Keynote

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Next-Generation SiC/GaN Three-Phase Variable-Speed Drive Inverter Concepts

Johann W. Kolar & Jonas E. Huber

Outline

- ▶ *Introduction to VSDs*

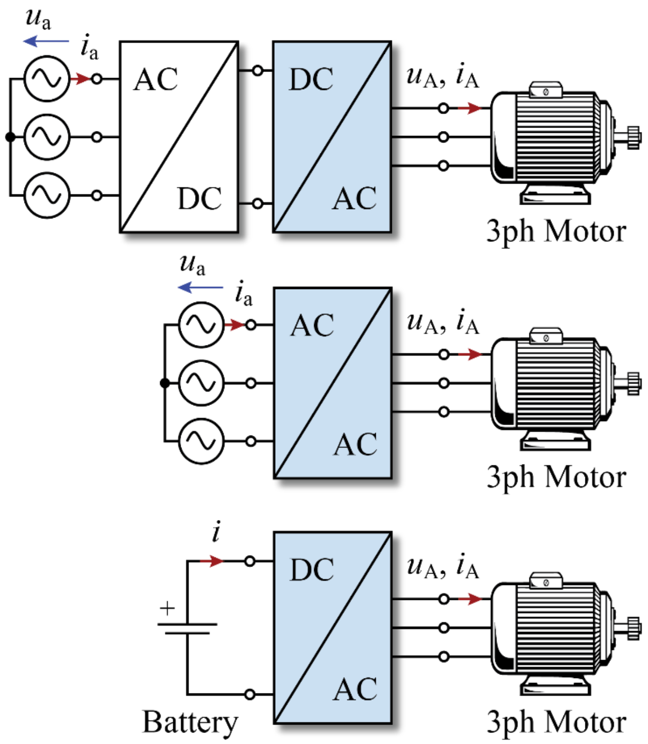
- ▶ *SiC Sinus-Inverter*
- ▶ *GaN Multi-Level Inverter*
- ▶ *SiC Buck-Boost Inverter*
- ▶ *I-DC Link Inverter & GaN AC-Switches*

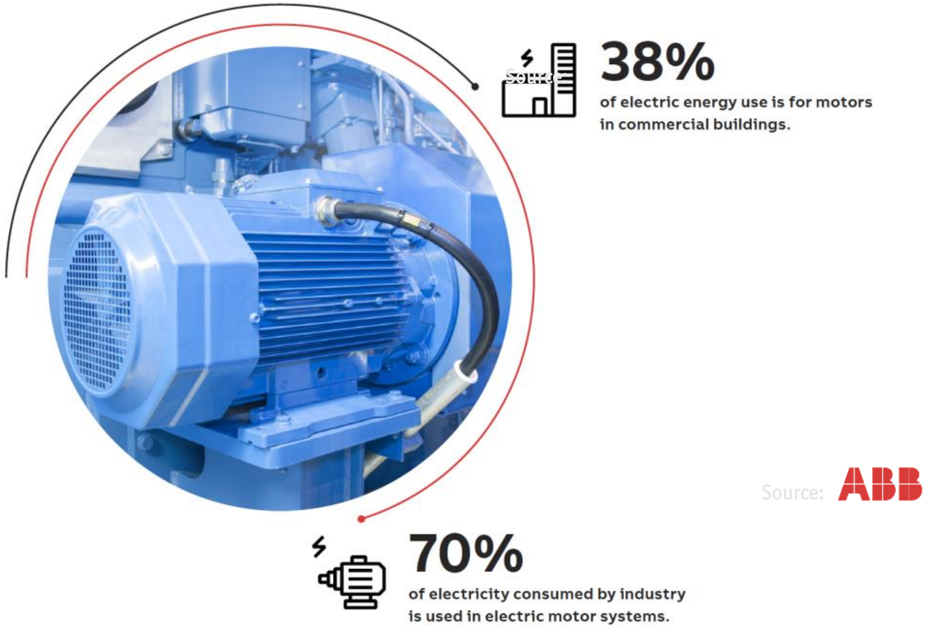
- ▶ *Conclusions*

Acknowledgement
M. Antivachis
J. Azurza
D. Bortis
M. Guacci
M. Haider
F. Krismer
S. Miric
J. Miniböck
N. Nain
P. Niklaus
G. Rohner
F. Vollmaier
D. Zhang
G. Zulauf

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*

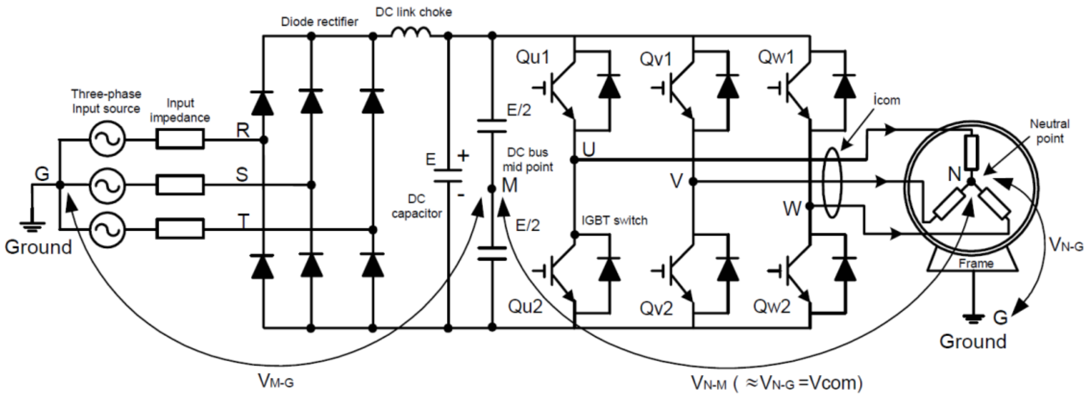




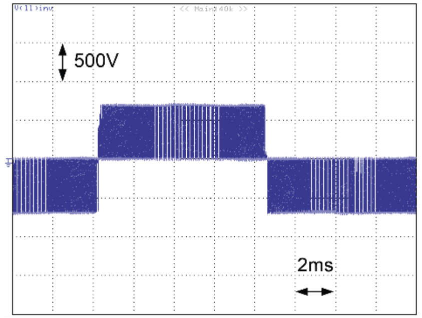
- *45% of World's Electricity Used for Motors in Buildings & Industrial Applications*

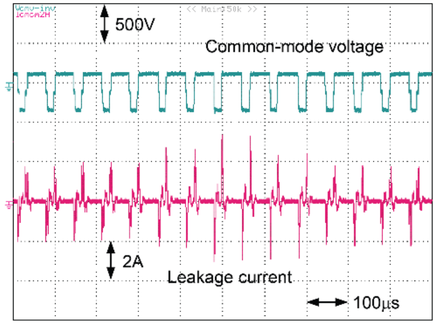
State-of-the-Art Drive System

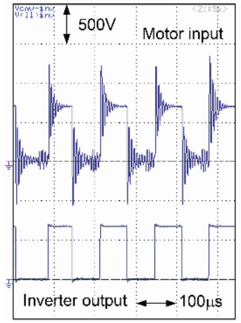
- *Standard 2-Level Inverter — Large Motor Inductance / Low Sw. Frequency*
- *Shielded Motor Cables / Limited Cable Length / Insulated Bearings / Acoustic Noise*

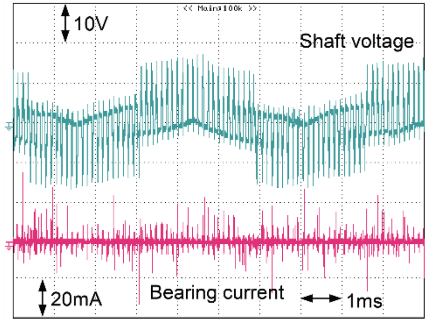


Source: YASKAWA





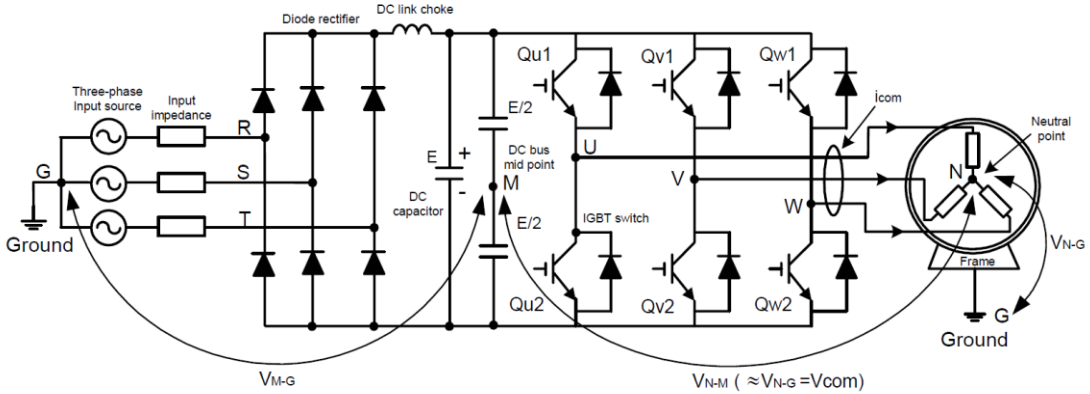




- *Line-to-Line Voltage* | *CM Leakage Current* | *Motor Surge Voltage* | *Bearing Current*

State-of-the-Art Drive System

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



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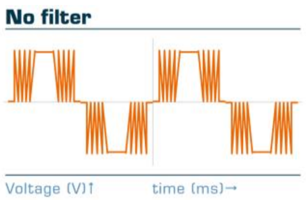
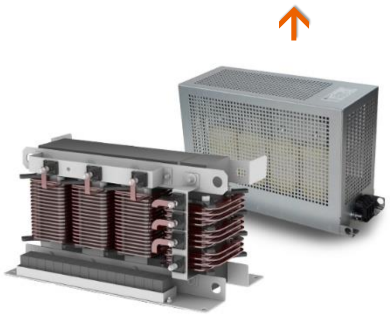
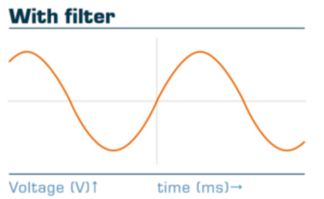
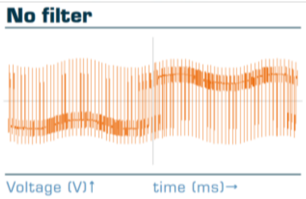
MOTOR VOLTAGE PHASE-PHASE

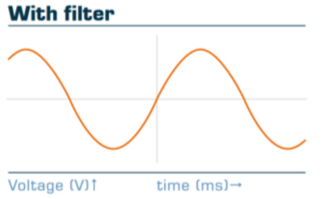






MOTOR VOLTAGE PHASE-GROUND





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

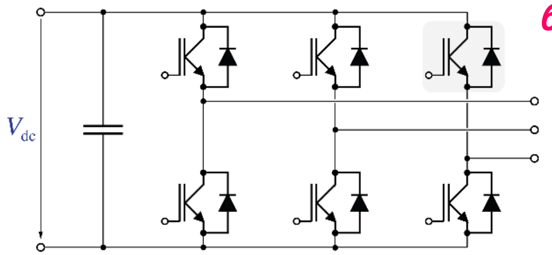
#1

Source: www.clipart-library.com

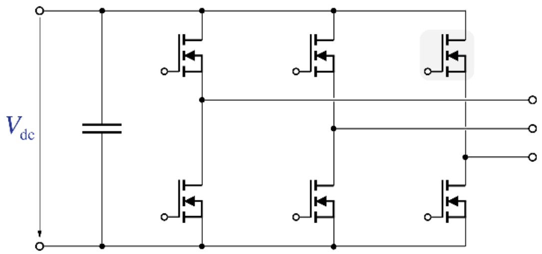
SiC | GaN

Si vs. SiC

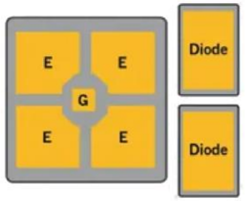
- **Si-IGBT / Diode** → Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current
- **SiC-MOSFET** → Loss Reduction @ Part Load BUT Higher R_{th}



6x Si-IGBT
6x Si-Diode



6x SiC-MOSFET



Source: ATZ elektronik

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

Source: Infineon

1200V 100A
Die Size: $25.6\,mm^2$

Source: Cree

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

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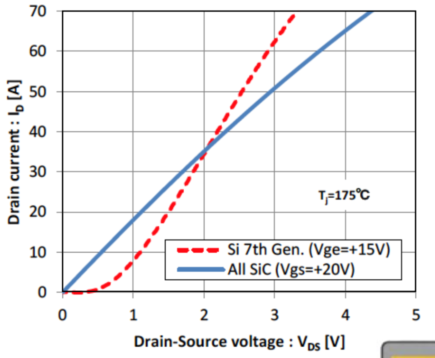
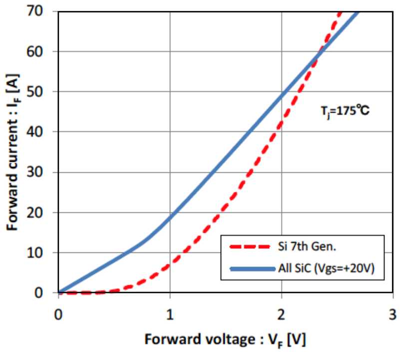
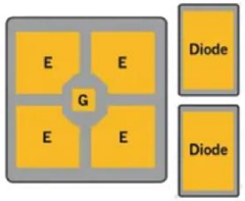


Source: Fuji Electric

Forward



Reverse



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

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Die Size: 25.6 mm^2

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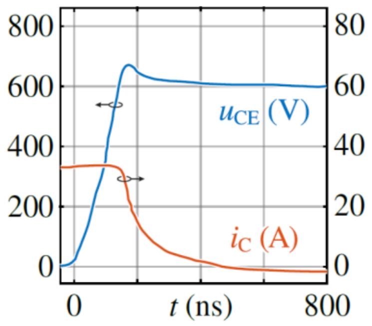
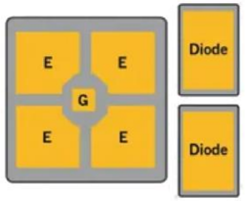


Source: Fuji Electric



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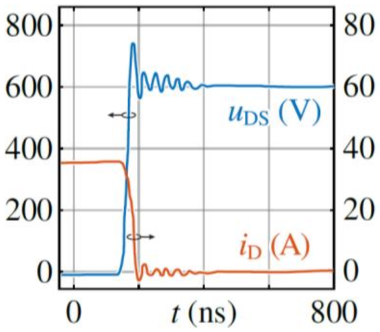

1200V 100A
Die Size: 25.6mm²

Source: Cree

- Space Saving of >30% on Module Level (!)
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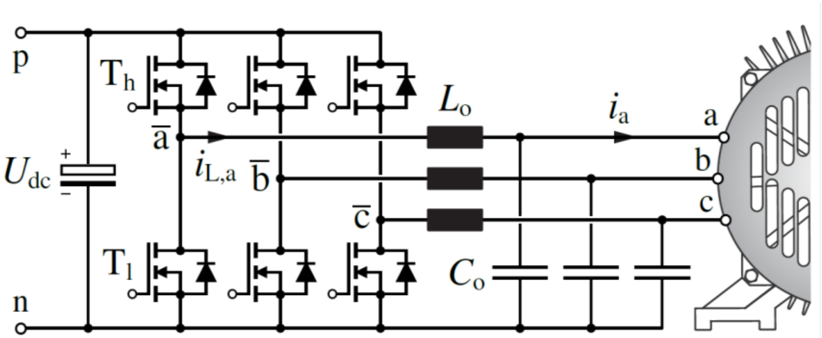
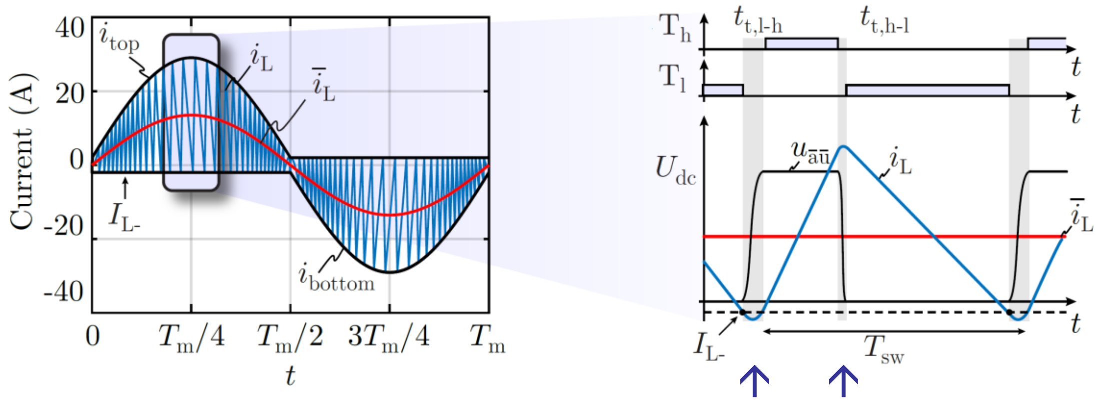
Full-Sinewave Filter & ZVS Operation

- *Sinusoidal Output Voltage*
- *Triangular Current Mode (TCM) → ZVS of Inv. Bridge-Legs*
- *High Sw. Frequency & TCM → Low Filter Inductor Volume*

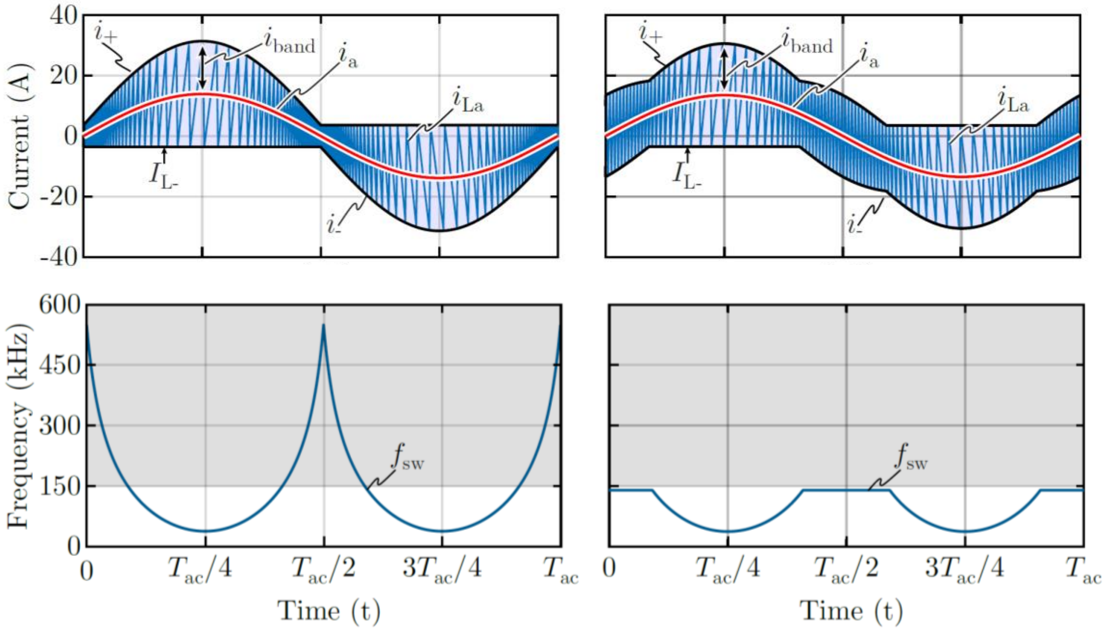




- *Only 33% Increase of Transistor Conduction Losses Compared to CCM (!)*
- *Very Wide Switching Frequency Variation*

Frequency-Bounded TCM — B-TCM

- *Very Wide Sw. Frequency Variation of Conventional TCM*
- *Allow Larger Current Ripple Around Zero Crossings*



99.7% Semicond. Eff.
99.5% Total Efficiency

B-TCM Bridge-Leg
1200V SiC MOSFETs

P = 2.2kW
U_{DC} = 800V
f_S = 50kHz...140kHz

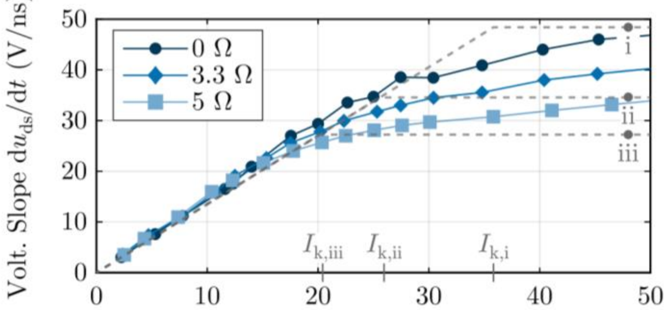
L = 52uH (106 cm^3)
C = 8.8uF

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

Remark: Residual ZVS Losses

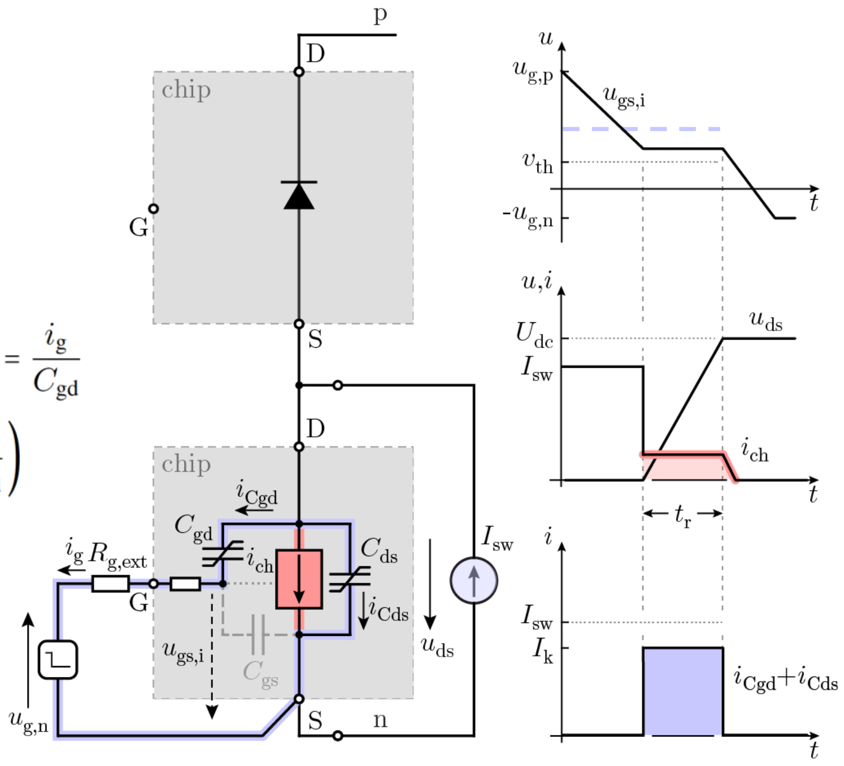
- Overlap of u_{DS} & Channel Current i_{ch} @ High $I_{sw} > I_k$
- Temporary Turn-on Due to $u_{GS,i} > u_{th}$

650V SiC @ U_{DC} = 400V



$$\left.\frac{\mathrm{d}u_{ds}}{\mathrm{d}t}\right|_{max} = \frac{I_k}{C_{ds} + C_{gd}} = \frac{i_g}{C_{gd}}$$

$$I_k = \frac{u_{th} + u_{g,n}}{R_g}\left(1 + \frac{C_{ds}}{C_{gd}}\right)$$



- "Kink" Current I_K Dependent on Inner & Outer Gate Resistance & $u_{g,n}$

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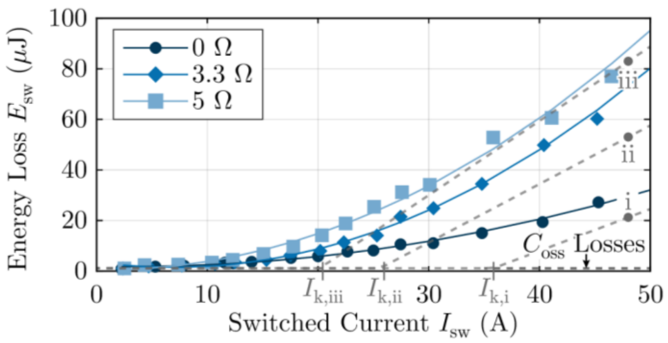

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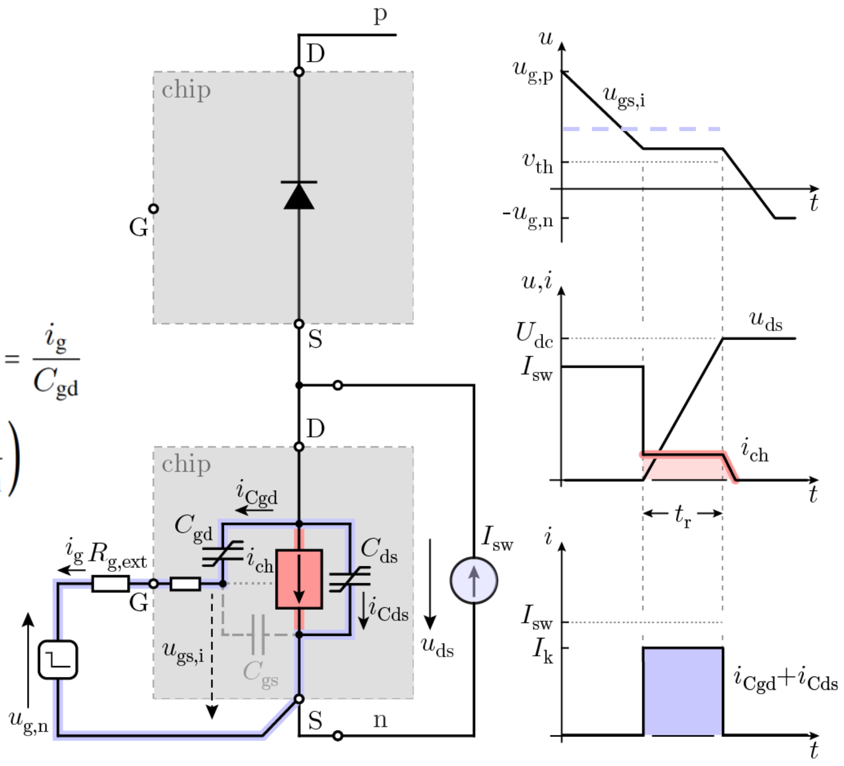
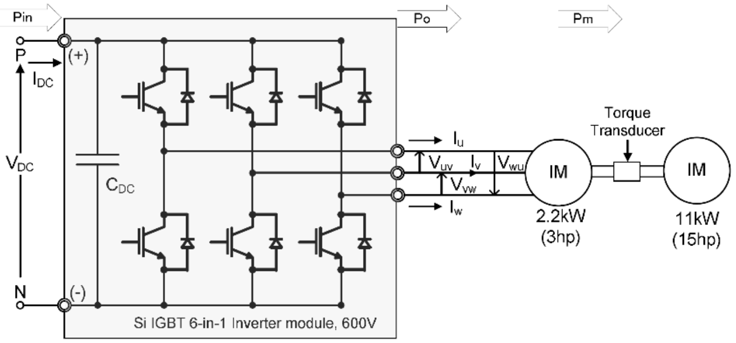


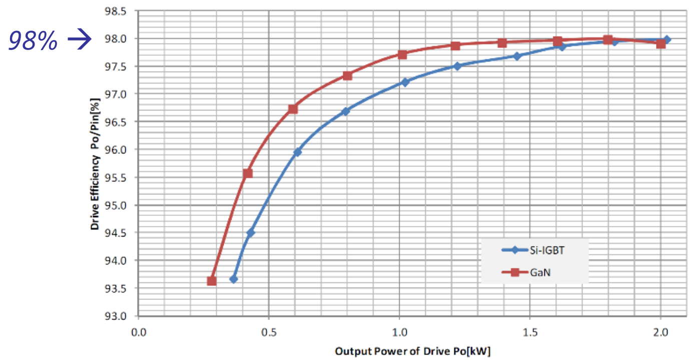
- "Kink" Current I_K Dependent on Inner & Outer Gate Resistance & $u_{g,n}$

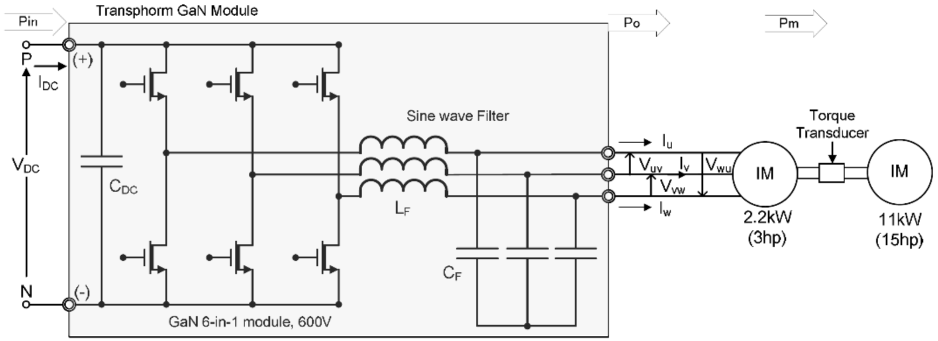
Si IGBT vs. GaN Inverter System

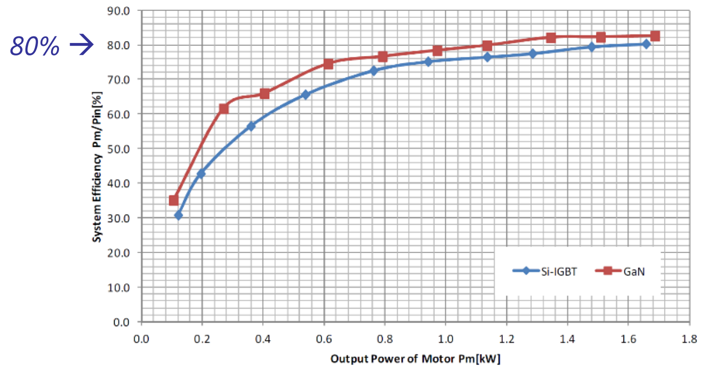
Source: YASKAWA

- *Comparison of GaN Inverter with LC-Filter (f_S=100kHz) to Si-IGBT System (No Filter, f_S=15kHz)*
- *Measurement of Inverter Stage & Overall Drive Losses @ 60Hz*









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

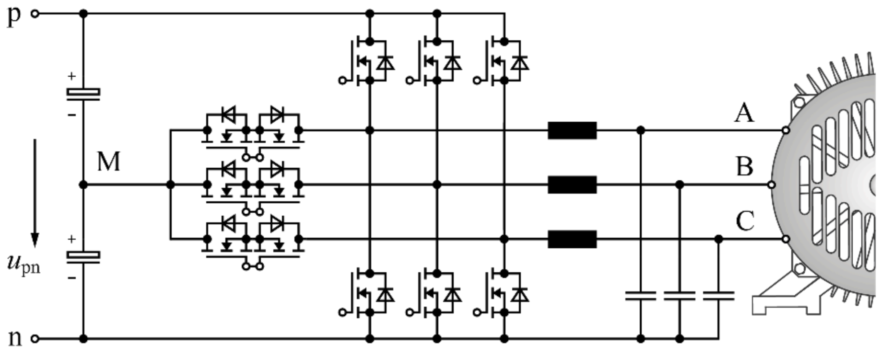
#2

Source: www.clipart-library.com

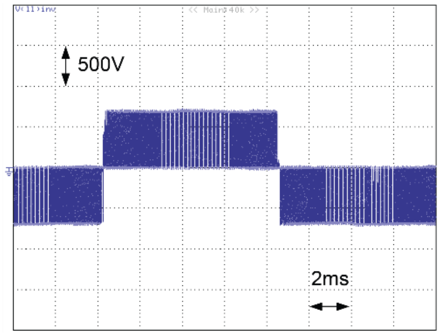
Multi-Level Inverter

3-Level Inverter Concepts

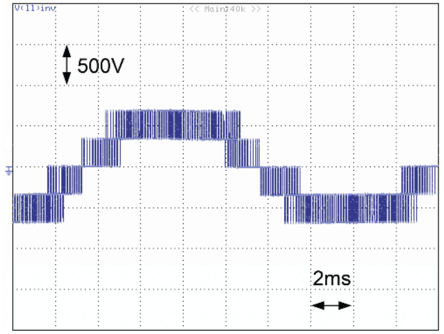
- *Higher Number of Output Voltage Levels / Lower CM Voltage Steps*
- *Neutral Point Clamped | Flying Capacitor | T-Type Bridge-Leg Topologies*



Line-to-Line Voltage



2-Level Bridge-Leg

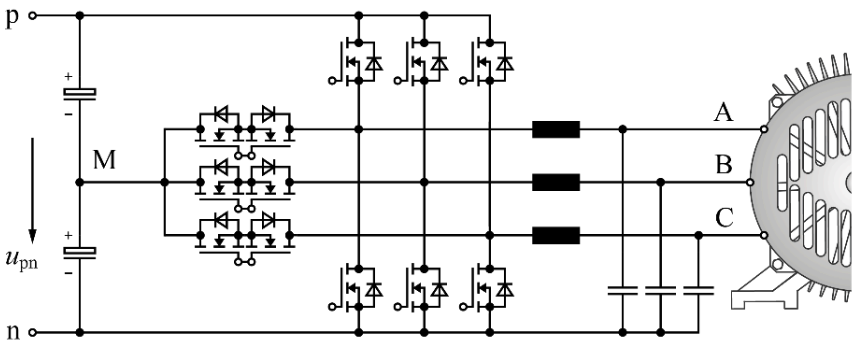


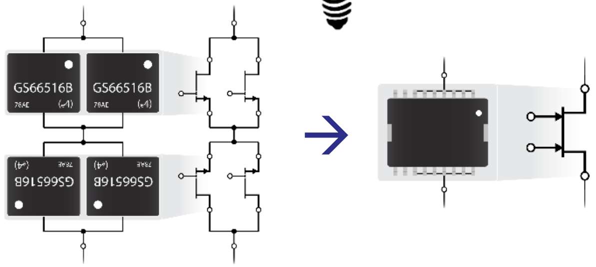
3-Level Bridge-Leg

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

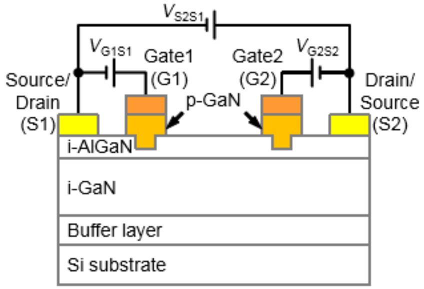
3-Level T-Type Inverter

- *Utilization of 600V Monolithic Bidirectional GaN Switches*
- *2-Gate Structure Provides Full Controllability*





Source: infineon, Panasonic ideas for life



- *Factor 4 (!) Reduction of Chip Area vs. Discrete Realization*

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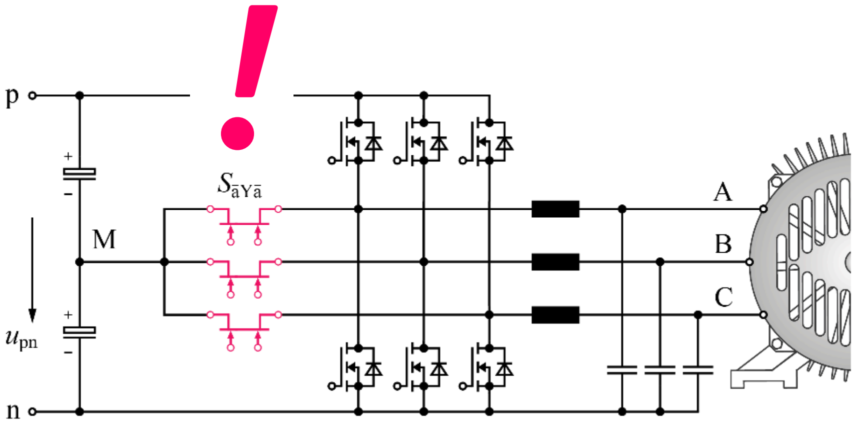

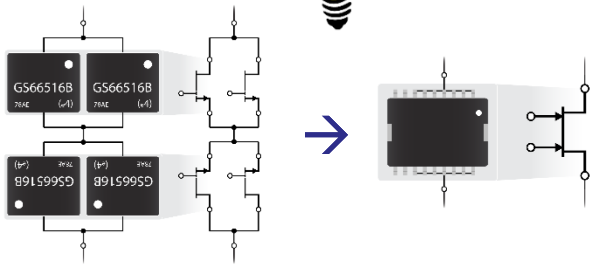

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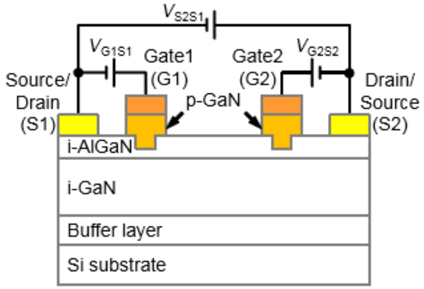
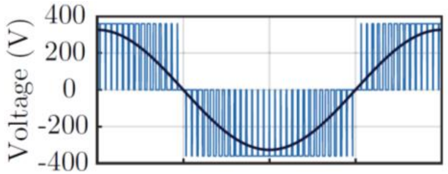
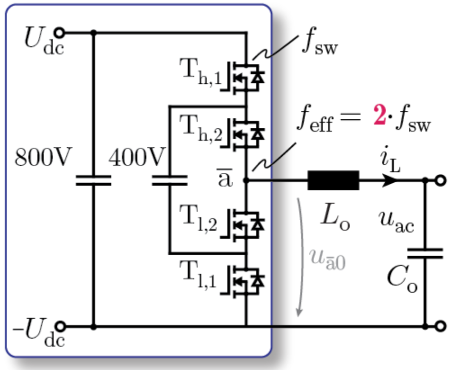


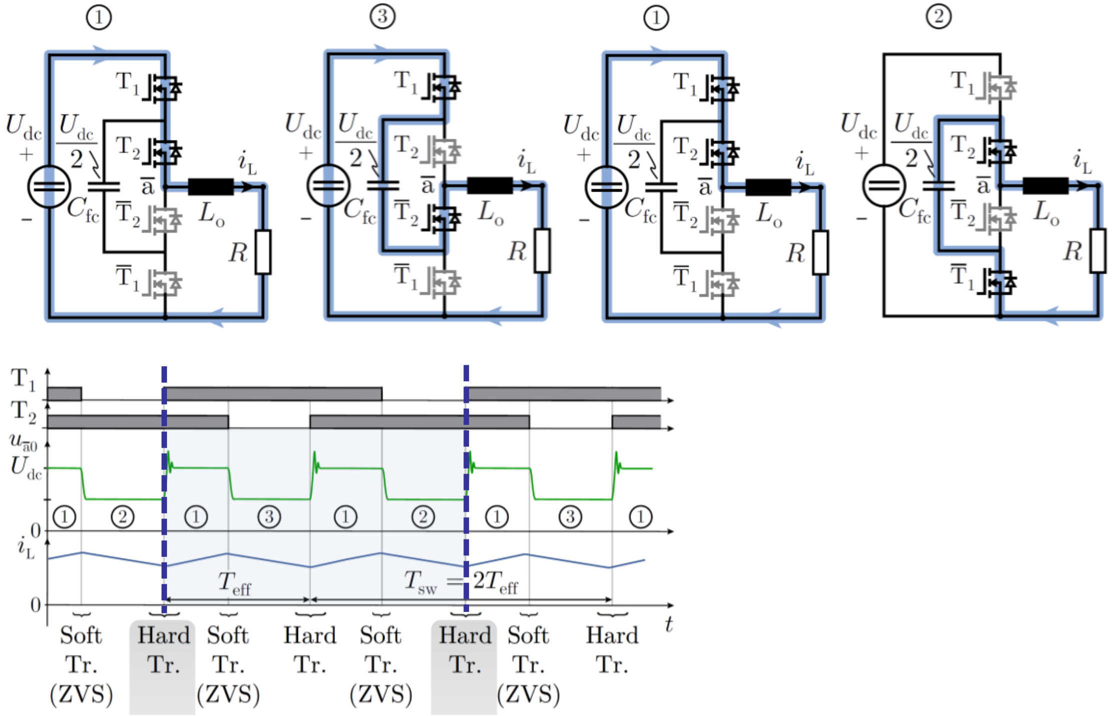
- *Factor 4 (!) Reduction of Chip Area vs. Discrete Realization*

Flying Cap. (FC) 3-Level Converter

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



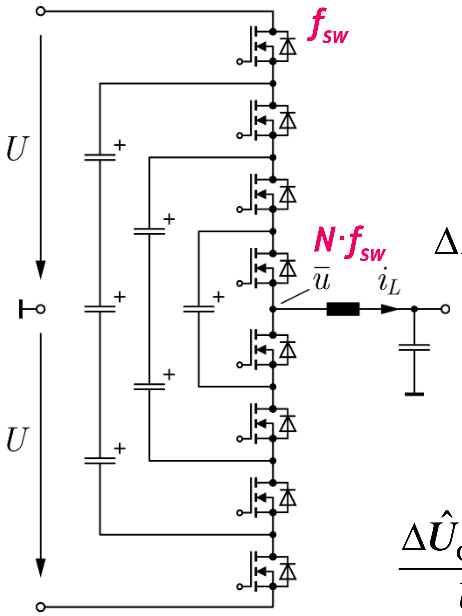




- *FC Voltage Balancing Possible also for DC Output*

Scaling of Flying Cap. Multi-Level Concepts

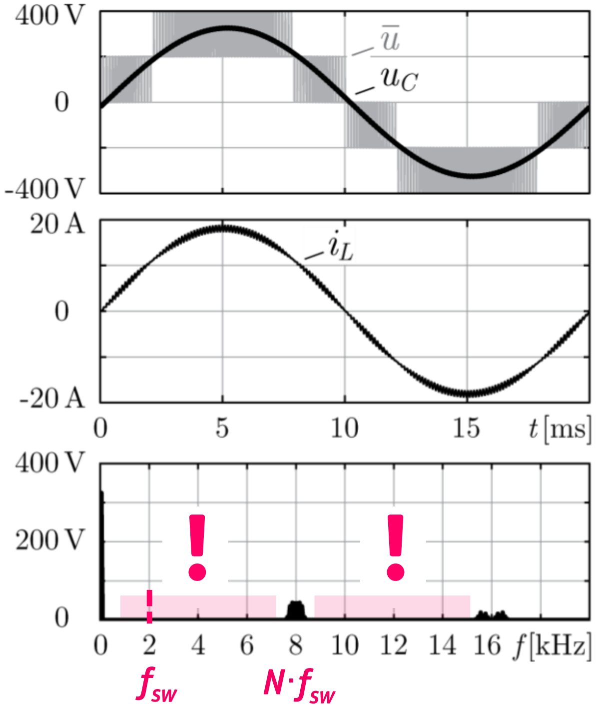
- *Series Interleaving → Reduced Ripple*
- *$f_{sw,eff} = N \cdot f_{sw}$ @ f_{sw}-Determined (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage*
- *Application of LV Technology to HV*



$$\Delta \hat{I}_{\max,N} = \frac{1}{N^2} \Delta \hat{I}_{\max,N=1}$$

$$\Delta \hat{I}_{\max,N=1} = \frac{U}{8 f_s L}$$

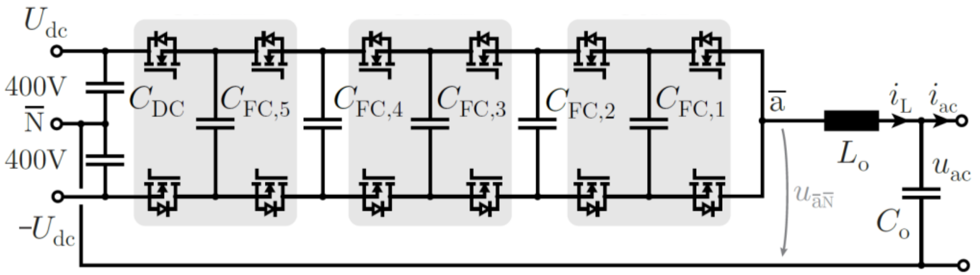
$$\frac{\Delta \hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32} \left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$

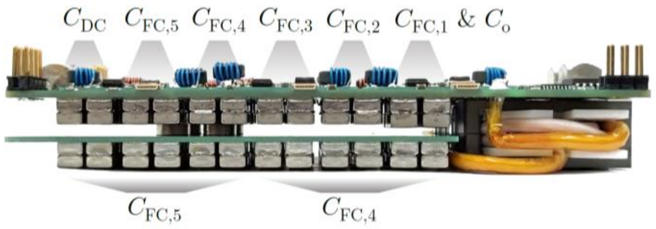


- *Scalability / Manufacturability / Standardization / Redundancy*

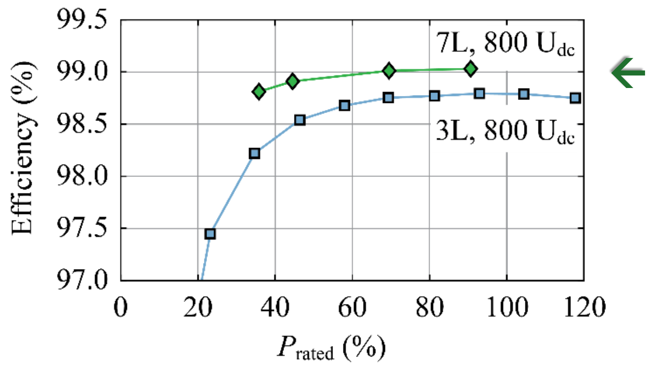
7-Level Flying Cap. 200V GaN Inverter

- *DC-Link Voltage* *800V*
- *Rated Power* *2.2 kW / Phase*
- *99% Efficiency → Natural Convection Cooling (!)*





★ *260 W/in³*



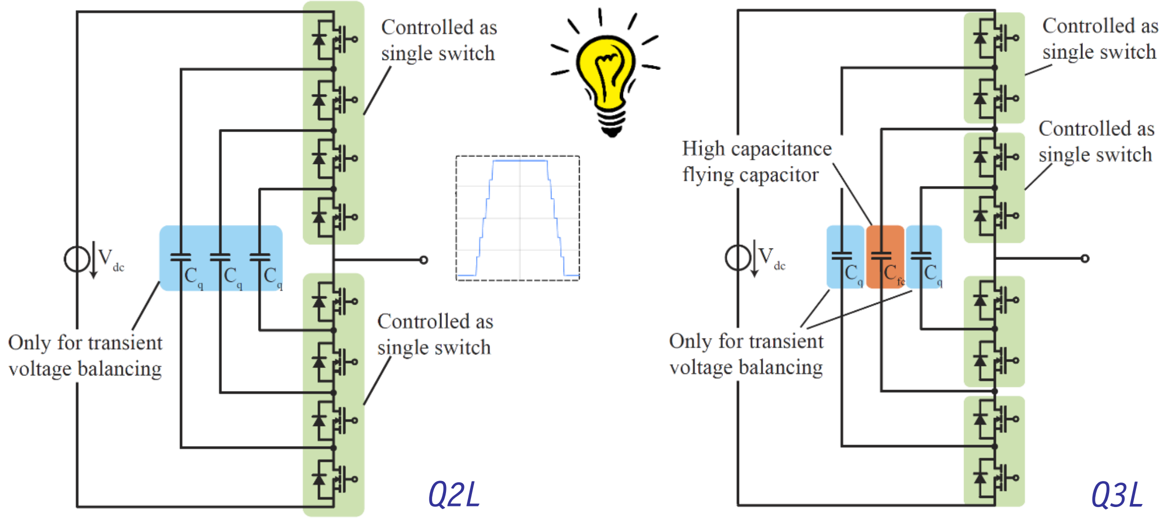
- *High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor L_0*

Quasi-2L & Quasi-3L Flying Cap. Inverters

- *Operation of N-Level Topology in 2-Level or 3-Level Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*

- Schweizer (2017)

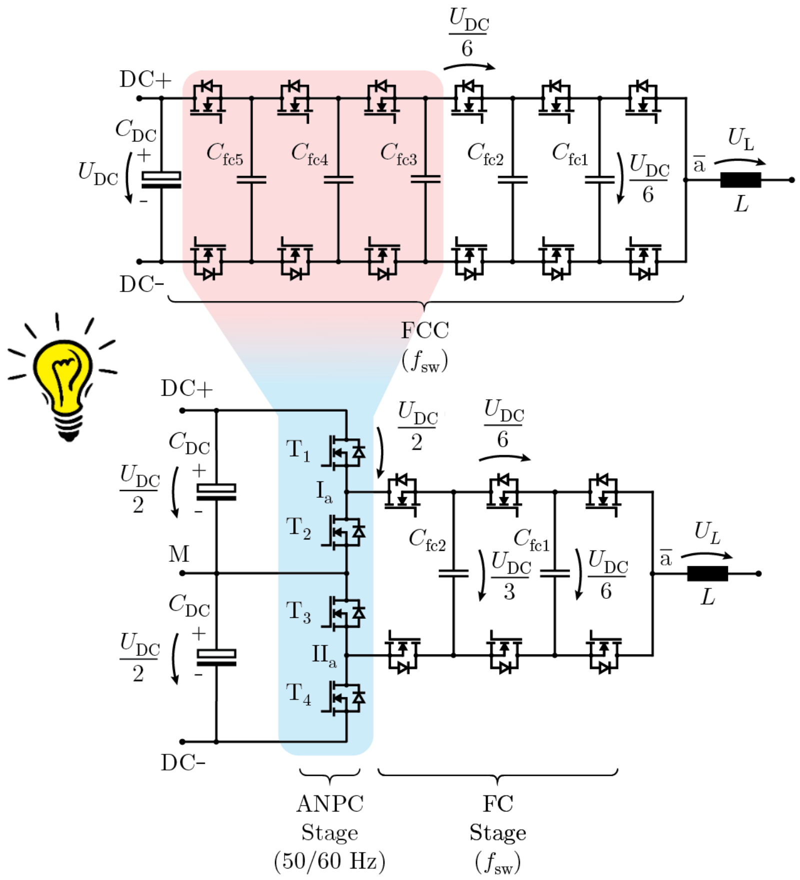
ABB

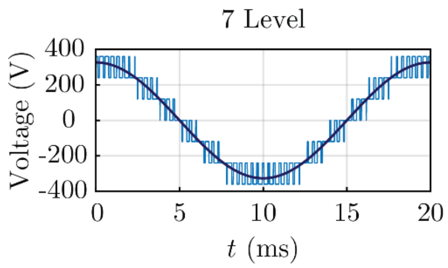


- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

3-Φ Hybrid 7-Level Inverter

- *Realization of a 99%++ Efficient 10kW 3-Φ 400V$_{rms,ll}$ Inverter System*
- *7-Level Hybrid Active NPC Topology / LV Si-Technology*





99.35%
2.6kW/kg
56 W/in³

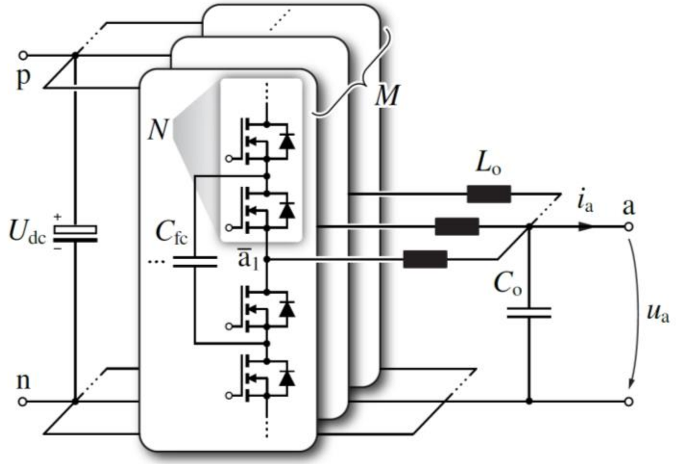
- *200V Si → 200V GaN Technology Results in 99.5% Efficiency*

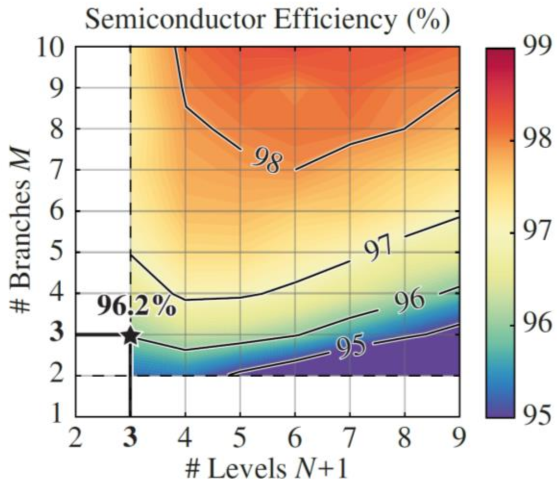
4.8MHz GaN Half-Bridge Module

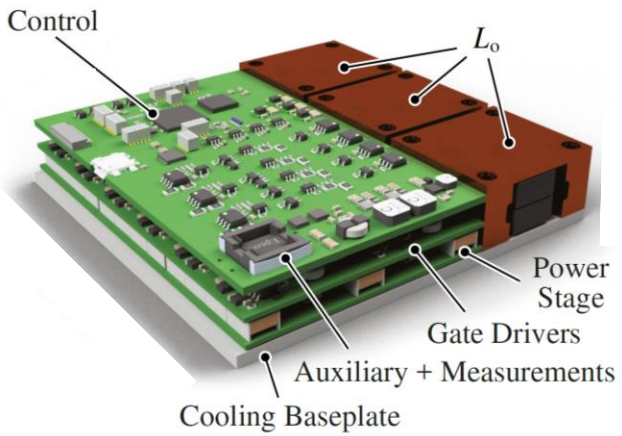
- Combination of Series & Parallel Interleaving

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

★ 820 W/in³



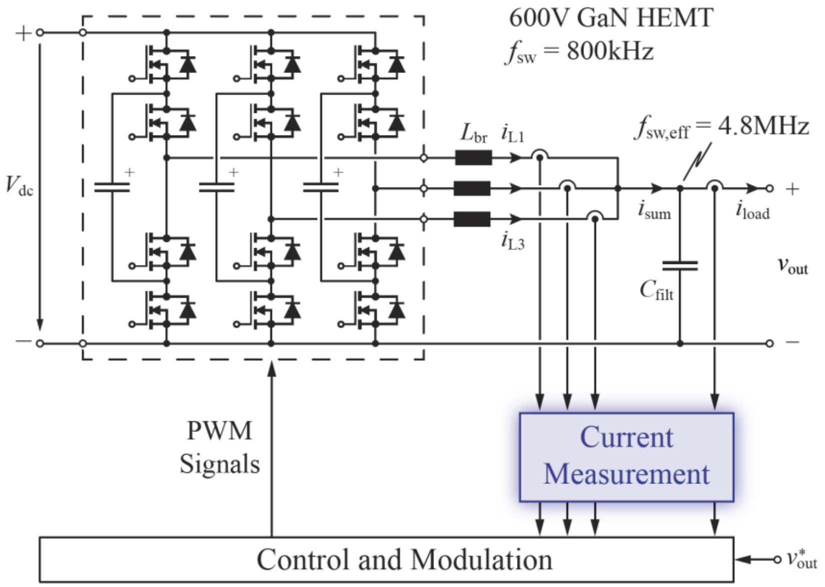


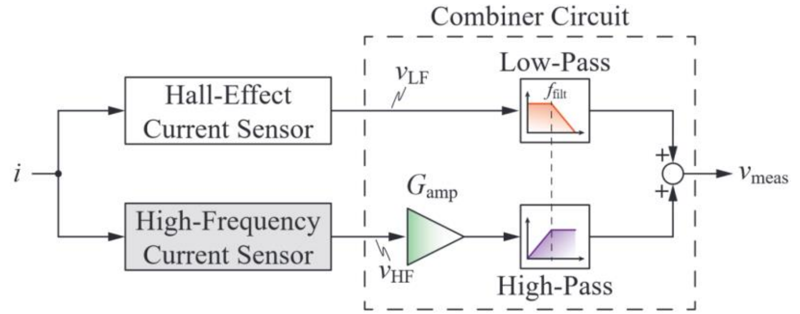


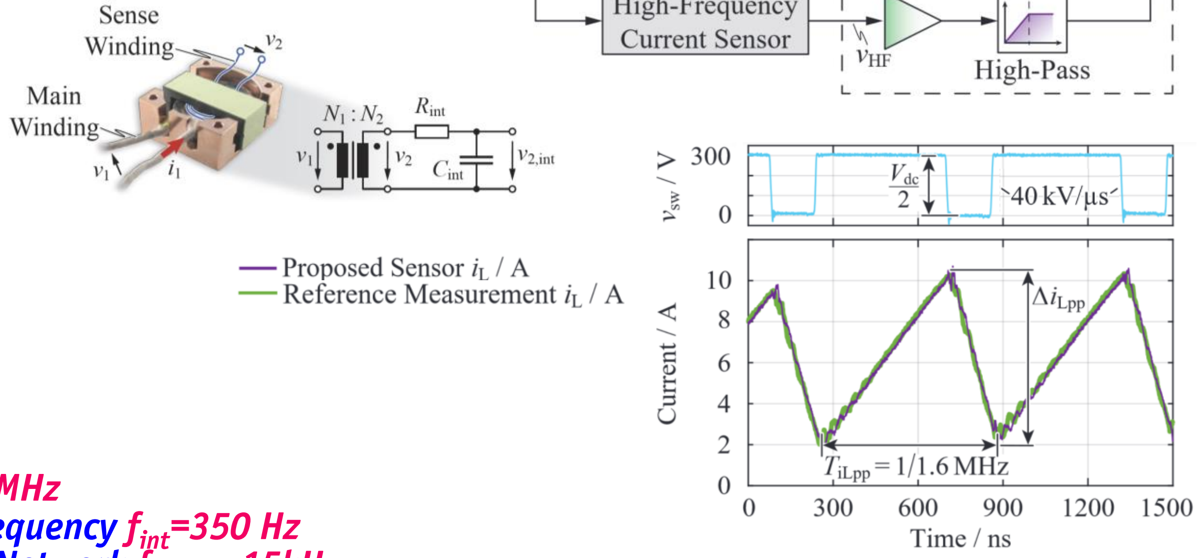
- Operation @ f_{out}=100kHz / $f_{S,eff}$= 4.8MHz, 10kW, U_{dc}=800V

Remark High-BW High-CMRR Current Measurement

- *Extension of Commercial Hall Sensor DC… f_{Hall}≈ 500kHz → DC… 10MHz*
- *Low-Pass & High-Pass Filter Network Combining HF-Sensor & LF Hall-Sensor*







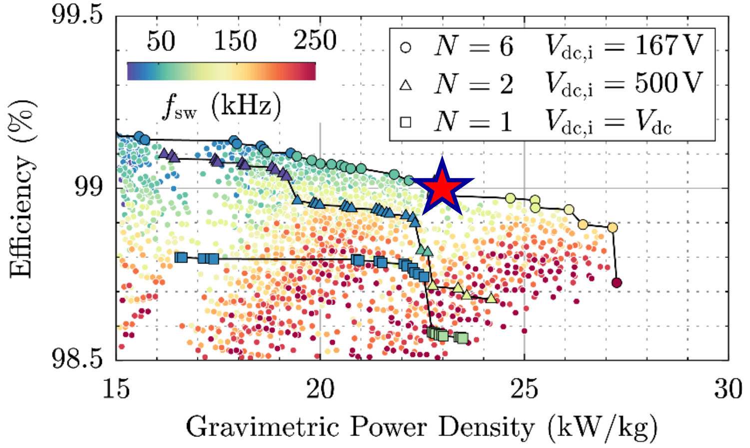
- *Hall Sensor Bandwidth f_{Hall} = 1.4MHz*
- *Sense Wdg. Integrator Corner Frequency f_{int}=350 Hz*
- *Low/High-Pass Filter Cross-Over Network f_{filter} = 15kHz*

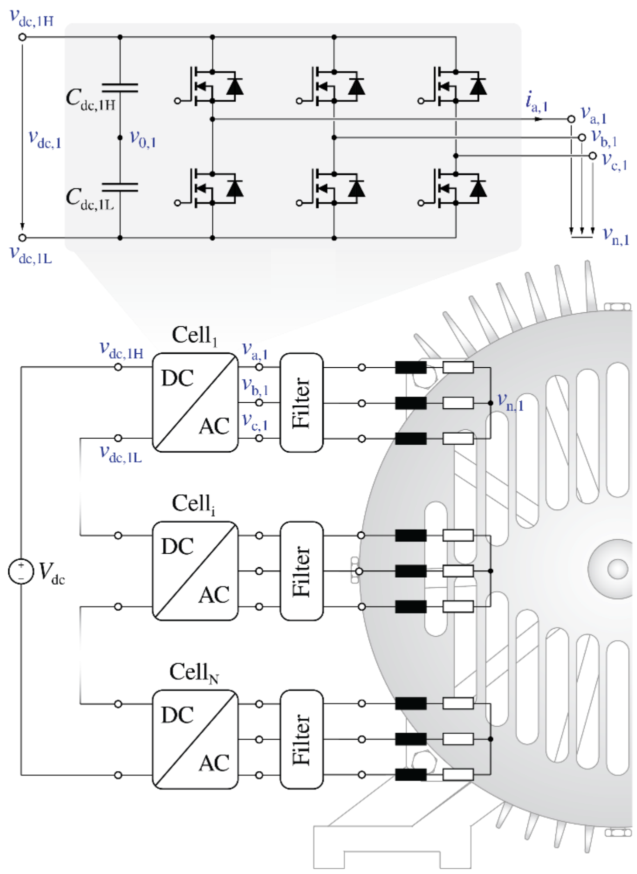
Motor-Integrated Inverter Systems

Stacked-Multi-Cell (SMC) Inverter

- *Fault-Tolerant VSD*
- *Low-Voltage Inverter Modules*
- *Very-High Efficiency / Power Density*
- *Autom. Manufacturing of Inverter Stage*

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

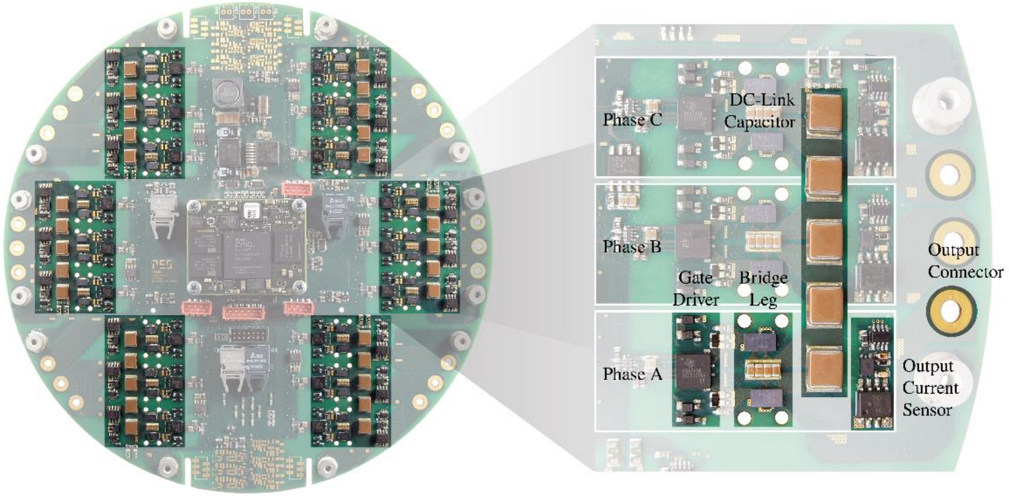


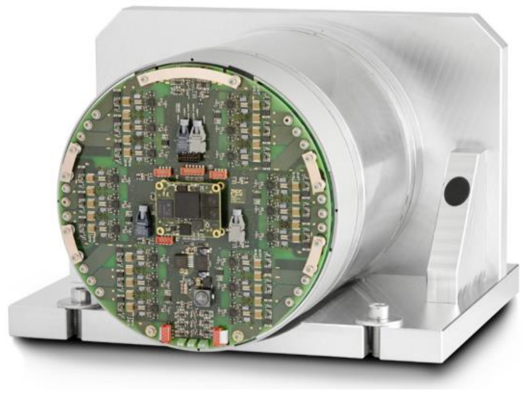


- *Smart Motor / Plug & Play* | *Connected / Intelligent VSD 4.0*

Motor-Integrated SMC-Inverter

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



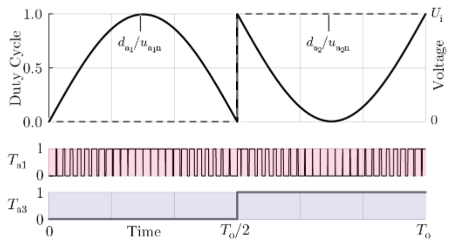


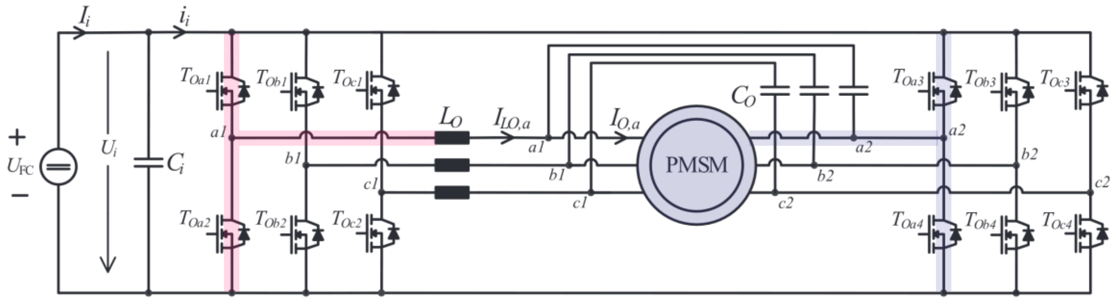
— Axial Stator Mount
— 200V GaN e-FETs
— Low-Capacitance DC-Links
— 45mm x 58mm / Cell

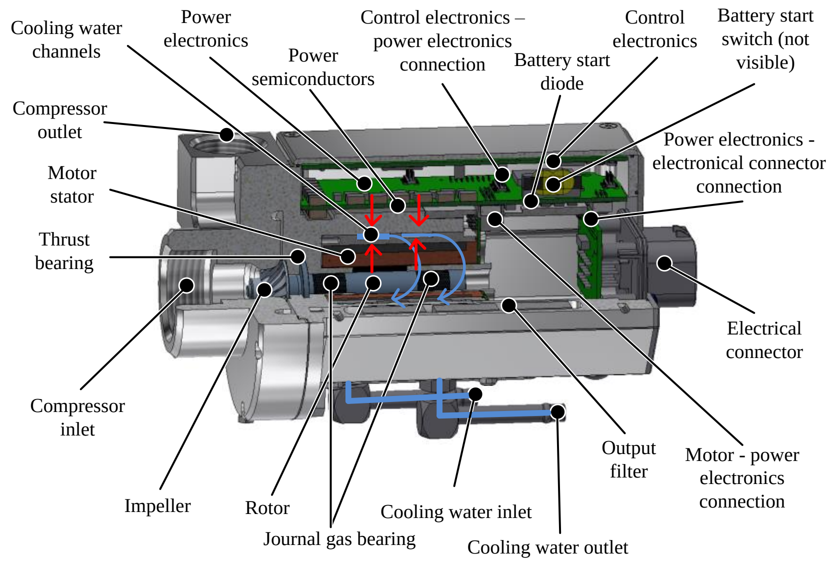
- Main Challenge — Thermal Coupling / Decoupling of Motor & Inverter

Compressor-Integrated DB GaN-Inverter

- *E-Mobility 5...15kW Fuel Cell Pressurized Air Supply*
- *1kW Rated Power, f_{sw}=300kHz | n= 280'000rpm / f_{out}= 4.6kHz*
- *Low EMI / Low Cabling Effort*





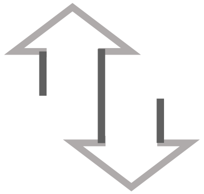


- *Integration → 2x System Power Density | 97% → 98.5% Inverter Efficiency*

#3


Source: www.clipart-library.com

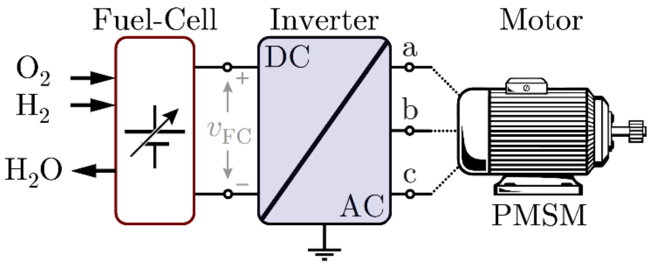
Buck-Boost Inverter

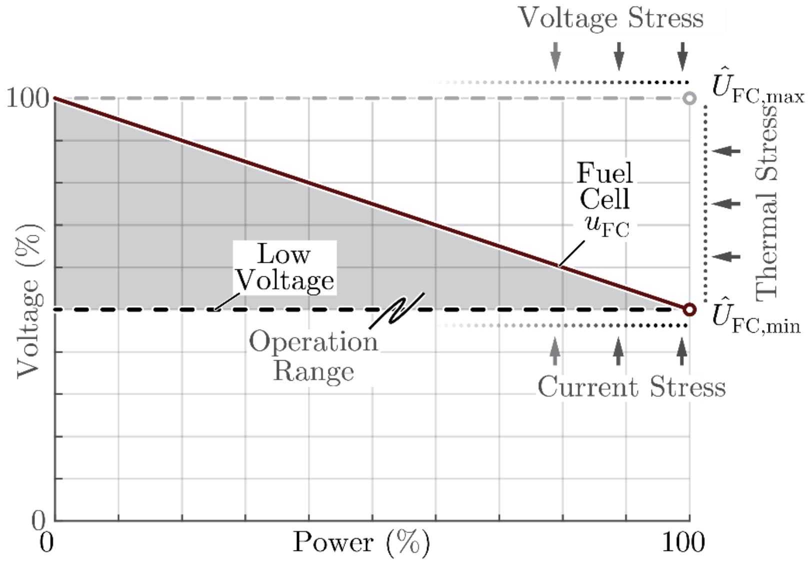


Motivation

- *General / Wide Applicability*

— *Adaption to Load-Dependent Battery | Fuel Cell Supply Voltage*
— *VSDs → Wide Output Voltage / Speed Range*

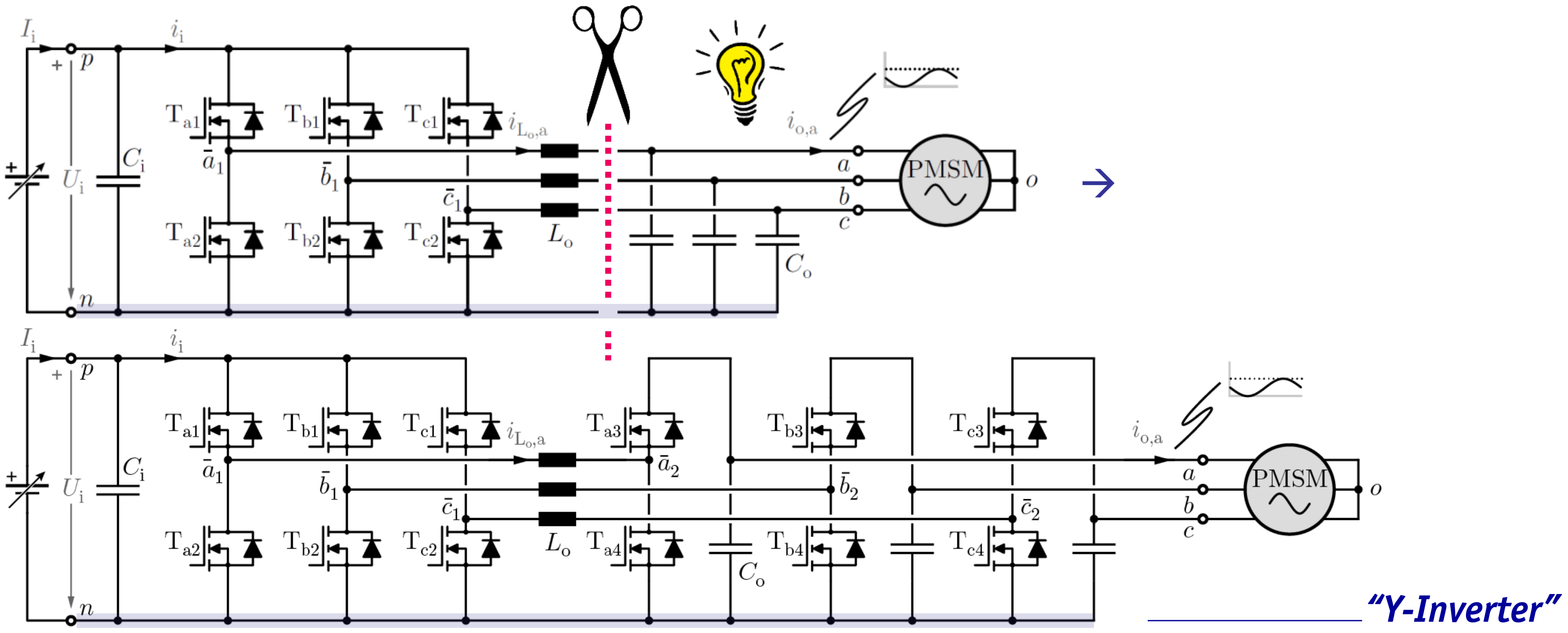




- *No Additional Converter for Voltage Adaption* → *Single-Stage Energy Conversion*

Example — Buck-Boost 3-Φ Inverter

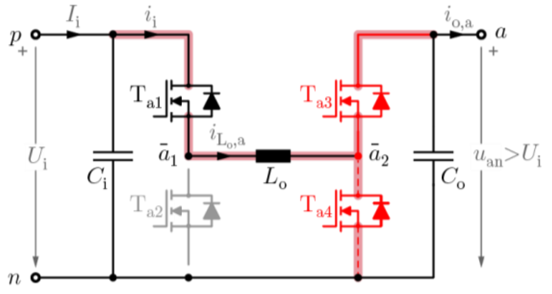
■ *Generation of AC-Voltages Using Unipolar Bridge-Legs*



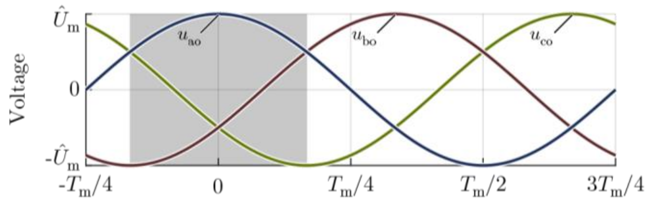
- *Switch-Mode Operation of Buck OR Boost Stage* → *Single-Stage Energy Conversion (!)*
- **3-Φ Continuous Sinusoidal Output / Low EMI** → *No Shielded Cables / No Motor Insul. Stress*

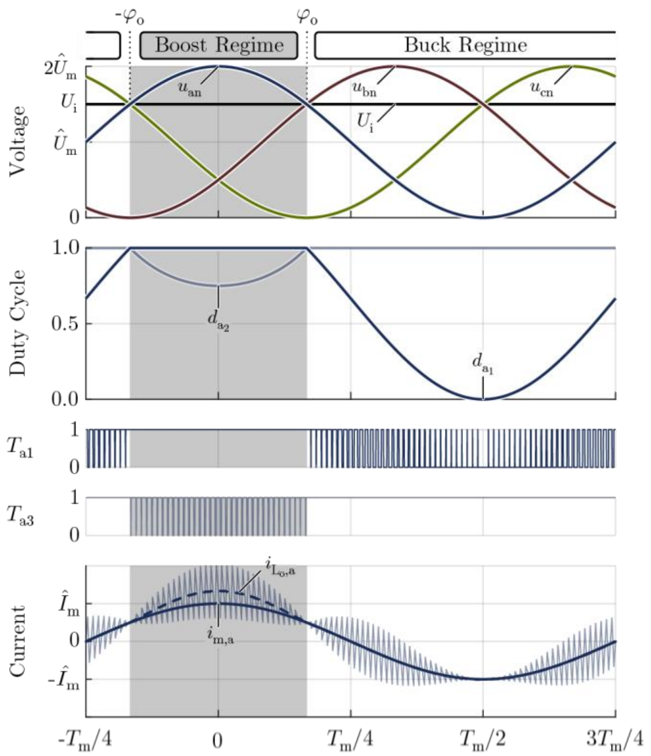
Boost-Operation $u_{an} > U_i$

- **Phase-Module**



- **Motor Phase Voltages**

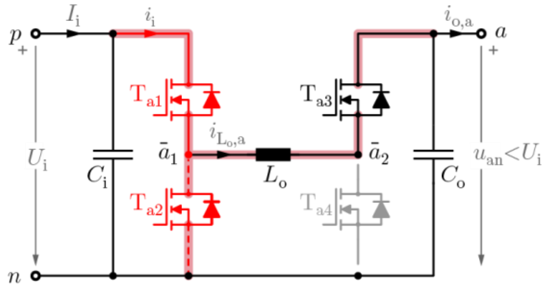




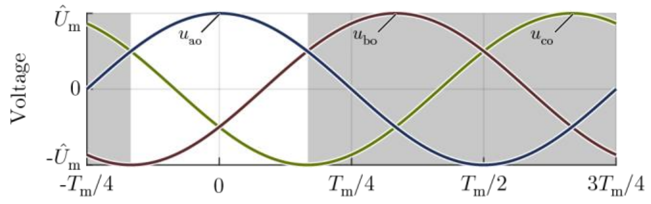
- *Current-Source-Type Operation*
- *Clamping of Buck-Bridge-Leg High-Side Switch → Quasi Single-Stage Energy Conversion*

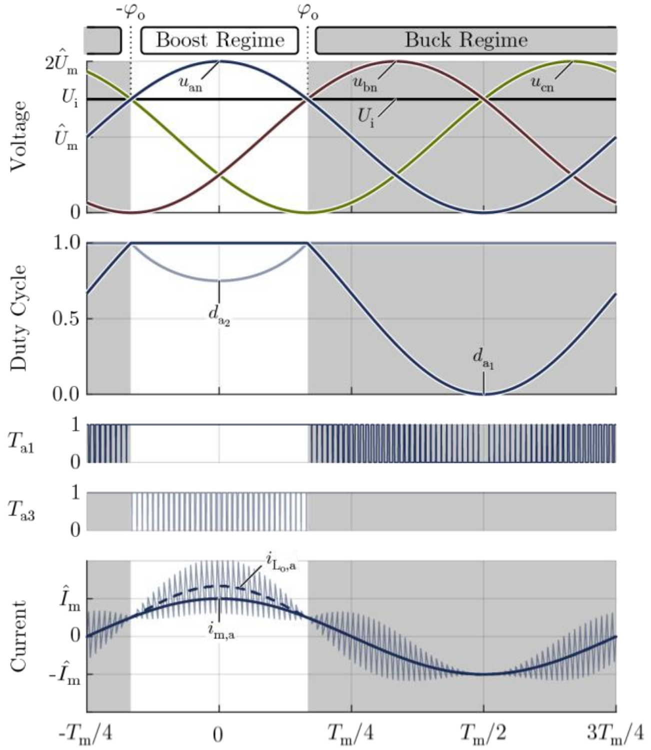
Buck-Operation $u_{an} < U_i$

- *Phase-Module*



- *Motor Phase Voltages*



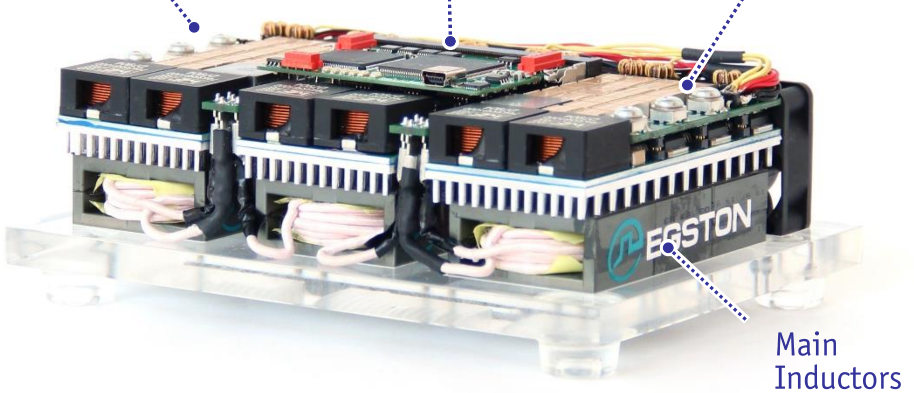


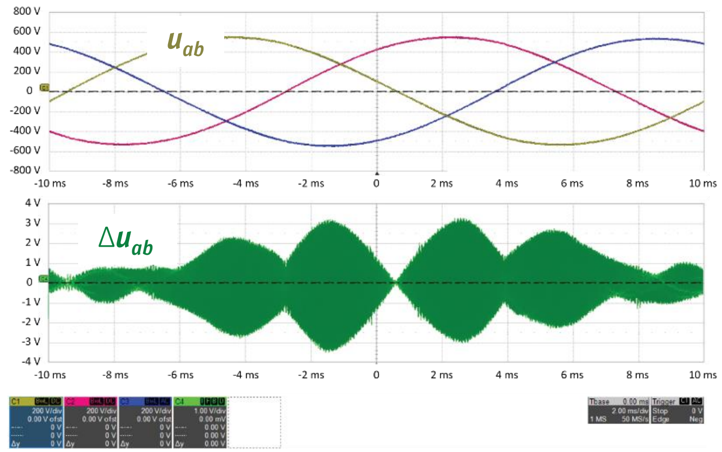
- *Voltage-Source-Type Operation*
- *Clamping of Boost-Bridge-Leg High-Side Switch → Quasi Single-Stage Energy Conversion*

3-Φ Buck-Boost Inverter Lighthouse Project

- Rated Power — 10 kVA
- DC Input Range — 400…750V_{DC}
- AC Output — 0…230V_{rms} (Phase), 0…500Hz
- 1200V SiC MOSFETs — 25mΩ | 100kHz

★ *245 W/in³*
98.3%





- No Shielded Motor Cables / Cond. & Radiated EMI Complient to IEC 61800-3

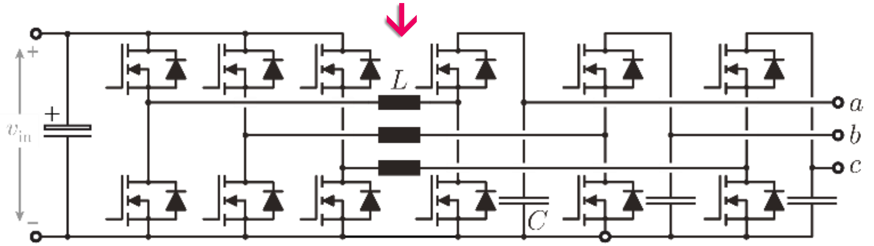
#4

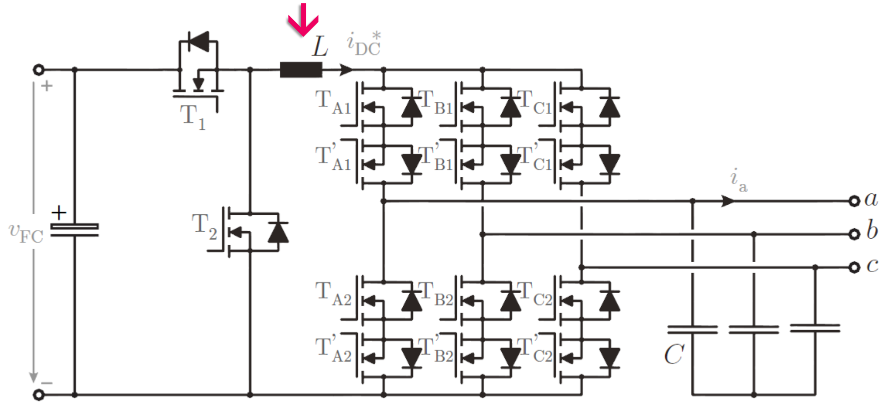
Source: www.clipart-library.com

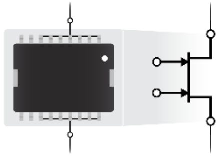
I-DC Link Inverters

3-Φ Current DC-Link Topologies

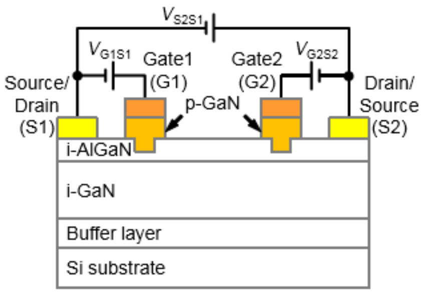
- *3-Φ Buck-Boost Inverter* → *Phase Modules w/ Buck-Stage | Current Link | Boost-Stage*
- *3-Φ Current DC-Link Inv.* → *Buck-Stage V-I-Converter | Current DC-Link DC/AC-Stage*







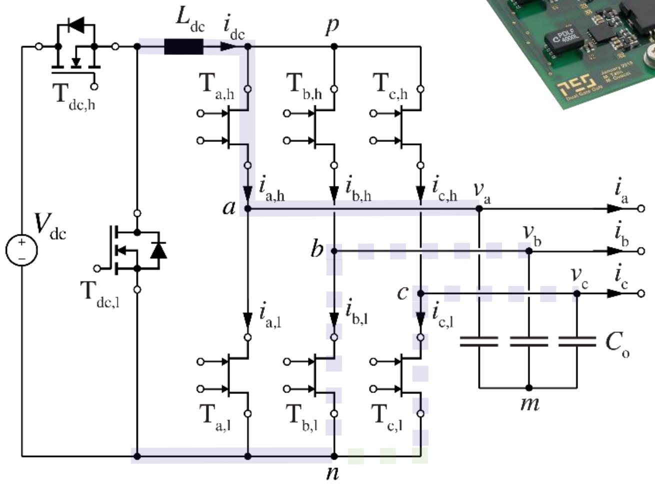
Source: Infineon, Panasonic ideas for life

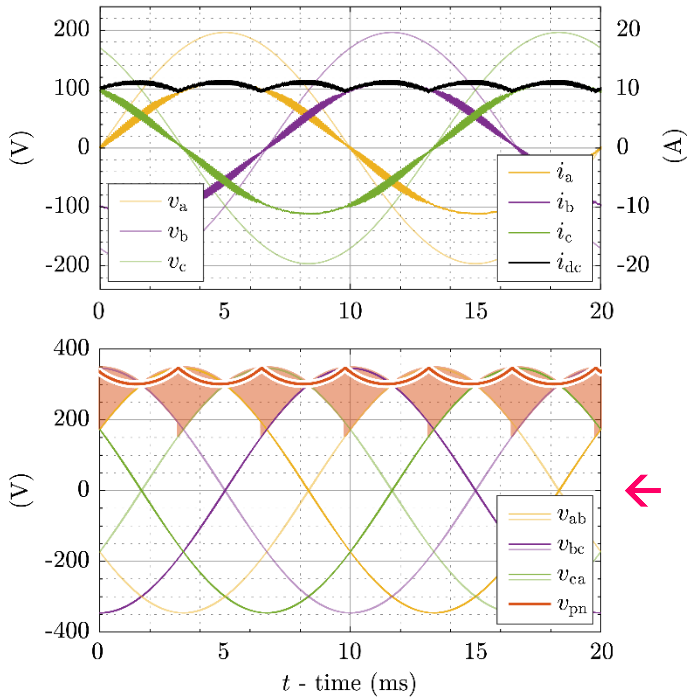


→ *Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches*

3-Φ-Integrated Buck-Boost CSI

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



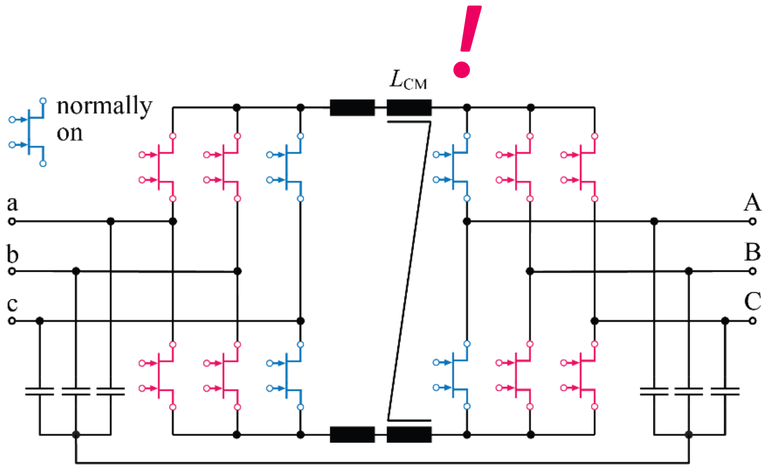


- *Switching of Only 2 of 3 Phase Legs → Reduction of Sw. Losses by ≈ 86% (!)*

3-Φ AC/AC Converter Topologies

■ *Current DC-Link Topology*

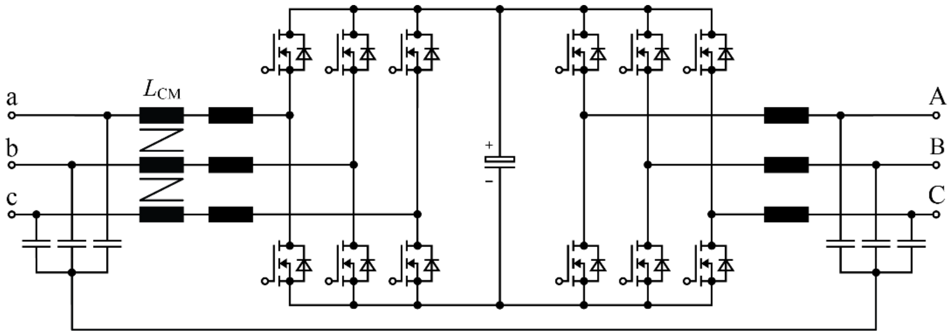
- *Application of M-BDSs*
- *Complex 4-Step Commutation*
- *Low Filter Volume*



- *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*

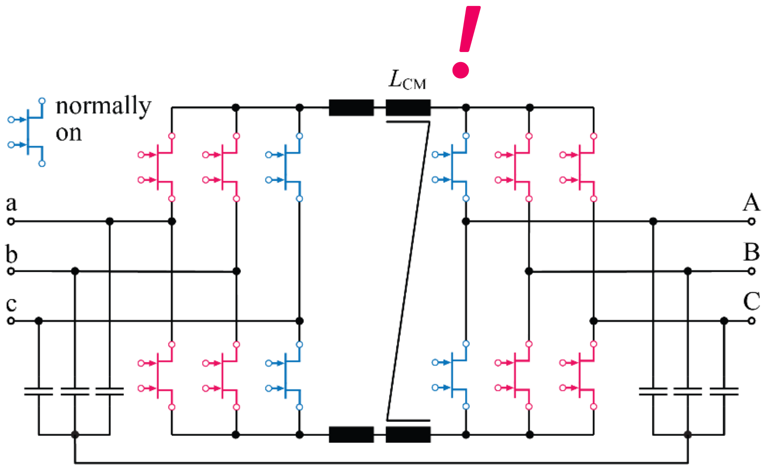


- *High Input / Output Filter Volume*

3-Φ AC/AC Converter Topologies

■ *Current DC-Link Topology*

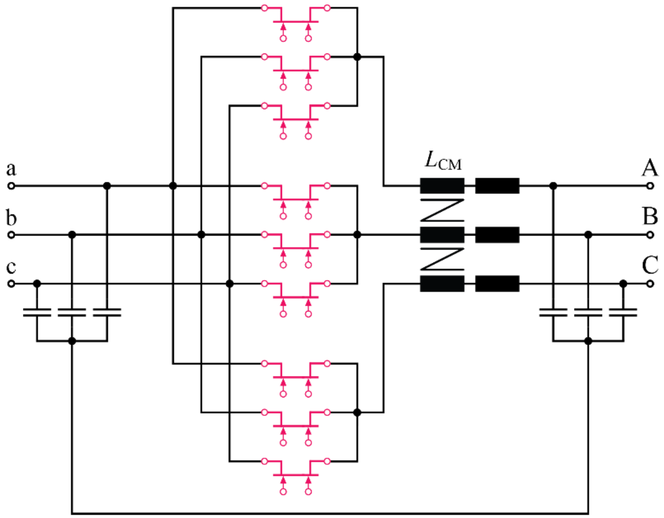
- *Application of M-BDSs | 12 Switches*
- *4-Step Commutation*
- *Buck-Boost Functionality*
- *Low Filter Volume*



- *Challenging Overvoltage Protection*

■ *Direct Matrix Converter*

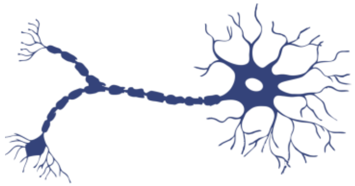
- *Application of M-BDSs | 9 Switches*
- *4-Step Commutation*
- *Complex Space Vector Modulation*
- *Limited to Buck-Operation (!)*



- *Challenging Overvoltage Protection*

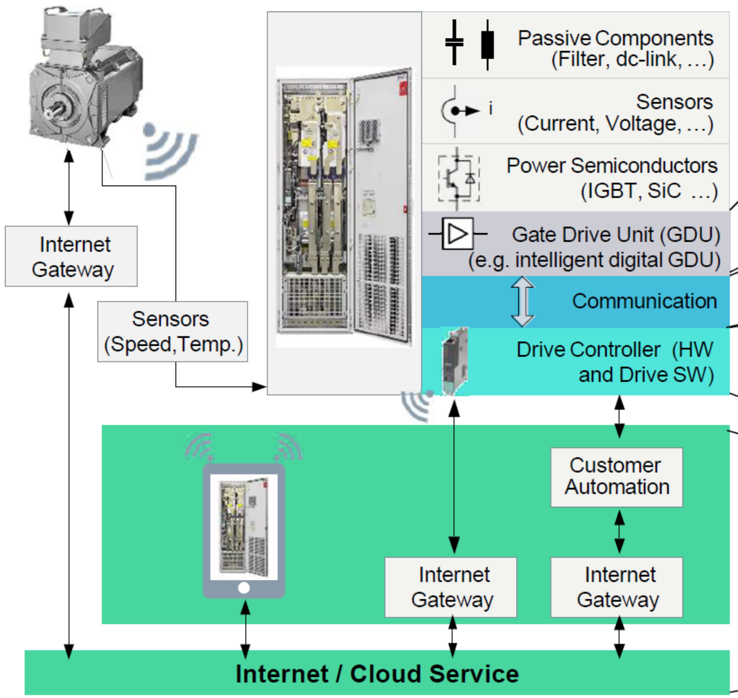
Conclusion

Smart Inverter Concept



- *Utilize High Computing Power & Network Effects in the Cloud → Cognitive Power Electronics*

Source: Dr. R. Sommer
SIEMENS



Intelligent Gate Drive Unit

- Semiconductor protection (overcurrent, overvoltage, …)
- Collecting and preprocessing of sensor data (current, voltage, temperature, …)
- Semiconductor specific condition monitoring functions

Communication

- Communication protocol instead of on/off signals

Drive Controller

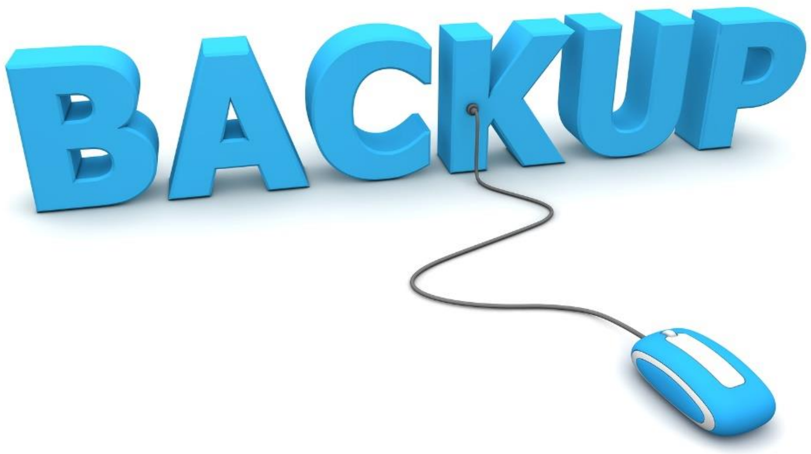
- Observer based condition monitoring functions
- Predictive maintenance functions
- Data Processing and data compression
- Communication to customer automation and/or internet

Internet / Cloud

- Service and commissioning tools
- Algorithms for „Big Data“ analysis
- Smart documentation (e.g. video to support service)
- …

- *Component Level | Converter Level | System Level | Application Level*

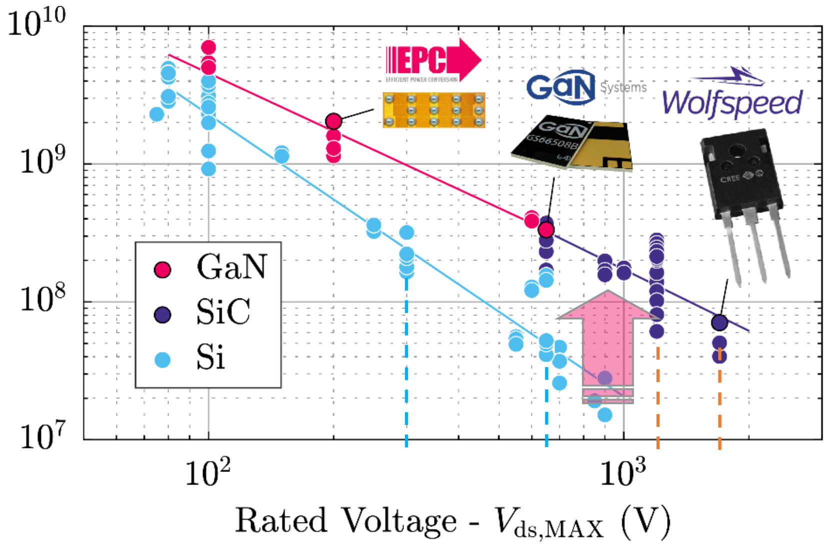
Thank you!


BACKUP

SiC/GaN Figure-of-Merit

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

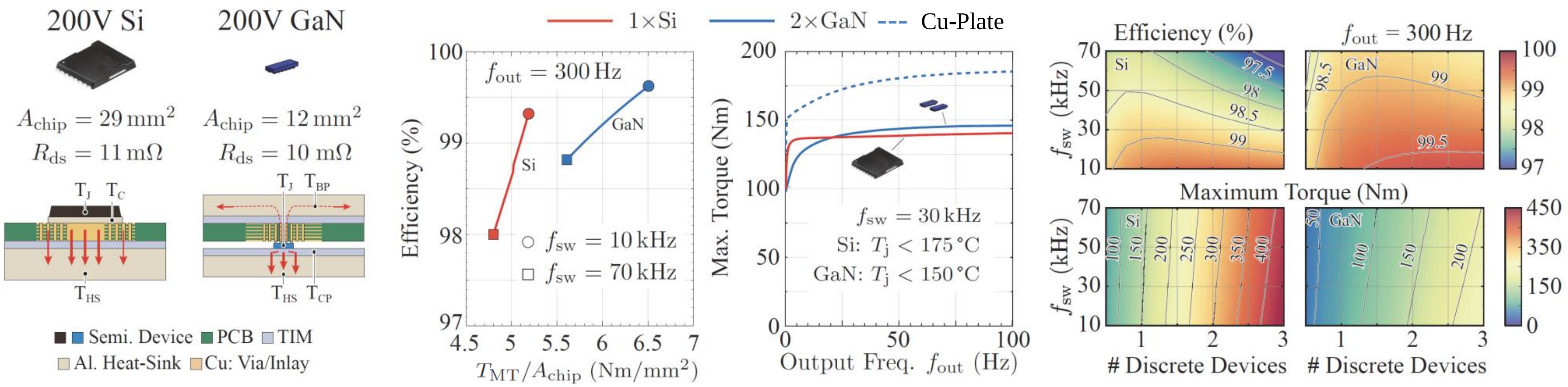
$$\text{FOM} = \frac{1}{R_{\text{ds,on}} Q_{\text{oss}}}$$



- *Advantage of Multi-Level over 2-Level Converter Topologies*

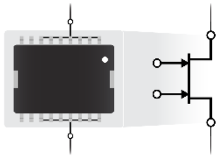
Remark GaN Overload Capability

- Highly Dynamic Robotics VSDs → 3x ... 5x Rated Torque for Seconds
- Smaller Chip Area → Lower Thermal Time Constant of GaN HEMTs
- Trade-Off Between Overload Rating & Rated Power Efficiency

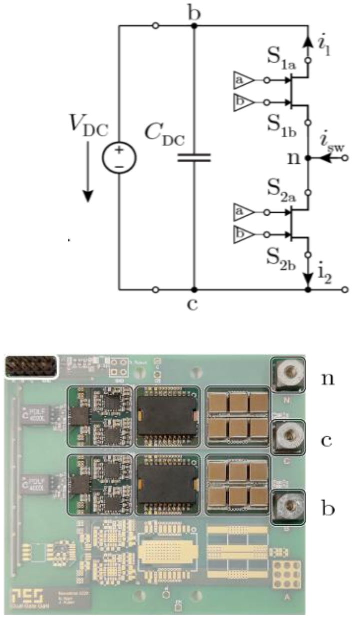


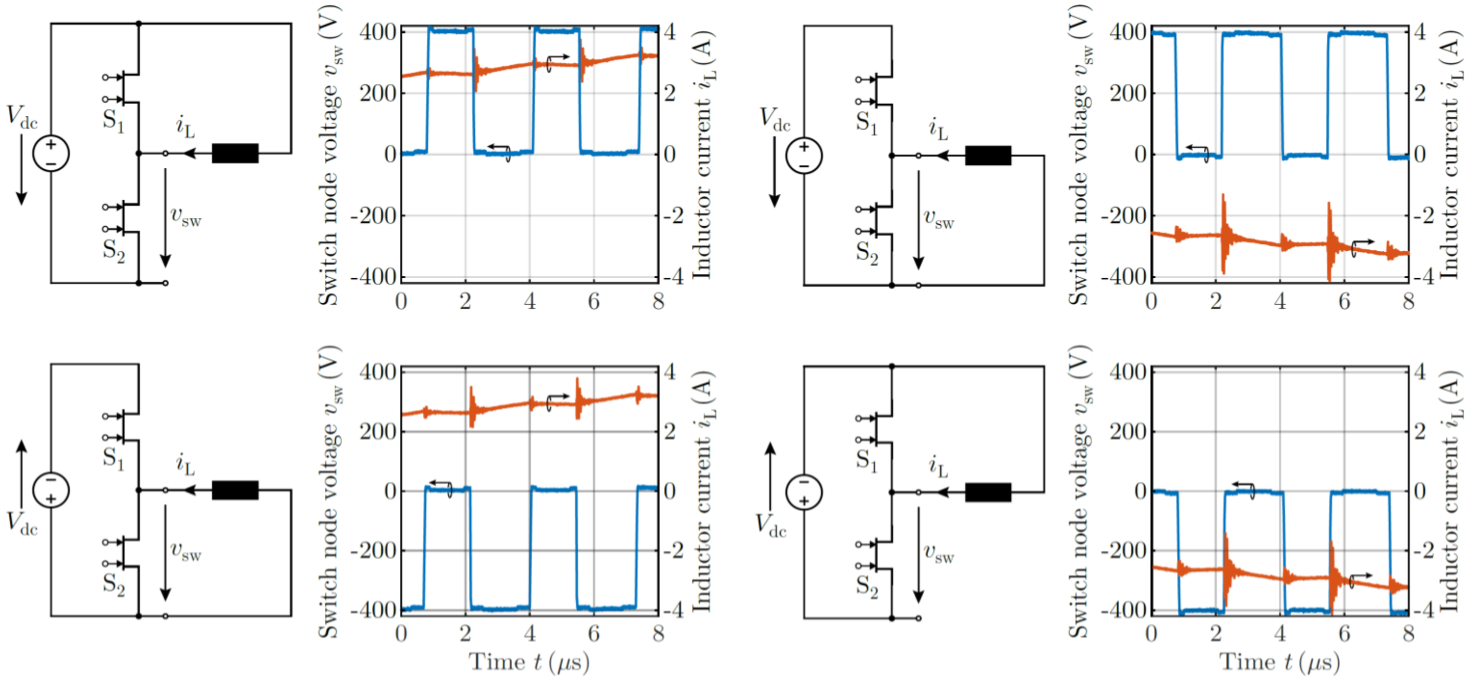
- 200V GaN vs. Si (Multi-Level Inverter) Comparison

600V GaN Monolithic Bidir. Switch



- *Power America Project — Based on Infineon's CoolGaN™ HEMT Technology ($R_{DS(on)}$= 70mΩ)* infineon
- *Dual-Gate Device / Controllability of Both Current Directions*
- *Bipolar Voltage Blocking Capability | Normally On or Off*



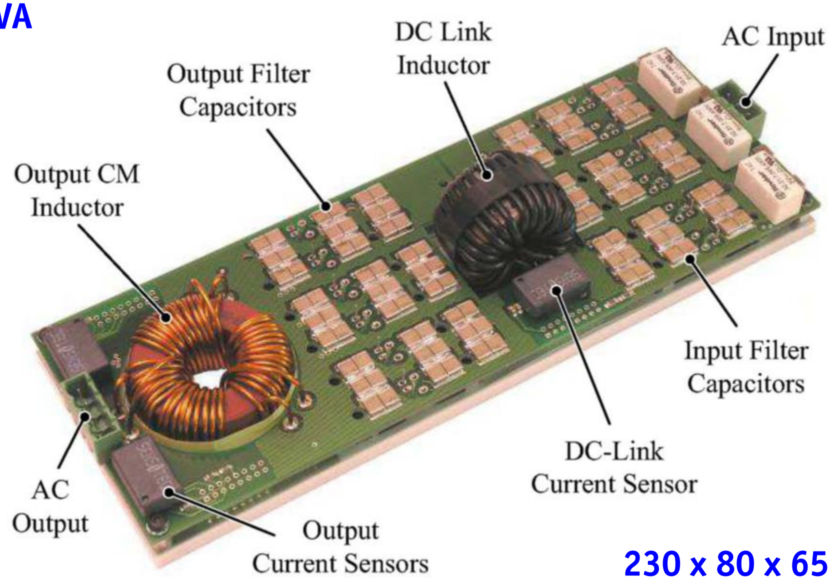


- *Analysis of 4-Quardant Operation of $R_{DS(on)}$= 140mΩ Sample @ ±400V*

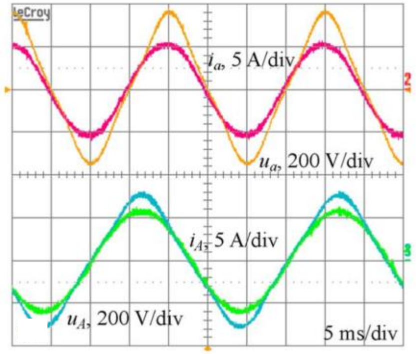
200kHz SiC Current DC-Link AC/AC Converter

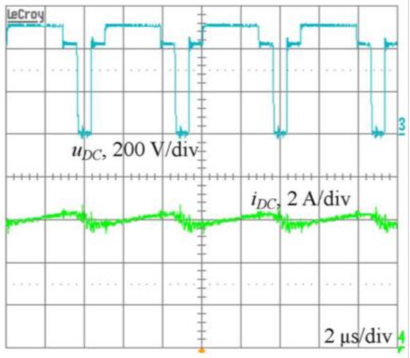
- *7kHz DC-Link Current Control Bandwidth*
- *PCB-Stack Construction — Power | Gate-Drive | Control Board*
- *Coldplate Cooling*

Input 400V_{rms} Line-to-Line
Output 0...300Hz
Rated Power 2.5 kVA
2.4 kVA / dm^3
(40 W/in^3)



230 x 80 x 65 mm^3



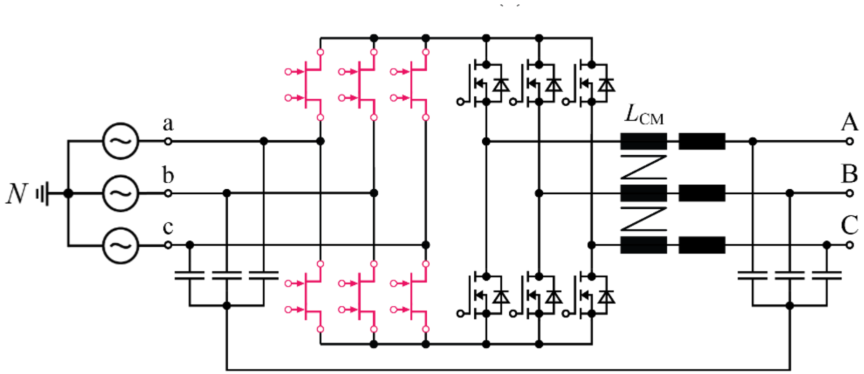


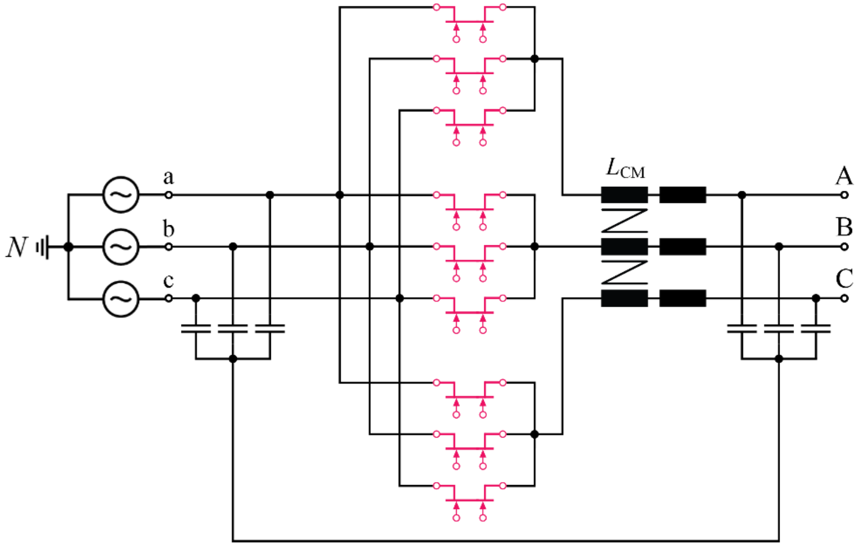
- *Low Volume Toroidal Powder Core DC-Link Inductor (320uH)*

Remark 3-Φ AC/AC Matrix Converter

- *Indirect Matrix Converter (IMC)*
  - CSI GaN M-BDS AC/DC Front-End
  - ZCS Commutation of CSI Stage @ i_{DC}=0
  - No 4-Step Commutation

- *Direct Matrix Converter (CMC)*
  - 4-Step Commutation
  - Exclusive Use of GaN M-BDSs





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

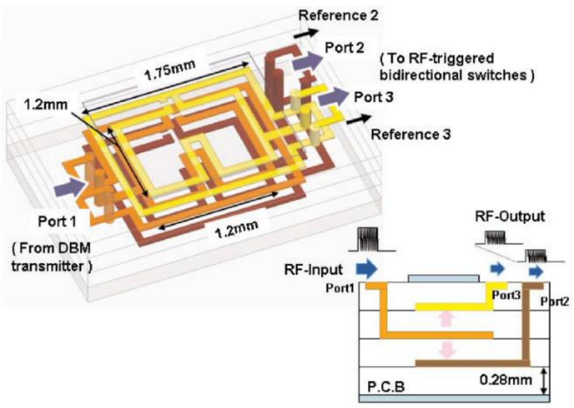
— Thermally Critical @ $f_{out} \approx f_{in}$

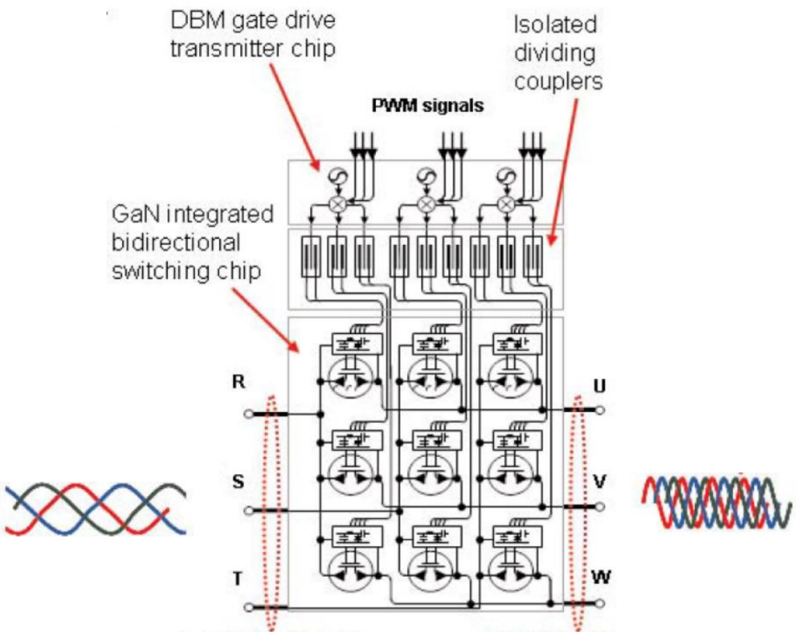
Monolithic 3D-Integration

Source: Panasonic ISSCC 2014

- *GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology*
  - *9 Dual-Gate GaN AC-Switches*
  - *DBM Gate Drive Transmitter Chip & Isolating Couplers*
  - *Ultra Compact → 25 x 18 mm² (600V, 10A – 5kW Motor)*

5.0GHz Isolated (5kVDC) Dividing Coupler

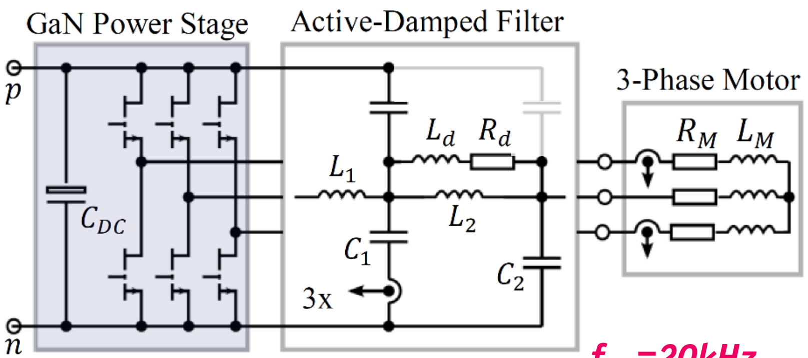




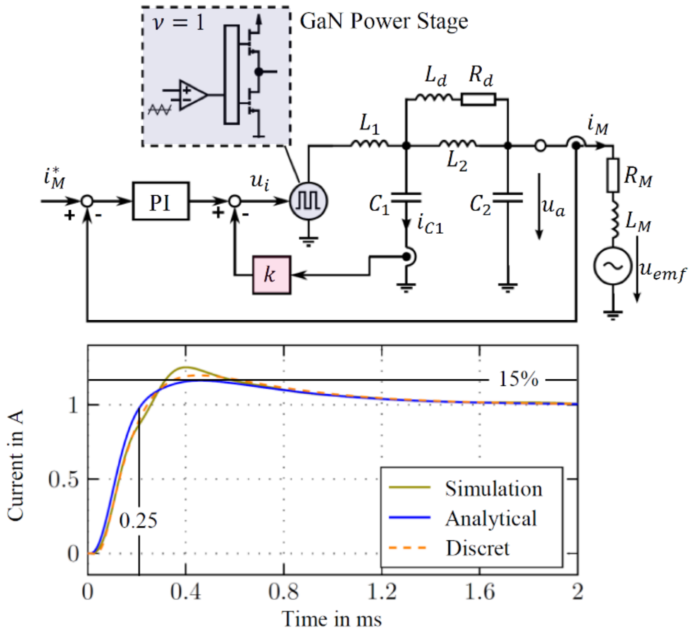
2-Stage Full-Sinewave Output Filter

- *2kW / 400V DC-Link 3-Φ 650V GaN Inverter (I_M=5A), $f_{out,max}$ = 500Hz*
- *Sinewave Output & IEC/EN 55011 Class-A*
- *Sw. Frequency f_S= 100kHz*

$f_{C,1}$=7kHz



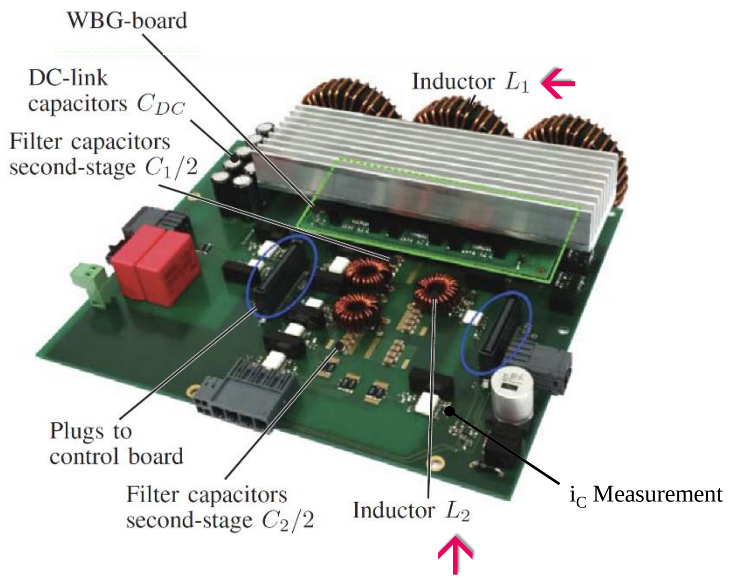
$f_{C,2}$=20kHz

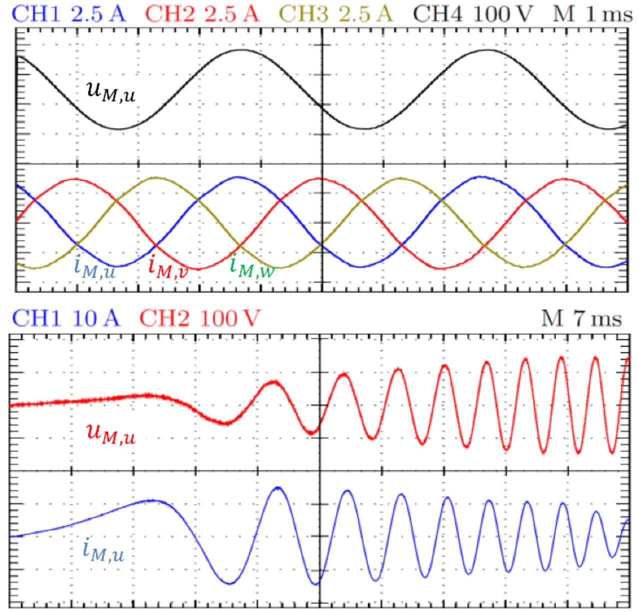


→ *Soft Saturation Toroidal Iron Powder Cores*
→ *Active & Passive Damping of the Filter Stages*

2-Stage Full-Sinewave Output Filter

- Exp. Verification — 650V E-Mode GaN Systems Transistors (50mΩ)
- Sw. Frequency f_S= 100kHz, Efficiency ≈98%
- 200mm x 250mm

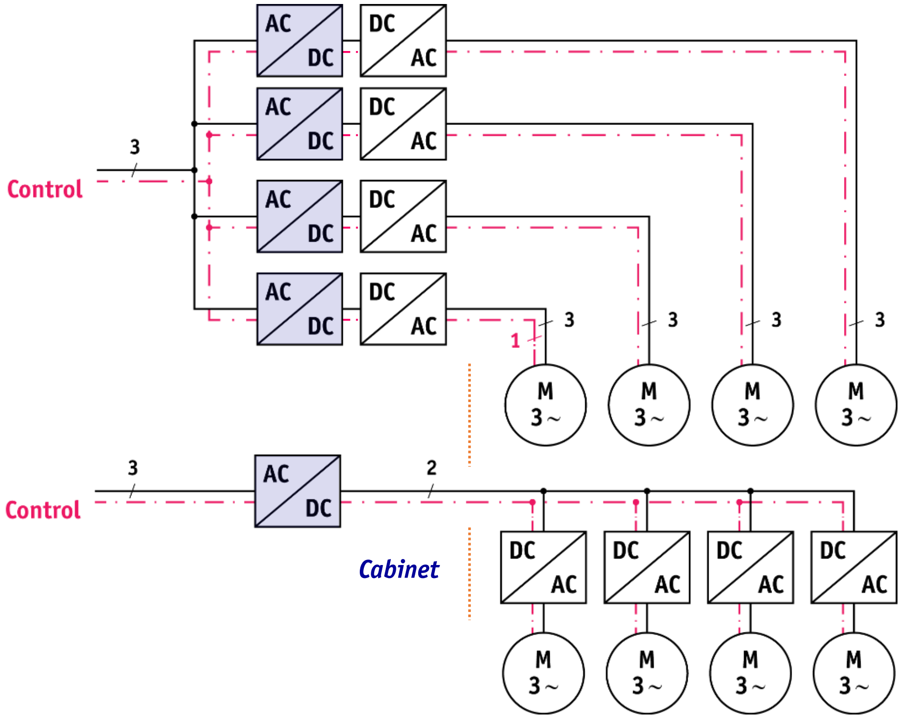


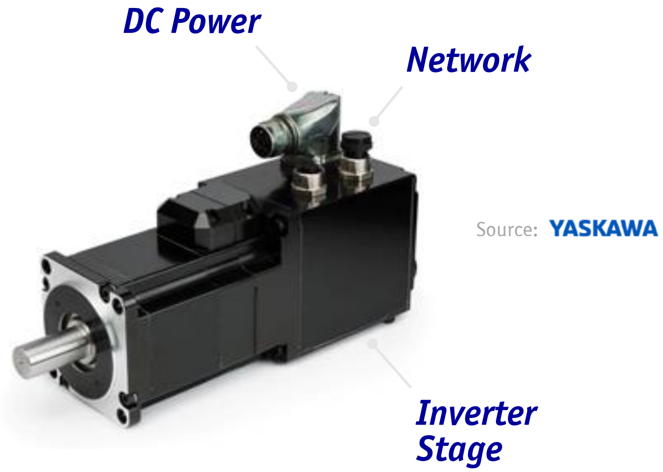


- Stationary Motor Phase Curr. /Voltage @ 2.5Nm & f_{out}=250Hz
- Speed Increase from Standstill to n = 3000rpm in 60ms

Multi-Axis Drive Systems

- *Common DC-Bus — Single AC/DC Converter / Smaller Cabinet*
- *Motor Integration of DC/AC Stage — Massive Saving in Cabling Effort / Simplified Installation*

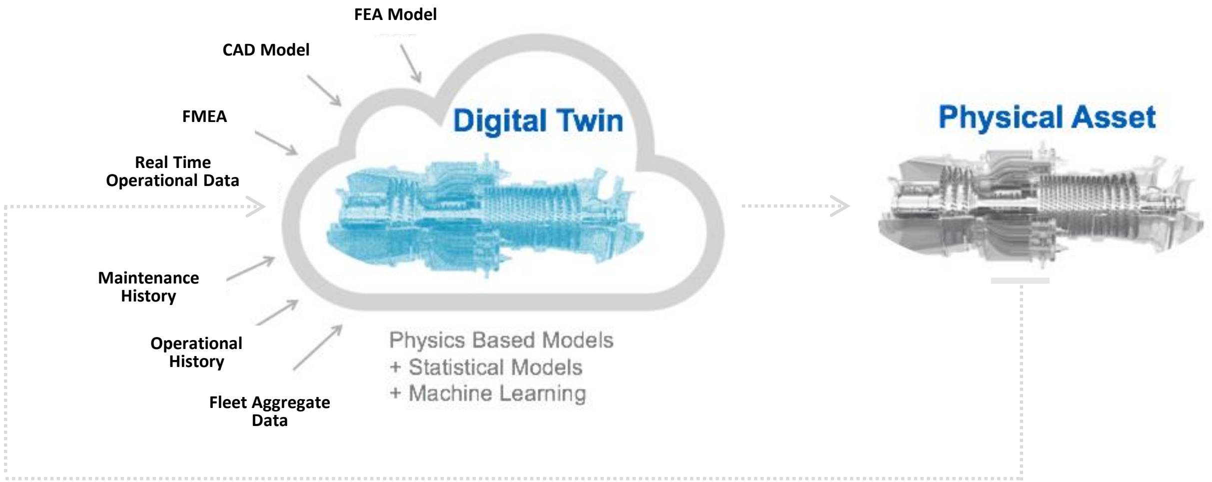




- *Facilitates DC-Bus Energy Buffer*
- *Direct Energy Exchange @ DC-Bus / Higher Efficiency / Unidir. Front-End*

IIoT in Power Electronics

- *Digital Twin → Physics-Based Digital Mirror Image*
- *Digital Thread → "Weaving" Real/Physical & Virtual World Together*



Source: www.railwayage.com

- *Requires Proper Interfaces for Models & Automated Design*
- *Model of System´s Past/Current/Future State → Design Corrections / Prev. Maintenance etc.*

End