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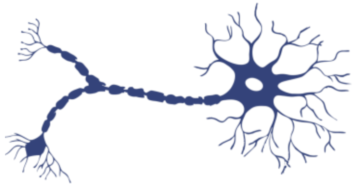

Future Power Electronics 4.0
3-Φ SiC/GaN Converter Systems

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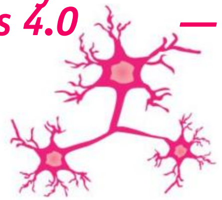
Outline

- ► *Introduction*

- ► *3-Φ PFC Rectifier Systems — Pt. I*
- ► *3-Φ VSD Inverter Systems — Pt. II*
- ► *Power Electronics 4.0 — Pt. III*



- ► *Conclusions*

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Part I

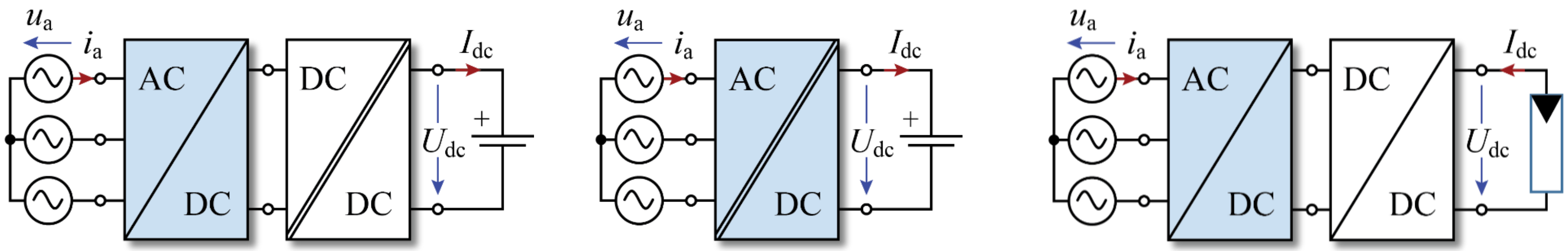
3-Φ PFC Rectifier Systems

3rd Harmonic Injection
Vienna Rectifier & Buck-Boost Topologies
Two-Stage & Single-Stage Isolated Concepts

Application Areas

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

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



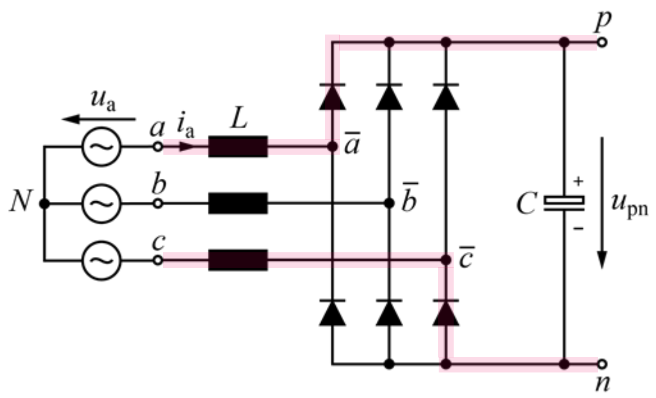
320...530 V_{rms} Line-to-Line

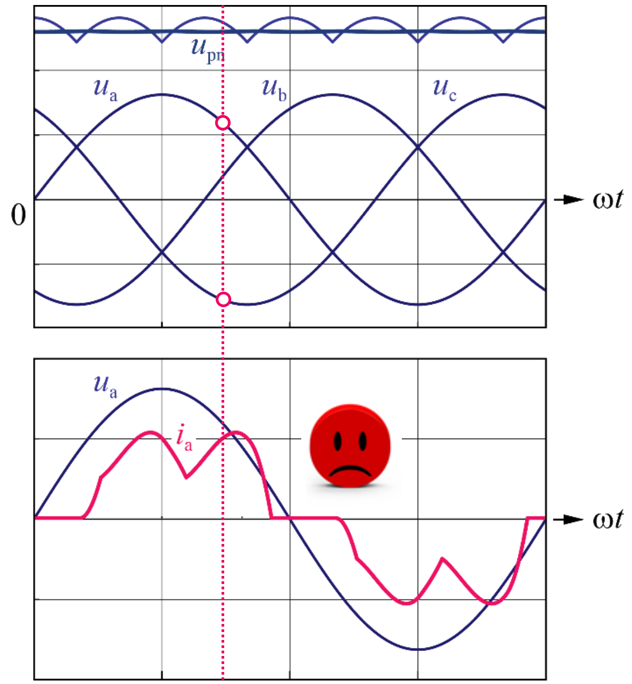
MPP Tracking in 60...90% of Max. Open Circuit Voltage

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

3-Φ Diode Bridge Rectifier

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



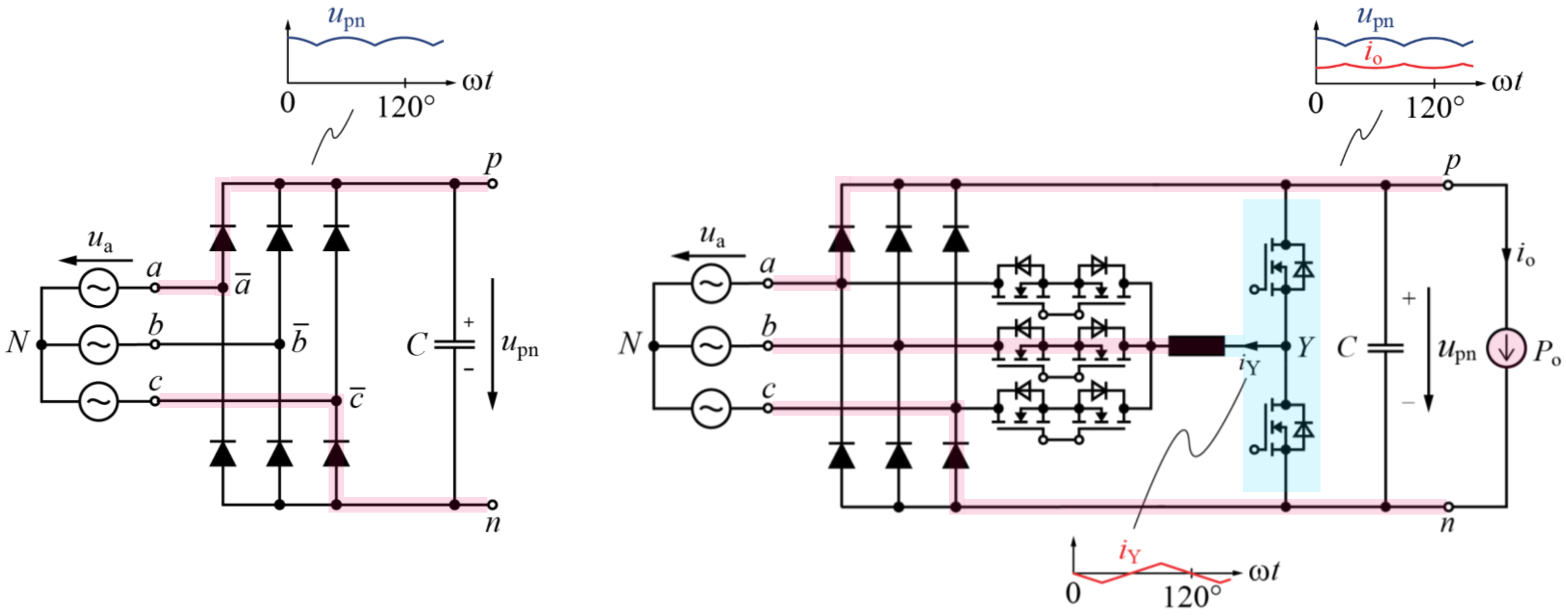


→ *Active Mains Current Shaping* / Simultaneous Current Flow in All Phases

3^{rd} Harmonic Current Injection

Integrated Active Filter (IAF) PFC Rectifier

- *3rd Harmonic Current Injection into Phase with Lowest Voltage*
- *Phase Selector AC Switches Operated @ Mains Frequency*

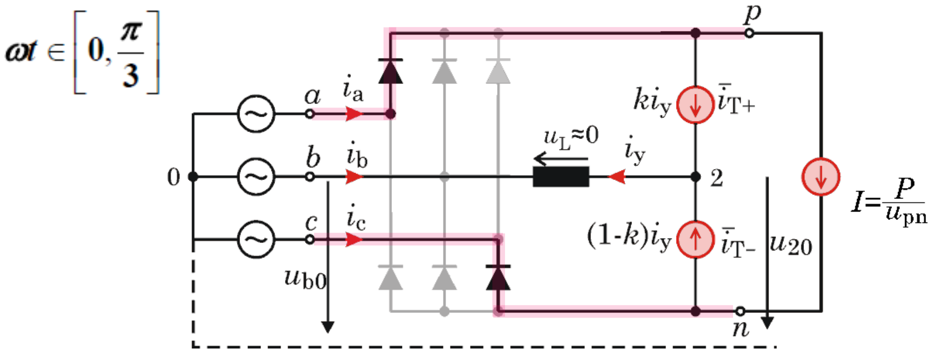


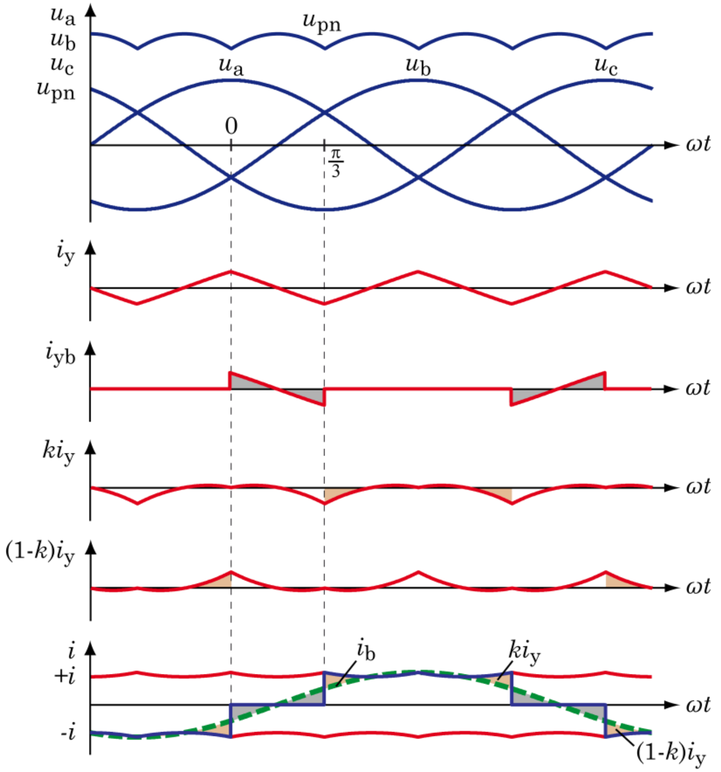
- *Non-Sinusoidal Mains Current*

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

IAF Rectifier (1)

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

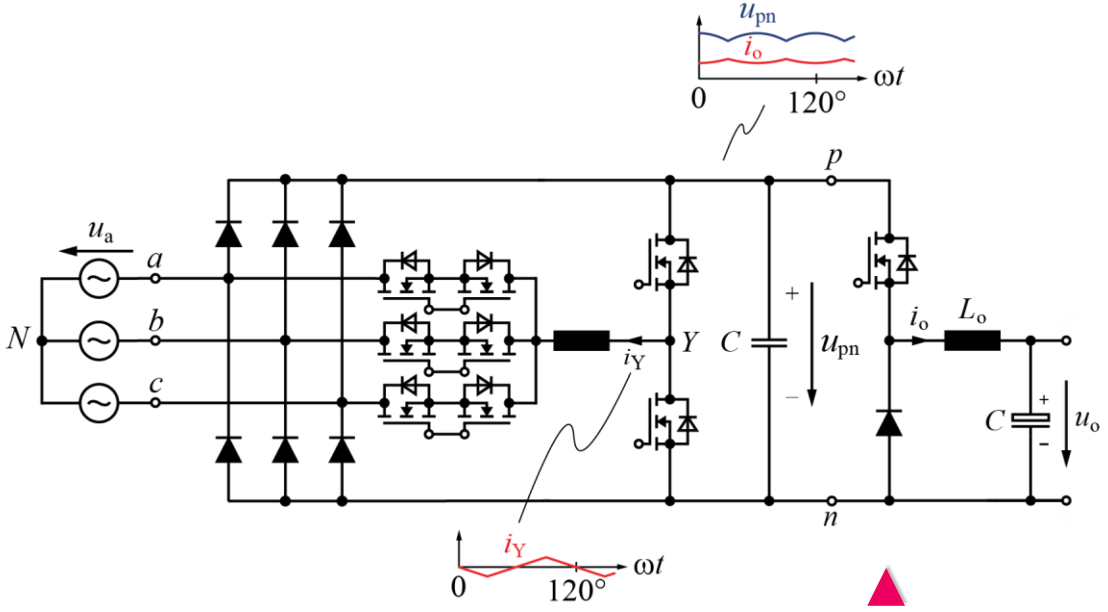




- Transistors T_+, T_- Could be Replaced by Passive Network

IAF Rectifier (2)

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

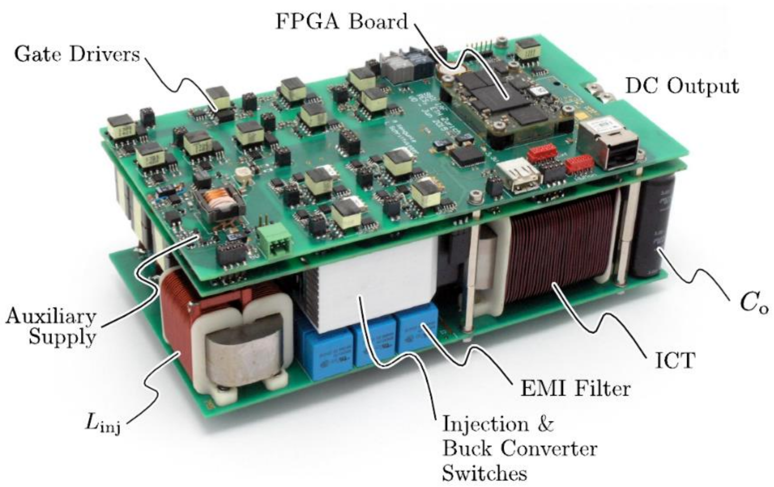


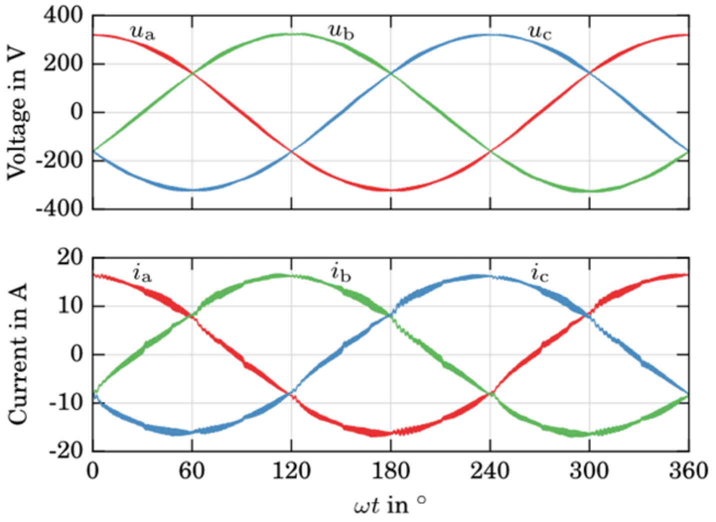
- *Buck-Stage Could be Replaced by Isolated DC/DC Conv. or Inverter*

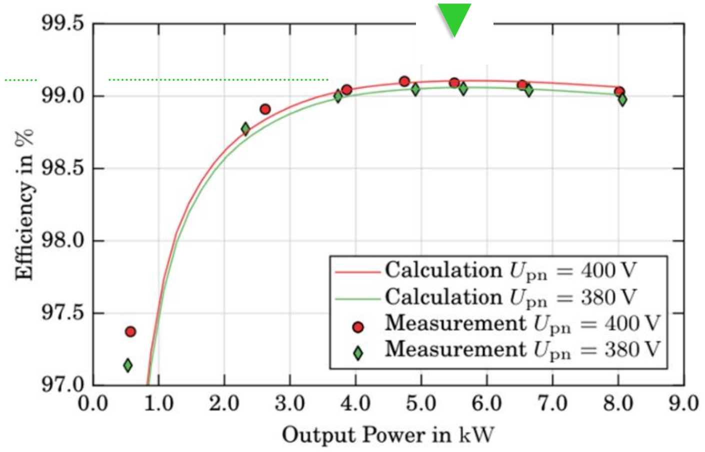
IAF Rectifier Demonstrator

- Efficiency η > 99.1% @ 60% Rated Load
- Mains Current THD_I ≈ 2% @ Rated Load
- Power Density ρ ≈ 65W/in^3

P_O= 8 kW
U_N= 400V$_{AC}$ → U_O= 400V$_{DC}$
f_S = 27kHz



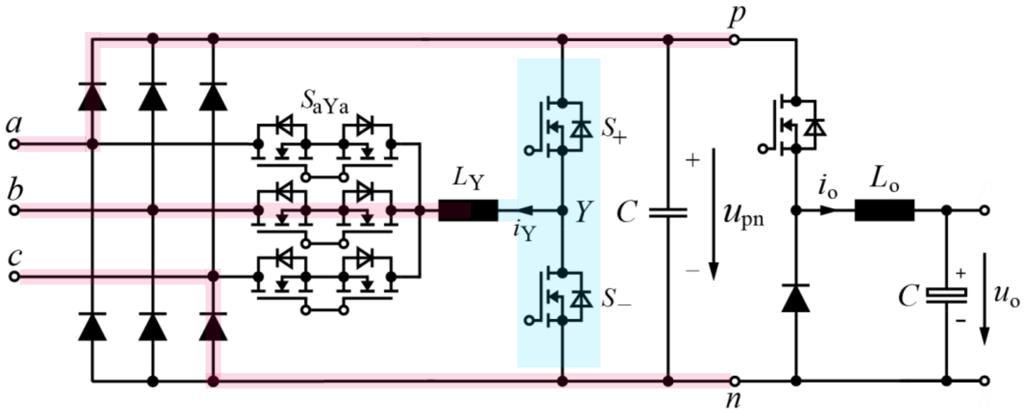


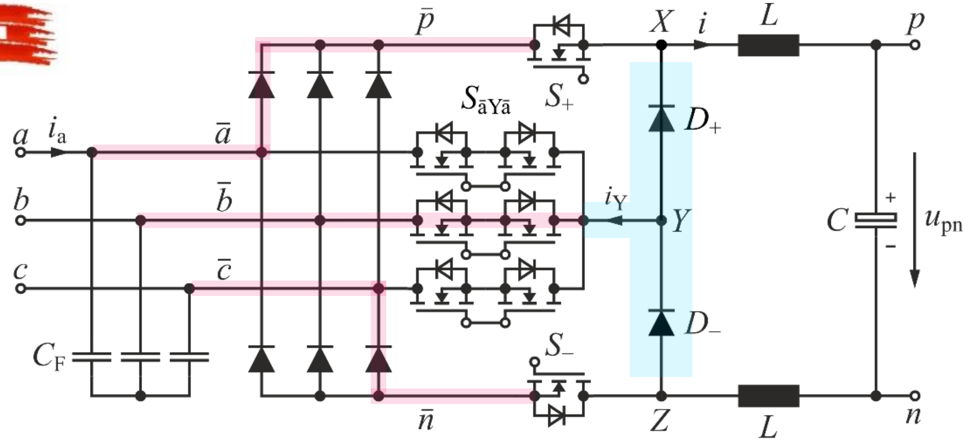


- SiC Power MOSFETs & Diodes
- 2 Interleaved Buck Output Stages

Swiss Rectifier

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



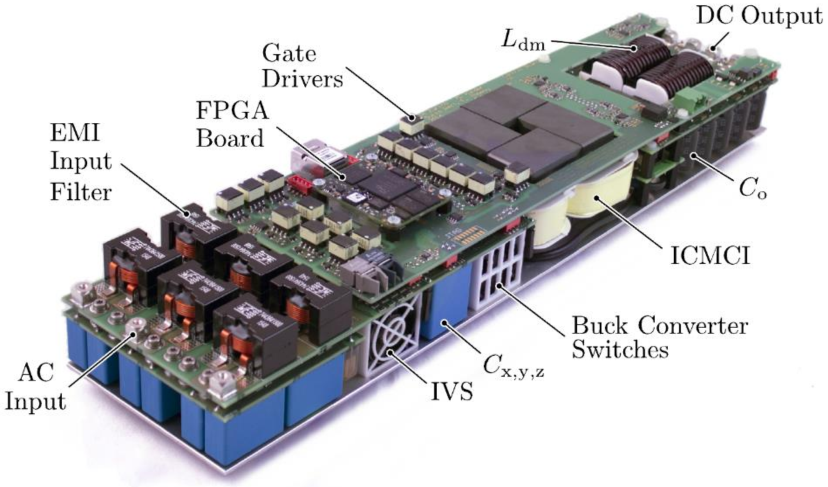


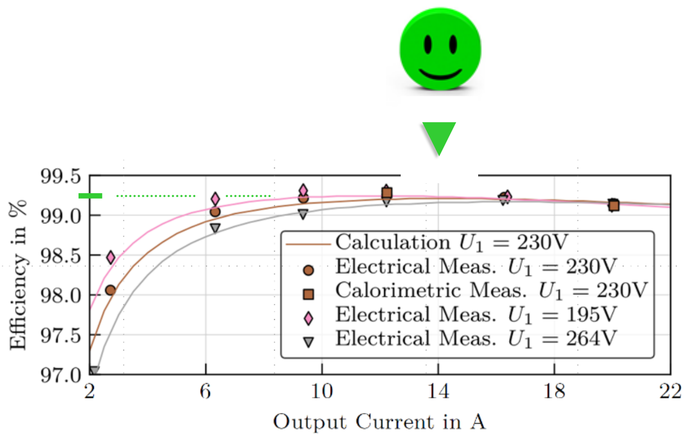
- Low Complexity

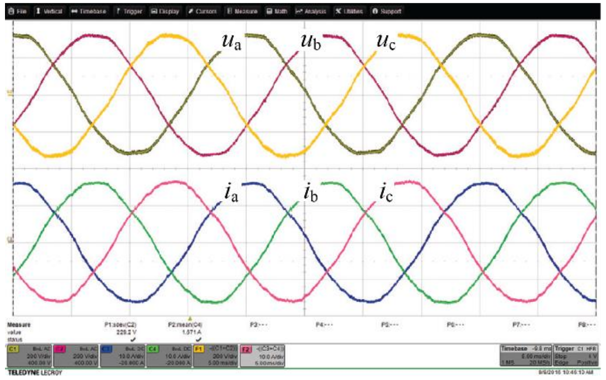
Swiss Rectifier Demonstrator

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

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



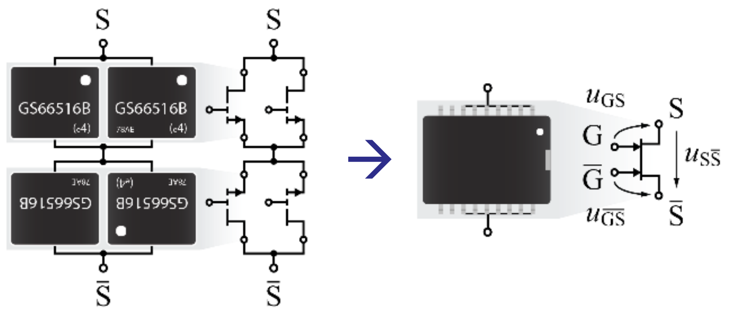


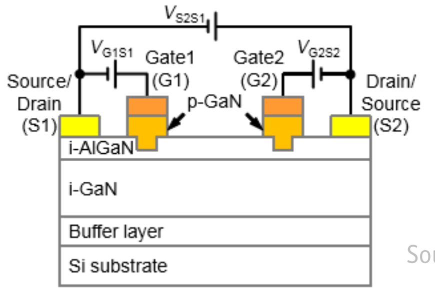


- *SiC Power MOSFETs & Diodes*
- *Integr. CM & Output Coupling Inductors (ICMCI)*

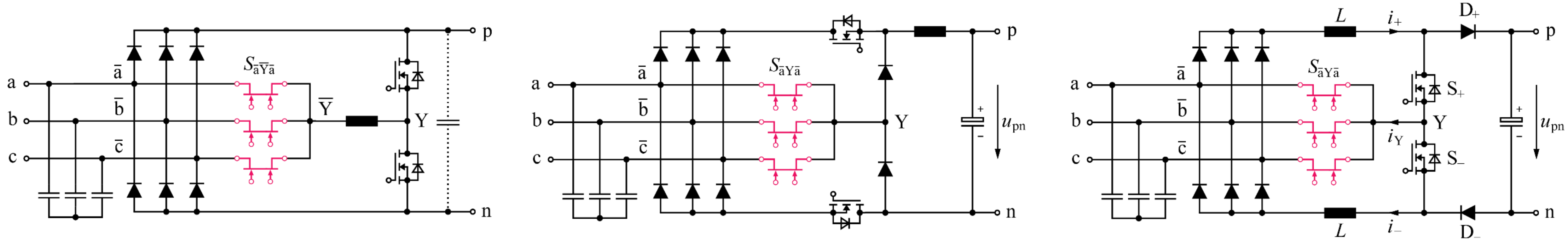
Remark Monolithic GaN Bidirectional Switch

- *Bipolar Voltage Blocking Capability*
- *2 Gates → Controllability of Both Current Directions*
- *Factor of 4 Reduction of Chip Area Comp. to Discrete Realization of Same $R_{(on)}$*



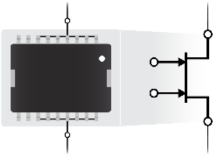


Source: Panasonic ideas for life

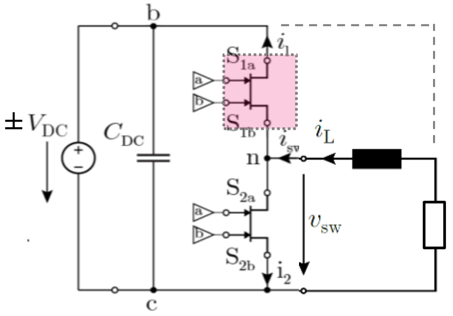


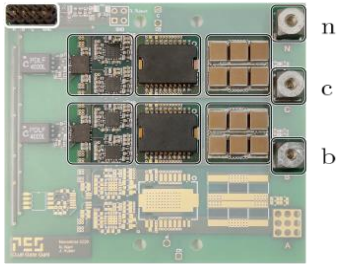
- *M-BDS Application for Phase Selector Switches of 3rd Harmonic Inj. PFC Rectifiers*

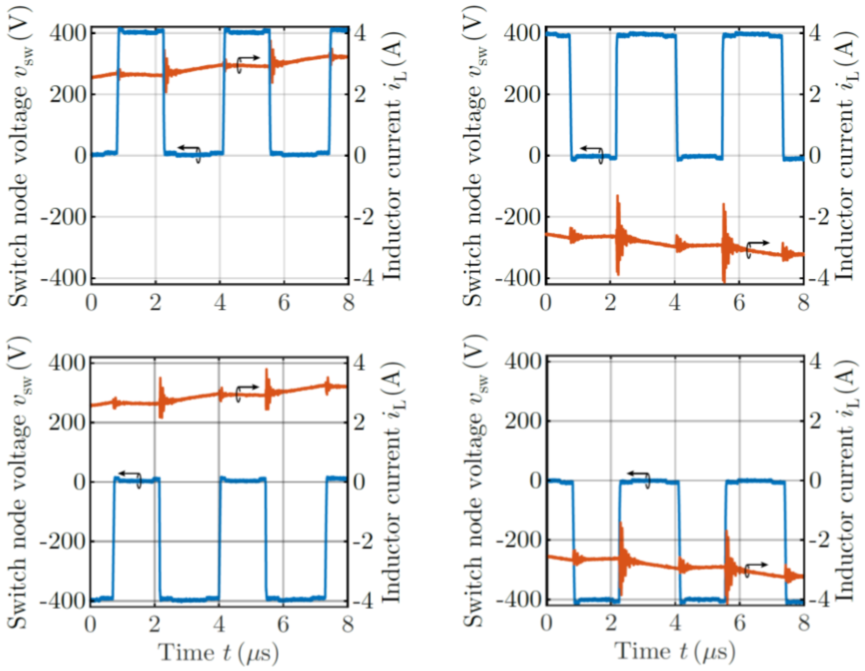
600V GaN Monolithic Bidir. Switch



- PowerAmerica *Project — Based on Infineon's 600V CoolGaN™ Technology* infineon
- *Dual-Gate Device / Controllability of Both Current Directions*
- *Bipolar Voltage Blocking Capability | Normally-On or -Off*





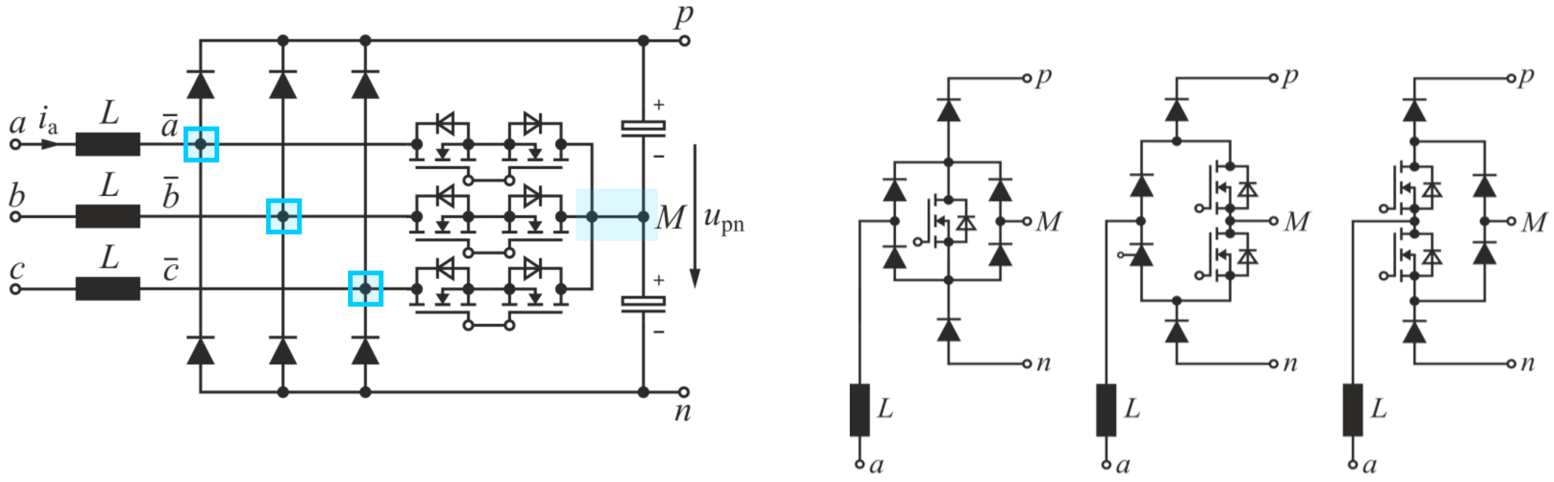


- *Analysis of 4-Quardant Operation of $R_{(on)}$= 140mΩ Sample @ ±400V*

Active Control of Diode Bridge Conduction States

Vienna Rectifier (1)

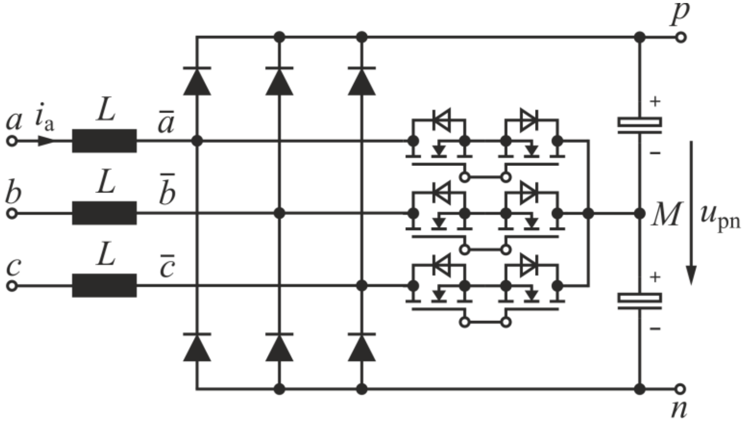
- *Active Control of Diode Bridge Conduction States / Input Voltages*
- Bridge Leg Topologies with Different Voltage Stresses / Cond. Losses
- Phase & Bridge Symmetry !



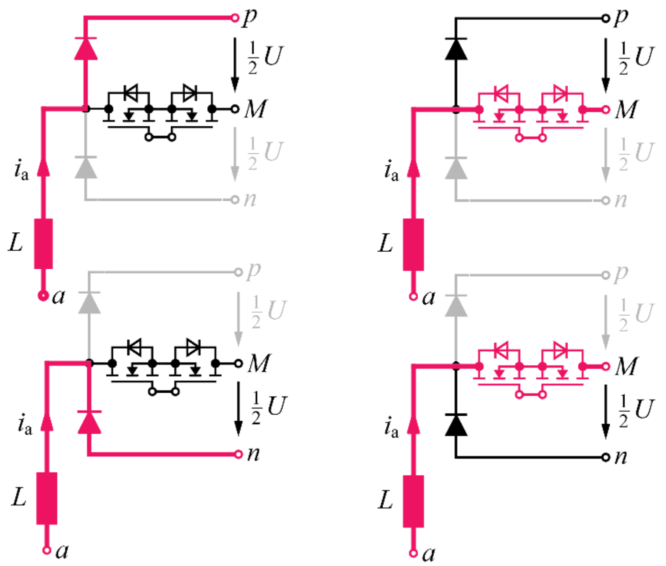
→ Analysis of Input Voltage Formation

Vienna Rectifier (2)

- *Diode Bridge Input Voltage Formation Dependent on Current Direction & Sw. State*
- Min. Output Voltage Defined by Mains *Line-to-Line* Voltage Amplitude
- Boost-Type



$u_a, i_a > 0$

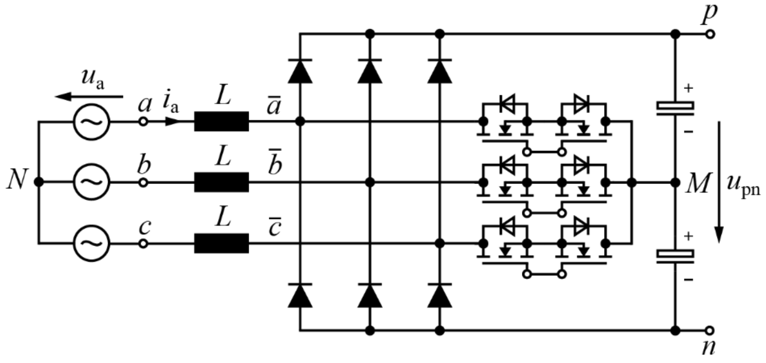


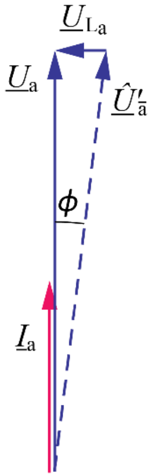
$u_a, i_a < 0$

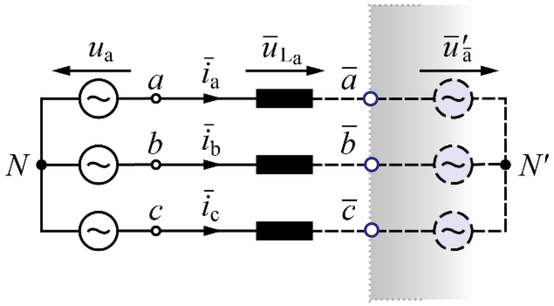
→ Sinusoidal Input Current Shaping

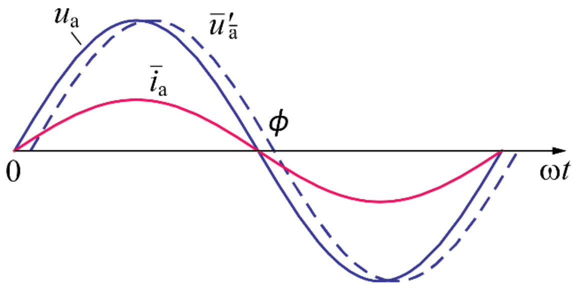
Vienna Rectifier (3)

- *Input Current Impressed by Difference of Mains & Diode Bridge Input Voltage*
- Φ = (-30°,+30°) *Limit* Due to Current-Dependent Voltage Formation





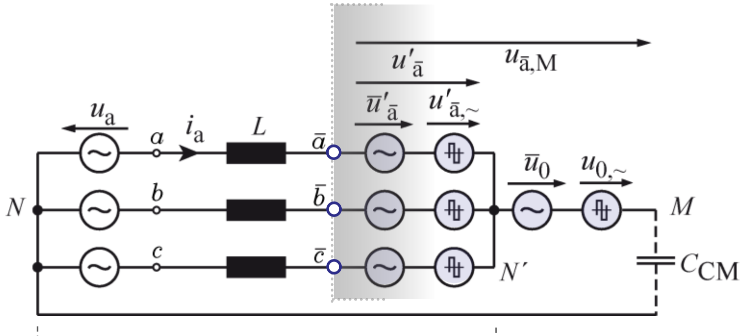


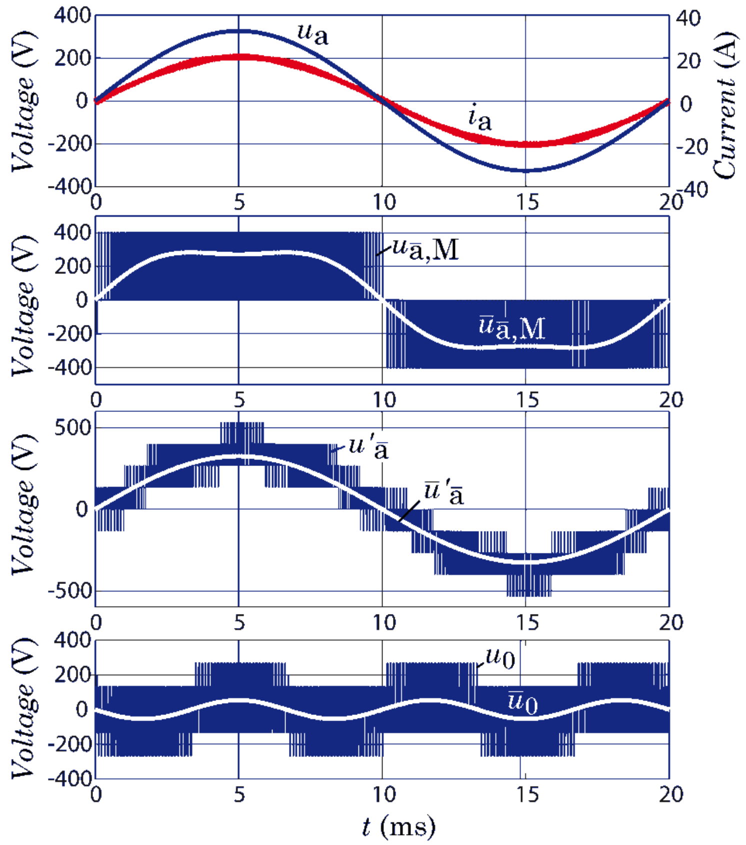


→ Time Behavior of PWM Voltages

Vienna Rectifier (4)

- *3-Level Bridge-Leg Characteristic / 9-Level Current Impressing Phase Voltage*
- Low Input Current Ripple / *Low Inductance L*
- Switching Frequency CM Output Voltage



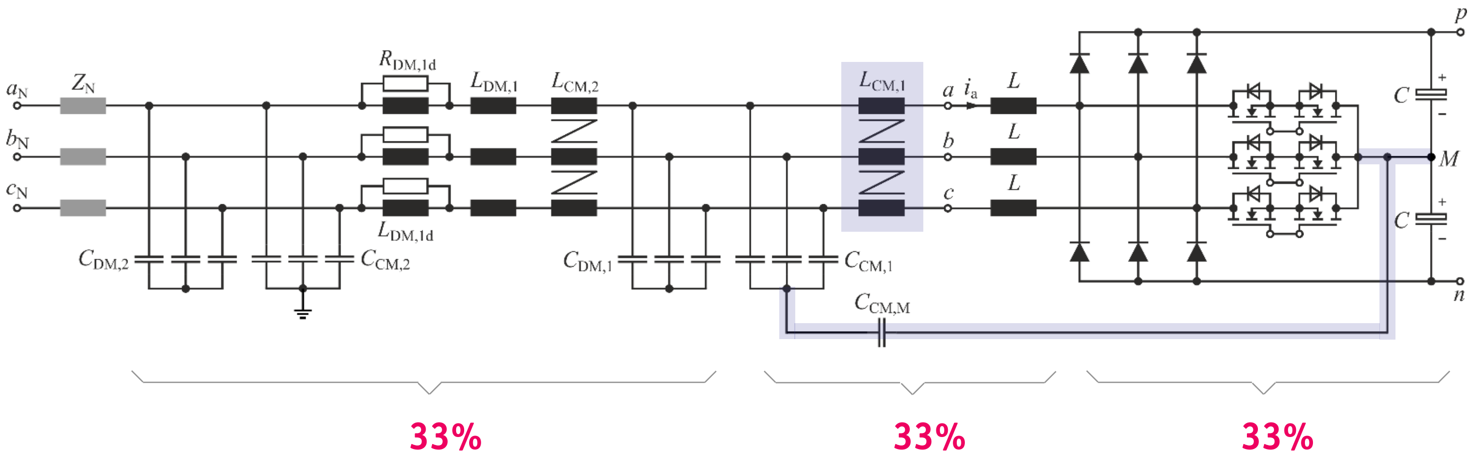


$$u_{NN'} = 0$$

→ *CM EMI Filtering*

Vienna Rectifier (5)

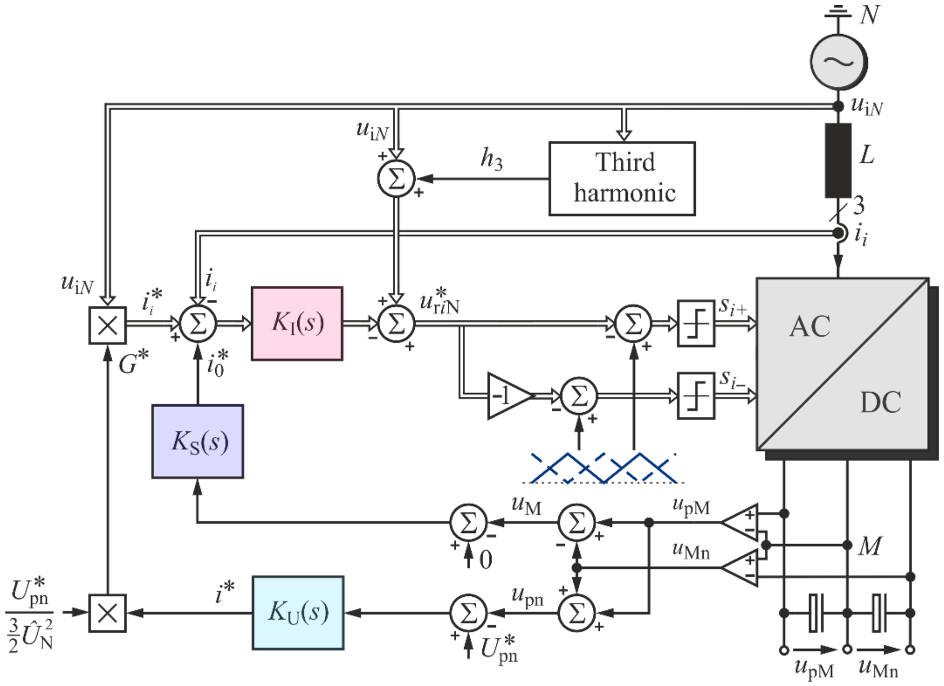
- *CM EMI Filtering / Internal Cap. Connection to Virtual Star Point*
- No Limit of CM Capacitance by Max. Leakage Current
- CM Filter Stage(s) on DC-Side as Alternative

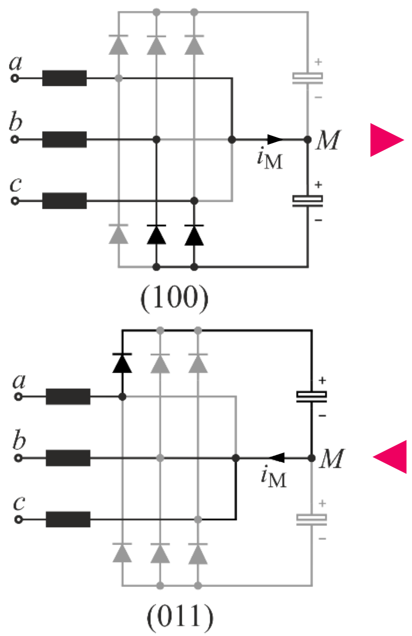


- Number of Filter Stages Dependent on Sw. Frequency

Vienna Rectifier (6)

- *Output Voltage Control / Inner Mains Current Control*
- Add. Control Loop for DC Midpoint Balancing
- Redundant Sw. States Utilized for DC Midpoint Balancing

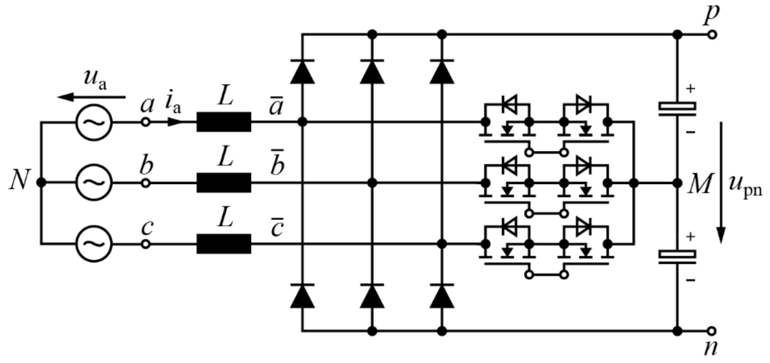




→ Hardware Realization

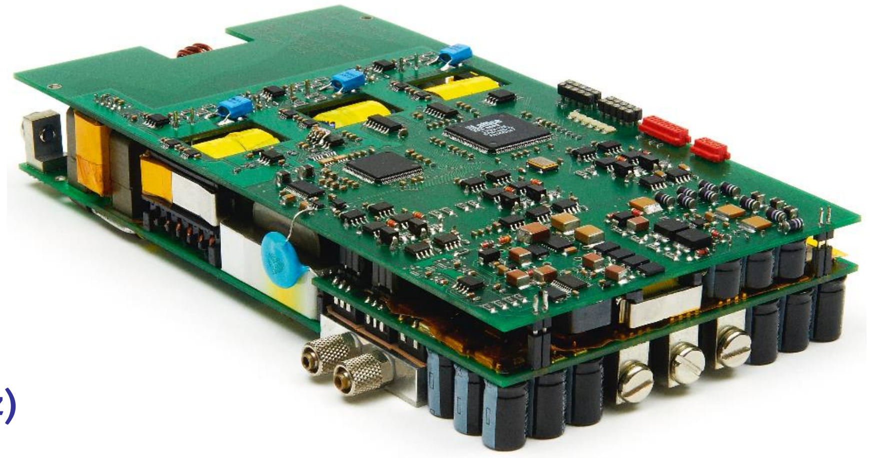
Vienna Rectifier (7)

- Highly-Compact Demonstrator System
- CoolMOS & 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/in^3

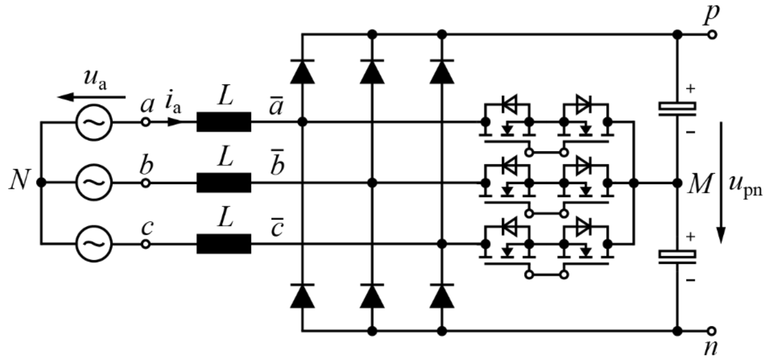
- THD_i = 1.6% @ f_N = 800Hz (f_P= 250kHz)

Vienna Rectifier (8)

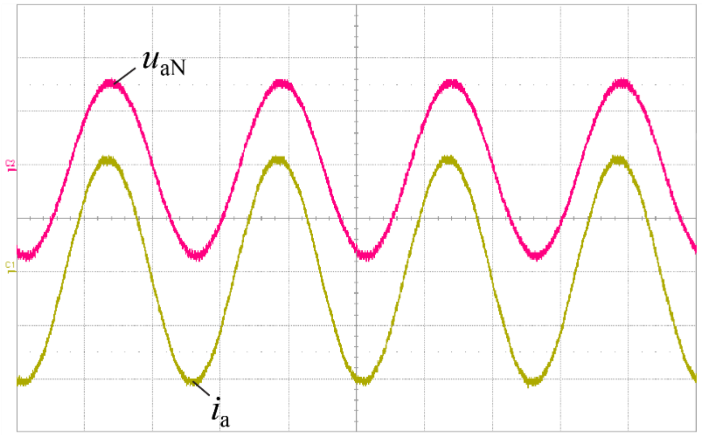
- Highly-Compact Demonstrator System
- CoolMOS & SiC Diodes
- Coldplate Cooling

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



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

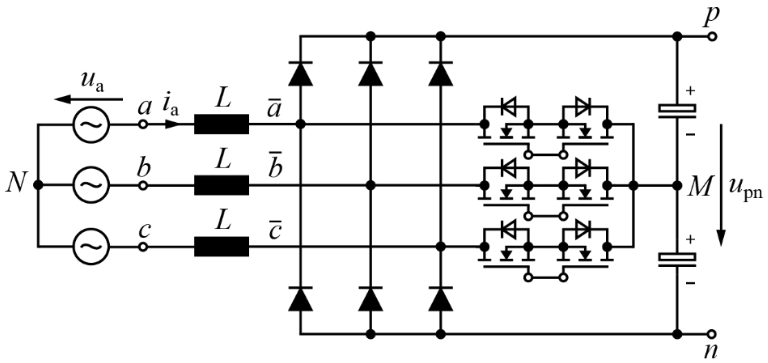


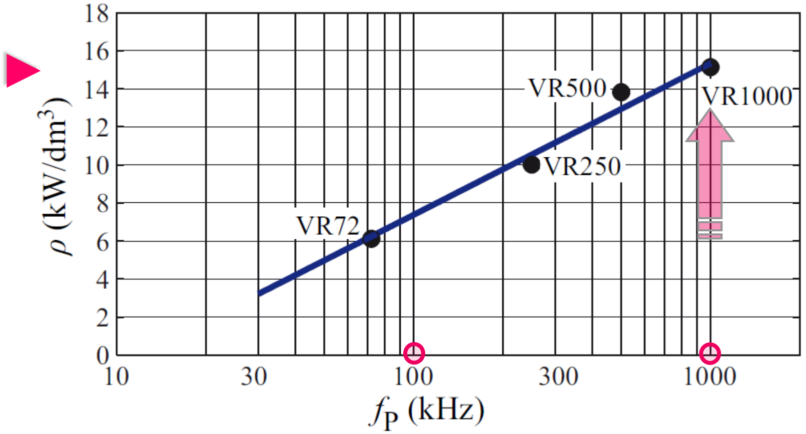
- THD_i = 1.6% @ f_N = 800Hz
- System Allows 2-Φ Operation

Vienna Rectifier (9)

- Dependency of Power Density on Sw. Frequency f_P
- CoolMOS & SiC Diodes
- Coldplate Cooling

$P_0 = 10$ kW
$U_N = 230V_{AC} \pm 10\%$
f_N = 50Hz or 360…800Hz
$U_0 = 800V_{DC}$

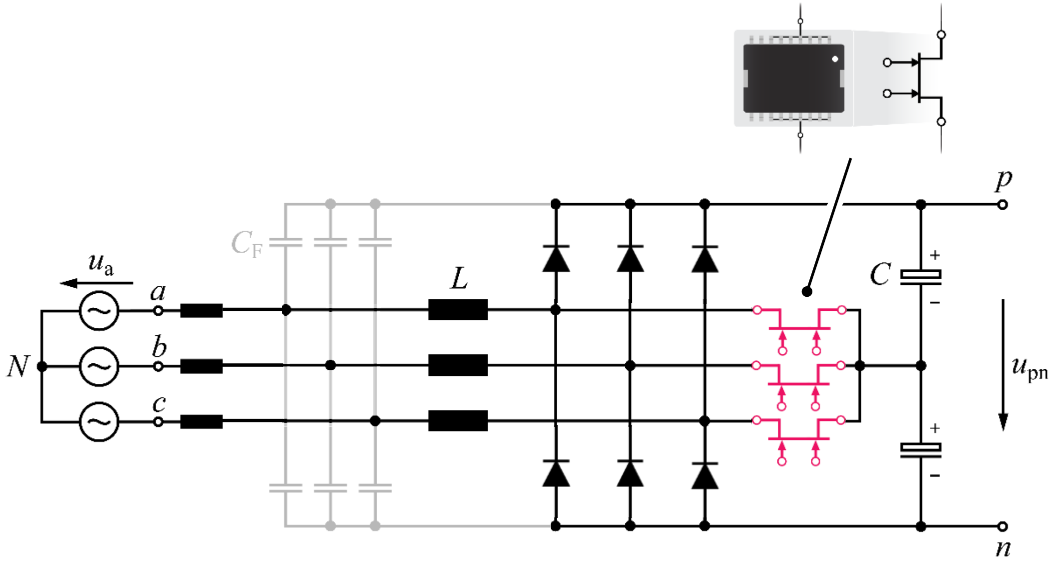


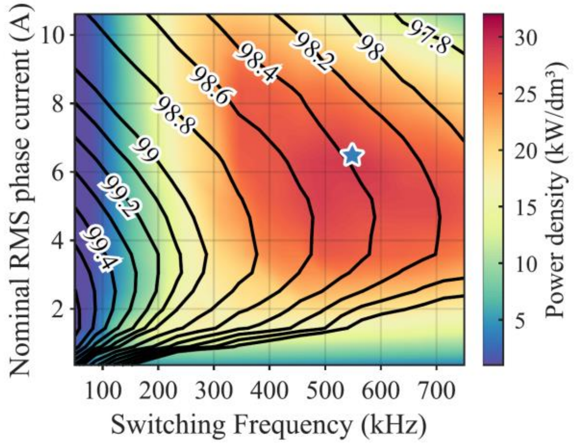


- Factor 10 in f_P → Factor 2 in Power Density
- Systems with f_P = 72/250/500/1000kHz

Remark Application of GaN M-BDS (1)

- *Vienna Rectifier*
- *600V GaN Monolithic Bidirectional Switch (M-BDS) @ U_{pn}= 800V, $R_{(on)}$=140mΩ* infineon
- *Continuous Current Mode, L=33uH, f_{sw}=620kHz*
- *1200V SiC Diodes*



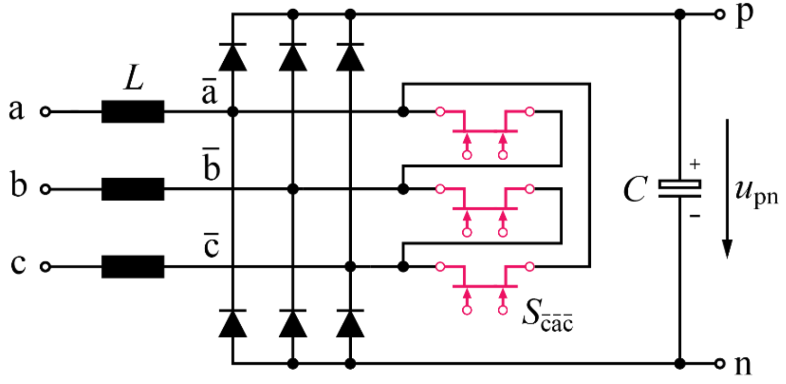


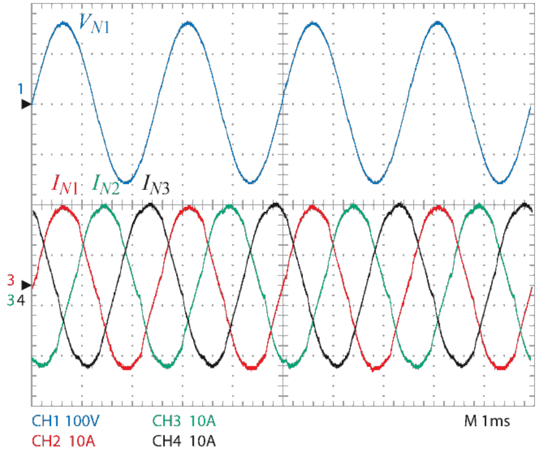
- *Max. Power Density of 25kW/dm³ (w/o Full EMI Filter) @ 98.4% Efficiency*

Remark Application of GaN M-BDS (2)

- *Δ-Switch Rectifier*
- *600V M-BDSs for 115V / 360...800Hz Aircraft Applications*
- *Low Conduction Losses / No DC-Link Midpoint Required*

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





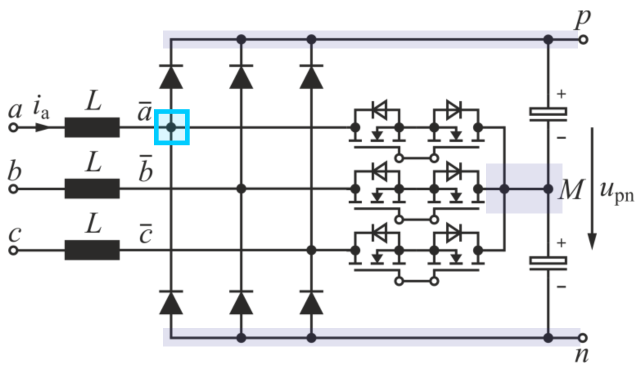
- *Always Only 2 Switches are Operated*
- *Phase Current Controller Outputs Transformed into Δ-Quantities*

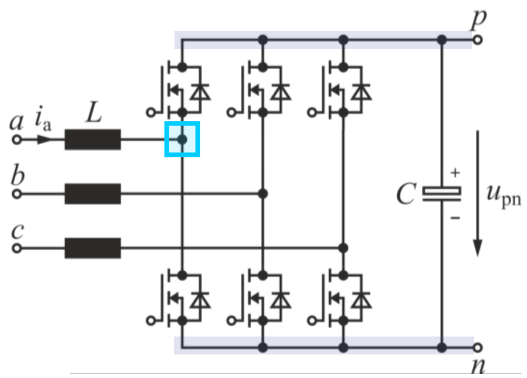
Comparative Evaluation

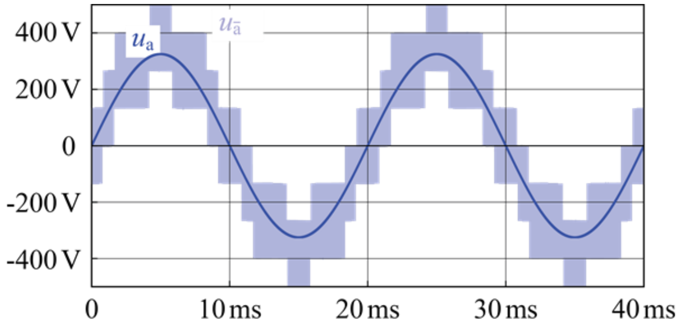
3L-Topology vs. 2L-Topology

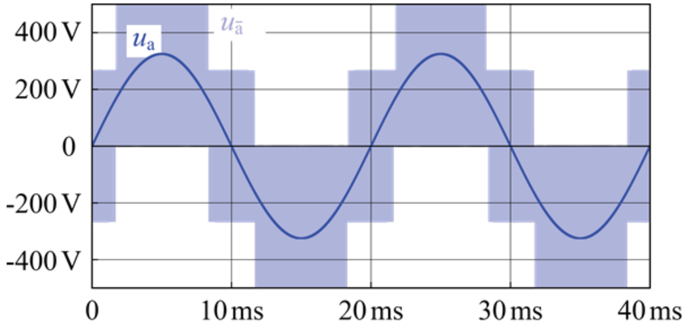
Comparative Evaluation (1)

- Comparison of *3-Level* to Standard *2-Level* PWM Rectifier
- *9 vs. 5 Volt. Levels & Factor 2...3 Lower Sw. Losses → Factor 4...6 (!) Lower L*





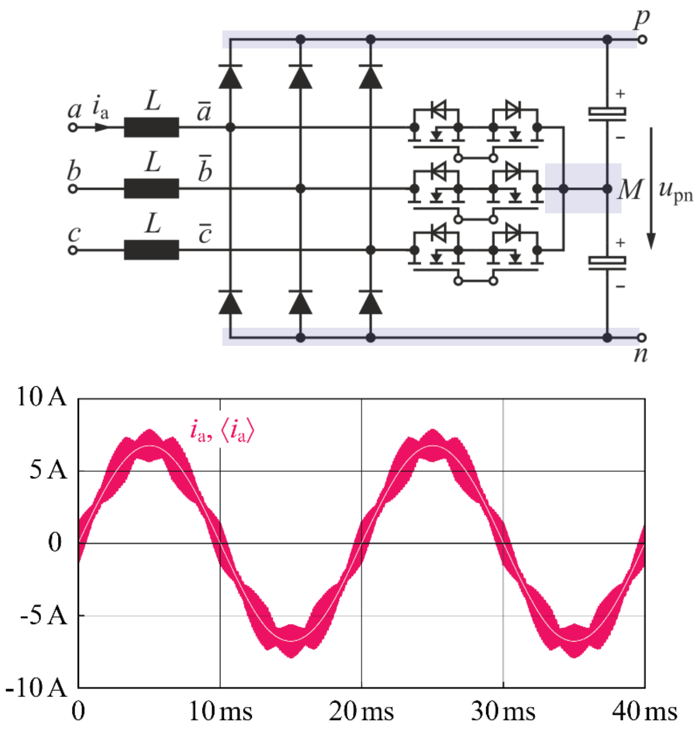


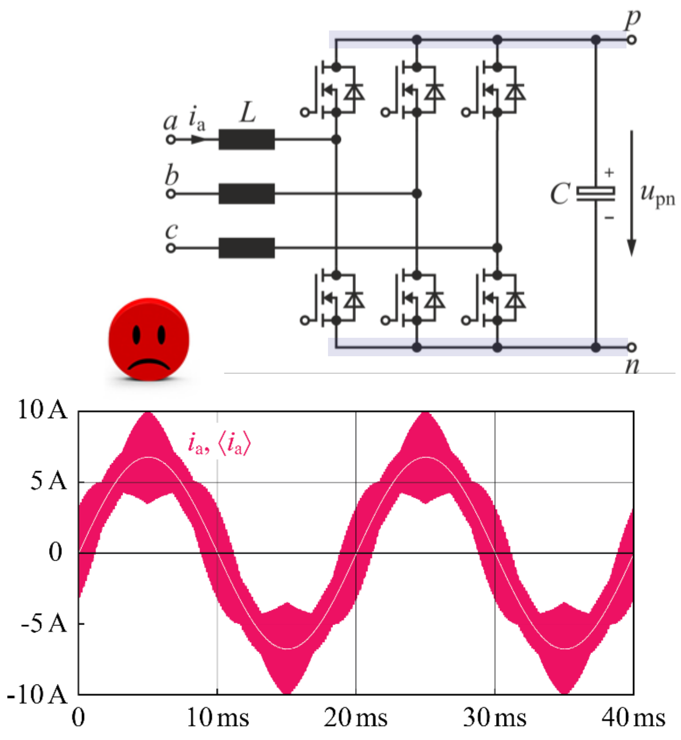


- Vienna Rectifier
- Standard PWM Rectifier

Comparative Evaluation (2)

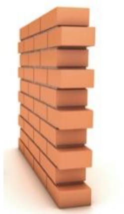
- Comparison of *3-Level* to Standard *2-Level* PWM Rectifier
- *9 vs. 5 Volt. Levels & Factor 2..3 Lower Sw. Losses → 12 kW/dm³ vs. 8 kW/dm³* @ 22kW



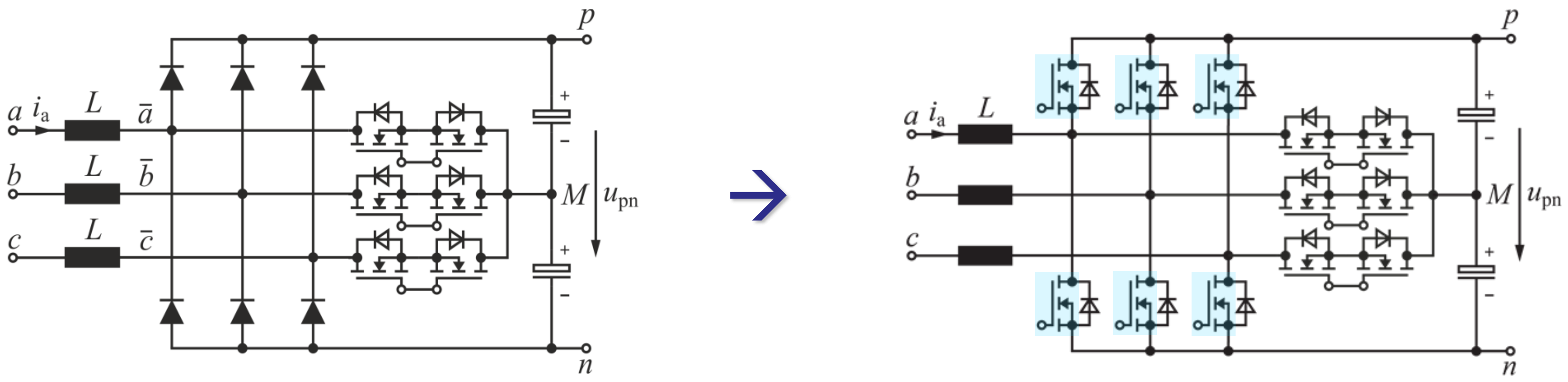


- Vienna Rectifier
- Standard PWM Rectifier

Vienna Rectifier — Conceptual Limits



- *Boost-Type*
- *No Isolation*
- Unidirectional (in Basic Form)



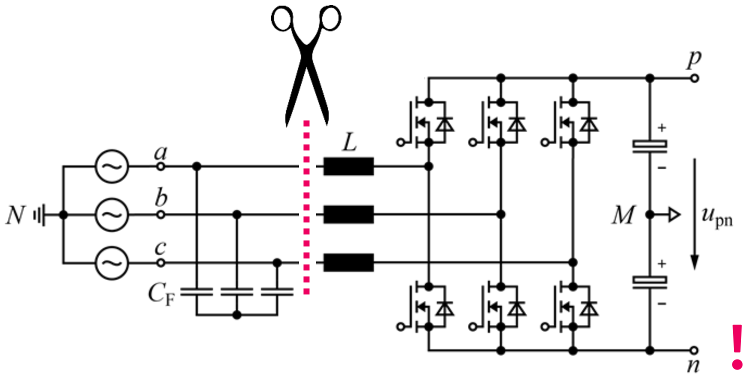
→ Buck-Boost & Buck-Type Topologies / Isolated Systems

Buck+Boost-Type

Y-Rectifier

Buck+Boost PFC Y–Rectifier

- *Switching Stage of 2-Level PFC Rectifier → 3 DC/DC Boost-Converters w/ Ref. to Neg. DC-Link Rail*
- *Insert Front-End Buck-Stage / Phase → Buck+Boost Operation*



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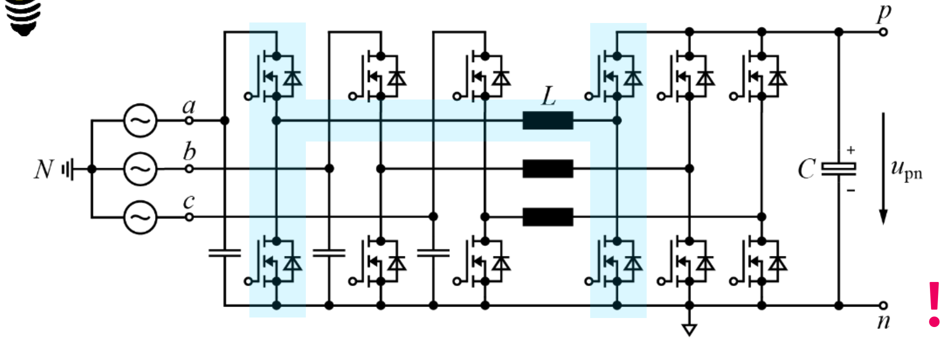

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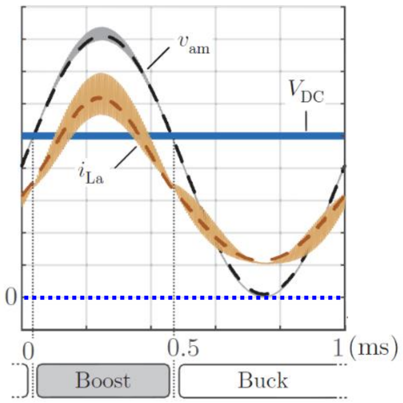
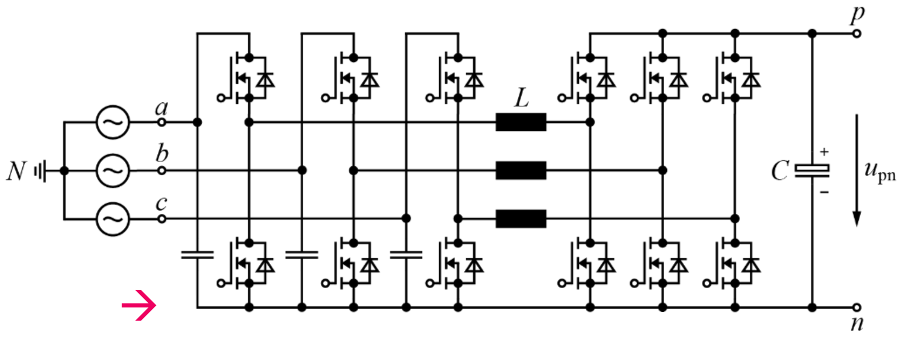
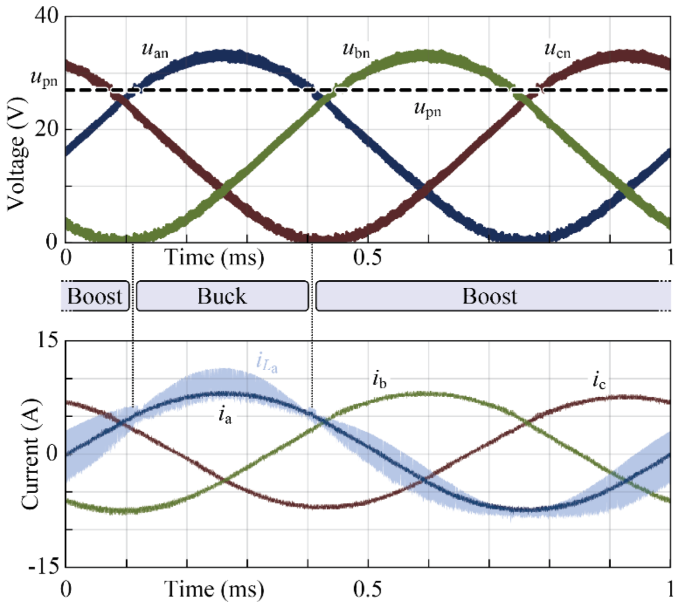


- *Bidirectional* & Wide Input / Output Voltage Range

Y–Rectifier

- *Rectifier Input Filter Inductor Used as Buck-Boost Inductor*
- *Allows Inverter Operation with Continuous Output Voltage (!)*
- All-GaN Demonstrator



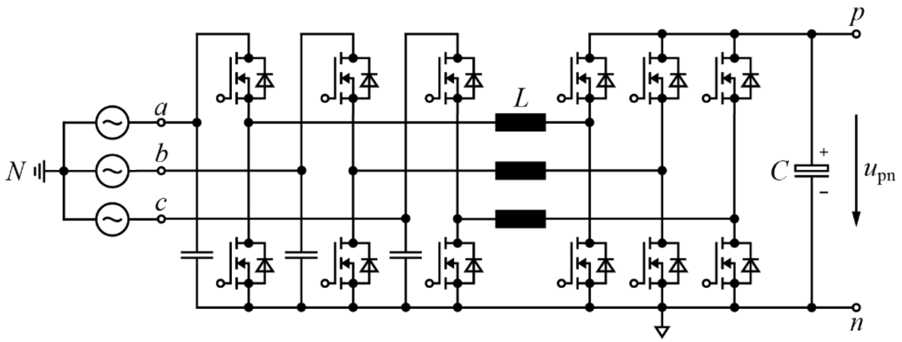


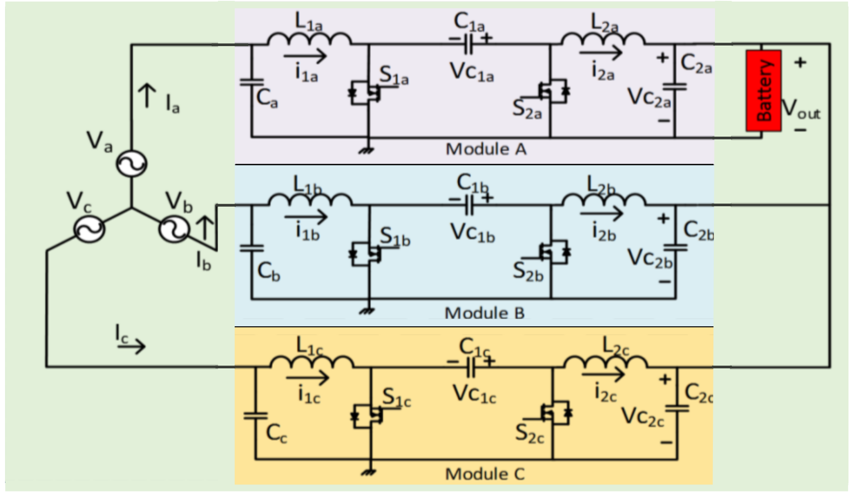
- *Bidirectional* & Wide Input / Output Voltage Range

Y−Rectifier vs. 3-Φ Cuk-Type Rectifier

- 3 Main Inductive Components
- 12 Power Transistors Blocking U_{in} OR U_{out}
- Discontinuous Input & Output Current

- 6 Main Inductive Components
- 6 Power Transistors Blocking U_{in} AND U_{out}
- Continuous Input & Output Current



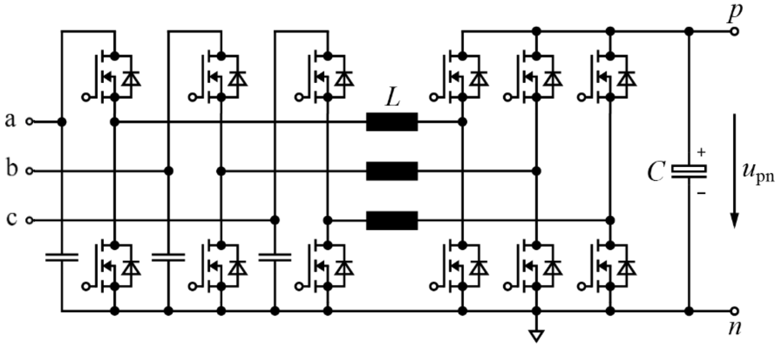


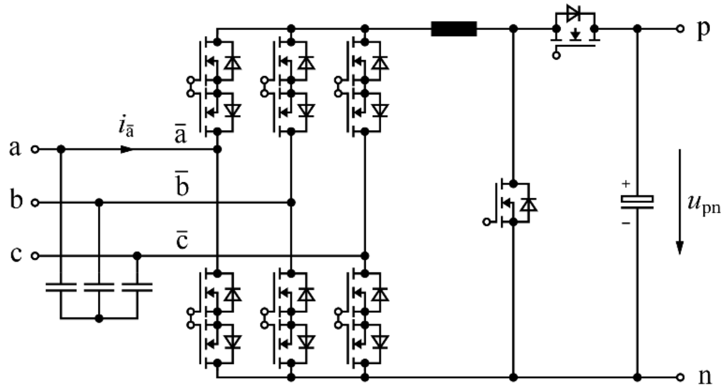
Source: N. Kumar, S. Mazumder, A. Gupta | 2018

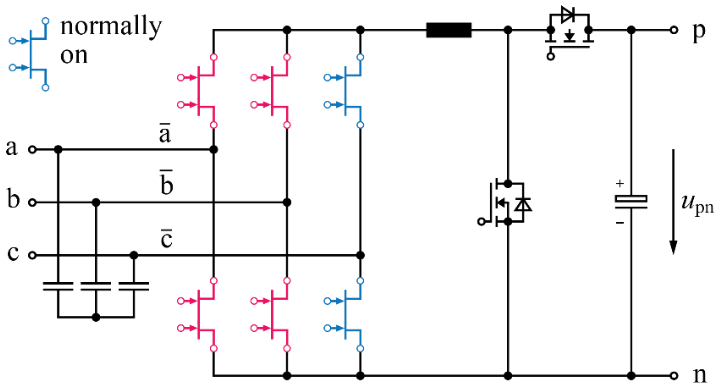
- Bidirectional & Wide Input / Output Voltage Range

3-Φ I-DC-Link Buck-Boost Rectifier

- *Combination of Y-Rectifier Boost-Stages*
- *Main Power Circuit w/ Single Inductor*
- *Input-Side AC-Switches*







- *Low Complexity Realization w/ Monolithic Bidirectional Switches*

Isolated 3-Φ PFC Rectifier Systems

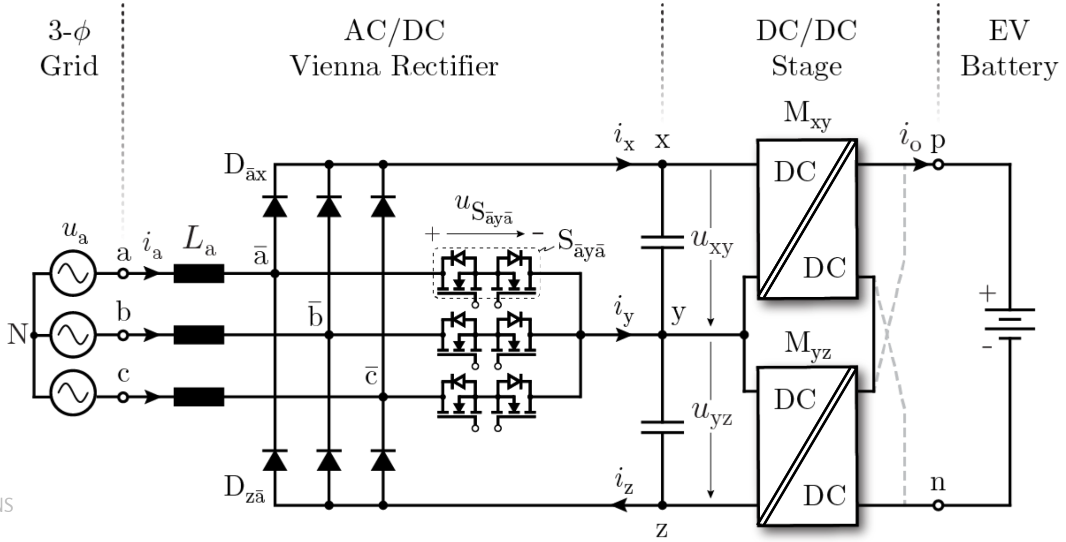
Synergetic Control
Matrix-Type Isolated Topology

Source: Porsche Mission-E Project

Selected EV-Charger Topology

- Isolated Controlled Output Voltage
- Buck-Boost Functionality & Sinusoidal Input Current
- *Applicability of 600V GaN Semiconductor Technology*
- *High Power Density / Low Costs*

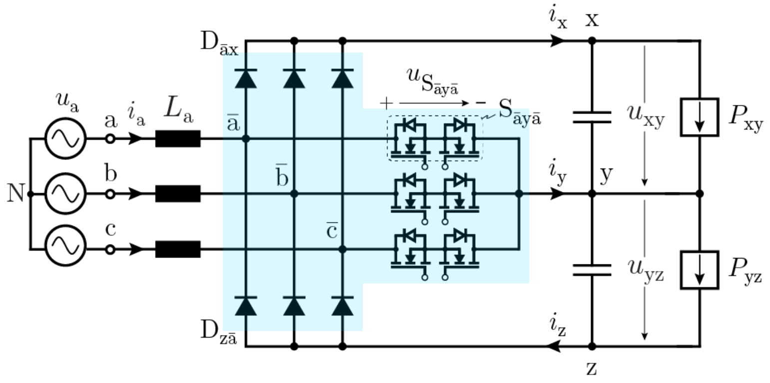
Source: SIEMENS

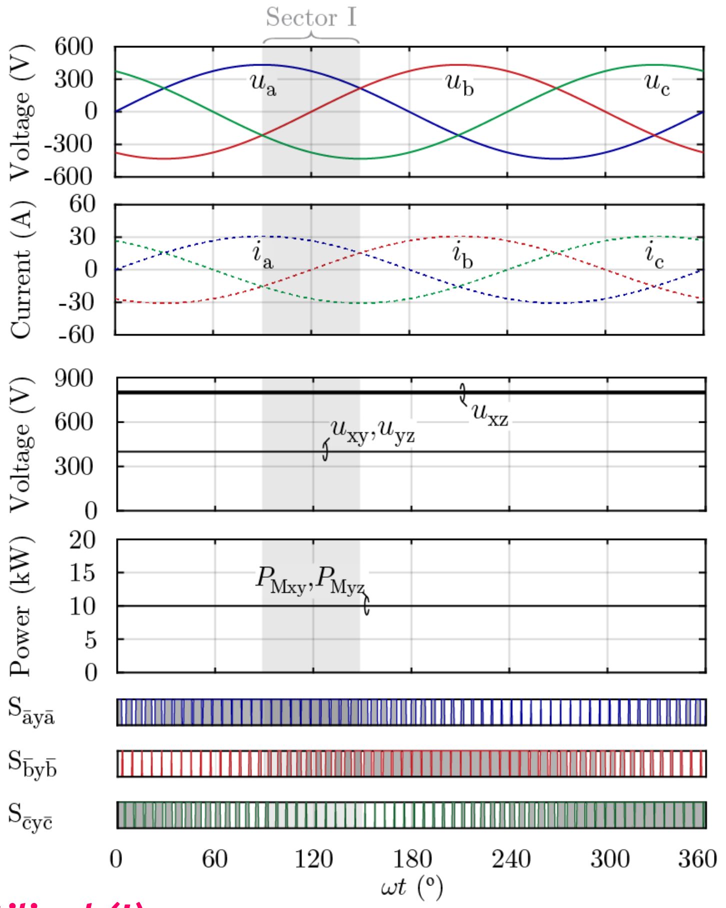


→ *Conventional / Independent* *OR* *"Synergetic Control" of Input & Output Stage*

Conventional Control

- *Decoupled Control of AC/DC & DC/DC-Stage*
- *Constant DC-Link Voltage (Equally Splitted)*
- *Cont. Sw. of All 3 Phases → 3/3 PWM*

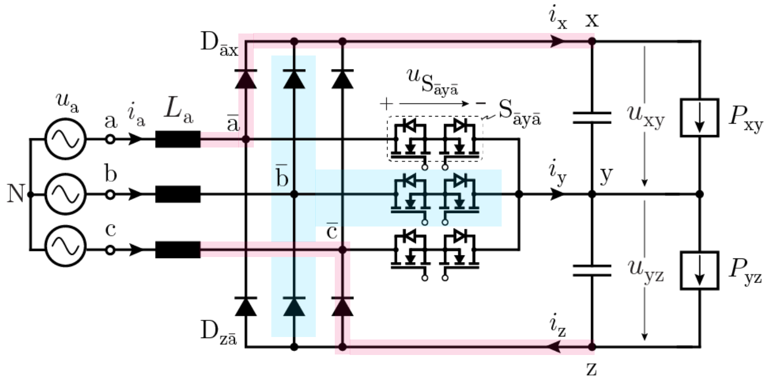


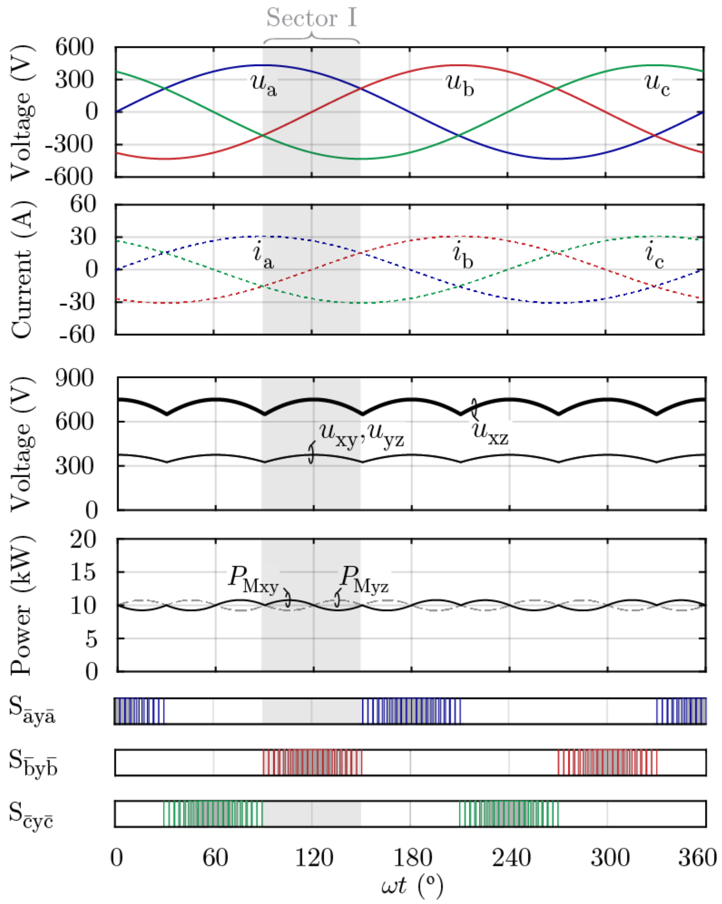


→ *Control Capability & Control DOFs NOT Fully Utilized (!)*

"Synergetic" Control

- *Only Phase with Lowest Current Switched*
- *Control of 2 Phase Currents by DC/DC-Stage*
- *Low Stresses on Power Switches*
- *600V GaN HEMTs Can be Used (!)*



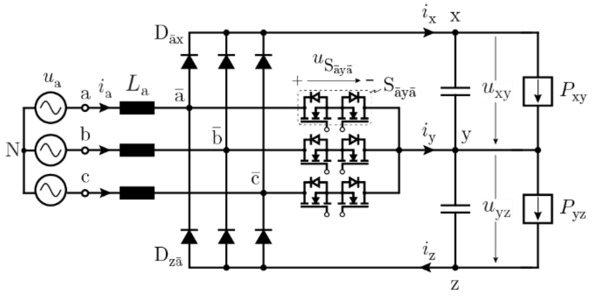


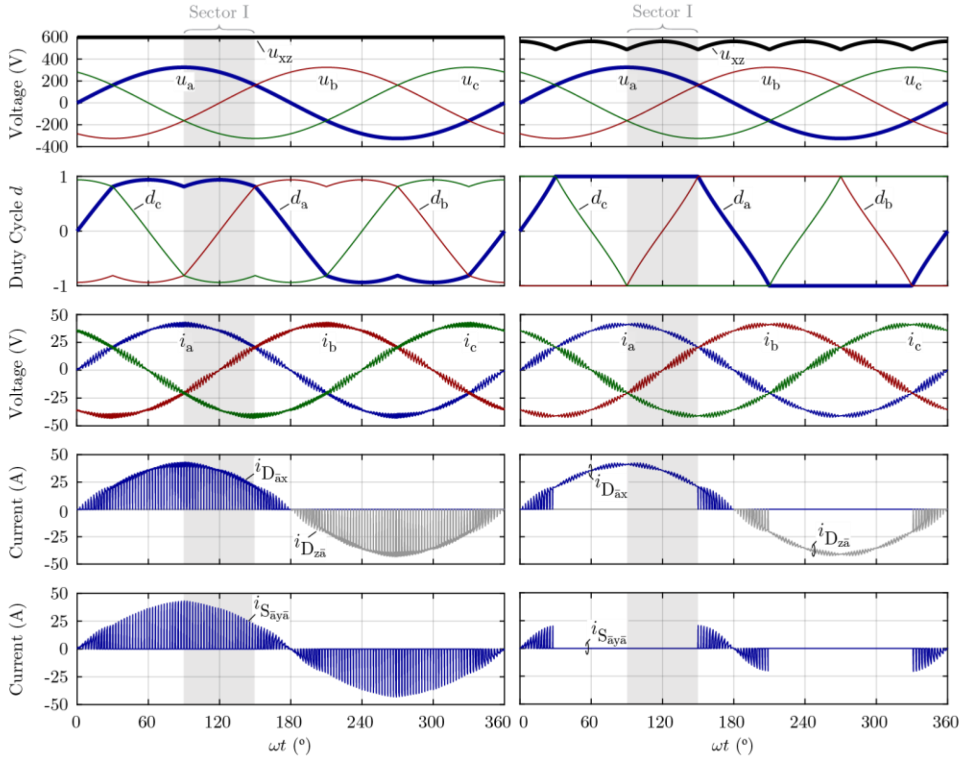
→ *Boost Capability Maintained (Transition from 1/3 to 3/3-PWM)*

Conventional vs. "*Synergetic*" Control

- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*

- *Conduction Losses ≈ -80%*
- *Switching Losses ≈ -70%*



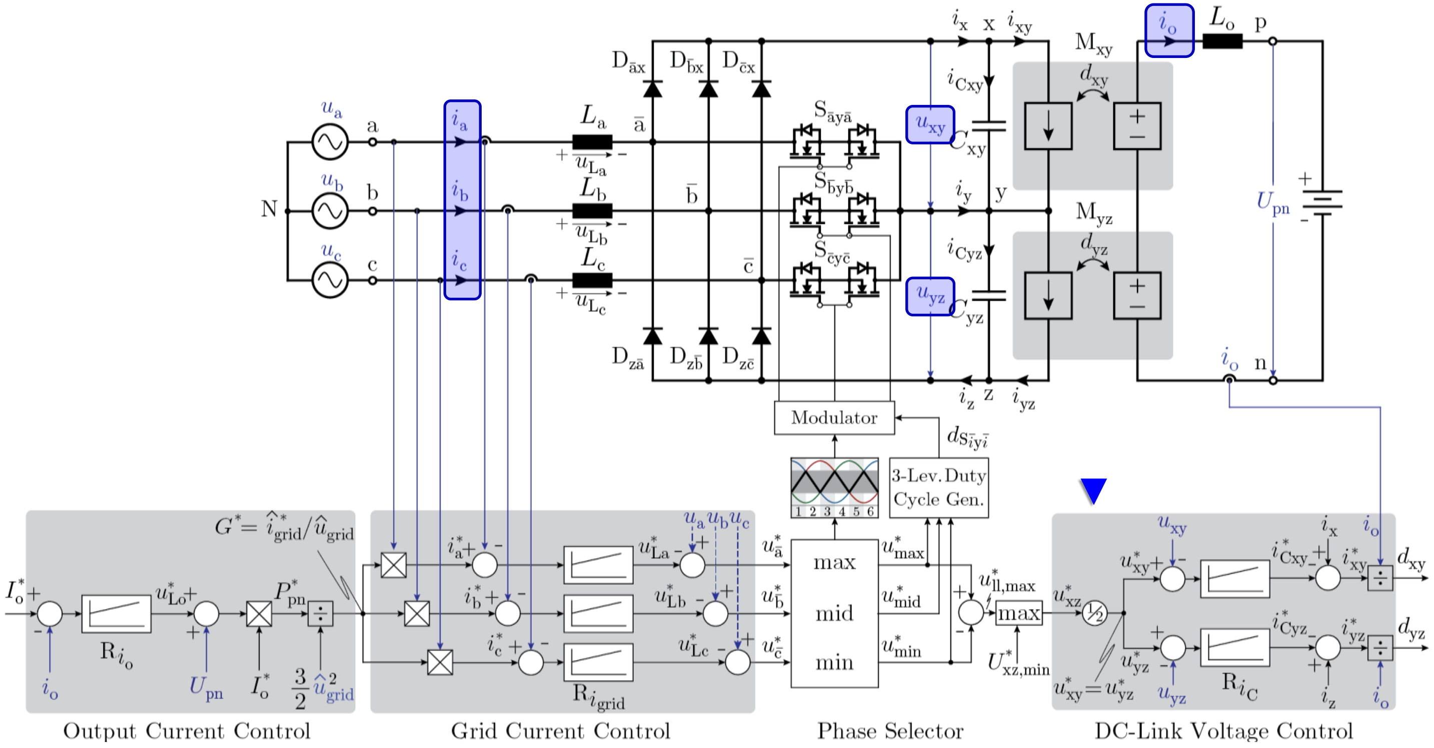


→ *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

“Synergetic” Cascaded Control Structure

"Synergetic" Control Structure

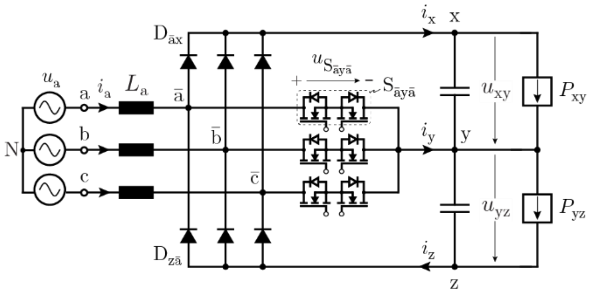
- *Cascaded Control of Output & Input Current (Direct & Through DC-Link Voltage)*
- *Active Equal DC-Link Voltage Splitting*

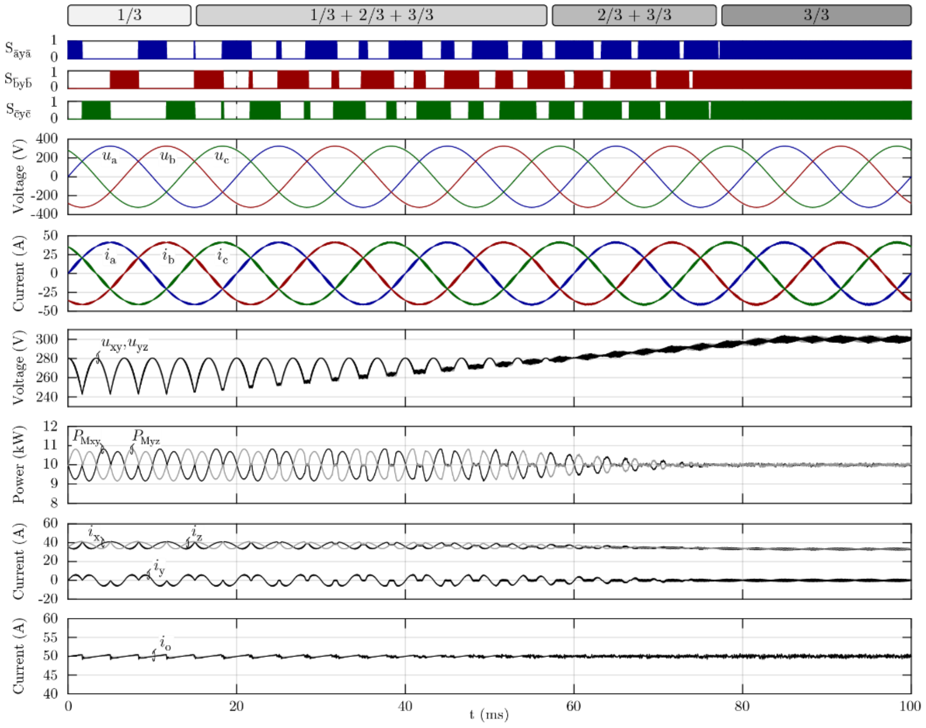


→ *Same Control Structure for 3/3-PWM (Full-Boost Mode) Using Diff. Ref. Values*

AC/DC-Stage Transition to Full-Boost Operation

- *Different Operating Regimes* → *Synergetic* | *Partial-Boost* | *Full-Boost*





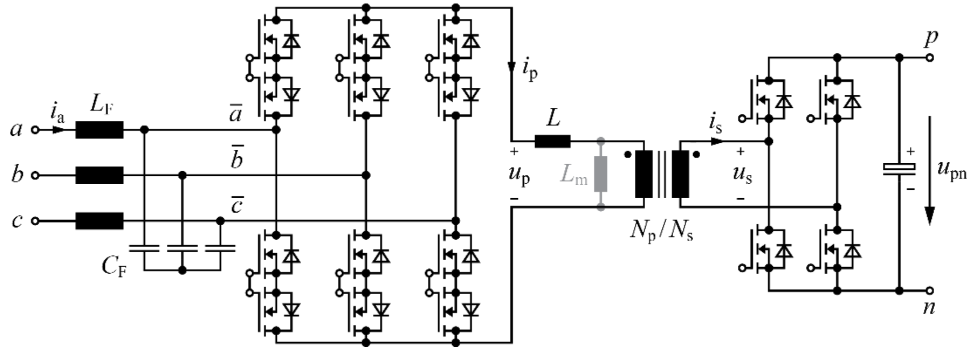
→ *Intermediate 2/3-Operation for Limiting DC-Link Center Point Current (Low DC-Cap.)*

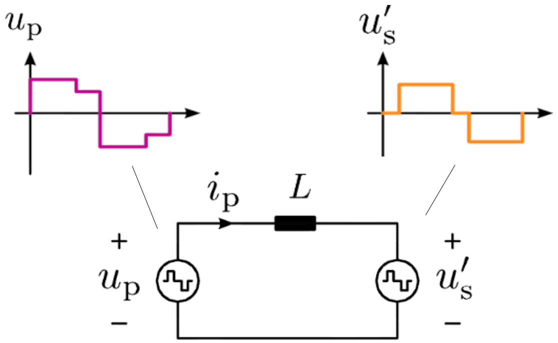
Isolated Single-Stage PFC Rectifiers

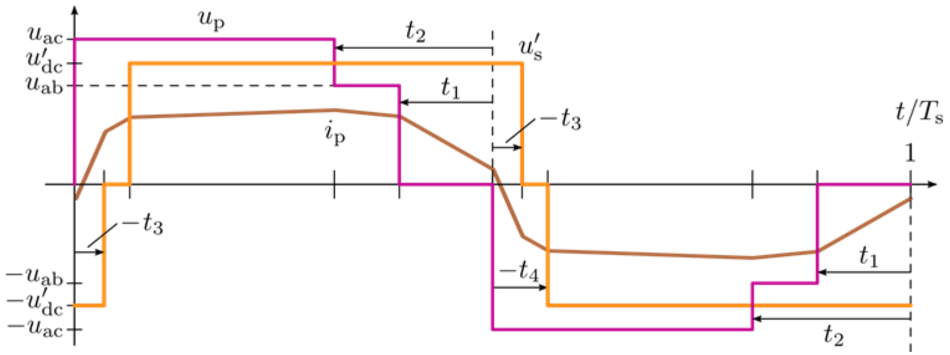
Matrix-Type PFC Rectifier
Vienna-Rectifier II, III

Isolated Matrix-Type PFC Rectifier (1)

- *Based on Dual Active Bridge* (DAB) Concept
- *Optimal Modulation* ($t_1 \dots t_4$) for Min. Transformer RMS Curr. & ZVS or ZCS
- Allows Buck-Boost Operation





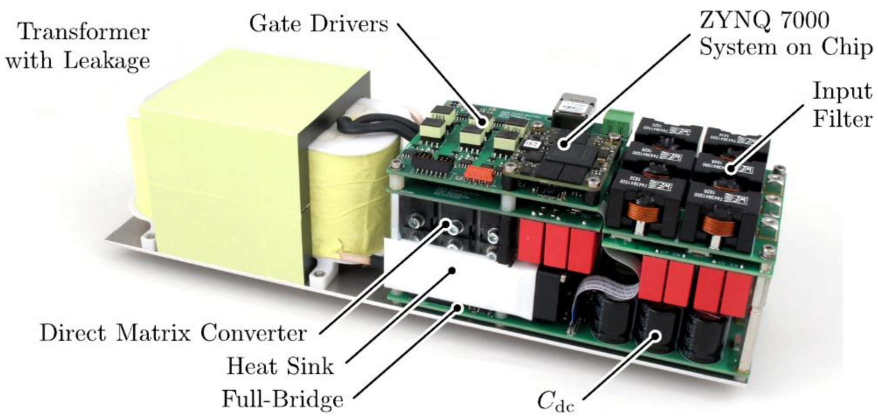


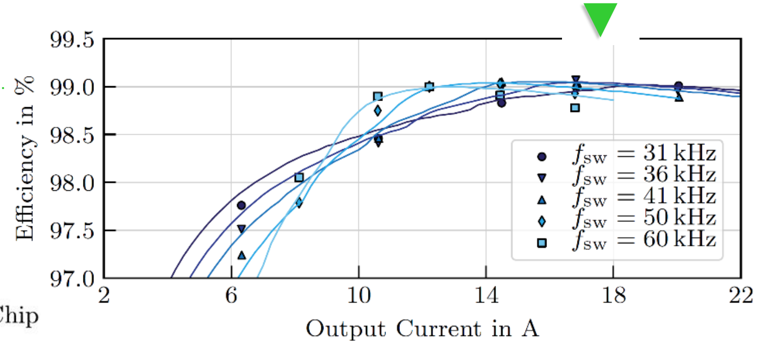
- Equivalent Circuit
- Transformer Voltages / Currents

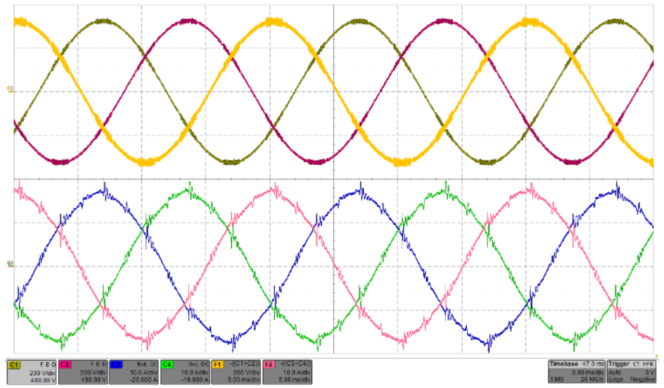
Isolated Matrix-Type PFC Rectifier (2)

- Efficiency η = 98.9% @ 60% Rated Load (ZVS)
- Mains Current $THD_I \approx 4\%$ @ Rated Load
- Power Density $\rho \approx 65 W/in^3$

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



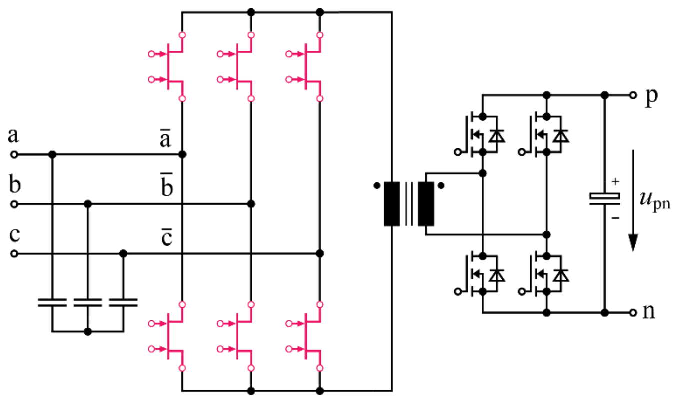


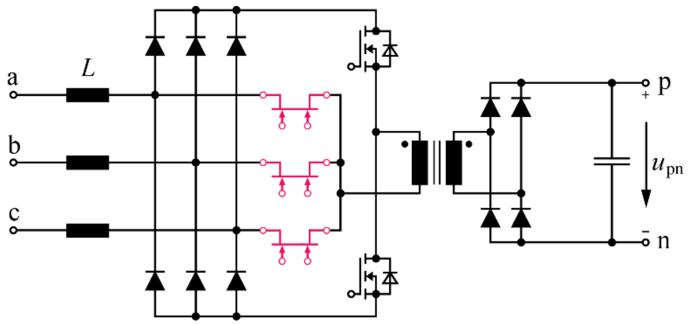


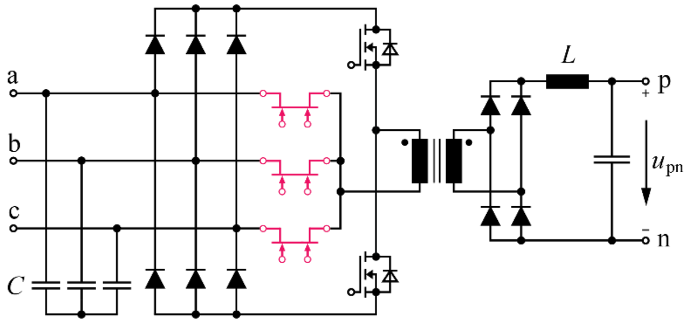
- 900V / 10mΩ SiC Power MOSFETs
- Opt. Modulation Based on 3D Look-Up Table

Remark Application of M-BDS

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







- Integration → Lower Complexity *BUT* Limited Controllability

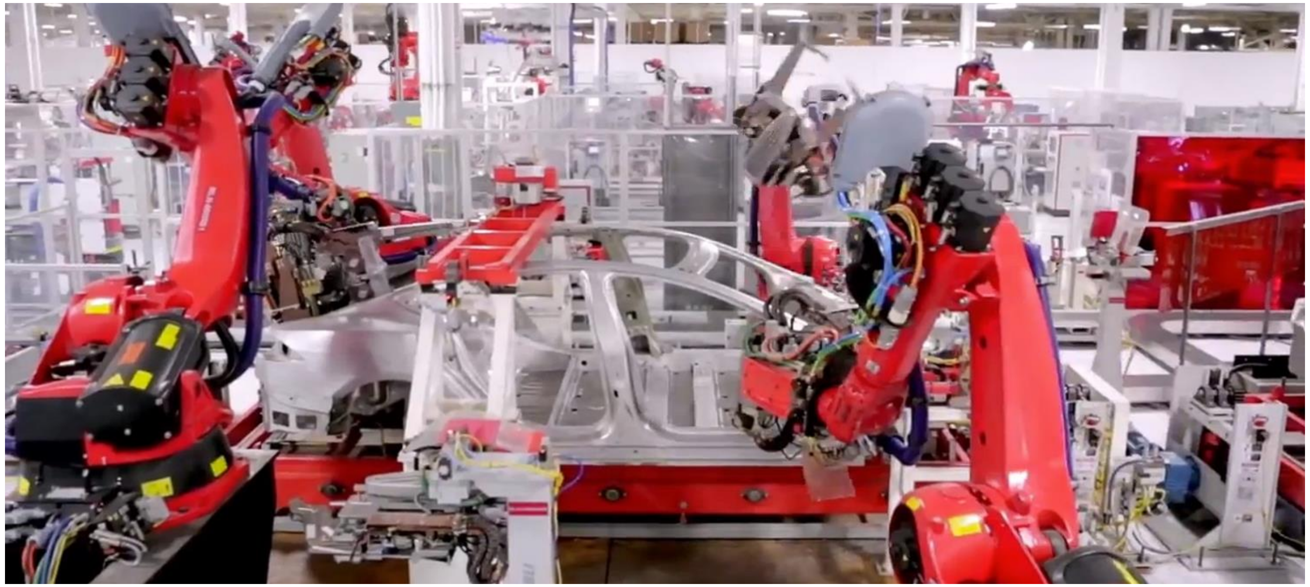
Part II

3-Φ Variable Speed Drive Inverter Systems

Full-Sinewave Filtering
Multi-Level Inverter Concepts
Buck-Boost Inverter
Current DC-Link Inverter

Variable Speed Drive (VSD) Systems

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

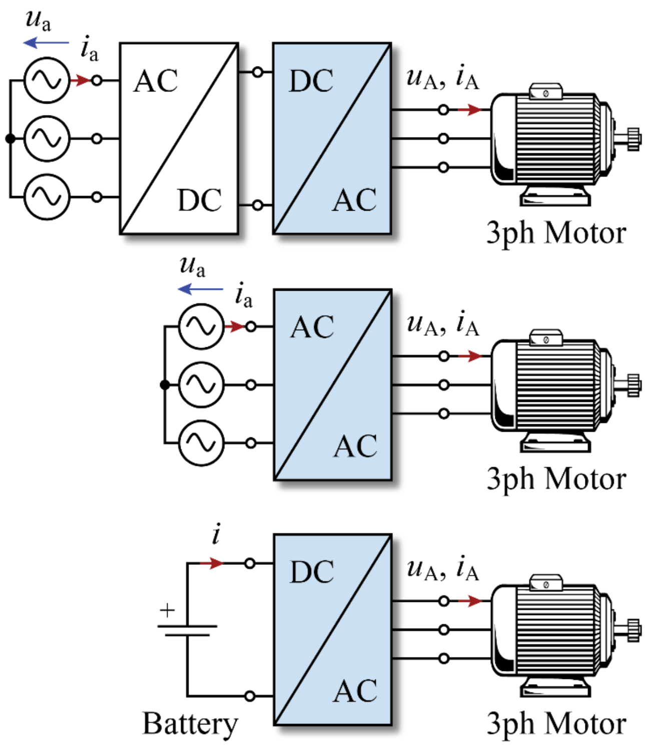


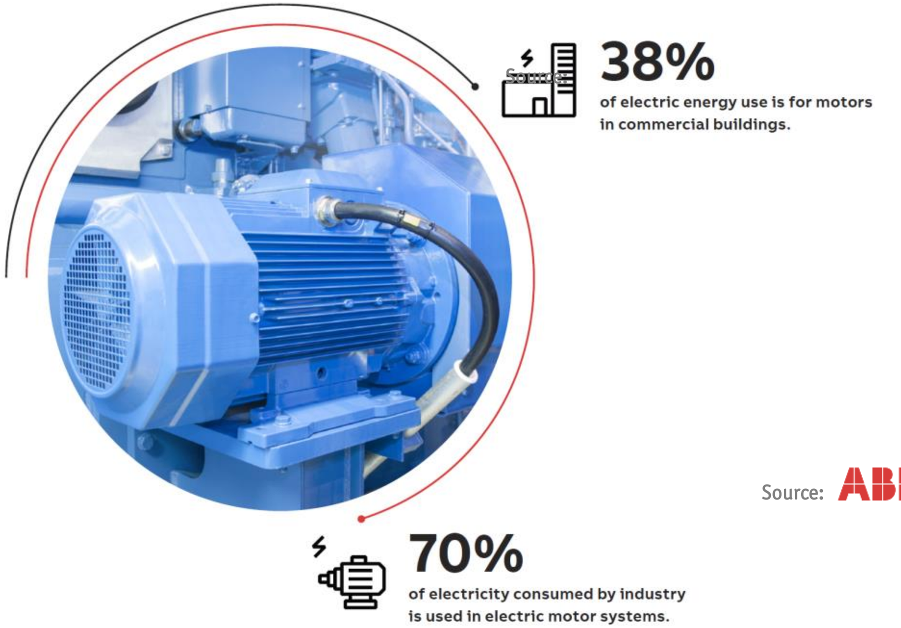
Source: TESLA MOTORS

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

Variable Speed Drive Inverter Concepts

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



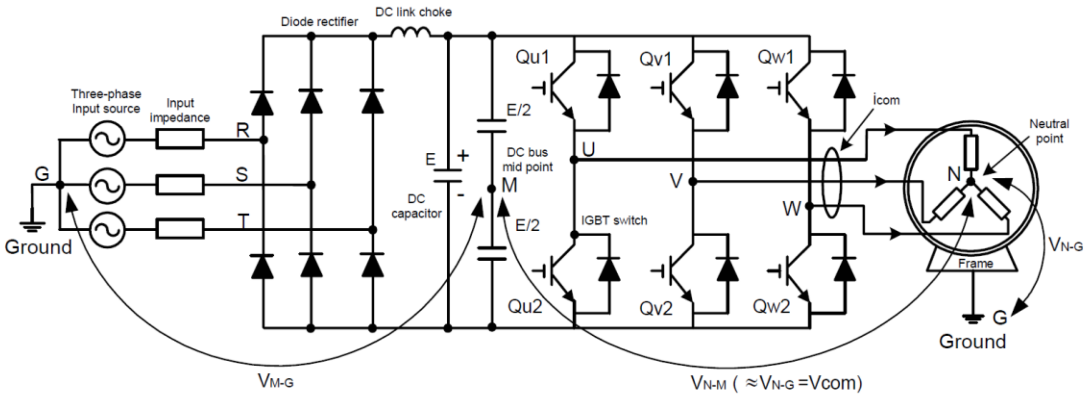


Source: ABB

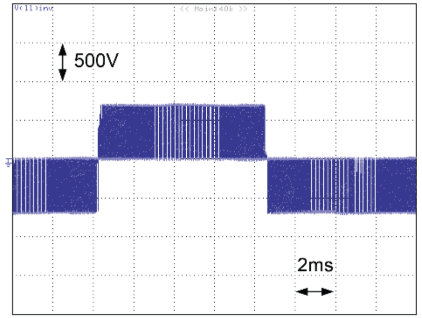
- *45% of World's Electricity Used to Power Motors in Buildings & Industrial Applications*

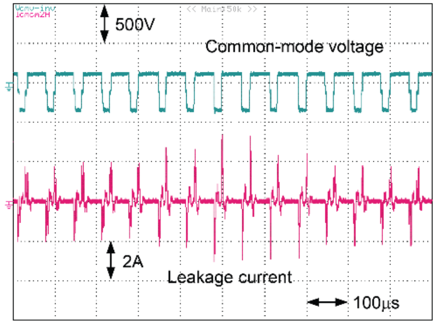
State-of-the-Art Drive System

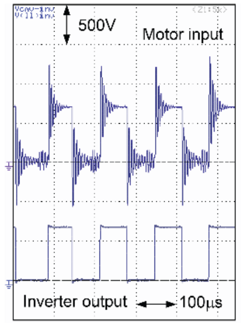
- Standard 2-Level Inverter — Large Motor Inductance / Low Sw. Frequency
- Shielded Motor Cables / Limited Cable Length / Insulated Bearings / Acoustic Noise

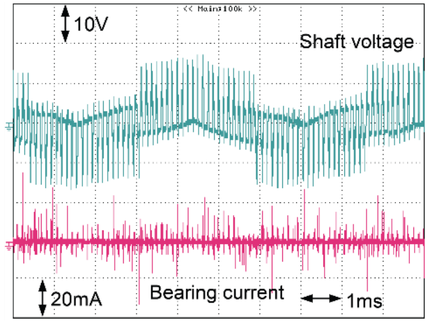


Source: YASKAWA







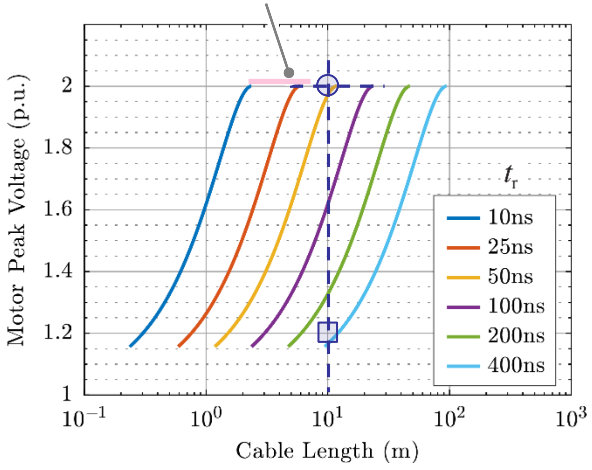


- Line-to-Line Voltage | CM Leakage Current | Motor Surge Voltage | Bearing Current

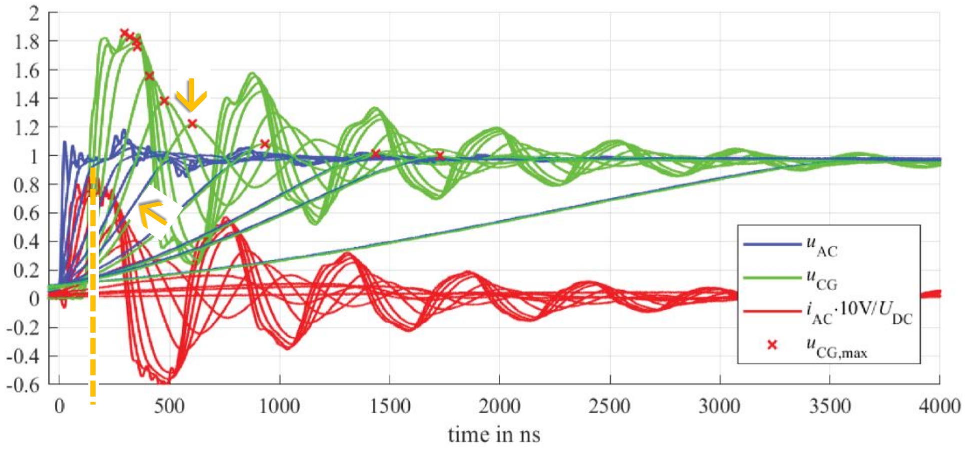
Surge Voltage Reflections

- *Long Motor Cable $l_c \geq \frac{1}{2}\, t_r v$*
- *Short Rise Time of Inverter Output Voltage*
- *Impedance Mismatch of Cable & Motor → Reflect. @ Motor Terminals / High Insul. Stress*

SiC



Source: Bakran / ECPE 2019

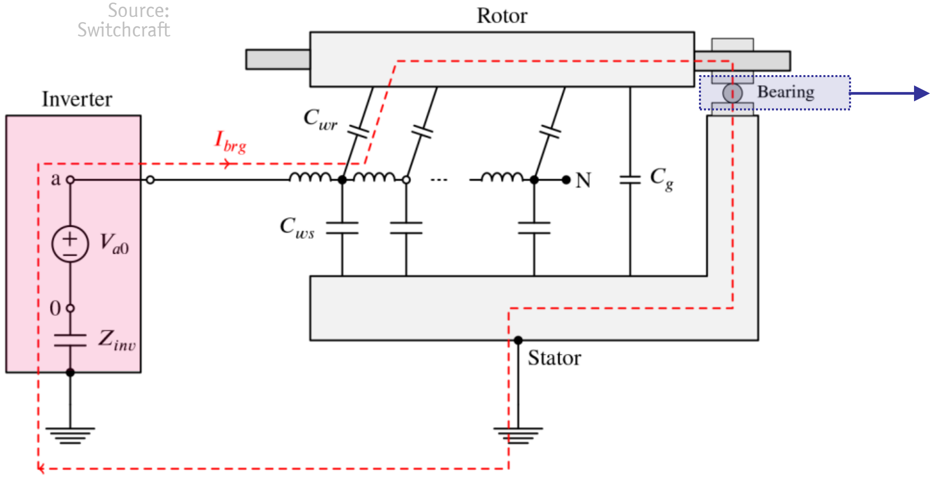


→ *dv/dt- OR Full-Sinewave Filtering / Termination & Matching Networks etc.*

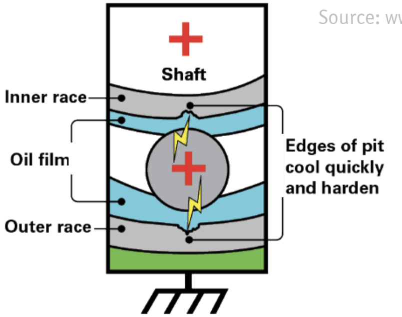
Motor Bearing Currents

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

Source: Switchcraft



Source: www.est-aegis.com



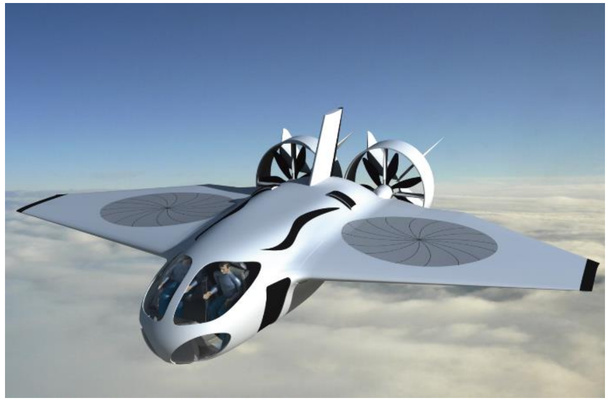
Source: BOSCH

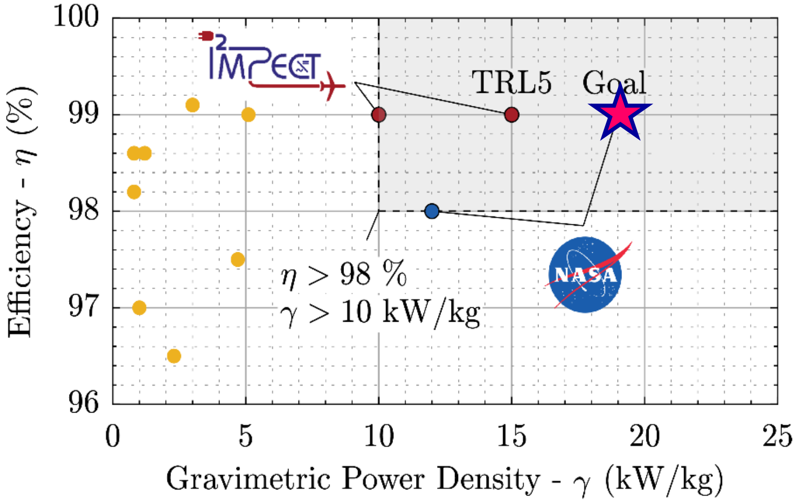
→ *Cond. Grease / Ceram. Bearings / Shaft Grndg Brushes / dv/dt- OR Full-Sinewave Filters*

VSD Inverter - Future Requirements

- *"Sinus-Inverter" / "Non-Expert" Installation — Motor-Integrated Inverter*
- *Low Losses & Low HF Motor Losses*
- *Low Volume & Weight*
- *Wide Output Voltage Range*
- *High Output Frequencies (High-Speed Motors)*

Source: Georgia Tech





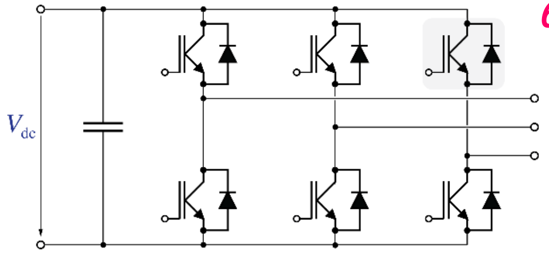
- *Main "Enablers" → SiC/GaN Power Semiconductors & Adv. Inverter Topologies*

SiC vs. Si

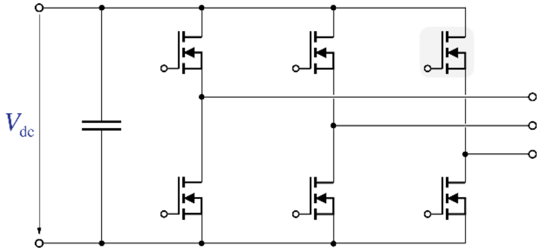
Si vs. SiC

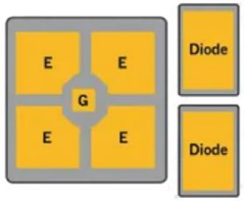
- *Si-IGBT / Diode* → *Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current*
- *SiC-MOSFET* → *Loss Reduction @ Part Load BUT Higher R_{th}*

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 (!)*

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

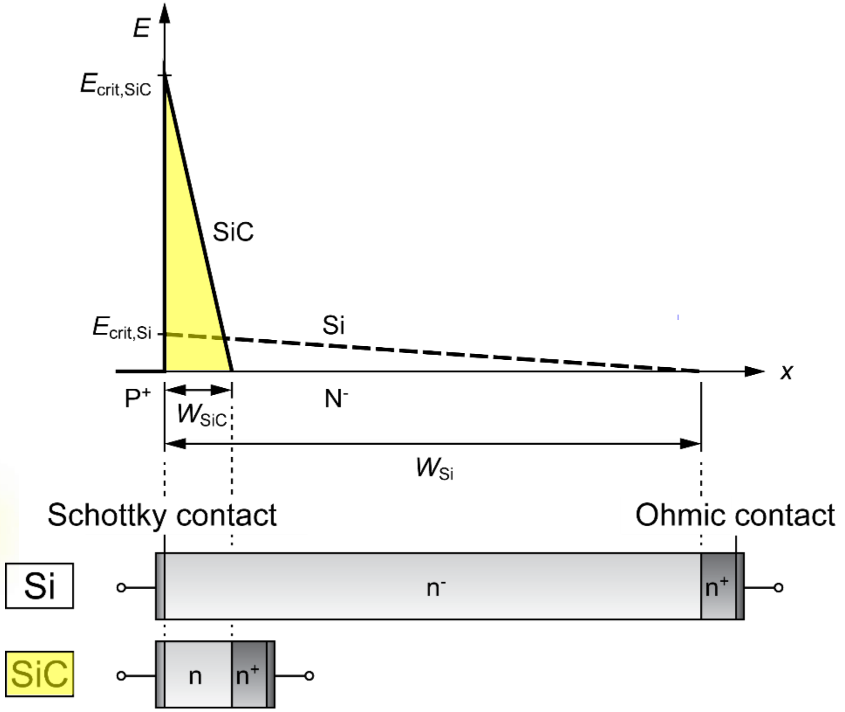
- *Higher Critical E-Field of SiC → Thinner Drift Layer*
- *Higher Maximum Junction Temperature $T_{j,max}$*

at 300 K	Si	GaAs	4H/6H-SiC	GaN
Eg (eV)	1.12	1.4	3.0-3.2	3.4
Ec (MV/cm)	0.25	0.3	2.2-2.5	3
μn (cm^2/Vs)	1350	8500	100-1000	1000
εr	11.9	13	10	9.5
Vsat (cm/s)	$1x10^7$	$1x10^7$	$2x10^7$	$3x10^7$
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}

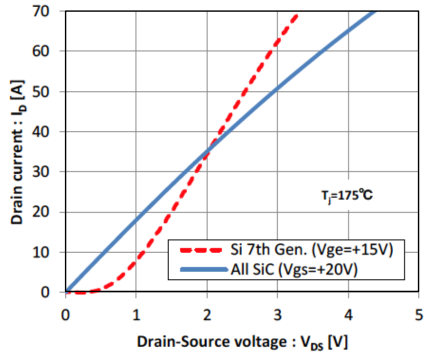
$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$



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

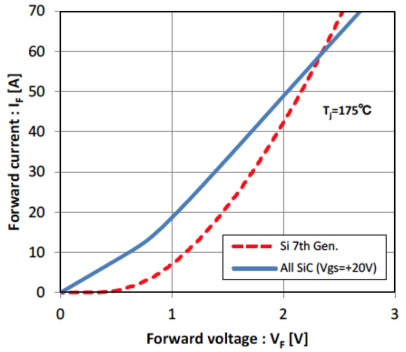
Si vs. SiC Conduction Behavior (1)

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

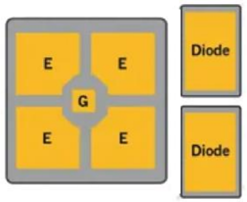


Source: Fuji Electric

Forward



Reverse



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

Source: Infineon

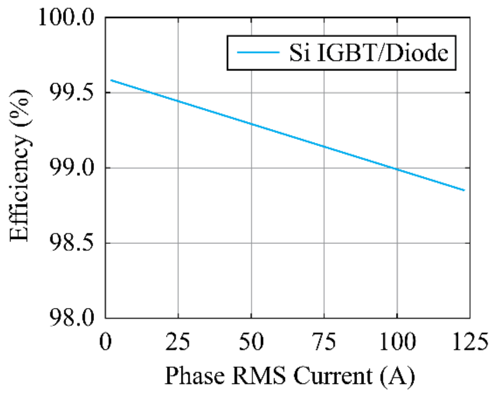
1200V 100A
Die Size: 25.6 mm²

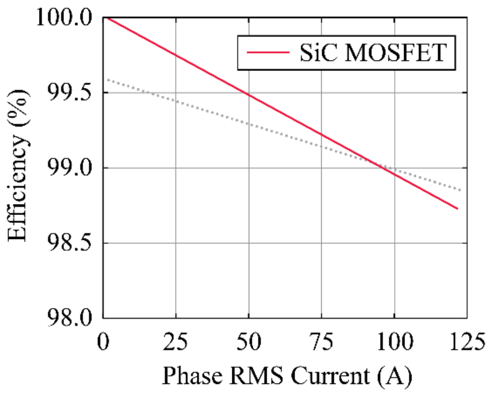
Source: Cree

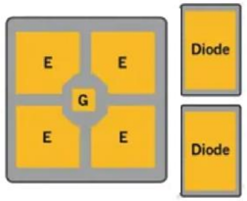
- SiC MOSFETS Facilitate Higher Part Load Efficiency

Si vs. SiC Conduction Behavior (2)

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







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

Source: Infineon

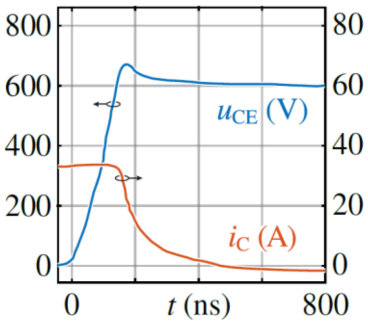
1200V 100A
Die Size: 25.6 mm²

Source: Cree

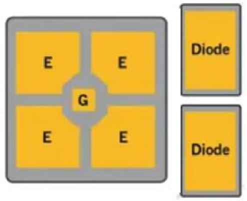
- Efficiency Characteristic Considering Only Conduction Losses

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*

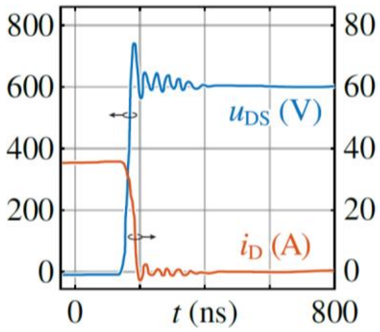


Source: Fuji Electric



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

Source: Infineon

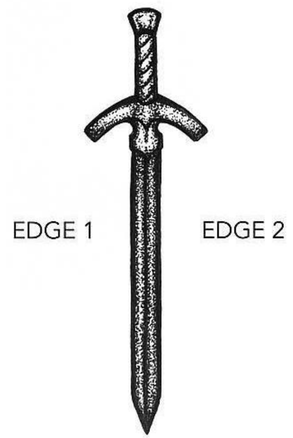


1200V 100A
Die Size: 25.6 mm²

Source: Cree

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

Challenges



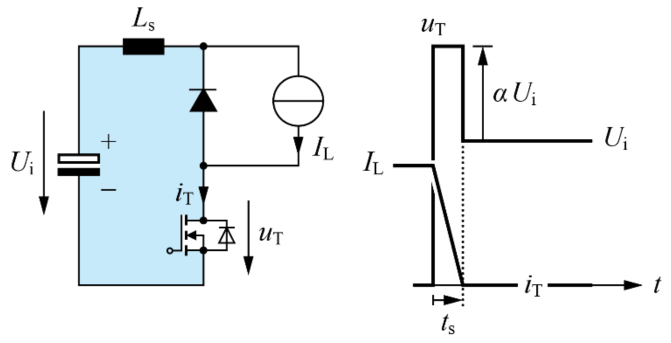
Circuit Parasitics

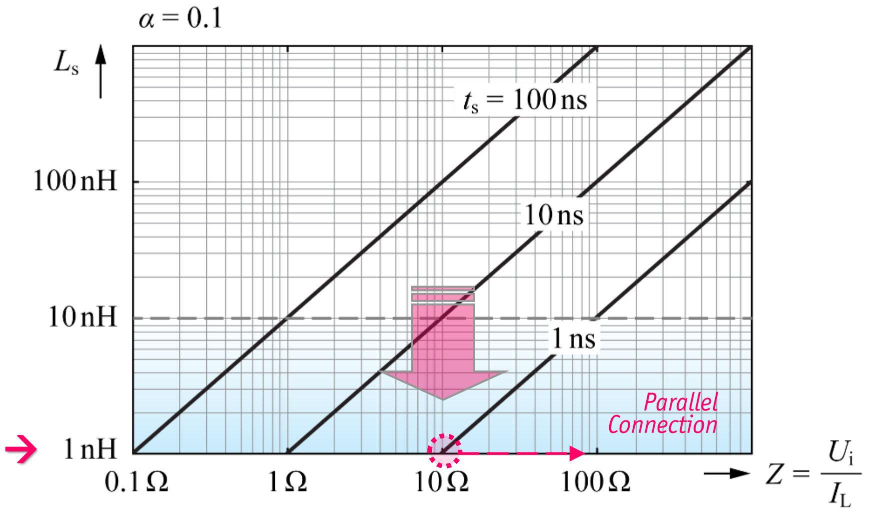
$$L\frac{di}{dt} = u$$

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

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

Z





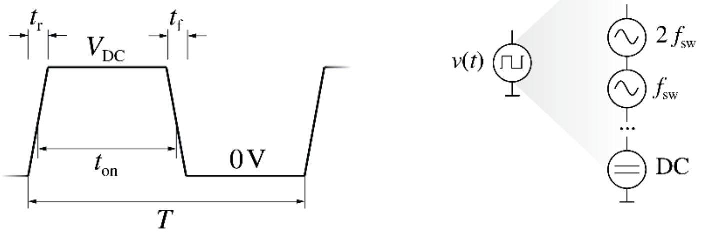
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents (Z-Matching)*

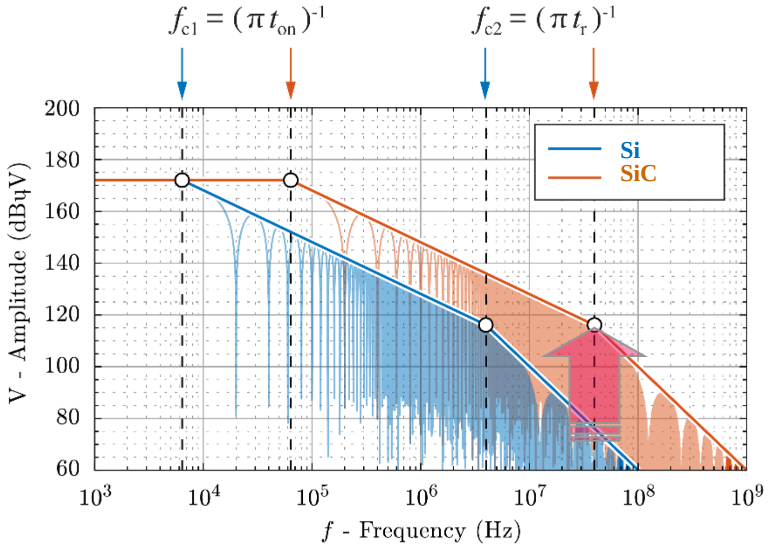
Si vs. SiC EMI Emissions

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

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

V_{DC} = 800V
DC/DC @ D= 50%





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

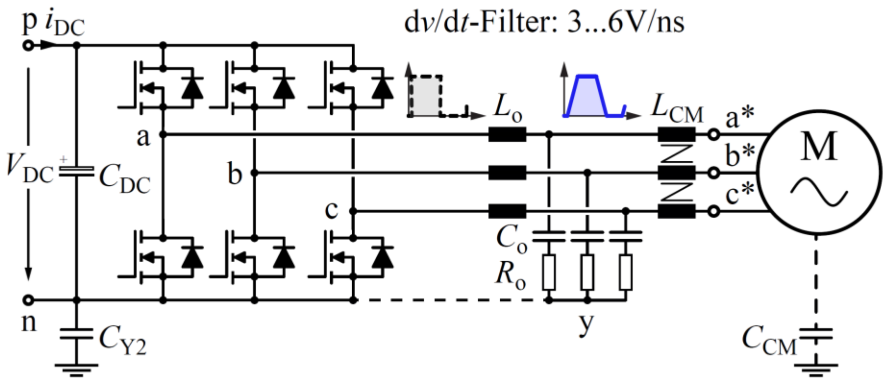
Inverter Output Filters

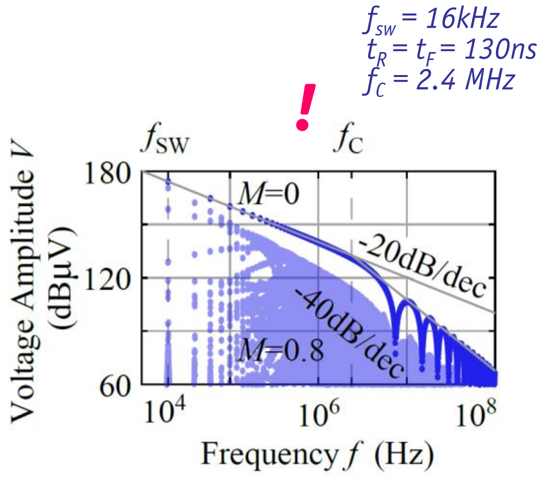
dv/dt-Filters
Full-Sinewave Filters

dv/dt-Control

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*

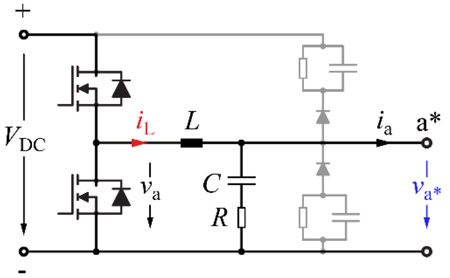


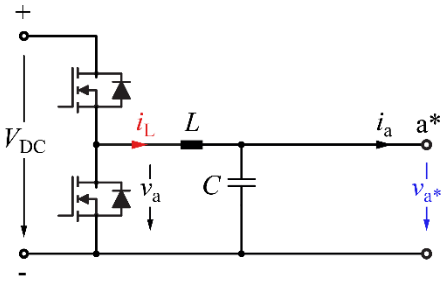


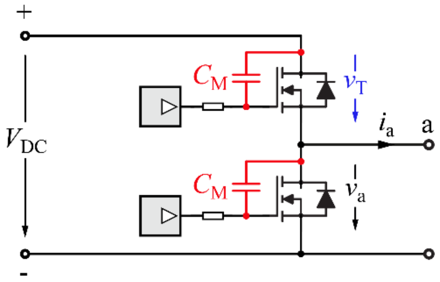
- *Connection to DC-Minus & CM Inductor → Limit CM Curr. Spikes / EMI / Bearing Currents*

Comparison of dv/dt-Filtering Techniques (1)

- **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

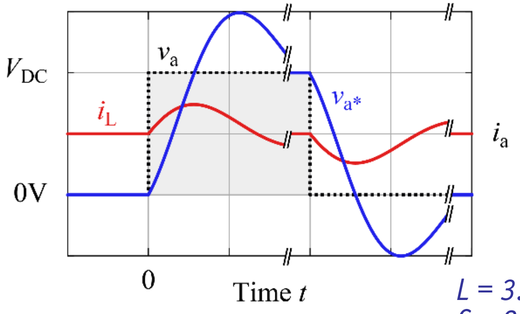




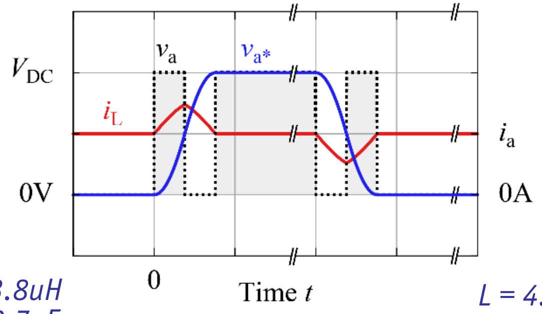


- **Output Voltage Waveforms — V_{DC} = 800V, P_{out} = 10kW, 6kV/us**

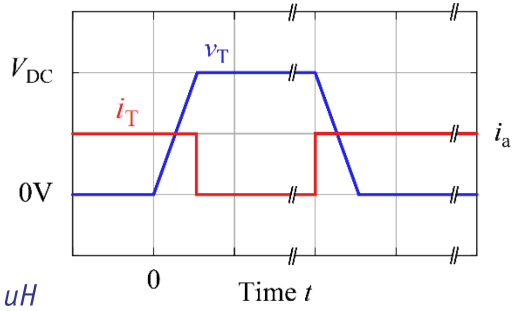
1200V SiC / 16mΩ
C_M = 120pF



L = 3.8uH
C = 2.7nF
R = 19Ω

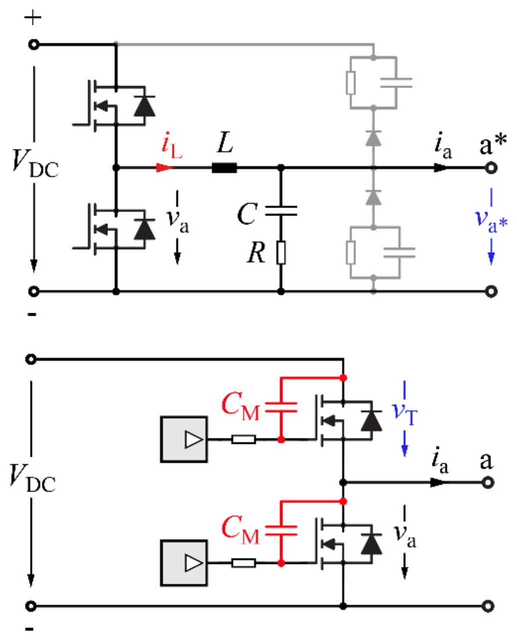


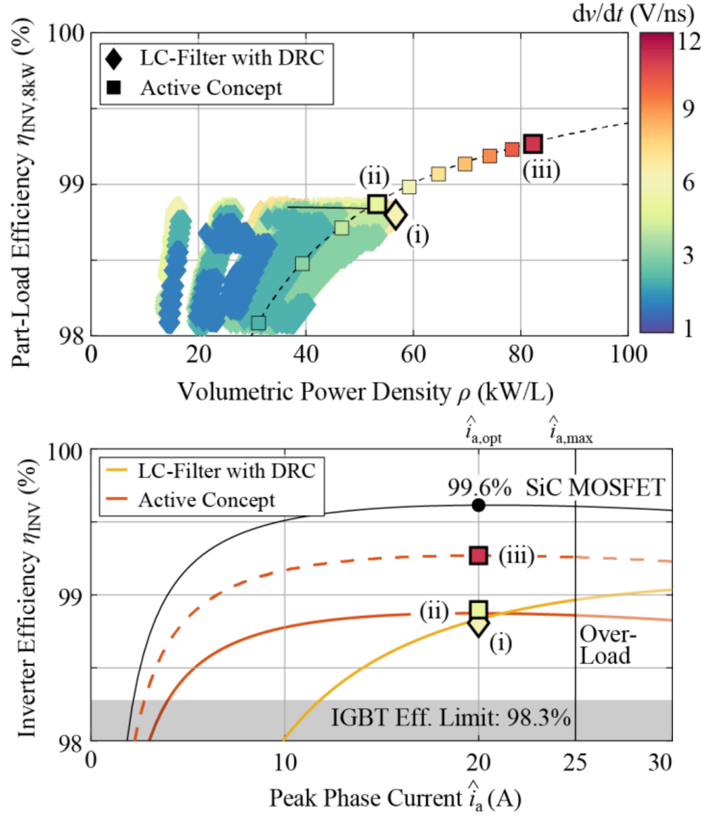
L = 4.1uH
C = 1.3nF



Comparison of dv/dt-Filtering Techniques (2)

- *Comparative Evaluation of Passive & Active Concept*

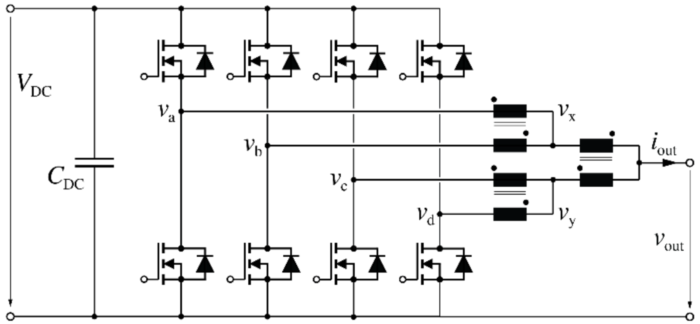


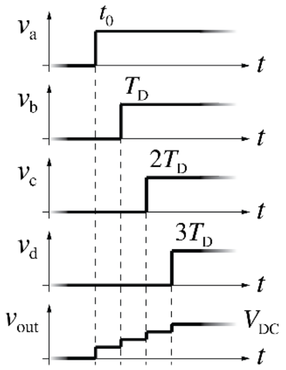


- ***Losses / Power Density*** – V_{DC} = 800V, P_{out} = 10kW, f_{sw} = 16kHz, 1200V SiC-MOSFETs (16mΩ)

Multi-Bridge-Leg dv/dt-Control

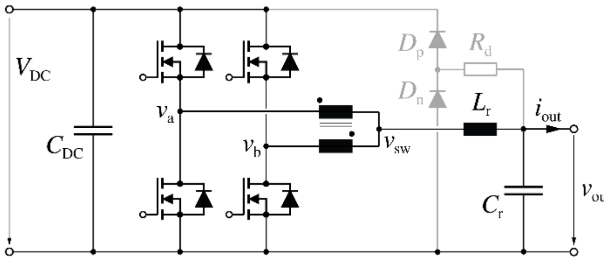
- *Staggered Sw. Parallel Bridge-Legs → Non-Resonant Multi-Step Transistion*

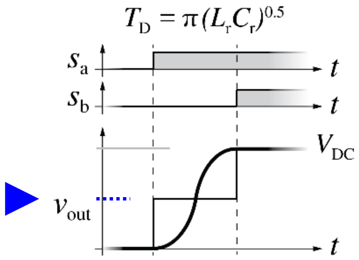




Source: J. Ertl et al.
PCIM Europe 2017

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



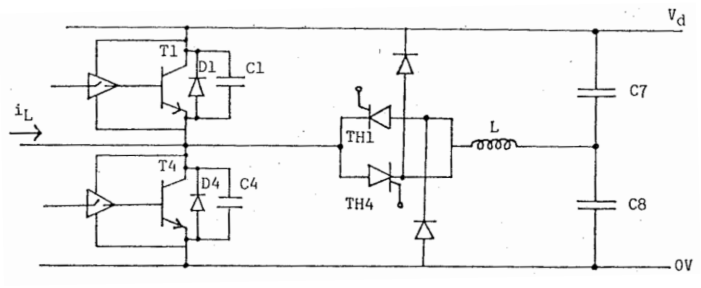


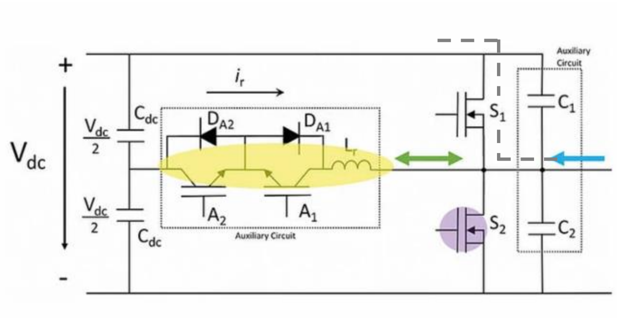
Source: J. Ertl et al.
PCIM Europe 2018

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

Remark Aux. Resonant Commutated Pole

- dv/dt-Limitation w/ Snubber Cap. & Aux. Switches → 1 ... 1.5 kV/us
- Opt. Timing of Aux. & Main Switches → Pre-Flex^{TM} Self-Learning AI Algorithm of Pre-Switch, Inc. We take the hard out of switching.
- Concept Proposed by M. Lockwood & A. Fox @ IPEC 1983



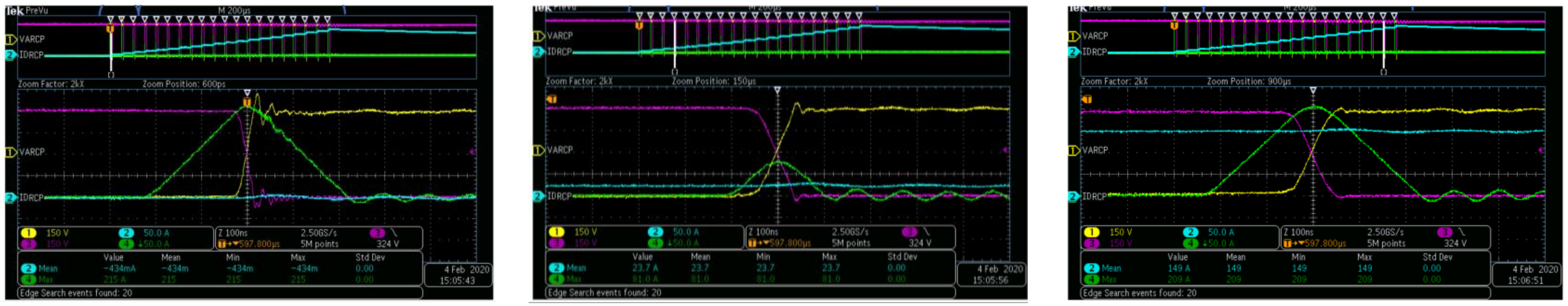


Green: Lr Resonant inductor current (varies with load)

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

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

Blue: Load current varies 0-160A

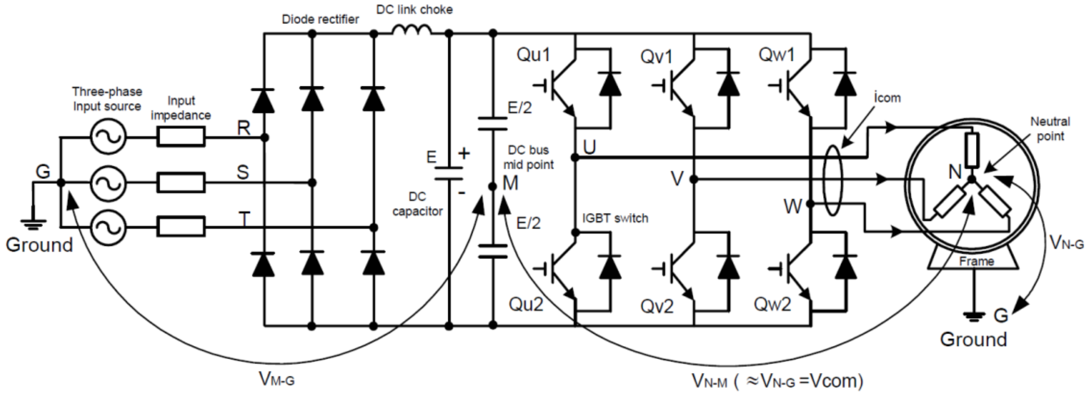


- 99.5% Half-Load | 99.35% Full-Load (100kW/800V_{DC}) Eff. @ 50kHz (1200V/12mΩ SiC MOSFETs)

Inverter Systems w/ Sinusoidal Output Voltages

Output Voltage Filtering

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

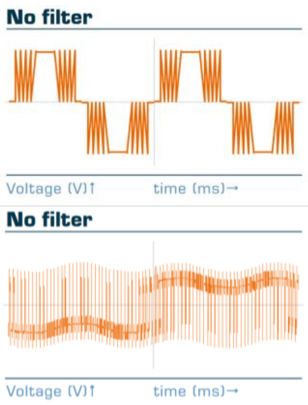


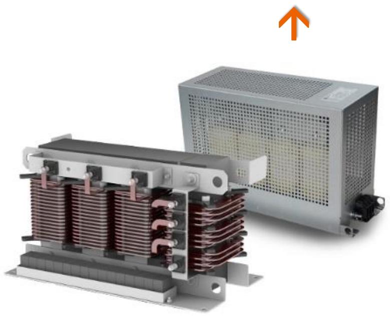
Source: YASKAWA

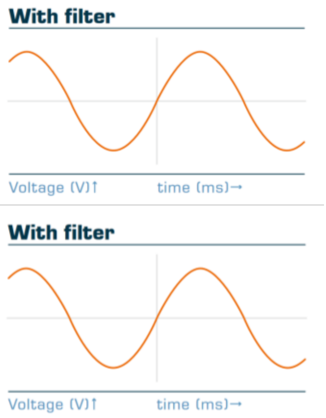
Source: BLOCK

MOTOR VOLTAGE PHASE-PHASE

MOTOR VOLTAGE PHASE-GROUND



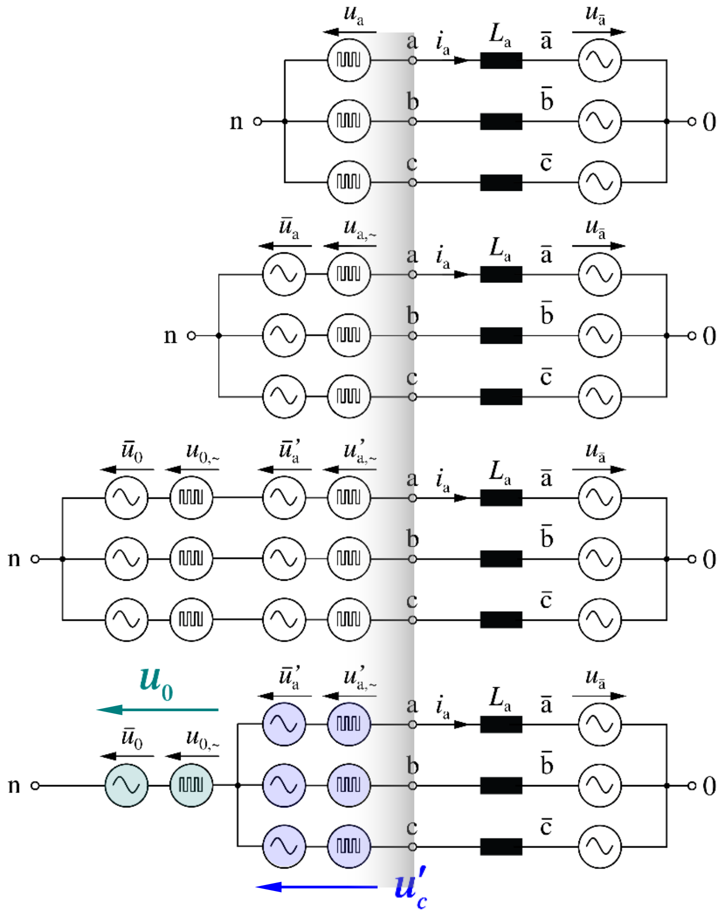




- *Small Filter Size →*
  High Sw. Frequ. → SiC|GaN

Inverter DM & CM Output Voltage Components

Equivalent Circuit (1)



$$u_a = \bar{u}_a + u_{a\sim}$$
$$u_b = \bar{u}_b + u_{b\sim}$$
$$u_c = \bar{u}_c + u_{c\sim}$$

$$u_a = u'_a + u_0$$
$$u_b = u'_b + u_0$$
$$u_c = u'_c + u_0$$

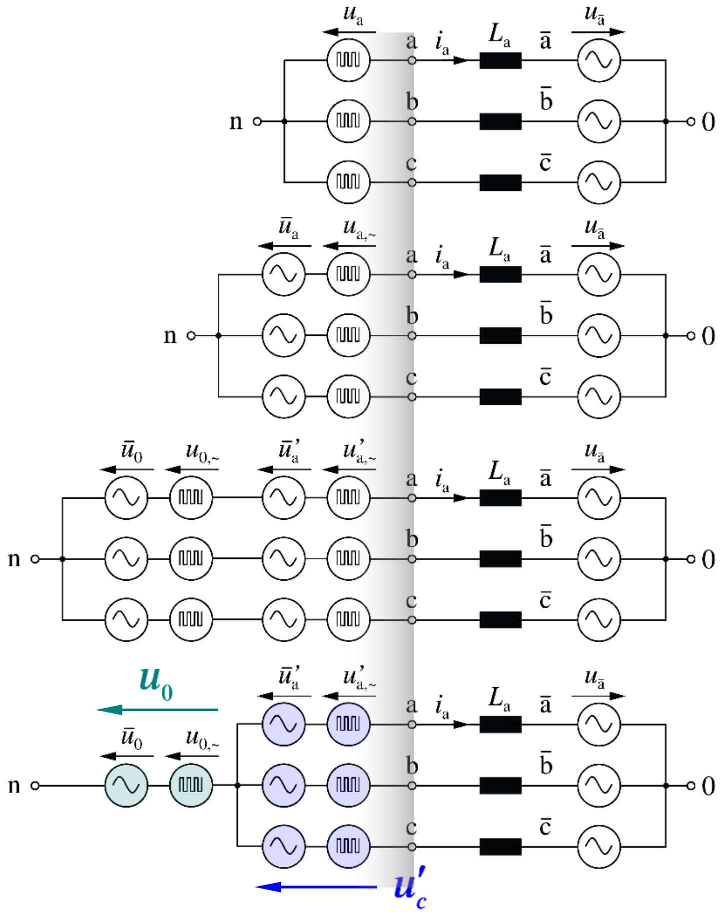
$$u'_a + u'_b + u'_c = 0$$

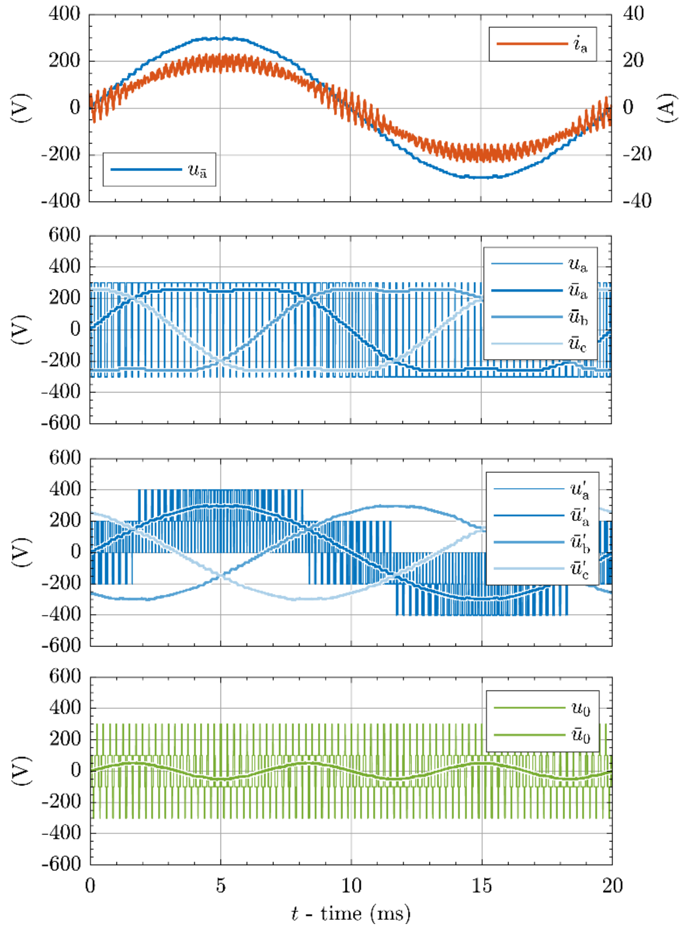
$$u_0 = \tfrac{1}{3}(u_a + u_b + u_c)$$

$$u_a = \bar{u}_a + u_{a\sim}$$
$$u_0 = \bar{u}_0 + u_{0\sim}$$

- *Active DM Voltage Component* u'_c
- *Inactive CM Zero Sequence Voltage* u_0
- *Low-Frequ. & Sw.-Frequ. Components*

Equivalent Circuit (2)



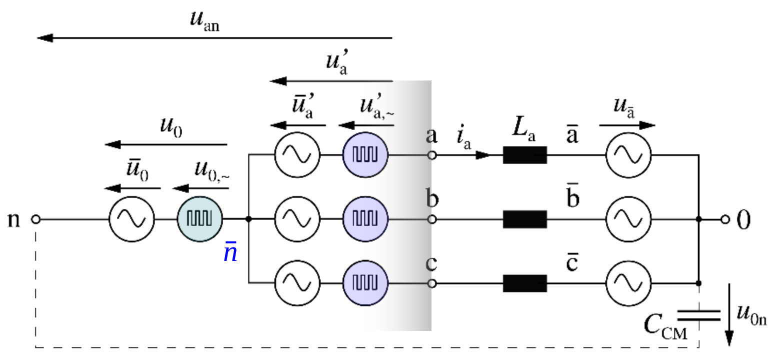


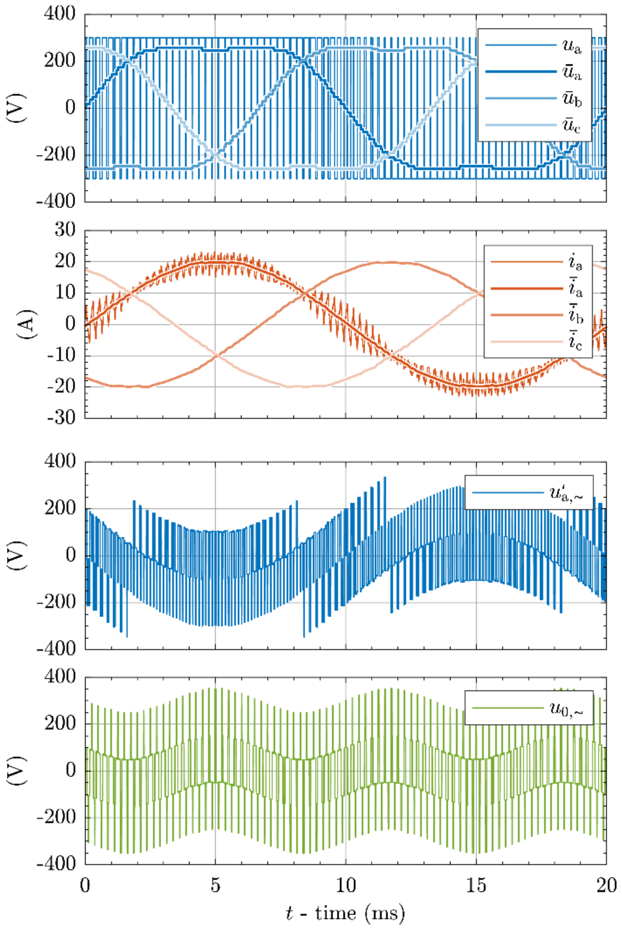
Equivalent Circuit (3)

- *Active Sw.-Frequ. DM Voltage*
- *Inactive Sw.-Frequ. CM Voltage*

$$u_0 = u_{0n} \quad \rightarrow \quad u_{\bar{n}0} \equiv 0$$

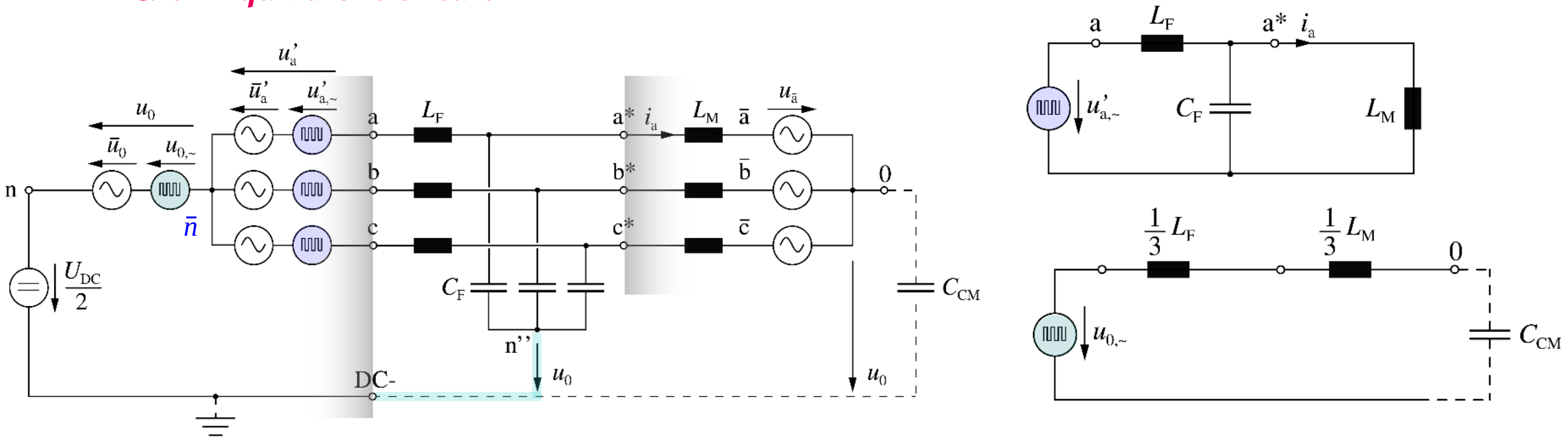
$$u_0 + u'_a = L\frac{di_a}{dt} + u_a + u_{0n}$$
$$u_0 + u'_b = L\frac{di_b}{dt} + u_b + u_{0n}$$
$$u_0 + u'_c = L\frac{di_c}{dt} + u_c + u_{0n}$$
$$3u_0 + 0 = 0 + 0 + 3u_{0n}$$



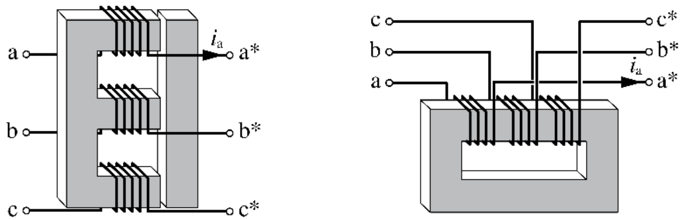


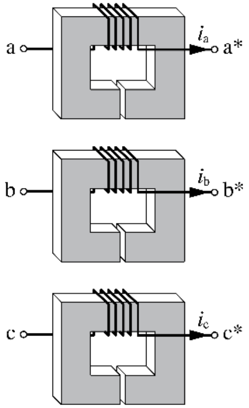
Differential- / Common-Mode Filtering

■ *DM & CM Equivalent Circuit*



■ *Filter Inductor Types*



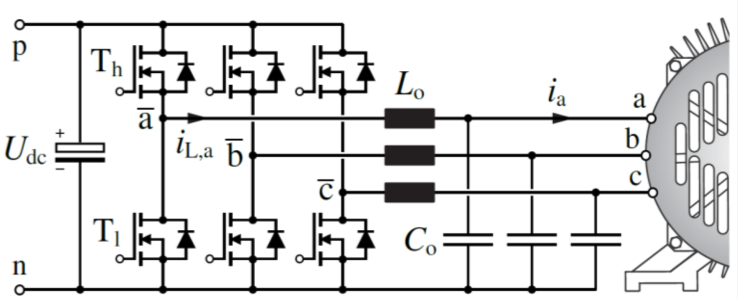


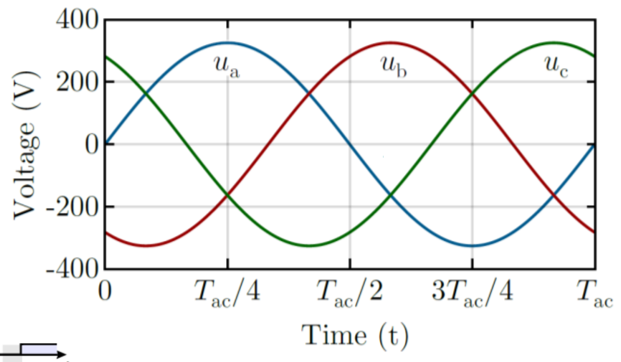
- *DM Inductor / CM Inductor / Phase Inductors*

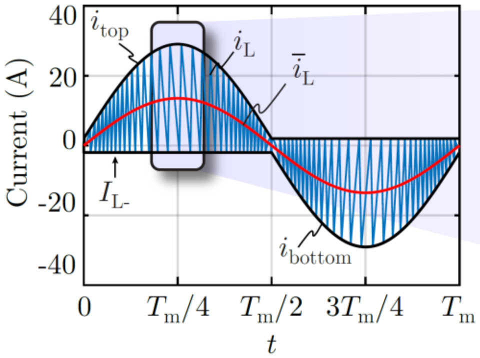
Triangular Current Mode (TCM) ZVS Operation

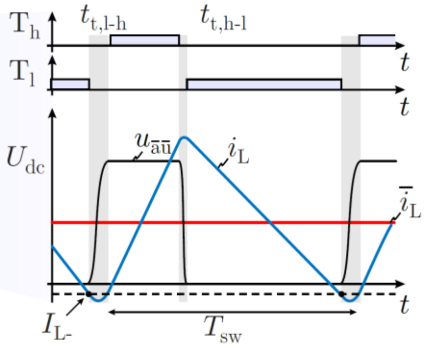
Full-Sinewave Filter & ZVS Operation

- *Sinusoidal Output Voltage*
- *ZVS of Inverter Bridge-Legs*
- *High Sw. Frequency & TCM → Low Filter Inductor Volume*





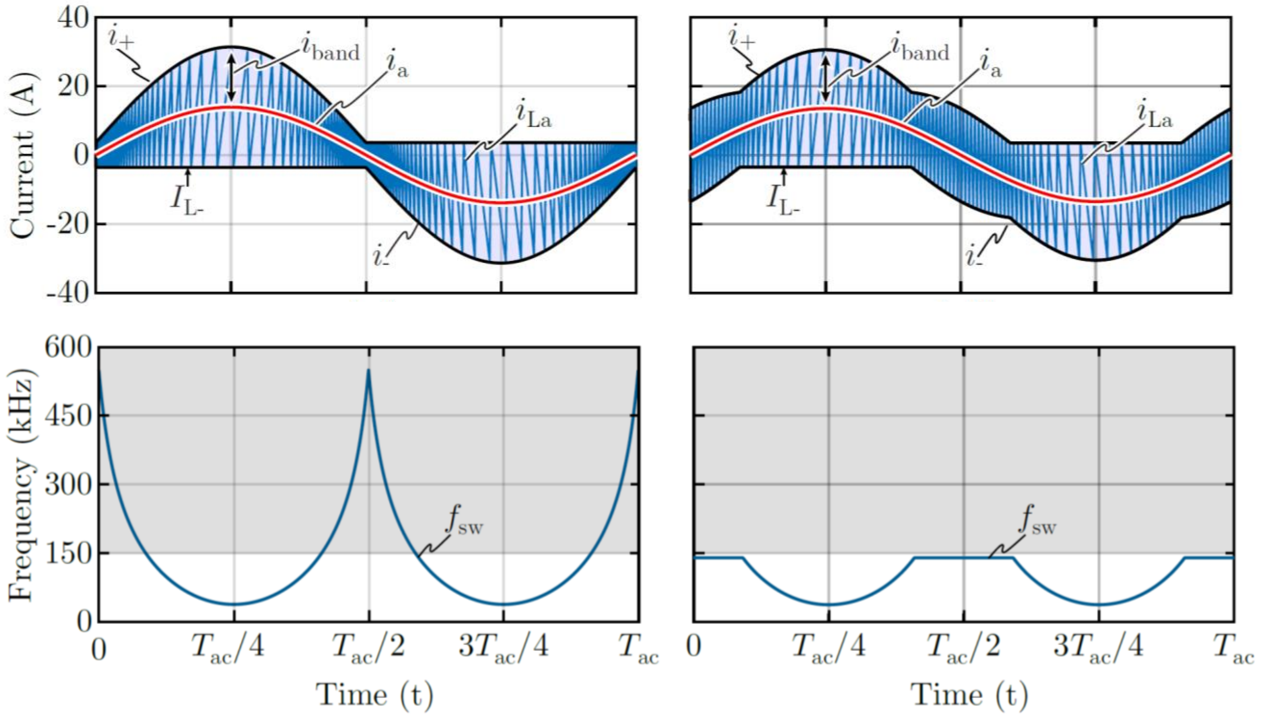




- *Only 33% Increase of Transistor Conduction Losses Compared to CCM (!)*
- *Very Wide Switching Frequency Variation*

Frequency-Bounded TCM → B-TCM

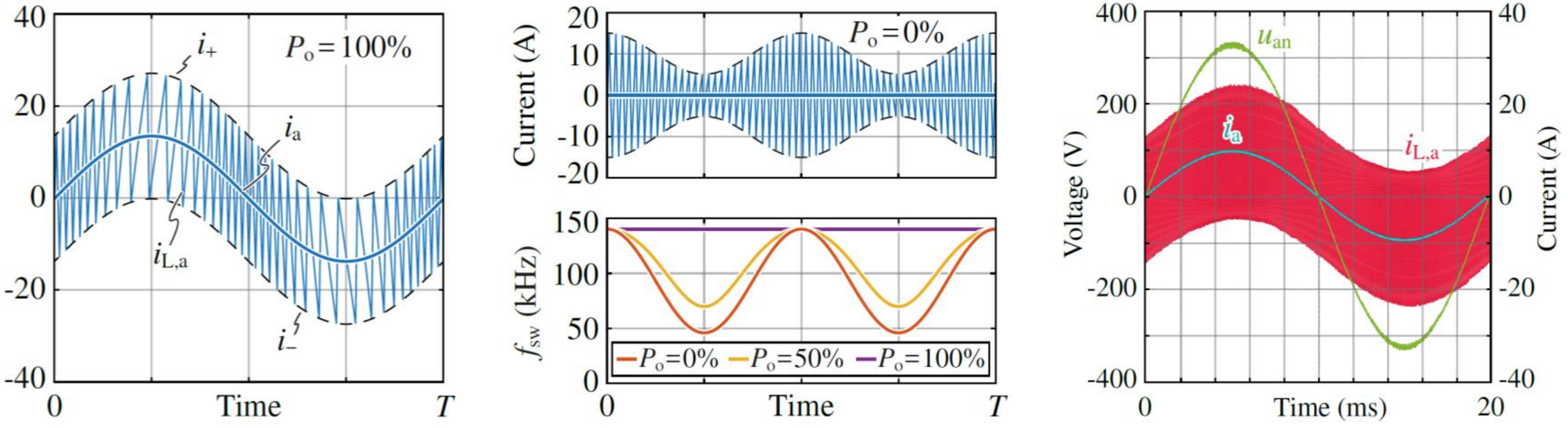
- *Very Wide Switching Frequency Variation of TCM → B-TCM*



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

Frequency-Bounded B-TCM → S-TCM

- *Sinusoidal Switching Boundaries* → *S-TCM*
- *Adaption for Low Output Power Considering* $f_{sw,max}$ *= 140kHz*

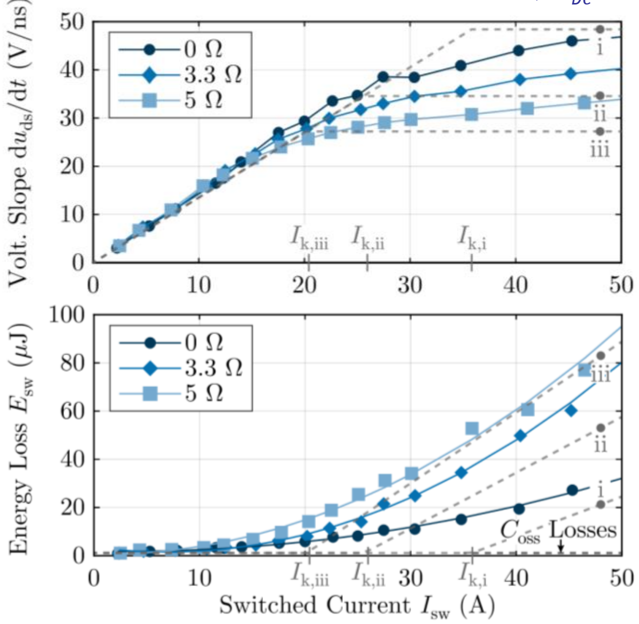


- *TCM → S-TCM ≈ 10% Further Increase of Transistor Conduction Losses*

Remark Residual ZVS Losses

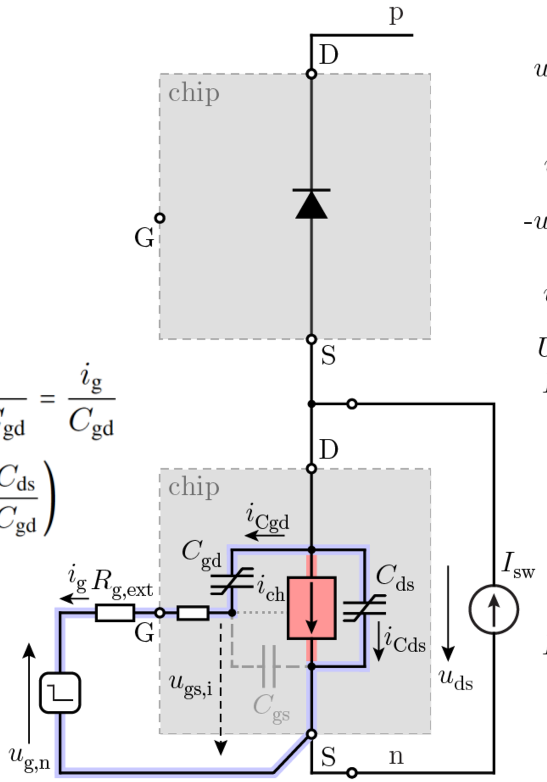
- Overlap of u_{DS} & Channel Current i_{ch} @ High $I_{sw} > I_k$
- Temporary Turn-on Due to $u_{GS,i} > u_{th}$

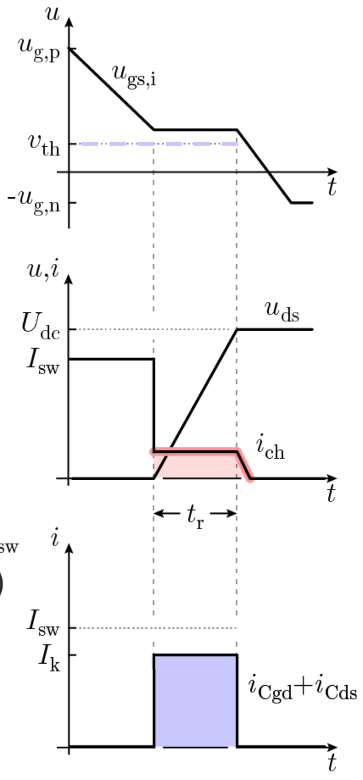
650V SiC, U_{DC} = 400V



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

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

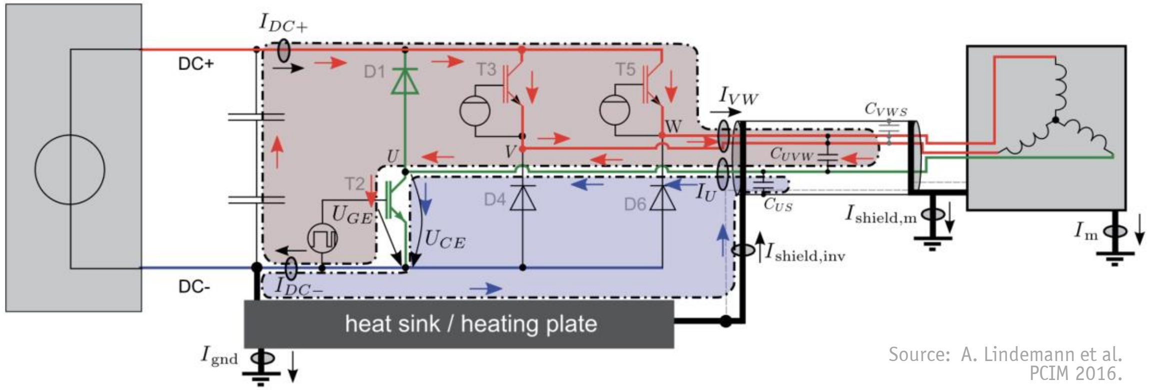




- "Kink" Current I_K Dependent on Inner & Outer Gate Resistance & $u_{g,n}$

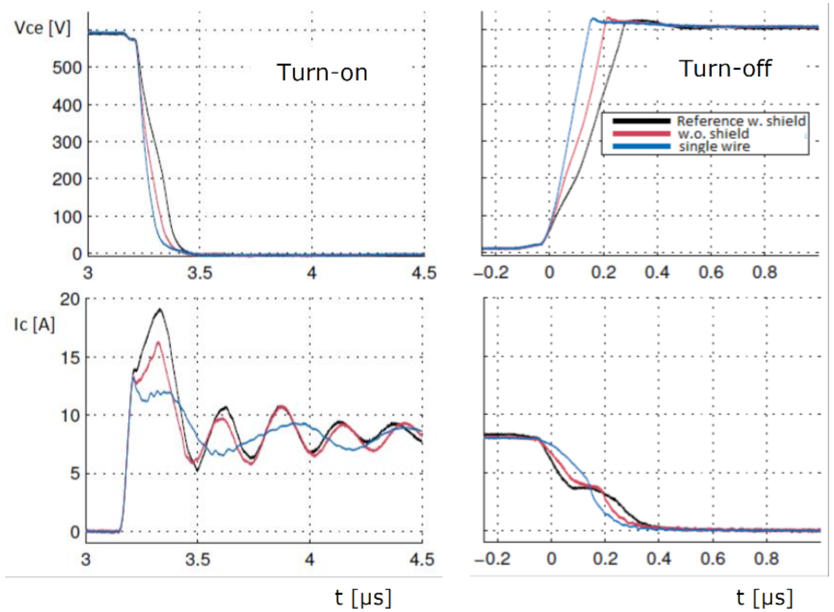
Remark Influence of Motor Cable Capacitance

- *Cable Capacitance of Several 100pF/m (!)*
- *Large Charging / Discharging Current Peaks @ Sw. Transitions*
- *Increase of Turn-On / Decrease of Turn-Off Losses*
- *Analysis for IGBTs shows 30% Overall Increase of Sw. Losses (50m Cable)*



Source: A. Lindemann et al. PCIM 2016.

L_{Cable}=10m



→ *Output Inductor for Decoupling OR Full-Sinewave Output Filter*

Source: AN17-002 SEMIKRON

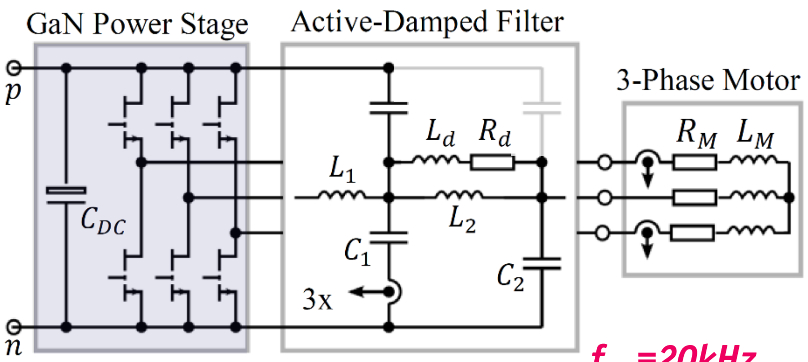
Continuous Current Mode (CCM) Operation

Full-Sinewave 2-Stage Output Filter (1)

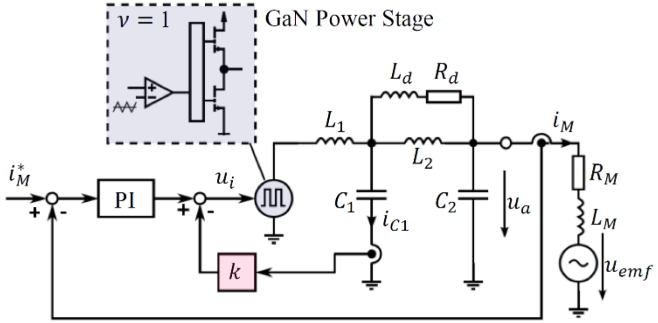
PERFECTION IN AUTOMATION
A MEMBER OF THE ABB GROUP
TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

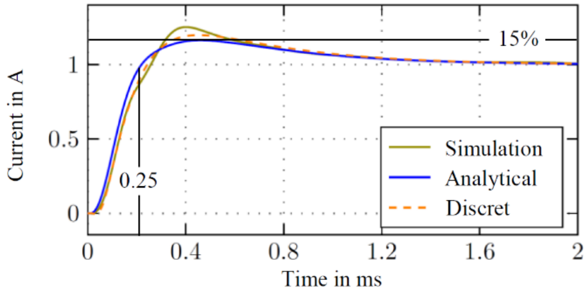
- *Sinewave Output & IEC/EN 55011 Class-A*
- *Low-Loss Active Damping of 1st Filter Stage — Neg. Cap. Current Feedback*
- *2kW / 400V DC-Link 3-Φ 650V GaN Inverter (I_M=5A), $f_{out,max}$ = 500Hz*
- *Sw. Frequency f_{sw}= 100kHz*

$f_{C,1}$=7kHz



$f_{C,2}$=20kHz

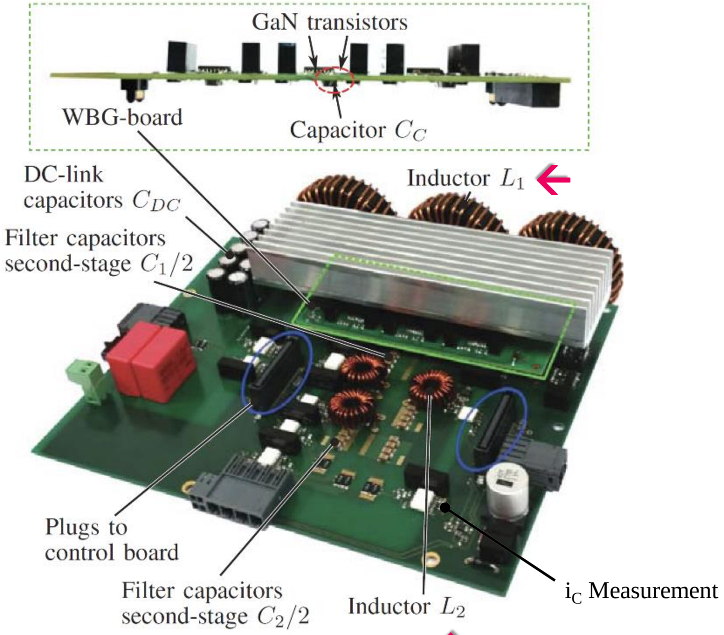


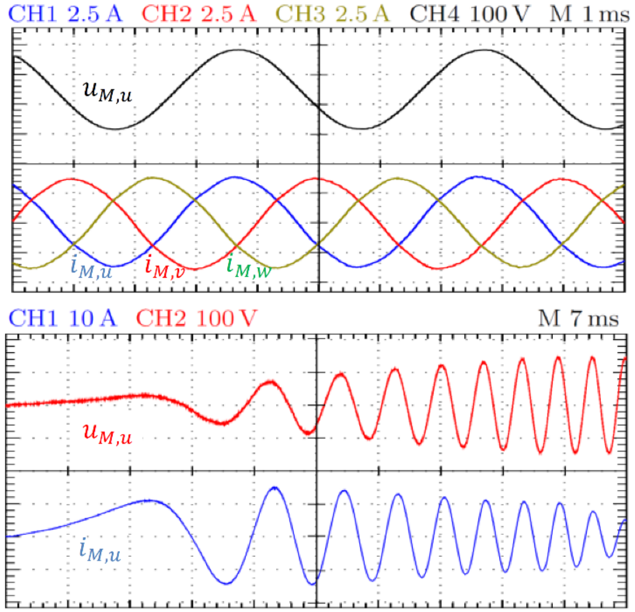


→ *Evaluation of Optimized Inductors — Soft Sat. Toroidal Iron Powder Cores*
→ *L_1=200uH / C_1=2.5uF | L_2=25uH / C_2=2.5uF / L_d=33uH / R_d=5.6Ω*

Full-Sinewave 2-Stage Output Filter (2)

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

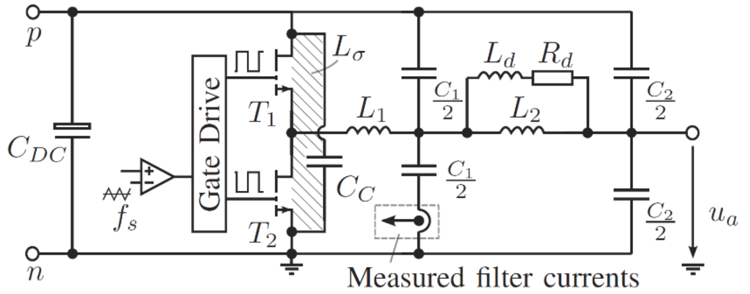


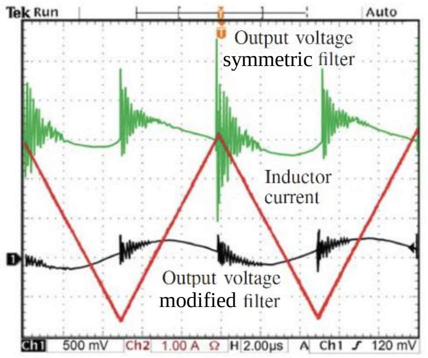


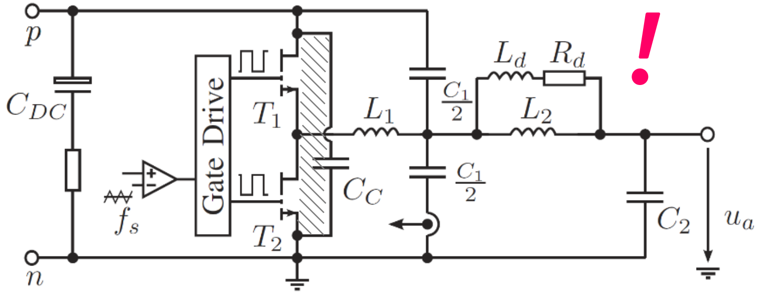
- *Stationary Motor Phase Curr. /Voltage @ 2.5Nm & f_{out}=250Hz*
- *Speed Increase from Standstill to n = 3000rpm in 60ms*

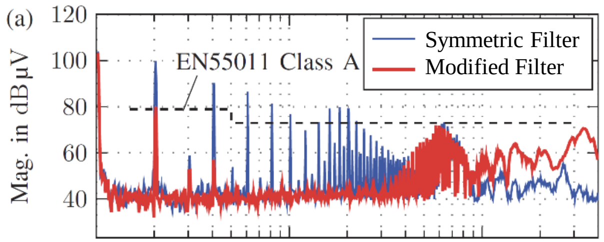
Full-Sinewave 2-Stage Output Filter (3)

- *Modification of Output Filter Structure*
- *Elimination of Direct Cap. Coupling Between Output and Noisy (!) DC+ (Due to ESR of C_{DC})*
- *For Opt. i_C-Feedback C_1 Realized Using ≈Linear Kemet KC-Link*





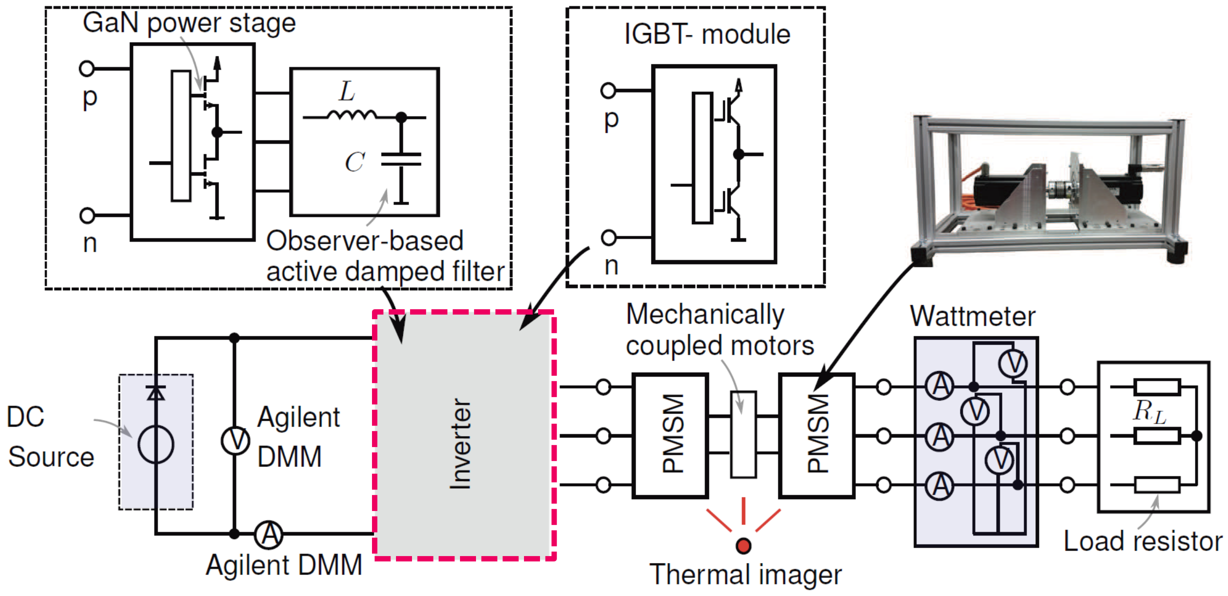


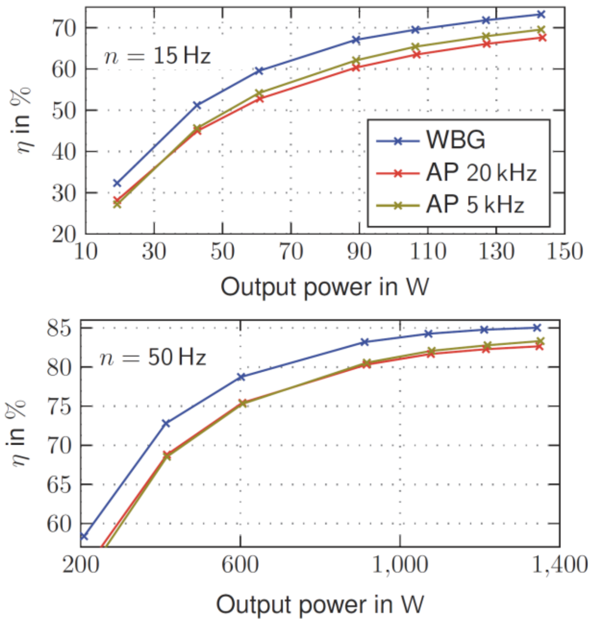


- *Modified Filter → Compliance to EMI Standard EN55011 Class-A*

GaN vs. IGBT Inverter Efficiency Comparison

- *Si Easypack 1200V/35A vs. GaN 650V/30A (50mΩ)*
- *5...20kHz Standard PWM IGBT Motor Inverter (B&R Industrial Automation)*
- *Efficiency Measurement — Inverter DC Input → Load Machine AC Output*



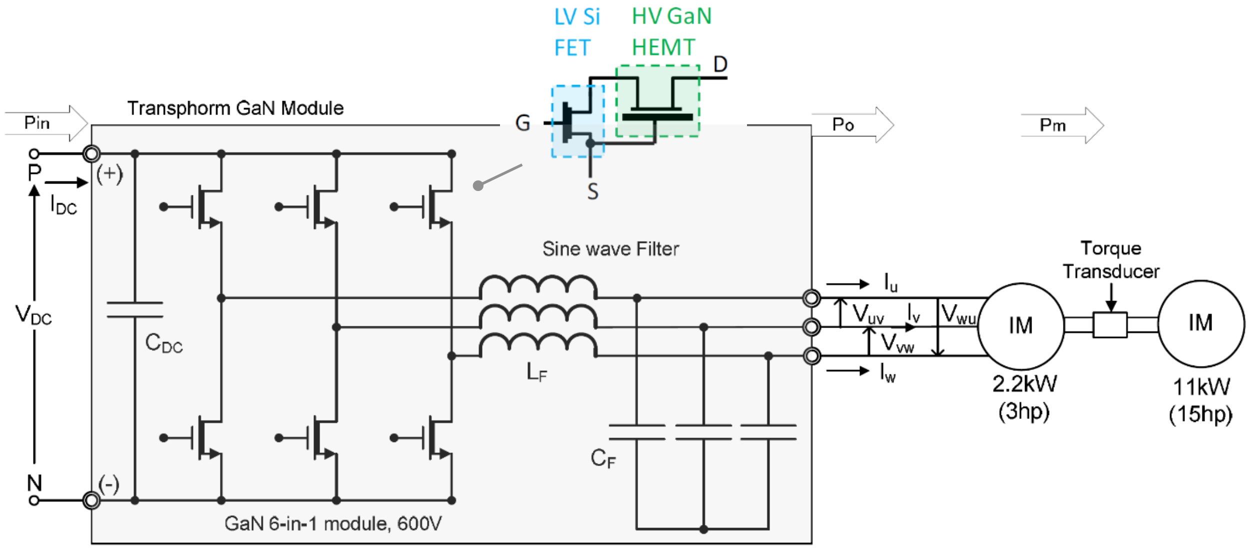


- *Efficiency Improvement of 2-4% in Whole Operating Range*
- *Low Sw. Losses of GaN Inverter & Low Output Filter Losses & Low Motor Iron Losses*

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*



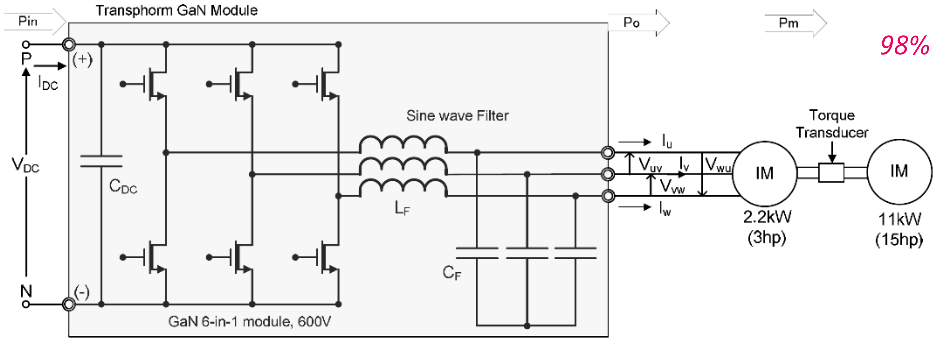
600V/14A

→ *Comparison to Si-IGBT Drive Systems*

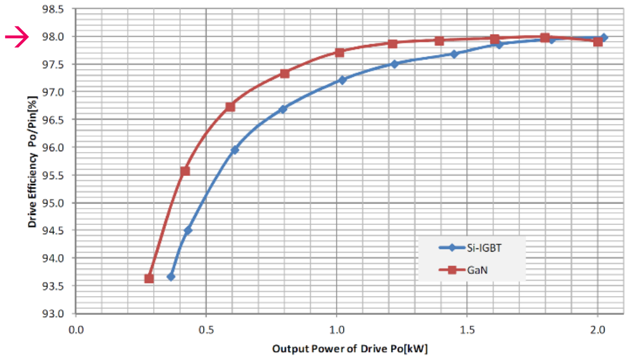
3-Φ 650V GaN Inverter System (2)

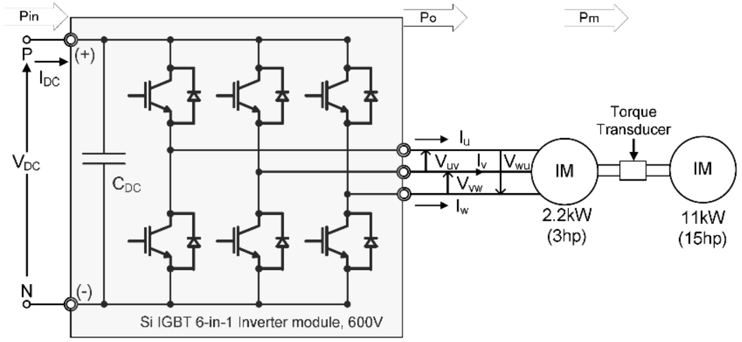
Source: YASKAWA

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

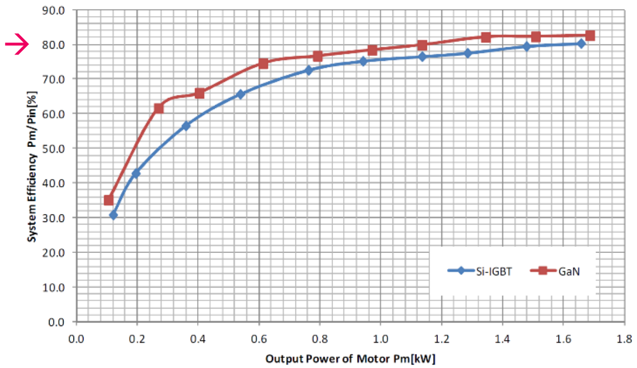


98% →





80% →

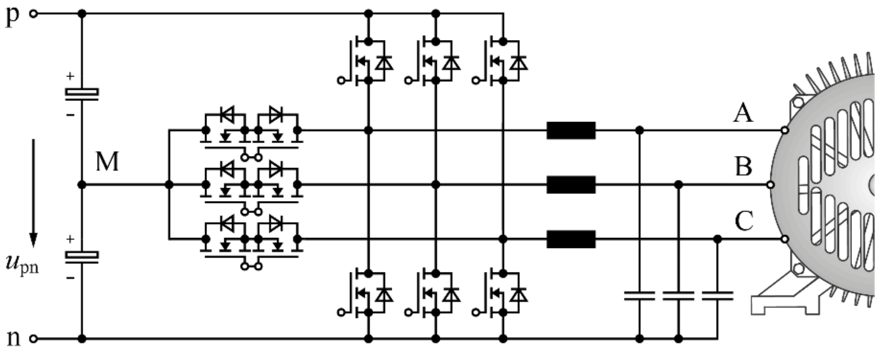


→ *2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses) !*

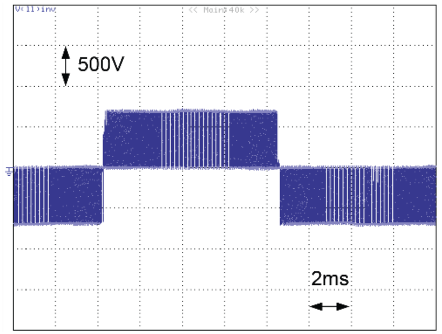
Multi-Level / Multi-Cell Converters & Modularity

3-Level T-Type Inverter (1)

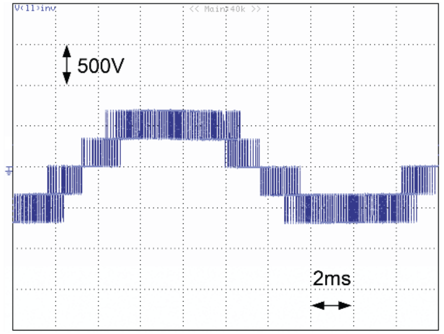
- *Higher Number of Output Voltage Levels / Lower CM Voltage Steps*
- *Neutral Point Clamped | Flying Capacitor | T-Type Bridge-Leg Topologies*



Line-to-Line Voltage



2-Level Bridge-Leg

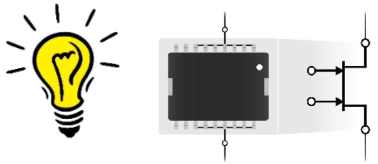


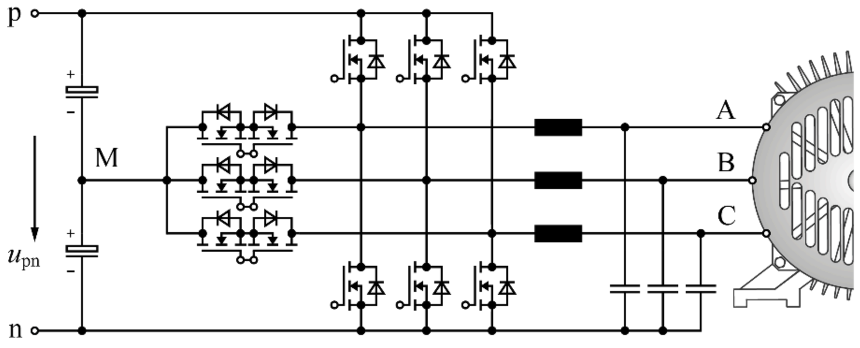
3-Level Bridge-Leg

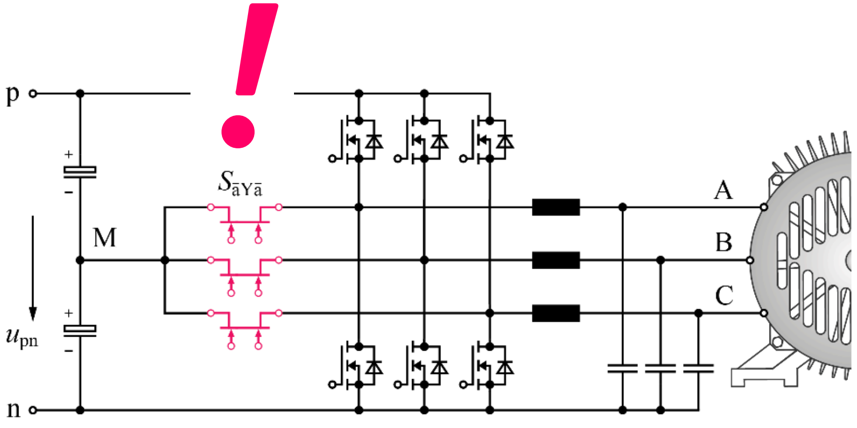
- *More Complicated Bridge-Leg Structure*
- *On-State-Losses of Series-Connected Switches*

3-Level T-Type Inverter (2)

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



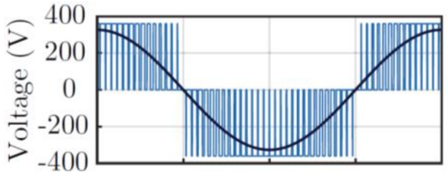


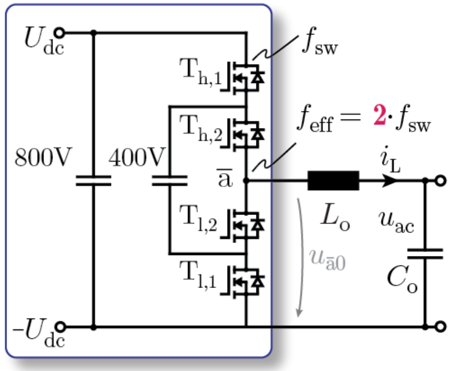


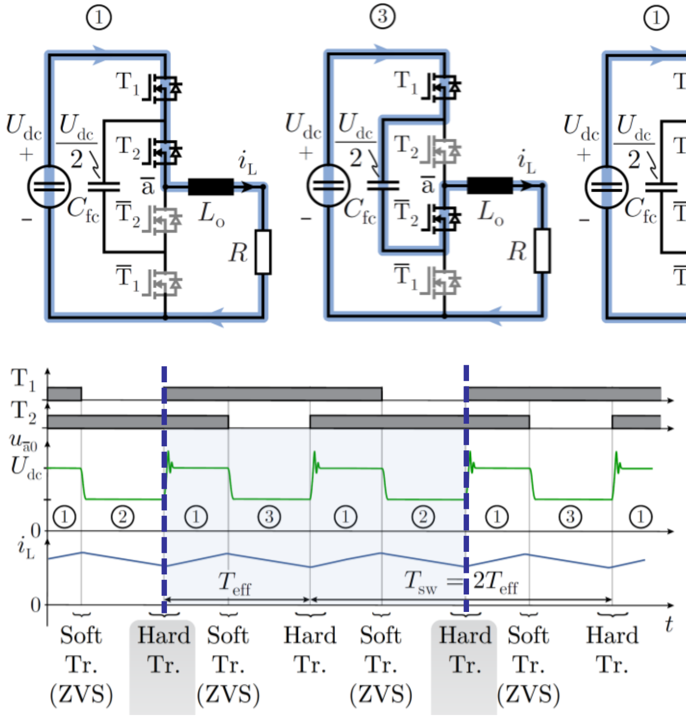
- *Factor 4 (!) Reduction of Chip Area vs. Discrete Realization @ Same $R_{(on)}$*

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



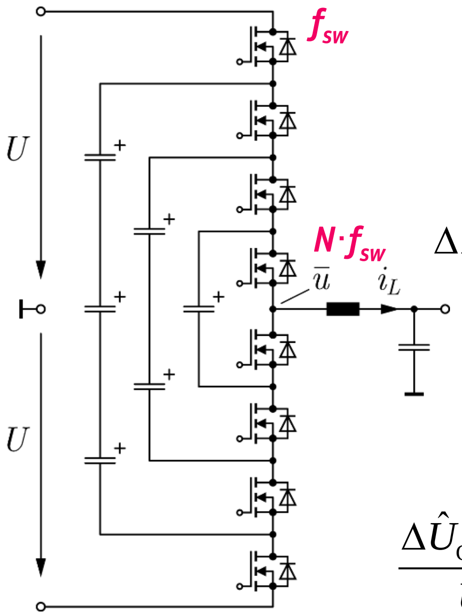




- FC Voltage Balancing Possible also for DC Output

Scaling of Flying Cap. Multi-Level Concepts

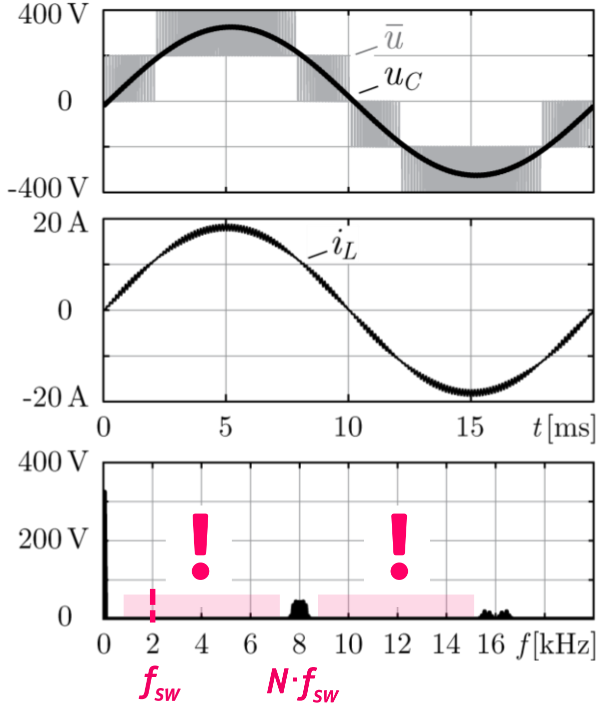
- Series Interleaving → Reduced Ripple
- $f_{sw,eff} = N \cdot f_{sw}$ @ f_{sw}-Determined (!) Switching Losses
- Lower Overall On-Resistance @ Given Blocking Voltage
- Application of LV Technology @ HV



$$\frac{U}{8 f_s L}$$

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

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

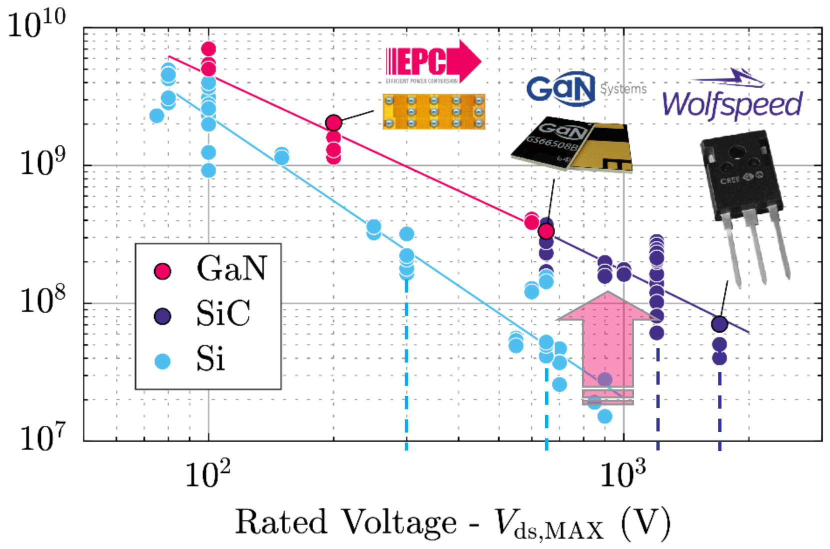


- Scalability / Manufacturability / Standardization / Redundancy

SiC/GaN Figure-of-Merit

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

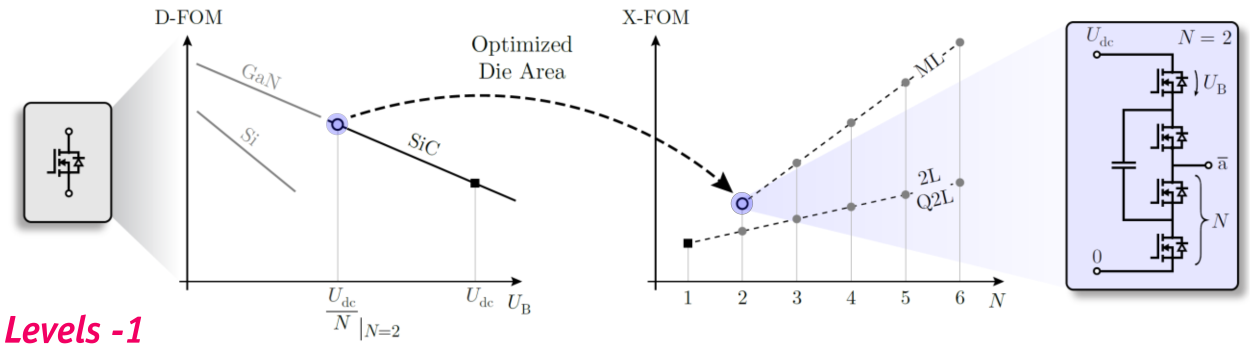
$$\mathrm{FOM} = \frac{1}{R_{\mathrm{ds,on}} Q_{\mathrm{oss}}}$$



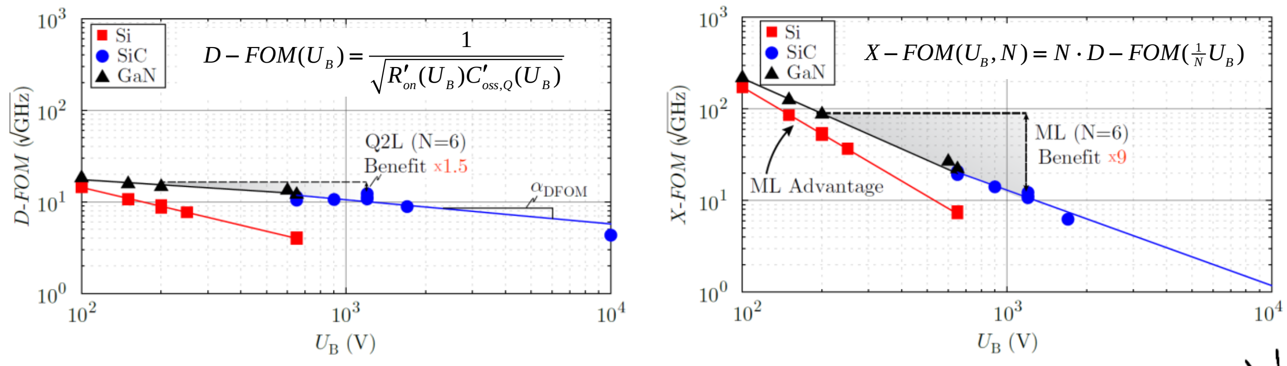
- *Advantage of LV over HV Power Semiconductors*
- *Advantage of Multi-Level over 2-Level Converter Topologies*

X-FOM of ML-Bridge-Legs

- *Quantifies Bridge-Leg Performance of N-Level FC Converters*
- *Identifies Max. Achievable Efficiency & Loss Opt. Chip Area @ Given Sw. Frequ.*



N= # of Levels -1



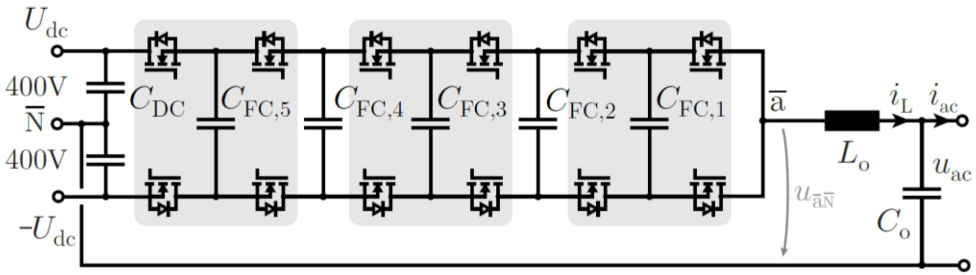
- *Compared to 2-Level Benchmark @ Same Filter Ind. Volt-Seconds* →

$P_{semi,min,ML} \approx 1/N^{1.2} P_{semi,min,2L}$

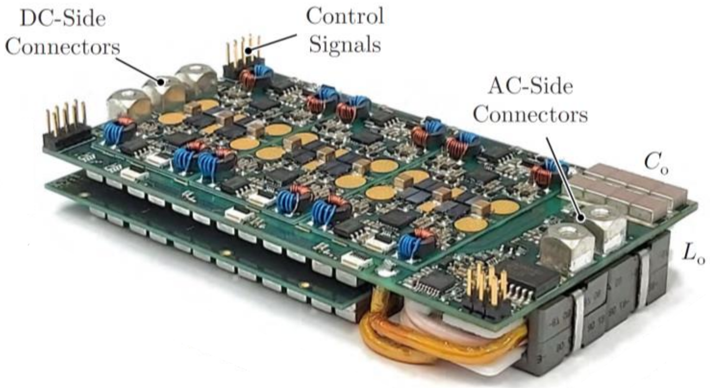
$A_{chip,ML} \approx N^{1.2} A_{chip,2L}$

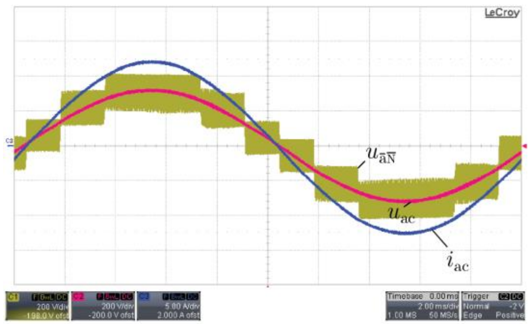
7-Level Flying Cap. 200V GaN Inverter (1)

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



★ 260 W/in^3

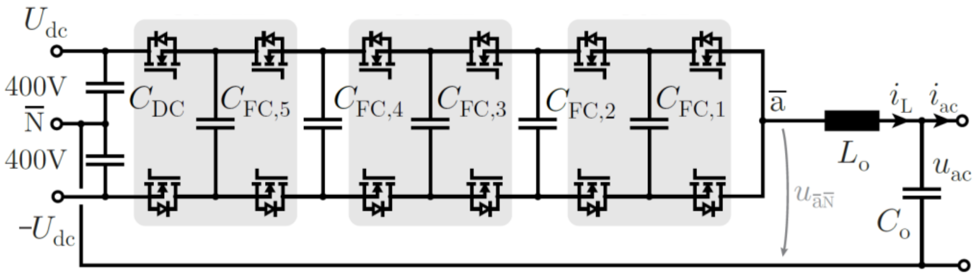




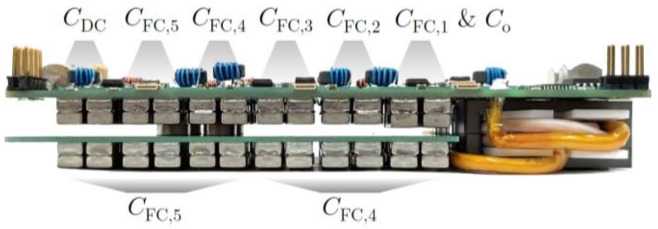
- High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor L_0

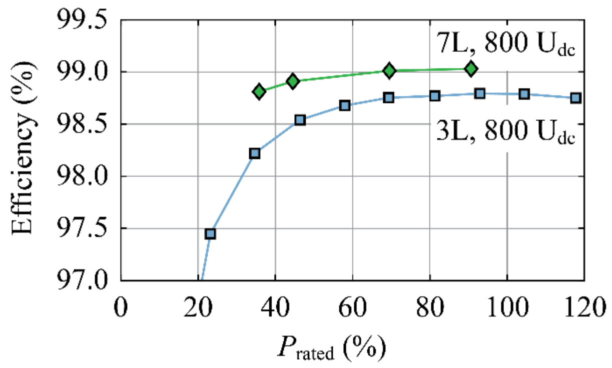
7-Level Flying Cap. 200V GaN Inverter (2)

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



★ 260 W/in³

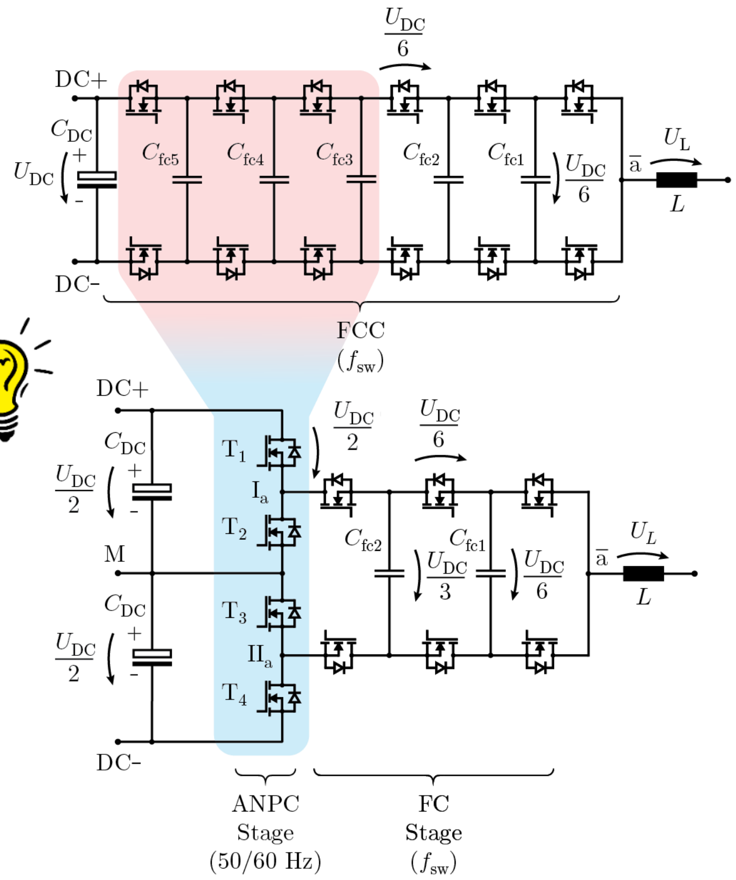


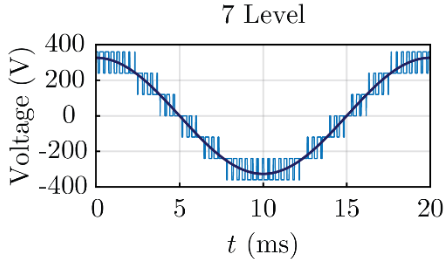


- High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor L_o

3-Φ Hybrid Multi-Level Inverter Demonstrator

- *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*

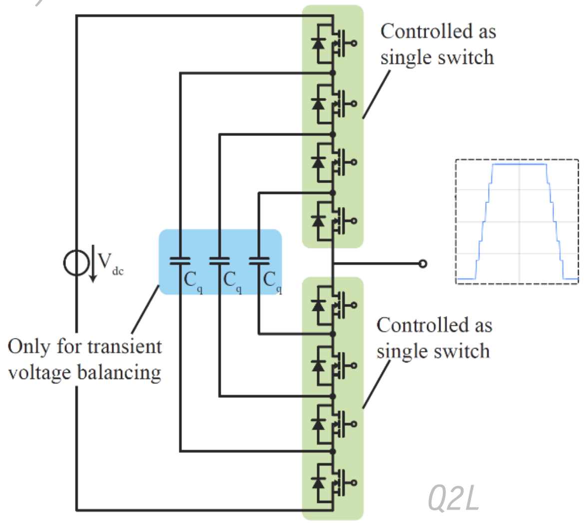
Quasi-2L/3L
Flying Capacitor Inverter

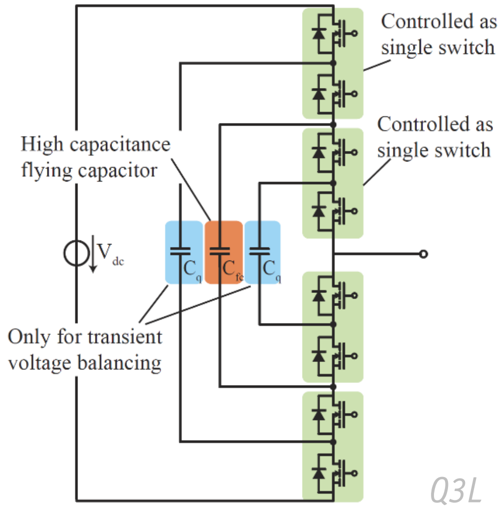
Quasi-2L & Quasi-3L Inverters (1)

- *Operation of N-Level Topology in 2-Level or 3-Level Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

- Schweizer (2017)

ABB





- *Reduced Avg. dv/dt → Lower EMI & Lower Overvoltages @ Motor Terminals*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

Quasi-2L & Quasi-3L Inverters (2)

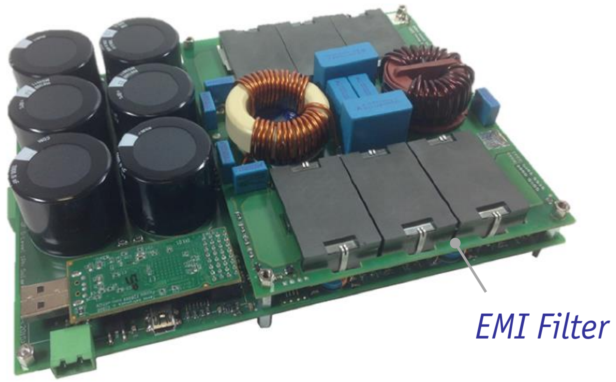
- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

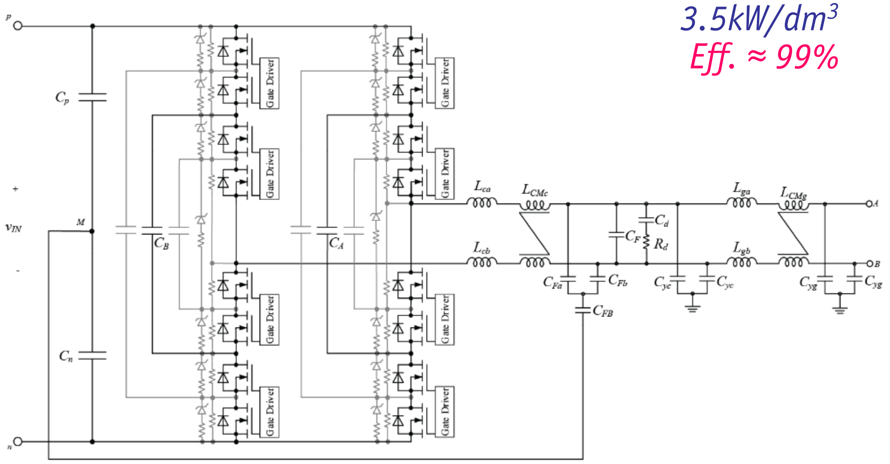
3.3kW @ 230V_{rms}/50Hz
Equiv. f_{sw}= 48kHz

3.5kW/dm^3
Eff. ≈ 99%

- Schweizer (2017)

ABB





- *Reduced Avg. dv/dt → Lower EMI & Lower Overvoltages @ Motor Terminals*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

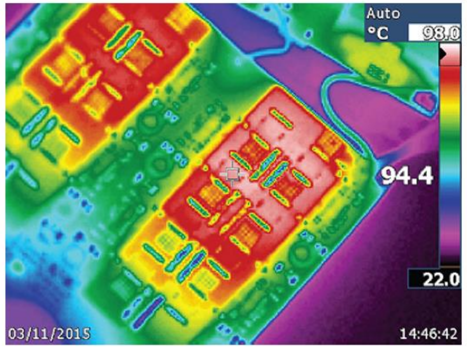
Quasi-2L & Quasi-3L Inverters (3)

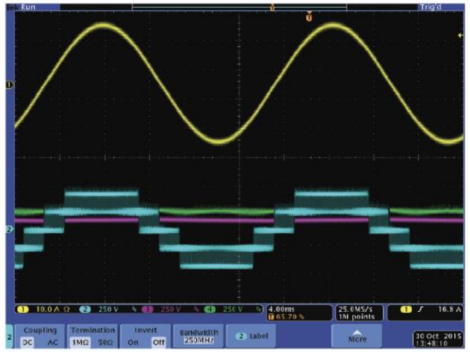
- Schweizer (2017)

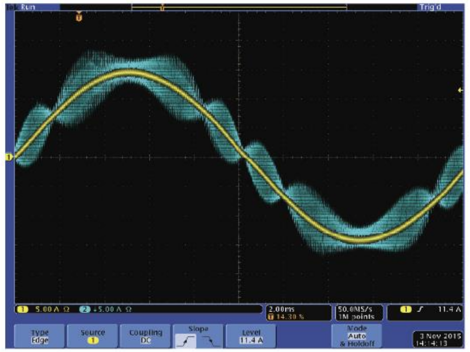
ABB

- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

Operation @ 3.2kW







— *Conv. Output Voltage*
— *Sw. Stage Output Voltage*
— *Flying Cap. (FC) Voltage*
— *Q-FC Voltage (Uncntrl.)*

— *Output Current*
— *Conv. Side Current*

- *Reduced Avg. dv/dt → Lower EMI & Lower Overvoltages @ Motor Terminals*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

Ultra-Compact Power Module with Integrated Filter

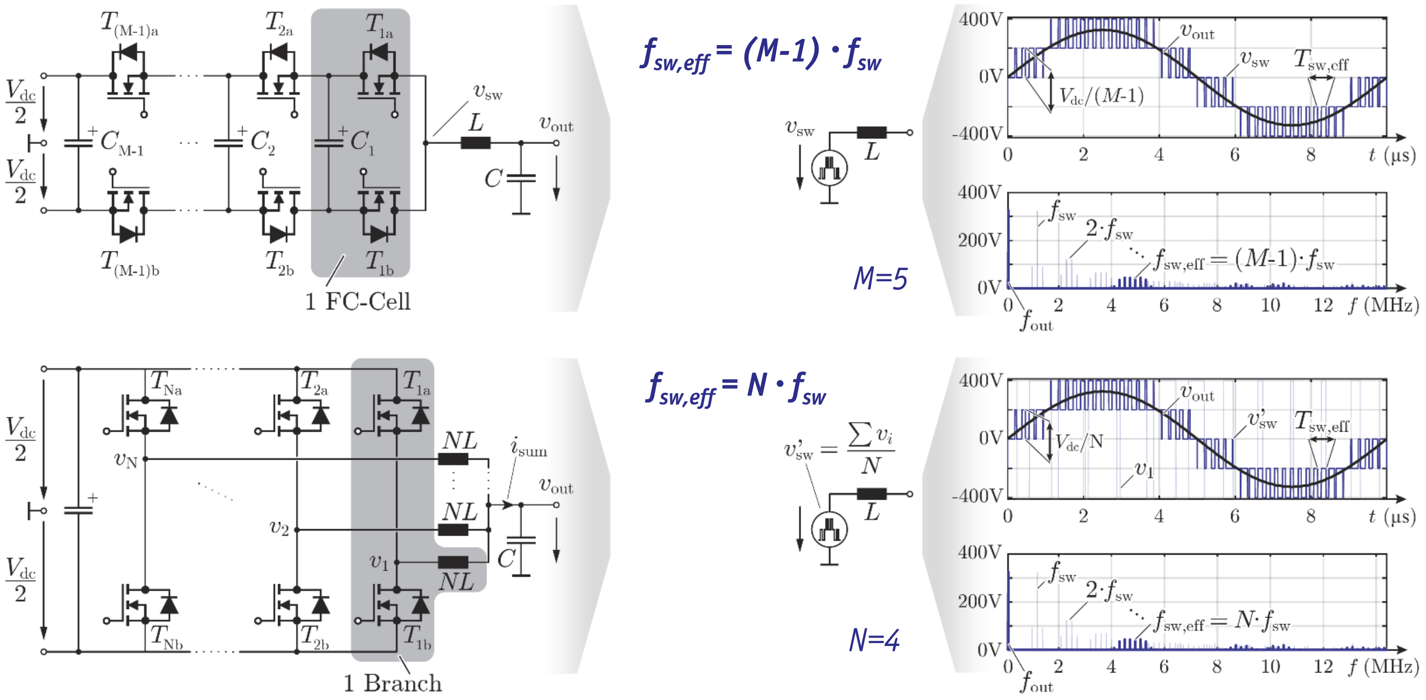
650V GaN E-HEMT Technology

$f_{sw,eff}$ = 4.8MHz

f_{out} = 100kHz

Integrated Filter GaN Half-Bridge Module

- *Minimization of Filter Volume by Series & Parallel Interleaving & Extreme Sw. Frequency*
- *Handling of DC Output Requires Flying Capacitor Approach for Series Interleaving*



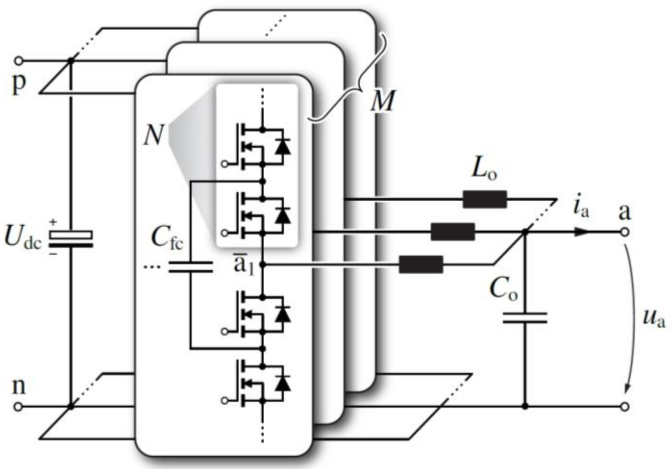
→ ***Target:*** *Best Combination of Multiple Levels (M) & Parallel Branches (N)*

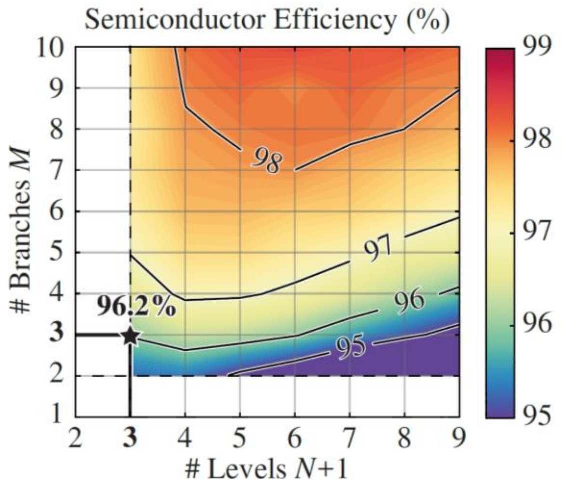
4.8MHz GaN Half-Bridge Phase Module

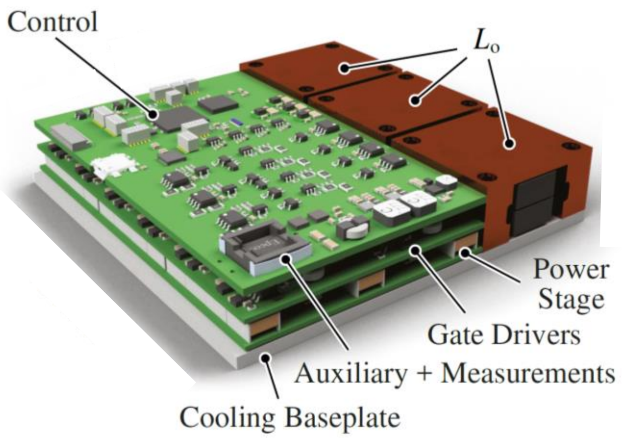
- Combination of Series & Parallel Interleaving

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

★ 820 W/in³



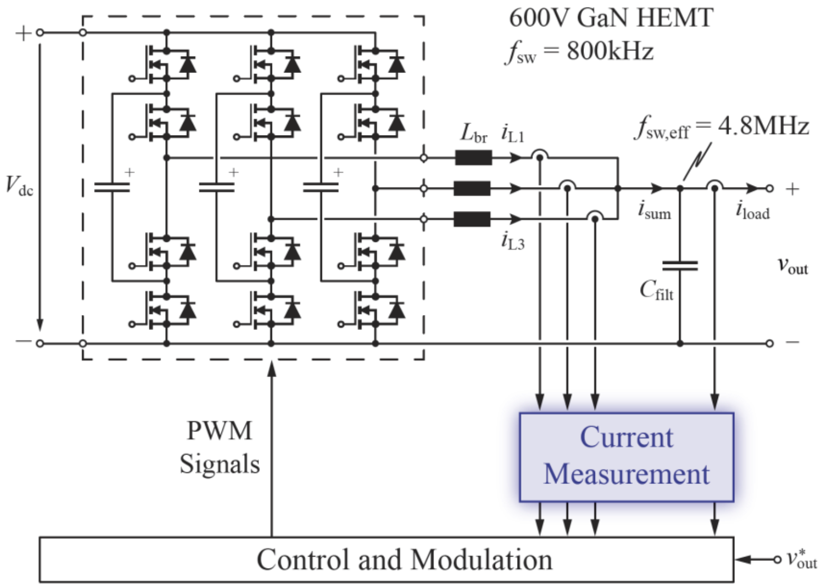


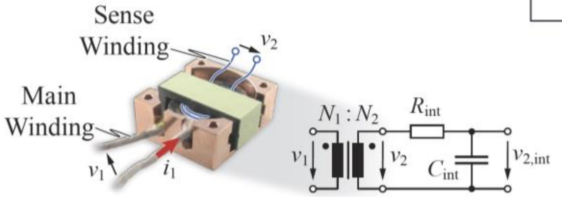


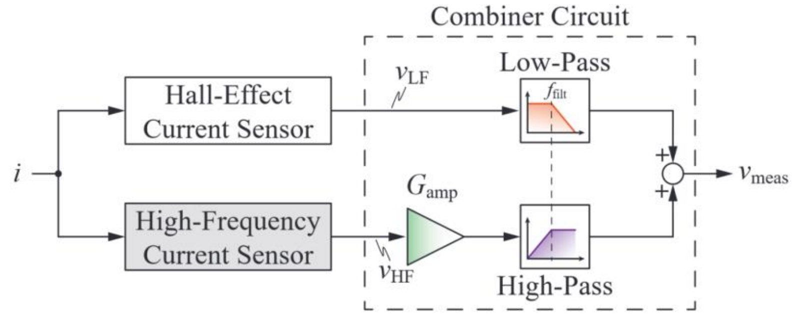
- Operation @ f_{out}=100kHz / $f_{sw,eff}$ = 4.8MHz, 10kW, U_{dc}=800V

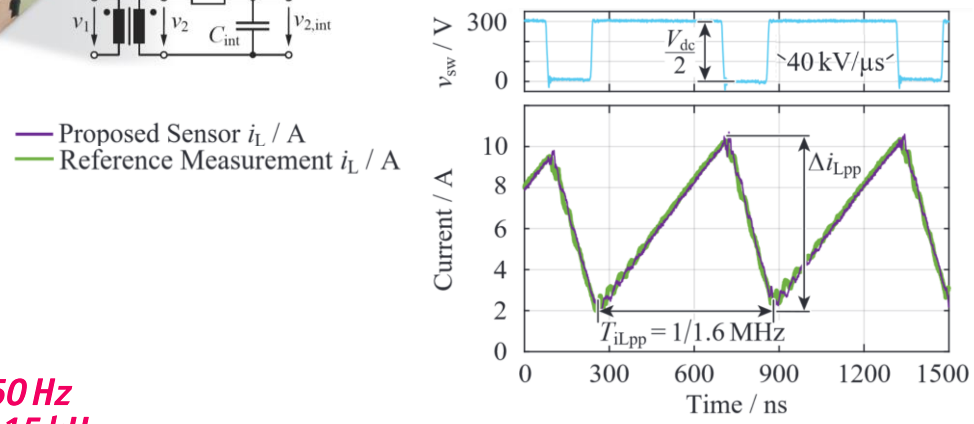
Remark High-BW High-CMRR Current Measurement

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









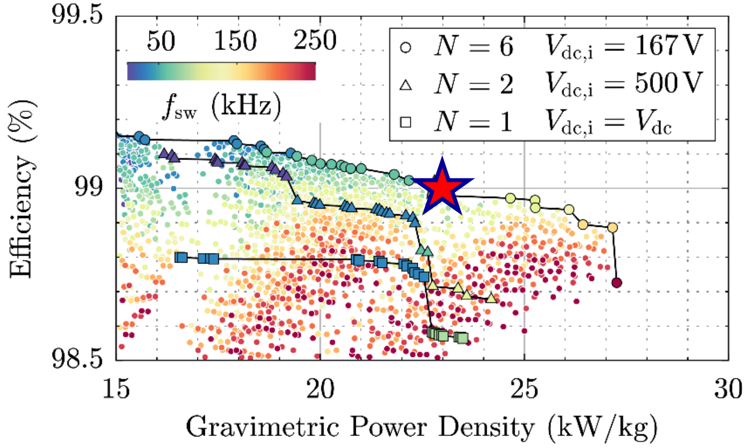
- Hall Sensor Bandwidth f_{Hall} = 1.4 MHz
- Sense Wdg. Integrator Corner Frequency f_{int}=350 Hz
- Low/High-Pass Filter Combiner Network f_{filter} = 15 kHz

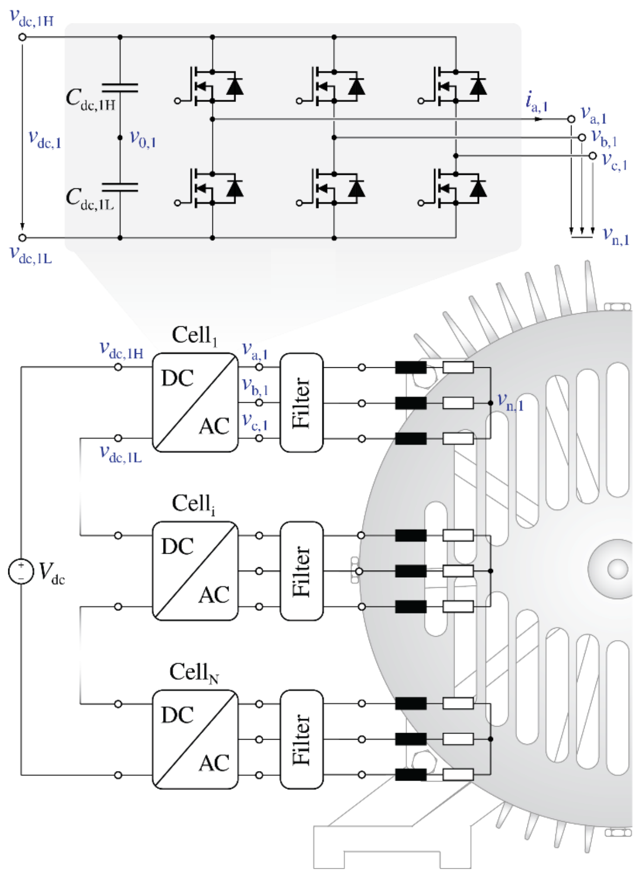
Motor-Integrated Inverter Systems

Stacked-Multi-Cell (SMC) Inverter

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

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

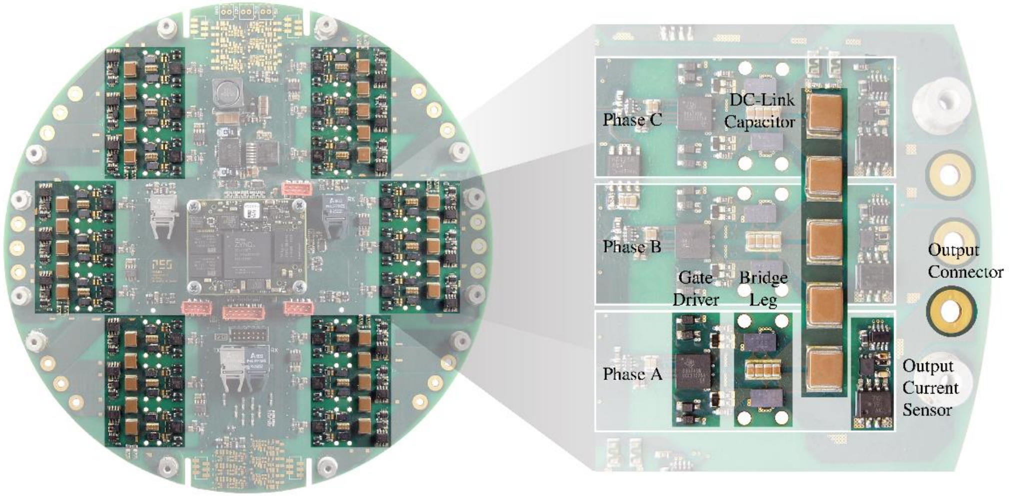


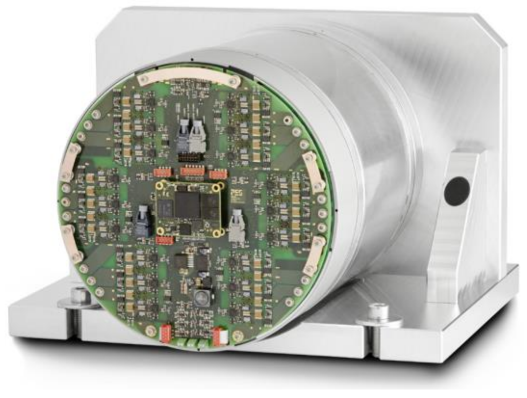


- *Smart Motor / Plug & Play* | *Connected / Intelligent VSD 4.0*

Motor-Integrated SMC-Inverter

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



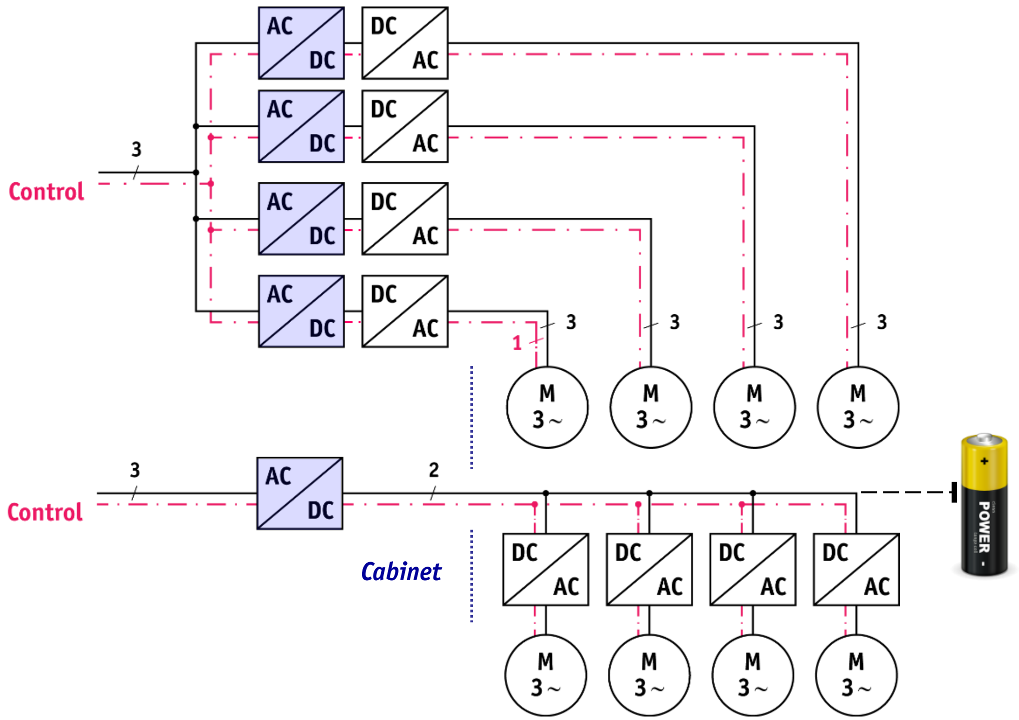


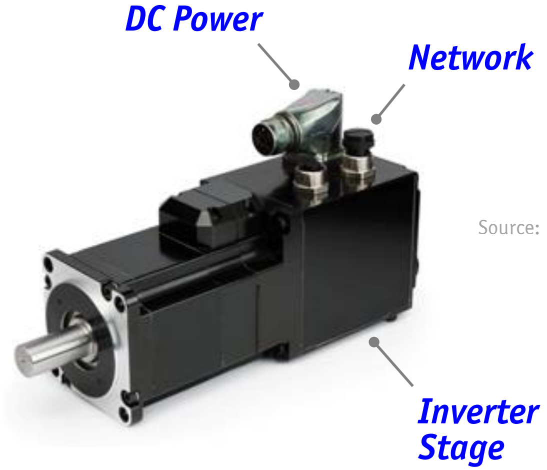
— *Axial Stator Mount*
— *200V GaN e-FETs*
— *Low-Capacitance DC-Links*
— *45mm x 58mm / Cell*

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

Remark 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





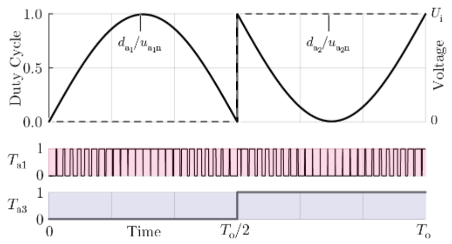
Source: YASKAWA

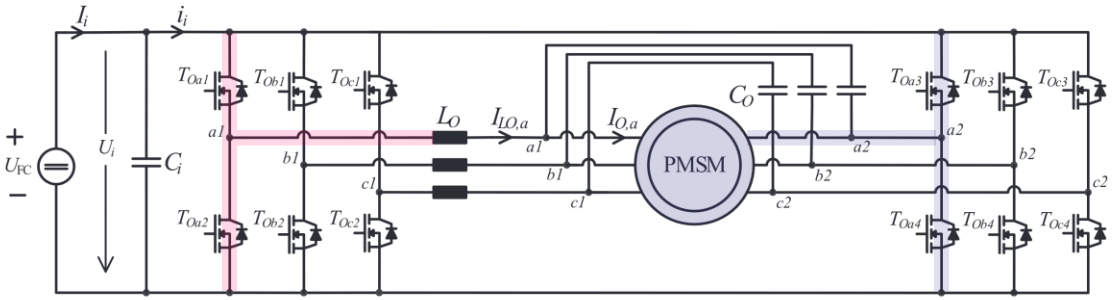
- Facilitates DC-Bus Energy Buffer
- Direct Energy Exchange @ DC-Bus / Higher Efficiency / Unidir. Front-End

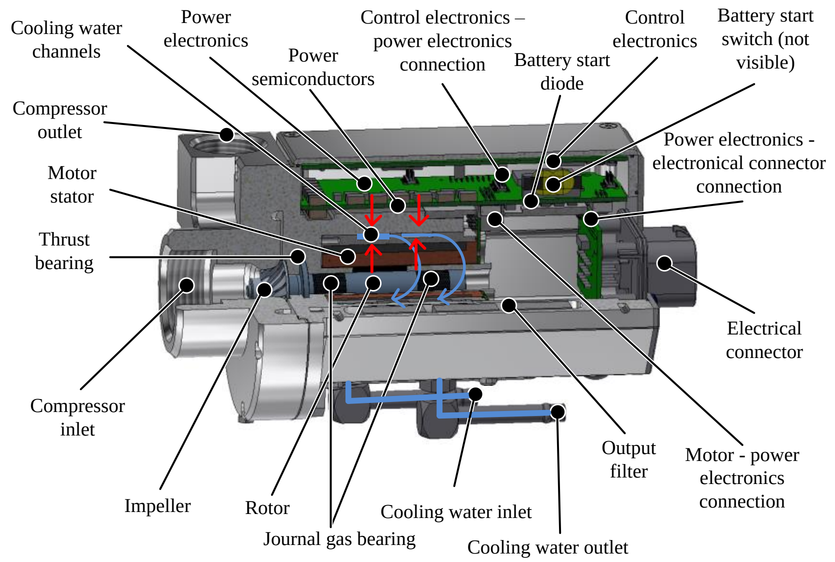
Double-Bridge (DB) Inverter

Compressor-Integrated DB-GaN-Inverter

- *E-Mobility 5…15kW Fuel Cell Pressurized Air Supply*
- *1kW Rated Power | U_{FC}= 40…130V | f_{sw}=300kHz | n= 280'000rpm / f_{out}= 4.6kHz*
- *Low EMI / Low Cabling Effort*



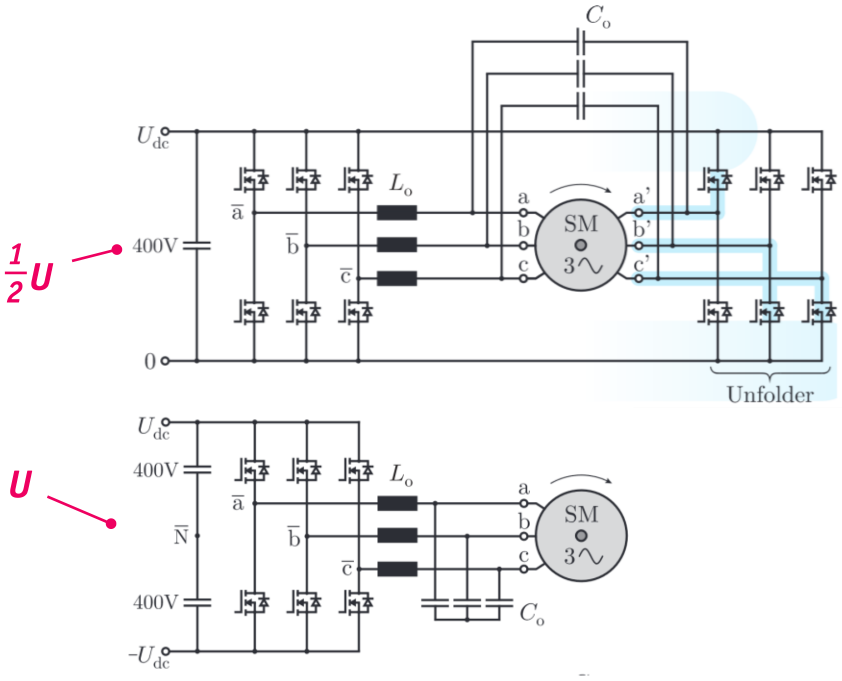


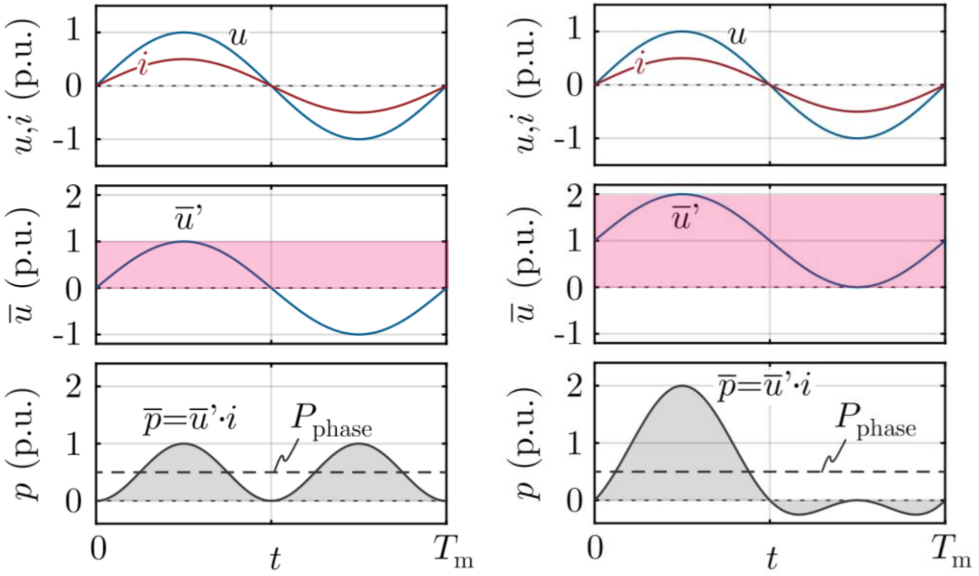


- *Integration → 2x System Power Density | 97% → 98.5% Inverter Efficiency*

Double-Bridge (DB)-Inverter Advantages

- *Unfolder → Factor 2 Lower DC-Link Voltage*
- *Lower Transistor Voltage Stress / Lower Switching Losses*
- *Conventional Inverter Bridge-Leg Processes 2x Instantaneous Peak Power*



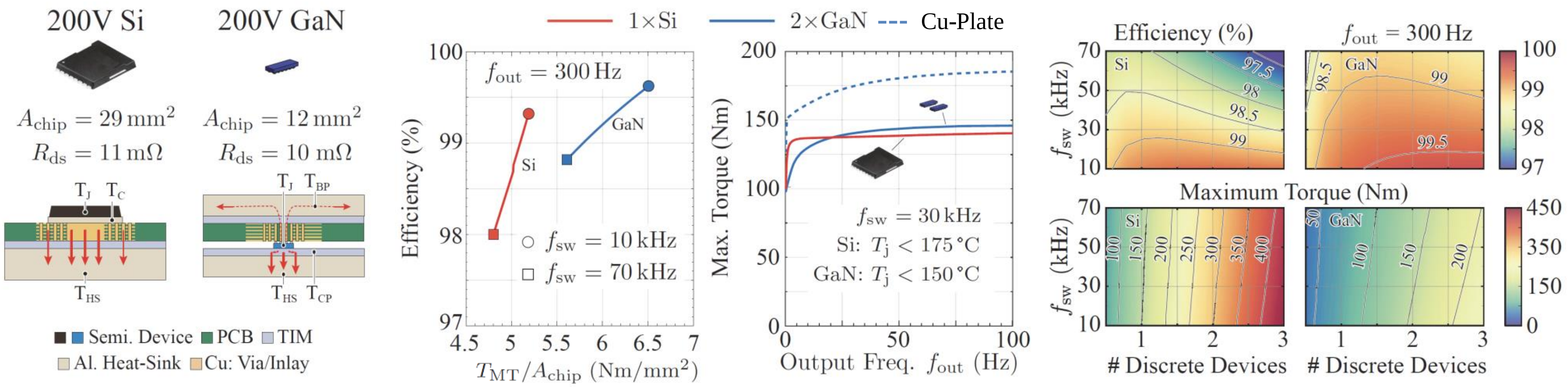


- *Access to All Wdg. Terminals — No Problem for Inverter/Motor Integration*

Overload | Thermal Limit

Remark GaN Overload Capability

- Highly Dynamic Robotics VSDs → 3x ... 5x Rated Torque for Seconds
- Smaller GaN Chip Area → Lower Thermal Time Constant
- Packaging Essentially Defines GaN Usability (!)



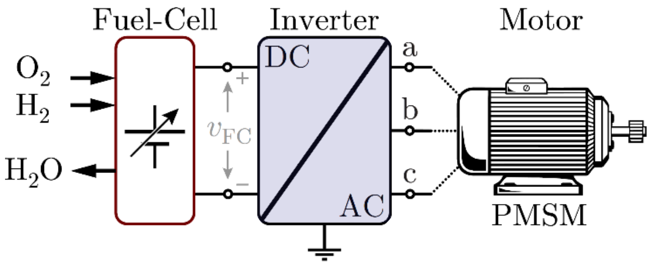
- 200V GaN vs. Si (Multi-Level Inverter) Comparison

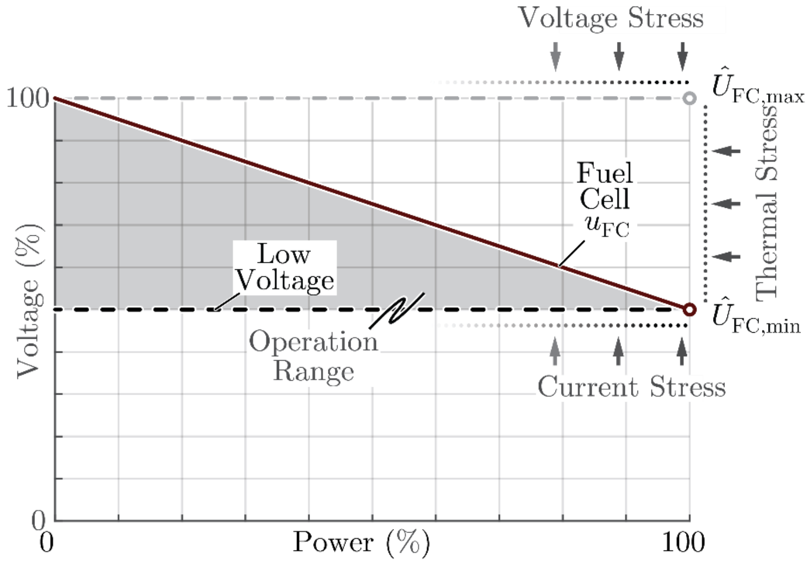
**Buck-Boost
Y-Inverter**

Motivation

- *General / Wide Applicability*

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

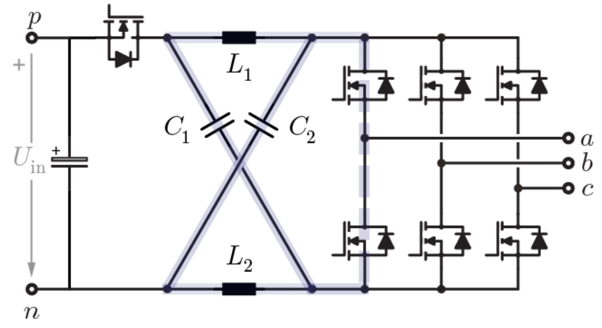




- *No Additional Converter for Voltage Adaption* → *Single-Stage Energy Conversion*

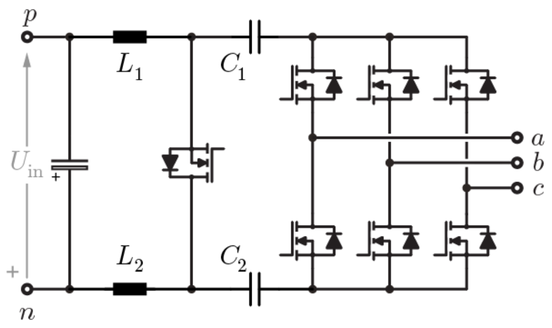
"Outside-the-Box" Topologies

- *Z-Source Inverter → Shoot-Through States Utilized for Boost Function*
- *Higher Component Stress Eff. Limits Boost Operation to ≈120% U_{in}*



Source: F.Z. Peng / 2003
J. Rabkowski / 2007

- *3-Φ Back-End DC/AC Cuk-Converter*

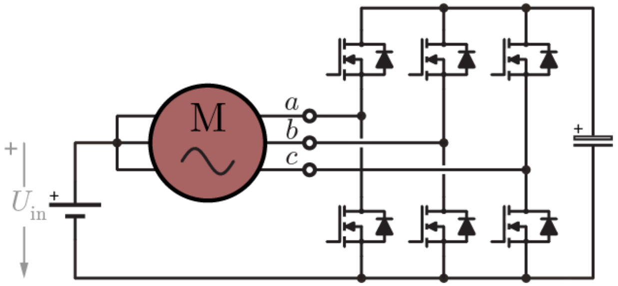


Source: T.A. Lipo et al. /2002 & K.D.T Ngo / 1984

- *Integration Typ. Results in Higher Comp. Stresses & Complexity / Lower Performance*

Boost Converter DC-Link Voltage Adaption

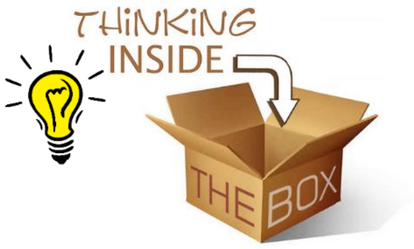
- *Inverter-Integr. DC/DC Boost Conv. → Higher DC-Link Voltage / Lower Motor Current*
- *Access to Motor Star-Point & Specific Motor Design Required*
- *No Add. Components*

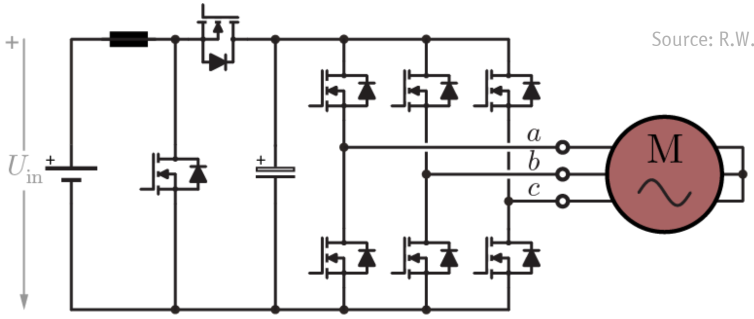


Source: J. Pforr et al. / 2009

- *Explicit Front-End DC/DC Boost-Stage*

Source: www.rick-gerber.com



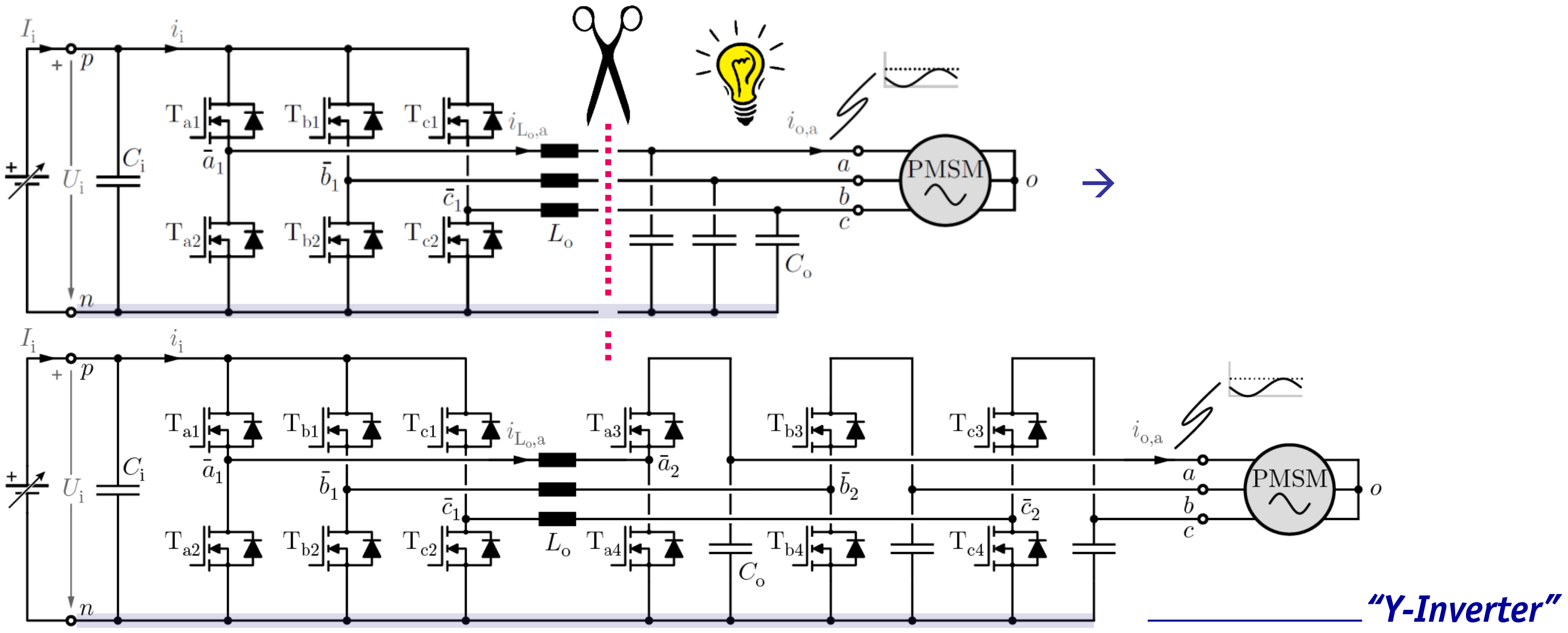


Source: R.W. Erickson et al. / 1986

→ Coupling of the Control of Both Converter Stages → "Synergetic Control"

Buck-Boost Y–Inverter

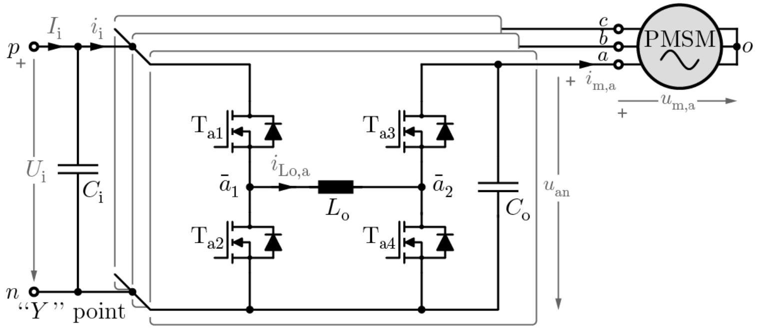
■ *Generation of AC-Voltages Using Unipolar Bridge-Legs*

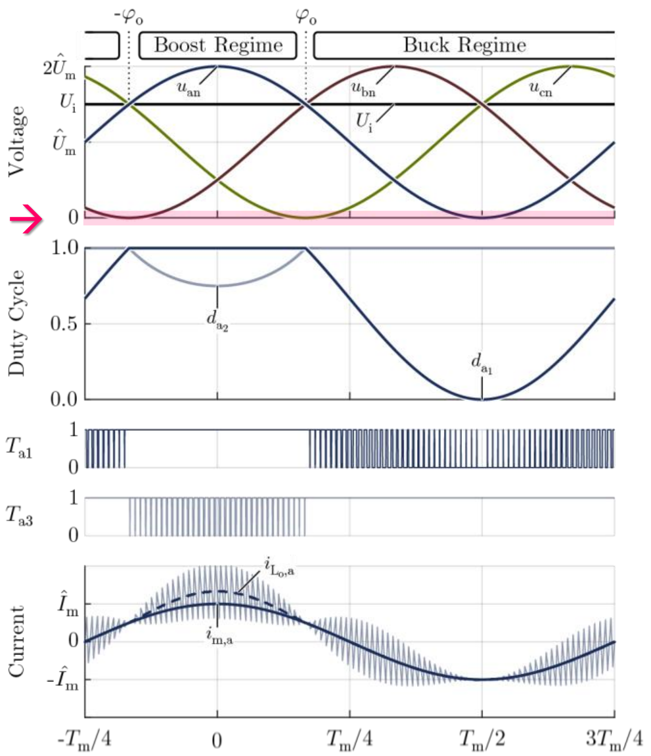


- *Switch-Mode Operation of Buck OR Boost Stage* → *Single-Stage Energy Conversion (!)*
- **3-Φ Continuous Sinusoidal Output / Low EMI** → *No Shielded Cables / No Motor Insul. Stress*

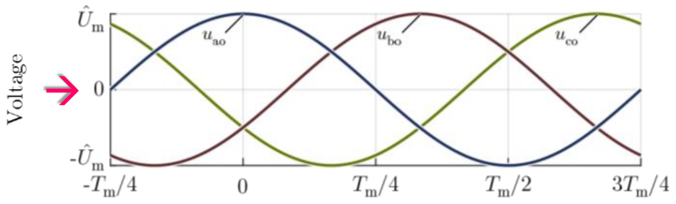
Sinusoidal Modulation

- **_Y-Inverter_**





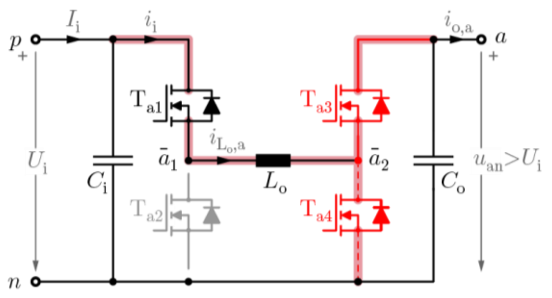
- **_Motor Phase Voltages_**

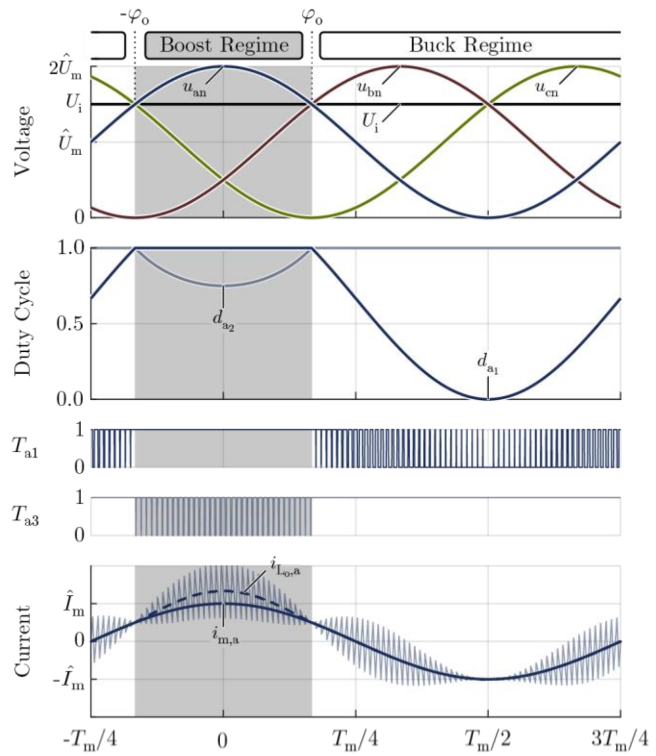


- *Const. DC Offset → Strictly Positive Output Voltages u_{aN}, u_{bN}, u_{cN}*
- *Mutually Exclusive Operation of the Half-Bridges → Low Switching Losses*

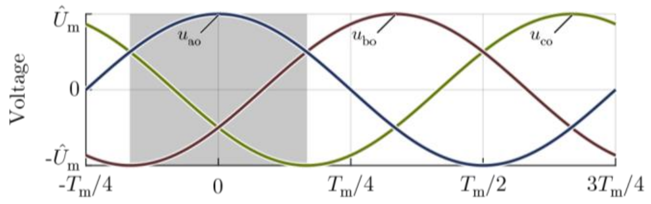
Boost-Operation $u_{an} > U_i$

- **Phase-Module**





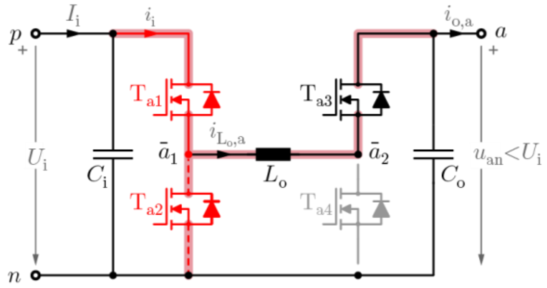
- **Motor Phase Voltages**



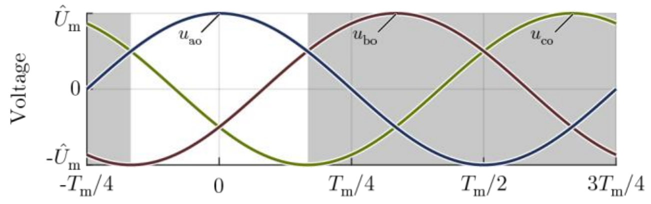
- *Current-Source-Type Operation*
- *Clamping of Buck-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion*

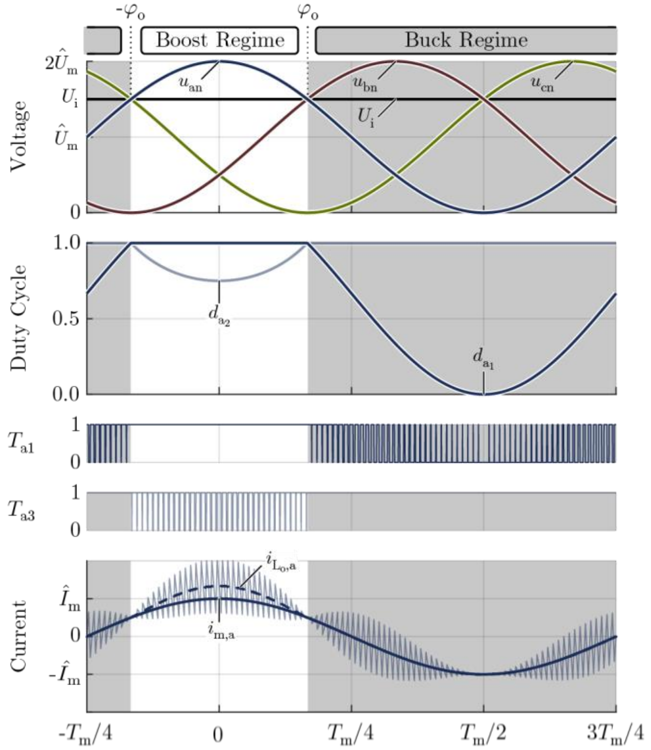
Buck-Operation $u_{an} < U_i$

■ *Phase-Module*



■ *Motor Phase Voltages*

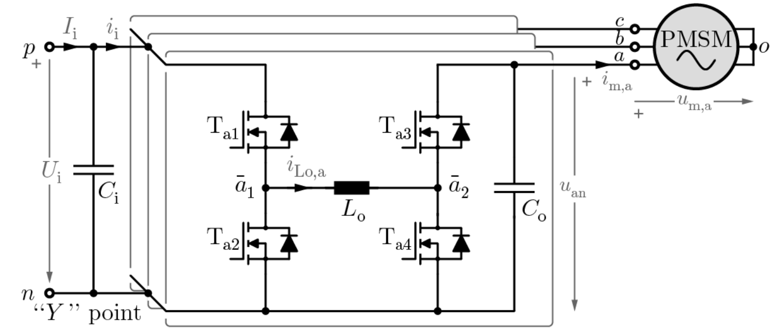


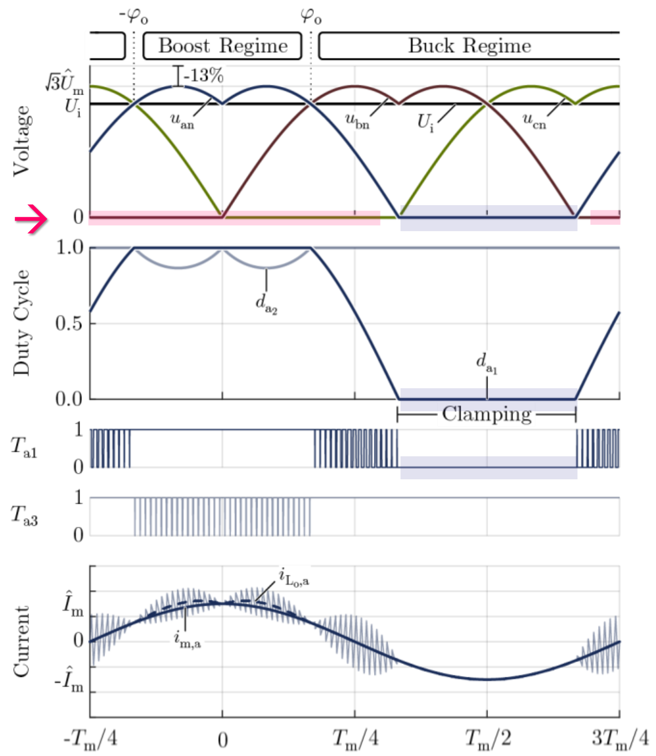


- *Voltage-Source-Type Operation*
- *Clamping of Boost-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion*

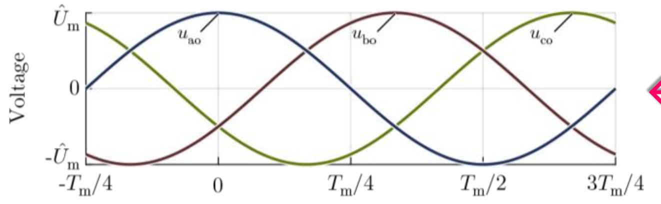
Discontinuous Modulation

- *Y-Inverter*





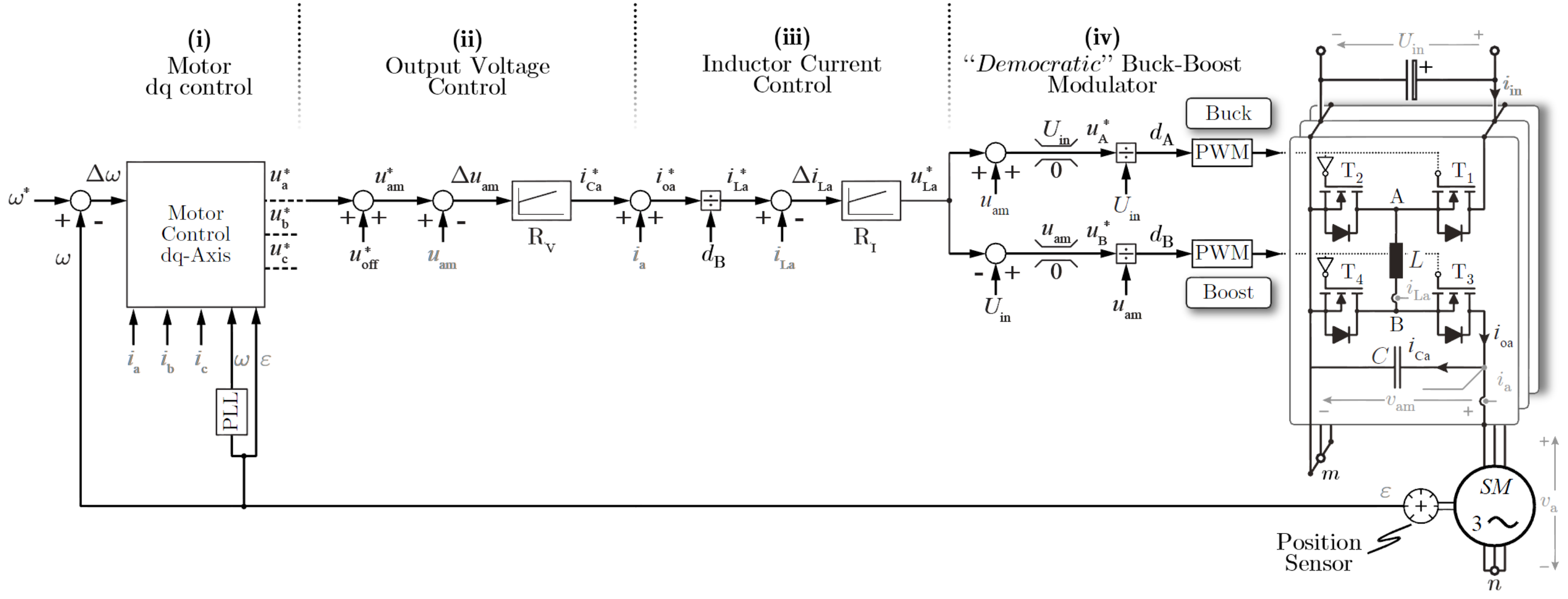
- *Motor Phase Voltages*



- *Clamping of Each Phase for 1/3 of the Fund. Period → Low Switching Losses (!)*
- *Non-Sinusoidal Module Output Voltages / Sinusoidal Line-to-Line Voltages*

Control Structure

- *Motor Speed Control*

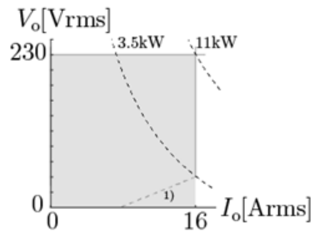


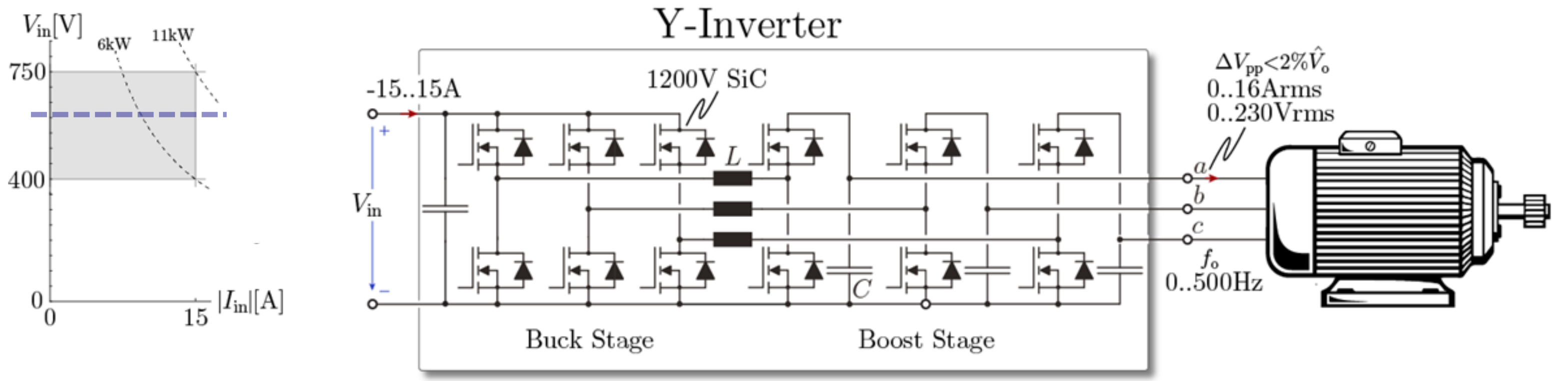
- *Cascaded Current / Voltage / Current Control Loops*
- *Seamless Transition between Boost- & Buck-Mode → "Democratic" Control*

Y–Inverter VSD

■ *Demonstrator Specifications*

- Wide DC Input Voltage Range → 400…750V_{DC}
- Max. Input Current → ± 15A

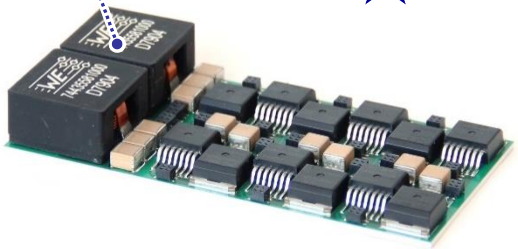




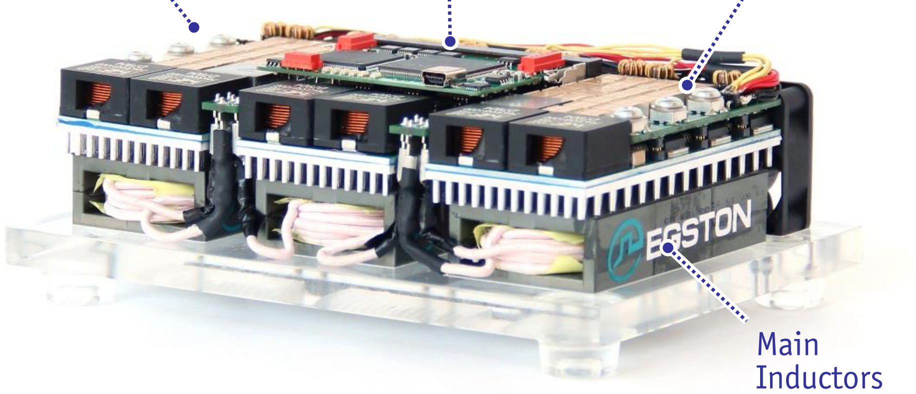
- Max. Output Power → 6…11 kW
- Output Frequency Range → 0…500Hz
- Output Voltage Ripple → 3.2V Peak @ Output of Add. LC-Filter

Y–Inverter Demonstrator

- DC Voltage Range 400...750V_{DC}
- Max. Input Current ± 15A
- Output Voltage 0...230V_{rms} (Phase)
- Output Frequency 0...500Hz
- Sw. Frequency 100kHz
- 3x SiC (75mΩ)/1200V per Switch
- IMS Carrying Buck/Boost-Stage Transistors & Comm. Caps & 2nd Filter Ind.



★ 245 W/in³



- Dimensions → 160 x 110 x 42 mm³

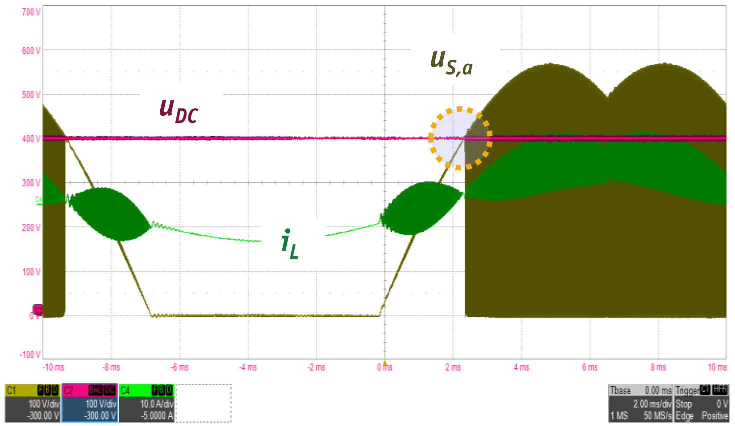
Y–Inverter - Measurement Results

- *Stationary Operation*

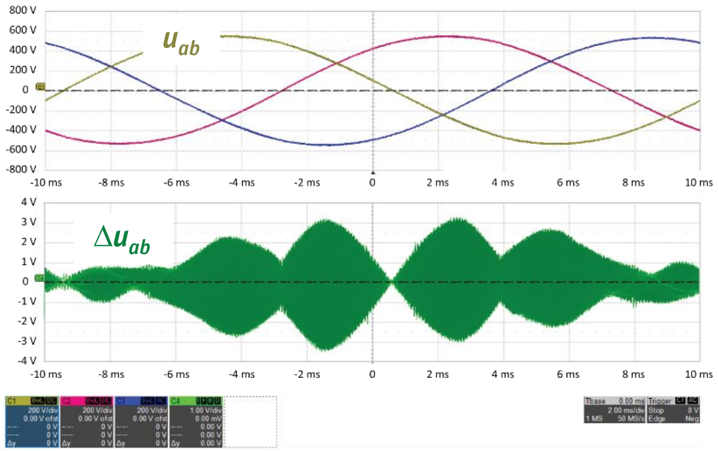
U_{DC} = 400V
U_{AC} = 400V$_{rms}$ (Motor Line-to-Line Voltage)
f_O = 50Hz
f_{sw} = 100kHz / *Discontinuous PWM*

P = 6.5kW

100V/div
10A/div



200V/div
1V/div

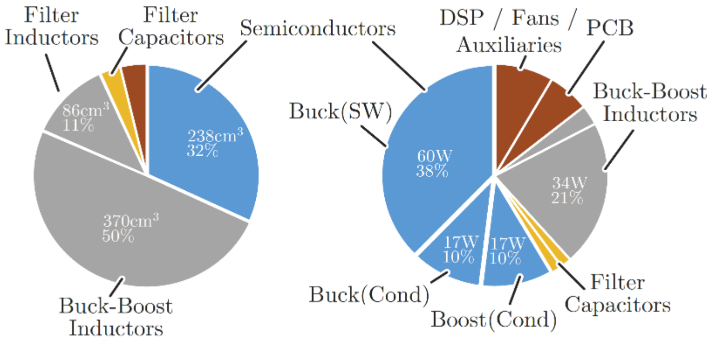


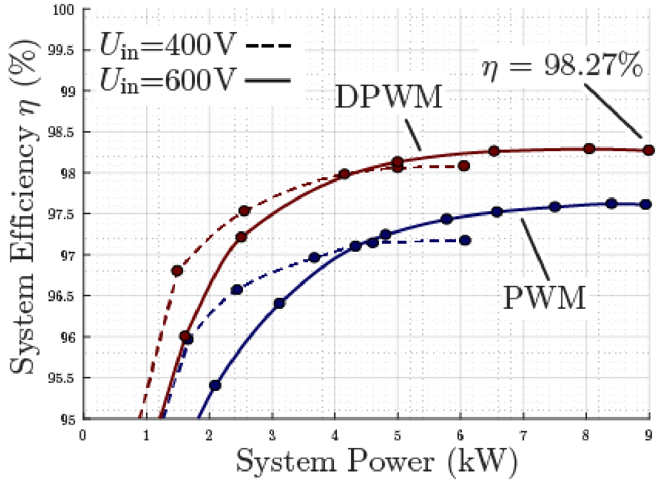
- *Line-to-Line Output Voltage Ripple < 3.2V*

Efficiency Measurements

- *Dependency on Input Voltage & Output Power Level*

U_{DC} = 400V / 600V
U_{AC} = 230V_{rms} (Motor Phase-Voltage)
f_{sw} = 100kHz

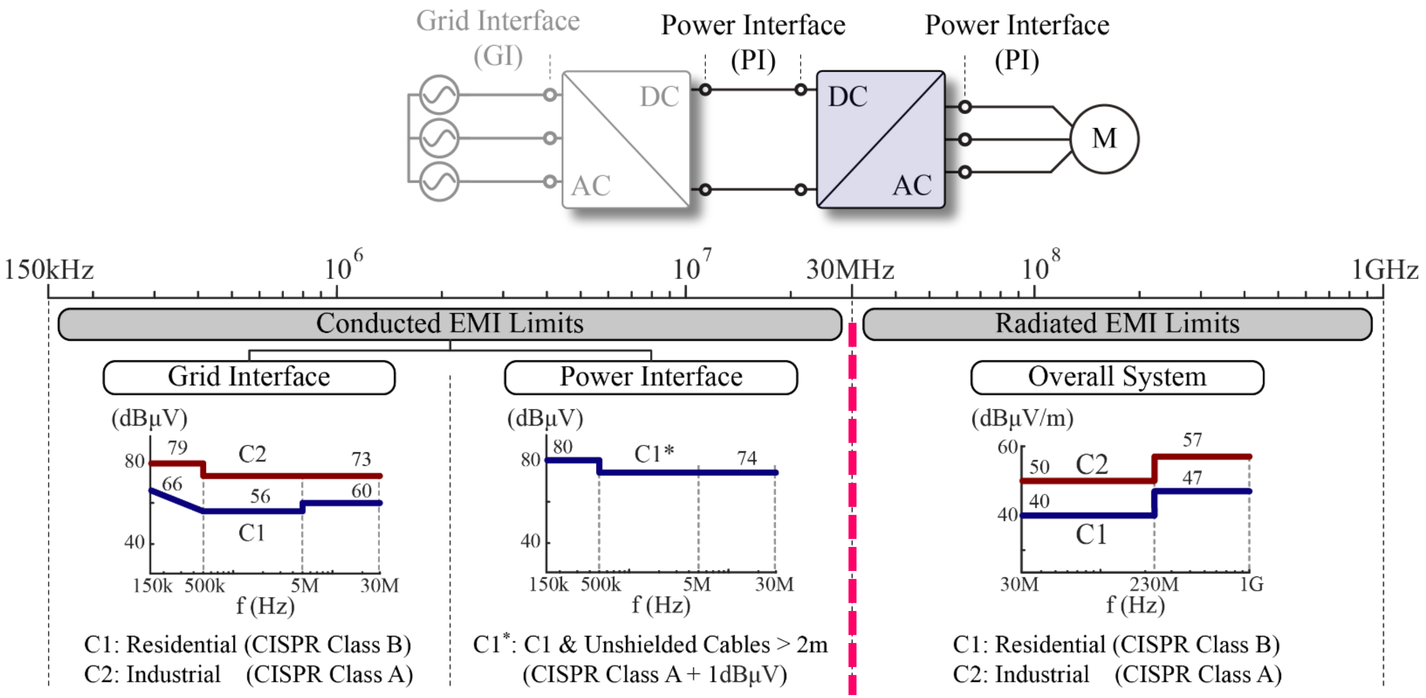




→ *Multi-Level Bridge-Leg Structure for Increase of Power Density @ Same Efficiency*

EMI-Limits (VSD Product Standard)

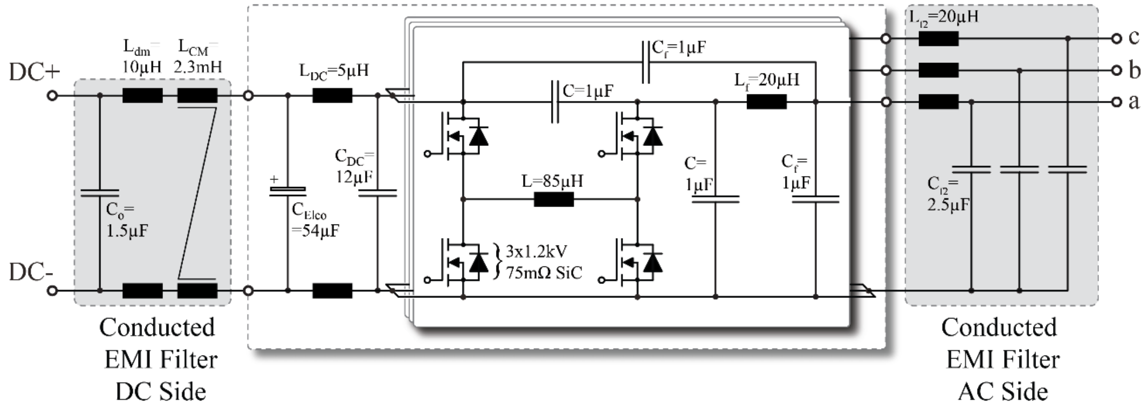
- IEC 61800-3 → Product Standard for Variable-Speed Motor Drives
- EMI Emission Limits → Grid Interface (GI) and Power Interfaces (PI)
- Application → Residential (C1) or Industrial (C2)

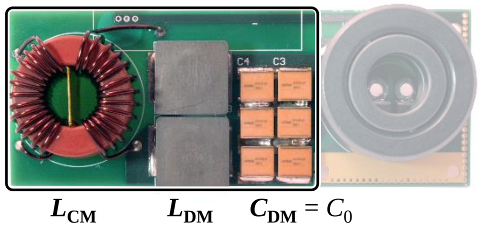


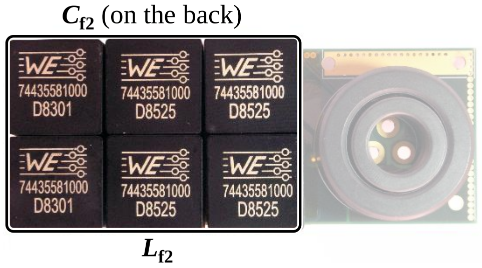
- *EMI-Filter Design for Unshielded Cables > 2m and Resid. Applications (Cond. & Rad.)*

Conducted EMI-Filter

- Separate Cond. DM & CM EMI-Filter on DC-Side & DC-Minus Ref. EMI-Filter on AC-Side



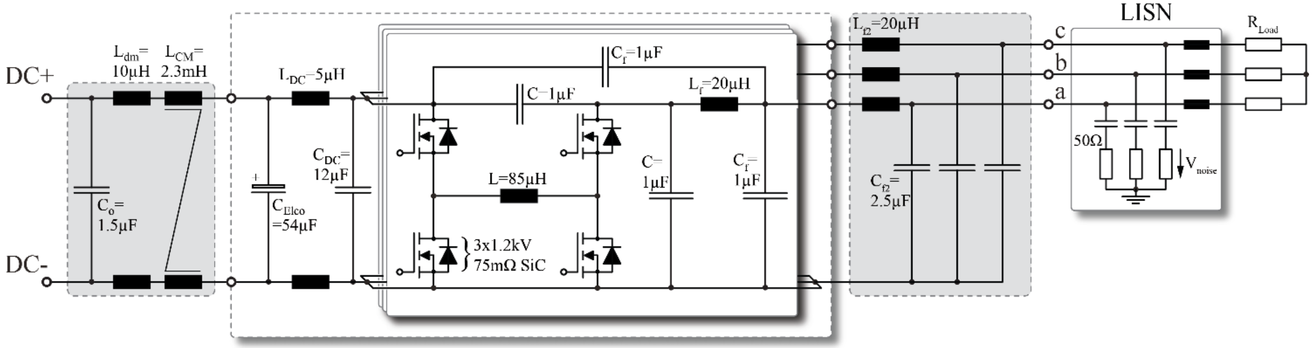


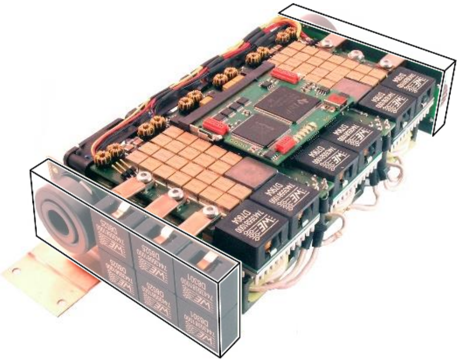


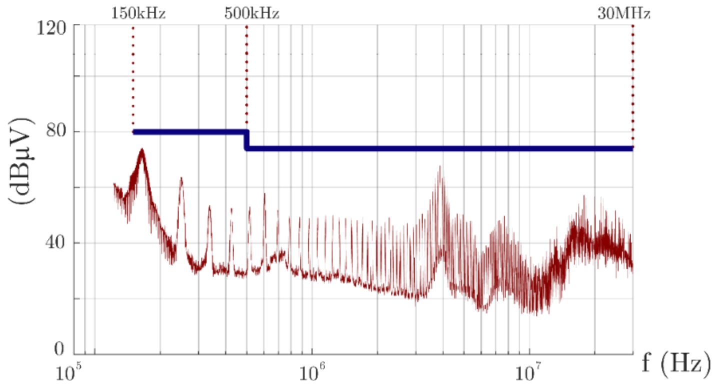
→ *Low Add. EMI Filter Volume — 74 cm³ for Each Filter (incl. Toroid. Radiated EMI Filter)*
→ *Total Power Density Reduces — 15 kW/dm³ (740 cm³) → 12 kW/dm³ (890 cm³)*

Conducted EMI - Experimental Results

- Measurements of the Cond. EMI Noise on the AC-Side (QP, with 50Hz AC-LISN)



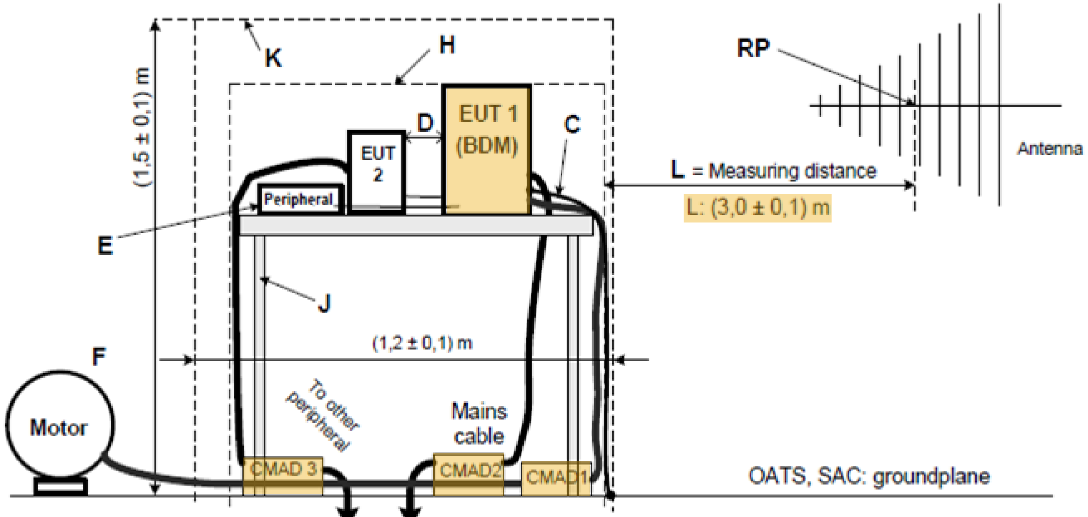




→ *Small 80uH CM-Ind. Added on AC-Side - (3 cm³ of Add. Volume = 0.5% of Converter Vol.)*
→ *Conducted EMI with Unshielded Motor Cable Fulfilled*

Measurement of Radiated EMI-Noise (1)

- Equipment Under Test (EUT) Placed on Wooden Table with Specified Arrangement
- CM Absorption Devices (CMAD) Terminate All Cables on AC-Side & DC-Side (Total $l_{cable} \approx 1.5$m)
- Measurement of Radiated Noise with Antenna in 3m Distance



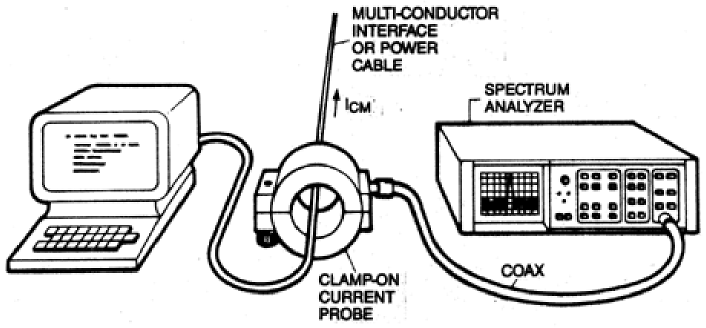
[IEC 61800-3]

[Schwarzbeck]

- *Either Open-Area Test Site (OATS) or Special Semi-Anechoic Chamber (SAC) Needed*
- *Alternative Pre-Compliance Measurement Method*

Measurement of Radiated EMI-Noise (2)

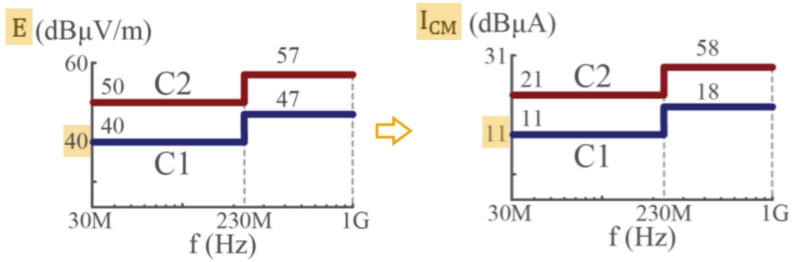
- CM-Currents NOT Returning IN THE CABLE are Dominant Source of Radiation
- Relation Between Radiated Electric Field and CM-Currents (!)



$$E = \begin{cases} \dfrac{\mu_0 \cdot f \cdot l_{cable} \cdot I_{cm}}{r} & \dfrac{\lambda}{4} \leq l_{cable} \\ \dfrac{\mu_0 \cdot \frac{c_0}{4} \cdot I_{cm}}{r} & \dfrac{\lambda}{4} > l_{cable} \end{cases}$$

[Electromagnetic Compatibility Engineering, H. Ott]

[Fischer FCC F-33-1]
up to 250MHz
$Z_{nom} = 6.3\Omega$

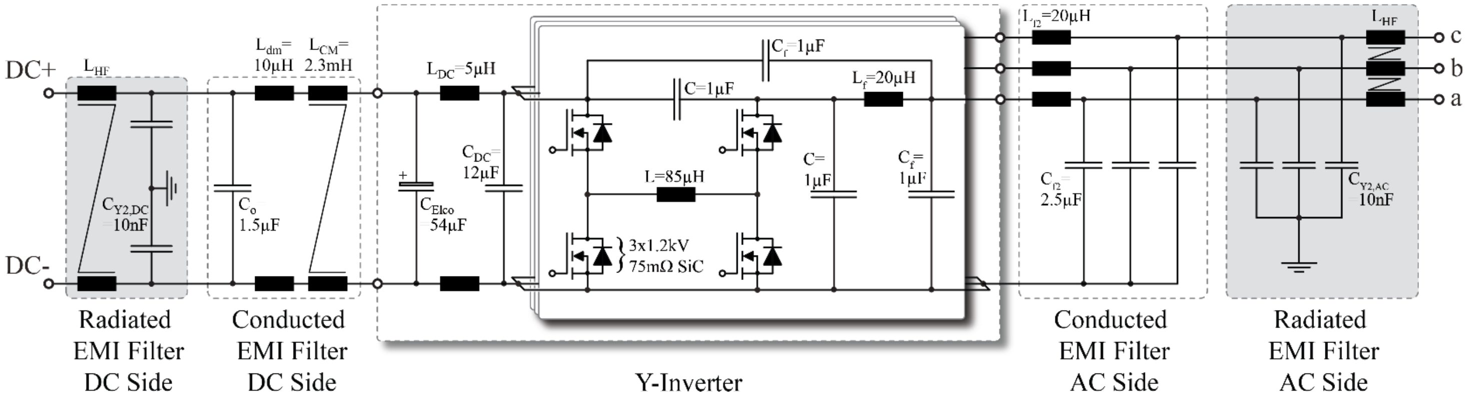


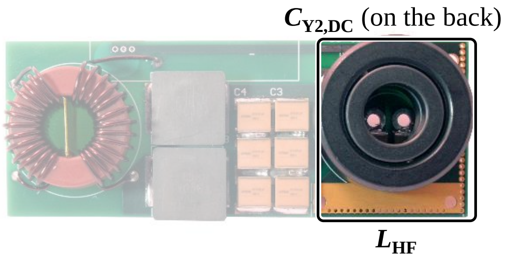
C1: Residential (CISPR Class B)
C2: Industrial (CISPR Class A)

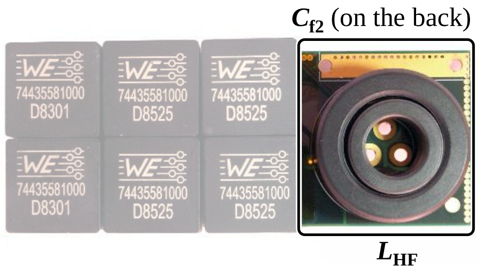
- *Max. Allow. El. Field Strength of 40dBuV/m → Max. CM-Current of 3.5uA (11dBuA)*
- *Current Probe Impedance of 6.3Ω (F-33-1) → Max. Noise Volt. of 26dBuV @ Test Receiver*

Radiated EMI-Filter Design

- Single-Stage HF CM-Filter on DC-Side and AC-Side
- Plug-On CM-Cores (NiZn-Ferrites) → Low Parasitics & Good HF-Att. up to 1GHz



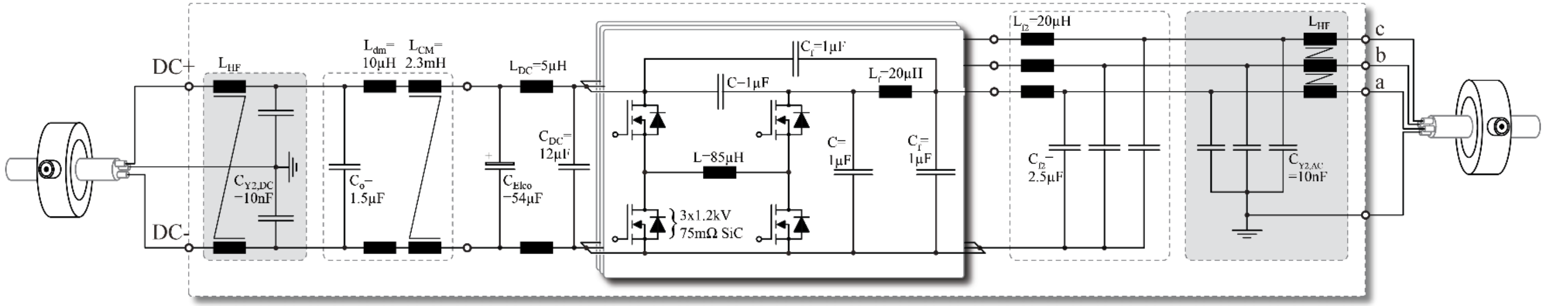


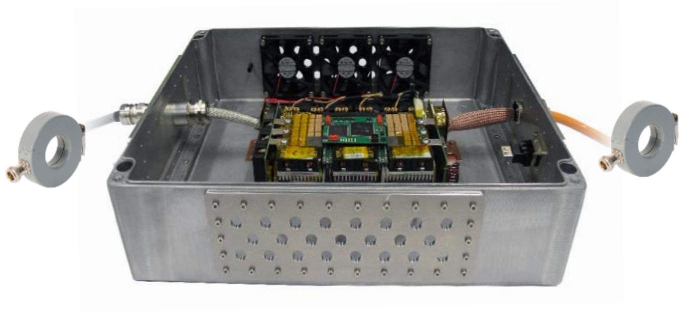


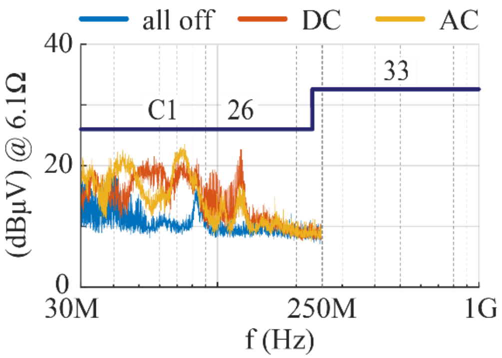
→ *Additional EMI Filter Volume Already Considered with Conducted EMI Filter*
→ *Total Power Density Slightly Reduces — 15 kW/dm³ → 12 kW/dm³*

Experimental Results - Radiated EMI

- Y-Inverter Placed in Metallic Enclosure → Emulate Housing, but UNshielded Cables (!)
- Measurement Setup → According IEC 61800-3
- Alternative Measurement Principle → Conducted CM-Current Instead of Radiation





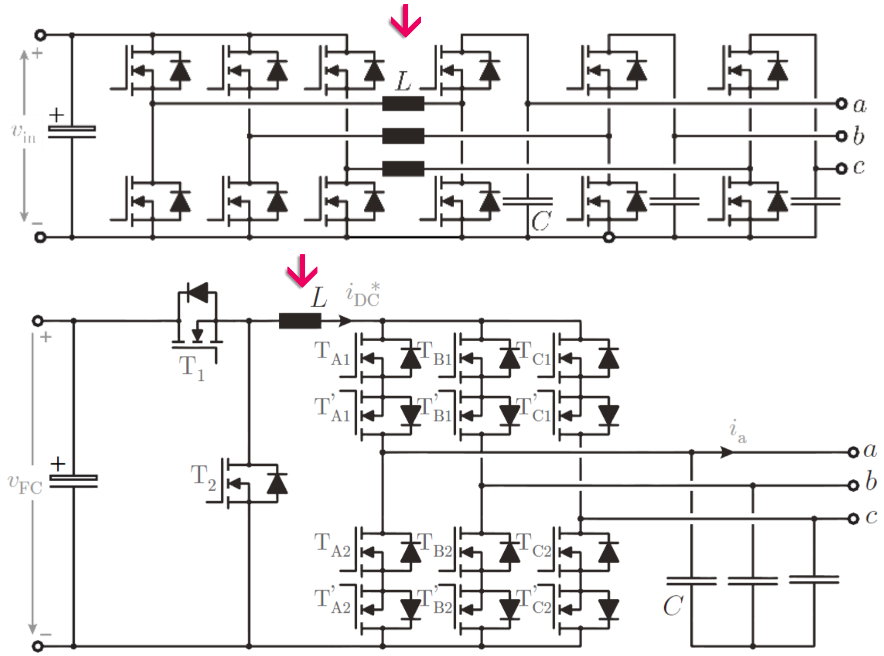


→ *Already Noticeable Noise Floor*
→ *HF-Emissions Well Below Equivalent EMI-Limit* → ***Final Step:*** *Verification Using Antenna*

Buck-Boost
Current Source Inverter

3-Φ Current Source Inverter Topology Derivation

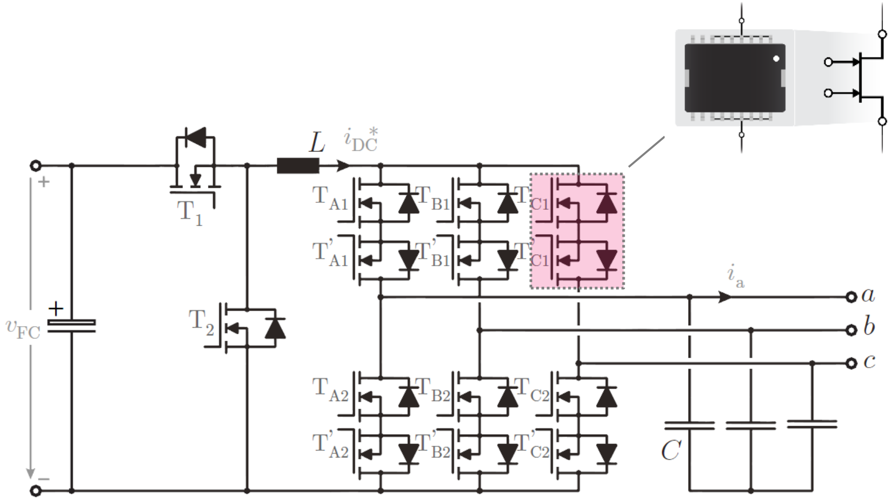
- *Y-Inverter* → *Phase Modules w/ Buck-Stage | Current Link | Boost-Stage*
- *3-Φ CSI* → *Buck-Stage V-I-Converter | Current DC-Link DC/AC-Stage*

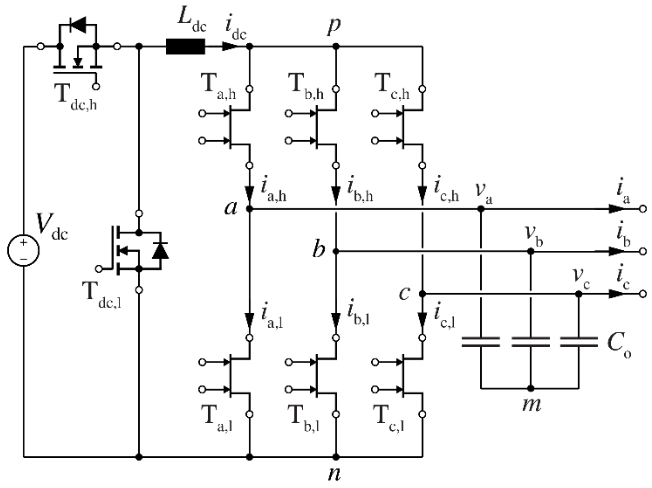


→ *Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches*

3-Φ Current Source Inverter (CSI)

- *Bidirectional/Bipolar Switches* → *Positive DC-Side Voltage for Both Directions of Power Flow*

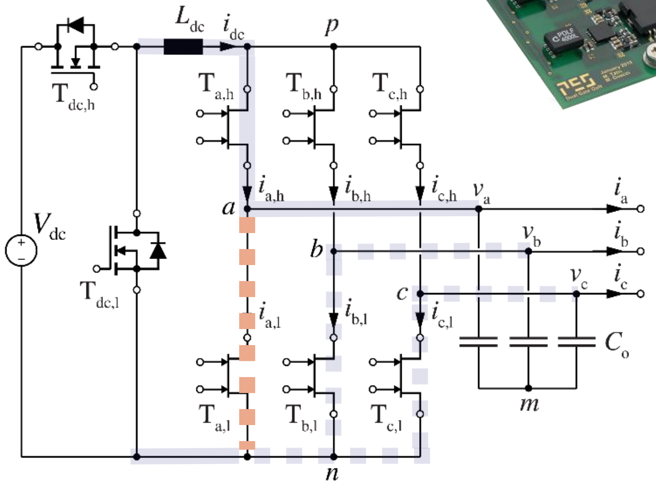


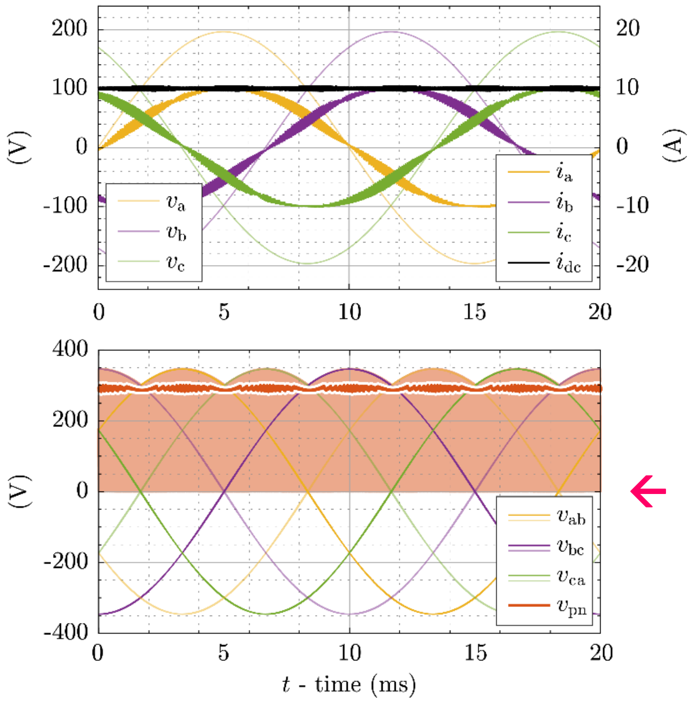


- *Monolithic Bidir. GaN Switches* → *Factor 4 (!) Reduction of Chip Area Comp. to Discrete Realization*

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*

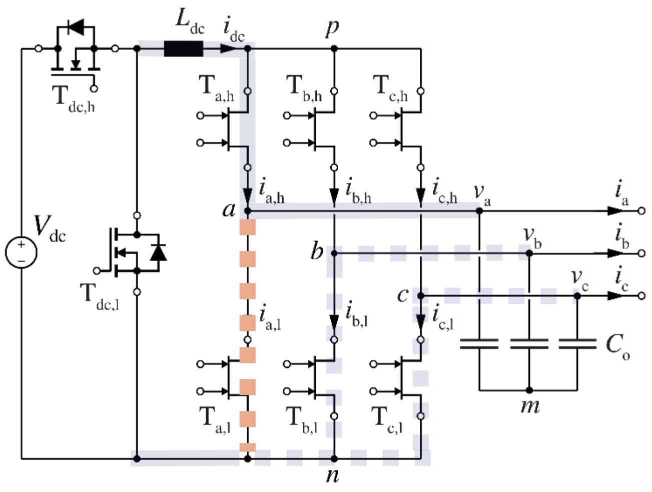


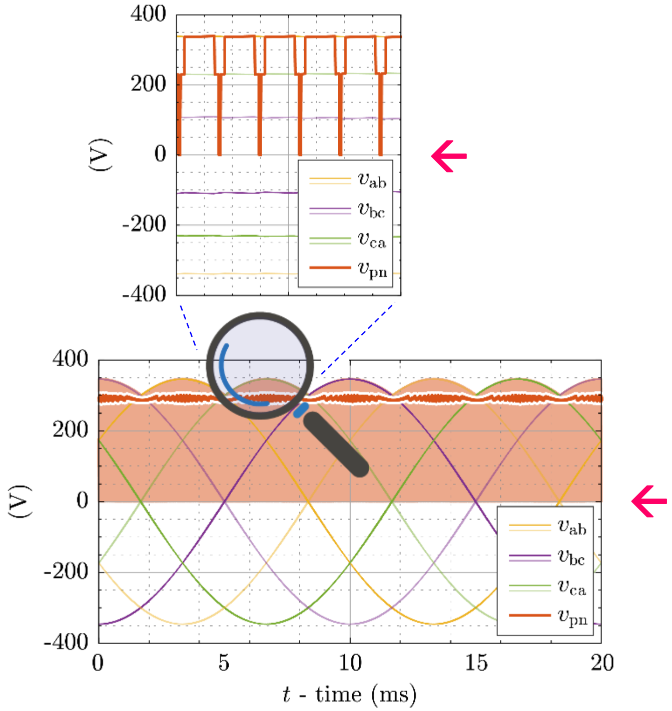


- *Conventional Control of Inverter Stage → Switching of All 3 Phase Legs (3/3)*

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***

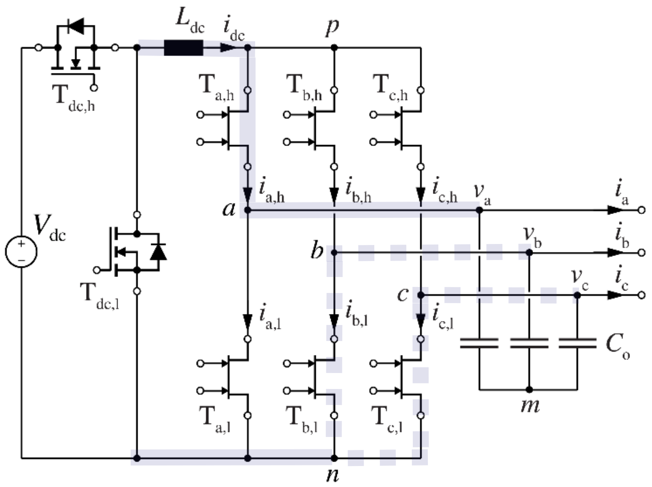


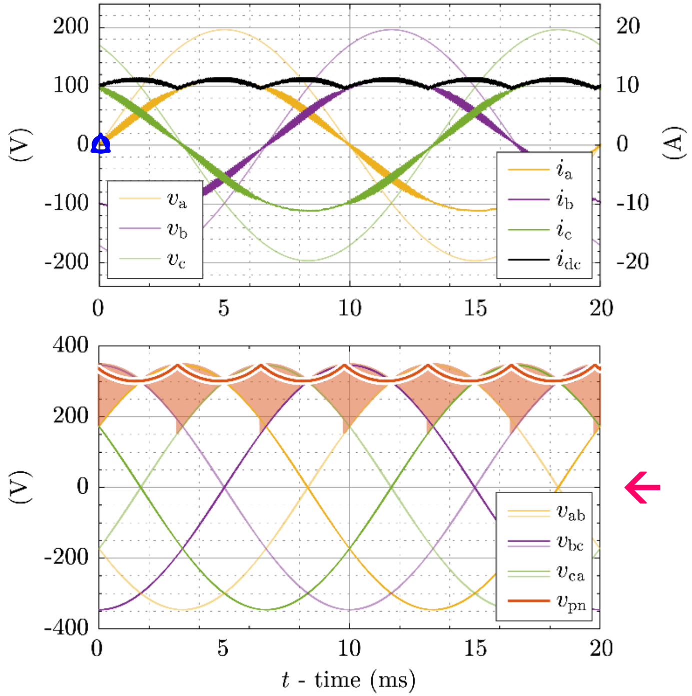


- ***Conventional Control of Inverter Stage → Rel. High CSI-Stage Sw. Losses***

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 a CSI-Phase*

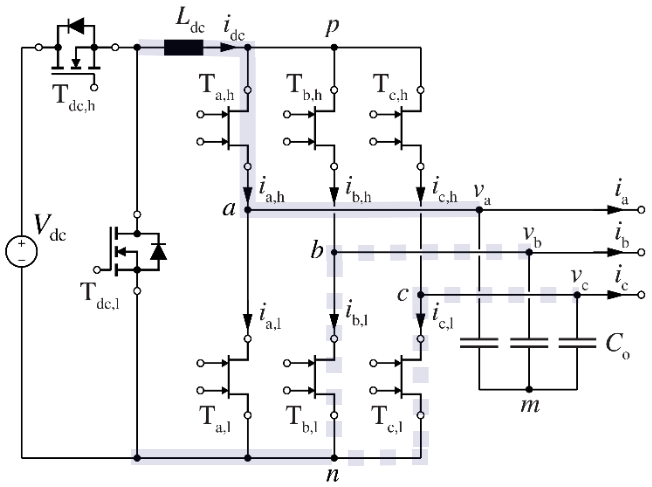


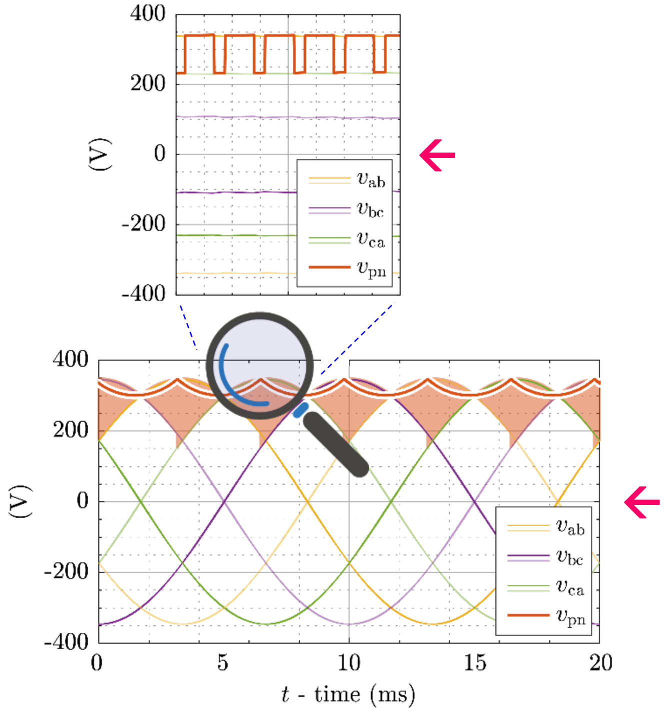


- *Switching of Only 2 of 3 Phase Legs (2/3 Mode) → Significant Reduction of Sw. Losses*

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 a CSI-Phase*

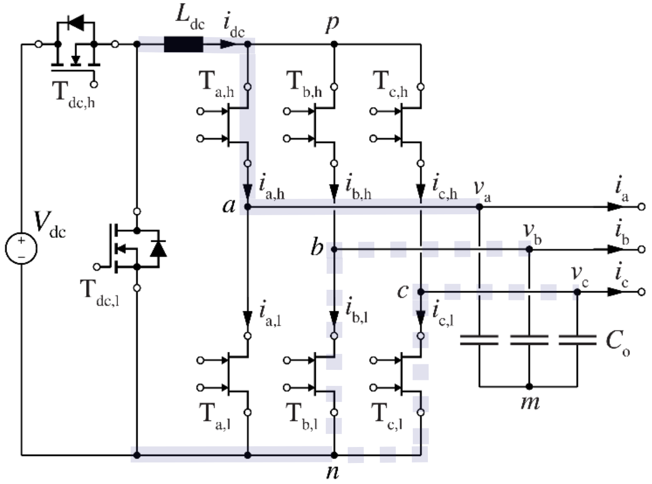


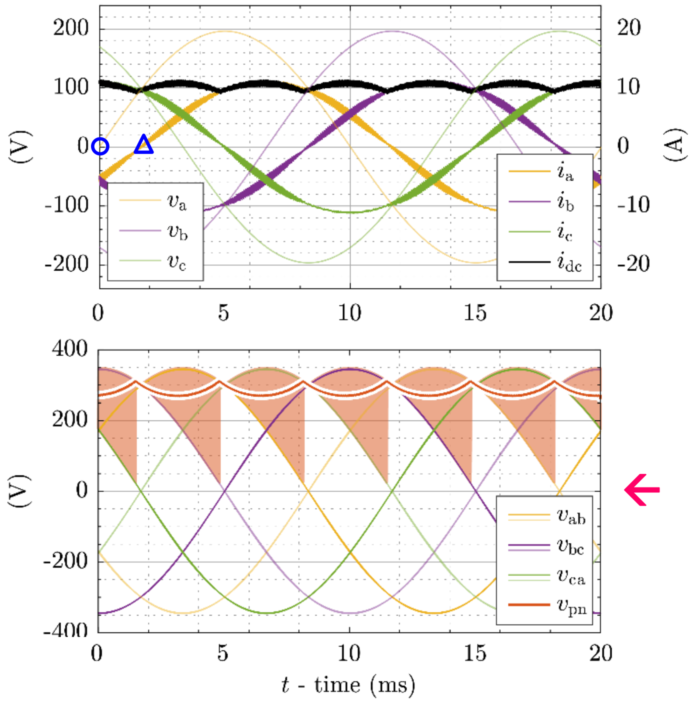


- *Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)*

3-Φ Buck-Boost CSI (5)

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

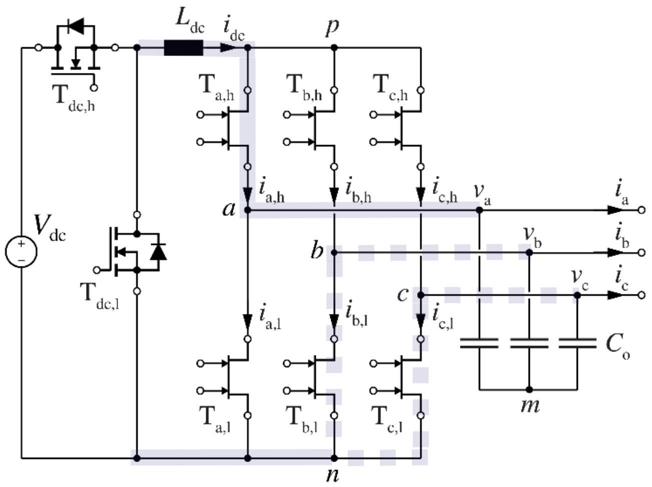


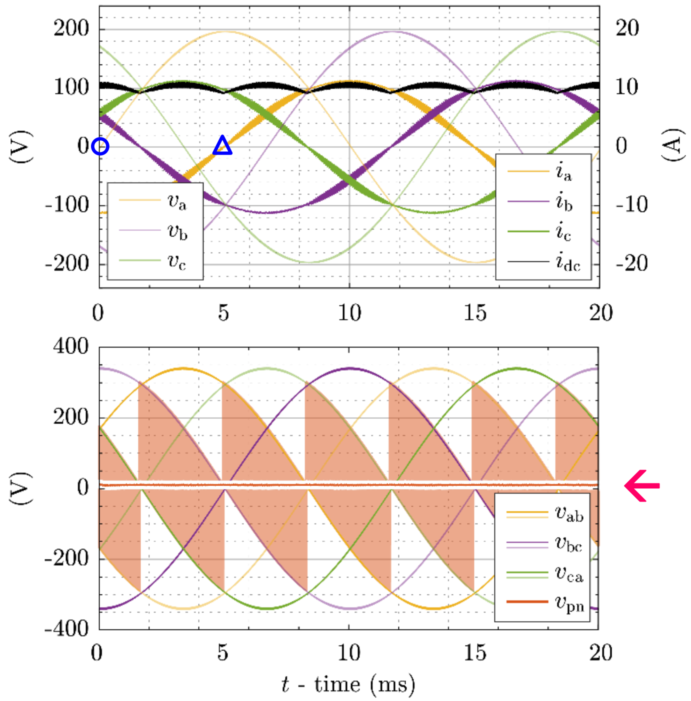


- *Operation for 30° Phase Shift of AC-Side Voltage & Current*

3-Φ Buck-Boost CSI (6)

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

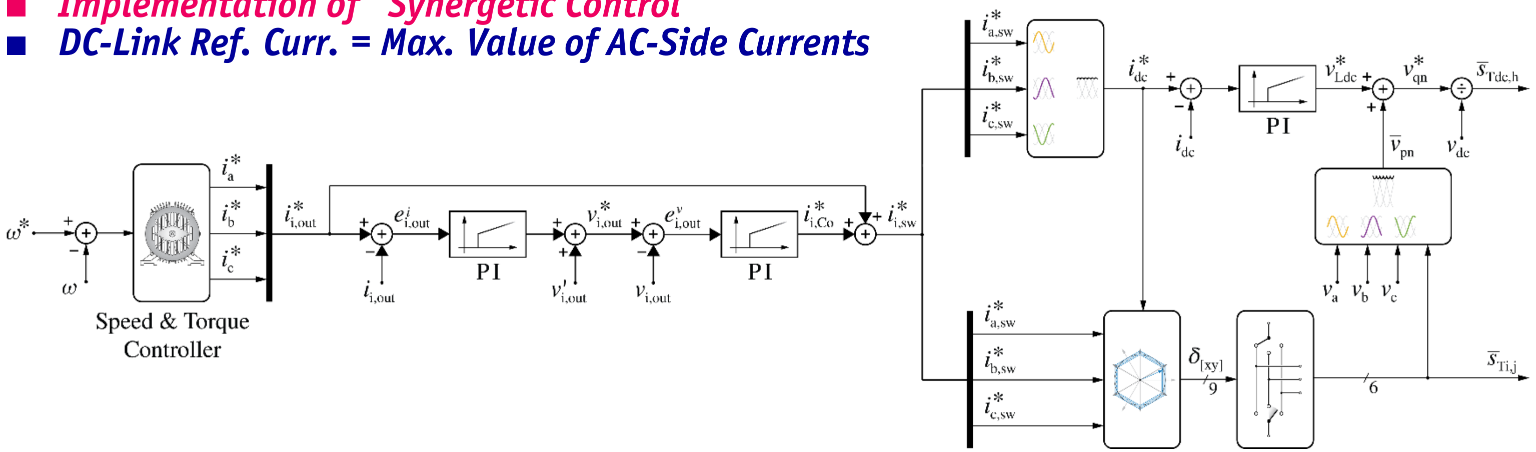




- *Operation for 90° Phase Shift (±90° — Limit Case for Buck-Stage Current Control)*

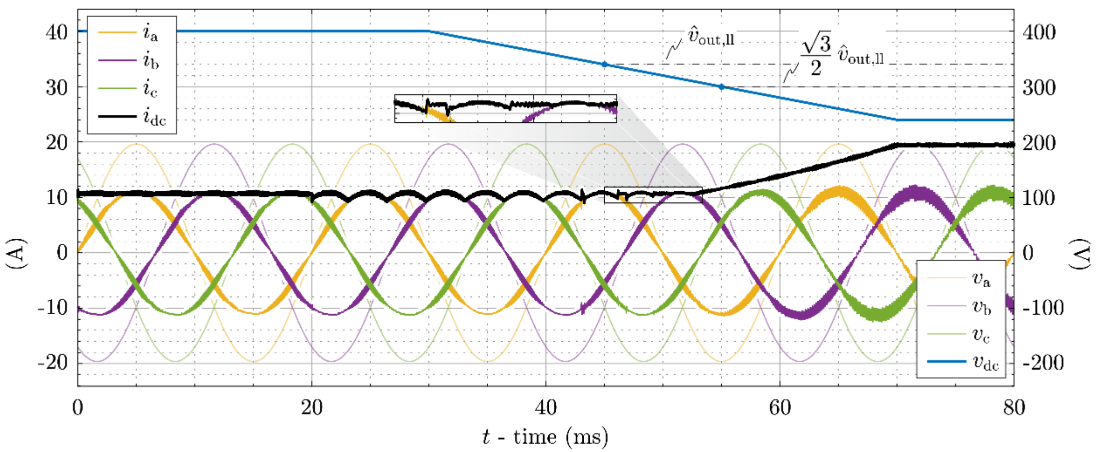
3-Φ Buck-Boost CSI (7)

- *Implementation of "Synergetic Control"*
- *DC-Link Ref. Curr. = Max. Value of AC-Side Currents*



3/3 Mod. (i_{DC}=const.) →
2/3 Mod. (6-Pulse i_{DC}) →
Partial 2/3 Mod. →
Full-Boost Operation

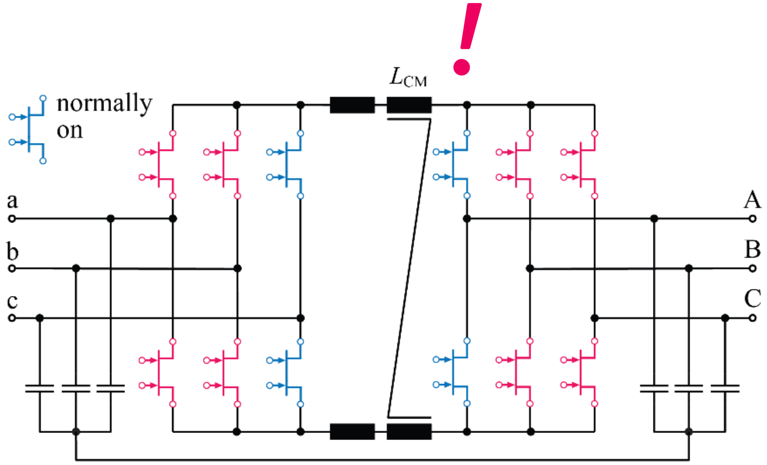
- *Seamless Transition from Buck to Boost Operation*



3-Φ DC-Link AC/AC Converter Topologies

■ *Current DC-Link Topology*

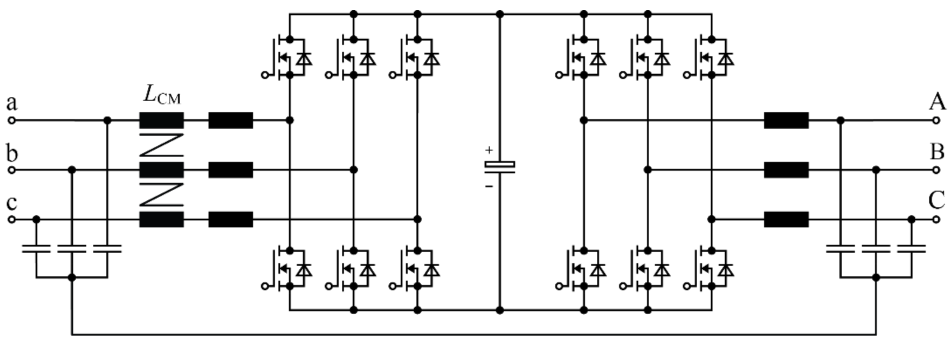
- *Application of M-BDSs*
- *Complex 4-Step Commutation*
- *Low Filter Volume*



- *Challenging Overvoltage Protection*
- *Lower Control Dynamics*

■ *Voltage DC-Link Topology*

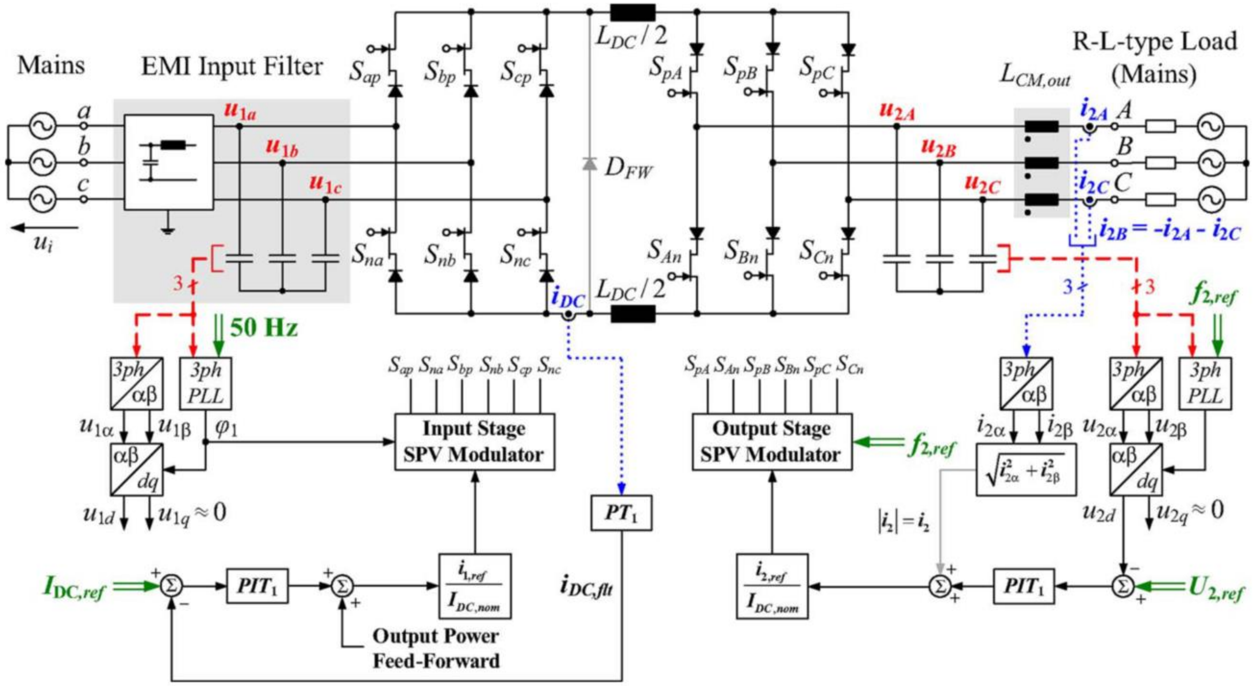
- *Standard Bridge-Legs*
- *Low-Complexity Commutation*
- *Defined Semiconductor Voltage Stress*
- *Facilitates DC-Link Energy Storage*



- *High Input / Output Filter Volume*

200kHz SiC Current DC-Link AC/AC Converter (1)

- *Normally-On TO-220 1200V/6A SiC J-FETs — Built in 2008 (!)*
- *1200V/10A SiC Schottky Series Diodes*
- *X7R Ceramic Filter Capacitors*

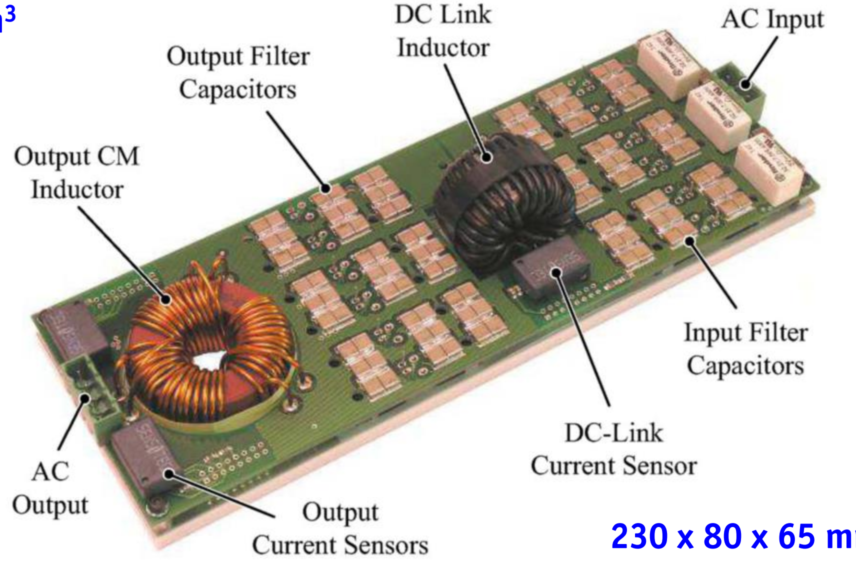


- *Natural Free-Wheeling Current Path for Gate Driver Power Supply Loss*

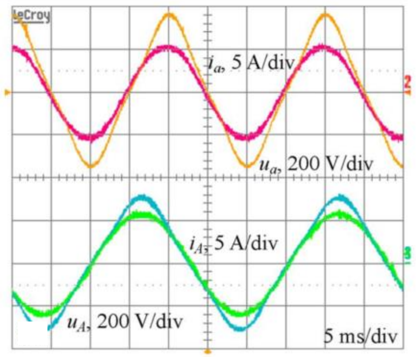
200kHz SiC Current DC-Link AC/AC Converter (2)

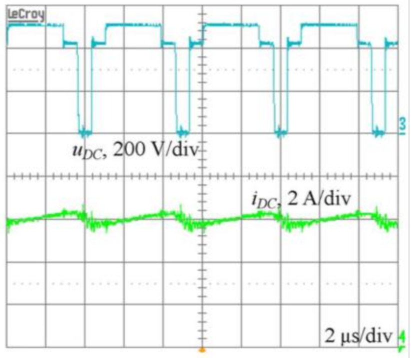
- *7kHz DC-Link Current Control Bandwidth*
- *PCB-Stack Construction — Power | Gate-Drive | Control Board*
- *Coldplate Cooling*

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



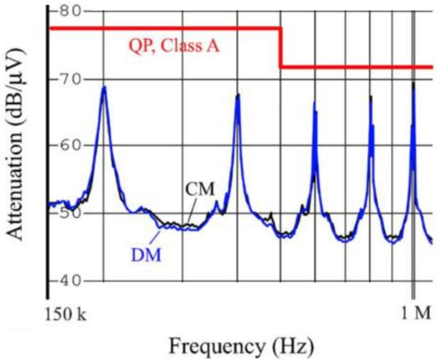


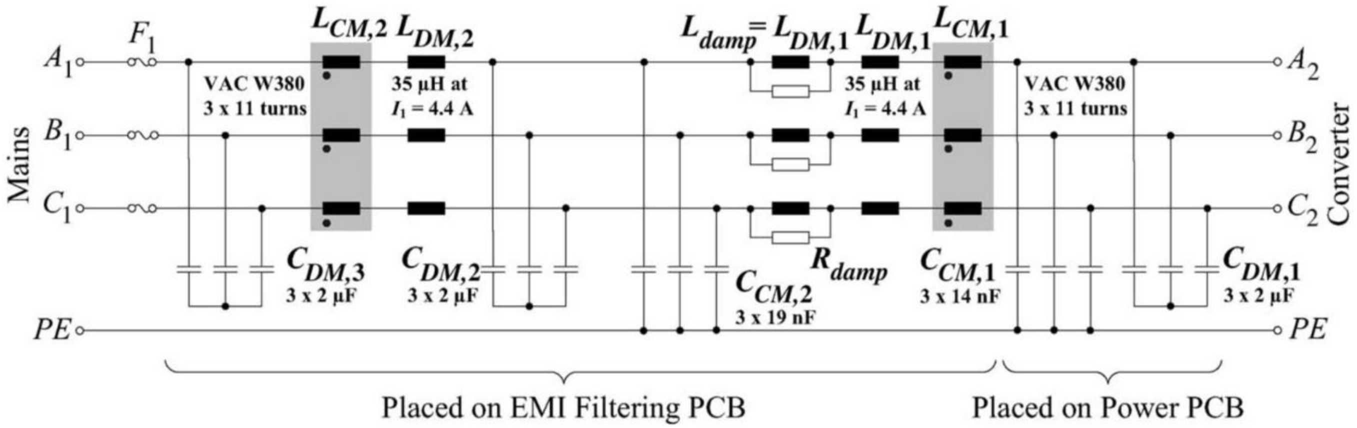
- *Low Volume Powder Core DC-Link Inductor (320uH)*

200kHz SiC Current DC-Link AC/AC Converter (3)

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

— Conducted EMI | EMI Filter

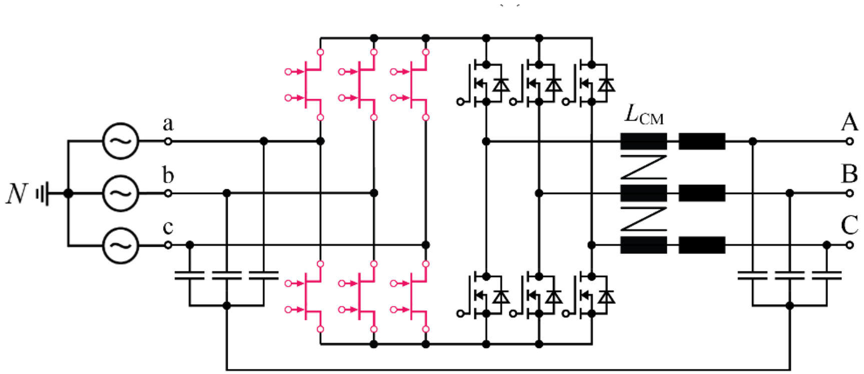




- *Low Volume Powder Core DC-Link Inductor (320uH)*

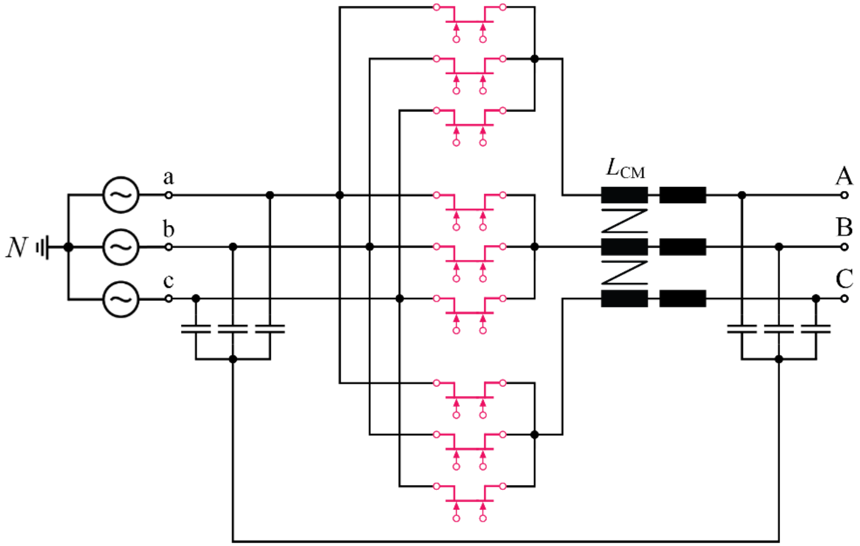
Remark 3-Φ AC/AC Matrix Converter

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



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

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

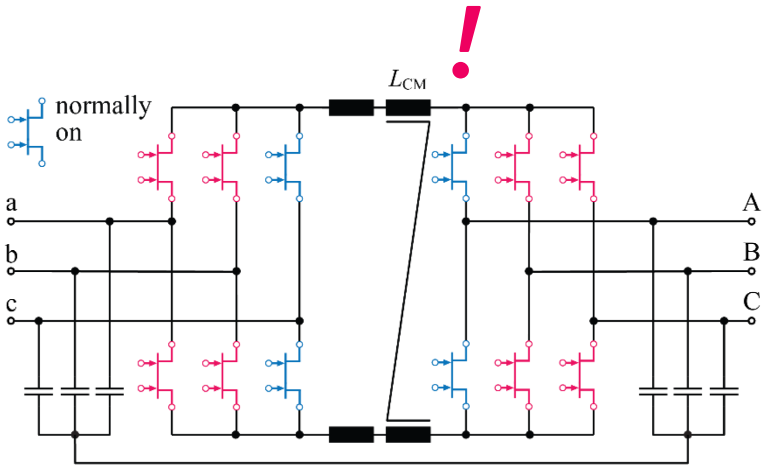


- — Thermally Critical @ $f_{out} \approx f_{in}$

3-Φ AC/AC Converter Comparison

- **Current DC-Link Topology**

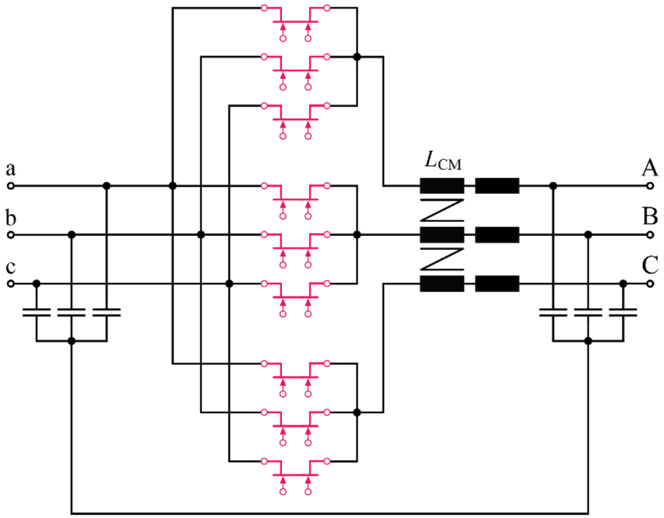
- *Application of M-BDSs | 12 Switches*
- *4-Step Commutation*
- *Buck-Boost Functionality*
- *Low Filter Volume*



- *Challenging Overvoltage Protection*

- **Direct Matrix Converter**

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



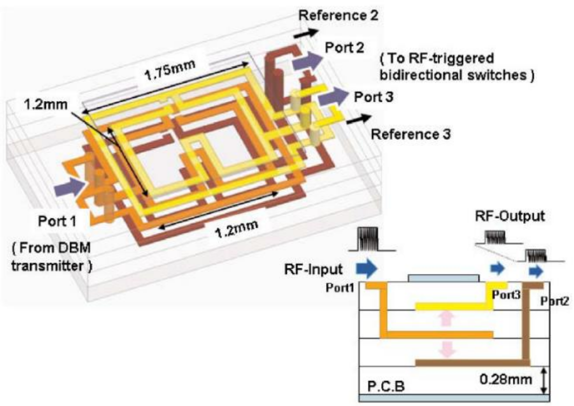
- *Challenging Overvoltage Protection*

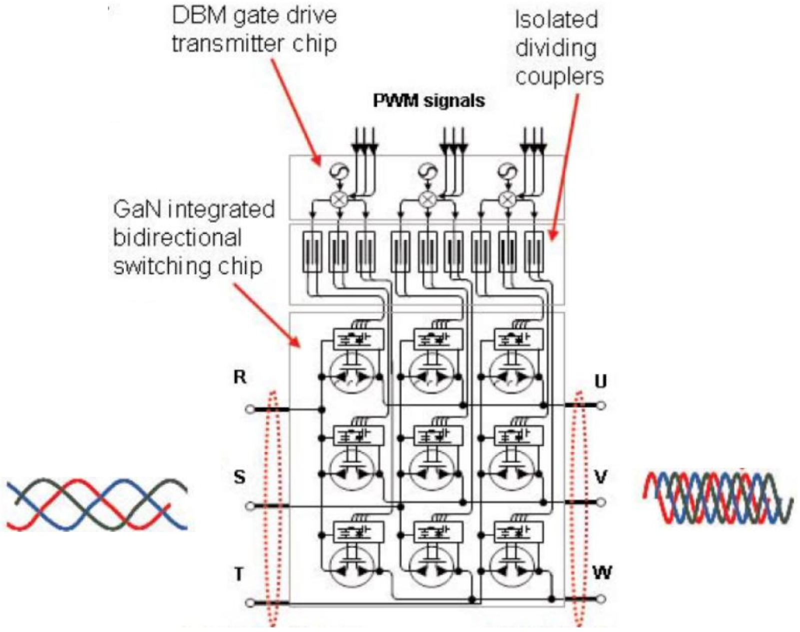
Matrix Converter Monolithic 3D-Integration

- *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)*

Source: Panasonic ISSCC 2014

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



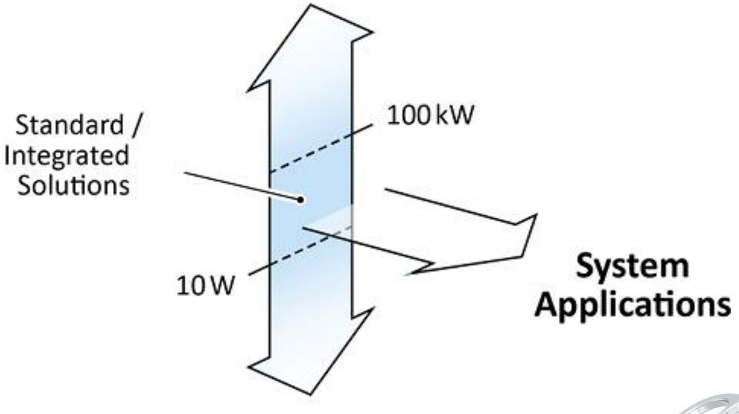


Conclusion

Future Development

- Commoditization / Standardization
- Extreme Cost Pressure (!)

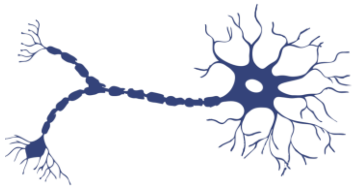
"There is Plenty of Room at the Top" → *Medium Voltage/Frequency Solid-State Transformers*



Power-Supplies on Chip ← "There is Plenty of Room at the Bottom"

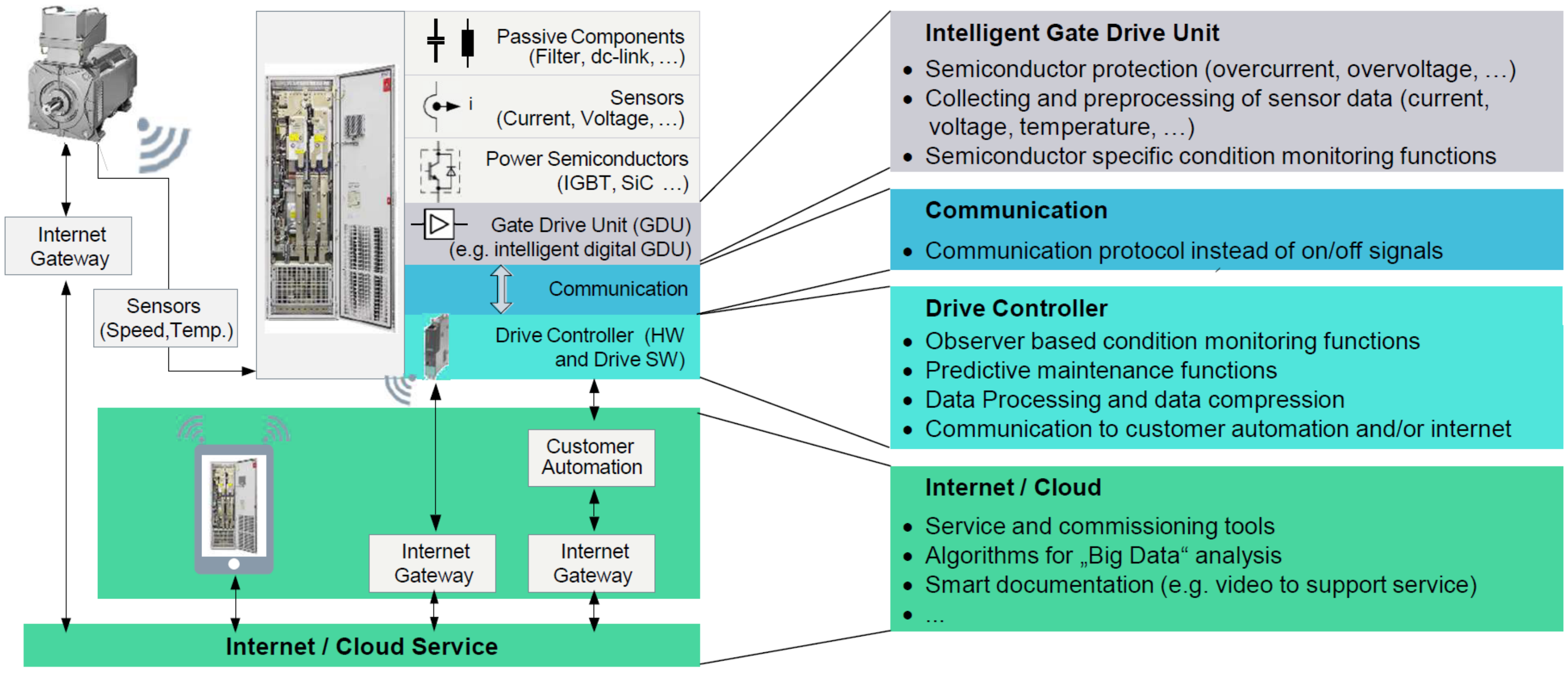
- *Key Importance of Technology Partnerships of Academia & Industry*

Smart Converter Concept



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

Source: Dr. R. Sommer SIEMENS



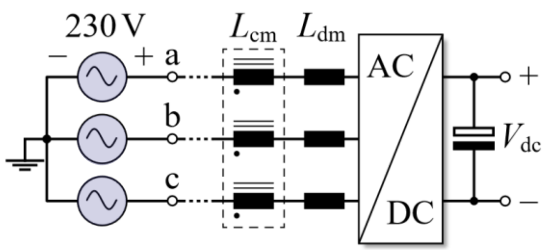
- *Sensing & Computing on Component Level | Converter Level | System Level | Application Level*

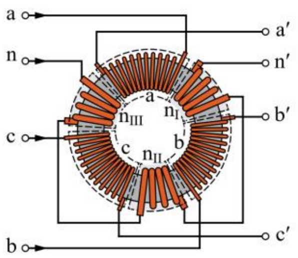
Appendix A

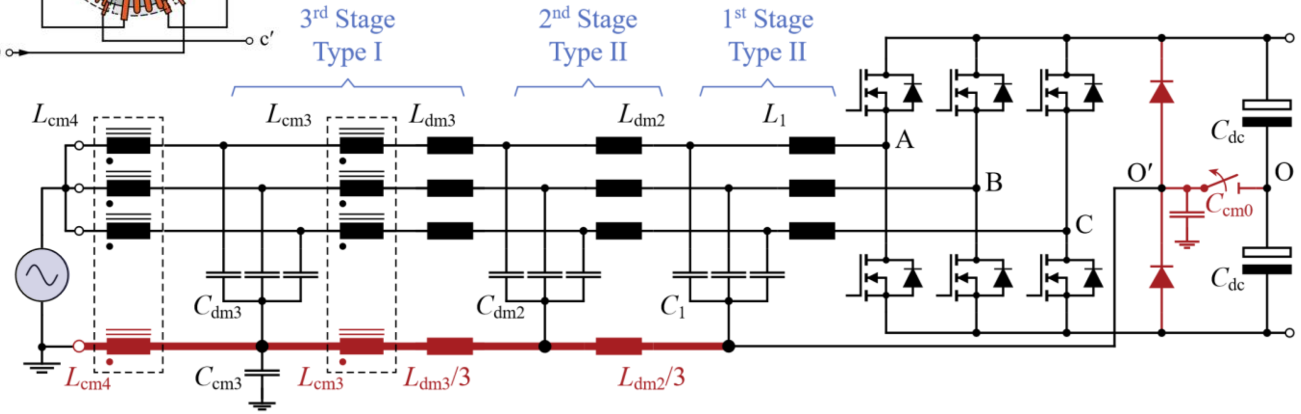
3-Φ / 1-Φ Full-Power Operation of PFC Rectifier Systems

3-Φ / 1-Φ Full-Power PFC Rectifier

- *4-Wdg. CM Filter Inductors & Add. Diode Bridge-Leg*
- *Interleaving of Bridge-Legs in 1-Φ Operation*
- *Application as EU/USA EV-Charger Front-End*







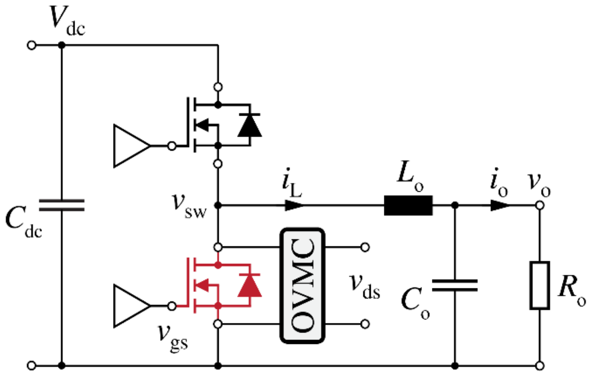
- *22kW / U_{DC}=750V / U_{AC}= 3-Φ 400V OR 1-Φ 240V | 98.4 % Efficiency | 6.8 kW/dm³ Power Density*

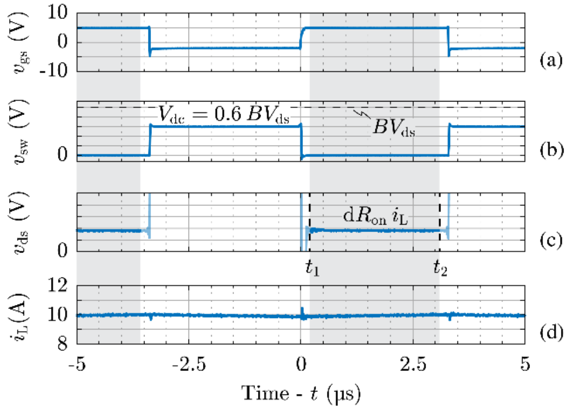
Appendix B

Accurate Measurement of
SiC/GaN Power Semiconductor
On-State & Switching Losses

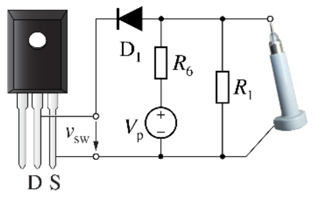
On-State Voltage Measurement (1)

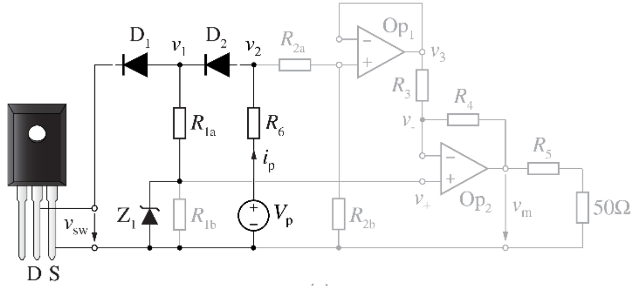
- *Device / Load Current / Gate Voltage / Junction Temp. → On State-Resistance $R_{DS(on)}$*





$$R_{DS(on)} = v_{DS(on)} / i_L$$

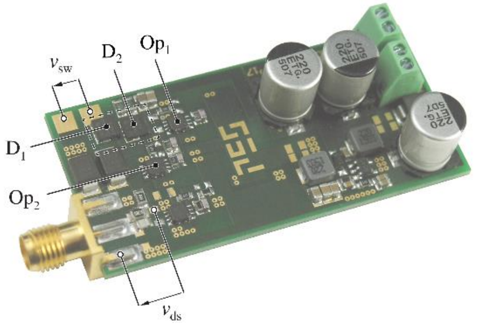


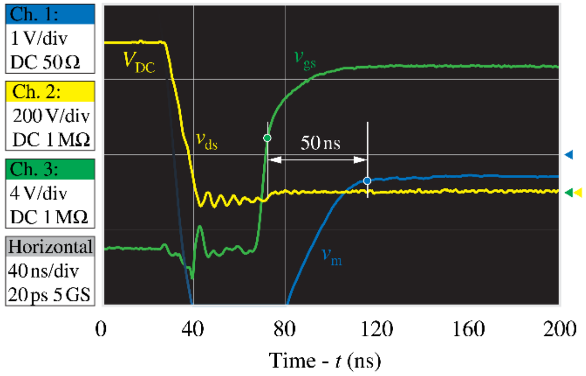


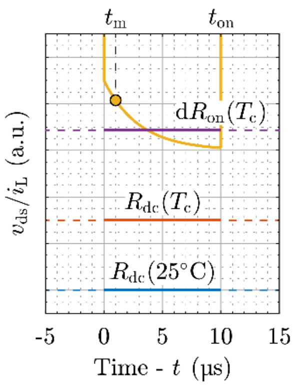
- *Decoupling High Blocking Voltage and (Very) Low On-State Voltage (≈1V << BV_{DS})*

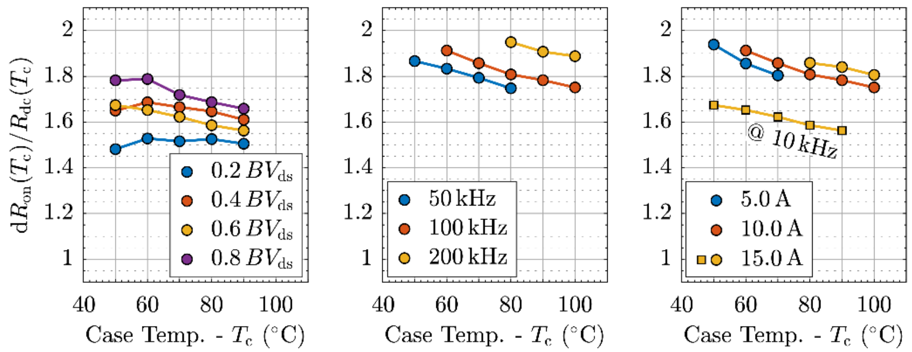
On-State Voltage Measurement (2)

- *High Accuracy* → *Compensation of Decoupling Diode Forward Voltage*
- *Fast Dyn. Response* → *Valid Measurement 50ns After Turn-On*





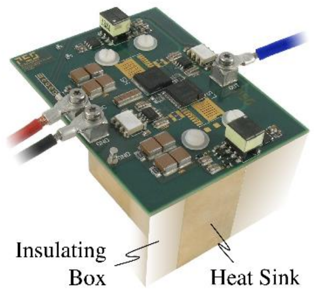


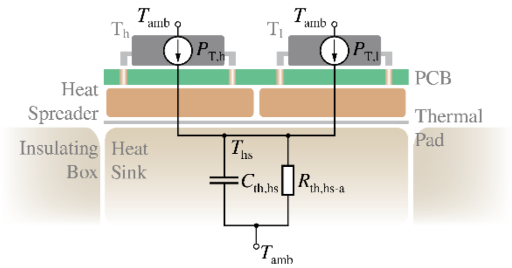


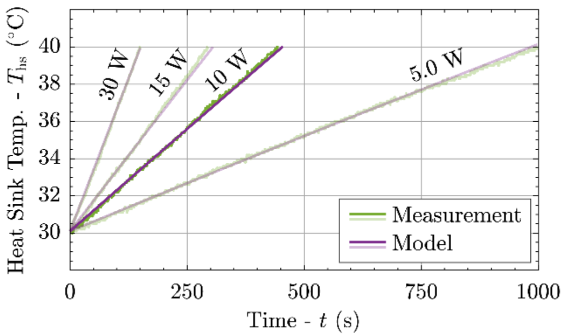
- *Example — Dyn. $R_{DS(on)}$ of GaN HEMTs → 2x $R_{DS(on)}$ @ 100kHz - 0.6BV_{DS}*

Switching Loss Measurement

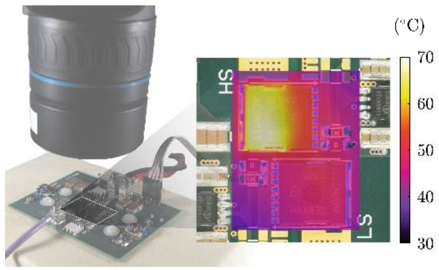
- *Heat-Sink Temp.-Based Transient Calorim. Method → 15 min / Measurement*

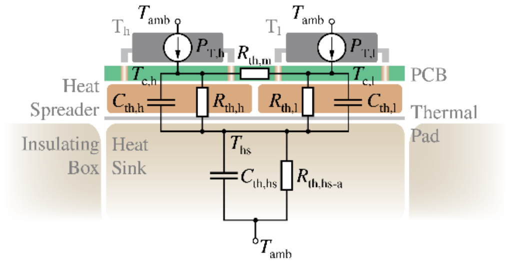


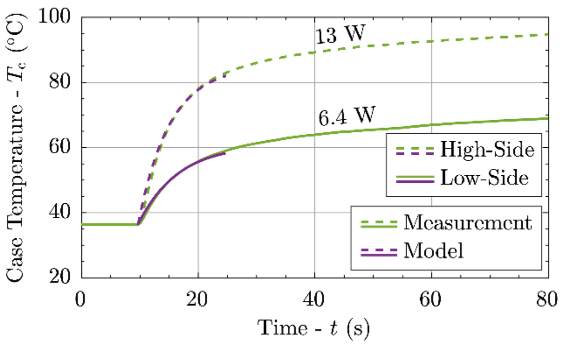




- *Case Temp.-Based Ultra-Fast Method → 15 sec / Measurement*

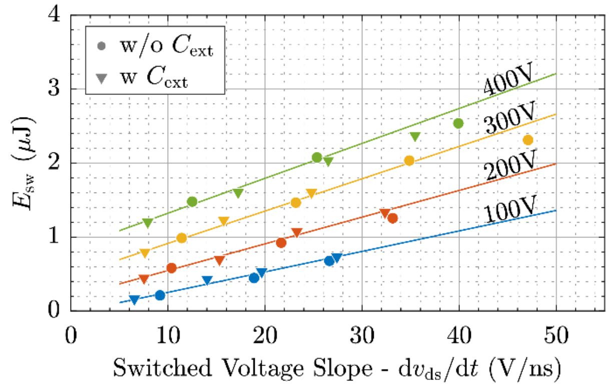


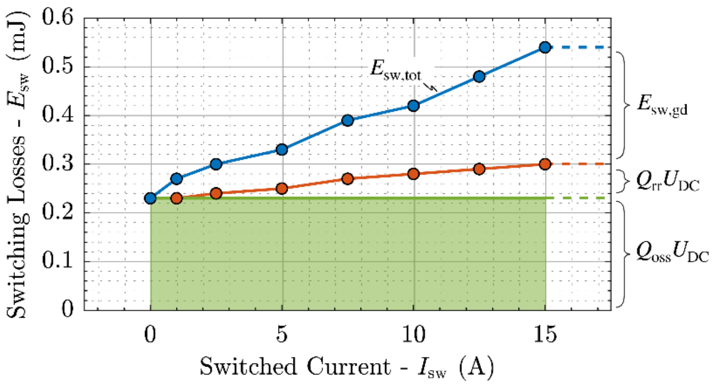




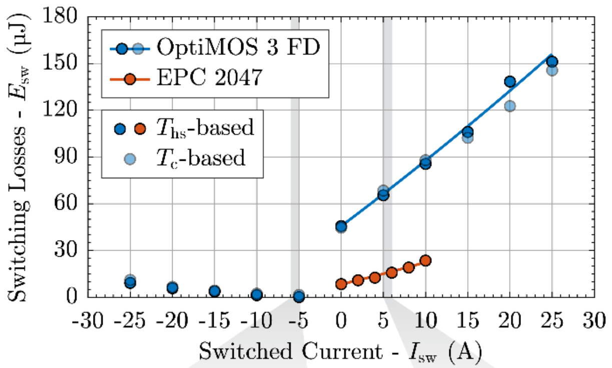
Example Measurement Results

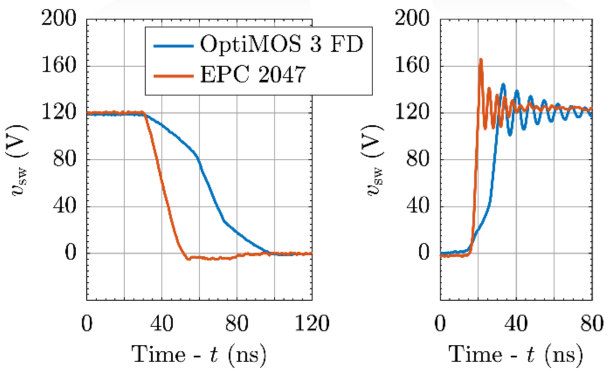
- 650V GaN (ZVS)





- 200V Si vs. GaN (Hard-Sw. & ZVS)





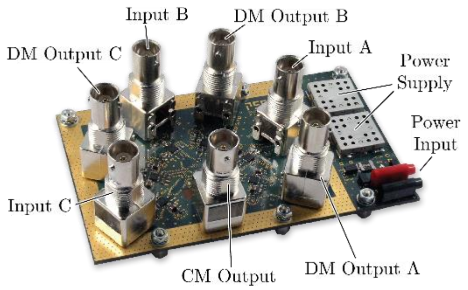
- 1.2kV SiC (Hard-Sw.)

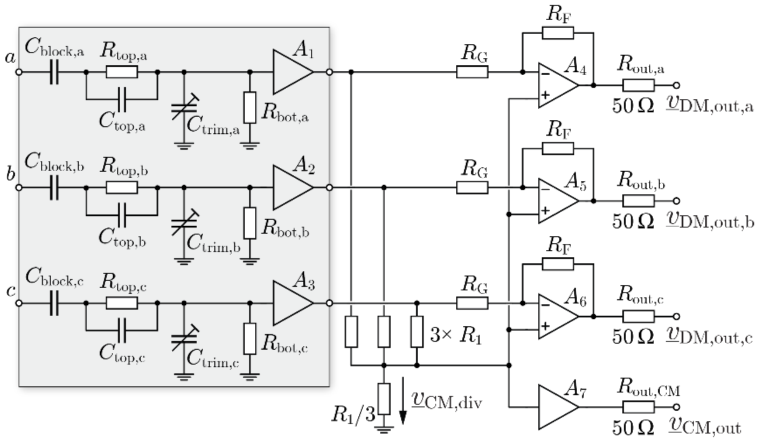
Appendix C

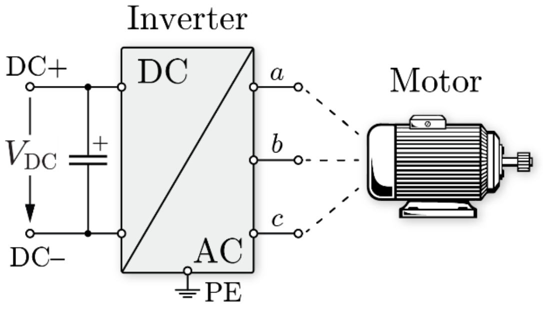
CM/DM EMI Separation

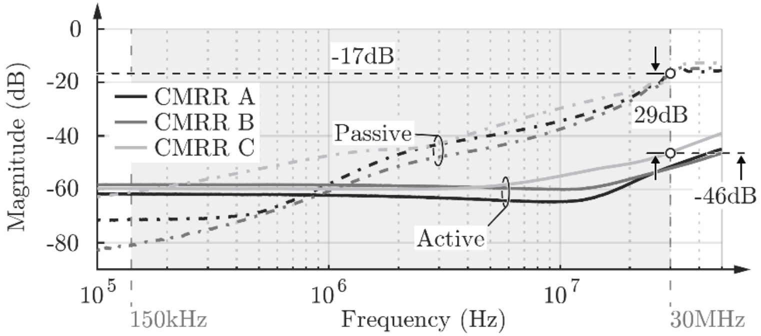
▶ 3-Φ DM/CM EMI Measurement & Separation

- EMI Measurement @ Inverter Output
- DM/CM Splitting for Specific Filter Design









- Cap. Coupled Interface Circuit as Replacement for LISN (Var. Output Frequ.)

Power Electronics 4.0
Cognitive Power Electronic Converters

A Few Spotlights

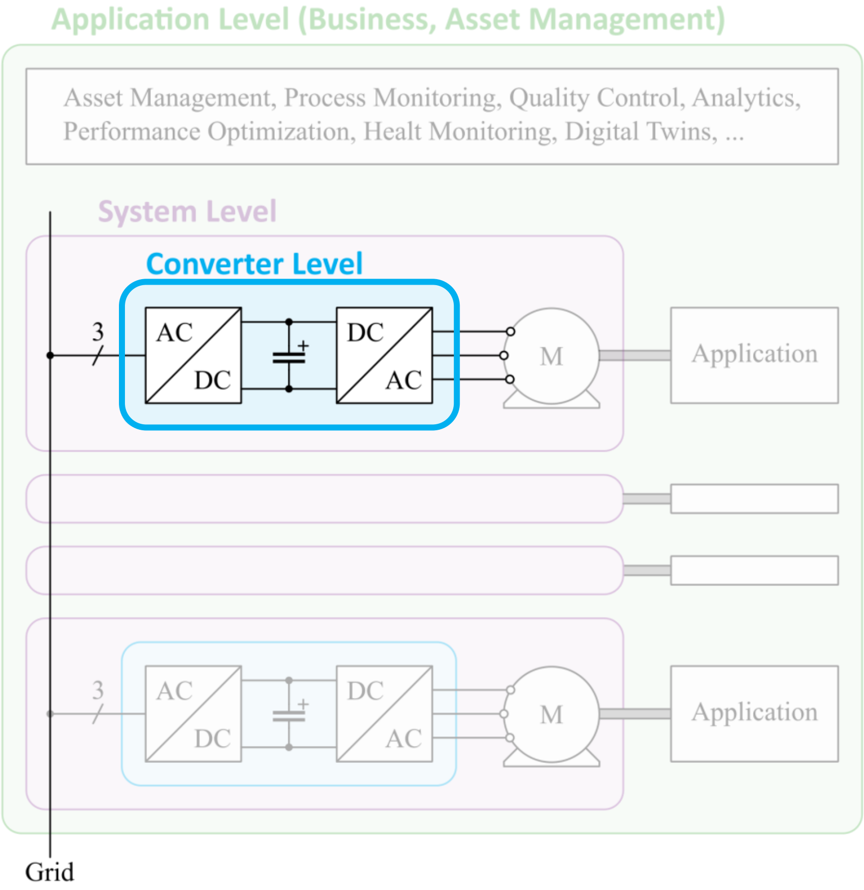
Cognitive Power Electronics: Converter Level

Key Question

- How to leverage artificial intelligence / machine learning (ML) techniques in the context of power electronics?

Converter Level

- Design
- Control / Operation
- Maintenance

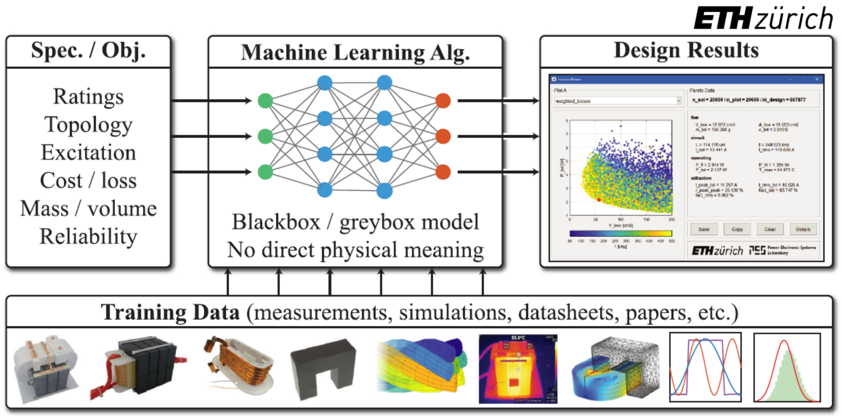


ML Applications in Power Electronics Life Cycle (Examples)

Design → Control → Maintenance

Inductor Modeling

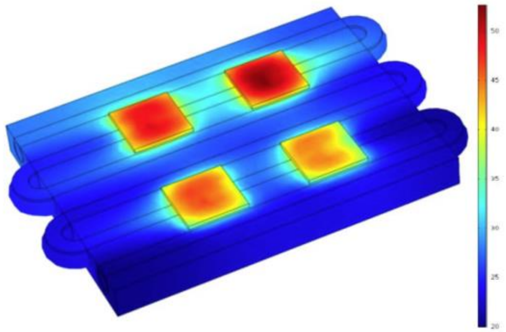
- Design **speedup** (50’000 designs/s) by replacing FEM simulations with trained ML model



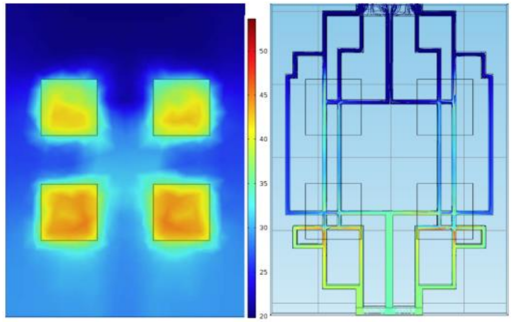
https://ai-mag.github.io/

Heat Sink Optimization with Genetic Algorithms

- Commercial



- Optimized



30% lower weight
10 K lower temp. rise
Better temp. homogeneity

T. Guillod et al., “Artificial neural network (ANN) based fast and accurate inductor modeling and design,” *IEEE Open J. Power Electron.*, vol. 1, 2020.

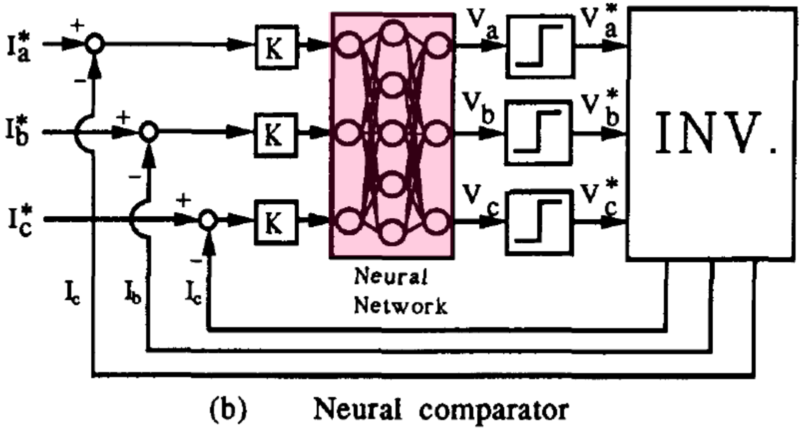
T. Wu, B. Ozpineci, and C. Ayers, “Genetic algorithm design of a 3D printed heat sink,” in *Proc. Appl. Power Electron. Conf. and Expo. (APEC)*, Long Beach, CA, USA, Mar. 2016.

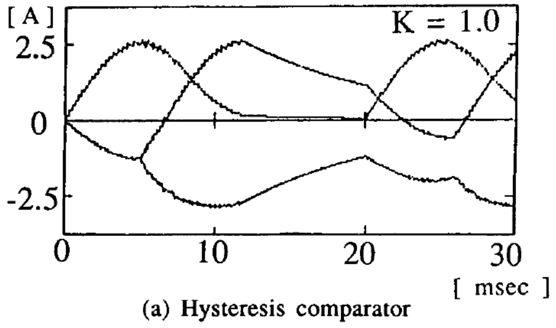
ML Applications in Power Electronics Life Cycle (Examples)

Design | **Control** | Maintenance

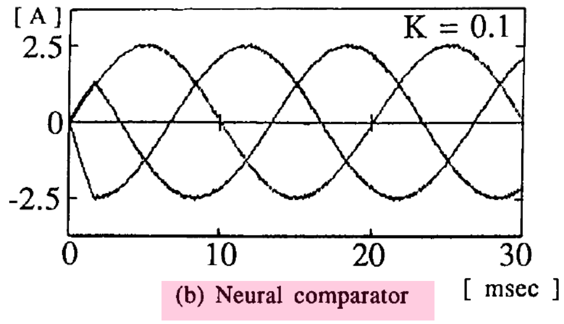
Current Control with Neural Network

- ► "Neural Comparator" replaces hysteresis comp.





- ► Hysteresis Comparator



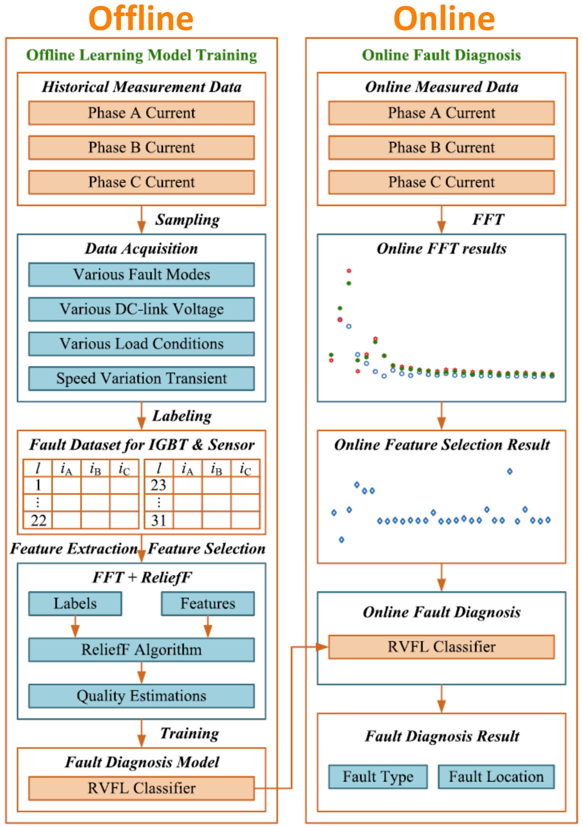
- ► Neural Comparator
  Better fault tolerance
  (loss of phase c current meas.)

1989 (!)

F. Harashima et al., "Application of neutral networks to power converter control," in *Conf. Rec. IEEE Ind. Appl. Soc. Society Annu. Meeting*, San Diego, CA, USA, Oct. 1989.

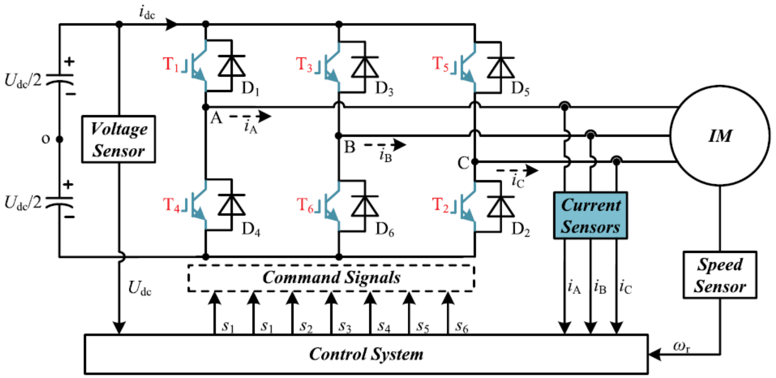
ML Applications in Power Electronics Life Cycle (Examples)

Design | Control | **Maintenance**

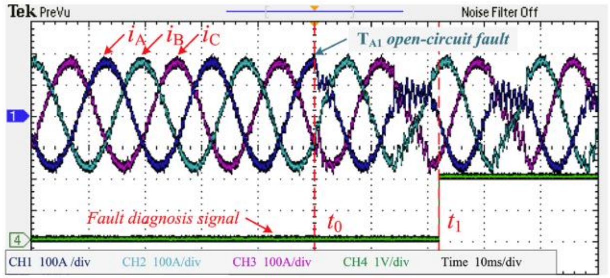


Data-Driven Detection of IGBT and Current Sensor Faults

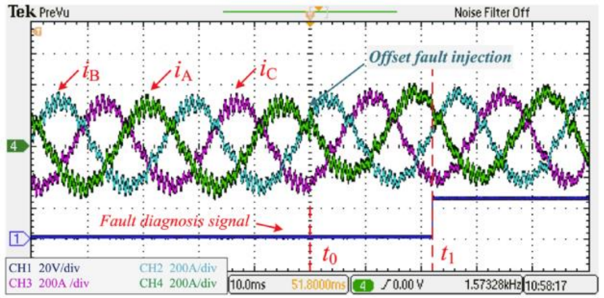
- Inputs: phase current measurements
- Output: fault type and location



IGBT open-circuit fault



Sensor offset fault



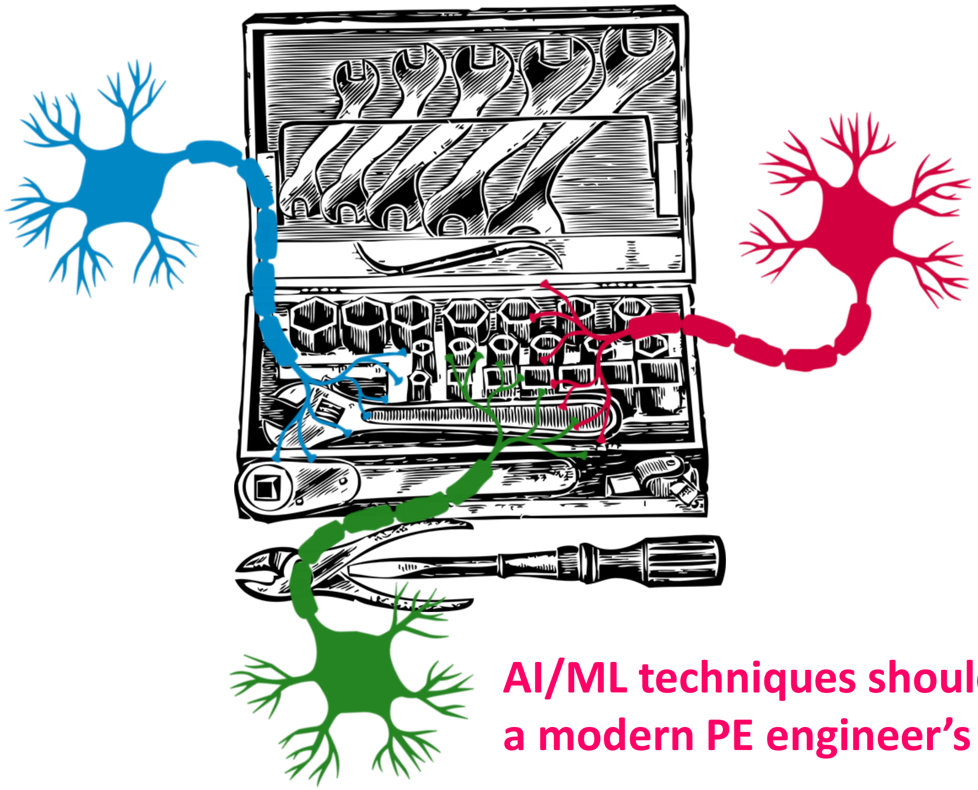
B. Gou, Y. Xu, Y. Xia, Q. Deng, and X. Ge, "An online data-driven method for simultaneous diagnosis of IGBT and current sensor fault of three-phase PWM inverter in induction motor drives," *IEEE Trans. Power Electron.*, vol. 35, no. 12, Dec. 2020.

ML Applications in Power Electronics Life Cycle: There are many!

Design → Control → Maintenance

- **Opportunities**
  - Mighty **tool** for a wide variety of engineering activities
  - High computing power becomes cheap and ubiquitous
  - **Use-case-specific** benefits over conventional / deterministic methods must be clarified

- **Challenges**
  - Training data quality and quantity / ability to generalize
  - Black-box / statistical nature of ML models vs. safety requirements
  - Cybersecurity



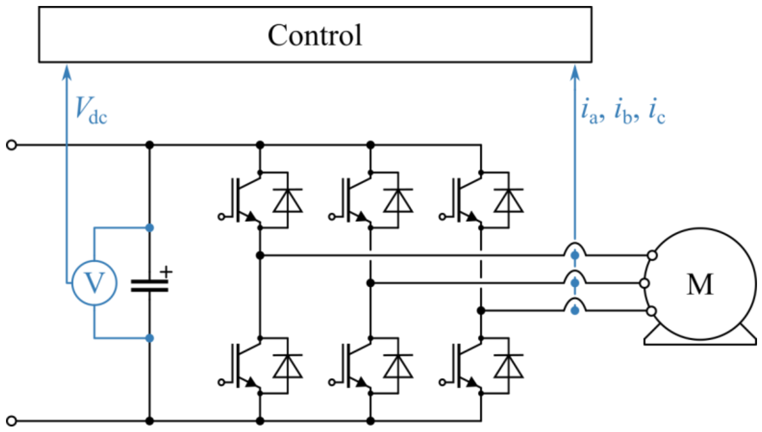
AI/ML techniques should be part of a modern PE engineer's toolbox!

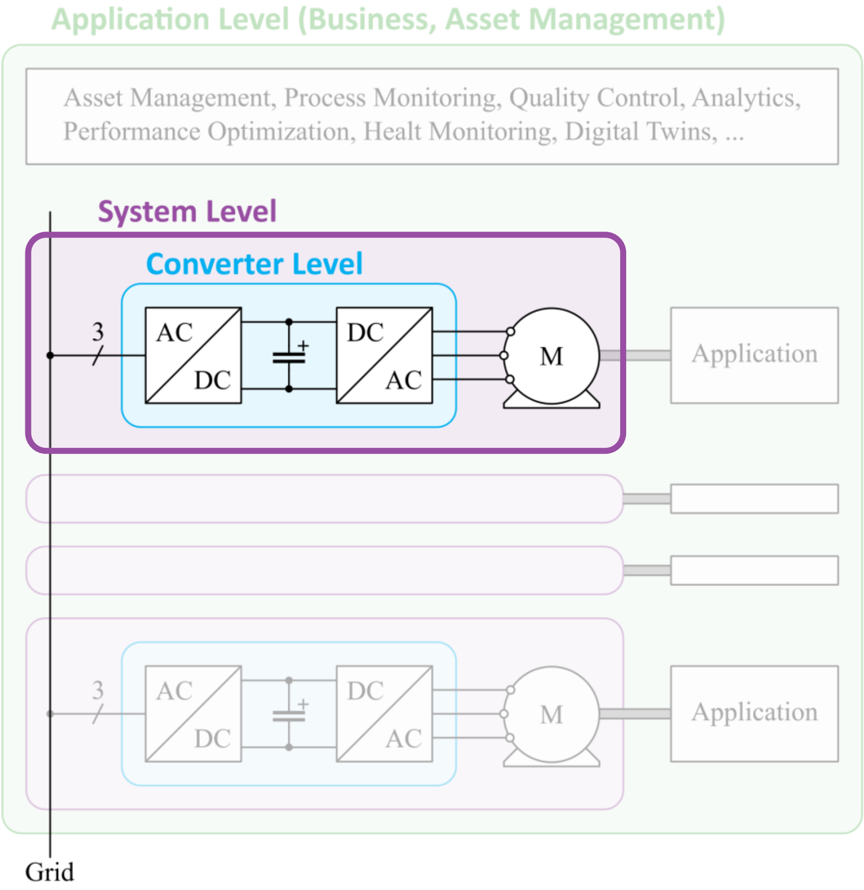
Cognitive Power Electronics: Beyond the Converter

Key Question

- How to utilize PE sensing / computing capabilities for improved interaction with immediate surroundings?

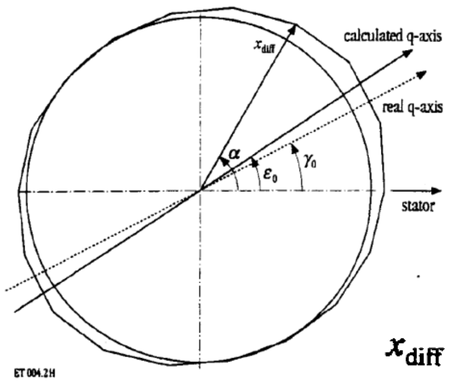
- Example: VSI with necessary sensors
  - DC Voltage
  - Phase currents





Example: INFORM (Indirect Flux detection by On-line Reactance Measurement)

- Proposed in 1988/1991 for PMSM rotor position estimation
- Based on measuring position-dependent differential reactance x_{diff}



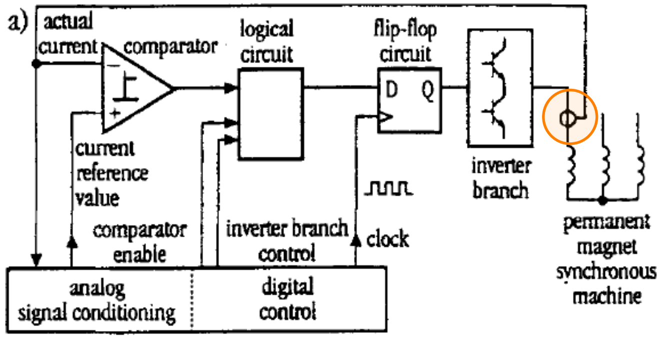
$$x_{\text{diff}}(\alpha,\gamma) = |\underline{u}_s| \,/\, |(\Delta \underline{i}_s \,/\, \Delta\tau)|_{\alpha,\gamma;\omega_m=0}$$

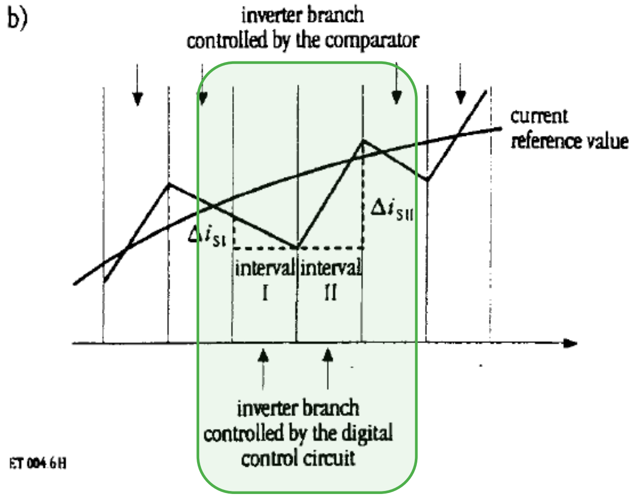
Switching state during test sequence

Phase current measurement

PE 4.0 Concept

- Utilize already available inverter capabilities
  - Current sensors
  - Test signal injection (minor SW modification)

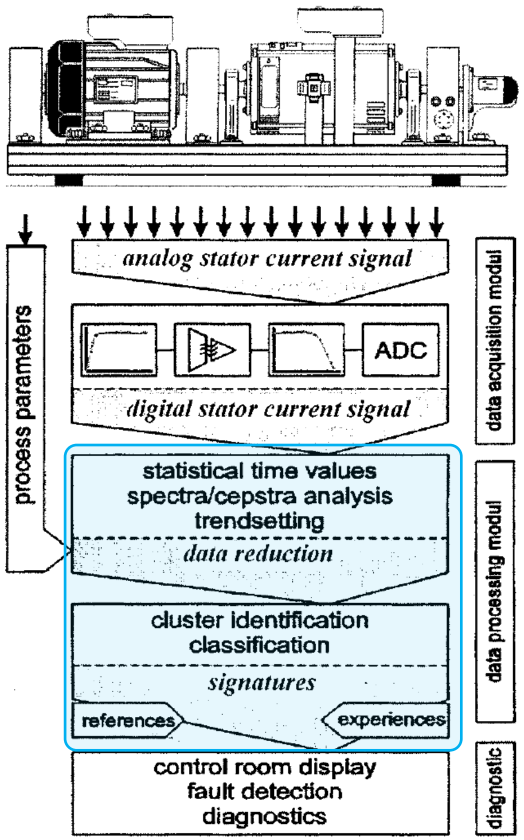


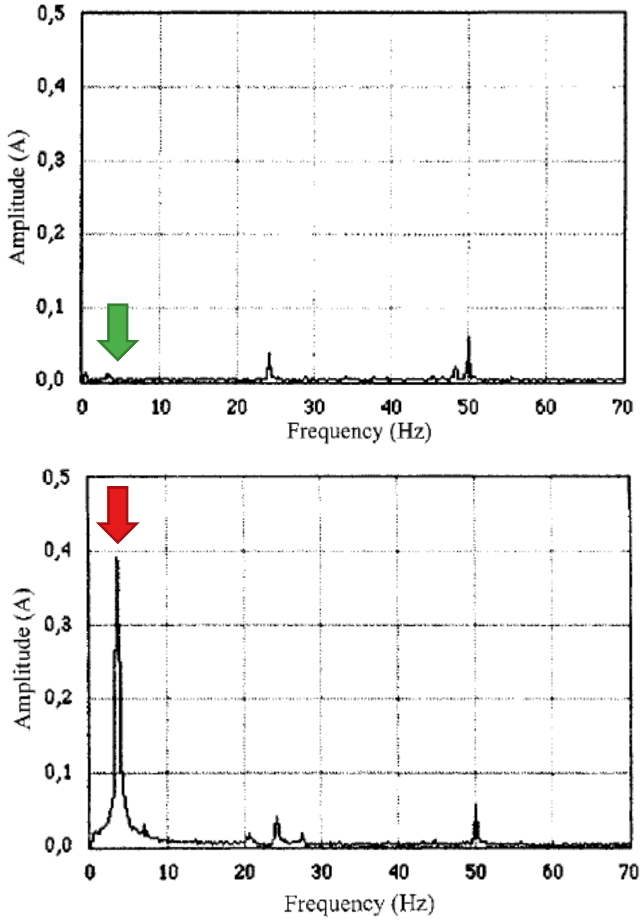


M. Schrödl and T. Stefan, "New rotor position detector for permanent magnet synchronous machines using the „Inform"-method," *Europ. Trans. Electr. Power*, vol. 1, no. 1, pp. 47–53, 1991.

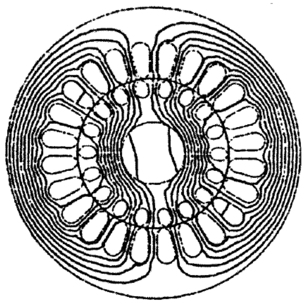
Example: Induction Motor Fault Detection

- Fault detection based on stator current monitoring
- Research topic since the 1980ies
- Inverter-as-a-sensor

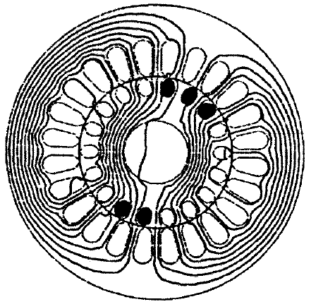




Healthy



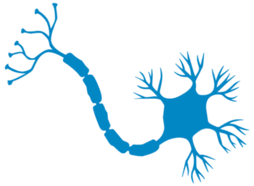
Broken Bars



2000 (!)

Today

- Basic workflow unchanged
- Improvements through
  - Higher computing performance
  - New machine learning algorithms



M. E. H. Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *IEEE Trans. Ind. Electron.*, vol. 47, no. 5, Oct. 2000.

Example: Data-Driven Machine Bearing Damage Detection

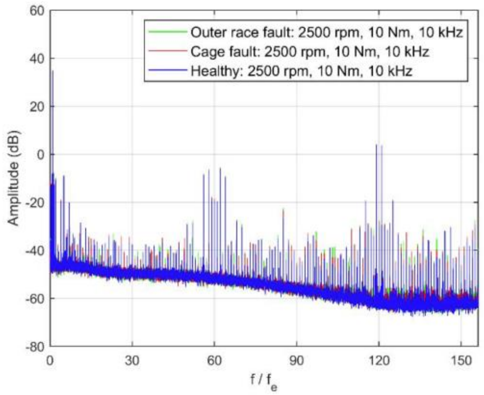
Fraunhofer IISB

Cognitive Power Electronics for Intelligent Drive Technology

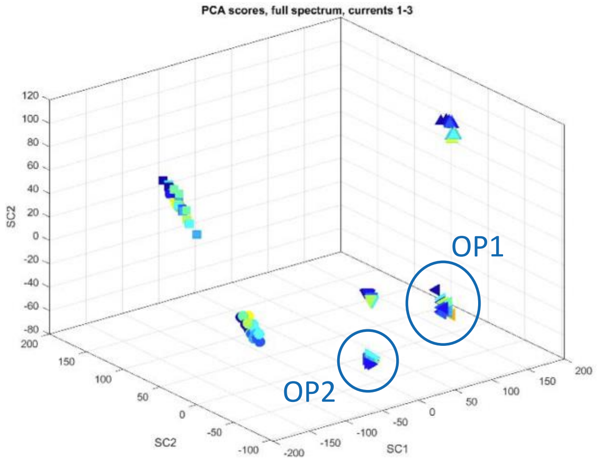
Challenge: Quantity + Quality!

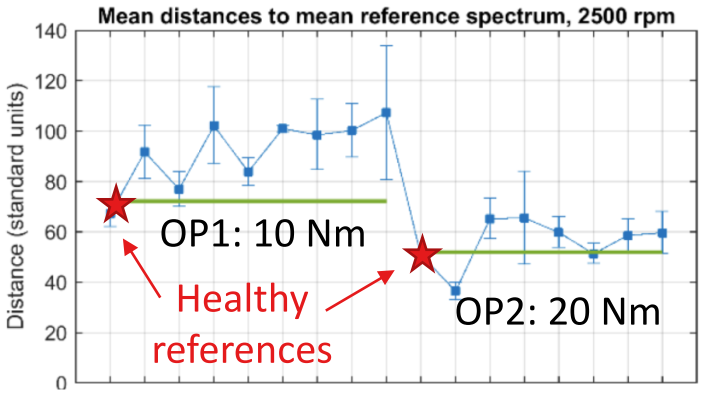
- Artificial damage for **training data** set generation

- Current spectra differences dominated by operating point, not by bearing damage



Principal Component Analysis (PCA)



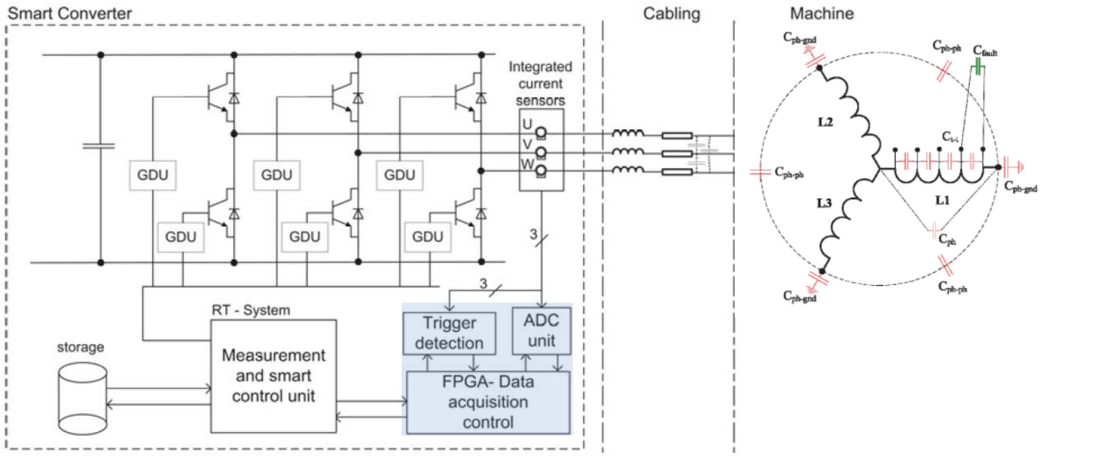


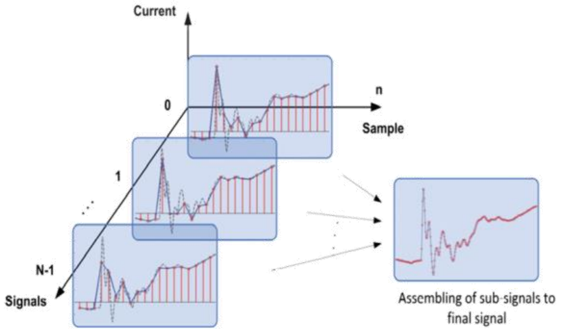
- Fault detection requires referencing to a healthy case for each operating point!
- Ongoing research

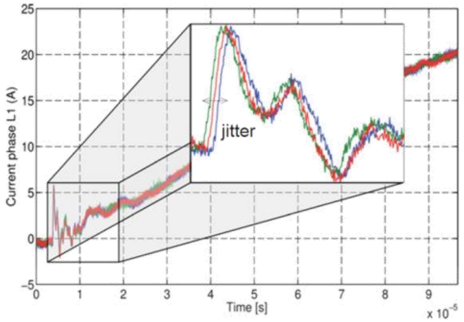
G. Roeder, X. Liu, and M. Hofmann, "Cognitive power electronics for intelligent drive technology," in *Proc. Electr. Drives Production Conf (EDPC)*, Ludwigsburg, Germany, Dec. 2020.

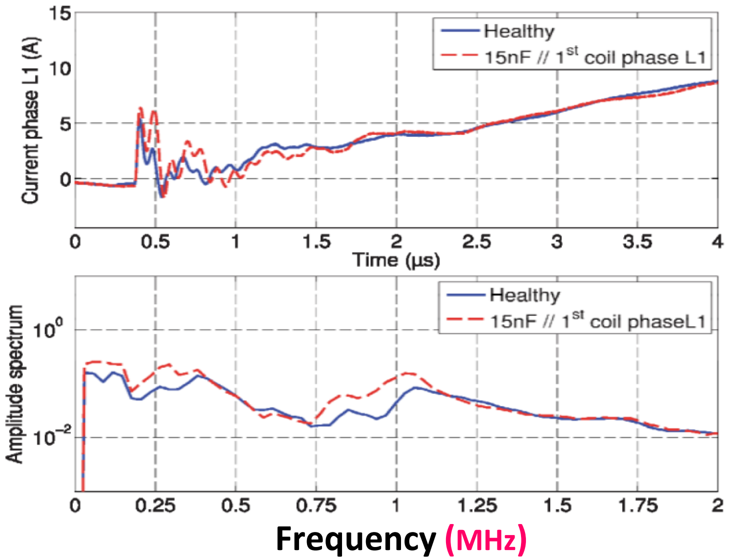
Example: Isolation Health Monitoring for MV Traction Motors

- ▶ Isolation faults change current response to test voltage pulses (pre-startup)

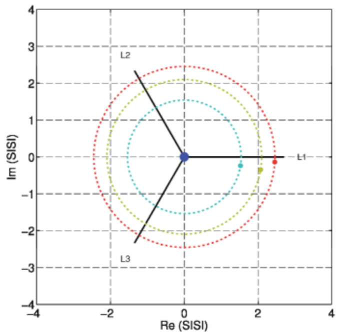








Fault detection
incl. location



Tricks to achieve required measurement bandwidth:

- ▶ 15 MS/s with 1 MS/s ADC
  → **Interleaving of multiple measurement seq.**
- ▶ Jitter can become critical for higher BW

M. A. Vogelsberger, C. Zoeller, J. Bellingen, and T. M. Wolbank, "Using smart converter to obtain traction-machine insulation health state information," Nuremberg, Germany, May 2016.

! Remark: Need for Extended Sensing Capabilities?

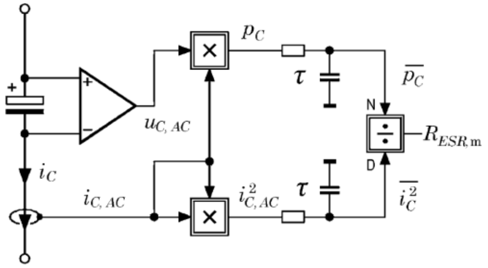
- Data (quality & quantity) is key for successful ML applications

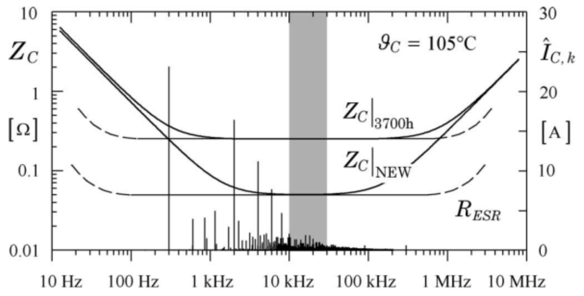
- **Improved Sensors**
  - Higher bandwidth
  - Higher sampling rate
  - Higher resolution

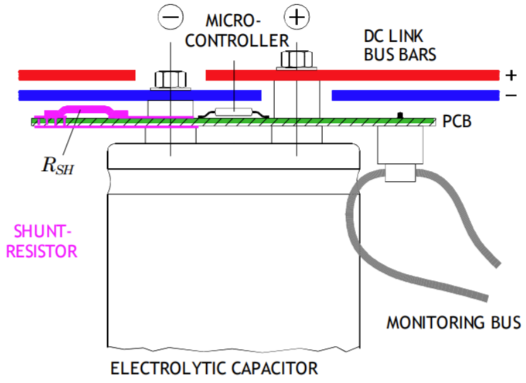
  ⇒ Memory
  Processing power
  Uplink bandwidth

- **Additional Sensors**
  - ESR of Capacitors
  - On-state voltages of semiconductors
  - Component / heat sink temperatures
  - Vibrations
  - …

Example: Capacitor ESR Meas. for Condition Monitoring







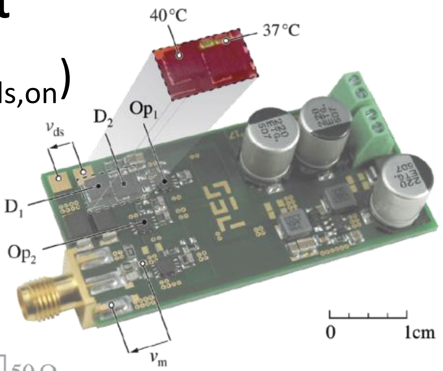
- Measurement of ESR in "frequency window" (temp. comp.)
- Data transfer by opt. fiber or near-field RF link

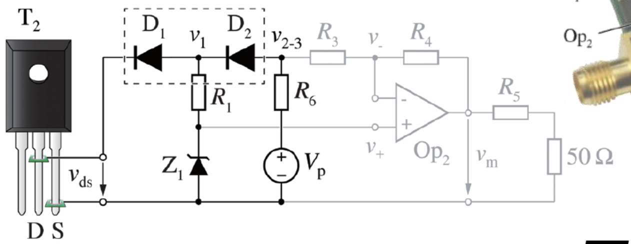
M. A. Vogelsberger, T. Wiesinger, and H. Ertl, "Life-cycle monitoring and voltage-managing unit for DC-link electrolytic capacitors in PWM converters," *IEEE Trans. Power Electron.*, vol. 26, no. 2, Feb. 2011.

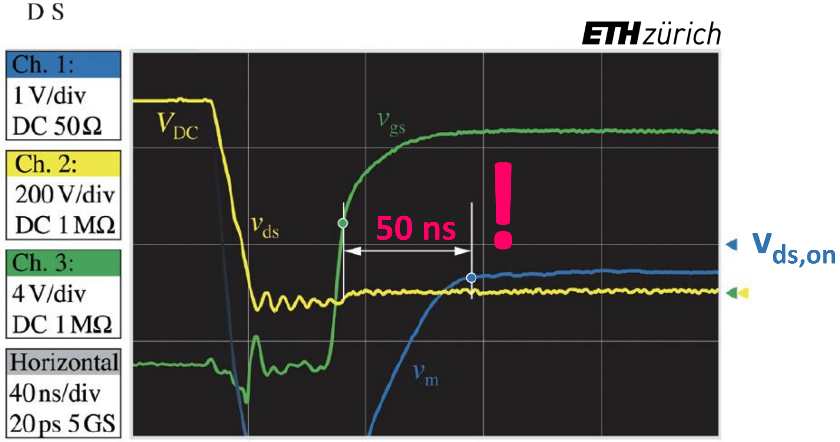
Remark: Sensing Concepts (1)

On-State Voltage Measurement

- Characterization (dynamic $R_{ds,on}$)
- Condition monitoring

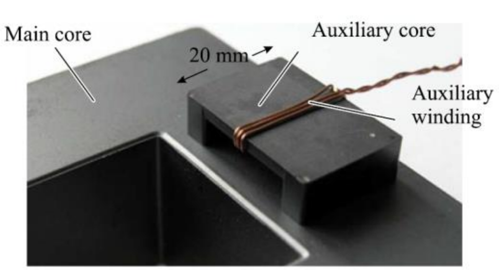


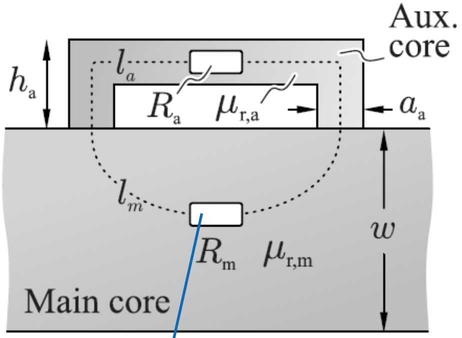


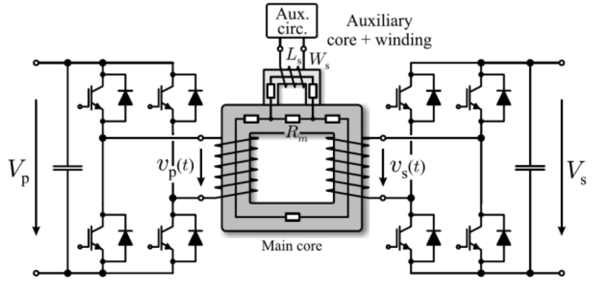


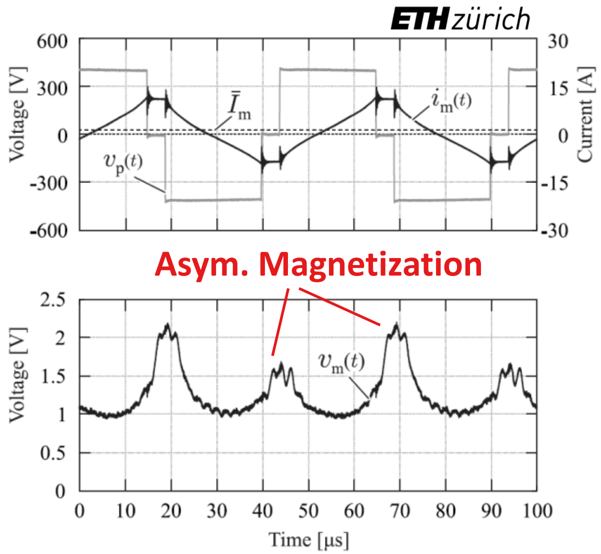
M. Guacci, D. Bortis, and J. W. Kolar, "On-state voltage measurement of fast switching power semiconductors," *CPSS Trans. Power Electron. Appl.*, vol. 3, no. 2, Jun. 2018.

Core Flux Density Sensing – The Magnetic Ear









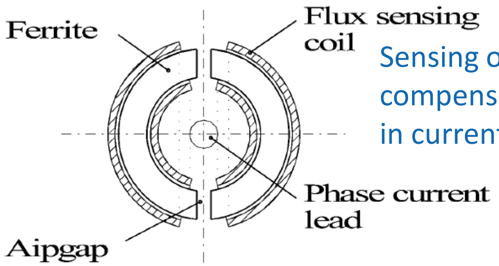
- **Shared magnetic path:**
  $L_{aux} = f(B_{main})$
- Meas. circuit: $L_{aux} \rightarrow v_m$

G. Ortiz, L. Fässler, J. W. Kolar, and O. Apeldoorn, "Flux balancing of isolation transformers and application of 'The Magnetic Ear' for closed-loop volt–second compensation," *IEEE Trans. Power Electron.*, vol. 29, no. 8, Aug. 2014.

Remark: Sensing Concepts (2)

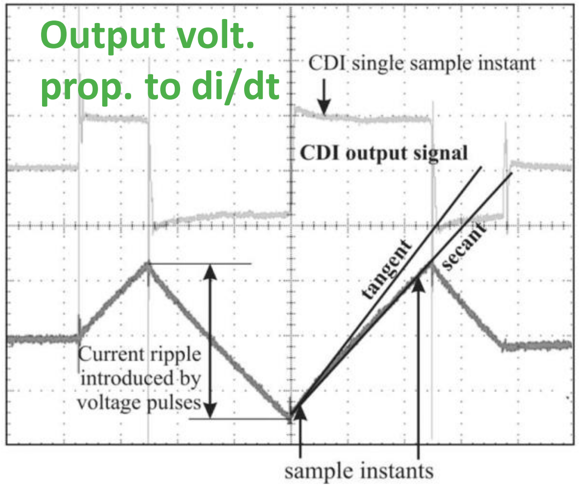
Direct di/dt Sensing

- E.g., INFORM: $x_{\text{diff}}(\alpha,\gamma) = |\underline{u}_s| \,/\, |(\Delta \underline{i}_s \,/\, \Delta\tau)|_{\alpha,\gamma:\omega_m=0}$



Sensing only, no compensating EMF as in current transformer!

Needed to avoid saturation (no compensating current)

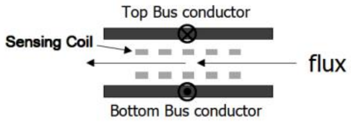


Output volt. prop. to di/dt

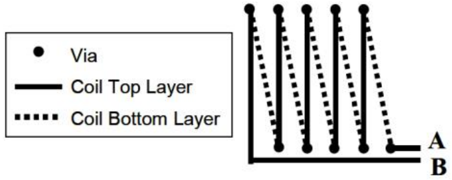
T. M. Wolbank, J. L. Machl, and H. Hauser, "Closed-loop compensating sensors versus new current derivative sensors for shaft-sensorless control of inverter fed induction machines," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 4, Aug. 2004.

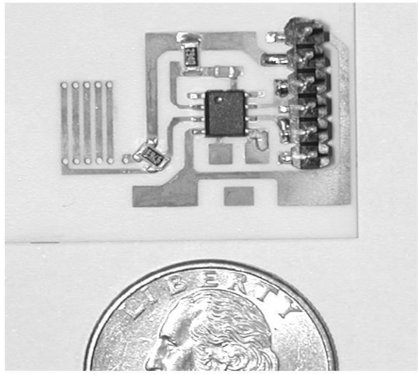
Integrable Current Sensors

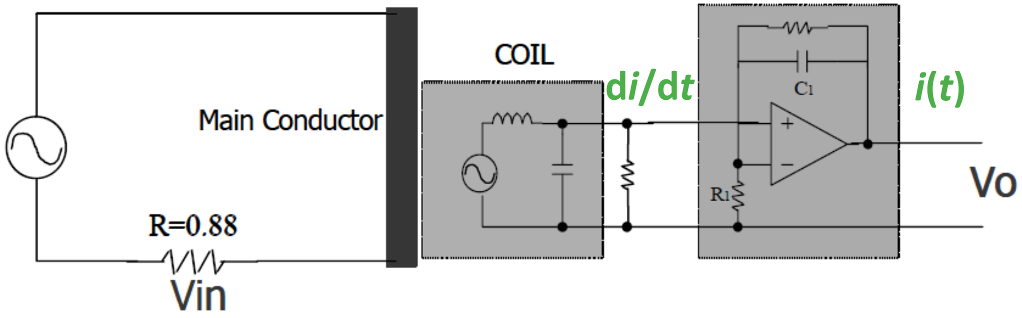
- Planar Rogowski Coil



(a) Cross-sectional view



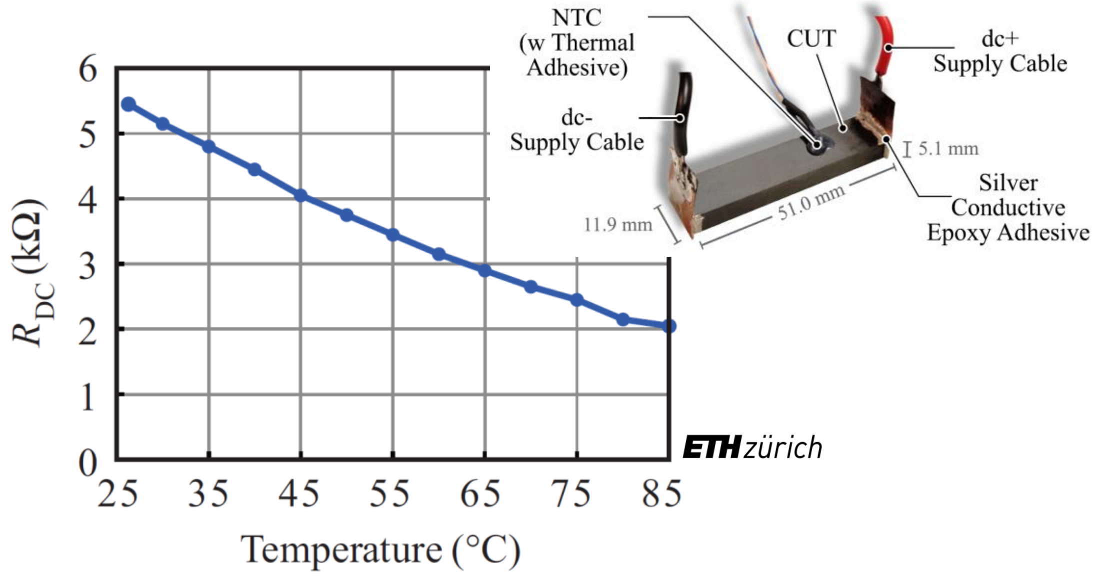




C. Xiao, L. Zhao, T. Asada, W. G. Odendaal, and J. D. van Wyk, "An overview of integratable current sensor technologies," in *Conf. Rec. 38th Ind. Appl. Soc. Annu. Meet.*, Salt Lake City, UT, USA, Oct. 2003.

Remark: Sensing Concepts (3) – Utilization of "Parasitic" Physical Effects

Ferrite Core Temperature Sensing via El. Resistance

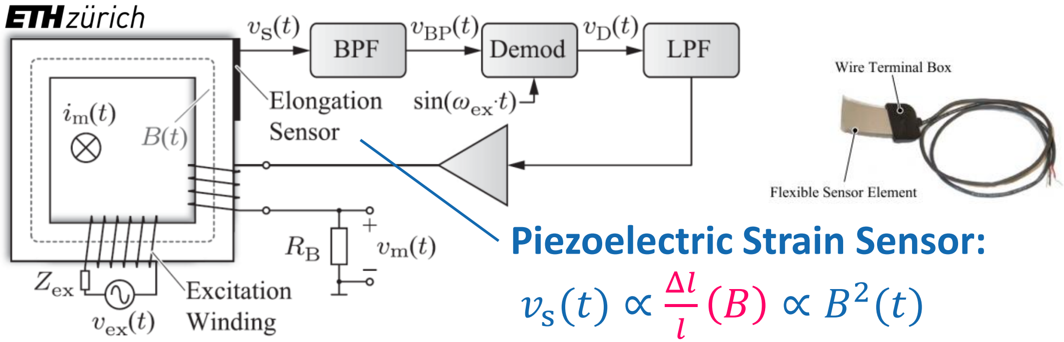


- Temperature-dependent electrical cond. of ferrites
- Could be utilized for integrated temp. sensing in **Smart Passives**

D. Neumayr, D. Bortis, J. W. Kolar, S. Hoffmann, and E. Hoene, "Origin and quantification of increased core loss in MnZn ferrite plates of a multi-gap inductor," *CPSS Trans. Power Electron. Appl.*, vol. 4, no. 1, Mar. 2019.

P. Papamanolis, T. Guillod, F. Krismer, and J. W. Kolar, "Transient calorimetric measurement of ferrite core losses up to 50 MHz," *IEEE Trans. Power Electron.*, vol. 36, no. 3, Mar. 2021.

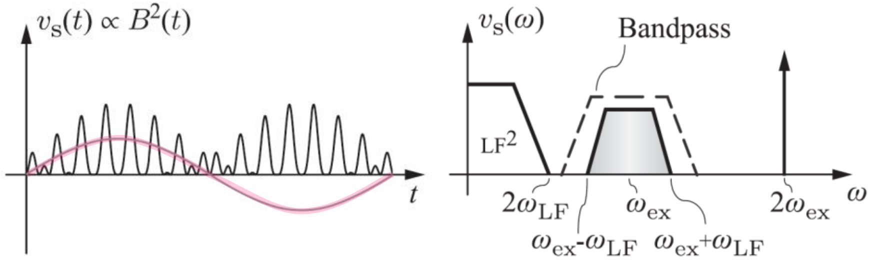
Magnetostriction-Based DC+AC Current Sensor



Piezoelectric Strain Sensor:

$$v_s(t) \propto \frac{\Delta l}{l}(B) \propto B^2(t)$$

- Amplitude modulation/demodulation to measure DC/LF



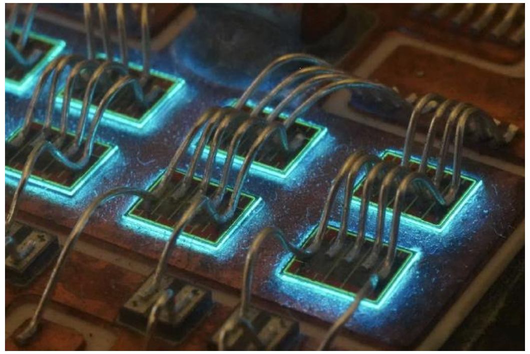
- Closed-loop performance: **±20 A, DC…20 MHz**

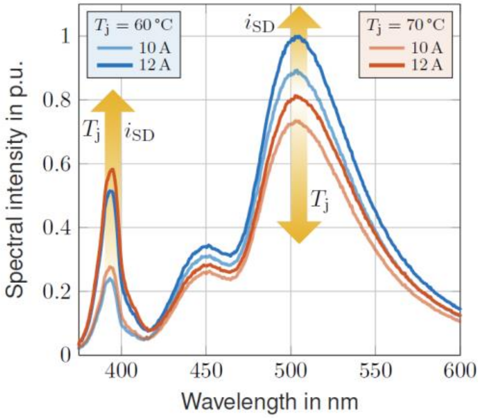
L. Schrittwieser, M. Mauerer, D. Bortis, G. Ortiz, and J. W. Kolar, "Novel principle for flux sensing in the application of a DC + AC current sensor," *IEEE Trans. Ind. Appl.*, vol. 51, no. 5, Sep. 2015.

Remark: Sensing Concepts (4) – Utilization of "Parasitic" Physical Effects

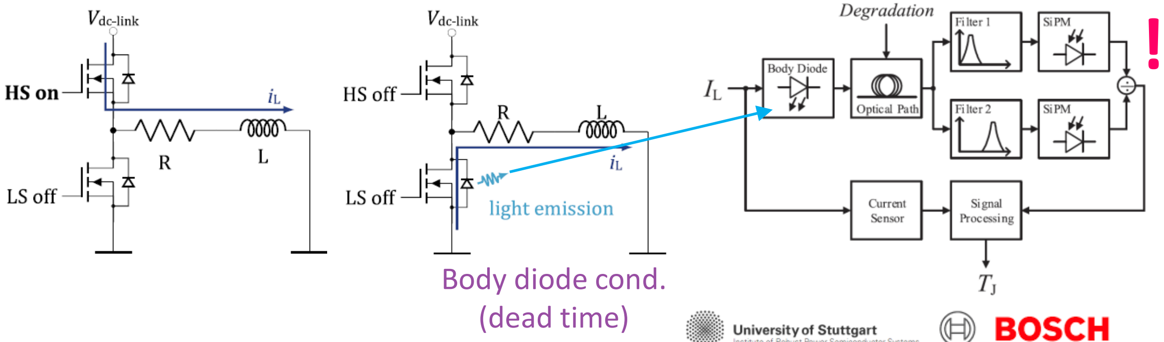
Electroluminescence (EL) in Power Semiconductors

- Every p-n junction can emit light (e.g., LEDs)
  - Si: invisible near IR / SiC: visible (discovered **1907** by H. J. Round)
- Example: SiC MOSFET Body Diode's EL Spectrum depends on **temperature** and **current**



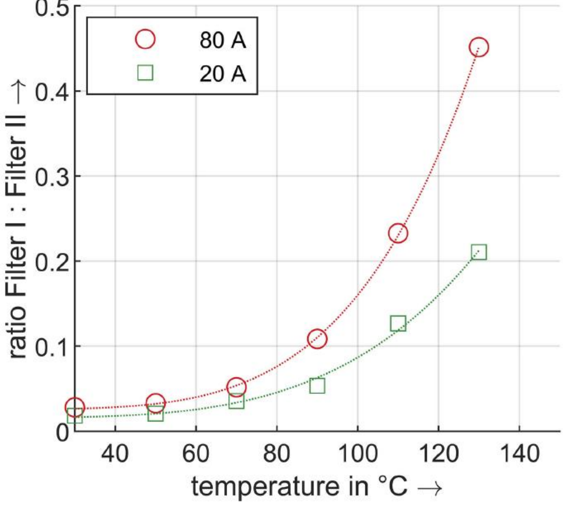


L. A. Ruppert, S. Kalker, C. van der Broeck, and R. W. De Doncker, "Analyzing spectral electroluminescence sensitivities of SiC MOSFETs and their impact on power device monitoring," in *Proc. PCIM Europe Conf.*, 2021.



First Applications (2018)

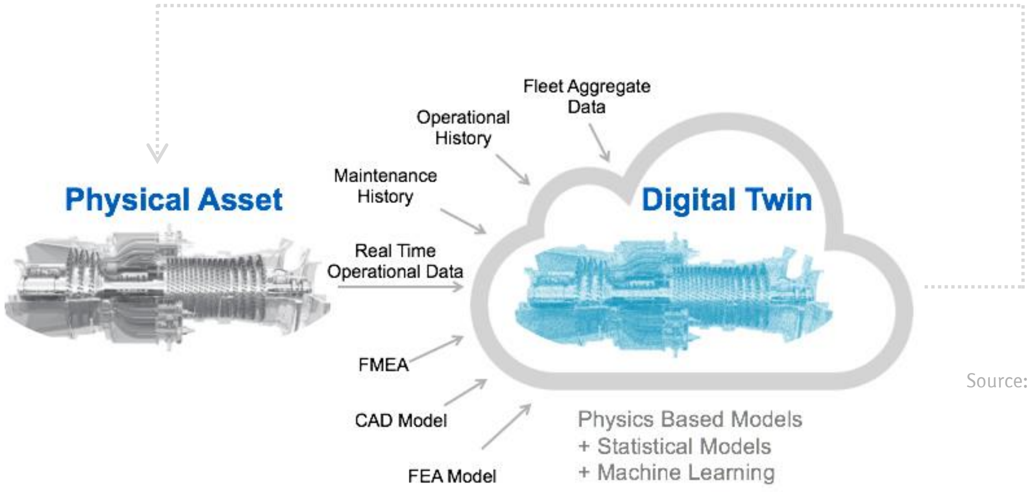
- Current sensing via intensity
- **Junction temperature sensing** via **ratio** of peak intensities →
  - Increased robustness against optical path degradation



J. Winkler, J. Homoth, and I. Kallfass, "Utilization of parasitic luminescence from power semiconductor devices for current sensing," in *Proc. PCIM Europ. Conf.*, Jun. 2018.
J. Winkler, J. Homoth, and I. Kallfass, "Electroluminescence-based junction temperature measurement approach for SiC power MOSFETs," *IEEE Trans. Power Electron.*, vol. 35, no. 3, 2020.

! Remark: Digital Transformation & Digital Twins

- Digital Thread / **Digital Twin** → "Weaving" real/physical & virtual world together
- "Digital Birth Certificate" → Keep track of each part/machine through whole lifetime
- Fully Digital Product Lifecycle → "Digital Tapestry" (Lockheed Martin)



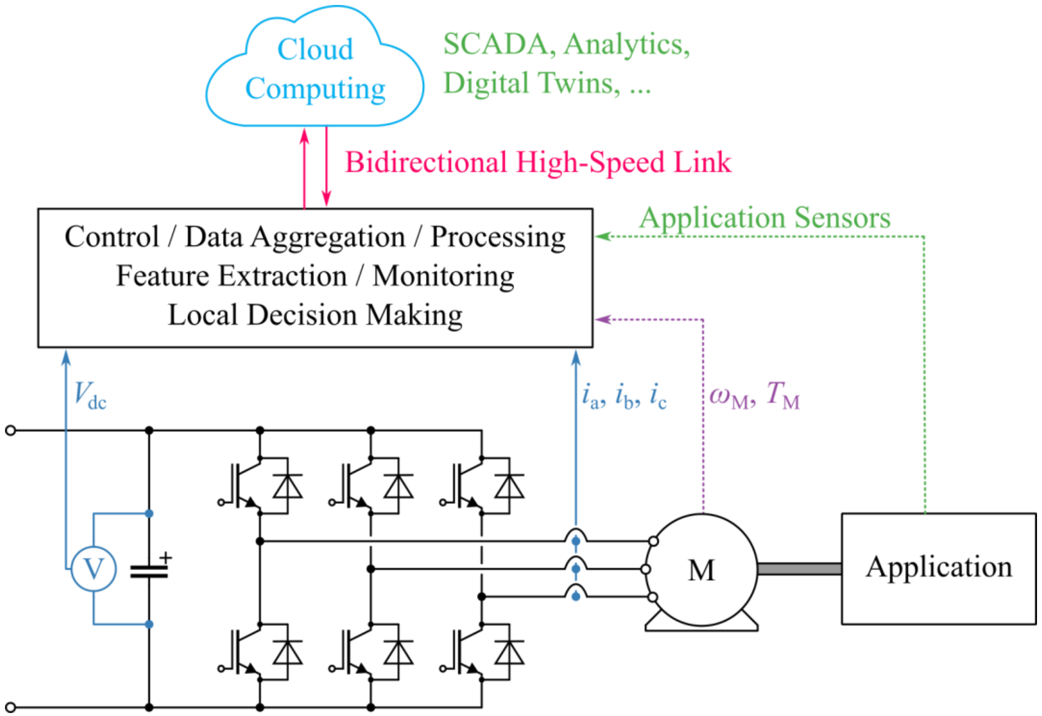
Source: www.railwayage.com

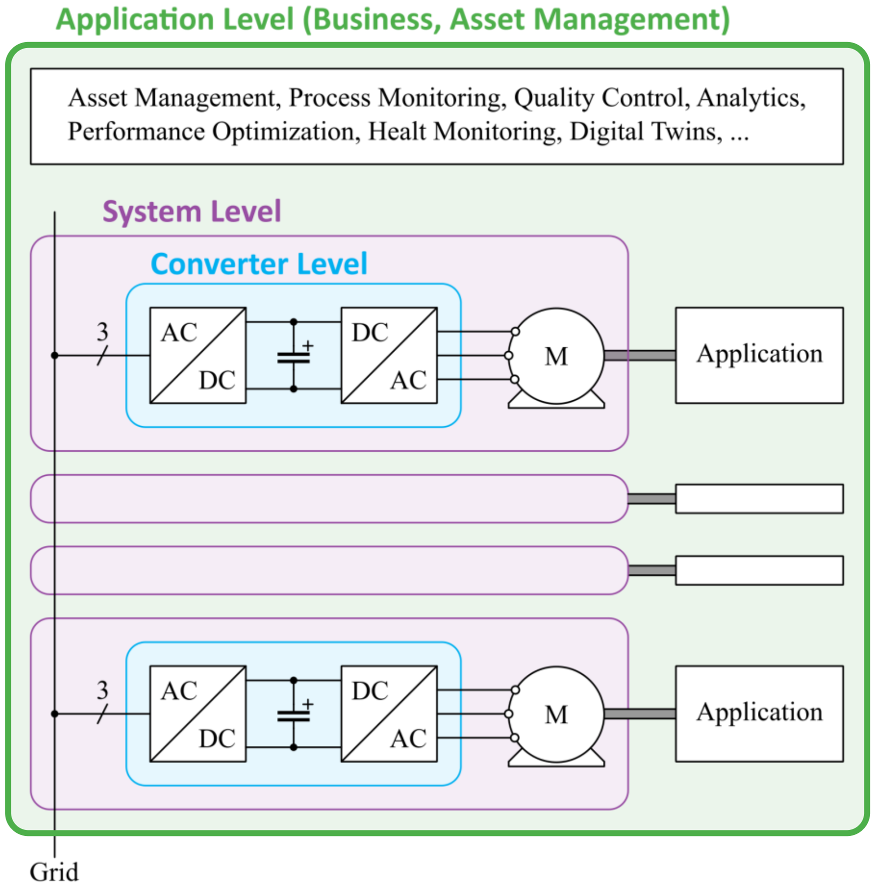
- **Smart components** with **integrated sensors** connect to Digital Twin
  → Design Improvements / Preventive Maintenance, etc.

Cognitive Power Electronics: Application Level – Power Electronics 4.0

Key Question

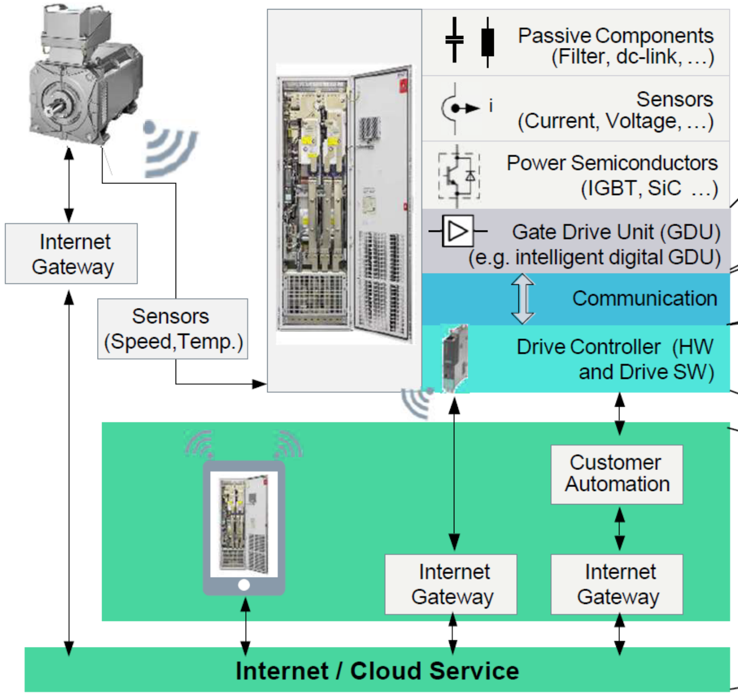
- **Future role of power electronic converters** in the application/business context?





Example: From Gate Drive to Cloud

▶ **SIEMENS** Smart Inverter Concept



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)
- …

▶ Utilize high computing power and network effects in the cloud

R. Sommer, "Smart inverter: requirements for PE-specific monitoring capabilities," *ECPE Workshop Power Electronics and Digitalization, Nov. 2020.*

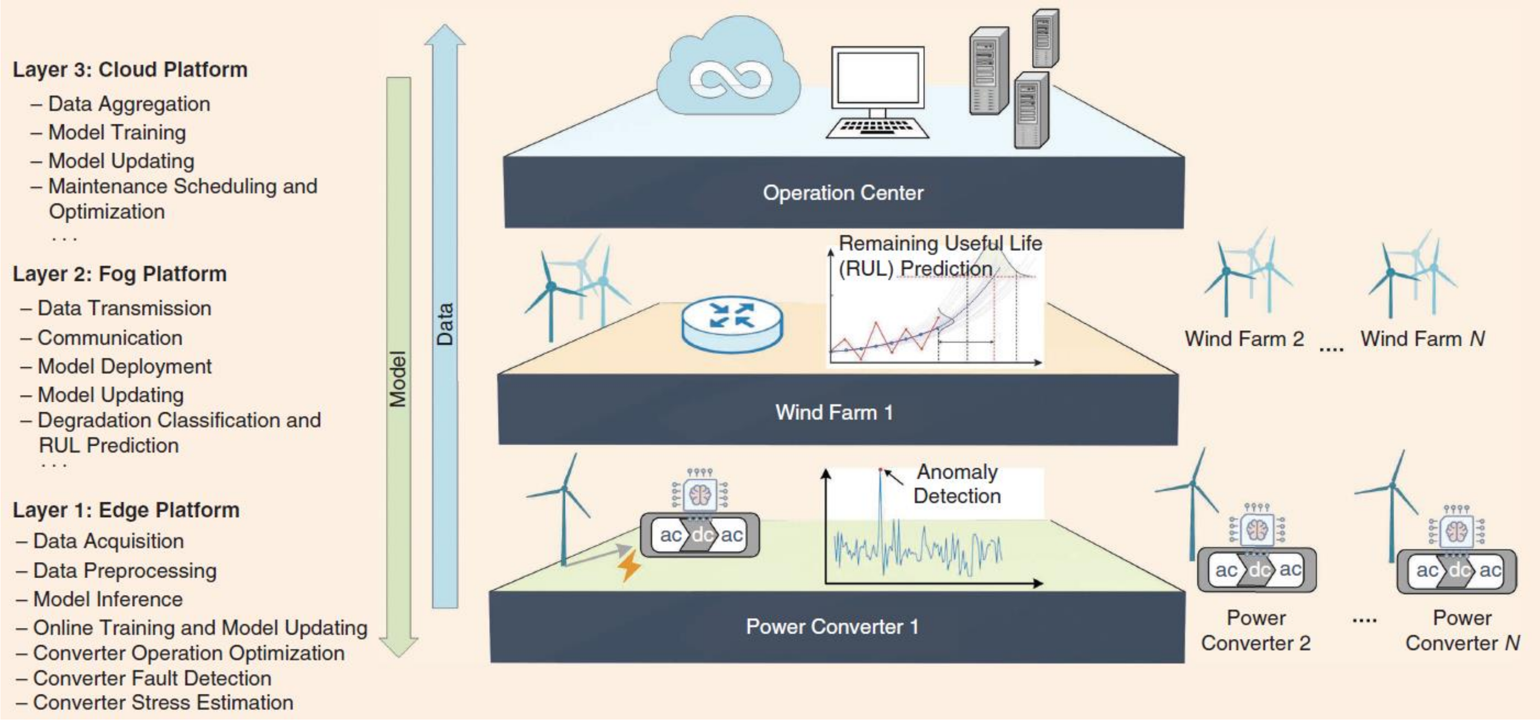
Example: Wind Park Condition Monitoring

Computing Power

- Scalable computing resources (cloud) for resource-intensive tasks

Azure Google Cloud aws

- PE controllers as edge computing platforms
- PE as piece in a puzzle



S. Zhao and H. Wang, "Enabling data-driven condition monitoring of power electronic systems with artificial intelligence: concepts, tools, and developments," *IEEE Power Electron. Mag.*, vol. 8, no. 1, Mar. 2021.

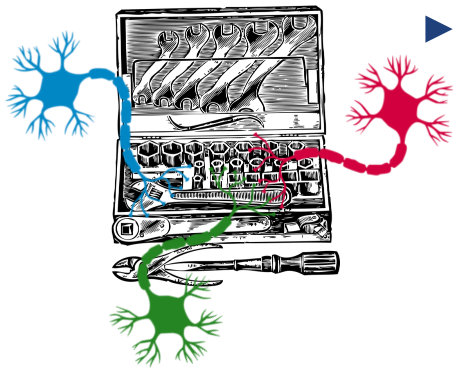
Example: PE 4.0 as Part of Digital Ecosystems

▶ ABB Ability **"Digital Power Train"**

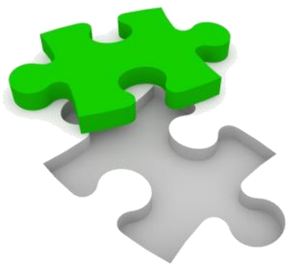
▶ Schneider Electric EcoStruxure Innovation At Every Level

Power electronic converters are "pieces in a larger puzzle"
→ **Similar to other IIoT-enabled devices**

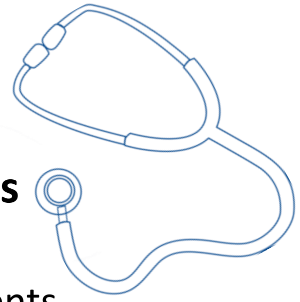
Conclusion & Requirements for PE 4.0 Readiness



- **AI/ML techniques are one of many means to an end**
  - Should become **part of an engineer's toolbox** (as circuit or FEM simulation) → Awareness / training
  - Method should follow from the problem to be solved (not the other way around)
  - **Training data** is a key challenge for data-driven methods (ability to generalize / reliability of predictions)



- **Power Electronics 4.0 for Industry 4.0**
  - **"Just another IIoT-enabled device"**
  - Converters act as sensors, sensor hubs, data aggregators, …
    → Standards for HW/SW integration
  - Value generation on the application/business level (e.g., improved asset management)



- **Advanced Sensing Capabilities**
  - Higher bandwidth/resolution; memory/CPU/uplink requirements
  - Measure additional quantities (ESR, on-state voltage, …)
  - Utilize "parasitic" physical effects
    → **Smart Components/Passives**

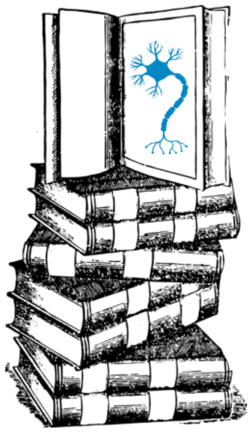
Further Reading

AI/ML Applications in Power Electronics

- J. O. P. Pinto, B. Ozpineci, and R. Cordero, "**Artificial intelligence applications to power electronics**," Tutorial at the ECCE USA 2019, Baltimore, MD, USA, Sep. 2019.
- B. K. Bose, "**Artificial intelligence techniques: How can it solve problems in power electronics?**," *IEEE Power Electron Mag.*, vol. 7, no. 4, Dec. 2020.
- S. Zhao, F. Blaabjerg, and H. Wang, "**An overview of artificial intelligence applications for power electronics**," *IEEE Trans. Power. Electron.*, vol. 36, no. 4, Apr. 2021.

Cognitive Power Electronics

- B. Wunder *et al.*, "**Droop controlled cognitive power electronics for DC microgrids**," in Proc. *IEEE Int. Telecom. Energy Conf. (INTELEC)*, Broadbeach, Australia, Oct. 2017.
- G. Roeder, X. Liu, and M. Hofmann, "**Cognitive power electronics for intelligent drive technology**," in *Proc. Electr. Drives Production Conf. (EDPC)*, Ludwigsburg, Germany, Dec. 2020.



Thank you!