ETH zürich

Advanced Low-Voltage & Medium-Voltage AC/DC Grid Interfaces for High Performance Computing

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Outline

- *Introduction*
- *Basic Considerations*
- *Adv. LV AC//DC-Interfaces*
- *Adv. MV AC//DC-Interfaces*
- *Remark on EV-Charging*
- *Conclusions*

Acknowledgement

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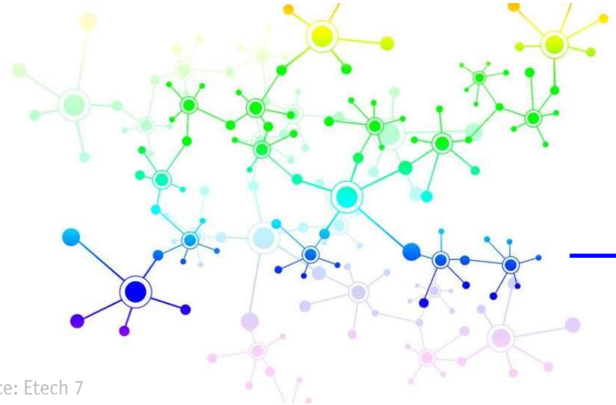


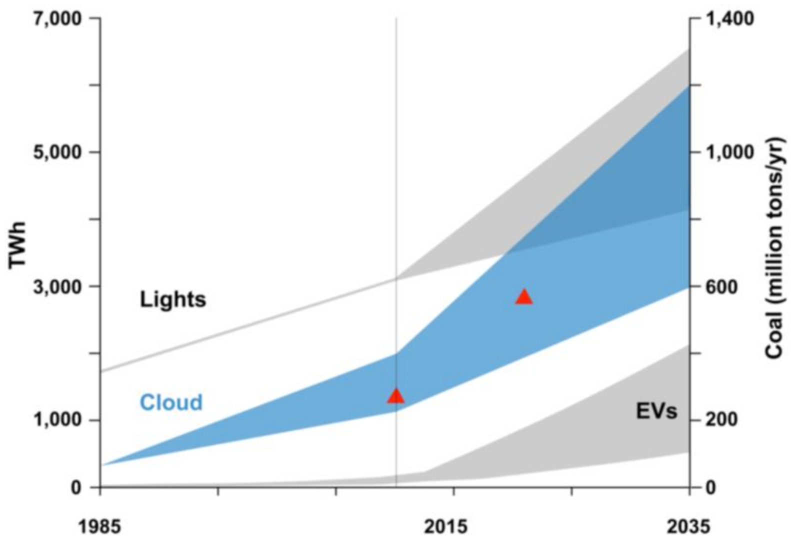
Source: Etech 7

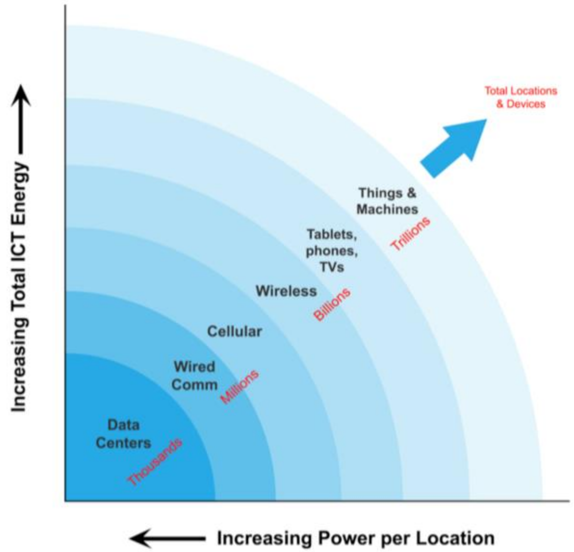
Datacenters

The Cloud / Hyper-Scale Datacenters

■ Global Electricity Demand & Digital Universe (Voice/Video/Internet) Consumption
▲... Greenpeace Estimates for ICT

Source: M.P. Mills, Digital Power Group, 2013





- "The Cloud is Powered By Coal" (40% Share of Electricity Generation)
- 100x Energy Used for i-Phone Charging is Used for Data Processing (1.6GB/Month Avg.)

Hyper-Scale Datacenters

- MV (kV) → Power-Supplies-on-Chip (0.9V) Power Conversion
- Short Innovation Cycles
- Modularity / Scalability

Server-Farms
up to **450 MW**
99.9999%/<30s/a
$1.0 Mio./Outage

Since 2006
Running Costs >
Initial Costs

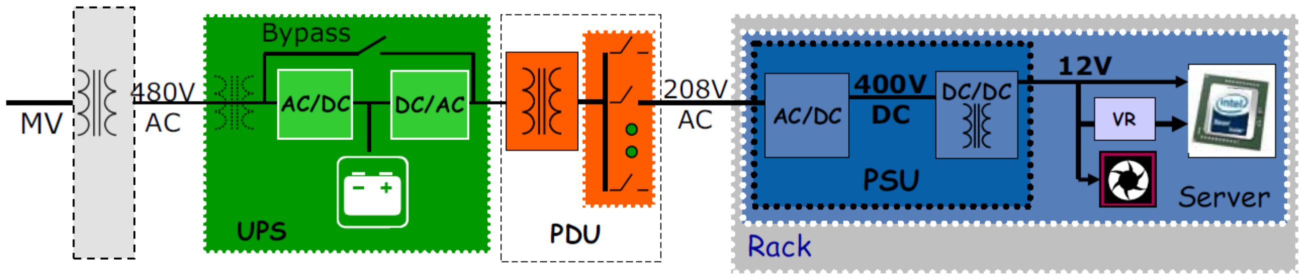
Source: Facebook

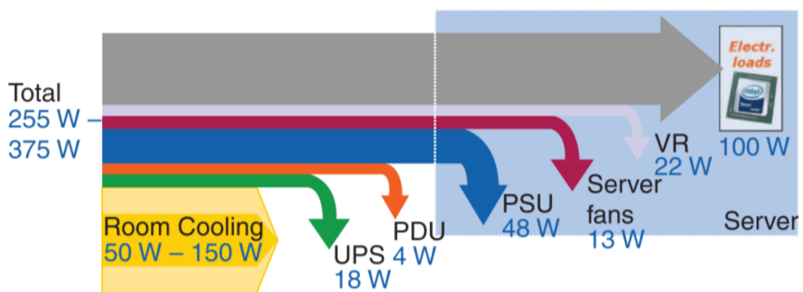
1. Higher Availability
2. Higher Efficiency
3. Higher Power Density
4. Lower Costs

State-of-the-Art Datacenters

■ Conventional $480V_{AC}$ Distribution / Energy Use

Source: intel 2007





Source: G. AlLee et al., IEEE Power & Energy Mag., 2012

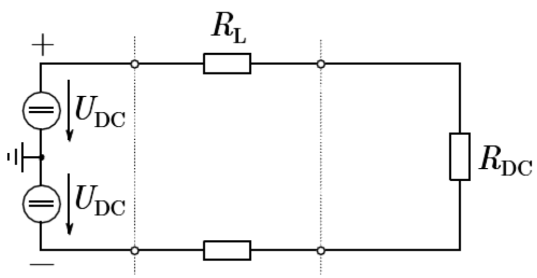
- Per 100W Compute Load → +200...300W typ. for Infrastructure & Cooling
- Eliminate Conversion Stages, Use High Distribution Voltage (Low $$$ → Select U_{DC} of PFC Rectifiers)

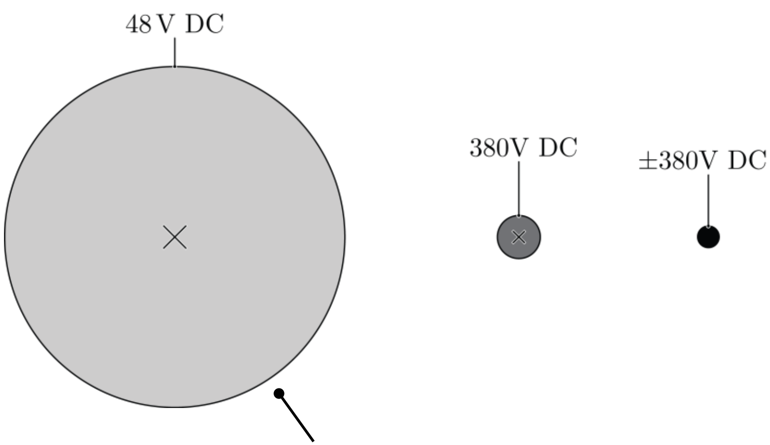
Source: 123clipartpng.com

Losses of DC Power Systems

- Increase of Transmission Line Resistance with Transmission Distance l
- Red. of Resistance for Fixed Voltage only Through Larger Conductor Cross Section A_{Cu}

→ Transmission Losses $P_{V,DC} = 2 \cdot \left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L \sim \frac{1}{U_{DC}^2}$



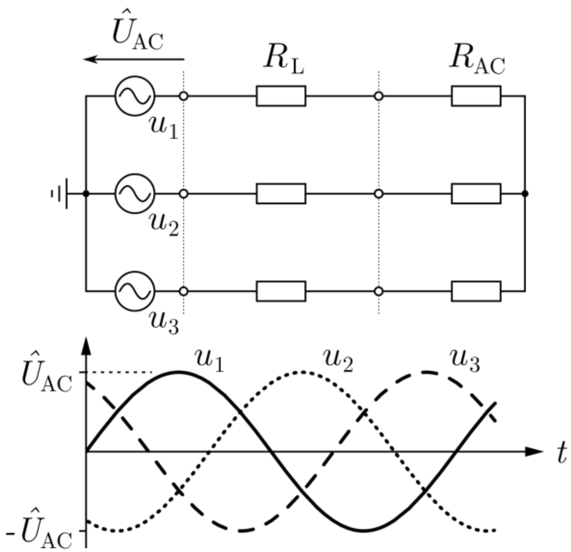


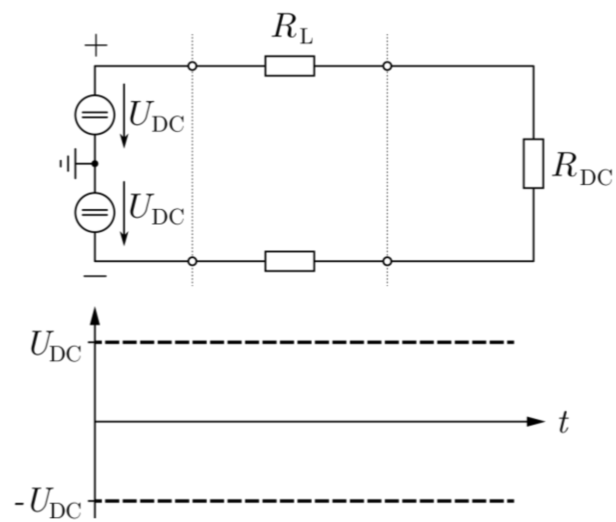
$$R_L = \frac{l}{\kappa A_{Cu}}$$

- Quadratic (!) Dependency of Losses on Voltage Level
- Allows Massive Reduction of Conductor Cross Section with Increasing Voltage Level

AC vs. DC Power Transmission

- *DC Voltage → Max. Utilization of Isol. Voltage → Lower Losses & Less Conductor Material (!)*





$$P_{V,AC} = 3 \cdot \left(\frac{\frac{1}{3}P}{U_{AC}}\right)^2 \cdot R_L$$

$$P_{V,DC} = 2 \cdot \left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L$$

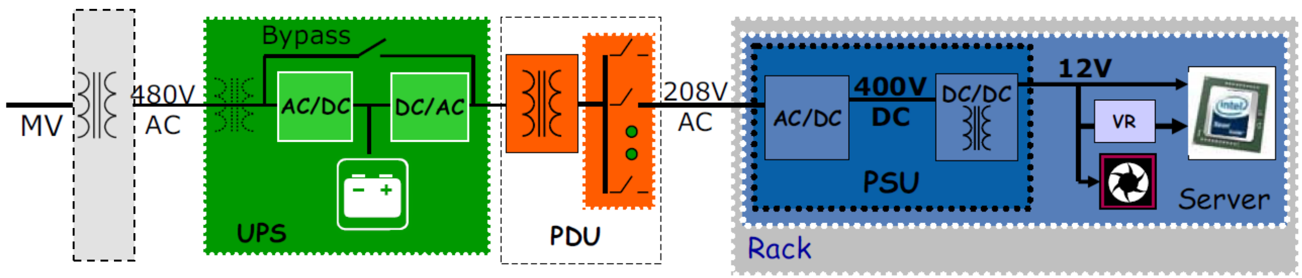
$$\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2} \cdot \left(\frac{U_{AC}}{U_{DC}}\right)^2 \Big|_{U_{DC}=\hat{U}_{AC}=\sqrt{2}\,U_{AC}} = 0.75$$

- *Transformation of DC Voltage Level Requires Power Electronics Interfaces (!)*

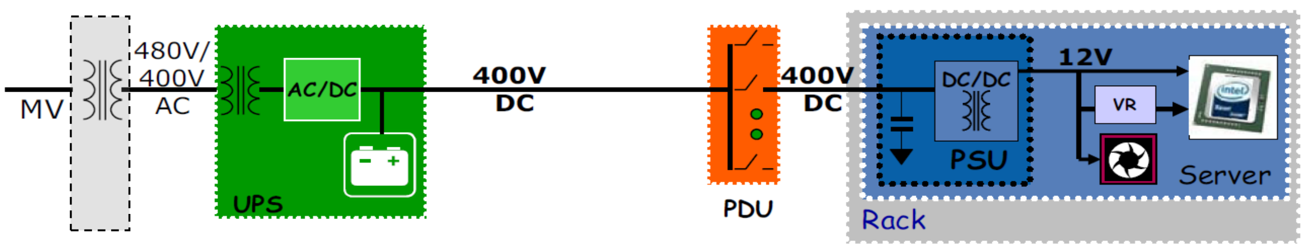
AC vs. 400V DC System

■ *Conventional 480V$_{AC}$ Distribution*

Source: intel 2007



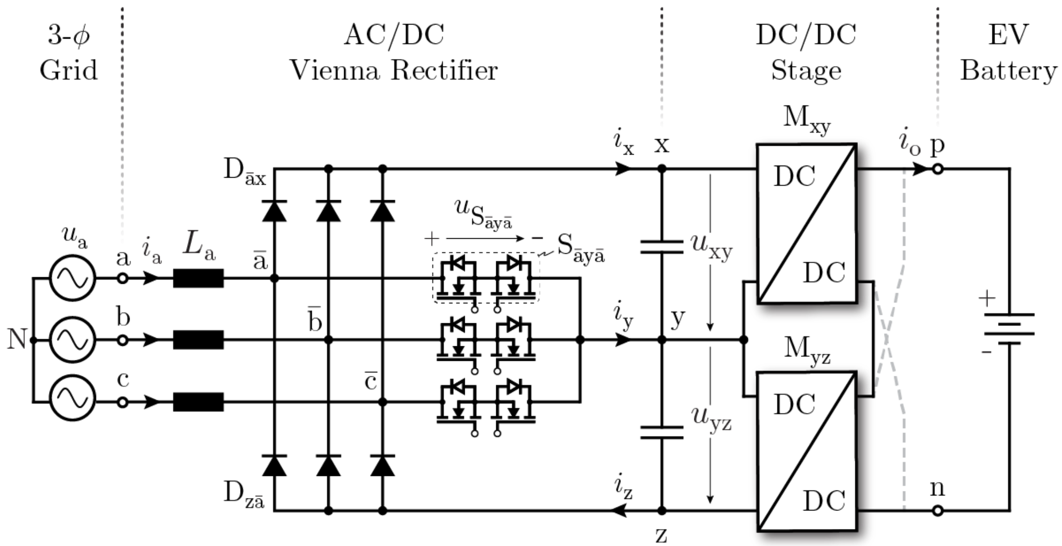
■ *Facility-Level 400 V$_{DC}$ Distribution; 380V Rated (± 190V), Range: 260V...410V (!)*



- *+ 5...7% Efficiency & -33% Floor Space & -36% Lifetime $$$ & 0.9999996 Availability*

3-Φ Low-Voltage Grid Interface

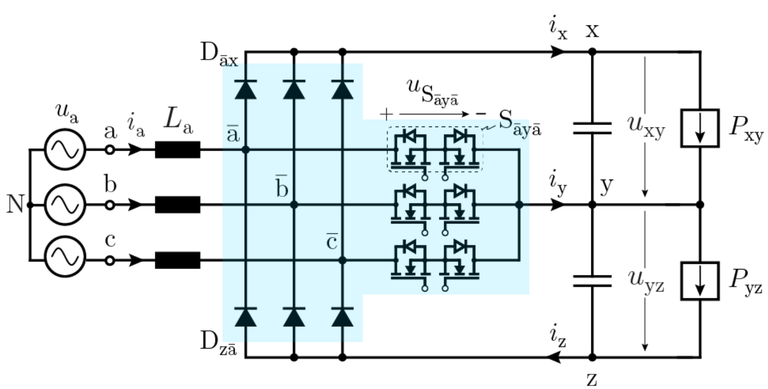
- *Isolated Controlled Output Voltage*
- *Buck-Boost Functionality & Sinusoidal Input Current*
- *Applicability of 600V GaN Semiconductor Technology*
- *High Power Density / Low Costs*

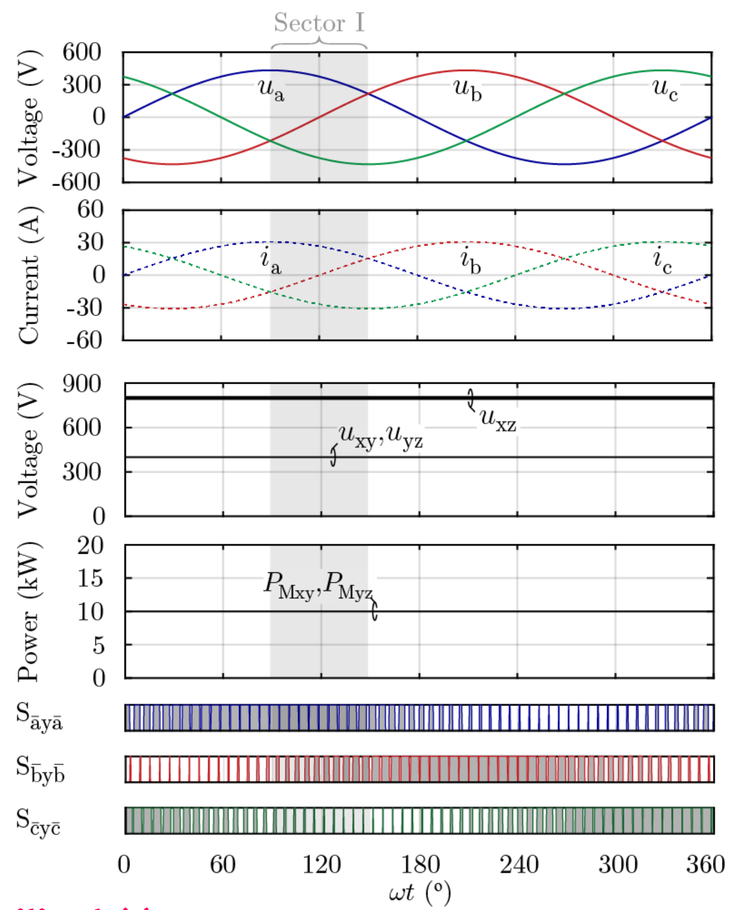


→ *Conventional / Independent* *OR* *"Synergetic Control" of Input & Output Stage*

Conventional Control

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

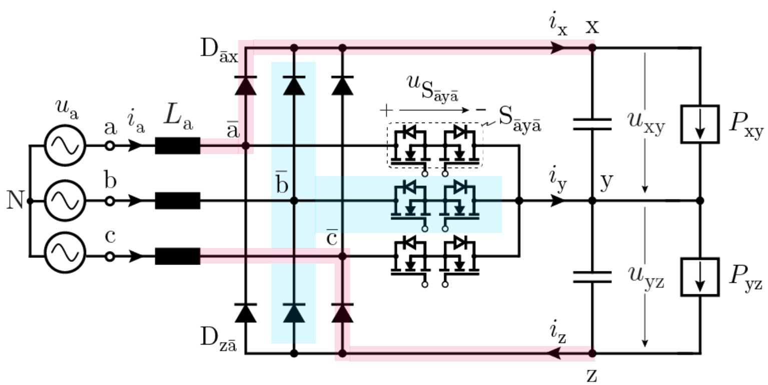


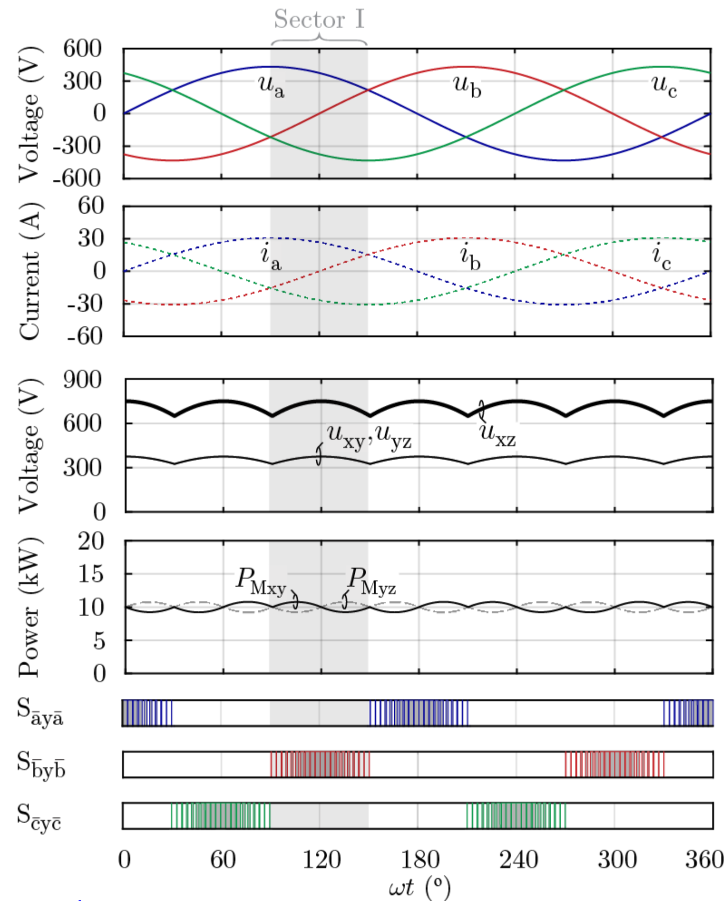


→ Control Capability & Control DOFs NOT Fully Utilized (!)

"Synergetic" Control

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



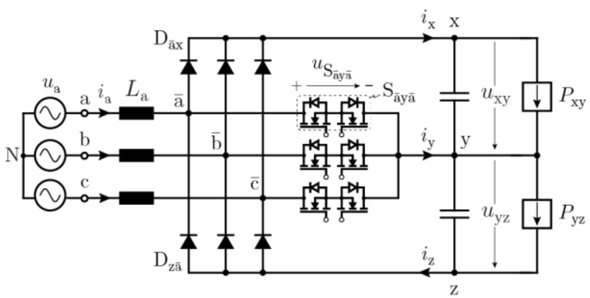


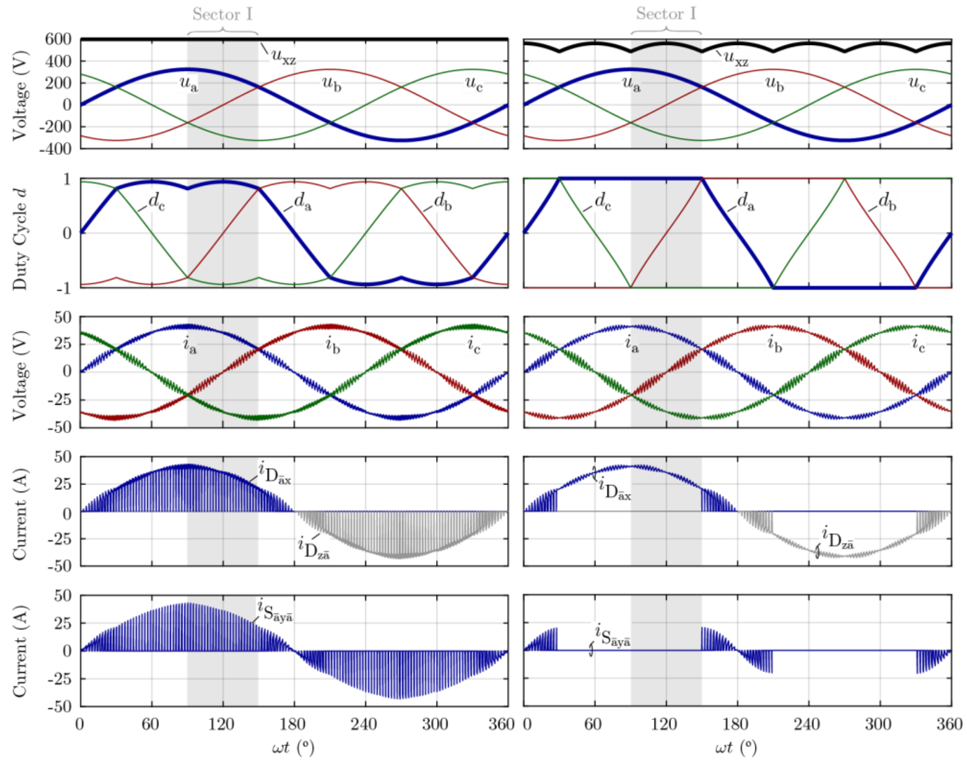
→ Boost Capability Maintained (Transition to 3/3-PWM)

Conventional vs. "Synergetic" Control

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

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

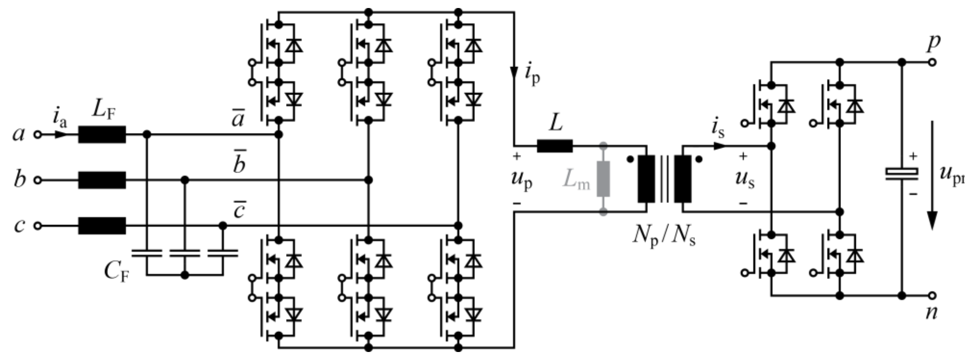


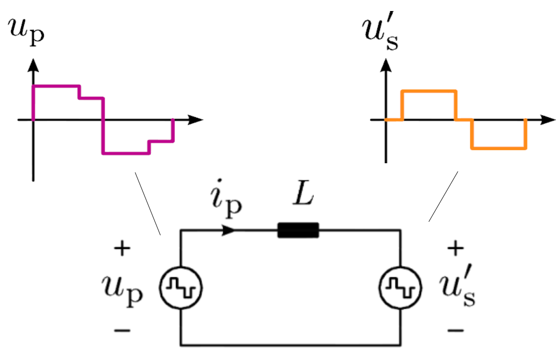


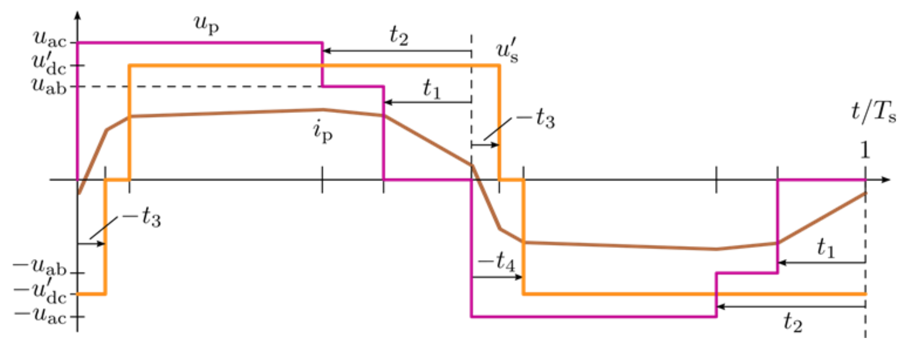
→ Operating Point Dependent Selection of 1/3-PWM OR 3/3-PWM for Min. Overall Losses

Isolated Matrix-Type 3-Φ *PFC Rectifier (1)*

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







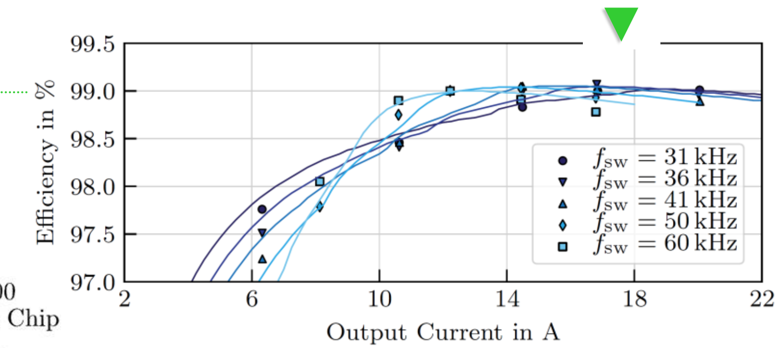
▶ *Equivalent Circuit*

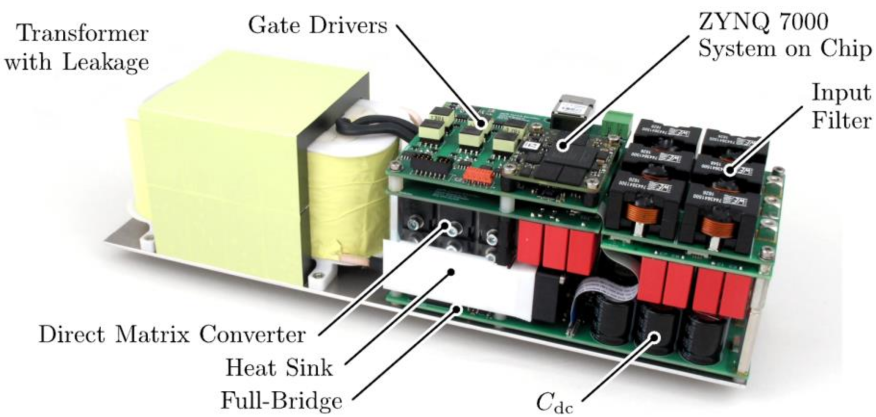
▶ *Transformer Voltages / Currents*

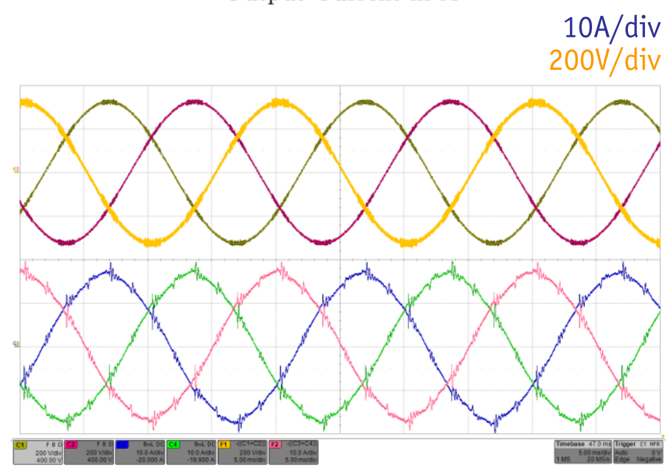
Isolated Matrix-Type 3-Φ *PFC Rectifier (2)*

- *Efficiency η = 98.9% @ 60% Rated Load (ZVS)*
- *Mains Current THD_I ≈ 4% @ Rated Load*
- *Power Density ρ ≈ 4kW/dm³*

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





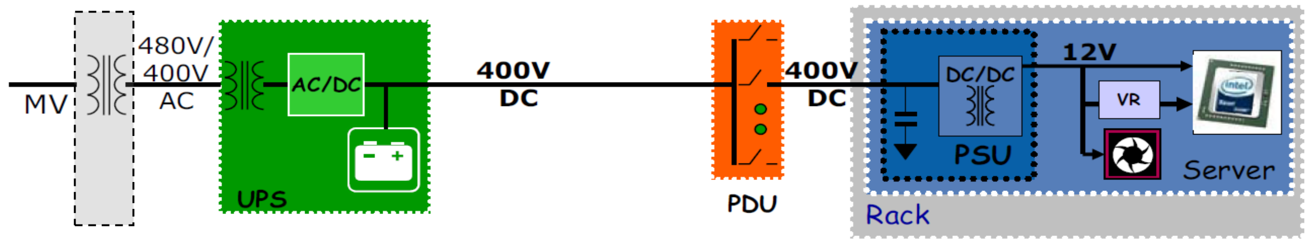


- *900V / 10mΩ SiC Power MOSFETs*
- *Opt. Modulation Based on 3D Look-Up Table*

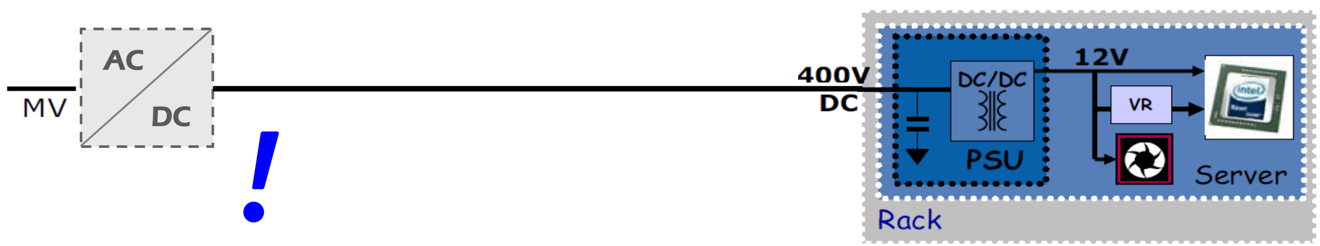
1-Φ Medium-Voltage Grid Interface

- *Facility-Level 400 V_{DC} Distribution*

Source: intel 2007



- *Solid-State Transformer-Based 6.6kV AC → 400V DC*

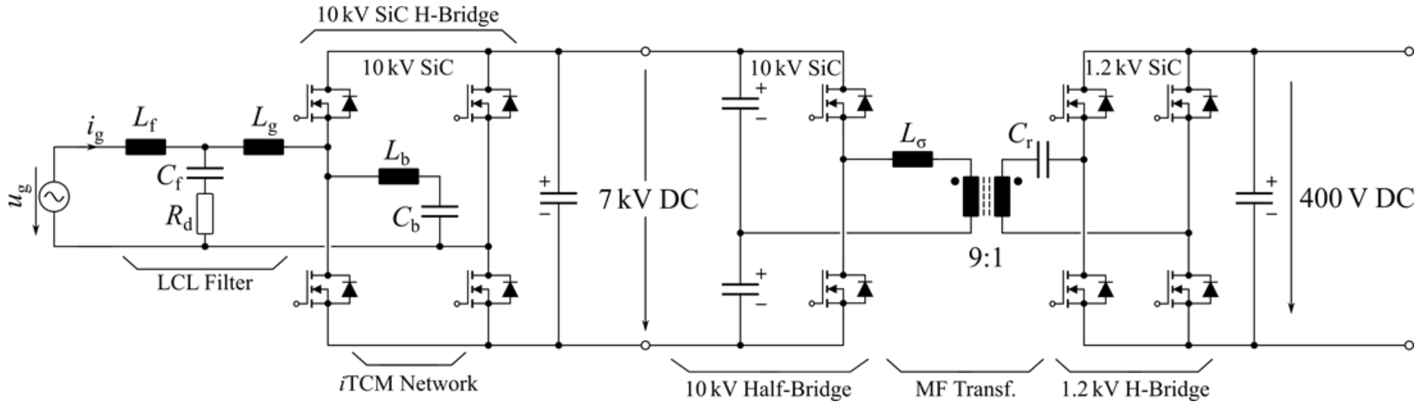


- *MV-Grid (kV) → Chip (0.9V) in 2 Steps → typ. 3% Efficiency Gain, Smaller Footprint, etc.*

25kW SwiSS-Transformer @ ETH Zurich

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

★ 3.3 kW/dm³



★ 3.8 kW/dm³

▶ 35...75kHz iTCM Input Stage

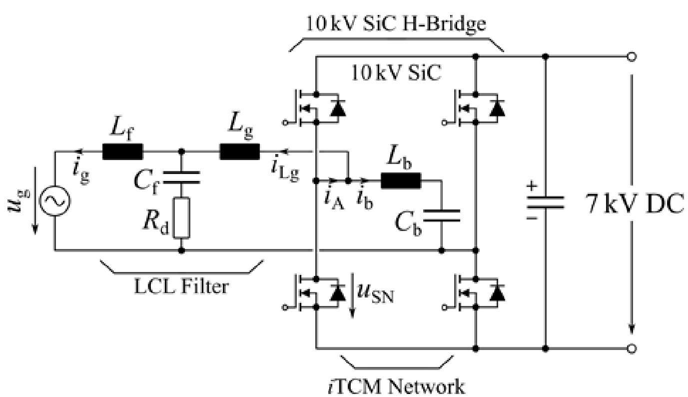
▶ 48kHz DC-Transformer Output Stage

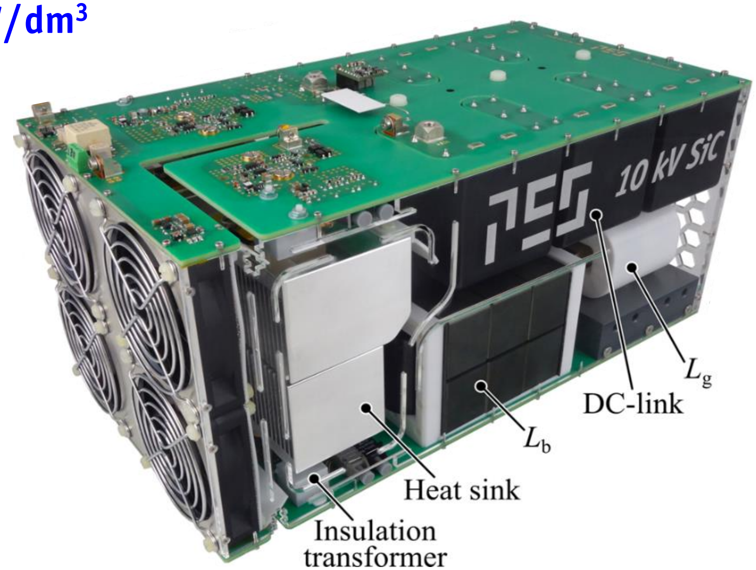
3.8kV → 7kV ZVS AC/DC Converter

- Full-Bridge iTCM – integrated Triang. Current Mode Operation Enables ZVS

— ZVS Requires Change of Sw. Current Direction in Each Sw. Period
— Open-Loop Variation of Sw. Frequency for Const. ZVS Current (35...75kHz)
— Separate Optim. of ZVS and Input Inductor Possible
— Low Ripple Input Current

★ 3.3 kW/dm³

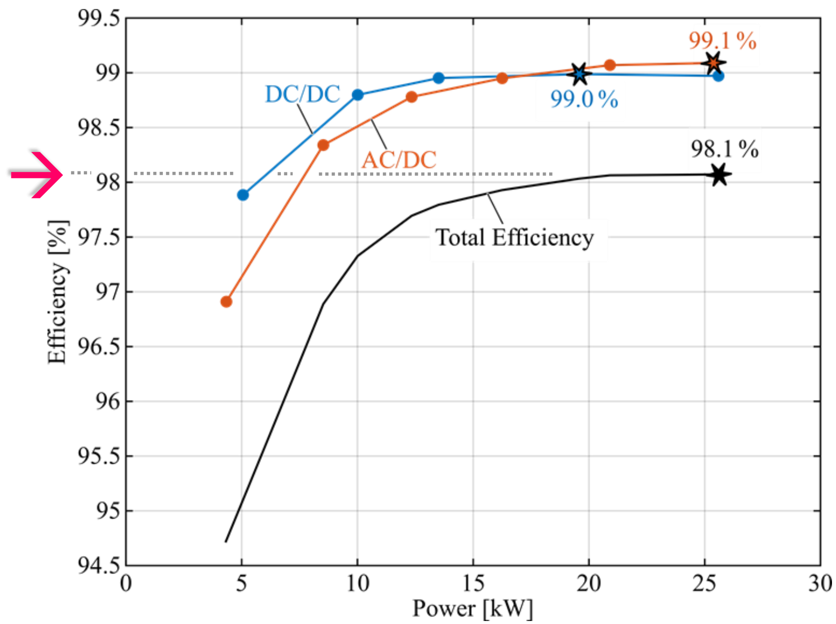




► Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)

Overall Performance

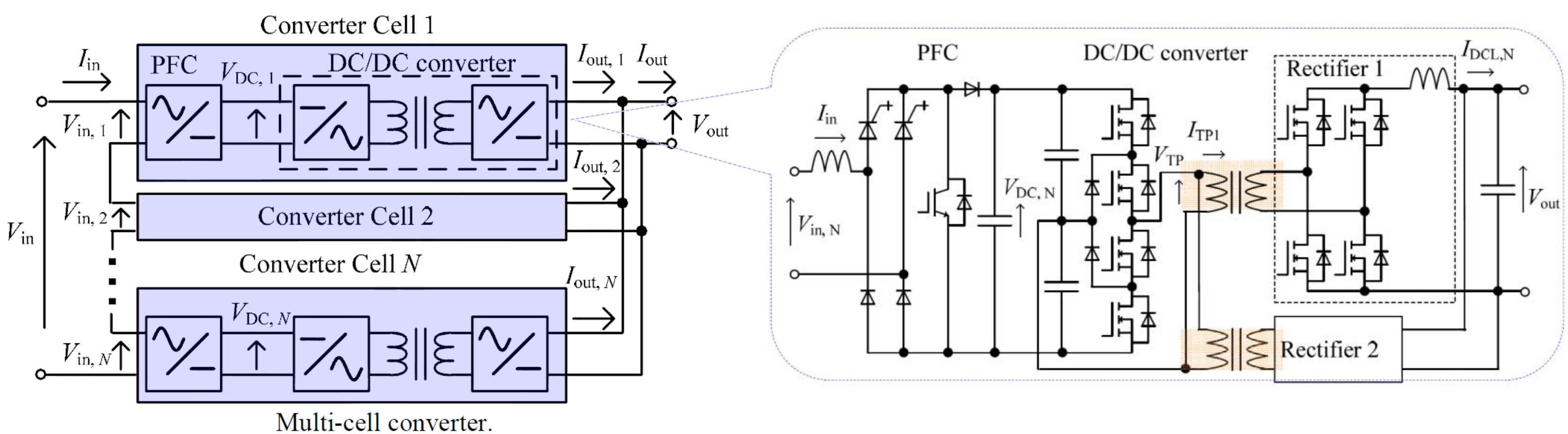
- *Full Soft-Switching*
- *98.1% Overall Efficiency @ 25kW*
- *1.8 kW/dm³ (30W/in³)*



- *Red. of Losses & Volume by Factor of >2 Comp. to Alternative Approaches (!)*
- *Significantly Simpler Compared to Multi-Module SST Approach*

Fuji Electric $2.4\,kV_{rms}\,AC \rightarrow 54V\,DC$

- *Published @ IEEE APEC 2017*
- *N=5 Cells @ MV-Side / Cost Optimum*
- *PFC Rectifier → 1.2kV Si IGBTs & SiC Diodes*
- *DC/DC Conv. → 600V SJ & 100V MOSFETs*



- *Power Density of 0.4kW/dm³ (6.6W/in³)*
- *96% Overall Efficiency @ 25kW*

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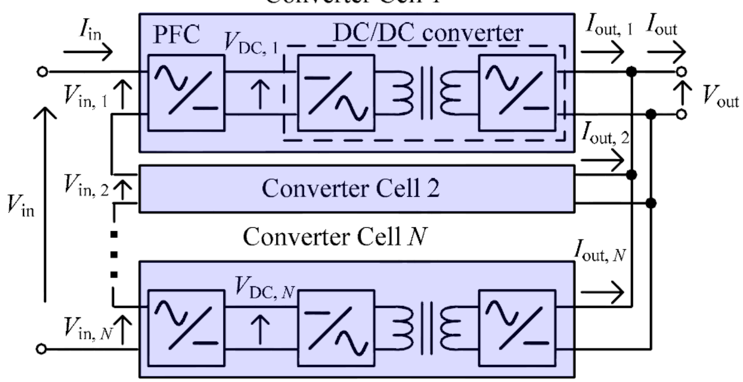
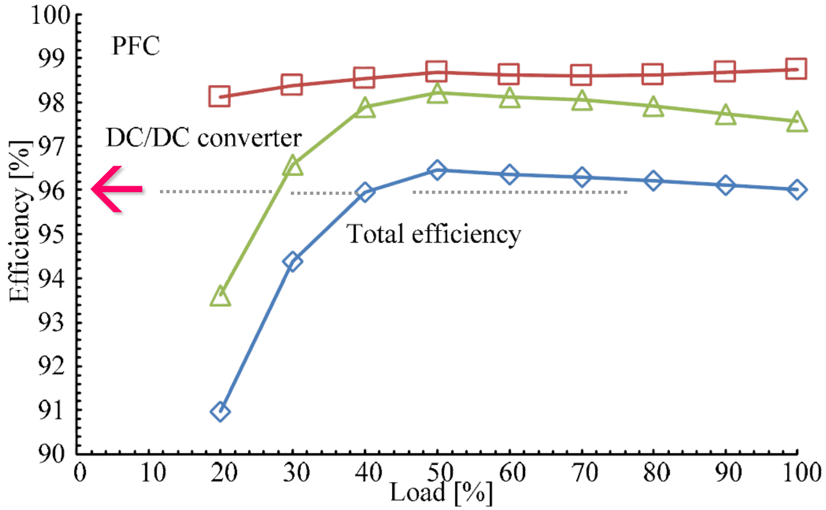


Multi-cell converter.



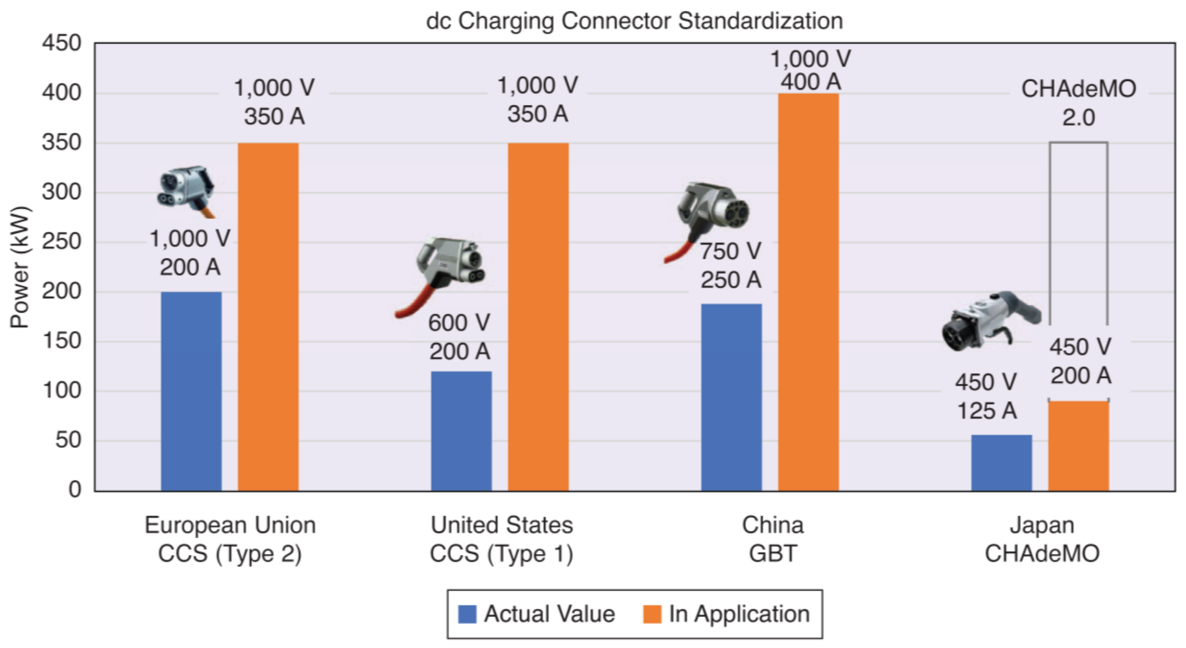
Efficiency of the prototype

- Power Density of 0.4 kW/dm^3 (6.6 W/in^3)
- 96% Overall Efficiency @ 25kW

… X-Fast Charging $T_{chg} = \frac{E}{P_{chg}}$

DC Charging Connectors

- Practical Limit Due to Safety Effort, etc.
- "Low Voltage" Def. as < 1000V AC / < 1500V DC in Standards



Source: C. Jung, IEEE Electr. Mag., 2017

- Typ. Infrastructure Delivers 500V DC (600V IGBTs) & 50kW
- Charging Time Defined by $U \cdot I$ → Current Limited by Connector System
- Significantly Higher DC Voltages Compared to Datacenters (!)

Conclusions

- **Advanced AC//DC Interfaces**

— Synergetic AC/DC & DC//DC-Stage Control
— Efficiency of 2-Level 1-Φ AC/DC Interface → 7-Level 3-Φ System
— 99% Efficiency of LVAC//DC Conversion
— Gain of ≈3% Efficiency for Direct MV-Connection

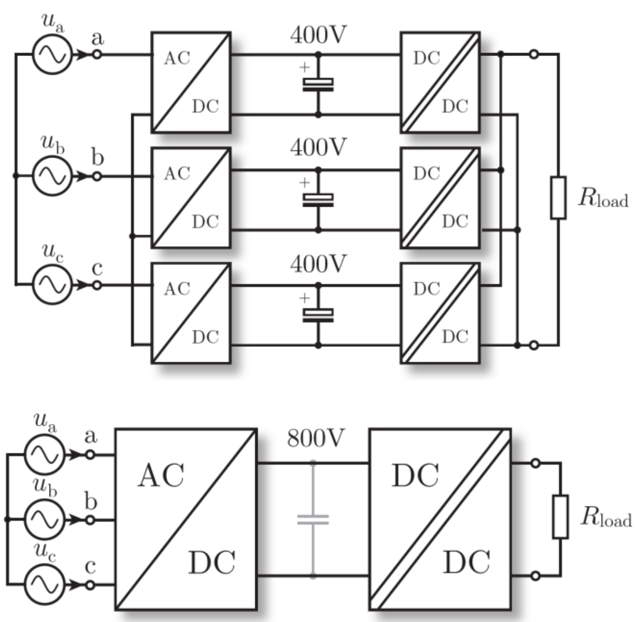
- **Future**

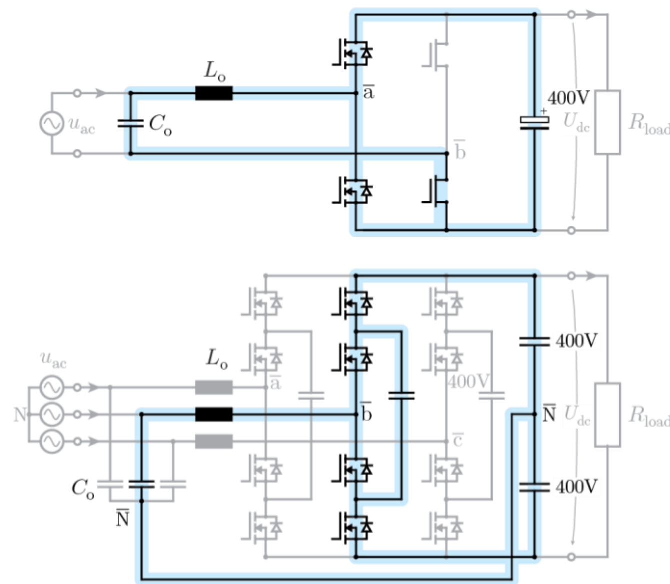
— $380V_{DC}$ Sufficient ?
— Bidirectional AC//DC Interfaces for Grid Services
— Life-Cycle vs. Initial Costs !

Thank you!

Remark 3-Φ Low-Voltage AC/DC Grid Interfaces

- 3 x 1-Φ AC/DC Conv. — 650V GaN/SiC in 2-Level Topology & Unfolder; $f_{eff} = f_{sw,1}$
- 3-Φ AC/DC Conv. — 650V GaN/SiC in 3-Level Topology; $f_{eff} = 2f_{sw,1}$





▶ 3-Level Approach → $\sqrt{2} \cdot P_{semi,2\text{-}Level}$ @ Opt. Chip Area (!)

Remark 3-Φ Low-Voltage AC/DC Grid Interfaces

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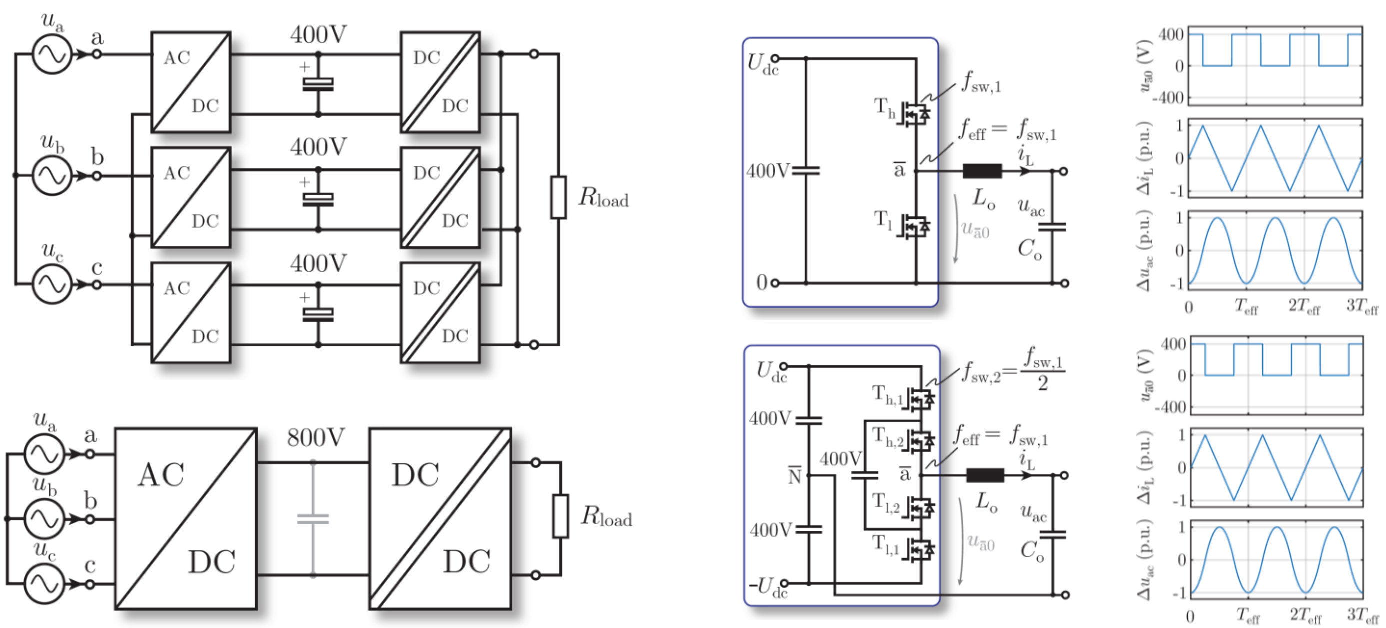
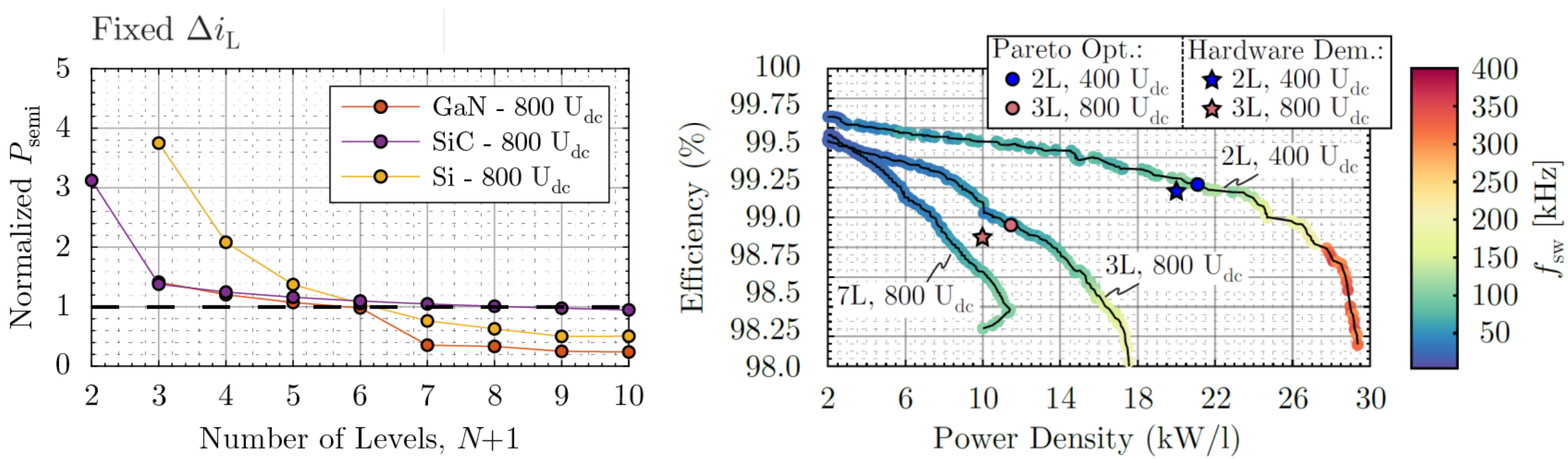


▶ 3-Level Approach → $\sqrt{2} \cdot P_{semi,2\text{-}Level}$ @ Opt. Chip Area (!)

"3 Levels Are Not Enough" (!)

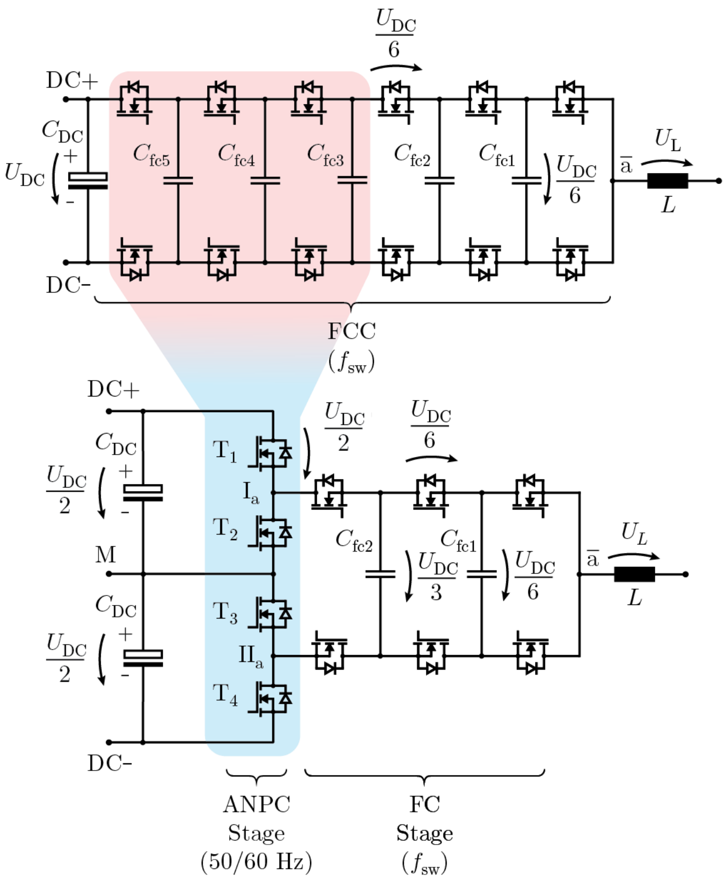
- Analysis of Higher Number of Levels
- Semiconductor Losses P_{semi} for Fixed L_0C_0-Filter & Fixed Inductor Current Ripple
- $\eta\rho$-Pareto Front for 2-Level / 3-Level / 7-Level System with Optimized Filter

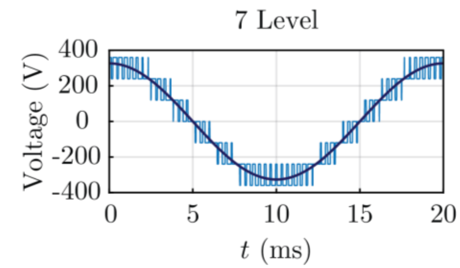


► 6-Level or 7-Levels (!) for $800V_{DC}$ to Exceed Efficiency of 2-Level $400V_{DC}$ Benchmark P_{semi}

Example — Ultra-High Efficiency PV Inverter

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





99.35%
2.6kW/kg
56 W/in^3