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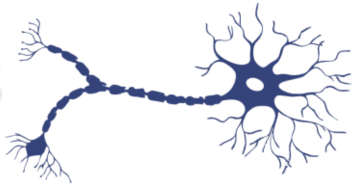
Source: next-gen-forum.com

NEXT GENERATION

SiC/GaN 3-Φ Variable-Speed Drive PWM Inverter Concepts



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www.pes.ee.ethz.ch

April 25, 2021

Outline

- ► *Introduction*
- ► *3-Φ VSD Inverter Systems — Pt. 1*
- ► *Power Electronics 4.0 — Pt. 2*
- ► *Conclusions*

Acknowledgement

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

Power Electronic Systems @ ETH Zurich

Johann W. Kolar

Industry Relations
R. Coccia

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
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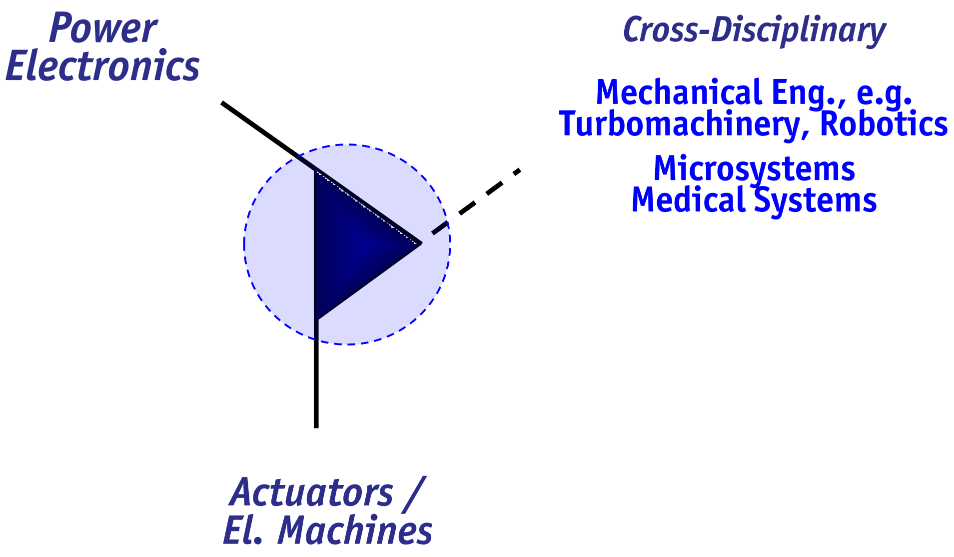
Research Scope



- *Explore the Limits / Create New Concepts / Push the Envelope*
- *Maximize Technology Utilization*
- *Enable New Applications*

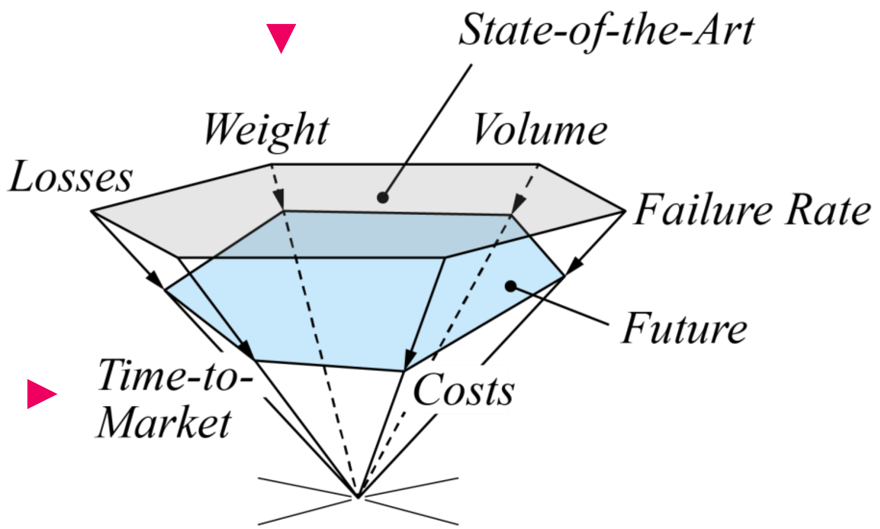
Introduction

Market Pull
Technology Push

Required Performance Improvements

Environmental Impact... [kg_{Fe} /kW] [kg_{Cu} /kW] [kg_{Al} /kW] [cm^2_{Si} /kW]

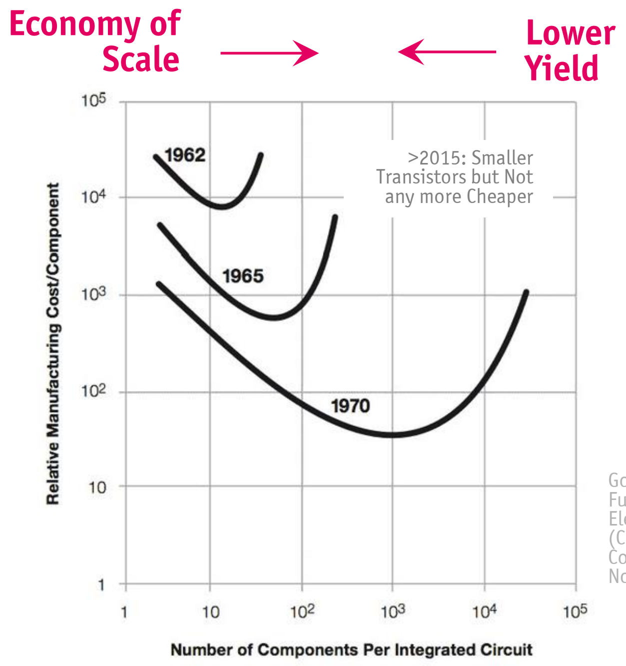
- Power Density [kW/dm^3]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h^{-1}]



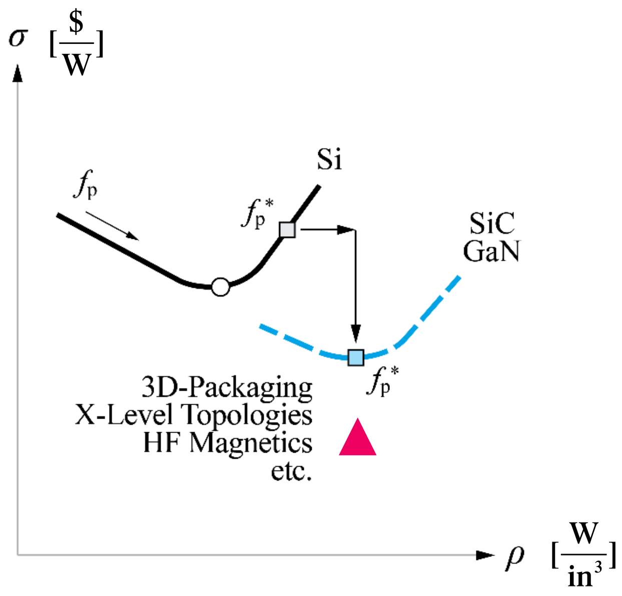
- *Mutual Coupling Performance Indices → Multi-Objective Optimization*

Comparison to "Moore´s Law"

- "Moore´s Law" Defines Consecutive Technology Nodes for Min. $$$ per Integr. Circuit (!)
- Complexity for Min. Comp. Costs Increases approx. by Factor of ≈2/18 months



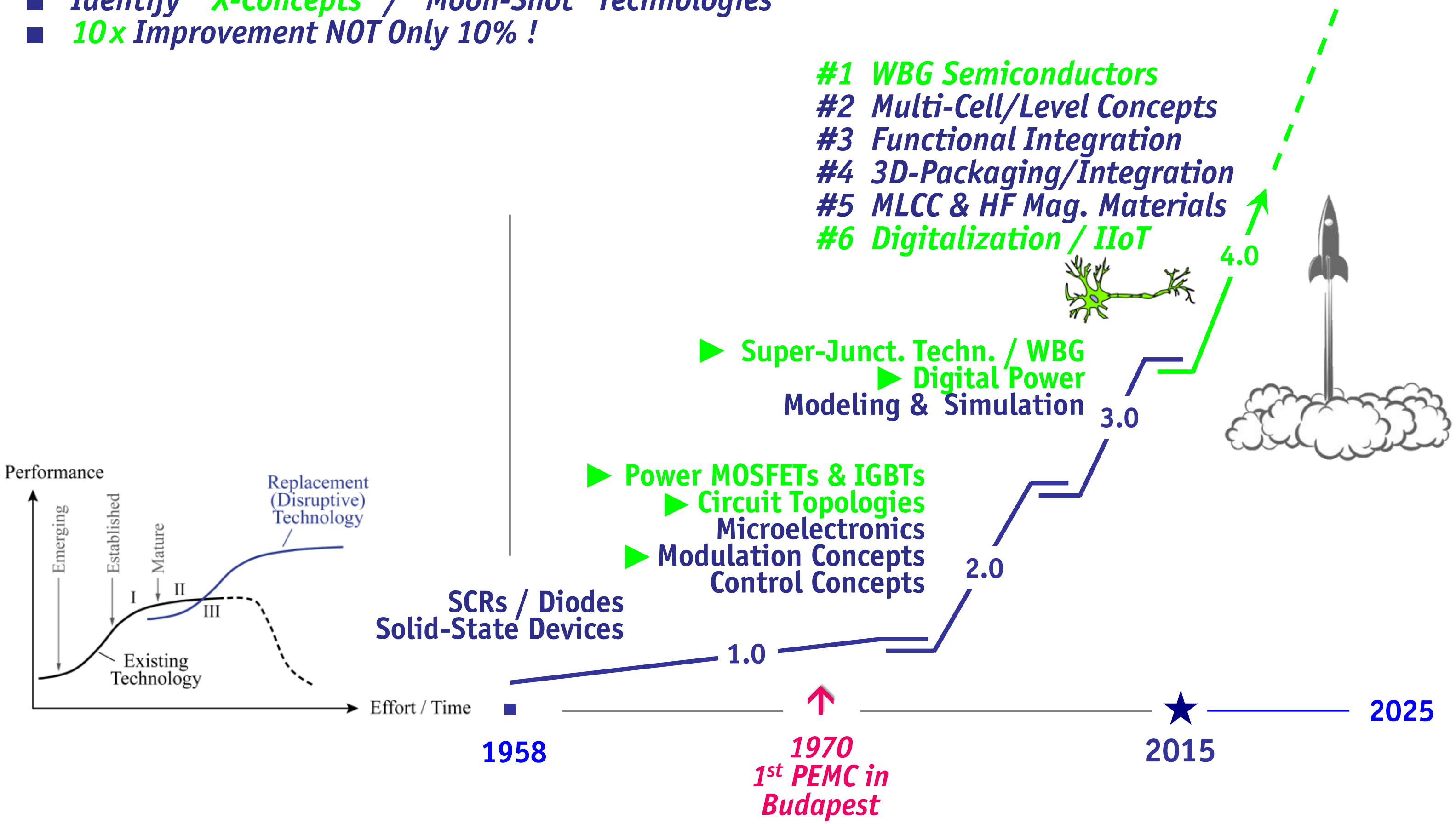
Gordon Moore: The Future of Integrated Electronics, 1965 (Consideration of Three Consecutive Technology Nodes)



- Definition of "η*,ρ*,σ*,f_P*–Node" Must Consider Conv. Type / Operating Range etc. (!)

S-Curve of Power Electronics

- *Power Electronics 1.0 → Power Electronics 4.0*
- *Identify "X-Concepts" / "Moon-Shot" Technologies*
- *10x Improvement NOT Only 10% !*



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3-Φ Variable Speed Drive Inverter Systems

Voltage Source Inverters
Buck-Boost Type Topologies
Current Source Inverters

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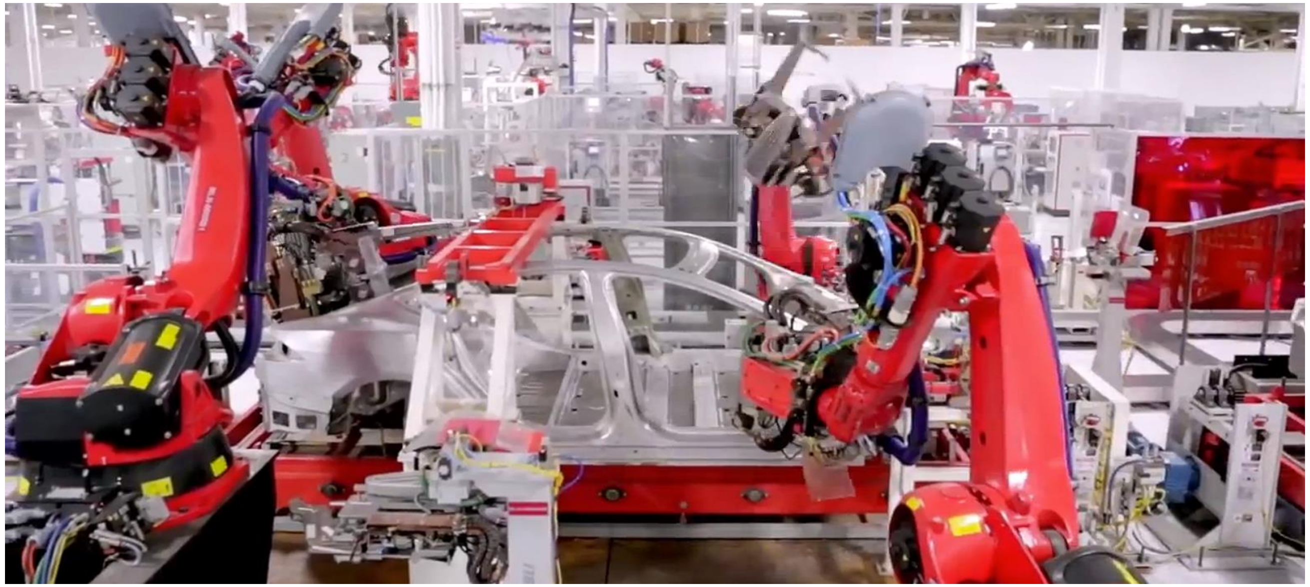
Variable Speed Drive (VSD) Systems

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

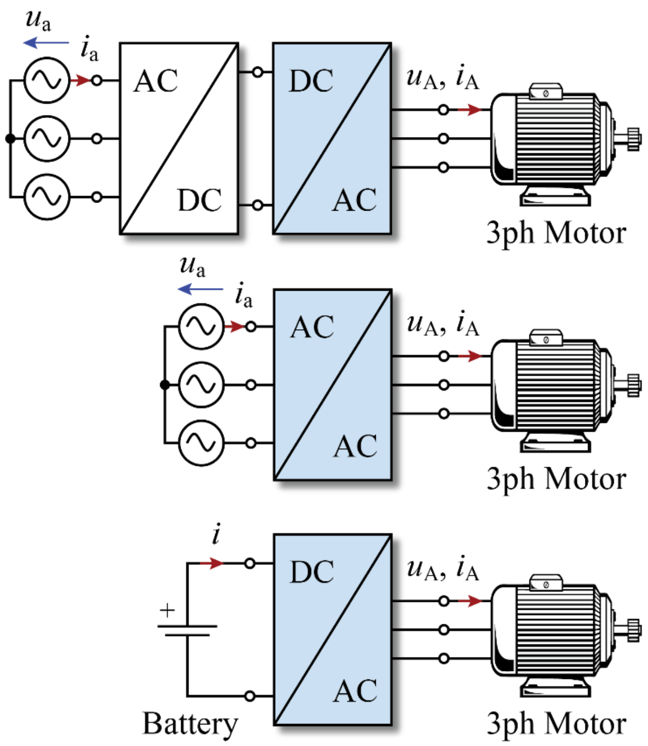
Source: TESLA MOTORS

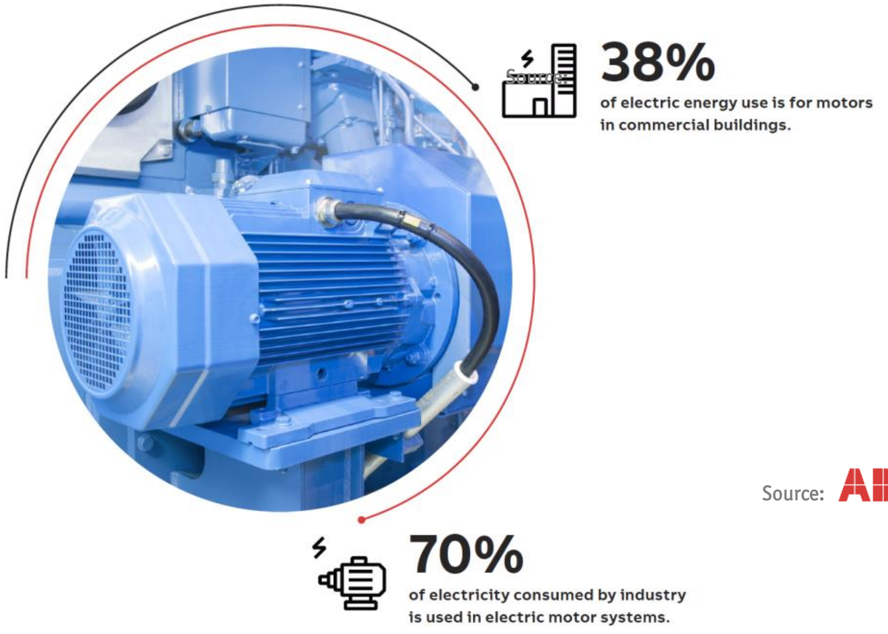


- *60...70 % of All Electric Energy Used in Industry Consumed by VSDs*

Variable Speed Drive Inverter Concepts

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



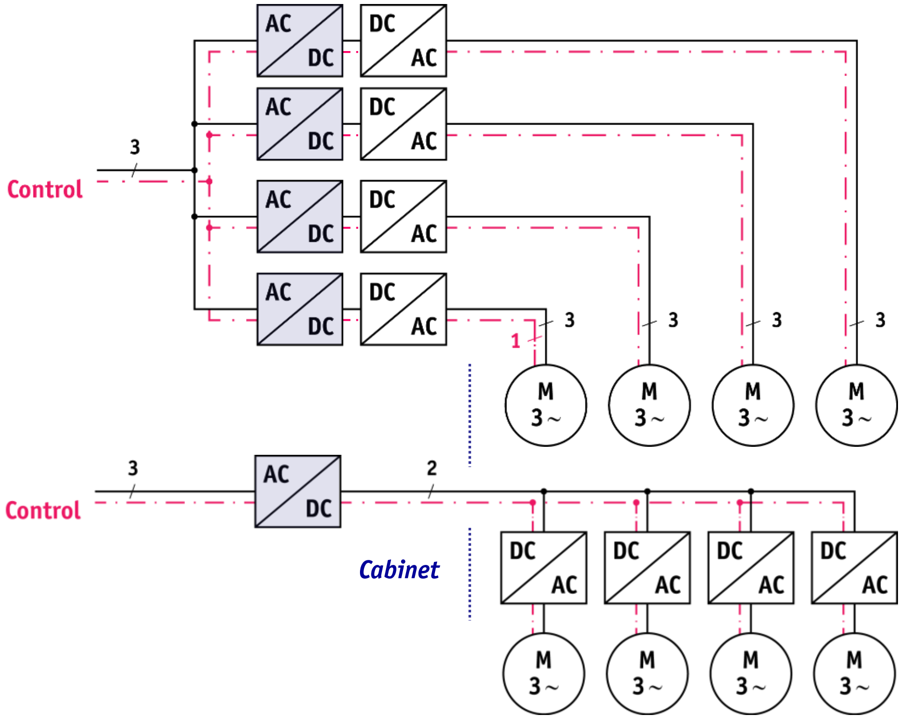


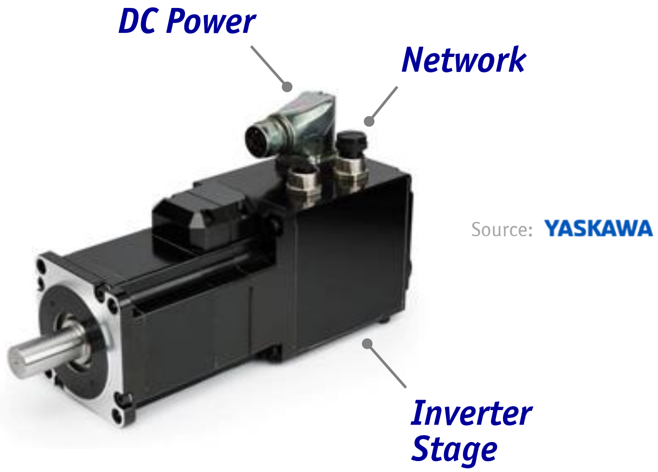
Source: ABB

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

Multi-Axis Drive Systems

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

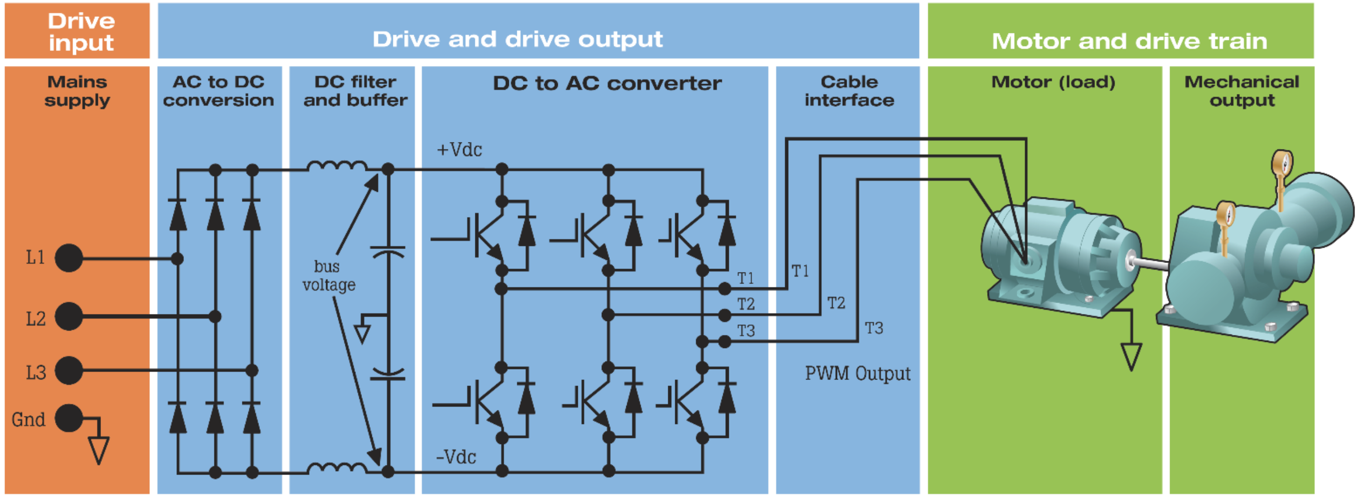




- *Facilitates DC-Bus Energy Buffer*
- *Direct Energy Exchange @ DC-Bus / Higher Efficiency / Unidir. Front-End*

State-of-the-Art

- Mains Interface / 3-Φ PWM Inverter / Cable / Motor — Large Installation Space / Complicated
- Conducted EMI / Radiated EMI / Reflections on Long Motor Cables / Bearing Currents

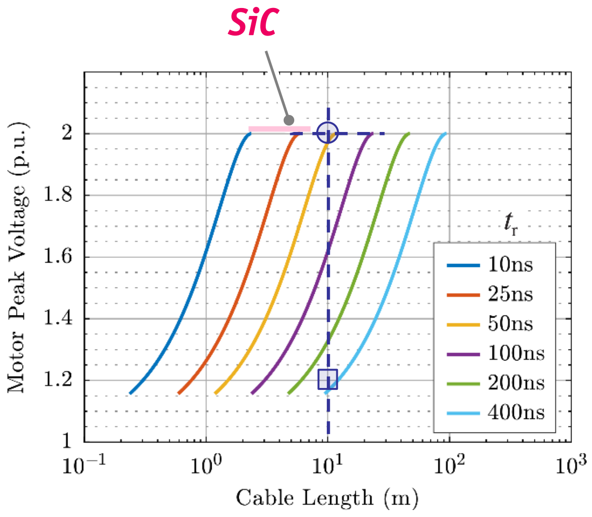


Source: FLUKE

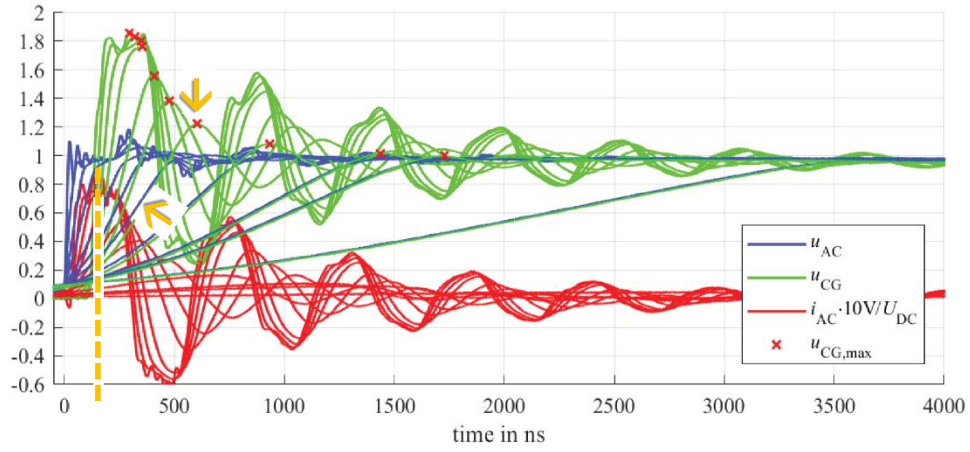
- High Performance @ High Level of Complexity / High Costs (!)

Surge Voltage Reflections

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



Source: Bakran / ECPE 2019

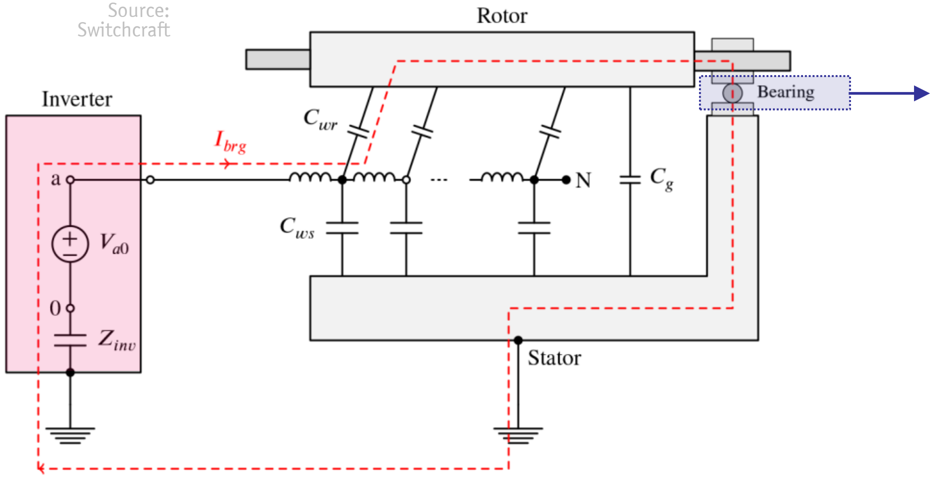


→ *dv/dt- OR Full-Sinewave Filtering / Termination & Matching Networks etc.*

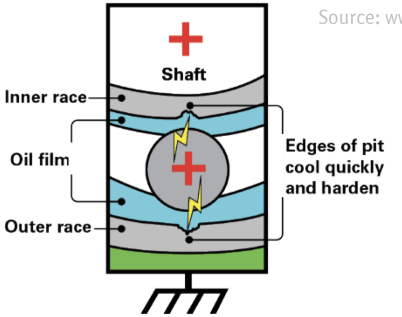
Motor Bearing Currents

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

Source: Switchcraft



Source: www.est-aegis.com



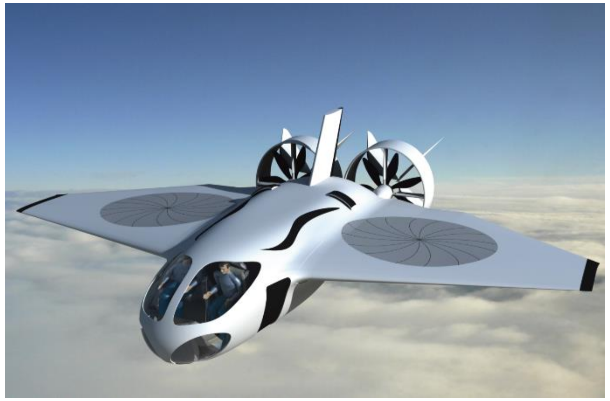
Source: BOSCH

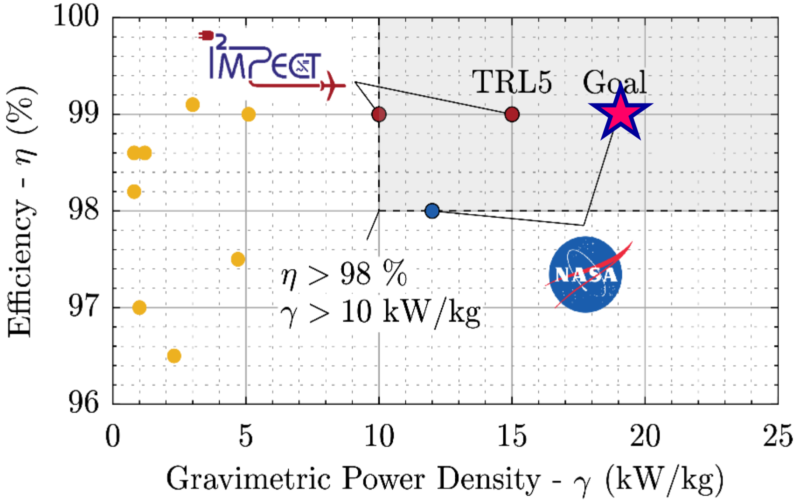
→ *Cond. Grease / Ceram. Bearings / Shaft Grndg Brushes / dv/dt- OR Full-Sinewave Filters*

VSD Inverter - Future Requirements

- *"Non-Expert" Installation / "Sinus-Inverter" OR Motor-Integrated Inverter*
- *Low Losses & Low HF Motor Losses*
- *Low Volume & Weight*
- *Wide Output Voltage Range*
- *High Output Frequencies*

Source: Georgia Tech





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

#1

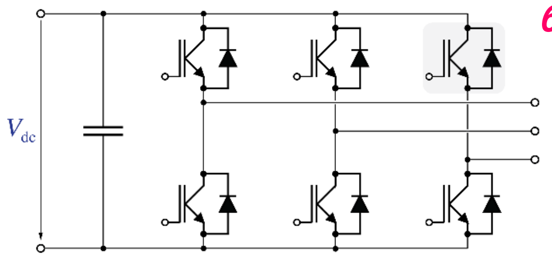
Source: www.clipart-library.com

SiC MOSFETs

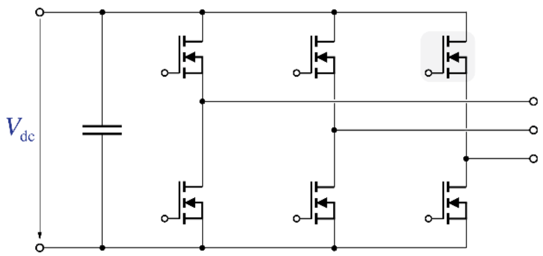
Si vs. SiC

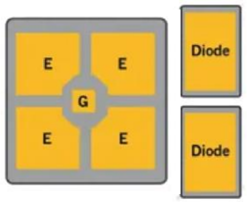
- Si-IGBT / Diode → Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current
- SiC-MOSFET → Massive Loss Reduction @ Part Load BUT Higher R_{th}

6x Si-IGBT
6x Si-Diode



6x SiC-MOSFET





Source: ATZ elektronik 2018

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

1200V 100A
Die Size: 25.6 mm^2

Source: Cree

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

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

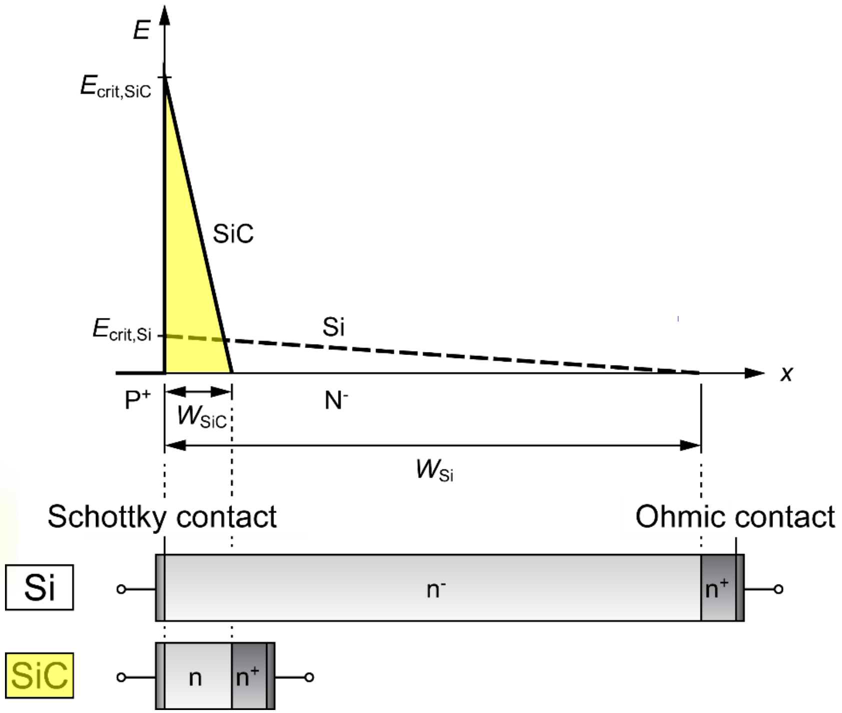
- *Higher Critical E-Field of SiC → Thinner Drift Layer*
- *Higher Maximum Junction Temperature $T_{j,max}$*

at 300 K	Si	GaAs	4H/6H-SiC	GaN
E_g (eV)	1.12	1.4	3.0-3.2	3.4
E_c (MV/cm)	0.25	0.3	2.2-2.5	3
μ_n (cm^2/Vs)	1350	8500	100-1000	1000
ε_r	11.9	13	10	9.5
v_{sat} (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}

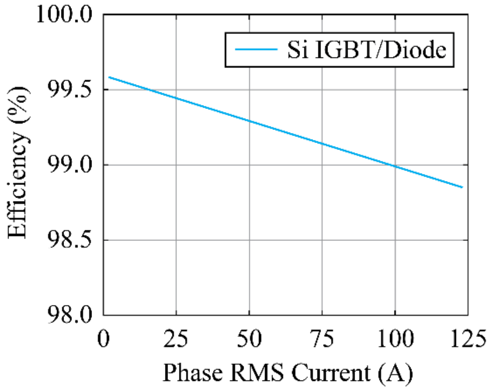
$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$

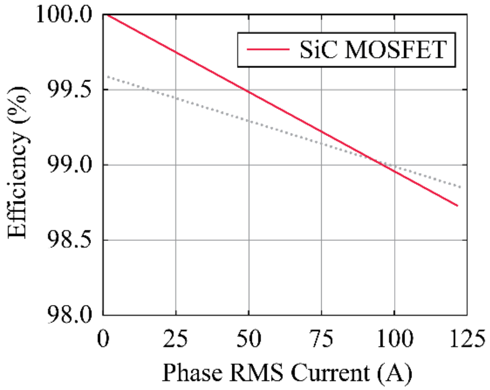


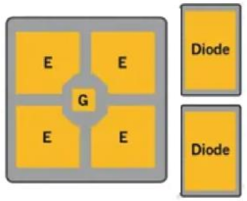
- *Massive Reduction of Relative On-Resistance → High Blocking Voltage Unipolar Devices*

Si vs. SiC Conduction Behavior

- *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: 98.8mm² + 39.4mm²

Source: Infineon

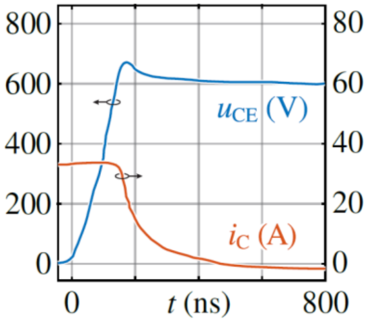
1200V 100A
Die Size: 25.6mm²

Source: Cree

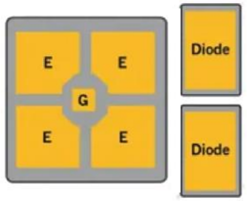
- *Efficiency Characteristic Considering Only Conduction Losses*

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*

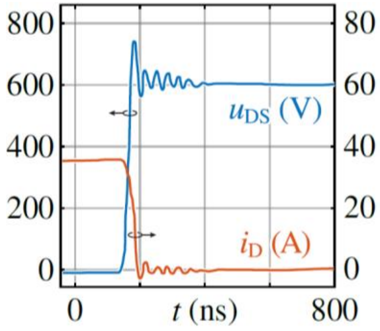


Source: Fuji Electric



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

Source: Infineon

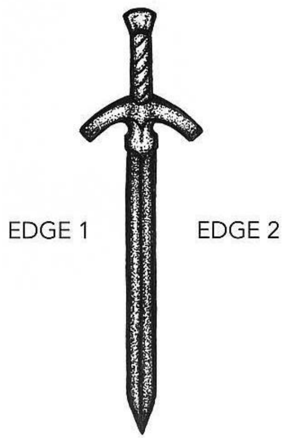


1200V 100A
Die Size: 25.6mm²

Source: Cree

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

Challenges



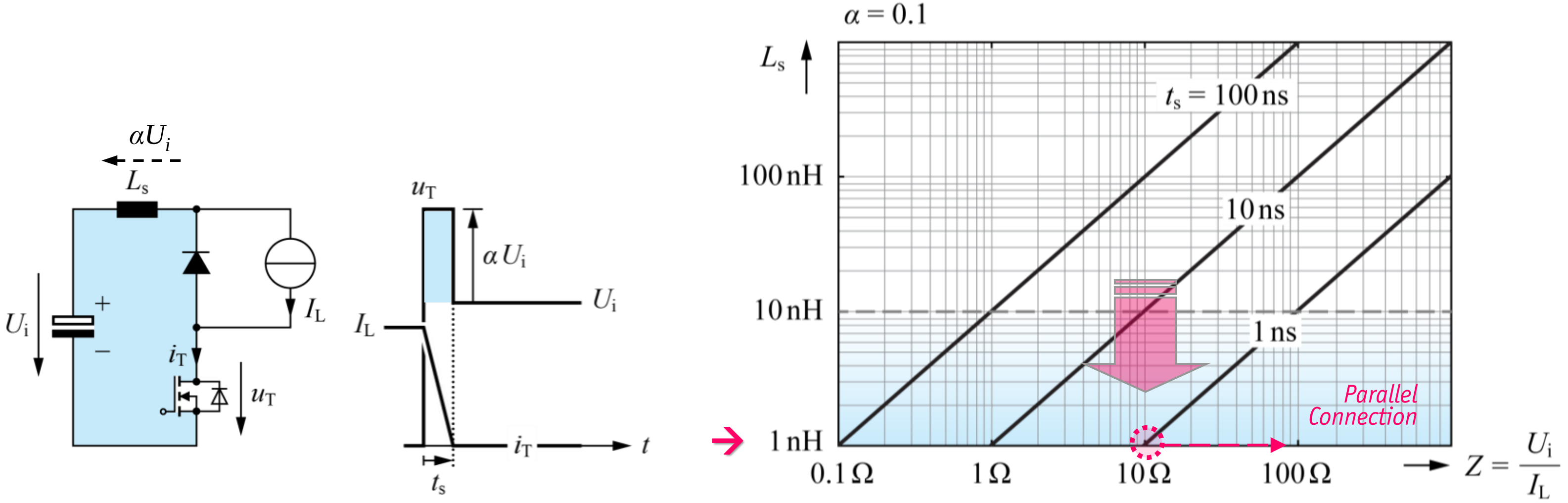
Circuit Parasitics

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

- *Extremely 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

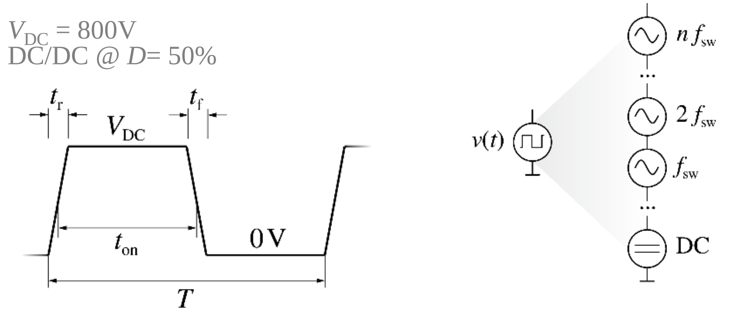


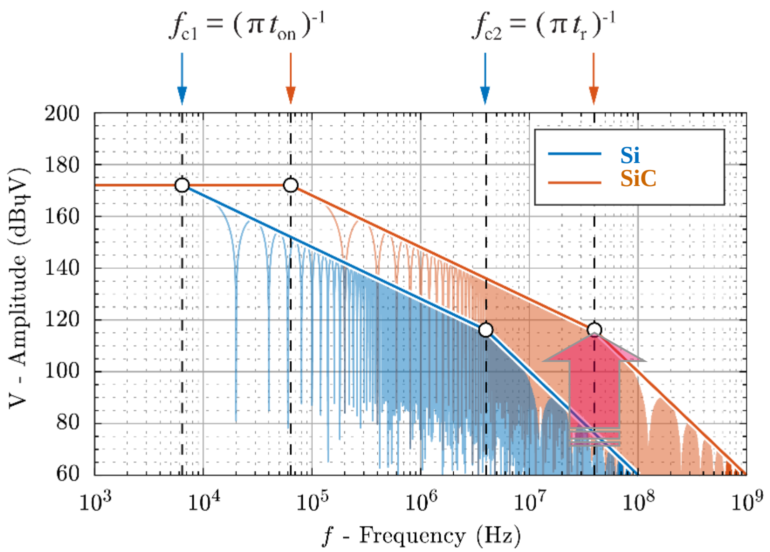
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents*

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)

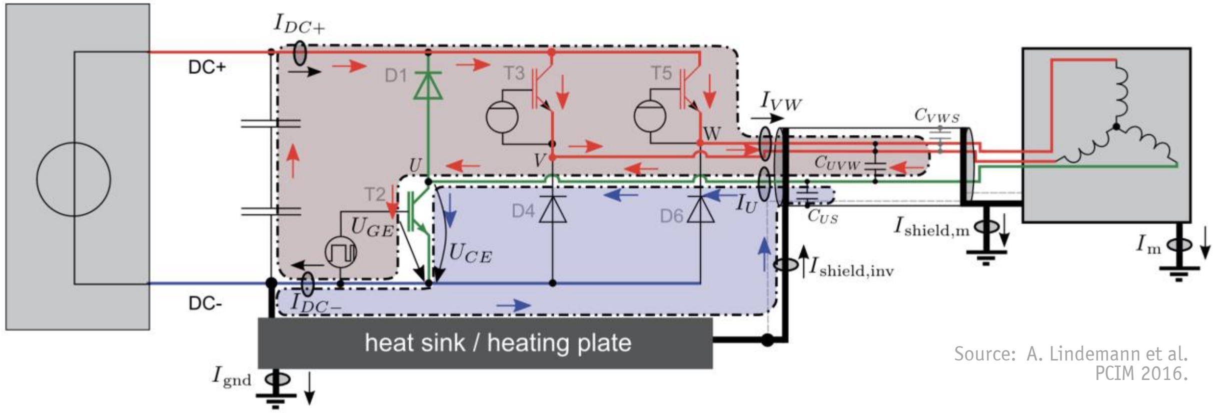




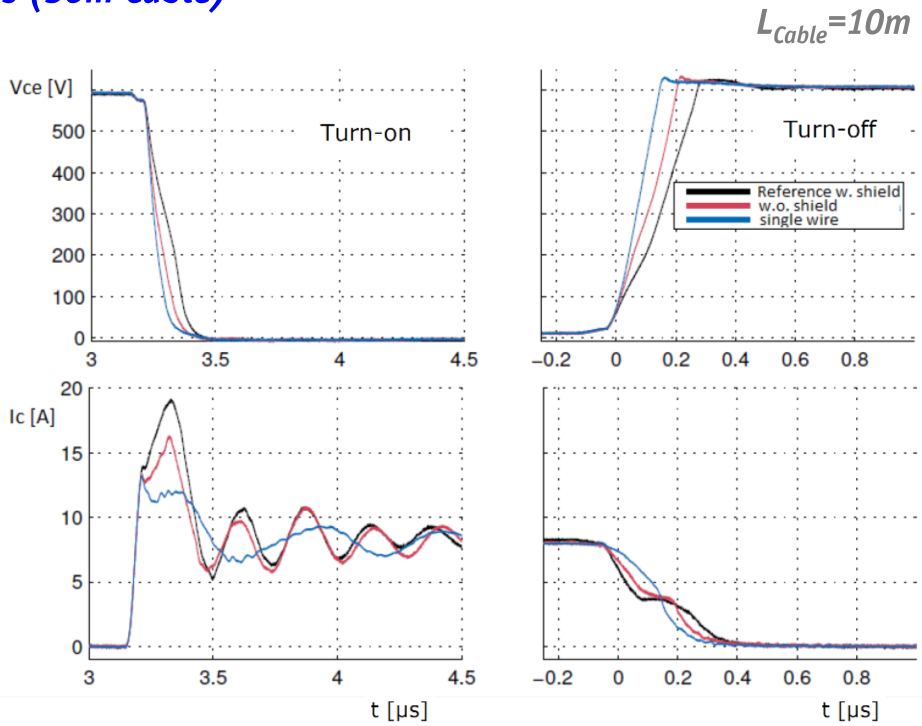
- *Higher Influence of Filter Component Parasitics & Couplings* → *Advanced Design*

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.



Source: AN17-002 SEMIKRON

→ Output Inductor for Decoupling OR Full Output Filter

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Inverter Output Filters

dv/dt-Filters
Full-Sinewave Filters

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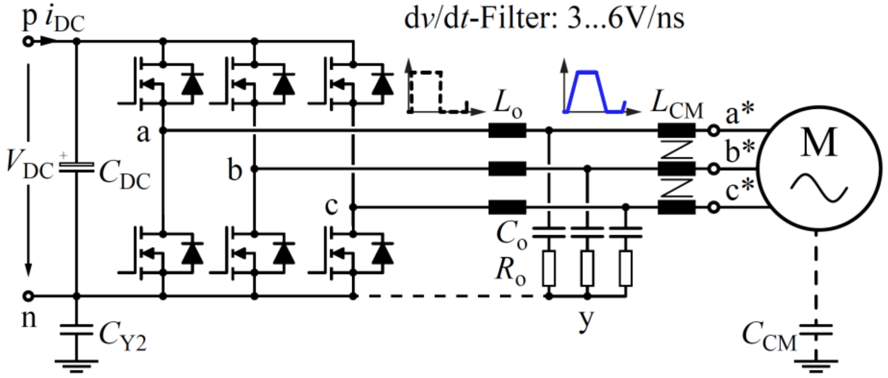
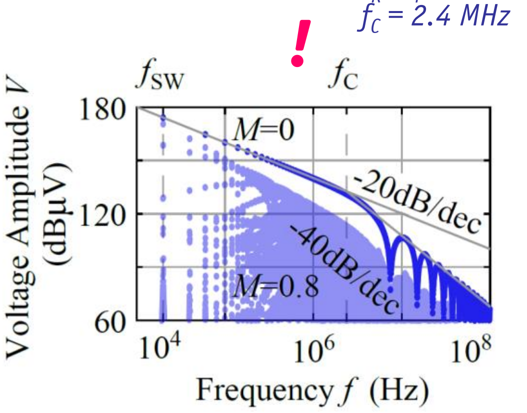
dv/dt-Control

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*

f_{sw} = 16kHz
t_R= t_F= 130ns
f_C = 2.4 MHz

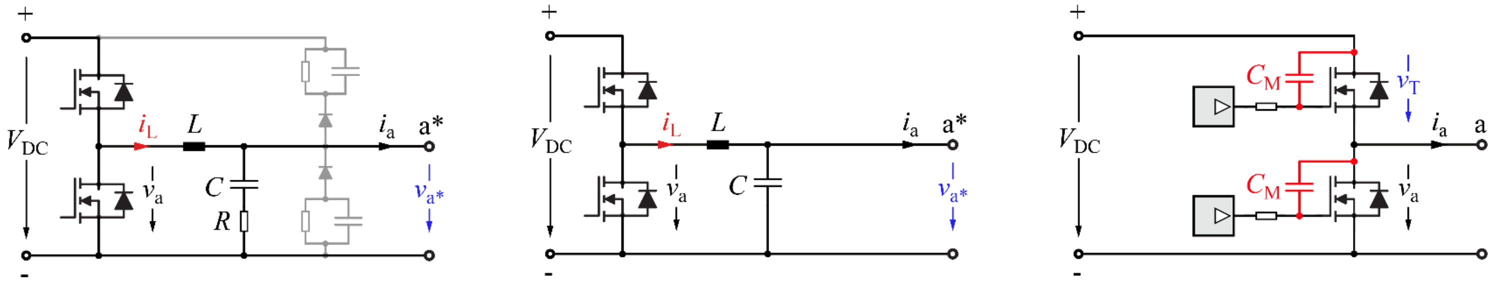




- *Connection to DC-Minus & CM Inductor → Limit CM Curr. Spikes / EMI / Bearing Currents*

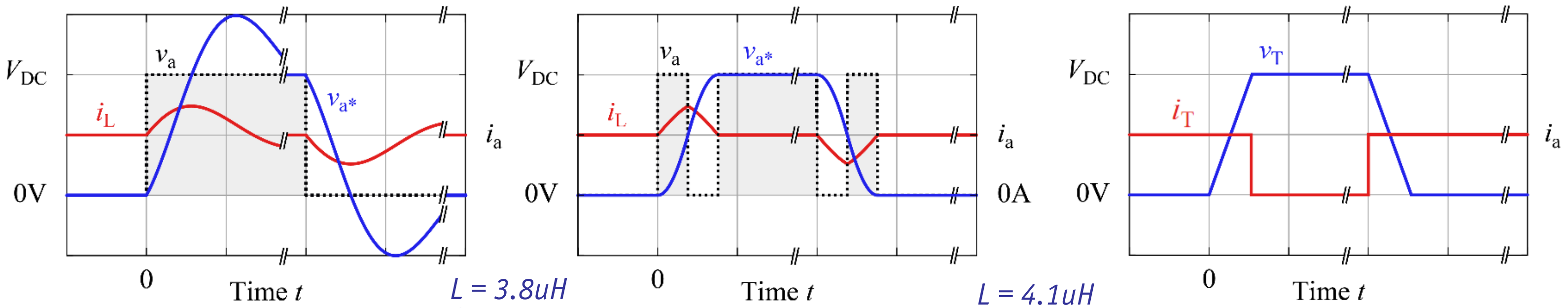
Comparison of dv/dt-Filtering Techniques (1)

- ***Passive Concept***
  1. ***LCR-Filter***
  2. ***Clamped LC-Filter***
- ***Hybrid Concept ($3f_S$)***
  1. ***LC-Filter***
  2. ***Multi-Step Switching***
- ***Active Concept***
  1. ***Miller Capacitor***
  2. ***Gate Curr. Control***



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

1200V SiC / 16mΩ
C_M = 120pF

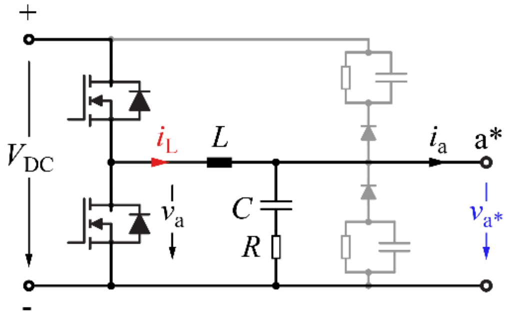


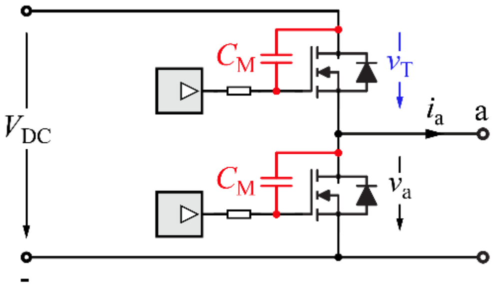
L = 3.8uH
C = 2.7nF
R = 19Ω

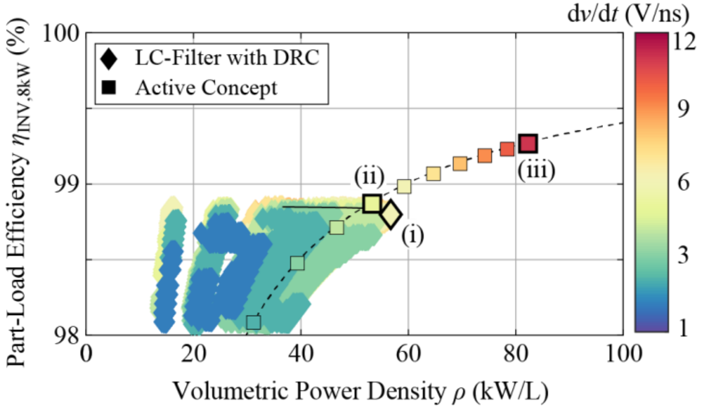
L = 4.1uH
C = 1.3nF

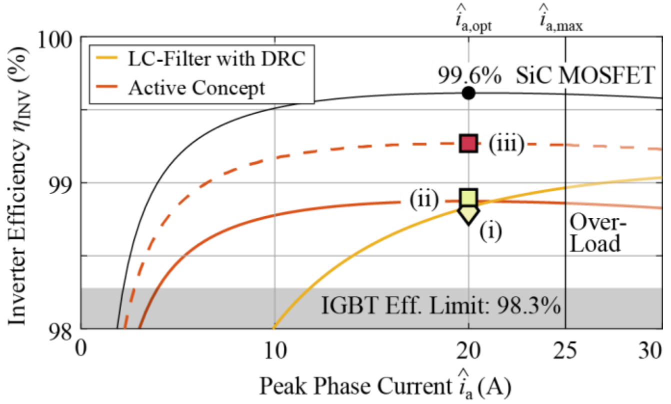
Comparison of dv/dt-Filtering Techniques (2)

- *Comparative Evaluation of Passive & Active Concept*





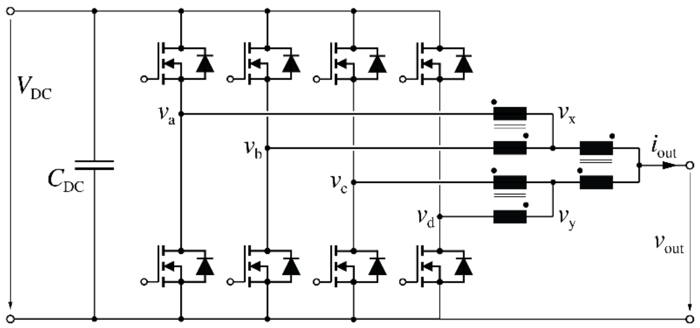


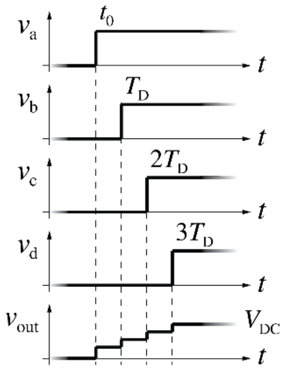


- ***Losses / Power Density** – V_{DC} = 800V, P_{out} = 10kW, f_{sw} = 16kHz, 1200V SiC-MOSFETs (16mΩ)*

Multi-Bridge-Leg dv/dt-Control

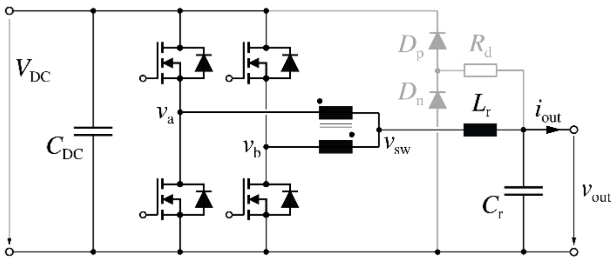
■ *Staggered Sw. Parallel Bridge-Legs → Non-Resonant Multi-Step Transistion*

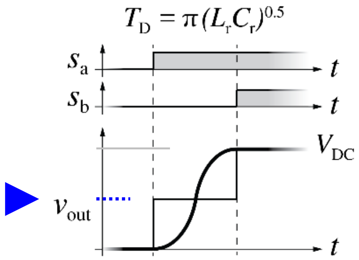




Source: J. Ertl et al.
PCIM Europe 2017

■ *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.*

Power Electronic Systems Laboratory

Output Voltage Filtering

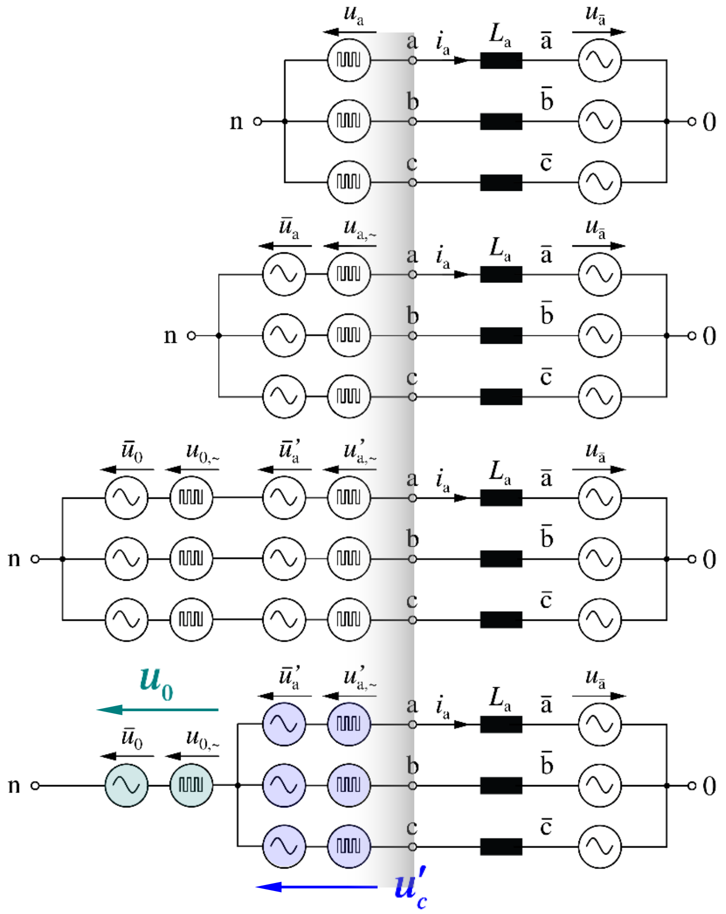
ETH zürich

IEEE PEMC

INDUSTRY ACADEMIA

TECHNOLOGY BRIDGE

Equivalent Circuit (1)



$$u_a = \bar u_a + u_{a\sim}$$
$$u_b = \bar u_b + u_{b\sim}$$
$$u_c = \bar u_c + u_{c\sim}$$

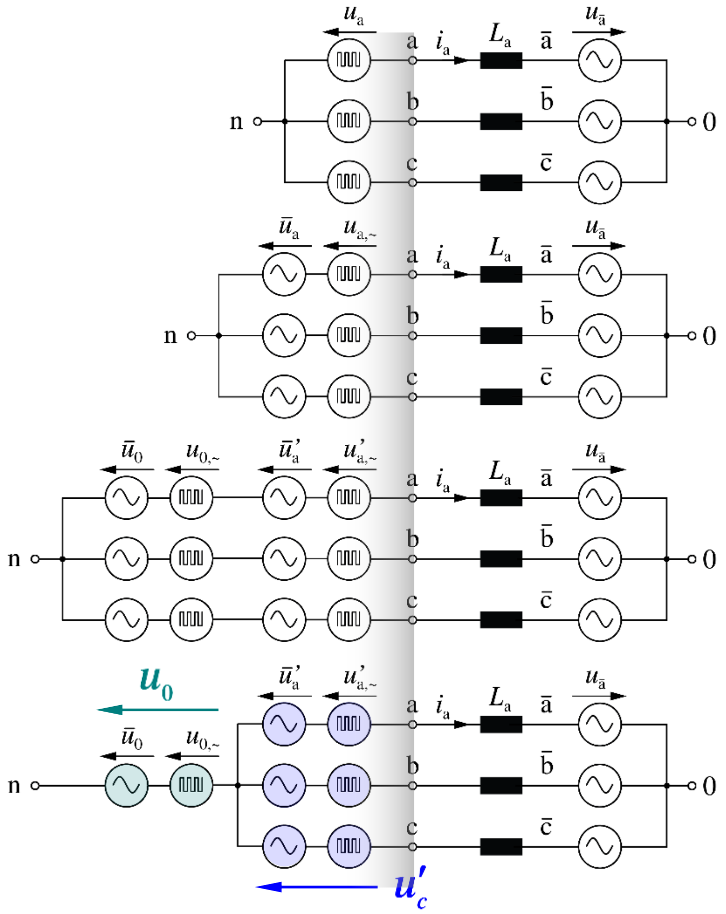
$$u_a = u'_a + u_0 \qquad u'_a + u'_b + u'_c = 0$$
$$u_b = u'_b + u_0$$
$$u_c = u'_c + u_0$$

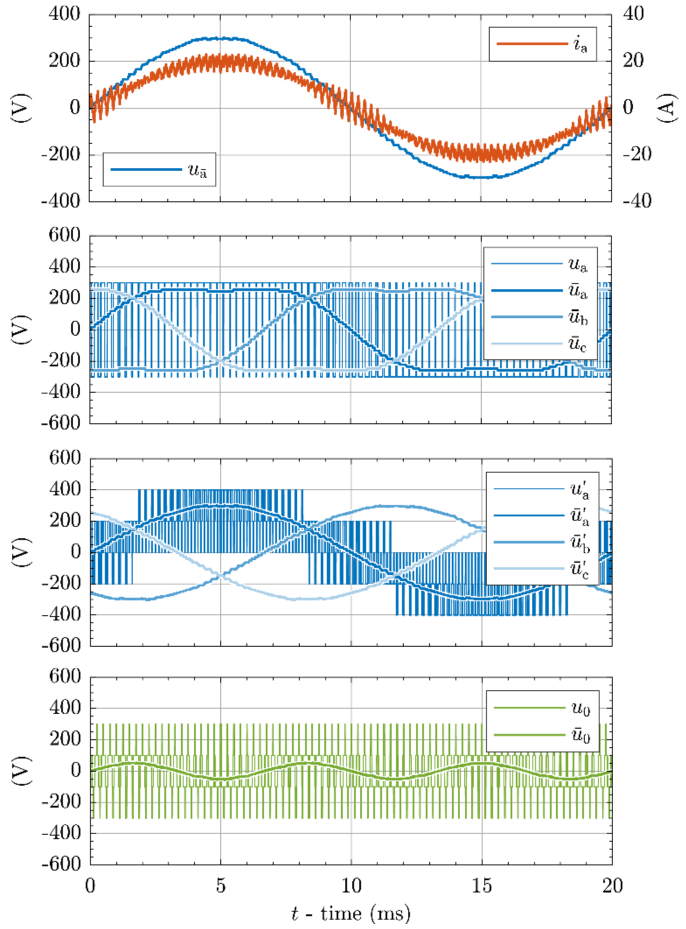
$$u_0 = \tfrac{1}{3}(u_a + u_b + u_c)$$

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

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

Equivalent Circuit (2)



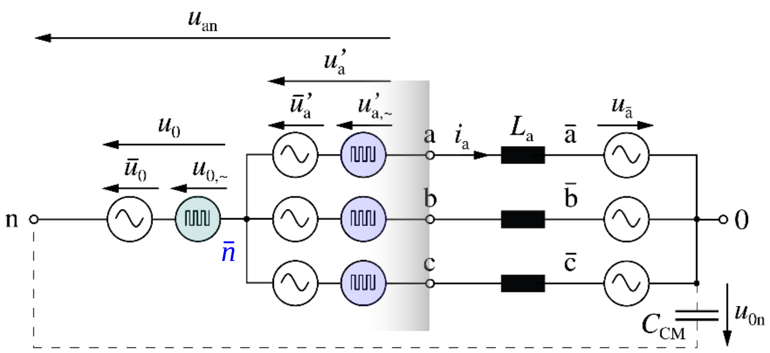


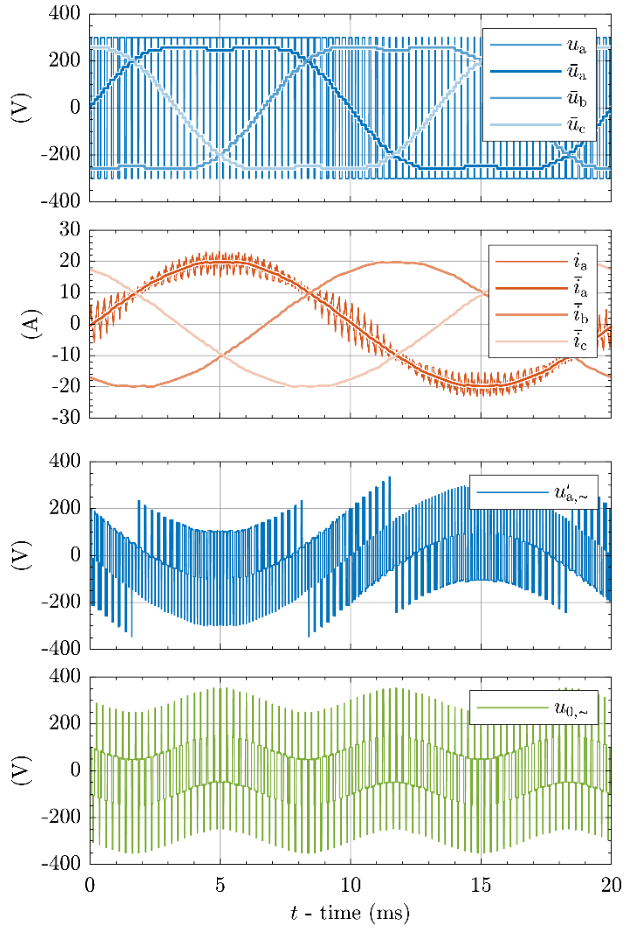
Equivalent Circuit (3)

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

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

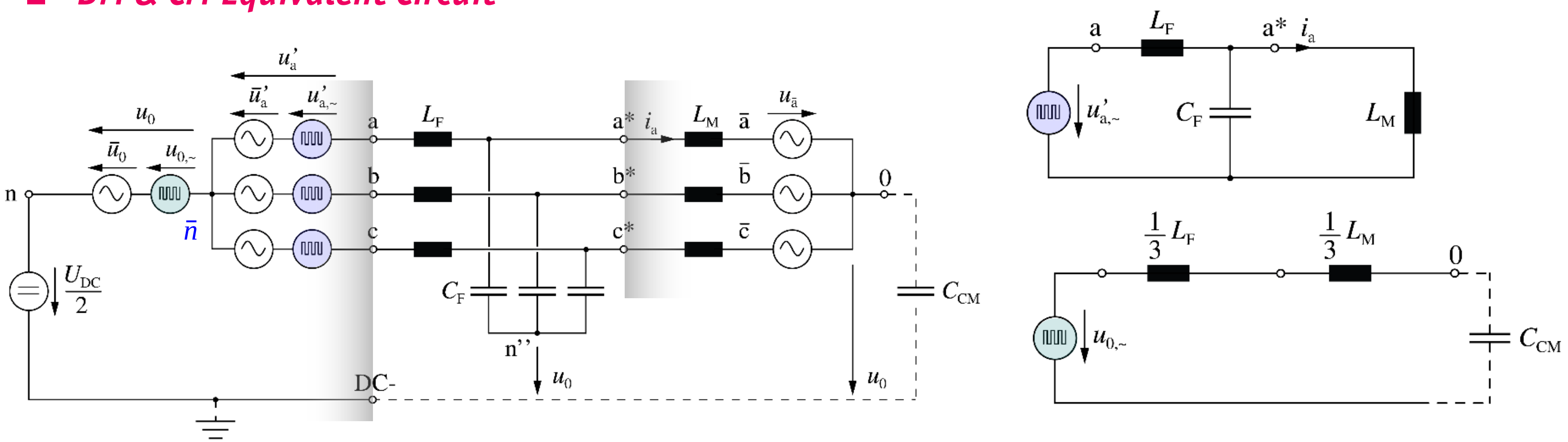
$$\begin{aligned} u_0 + u'_a &= L\frac{di_a}{dt} + u_a + u_{0n} \\ u_0 + u'_b &= L\frac{di_b}{dt} + u_b + u_{0n} \\ u_0 + u'_c &= L\frac{di_c}{dt} + u_c + u_{0n} \\ \hline 3u_0 + 0 &= \quad 0 \;+ 0 \;+ 3u_{0n} \end{aligned}$$



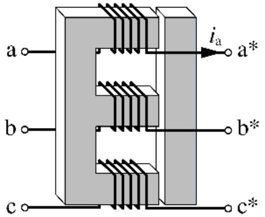


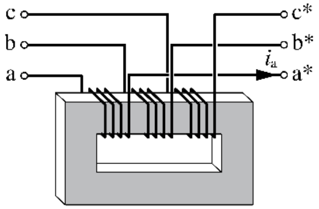
Differential / Common-Mode Filtering

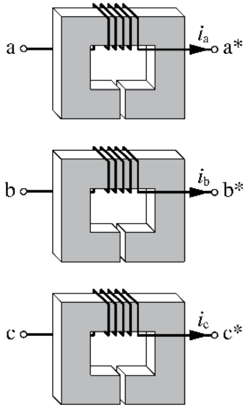
■ DM & CM Equivalent Circuit



■ Filter Inductor Types







- *DM Inductor / CM Inductor / Phase Inductors*

Inverter Systems w/ Sinusoidal Output Voltages

Continuous Current Mode (CCM) Operation

CCM & 2-Stage Full-Sinewave Output Filter (1)

PERFECTION IN AUTOMATION
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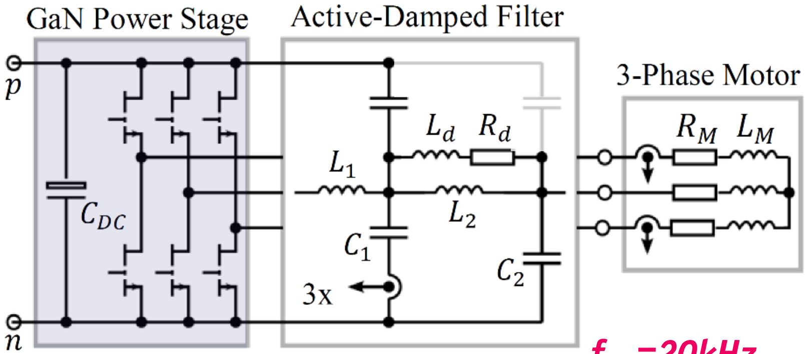
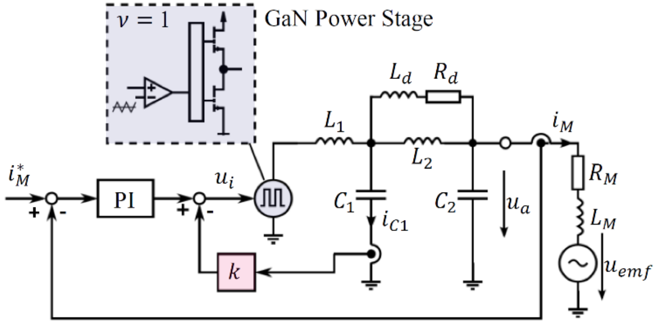
Vienna | Austria

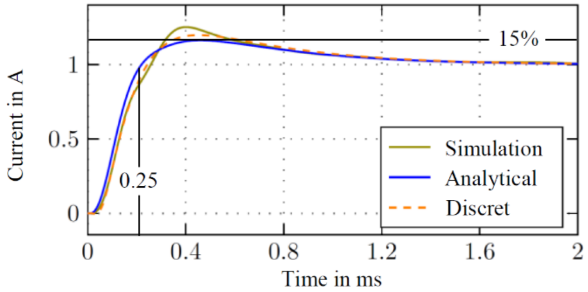
- *Sinewave Output & IEC/EN 55011 Class-A*
- *Low-Loss Active Damping of 1st Filter Stage — Neg. Cap. Current Feedback*
- *2kW / 400V DC-Link 3-Φ 650V GaN Inverter (I_M=5A), $f_{out,max}$ = 500Hz*
- *Sw. Frequency f_S= 100kHz*

$f_{C,1}$=7kHz



$f_{C,2}$=20kHz

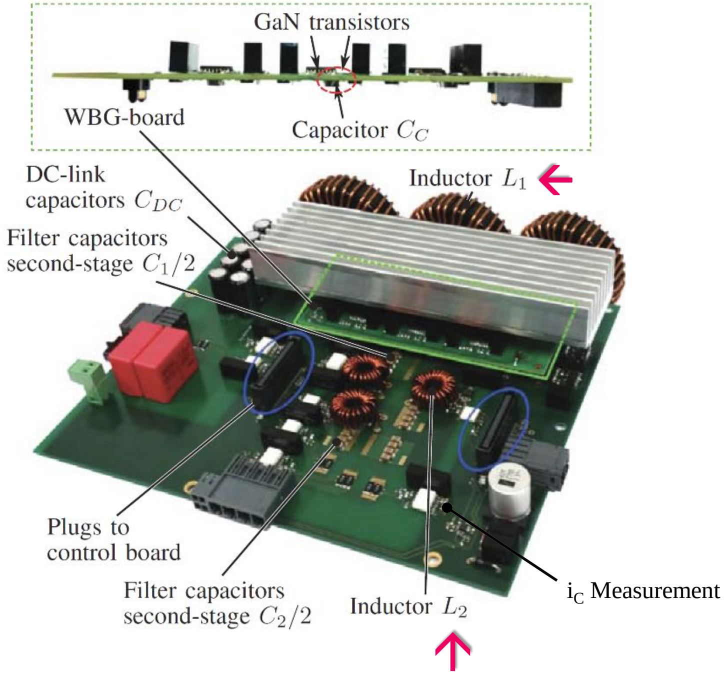


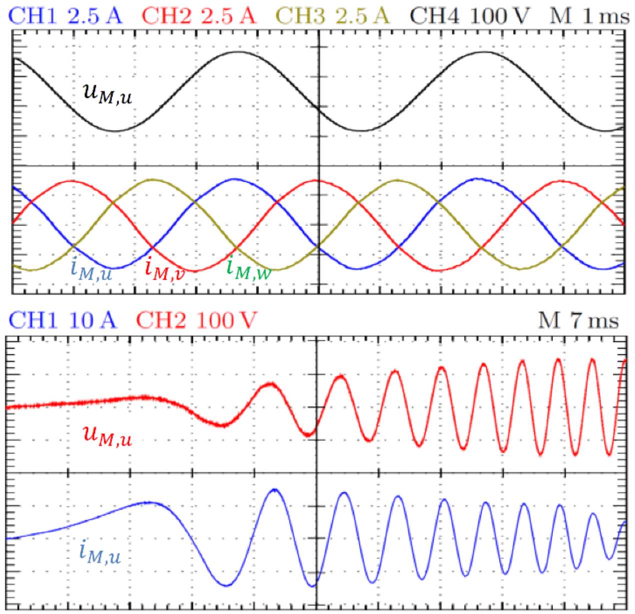


→ *Evaluation of Optimized Inductors — Soft Sat. Toroidal Iron Powder Cores*
→ *L_1=200uH (OD57S) / C_1=2.5uF / L_2=25uH (OD20S) / C_2=2.5uF / L_d=33uH / R_d=5.6Ω*

CCM & 2-Stage Full-Sinewave Output Filter (2)

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

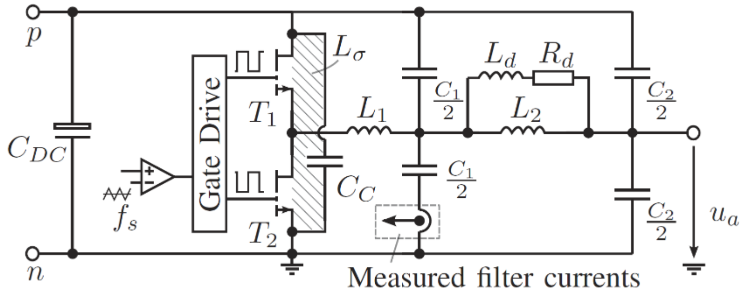


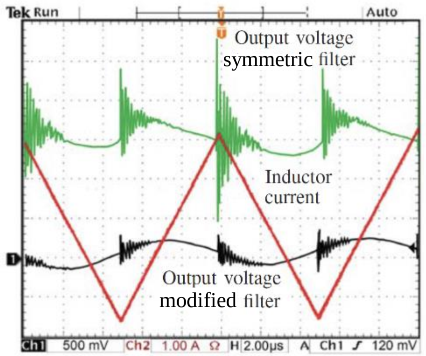


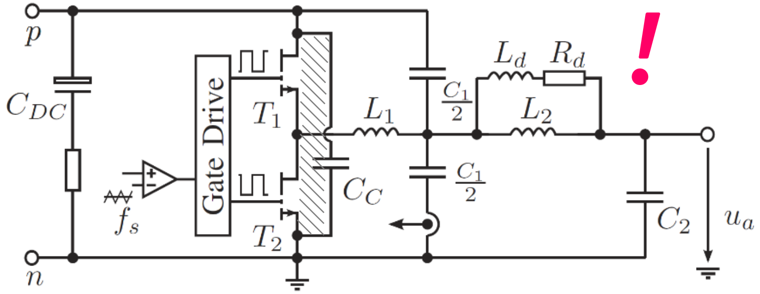
- *Stationary Motor Phase Curr. /Voltage @ 2.5Nm & f_{out}=250Hz*
- *Speed Increase from Standstill to n = 3000rpm in 60ms*

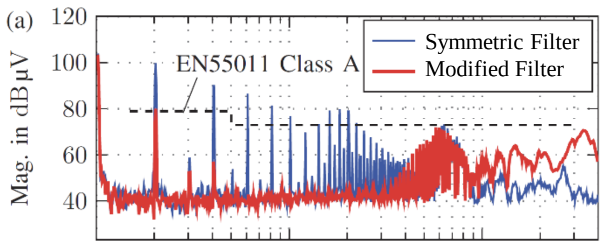
CCM & 2-Stage Full-Sinewave Output Filter (3)

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





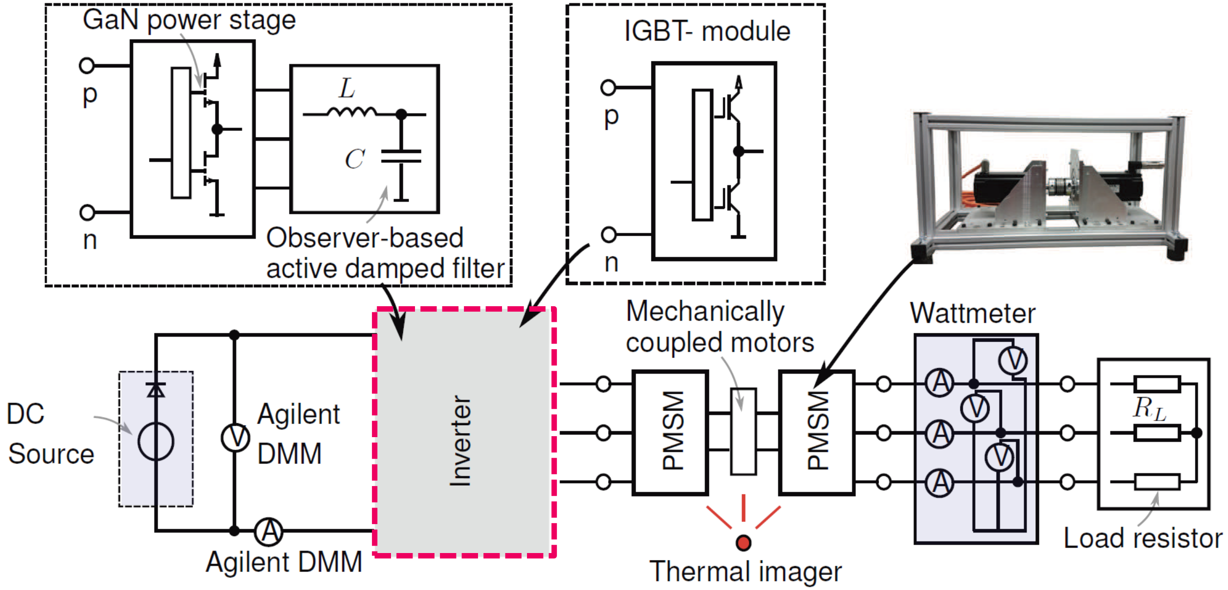


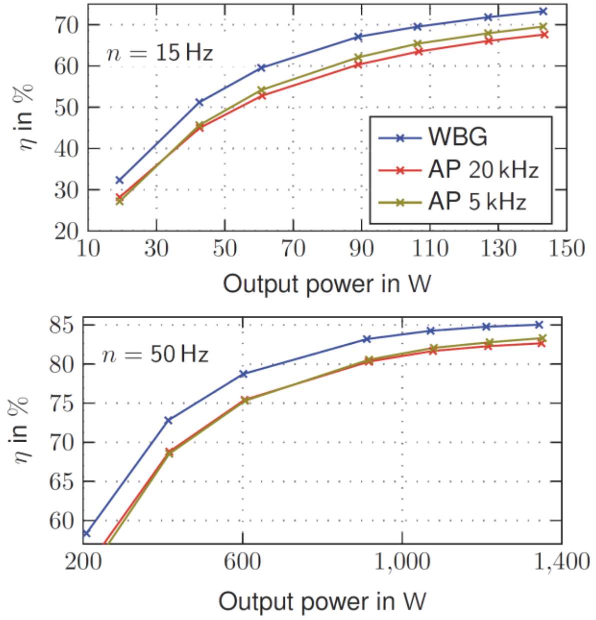


- *Modified Filter → Compliance to EMI Standard EN55011 Class-A*

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 Considering Load Machine AC Output & Inverter DC Input*



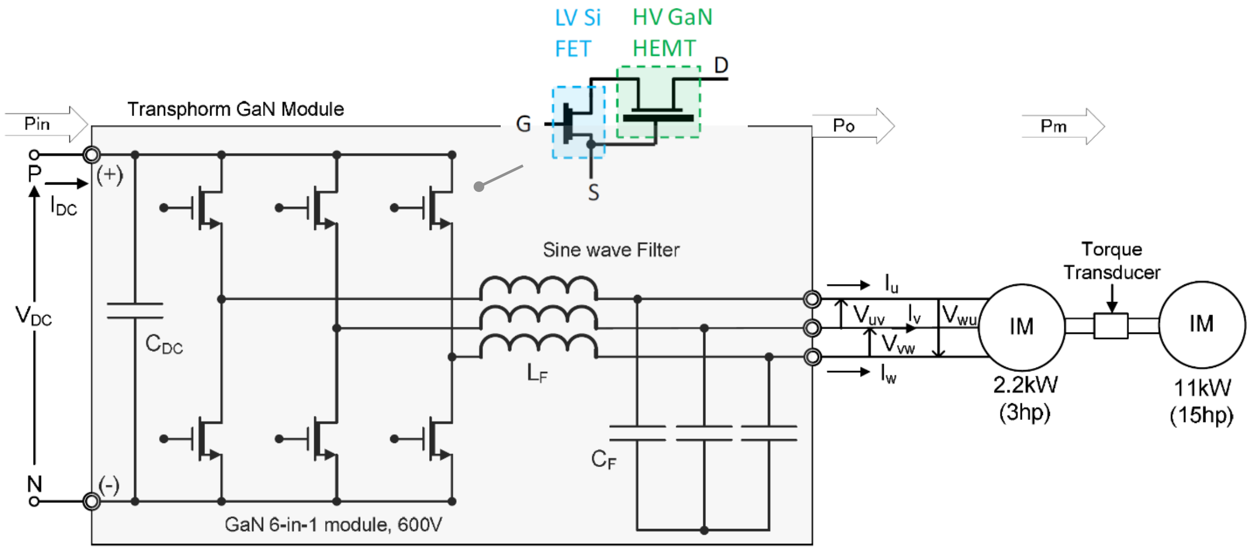


- *Efficiency Improvement of 2-4% in Whole Operating Range*
- *Low Sw. Losses of GaN Inverter & Low Output Filter Losses & Low Motor Iron Losses*

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_S= 100kHz)
- No Freewheeling Diodes



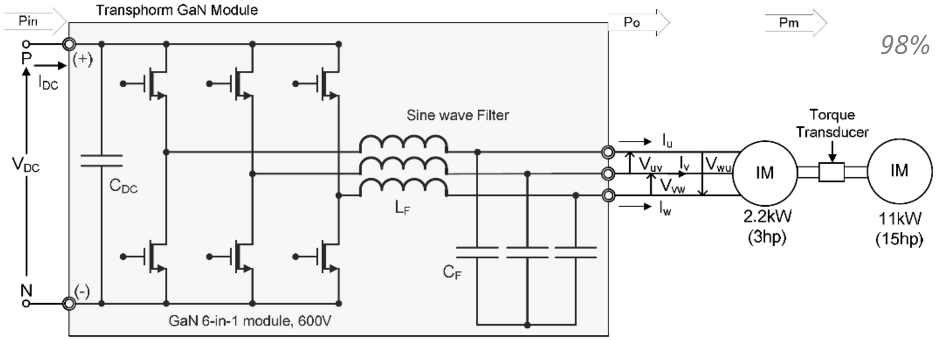
600V/14A

→ Very Low Filter Volume Compared to Si-IGBT Drive Systems (f_C= 0.8kHz @ f_S ≈ 3kHz)

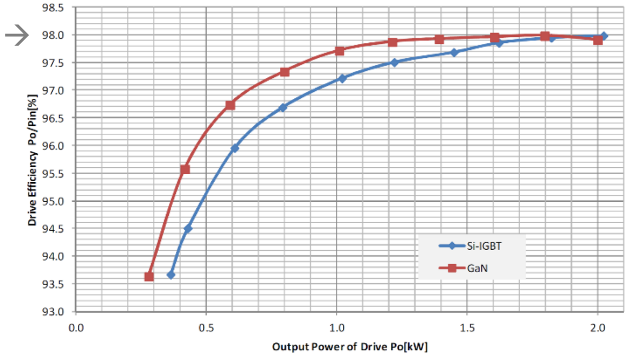
3-Φ 650V GaN Inverter System (2)

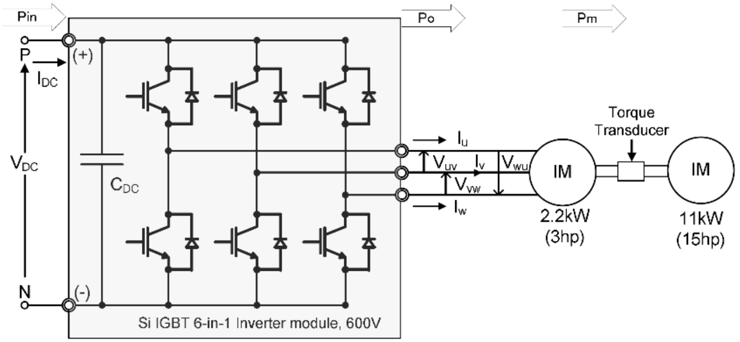
Source: YASKAWA

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

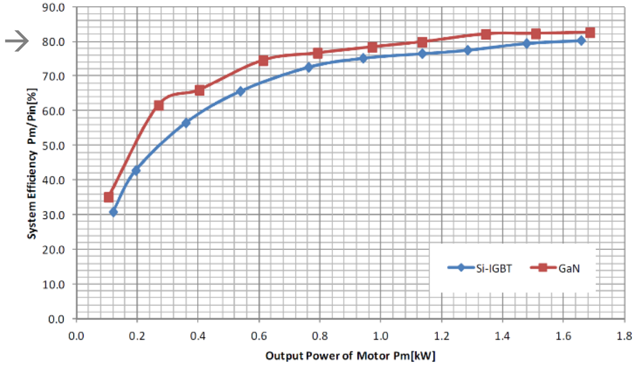


98% →





80% →



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

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Triangular Current Mode (TCM) Operation

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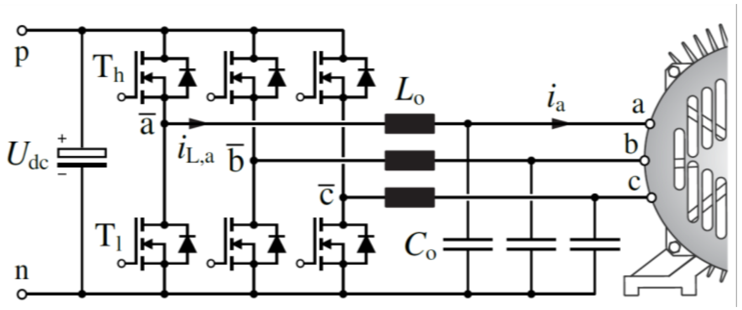
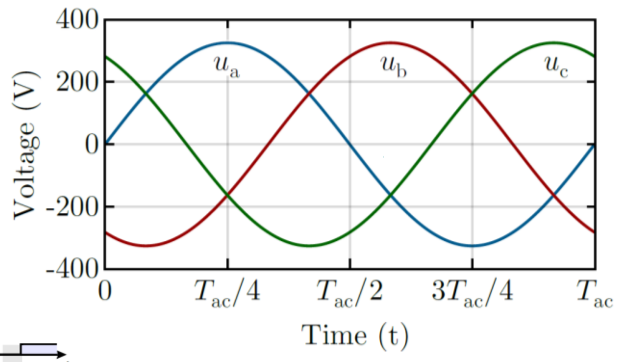
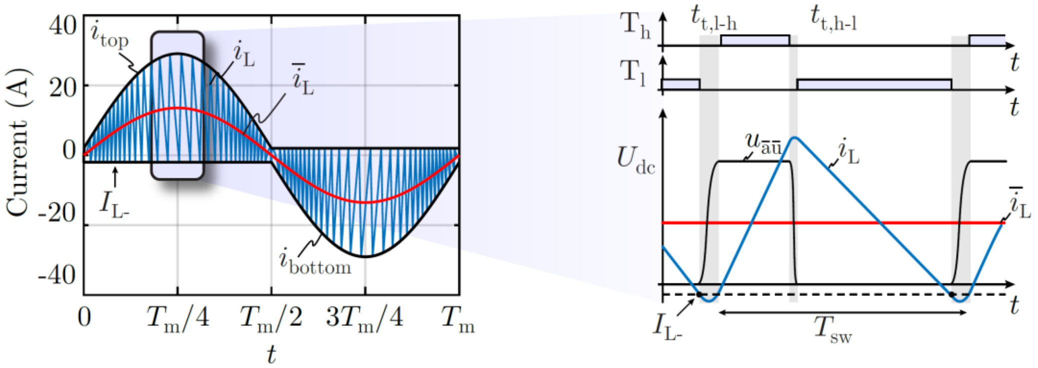
Triangular Current Mode – ZVS Operation

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



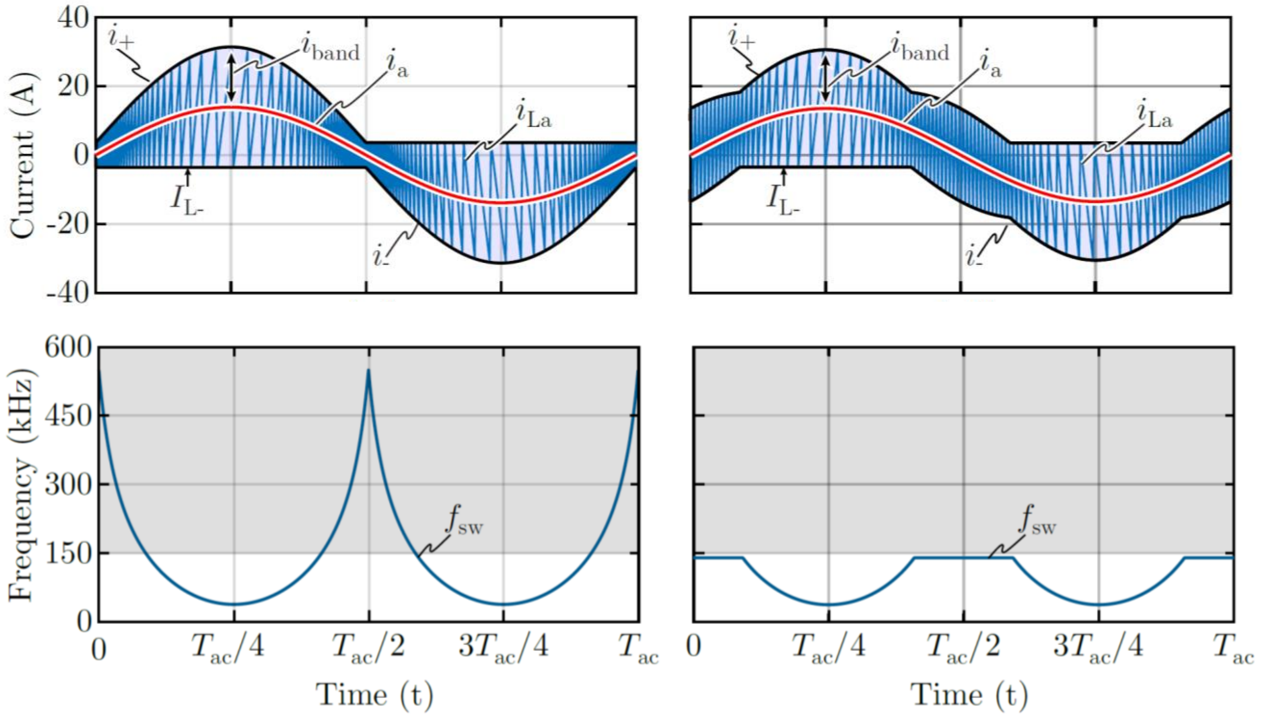




- *Only 33% Increase of Transistor Conduction Losses Compared to CCM (!)*
- *Very Wide Switching Frequency Variation*

TCM → B-TCM

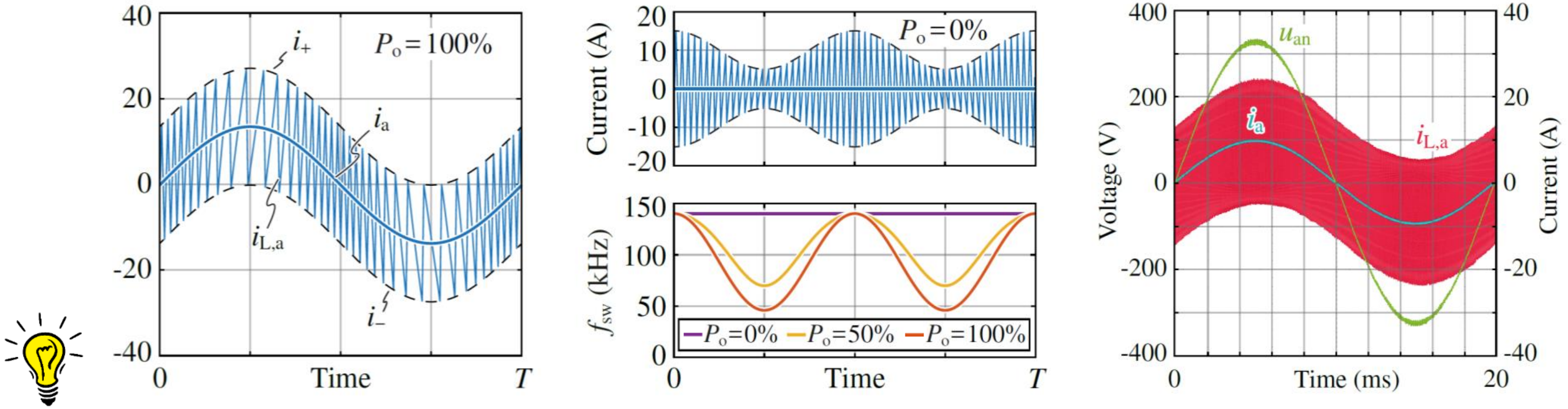
- *Very Wide Switching Frequency Variation of TCM → B-TCM*



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

B-TCM → S-TCM

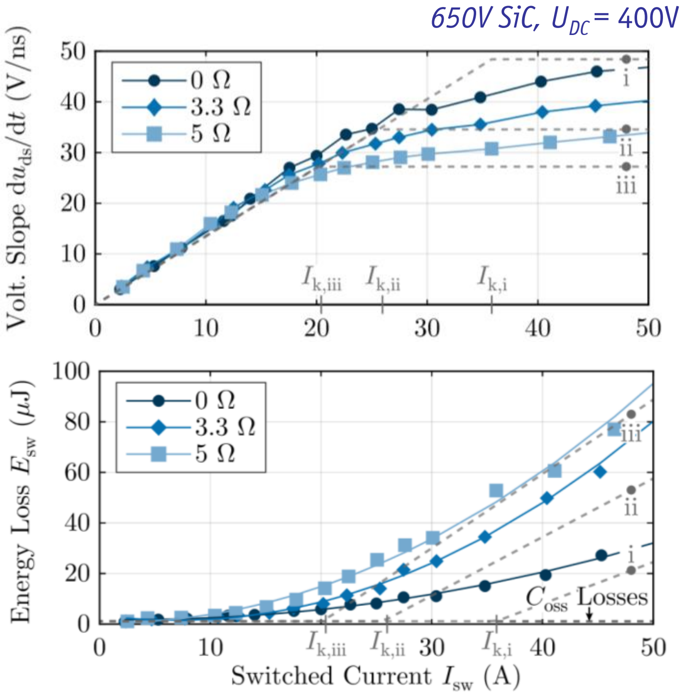
- *Sinusoidal Switching Boundaries → S-TCM*
- *Adaption for Low Output Power Considering $f_{sw,max}$ = 140kHz*



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

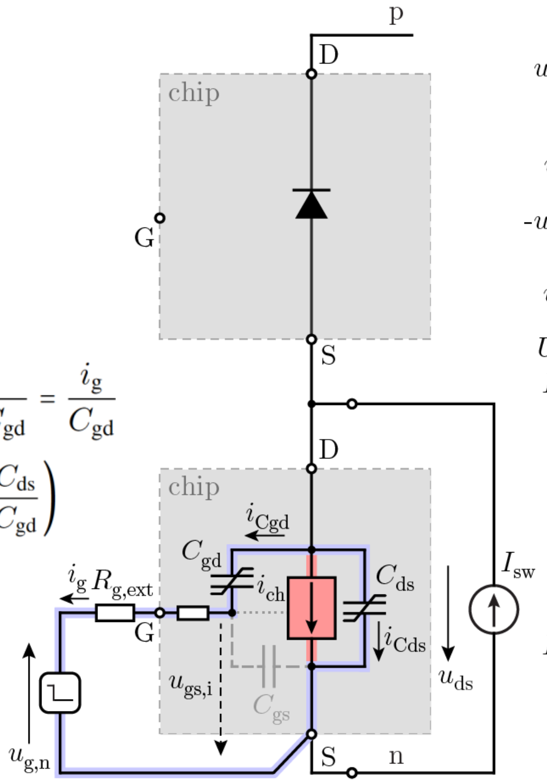
Remark Residual ZVS Losses

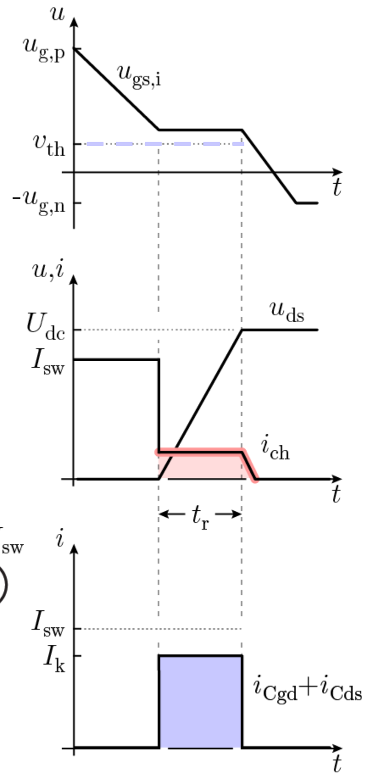
- *Overlap of u_{DS} & Channel Current i_{ch} @ High $I_{sw} > I_k$*
- *Temporary Turn-on Due to $u_{GS,i} > u_{th}$*



$$\left.\frac{du_{ds}}{dt}\right|_{max} = \frac{I_k}{C_{ds} + C_{gd}} = \frac{i_g}{C_{gd}}$$

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





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

#2

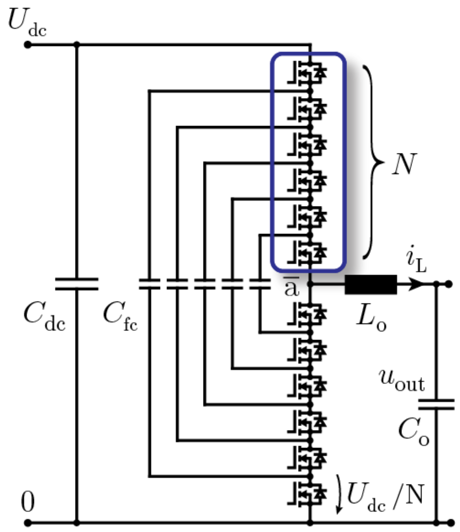
Source: www.clipart-library.com

Multi-Level Inverter

Multi-Level (ML) Converter Scaling

- 1/N Reduction of Blocking Voltage → Lower $R_{DS,(on)}$ Semiconductors ($R_{on}' \sim U_B^2$)
- Eff. Increase of Sw. Frequency → $f_{sw,eff} = N\, f_{sw}$ (f_{sw} ... Individual Device)
- Larger Chip Area and/or Smaller L_0

N= # of Levels -1

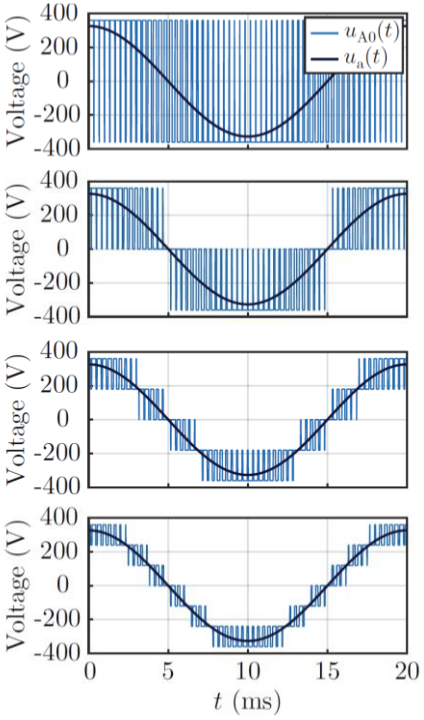


# of Levels= 2

= 3

=5

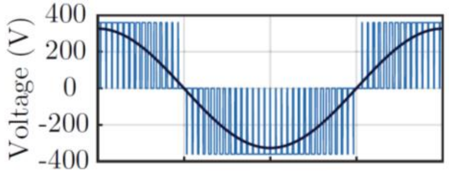
=7

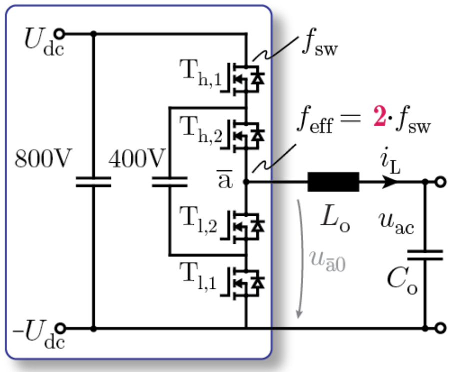


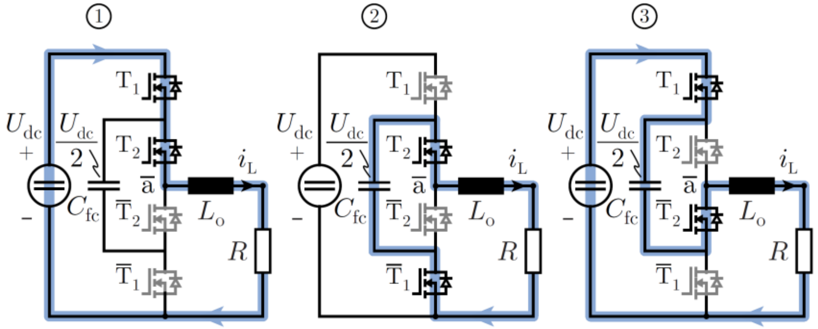
- D-FOM = D-FOM(U_{dc}/N) → Results in ML-Performance (X-FOM) Dependent on N

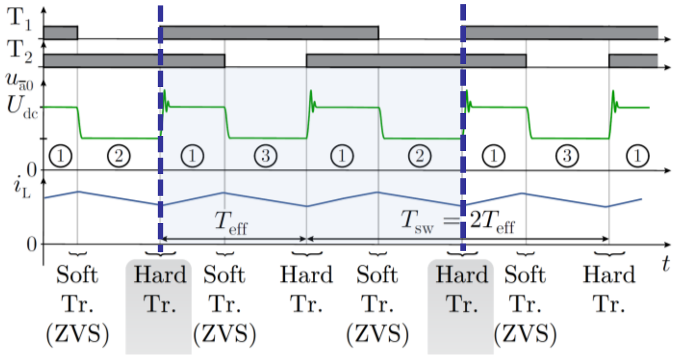
Functional Principle of ML-Converters

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





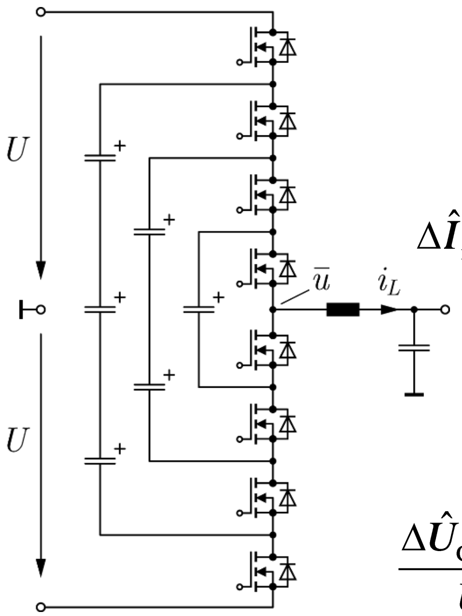




- *Risk of Transistor Overvoltage for Steep U_{dc} Changes*

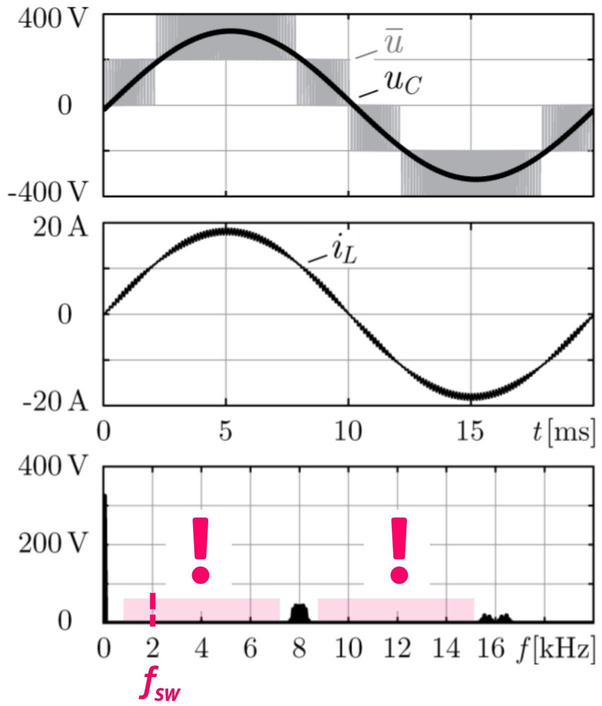
Scaling of ML Bridge-Leg Concepts

- *Reduced Ripple @ Same (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage → 1+1=2 NOT 2 ^{2} = 4 (!)*
- *Application of LV Technology to HV*



$$\Delta\hat{I}_{\max,N} = \frac{1}{N^2}\Delta\hat{I}_{\max,N=1}, \quad \Delta\hat{I}_{\max,N=1} = \frac{U}{8 f_s L}$$

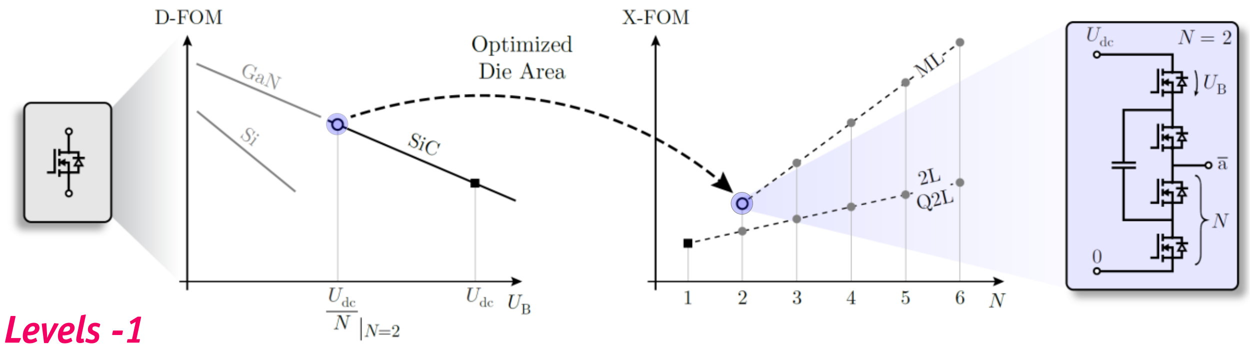
$$\frac{\Delta\hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32}\left(\frac{f_O}{f_S}\right)^2 \frac{1}{N^3}$$



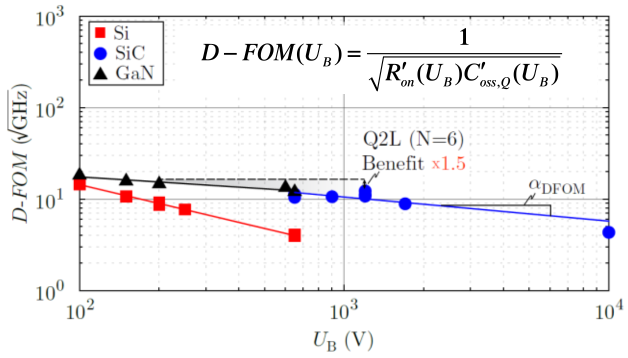
- *Scalability / Manufacturability / Standardization / Impedance Matching / Redundancy*

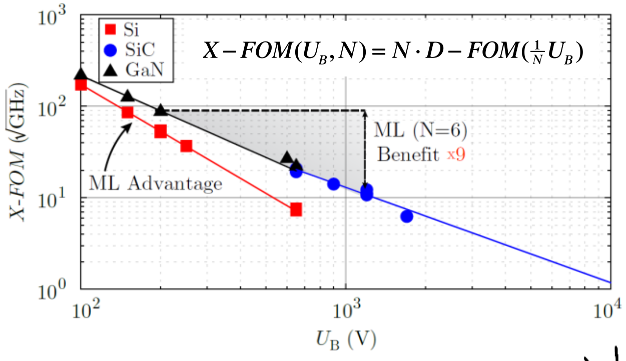
X-FOM of ML-Bridge-Legs

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



N= # of Levels -1





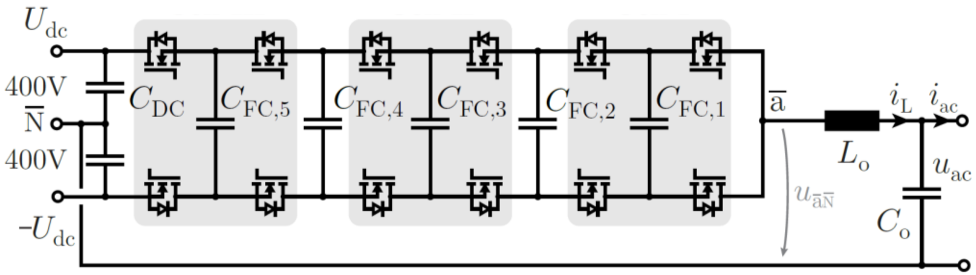
- *Compared to 2-Level Benchmark @ Same Filter Ind. Volt-Seconds* →

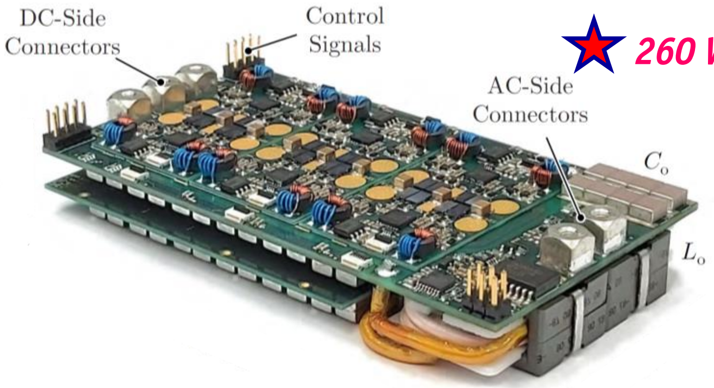
$P_{semi,min,ML} \approx 1/N^{1.2}\, P_{semi,min,2L}$

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

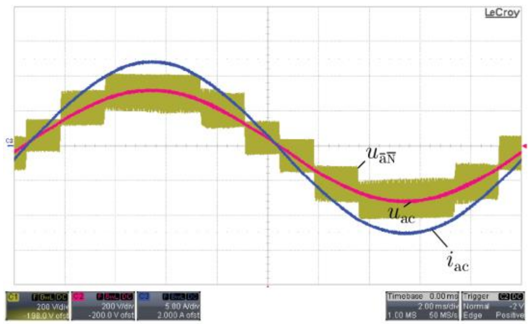
7-Level Flying Cap. 200V GaN Inverter (1)

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





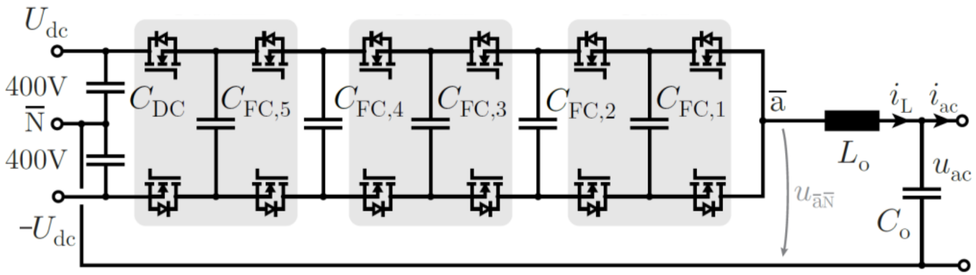
★ 260 W/in³



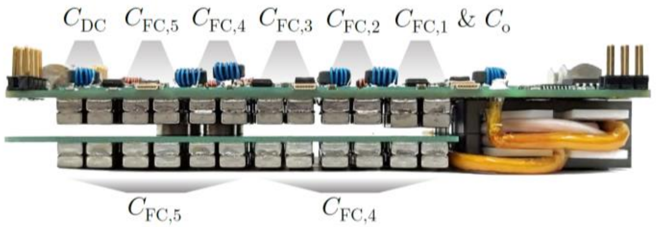
- High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor L_0

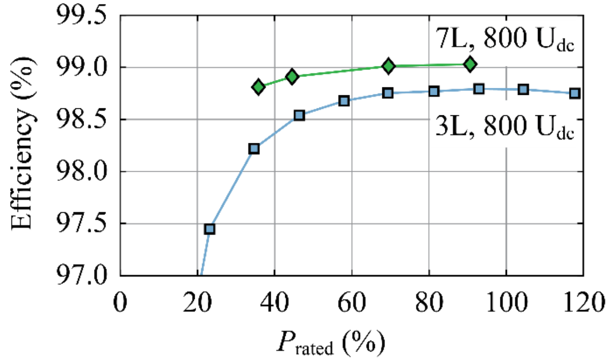
7-Level Flying Cap. 200V GaN Inverter (2)

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



★ *260 W/in³*

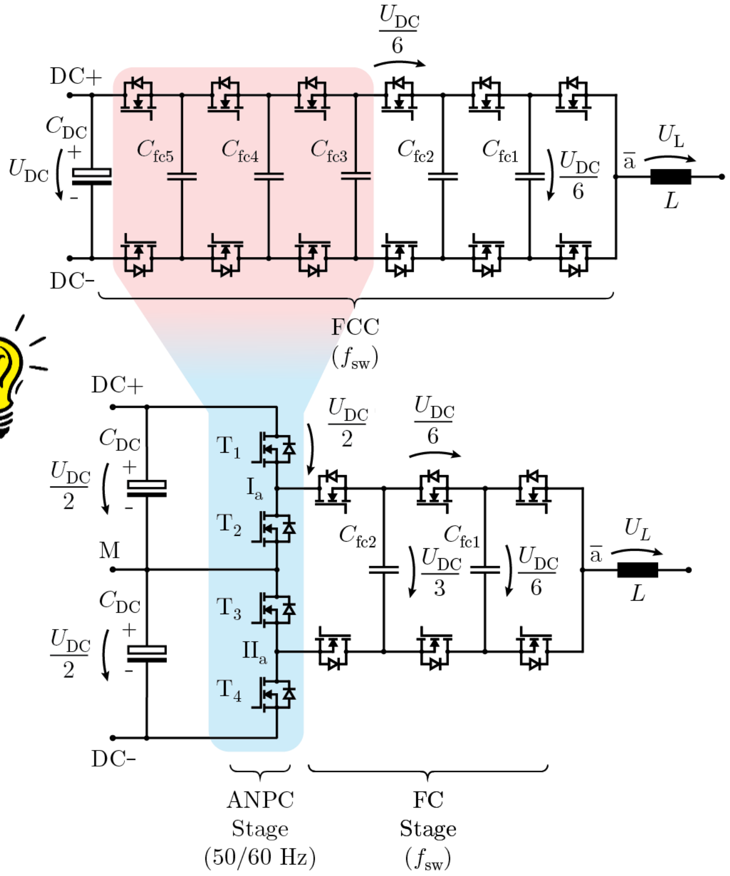


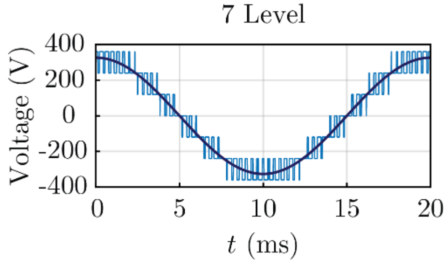


- *High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor L_o*

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/in^3

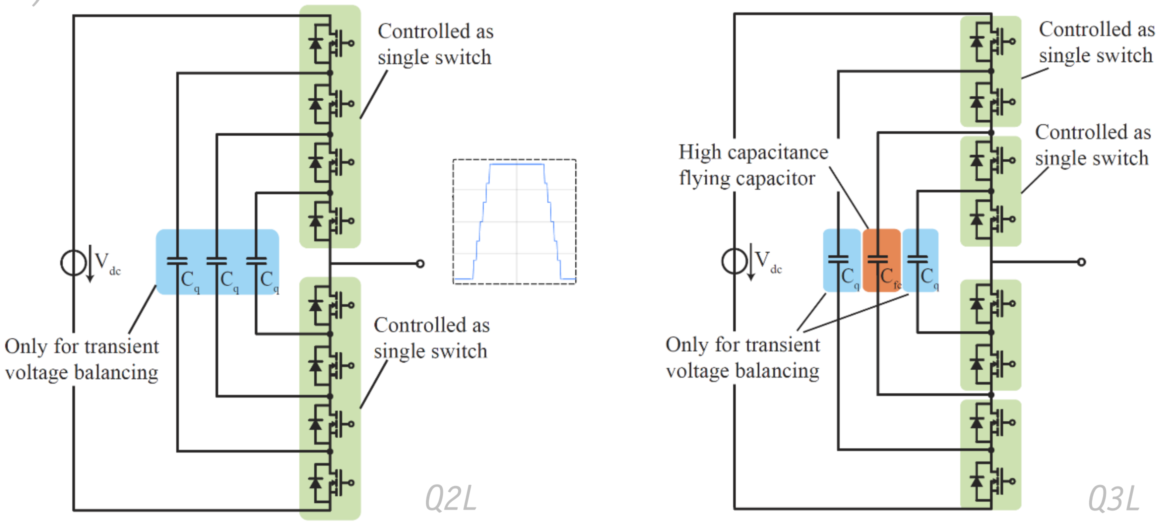
- *200V Si → 200V GaN Technology Results in 99.5% Efficiency*

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



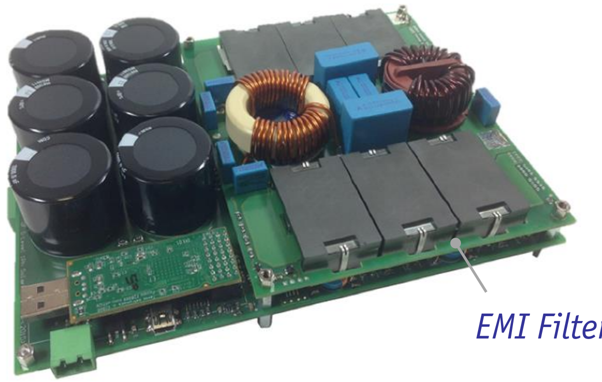
- *Reduced Average dv/dt → Lower EMI / Lower Reflection Overvoltages*
- *Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors*
- *Low Voltage/Low $R_{DS(on)}$/Low $ MOSFETs → High Efficiency / No Heatsinks / SMD Packages*

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

- Schweizer (2017)

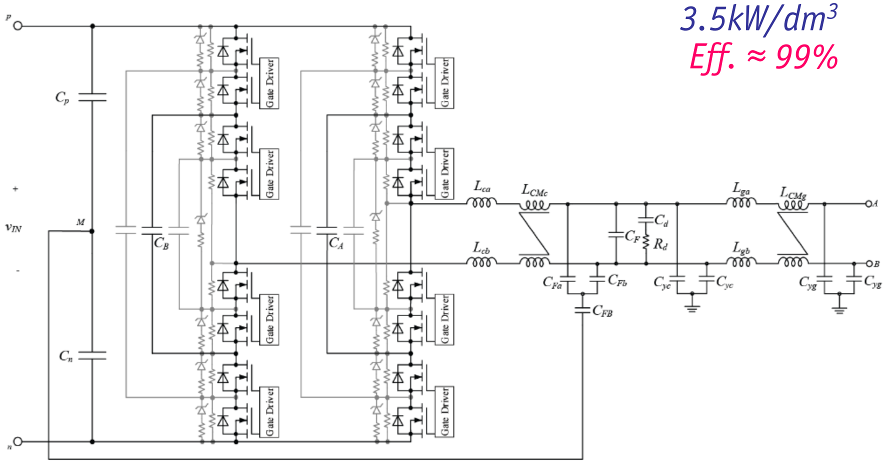
ABB



EMI Filter

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

3.5kW/dm³
Eff. ≈ 99%



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

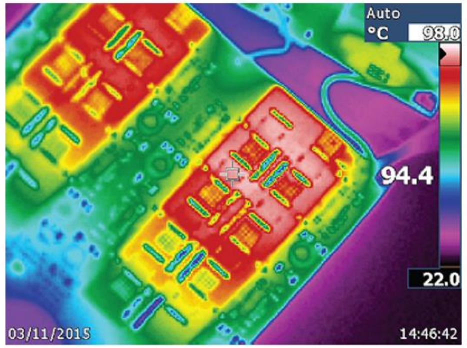
Quasi-2L & Quasi-3L Inverters (3)

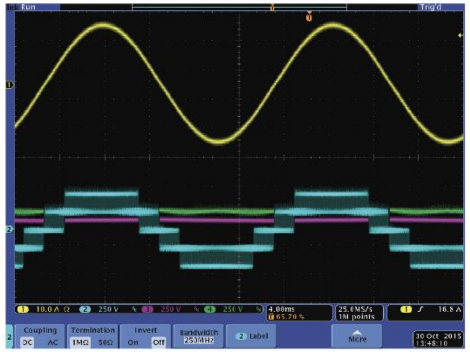
- Schweizer (2017)

ABB

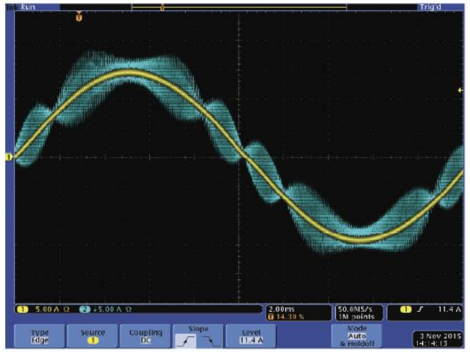
- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

Operation @ 3.2kW





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



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

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

Power Electronic Systems Laboratory

Ultra-Compact Power Module with Integrated Filter

650V GaN E-HEMT Technology

$f_{S,eff} = 4.8MHz$

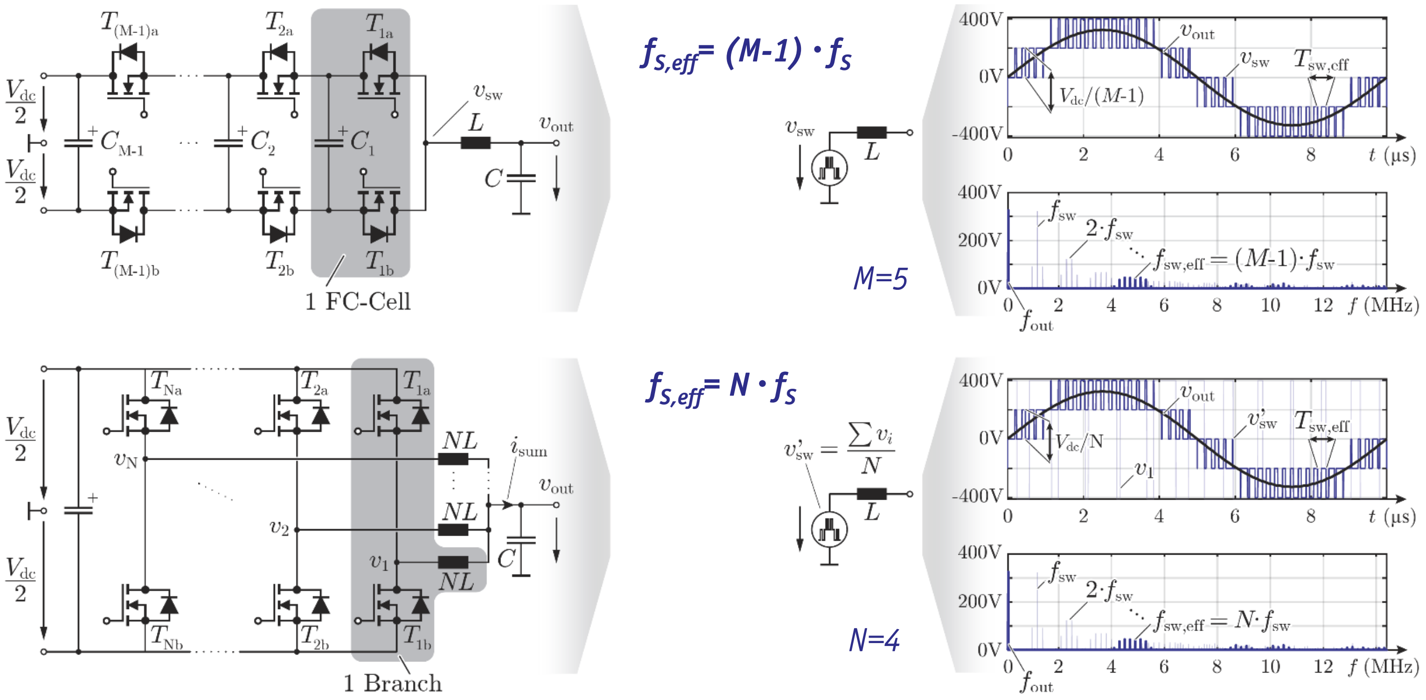
$f_{out} = 100kHz$

ETH zürich

IEEE PEMC
INDUSTRY ACADEMIA
TECHNOLOGY BRIDGE

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*



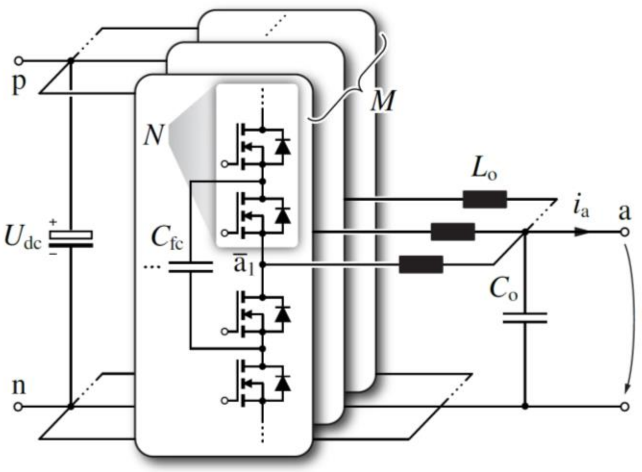
→ *Target: Best Combination of Multiple Levels (M) & Parallel Branches (N)*

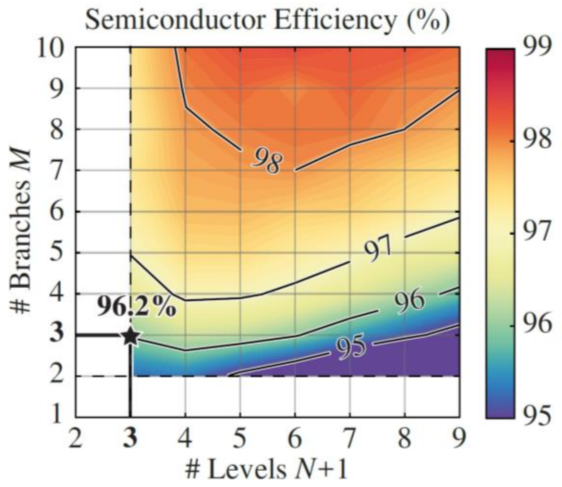
4.8MHz GaN Half-Bridge Phase Module

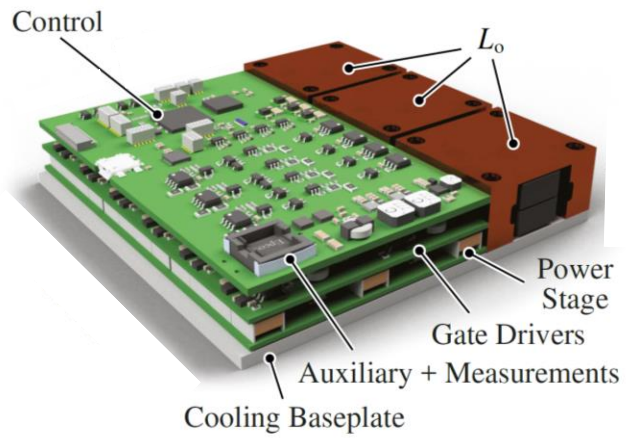
- *Combination of Series & Parallel Interleaving*

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

≈ 820 W/in³



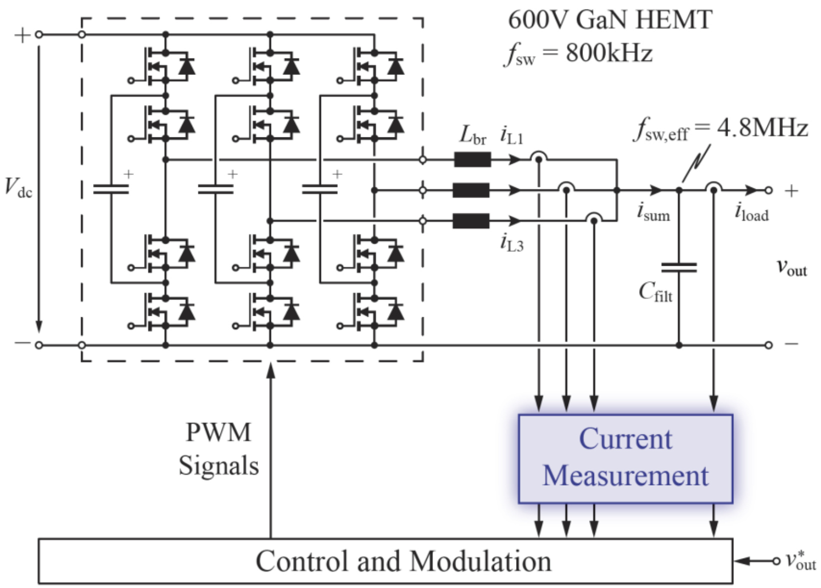


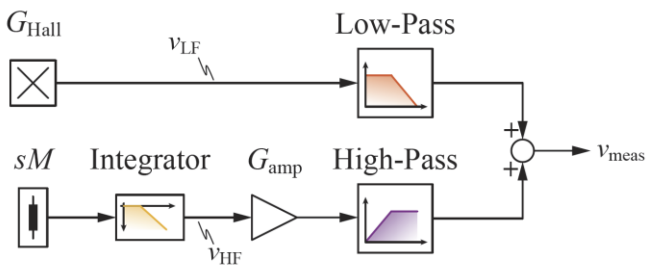


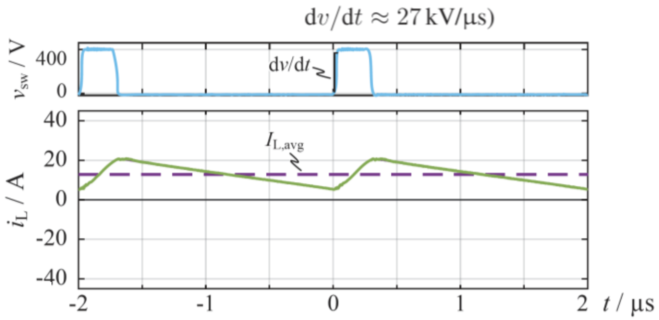
- *Operation @ f_{out}=100kHz / $f_{S,eff}$= 4.8MHz, 10kW, U_{dc}=800V*

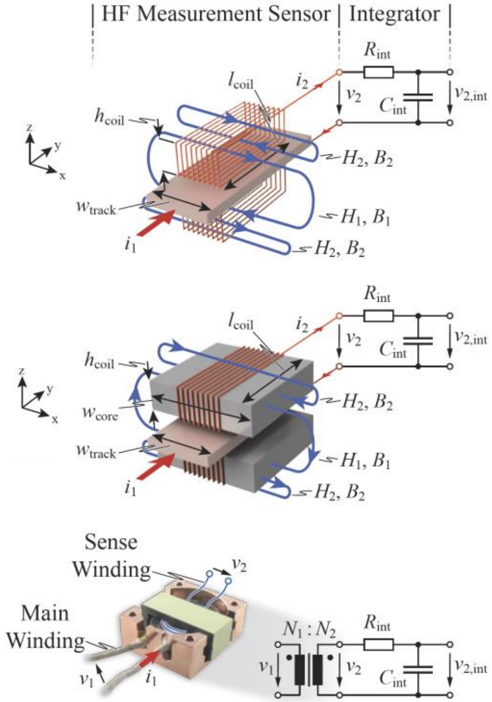
Remark High-BW High-CMRR Current Measurement

- ***Extension of Commercial Hall Sensor DC… f_{Hall}≈ 500kHz → DC…20MHz***
- ***Low-Pass & High-Pass Filter Network Combining HF-Sensor & LF Hall-Sensor***









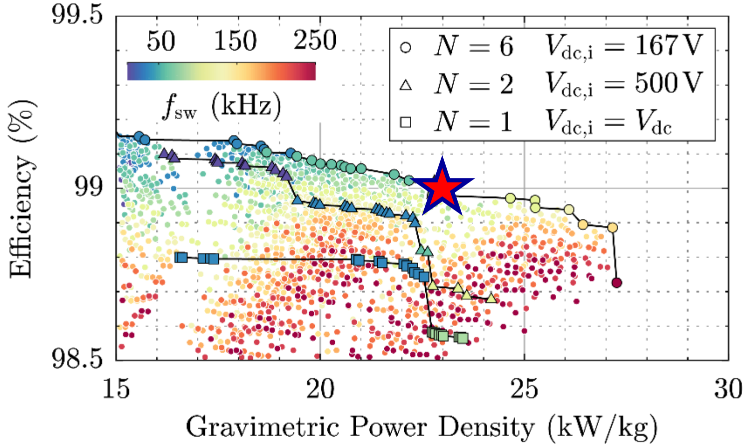
- ***Hall Sensor Bandwidth f_{Hall} = 1.6MHz***
- ***Rogowski Coil High-Pass Corner Frequency f_{int}=1kHz***
- ***Low/High-Pass Filter Cross-Over Network f_{filter} = 24kHz***

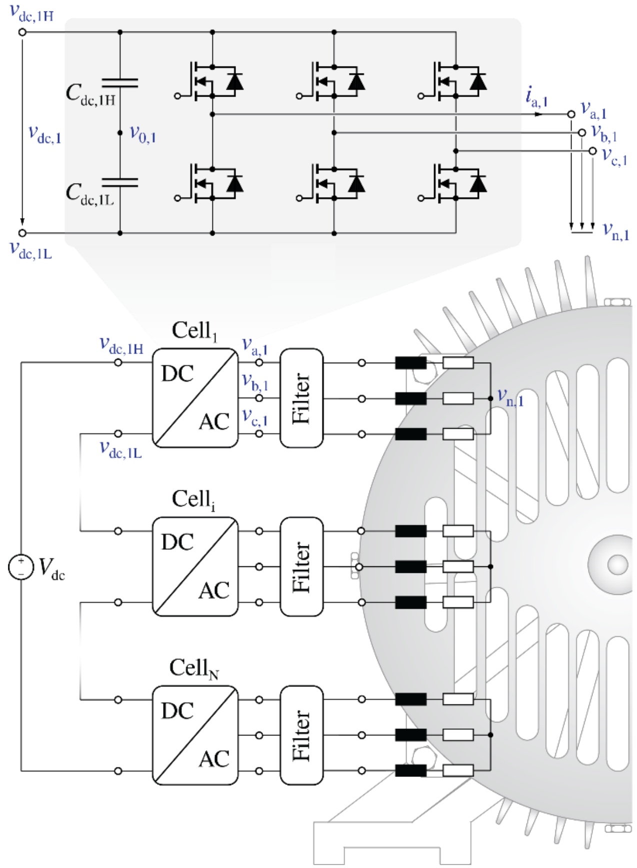
Motor-Integrated Inverter Systems

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*

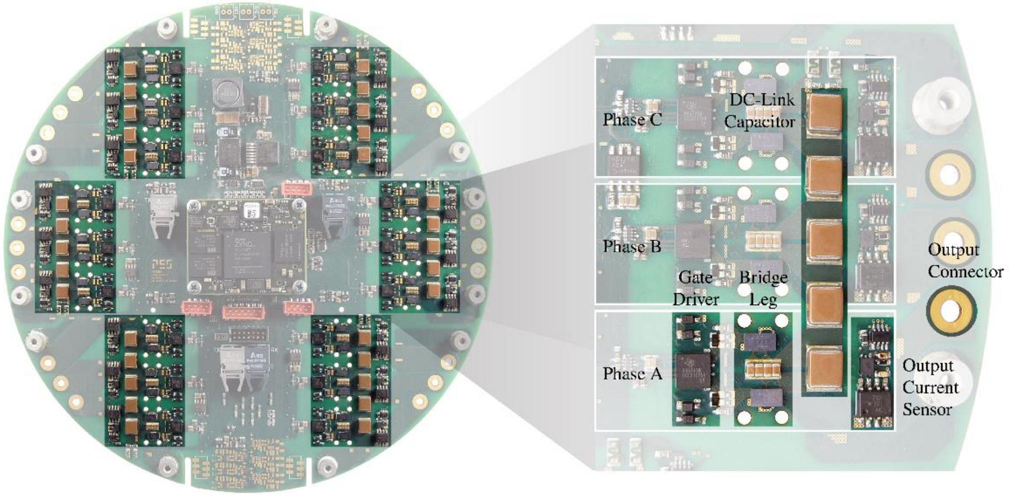




- *Smart Motor / Plug & Play* | *Connected / Intelligent VSD 4.0*

Motor-Integrated SMC-Inverter

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

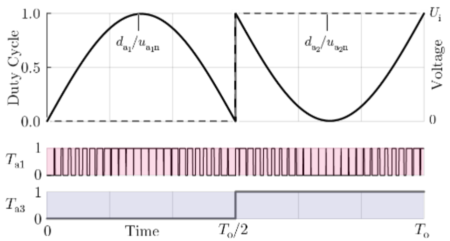


— Axial Stator Mount
— 200V GaN e-FETs
— Low-Capacitance DC-Links
— 45mm x 58mm / Cell

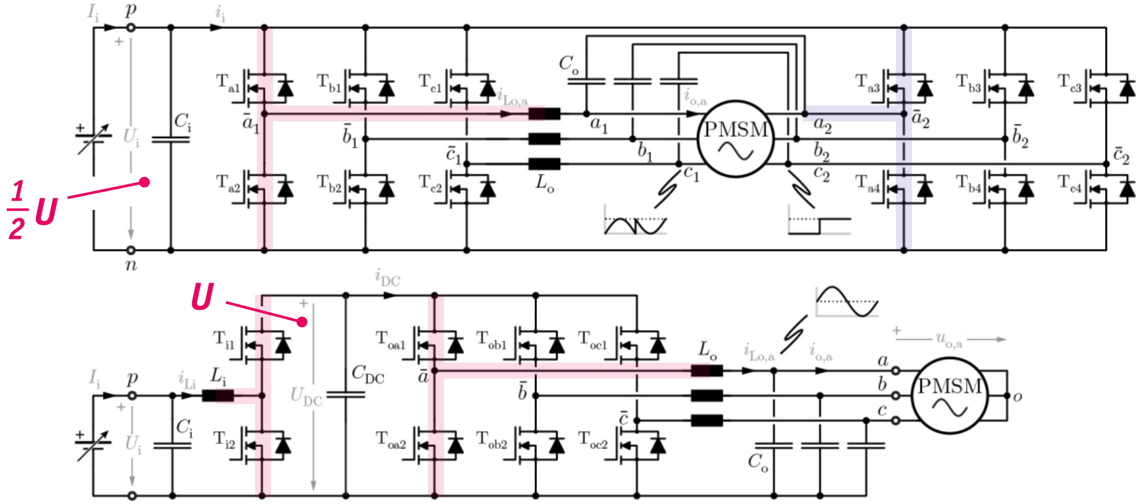
- Main Challenge — Thermal Coupling/Decoupling of Motor & Inverter

Double-Bridge (DB) Inverter

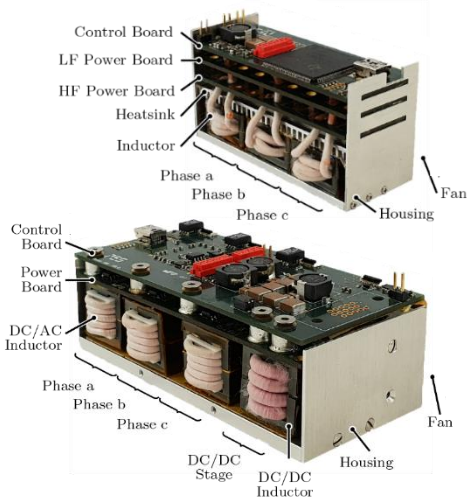
- ***Comparison to Conv.***
  2-Level Inverter + Front-End
  DC/DC Boost-Stage



U_b = 40V…120V
P = 1.0kW
f_s = 300kHz (200V EPC GaN)
f_o = 5kHz



210 W/in³

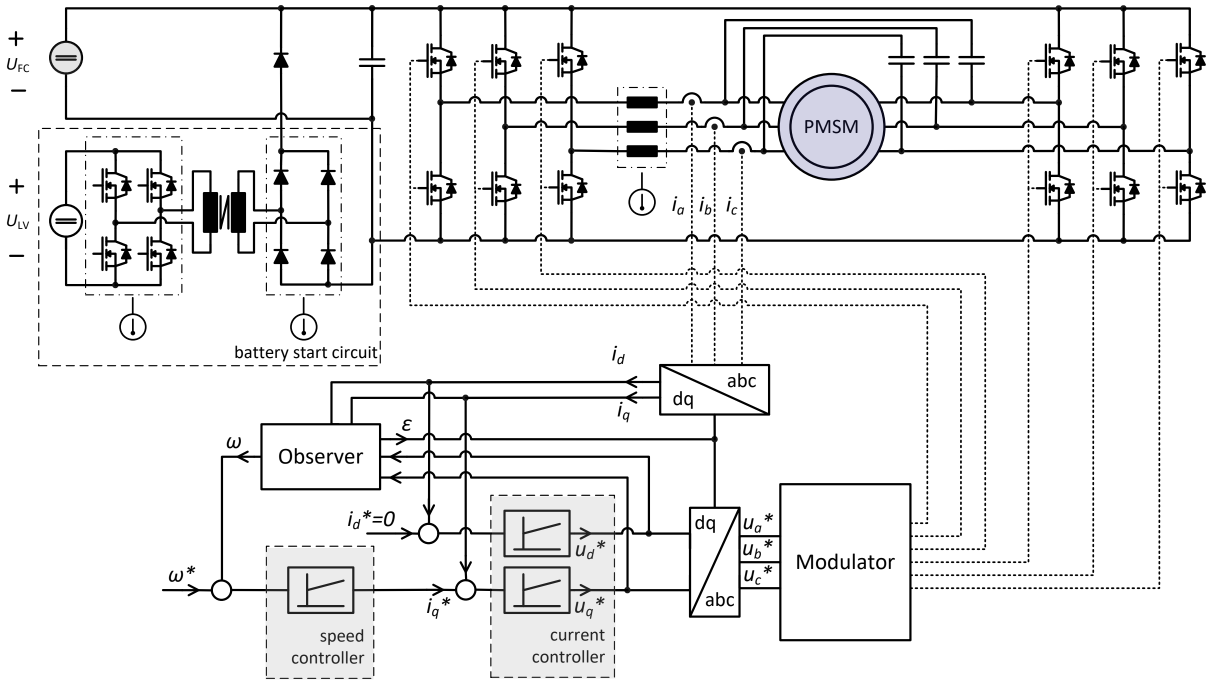


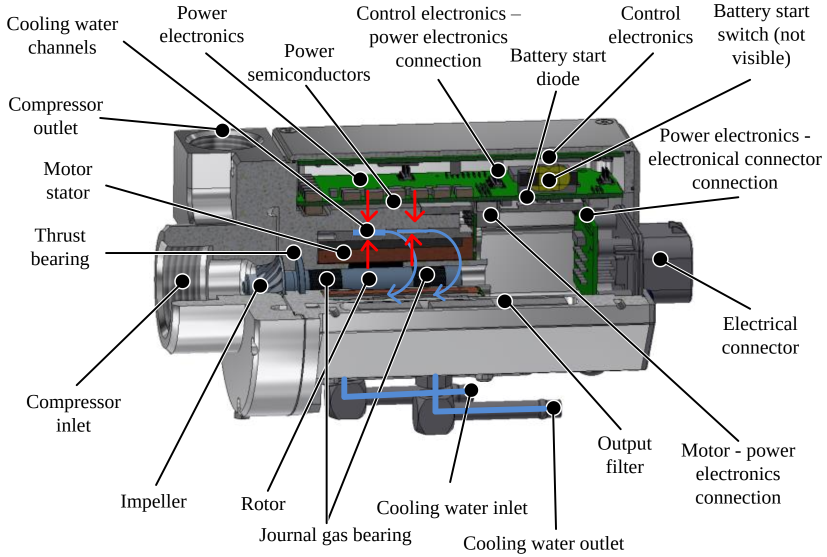
98 W/in³

- ***Advantages — Lower Sw. Losses & Lower # of Filter Inductors***

Compressor-Integrated DB GaN-Inverter

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

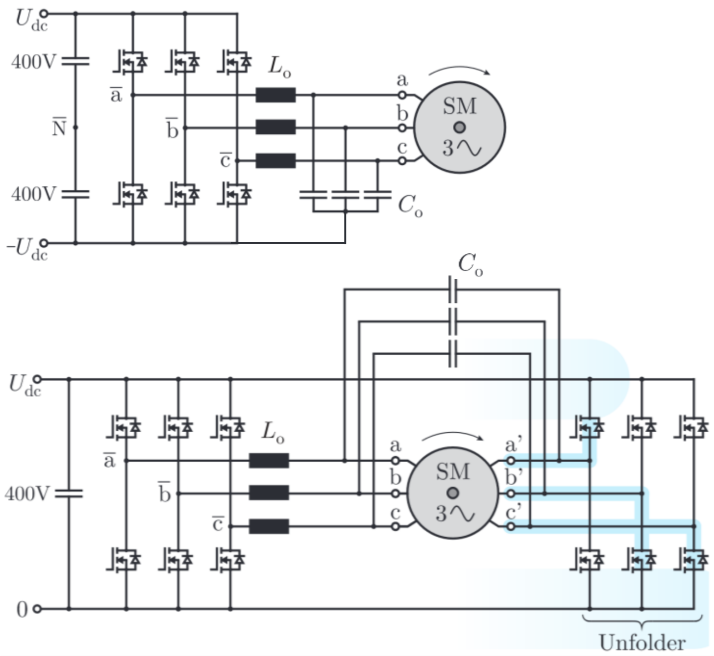


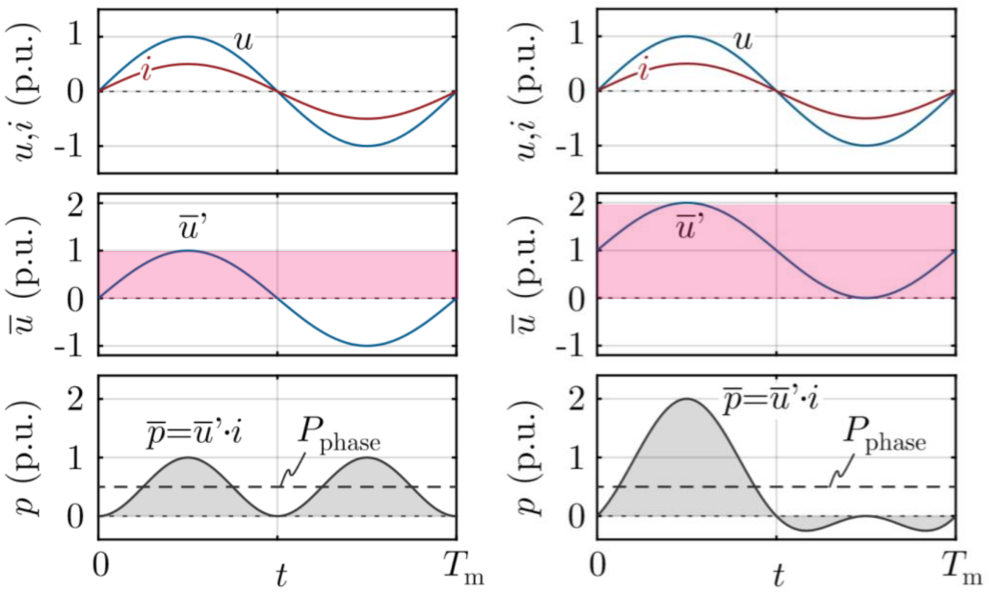


- *Integration → 2x System Power Density | 97% → 98.5% Inverter Efficiency*

Fundamental 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*



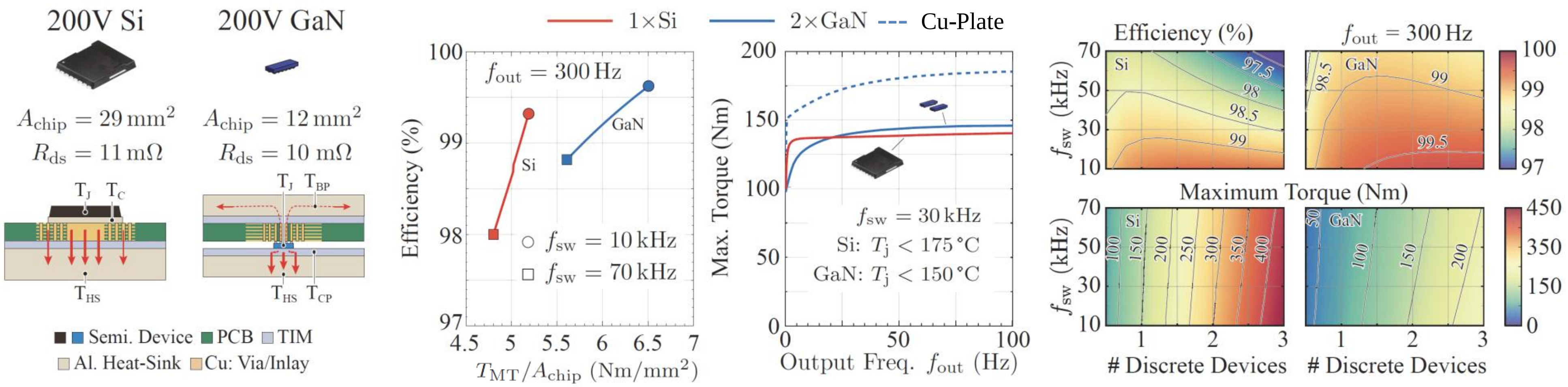


- *Access to All Wdg. Terminals — No Problem for Inverter/Motor Integration*

Overload | Thermal Limit

Remark GaN Overload Capability

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



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

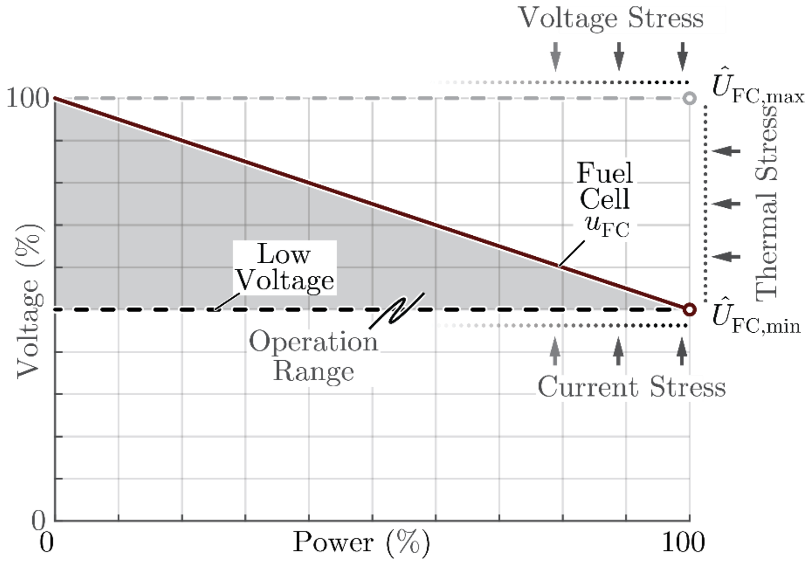
#3

Source: www.clipart-library.com

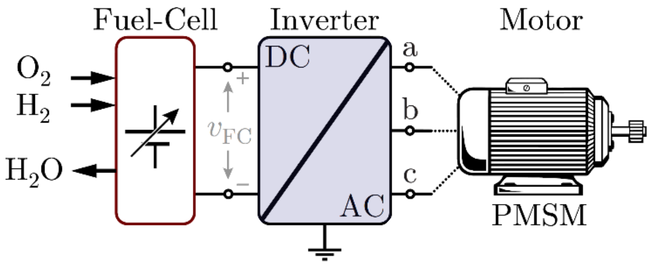
Buck-Boost Inverter

Motivation

- **General / Wide Applicability**
  - Adaption of (Load-Dependent) Supply Voltage & Motor Voltage
  - Wide Speed Range → Wide Output Voltage Range



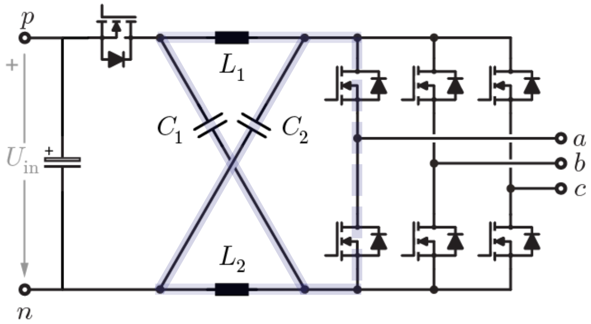
Source: magazine.fev.com



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

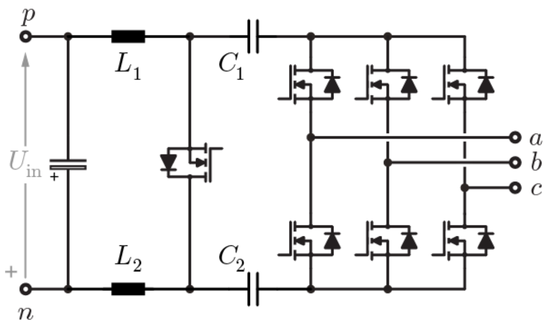
"Outside-the-Box" Topologies

- *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*

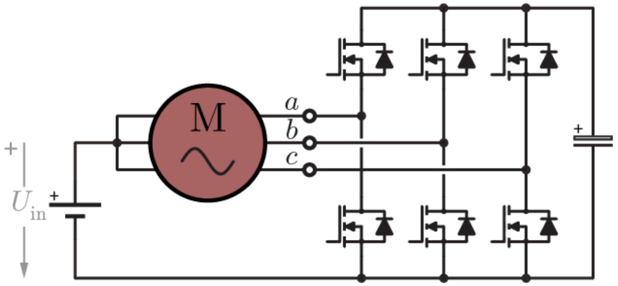


Source: T.A. Lipo et al. /2002 & K.D.T Ngo / 1984

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

Boost Converter DC-Link Voltage Adaption

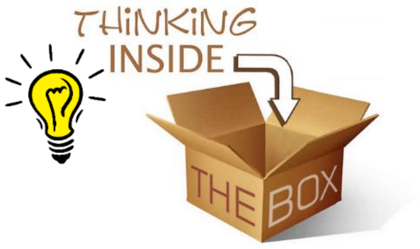
- Inverter-Integr. DC/DC Boost Conv. → Higher DC-Link Voltage / Lower Motor Current
- Access to Motor Star-Point & Specific Motor Design Required
- No Add. Components

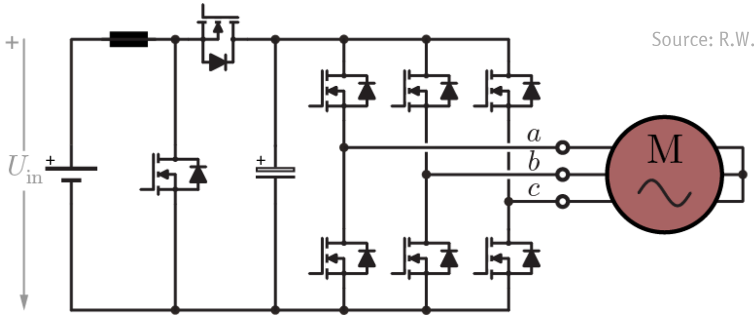


Source: J. Pforr et al. / 2009

- Explicit Front-End DC/DC Boost-Stage

Source: www.rick-gerber.com



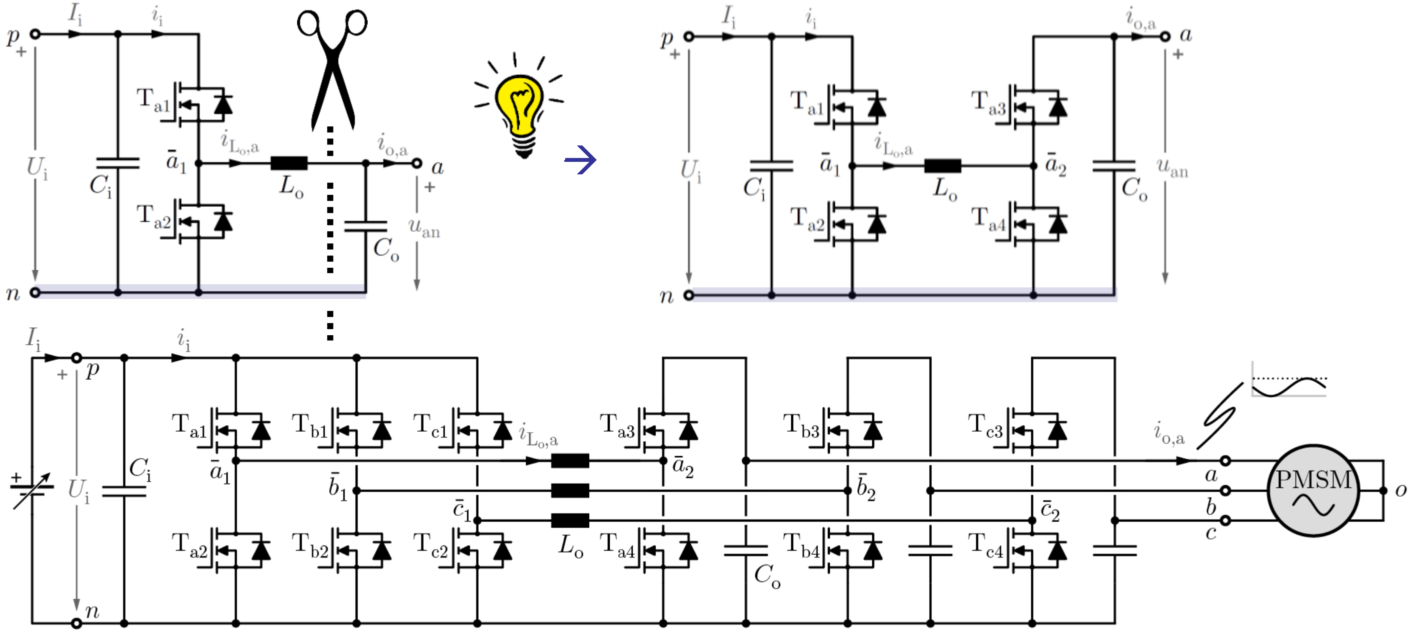


Source: R.W. Erickson et al. / 1986

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

Derivation of Buck-Boost Y-Inverter

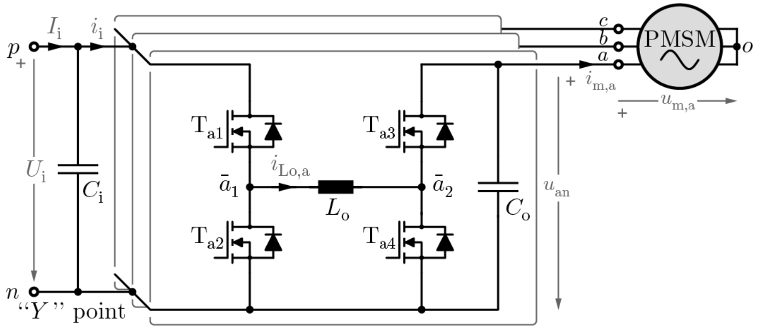
■ *Generation of AC-Voltages Using Unipolar Bridge-Legs*

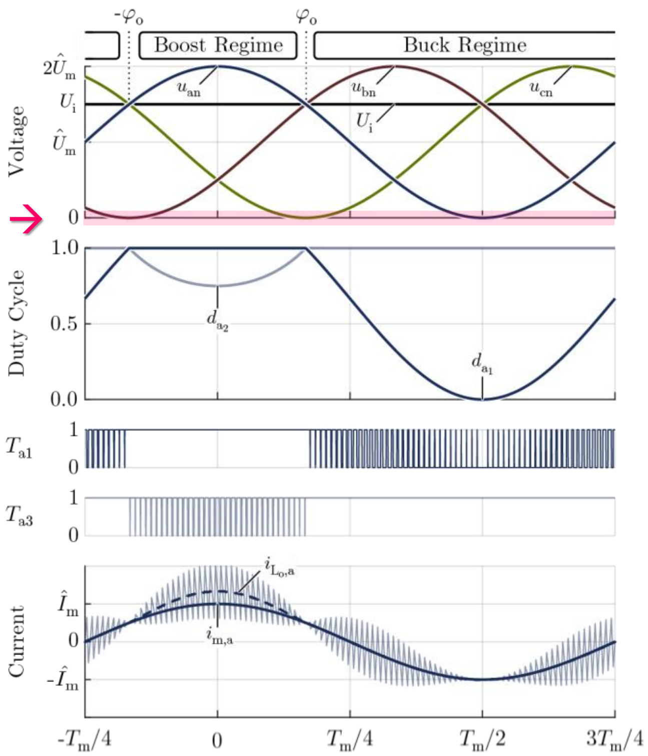


- *Switch-Mode Operation of Buck OR Boost Stage* → *Single-Stage Energy Conversion (!)*
- 3-Φ Continuous Sinusoidal Output / Low EMI → *No Shielded Cables / No Insul. Stress*
- Standard Bridge-Legs / Building Blocks → *1.2kV SiC MOSFETs*

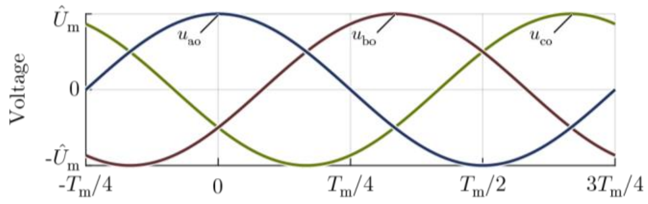
Sinusoidal Modulation

- **_Y-Inverter_**





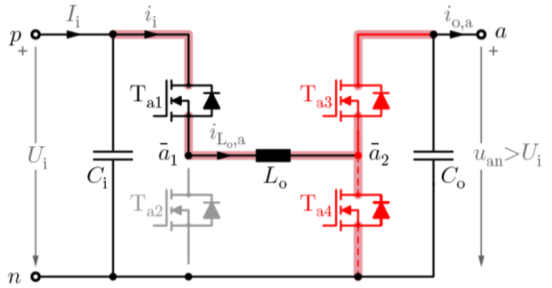
- **_Motor Phase Voltages_**



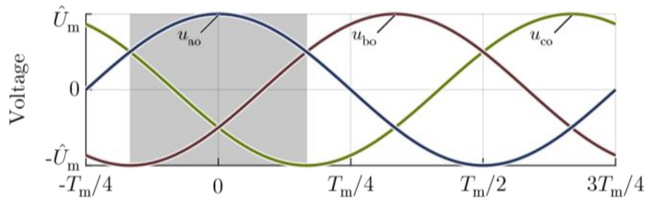
- *Const. DC Offset → Strictly Positive Output Voltages u_{aN}, u_{bN}, u_{cN}*
- *Mutually Exclusive Operation of the Half-Bridges → Low Switching Losses*

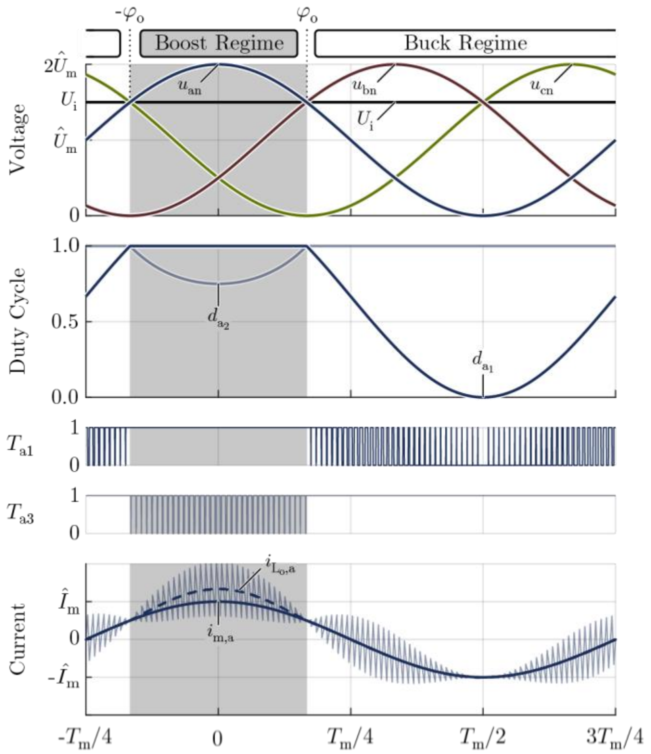
Boost-Operation $u_{an} > U_i$

- **Phase-Module**



- **Motor Phase Voltages**

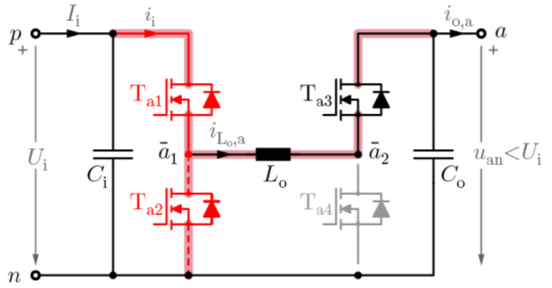


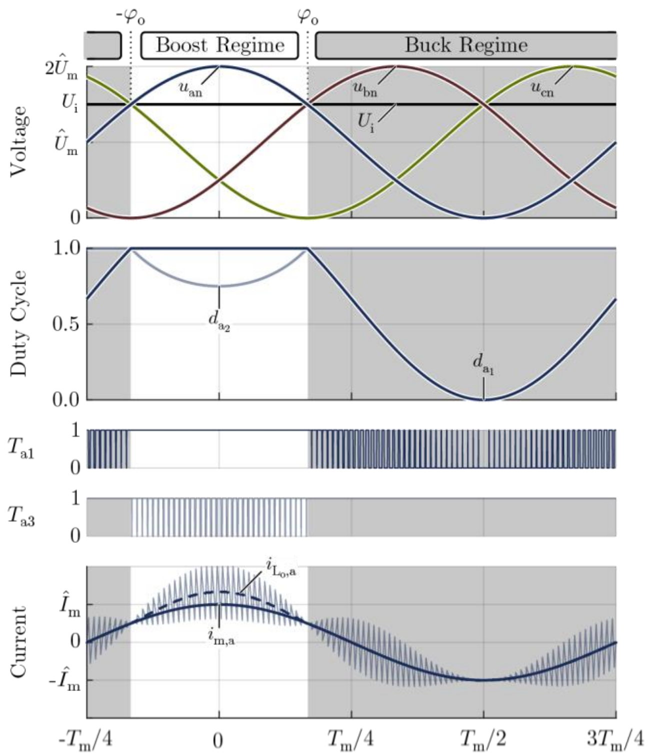


- *Current-Source-Type Operation*
- *Clamping of Buck-Bridge High-Side Switch* → *Quasi Single-Stage Energy Conversion*

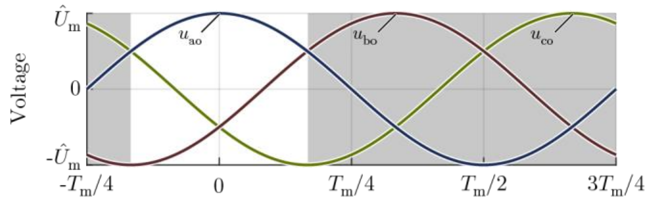
Buck-Operation $u_{an} < U_i$

■ *Phase-Module*





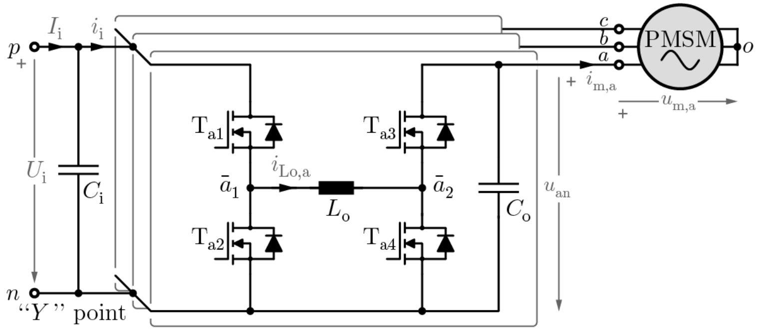
■ *Motor Phase Voltages*



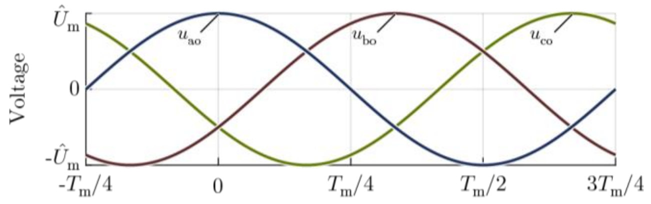
- *Voltage-Source-Type Operation*
- *Clamping of Boost-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion*

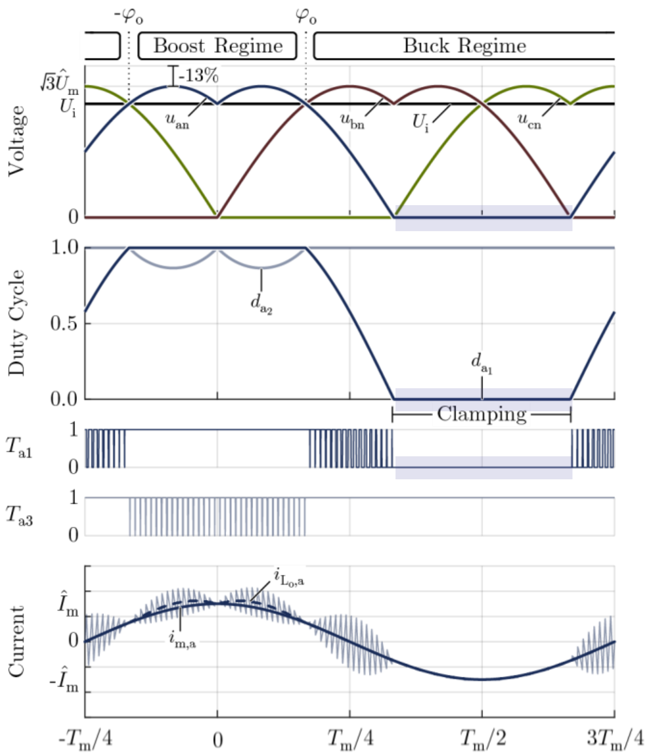
Discontinuous Modulation

- *Y-Inverter*



- *Motor Phase Voltages*

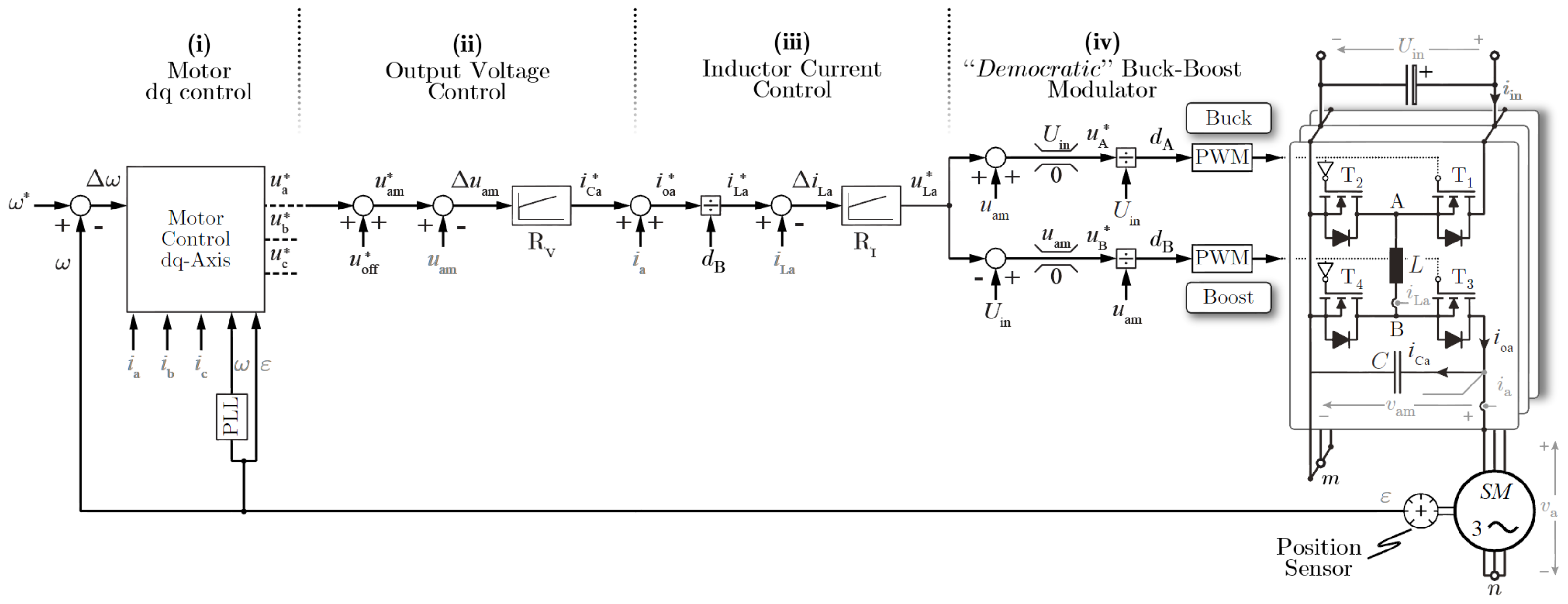




- *Clamping of Each Phase for 1/3 of the Fund. Period → Low Switching Losses (!)*
- *Non-Sinusoidal Module Output Voltages / Sinusoidal Line-to-Line Voltages*

Control Structure

- *Motor Speed Control*

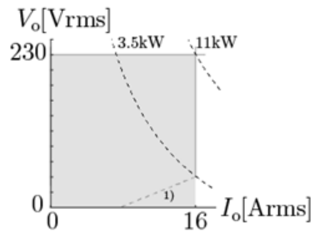


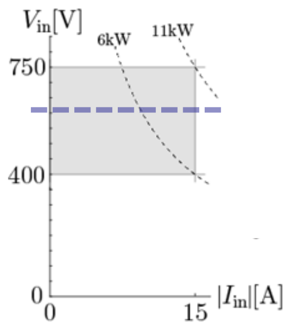
- *Cascaded Current / Voltage / Current Control Loops*
- *Seamless Transition between Boost- & Buck-Mode → "Democratic" Control*

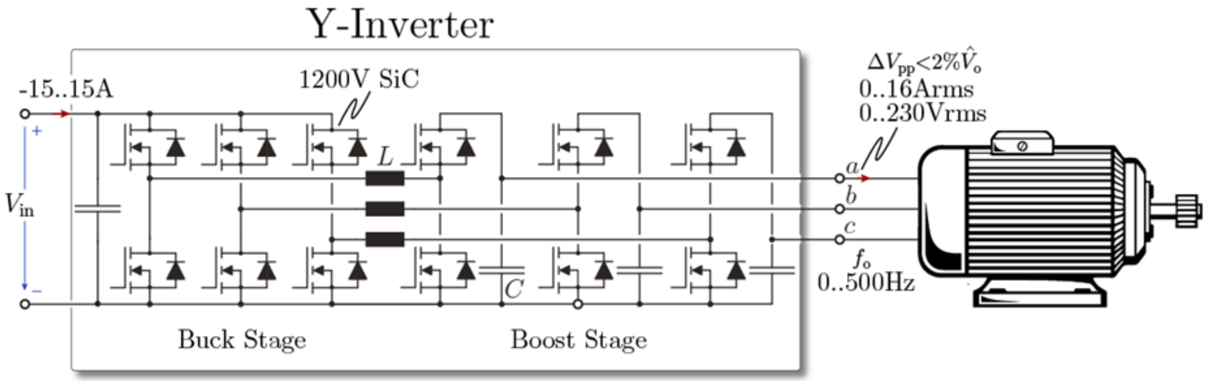
Y-Inverter VSD

■ *Demonstrator Specifications*

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



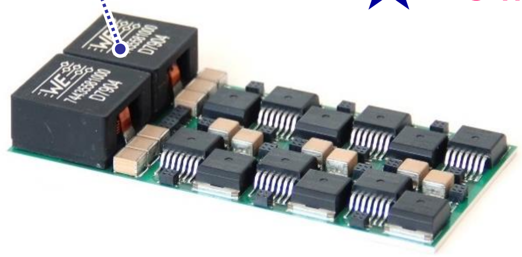




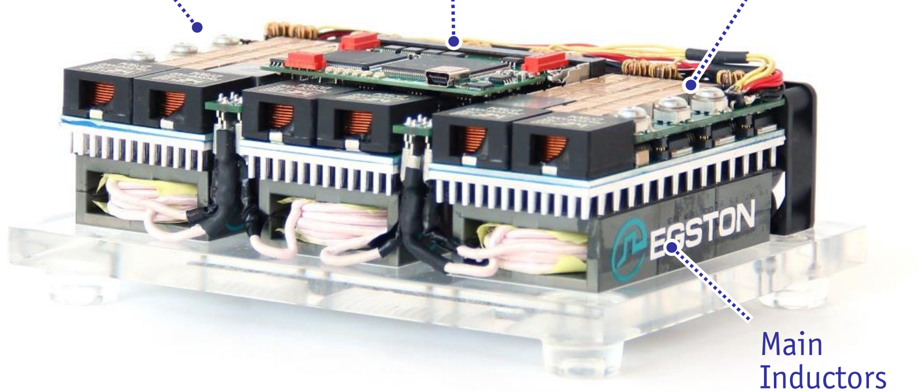
- Max. Output Power → 6...11 kW
- Output Frequency Range → 0...500Hz
- Output Voltage Ripple → 3.2V Peak @ Output of Add. LC-Filter

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*



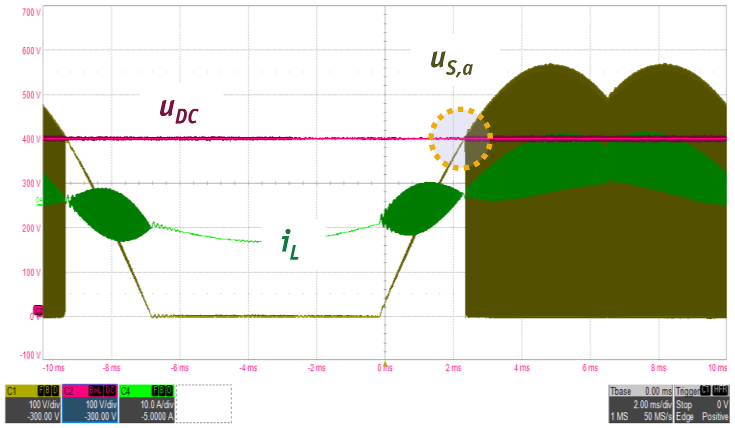
- Dimensions → 160 x 110 x 42 mm³

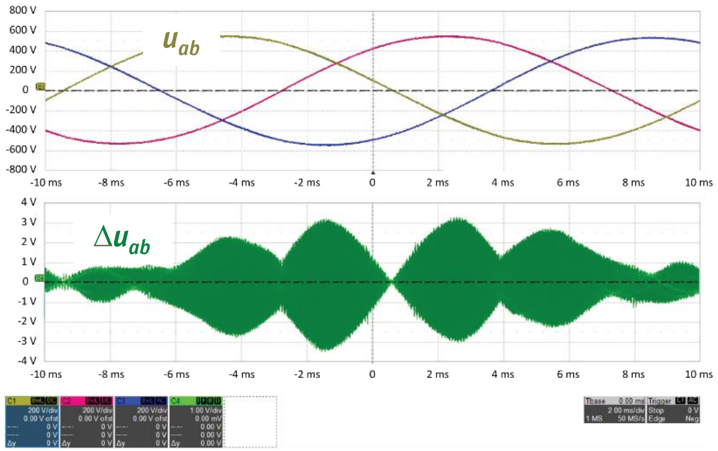
Y-Inverter - Measurement Results

- *Stationary Operation*

U_{DC} = 400V
U_{AC} = 400V$_{rms}$ (Motor Line-to-Line Voltage)
f_0 = 50Hz
f_S = 100kHz / *Discontinuous PWM*

P = 6.5kW





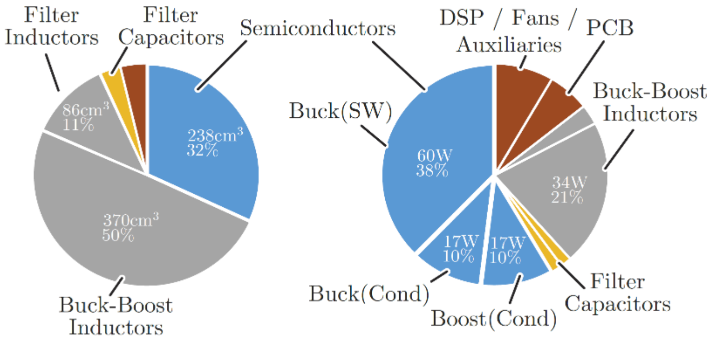
- *Line-to-Line Output Voltage Ripple < 3.2V*

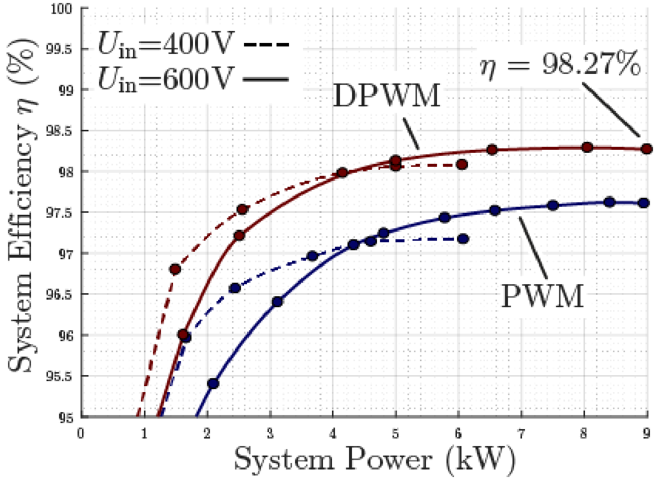
Efficiency Measurements

- *Dependency on Input Voltage & Output Power Level*

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

— *Volume* — *Losses*

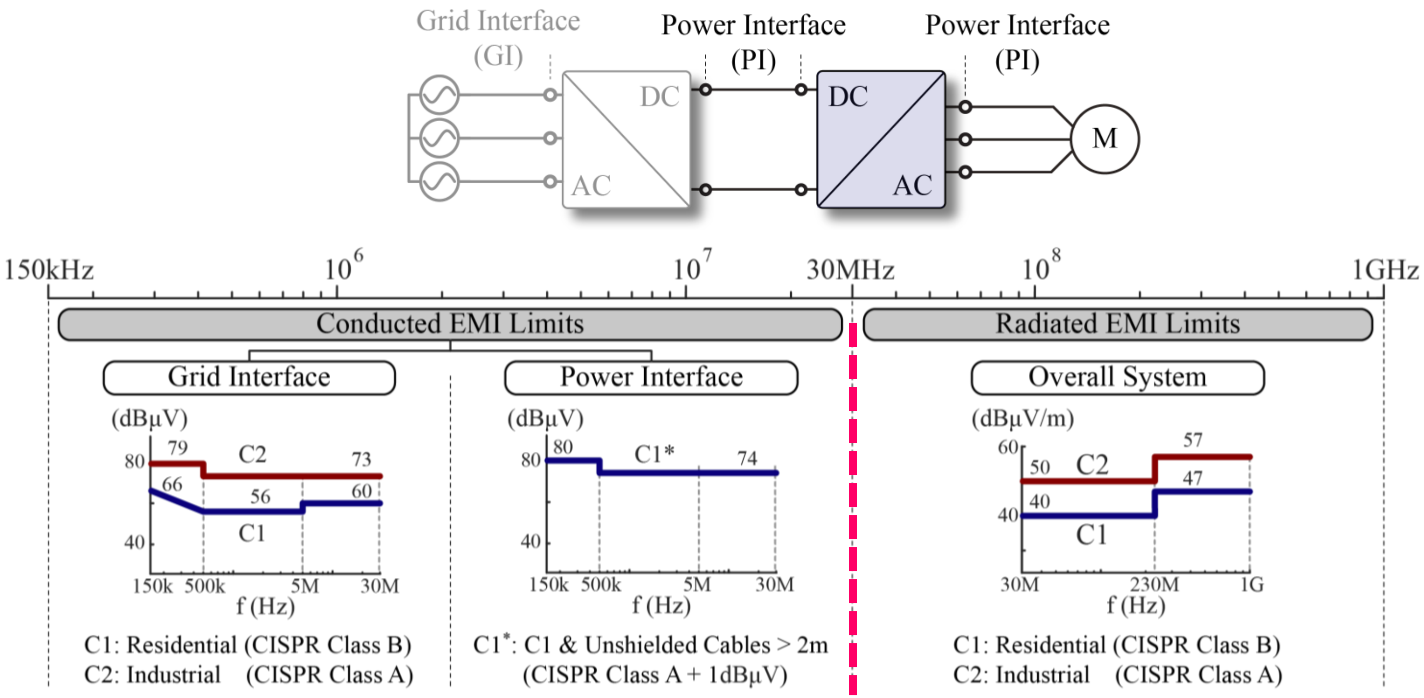




→ *Multi-Level Bridge-Leg Structure for Increase of Power Density @ Same Efficiency*

EMI-Limits (VSD Product Standard)

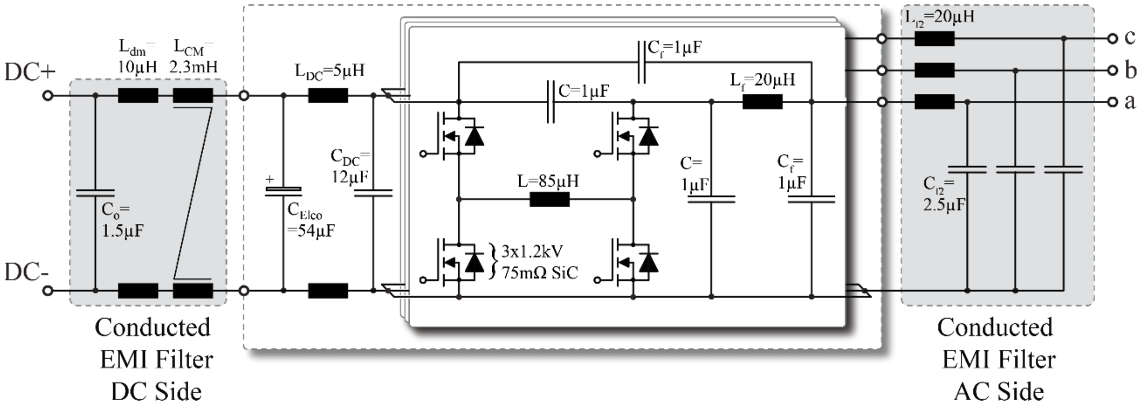
- IEC 61800-3 → Product Standard for Variable-Speed Motor Drives
- EMI Emission Limits → Grid Interface (GI) and Power Interface (PI)
- Application → Residential (C1) or Industrial (C2)



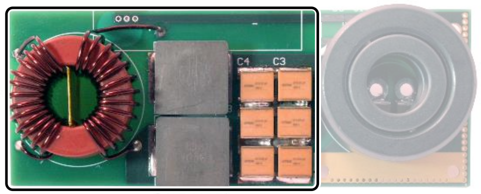
- *EMI-Filter Design for Unshielded Cables > 2m and Resid. Applications (Cond. & Rad.)*

Conducted EMI-Filter

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



C_{f2} (on the back)



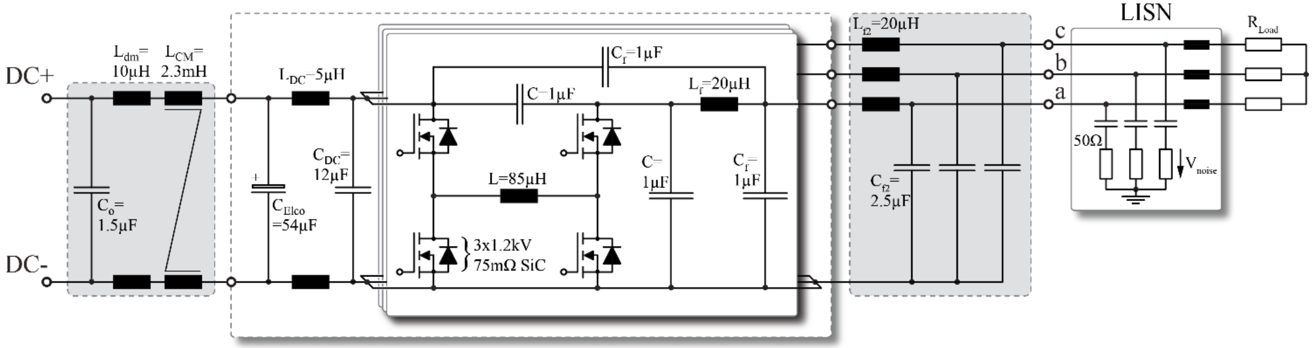
L_{CM} L_{DM} $C_{DM} = C_0$

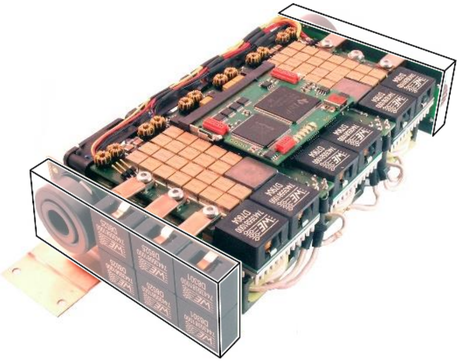
L_{f2}

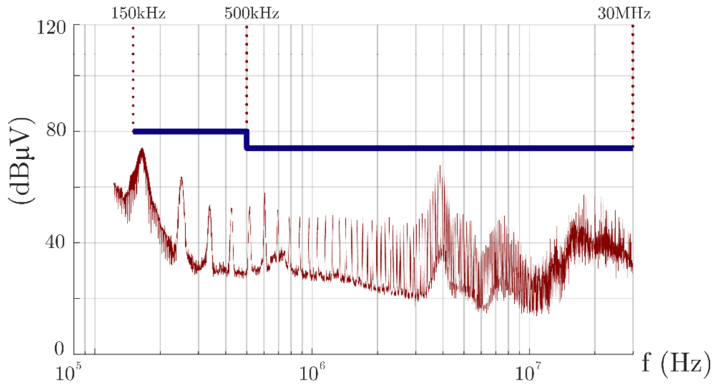
→ *Low Add. EMI Filter Volume — 74cm³ for Each Filter (incl. Toroid. Rad. EMI Filter)*
→ *Total Power Density Reduces — 15kW/dm³ (740cm³) → 12kW/dm³ (890cm³)*

Conducted EMI - Experimental Results

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



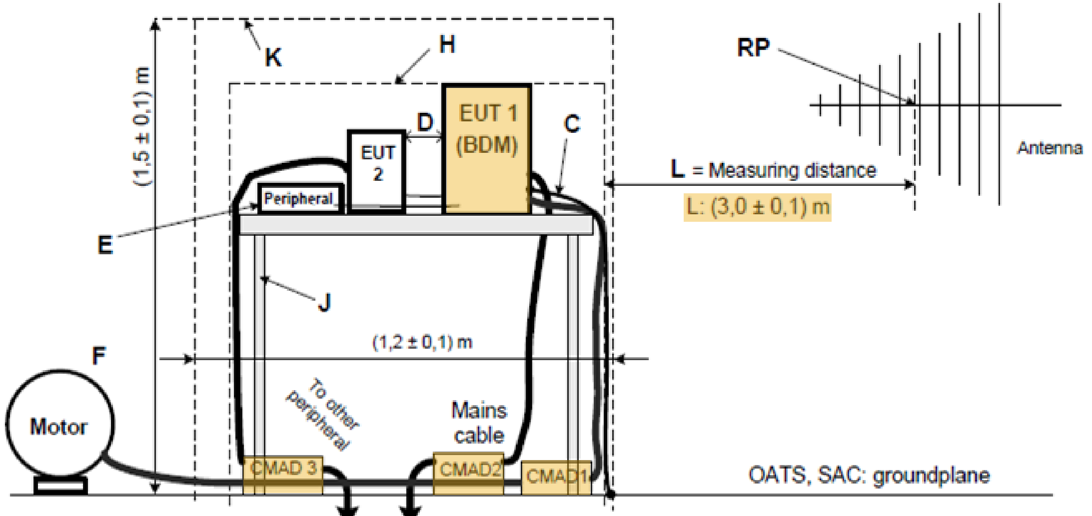




→ *Small 80uH CM-Ind. Added on AC-Side - (3cm³ of Add. Volume = 0.5% of Converter Vol.)*
→ *Conducted EMI with Unshielded Motor Cable Fulfilled*

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



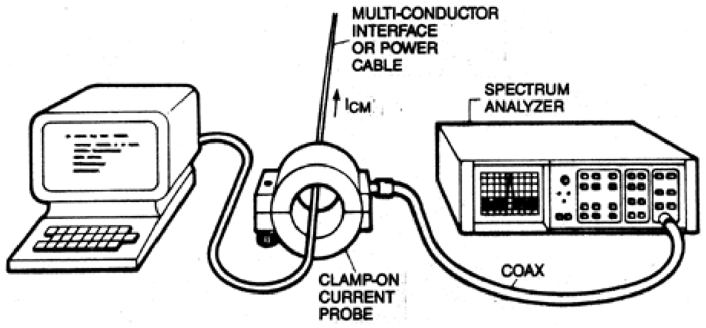
[IEC 61800-3]

[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)

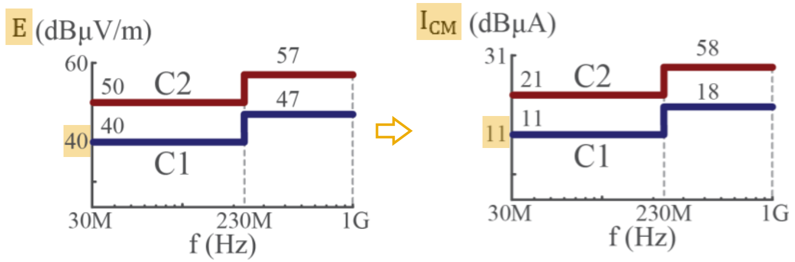
- CM-Currents NOT Returning IN THE CABLE are Dominant Source of Radiation
- Relation Between Radiated Electric Field and CM-Currents (!)



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

[Electromagnetic Compatibility Engineering, H. Ott]

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

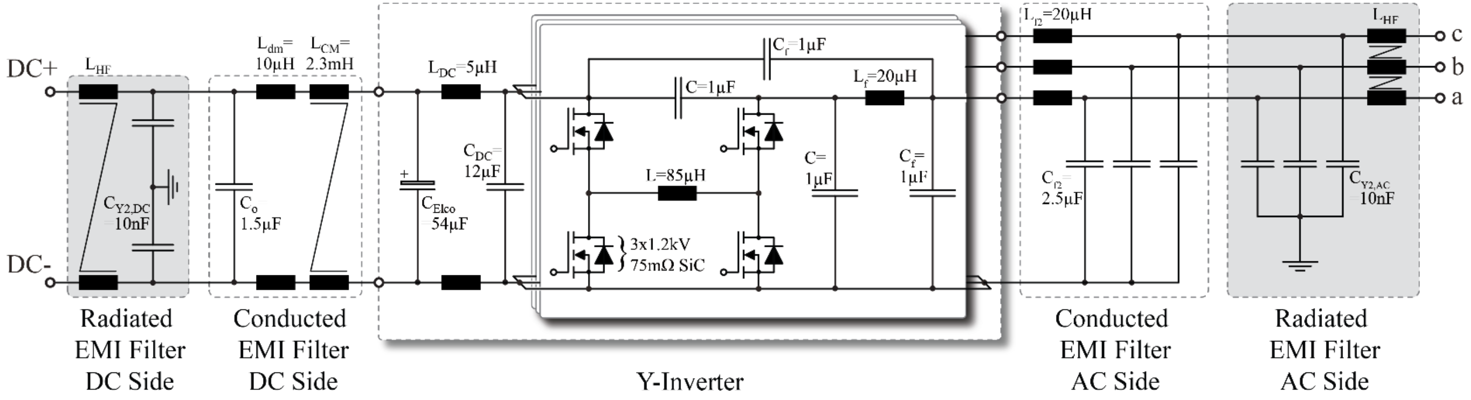


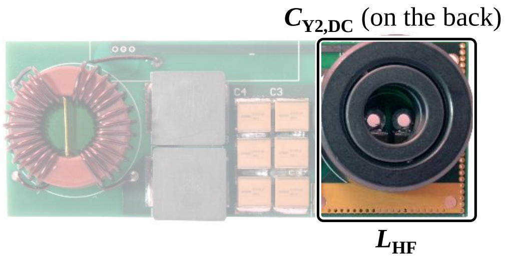
C1: Residential (CISPR Class B)
C2: Industrial (CISPR Class A)

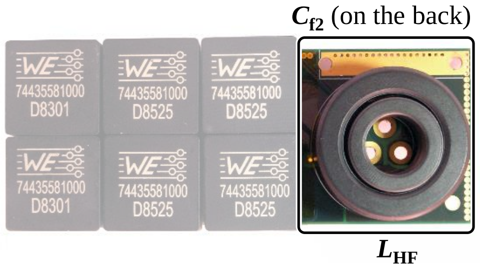
- *Max. Allow. El. Field Strength of 40dBuV/m → Max. CM-Current of 3.5uA (11dBuA)*
- *Current Probe Impedance of 6.3Ω (F-33-1) → Max. Noise Volt. of 26dBuV @ Test Receiver*

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



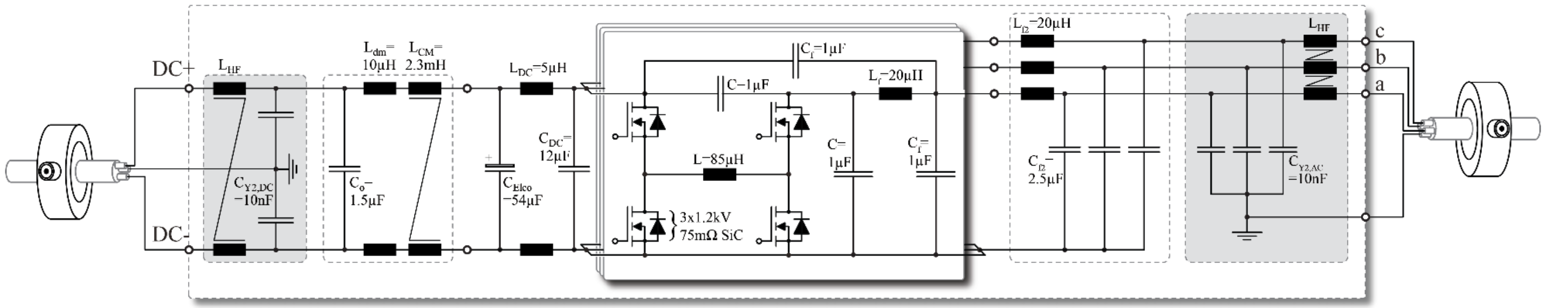


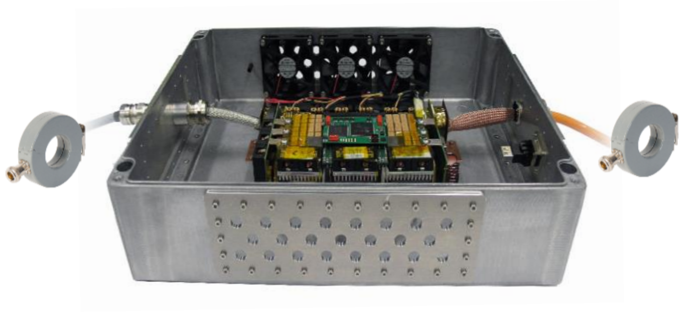


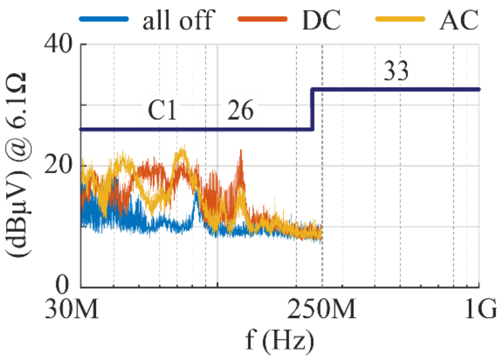
→ *Additional EMI Filter Volume Already Considered with Conducted EMI Filter*
→ *Total Power Density Slightly Reduces — 15kW/dm³ → 12kW/dm³*

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*

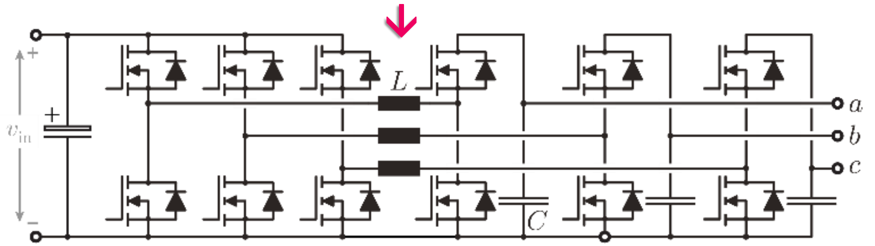
#4

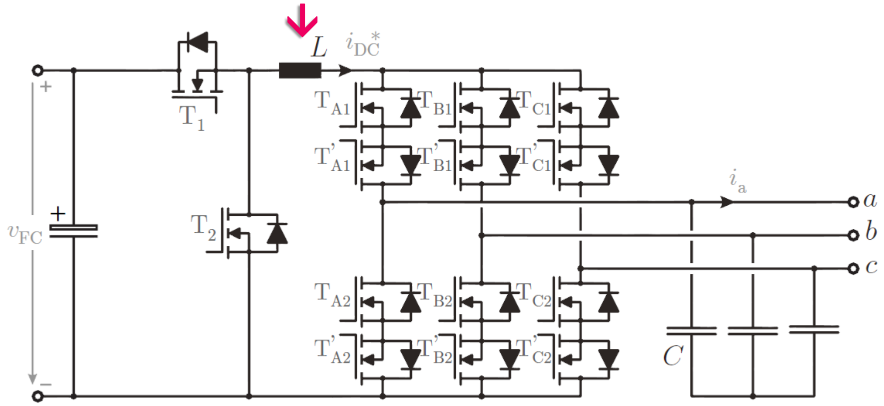
Source: www.clipart-library.com

I-DC-Link Inverters & Monolithic GaN AC-Switches

3-Φ Current Source Inverter (CSI) Topologies

- *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*

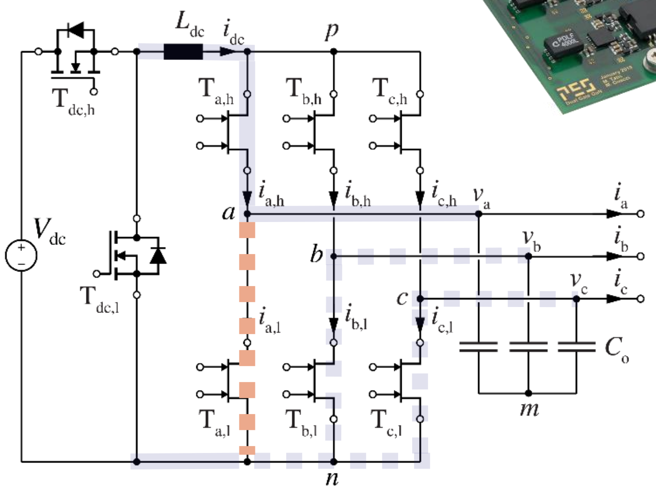


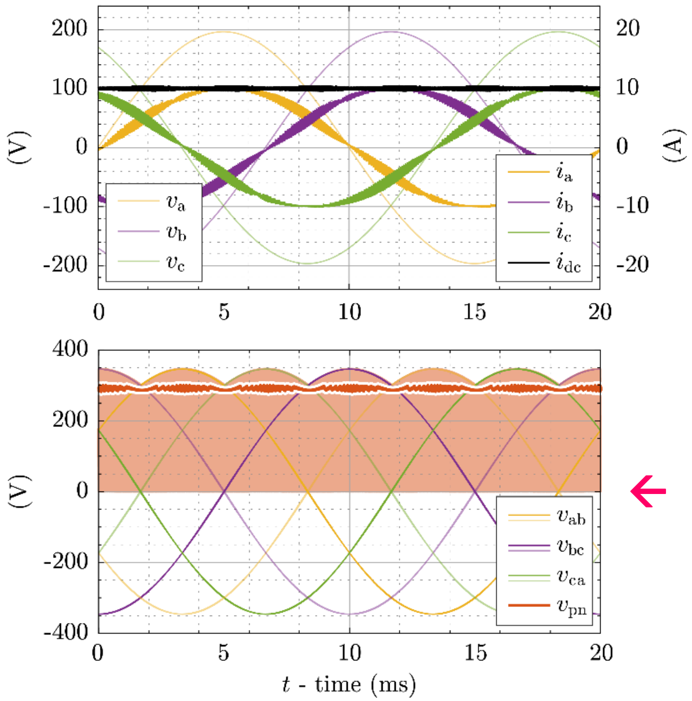


→ *Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches*

3-Φ Buck-Boost CSI (1)

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

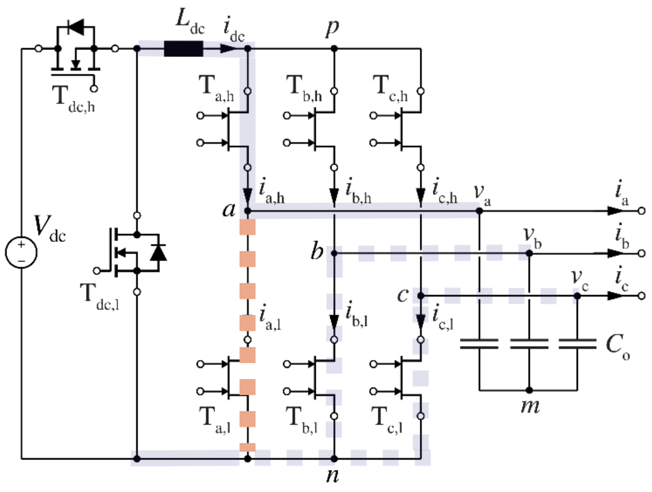


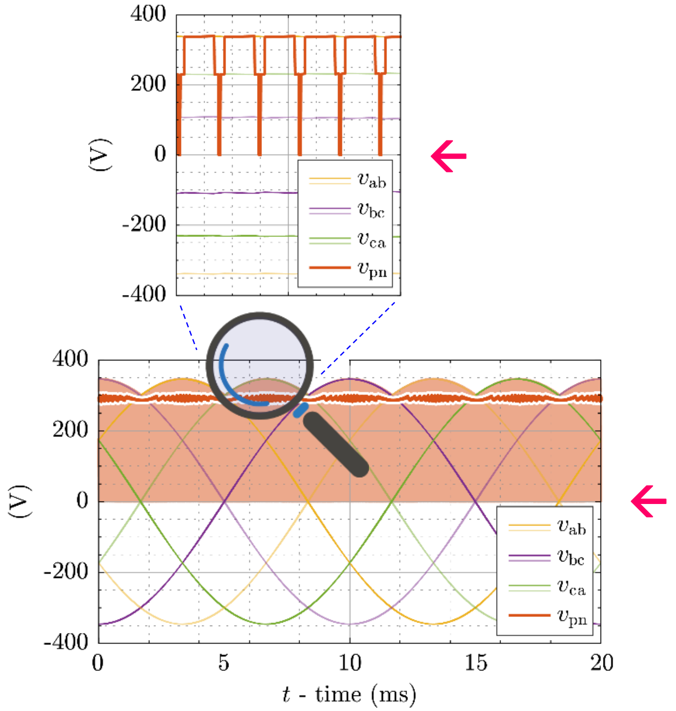


- *Conventional Control of Inverter Stage → Switching of All 3 Phase Legs (3/3)*

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

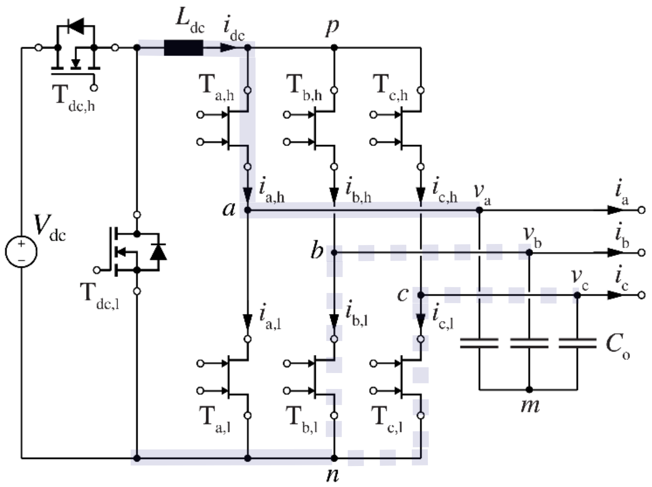


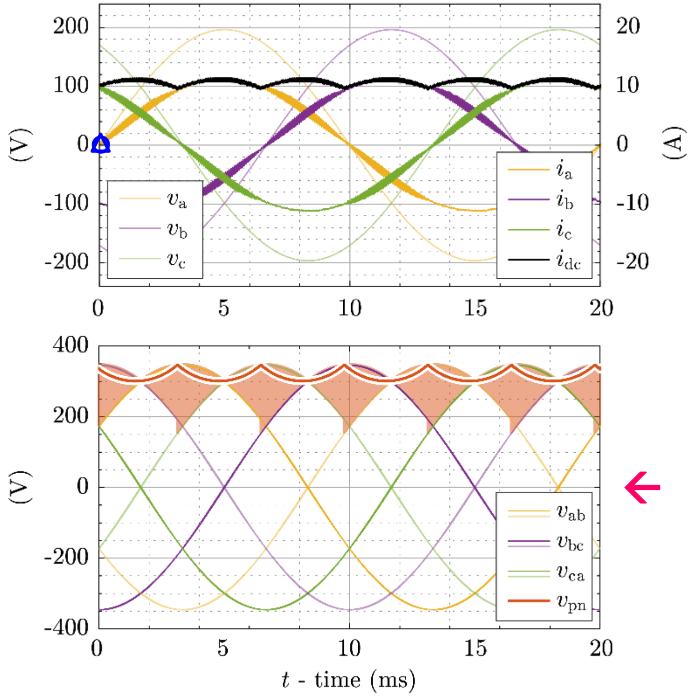


- Conventional Control of Inverter Stage → Rel. High CSI-Stage Sw. Losses

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

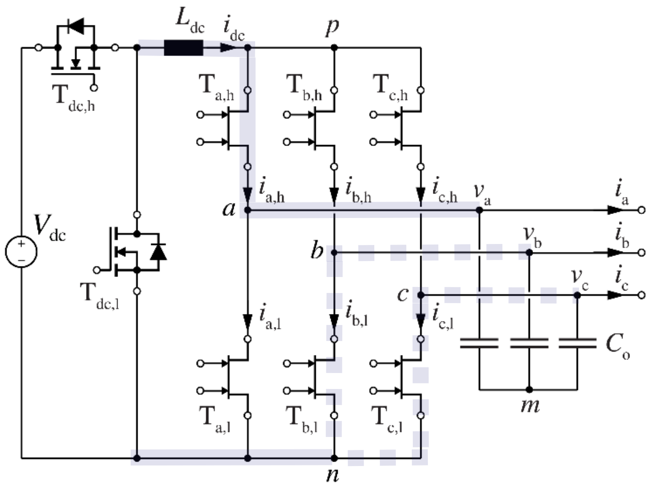


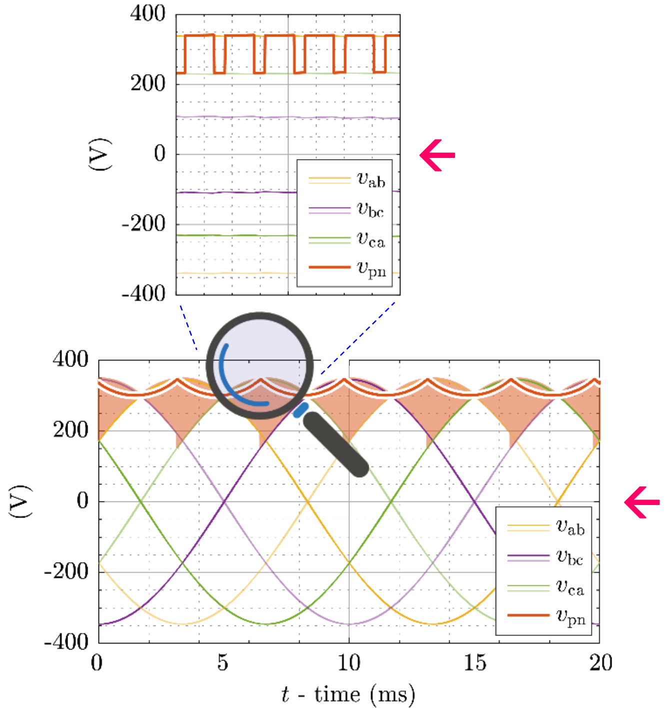


- Switching of Only 2 of 3 Phase Legs → Significant Reduction of Sw. Losses

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

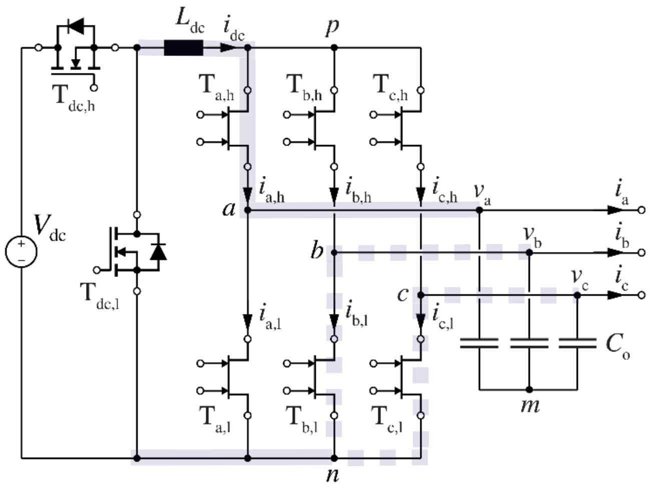


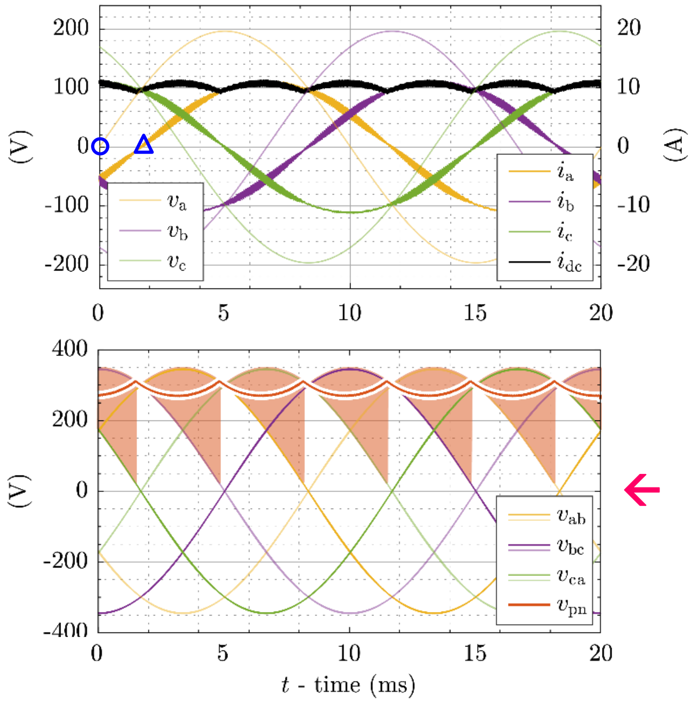


- Switching of Only 2 of 3 Phase Legs → Significant Red. of Sw. Losses (≈ -86% for R-Load)

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

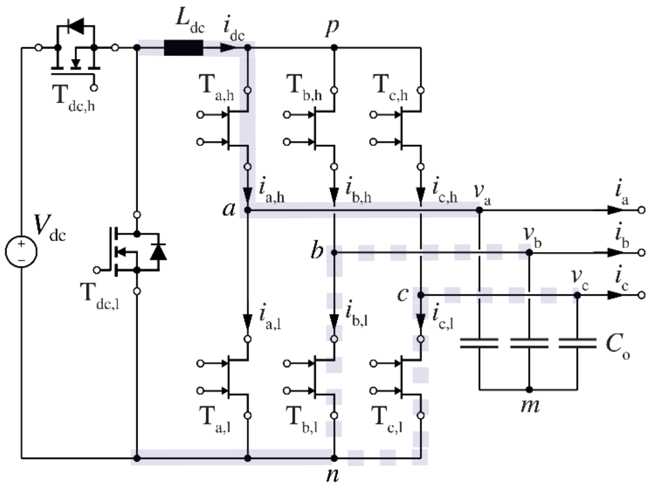


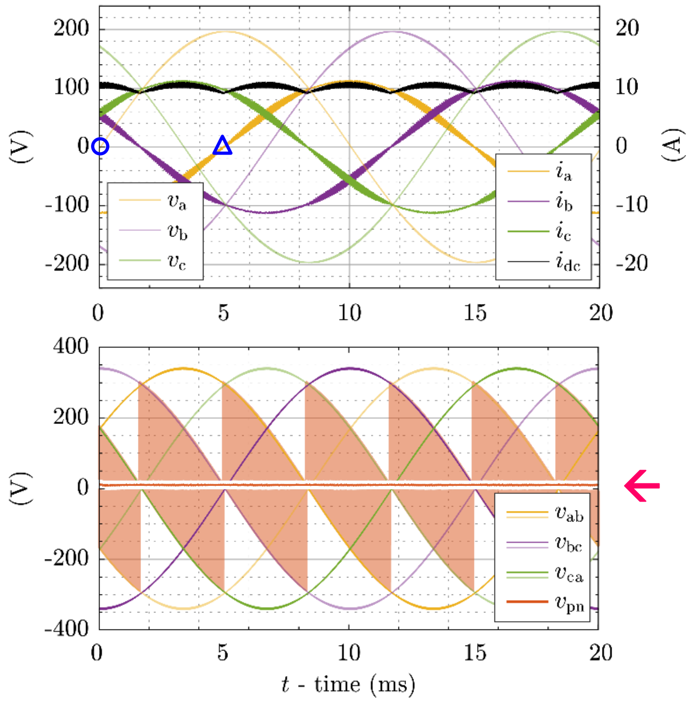


- Operation for 30° Phase Shift of AC-Side Voltage & Current

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

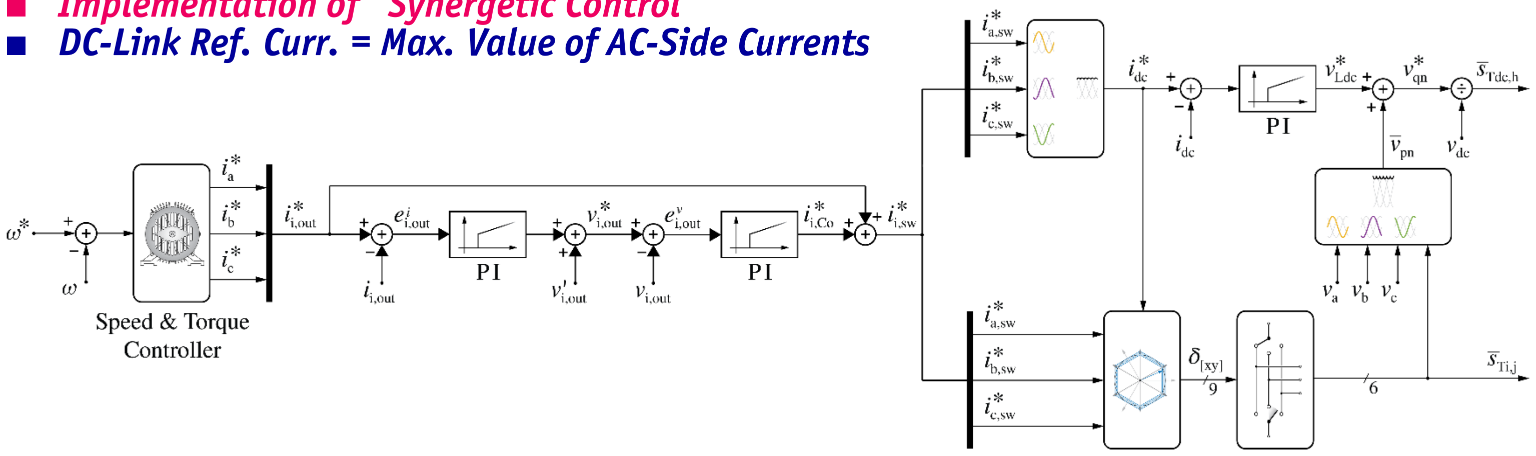




- Operation for 90° Phase Shift (±90° — Limit Case for Buck-Stage Current Control)

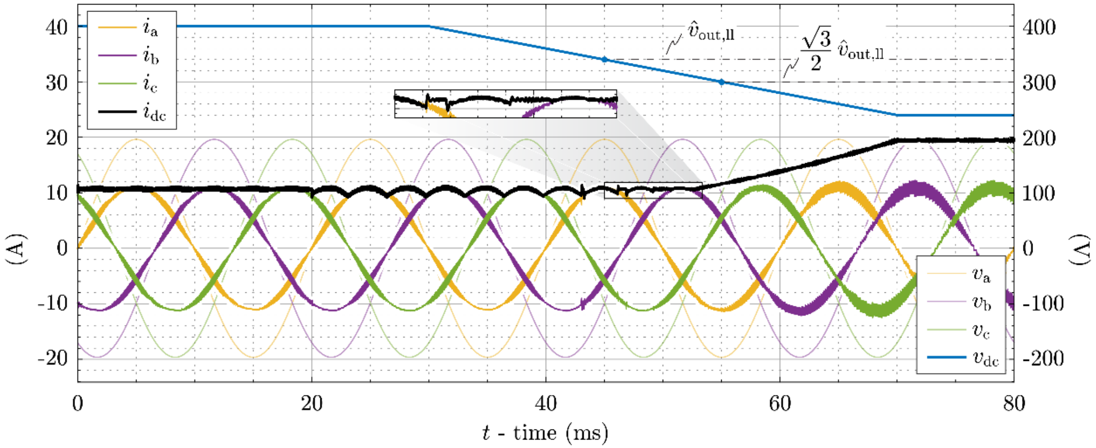
3-Φ Buck-Boost CSI (7)

- *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

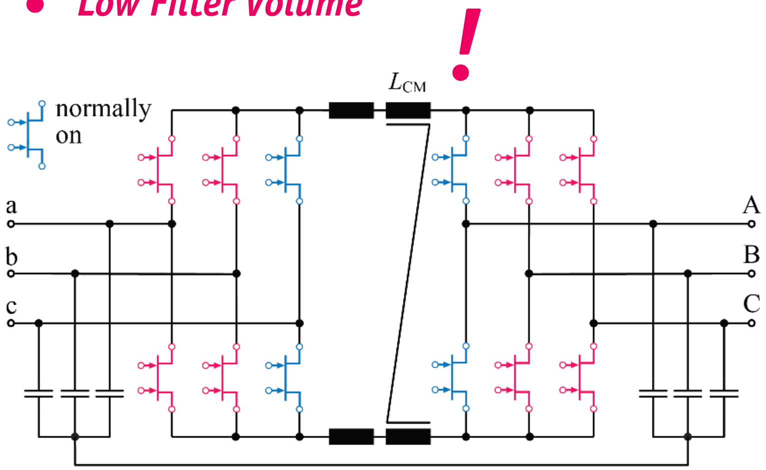
- *Seamless Transition from Buck to Boost Operation*



3-Φ AC/AC Converter Topologies

■ Current DC-Link Topology

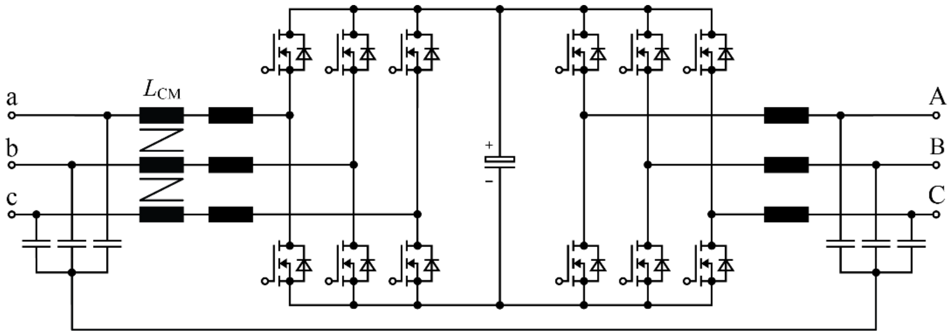
- Application of M-BDSs
- Complex 4-Step Commutation
- Advantageous Over Matrix Converters
- Low Filter Volume



- Challenging Overvoltage Protection
- Limited Control Dynamics

■ Voltage DC-Link Topology

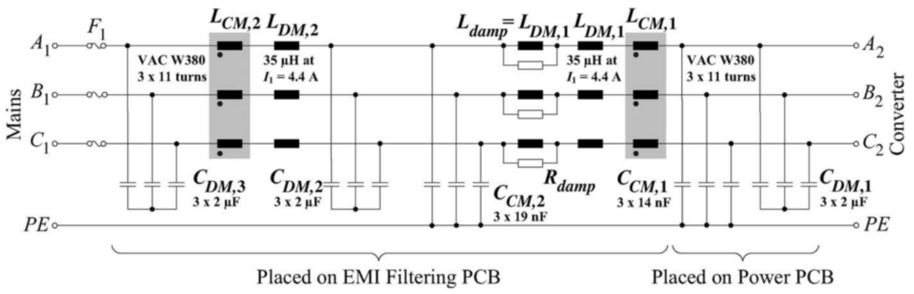
- Standard Bridge-Legs
- Low-Complexity Commutation
- Defined Semiconductor Voltage Stress
- Facilitates DC-Link Energy Storage

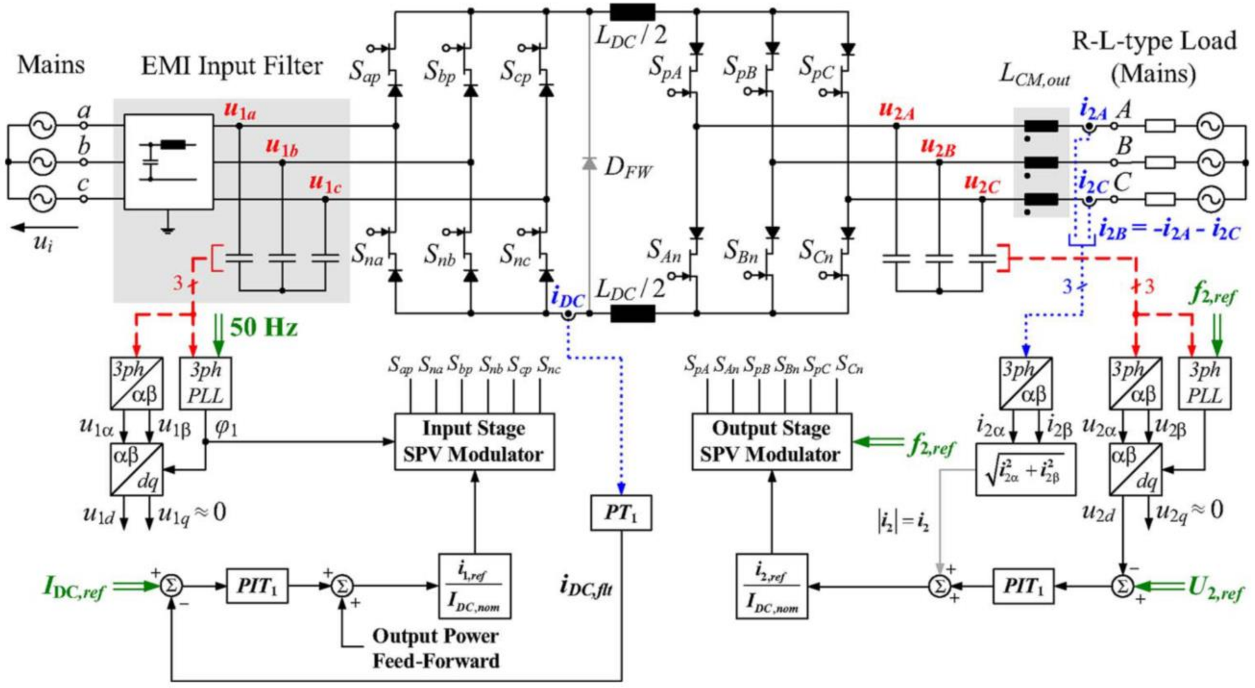


- High Input / Output Filter Volume

200kHz SiC Current DC-Link AC/AC Converter

- Normally-On TO220 1200V/6A SiC J-FETs — Built in 2008 (!)
- 1200V/10A SiC Schottky Series Diodes
- X7R Ceramic Filter Capacitors



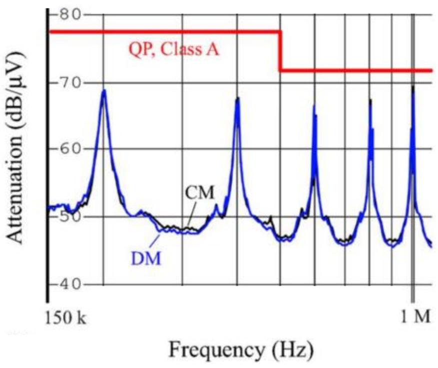


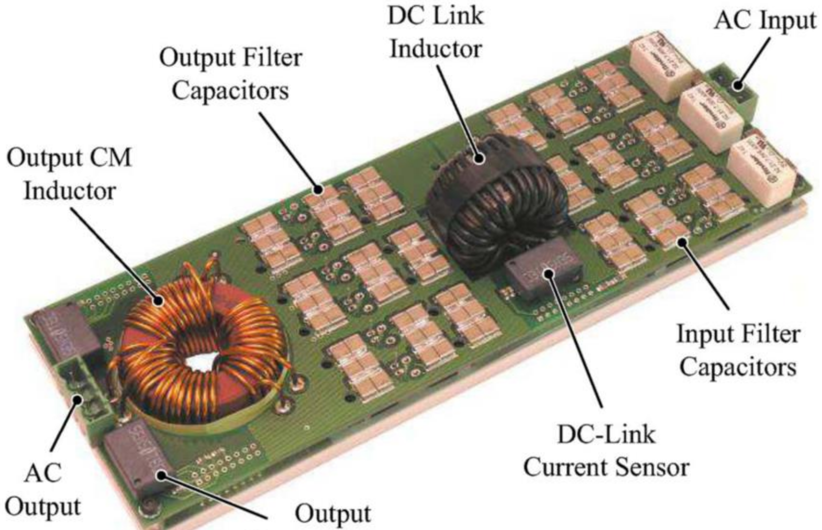
- Natural Free-Wheeling Current Path for Gate Driver Supply Loss

200kHz SiC Current DC-Link AC/AC Converter

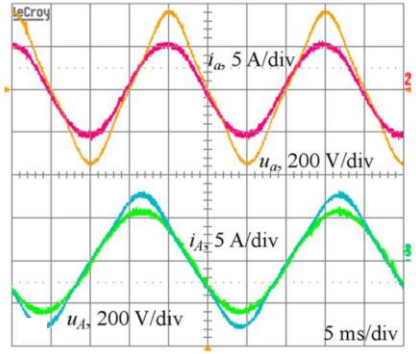
- *7kHz DC-Link Current Control Bandwidth*
- *PCB-Stack Construction — Power | Gate-Drive | Control Board*
- *Coldplate Cooling*

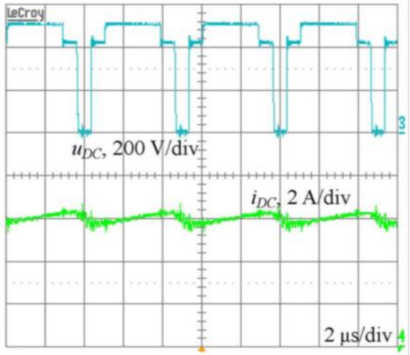
Input	400V_{rms} Line-to-Line
Output	0...300Hz
Rated Power	2.5 kVA
2.4 kVA / dm^3	
(40 W/in^3)	





230 x 80 x 65 mm^3

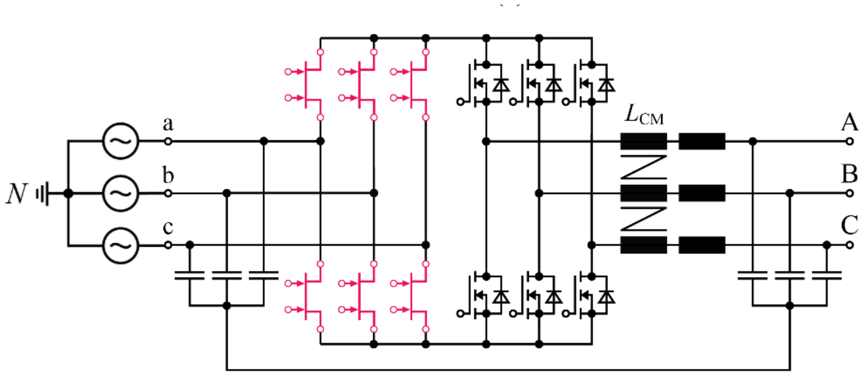




- *Low Volume Toroidal Powder Core DC-Link Inductor (320uH)*

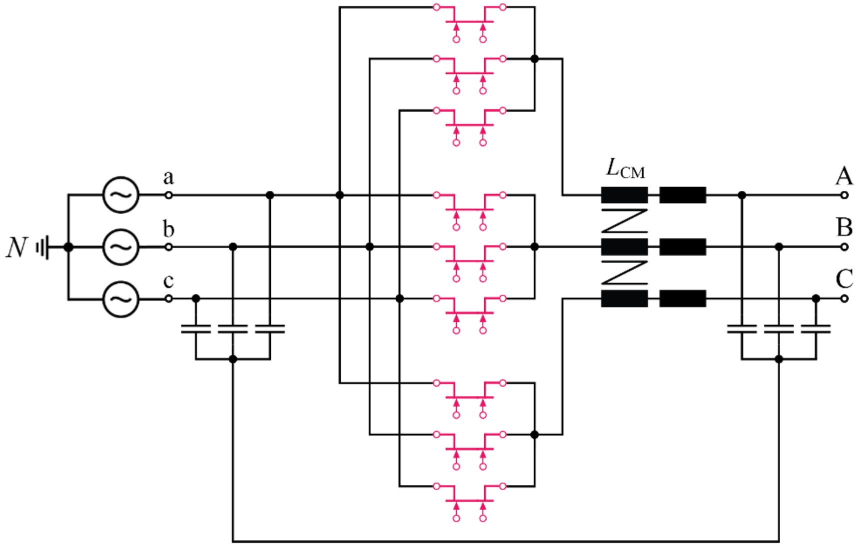
Remark 3-Φ AC/AC Matrix Converter

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



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

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



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

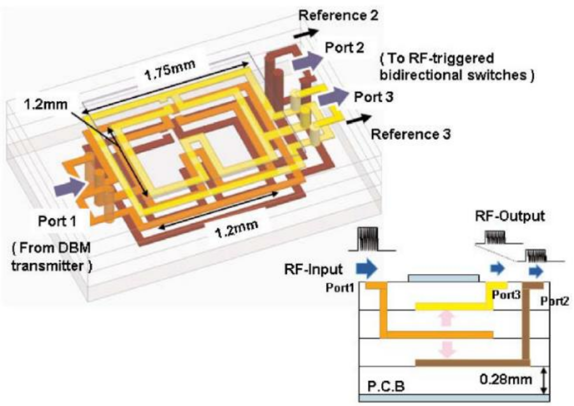
Monolithic 3D-Integration

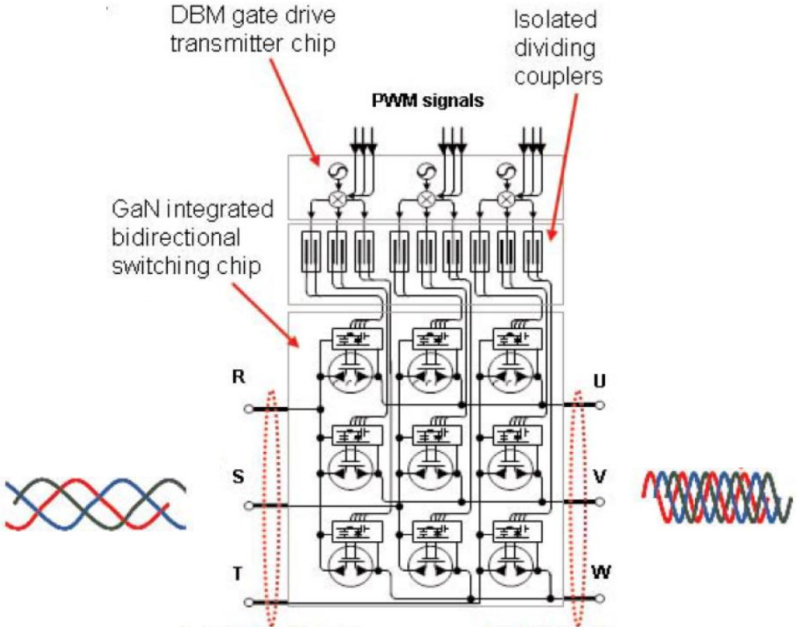
Source: Panasonic ISSCC 2014

- GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology

– 9 Dual-Gate GaN AC-Switches
– DBM Gate Drive Transmitter Chip & Isolating Couplers
– Ultra Compact → 25 x 18 mm² (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler





Conclusion

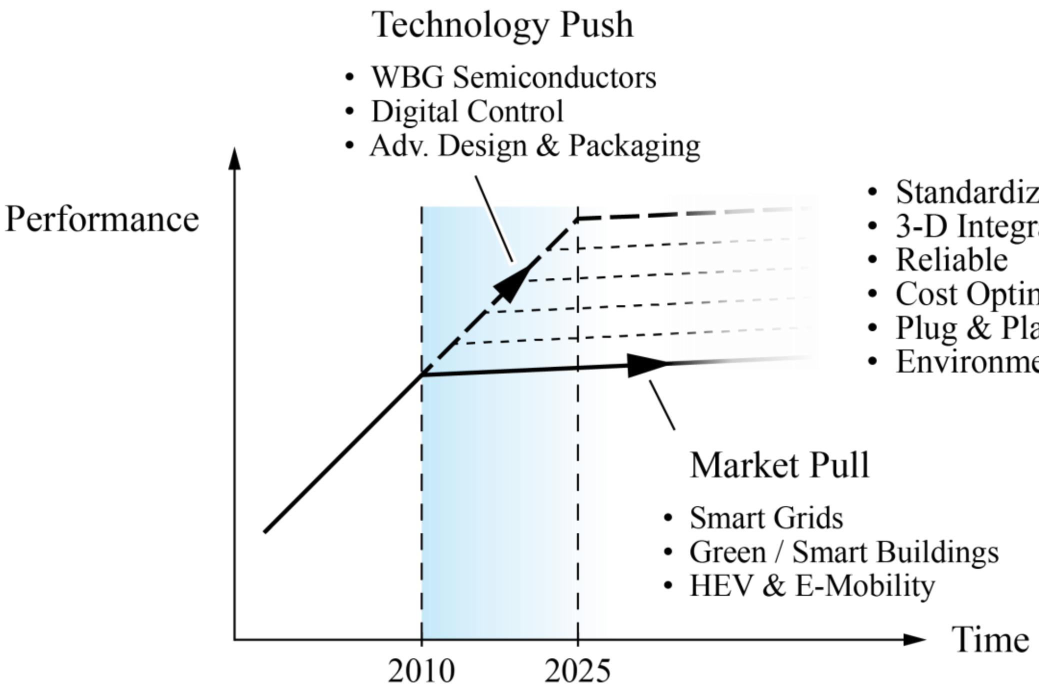
— *Low On-Resistance & High Sw. Speed SiC / GaN*
— *Monolithic Bidirectional GaN*
— *Integration of Switch / Gate Drive / Sensing / Monitoring*
— *3D-Packaging / PCB Integration / Adv. Cooling*

Summary

— *S-TCM Full ZVS Inverters*
— *Multi-Level/Cell Inverter Topologies*
— *Buck-Boost Inverter w/ Integrated Output Filter*
— *Inverter Motor Integration*
— *System Level / Distrib. DC Bus, Integr. of Storage*
— *Power Electronics 4.0*

Future Development

- Commoditization / Standardization
- Converters → Systems / Power → Energy
- Extreme Cost Pressure (!)



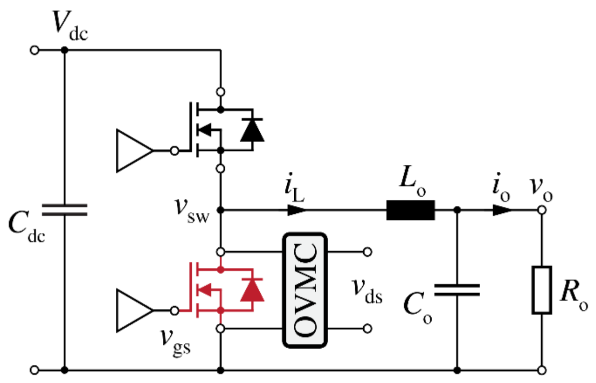
- Key Importance of Technology Partnerships of Academia & Industry

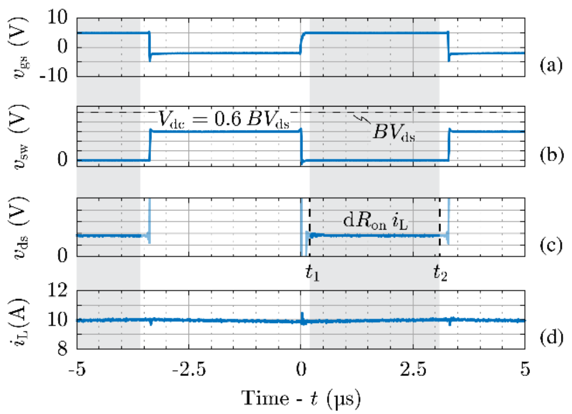
Appendix A

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

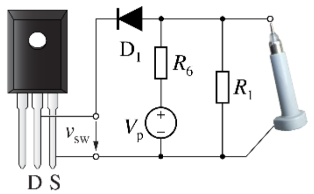
On-State Voltage Measurement (1)

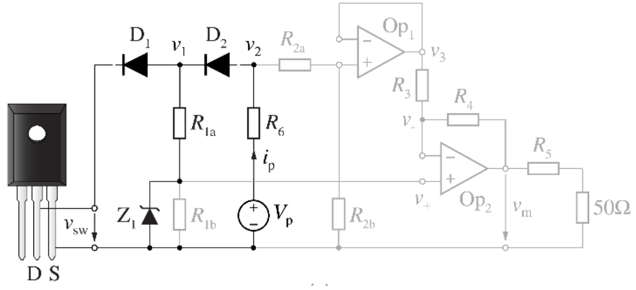
- *Device / Load Current / Gate Voltage / Junction Temp. → On State-Resistance $R_{DS(on)}$*





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

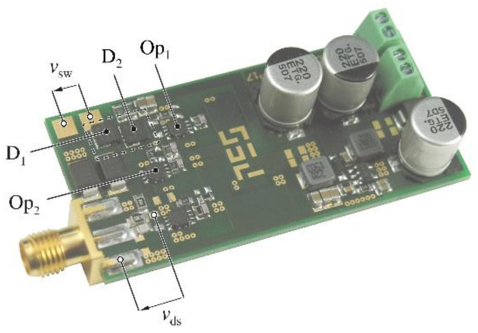


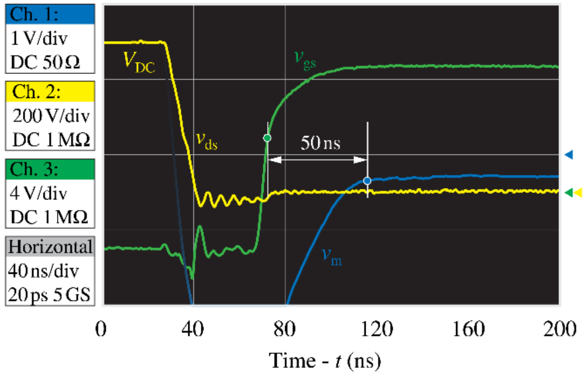


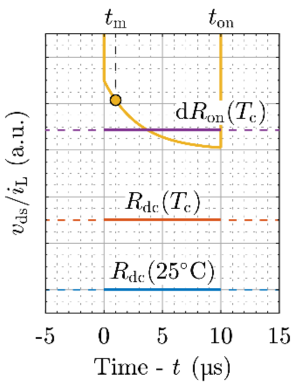
- *Decoupling High Blocking Voltage and (Very) Low On-State Voltage (≈1V << BV_{DS})*

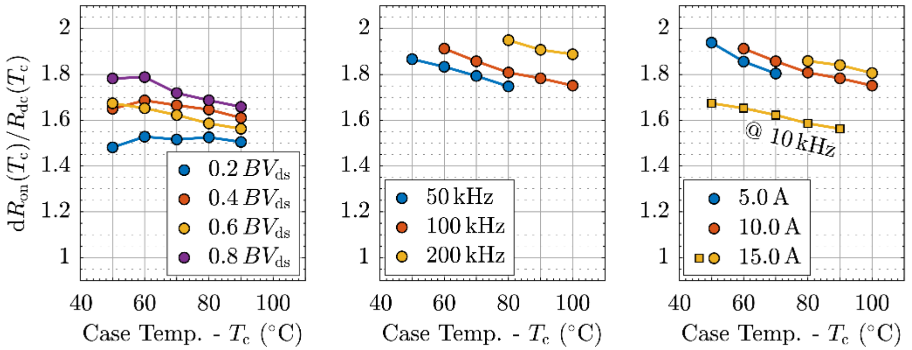
On-State Voltage Measurement (2)

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





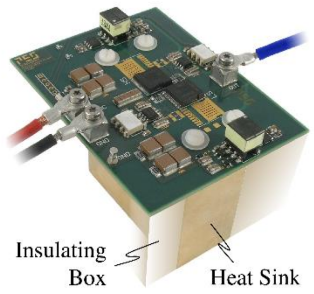


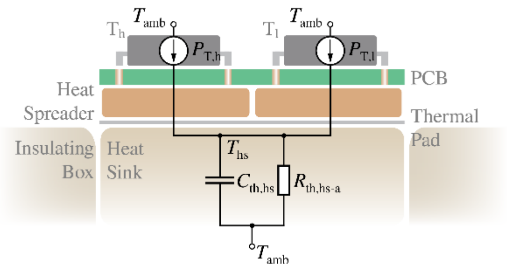


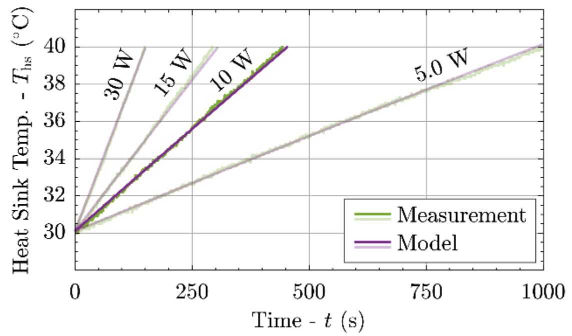
- *Example — Dyn. $R_{DS(on)}$ of GaN HEMTs → 2x $R_{DS(on)}$ @ 100kHz - 0.6BV_{DS}*

Switching Loss Measurement

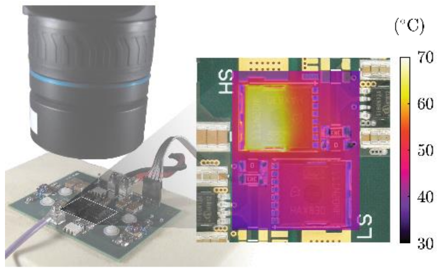
- *Heat-Sink Temp.-Based Transient Calorim. Method → 15 min / Measurement*

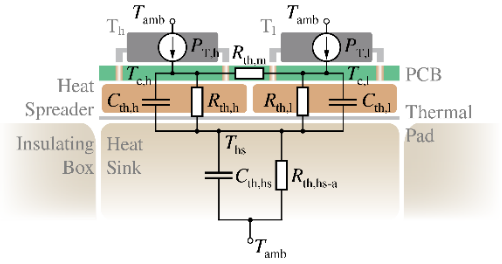


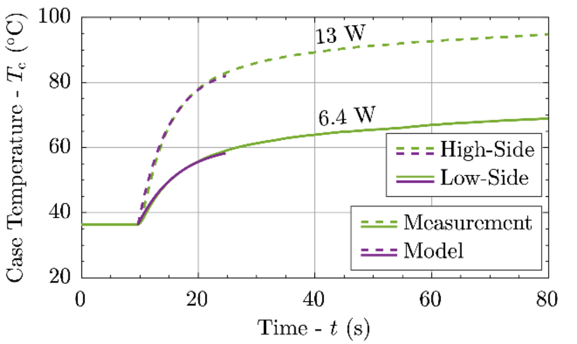




- *Case Temp.-Based Ultra-Fast Method → 15 sec / Measurement*

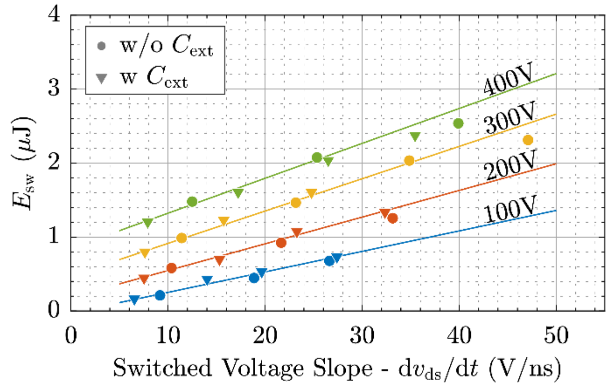


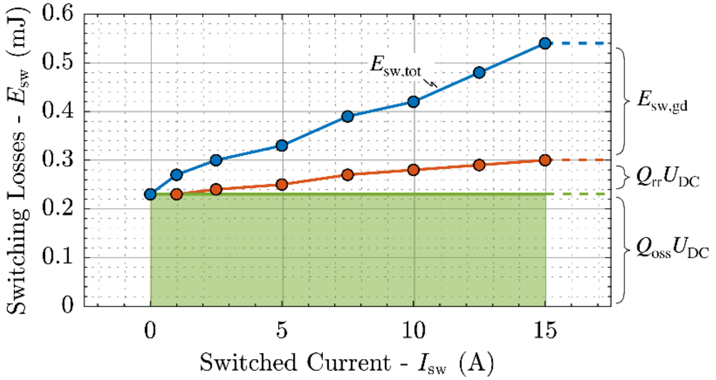




Example Measurement Results

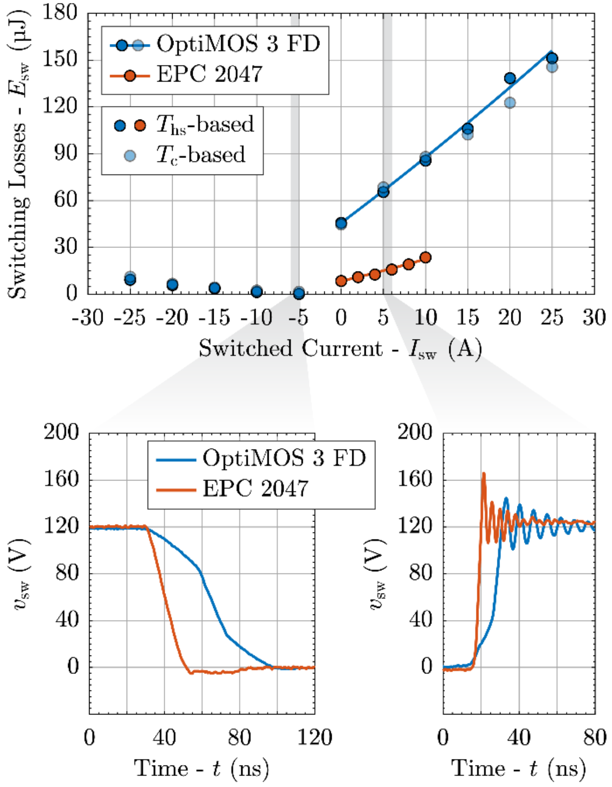
- *650V GaN (ZVS)*





- *1.2kV SiC (Hard-Sw.)*

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

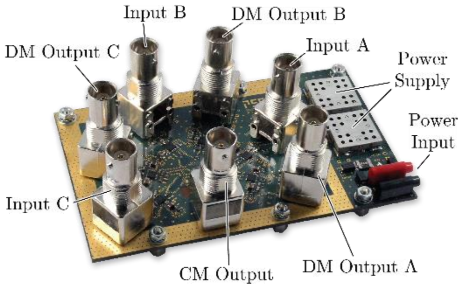


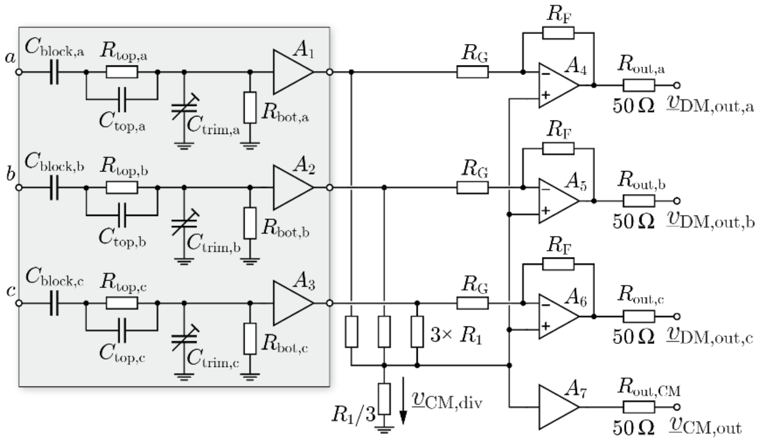
Appendix B

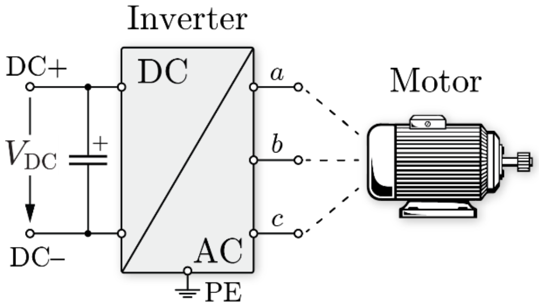
CM/DM EMI Separation

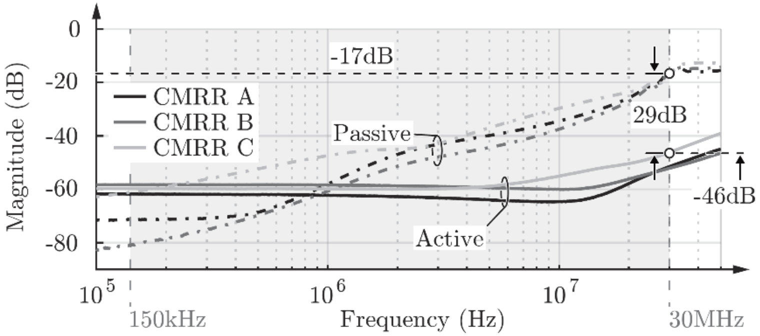
► 3-Φ DM/CM EMI Measurement & Separation

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









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

Power Electronic Systems
Laboratory

Power Electronics 4.0
Cognitive Power Electronic Converters

A Few Spotlights

ETH zürich

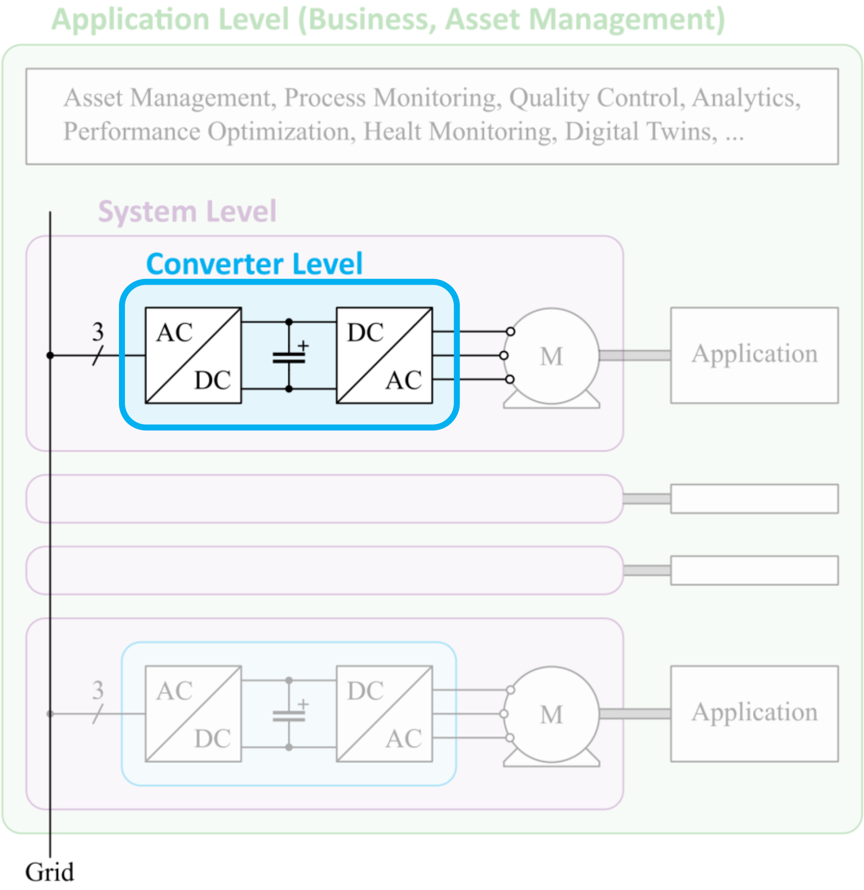
Cognitive Power Electronics: Converter Level

Key Question

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

Converter Level

- Design
- Control / Operation
- Maintenance

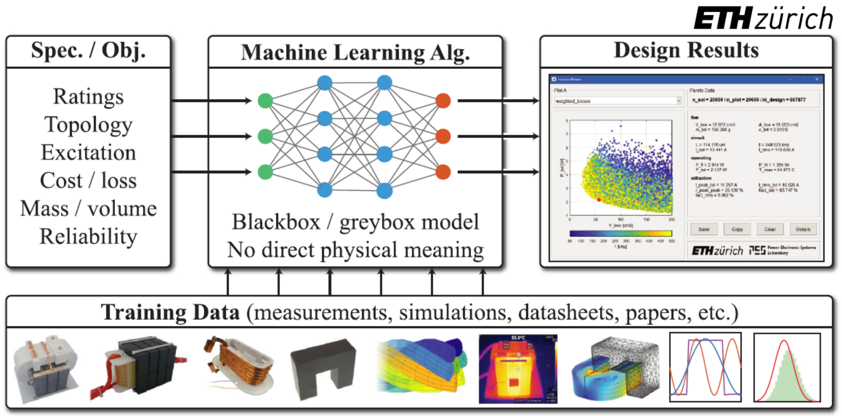


ML Applications in Power Electronics Life Cycle (Examples)

Design | Control | Maintenance

Inductor Modeling

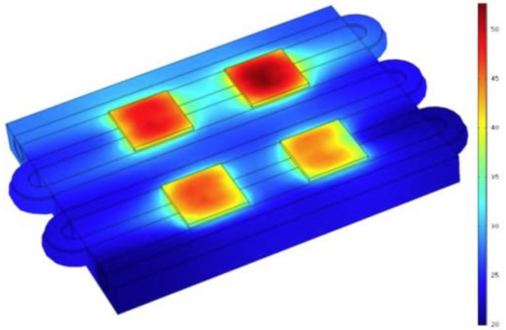
- Design **speedup** (50’000 designs/s) by replacing FEM simulations with trained ML model



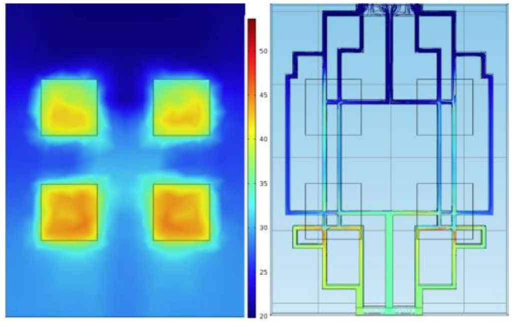
https://ai-mag.github.io/

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.

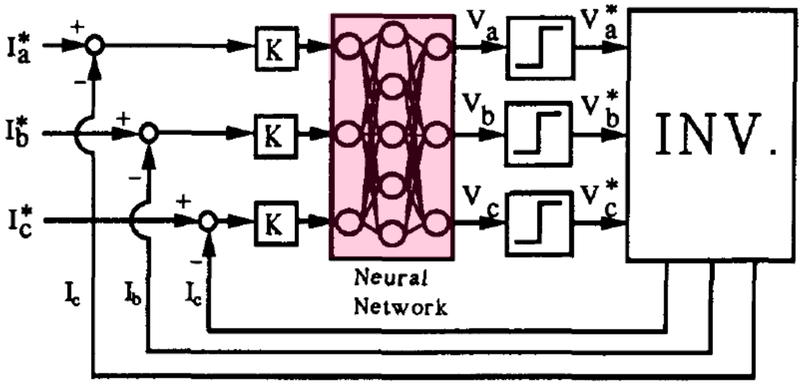
T. Wu, B. Ozpineci, and C. Ayers, “Genetic algorithm design of a 3D printed heat sink,” in *Proc. Appl. Power Electron. Conf. and Expo. (APEC)*, Long Beach, CA, USA, Mar. 2016.

ML Applications in Power Electronics Life Cycle (Examples)

Design → **Control** → Maintenance

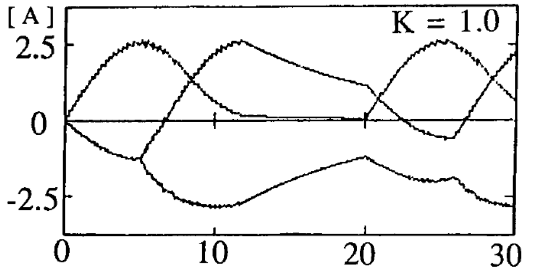
Current Control with Neural Network

- "Neural Comparator" replaces hysteresis comp.



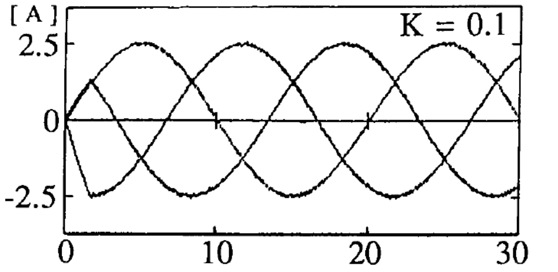
(b) Neural comparator

1989 (!)



(a) Hysteresis comparator

- Hysteresis Comparator



(b) Neural comparator

- Neural Comparator

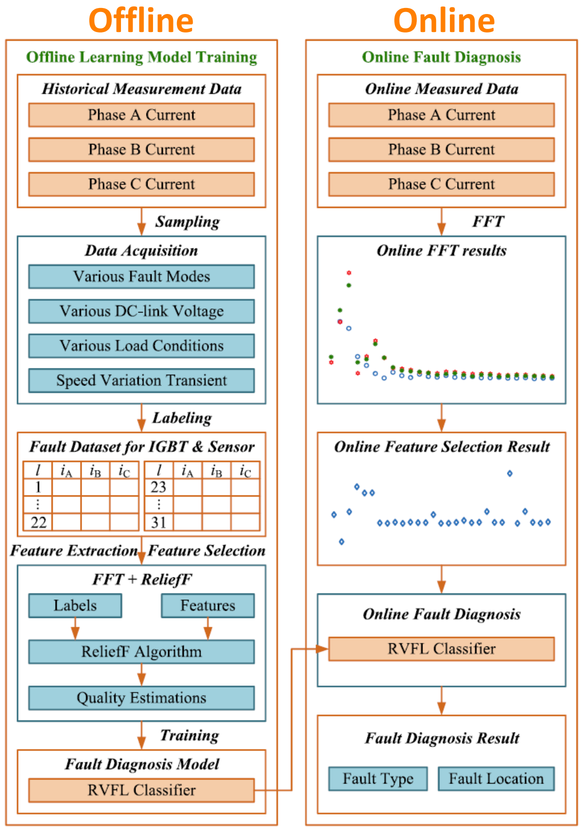
  Better fault tolerance

  (loss of phase c current meas.)

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.

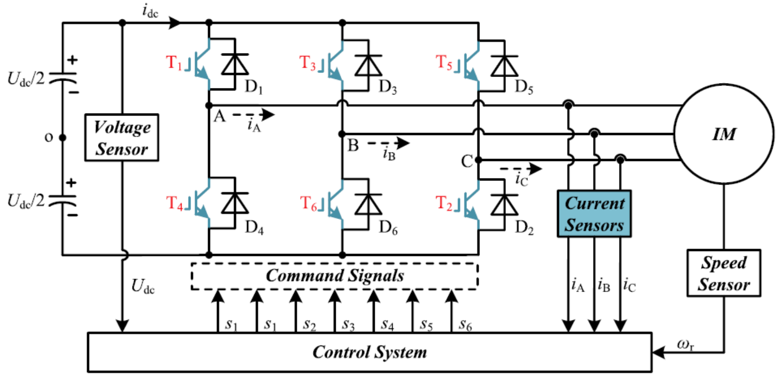
ML Applications in Power Electronics Life Cycle (Examples)

Design → Control → **Maintenance**

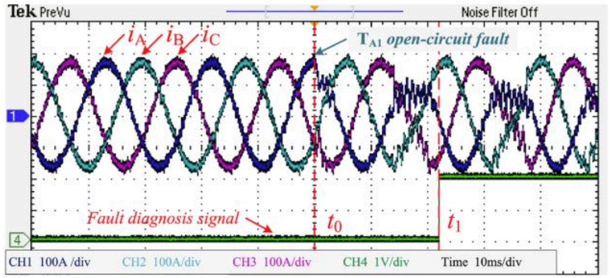


Data-Driven Detection of IGBT and Current Sensor Faults

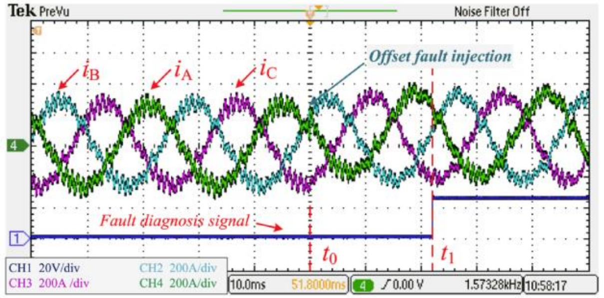
- Inputs: phase current measurements
- Output: fault type and location



IGBT open-circuit fault



Sensor offset fault



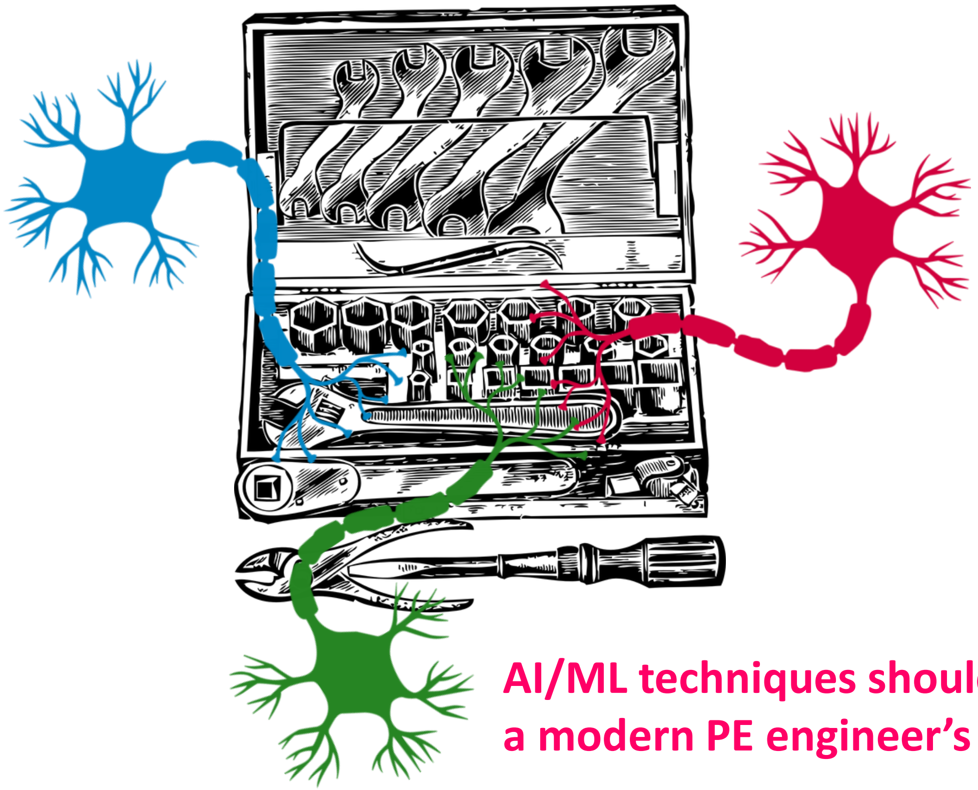
B. Gou, Y. Xu, Y. Xia, Q. Deng, and X. Ge, "An online data-driven method for simultaneous diagnosis of IGBT and current sensor fault of three-phase PWM inverter in induction motor drives," *IEEE Trans. Power Electron.*, vol. 35, no. 12, Dec. 2020.

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



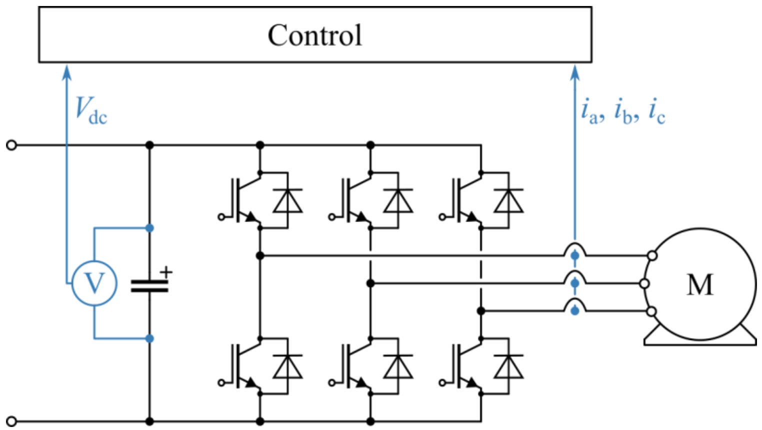
AI/ML techniques should be part of a modern PE engineer's toolbox!

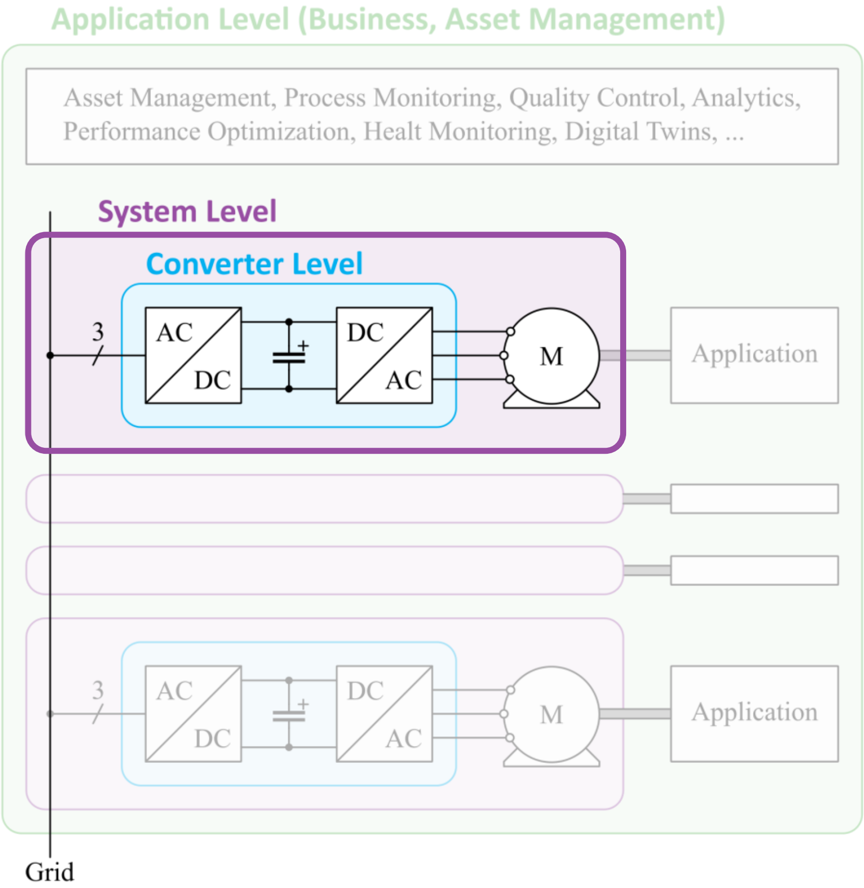
Cognitive Power Electronics: Beyond the Converter

Key Question

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

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



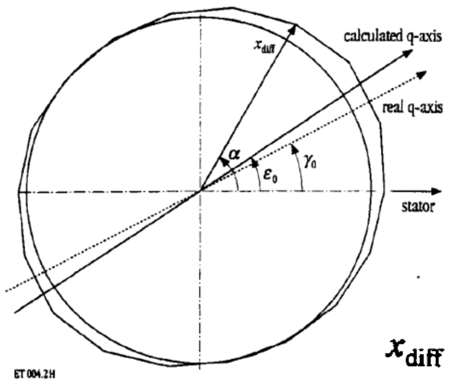


Example: INFORM (Indirect Flux detection by On-line Reactance Measurement)

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

PE 4.0 Concept

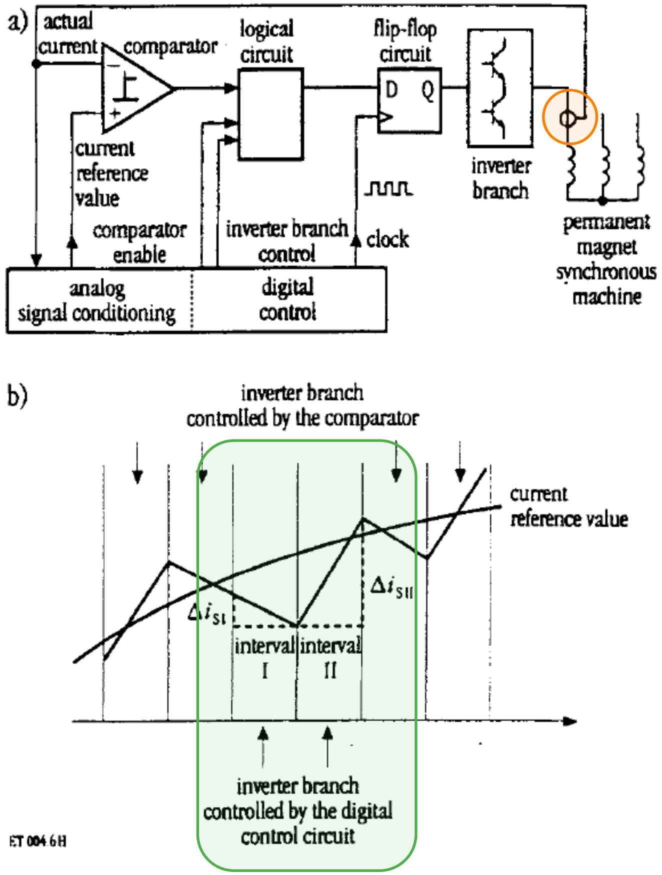
- Utilize already available inverter capabilities
  - Current sensors
  - Test signal injection (minor SW modification)



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

Switching state during test sequence

Phase current measurement



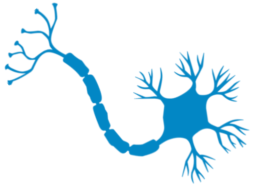
M. Schrödl and T. Stefan, "New rotor position detector for permanent magnet synchronous machines using the „Inform"-method," *Europ. Trans. Electr. Power*, vol. 1, no. 1, pp. 47–53, 1991.

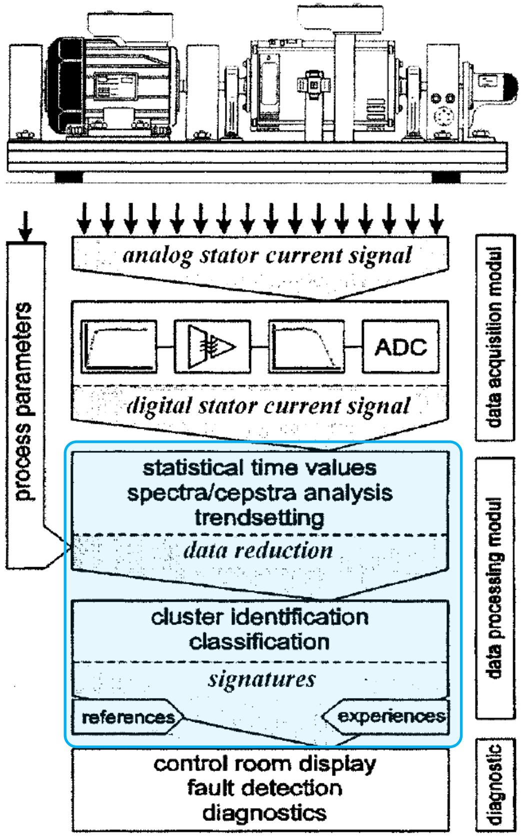
Example: Induction Motor Fault Detection

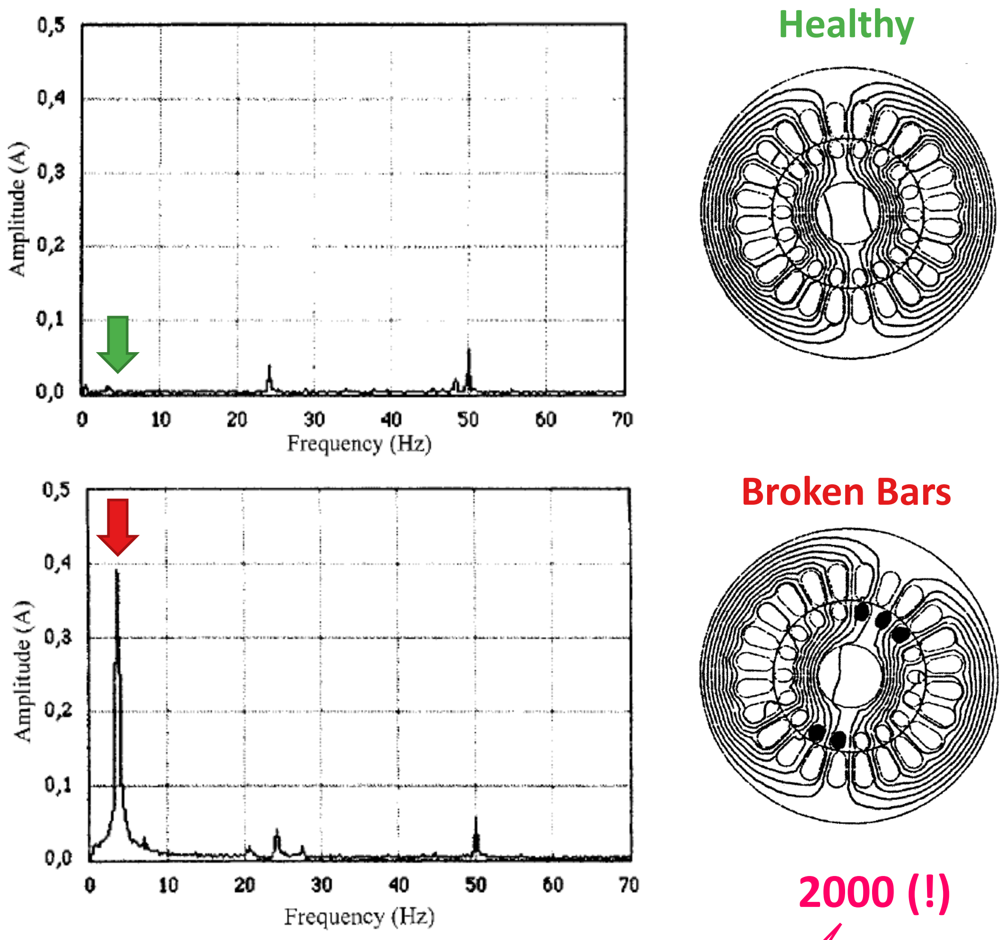
- Fault detection based on stator current monitoring
- Research topic since the 1980ies
- Inverter-as-a-sensor

Today

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







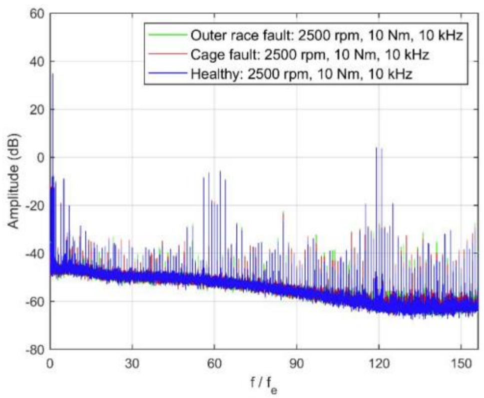
M. E. H. Benbouzid, "A review of induction motors signature analysis as a medium for faults detection," *IEEE Trans. Ind. Electron.*, vol. 47, no. 5, Oct. 2000.

Example: Data-Driven Machine Bearing Damage Detection

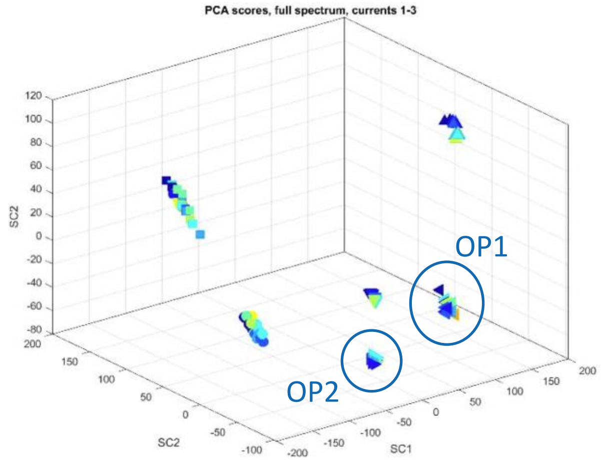
Challenge: Quantity + Quality!

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

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

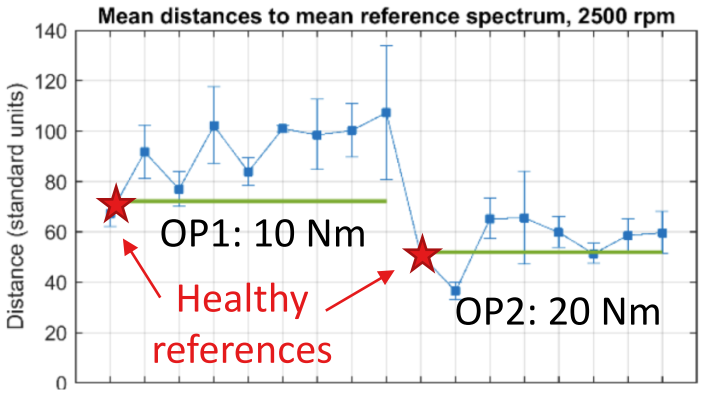


Principal Component Analysis (PCA)



Fraunhofer IISB

Cognitive Power Electronics for Intelligent Drive Technology

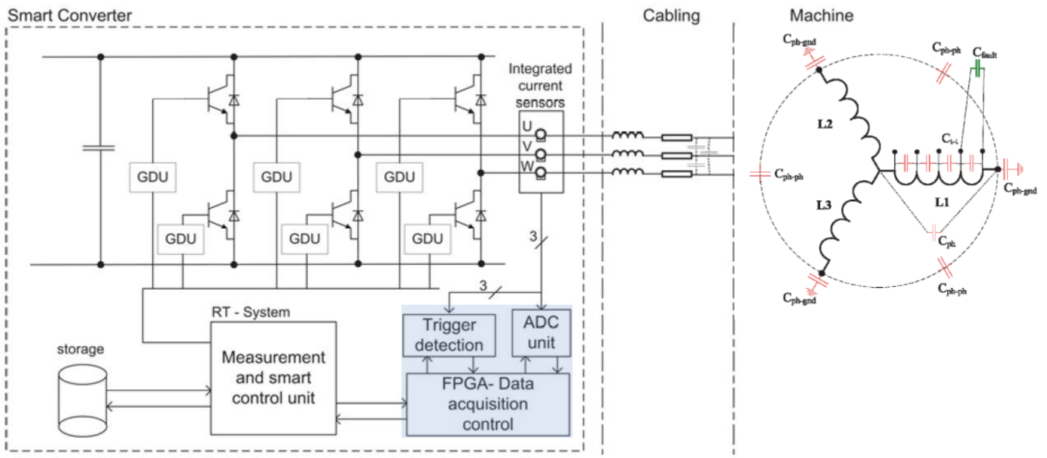


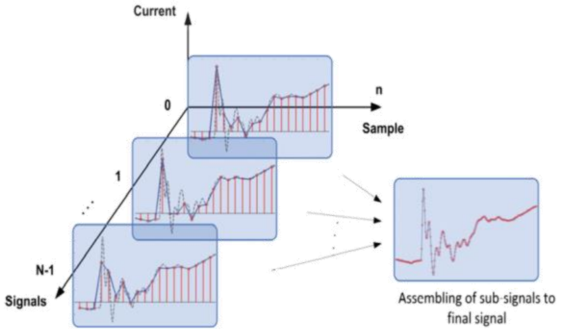
- Fault detection requires referencing to a healthy case for each operating point!
- Ongoing research

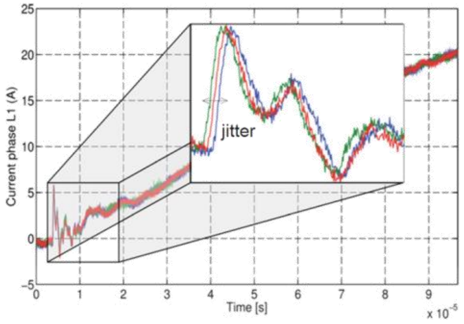
G. Roeder, X. Liu, and M. Hofmann, "Cognitive power electronics for intelligent drive technology," in *Proc. Electr. Drives Production Conf (EDPC)*, Ludwigsburg, Germany, Dec. 2020.

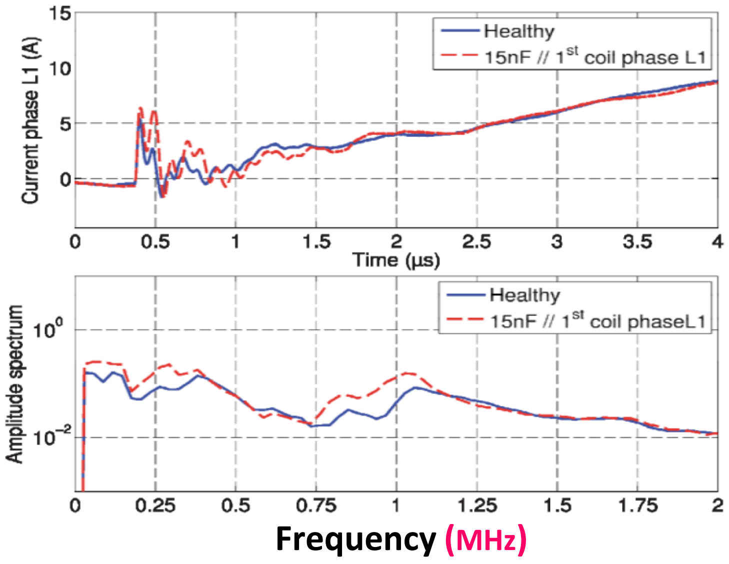
Example: Isolation Health Monitoring for MV Traction Motors

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

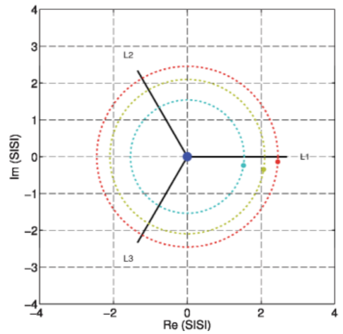








Fault detection incl. location



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?

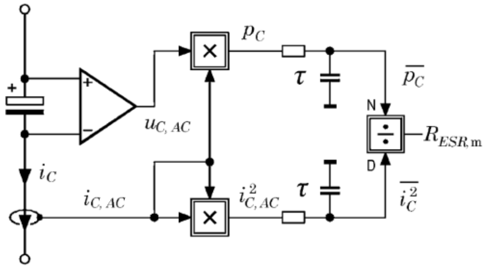
- Data (quality & quantity) is key for successful ML applications

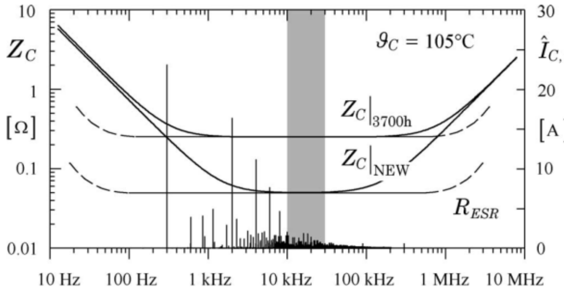
- **Improved Sensors**
  - Higher bandwidth
  - Higher sampling rate
  - Higher resolution

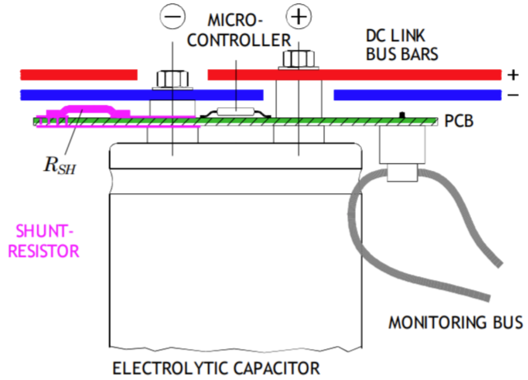
  ⇒ Memory
  Processing power
  Uplink bandwidth

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

Example: Capacitor ESR Meas. for Condition Monitoring







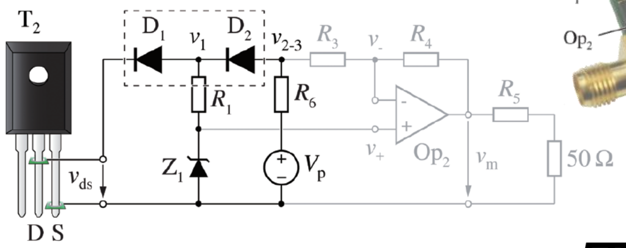
- Measurement of ESR in "frequency window" (temp. comp.)
- Data transfer by opt. fiber or near-field RF link

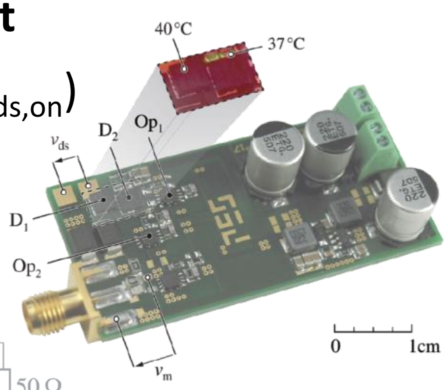
M. A. Vogelsberger, T. Wiesinger, and H. Ertl, "Life-cycle monitoring and voltage-managing unit for DC-link electrolytic capacitors in PWM converters," *IEEE Trans. Power Electron.*, vol. 26, no. 2, Feb. 2011.

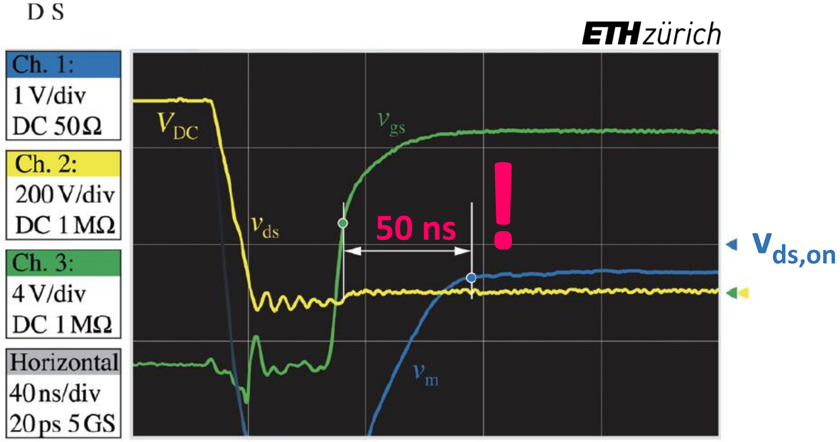
Remark: Sensing Concepts (1)

On-State Voltage Measurement

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

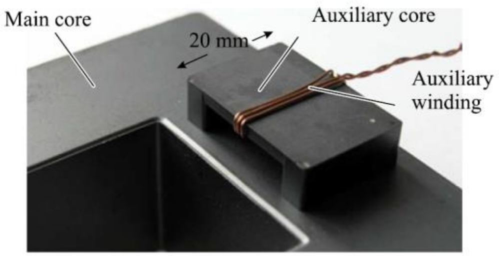


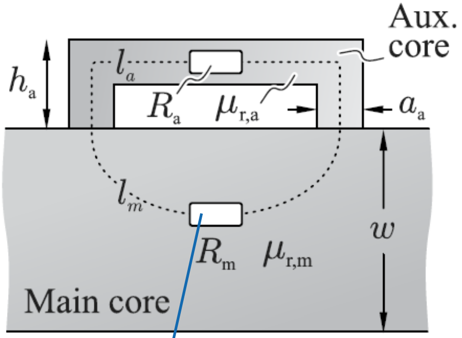


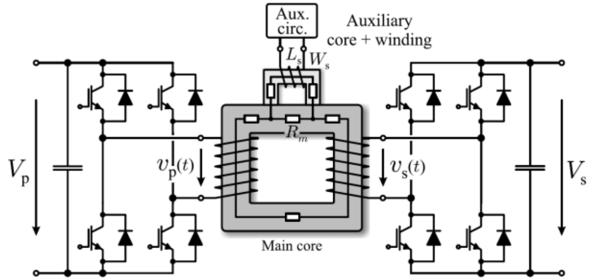


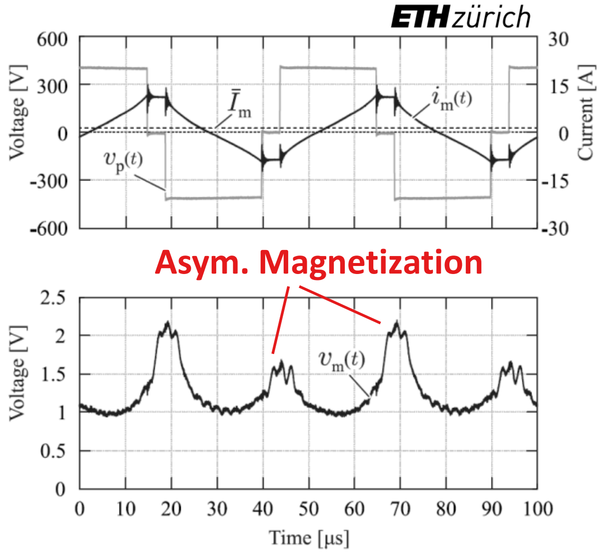
M. Guacci, D. Bortis, and J. W. Kolar, "On-state voltage measurement of fast switching power semiconductors," *CPSS Trans. Power Electron. Appl.*, vol. 3, no. 2, Jun. 2018.

Core Flux Density Sensing – The Magnetic Ear









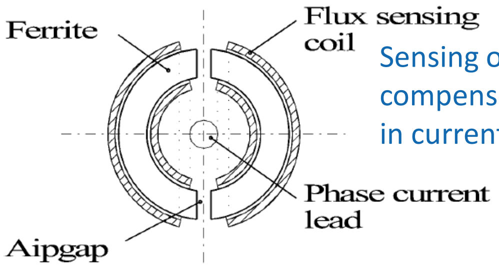
- **Shared magnetic path:** $L_{aux} = f(B_{main})$
- Meas. circuit: $L_{aux} \rightarrow v_m$

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)

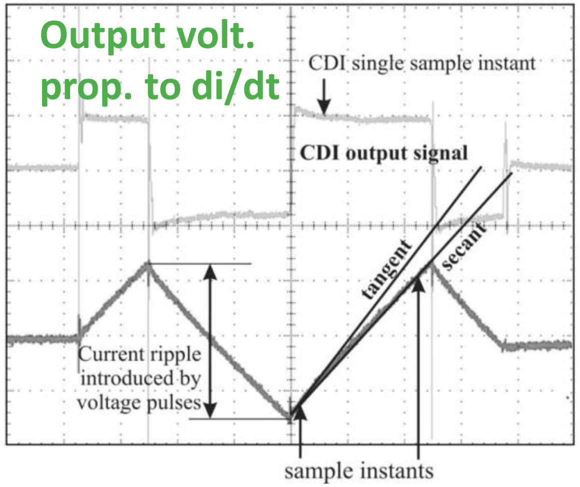
Direct di/dt Sensing

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



Sensing only, no compensating EMF as in current transformer!

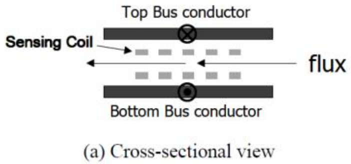
Needed to avoid saturation (no compensating current)

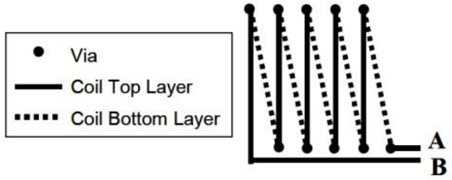


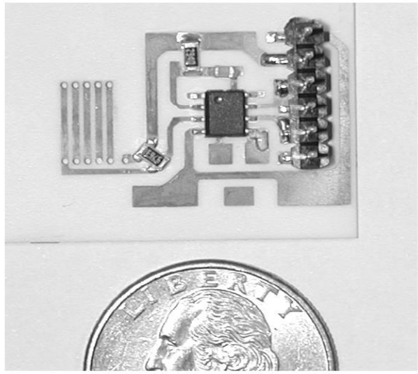
T. M. Wolbank, J. L. Machl, and H. Hauser, "Closed-loop compensating sensors versus new current derivative sensors for shaft-sensorless control of inverter fed induction machines," *IEEE Trans. Instrum. Meas.*, vol. 53, no. 4, Aug. 2004.

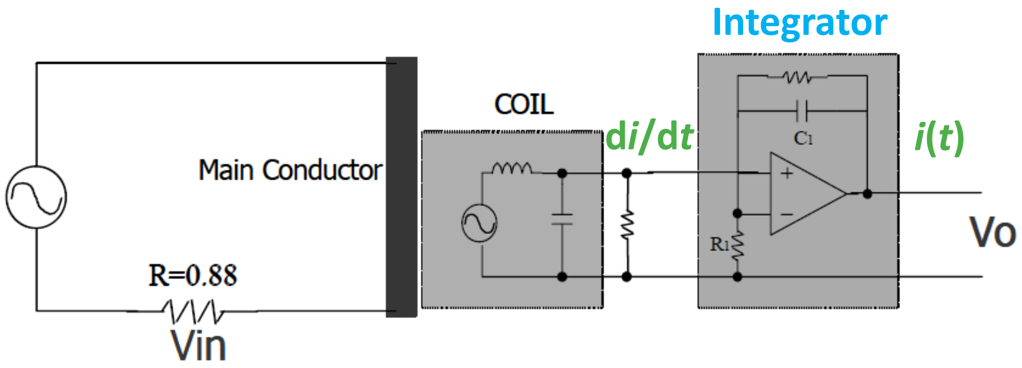
Integrable Current Sensors

- Planar Rogowski Coil





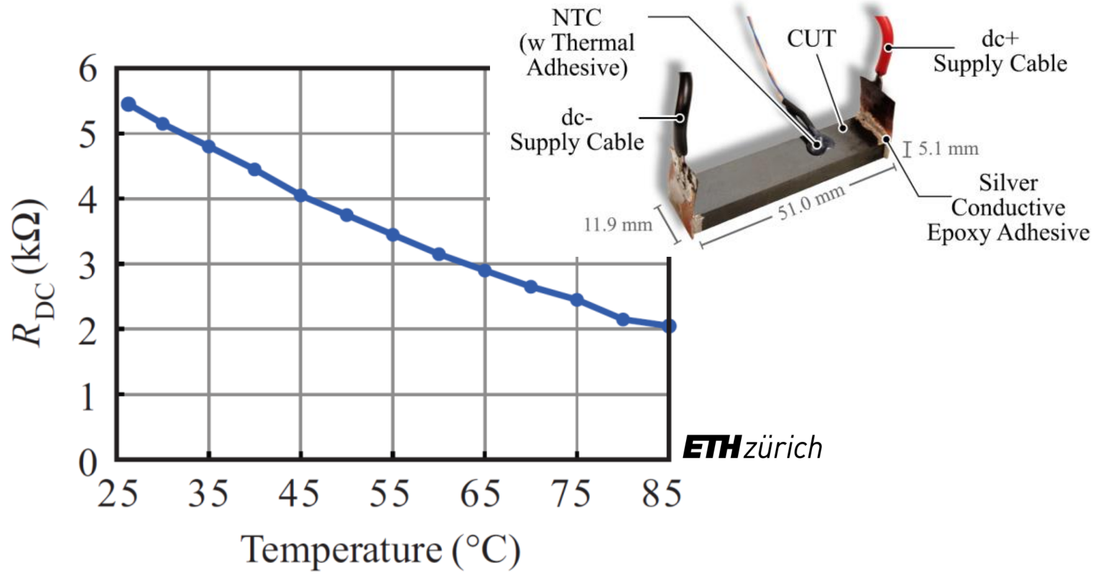




Chucheng Xiao, Lingyin Zhao, T. Asada, W. G. Odendaal, and J. D. van Wyk, "An overview of integratable current sensor technologies," in *Conf. Rec. 38th Ind. Appl. Soc. Annu. Meet.*, Salt Lake City, UT, USA, Oct. 2003.

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

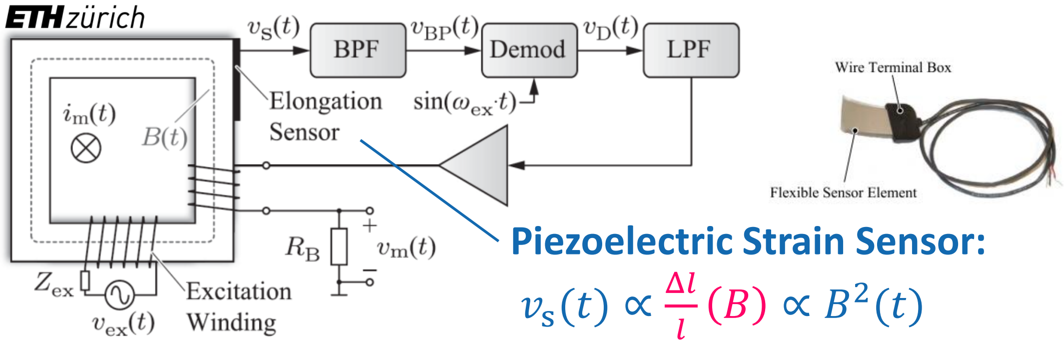
Ferrite Core Temperature Sensing via El. Resistance



- 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.

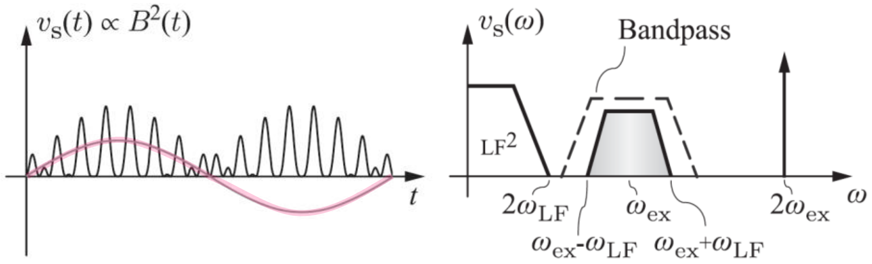
Magnetostriction-Based DC+AC Current Sensor



Piezoelectric Strain Sensor:

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

- Amplitude modulation/demodulation to measure DC/LF

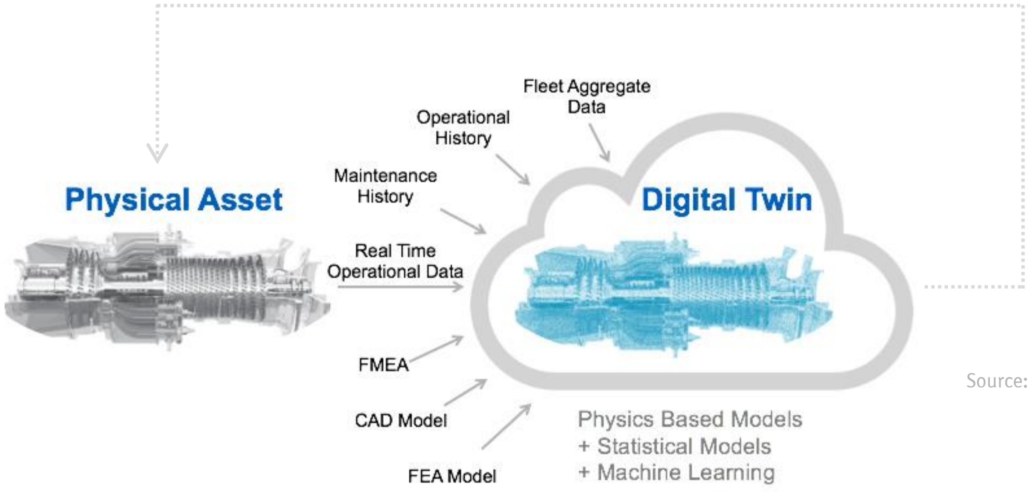


- Closed-loop performance: **±20 A, DC…20 MHz**

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: 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)



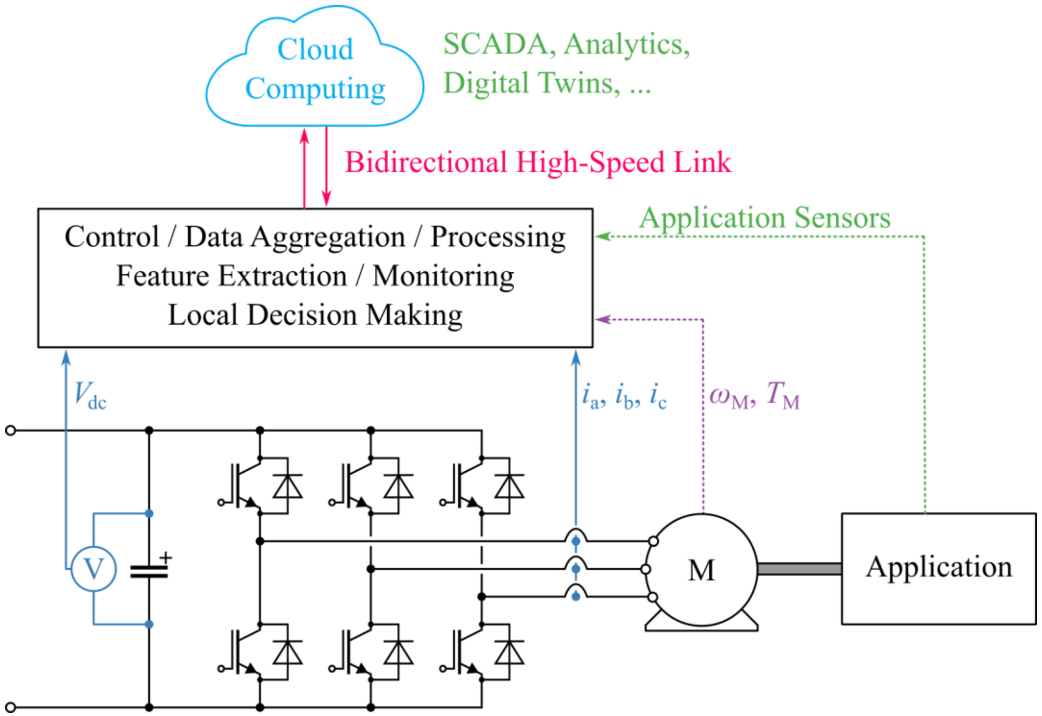
Source: www.railwayage.com

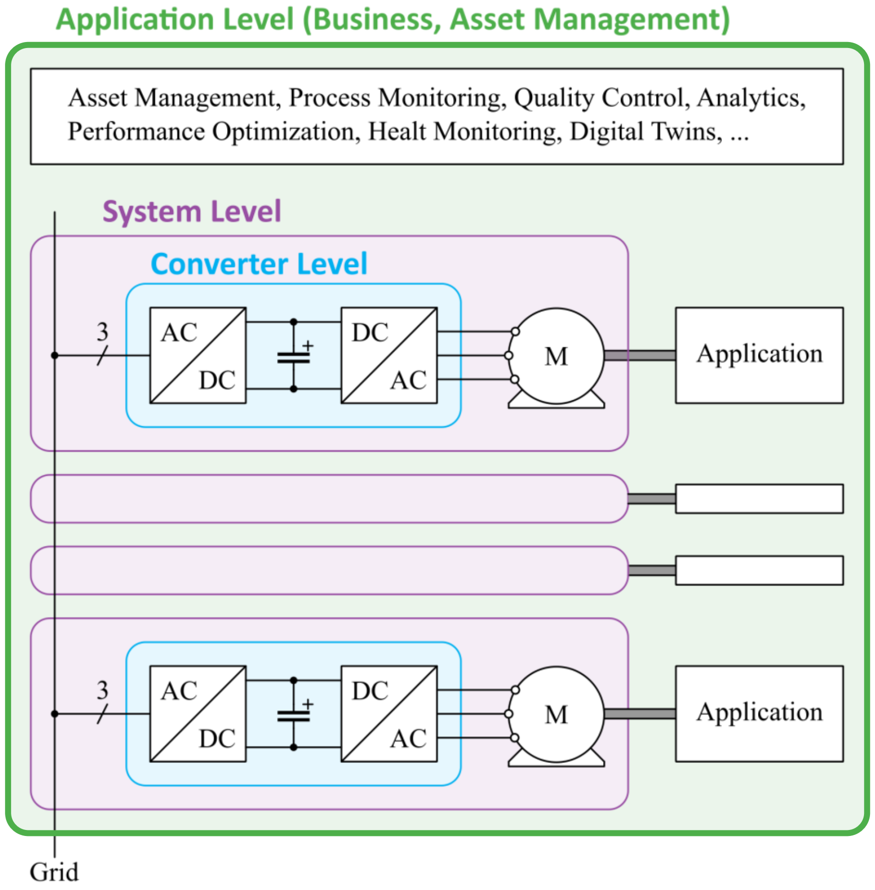
- **Smart components** with **integrated sensors** connect to Digital Twin
  → Design Improvements / Preventive Maintenance, etc.

Cognitive Power Electronics: Application Level – Power Electronics 4.0

Key Question

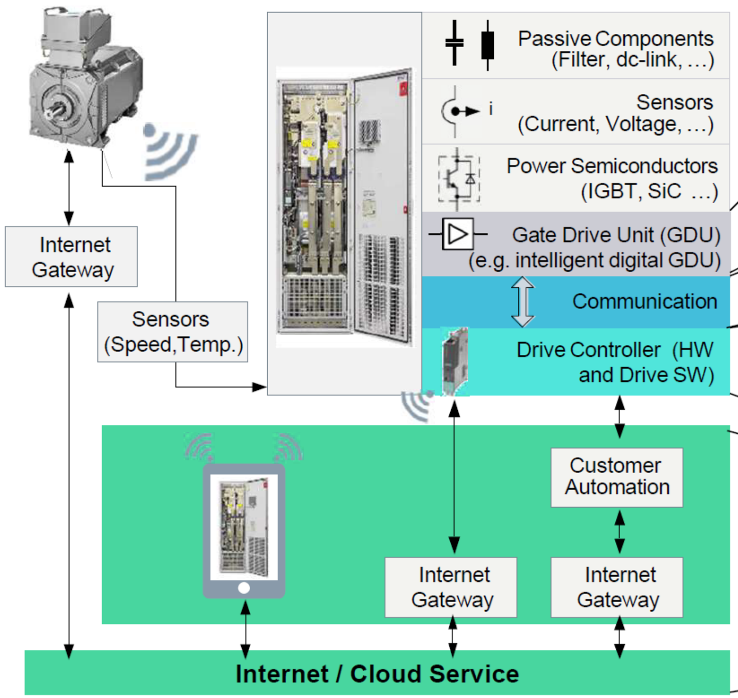
- **Future role of power electronic converters** in the application/business context?





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)
- …

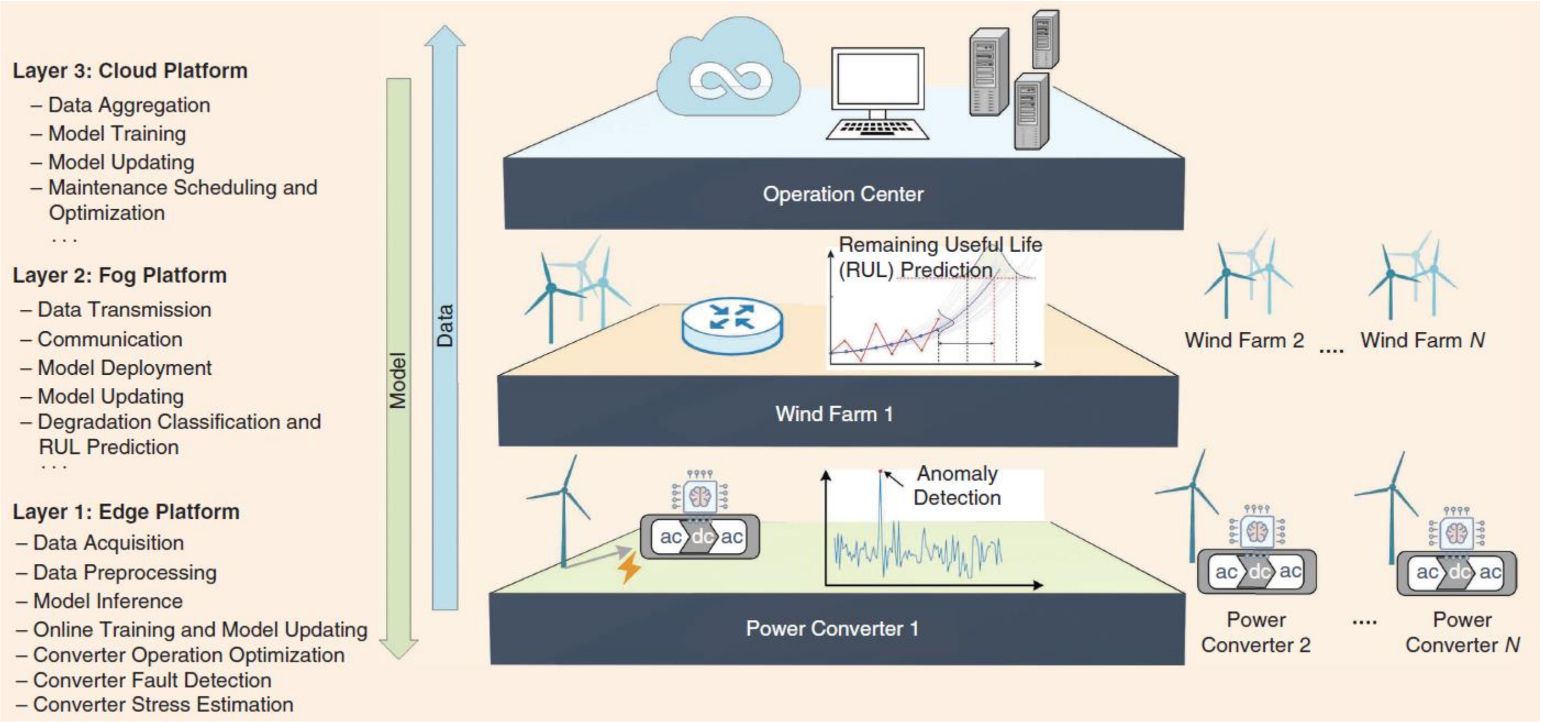
▶ Utilize high computing power and network effects in the cloud

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

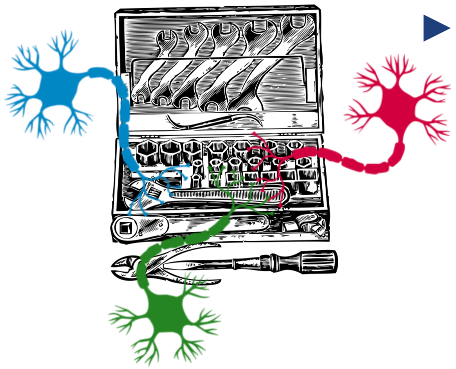
► ABB Ability **"Digital Power Train"**

► Schneider Electric EcoStruxure Innovation At Every Level

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

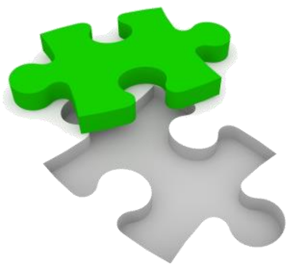
https://search.abb.com/library/Download.aspx?DocumentID=3AXD50000477821
https://www.se.com/ww/en/download/document/DT_eguide_09-10-19AR0_EN/

Conclusion & Requirements for PE 4.0 Readiness

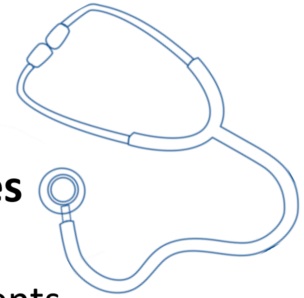


- **AI/ML techniques are one of many means to an end**
  - Should become **part of an engineer's toolbox** (as circuit or FEM simulation) → Awareness / training
  - Method should follow from the problem to be solved (not the other way around)
  - **Training data** is a key challenge for data-driven methods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



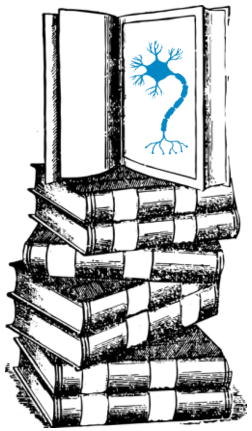
Further Reading

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!