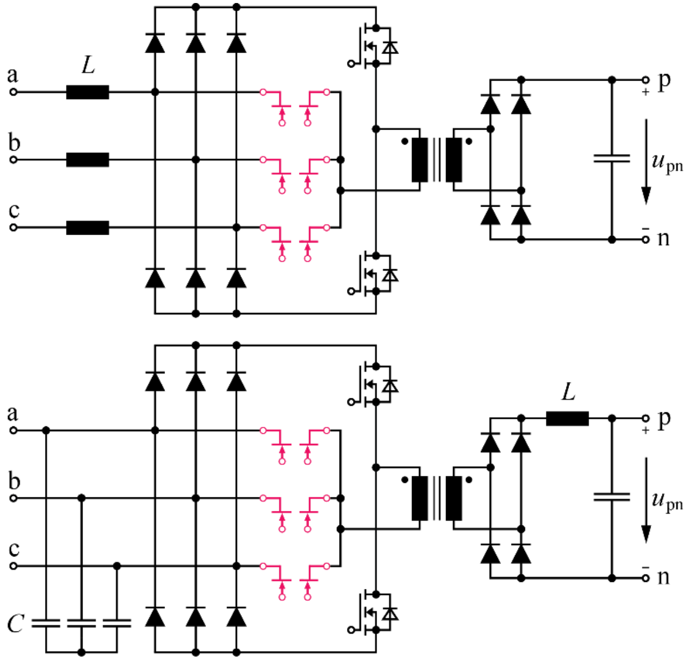


- *900V / 10mΩ SiC Power MOSFETs*
- *Opt. Modulation Based on 3D Look-Up Table*

Remark Application of M-BDSs

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



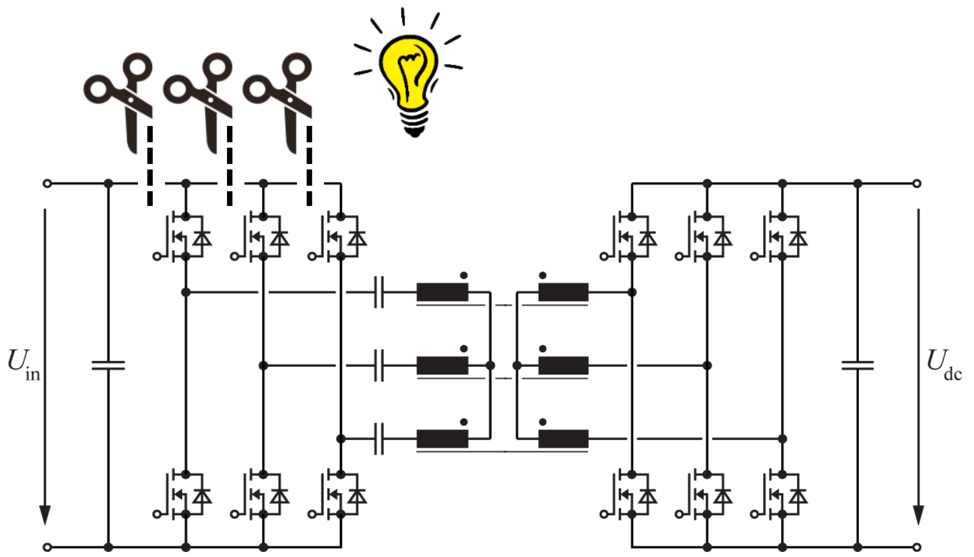


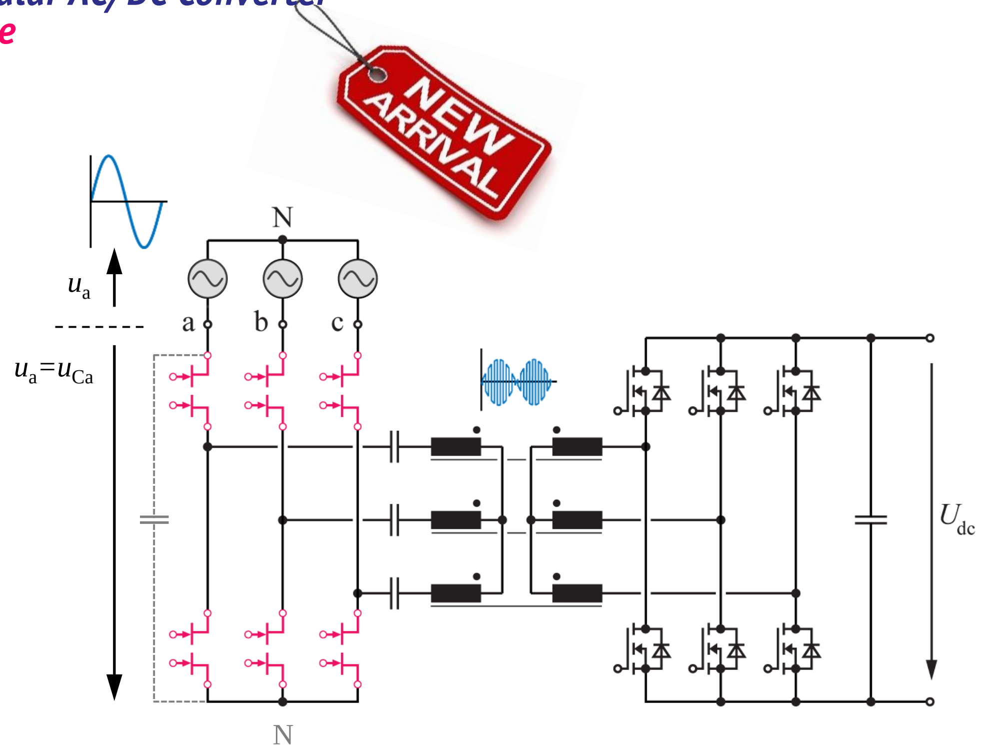
- *Functional Integration → Lower Complexity BUT Limited Controllability*
- *Rated 3-Φ Output Power NOT Available in 1-Φ Line-to-Line Operation*
- *Rated Power Operation for 3-Φ AND 1-Φ Grid Connection → Requires Phase-Modular Input Stage*

New 3-Φ OR 1-Φ Input
Full Rated Power Operable Single-Stage Isolated PFC Rectifier

3-Φ Input DAB-Type AC/DC Converter

- *Modification of 3-Φ Xfrm DAB → Prim.-Side Phase-Modular AC/DC Converter*
- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle*
- *DAB-Type OR Series Res. Converter Operation*

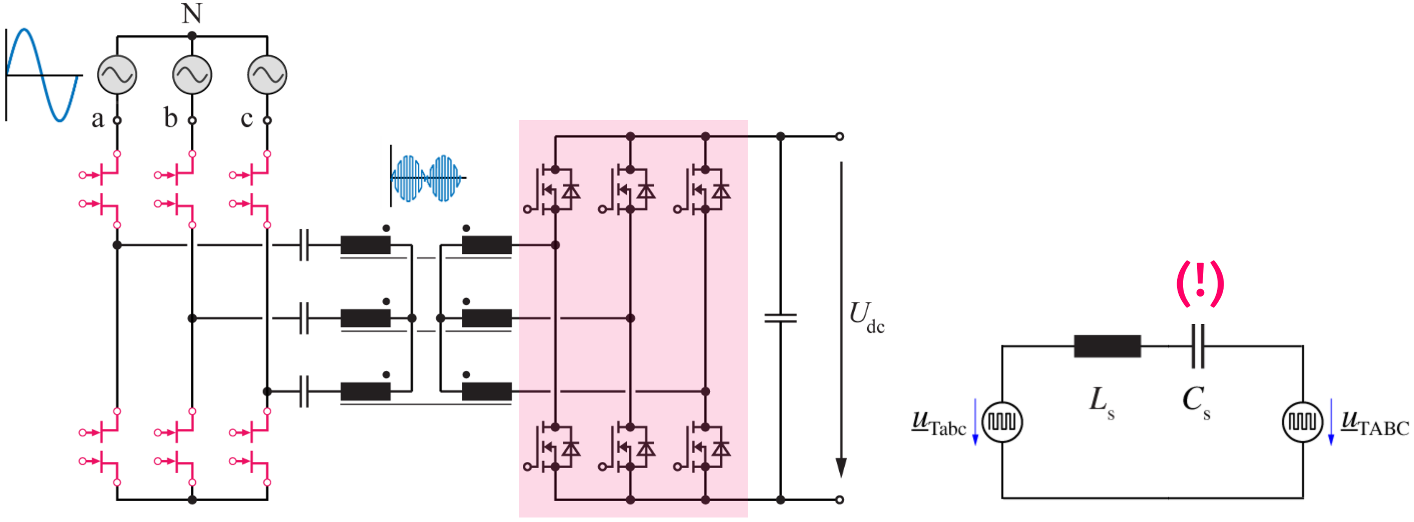


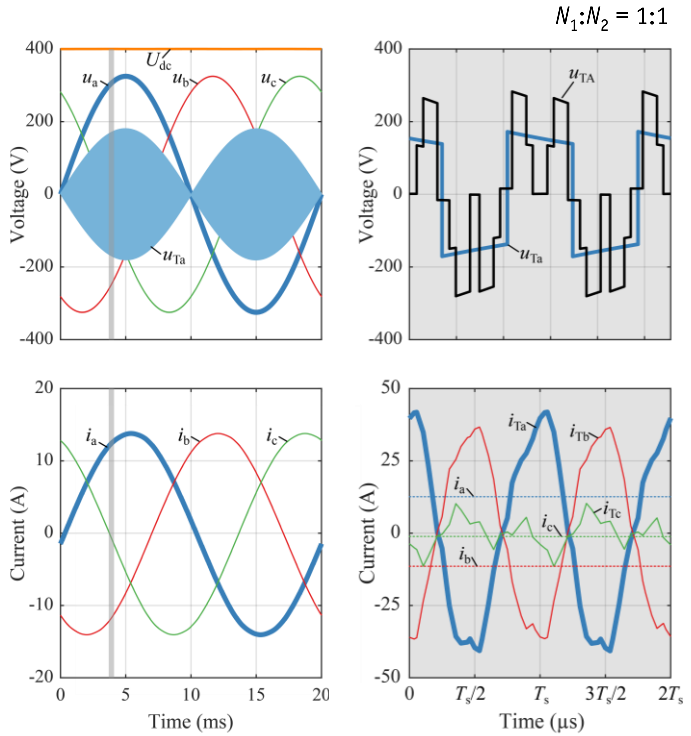


- *Voltage Stress on AC-Side Power Transistors Determined by PHASE Voltage Amplitude (!)*
- *600V GaN MBDS for 400V RMS Line-to-Line Grid (U_{pk} = 560V)*
- *Unity Power Factor / Bidirectional*

Remark 3-Φ Input Single-Stage Isol. PFC Rectifier

- *Full Rated Power Operation @ 3-Φ AND 1-Φ Grid Input (!)*
- *Synchronized (!) Prim.-Side Switching @ 50% Duty Cycle | L_{stray}, C_{res} Tuned to f_{sw}*
- *Sec.-Side Replicates Prim.-Side Voltage Local Avg. Values @ 2 x f_{sw}*

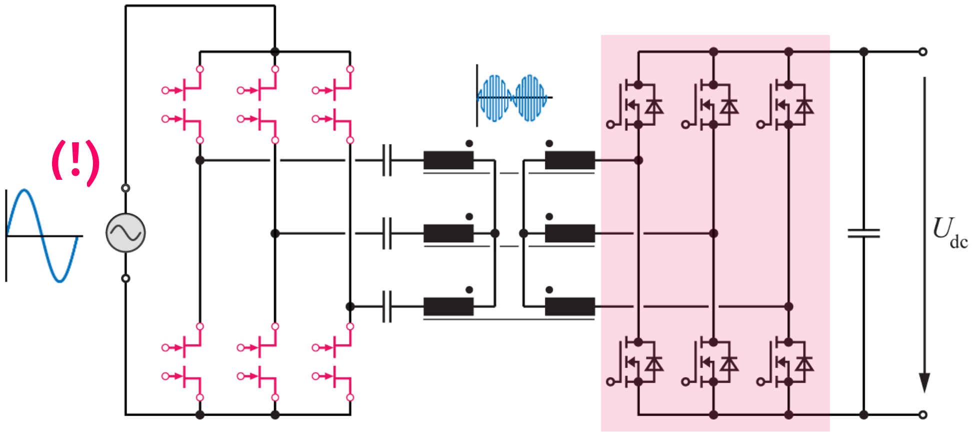


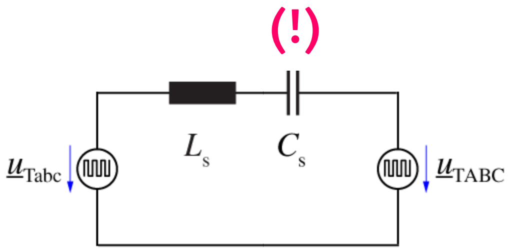


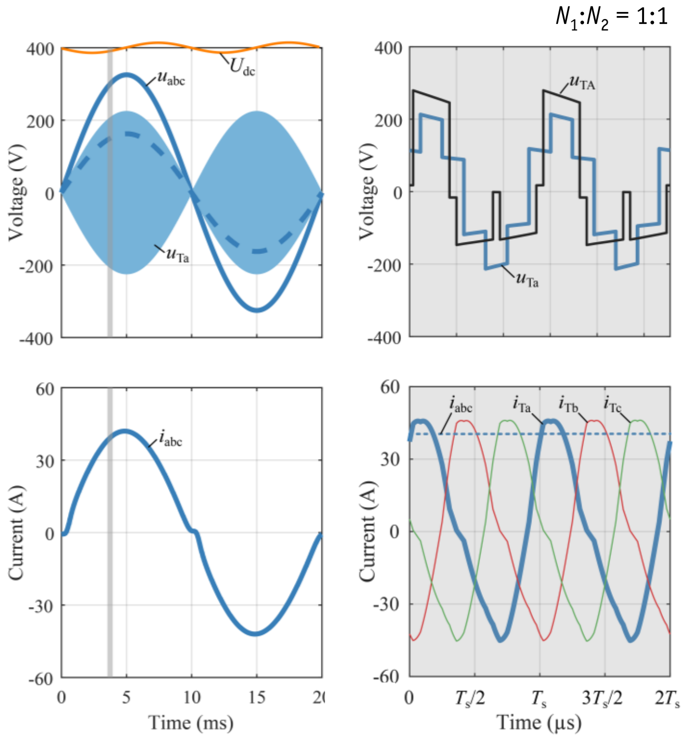
- *Boost Operation w/ Sec.-Side Zero Volt. Intervals | Buck Operation w/ Prim.-Side Zero Volt. Intervals*
- *Sinusoidal Grid Currents / Bidirectional Power Flow*

Remark 1-Φ Input Single-Stage Isol. PFC Rectifier

- *All Prim.-Side Phase Modules Operated in Parallel*
- *120° Phase-Shifted Sw. @ 50% Duty Cycle & Res. Frequency*
- *3-Φ Sw. Frequ. Six-Step Voltage Syst. Applied to Xfrm Primary*
- *Sec.-Side Mod. Replicates Prim.-Side Phase Voltage Local Avg. Values*





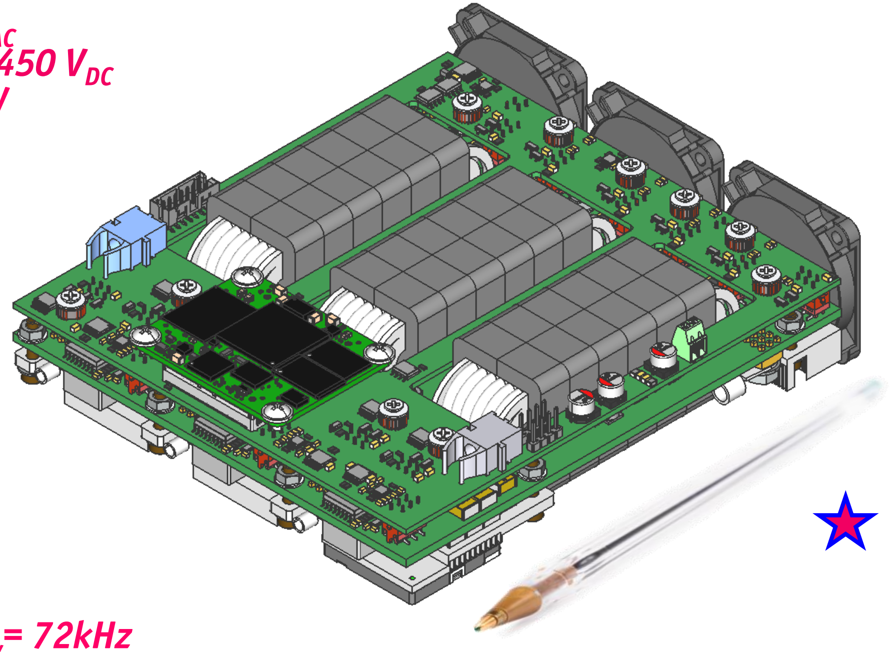


- *Boost Operation w/ Sec.-Side Zero Volt. Intervals* | *Buck Operation w/ Prim.-Side Zero Volt. Intervals*
- *Sinusoidal Grid Currents / Bidirectional Power Flow*

3-Φ & 1-Φ Full Power Operable PFC Rectifier

- *Voltage Stress on AC-Side Power Transistors Determined by PHASE Voltage Amplitude (!)*
- *600V GaN MBDS for 400V RMS Line-to-Line Grid ($U_{L\text{-}L,pk}$ = 560V)*
- *Unity Power Factor / Bidirectional*

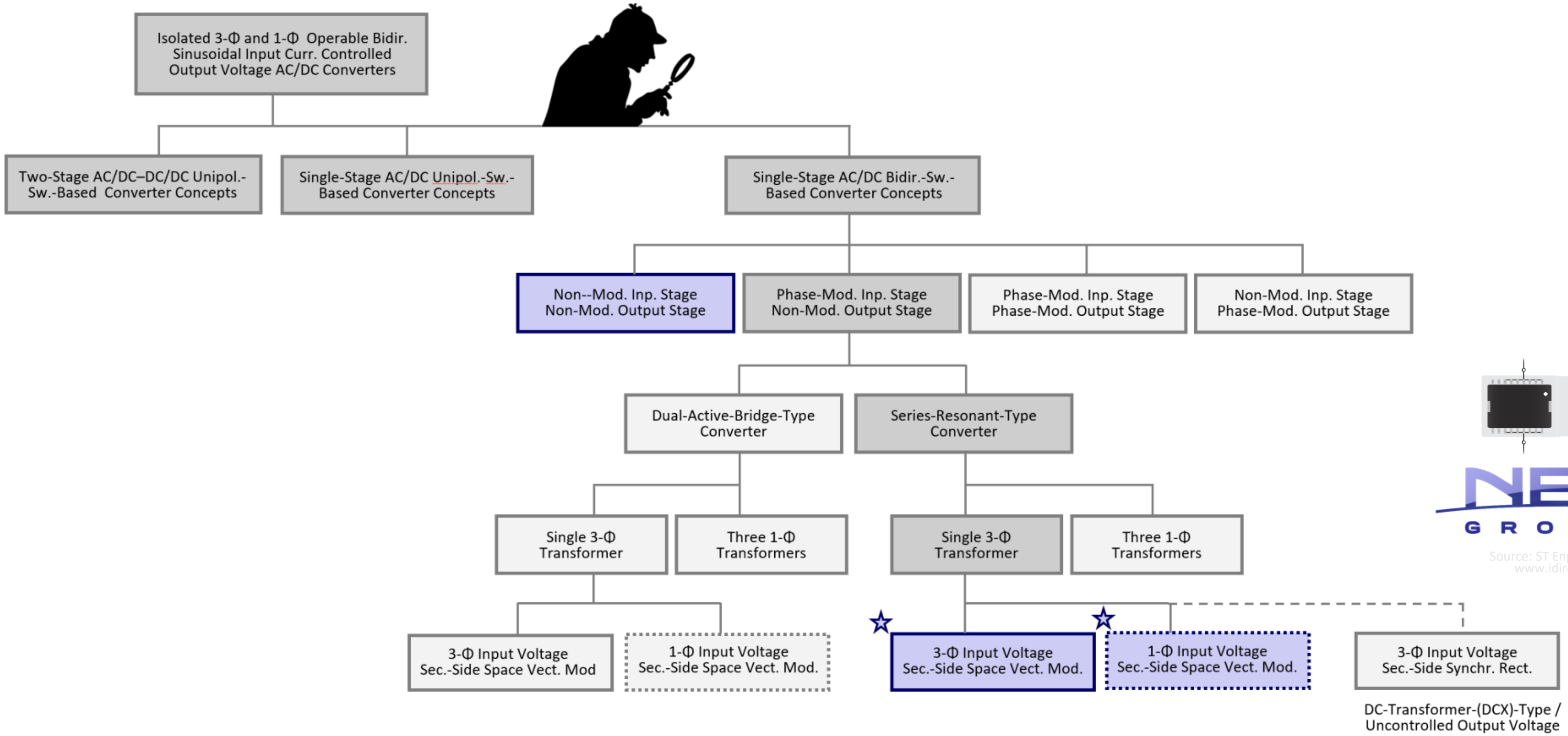
- *Line-to-Line Input* 400 V_{AC}
- *DC Output* 250…450 V_{DC}
- *Rated Output Power* 6.6 kW

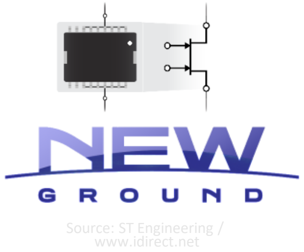


★ *98% (typ.) @ 8kW/dm³*

- *Prim.-Side Sw. Frequency f_{sw} = 72kHz*
- *14.5 x 13.1 x 3.7 cm³ / 5.7 x 5.2 x 1.5 in³*
- *Power Density w/ EMI-Filter ≈ 6kW/dm³ (98W/in³)*

Classification of Isolated PFC Rectifier Topologies





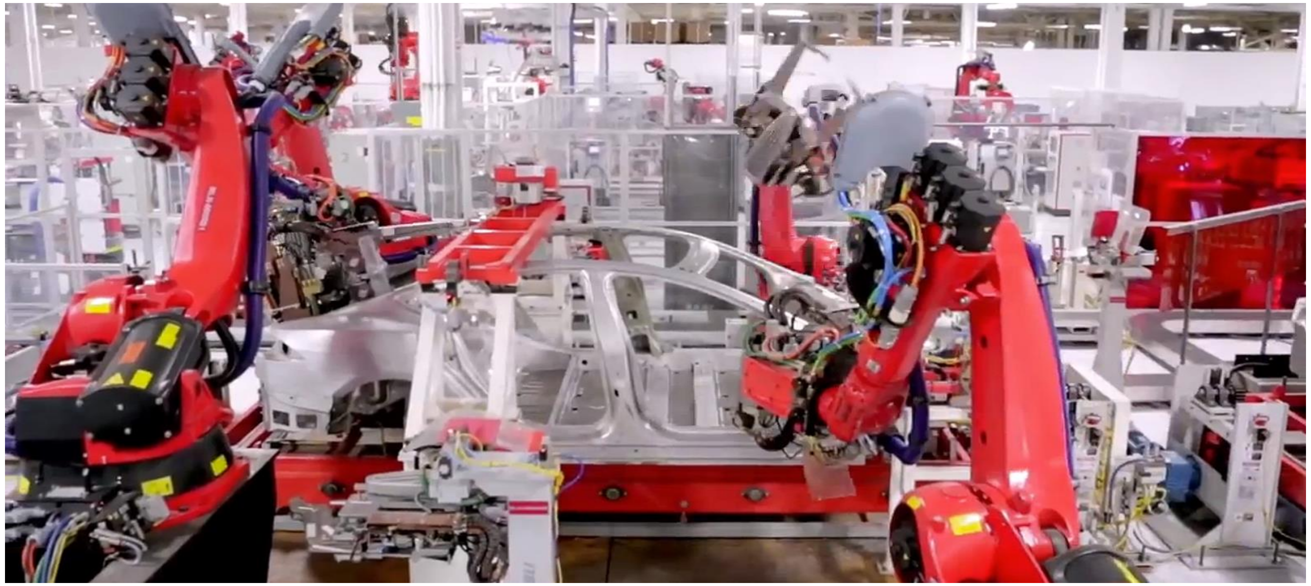
- *Numerous New BDS-Based Single-Stage Conv. Concepts & Related Mod. Schemes (!)*

Global Megatrends

- *Digitalization*
- *Sustainable Mobility*
- *Renewable Energy*
- ***Industry Automation*** →
- *Etc.*

Variable Speed Motor Drive (VSD) Systems

- *Industry Automation / Robotics*
- *Material Machining / Processing – Drilling, Milling, etc.*
- *Compressors / Pumps / Fans*
- *Transportation*
- *etc., etc.* *.... Everywhere !*

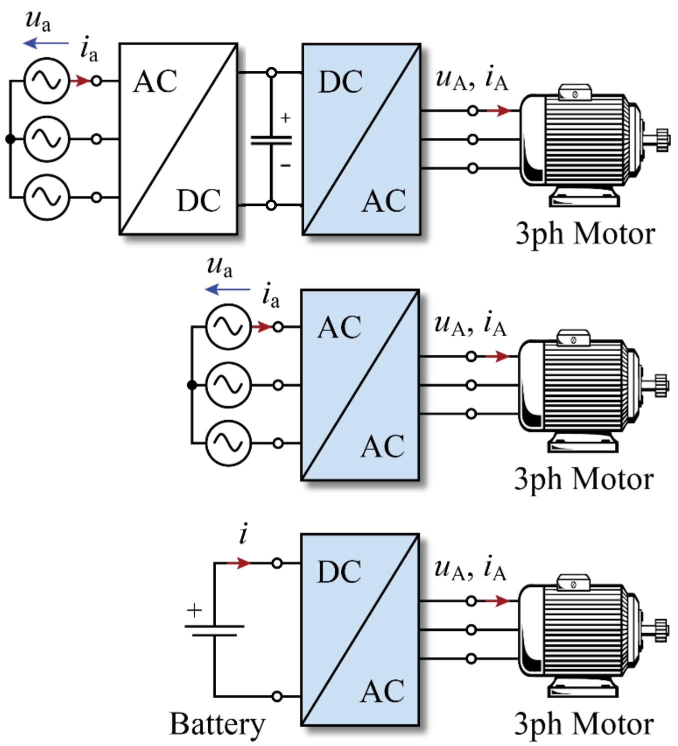


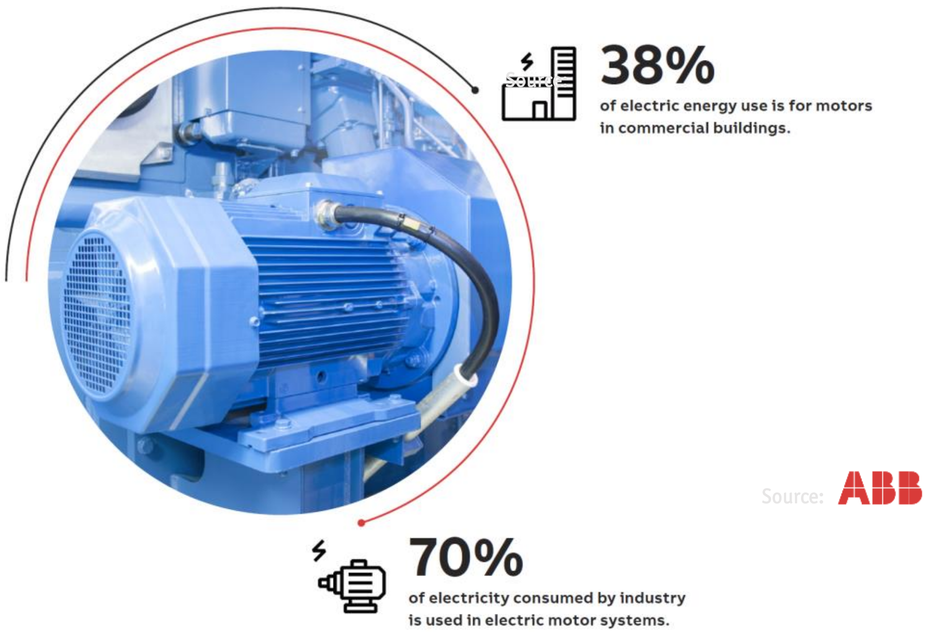
Source: TESLA MOTORS

- *60...70 % of All Electric Energy Used in Industry Consumed by VSDs*

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*

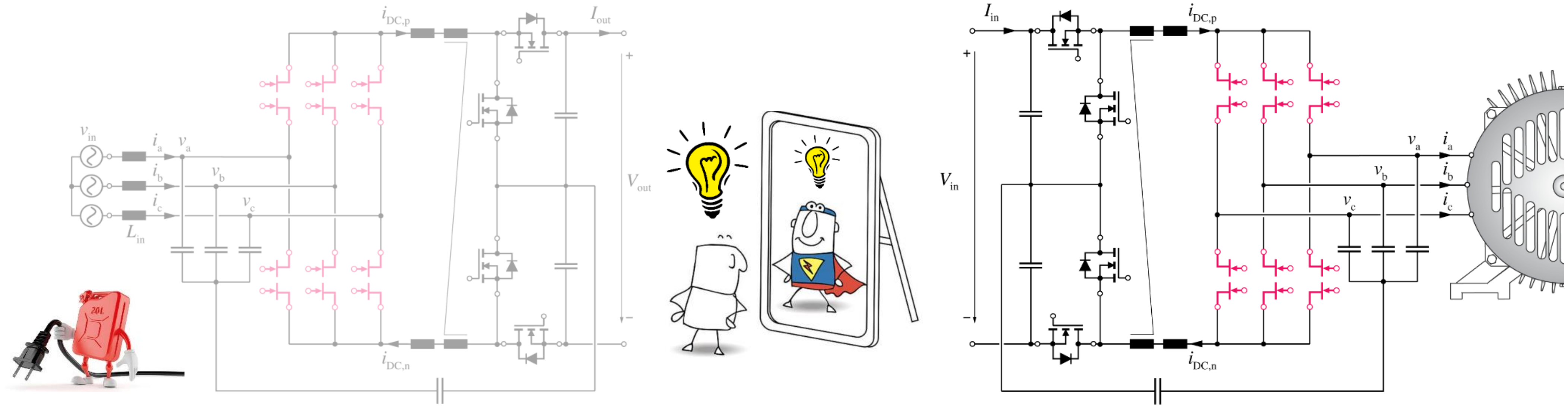




- *45% of World's Electricity Used for Motors in Buildings & Industrial Applications*

Current DC-Link *Buck-Boost* Inverter (1)

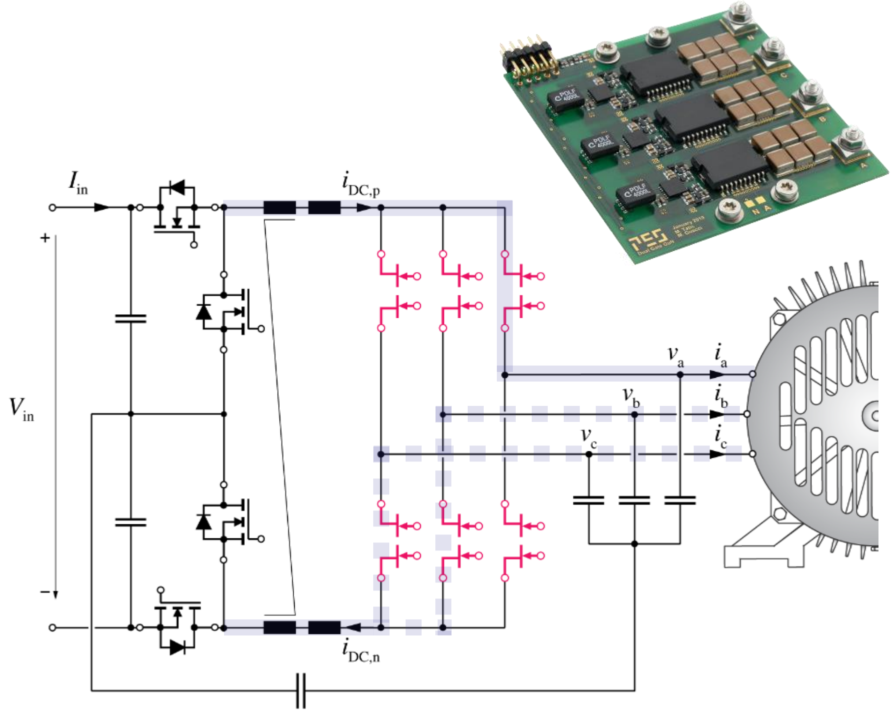
- *Derivation Based on Bidirectional Buck-Boost PFC Rectifier Topology (EV Charger)*
- *Lower # of Ind. Components Compared to Boost-Buck Approach*

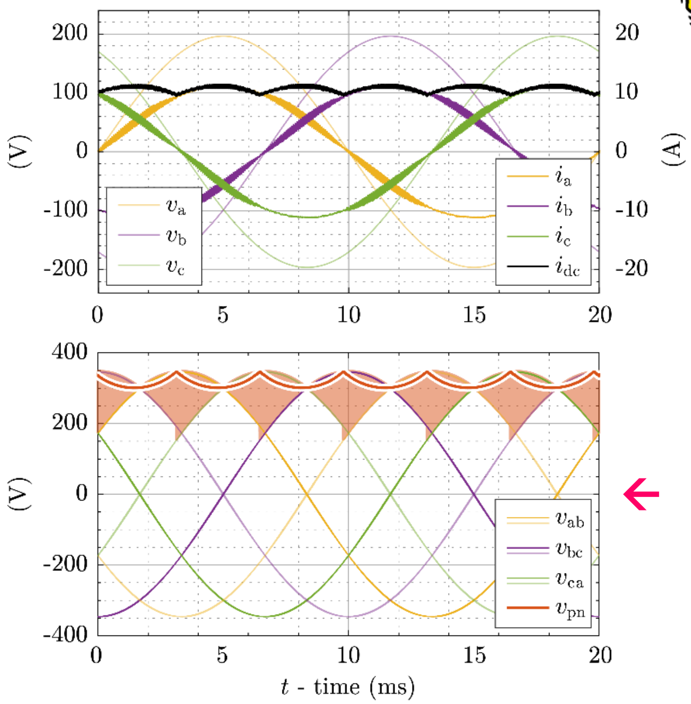


- *DC/DC Buck Converter Performs Voltage → Current Translation*
- *Coordinated Control / Modulation of DC/DC & Inverter Stage for Min. Sw. Losses*

Current DC-Link *Buck-Boost* Inverter (2)

- *"Synergetic" Control of DC/DC Buck Converter & Current DC-Link Inverter Stage*
- *6-Pulse-Shaping of DC Current by Buck-Stage → Allows Inverter Phase Clamping*



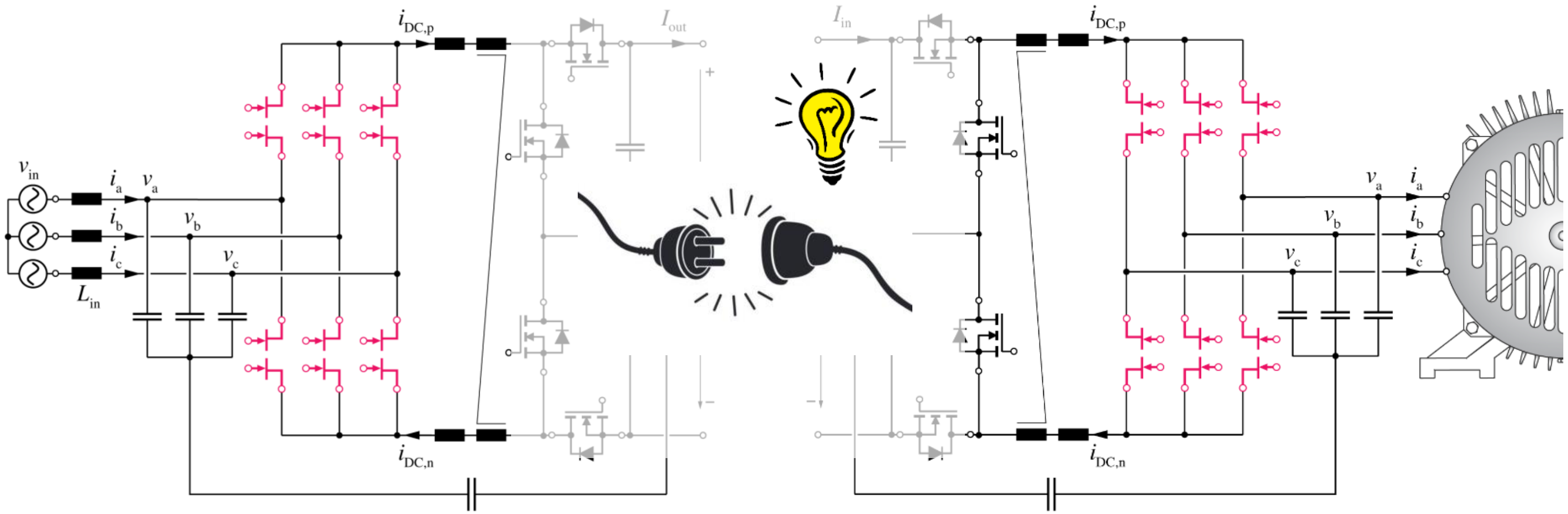


- *Switching of Only 2 of 3 Phase Legs → Reduction of Sw. Losses by ≈ 86% (!)*

3-Φ AC/AC Conversion

3-Φ Current DC-Link AC/AC Converter (1)

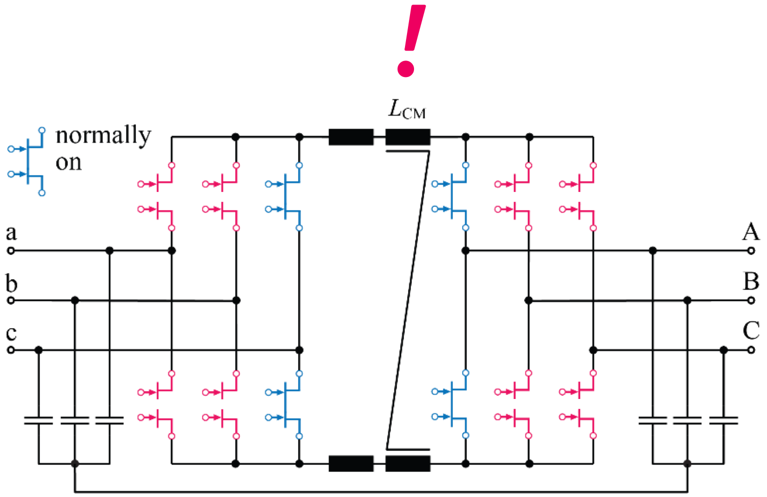
- *DC-Side Coupling of Buck-Boost Current DC-Link PFC Rectifier & Inverter — AC/DC/AC*
- *Full Sinewave Filtering @ Input & Output w/ Single Magnetic Component*



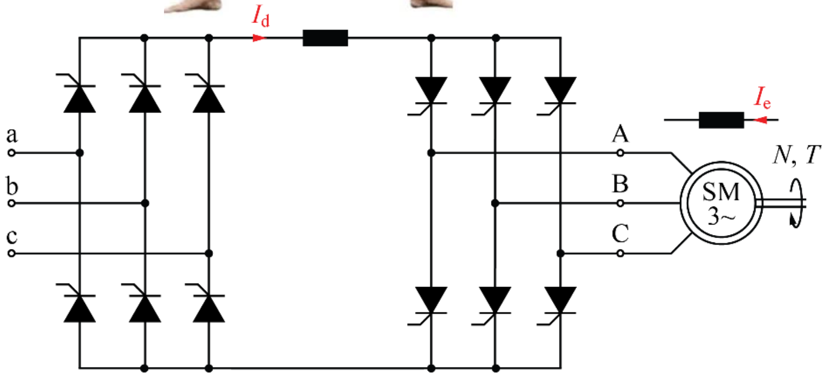
- *Bipolar Blocking / Unidir. Switches / Unidir. DC-Link Current Sufficient for Bidir. Power Conversion*
- *Modulation-Based Inversion of DC-Link Voltage Polarity → Inv. of Power Flow Direction*

3-Φ Current DC-Link AC/AC Converter (2)

- *Sinusoidal Motor Voltage Achieved w/ Single Ind. Component*
- *Unidir. Valves Sufficient for Bidir. Power Conversion*
- *M-BDSs — Synchronous Rectification*



Source: www.mb-drive-services.com

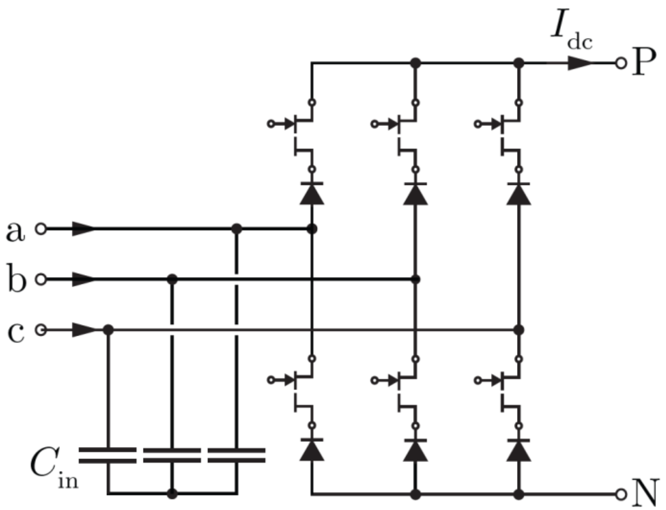


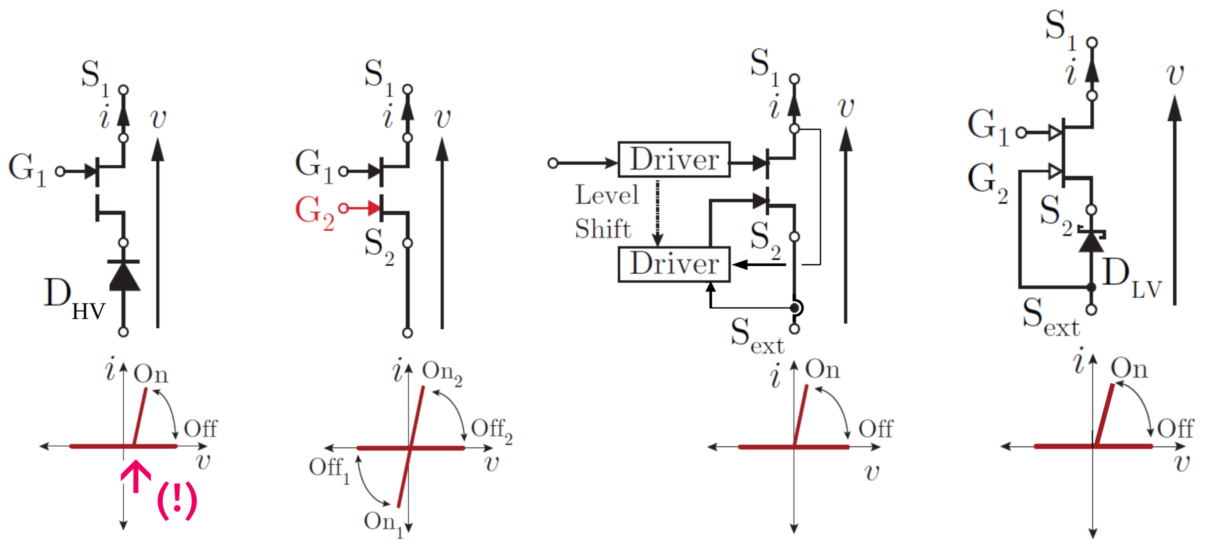
- *Relation to High-Power Thyristor-Based Medium Voltage Synchr. Machine Variable Speed Drives*

Remark Self Reverse-Blocking M-BDS (1)

- *Bidir. Curr. DC-Link Converters — Unidir. I_{dc} & Bipolar U_{dc} OR Bidir. I_{dc} & Unipolar U_{dc}*

- *HV Switch + HV Diode* — *HV Diode Characteristic / High Cond. Losses*
- *M-BDS* — *Ohmic Cond. Char. BUT 2 External Gate Signals / 2 Gate Drives*
- *"Self-Switching"* — *Ohmic Cond. Char. BUT High Local Complexity (Sensing)*



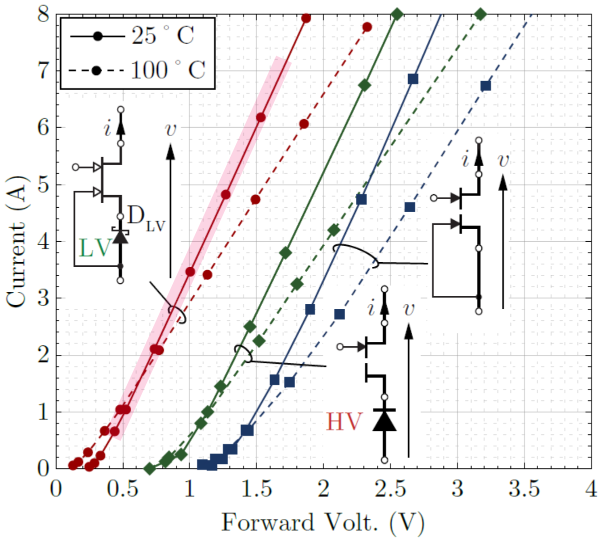


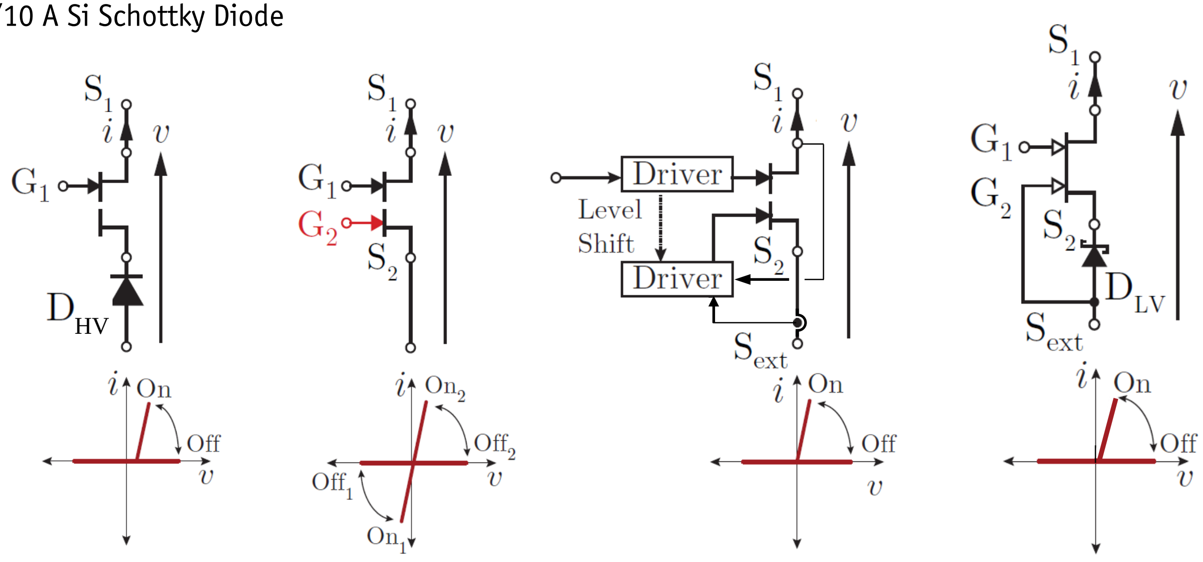
- *SRB-MBDS* — *Quasi-Ohmic Cond. Char. (Cascode w/ LV Si Schottky Diode) & 1 External Gate*

Remark Self Reverse-Blocking M-BDS (2)

- *Bidir. Curr. DC-Link Converters — Unidir. I_{dc} & Bipolar U_{dc} OR Bidir. I_{dc} & Unipolar U_{dc}*
  - *HV Switch + HV Diode* — *HV Diode Characteristic / High Cond. Losses*
  - *M-BDS* — *Ohmic Cond. Char. BUT 2 External Gate Signals / 2 Gate Drives*
  - *"Self-Switching"* — *Ohmic Cond. Char. BUT High Local Complexity (Sensing)*

600 V 190 mΩ GaN M-BDS
40 V/10 A Si Schottky Diode





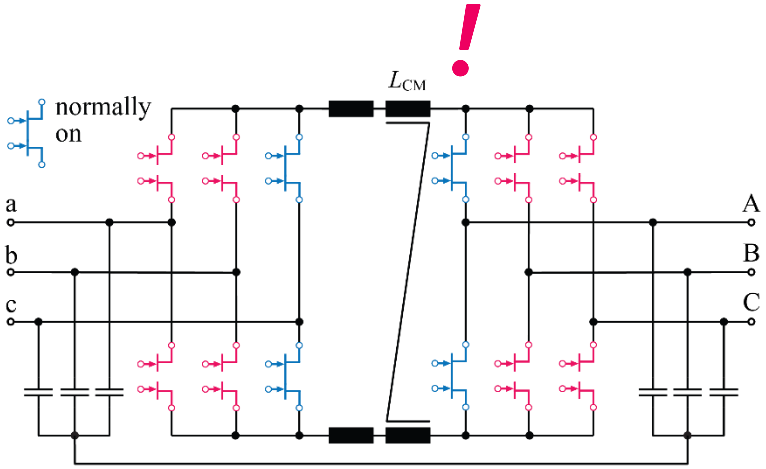
(!)

- *SRB-MBDS* — *Quasi-Ohmic Cond. Char. (Cascode w/ LV Si Schottky Diode) & 1 External Gate*

DUALITY

Current DC-Link Topology

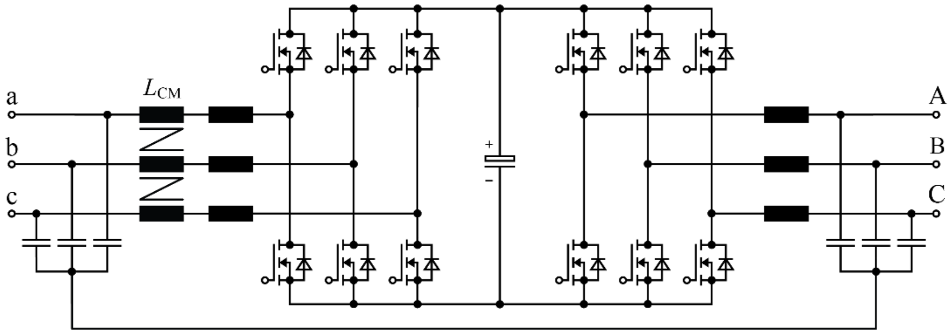
- *Application of* ***(SRB)-M-BDSs***
- *Complex 4-Step Commutation OR SRB-M-BDSs*
- ***Moderate Filter Volume***



- *Challenging* ***Overvoltage Protection***
- *Limited Control Dynamics*

Voltage DC-Link Topology

- ***Standard Bridge-Legs***
- ***Low-Complexity Commutation***
- ***Defined Semiconductor Voltage Stress***
- ***Facilitates DC-Link Energy Storage***



- ***High Input / Output Filter Volume***

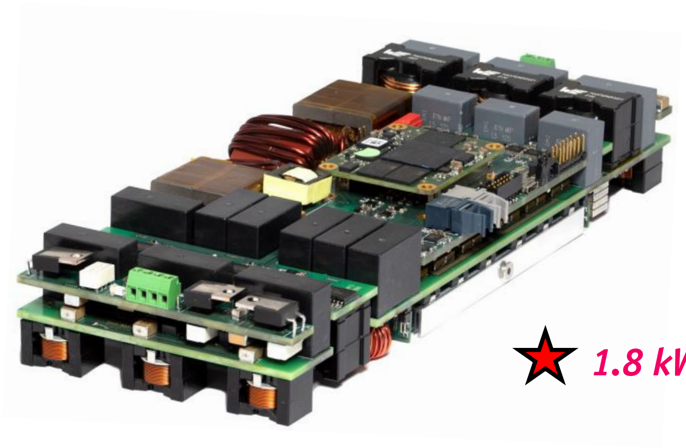
DUALITY

■ ***Current DC-Link Topology***

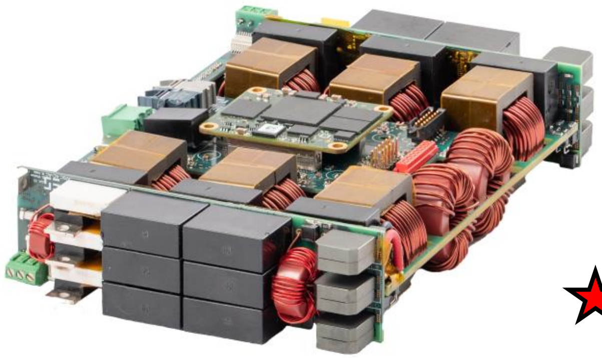
- *Application of (SRB)-M-BDSs*
- *Complex 4-Step Commutation OR SRB-M-BDSs*
- *Moderate Filter Volume*

■ ***Voltage DC-Link Topology***

- *Standard Bridge-Legs*
- *Low-Complexity Commutation*
- *Defined Semiconductor Voltage Stress*
- *Facilitates DC-Link Energy Storage*



★ *1.8 kW/dm³*



★ *1.7 kW/dm³*

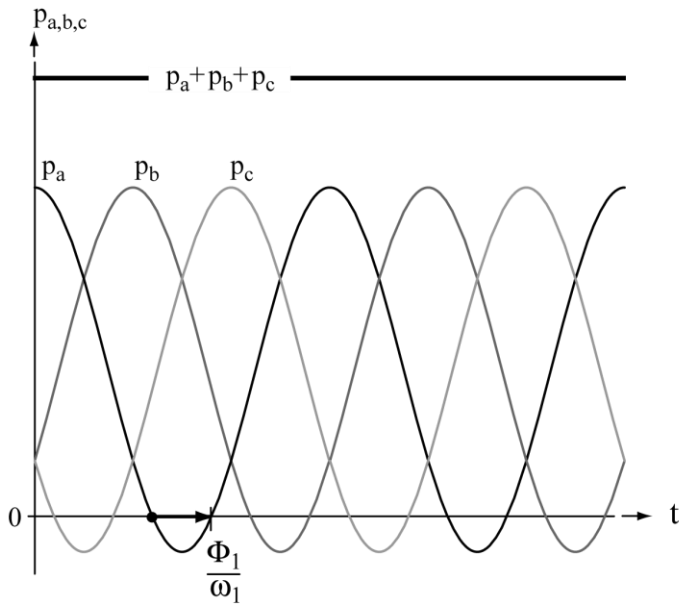
■ *All-600V-GaN AC-AC VSDs / 1.4 kW, 200 V L-L / Full EMI Filter (Grid & Motor) / 97% Nominal Eff.*

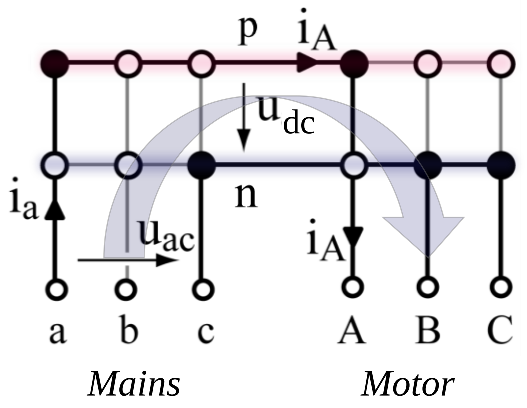
3-Φ AC/AC Matrix Converter

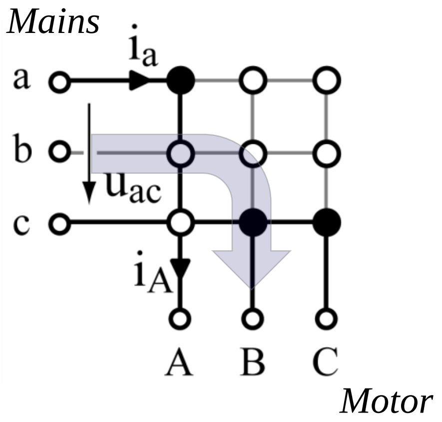
$$\left\{\begin{matrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 1 & 1\end{matrix}\right\}$$

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*



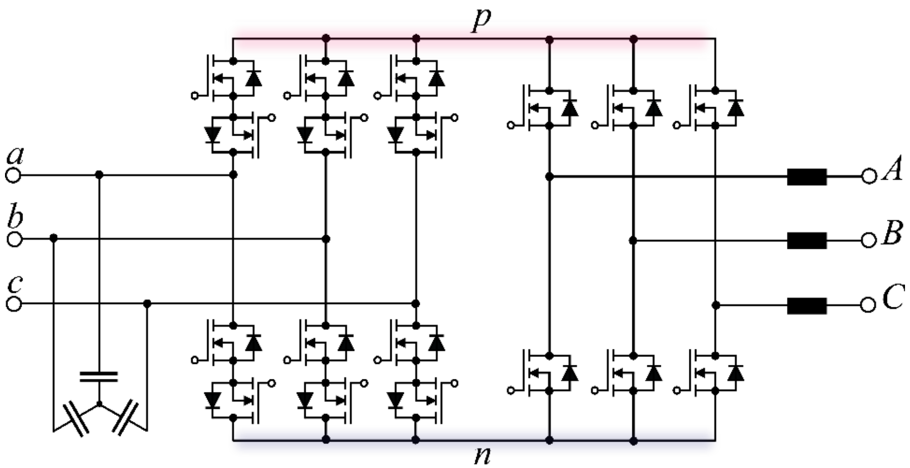


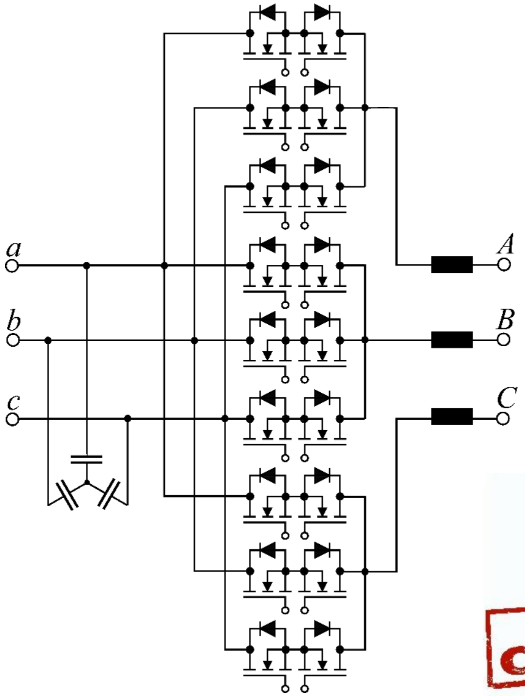


- *Output-Side Motor Inductor → Operation Limited to Buck-Type (Step-Down) Voltage Conversion*

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

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



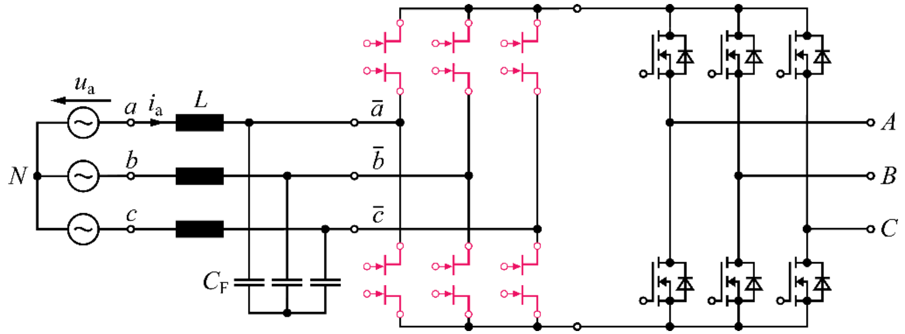


- IMC Relies on Strictly Pos. DC-Link Voltage / i=0 Input Stage Commutation
- M-BDS-Based Realization of DMC Features Lower # of Switches / 4-Step Commutation Required

Remark Application of M-BDSs

- **Indirect Matrix Converter (IMC)**

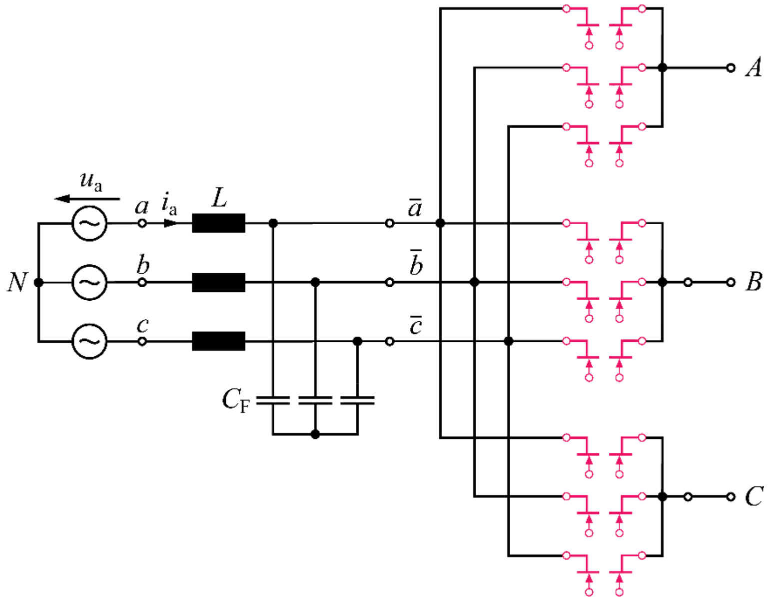
- M-BDS AC/DC Front-End
- ZCS Commutation of AC/DC Stage @ i_{DC}=0
- No 4-Step Commutation



- 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

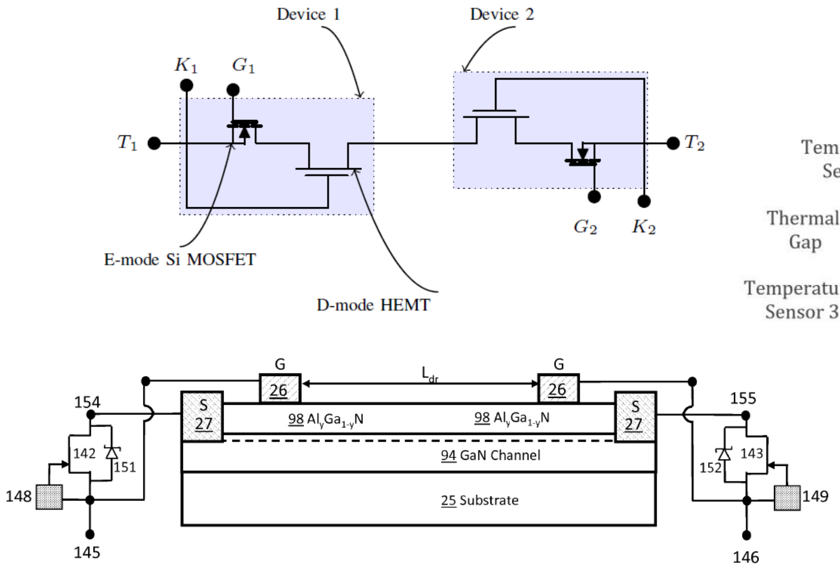


- Thermally Critical @ $f_{out} \approx f_{in}$

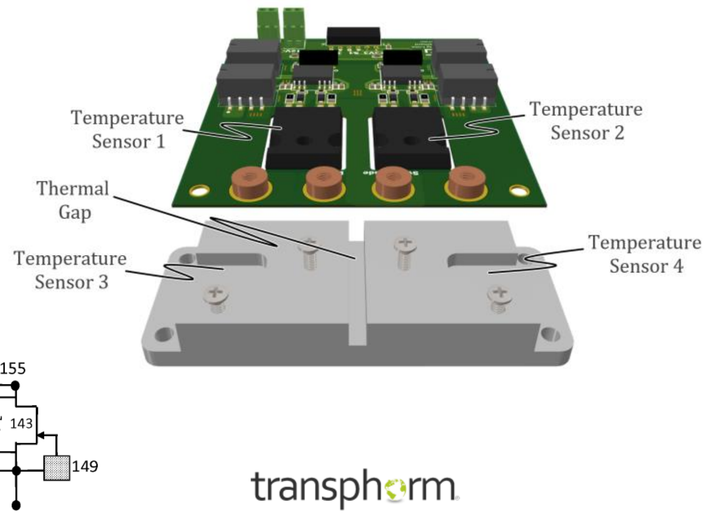
Selected
GaN & SiC M-BDS
R&D Activities

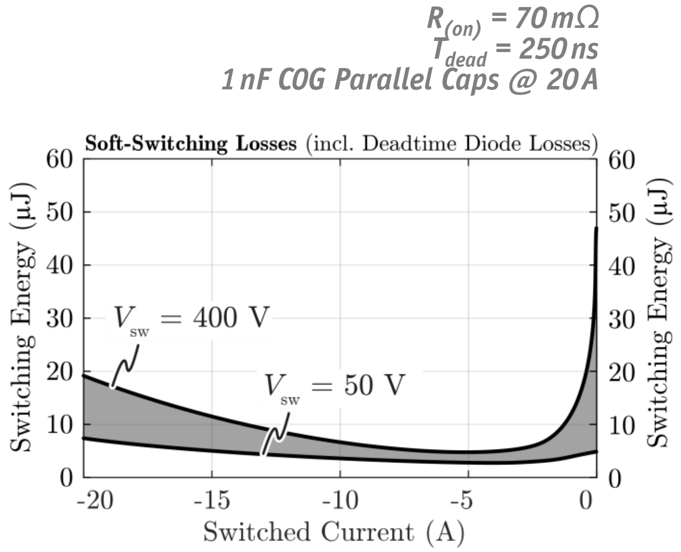
Four-Quadrant Cascode GaN Switch (FQS)

- *Common-Drain Arrangement of Two Cascode Switches (600 V GaN D-Mode HEMT + LV Si E-Mode MOSFET)*
- *Up to 1200 V Samples for Demonstration Purposes*



Honea et al., 2008

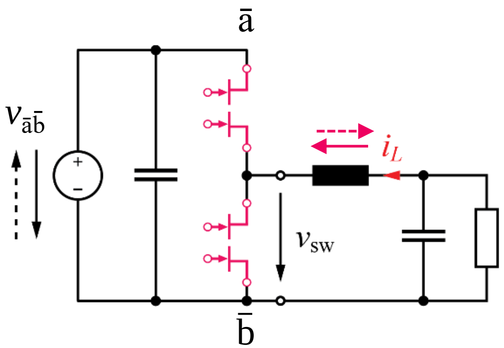


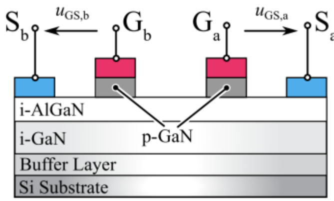


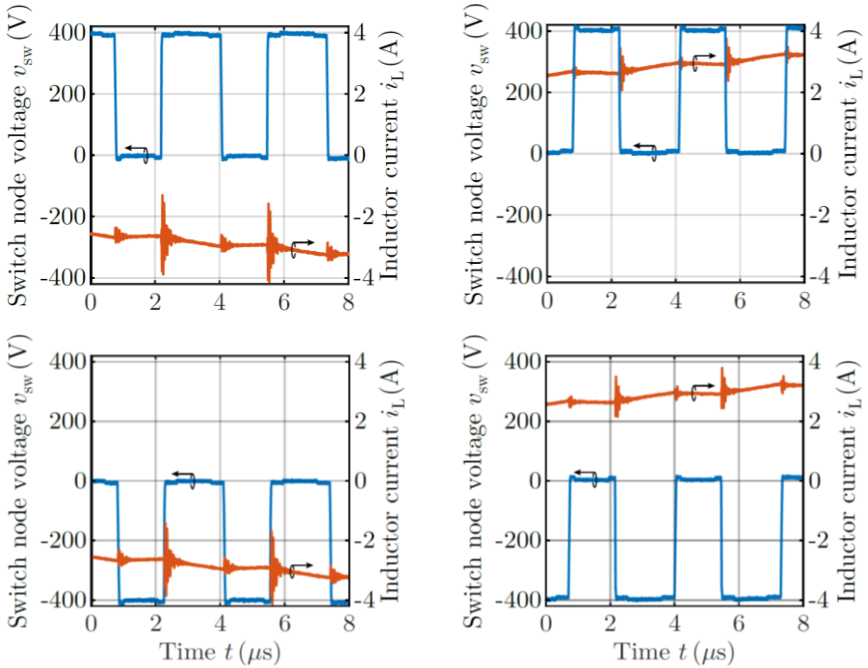
- *4Q — Current Conduction Only in Quadrants I & III*
- *Shared Drift Region for Blocking Pos. & Neg. Voltage & Separate Cascode MOSFETs*

Exp. 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



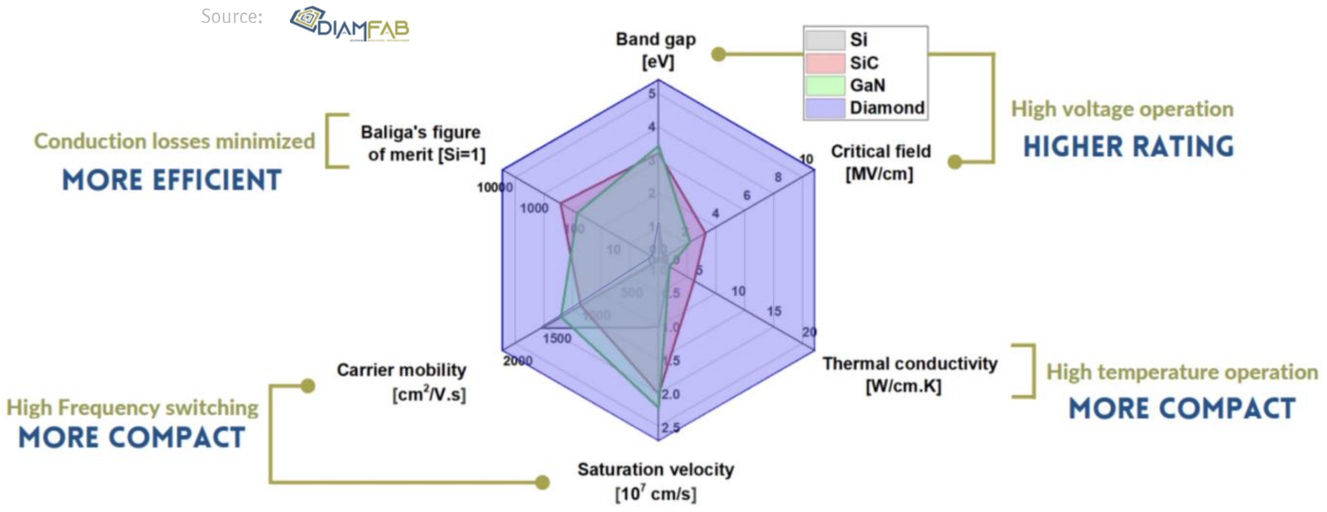


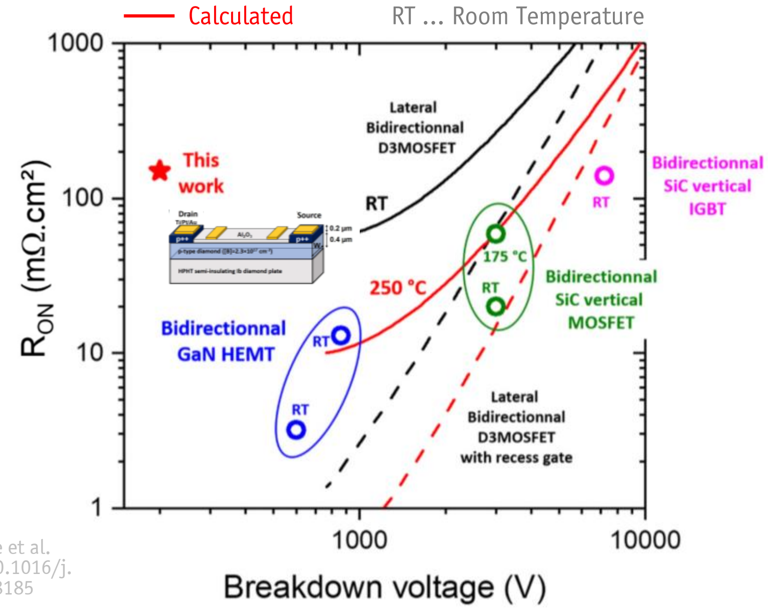


- Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ | 600V Sample @ ± 400V
- Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)

Monolithic Bidirectional Diamond Switch

- *Diamond — High Breakdown Field / High Carrier Mobility / High Therm. Conductivity*
- *Lateral / Single Drift Layer Double-Gate Reverse Blocking & Reverse Conducting Power MOSFET*





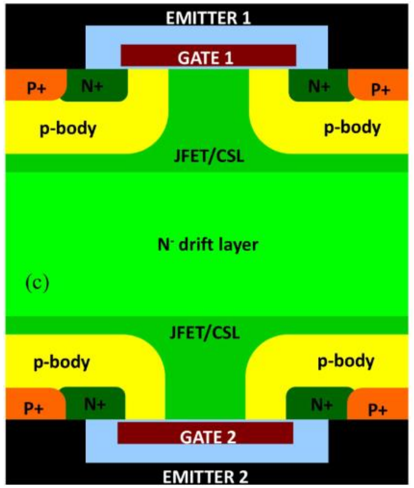
Source: C. Masante et al. https://doi.org/10.1016/j.diamond.2020.108185

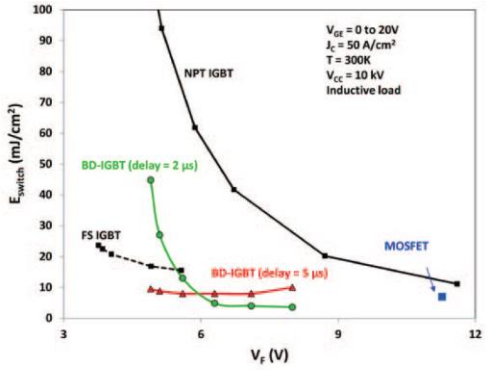
- *Very Basic Proof of Concept @ 250°C*
- *Lateral Bidir. Diamond Devices Could Outperform Bidir. Vertical 4H-SiC Devices @ High Temp.*

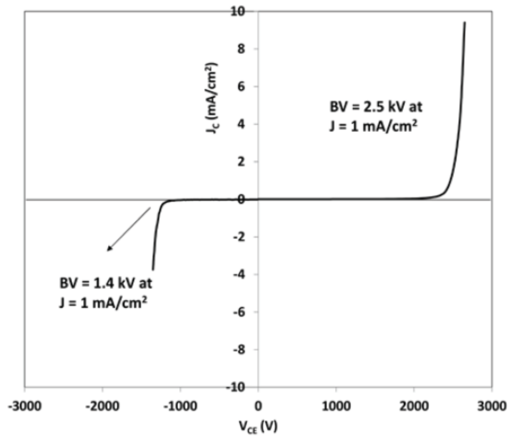
Monolithically Integr. Bi-Directional 15kV SiC IGBT

- *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



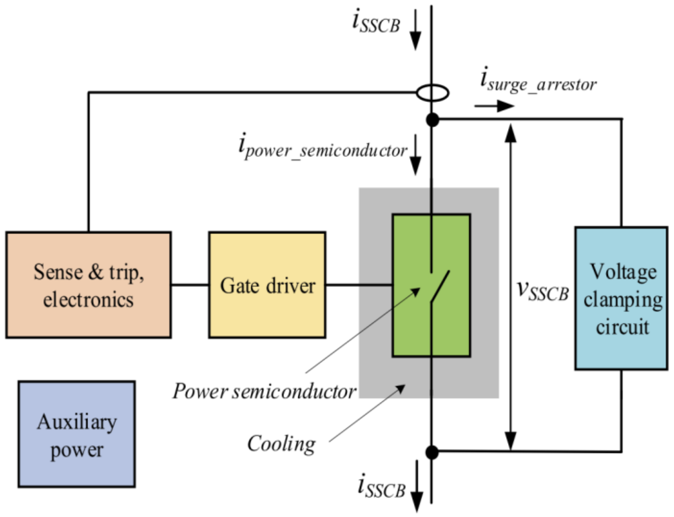




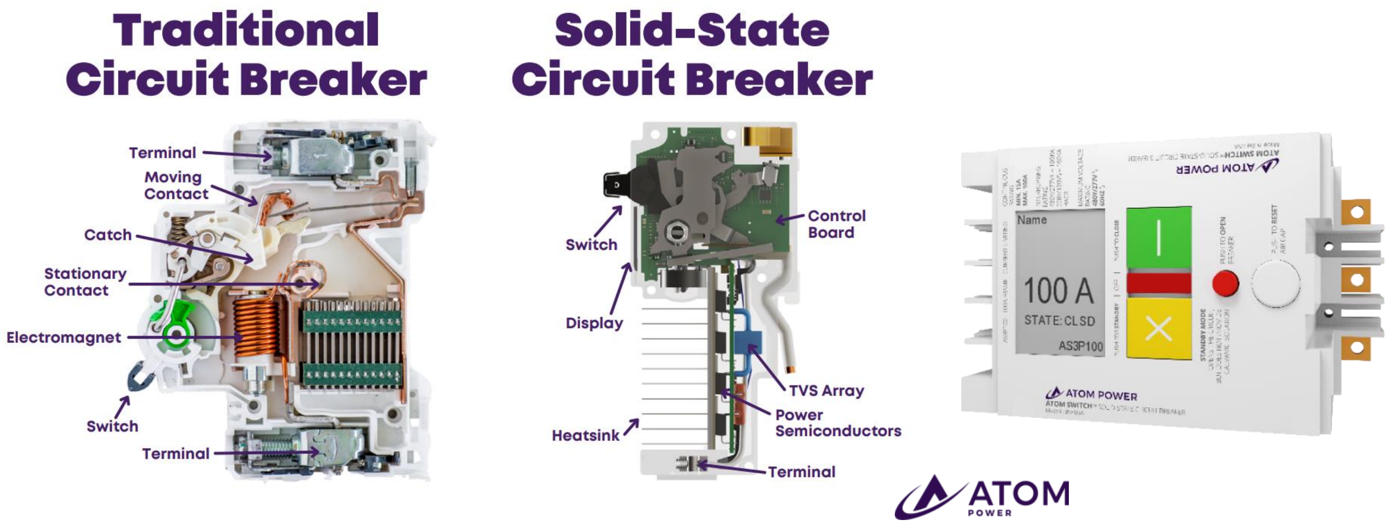
- *Simul. Performance of a 15kV BD-IGBT | Blocking Characteristic (max. 7.2 kV Meas.) – Epi Layer Defects etc.*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

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

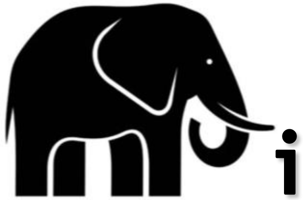


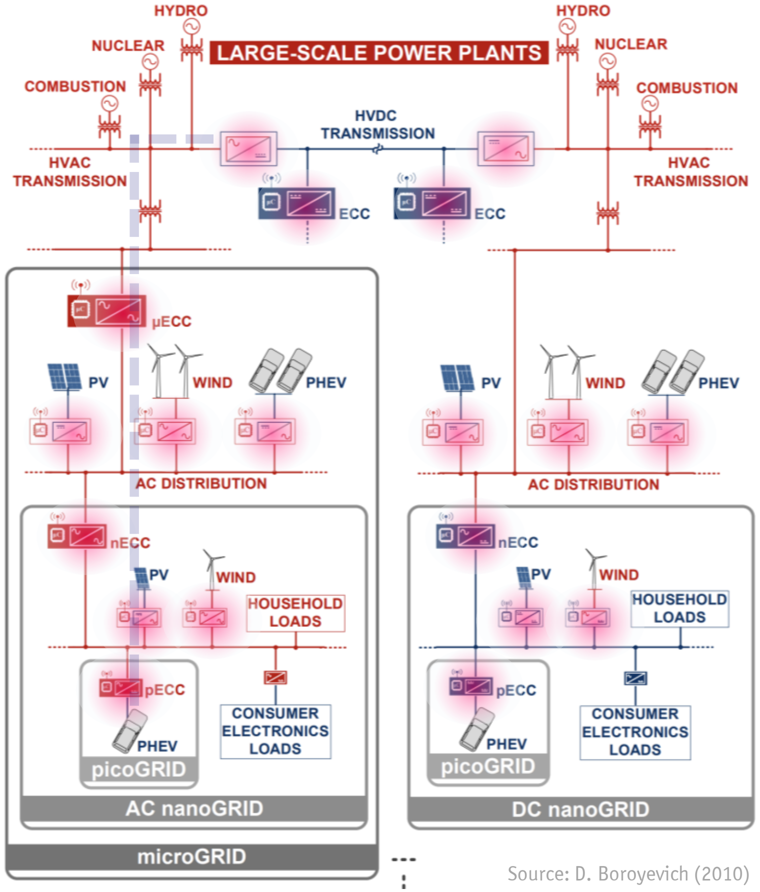
Rodrigues et al., 2021



- 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

The  in the Room



Source: D. Boroyevich (2010)

- *25´000 GW Installed Ren. Generation in 2050*
- *15´000 GWh Batt. Storage*

- *4x Power Electr. Conversion btw Generation & Load*
- *100´000 GW of Installed Converter Power*
- *20 Years of Useful Life*

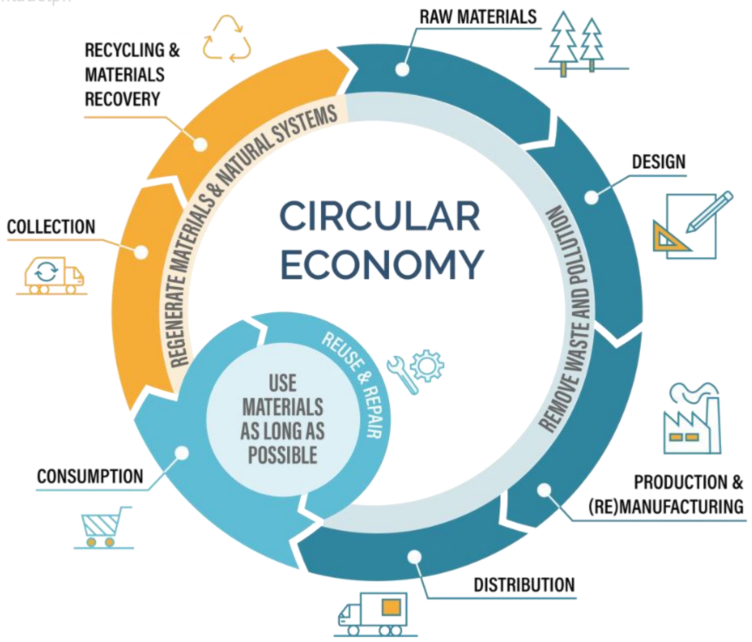
Source: www.e-waste-recyclers.co.in

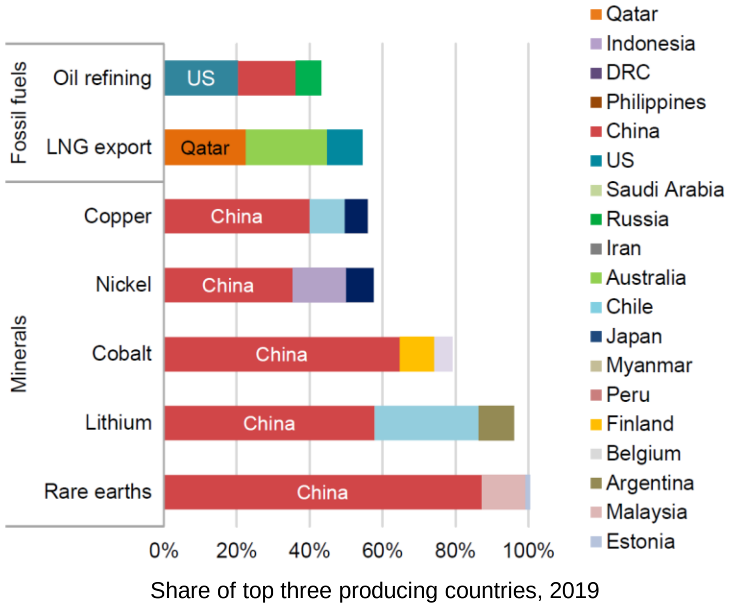
- *5´000 GW_{eq} = 5´000´000´000 kW_{eq} of E-Waste / Year (!)*
- *10´000´000´000 \$ of Potential Value*

The Paradigm Shift

- "Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources
- Resources Returned into the Product Cycle at the End of Use

Source: https://circularphiladelphia.org



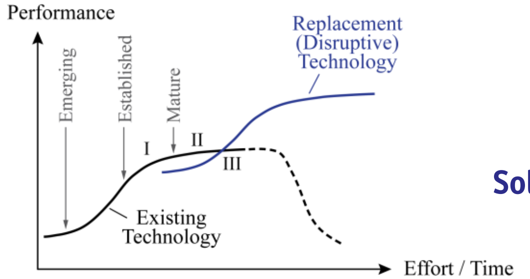


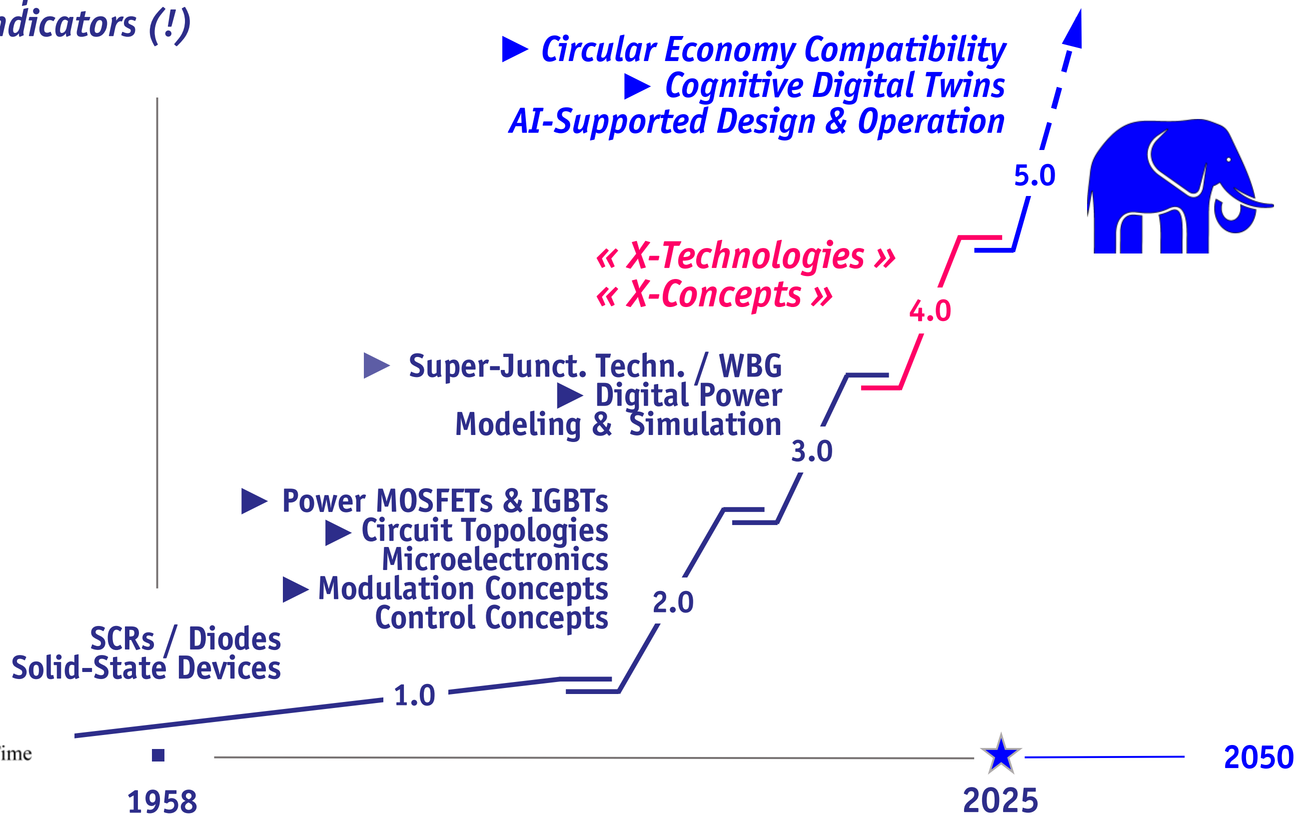
Source: IEA / The Role of Critical Minerals in Clean Energy Transitions (2021)

- Geographically Concentrated Production / Processing of Many Energy Transition Critical Minerals

Power Electronics 5.0

- *Power Electronics 1.0 → Power Electronics 5.0*
- *X-Technologies & X-Concepts*
- *New Main Performance Indicators (!)*





Thank You !