ETH zürich

WiPDA Europe

Source: next-gen-forum.com

NEXT GENERATION

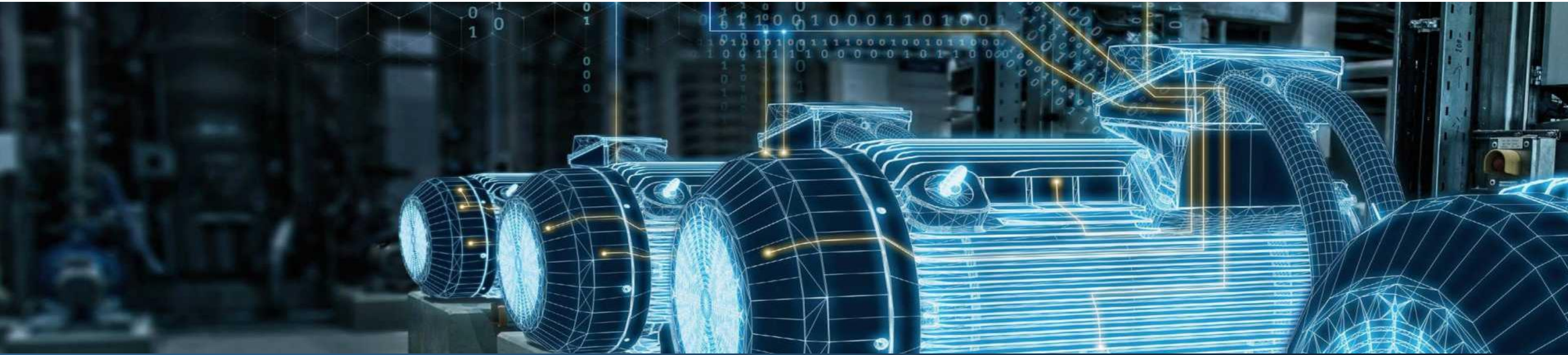
SiC/GaN 3-Φ Variable Speed Drive Systems

Johann W. Kolar et al.

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

Sept. 16, 2024

Source: SIEMENS



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SiC/GaN 3-Φ Variable Speed Drive Systems

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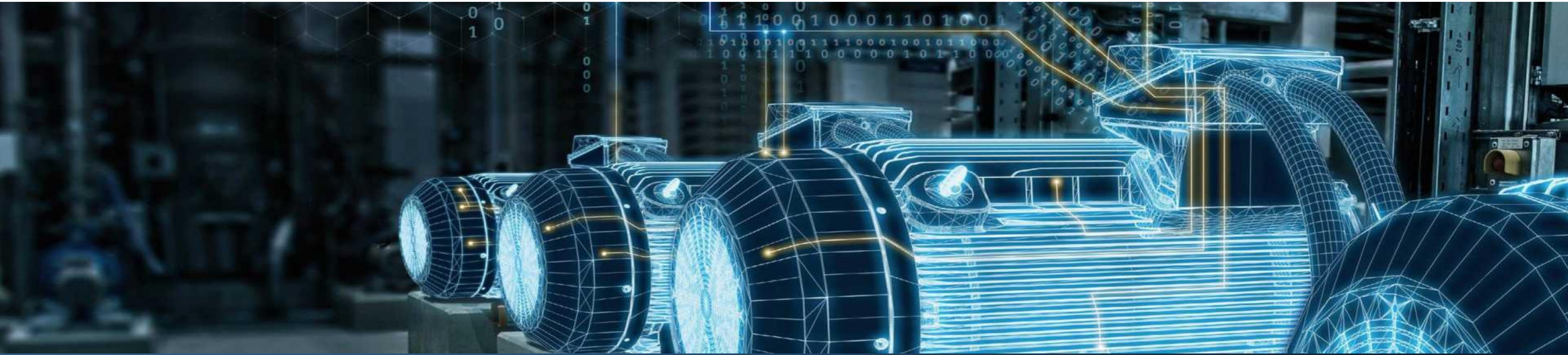
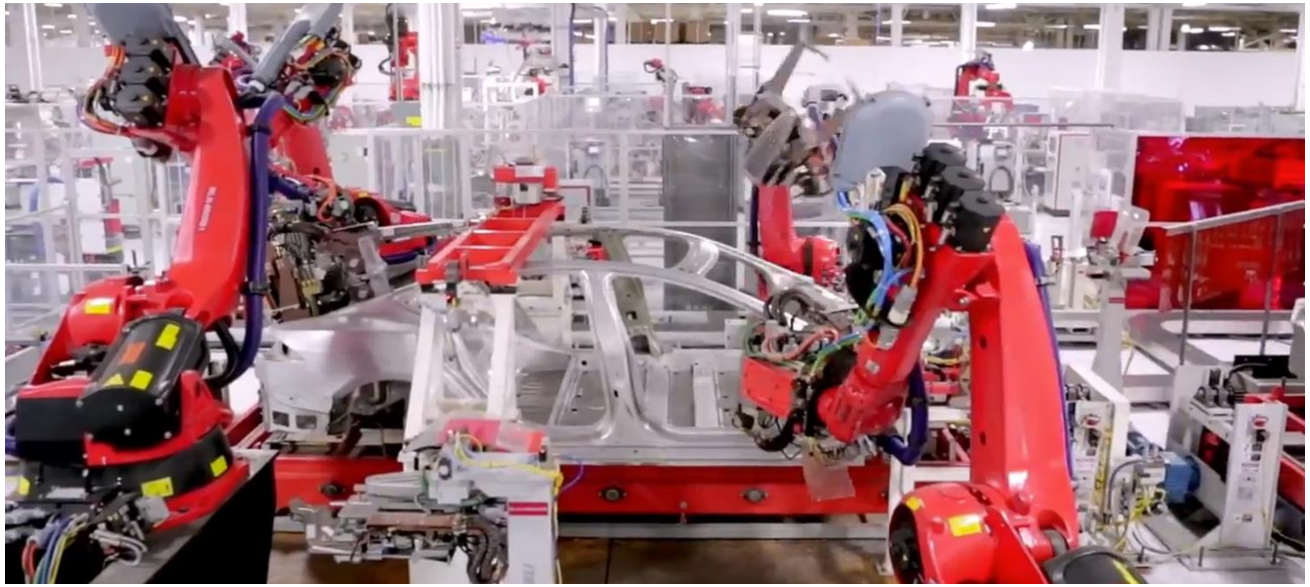


Variable Speed Motor Drive (VSD) Systems

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

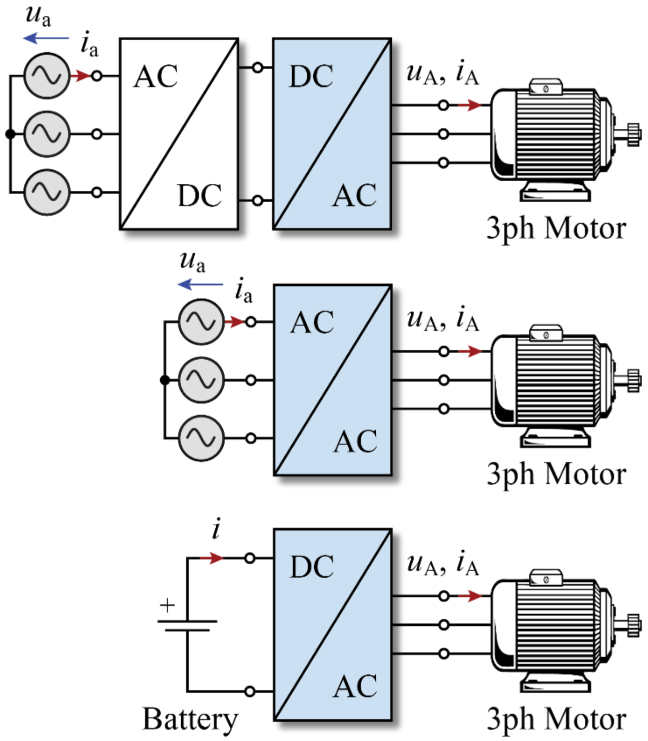
Source: TESLA MOTORS

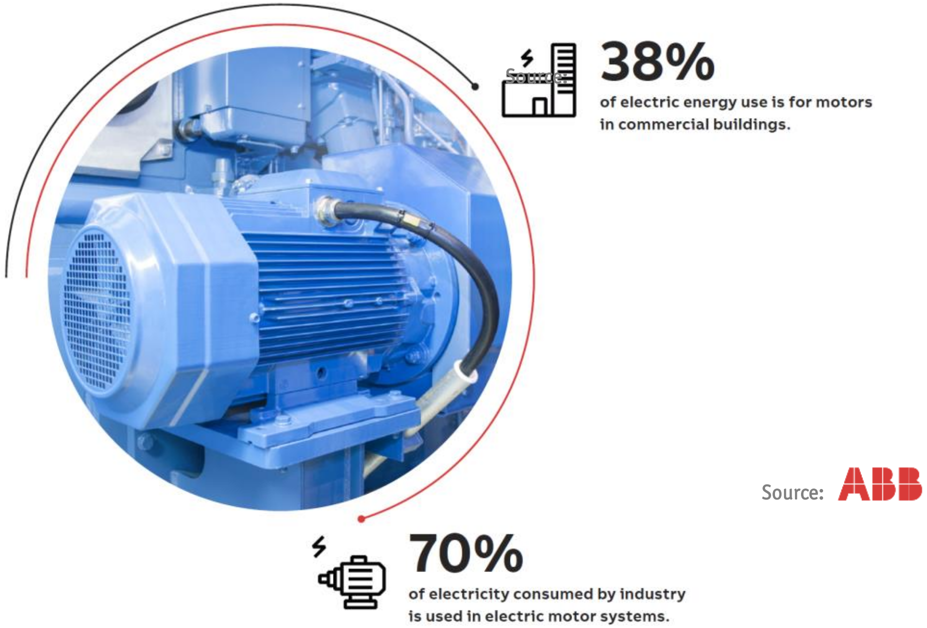


- *60...70 % of All Electric Energy Used in Industry Consumed by VSDs*

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*

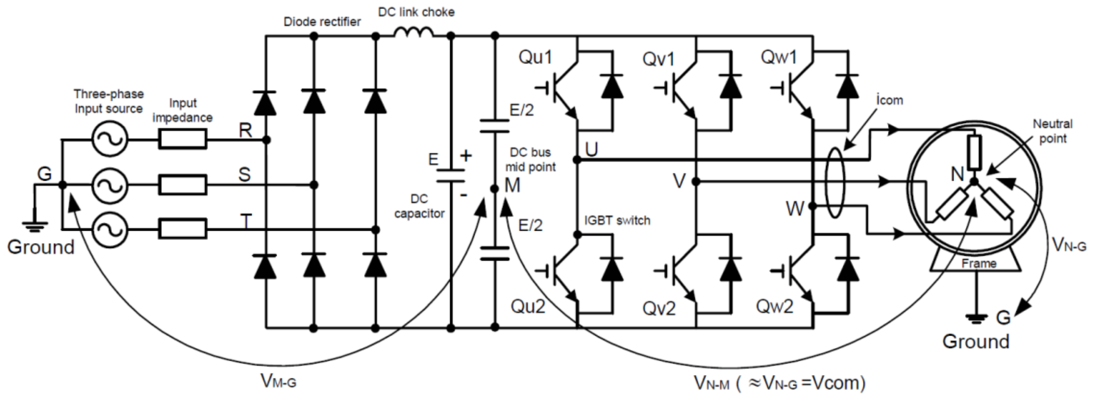




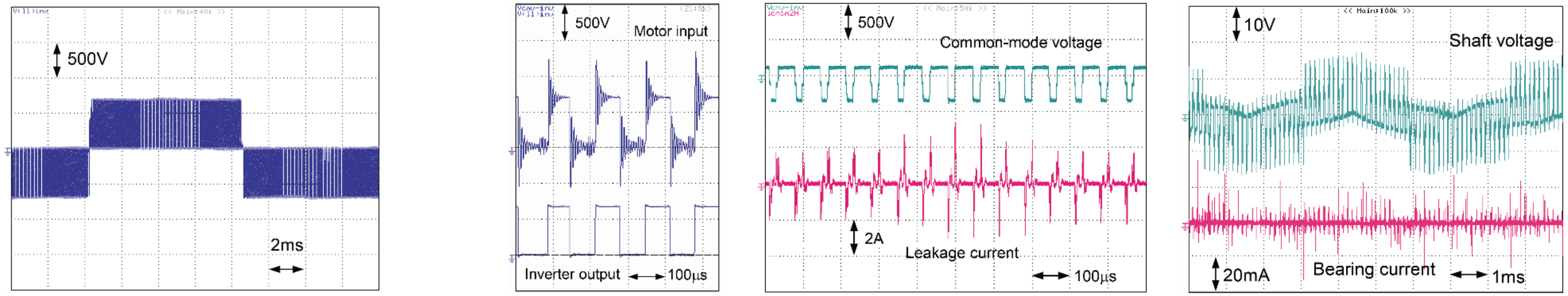
- *45% of World's Electricity Used for Motors in Buildings & Industrial Applications*

State-of-the-Art VSD System

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



Source: YASKAWA

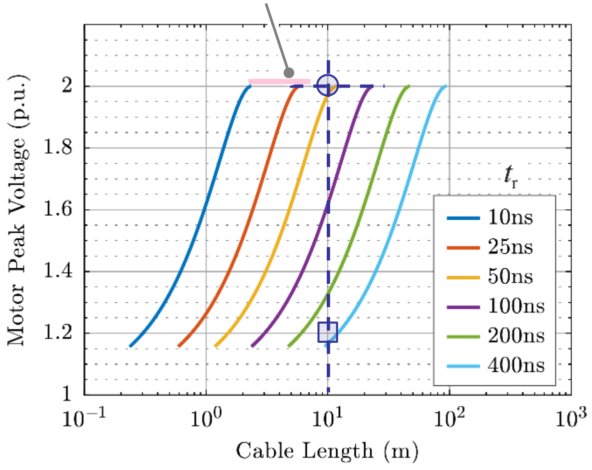


- *Line-to-Line Voltage* | *Motor Surge Voltage* | *CM Leakage Current* | *Bearing Current*

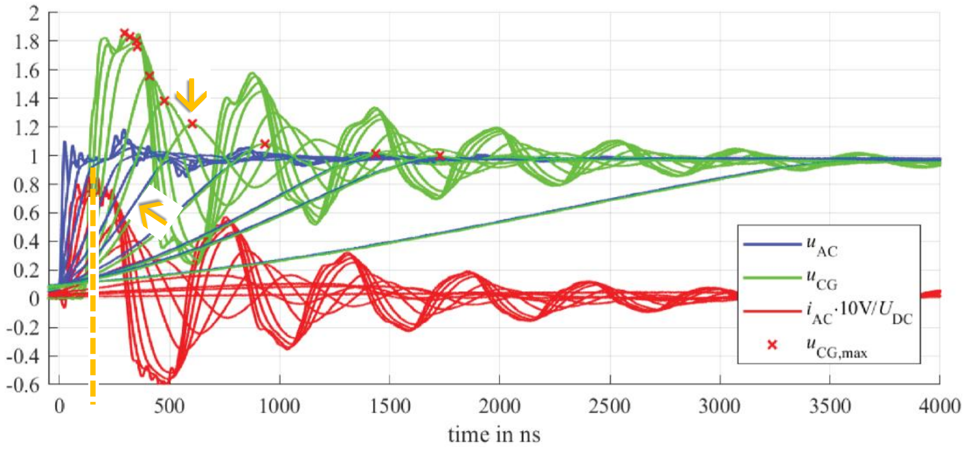
Surge Voltage Reflections

- *"Long Motor" Cable $l_c \geq ½\, t_r v$*
- *Short Rise Time of Inverter Output Voltage*
- *Impedance Mismatch of Cable & Motor → Reflect. @ Motor Terminals / High Insul. Stress*

SiC



Source: Bakran / ECPE 2019

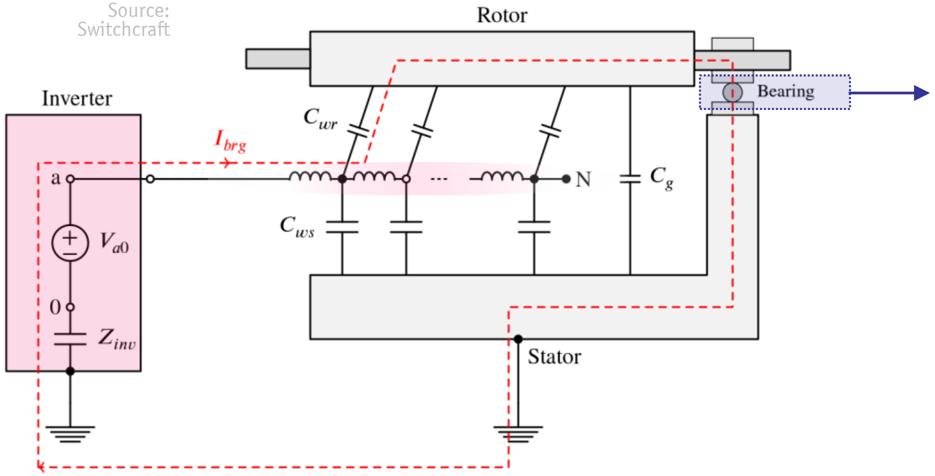


→ dv/dt-Filtering OR Full-Sinewave Filtering / Termination & Matching Networks etc.

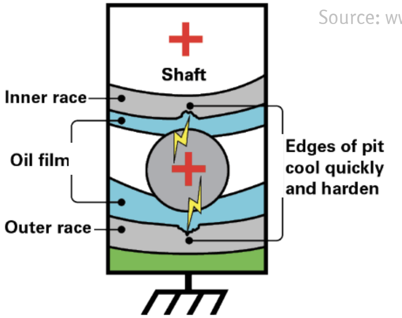
Motor Bearing Currents

- *Switching Frequency CM Inverter Output Voltage → Motor Shaft Voltage*
- *Electrical Discharge in the Bearing ("EDM")*

Source: Switchcraft



Source: www.est-aegis.com



Source: BOSCH

→ *Cond. Grease / Ceram. Bearings / Shaft Grndg Brushes / dv/dt-Filter OR Full-Sinewave Filters*

SiC vs. Si

Low $R_{DS(on)}$ High-Voltage Devices

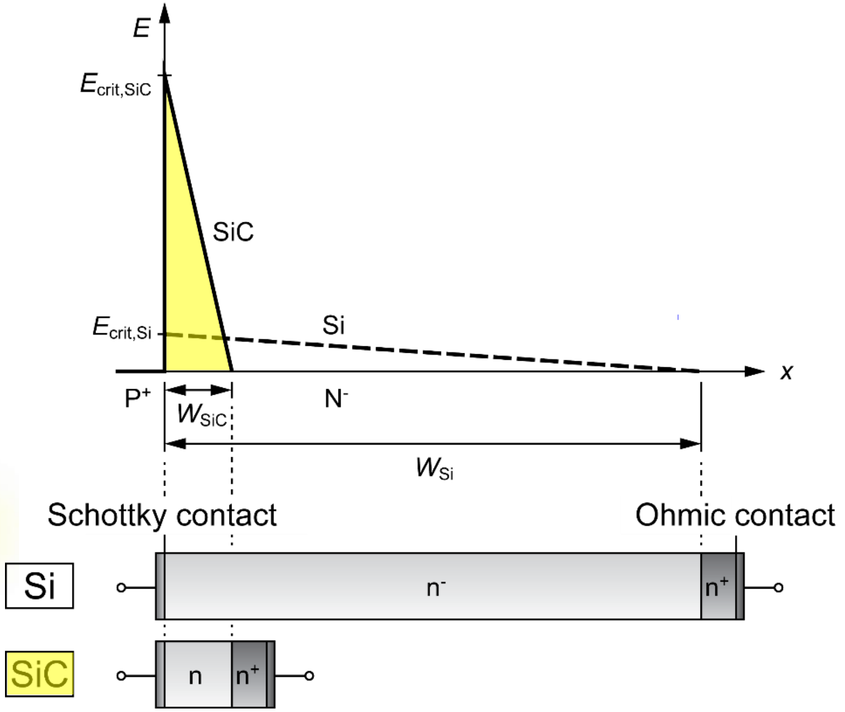
- *Higher Critical E-Field of SiC → Thinner Drift Layer*
- *Higher Maximum Junction Temperature $T_{j,max}$*

at 300 K	Si	GaAs	4H/6H-SiC	GaN
E_g (eV)	1.12	1.4	3.0-3.2	3.4
E_c (MV/cm)	0.25	0.3	2.2-2.5	3
μ_n (cm²/Vs)	1350	8500	100-1000	1000
ε_r	11.9	13	10	9.5
v_{sat} (cm/s)	1×10^7	1×10^7	2×10^7	3×10^7
λ (W/cmK)	1.5	0.5	3 - 5	1.3

$$R^*_{on} = \frac{4V_B^2}{\varepsilon\mu_n E_C^3} \leftarrow$$

For 1kV:	Si	SiC
W (µm)	100	10
N_D (cm⁻³)	10^{14}	10^{16}

$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$

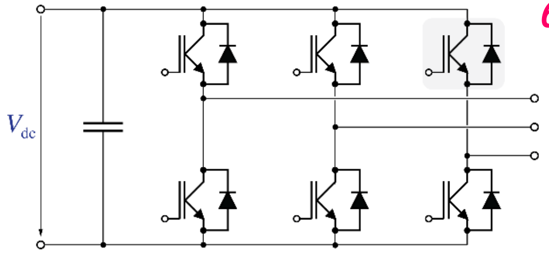


- *Massive Reduction of Relative On-Resistance → High Blocking Voltage Unipolar (!) Devices*

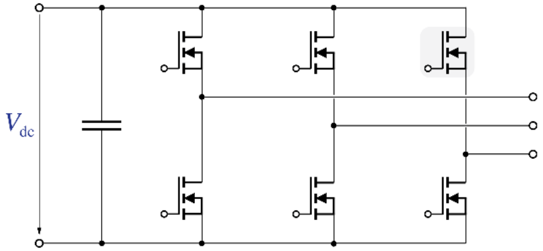
Si vs. SiC

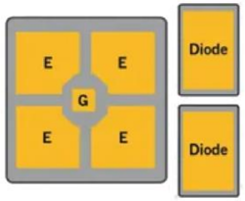
- *Si-IGBT / Diode* → *Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current*
- *SiC-MOSFET* → *Loss Reduction @ Part Load BUT Higher R_{th}*

6x Si-IGBT
6x Si-Diode



6x SiC-MOSFET





Source:
ATZ elektronik

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

Source: Infineon

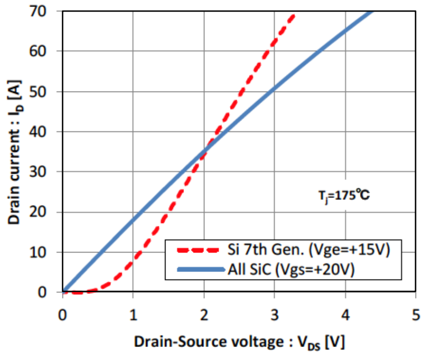
1200V 100A
Die Size: 25.6mm²

Source: Cree

- *Space Saving of >30% on Module Level (!)*

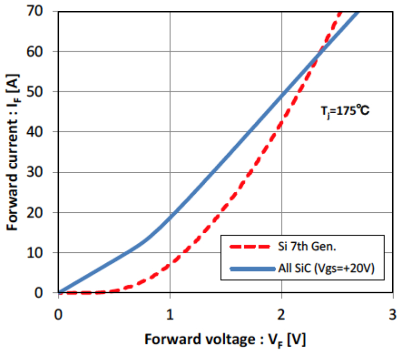
Si vs. SiC Conduction Behavior

- *Si-IGBT → Const. On-State Voltage Drop / Rel. Low Switching Speed*
- *SiC-MOSFETs → Resistive On-State Behavior / Factor 10 Higher Sw. Speed*

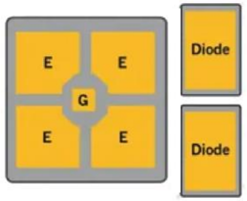


Source: Fuji Electric

Forward



Reverse



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

Source: Infineon

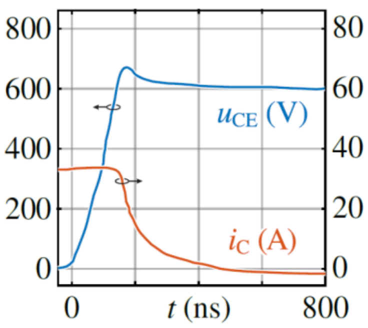
1200V 100A
Die Size: 25.6mm²

Source: Cree

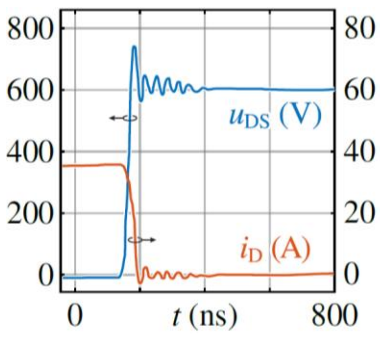
- *SiC MOSFETS Facilitate Higher Part Load Efficiency*

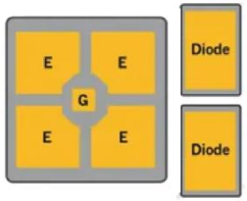
Si vs. SiC Switching Behavior

- *Si-IGBT* → *Const. On-State Voltage Drop / Rel. Low Switching Speed*
- *SiC-MOSFETs* → *Resistive On-State Behavior / Factor 10 Higher Sw. Speed*



Source: Fuji Electric





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

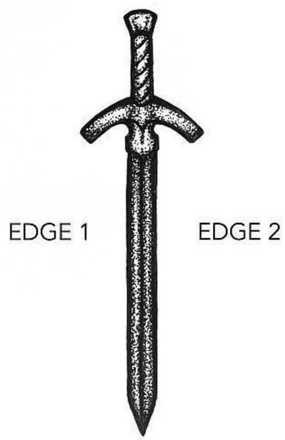
Source: Infineon

1200V 100A
Die Size: 25.6 mm²

Source: Cree

- *High di/dt & dv/dt* → *Challenges in Packaging / EMI / Motor Insulation / Bearing Currents*

Challenges

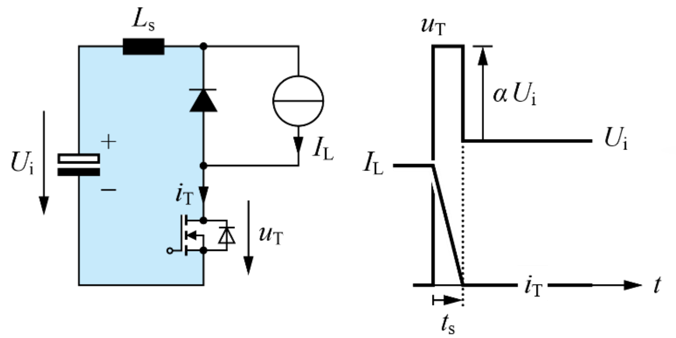


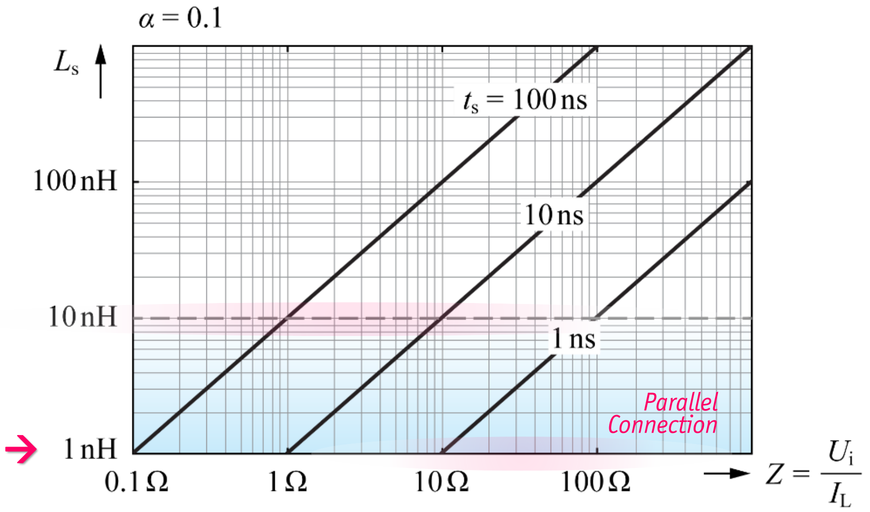
Circuit Parasitics

$$L\frac{di}{dt} = u$$

- *High di/dt*
- *Commutation Loop Inductance L_s*
- *Allowed L_s Directly Related to Switching Time t_s* →

$$L_s \le \frac{\alpha U_i}{\frac{I_L}{t_s}} = \alpha t_s \underbrace{\frac{U_i}{I_L}}_{Z}$$



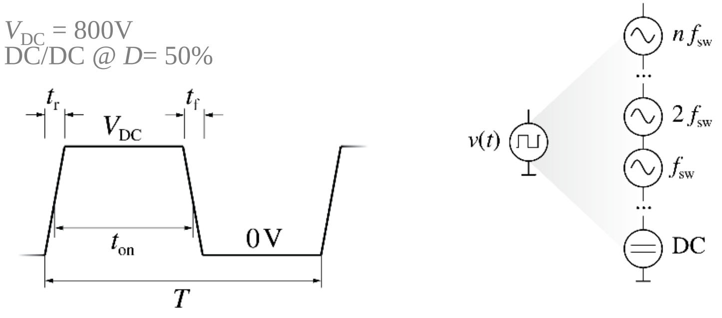


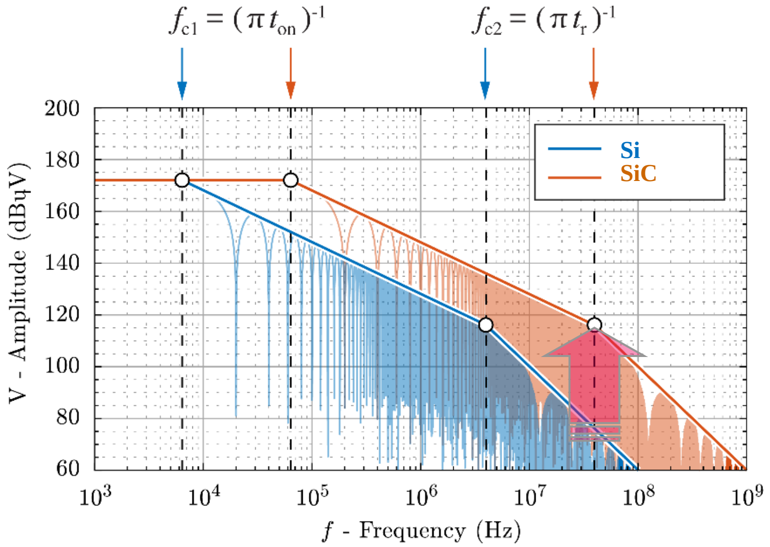
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents (Z-Matching)*

Si vs. SiC EMI Emissions

- *Higher dv/dt* → *Factor 10*
- *Higher Switching Frequencies* → *Factor 10*
- *EMI Envelope Shifted to Higher Frequencies*

f_S= 10 kHz & 5 kV/us for (Si IGBT)
f_S= 100 kHz & 50 kV/us for (SiC MOSFET)





- *Higher Influence of Filter Component Parasitics & Couplings* → *Advanced Design*

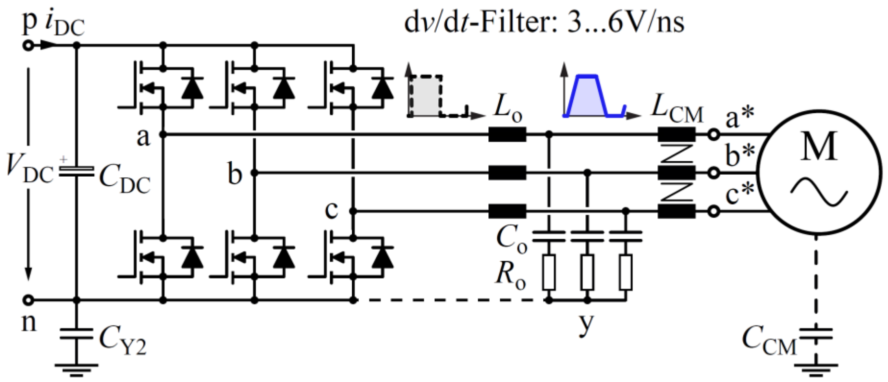
Inverter Output Filters

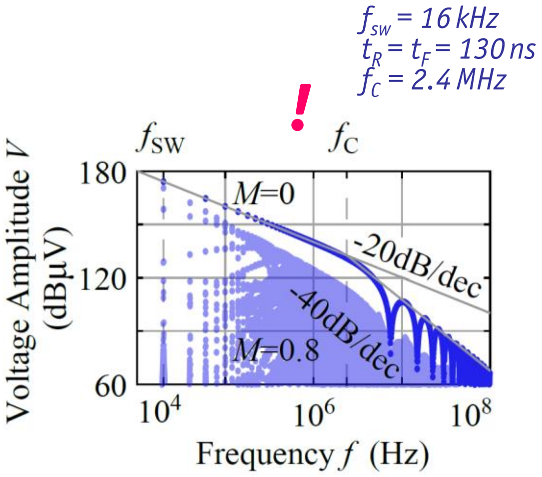
dv/dt-Filters
Full-Sinewave Filters

dv/dt-Limitation

Passive | Hybrid | Active dv/dt-Limitation

- **Passive** – Damped LC-Filter $f_C > f_S$
- **Hybrid** – Undamped LC-Filter & Multi-Step Sw. Transition
- **Active** – Gate-Drive Based Shaping of Sw. Transients

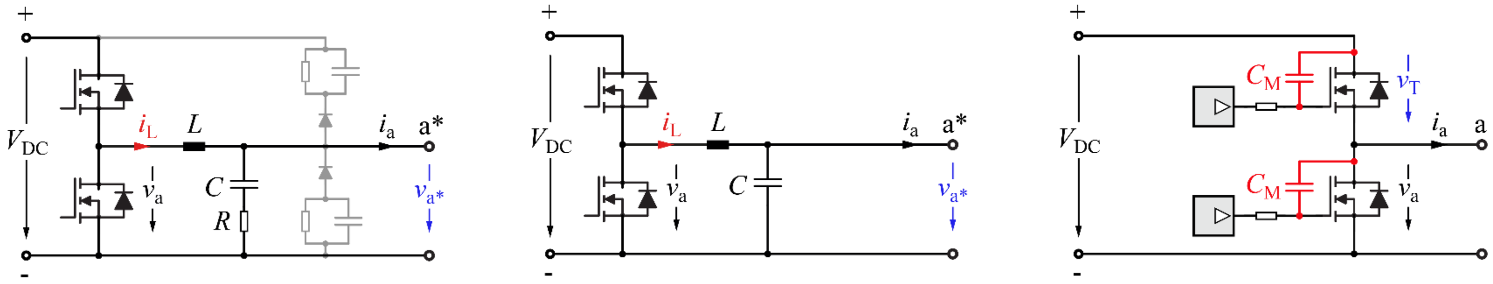




- Connection to DC-Minus & CM Inductor → Limit CM Curr. Spikes / EMI / Bearing Currents

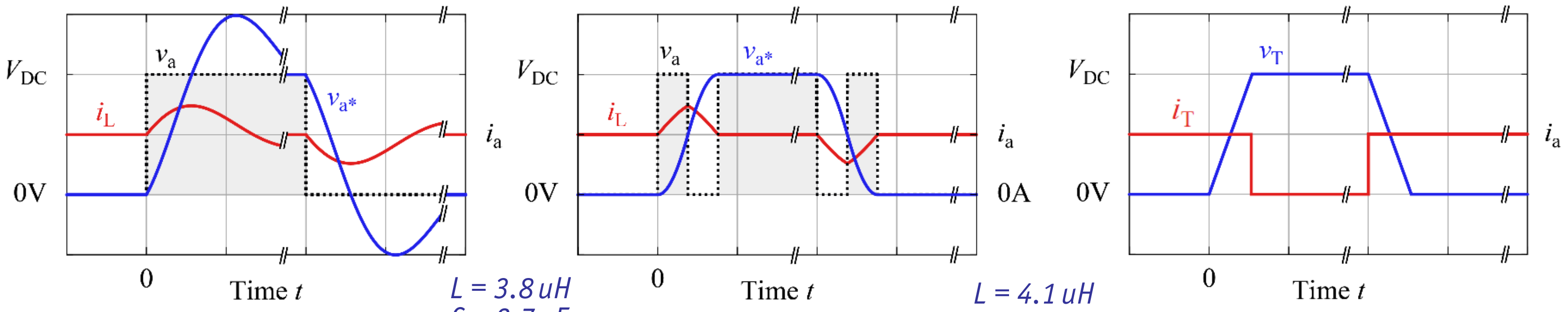
Comparison of dv/dt-Filtering Techniques

- *Passive Concept*
  1. *LCR-Filter*
  2. *Clamped LC-Filter*
- *Hybrid Concept ($3f_{sw}$)*
  1. *LC-Filter*
  2. *Multi-Step Switching*
- *Active Concept*
  1. *Miller Capacitor*
  2. *Gate Current Control*



- *Output Voltage Waveforms — V_{DC} = 800V, P_{out} = 10kW, 6kV/us*

1200V SiC / 16 mΩ
C_M = 120 pF

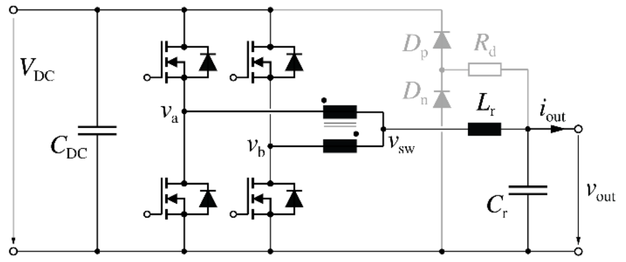


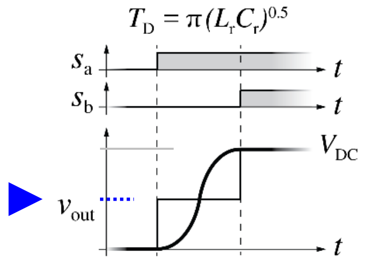
L = 3.8 uH
C = 2.7 nF
R = 19 Ω

L = 4.1 uH
C = 1.3 nF

Multi-Bridge-Leg dv/dt-Limitation

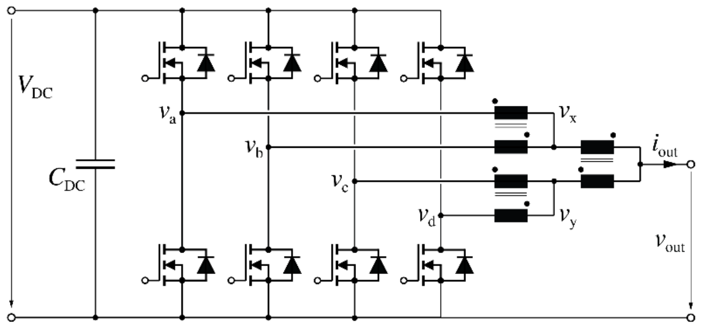
- *2-Step Switching / Resonant Transition (cf. Active dv/dt-Filter)*

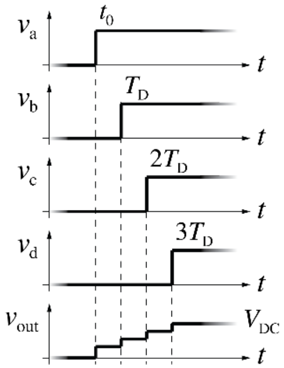




Source: J. Ertl et al.
PCIM Europe 2018

- *Staggered Sw. Parallel Bridge-Legs → Non-Resonant Multi-Step Transition*



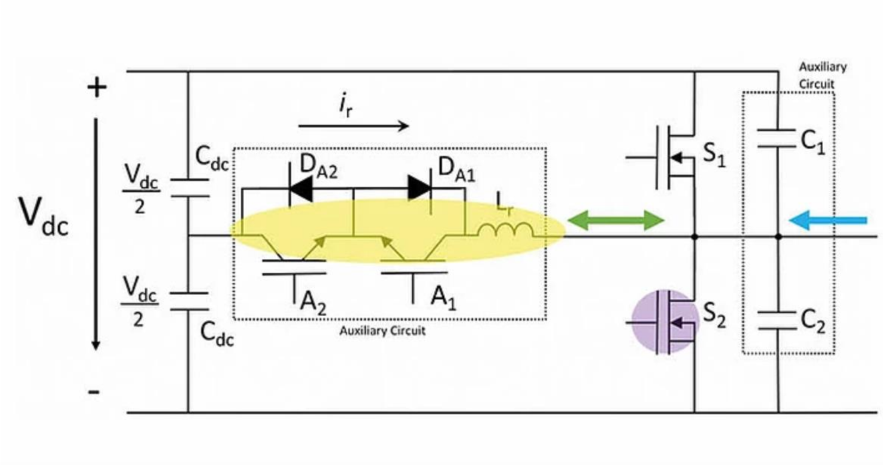


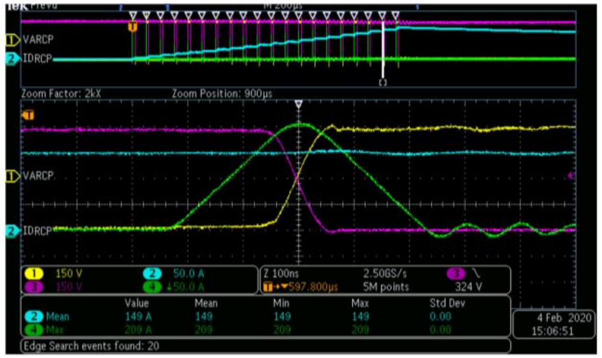
Source: J. Ertl et al.
PCIM Europe 2017

- *Adv. for High Power / High Output Curr. Syst. Employing Parallel Bridge-Legs & Local Comm. Caps*

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

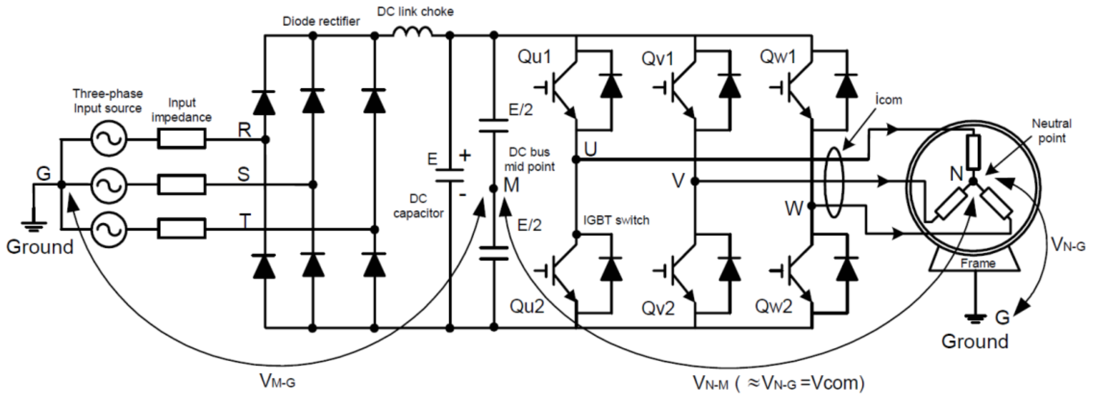
- *Complicated Implementation / Critical Timing for f_{sw} > 100 kHz*
- *99.5% Half-Load | 99.35% Full-Load Eff. @ 100 kW, 800 V_{DC}, f_{sw} = 50 kHz (1200V/12 mΩ SiC MOSFETs)*

Inverter Systems w/ Sinusoidal Output Voltages

Inverter Sinewave Output Filter

- *Measures Ensuring Longevity of Motor Insulation & Bearings / EMI Compliance*
- *DM-Sinus Filter OR DM & CM Full-Sinewave Filter*

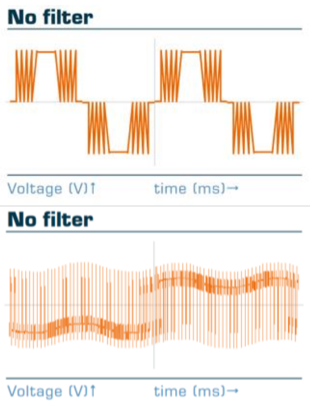
Source: YASKAWA

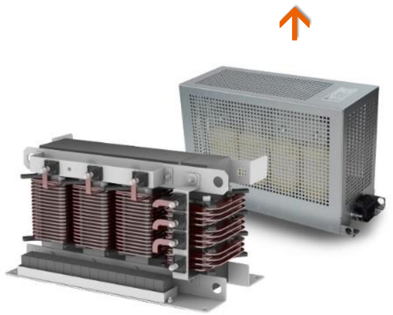


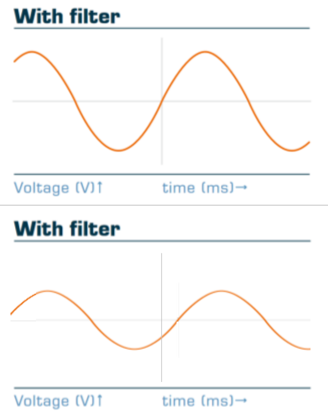
Source: BLOCK

MOTOR VOLTAGE PHASE-PHASE

MOTOR VOLTAGE PHASE-GROUND





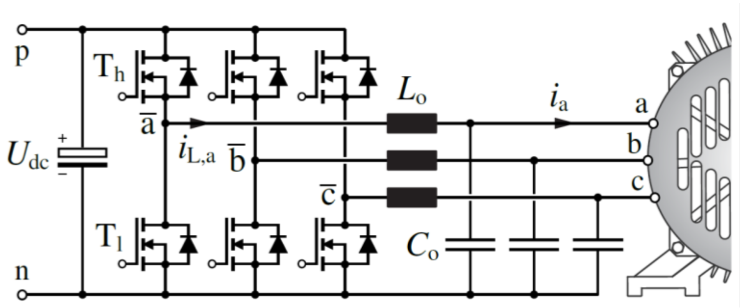


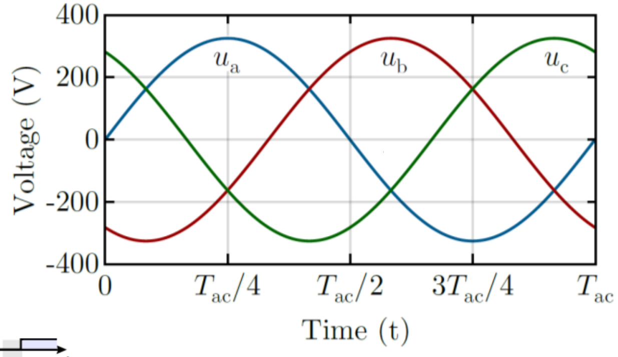
- *SiC|GaN High Sw. Frequ. →*
  Small Filter Size

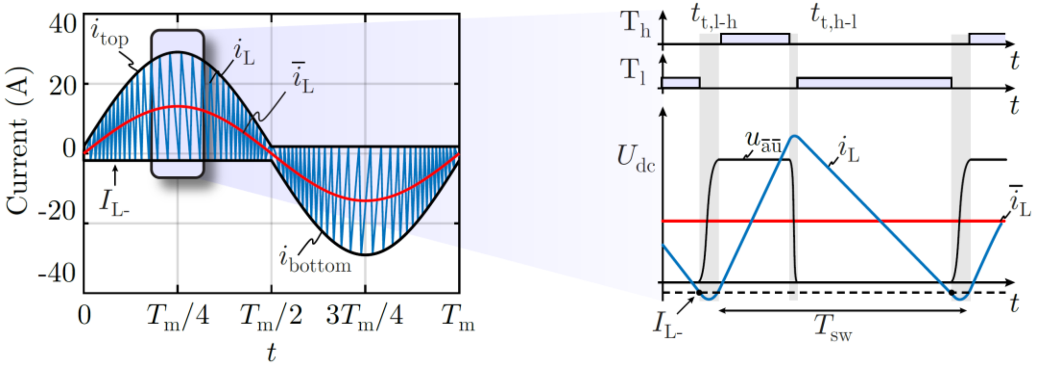
Triangular Current Mode (TCM)
ZVS Operation

Full-Sinewave Filter & ZVS Operation

- *Purely Sinusoidal Output Voltage (DM & CM Filtering)*
- *High Sw. Frequency & TCM → Low Filter Inductor Volume*
- *ZVS of Inverter Bridge-Legs*



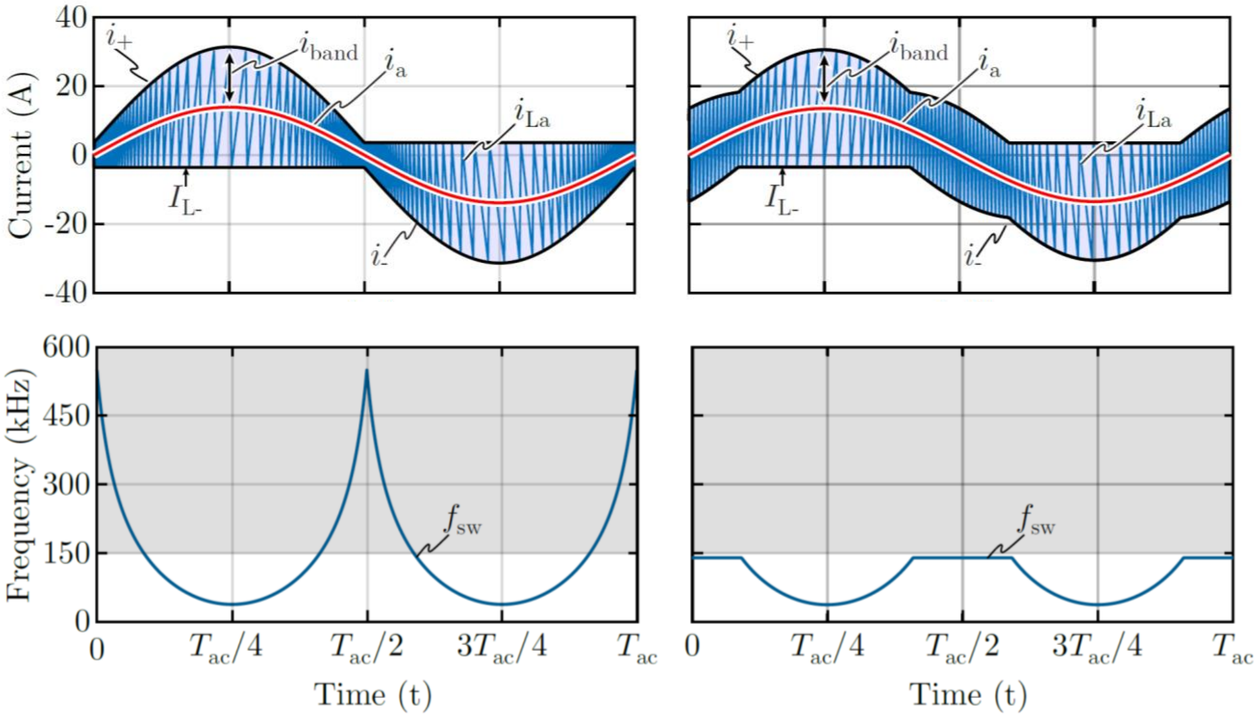




- *Only 33% Increase of Transistor Conduction Losses Compared to CCM (!)*
- *Very Wide Switching Frequency Variation*

Frequency-Bounded TCM → B-TCM

- *Very Wide Switching Frequency Variation of TCM → B-TCM*



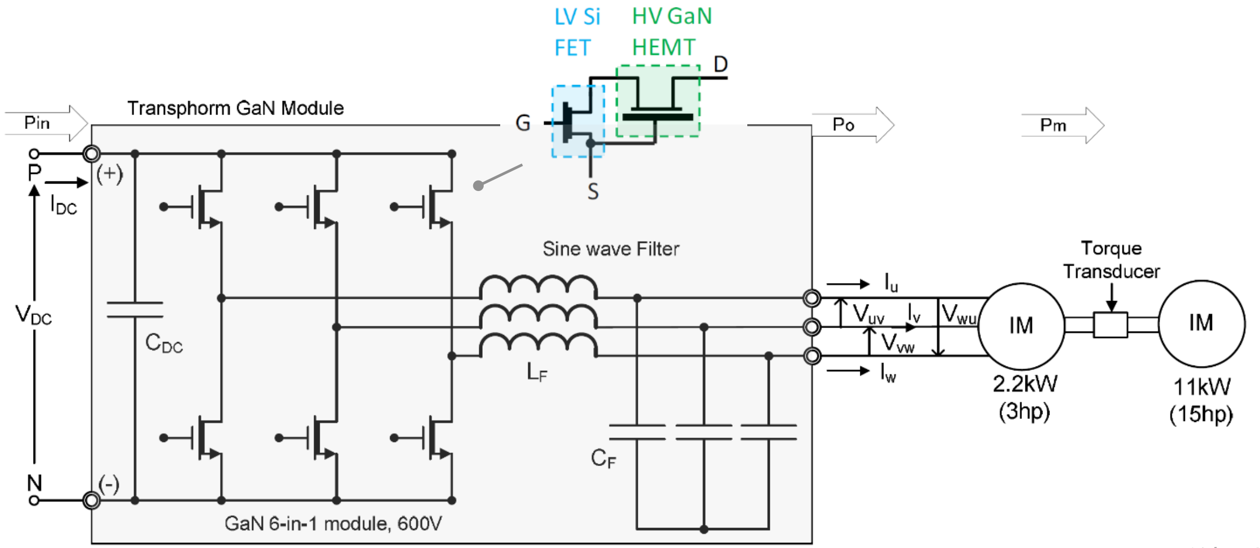
- *TCM → B-TCM — 10% Further Increase of Transistor Conduction Losses*

Continuous Current Mode (CCM) Operation

3-Φ 650V GaN Inverter System (1)

Source: YASKAWA

- *Transphorm 650V Normally-On GaN HEMT/30V Si-MOSFET Cascode 6-in-1 Power Module*
- *Sinewave LC Output Filter — Corner Frequency f_C= 34kHz (f_{sw}= 100kHz)*
- *No Freewheeling Diodes*



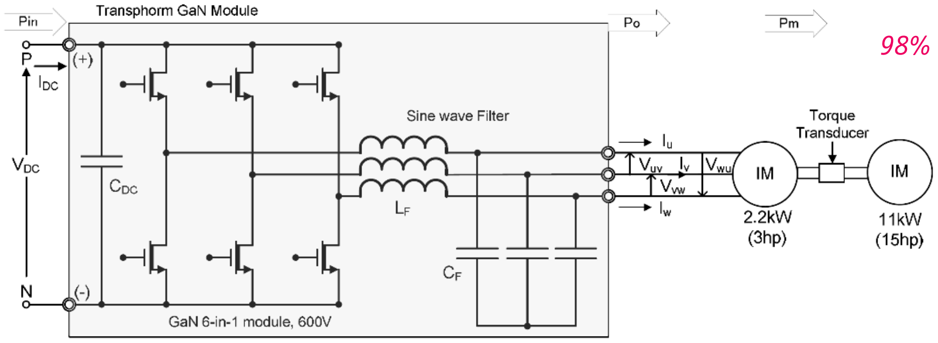
600V/14A

→ *Comparison to Si-IGBT Drive Systems*

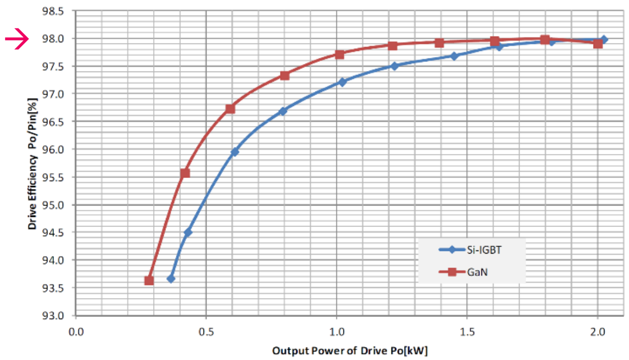
3-Φ 650V GaN Inverter System (2)

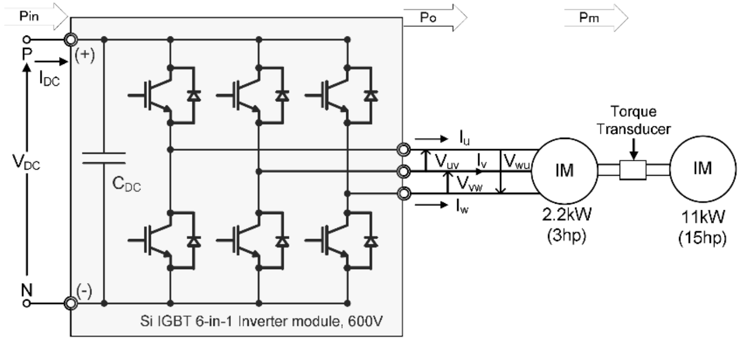
Source: YASKAWA

- *Comparison of GaN Inverter w/ LC-Filter to Si-IGBT System (No Filter, f_{sw}=15 kHz)*
- *Measurement of Inverter Stage & Overall Drive Losses @ 60 Hz*

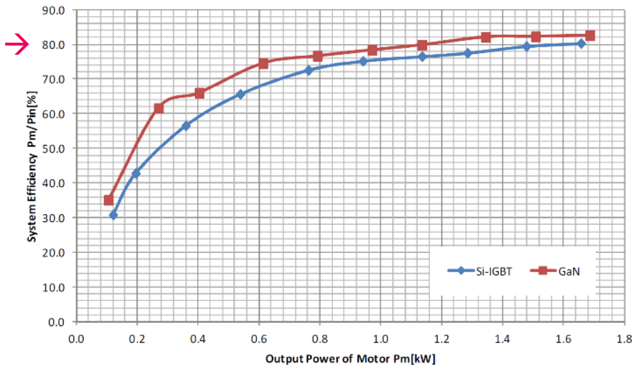


98% →





80% →

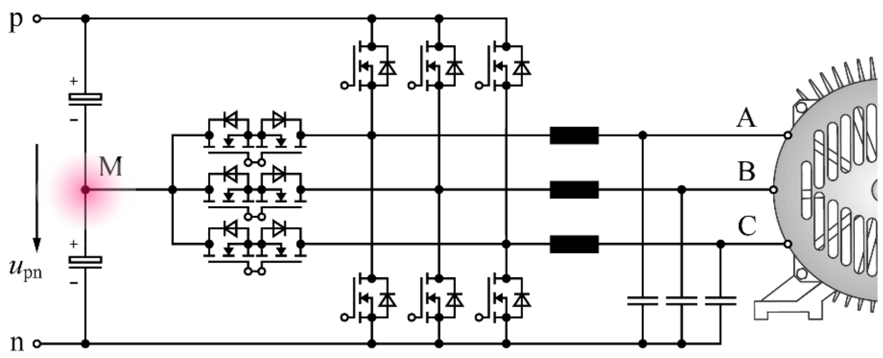


→ *2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses) !*

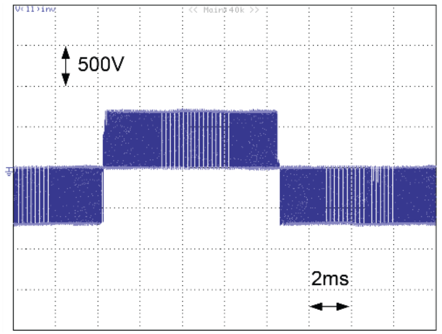
Multi-Level / Multi-Cell Converters & Modularity

3-Level T-Type Inverter (1)

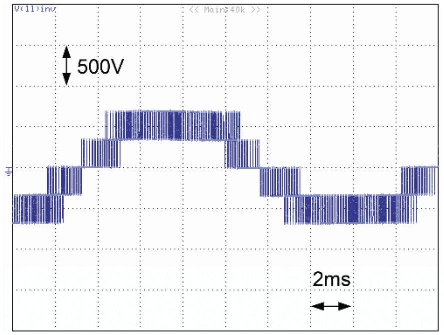
- Higher Number of Bridge-Leg Output Voltage Levels / Lower DM & CM Voltage Steps
- Neutral Point Clamped | Flying Capacitor | T-Type Bridge-Leg Topologies



Line-to-Line Voltage



2-Level Bridge-Leg

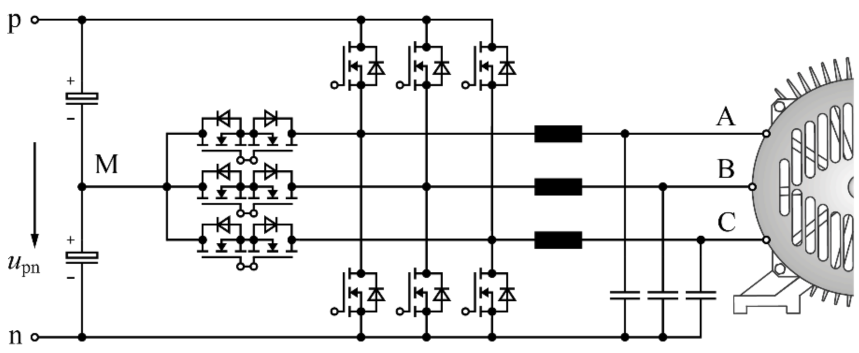


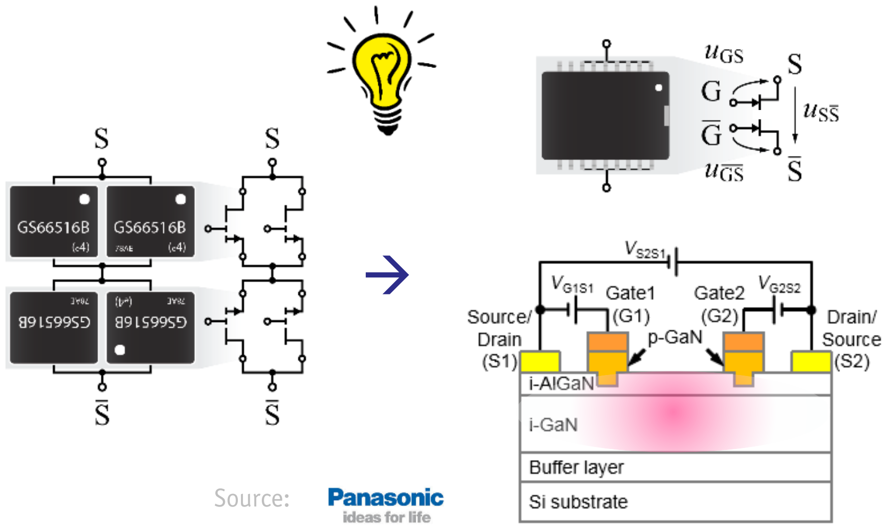
3-Level Bridge-Leg

- More Complicated Bridge-Leg Structure
- On-State-Losses of Series-Connected Switches

3-Level T-Type Inverter (2)

- *3-Level T-Type Inverter — 3-Level Phase Voltage / 5-Level Line-to-Line Voltage*
- *Lower DM & CM Voltage Steps Compared to 2-Level Converter*

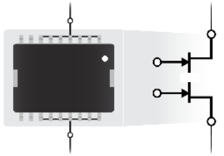


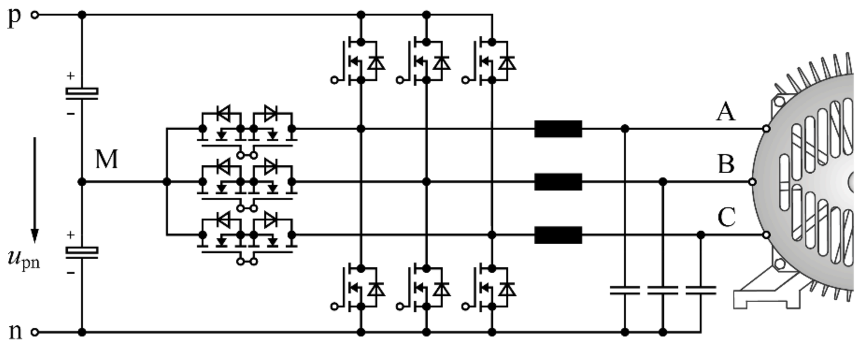


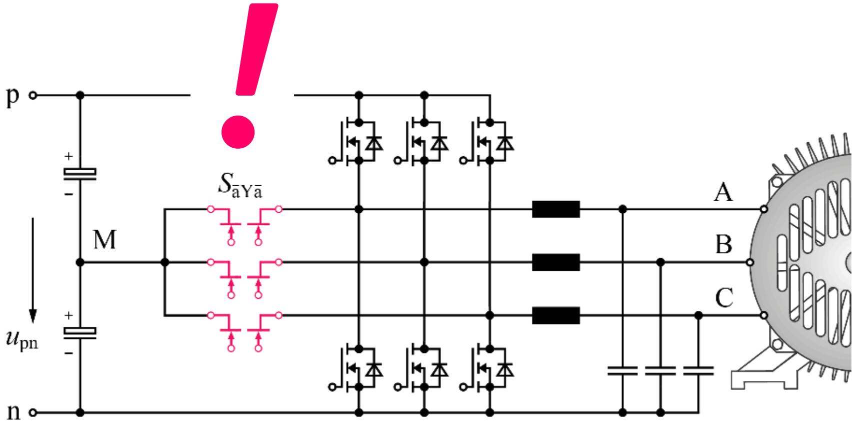
- *Full-Sinewave DC-Link Referenced LC-Filter — Elimination of DM & CM Sw. Frequ. Voltage Harmonics*
- *T-Type Topology Ensures Low Conduction Losses — Adv. Application of M-BDSs (!)*

3-Level T-Type Inverter (3)

- *3-Level T-Type Inverter — 3-Level Phase Voltage / 5-Level Line-to-Line Voltage*
- *Lower DM & CM Voltage Steps Compared to 2-Level Converter*





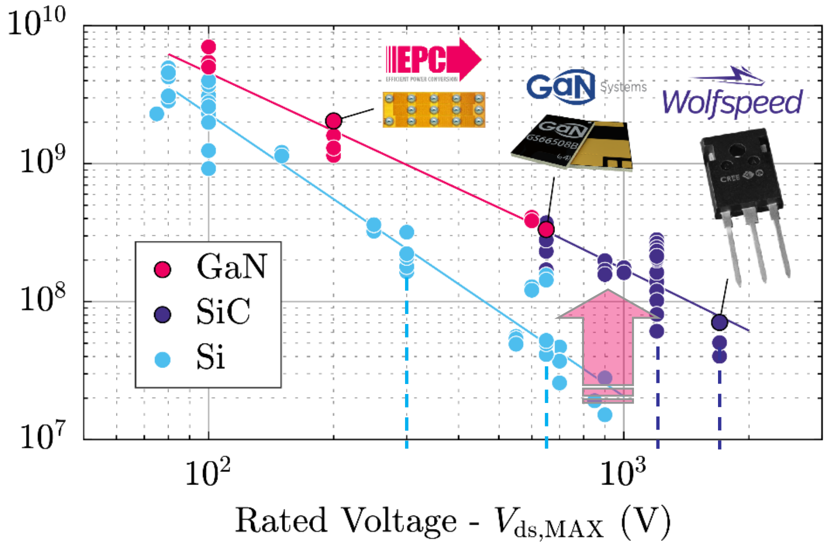


- *Full-Sinewave DC-Link Referenced LC-Filter — Elimination of DM & CM Sw. Frequ. Voltage Harmonics*
- *T-Type Topology Ensures Low Conduction Losses — Adv. Application of M-BDSs (!)*

SiC/GaN Figure-of-Merit

- *Figure-of-Merit (FOM) Quantifies Conduction & Switching Properties*
- *FOM Identifies Max. Achievable Efficiency @ Given Sw. Frequ.*

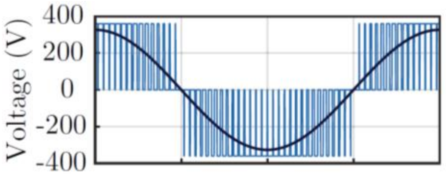
$$\mathrm{FOM} = \frac{1}{R_{\mathrm{ds,on}} Q_{\mathrm{oss}}}$$

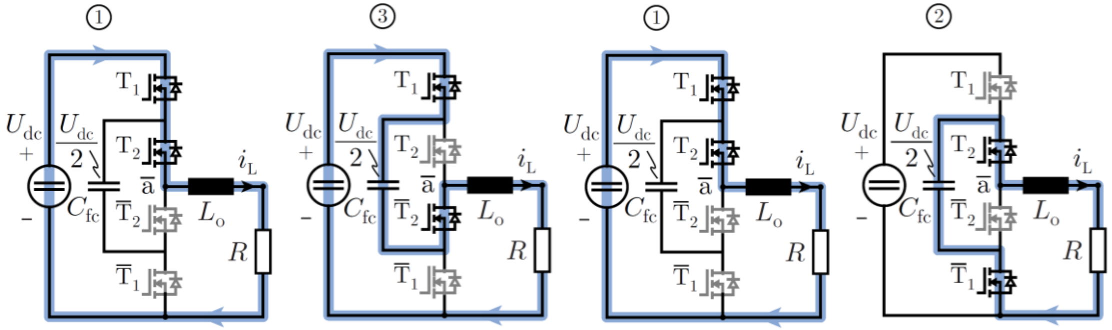


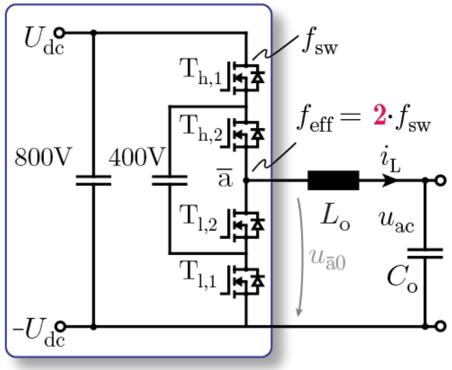
- *Advantage of LV over HV Power Semiconductors →*
- *Advantage of Multi-Level over 2-Level Converter Topologies*

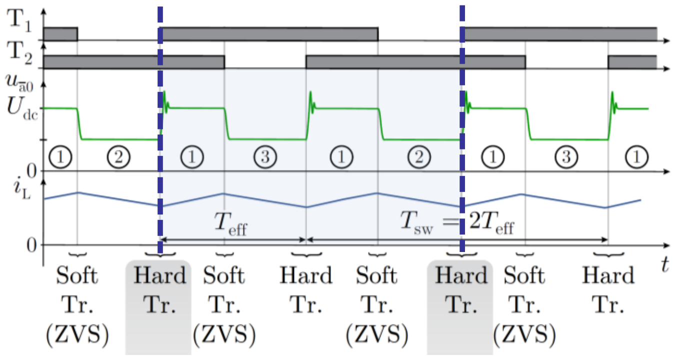
3-Level Flying Capacitor (FC) Converter

- *3-Level Flying Cap. (FC) Converter → No Connection to DC-Midpoint*
- *Involves All Switches in Voltage Generation → Eff. Doubles Device Sw. Frequency*









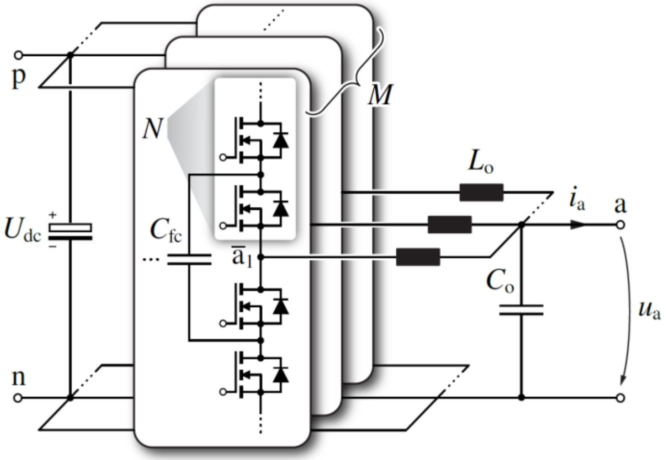
- *FC Voltage Balancing Possible also for DC Output*

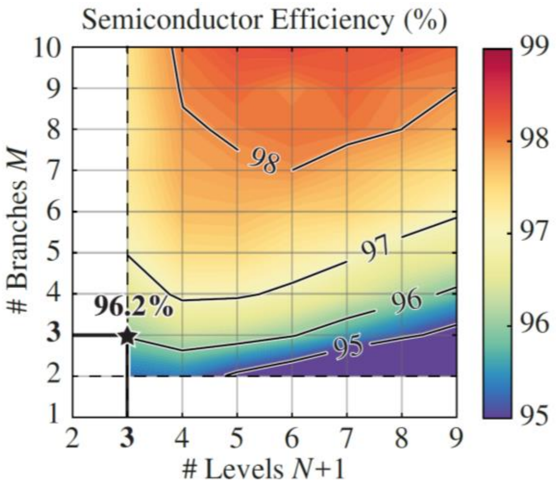
4.8MHz GaN Half-Bridge Phase Module

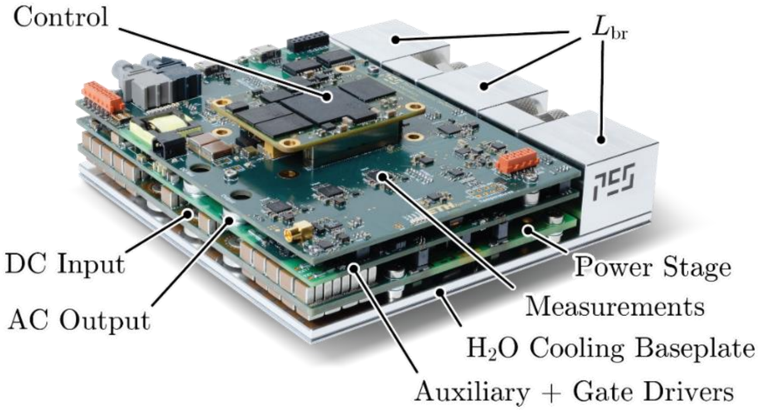
- *Combination of Series & Parallel Interleaving*

— *600 V GaN Power Semiconductors, f_{sw} = 800 kHz*
— *Volume of ≈180 cm³ (incl. Control etc.)*
— *H_2O Cooling Through Baseplate*

★ *25 kW/dm³*







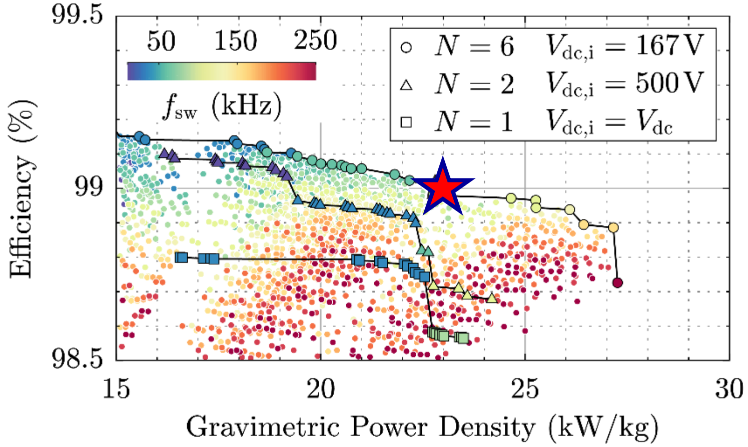
- *Operation @ f_{out} = 100 kHz / $f_{sw,eff}$ = 4.8 MHz, 10 kW, U_{dc} = 800 V*

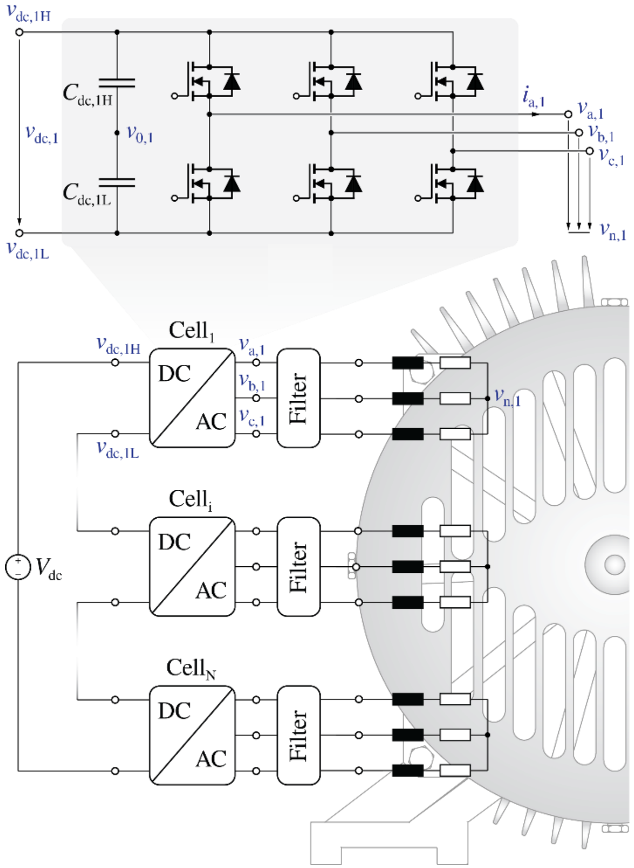
Motor-Integrated Inverter Systems

Stacked-Multi-Cell (SMC) Inverter

- *Fault-Tolerant VSD*
- *Low-Voltage Inverter Modules*
- *Very-High Efficiency / Power Density*
- *Automated Manufacturing*

- *Rated Power* *45 kW / f_{out} = 2 kHz*
- *DC-Link Voltage* *1 kV*

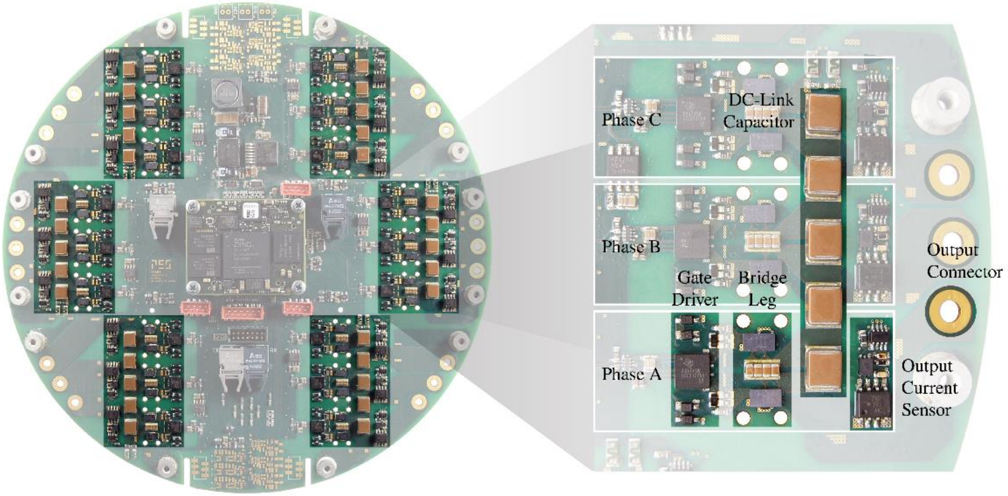




- *Smart Motor / All-in-One / Plug & Play* | *Connected / Intelligent VSD 4.0*

Motor-Integrated SMC-Inverter

- Rated Power 9 kW @ 3700 rpm
- DC-Link Voltage 650…720 V
- 3-Φ Power Cells 5+1
- Outer Diameter 220 mm



— Axial Stator Mount
— 200 V GaN e-FETs
— Low-Capacitance DC-Links
— 45 mm x 58 mm / Cell

- Main Challenge — Thermal Coupling OR Thermal Decoupling of Motor & Inverter

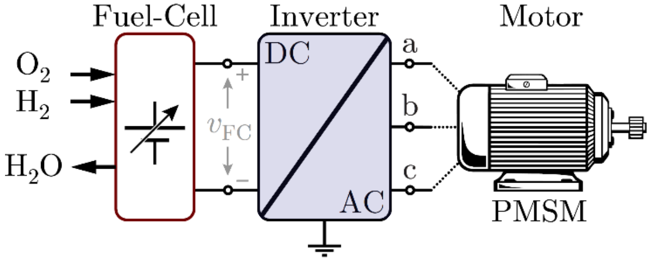
Buck-Boost Functionality

Motivation

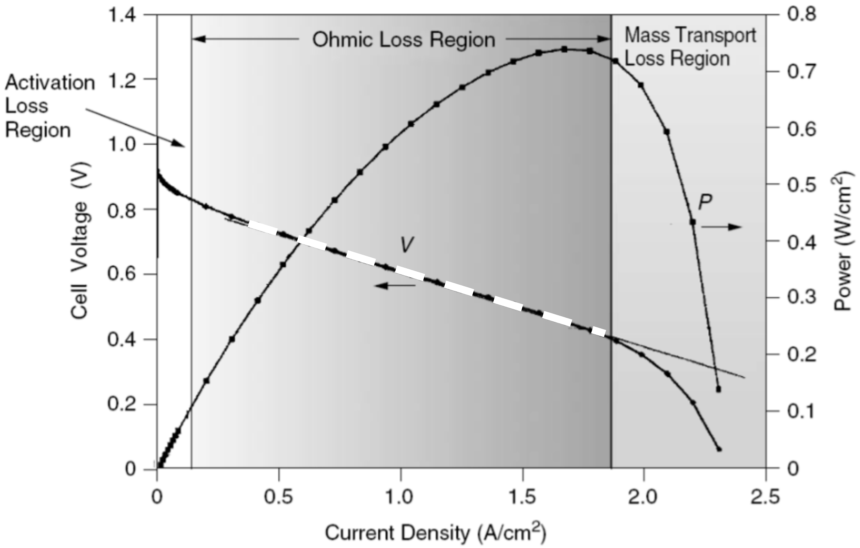
- *General / Wide Applicability*

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

Source: magazine.fev.com



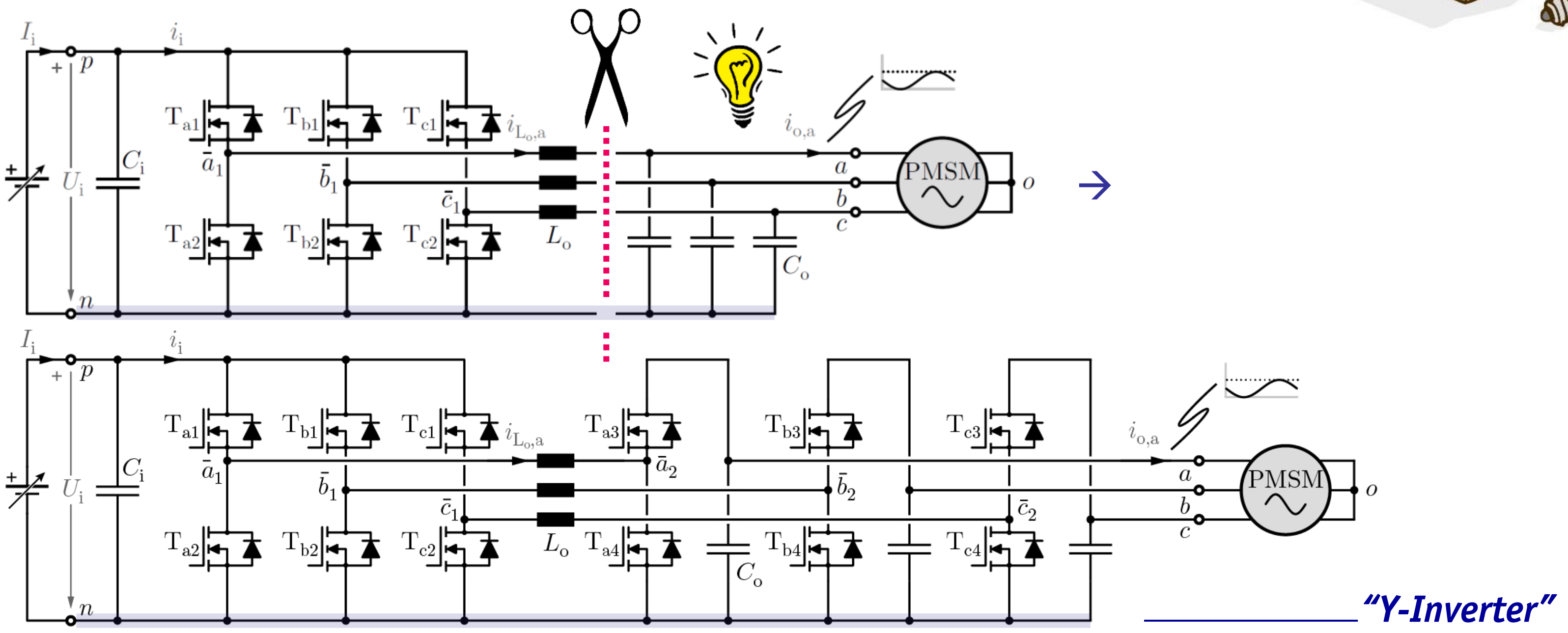
Source: www.chegg.com



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

Buck-Boost «Y–Inverter»

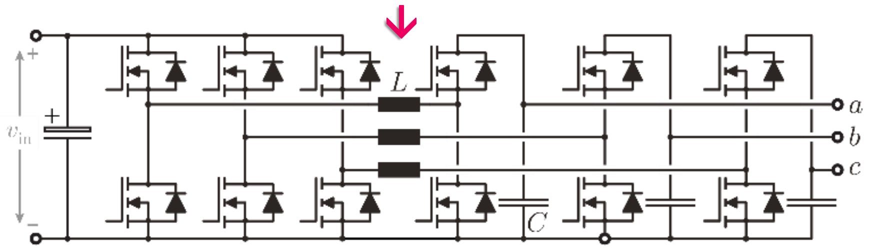
- *Generation of AC-Voltages Using Unipolar Bridge-Legs*

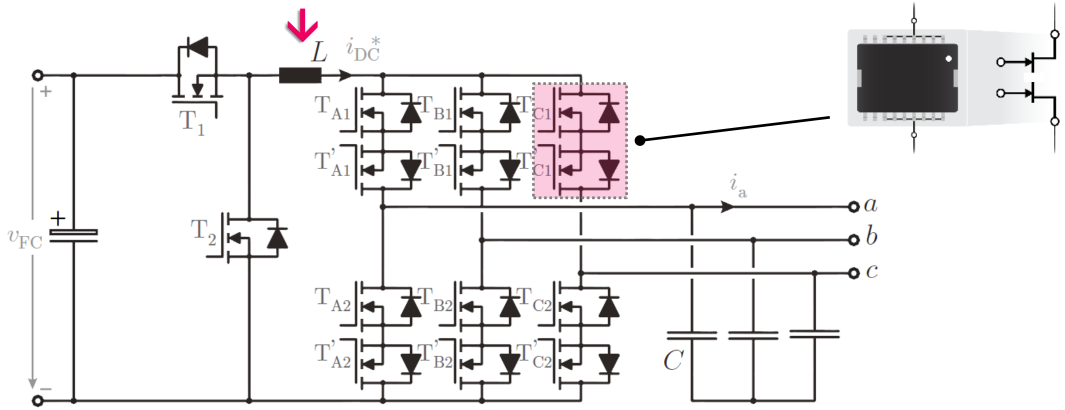


- *Switch-Mode Operation of Buck OR Boost Stage* → *Quasi Single-Stage Energy Conversion (!)*
- **3-Φ Continuous Sinusoidal Output / Low EMI** → *No Shielded Cables / No Motor Insul. Stress*

3-Φ Current Source Inverter (CSI) Topology

- *Y-Inverter → Phase Modules w/ Buck-Stage | Current Link | Boost-Stage*
- *3-Φ CSI → Buck-Stage V→I Converter | Current DC-Link DC/AC-Stage*

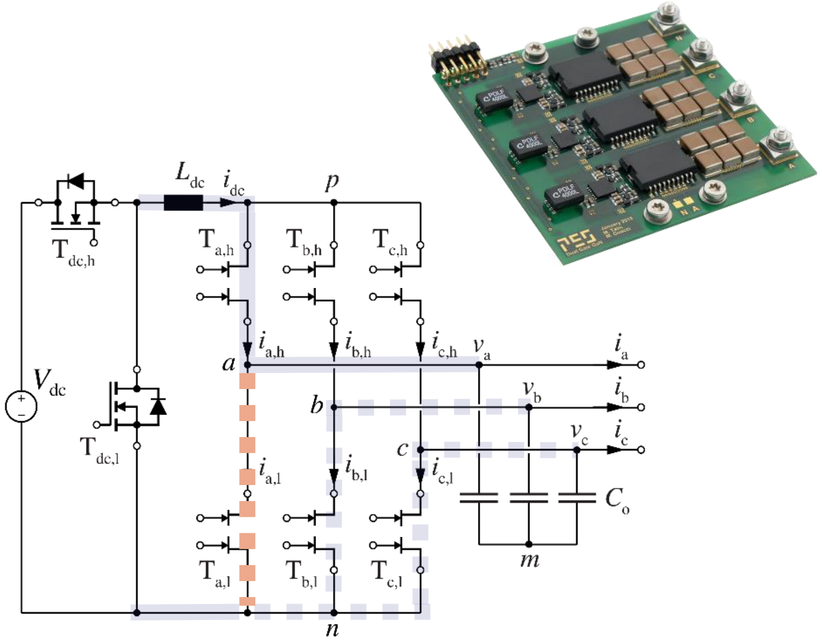


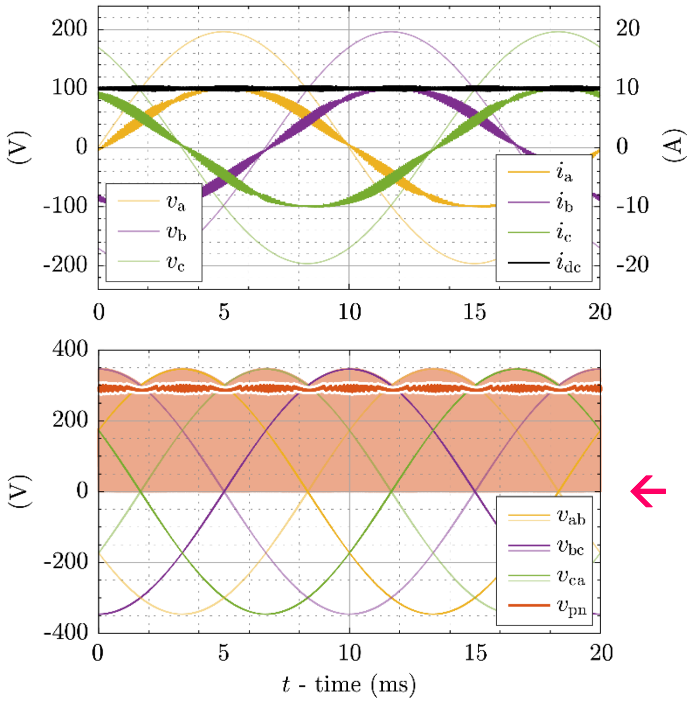


- *Single Inductive Component*
- *Positive DC-Side Voltage for Both Directions of Power Flow → Future Utilization of M-BDSs*

3-Φ Buck-Boost CSI (1)

- Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates → Full Controllability
- Buck-Stage for Impressing Const. DC Current / PWM of CSI for Output Voltage Control

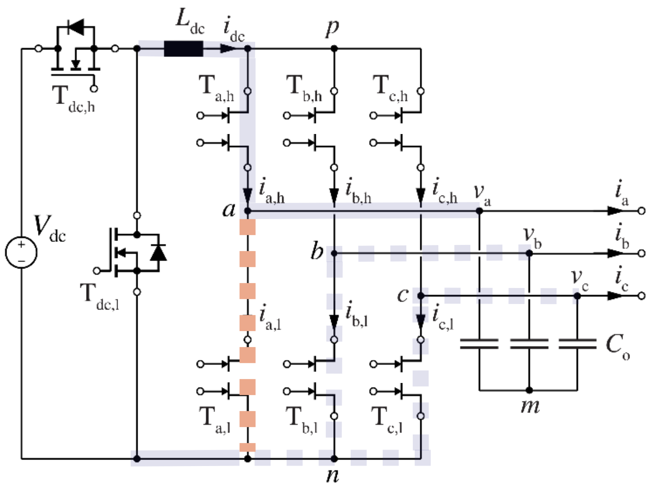


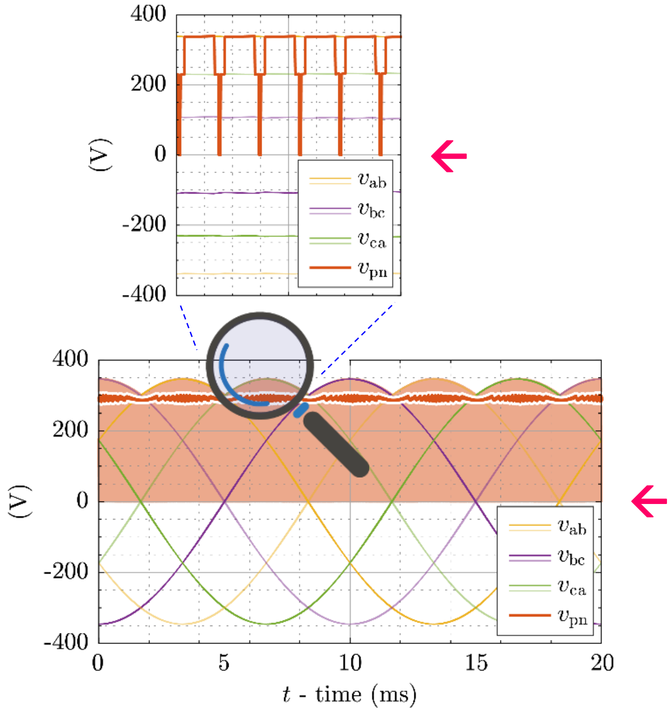


- Conventional Control of Inverter Stage → Switching of All 3 Phase Legs (3/3)

3-Φ Buck-Boost CSI (2)

- Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates → Full Controllability
- Buck-Stage for Impressing Const. DC Current / PWM of CSI for Output Voltage Control

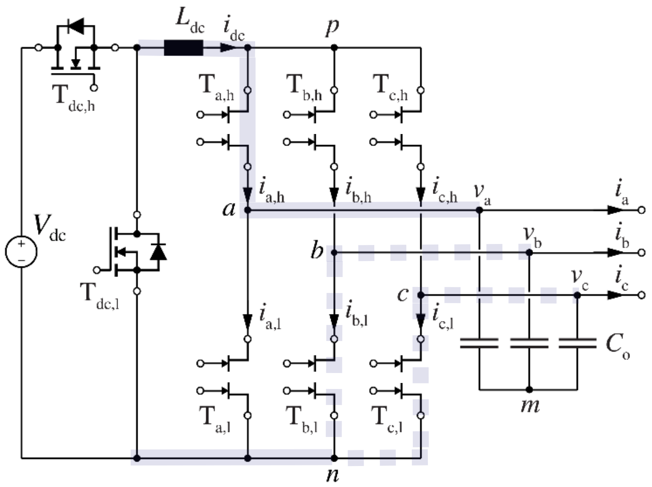


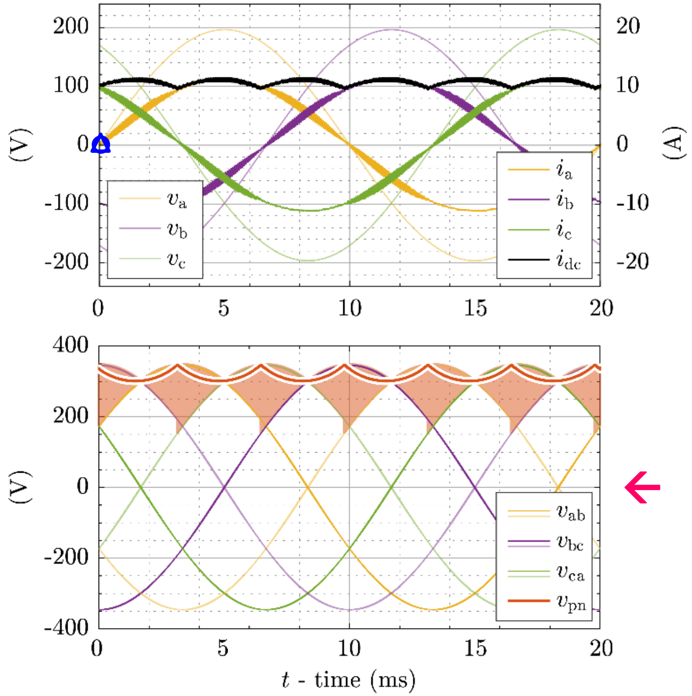


- Conventional Control of Inverter Stage → Rel. High CSI-Stage Sw. Losses

3-Φ Buck-Boost CSI (3)

- *"Synergetic" Control of Buck-Stage & CSI Stage*
- *6-Pulse-Shaping of DC Current by Buck-Stage → Allows Clamping of One CSI-Phase*

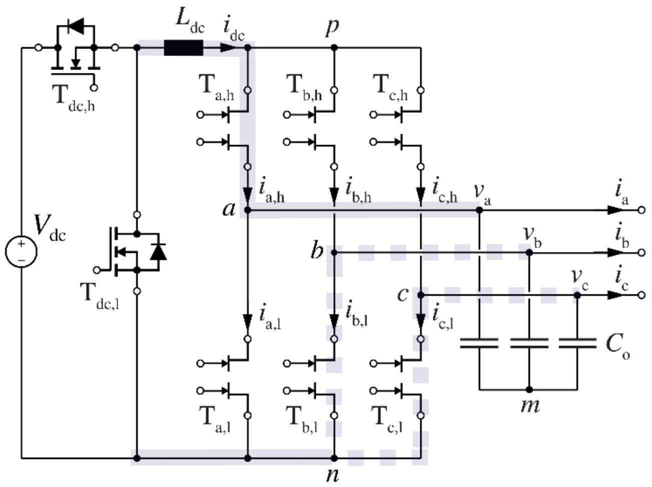


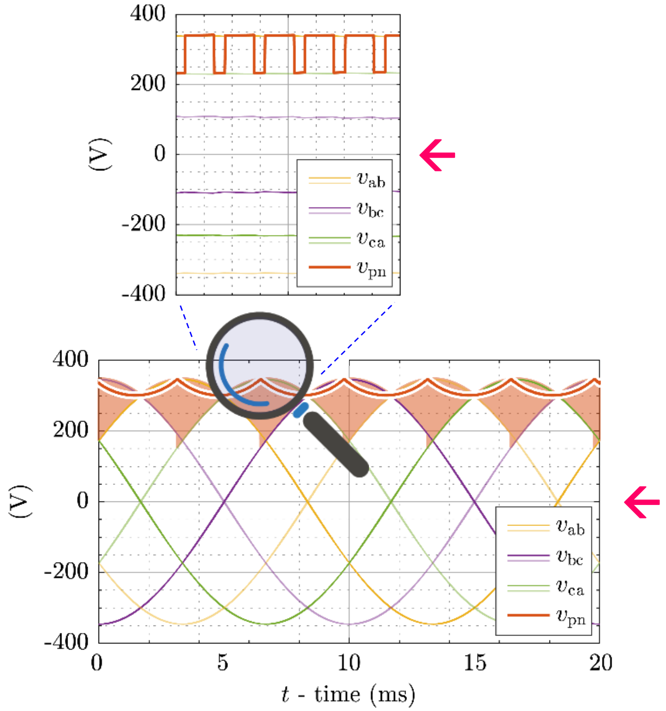


- *Switching of Only 2 of 3 Phase Legs (2/3 Mode) → Significant Reduction of Sw. Losses*

3-Φ Buck-Boost CSI (4)

- *"Synergetic" Control of Buck-Stage & CSI Stage*
- *6-Pulse-Shaping of DC Current by Buck-Stage → Allows Clamping of One CSI-Phase*



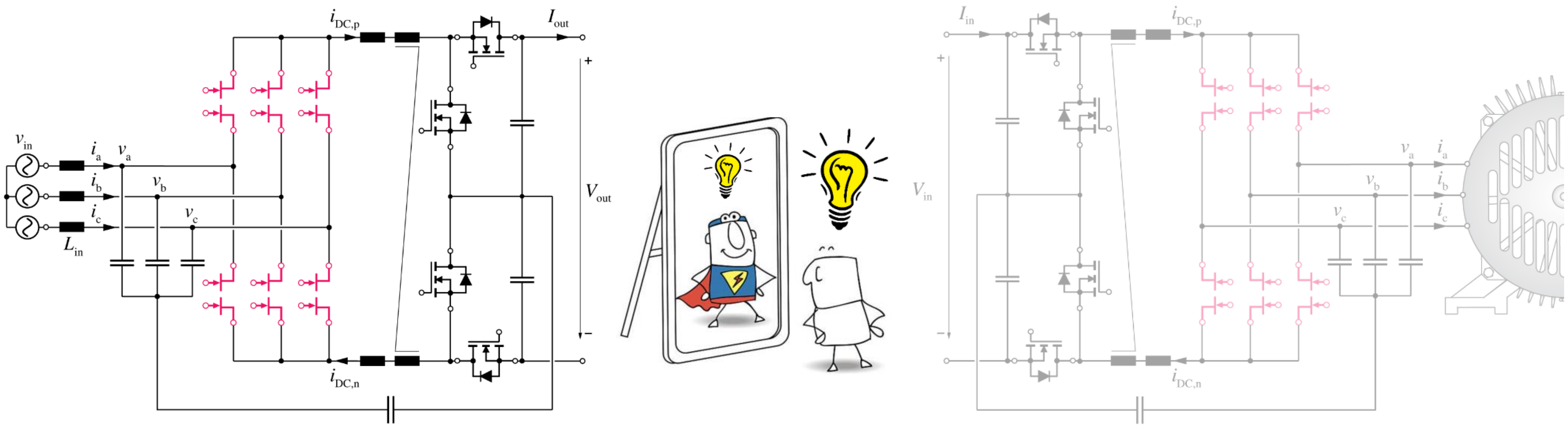


- *Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)*

3-Φ AC/AC Conversion

Current Source Buck-Boost Rectifier

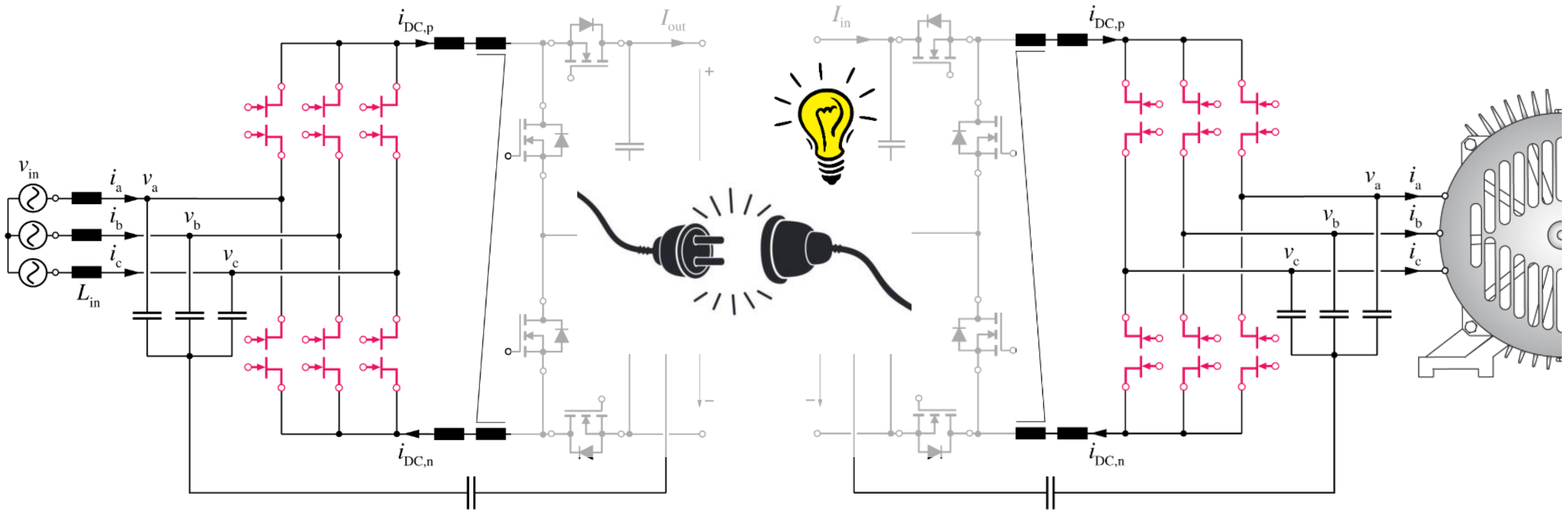
- *Derivation Based on Bidir. Buck-Boost Current Source Inverter (CSI) → Buck-Boost PFC Rectifier*
- *Lower # of Ind. Components Compared to Boost-Buck Rectifier Approach*



- *AC/DC Buck Stage Distributes DC-Link Current to Mains Phases — Sinusoidal Inp. Current*
- *Synergetic Control/Modulation of Rectifier Stage & DC/DC Stage for Min. Sw. Losses*

3-Φ Current DC-Link AC/AC Converter

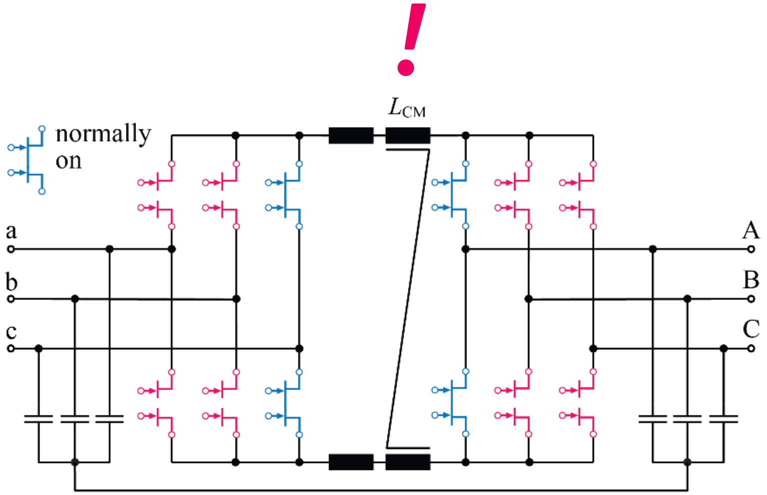
- *DC-Side Coupling of Buck-Boost Current DC-Link PFC Rectifier & Inverter — AC/DC/AC*
- *Full-Sinewave Filtering @ Input & Output w/ Single Magnetic Component*



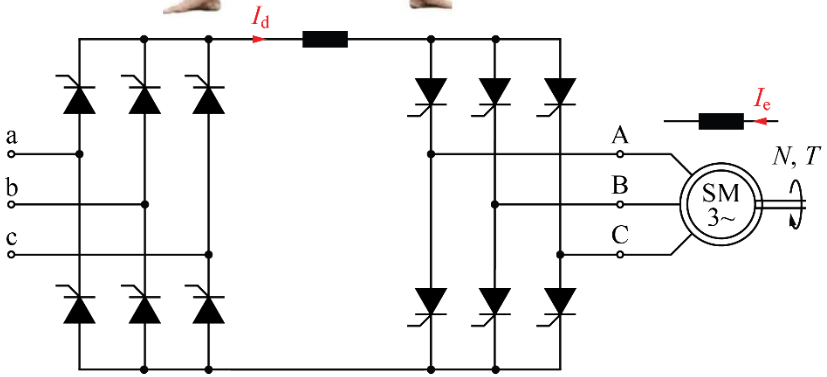
- *Bipolar Blocking / Unidir. Switches | Unidir. DC-Link Current Sufficient for Bidir. Power Conversion*
- *Modulation-Based Inversion of DC-Link Voltage Polarity → Inv. of Power Flow Direction*

Remark 3-Φ Current DC-Link AC/AC Converter

- *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

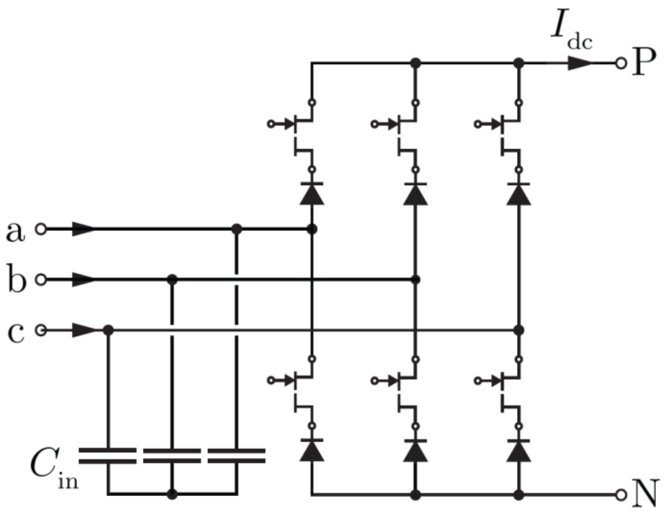


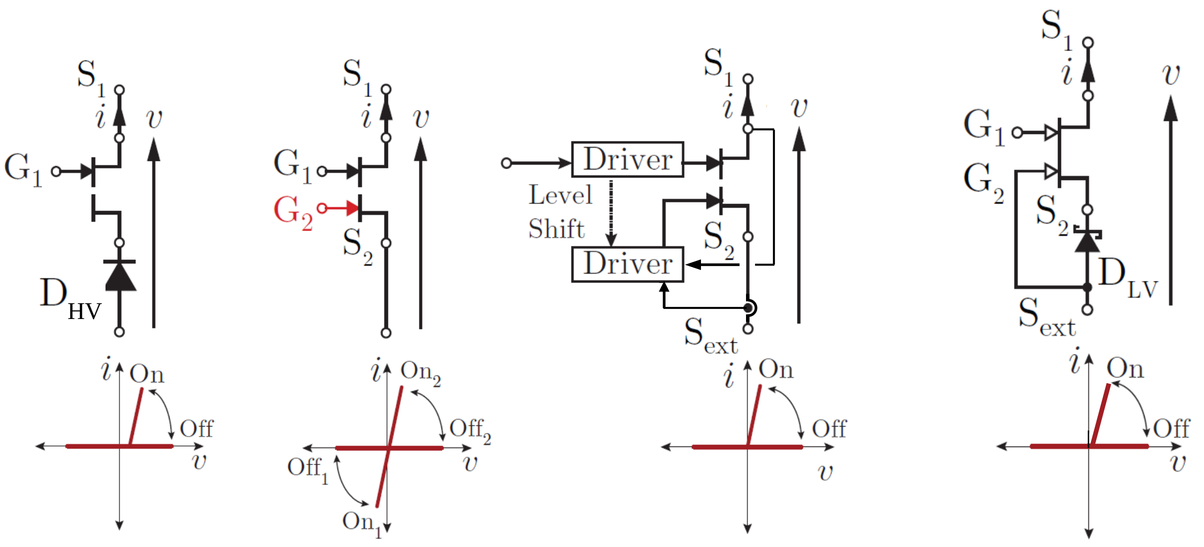
- *Relation to High-Power Thyristor-Based Medium-Voltage Synchr. Machine Variable Speed Drives*

Remark Self Reverse-Blocking M-BDS-Concept (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 Drivers*
- *"Self-Switching"* *Ohmic Cond. Char. BUT High Local Complexity (Sensing)*

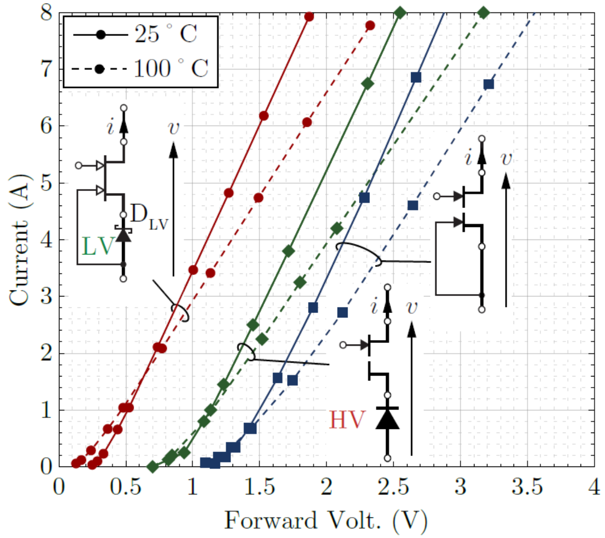




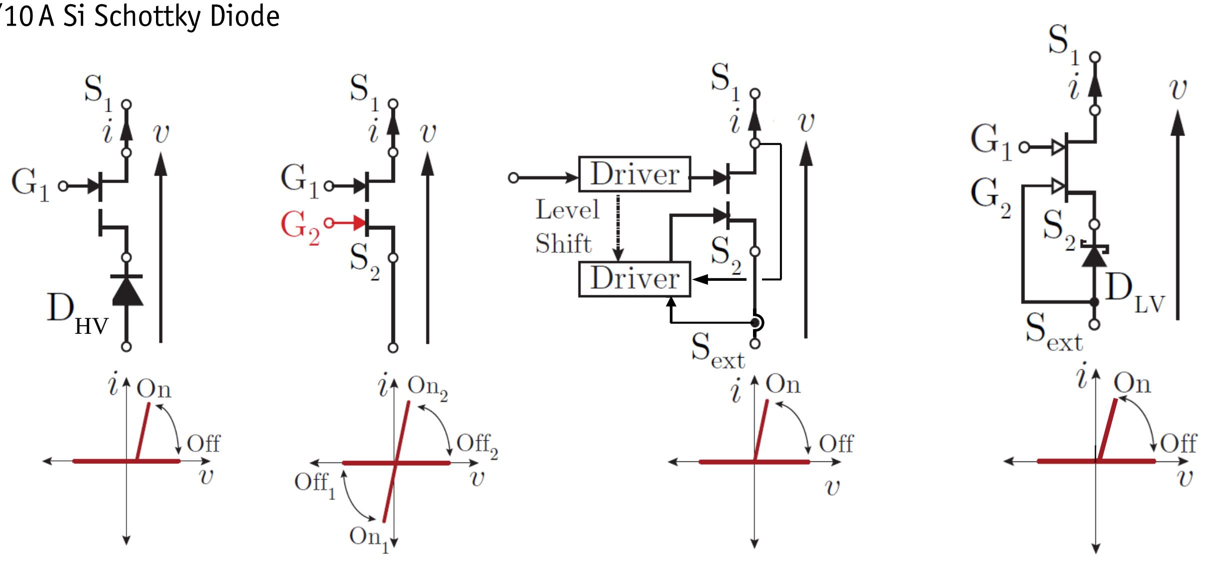
- *SRB-MBDS* *Quasi-Ohmic Cond. Char. (Cascode w/ LV Si Schottky Diode) & 1 External Gate*

Remark Self Reverse-Blocking M-BDS-Concept (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 Drivers
  - "Self-Switching" — Ohmic Cond. Char. BUT High Local Complexity (Sensing)



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



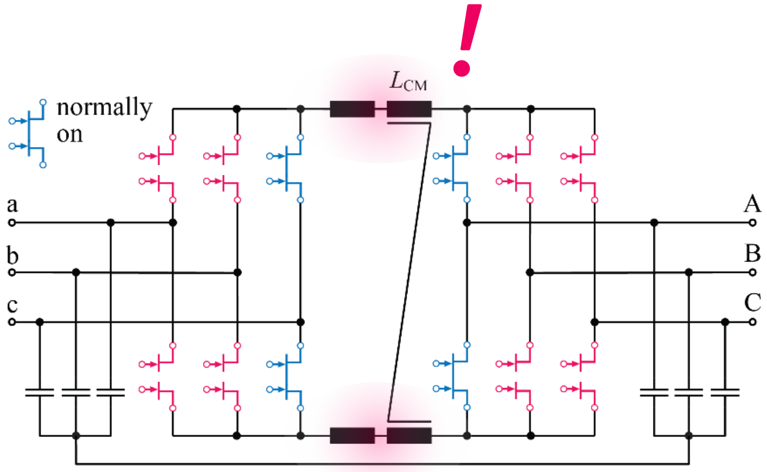
- **SRB-MBDS** — Quasi-Ohmic Cond. Char. (Cascode w/ LV Si Schottky Diode) & 1 External Gate


DUALITY
Buck-
Boost
Boost-
Buck
Source: www.reuts.com

DUALITY

■ *Current DC-Link Topology*

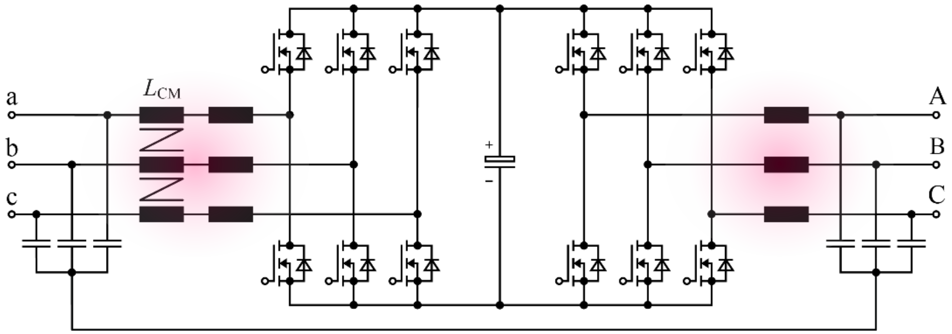
- *Application of M-BDSs*
- *Complex 4-Step Commutation OR SRB-MBDSs*
- *Low Filter Volume*



- *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*

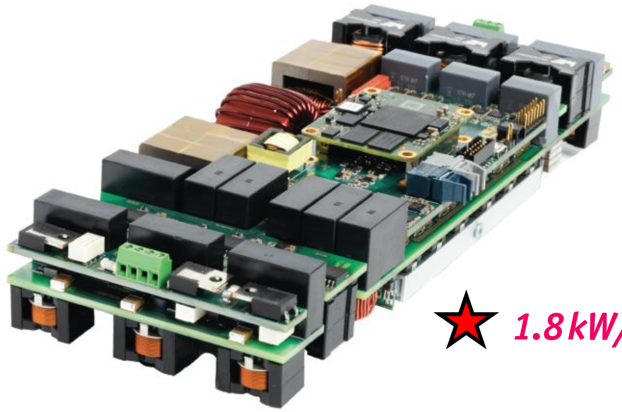


- *High Input / Output Filter Volume*

DUALITY

■ ***Current DC-Link Topology***

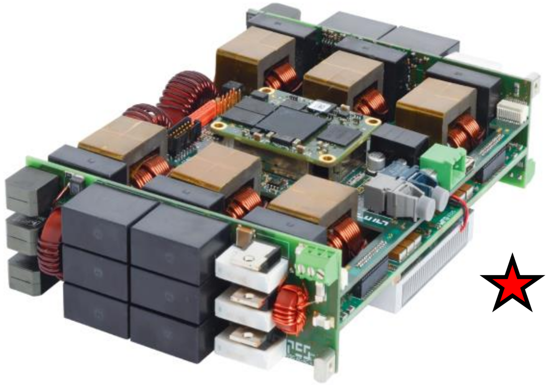
- *Application of M-BDSs*
- *Complex 4-Step Commutation*
- *Low Filter Volume*



★ 1.8 kW/dm³

■ ***Voltage DC-Link Topology***

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



★ 1.7 kW/dm³

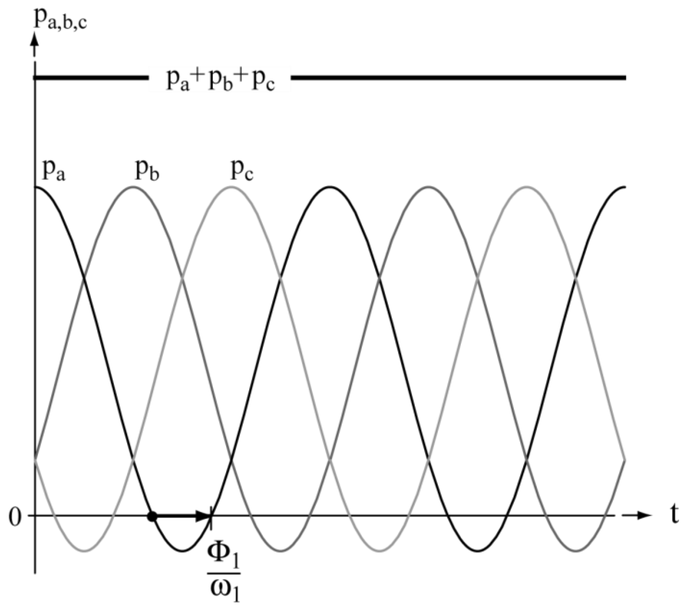
■ *All-600 V-GaN AC-AC VSDs / 1.4 kW, 200 V L-L / Full EMI Filter (Grid & Motor) / 97% Nominal Eff.*

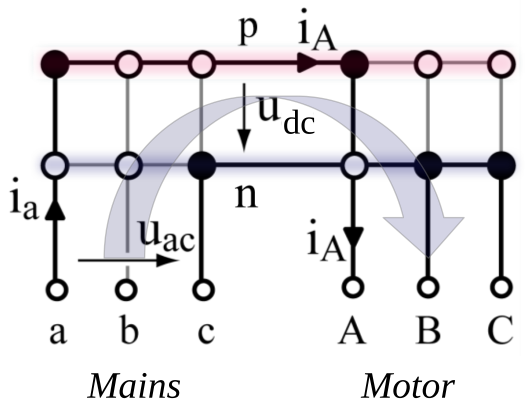
3-Φ AC/AC Matrix Converter

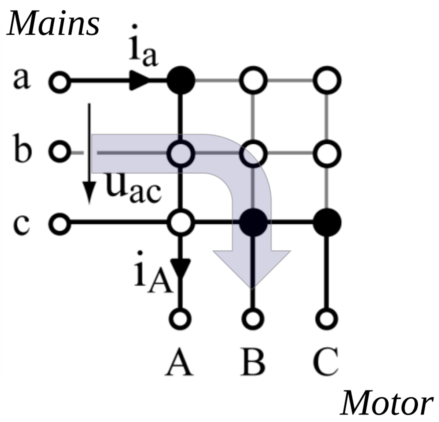
$$\left\{\begin{matrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 1 \end{matrix}\right\}$$

Indirect & Direct 3-Φ AC/AC Matrix Converter

- *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*
- *DMC → Switch Matrix w/ Bipolar Voltage Blocking & Current Carrying Devices*



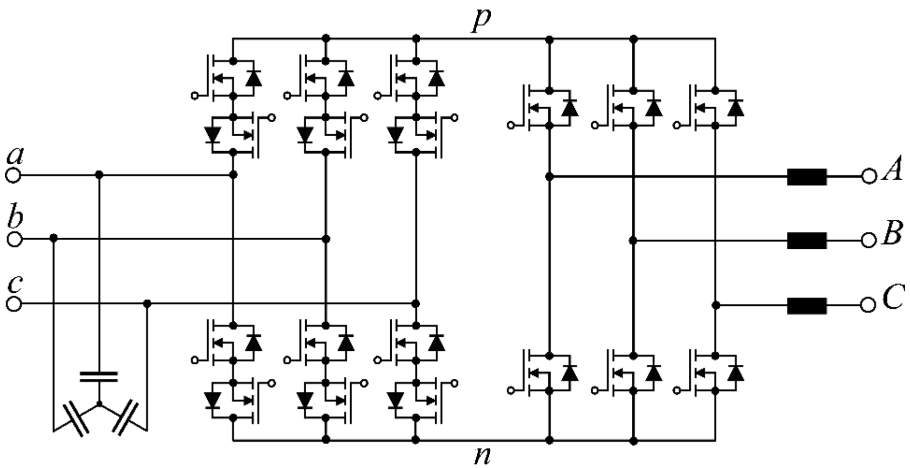


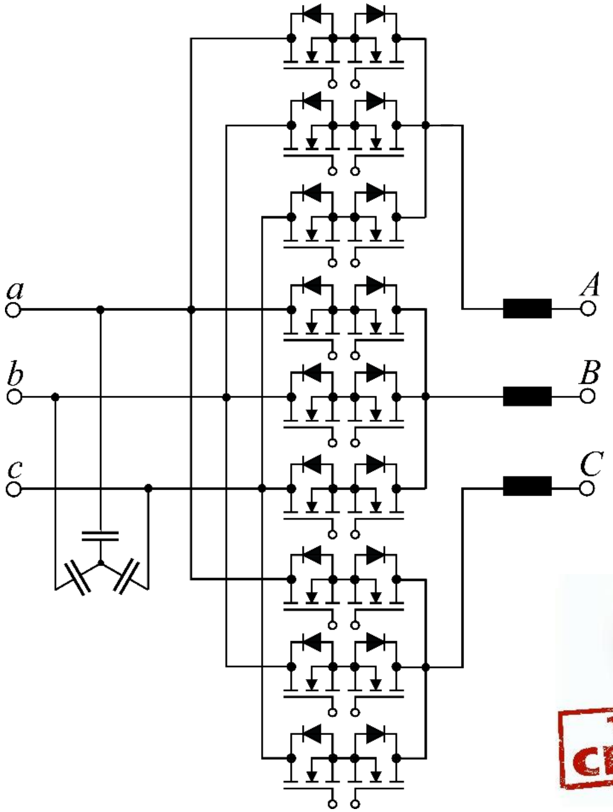


- *Input-Side Cap. / Output-Side Motor Ind. → Operation Limited to Buck-Type (Step-Down) Conversion*

Indirect & Direct 3-Φ AC/AC Matrix Converter

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

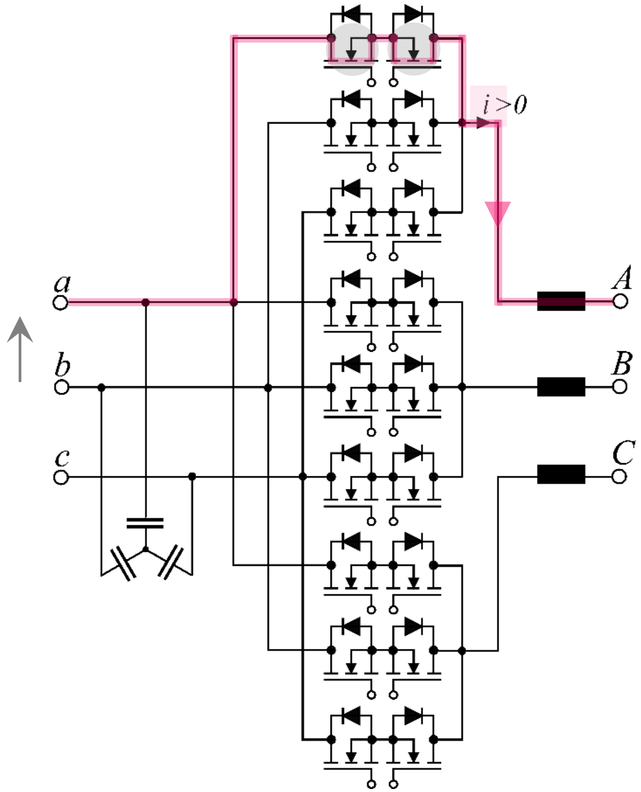




- *IMC Relies on Strictly Pos. DC-Link Voltage / i=0 Input Stage Commutation*
- *M-BDS-Based Realization of DMC Features Lower # of Switches / 4-Step Commutation*

4-Step Commutation of DMC

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



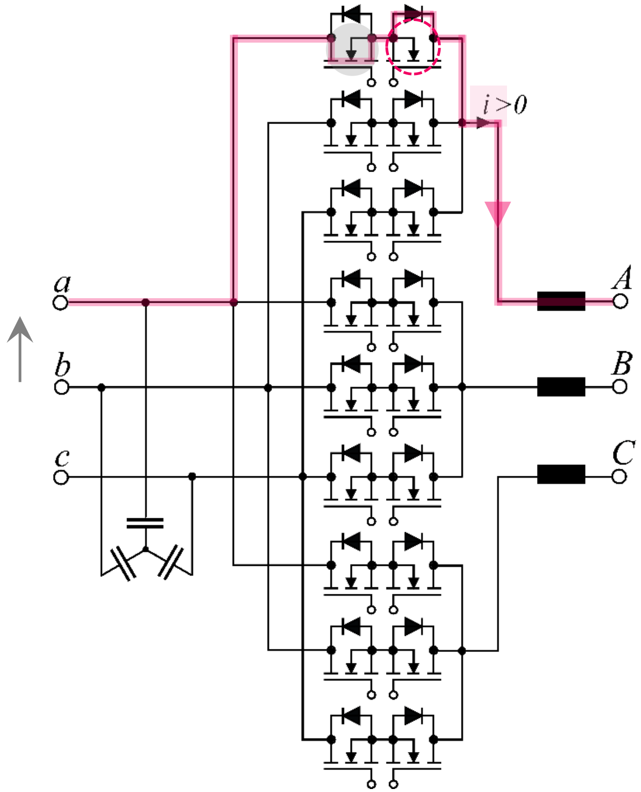
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (1)

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

1^{st} Step: Off



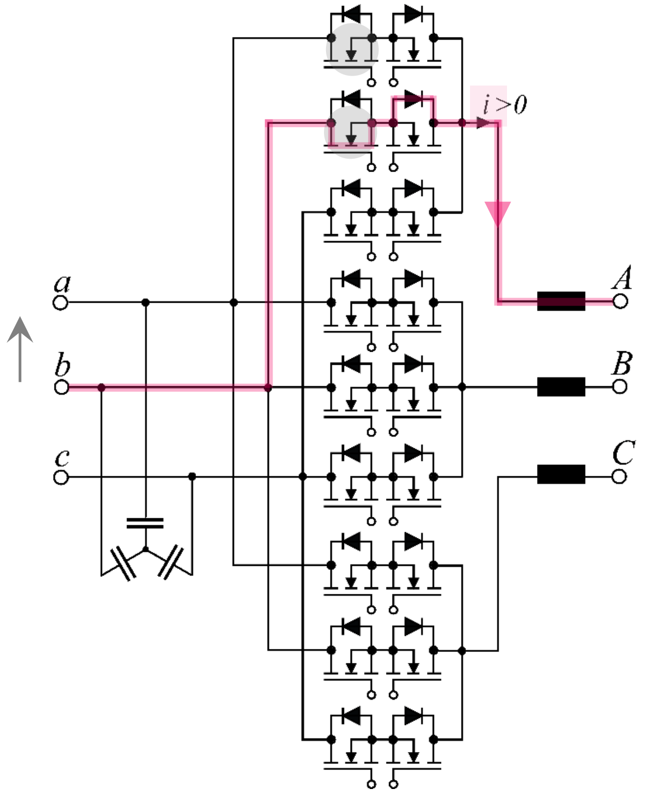
- *No Mains Short Circuit*
- *No Load Current Interruption*

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



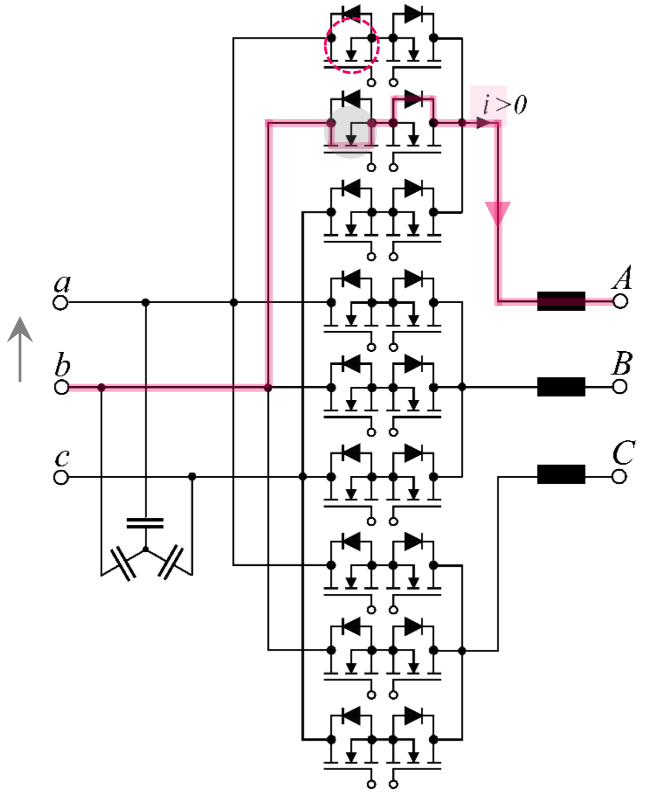
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (3)

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

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



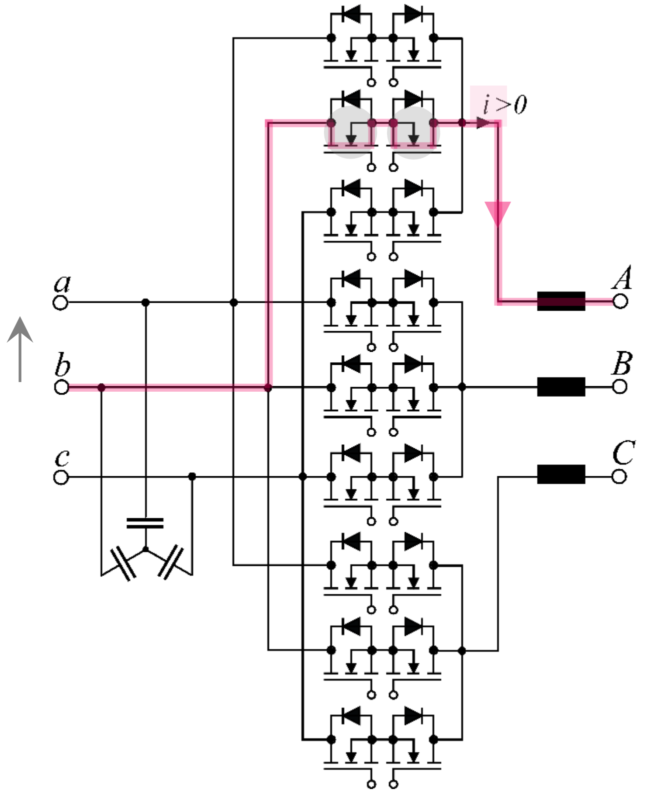
- *No Mains Short Circuit*
- *No Load Current Interruption*

Assumption $u_{ab} < 0$

4-Step Commutation of DMC (4)

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

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



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

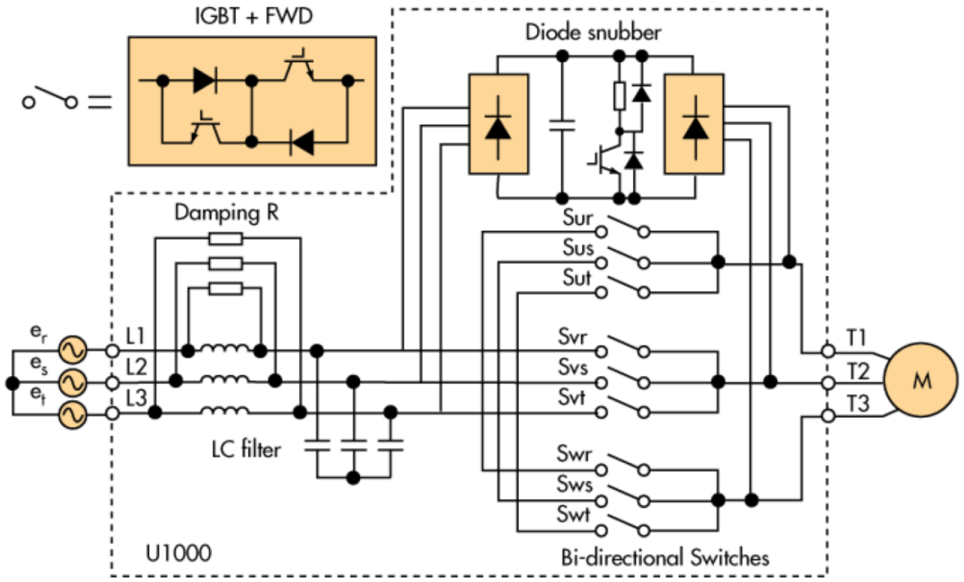
Assumption $u_{ab} < 0$

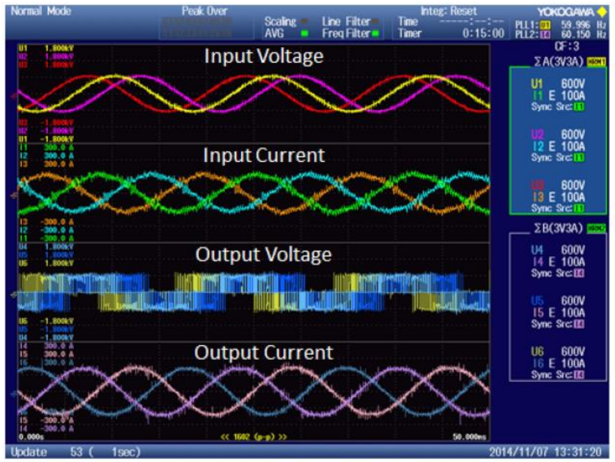
Industry Application of 3-Φ Matrix Converter

- *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

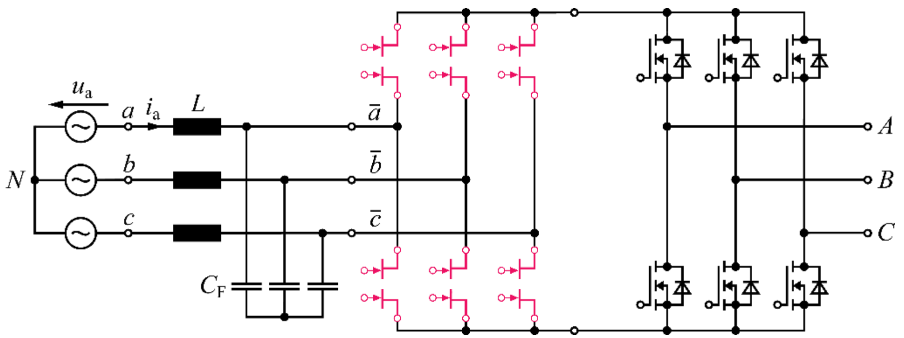




- *Challenging Overvoltage Protection*
- *Limited Output Voltage Range (!)*

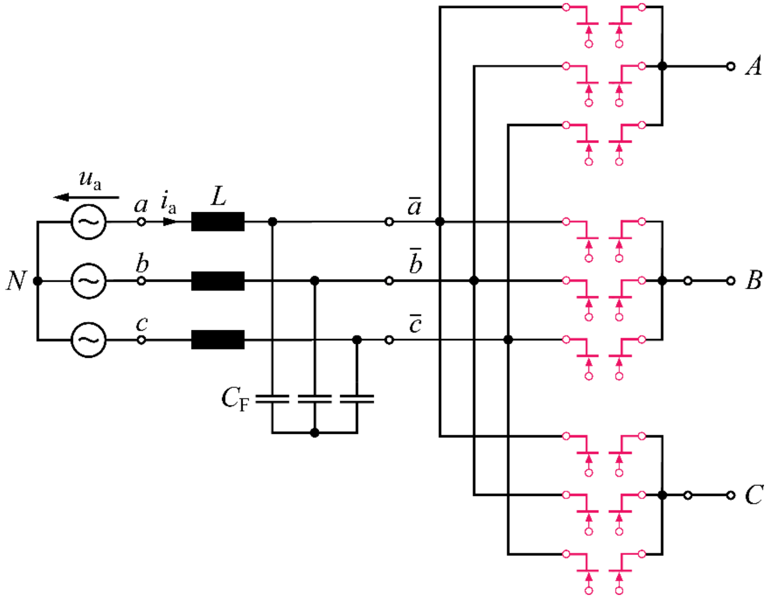
3-Φ AC/AC *Matrix* Converter Comparison

- ***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*

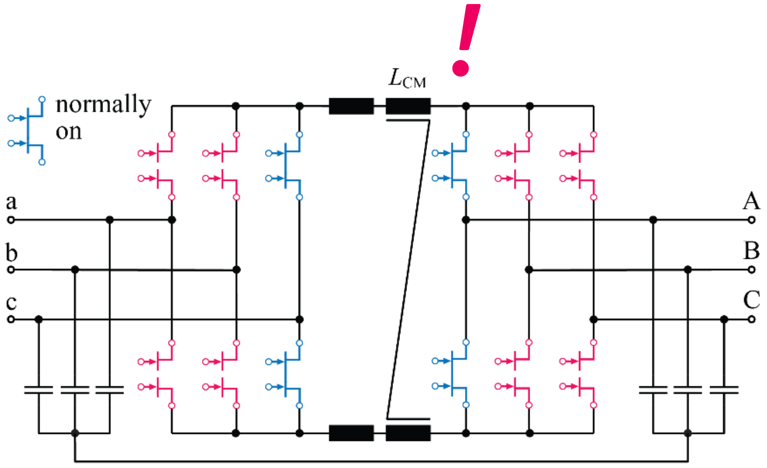


  - *Thermally Critical @ $f_{out} \approx f_{in}$*

3-Φ Current DC-Link vs. Matrix AC/AC Converter

■ *Current DC-Link Topology*

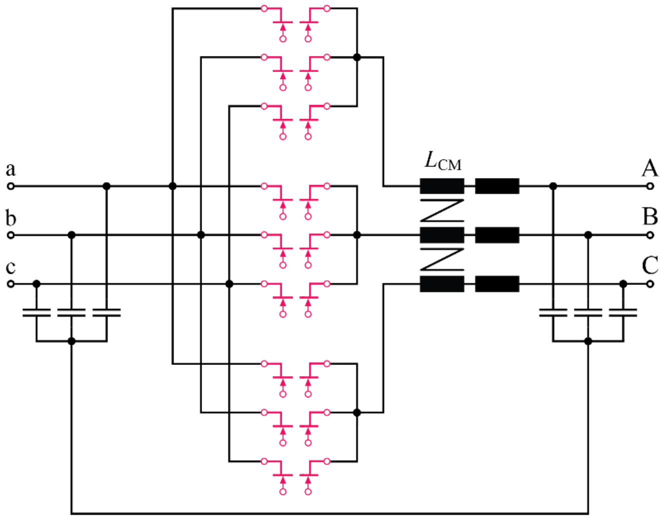
- *Application of M-BDSs | 12 Switches*
- *4-Step Commutation*
- *Buck-Boost Functionality*
- *Low Filter Volume*



- *Challenging Overvoltage Protection*

■ *Direct Matrix Converter*

- *Application of M-BDSs | 9 Switches*
- *4-Step Commutation*
- *Complex Space Vector Modulation*
- *Limited to Buck-Operation (!)*



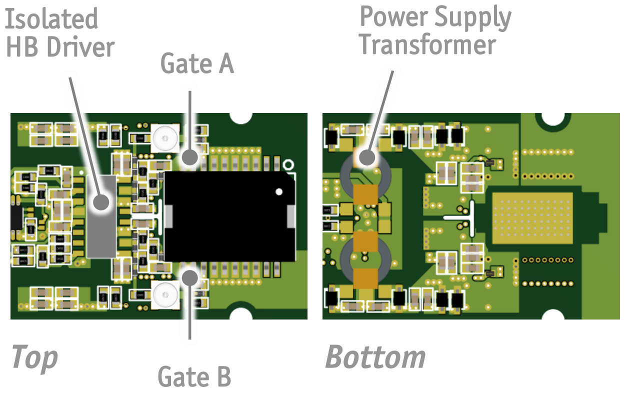
- *Challenging Overvoltage Protection*

Outlook

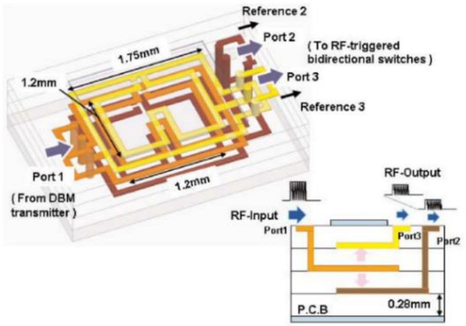
Monolithic 3D-Integration

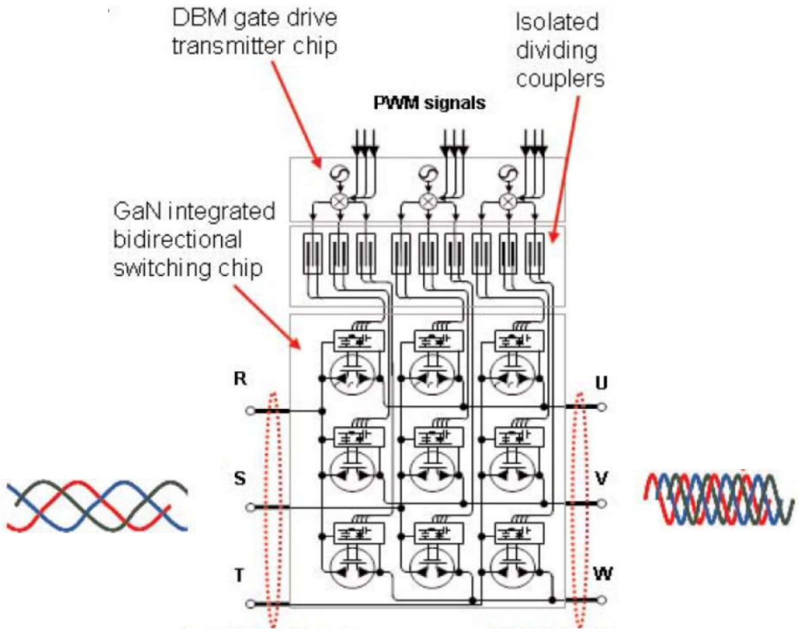
Source: Panasonic ISSCC 2014

- *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 (600 V, 10 A – 5 kW Motor)*



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

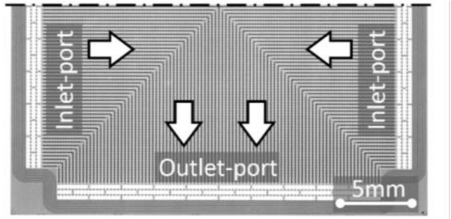


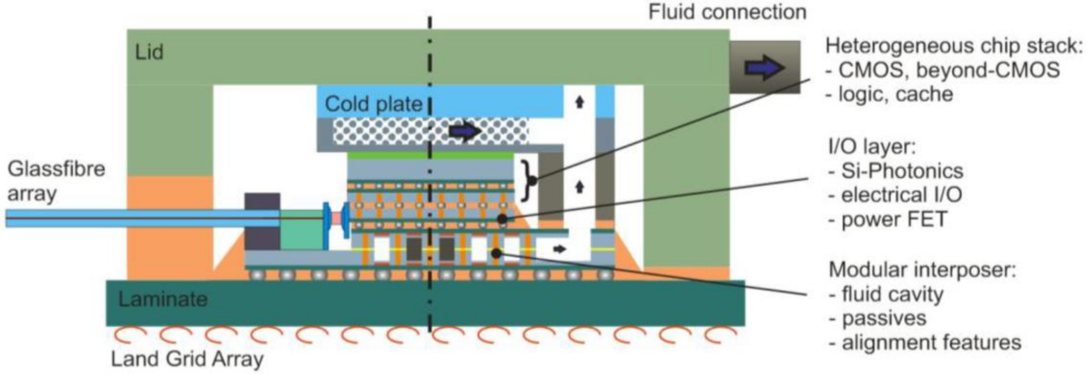


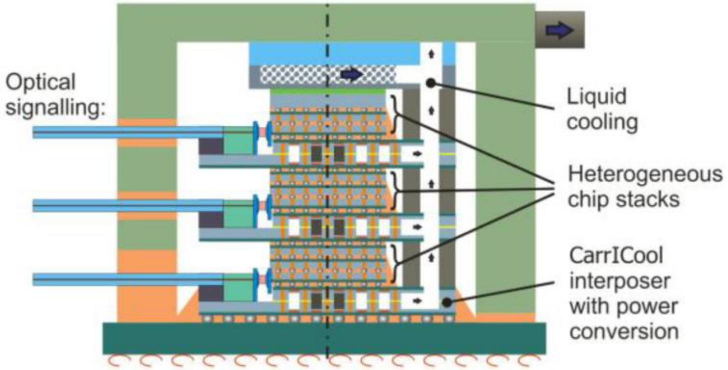
- *Massive Space Saving Compared to Discrete Realization (!)*

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!

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