ETH zürich

General Perspectives for Power Electronics....

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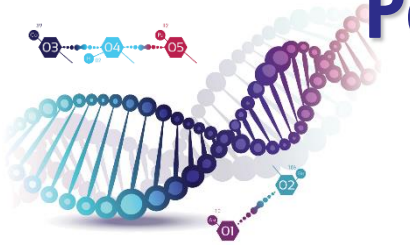
Dec. 2, 2021

The DNA of Future High-Performance Power Electronic Systems



Source: hathornconsultinggroup.com

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Outline

- *Introduction*
- *X-Technologies*
- *X-Concepts / «Genes»*
- *Conclusions*

Source: hathornconsultinggroup.com

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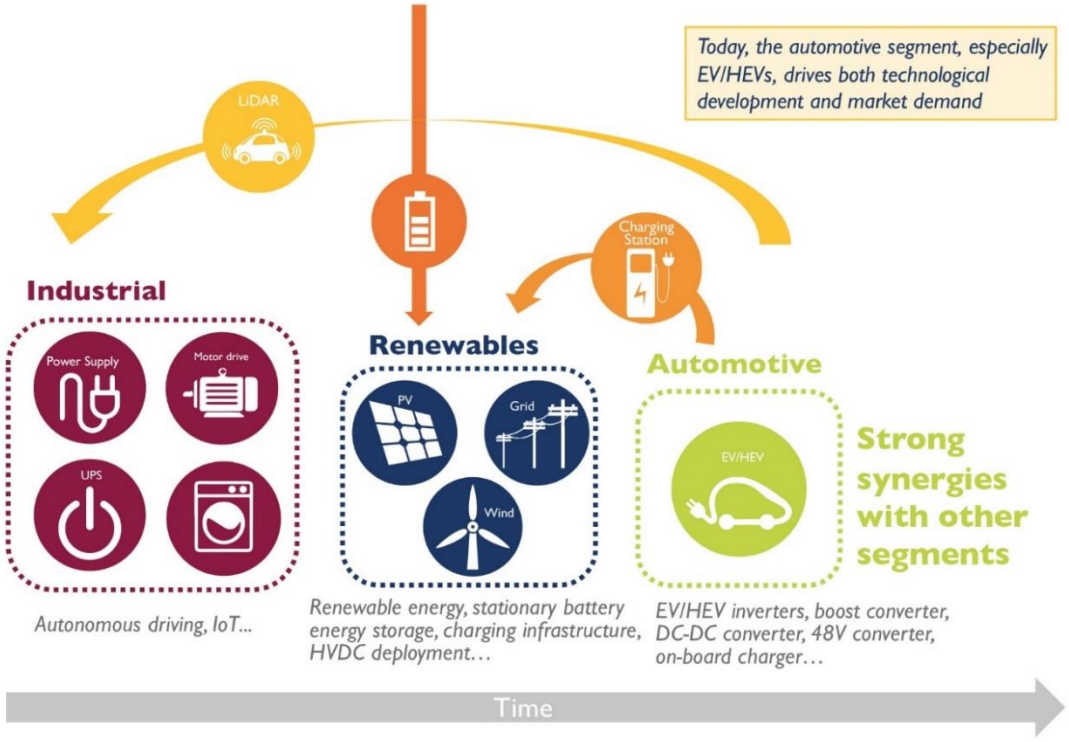
Power Electronics

Driving Applications
General Perspective
Performance Indicators / Trends
Technology S-Curve

Driving Applications

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

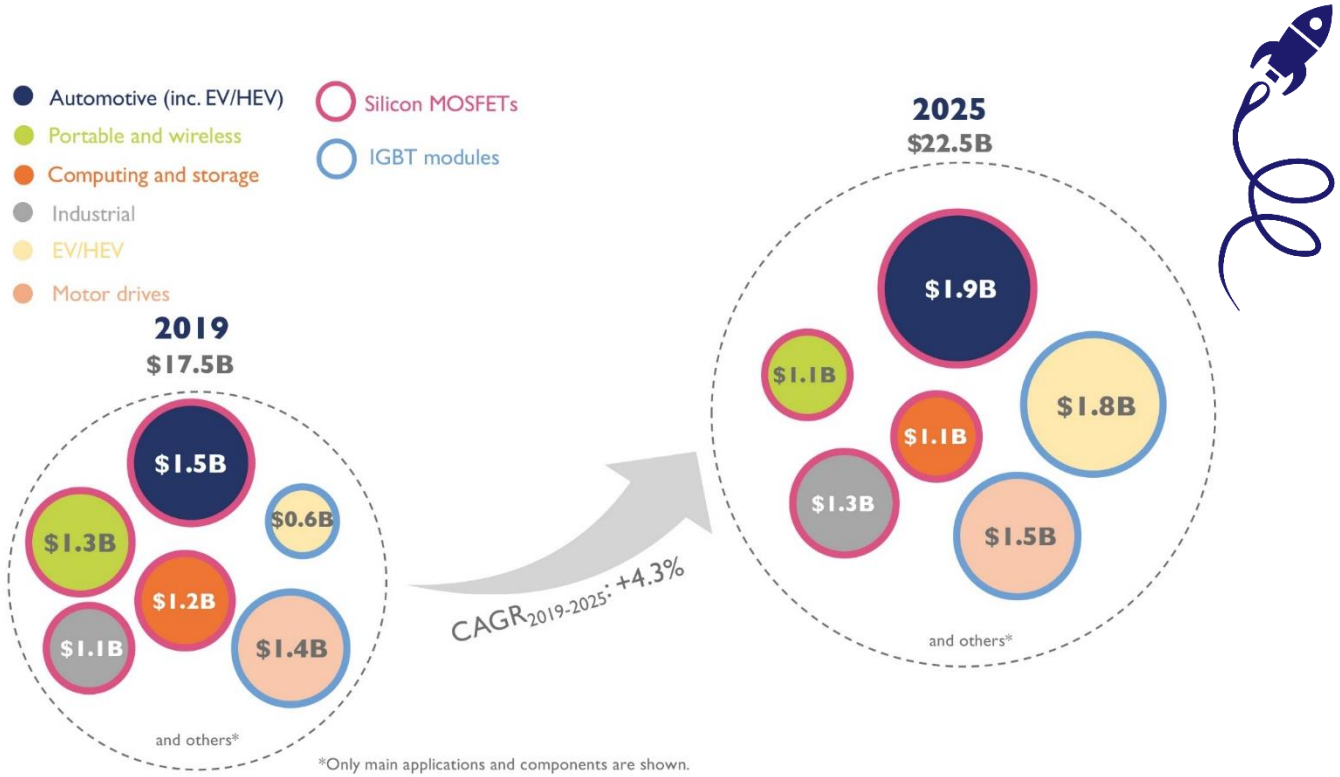


Source: Status of Power Electronics Industry 2019 Report

- *Clean Energy Transition → "All-Electric" Society*
- *UN Sustainable Development Agenda → There can be No "Plan B", because there is No "Planet B"* (Ban Ki-moon)

General Perspective

- *Power Electronics is Key to Clean Energy Utilization | Automation | etc. → "All-Electric Society"*
- *2019 — 2015 Power Electronics Market Evolution & Main Segments*



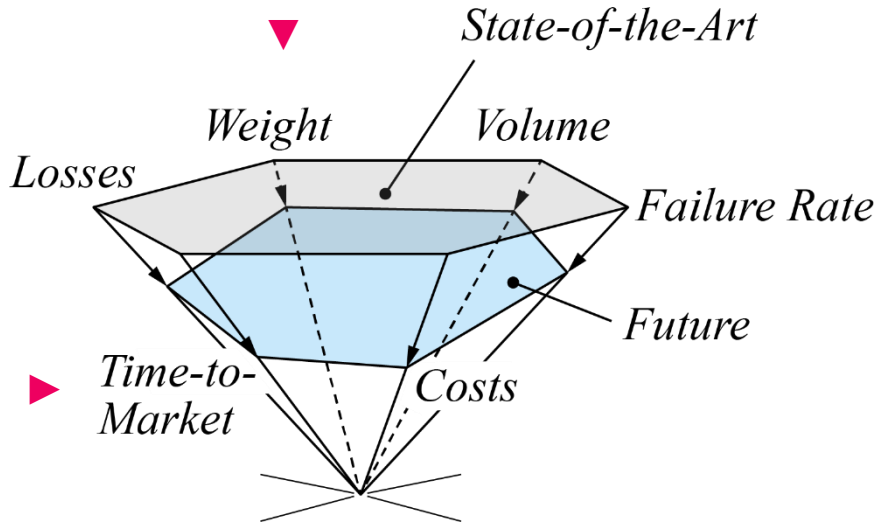
- *Source – Status of the Power Electronics Industry 2020 Report*

Performance Indicators / Trends

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}]

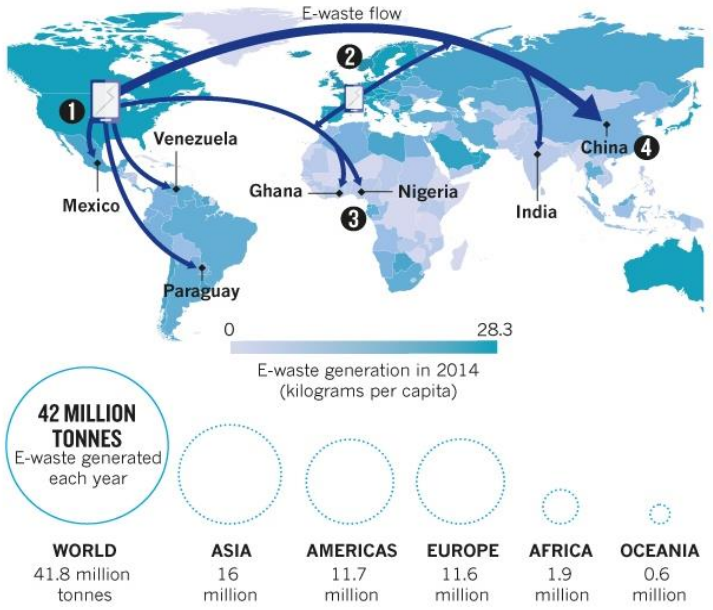
- Manufacturability
- Recyclability / Sustainability
- Networked / IIoT



Remark Increasing E-Waste Problem

- *53´000´000 Tons of Electronic Waste Produced Worldwide in 2019 → 74´000´000 Tons in 2030*
- *Large Proportion Ends up in Africa & China → Melting of PCBS & Cables etc. / Hazardous Substances*
- *Increasingly Complex Constructions → No Repair or Recycling*

Source: Green IT Solution

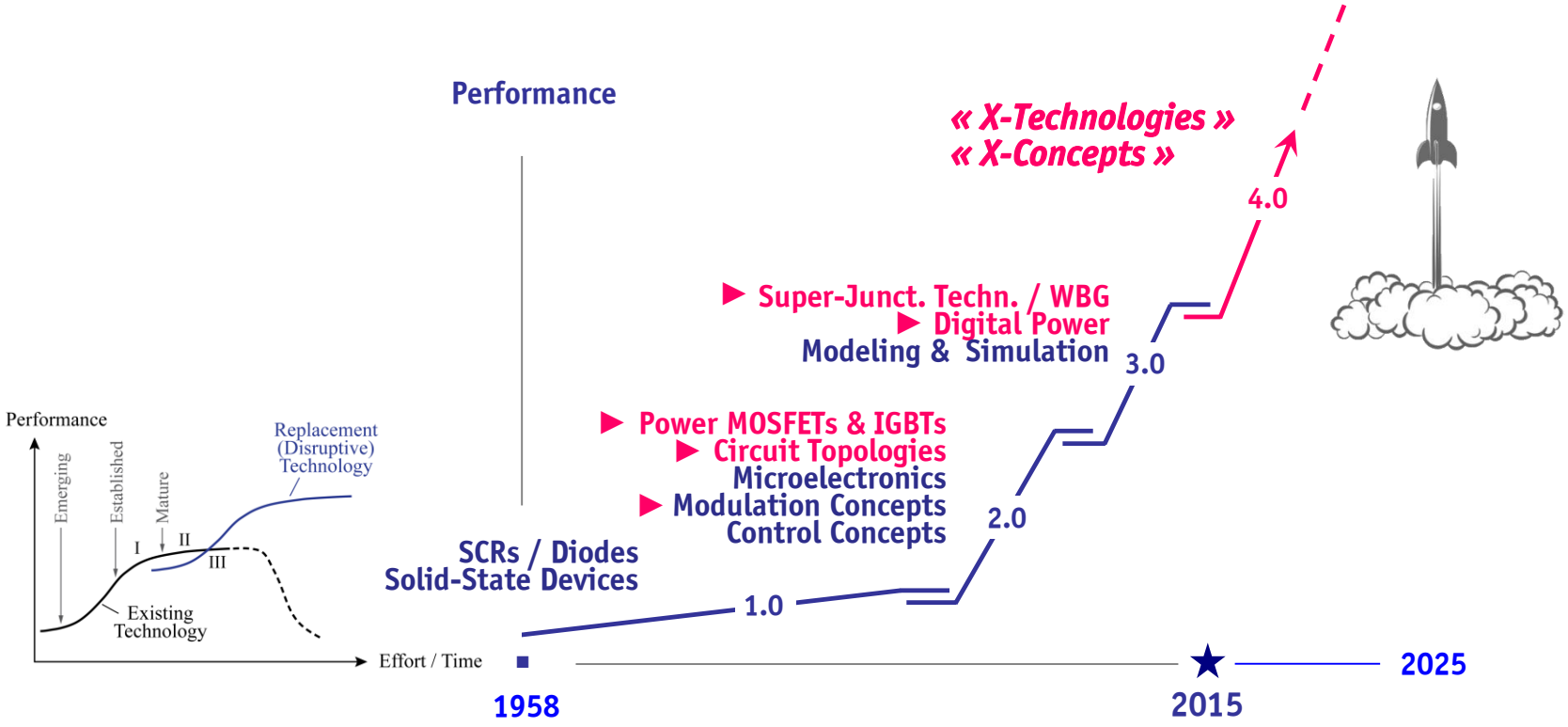


Source: nature

- *Growing Global E-Waste Streams → Increasing Attention of the Public / Upcoming Regulations*

S-Curve of Power Electronics

- *« X-Technologies » / "Moon-Shot" Technologies*
- *« X-Concepts » → Full Utilization of Basic Scaling Laws & « X-Technologies »*
- *Power Electronics 1.0 → Power Electronics 4.0*
- *2…5…10x Improvement NOT Only 10% !*



X-Technologies

SiC | GaN
3D-Packaging & Integration
Digital Signal Processing
Energy Storage

X-Technology

SiC | GaN

Low $R^*_{DS(on)}$ High-Voltage Devices

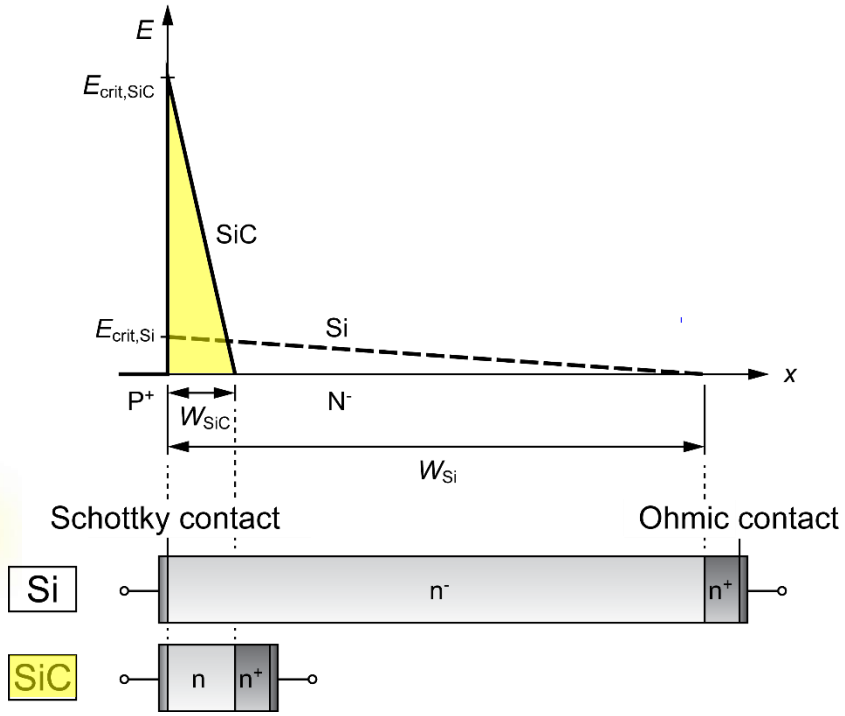
- *Higher Critical E-Field of SiC → Thinner Drift Layer*
- *Higher Maximum Junction Temperature $T_{j,max}$*

at 300 K	Si	GaAs	4H/6H-SiC	GaN
Eg (eV)	1.12	1.4	3.0-3.2	3.4
Ec (MV/cm)	0.25	0.3	2.2-2.5	3
μ_n (cm²/Vs)	1350	8500	100-1000	1000
ε_r	11.9	13	10	9.5
vsat (cm/s)	$1x10^7$	$1x10^7$	$2x10^7$	$3x10^7$
λ (W/cmK)	1.5	0.5	3 - 5	1.3

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

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

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



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

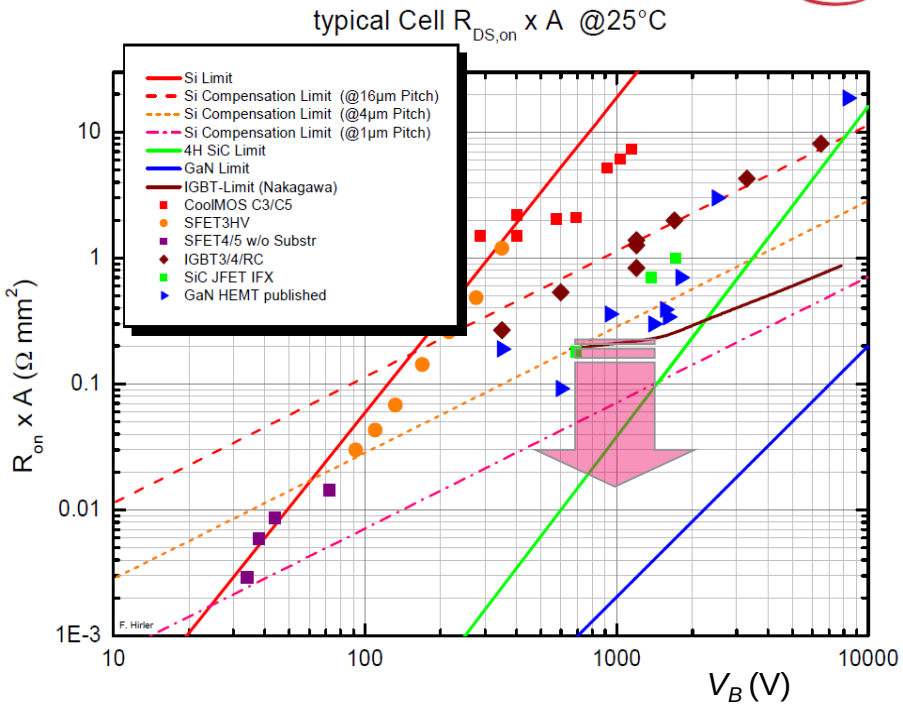
Low $R^*_{DS(on)}$ High-Voltage Devices

- *SiC MOSFETs / GaN HEMTs (Monolithic AC-Switch)*
- *Low Conduction Losses & ZVS*
- *High Efficiency*

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

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

Source: Infineon

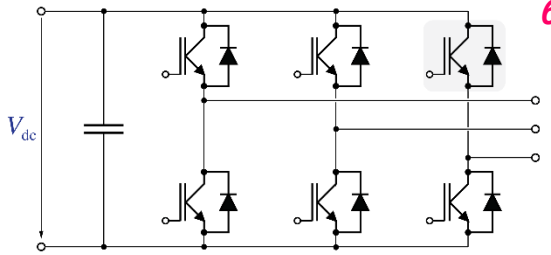


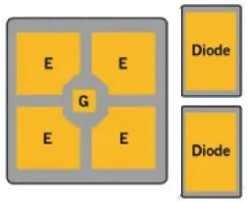
- *High-Voltage Unipolar (!) Devices → Excellent Switching Performance*

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

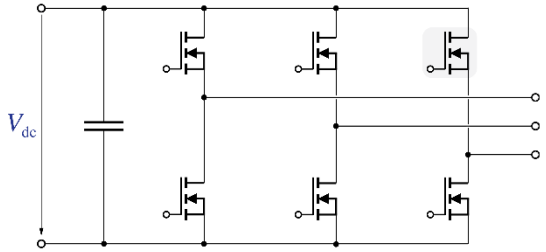


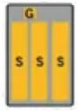


Source: ATZ elektronik 2018

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

6x SiC-MOSFET





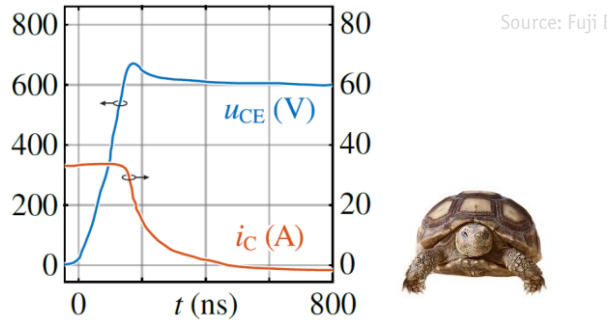
1200 V 100 A
Die Size: 25.6 mm²

Source: Cree

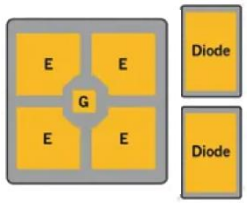
- *Space Saving of >30% on Module Level (!)*

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*

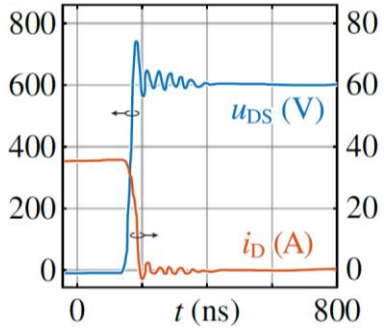


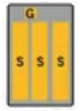
Source: Fuji Electric



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

Source: Infineon





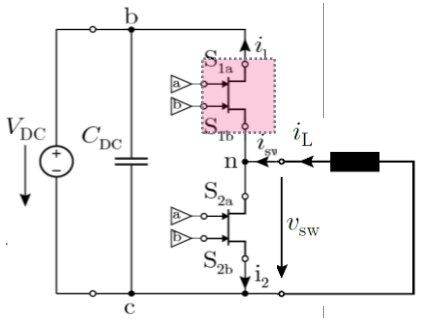
1200V 100A
Die Size: 25.6mm²

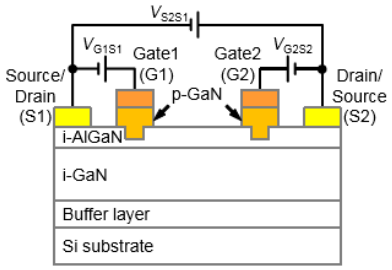
Source: Cree

- *Extremely High di/dt & dv/dt → Challenges in Packaging / EMI*

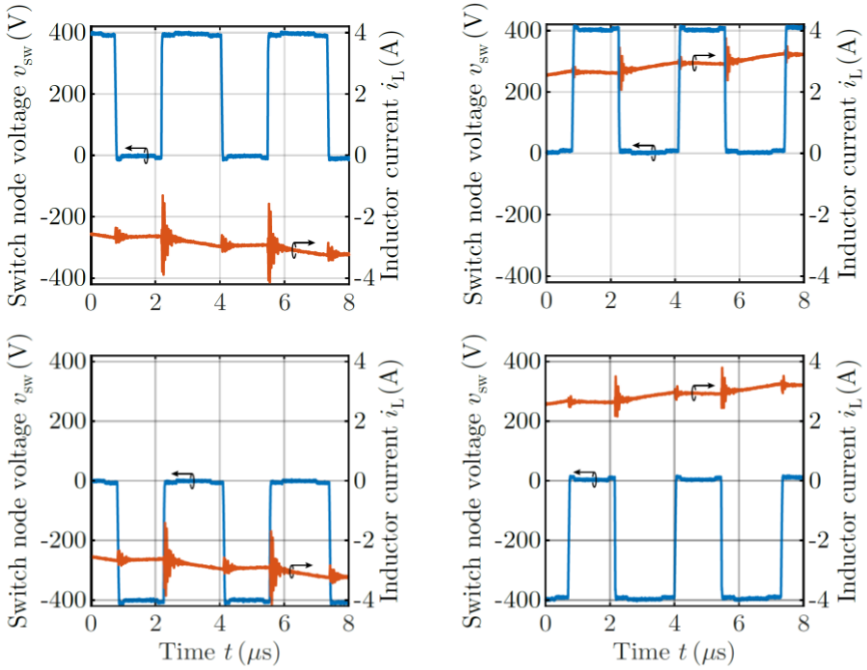
Monolithic 600V GaN Bidirectional/Bipolar Switch

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





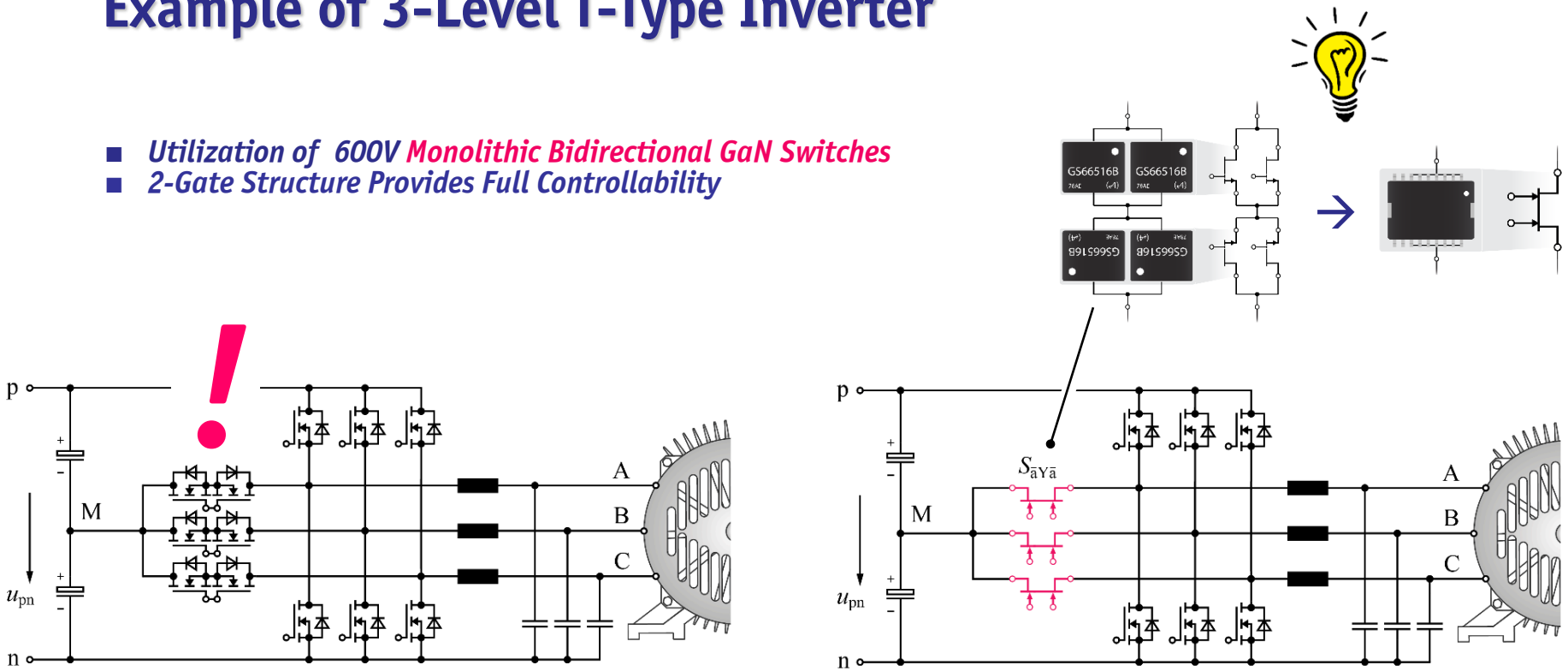
Source: Panasonic ideas for life



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

Example of 3-Level T-Type Inverter

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



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

X-Technology

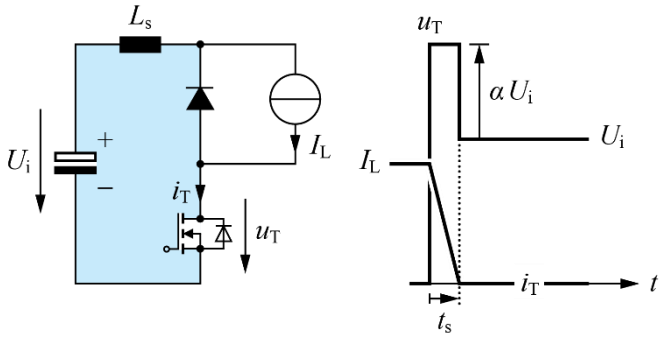
3D-Packaging / Integration

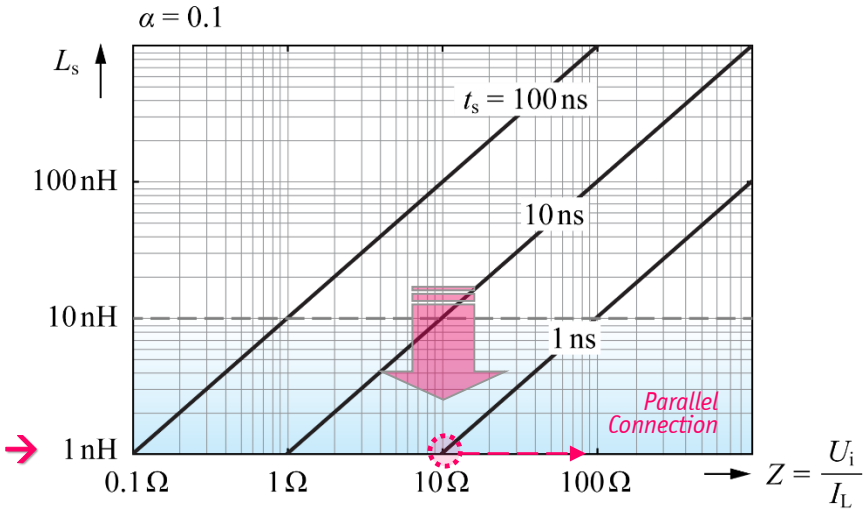
Circuit Parasitics

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

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

$$L_s \leq \frac{\alpha U_i}{\frac{I_L}{t_s}} = \alpha t_s \frac{U_i}{I_L} \qquad z$$



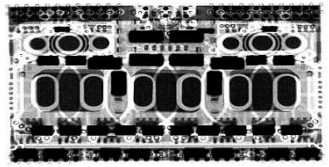


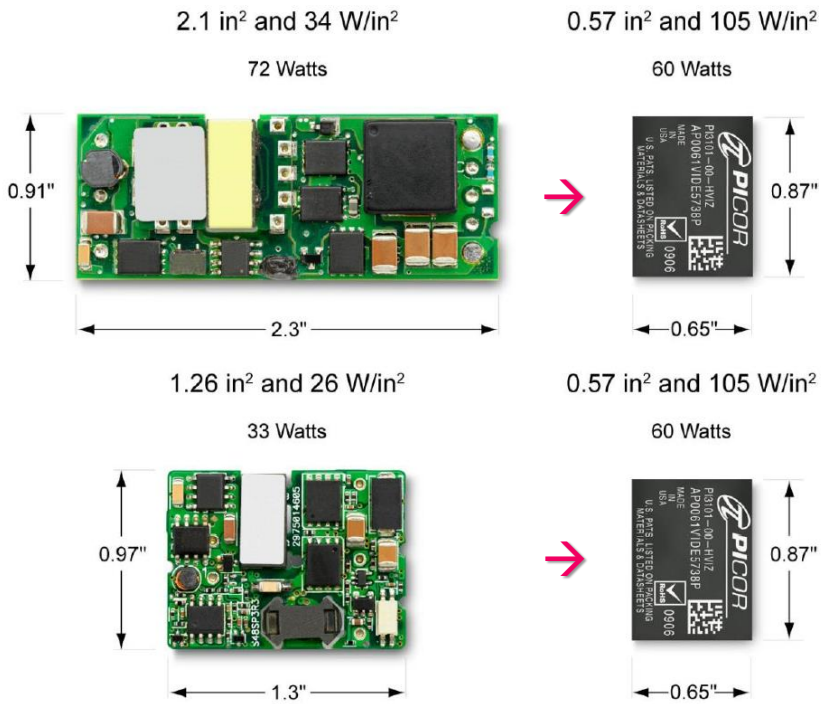
- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents (Z-Matching)*

3D-Packaging / Heterogeneous Integration

- *System in Package (SiP) Approach*
- *Minim. of Parasitic Inductances / EMI Shielding / Integr. Thermal Management*
- *Very High Power Density (No Bond Wires / Solder / Thermal Paste)*
- *PCBs Embedded Optic Fibres*
- *Automated Manufacturing*
- *Recycling (?)*

Source: VICOR

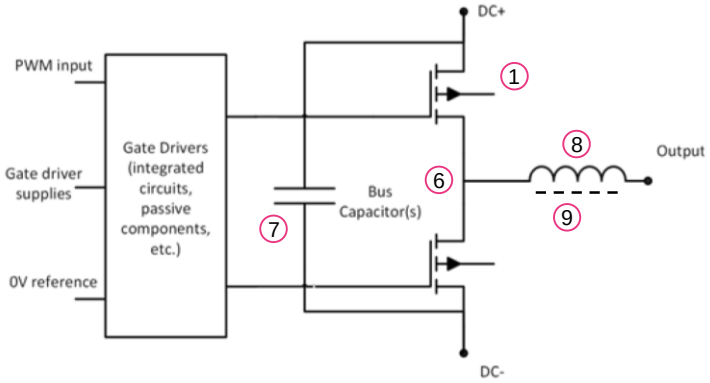




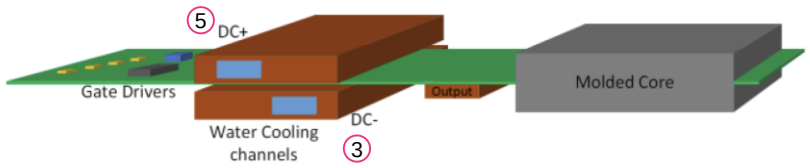
- *Future Application Up to 100kW (!)*
- *New Design Tools & Measurement Systems (!)*
- *University / Industry Technology Partnership (!)*

High-Power PCB-Embedding Technology

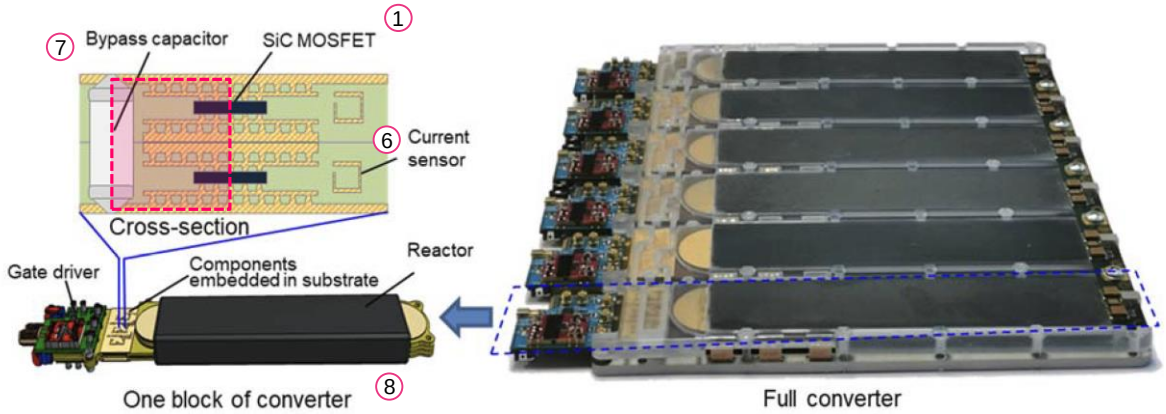
- *PCB Integr. of SiC Chips / Passives / Sensors etc. → PCB Design Software / Custom Design / Low $$$*
- *3D-Vertical Multilayer Structure → Ultra-Low Comm. & Gate Loop Ind. < 1nH / Low Sw. Losses & EMI*
- *Multi-Functional Use of Busbars → DC Supply & 2-Side Liquid Cooling of SiC Chips*
- *Results in Flat Structures (!)*



400um & 35um Cu Layers



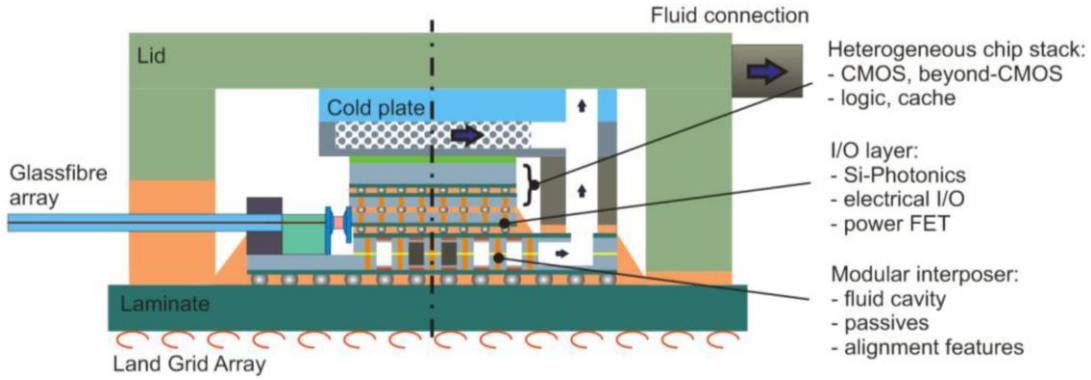
Source: MITSUBISHI ELECTRIC Changes for the Better St. Mollov et al., 2019

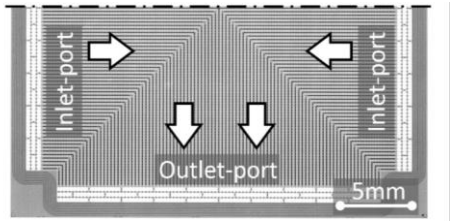


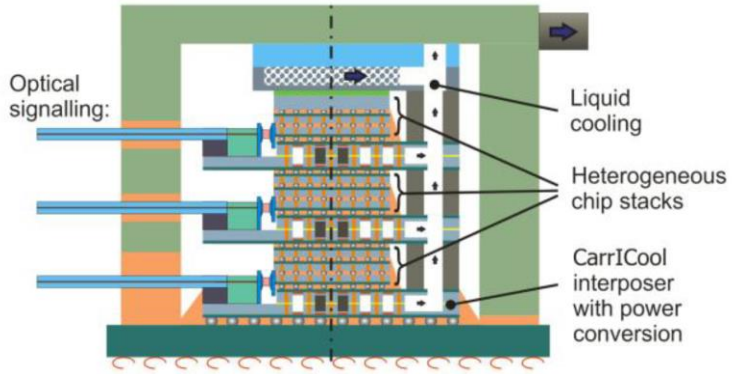
- *800V DC-Link Bidirectional 100kW SiC DC/DC-Converter (24 x 18 x 1.7cm)* ★ *≈ 136 kW/dm³*

Remark Future uP Chip-Stack Packaging

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





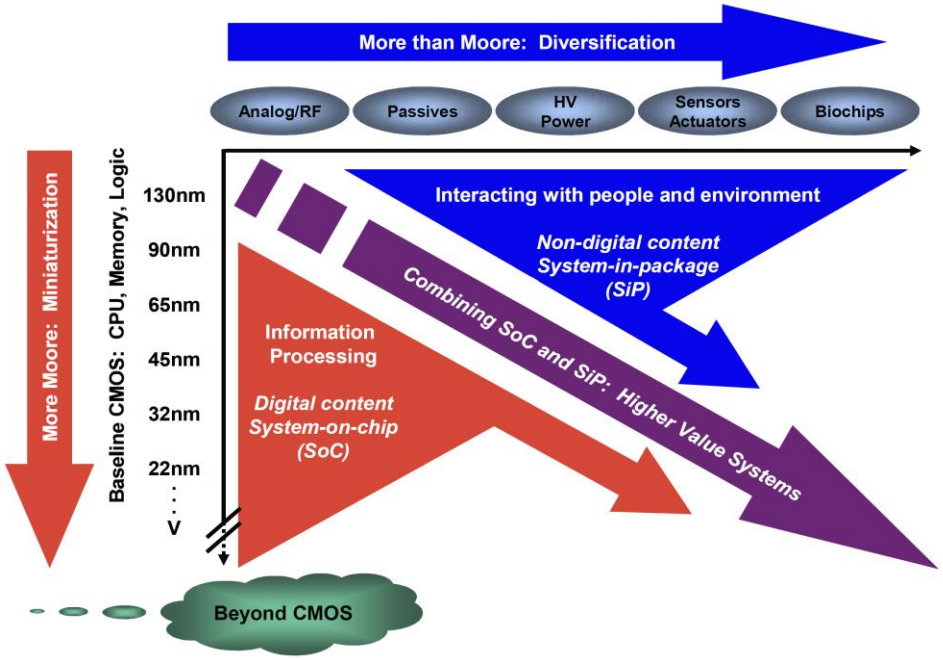


- Interposer Supporting *Optical Signaling / Volumetric Heat Removal / Power Conversion*

CarrICool
EU FP7 Project

Remark "More Moore" & "More-than-Moore"

- *CMOS-Based Digital Domain for Memory & uP → Technology Driven Miniaturization / "Moore´s Law*
- *Applications → Multi-Funct. Heterogeneous Analog & Mixed-Signal Systems → "More-than-Moore"*
- *Dual Trend → Int. Roadmap for Devices and Systems (ITRS → IRDS, since 2005)*



- *Development of Generic Appl.-Specific Technology Modules / Technology Platforms*
- *Close Analogy to WBG Power Semiconductors & Full Converter Systems*

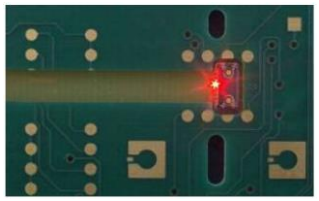
X-Technology

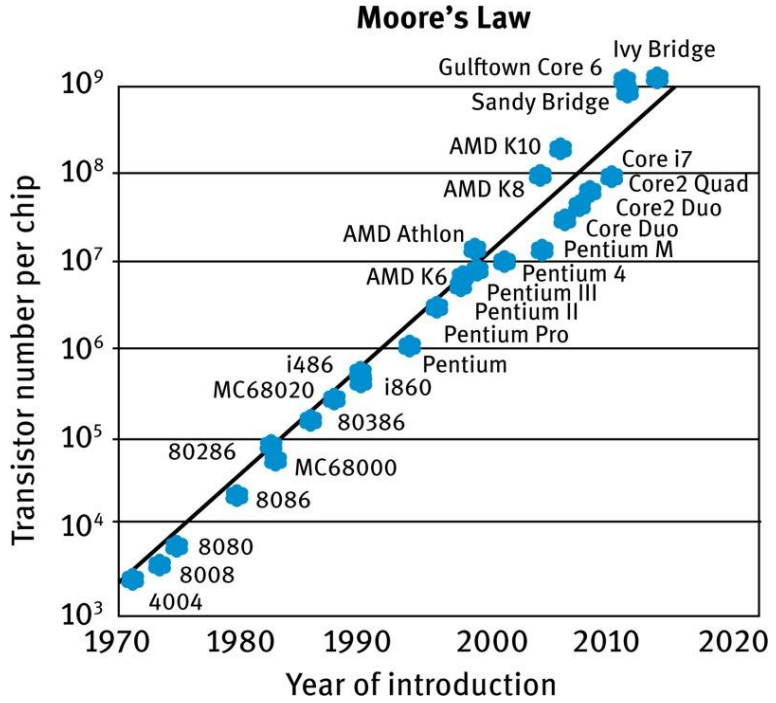
Digital Signal / Data Processing

Digital Signal & Data Processing

- *Exponentially Improving uC / Storage Technology (!)*
  - *Extreme Levels of Density / Processing Speed*
  - *Software Defined Functions / Flexibility*
  - *Continuous Relative Cost Reduction*

Source: vario-optics.ch/
Electro-Optical PCBs





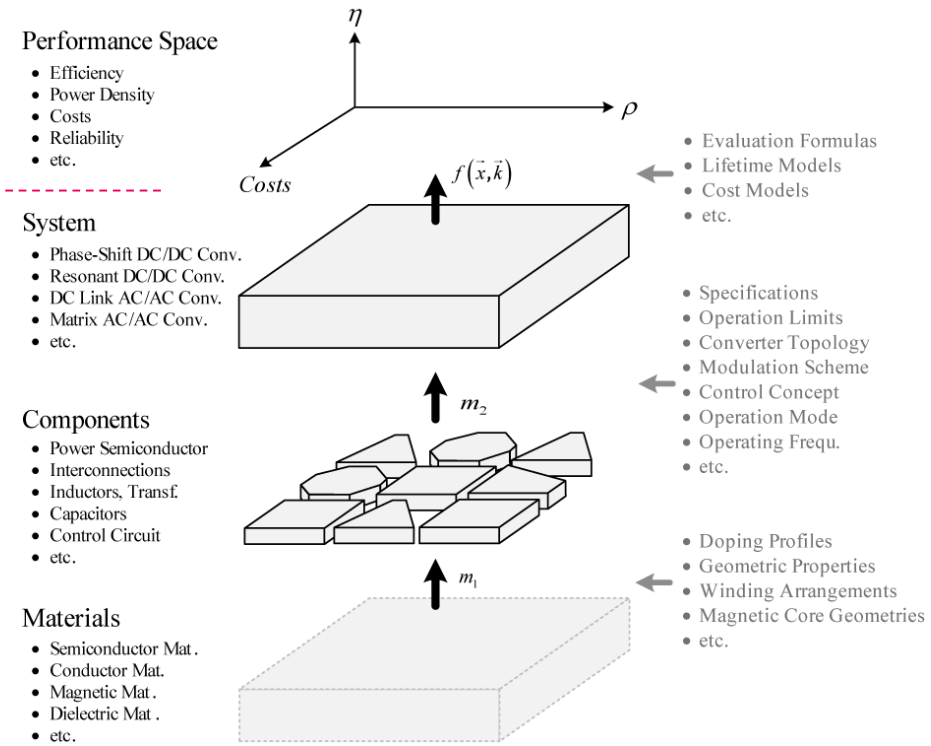
Source: Ostendorf & König /DeGruyter

- *Distributed Intelligence*
- *Fully Digital Control of Complex Systems – Electrical/Optical/Wireless Signal Transfer*
- *Massive Comp. Power → Fully Automated AI-Supported Design / Digital Twins / Industrial IoT (IIoT)*

Abstraction of Power Converter Design

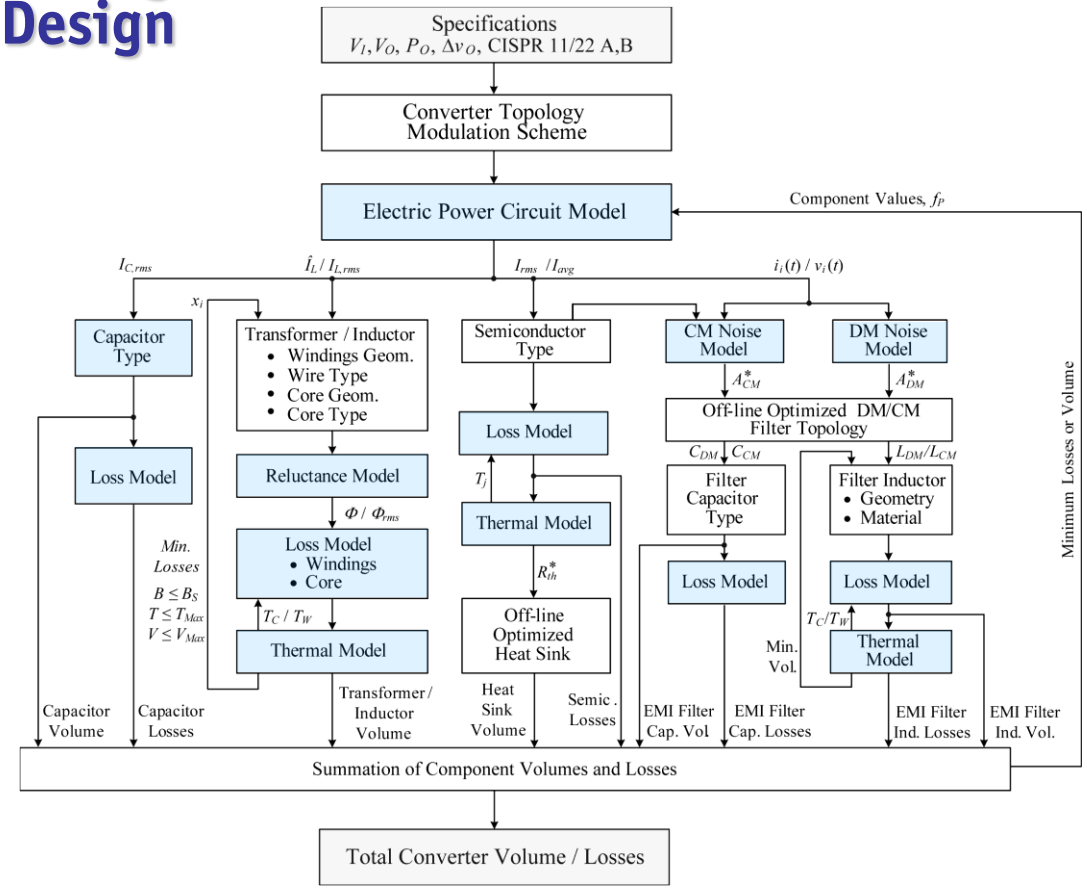
Performance Space

Design Space



- *Mapping of "Design Space" into Converter "η-ρ-σ-Performance Space"*
- *Design Space — Set of Selected Design- & Operating Parameters, Materials, Components, Topology, etc.*

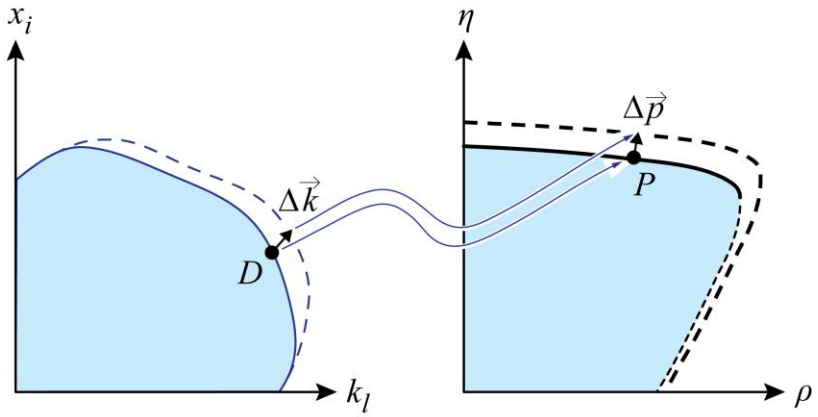
Mathematical Modeling of the Converter Design

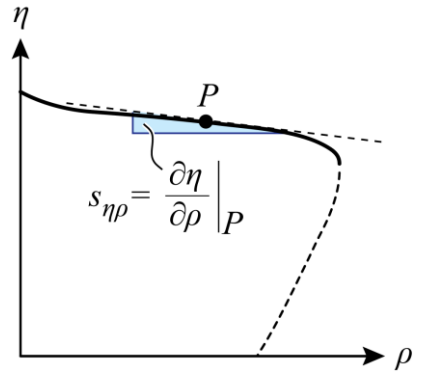


- *Best Utilization of All Degrees of Freedom → Multi-Objective Optimization*

Multi-Objective Optimization

- *Based on Mathematical Model of the Technology Mapping*
- *Multi-Objective Optimization → Best Utilization of the "Design Space"*
- *Identifies Absolute Performance Limits → Pareto Front / Surface*

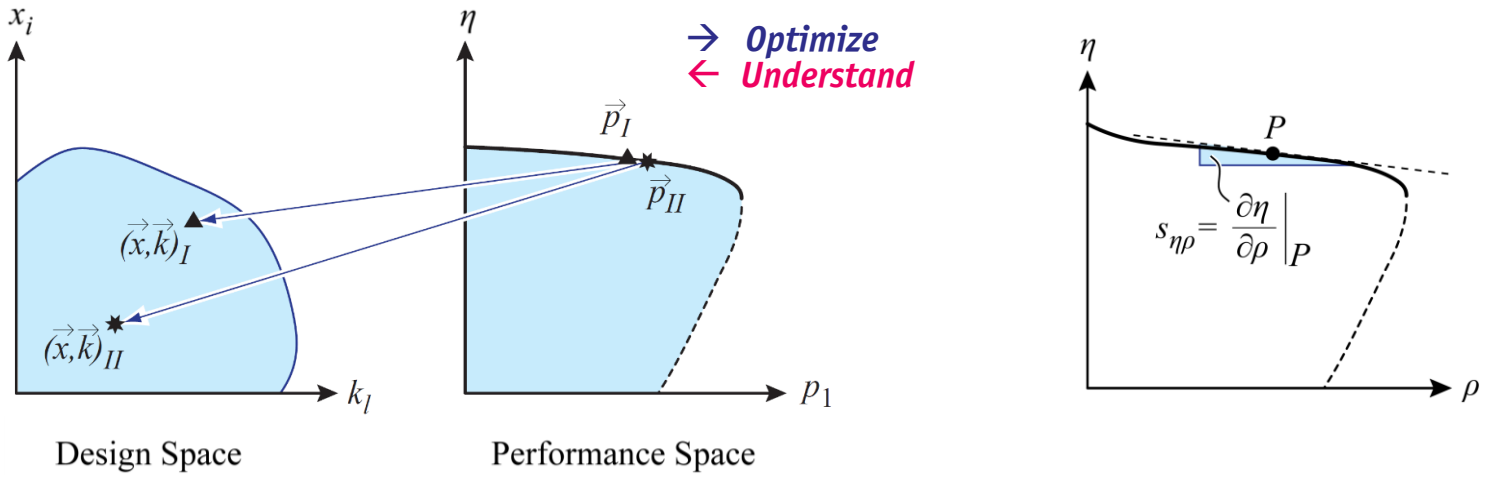




- Clarifies *Sensitivity* $\Delta\vec{p}$ / $\Delta\vec{k}$ to Improvements of Technologies
- *Trade-Off Analysis*

Design Space Diversity

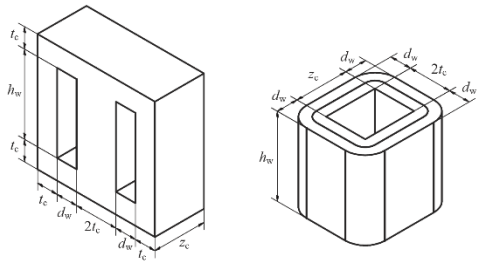
- *Equal Performance $\vec{p}_i$ for Largely Different Sets $(\vec{x},\vec{k})_i$ of Design Parameters*
- *E.g. Mutual Compensation of Volume or Loss Contributions (e.g. Cond. & Sw. Losses)*



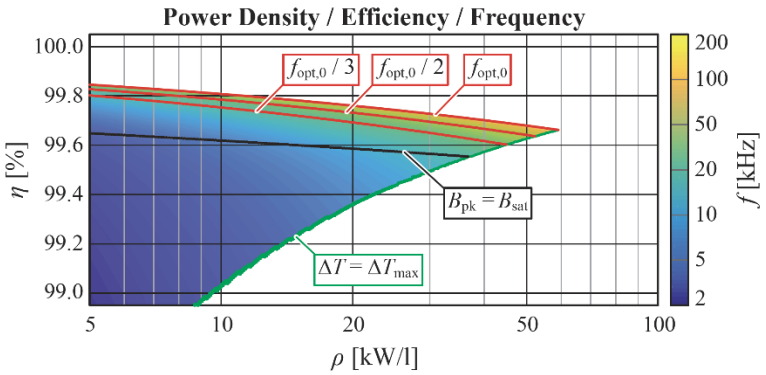
- *Allows Consideration of Additional Performance Targets (e.g. Costs)*

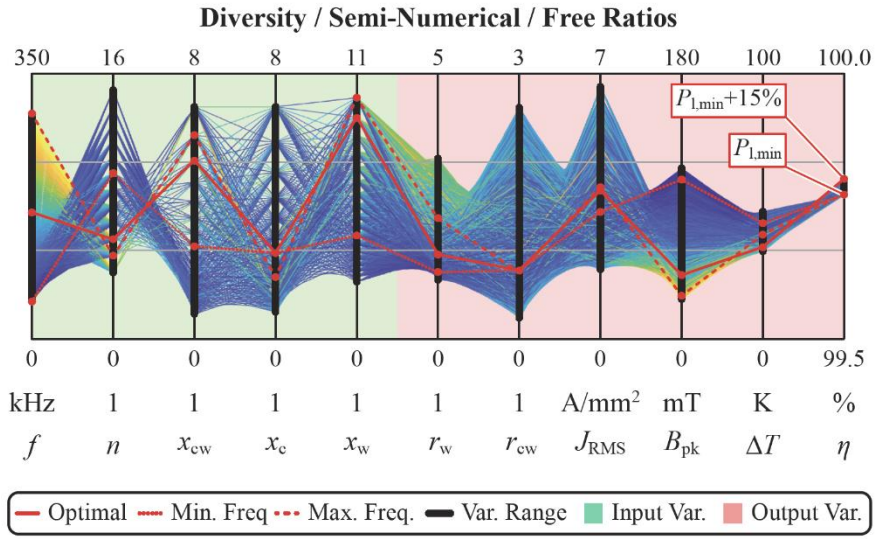
Design Space Diversity — Example

- *Design of a Medium-Frequency Transformer*
- *Power Level & Power Density = const.*
- *Wdg./Core Loss Ratio, Geometry, n etc. as Design Parameters*



Source: T. Guillod / ETH





$x_{cw} = A_c / A_w, \quad x_c = z_c / 2\,t_c, \quad x_w = h_w / d_w$

- *Mutual Compensation Core & Winding Losses Changes*
- *Limits on Part Load Efficiency / Costs / Fixed Geometry → Restricted Diversity*

Design Automation Roadmap

- *End-to-End Horizon — Cradle-to-Grave/Cradle — Modeling & Simulation*
- *Design for Cost / Volume / Efficiency / Manufacturing / Testing / Reliability / Recycling*

Autonomous Design → Design 4.0

– *Independent* Generation of Full Designs for Final Expert Judgement

Augmented Design

– *Suggestion* of Design Details Based on Previous Designs

Assisted Design

– *Support* of the User with Abstracted Database of Former Designs

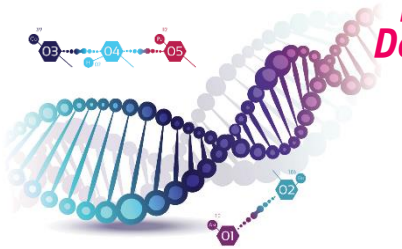
State-of-the-Art

– *User Defined* Models and Simulation / Fragmented

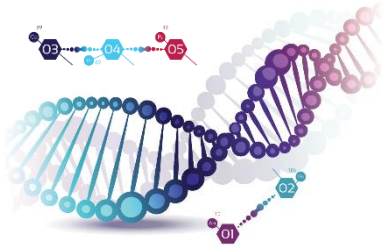
- *AI-Based Summaries → No Other Way to Survive in a World of Exp. Increasing # of Publications (!)*

X-Concepts

Modularization
Functional Integration
Synergetic Association
Hybridization
Decentralization



X-Concept



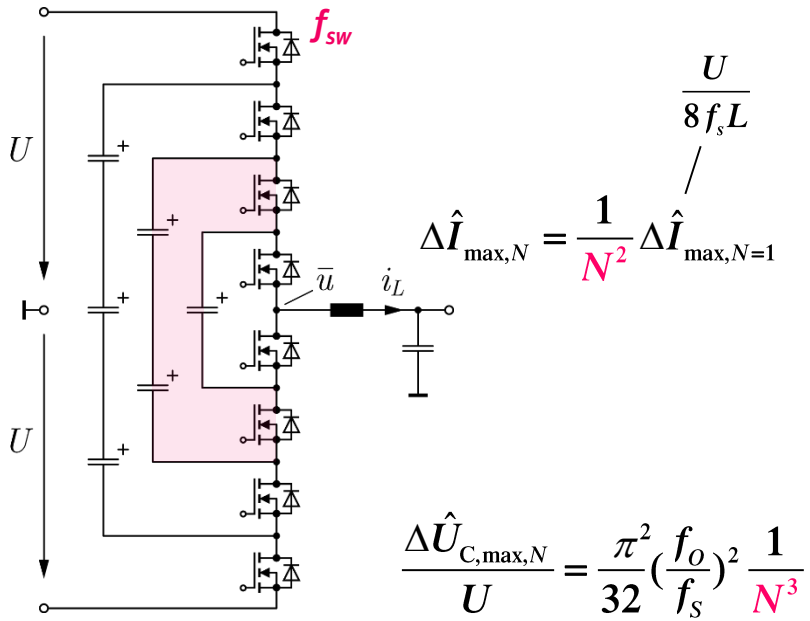
Modularization

Scaling of Multi-Cell/Level Concepts

- *Reduced Ripple @ Same (!) Switching Losses*
- *Lower Overall On-Resistance @ Given Blocking Voltage*
- *Application of LV Technology to HV*

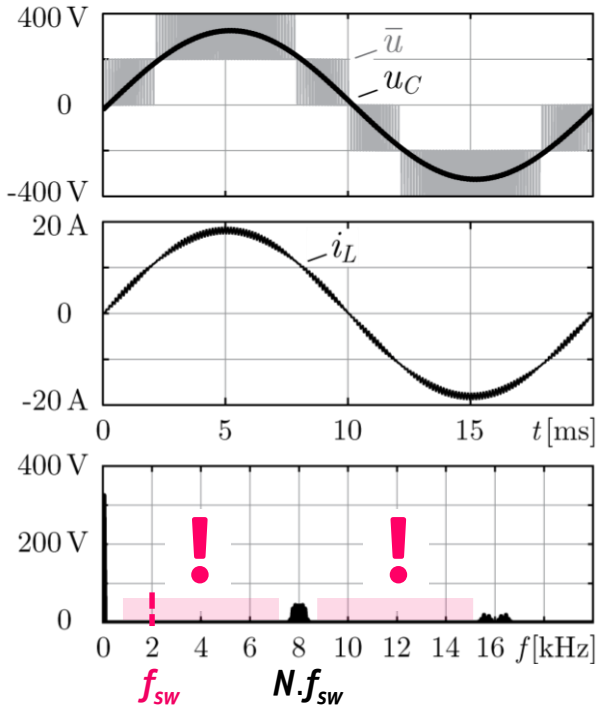
Source: R. Pilawa

Integrated Dual-Sided Half-Bridge Flying Capacitor Converter Switching Cell



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

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

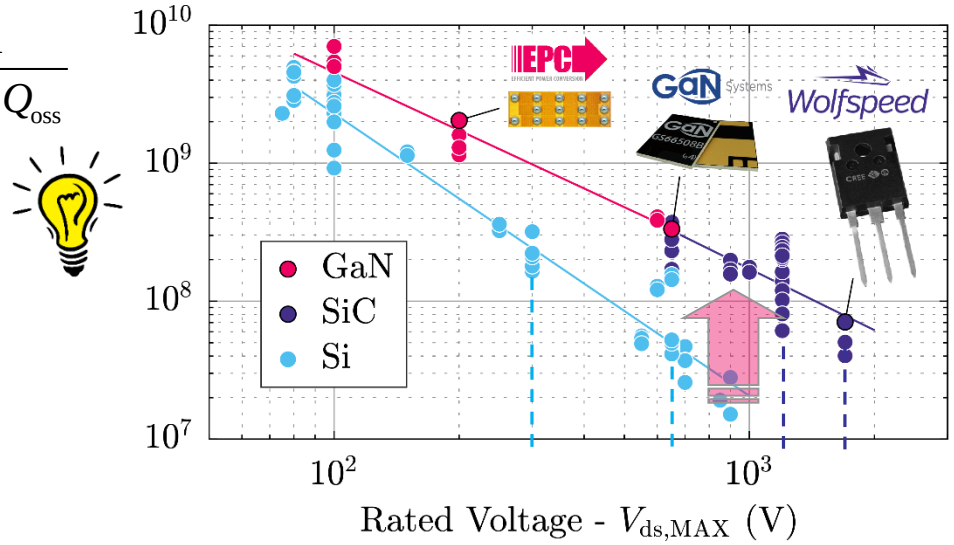


- *Scalability / Manufacturability / Standardization / Redundancy*

SiC/GaN Figure-of-Merit

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

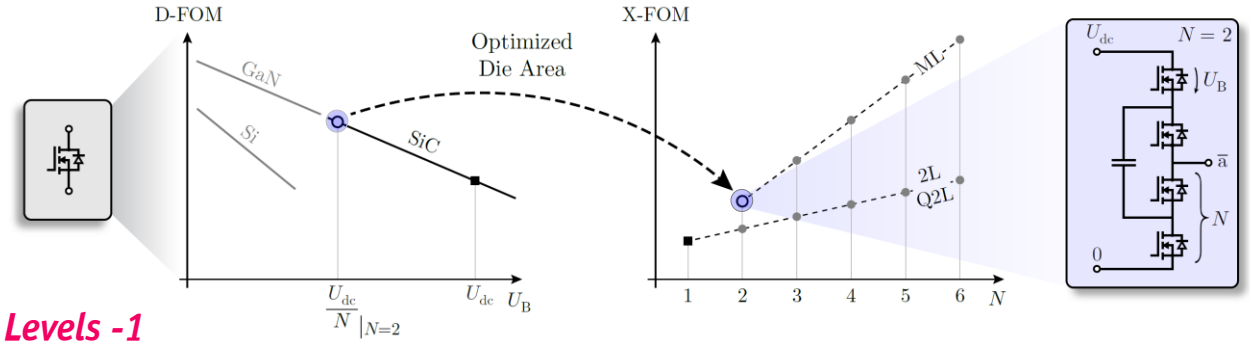
$$\text{FOM} = \frac{1}{R_{\text{ds,on}} Q_{\text{oss}}}$$



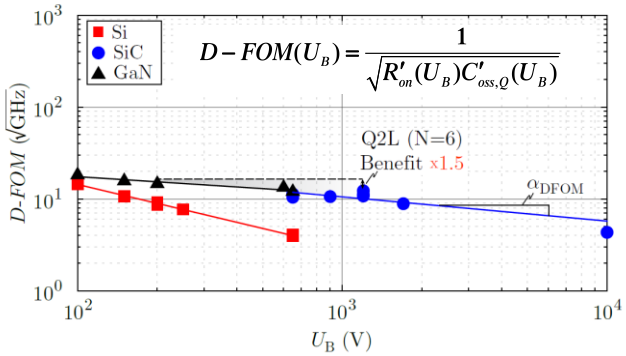
- *Advantage of Multi-Level over 2-Level Converter Topologies*

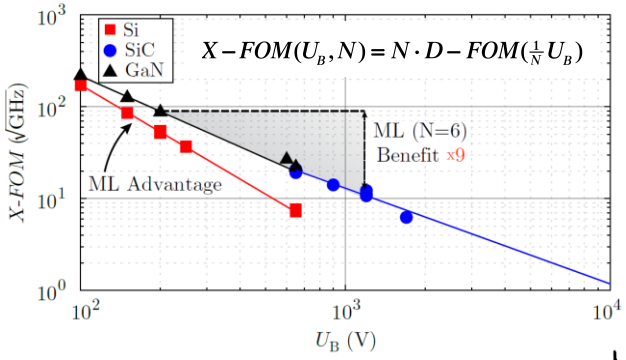
X-FOM of ML-Bridge-Legs

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



N= # of Levels -1

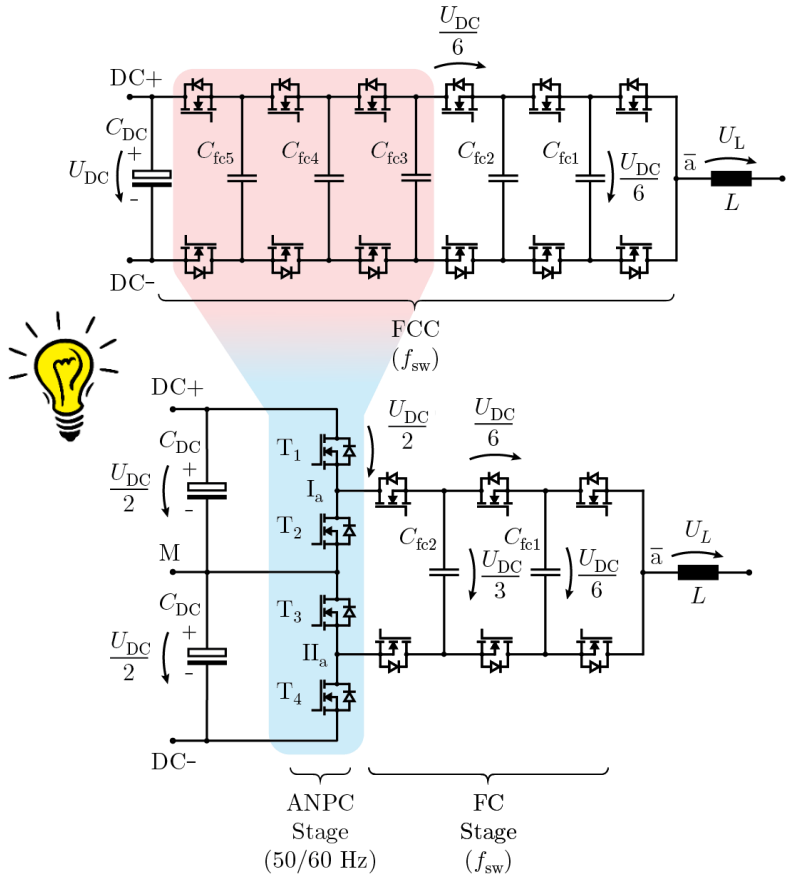


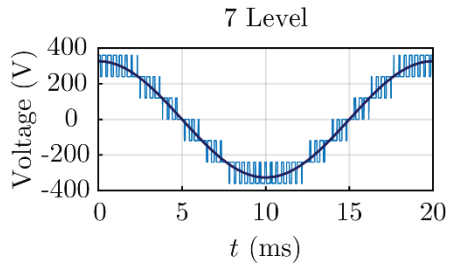


- *Compared to 2-Level Benchmark @ Same Filter Ind. Volt-Seconds* → $P_{semi,min,ML} \approx 1/N^{1.2}\, P_{semi,min,2L}$, $A_{chip,ML} \approx N^{1.2} A_{chip,2L}$

3-Φ Hybrid Multi-Level Inverter

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





★ *99.35%*
2.6kW/kg
56 W/in^3

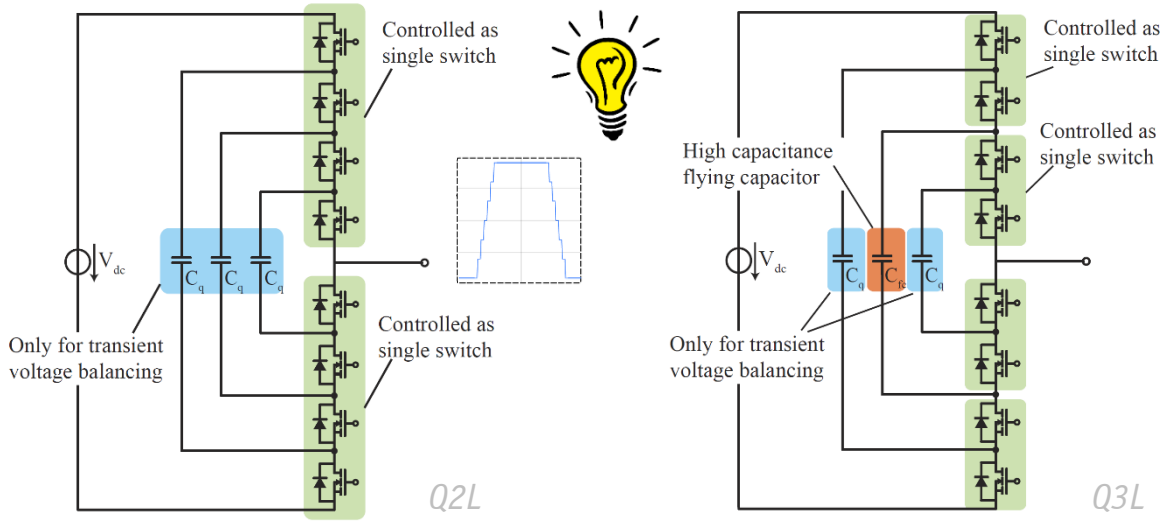
- *200V Si → 200V GaN Technology Results in 99.5% Efficiency*

Quasi-2L & Quasi-3L Inverters

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

Source: M. Schweizer

ABB



- *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

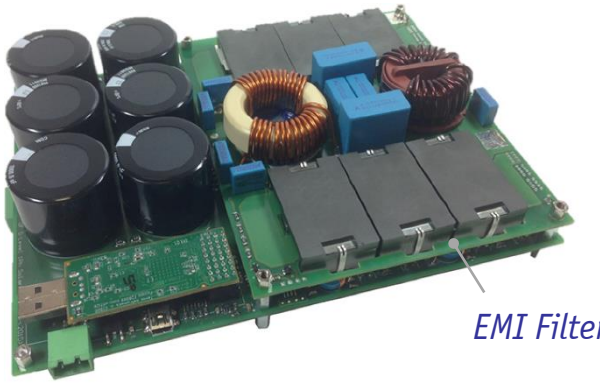
- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

Source: M. Schweizer

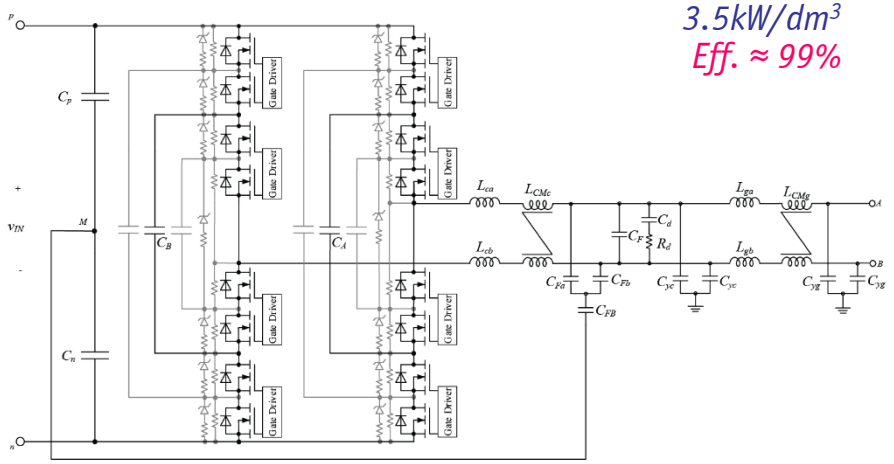
ABB

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

3.5kW/dm³
Eff. ≈ 99%



EMI Filter



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

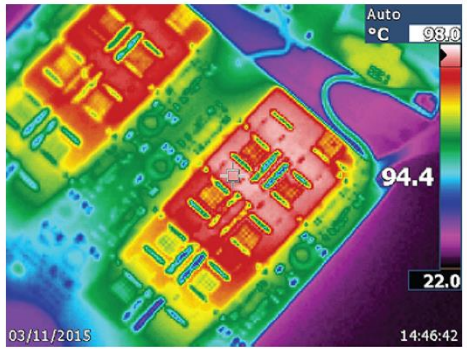
Quasi-2L & Quasi-3L Inverters

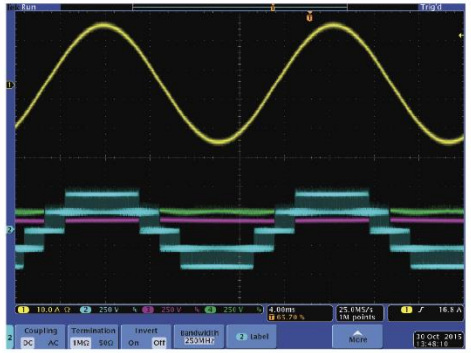
Source: M. Schweizer

ABB

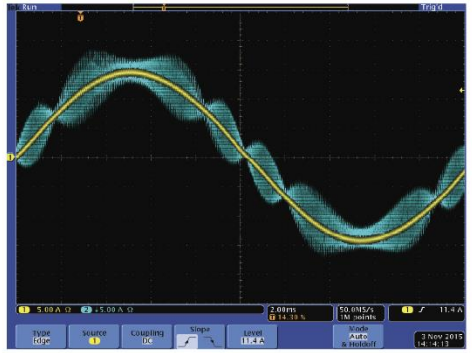
- *Operation of 5L Bridge-Leg Topology in Quasi-3L Mode*
- *Intermediate Voltage Levels Only Used During Sw. Transients*
- *Applicability to All Types of Multi-Level Converters*

Operation @ 3.2kW





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

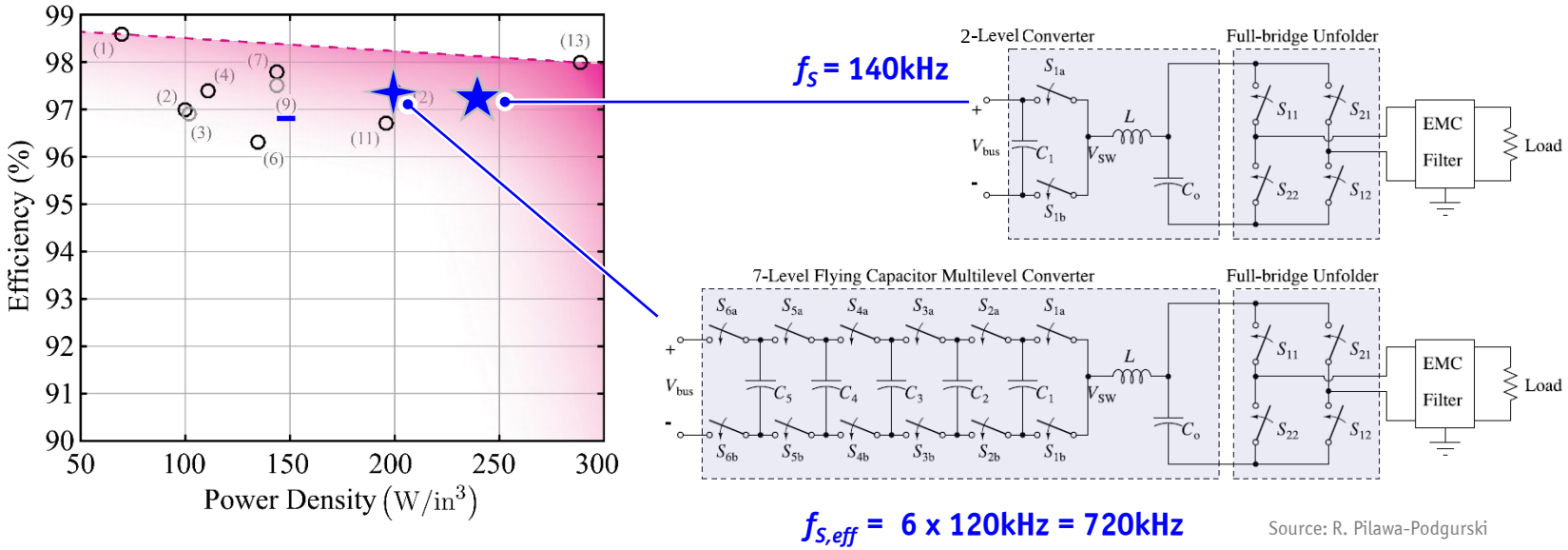


- *Output Current*
- *Conv. Side Current*

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

Remark 2-Level vs. Multi-Level Inverter

- *Example of Google Little Box Challenge*
- Target: *2kW 1-Φ Solar Inverter with Worldwide Highest Power Density*
- *Comparative Analysis of Approaches of the Finalists*



Source: R. Pilawa-Podgurski

- *3D-Packaging / Integration Highly Crucial for Utilizing Multi-Level Advantages (!)*

Remark 2-Level vs. Multi-Level Inverter

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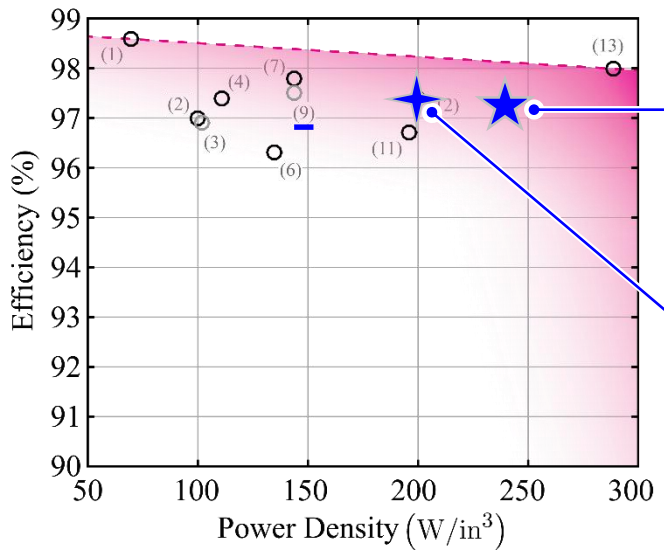
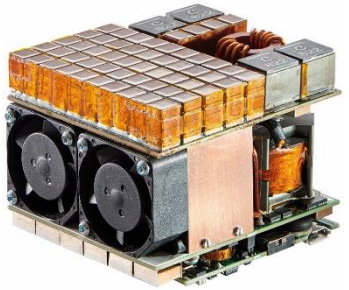
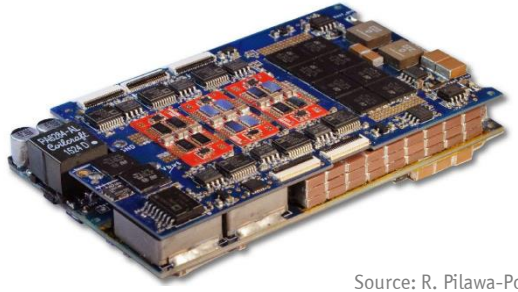


ETH zürich
Little-Box 2.0
240 W/in³
97.4%



ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
215 W/in³
97,6%

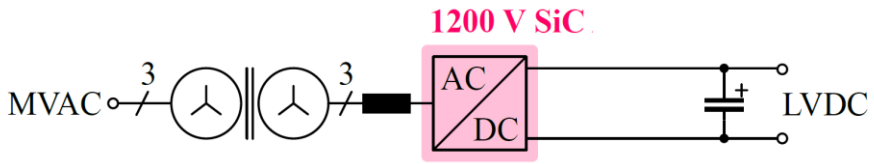


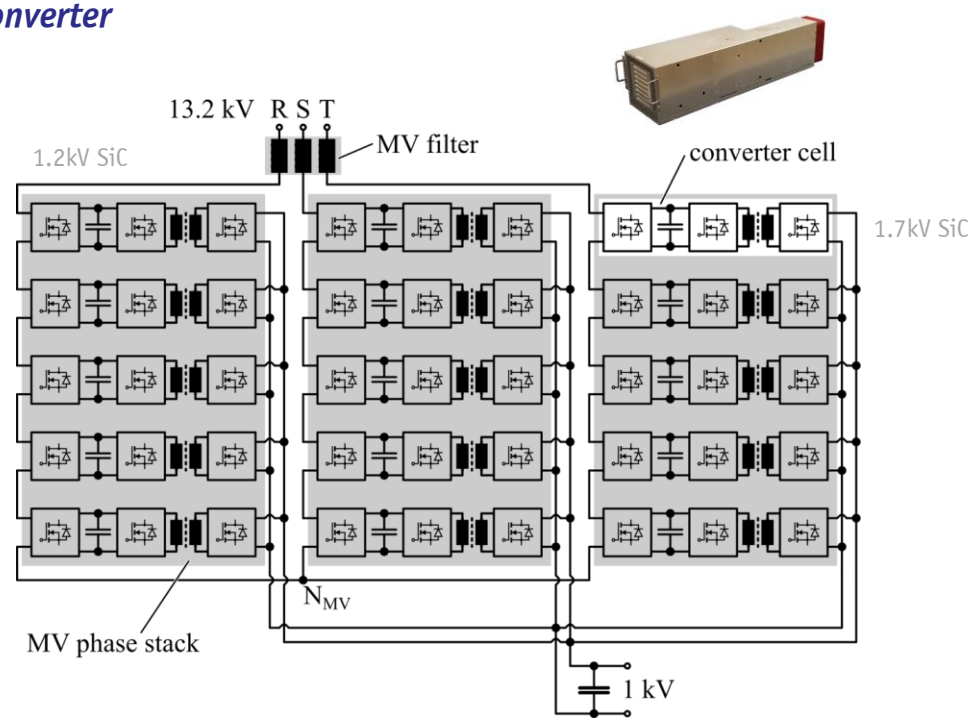
Source: R. Pilawa-Podgurski

- *3D-Packaging / Integration Highly Crucial for Utilizing Multi-Level Advantages (!)*

Remark 2-Level vs. Multi-Level Inverter

- *400kW Extreme Fast EV Charger | 3-Φ 13.2kV AC → 1kV DC*
- *Input Series Output Parallel (ISOP) Solid-State Transformer*
- *Alternative Low-Frequency Transformer & AC/DC Converter*

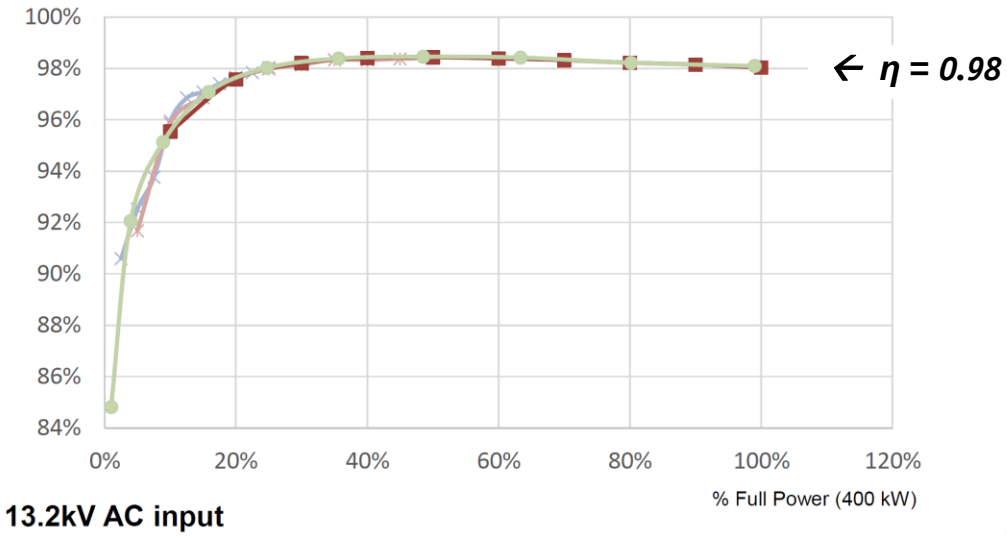




- *1.2kV SiC MOSFETs Utilized in Both Systems*
- *3 x 9 = 27 AC/DC—DC/DC Cells / 3-Level PFC Input Stage & Full-Bridge DC/DC Output Stage*

Remark 2-Level vs. Multi-Level Inverter

- *400kW Extreme Fast EV Charger | 3-Φ 13.2kV AC → 1kV DC*
- *Input Series Output Parallel (ISOP) Solid-State Transformer*

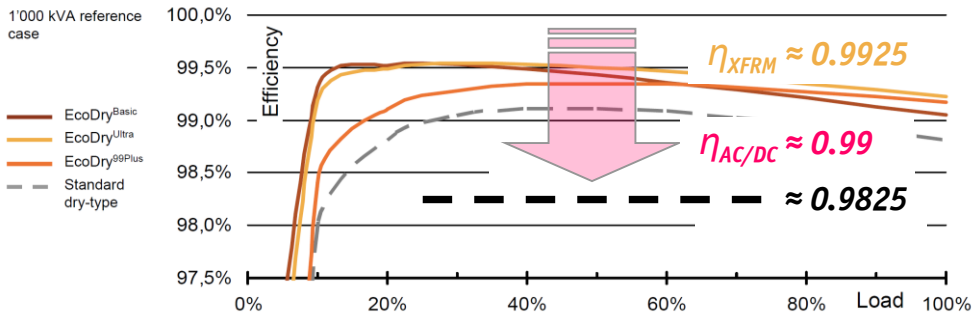


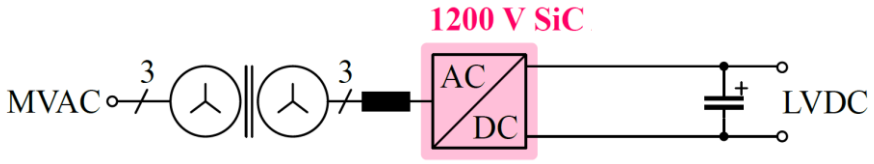
AC Input Cabinet | Converter Cabinets | Control Cabinet

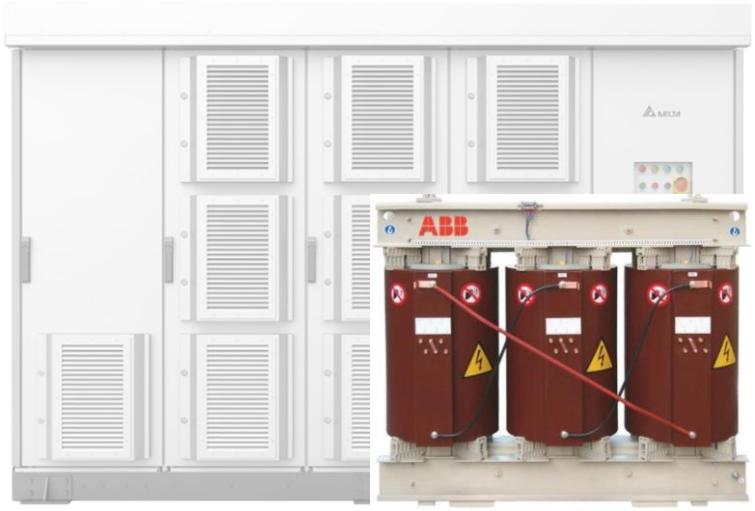
- *Forced Air Cooling*
- *3 x 9 = 27 AC/DC—DC/DC Cells*
- *98+ % Efficiency | 3000kgs Weight | 3100 x 1300 x 2100 mm Outer Dimensions*

Remark 2-Level vs. Multi-Level Inverter

- *400kVA EcoDry™ High-Efficiency Transformer & AC/DC Converter*
- *Vacuum Cast Coils → No Fire Hazard*
- *Amorphous Metal Core → Low No-Load Losses*
- *High Overvoltage / Overload Capability*

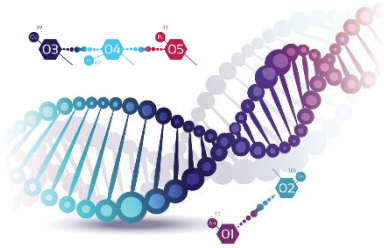






- *400kVA → 1400 x 750 x 1500 mm Outer Dimensions*
- *Utilizing SST SiC MOSFETs in AC/DC Stage → 99++ % Efficiency*
- *Higher Efficiency / Power Density / Robustness of LFT-Based Concept (!)*

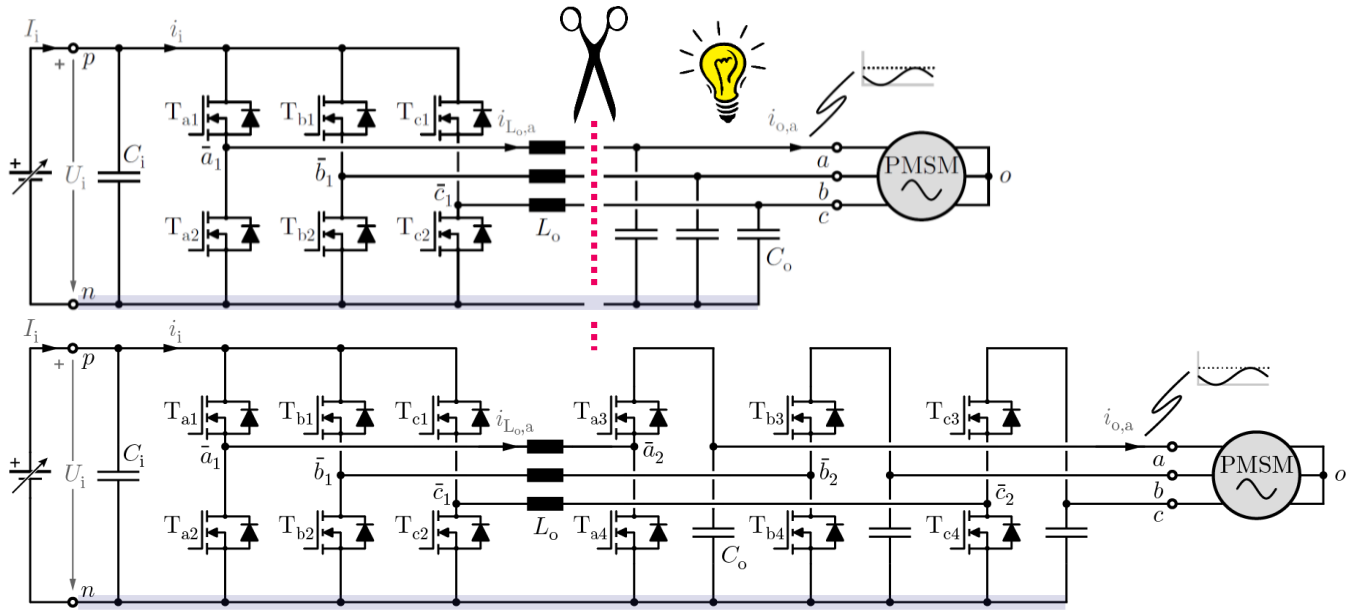
X-Concept



Functional Integration

Buck-Boost 3-Φ Variable Speed Drive Inverter

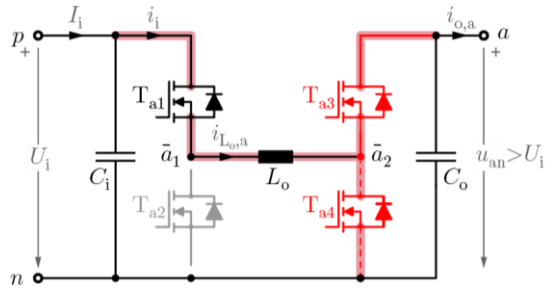
- *Generation of AC-Voltages Using Unipolar Bridge-Legs*
- *Utilize Filter Inductor for Boost Operation → Functional Integration*



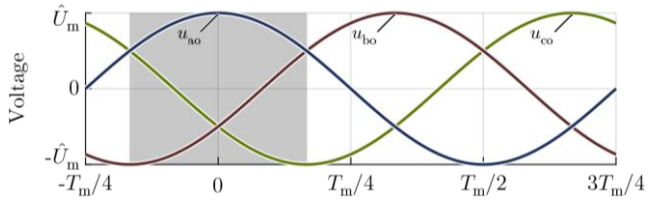
- *Switch-Mode Operation of Buck OR Boost Stage → Single-Stage Energy Conversion (!)*
- 3-Φ Continuous Sinusoidal Output / Low EMI → *No Shielded Cables / No Motor Insul. Stress*

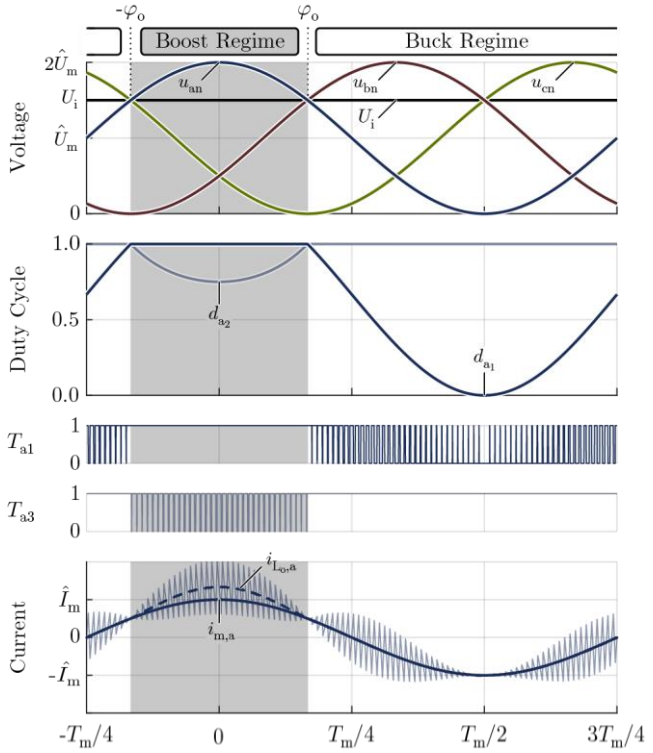
Boost-Operation $u_{an} > U_i$

- *Phase-Module*



- *Motor Phase Voltages*

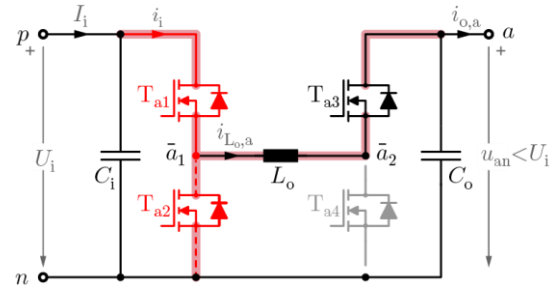




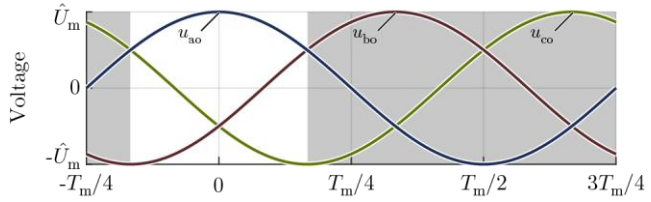
- *Current-Source-Type Operation*
- *Clamping of Buck-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion*

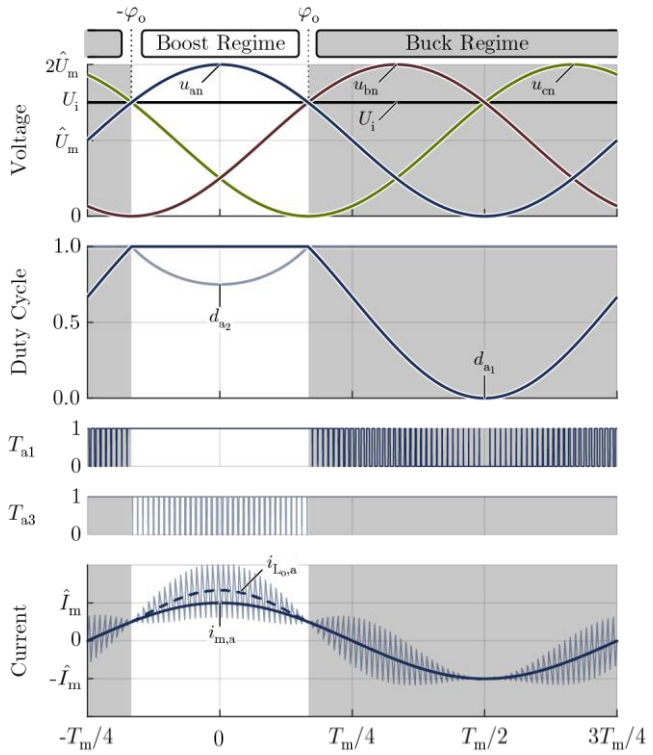
Buck-Operation $u_{an} < U_i$

- ***Phase-Module***



- ***Motor Phase Voltages***

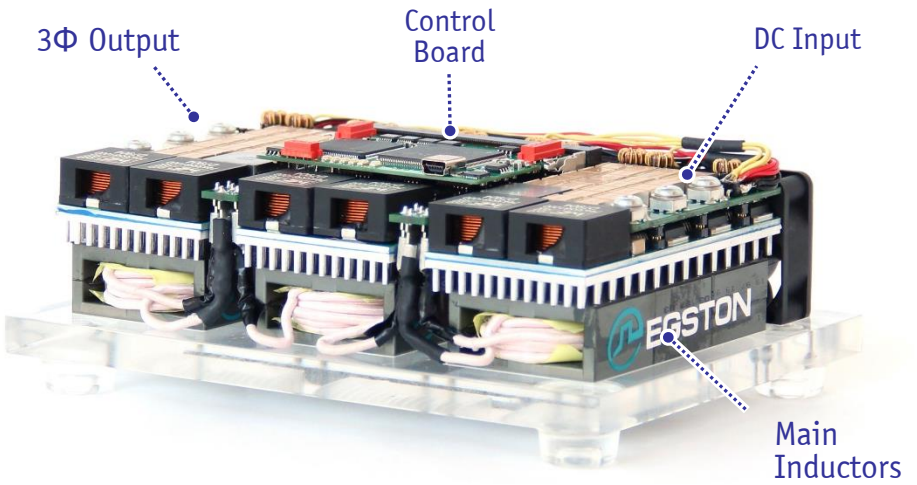


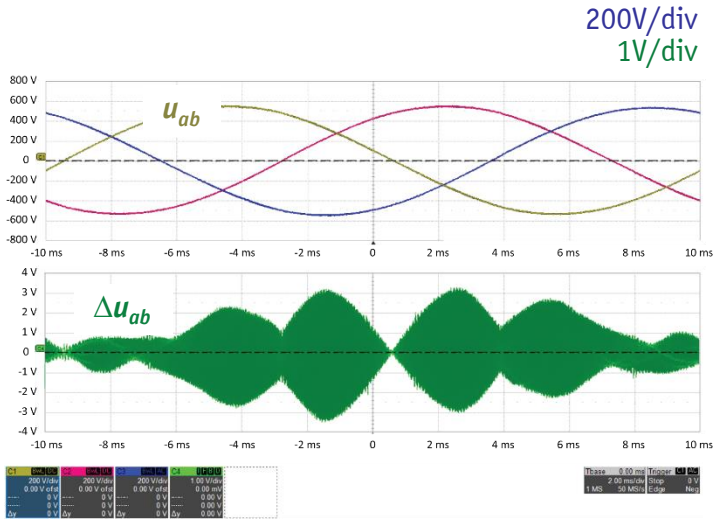


- ***Voltage-Source-Type Operation***
- ***Clamping of Boost-Bridge High-Side Switch → Quasi Single-Stage Energy Conversion***

SiC 3-Φ Buck-Boost 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





- *Dimensions → 160 x 110 x 42 mm³*

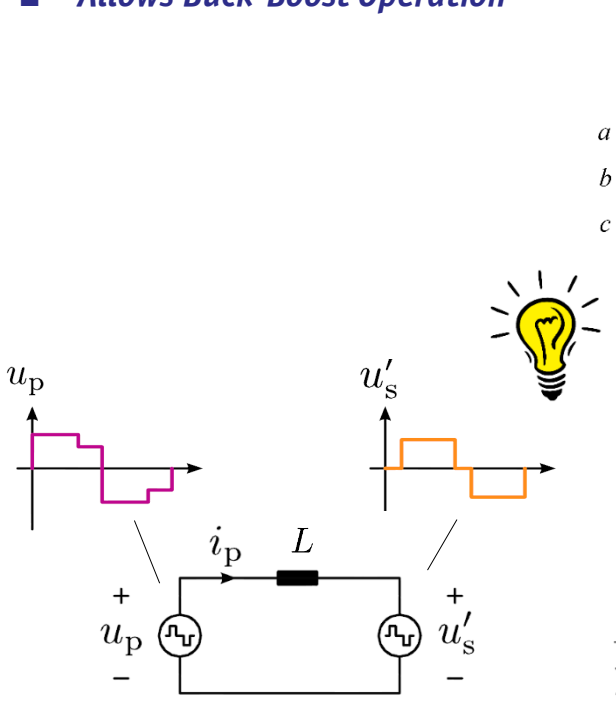
★ *≈ 245 W/in³*

Lighthouse Project

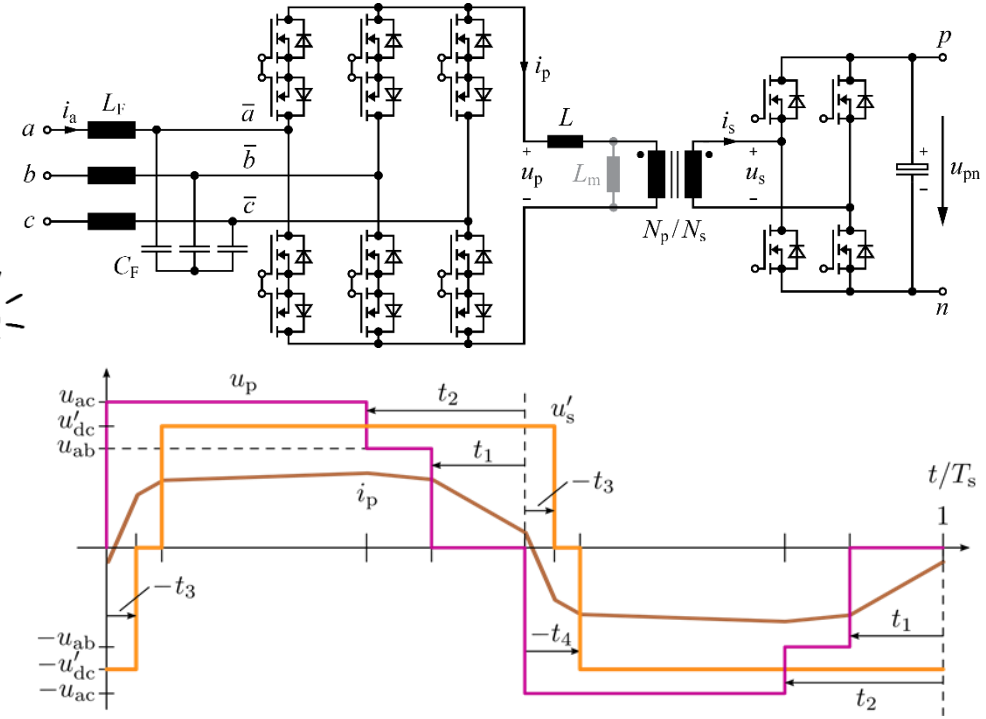
ETH zürich

Isolated Matrix-Type 3-Φ PFC Rectifier

- *Based on Dual Active Bridge (DAB) Concept*
- *Ingegration of 3-Φ PFC Rectifier & DC/DC Converter Stage*
- *Opt. Modulation (t_1...t_4) for Min. Transformer RMS Curr. & ZVS or ZCS*
- *Allows Buck-Boost Operation*



- *Equivalent Circuit*

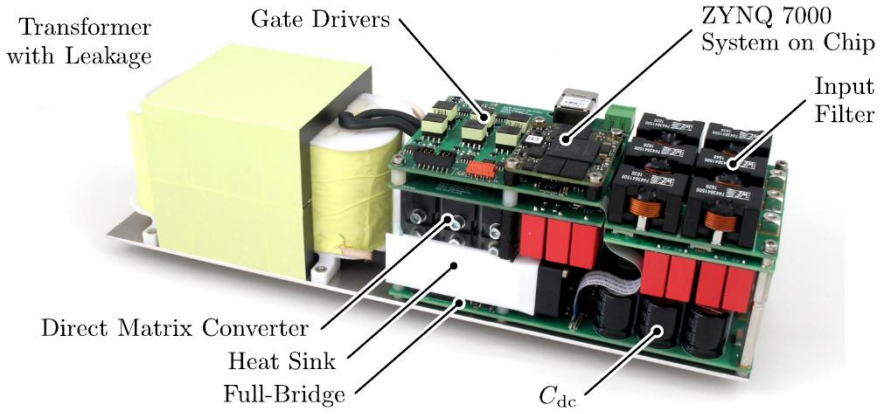


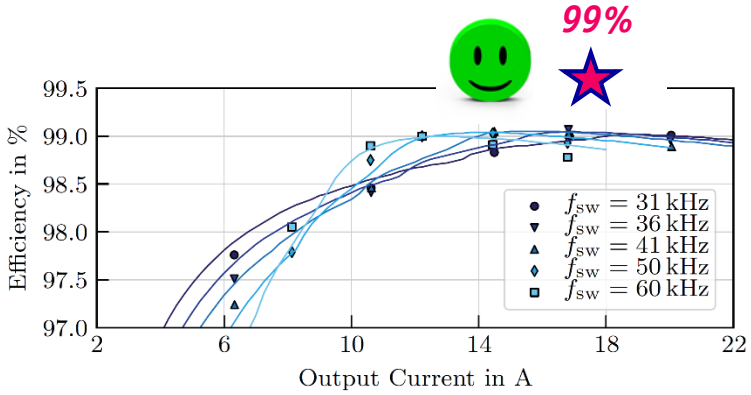
- *Transformer Voltages / Currents*

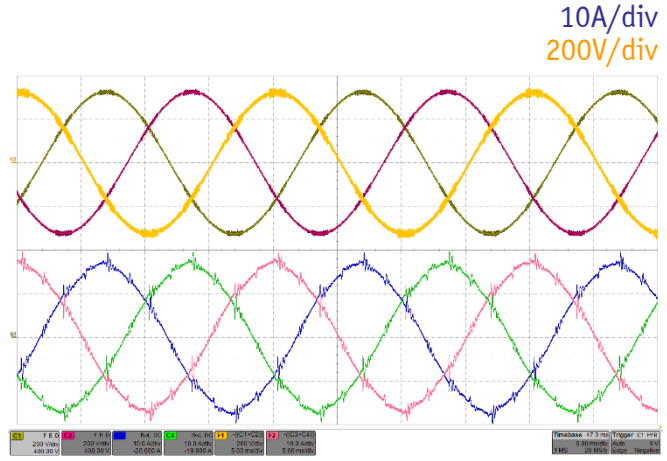
Isolated Matrix-Type 3-Φ PFC Rectifier

- **Efficiency η = 99% @ 60% Rated Load (ZVS)**
- *Mains Current $THD_I \approx 4\%$ @ Rated Load*
- *Power Density $\rho \approx 4 kW/dm^3$*

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



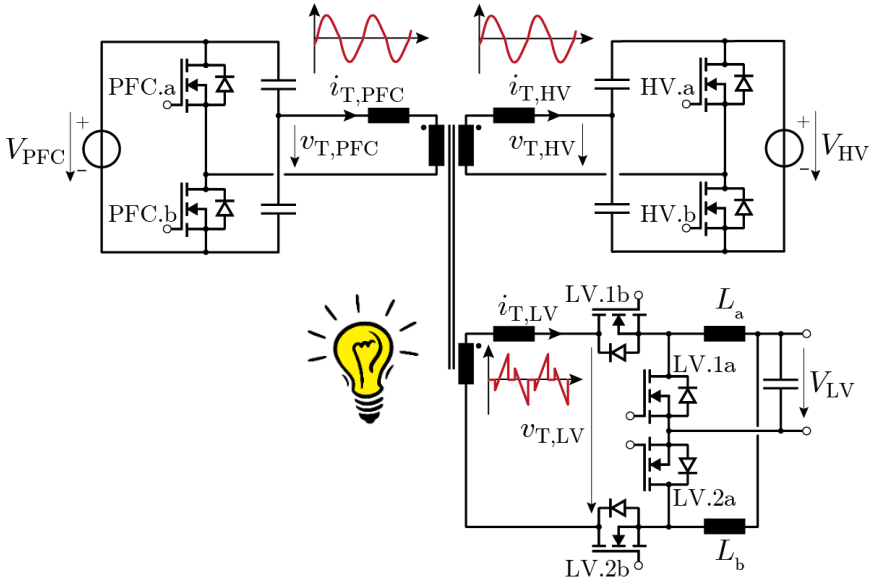


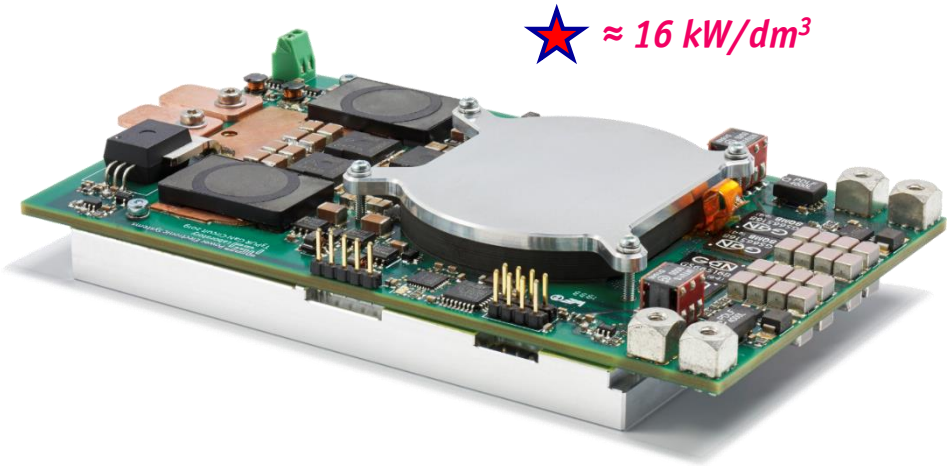


- *900V / 10mΩ SiC Power MOSFETs*
- *Opt. Modulation Based on 3D Look-Up Table*

3-Port Resonant GaN DC/DC Converter

- *Single Transformer & Decoupled Power Flow Control*
- *Charge Mode PFC → HV (250...500V) SRC DCX / Const. f_{sw}, Min. Series Inductance / ZVS*
- *Drive Mode HV → LV (10.5...15V) 2 Interleaved Buck-Converters / Var. f_{sw} / ZVS*
- *P = 3.6kW*

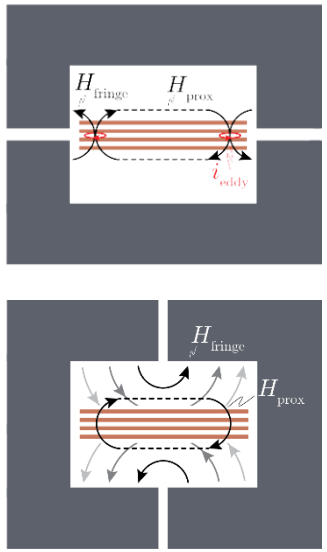


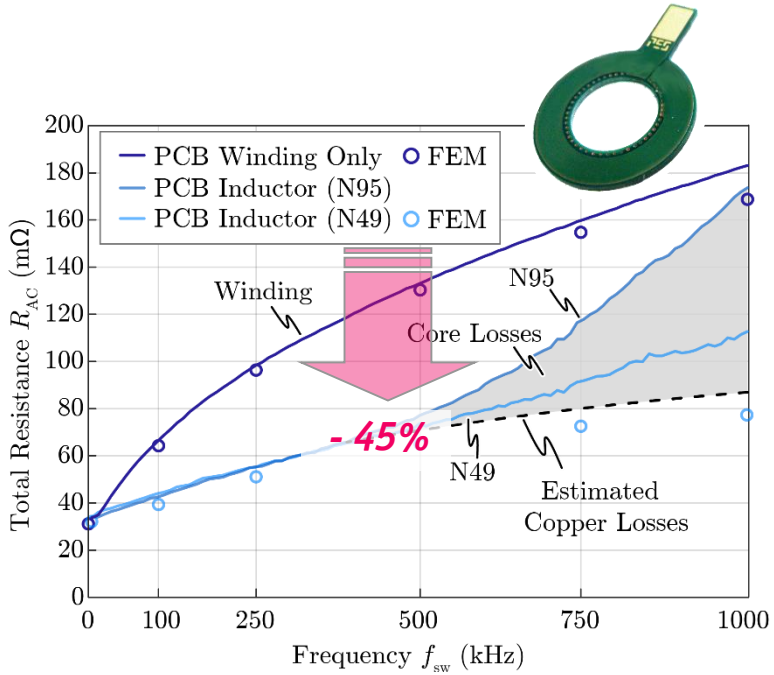


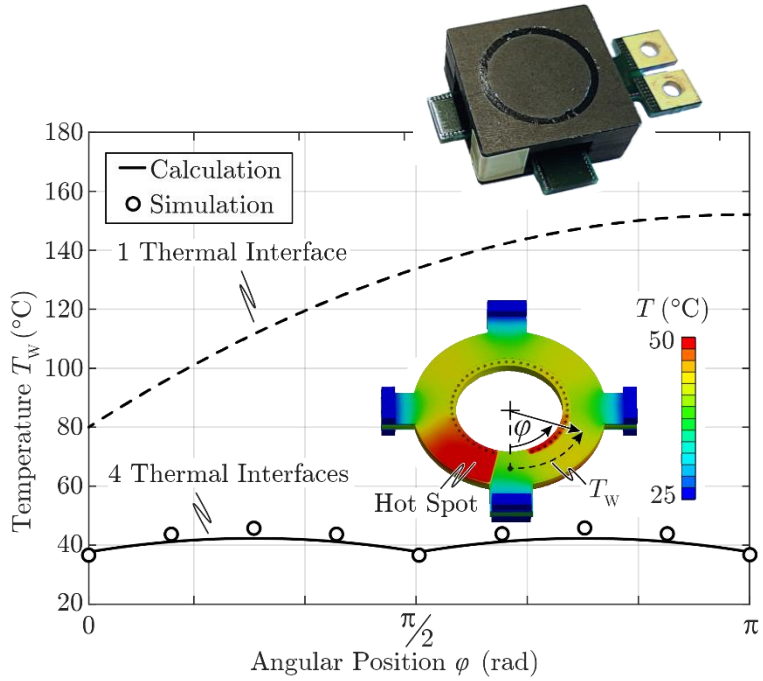
- *Peak Efficiency of 96.5% in Charge Mode / 95.5% in Drive Mode*
- *PCB-Based Windings / No Litz Wire Windings → Fully Automated Manufacturing*

Low-Loss PCB-Winding Inductor

- *Conv. PCB Windings & Airgaps → Skin / Proximity / Fringing Field ⊥ to PCB → Current Displacement*
- *Arrangement of Airgaps for Mutual Field Compensation*
- *Thermal Interfaces for Efficient Cooling*

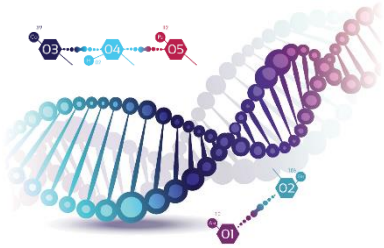






- *Optimal Positions & Wdg Distance of Airgaps for Multi-Airgap / Multi-Layer Inductors*
- *Factor of 3 Red. of Skin & Prox. Losses*

X-Concept

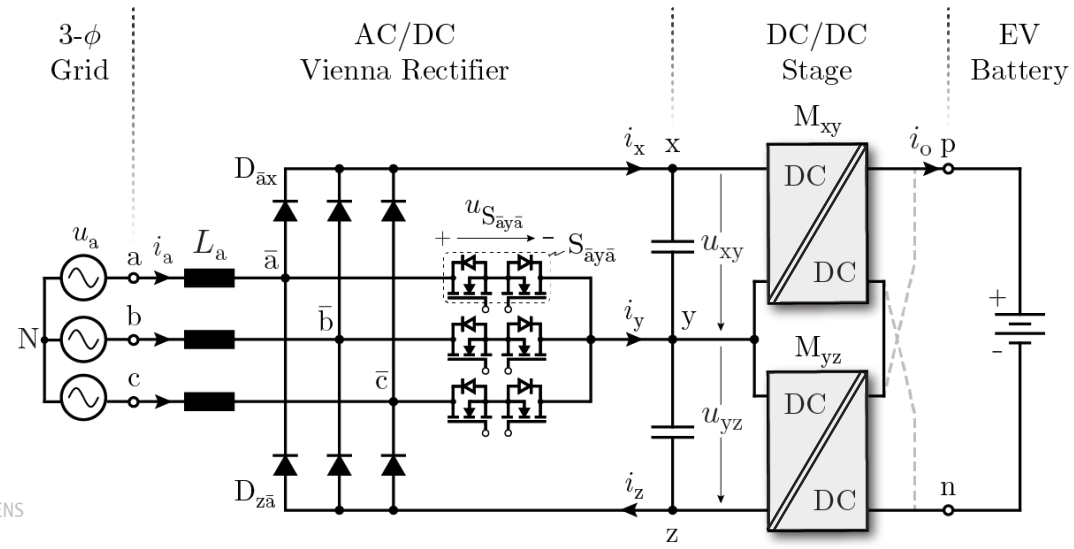


Synergetic Association

3-Φ EV-Charger Topology

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

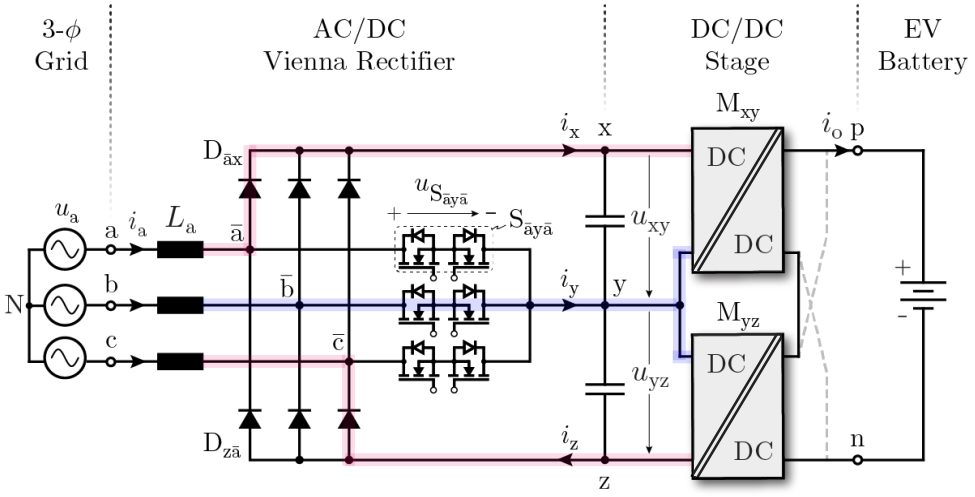
Source: SIEMENS

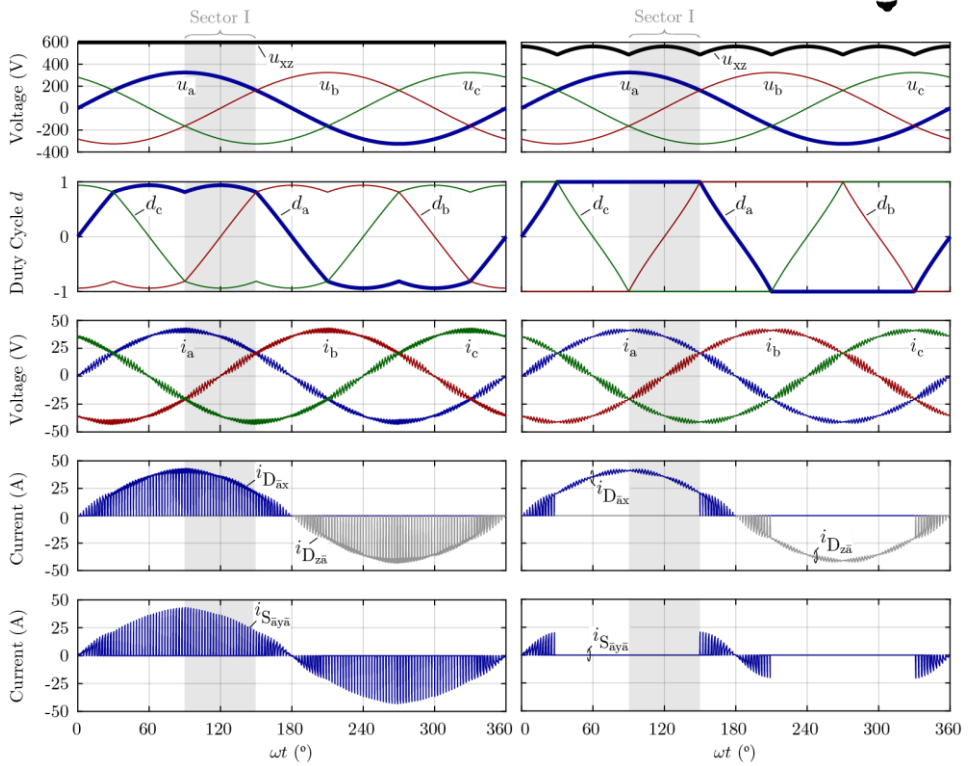


→ *Conventional / Independent* ***OR*** *"Synergetic Control" of Input & Output Stage*

Synergetic Association

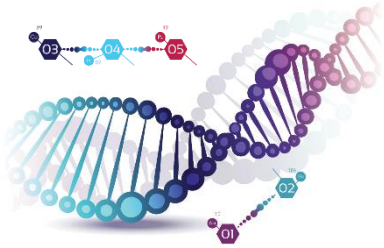
- *1/3-Modulation → Significant Red. of Losses of the Power Switches Comp. to 3/3-PWM*
- *Conduction Losses of the Switches ≈ -80%*
- *Switching Losses ≈ -70%*





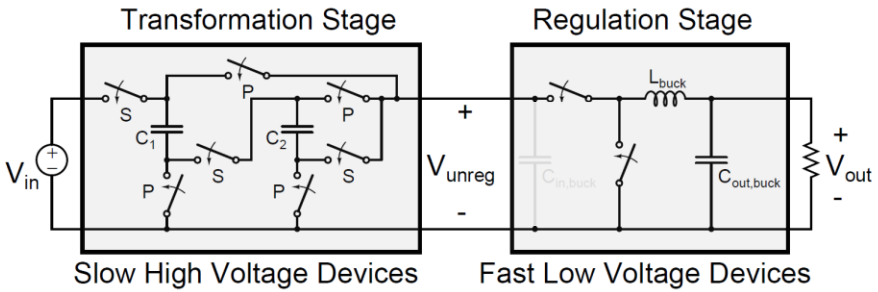
- *Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses*

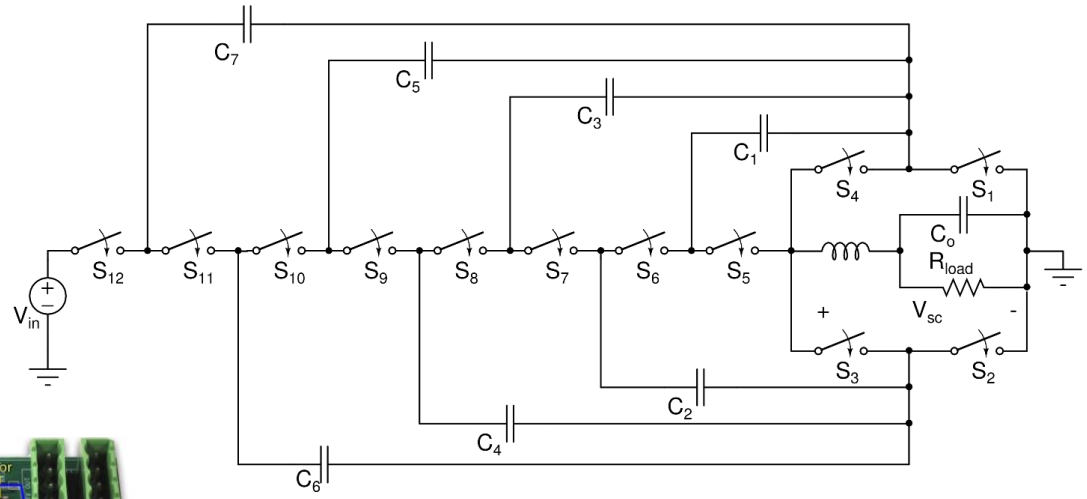
X-Concept Hybridization



Hybrid Switched-Capacitor Converters (SCC)

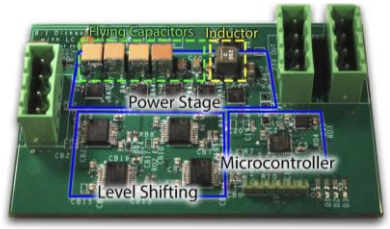
- *High Step-Down Ratio SCC / Voltage Adaption & High-Frequency Magnetic-Based Post-Regulation*
- *Current-Impressing Converter/Load → "Soft-Charging" / No Charging Curr. Spikes / High Efficiency*
- *High Energy Density of Caps. vs. Inductors → High Power Density / Suitable for Integration*





≈ 16 kW/dm³

U_{in} = 200V
U_{out} = 25V
I_{out} = 3A
f_{Sw} = 250kHz
η_{max} = 95.5%

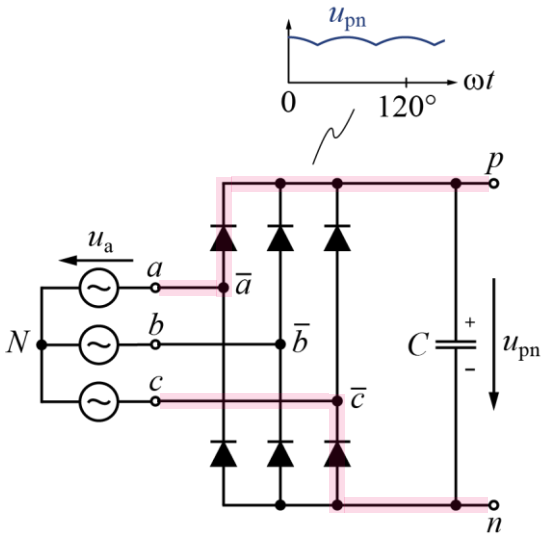


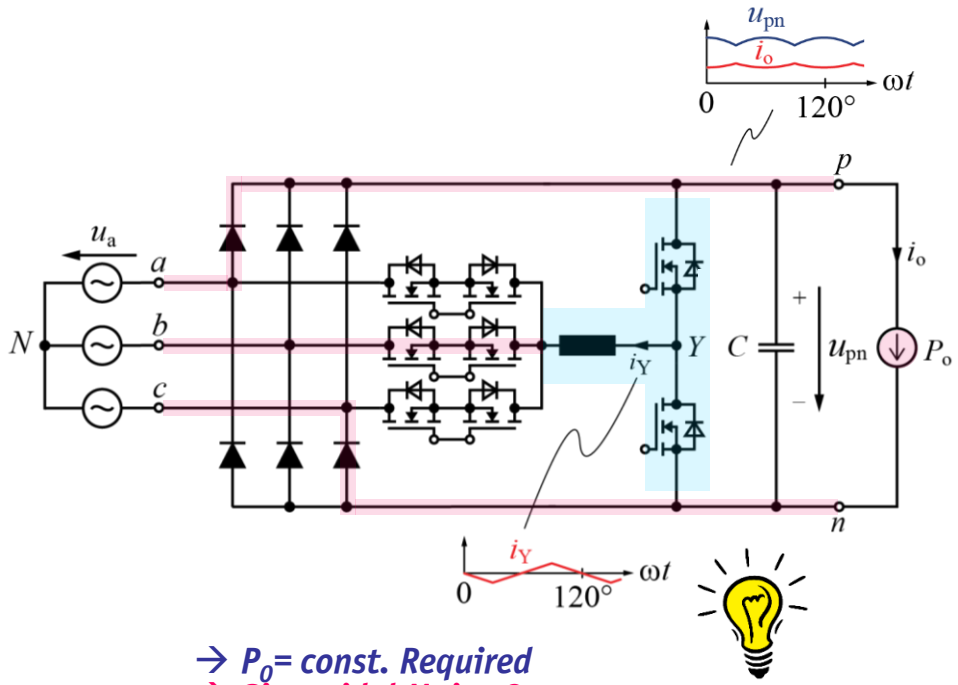
Source: Y. Lei & R. Pilawa-Podgurski, 2015

- *8-to-1 Dickson Soft-Charging SCC*
- 12 GaN Switches (40V & 100V) / 7 Flying Caps. (0.22uF & 2.2uF, 50|100|250V), 3.3uH

Hybrid Integrated Active Filter (IAF) PFC Rectifier

- *Hybrid Combination of Mains- and Forced-Commutated Converter*
- *3rd Harmonic Current Injection into Phase with Lowest Voltage*
- *Phase Selector AC Switches Operated @ Mains Frequency — 3-Φ Unfolder*





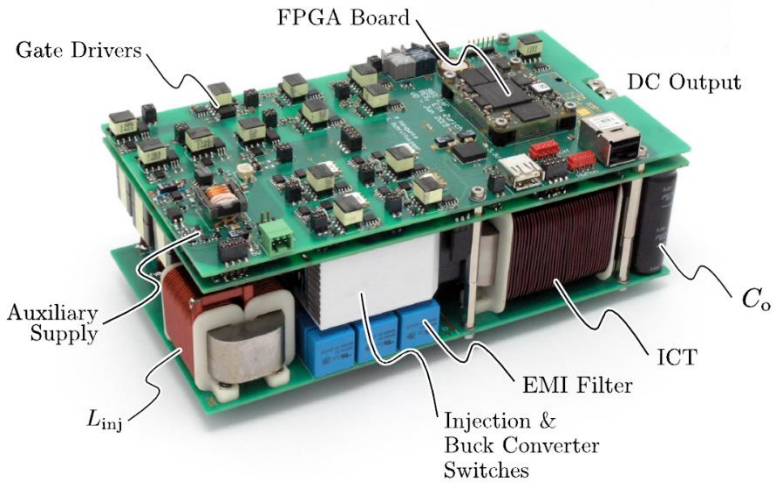
- *Non-Sinusoidal Mains Current*

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

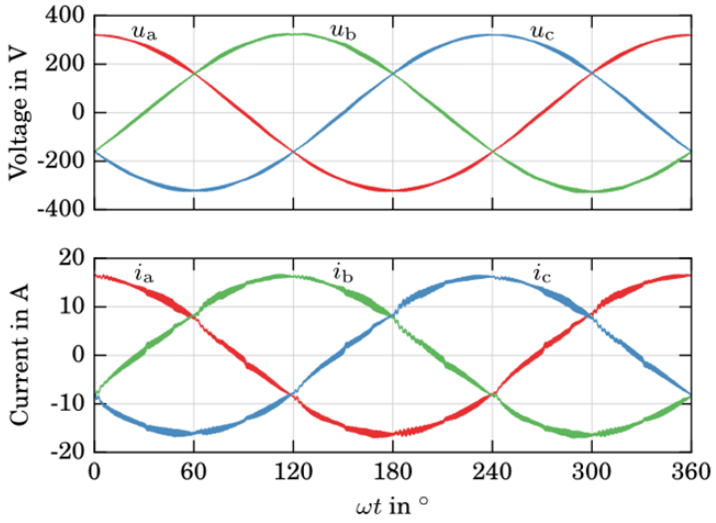
IAF PFC Rectifier & Buck Converter Demonstrator

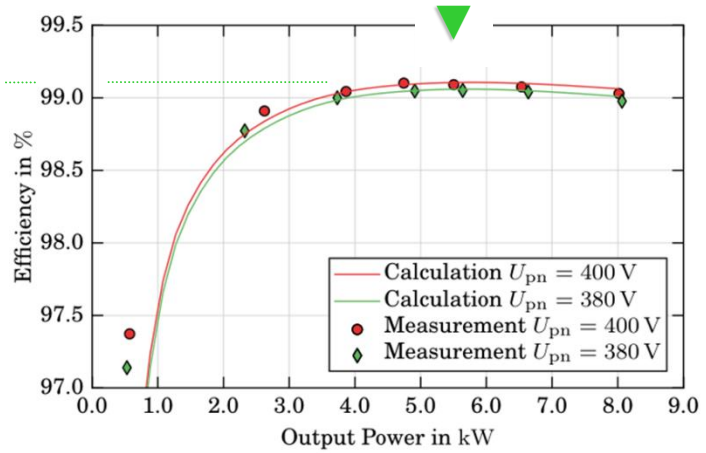
- *Efficiency η > 99.1% @ 60% Rated Load*
- *Mains Current THD_I ≈ 2% @ Rated Load*
- *Power Density ρ ≈ 4kW/dm³*

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



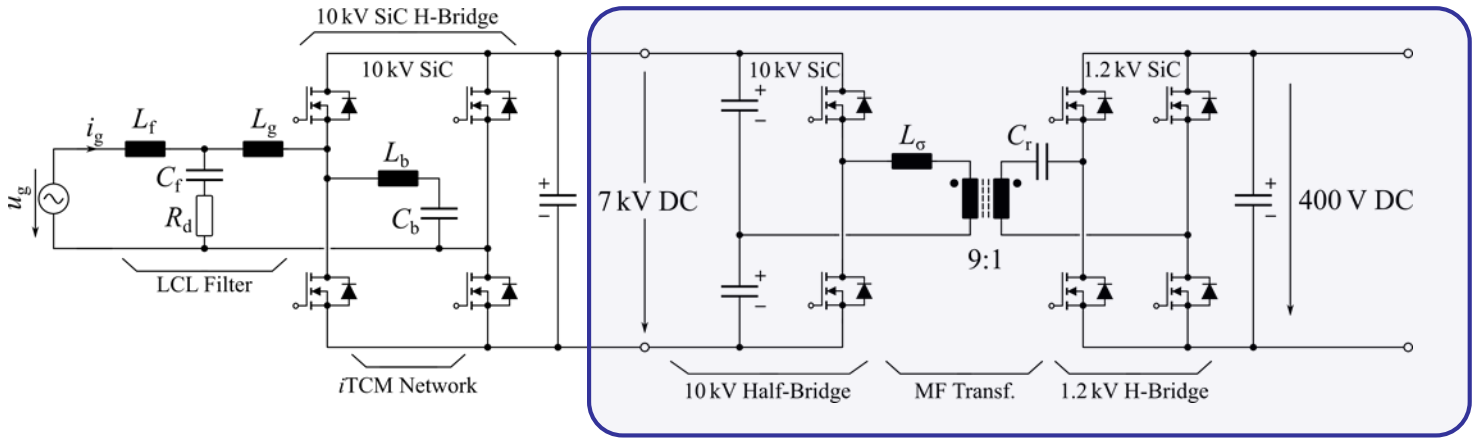
- *SiC Power MOSFETs & Diodes*
- *2 Interleaved Buck Output Stages*
- *Controlled Output Voltage*

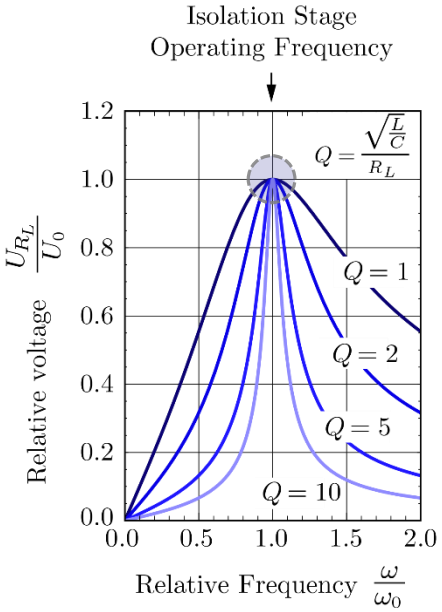




Hybrid 1-Φ AC/DC—DC/DC Solid-State Transformer

- *Bidirectional 3.8 kV_{rms} 1-Φ AC → 400V DC @ 25 kW Power Conversion*
- *Based on 10 kV SiC MOSFETs*
- *Full Soft-Switching*



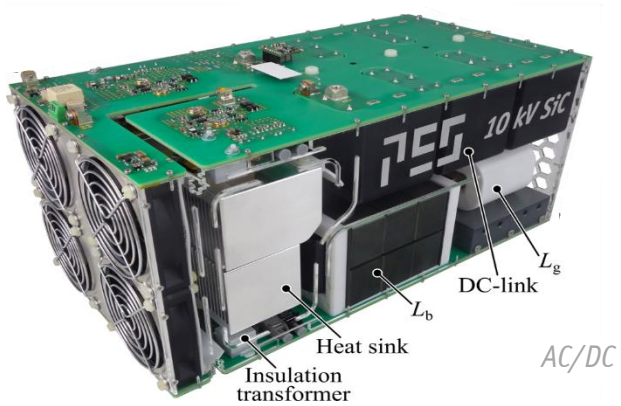


★ **3.3 kW/dm³** ★ **3.8 kW/dm³**

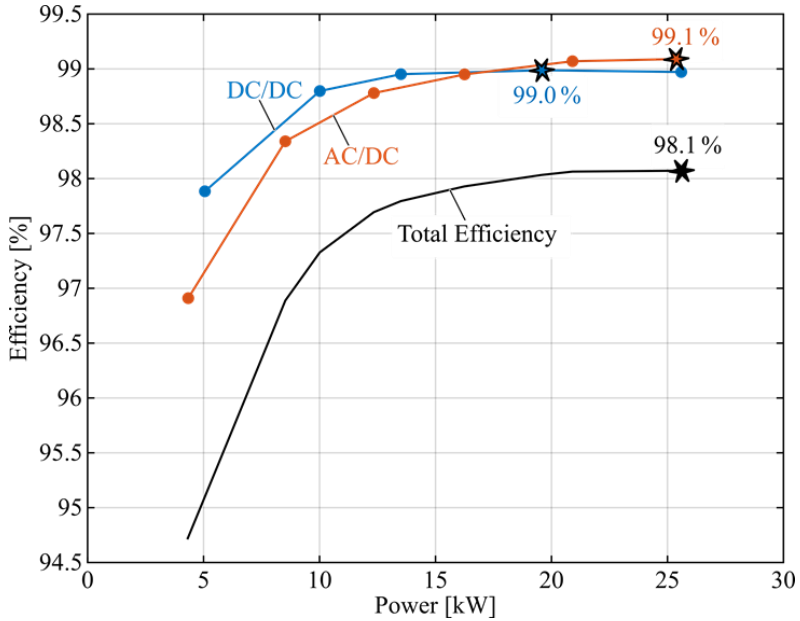
- *35...75 kHz iTCM Input Stage*
- *48 kHz «DC-Transformer» Output Stage*

Overall Performance AC/DC — DC/DC

- *Full Soft-Switching*
- *98.1% Overall Efficiency @ 25 kW*
- *1.8 kW/dm³ (30 W/in³)*

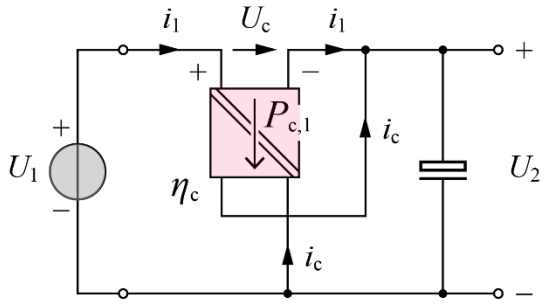


AC/DC Stage



- *Significantly Simpler System Structure Compared to Multi-Module (ISOP) SST Approach*

Partial/Differential Power Processing



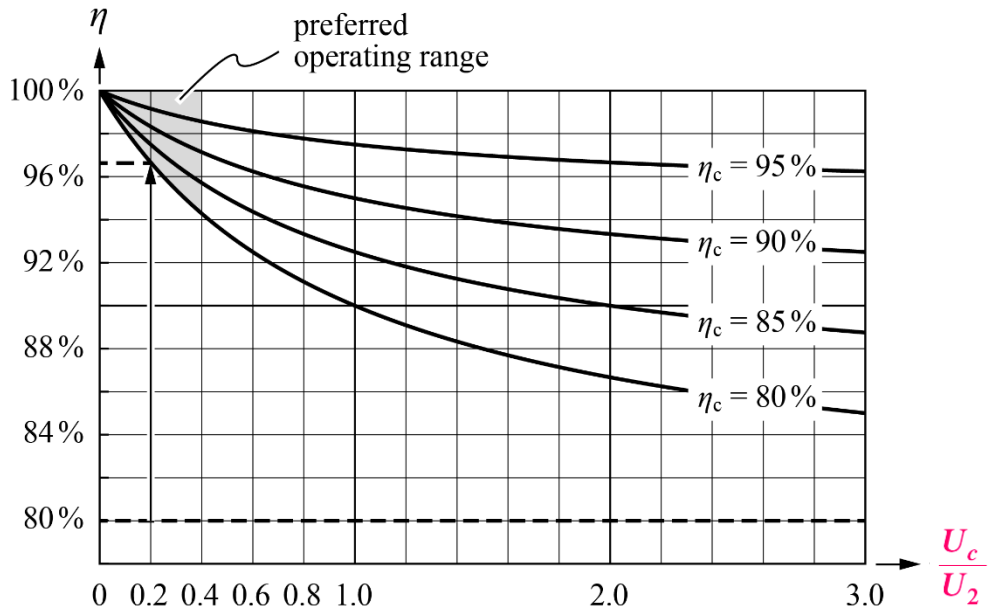
$$U_2 = U_1 - U_c$$

- ***Reduced Converter Rating***

$$p_c = \frac{P_{c,1}}{P_1} = \frac{\frac{U_c}{U_2}}{1+\frac{U_c}{U_2}}$$

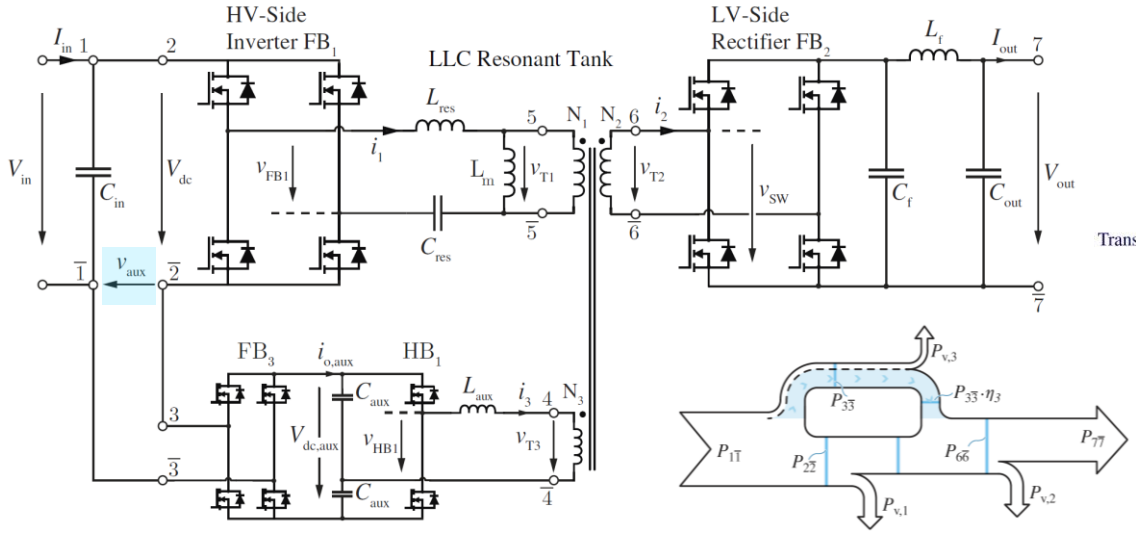
- ***Low Influence of Converter Efficiency on Overall Efficiency***

$$\eta = \frac{P_2}{P_1} = \frac{(1+\frac{U_c}{U_2}\eta_c)}{(1+\frac{U_c}{U_2})}$$

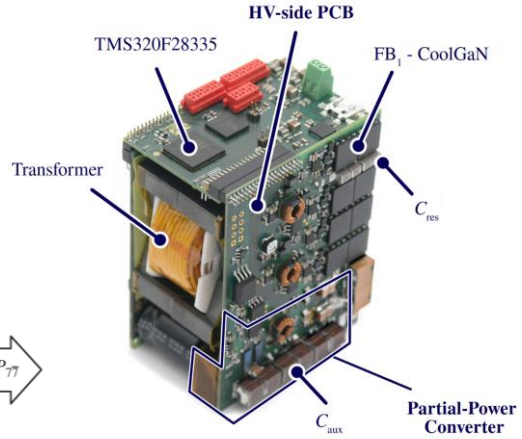


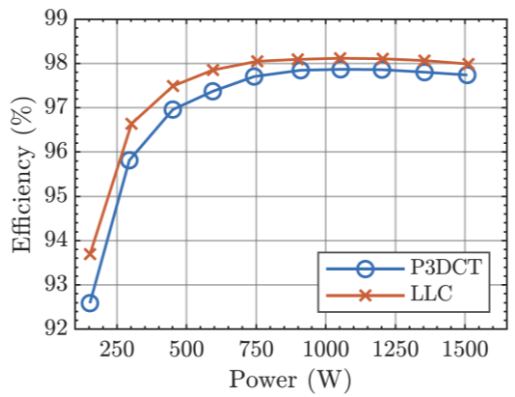
Partial-Power Pre-Regulated LLC DC-Transformer

- *Aux. Converter Stage for ± 10% V_{in} Compensation | V_{in} = 340V ... 420V*
- *Const. Voltage Transfer Ratio / High Efficiency LLC «DC/DC Transformer» @ Const. Frequency | f_{sw} = 100kHz*
- *Const. Output Voltage | V_{out} = 48V*



Partial-Power Pre-Regulation (P³) Converter



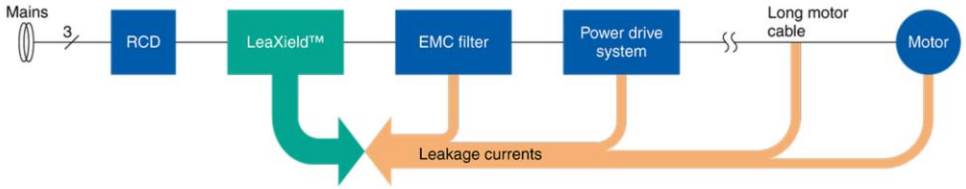


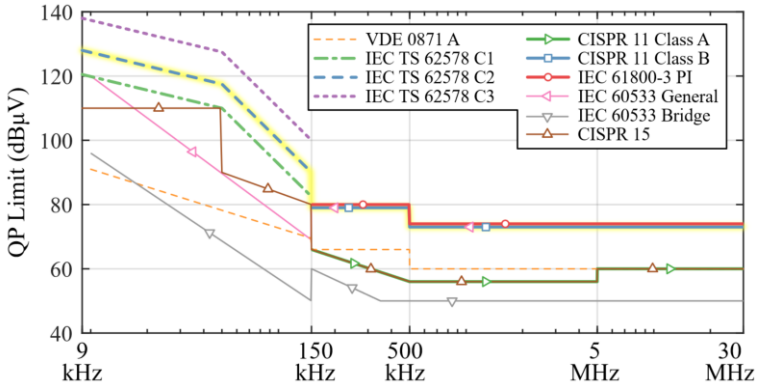
≈ 140 W/in³

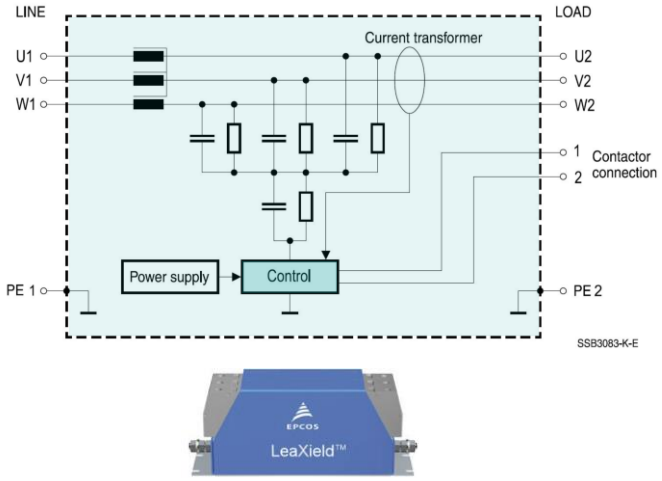
- *Rectangular Aux. Voltage Added or Subtracted (f_{aux} = 600kHz) from V_{in}*
- *Marginal Impact of Control on Overall Power Density & Efficiency*

Hybrid EMI-Filter / Leakage Current Reduction

- *Future Extension of EMI Limits — 9kHz ...150kHz | IEC TS 62578 Tech Spec. for Active Infeed Conv. Applications*
- *Earth Leakage Current "Compensation"*
- *Conducted CM EMI-Filter*

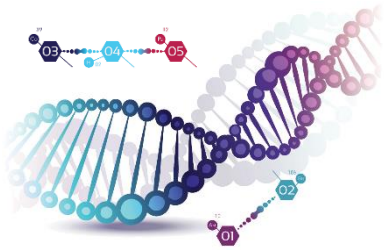






- *Prevents Unintentional Residual Current Device (RCD) Tripping w/o Isolation Transformer*
- *Attenuation of Cond. EMI Emissions in Wide Frequency Range 30/40/15dB @ 4/10/150kHz*

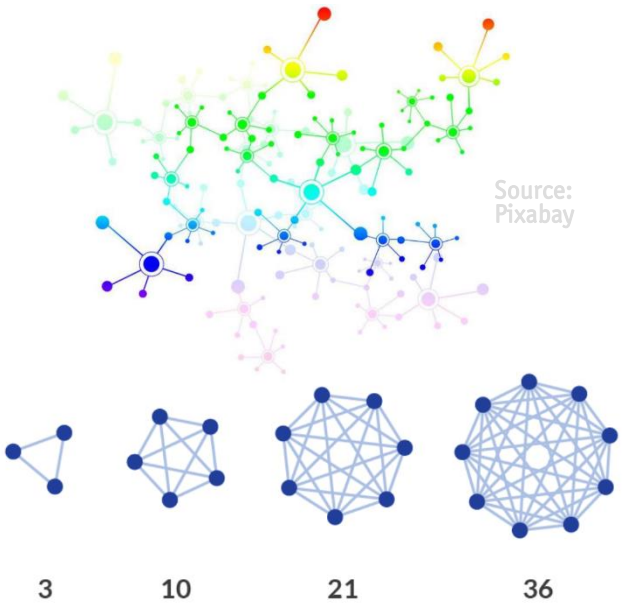
X-Concept

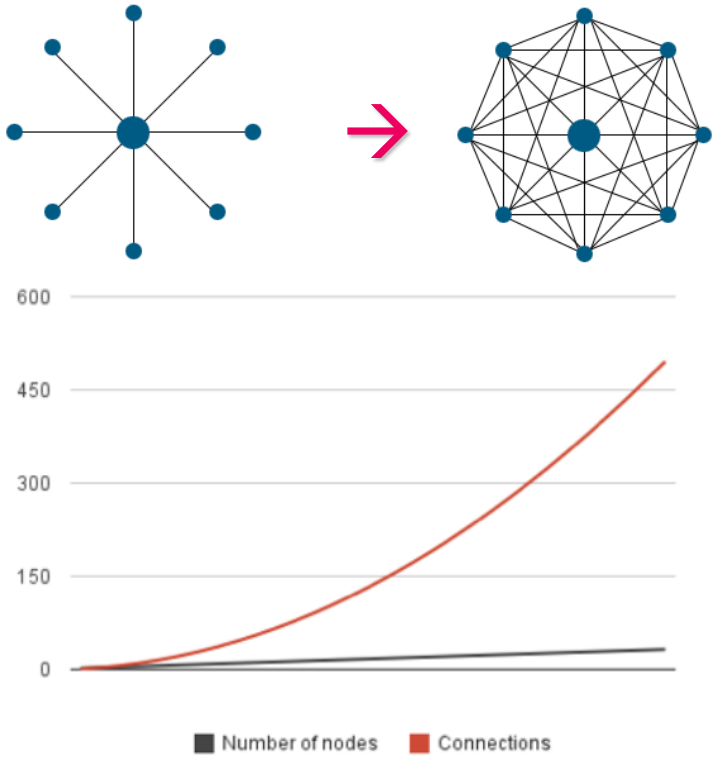


Decentralization

Networking Scaling

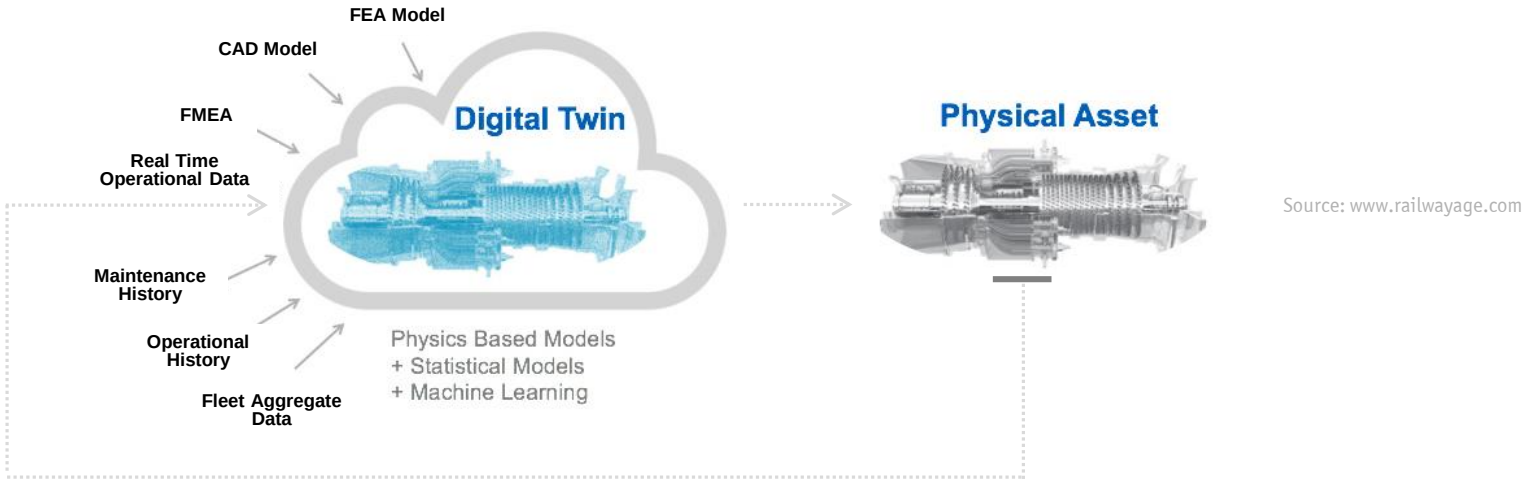
- **Metcalfe's Law**
  - **Moving from Hub-Based Concept to Community Concept Increases Potential Network Value Over-Proportional → ~n(n-1) or ~n log(n)**





IIoT in Power Electronics

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



Source: www.railwayage.com

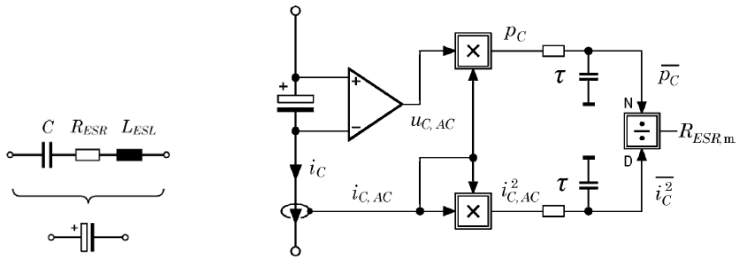
- *Requires Proper Interfaces for Models & Automated Design*
- *Model of System´s Past/Current/Future State → Design Corrections / Predictive Maintenance etc.*

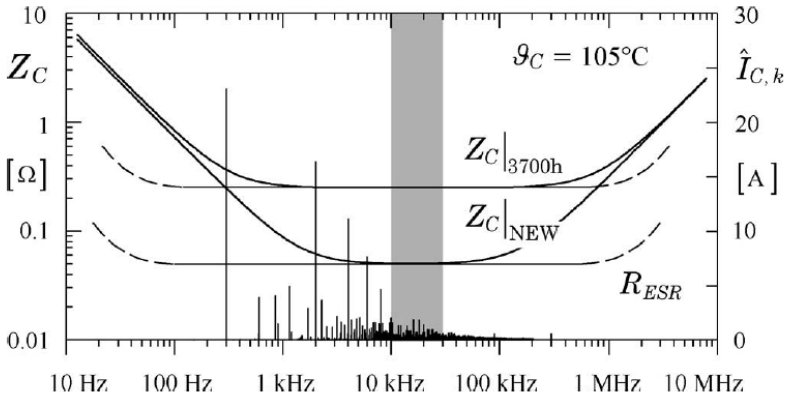
IIoT Starts with Sensors (!)

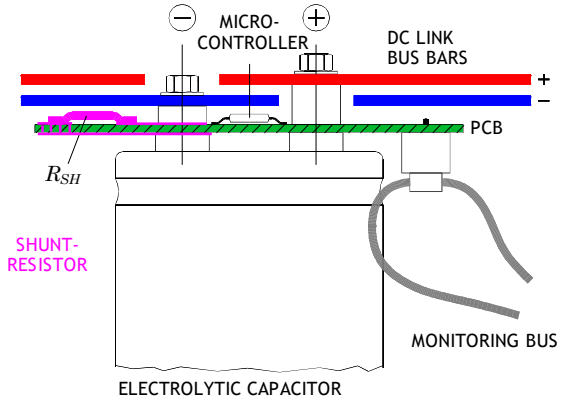
- *Condition Monitoring of DC Link Capacitors*
- *On-Line Measurement of the ESR in "Frequency Window" (Temp. Compensated)*
- *Data Transfer by Optical Fibre or Near-Field RF-Link*

TECHNISCHE UNIVERSITÄT WIEN Vienna | Austria

Source: Prof. Ertl
TU Vienna, 2011



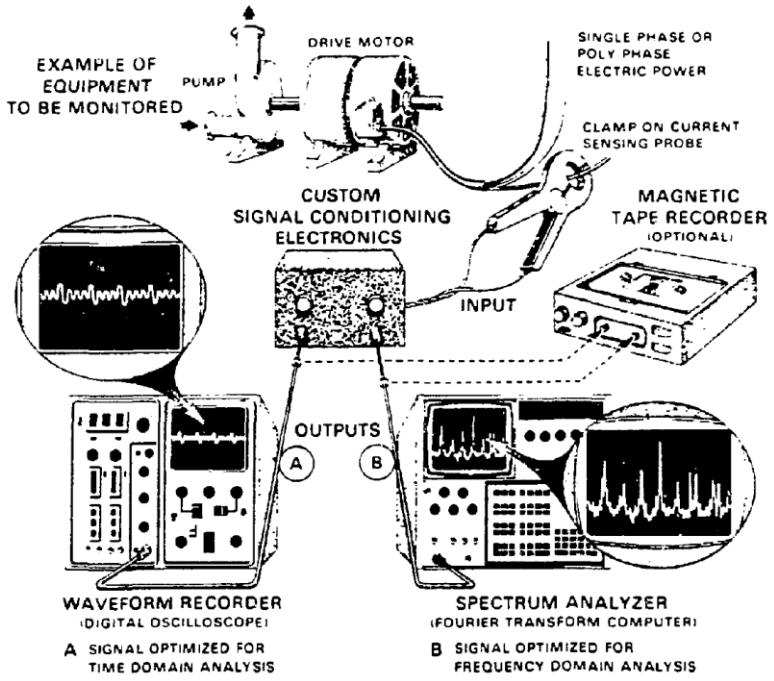




- *Possible Integration into Capacitor Housing or PCB*
- *Additionally features Series Connect. Voltage Balancing*

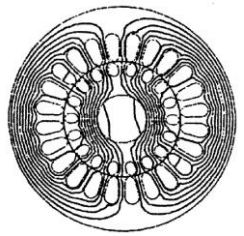
Motor Condition Monitoring / Fault Detection

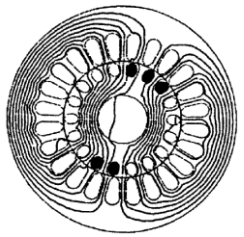
- *Utilize the "Motor as Transducer" for Determining Aging / Service Wear of Motor / Mechanical Load*
- *Non-Intrusive Detection of Mechanical or Electrical - Bearings or Stator & Rotor - Abnormalities*
- *Motor Current Signature Analysis (MCSA) in Time & Frequency Domain*



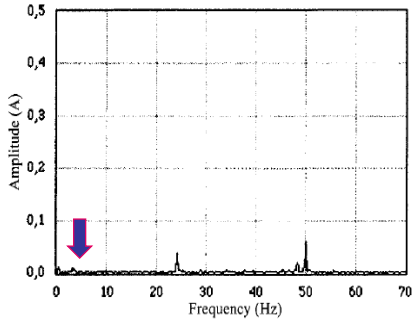
Source: ORNL, Kryter et al., 1989

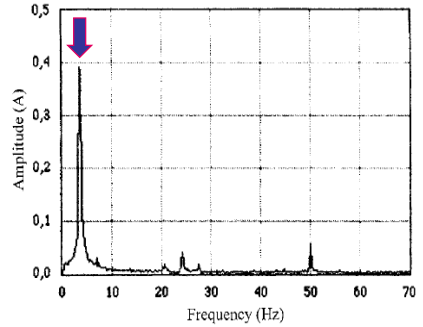
Source: R. Fiser et al, 1997





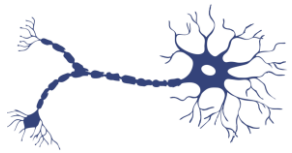
Source: S. Cruz et al, 1998





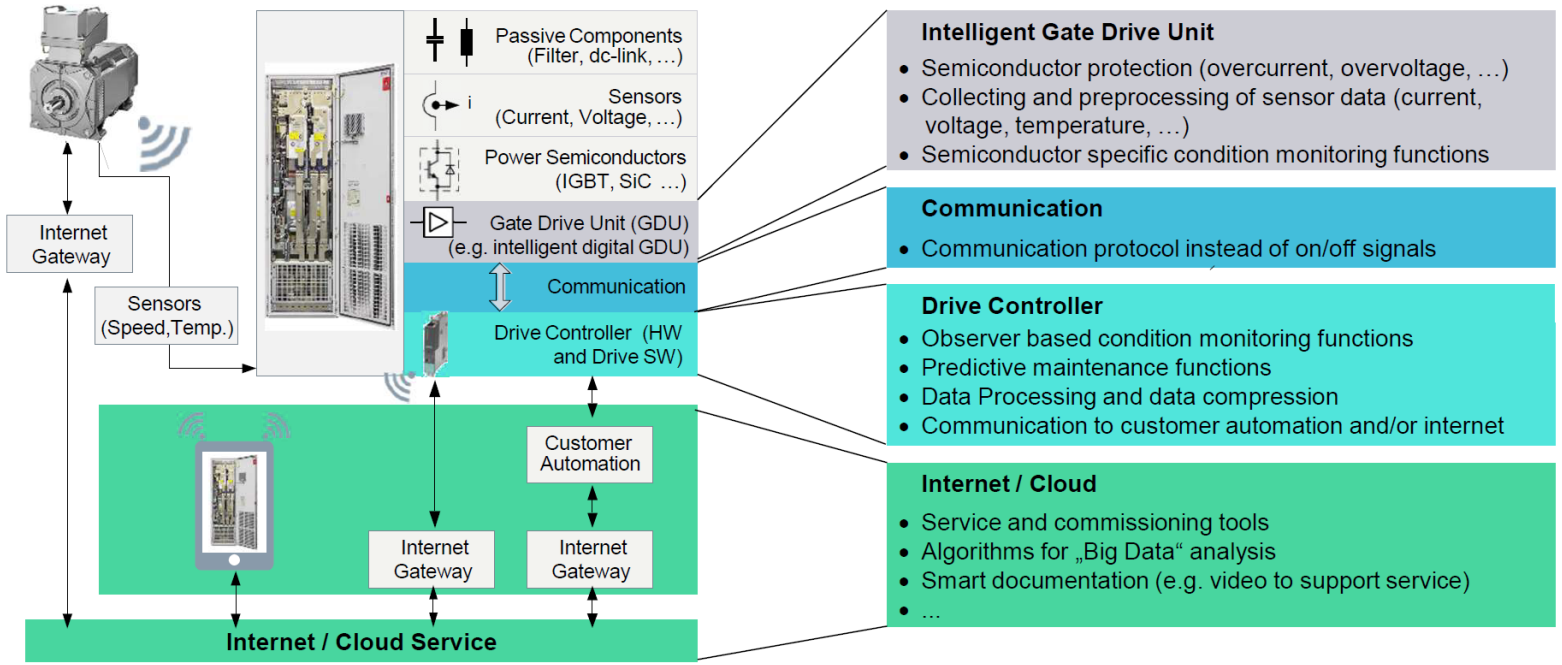
- *ORNL (1989) — MCSA Condition Monitoring of Motor-Valves in Nuclear Power Plant Safety Systems*
- *ANNs Discussed for Diagnostics since 25+ Years — Improvements w/ Computing Power of Modern Inverters*

Smart Inverter Concept



- *Utilize High Computing Power and Network Effects in the Cloud*

Source: R. Sommer
SIEMENS

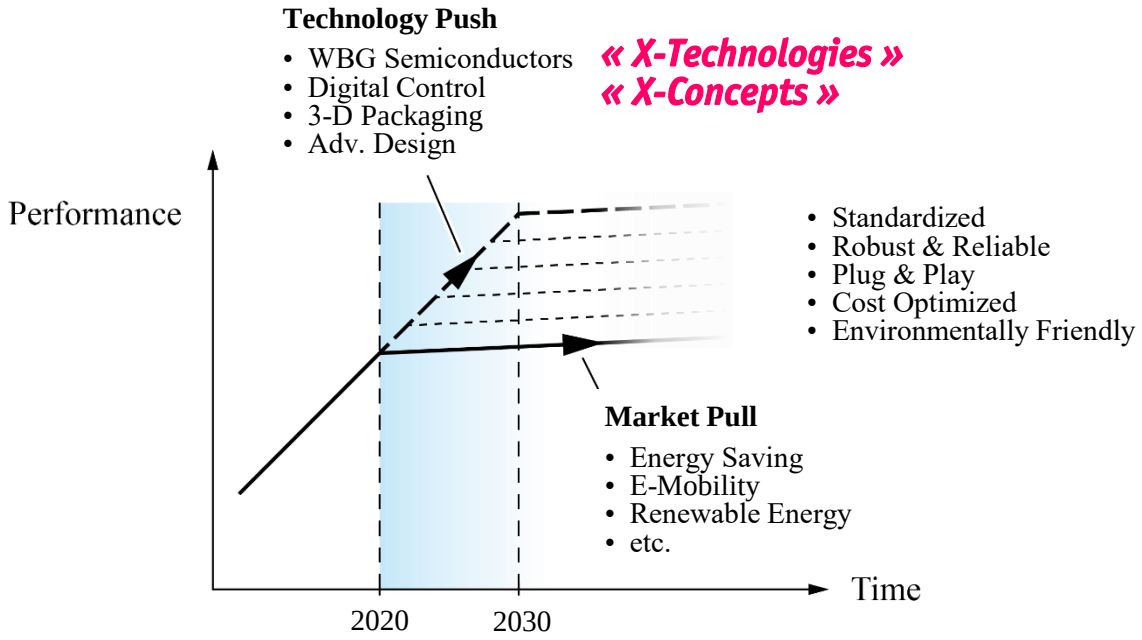


- *On-Line Protection / Monitoring / Optimization on Component | Converter | Drive | Application Level*

Conclusion

Future Development / Trends

- *MEGA-Trends — Renewable Energy / Energy Saving / E-Mobility / "SMART XXX"*
- *Power Electronics will Massively Spread in Highly Diverse Applications*

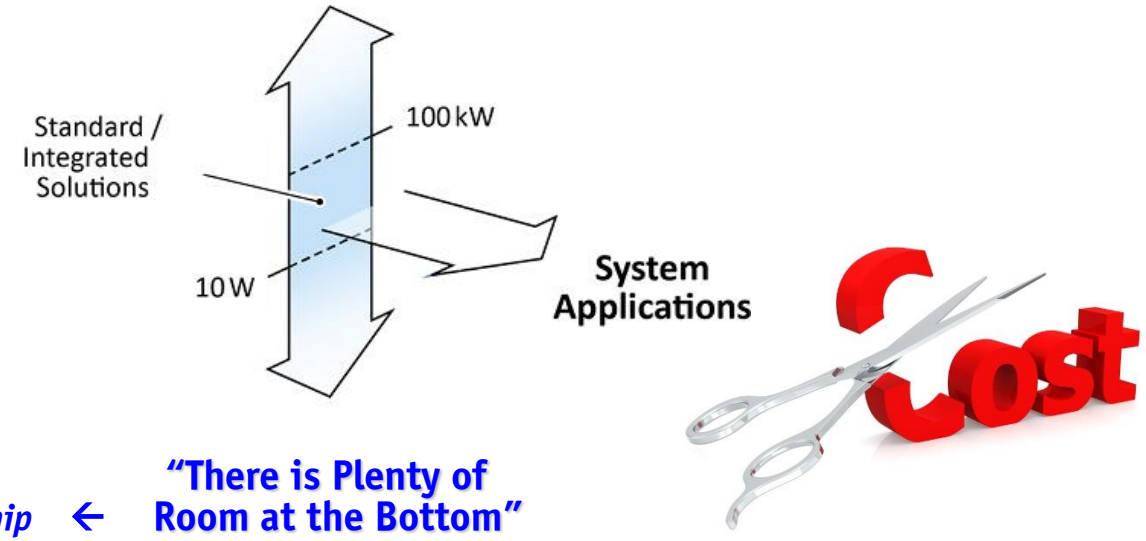


- *More Application Specific Solutions*
- *More Specific Requirements – High Peak/Avg. Ratio, Wide Volt. Range etc.*
- *Cost Optimization @ Given Performance Level for Standard Solutions*
- *Design / Optimize / Verify (All in Simulation) — Faster / Cheaper / Better*

Future Application Areas

- *WBG Driven Extension to Medium Voltage | Extension to Micro-Power Electronics*
- *Extreme Cost Pressure for Standardized Solutions (!)*

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

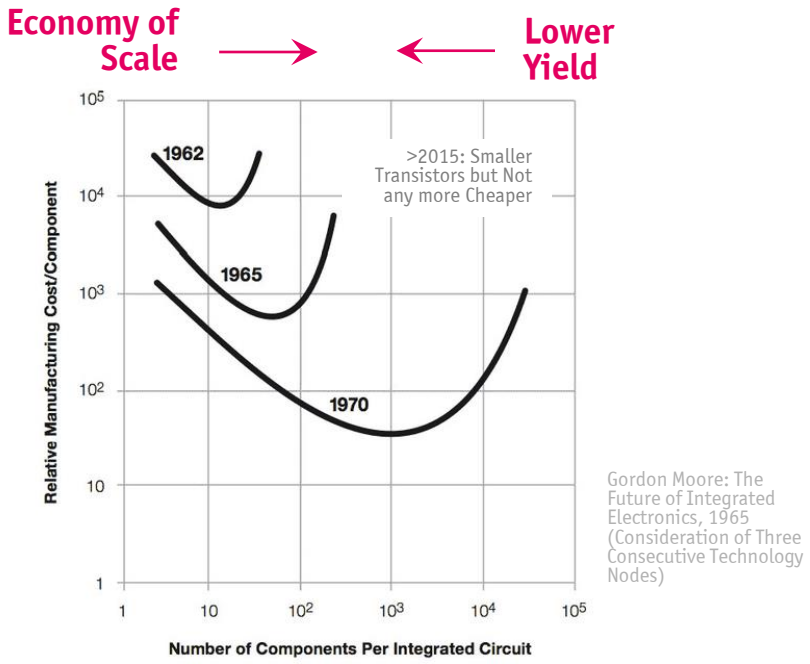


Power-Supplies on Chip ← **"There is Plenty of Room at the Bottom"**

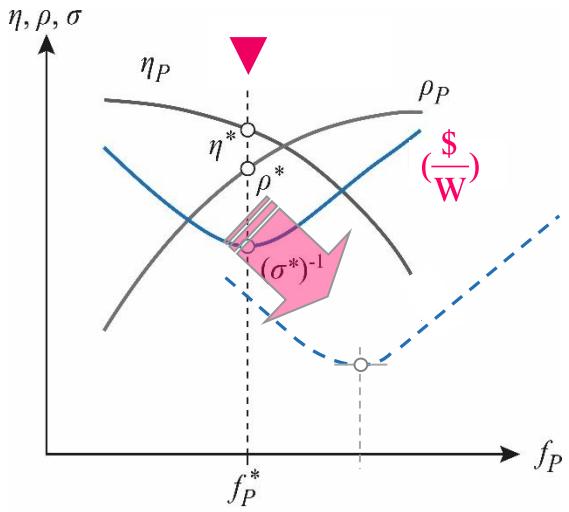
- *"There's Plenty of Room at the Bottom", Lecture by R. Feynman @ Caltech, 1959*
- *Key Importance of Technology Partnerships of Academia & Industry*

"Moore´s Law" of Power Electronics

- *"Moore´s Law" Defines Consecutive Technology Nodes Based on Min. Costs per Integr. Circuit (!)*
- *Complexity @ Min. Comp. Costs Increases approx. by Factor of 2 / Year*

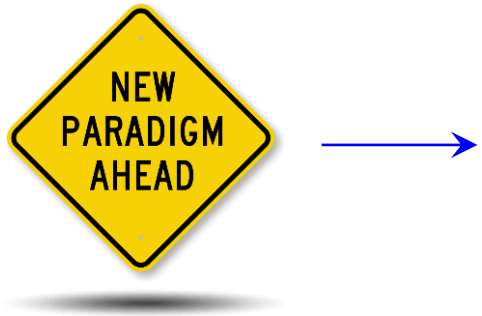


Gordon Moore: The Future of Integrated Electronics, 1965 (Consideration of Three Consecutive Technology Nodes)



- *Potential Power Density Improvement — Factor 2 ... 5 Until 2030*
- *Definition of "$\eta^*, \rho^*, \sigma^*, f_P^*$ – Technology Node" Must Consider Conv. Type / Operating Range etc. (!)*

Source:
www.roadtrafficsigns.com



Power Electronics → "Energy" Electronics

- *Design Considering Converters as Standardized "Integrated Circuits" (PEBBs)*
- *Extend Analysis to Converter Clusters / Power Supply Chains / etc.*

- *"Converter" → "Systems" (Microgrid) or "Hybrid Systems" (Automation / Aircraft)*
- *"Time" → "Integral over Time"*
- *"Power" → "Energy"*

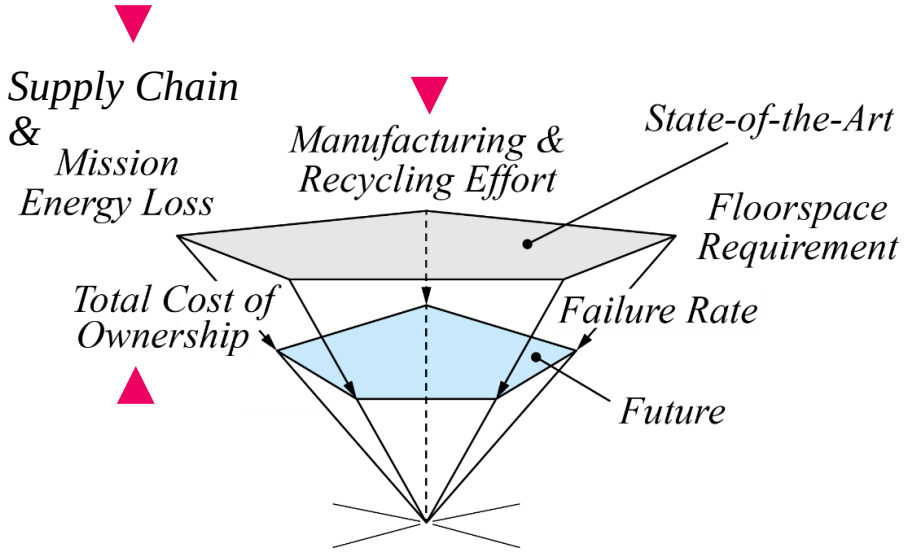
$$p(t) \quad \rightarrow \quad \int_0^t p(t)\,\mathrm{d}t$$

- *Power Conversion → Energy Management / Distribution*
- *Converter Analysis → System Analysis (incl. Interactions Conv. / Conv. or Load or Mains)*
- *Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)*
- *Cap. Filtering → Energy Storage & Demand Side Management*
- *Costs / Efficiency → Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency*
- *etc.*

Energy Electronics Systems Performance Figures/Trends

- *Complete Set of New Performance Indices*

— Power Density	[kW/m^2]
— Energy Density	[kWh/m^3]
— Environmental Impact	[kWs/kW]
— TCO	[$/kW]
— Mission Efficiency	[%]
— Failure Rate	[h^{-1}]



Thank you!