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

Johann W. Kolar et al.

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

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Sept. 16, 2022

Source: www.terencemauri.com

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

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 hyperscale datacenters to variable frequency drives for industry 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 contemplates on the potential advantages of M-BDSs for the realization of ultra-compact three-phase PFC rectifier systems and next generation inverter systems with low motor insulation stress. In this context the performance gain achievable utilizing three-level T-type VSC topologies 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 highlighted.

Final considerations are on the paramount importance of advanced integration and packaging technologies for a next disruptive performance improvement of power electronics systems.

Outline

- ▶ *Introduction*

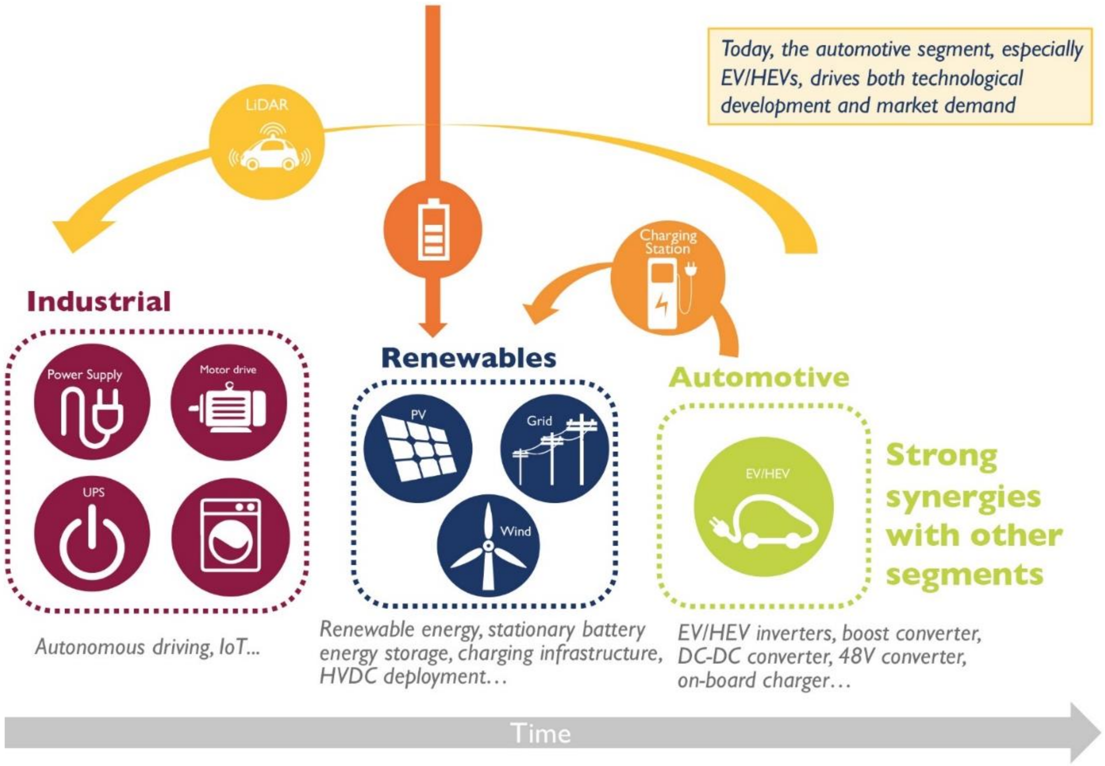
- ▶ *3-Φ AC/DC Grid Interfaces*
- ▶ *3-Φ Motor Drive Inverters*
- ▶ *SiC/GaN M-BDS R&D Activities*

- ▶ *Outlook*

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

Driving Applications

- Global *Megatrends* → *Industry Automation | Renewable Energy | Sustainable Mobility | Urbanization etc.*

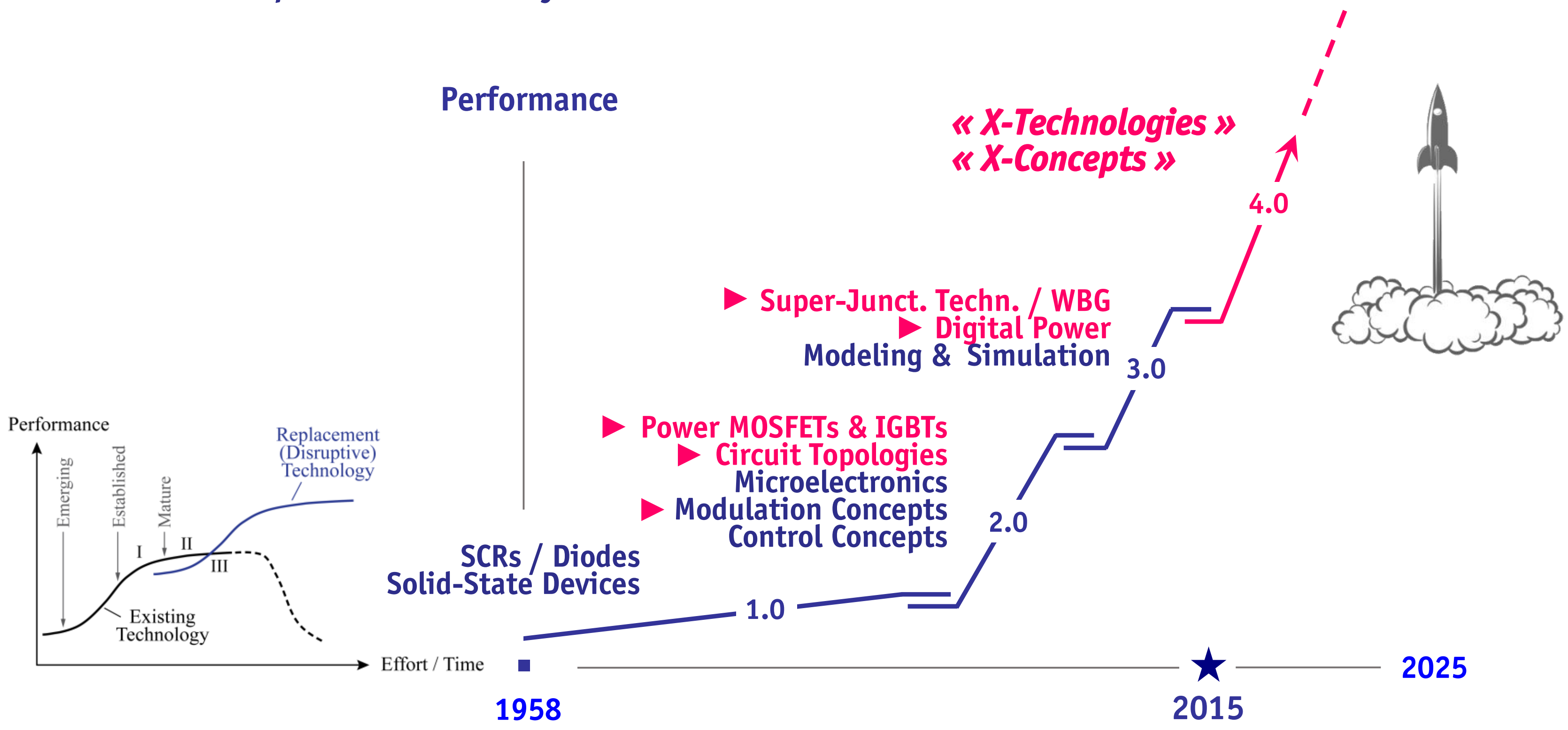


Source: Status of Power Electronics Industry 2019 Report
YOLE Développement

- Clean Energy Transition → "All-Electric" Society

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% !



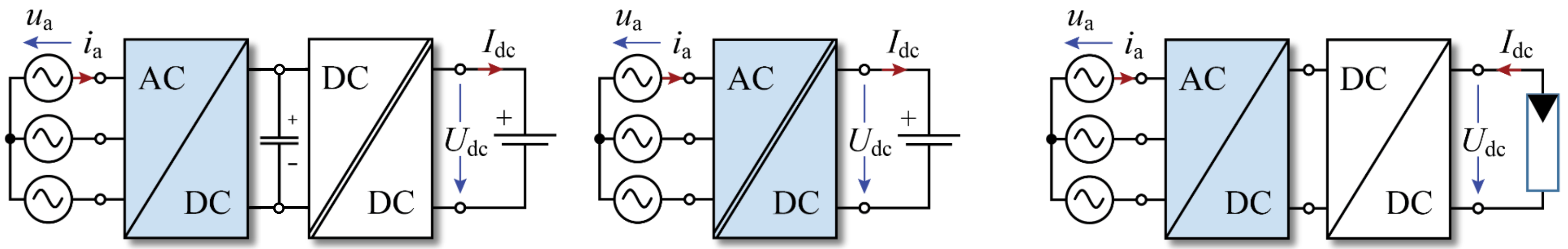
Global Megatrends

Renewable Energy
Digitalization
Sustainable Mobility
Industry Automation
Etc.

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*

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 2.7 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*

History of 3-Φ Diode Bridge Rectifiers

- *L. Kallir @ Techn. Hochschule Wien (25. Dec. 1898)*
- *Extension of 1-Φ Wilke/Pollak/Graetz Rectifier*

Zeitschrift für Elektrotechnik.

Organ des Elektrotechnischen Vereines in Wien.

Heft 52. WIEN, 25. December 1898. XVI. Jahrgang.

Gleichrichtung von Wechselströmen durch elektrische Ventile.

Von Ingenieur **Ludwig Kallir.**

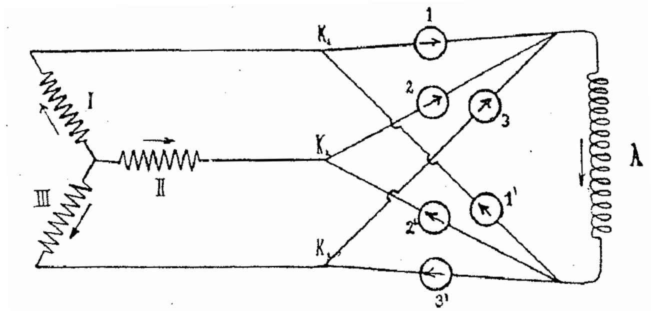


Fig. 7.

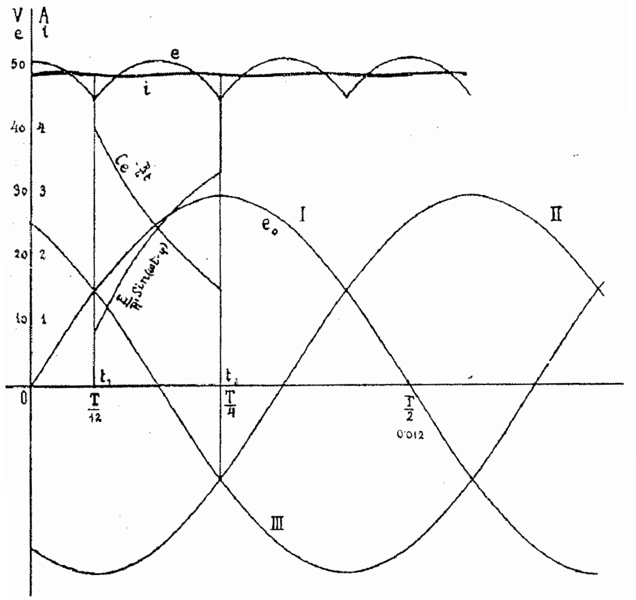
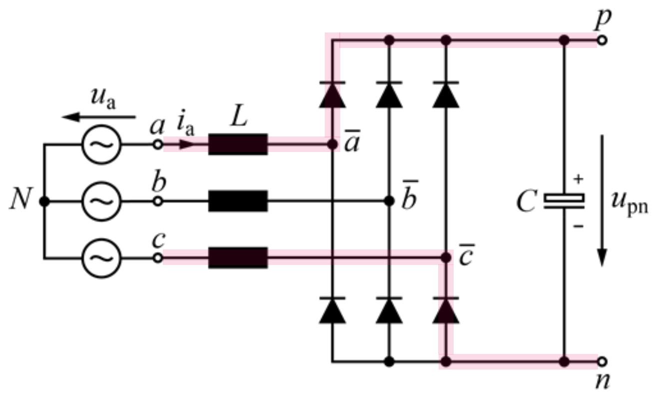


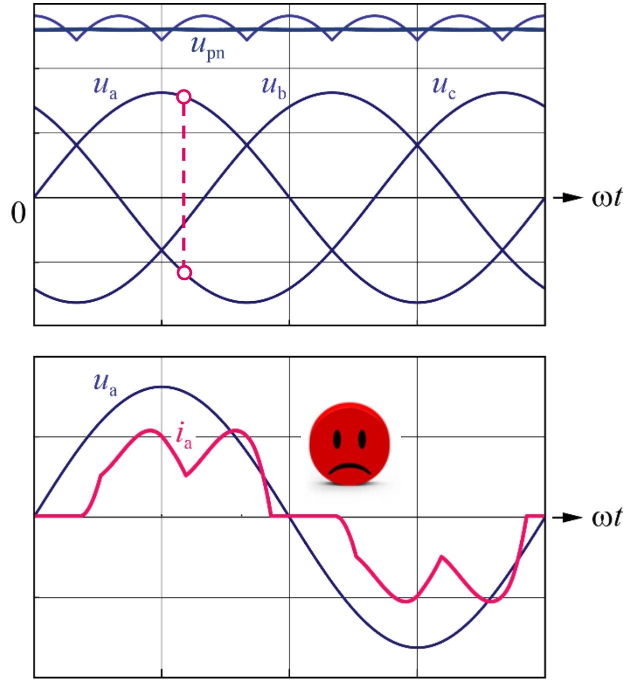
Fig. 8.

- *Electrolytic Cells, Sparc Gaps, Discharge Tubes as „Valves“*

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*



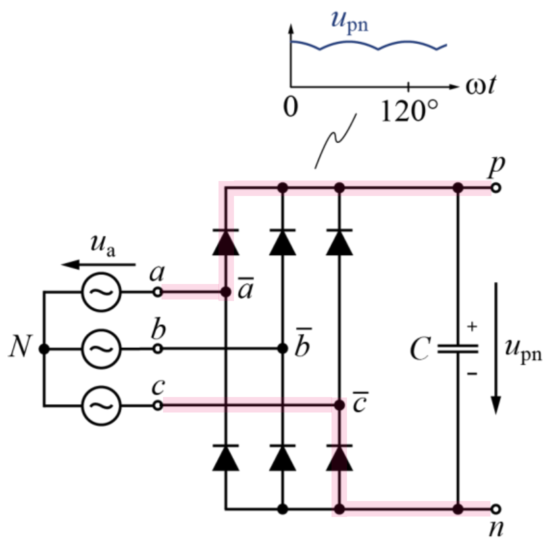


→ *Active Mains Current Shaping / Simultaneous Current Flow in All Phases*

3^{rd} 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



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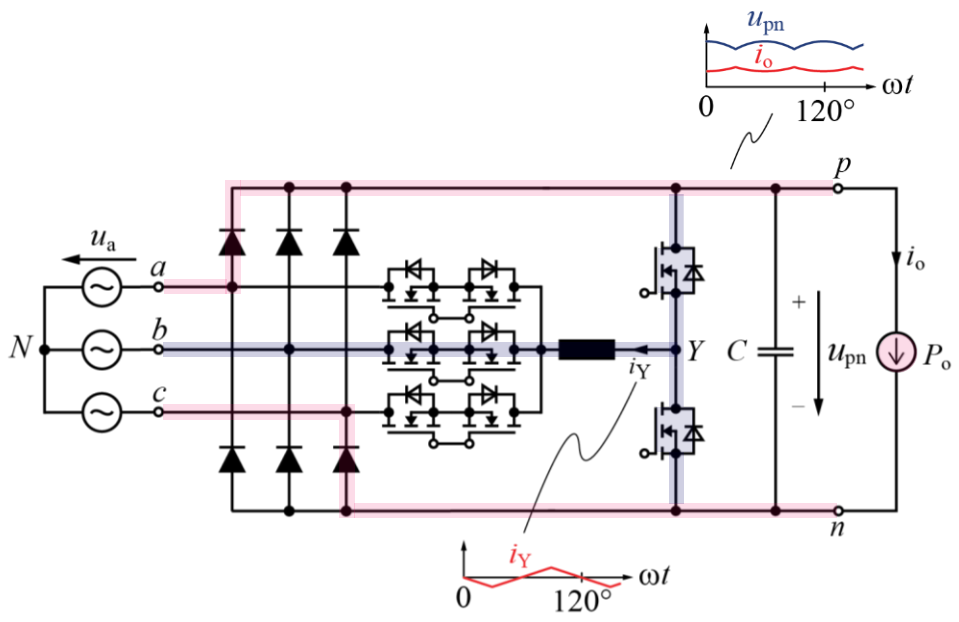


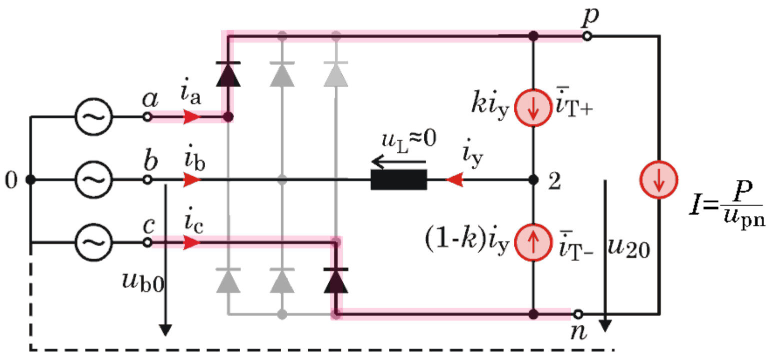
- Non-Sinusoidal Mains Current

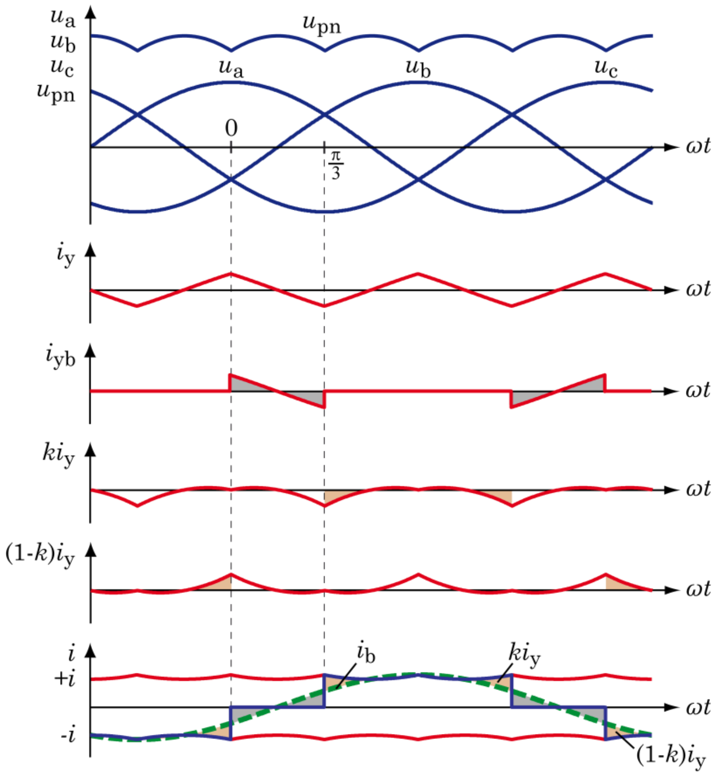
→ P_0= const. Required
→ Sinusoidal Mains Current
→ NO (!) DC Voltage Control

IAF Rectifier (1)

- *Low Complexity*
- *Low Transistor Current Stress / Sw. Losses*
- *Sinusoidal Mains Current @ Const. Power Load*
- *No Output Voltage Control*

$\omega t \in \left[0, \frac{\pi}{3}\right]$

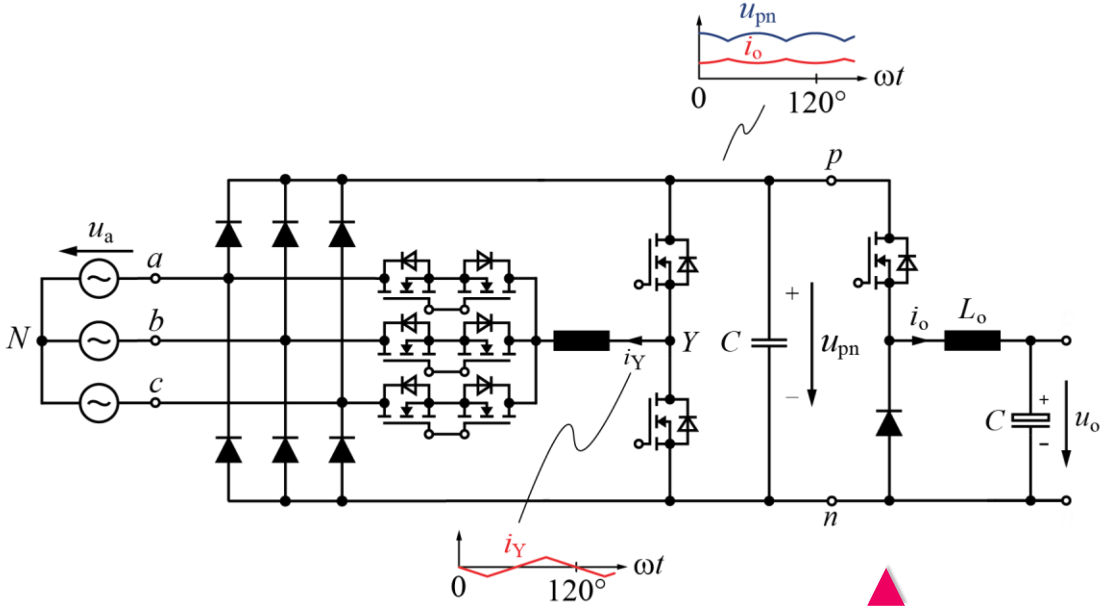




- *Transistors T_+, T_- Could be Replaced by Passive Network*

IAF Rectifier (2)

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

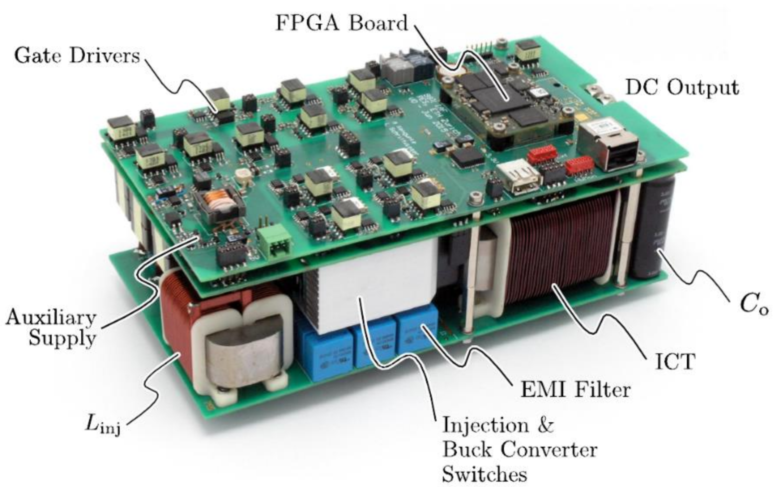


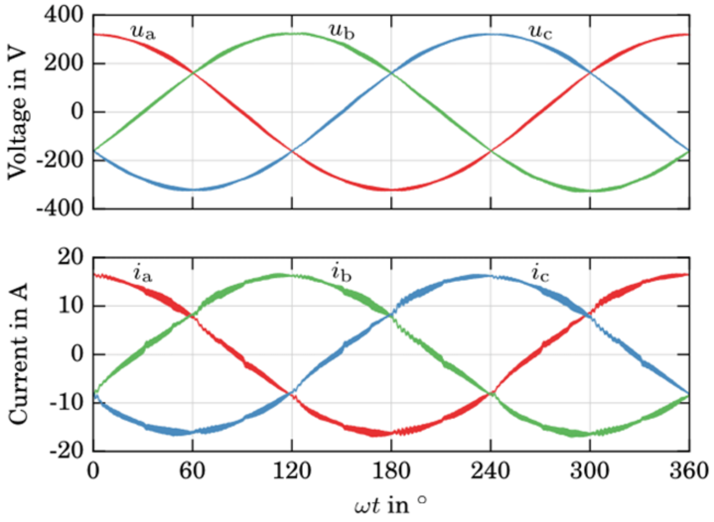
- *Buck-Stage Could be Replaced by Isolated DC/DC Conv. or Inverter*

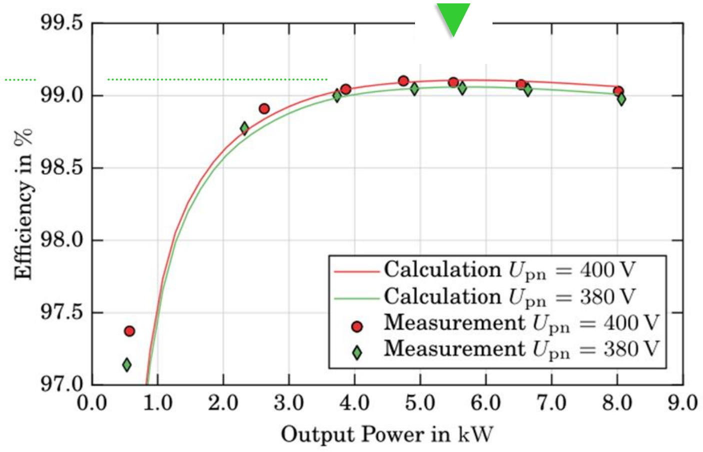
IAF Rectifier & Buck Output Stage

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

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





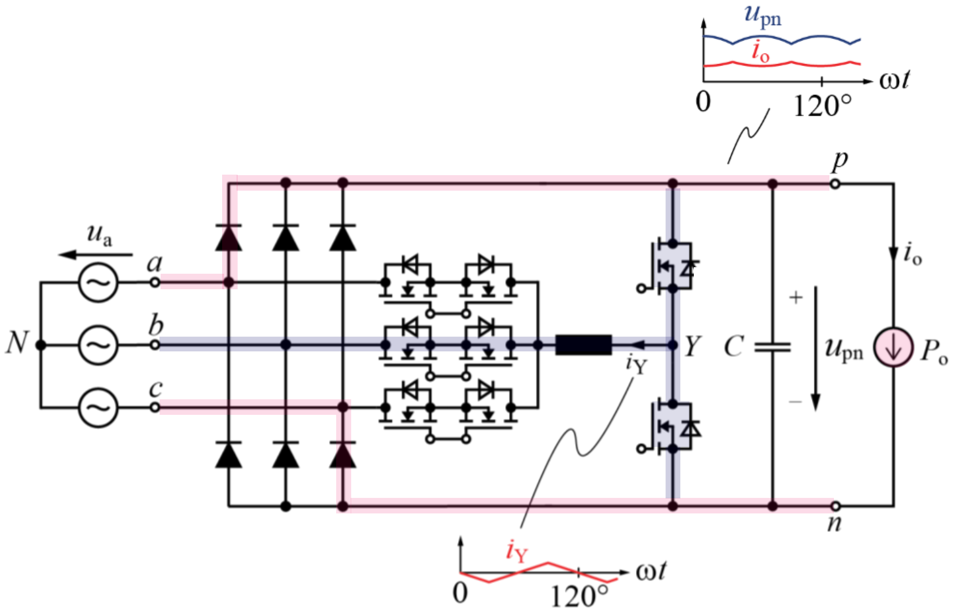


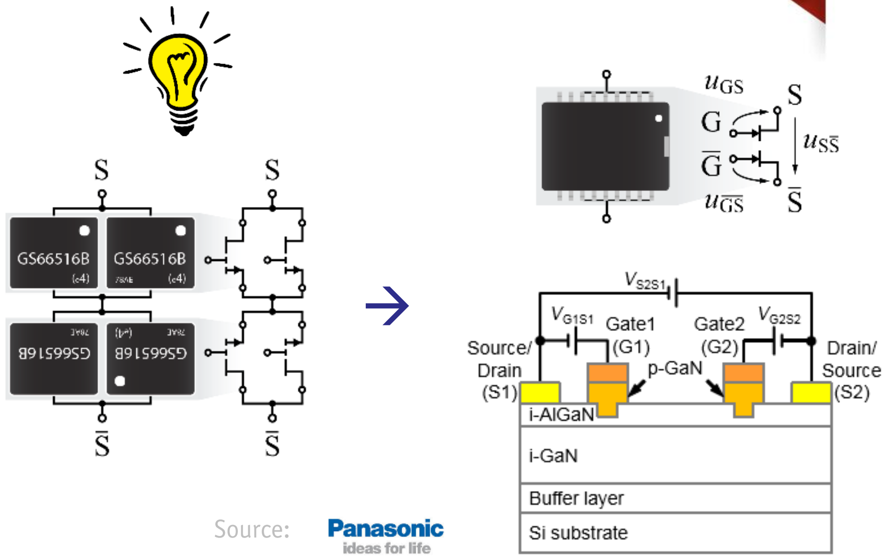
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck DC/DC Output Stages (!)*

Remark Application of M-BDS (1)

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

NEW ARRIVAL

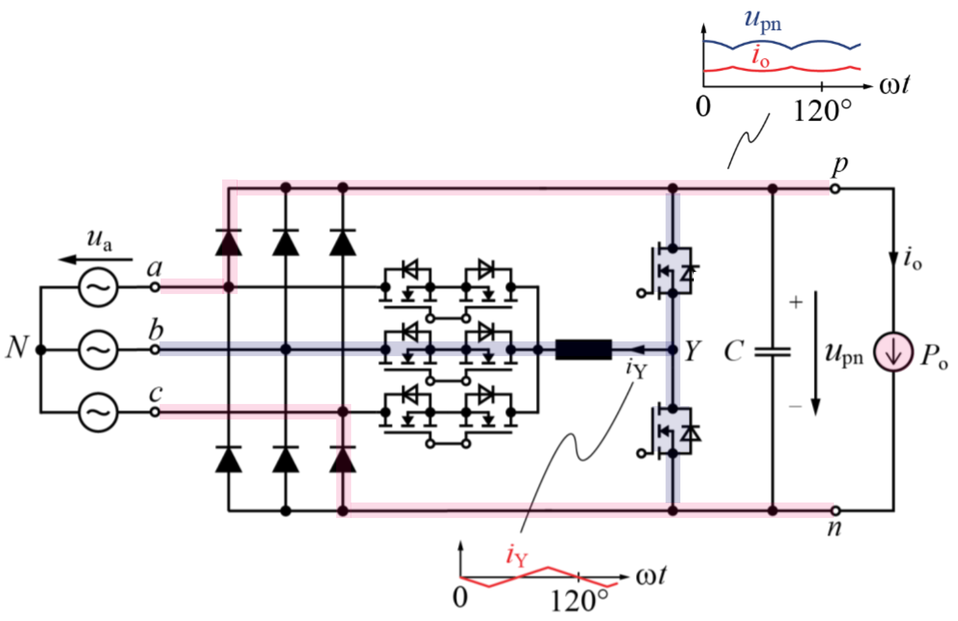


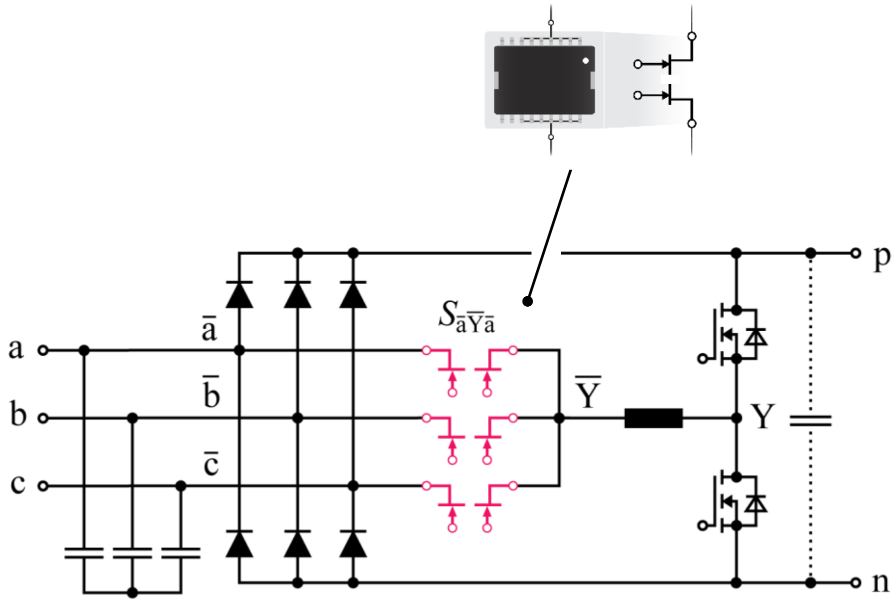


- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

Remark Application of M-BDS (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*

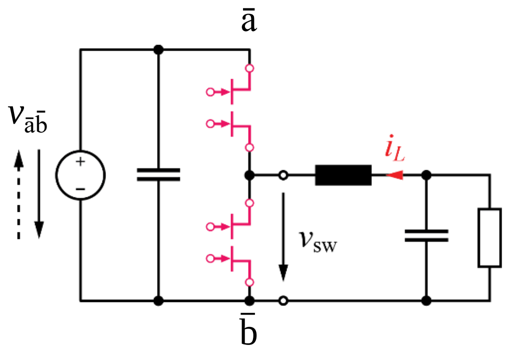


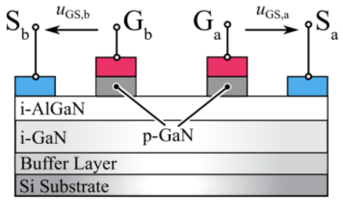


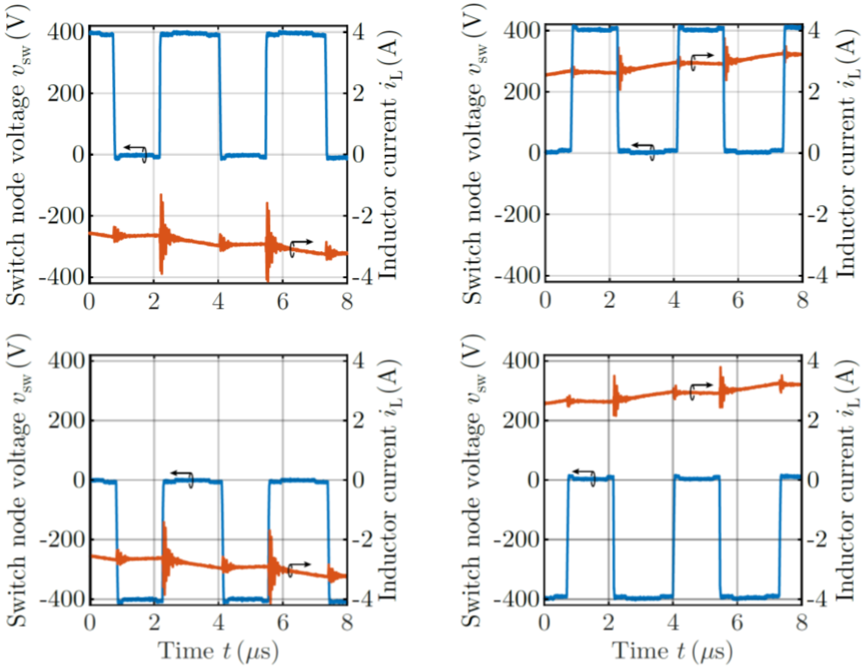
- *M-BDS → Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$ (!)*

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

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



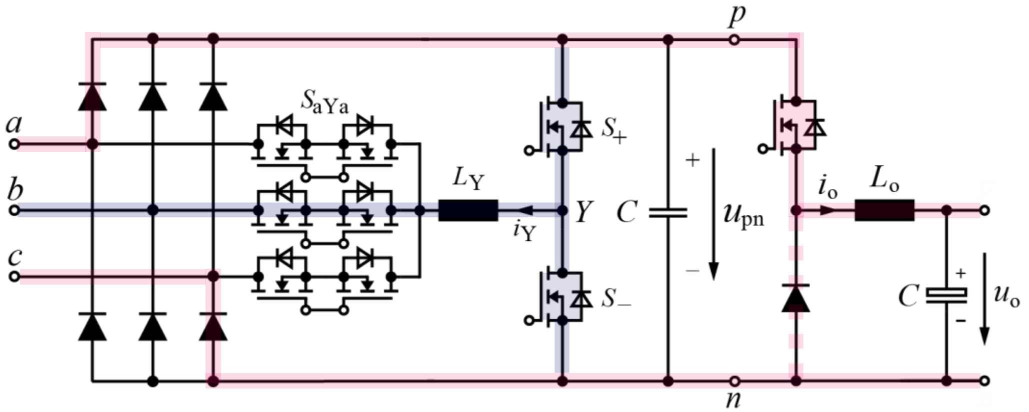


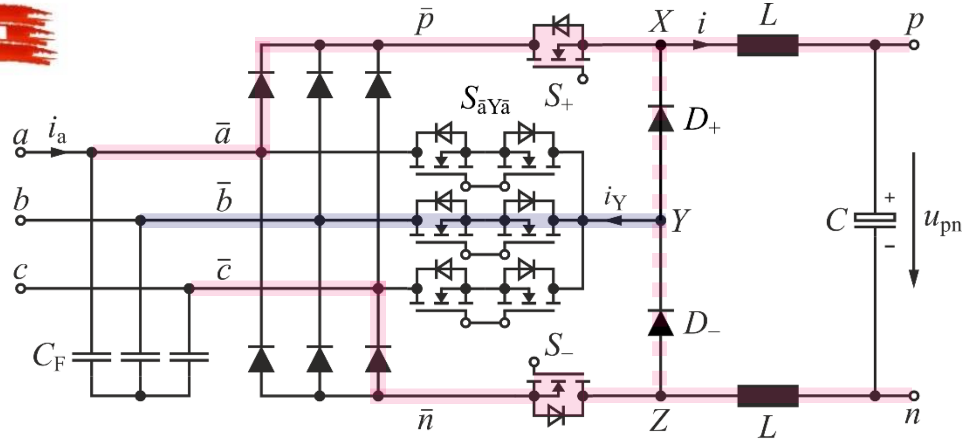


- *Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ | 600V Sample @ ± 400V*

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*



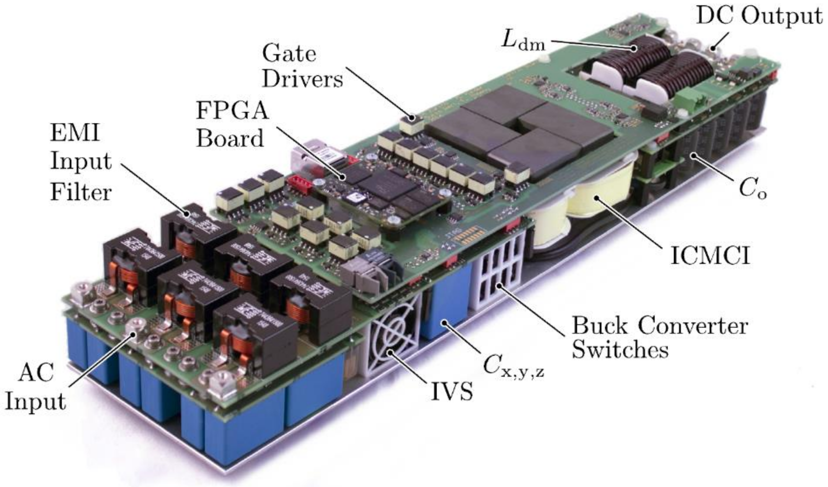


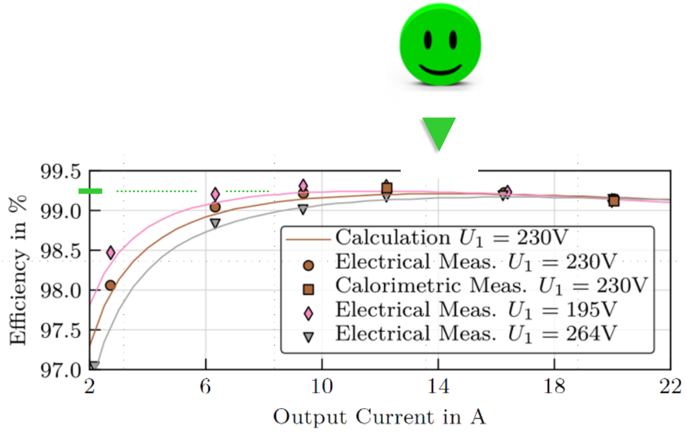
- *Low Complexity*

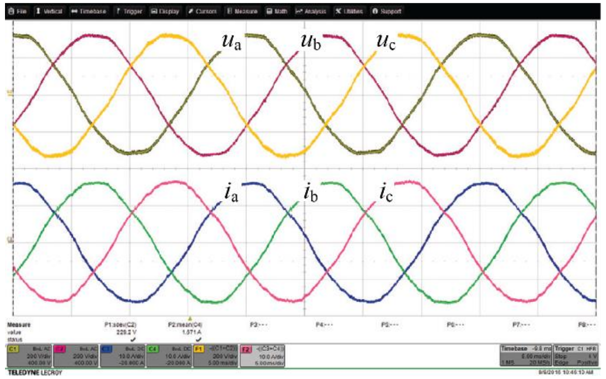
Swiss Rectifier Demonstrator

- *Efficiency η = 99.26% @ 60% Rated Load*
- *Mains Current $THD_I \approx 0.5\%$ @ Rated Load*
- *Power Density $\rho \approx 65W/in^3$*

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



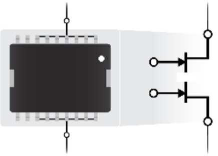




- *SiC Power MOSFETs & Diodes*
- *Integr. CM & Output Coupling Inductors (ICMCI)*

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 $R_{(on)}$*



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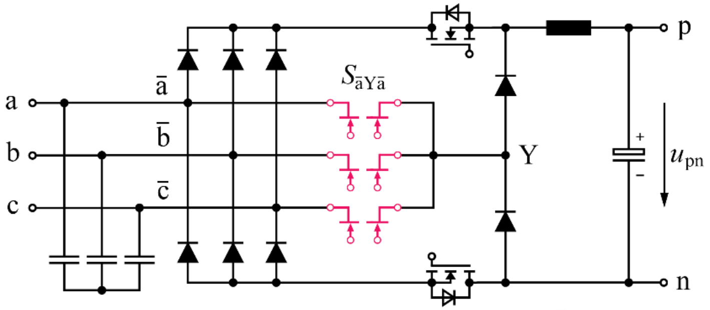
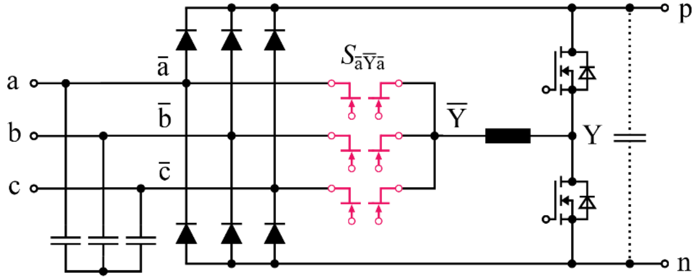
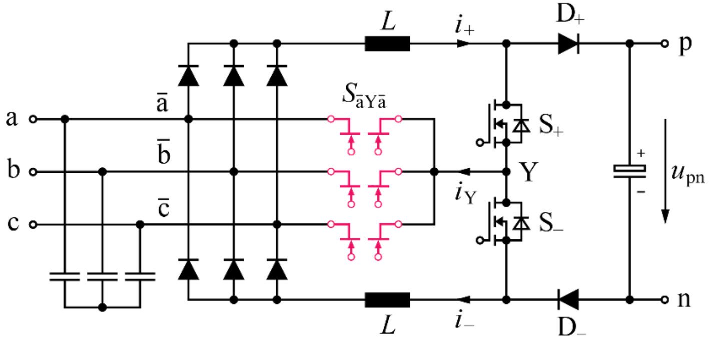
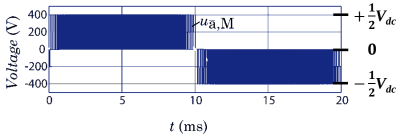






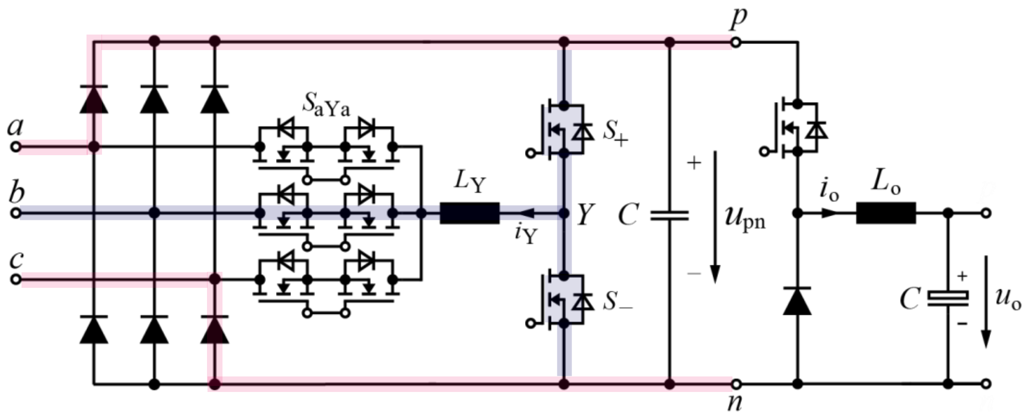
- *Mains Frequ. Operation of the Phase Selector Switches → Conduction Losses Only*

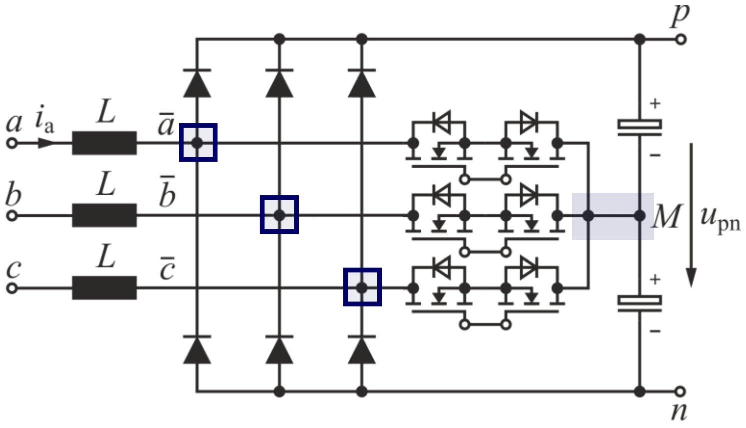
3-Level T-Type Boost PFC Rectifier



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

- *Patent filed Dec. 23, 1993*
- *Name Acknowledging*

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology


Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Veröffentlichungsnummer: **0 660 498 A2**

(12) **EUROPÄISCHE PATENTANMELDUNG**

(22) Anmeldetag: **20.12.94**

(30) Priorität: **23.12.93 AT 2612/93**

(43) Veröffentlichungstag der Anmeldung: **28.06.95 Patentblatt 95/26**

(72) Erfinder: **Kolar, Johann W.**
Straussengasse 2-10/2/68
A-1050 Wien (AT)

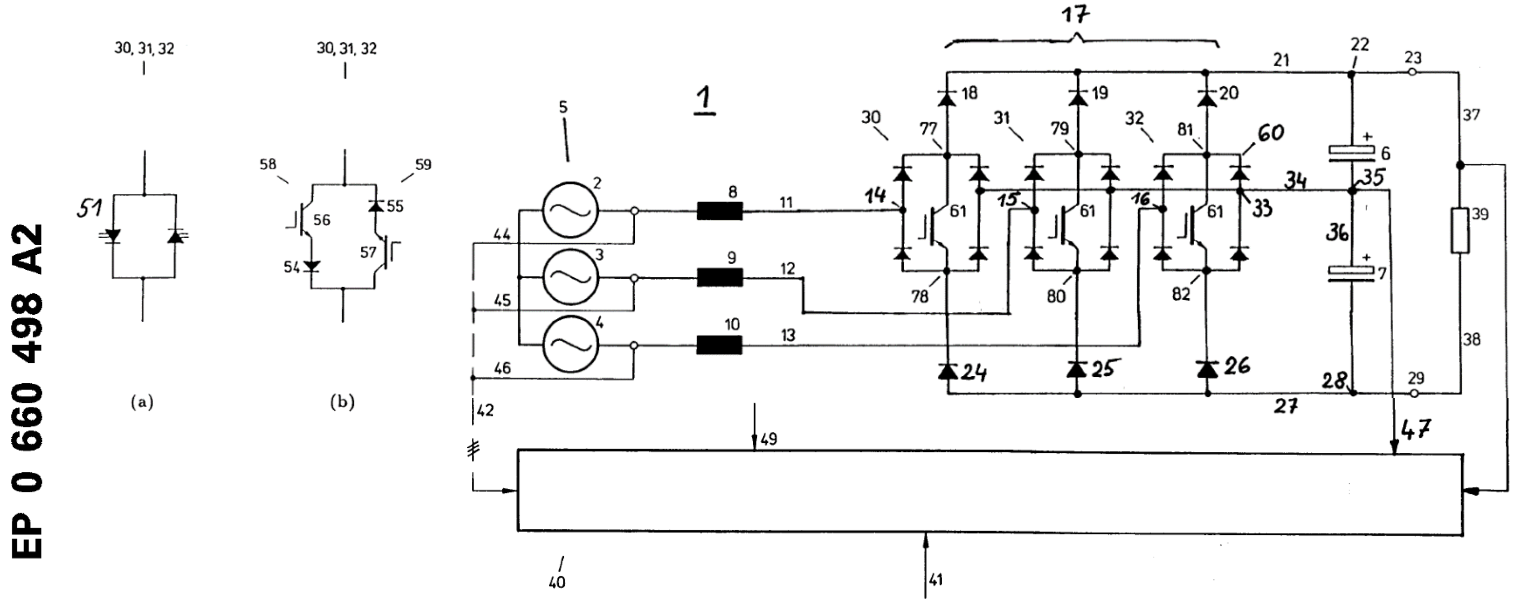
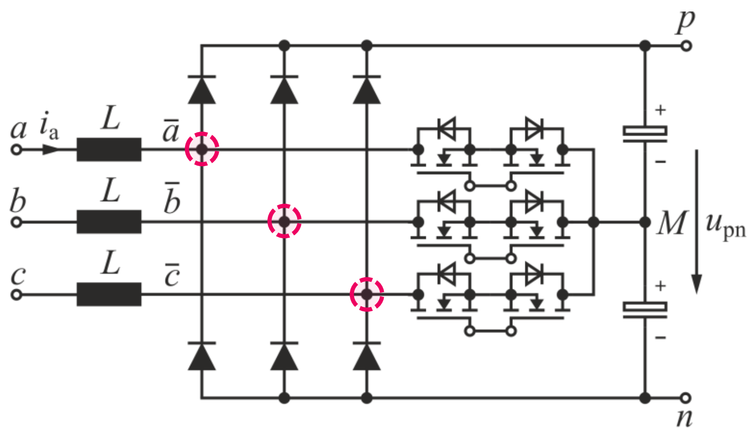


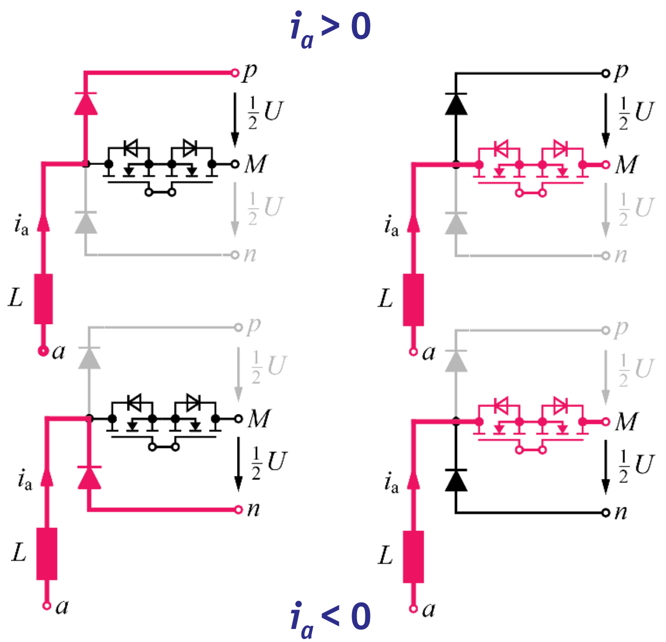
Fig. 1

- *First Ind. Demonstrator for High-Power Telecom Rectifiers in 2001*

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*

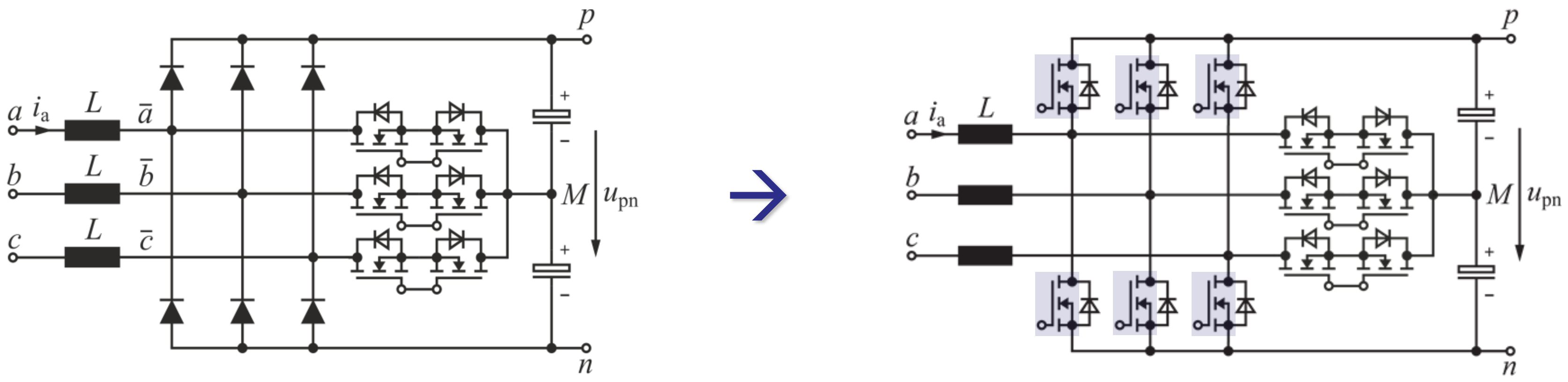




- *Voltage Stress of T-Type Switches Defined by Half (!) DC-Link Voltage*

Vienna Rectifier – Bidirectional Extension

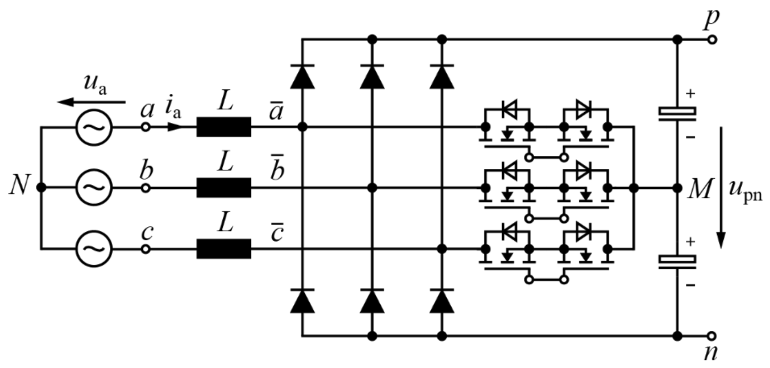
- Rectifier Diodes Replaced w/ SiC MOSFETs — Full DC-Link Voltage Blocking Capability
- Sw. Voltage Stress Still Def. by Half (!) DC-Link Voltage
- Synchronous Rectification



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

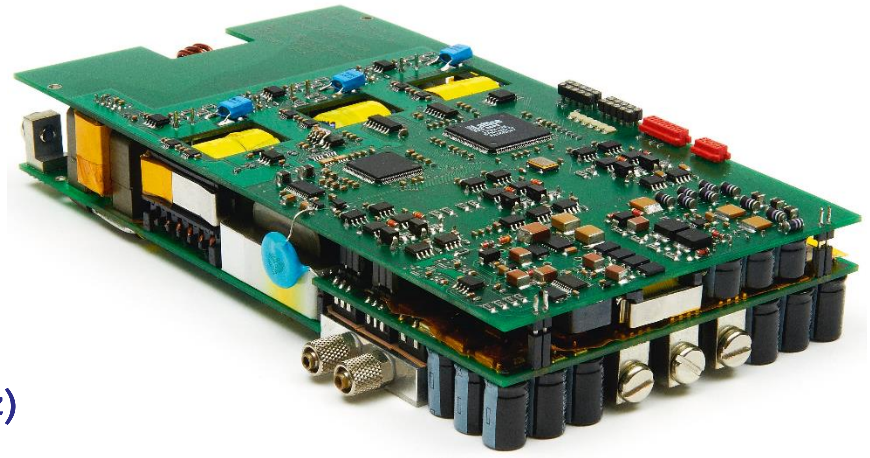
Vienna Rectifier Demonstrator (1)

- *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*

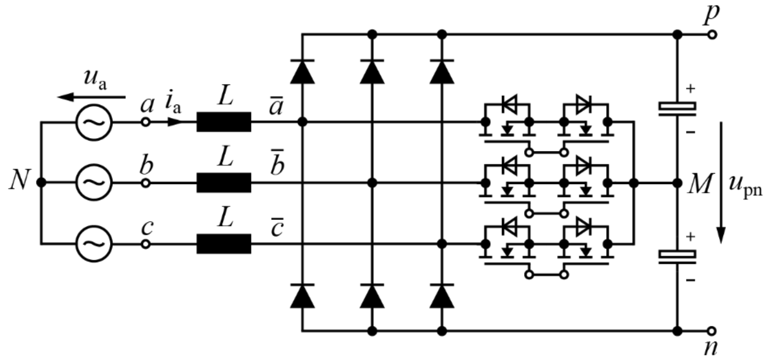
- *THD_i = 1.6%* @ f_N = 800Hz (f_P= 250kHz)

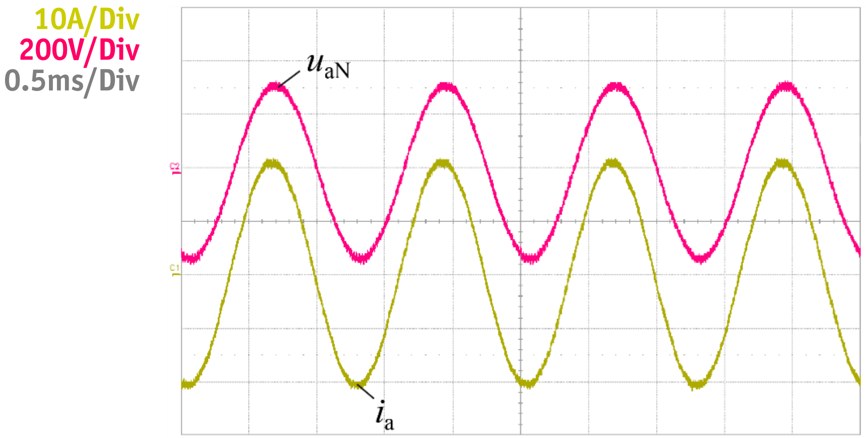
Vienna Rectifier Demonstrator (2)

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

P_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

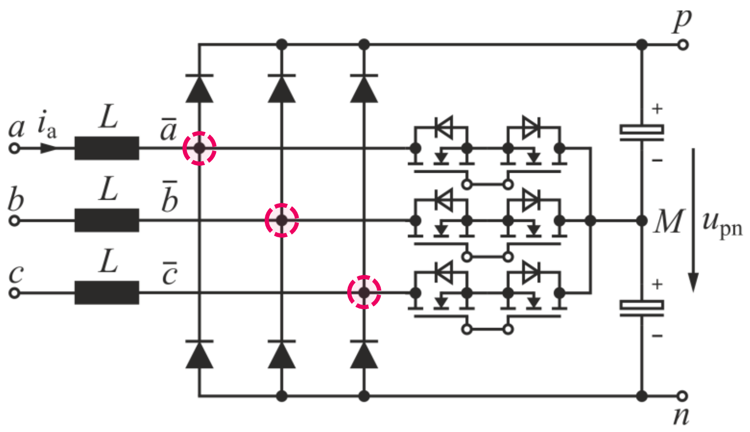


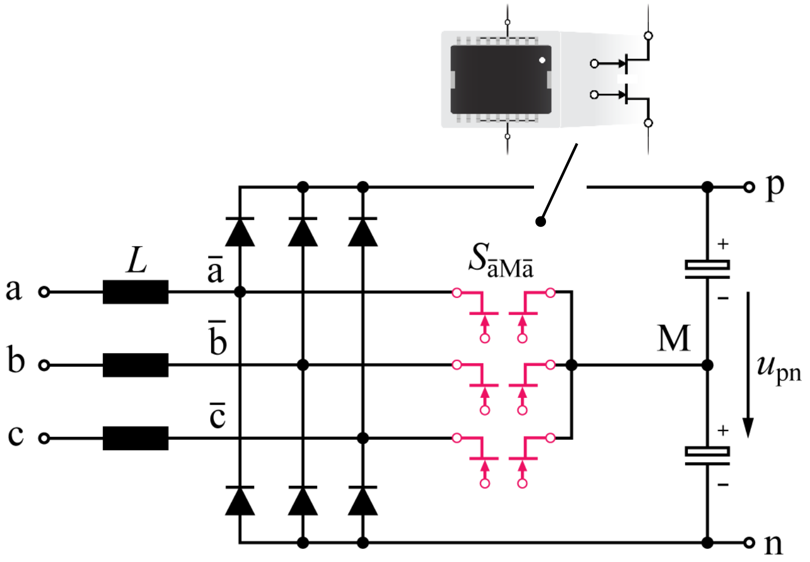


- *THD$_i$ = 1.6% @ f_N = 800Hz*
- *System Allows 2-Φ Operation*

Remark Application of M-BDS (1)

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



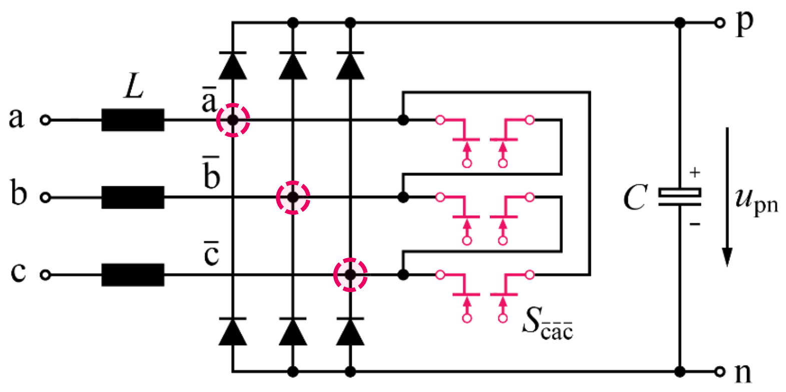


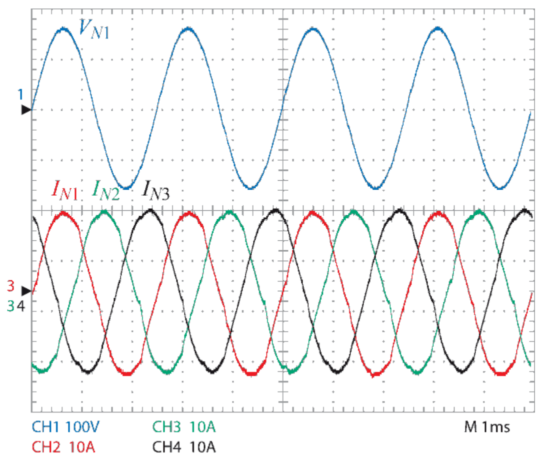
- 600 V *M-BDSs @ U_{pn}*= 800 V_{DC} *in Combination w/* 1200 V *SiC Diodes / MOSFETs*

Remark — Application of M-BDS (2)

- Δ-Switch Rectifier — Control of Rectifier Stage Line-to-Line Inp. Voltage w/ 2 Switches
- M-BDSs Voltage Stress Def. by Full DC-Link Voltage
- Low Conduction Losses / No DC-Link Midpoint Required

U_{LL} = 115 V@400Hz
U_o = 400 V
THD_I = 2.3%



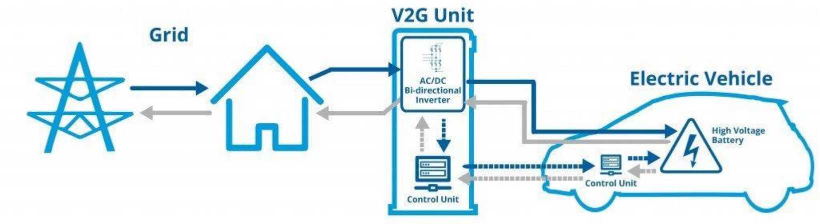


- 600V M-BDSs for 115V / 360...800Hz Aircraft Applications
- Only 2 Switches are Active @ a Time/ Phase Curr. Controller Outputs Transf. into Δ-Quantities

Global Megatrends

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

Bidirectional
Boost-Buck | Buck-Boost
PFC Rectifier Systems



Source: www.zhaw.ch

Ultra-Fast / High-Power EV Charging

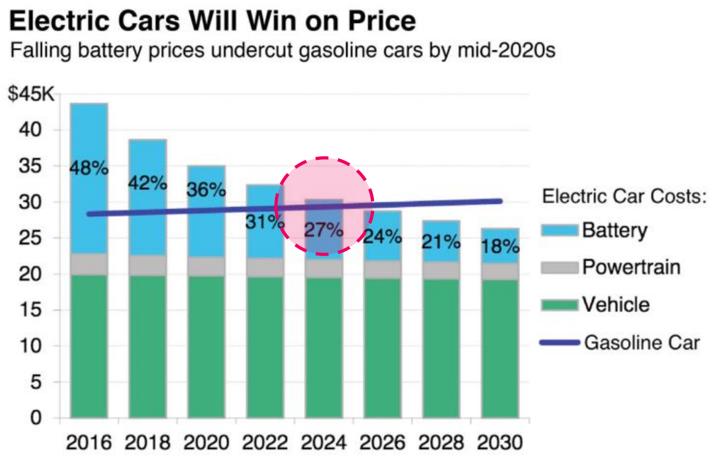
- *Modular Mains Interfaces | Future Non-Isolated Virtually Grounded Systems*
- *Very Wide Output Voltage Range (200...800V)*

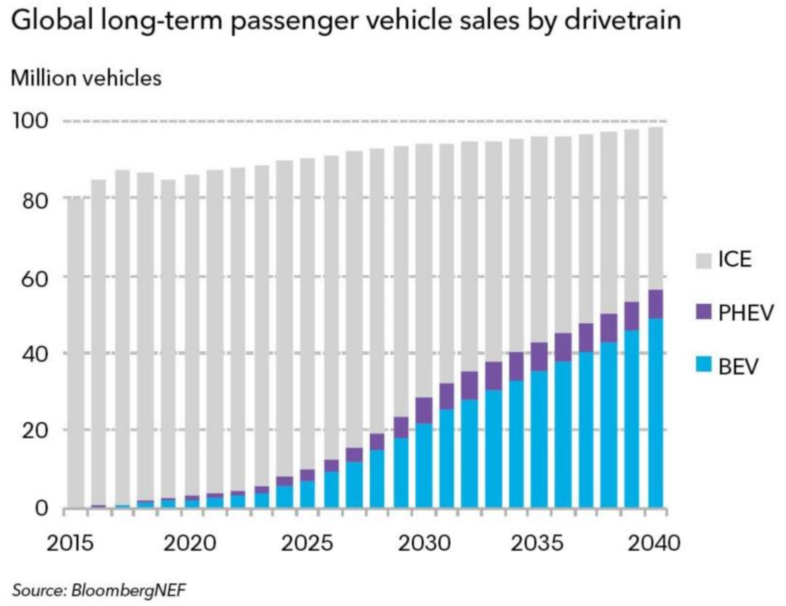
Source: www.autoevolution.com

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

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"

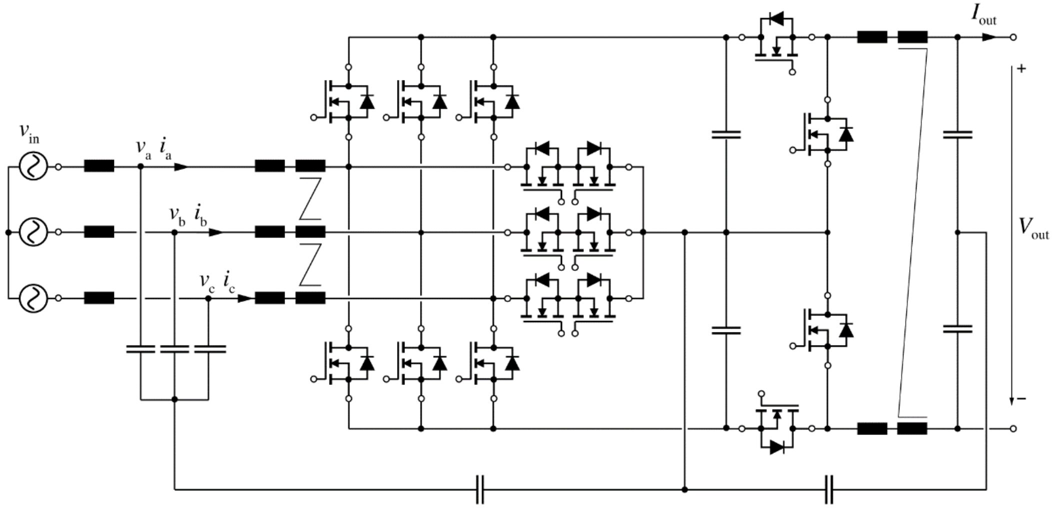
— NY City, 5th Av., Easter Parade → *Year 1900: One Motor Cycle / Year 1913: One Horse & Carriage (!)*

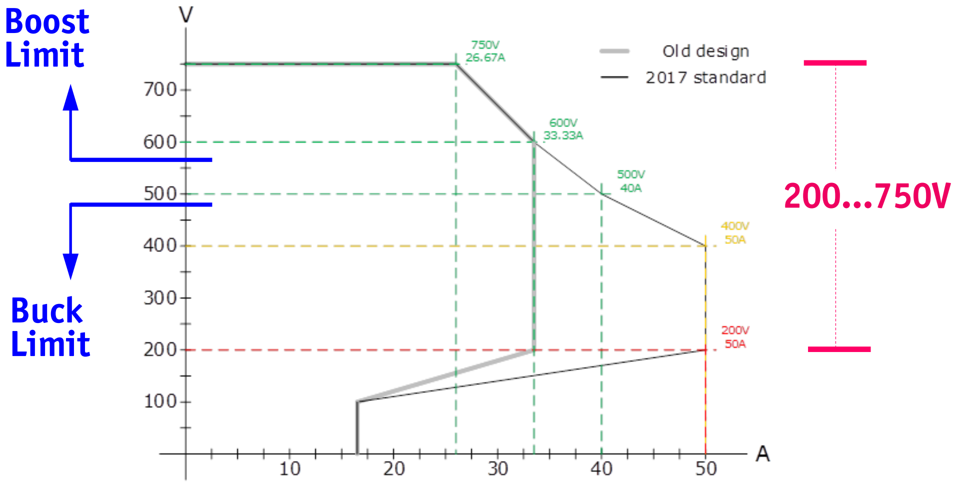
Source: Tony Seba

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

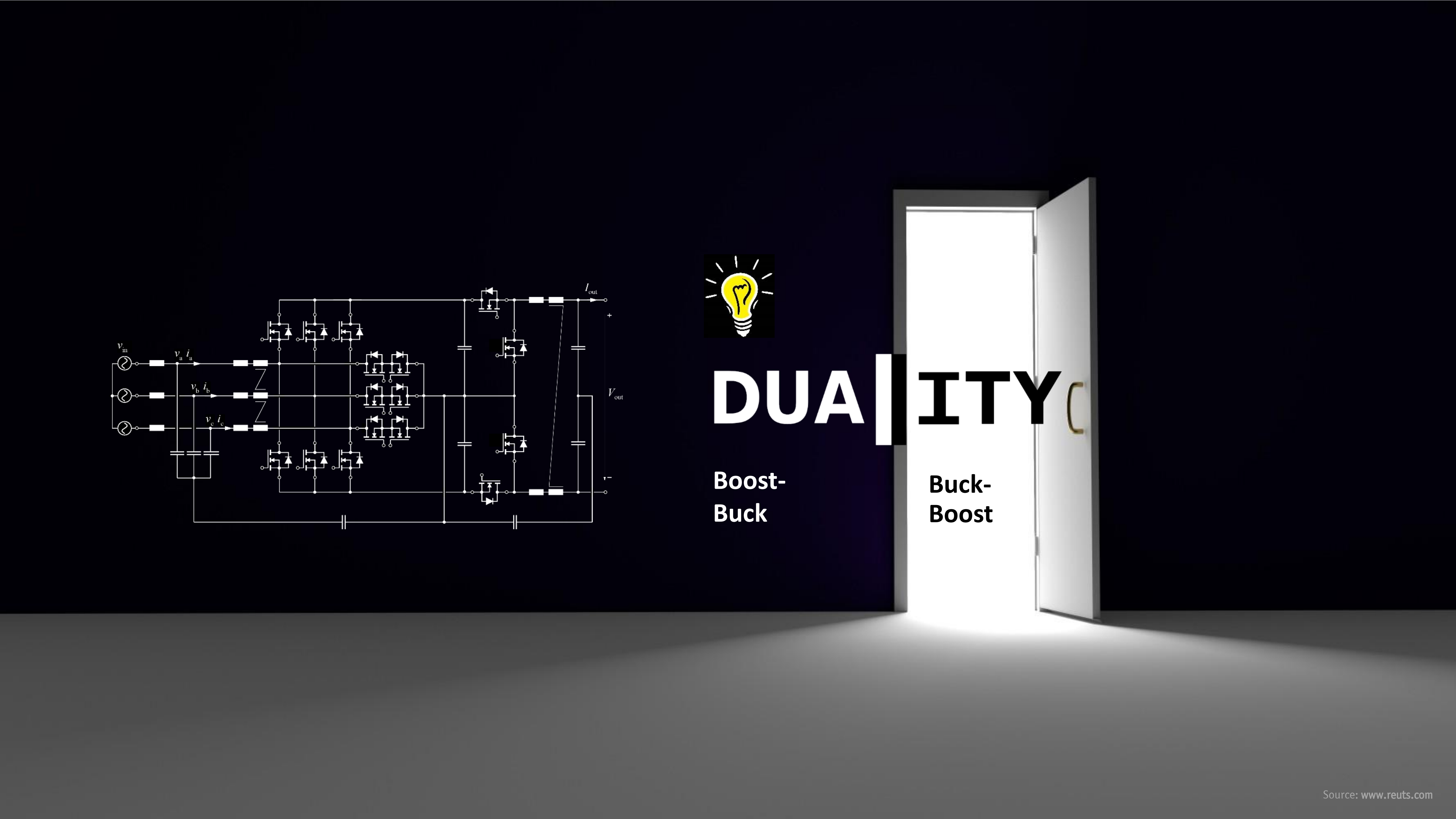
Bidirectional *Boost-Buck* PFC Rectifier Concepts

- *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 Modulation"*


v_{in}
v_a i_a
v_b i_b
v_c i_c
I_{out}
+
V_{out}
−
DUA|ITY
Boost-
Buck
Buck-
Boost
Source: www.reuts.com

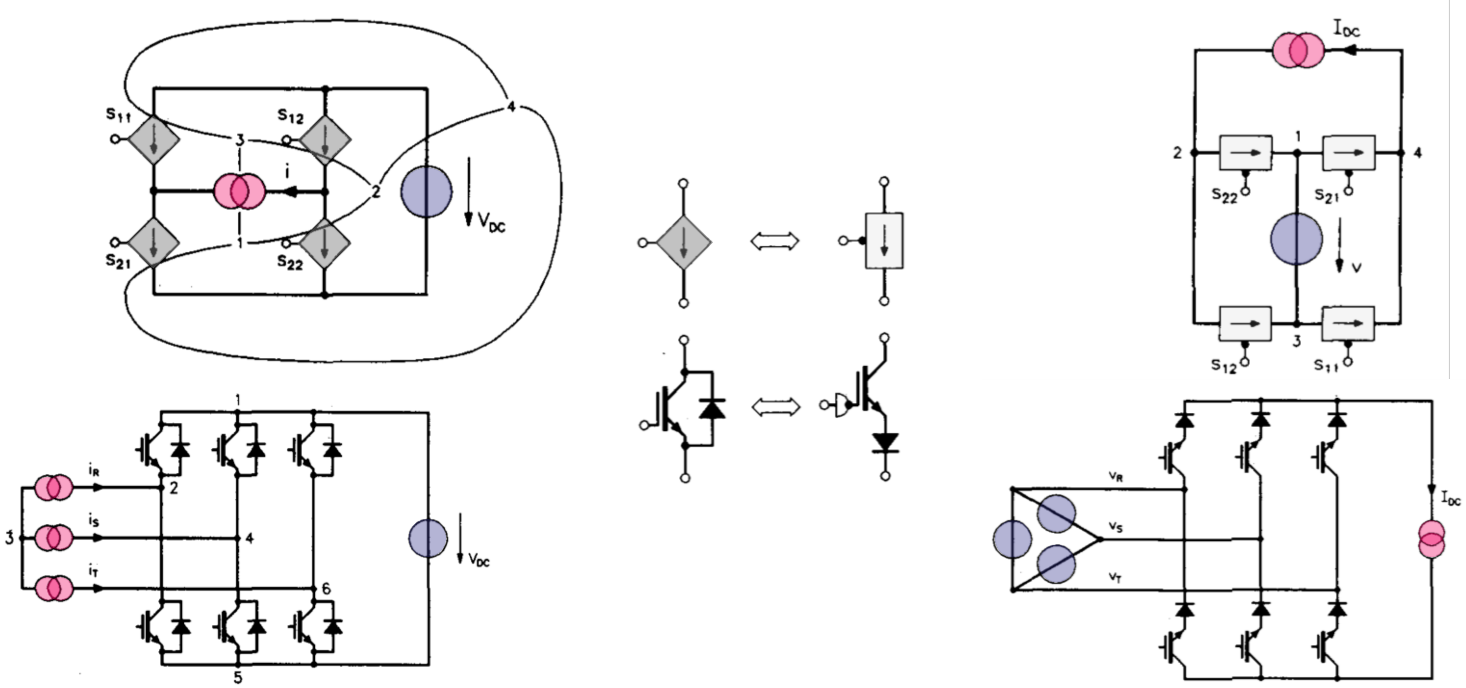
DUALITY

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*

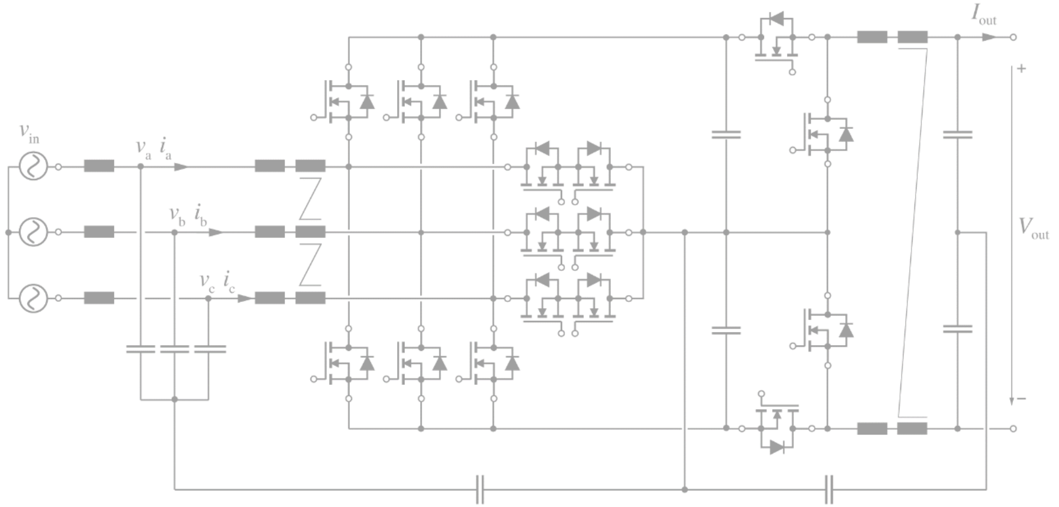
- *Duality of Voltage DC-Link & Current DC-Link Converter Circuits*
- *Unipolar Blocking / Bidir. Current → Bipolar Blocking Unidir. Switches → Appl. of M-BDSs (!)*

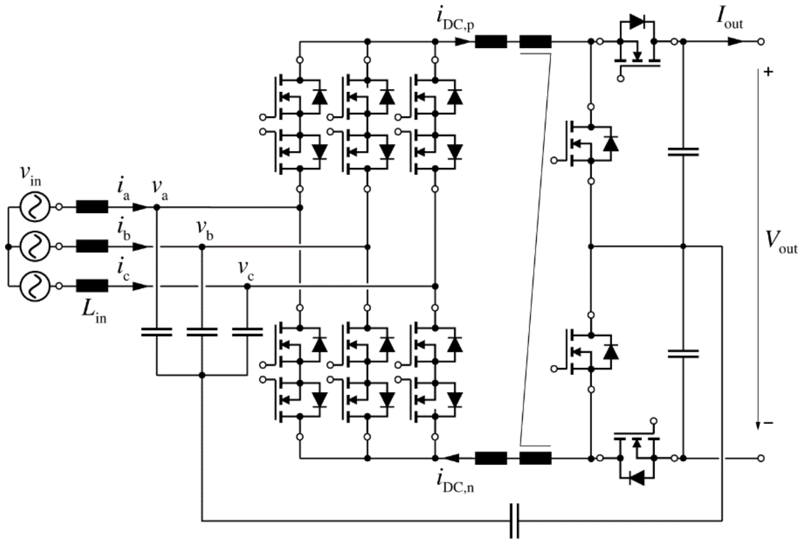


- *"Boost-Buck" Translated into "Buck-Boost" Functionality / Lower # of Ind. Components*

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*



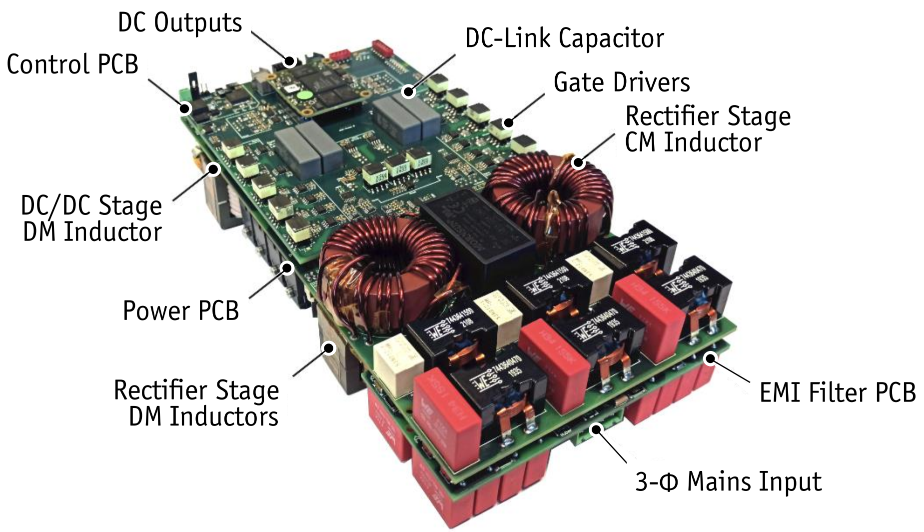


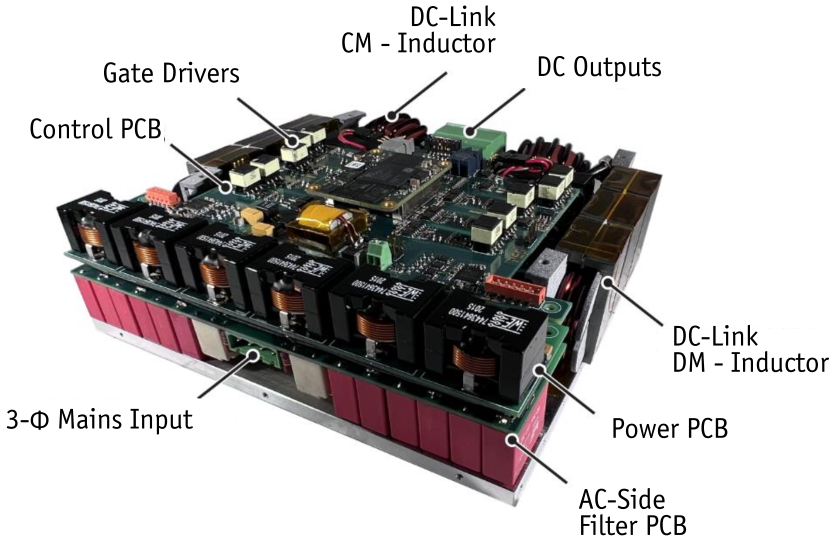
- *AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor → Min. # of Inductive Components*

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.*

- 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.*

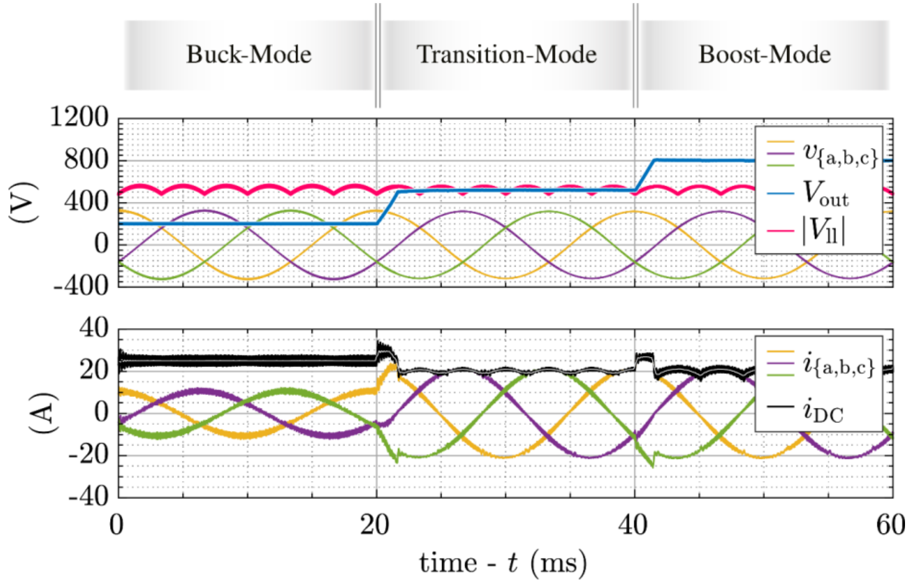


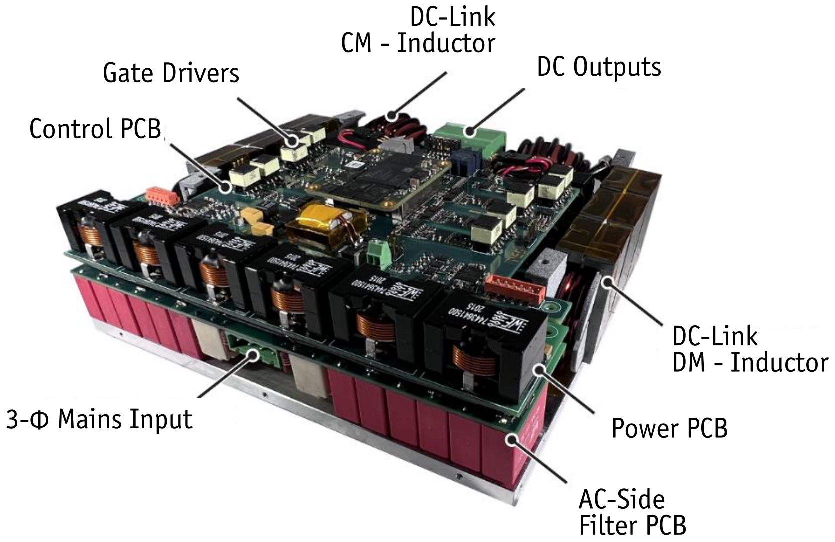


- ***Boost-Buck** Voltage DC-Link PFC Rectifier*
- ***Buck-Boost** Current DC-Link PFC Rectifier*

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.*

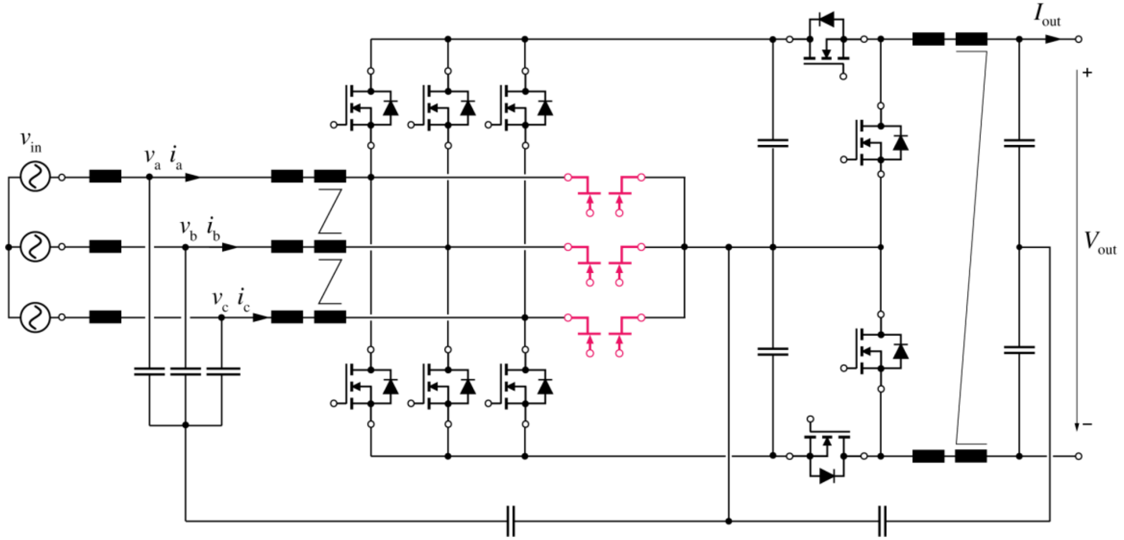


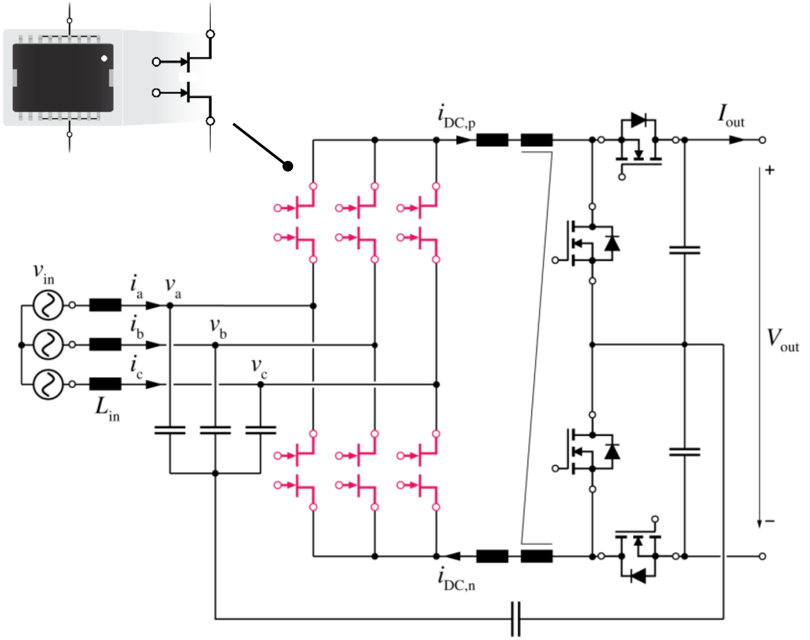


- *"Virtual Ground" Control of Output Voltage Midpoint → Non-Isolated EV Charger (!)*

Remark Application of M-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*



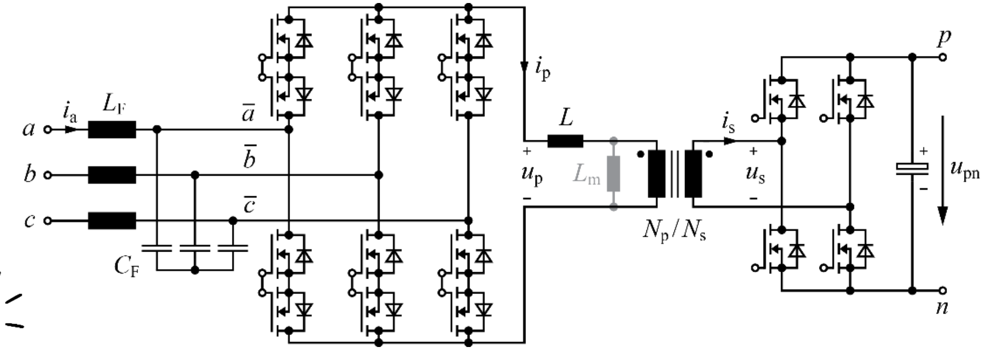


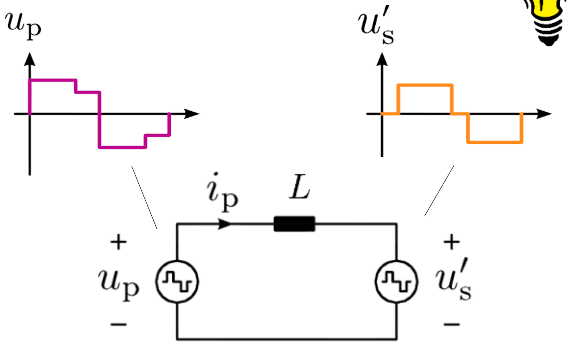
- 600 V *M-BDSs for Boost—Buck* & 1200 V *M-BDSs for Buck—Boost Combination @* 400 V_{rms} *Mains*

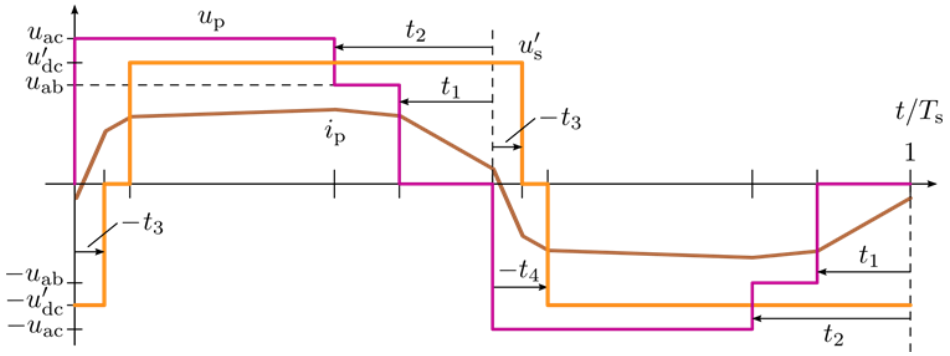
3-Φ Isolated Matrix-Type PFC Rectifier

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*





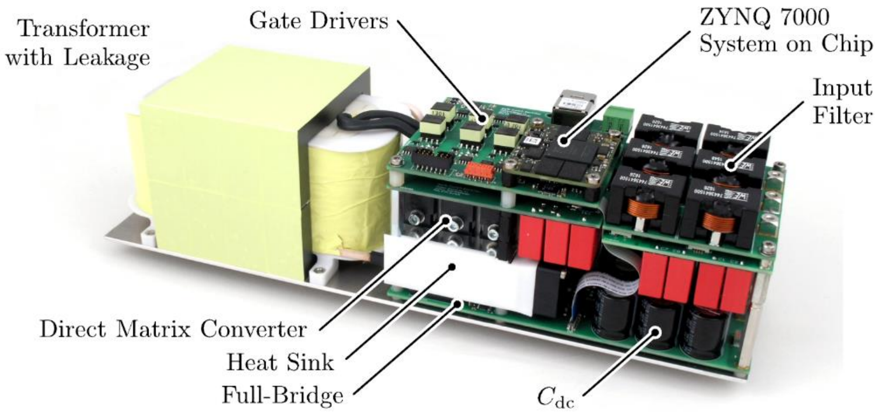


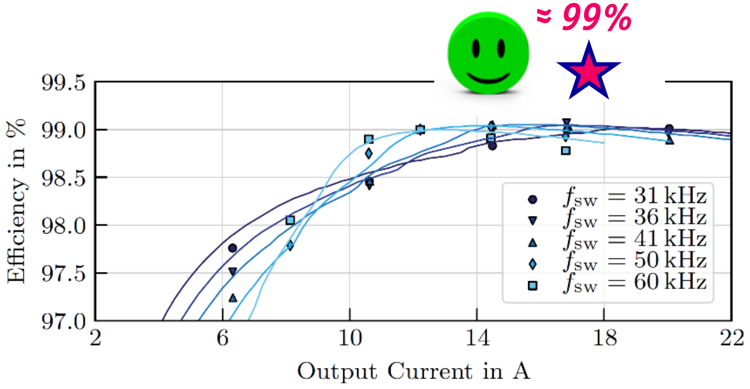
- *Equivalent Circuit*
- *Transformer Voltages / Currents*

Isolated Matrix-Type PFC Rectifier (2)

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

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

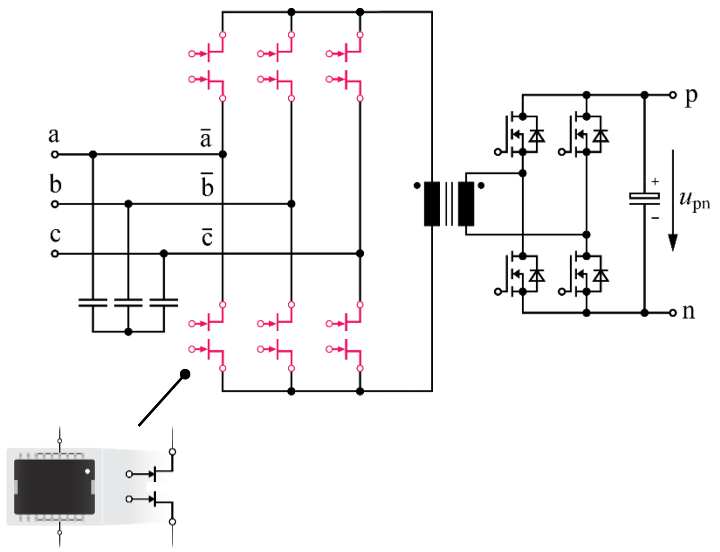


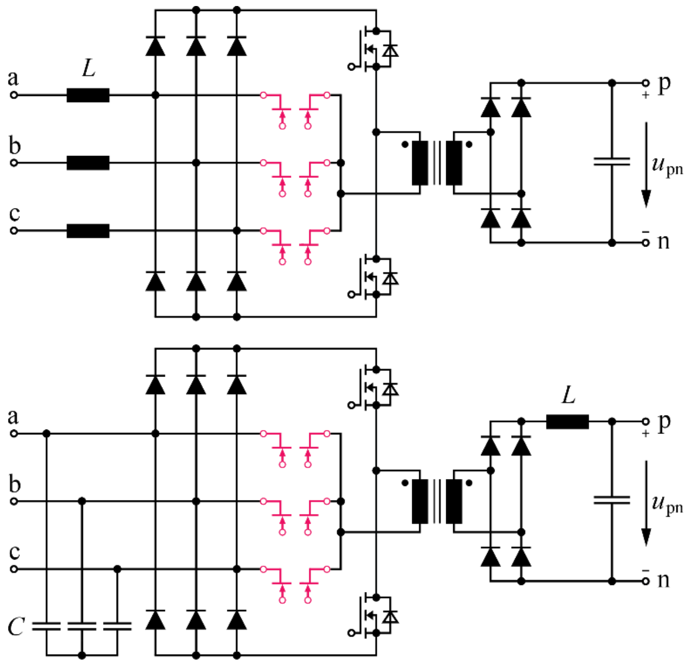


- 900V / 10mΩ SiC Power MOSFETs
- Opt. Modulation Based on 3D Look-Up Table

Remark Application of 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*

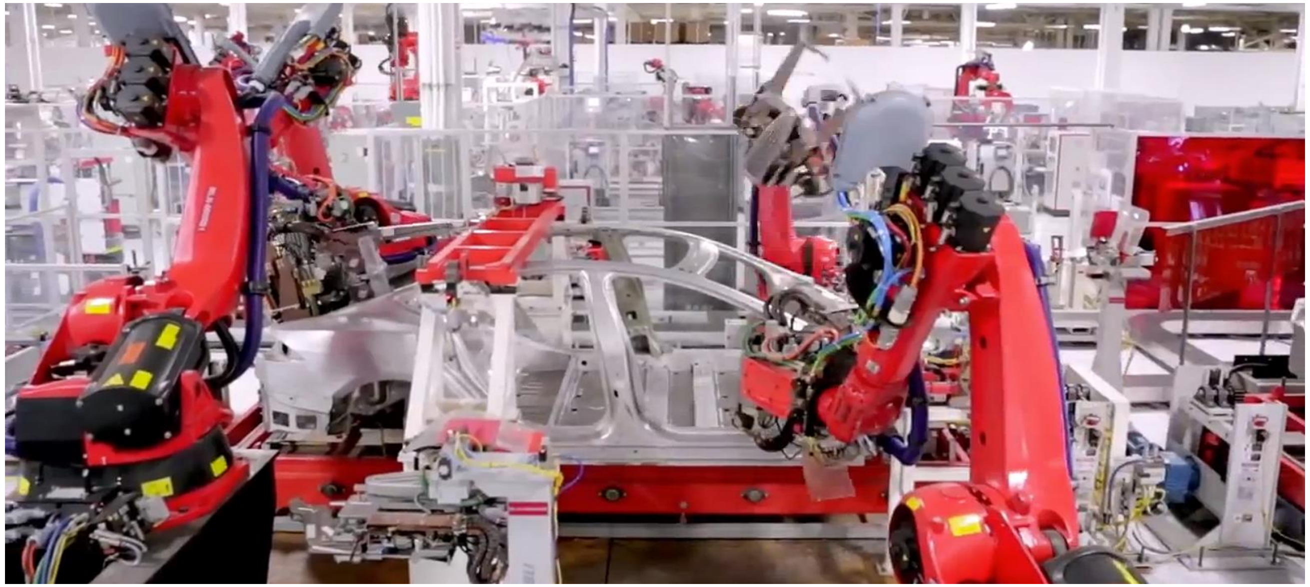
Global Megatrends

Digitalization
Renewable Energy
Sustainable Mobility
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 !*

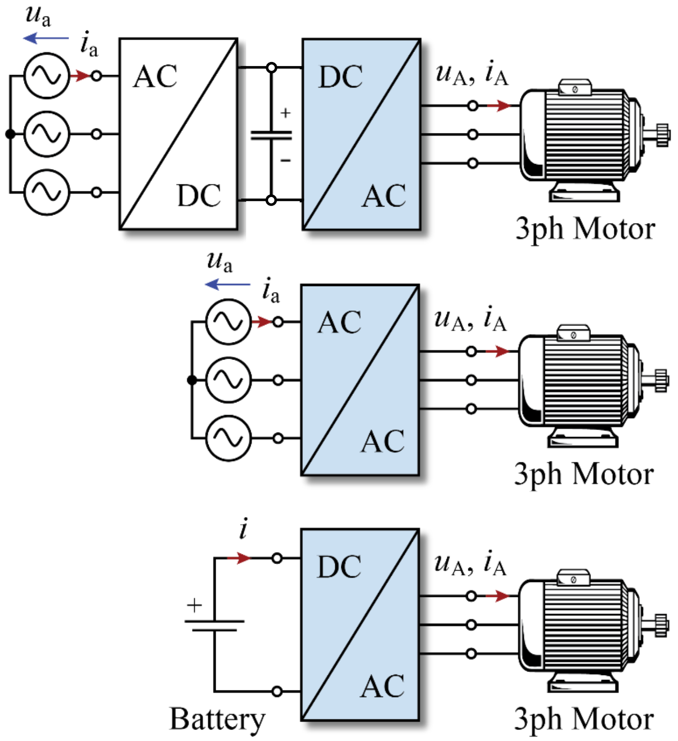
Source: TESLA MOTORS

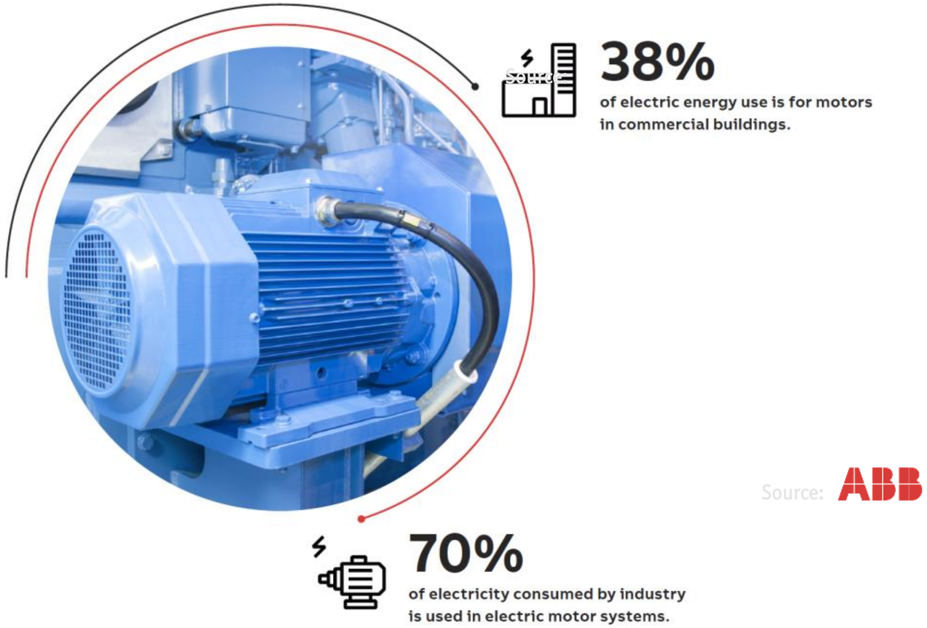


- *60...70 % of All Electric Energy Used in Industry Consumed by VSDs*

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*

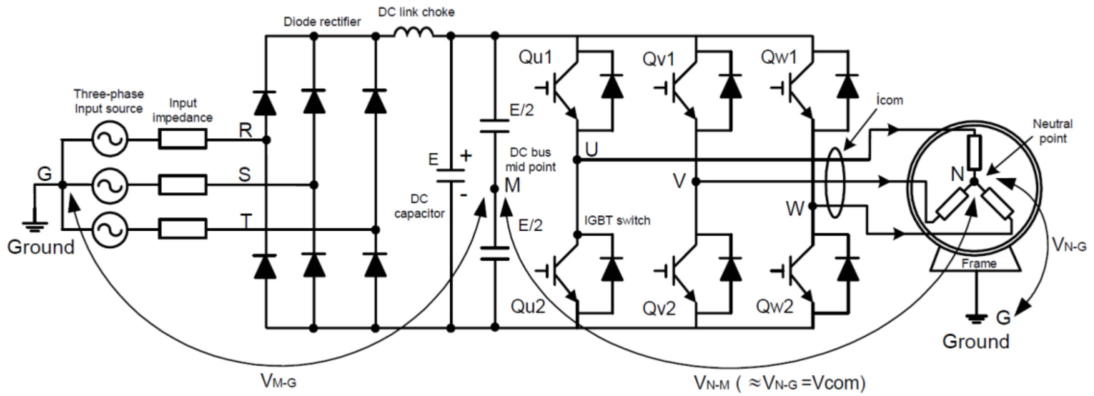




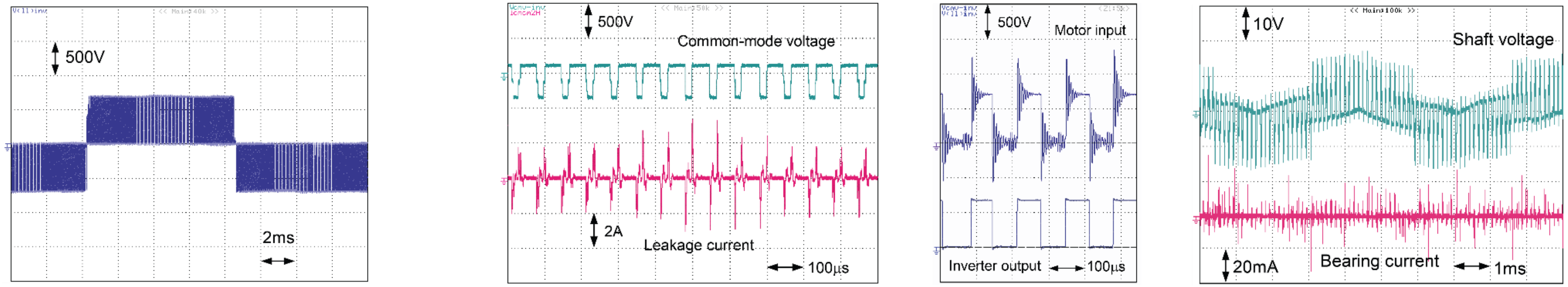
- *45% of World's Electricity Used for Motors in Buildings & Industrial Applications*

State-of-the-Art Drive System (1)

- *Standard 2-Level Inverter — Large Motor Inductance Allows Low Sw. Frequency*
- *Shielded Motor Cables / Cable Length Limited / Insulated Bearings / Acoustic Noise*



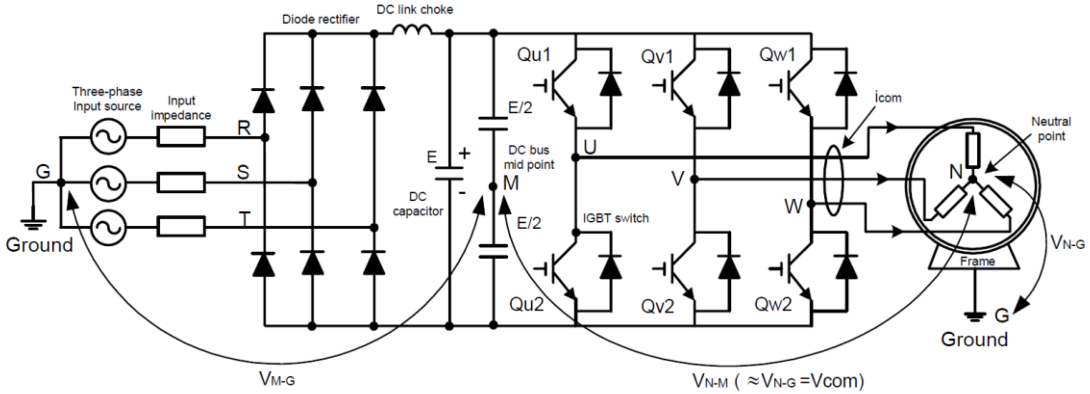
Source: YASKAWA

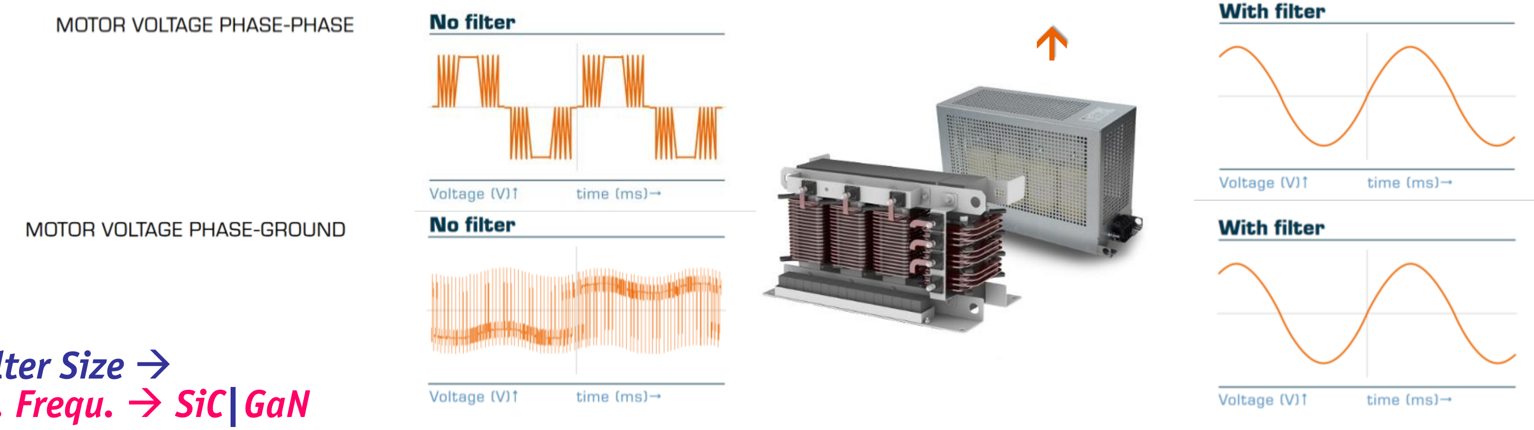


- *Line-to-Line Voltage* | *CM Leakage Current* | *Motor Surge Voltage* | *Bearing Current*

State-of-the-Art Drive System (2)

- *Measures Ensuring EMI Compliance / Longevity of Motor Insulation & Bearings*
- *Series Reactor | dv/dt-Filter | DM-Sinus Filter | Full-Sinus Filter | Multi-Level Inverter*



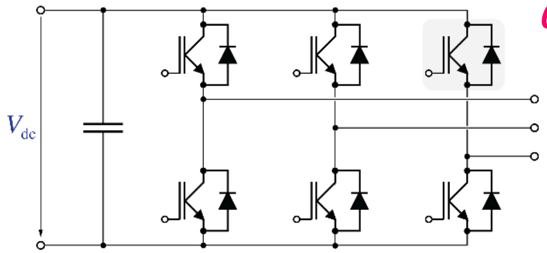


- *Small Filter Size →*
  High Sw. Frequ. → SiC | GaN

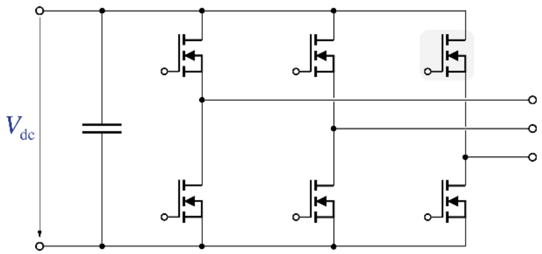
Si vs. SiC (1)

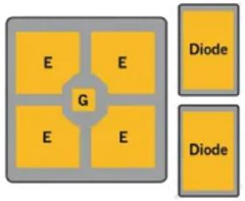
- *Si-IGBT / Diode → Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current*
- *SiC-MOSFET → Loss Reduction @ Part Load BUT Higher R_{th}*

6x Si-IGBT
6x Si-Diode



6x SiC-MOSFET





Source: ATZ elektronik

1200V 100A
Die Size: 98.8mm^2 + 39.4mm^2

Source: Infineon

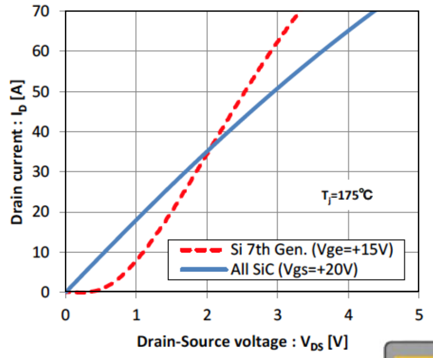
1200V 100A
Die Size: 25.6mm^2

Source: Cree

- *Space Saving of >30% on Module Level (!)*
- *Extremely High dv/dt → Motor Insul. Stress / Reflections / Bearing Curr. / EMI*

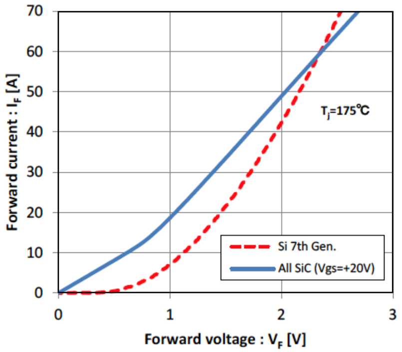
Si vs. SiC (2)

- *Si-IGBT / Diode → Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current*
- *SiC-MOSFET → Loss Reduction @ Part Load BUT Higher R_{th}*

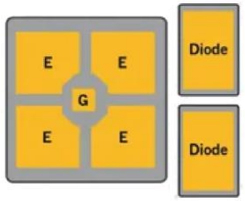


Source: Fuji Electric

Forward



Reverse



Source: ATZ elektronik

1200V 100A
Die Size: 98.8mm² + 39.4mm²

Source: Infineon

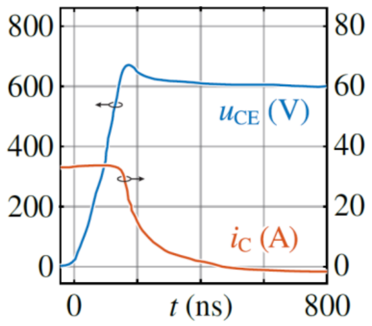
1200V 100A
Die Size: 25.6mm²

Source: Cree

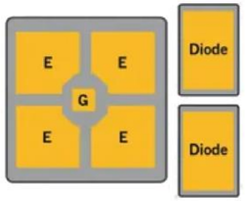
- *Space Saving of >30% on Module Level (!)*
- *Extremely High dv/dt → Motor Insul. Stress / Reflections / Bearing Curr. / EMI*

Si vs. SiC (3)

- *Si-IGBT / Diode* → *Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current*
- *SiC-MOSFET* → *Loss Reduction @ Part Load BUT Higher R_{th}*



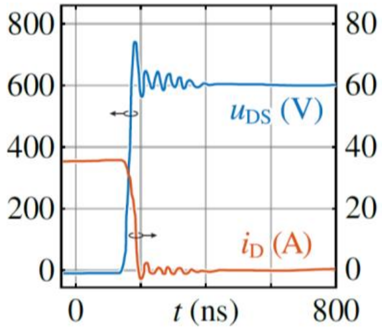
Source: Fuji Electric



Source: ATZ elektronik

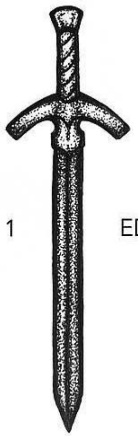
1200V 100A
Die Size: 98.8mm² + 39.4mm²

Source: Infineon



1200V 100A
Die Size: 25.6mm²

Source: Cree



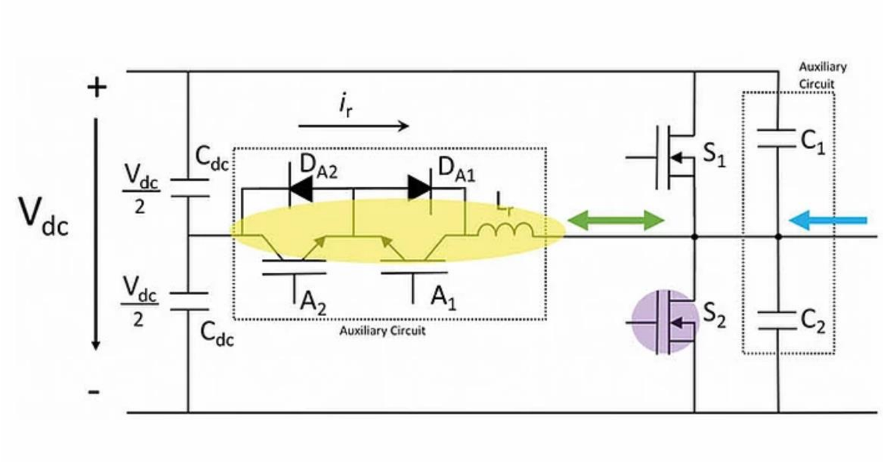
- *Space Saving of >30% on Module Level (!)*
- *Extremely High dv/dt* → *Motor Insul. Stress / Reflections / Bearing Curr. / EMI*

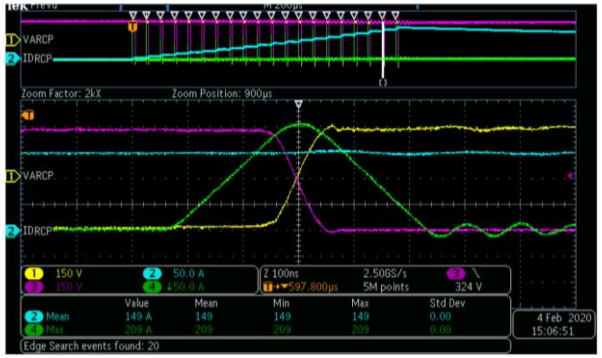
Inverter Output Filters

dv/dt-Filters
Full-Sinewave Filters

Aux. Resonant Commutated Pole

- *dv/dt-Limitation & Sw. Loss Red. w/ Snubber Cap. & Aux. Switches → 1 … 1.5 kV/us*
- *Opt. Timing of Aux. & Main Switches → Pre-Flex™ Self-Learning AI Algorithm*
- *Concept Proposed for BJTs by M. Lockwood & A. Fox @ IPEC 1983 (!)*





Pre-Switch, Inc.
We take the hard out of switching.

Green: Lr Resonant inductor current (varies with load)

Purple: S2 Vds switch voltage (600V-0V)

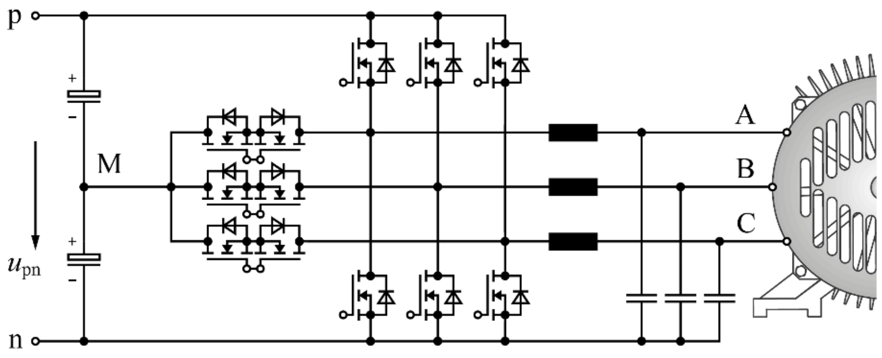
Yellow: Aux + Lr ARCP and inductor voltage (-300V to +300V)

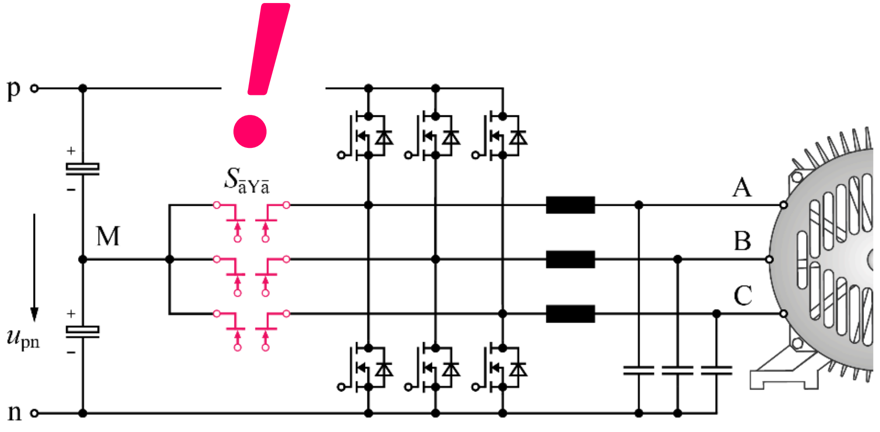
Blue: Load current varies 0-160A

- *Complicated Implementation / Critical Timing for f_{sw} > 100kHz*
- *99.5% Half-Load | 99.35% Full-Load Eff. @ 100kW, 800V_{DC}, f_{sw}= 50kHz (1200V/12mΩ SiC MOSFETs)*

Full-Sinewave LC Output Filter

- *3-Level T-Type Inverter — 3-Level Phase Voltage / 5-Level Line-to-Line Voltage*
- *Neutral Point Clamped | Flying Capacitor | T-Type Bridge-Leg Topology*
- *Lower CM Voltage Steps Compared to 2-Level Converter*





- *DC-Link Referenced LC-Filter — Elimination of DM & CM Sw. Frequ. Output Voltage Harmonics*
- *T-Type Topology Ensures Low Conduction Losses — Adv. Application of M-BDSs (!)*

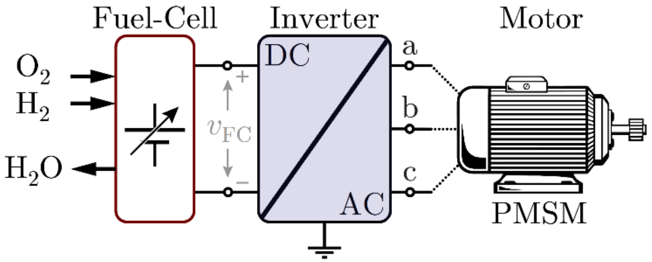
Buck-Boost Functionality

Motivation

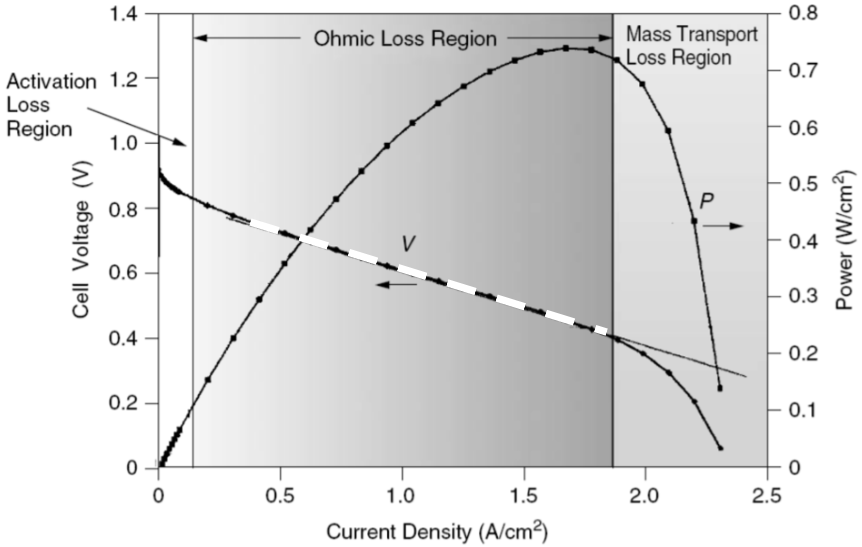
- *General / Wide Applicability*

— *Adaption to Load-Dependent Battery | Fuel Cell Supply Voltage*
— *Operation in Wide Output Voltage / Wide Motor Speed Range*

Source: magazine.fev.com



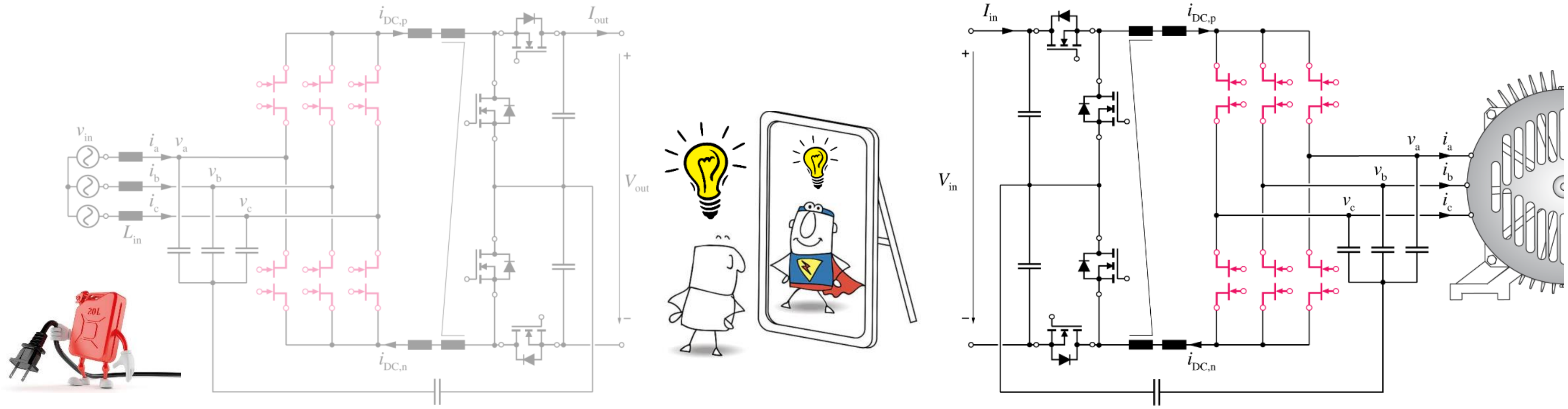
Source: www.chegg.com



- *Full-Sinewave Filtered Motor Supply Voltage*
- *LC Output Filter Inductor Advantageously Utilized as Buck-Boost-Inductor*

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

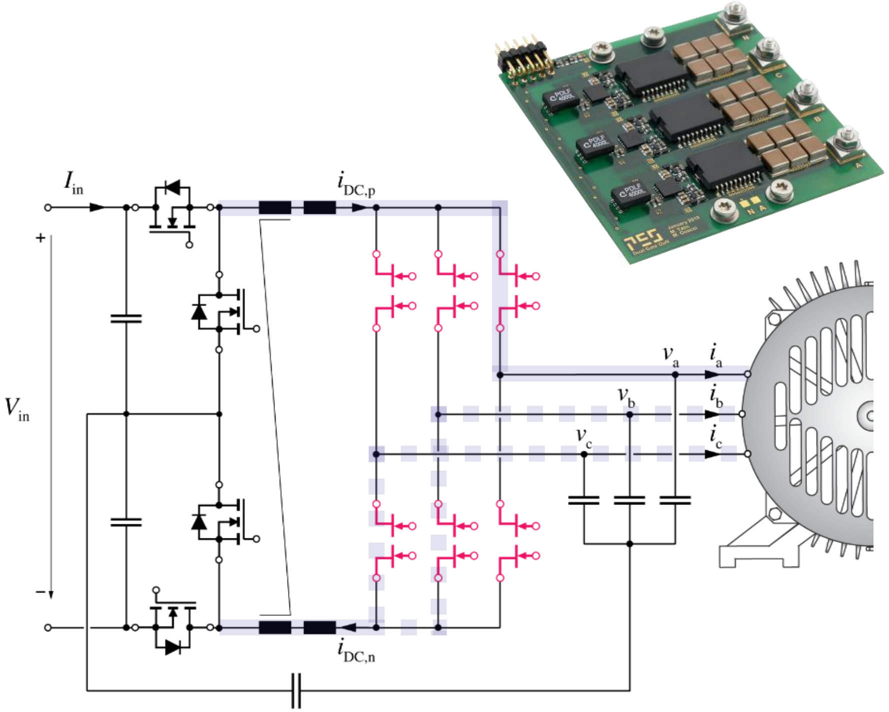
- *Derivation Based on Bidirectional Buck-Boost PFC Rectifier Topology (EV Charger)*
- *Lower # of Ind. Components Compared to Boost-Buck Approach*

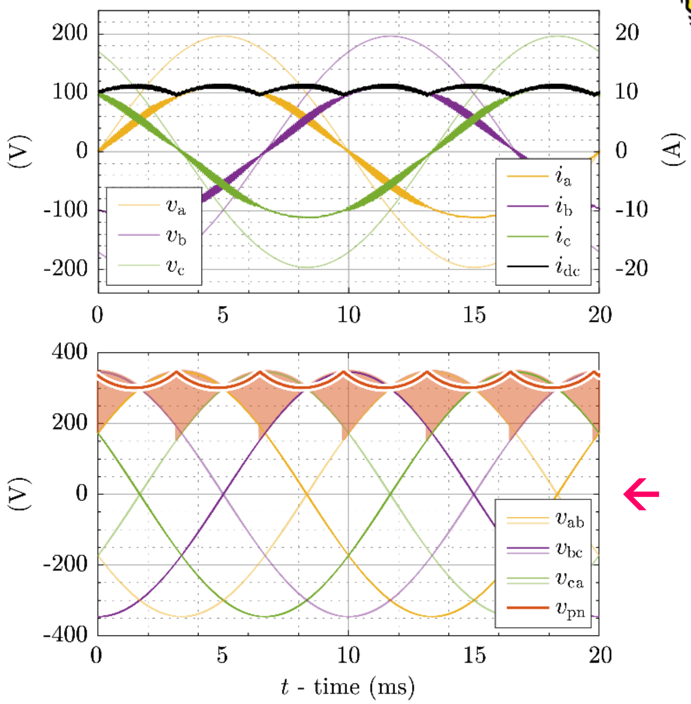


- *DC/DC Buck Converter Performs Voltage → Current Translation*
- *Coordinated Control / Modulation of DC/DC & Inverter Stage for Min. Sw. Losses*

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

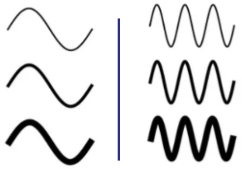
- *"Synergetic" Control of DC/DC Buck Converter & Current DC-Link Inverter Stage*
- *6-Pulse-Shaping of DC Current by Buck-Stage → Allows Inverter Phase Clamping*





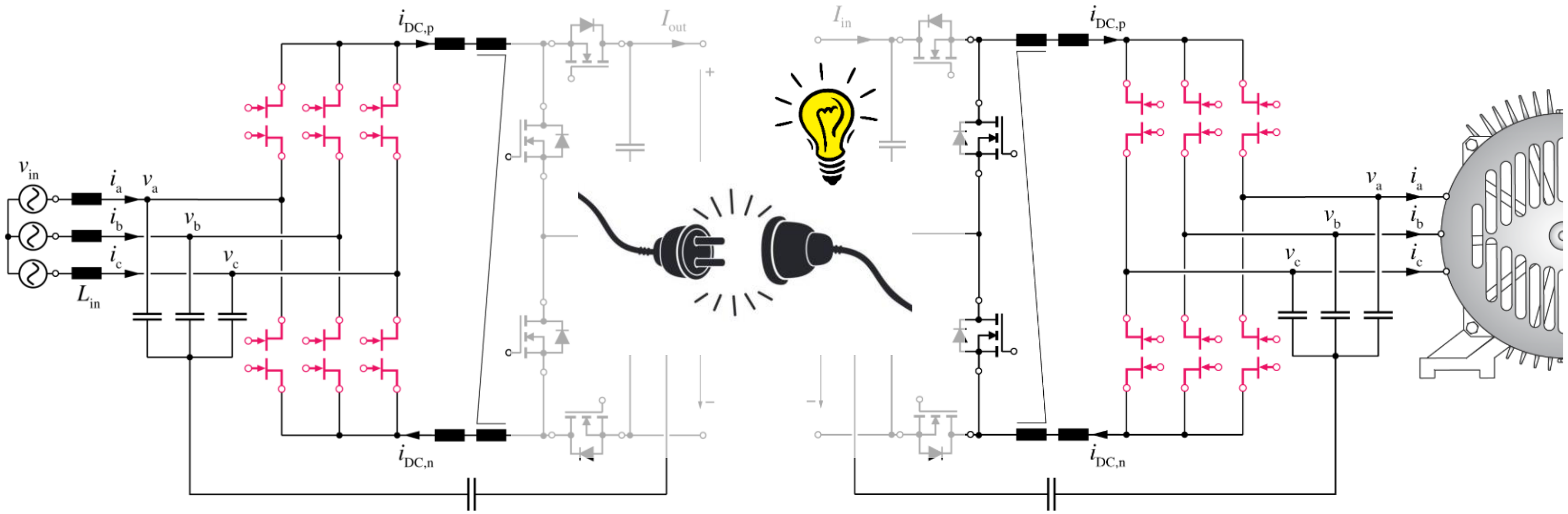
- *Switching of Only 2 of 3 Phase Legs → Reduction of Sw. Losses by ≈ 86% (!)*

3-Φ AC/AC Conversion



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

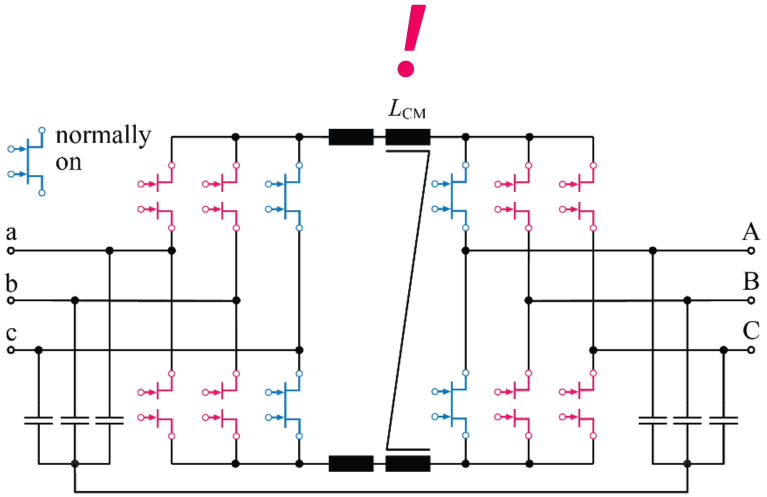
- DC-Side Coupling of Buck-Boost Current DC-Link PFC Rectifier & Inverter — AC/DC/AC
- Full Sinewave Filtering @ Input & Output w/ Single Magnetic Component



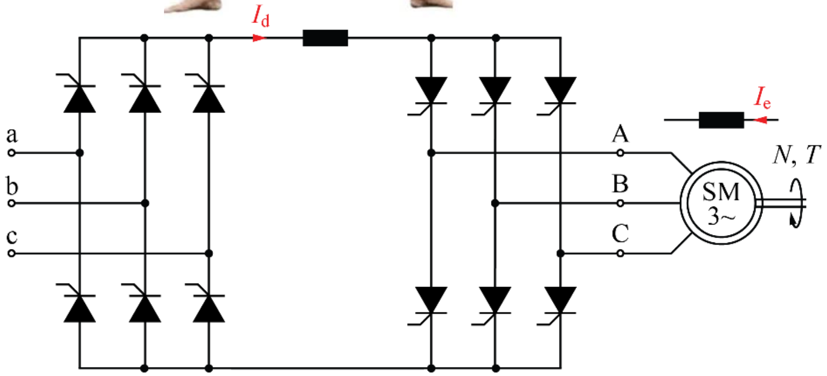
- Bipolar Blocking / Unidir. Switches / Unidir. DC-Link Current Sufficient for Bidir. Power Conversion
- Modulation-Based Inversion of DC-Link Voltage Polarity → Inv. of Power Flow Direction

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

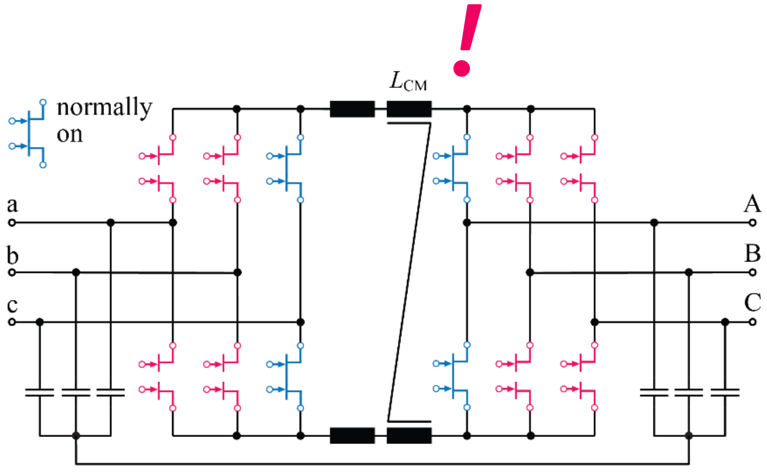


- *Relation to High-Power Thyristor-Based Medium Voltage Synchr. Machine Variable Speed Drives*

DUALITY

Current DC-Link Topology

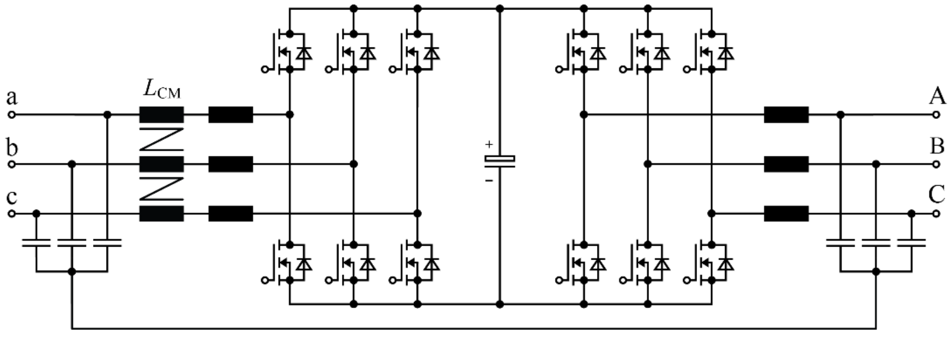
- Application of M-BDSs
- Complex 4-Step Commutation
- Low Filter Volume



- 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



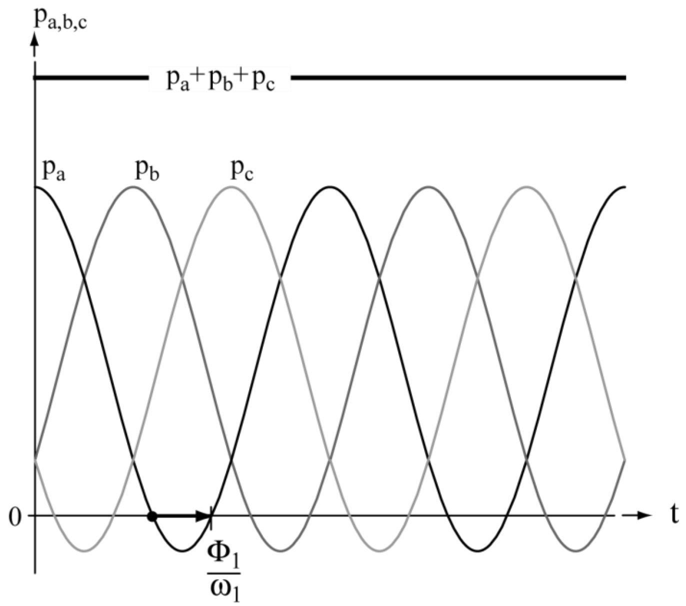
- High Input / Output Filter Volume

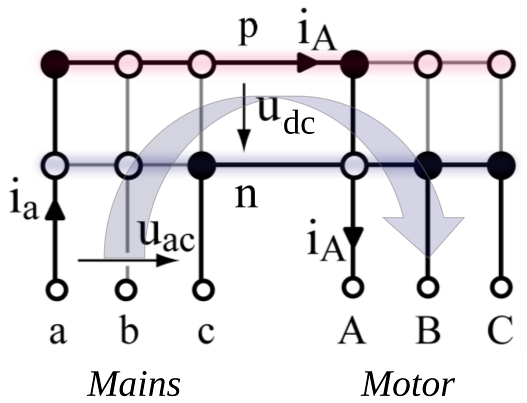
3-Φ AC/AC
Matrix Converter

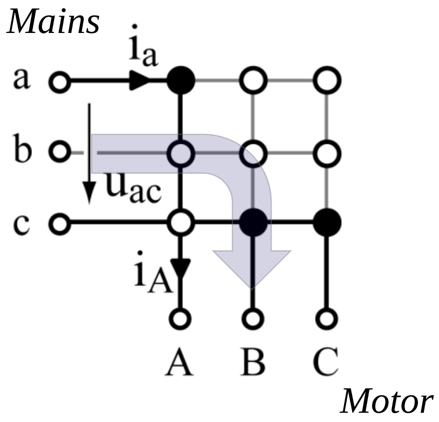
$$\begin{Bmatrix}1&0&0\\0&0&0\\0&1&1\end{Bmatrix}$$

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

- *Constant 3-Φ Instantaneous Power Flow → No Low-Frequ. DC-Link Power 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*



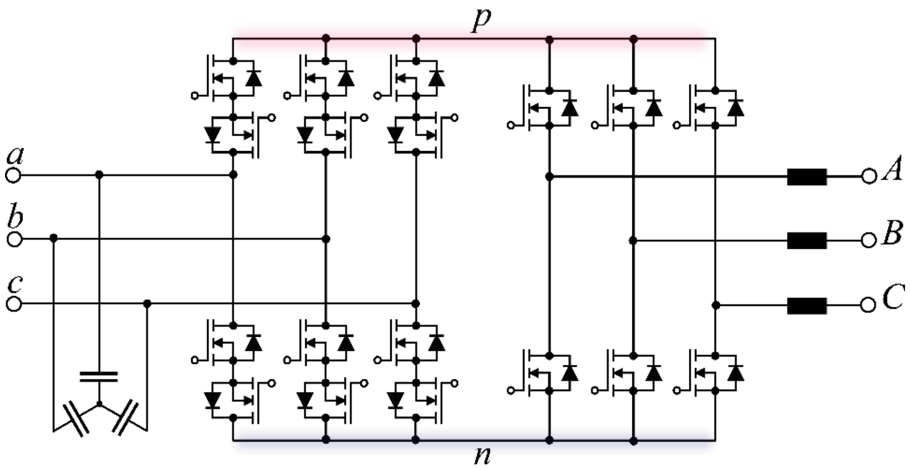


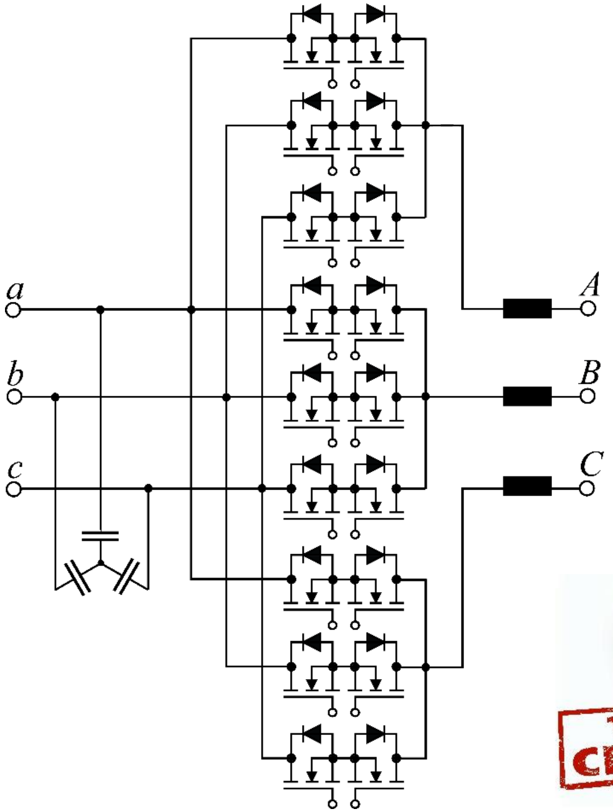


- *Output-Side Motor Inductor → Operation Limited to Buck-Type (Step-Down) Voltage Conversion*

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

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

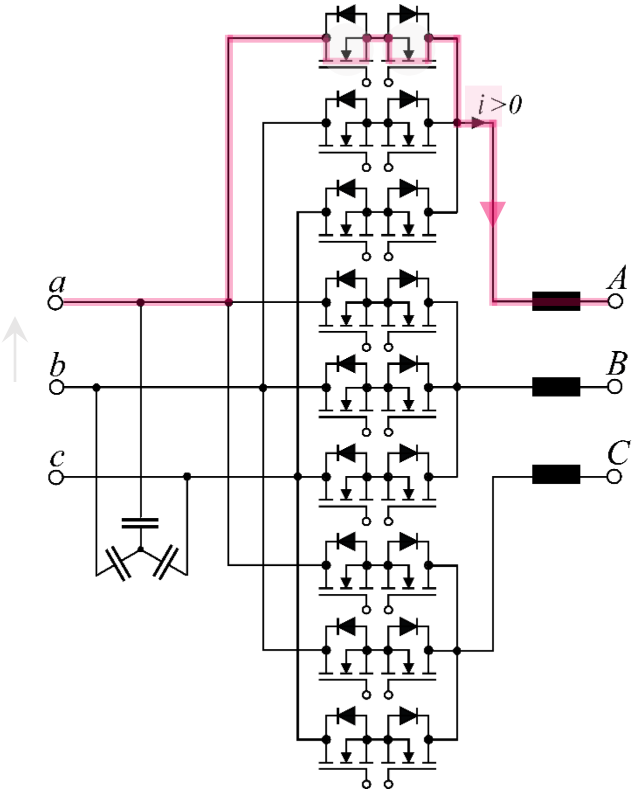




- IMC Relies on Strictly Pos. DC-Link Voltage / i=0 Input Stage Commutation
- M-BDS-Based Realization of DMC Features Lower # of Switches / 4-Step Commutation Required

4-Step Commutation of DMC

- *Example* *i-Dependent Commutation*
  $aA \rightarrow bA$ @ $i > 0$



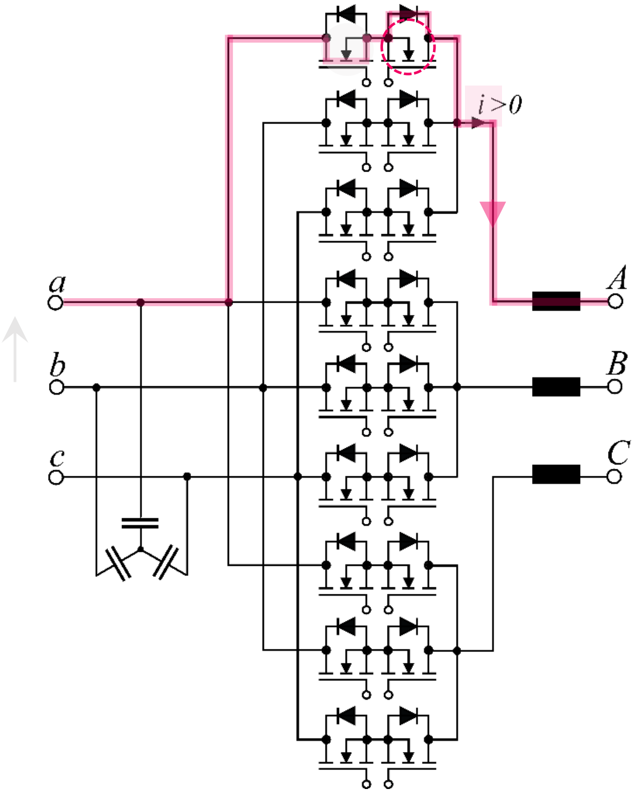
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (1)

- *Example* *i-Dependent Commutation*
  aA → bA @ i > 0

1st Step: Off



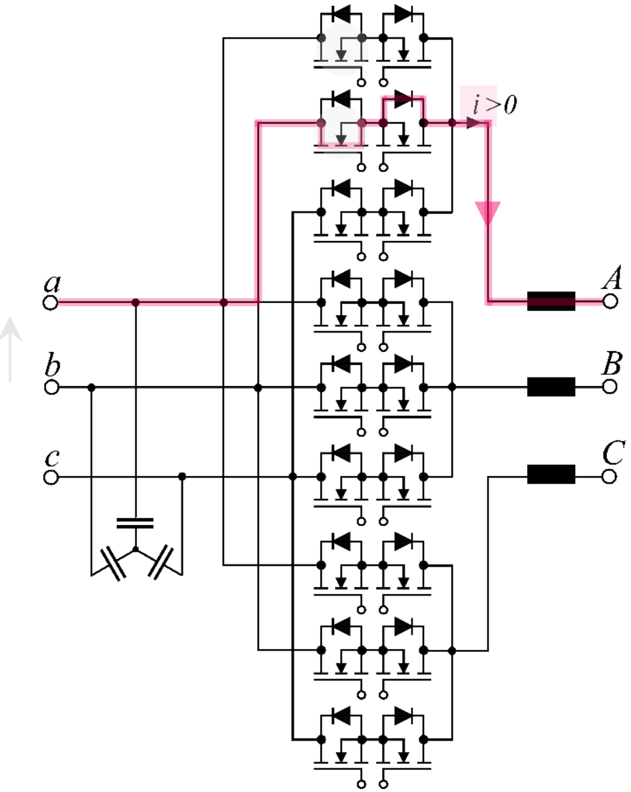
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (2)

- *Example* — *i-Dependent Commutation*
  aA → bA @ i > 0

1^{st} Step: Off
2^{nd} Step: On



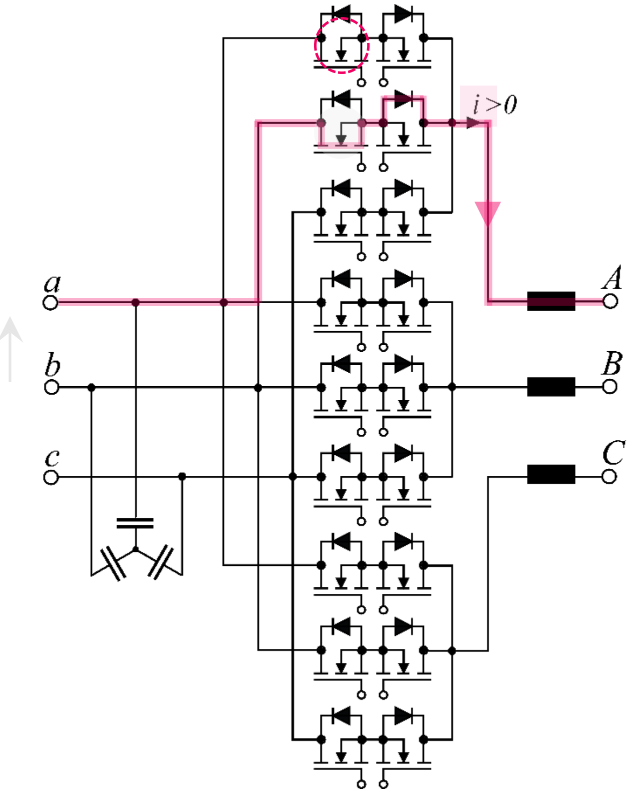
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (3)

- *Example* *i-Dependent Commutation*
  $aA \rightarrow bA$ @ $i > 0$

1st Step: Off
2nd Step: On
3rd Step: Off

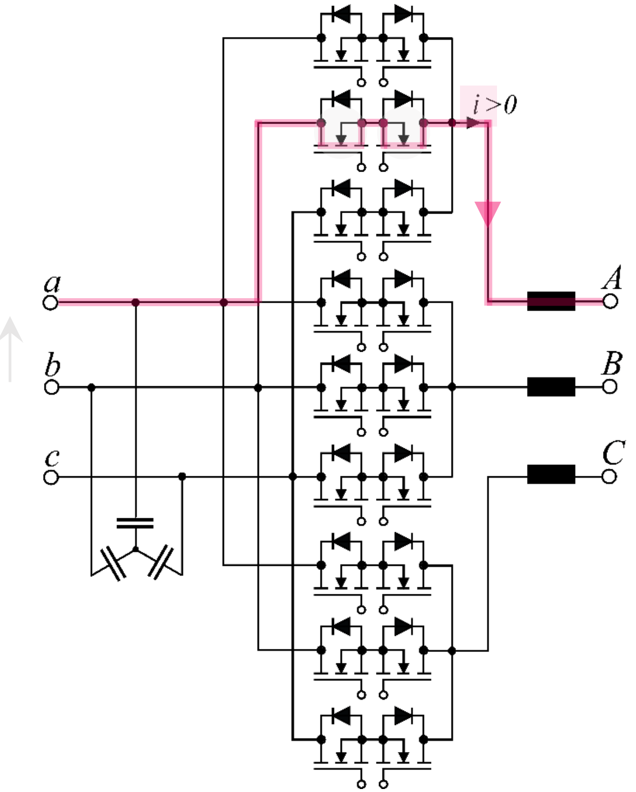


- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (4)

- *Example* *i-Dependent Commutation*
  $aA \rightarrow bA$ @ $i > 0$



1st Step: Off
2nd Step: On
3rd Step: Off
4th Step: On

- *No Mains Short Circuit*
- *No Load Current Interruption*

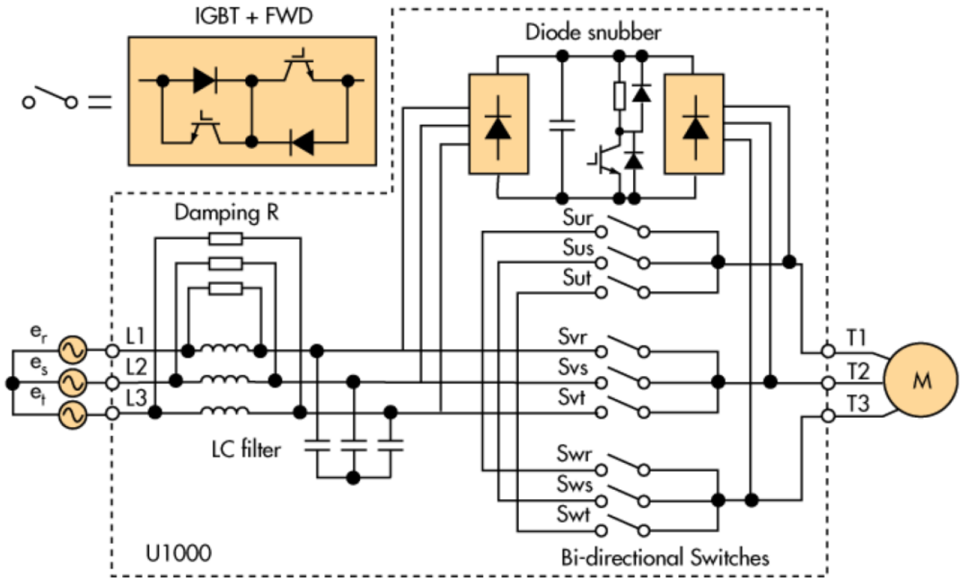
Assumption $u_{ab} < 0$

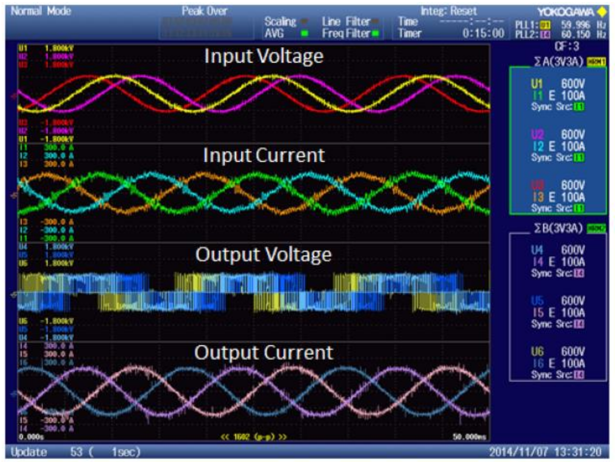
Industry Application of 3-Φ Matrix Converter

- *Fully Regenerative → e.g. Downhill Conveyor etc.*
- *Higher Power Density Compared to Voltage DC-Link System / No Front-End Boost Inductors*
- *Quasi Three-Level Output Characteristic*
- *No-Switching / Eco Operation for f_2=f_{Mains}*
- *Close to Unity Power Factor*

Source: YASKAWA

U1000



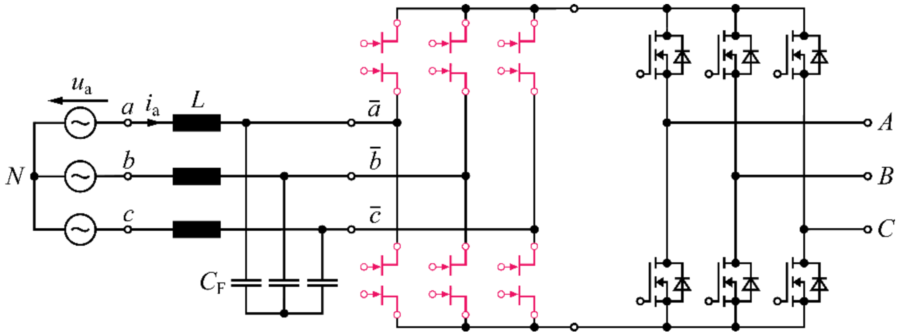


- *Challenging Overvoltage Protection*
- *Limited Output Voltage Range (!)*

Remark 3-Φ AC/AC Matrix Converter

■ *Indirect Matrix Converter (IMC)*

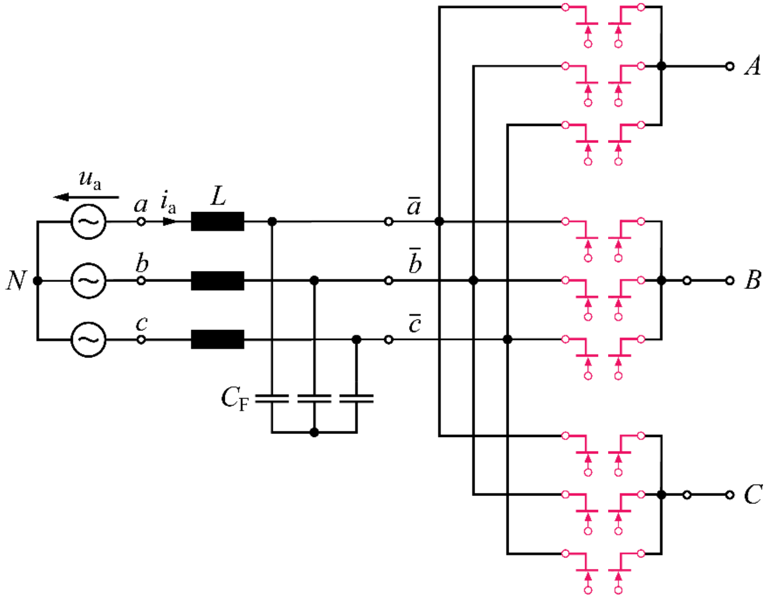
- GaN M-BDS AC/DC Front-End
- ZCS Commutation of AC/DC Stage @ i_{DC}=0
- No 4-Step Commutation



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

■ *Direct Matrix Converter (CMC)*

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

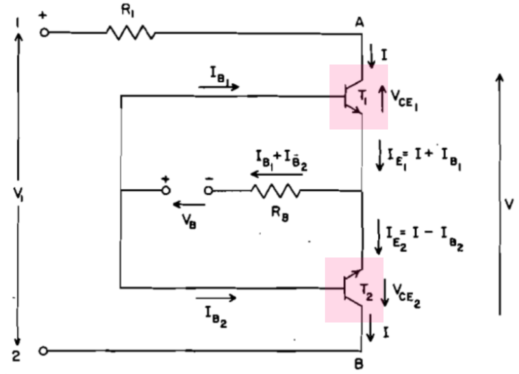


- Thermally Critical @ $f_{out} \approx f_{in}$

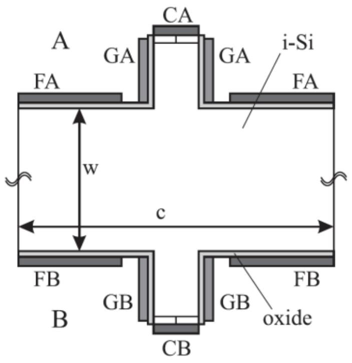
Selected SiC M-BDS R&D Activities

Early Si-BDS Realizations

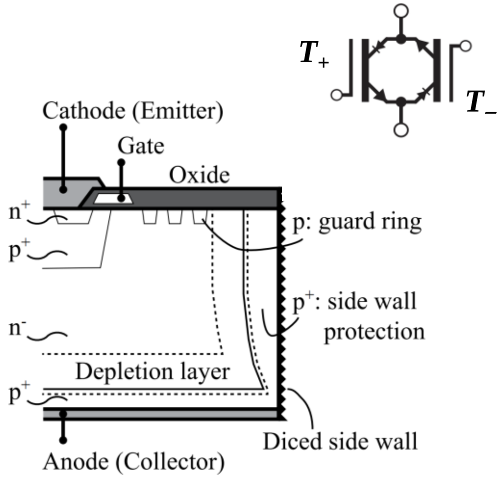
- *Combination of Unidirectional Devices — 4x Chip Area (MOSFETs) | Costs &/OR High On-State Volt. Drop*
- *"True" M-BDS — Single Drift Region for Blocking Voltages of Both Polarities | 2 Gates | Bidir. Curr. Cond.*



— BJT Inverse-Series AC-Switch
Jones & Bose, **1976**



— Monolithic Bidir. MOS-Switch (Simul.)
Heinke & Sittig, **2000**

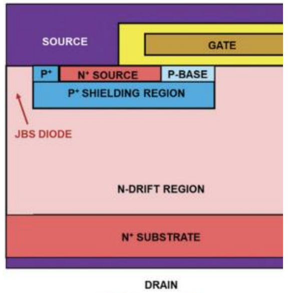


— Reverse-Blocking IGBT (RB-IGBT)
Fuji Electric, **2001**

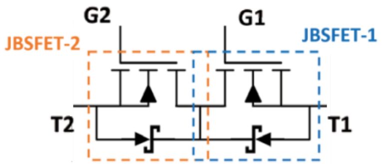
- *A "Monolithic" Bidirectional Switch (M-BDS) IS NOT Necessarily a "True" M-BDS (!) – "TM-BDS"*
- *TM-BDS — Common Drift Region Formed by Back-to-Back Wafer Bonding OR 2-Side Lithography Processing*

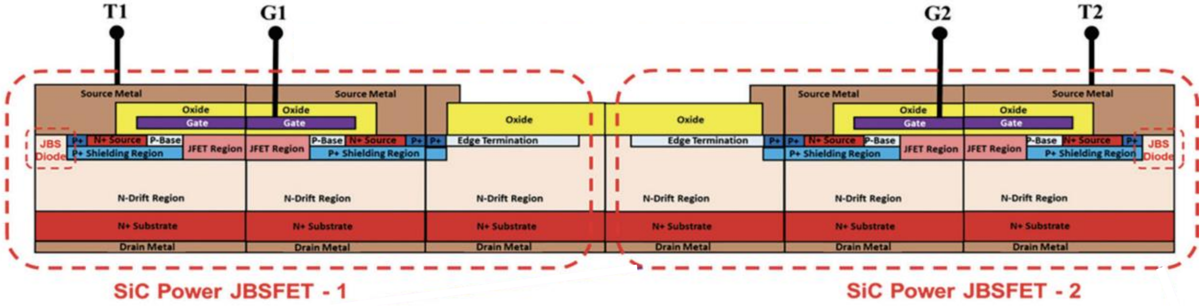
Monolithic 4-Terminal 1.2kV/20A SiC BiDFET

- *BiDFET — Two JBSFETs w/ Drains Connected via Common N^+ Substrate & Metallization | 50mΩ*
- *Junction Barrier Controlled Schottky (JBS) Diode Integr. into MOSFET — Prev. Curr. Flow via Body Diode*

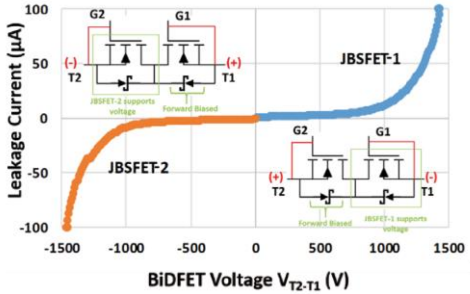


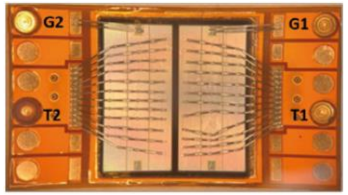
2016 SiC Planar-Gate JBSFET





Baliga et al., 2020

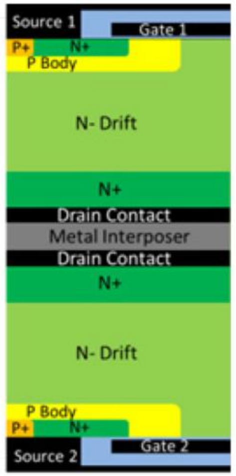


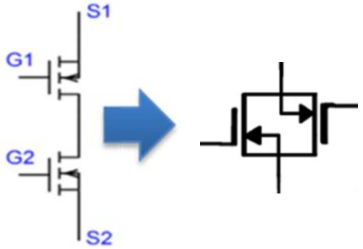


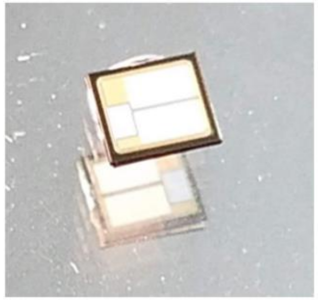
- *JBSFET — Low Sw. Losses & No Bipolar Degradation | Drift Layer of JBSFET-1 Blocks Pos. / JBSFET-2 Neg. Voltage*
- *A Monolithic Bidirectional Switch (M-BDS) IS NOT Necessarily a "True" M-BDS (!)*

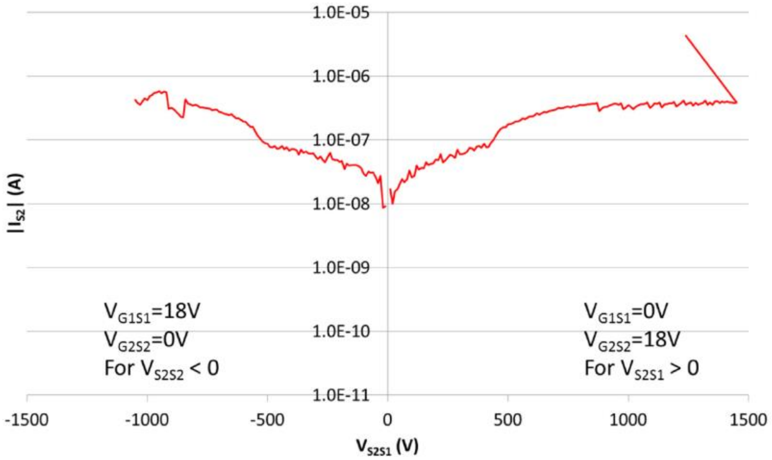
Common Drain Bidirectional 1.2kV SiC MOSFET

- *Direct Drain-to-Drain Connection of 2 MOSFET Bare Dies — Space-Efficient Comp. to Side-by-Side Pair*
- *Alternative to Semiconductor-to-Semiconductor Bonding / Low Fabrication Complexity*
- *Challenging Packaging & Cooling*









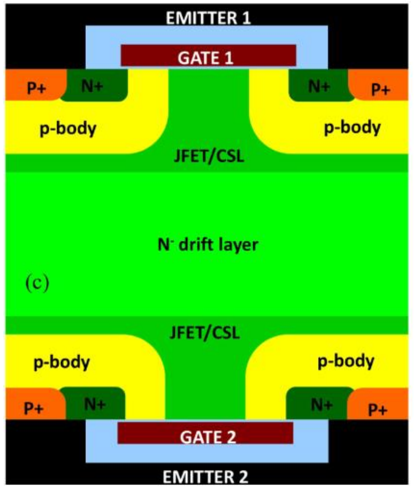
Chow et al., 2020

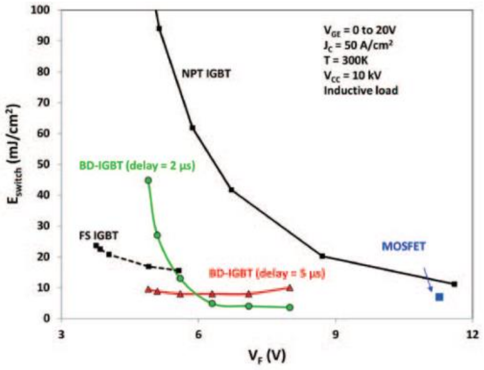
- *Blocking Capability Close to Rating of the Component MOSFETs*
- *Joining of the Existing Drain Metallizations — 2 Drift Regions — No "Monolithic"-BDS*

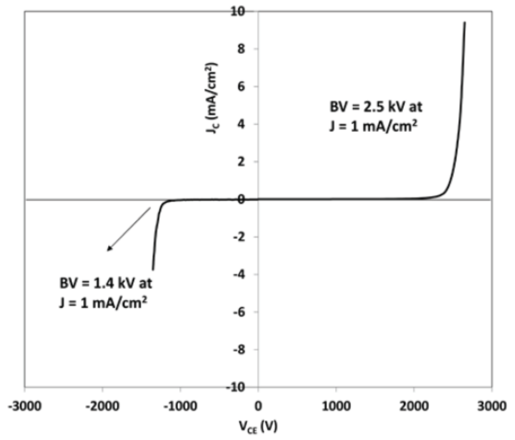
Monolithically Integrated Bi-Directional SiC IGBT

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

Chow et al., 2016



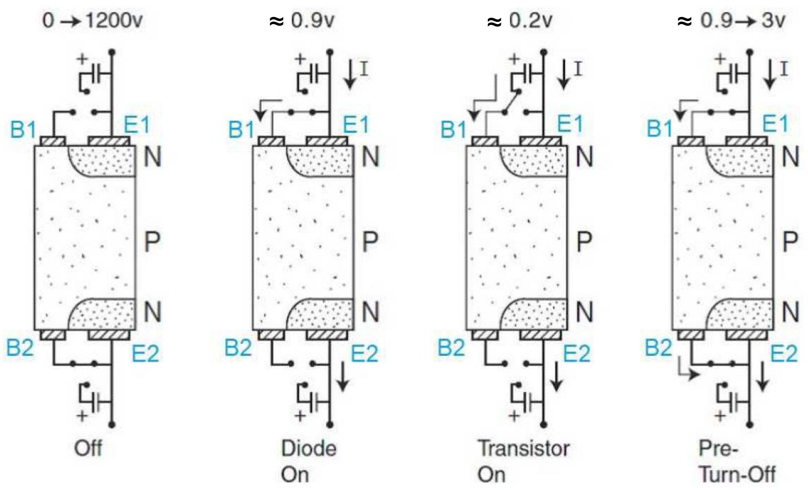


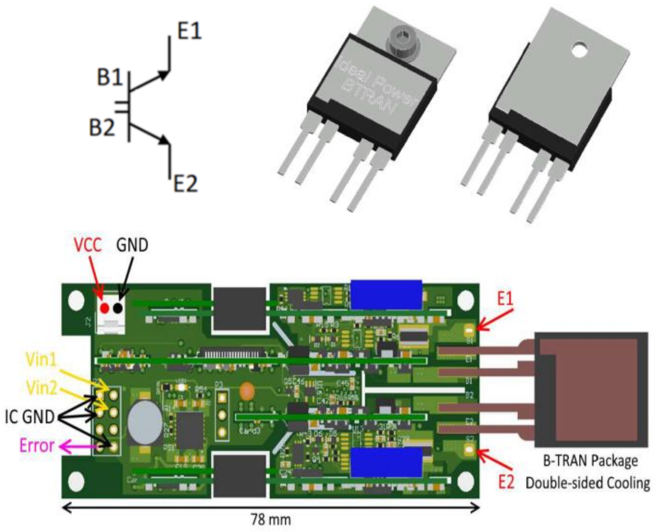


- *Simul. Performance of a 15kV BD-IGBT | Blocking Characteristic (max. 7.2 kV Meas.) – Epi Layer Defects etc.*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

1.2kV Bidir. Bipol. Junction Transistor (B-TRAN^{TM})

- *Back-to-Back Si-BJTs with Merged Collector Regions | Upcoming SiC Version*
- *1200 V / 25A @ 100°C Samples | Typ. 0.6 V On-State Voltage | Curr. Gain Typ. 3…4*



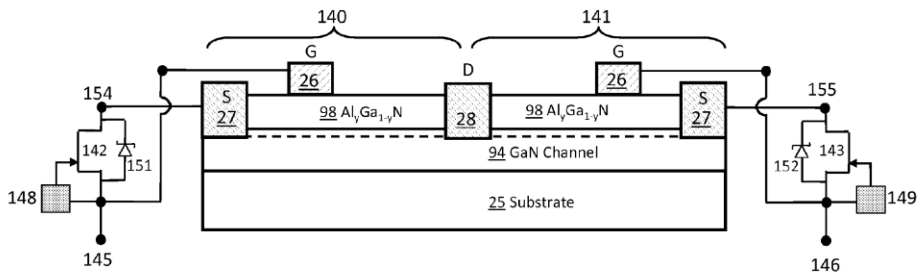


Knapp et al., 2022

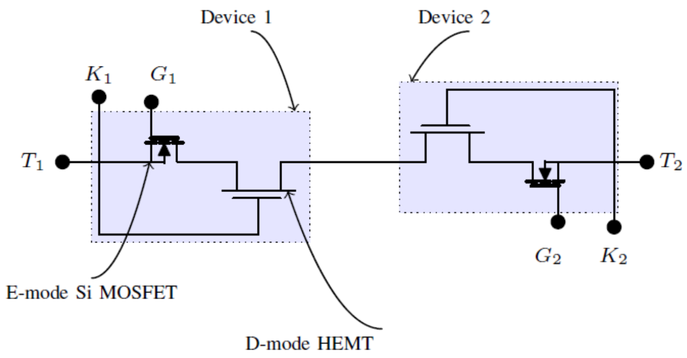
- *Rel. Complex Bidir. Gate-Drive / Special 4-Terminal TO-264 Package w. Double-Sided Cooling*
- *Shared Collector Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

Cascode GaN 4Q-Switch

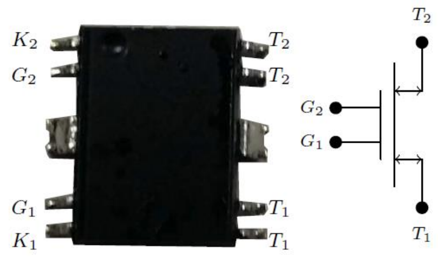
- *Common-Drain Arrangement of Two Cascode Switches (600 V GaN D-Mode HEMT + LV Si E-Mode MOSFET)*
- *Up to 1200 V, 200 mΩ Samples for Demonstration Purposes*



Honea et al., 2008



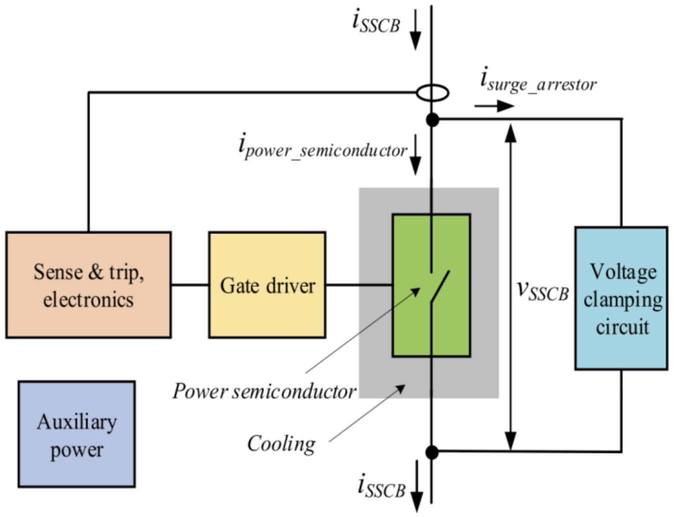
transphorm
2017



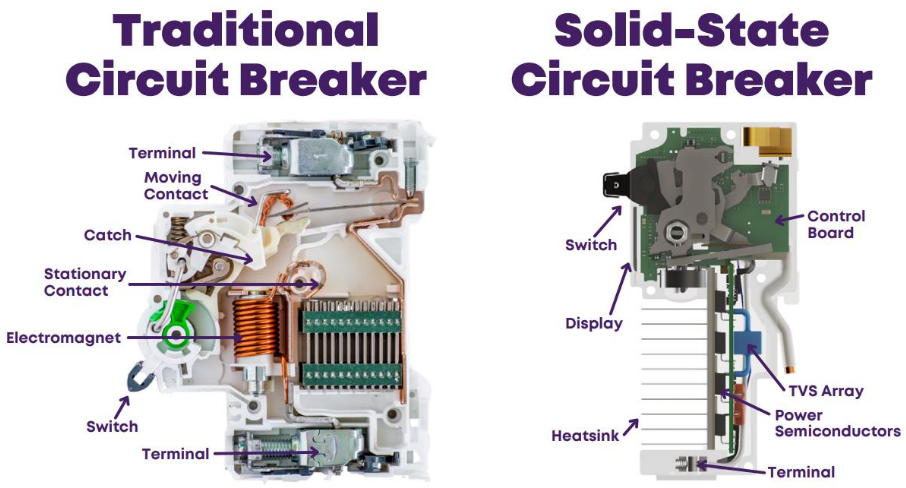
- *4Q — Current Conduction Only in Quadrants I & III*
- *Shared Drift Region for Blocking Pos. & Neg. Voltage & Separate (?) Cascode MOSFETs → True "Monolithic"(?)-BDS*

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. 100 A Cont. / UL Certified
- MBDSs — Low On-Resistance Mandatory (e.g. 1100V, 22mΩ M-BDS GaN) | Low Leakage Current

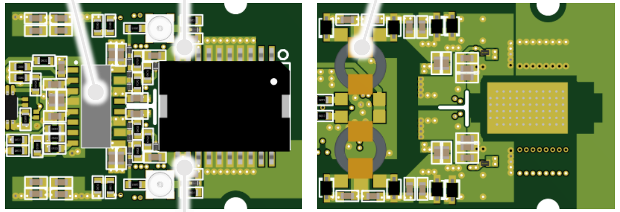
Outlook

Monolithic 3D-Integration

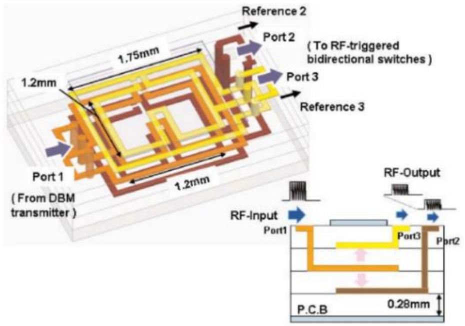
Source: Panasonic ISSCC 2014

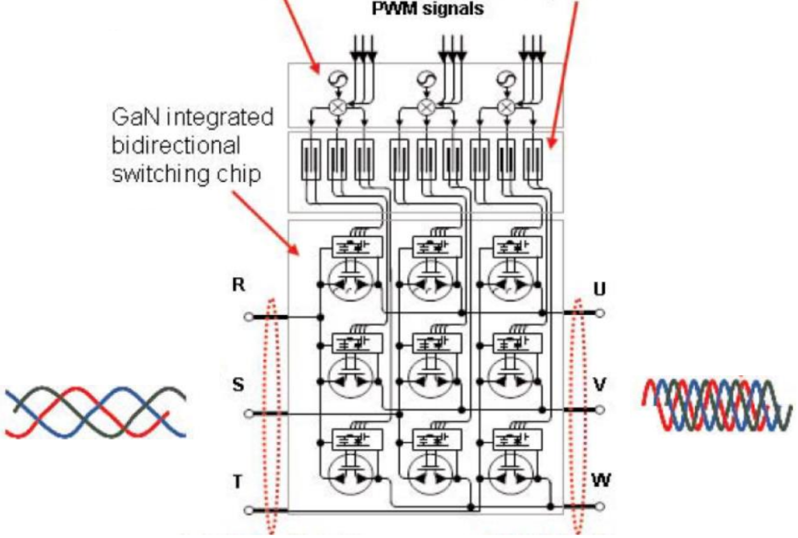
- *M-BDS GaN 3x3 Matrix Converter with Drive-By-Microwave (DBM) Technology*

- *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

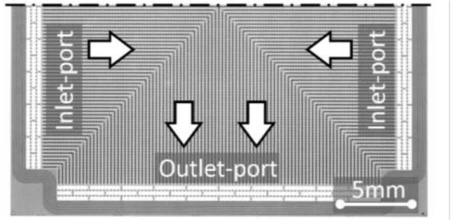


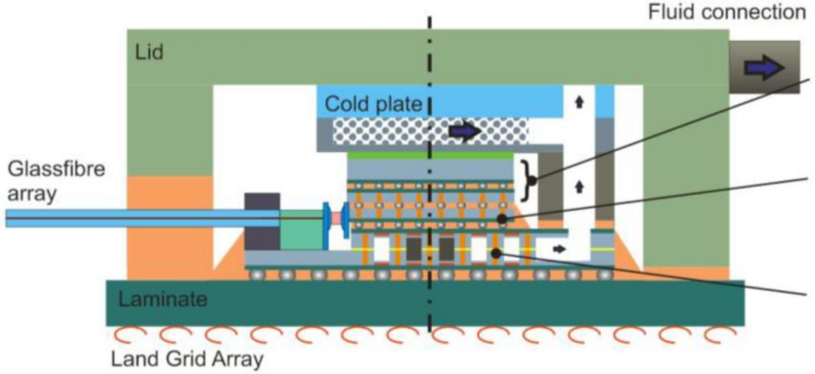


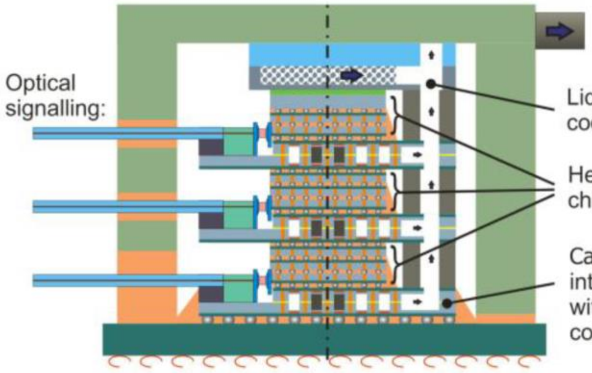
- *Massive Space Saving Compared to Discrete Realization (!)*

Remark Future uP Chip-Stack Packaging

- Slowing Transistor Node Scaling → Vertical & Heterogeneous Integr. of ICs for Performance Gains
- Extreme 3D-Integrated Cube-Sized Compute Nodes
- *Dual Side & Interlayer Microchannel Cooling*







- Interposer Supporting *Optical Signaling* / *Volumetric Heat Removal* / *Power Conversion*

CarrICool
EU FP7 Project

Thank you!