Power Electronic Systems Laboratory

ETH zürich

MVAC-LVDC Hybrid and Solid-State Transformer Concepts for Future Data Centers

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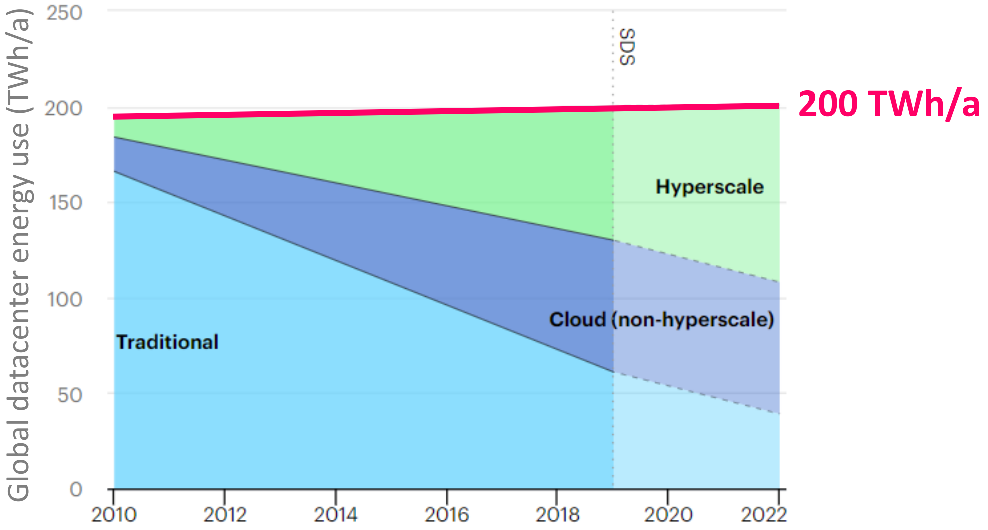
Agenda

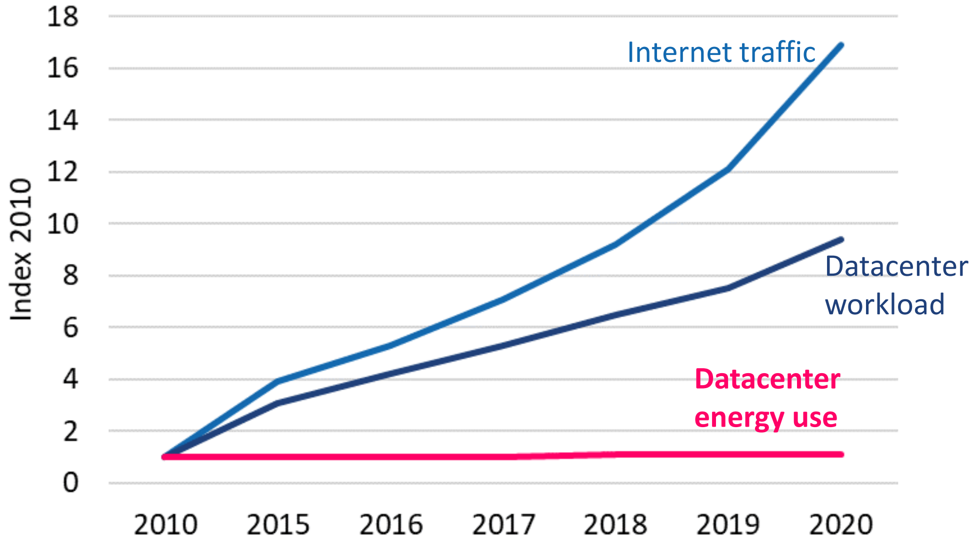
- Introduction
- AC vs. DC Distribution
- Medium-Voltage AC-DC Interfaces
- Comparative Evaluation
- Conclusion

Further Reading:
J. Huber, P. Wallmeier, R. Pieper, F. Schafmeister, and J. W. Kolar, "Comparative evaluation of MVAC-LVDC SST and hybrid transformer concepts for future datacenters," *Proc. Int. Power Electron. Conf. (IPEC/ECCE Asia),* Himeji, Japan, May 2022. [Download]

Global Datacenter Electricity Demand

- Datacenters consume > 200 TWh/a | About 1 % of global electricity demand
- Energy costs dominate overall life-cycle costs

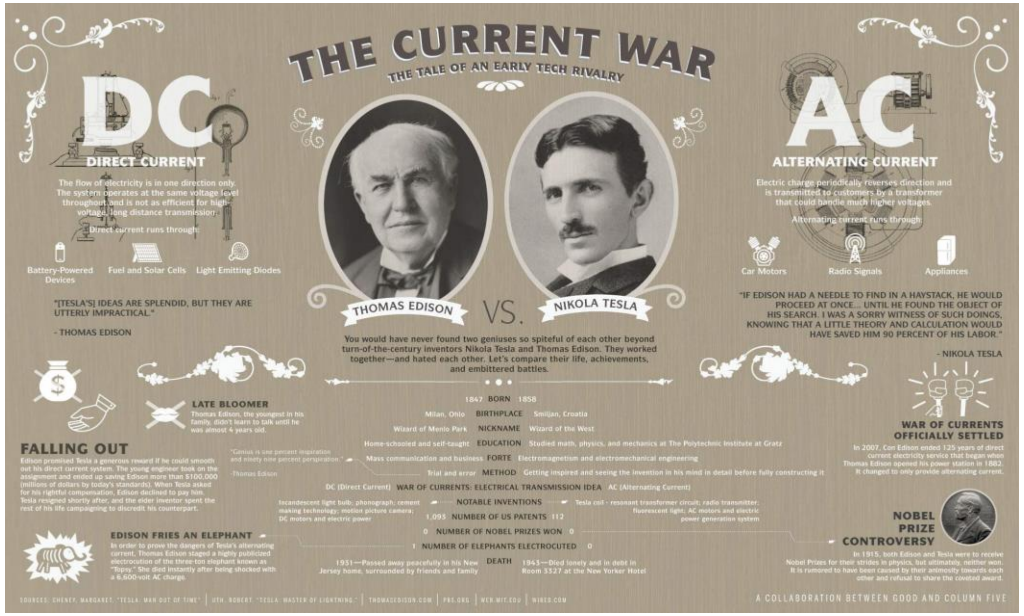




Source (left image, data): https://www.iea.org/reports/data-centres-and-data-transmission-networks

- Decoupling of computing workload from energy use
- Efficiency improvement on all levels: Computing equipment | HVAC | … | Power supply system!

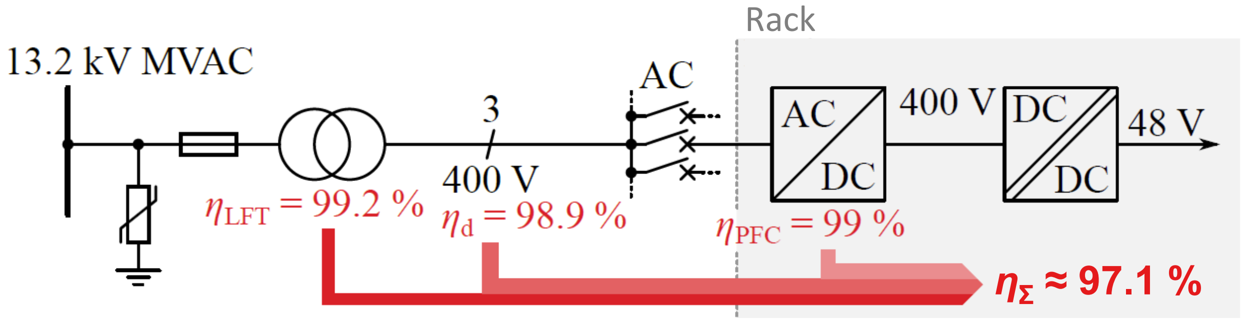
AC vs. DC Distribution



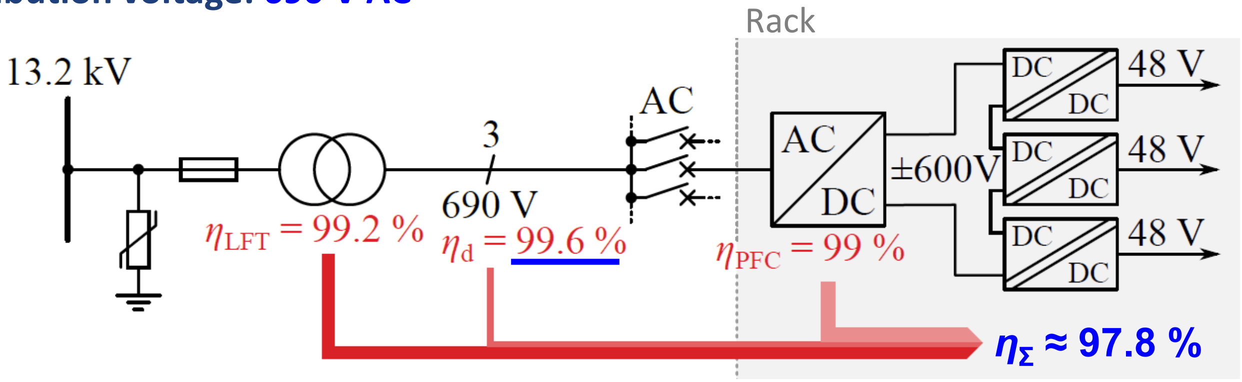
Source: GOOD/Column Five Media (https://good.is)

AC Power Distribution

- **State of the art: 400 V AC**



- **Increased distribution voltage: 690 V AC**

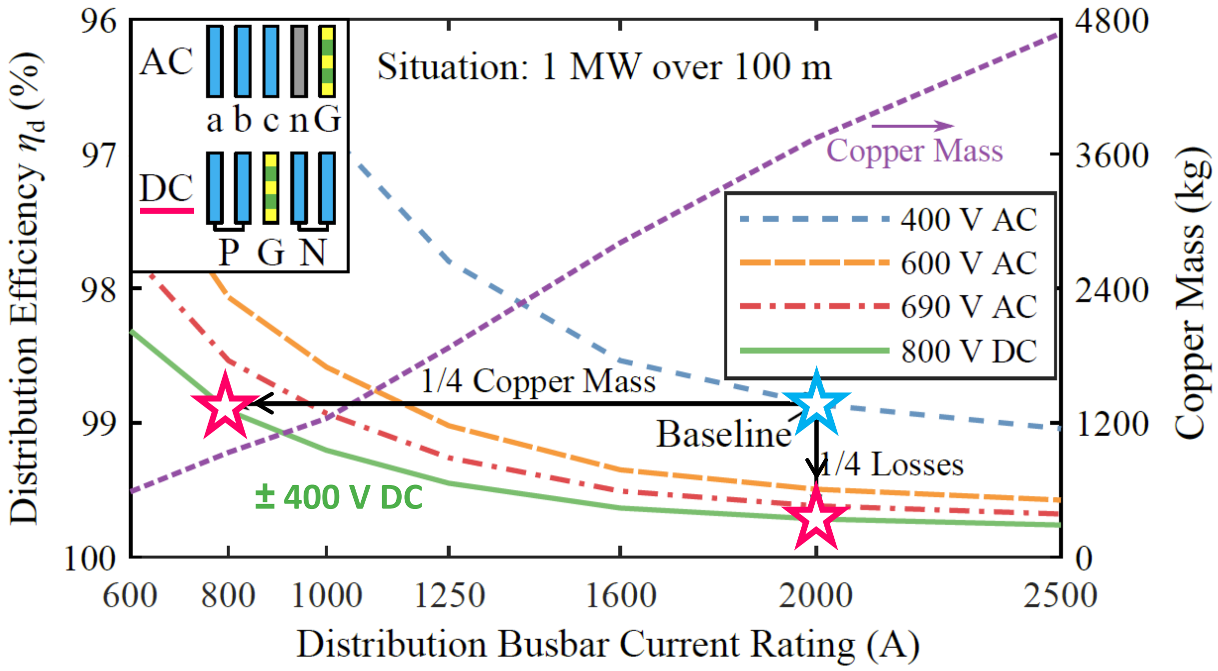


(w. 99% 3L PFC Rec.)

- **η_Σ: Efficiency from MVAC to input of rack-level 400 V / 48 V DC-DC conversion**
- η_d: Distribution efficiency for 1 MW over 100 m with Delta EcoTech BL 2000 A busbar
- η_{LFT}: Requirement by, e.g., EU Ecodesign directive 2009/125/EC

Distribution Losses

- **400 V AC → 690 V AC: Significant loss reduction <u>or</u> lower copper usage**

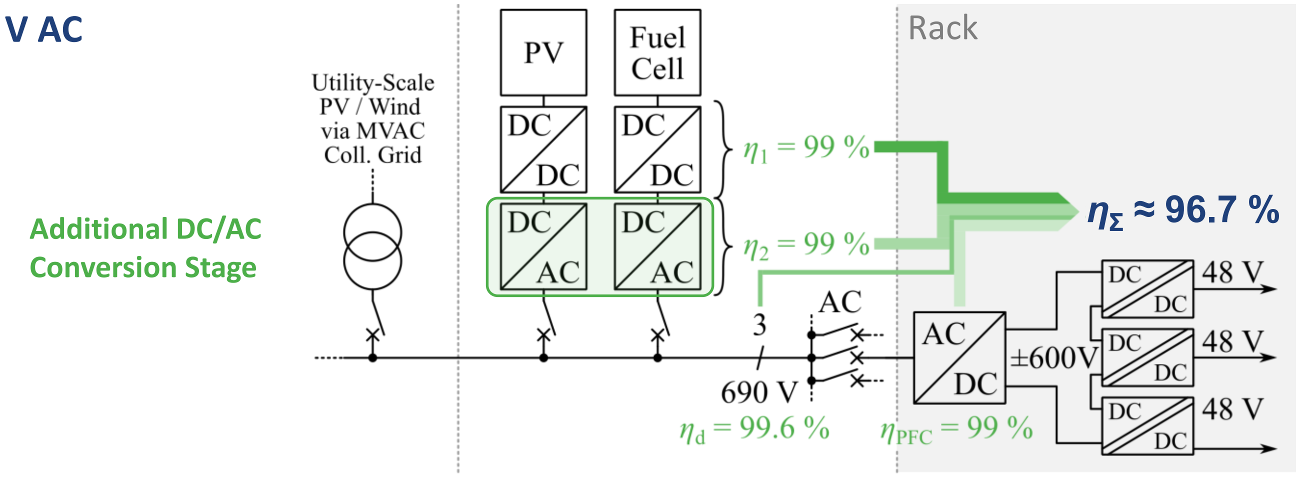


(Delta EcoTech BL busbars @ 60 °C)

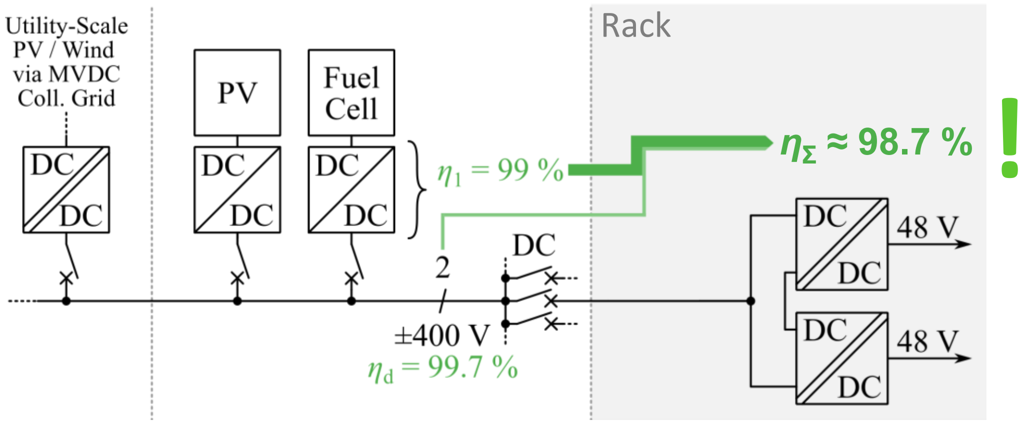
- **Same busbar in AC or DC configuration: 400 V AC → 800 V DC (± 400 V DC)**
  - –75% distribution losses (<u>or</u> –75% copper mass)
  - DC distribution challenges: Protection, DC breakers, DC PSUs, …

DC Power Distribution (1) – DC Sources

- 690 V AC



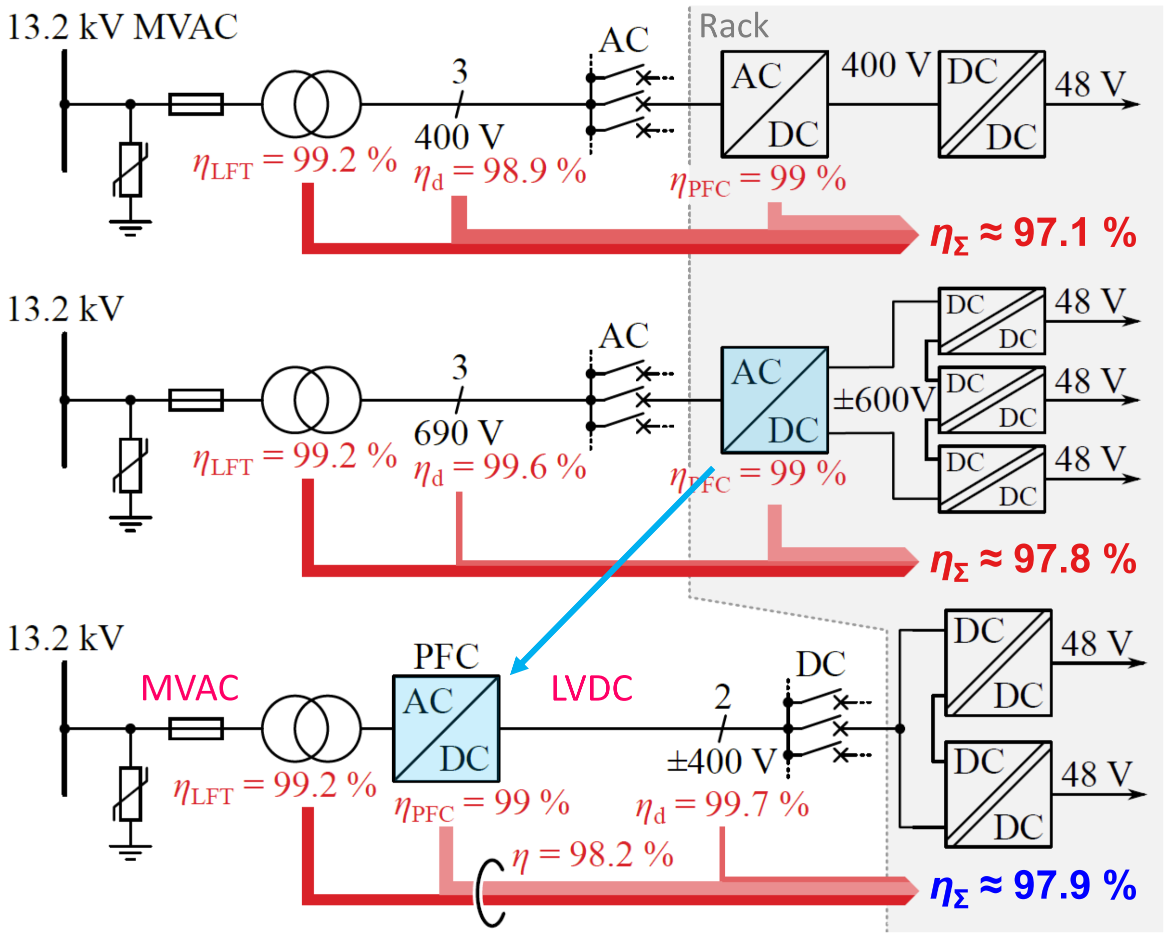
- ±400 V DC



- **DC distribution leverages DC output of fuel cells / batteries / PV**
  - Note: utility-scale renewable energy system requires higher-voltage DC collector grid

DC Power Distribution (2) – Grid Supply

- 400 V AC
- 690 V AC
- ±400 V DC



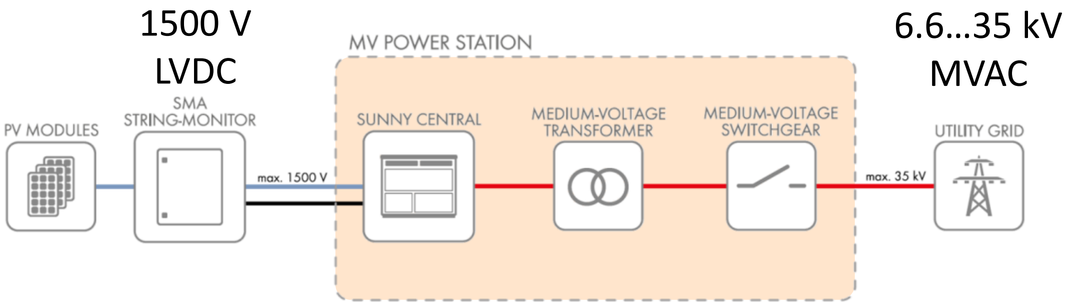
- Similar η_Σ as for 690 V AC distr.

- Simply centralizing the PFC rectifier functionality → Only minor efficiency gain!

Medium-Voltage AC-DC Interfaces

MV Power Station for **Photovoltaics**

- **State-of-the-art 3 MVA turnkey solution**
- **20 ft container: PV inverter, LFT, MV switchgear, etc.**
- **3 MVA | 6.1 m x 2.6 m x 2.4 m | ≈ 0.08 kW/dm³**



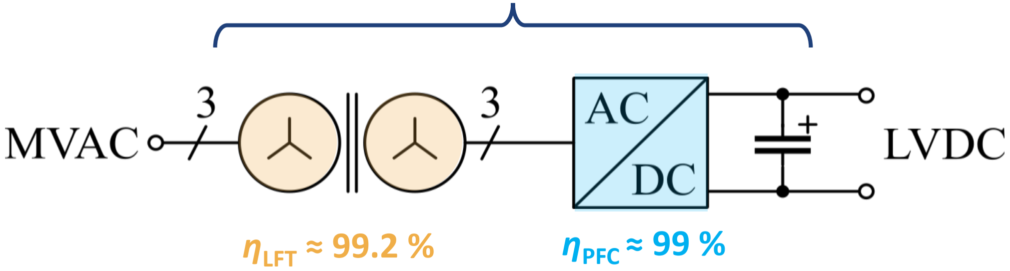
1200 V Si IGBT technology | Oil-filled LFT

- **Inverter efficiency: 98.5 % CEC**
- **Transformer efficiency: 99 % (EcoDesign, oil-filled)**
- **Overall efficiency ≈ 97.5 % → Improvements expected for SiC and Dry-Type LFT → 98+ %**

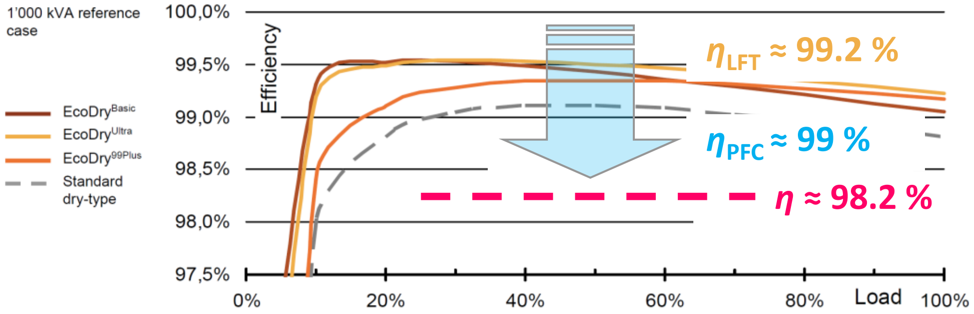
MVAC-LVDC with LFT and Central SiC PFC Rectifier

■ Centralized PFC rectifier with 1200 V SiC technology & high-efficiency dry-type/Ecodesign LFT

MVAC-LVDC: $\eta \approx 98.2$ %, $\rho \approx 0.25$ kW/dm^3



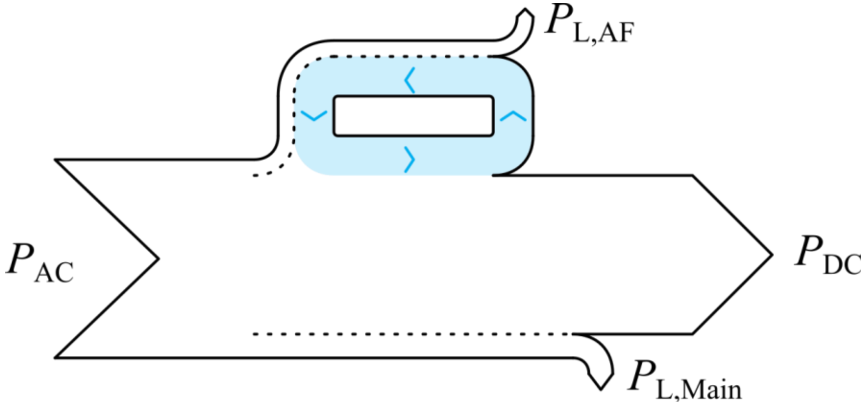
Example: ABB EcoDry™ high-efficiency transformers
(ABB, 2011 – today, 99.2% required by, e.g., EU EcoDesign directive)



400 kVA

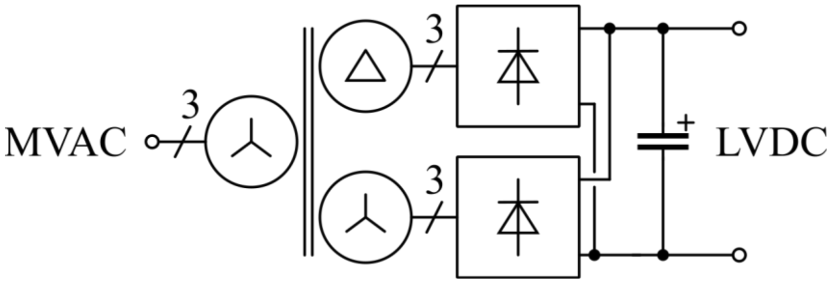
- Full functionality (reactive. power, bidir. power flow, …)
- High robustness & Low complexity
- Scalability to higher MVAC levels
- Proven LV converter design paradigms | Parallel-interleaving (modularization, redundancy)
- Compatible with existing MV-side infrastructure
- No DC fault current limiting

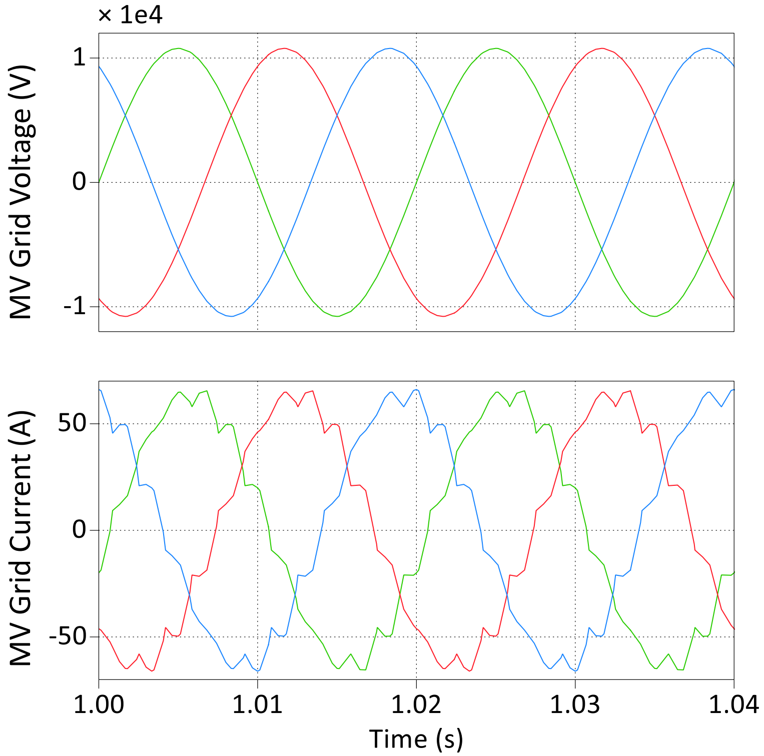
MVAC-LVDC Hybrid Transformers



12-Pulse / Multi-Pulse Rectifiers

- No explicit PFC stage (!) → Passive realization of PFC functionality with phase-shifting transformer
- High robustness
- Low complexity
- High efficiency (≈ 0.25% diode losses)
- No DC-side inductors required (!)
- 18-Pulse or 24-Pulse for higher power levels



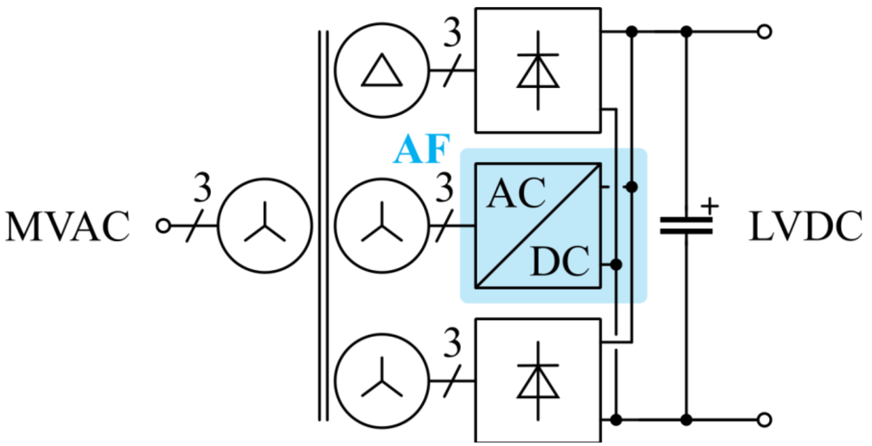


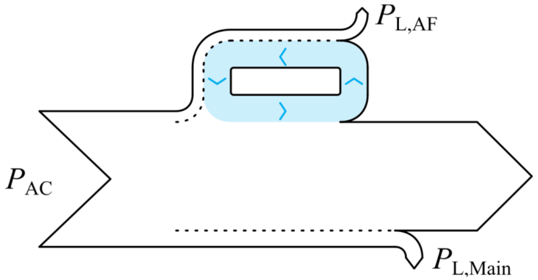
- Unidirectional
- No active output voltage control (Tap changer: wear & tear, limited dynamics / Thyristors: high VAr consumption)
- Remaining current distortions / reactive power consumption

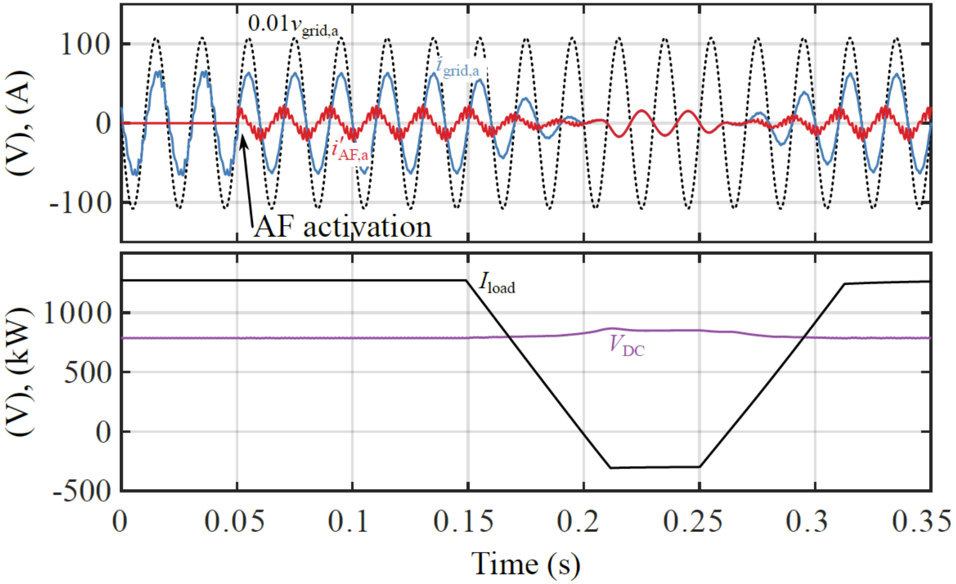
MVAC-LVDC Hybrid Transformer

- Hybridization: Partial switch-mode power processing
- Active Filter (AF) modules with ≈ 25 % power rating
  → Sinusoidal grid currents & Reactive power compensation

MVAC-LVDC: $\eta \approx 98.5\ \%$, $\rho \approx 0.2\ \mathrm{kW/dm^3}$

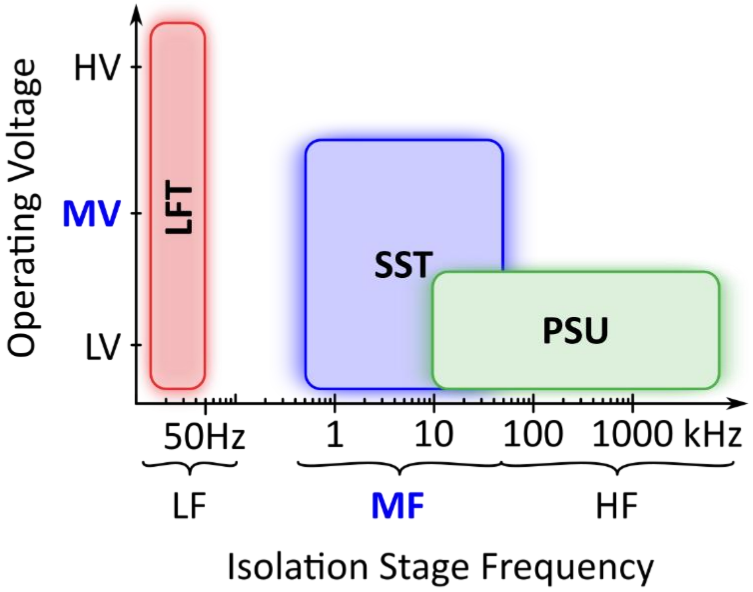


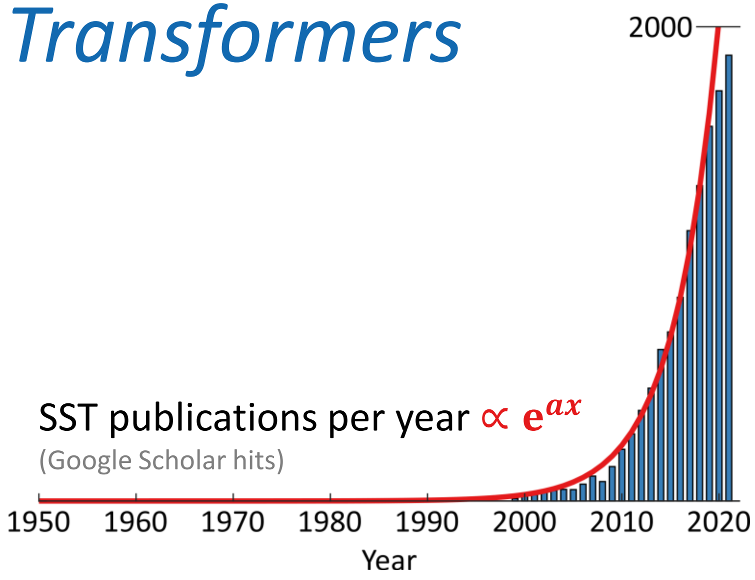




- Remaining 12-pulse operation in case of AF failure | Central, shared FACTs as complement/alternative
- Connection of AF to output DC bus → Reverse power flow capability
- No active output voltage control (Tap changer: wear & tear, limited dynamics / Thyristors: high VAr consumption)

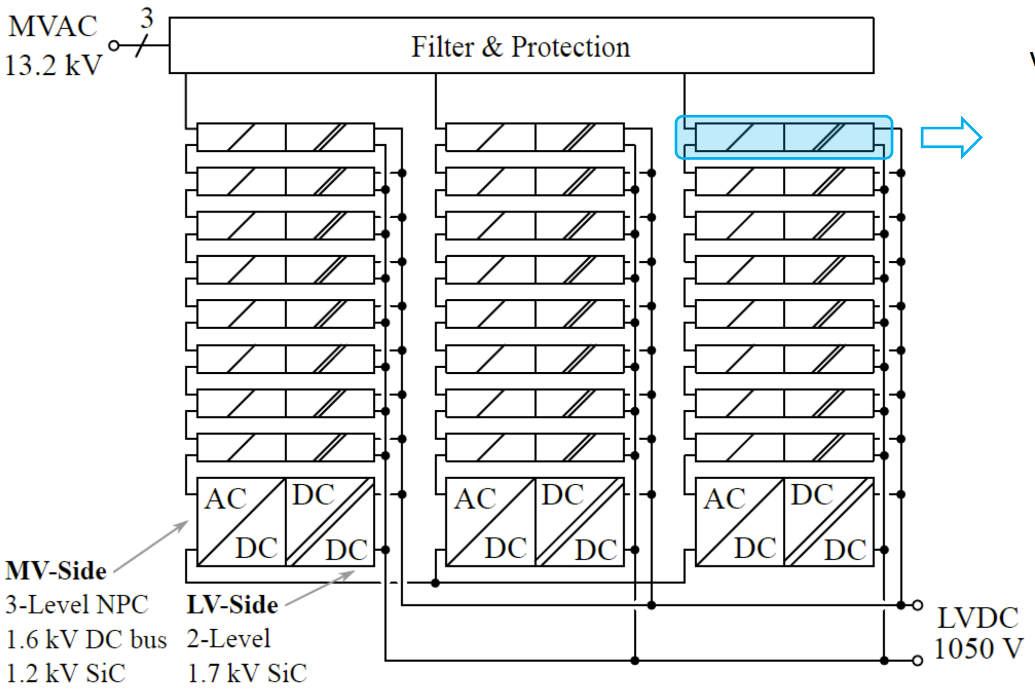
MVAC-LVDC Solid-State Transformers

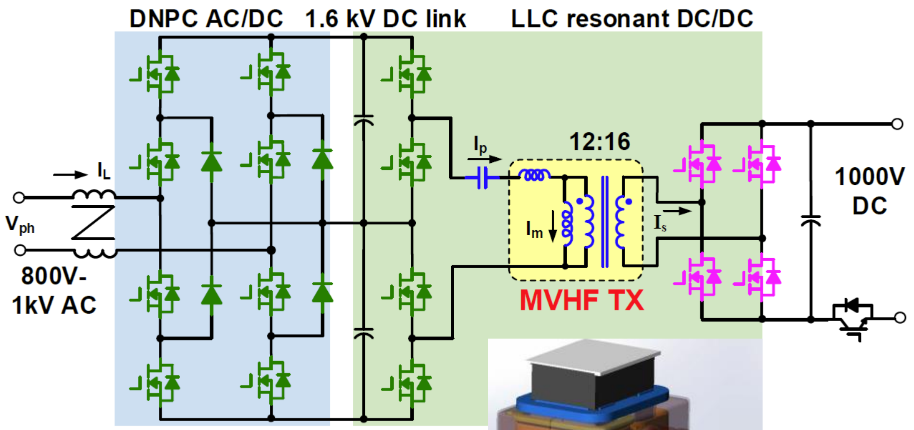


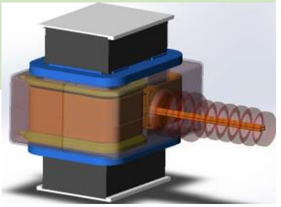


13.2 kV / 400 kW SST-Based EV Charger (1)

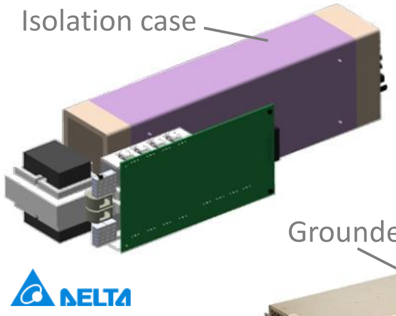
- **Fully modular** input-series-output-parallel (ISOP) topology
- 3 x 9 = 27 AC-DC/DC-DC Cells | **438 switches**
- 15 kW per cell | All-SiC realization | Forced-air cooling

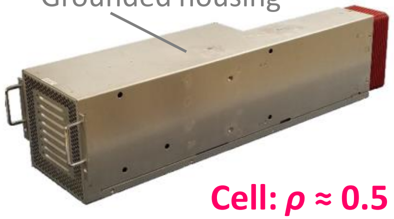






MFT: $\rho \approx 8.4$ kW/dm^3
(w/o 30 kV bushing!)



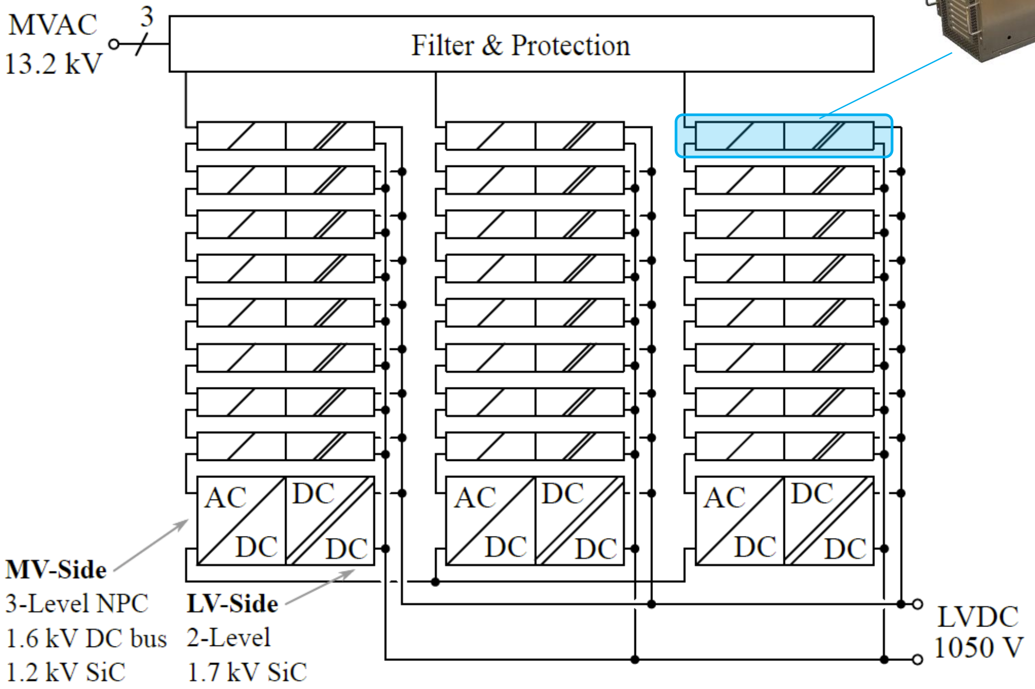


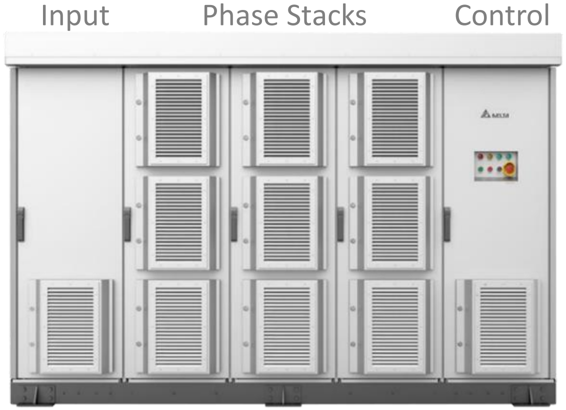
Cell: $\rho \approx 0.5$ kW/dm^3

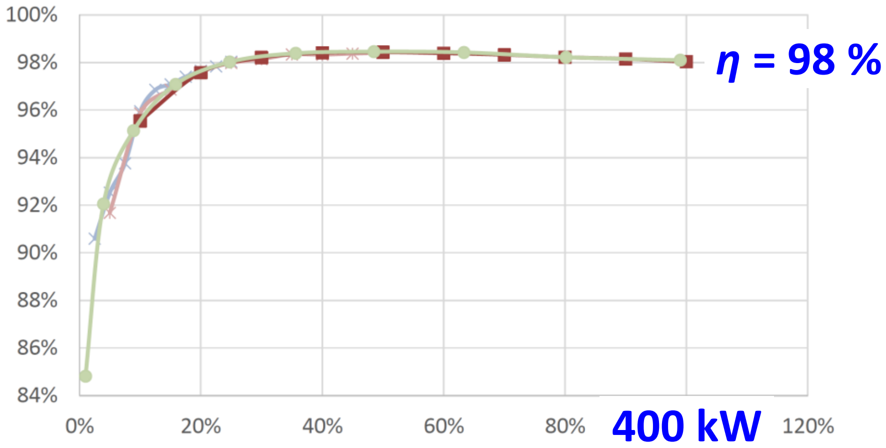
Source: C. Zhu, DOE Presentations, 2019…2021.

13.2 kV / 400 kW SST-Based EV Charger (2)

- **Most advanced industrial MVAC-LVDC SST prototype**
- 3 x 9 = 27 AC-DC/DC-DC Cells | 438 switches
- 15 kW per cell | All-SiC realization | Forced-air cooling







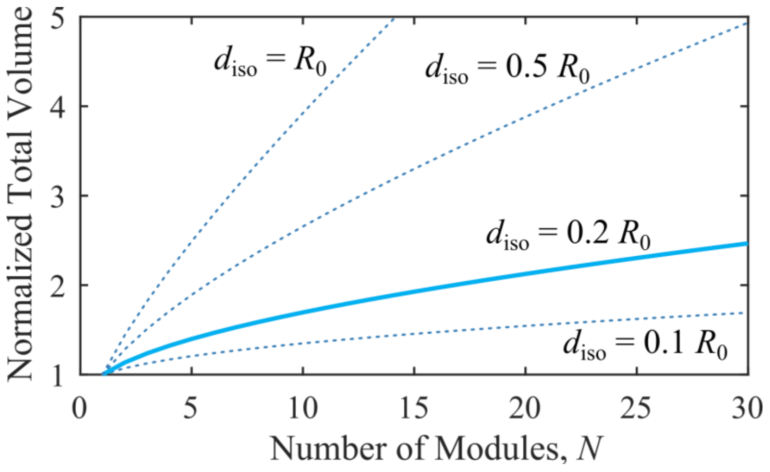
- 3000 kg weight | 3.1 m x 1.3 m x 2.1 m outer dimensions
- **Power density: $\rho \approx 0.05$ kW/dm³ | 0.5 kW/dm³ (Cells) | 8.4 kW/dm³ (MFT)**

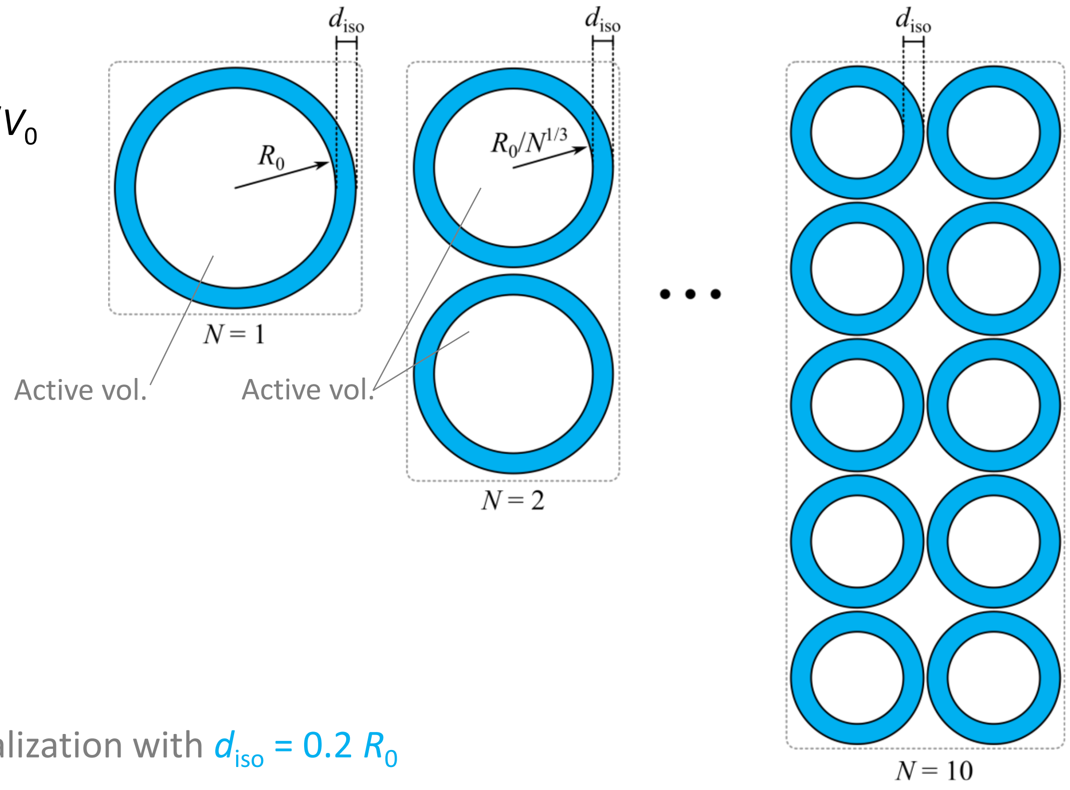
Source: C. Zhu, DOE Presentations, 2019…2021.

Intuition: Modularization Penalty

- ***Highly (!)* simplified consideration**
- Power P processed in sphere with radius R_0
- Modularizing assuming constant power density P/V_0
- Const. isolation / overhead distance d_{iso}

$$V(N) = \frac{4}{3}\pi\left(\frac{R_0}{N^{1/3}} + d_{iso}\right)^3 \cdot N$$





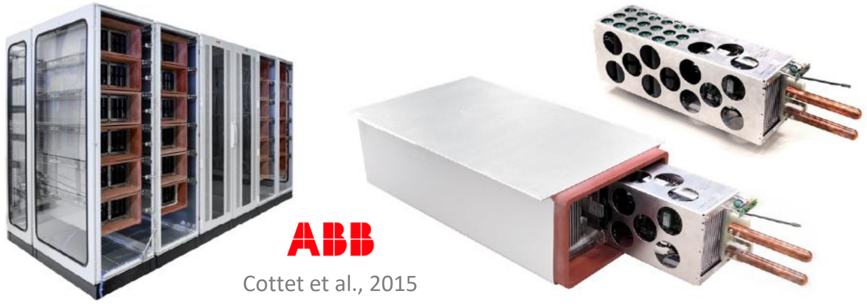
2D visualization with d_{iso} = 0.2 R_0

- **High module count → Massive reduction of overall power density**
- **Additional overhead: Input & output filters | Protection Equipment | Mech. assembly | Cabinets etc.**

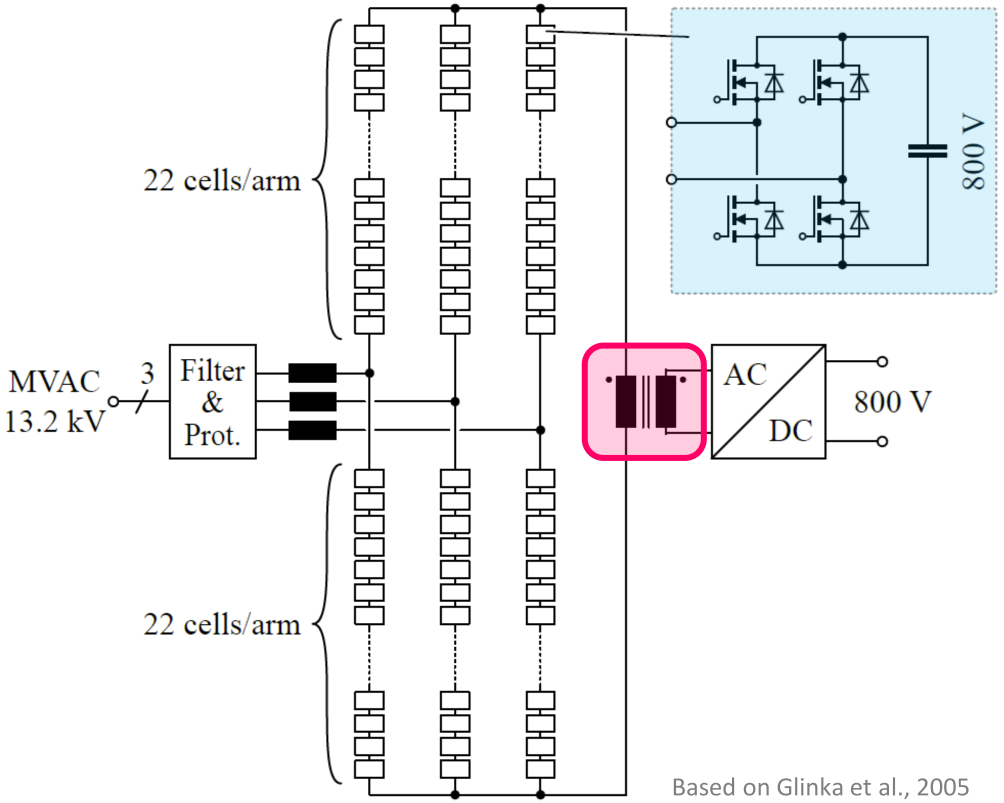
MMC-Based SST Concepts

- **Limit modularity to PE | Single MF transformer**
  - Example for 13.2 kV grid
  - 22 full-bridge cells per MMC arm | 6 arms
  - 528 switches (1200 V, MV-side only)

- **Example of Advanced Integration Technology**
  - 4 MMC arms
  - 9 half-bridge cells (1 kV, 600 A) per arm
  - Hot-pluggable cells



Cottet et al., 2015



Based on Glinka et al., 2005

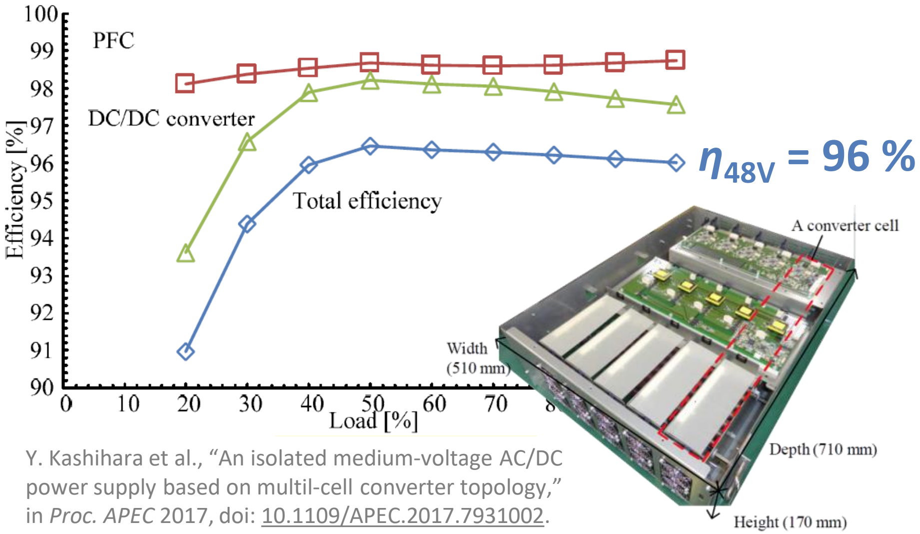
- **Benefits of Modularity → Redundancy | Availability | Economies of Scale | Transportability**

Remark: Rack-Level MVAC-LVDC SSTs

- **MVAC distribution to the rack & small rack-level SSTs**

Fuji Electric, 2017

- 2.4 kV rms (l-n) | 25 kW | **48 V DC**
- LV Si multicell ISOP | 0.4 kW/dm^3

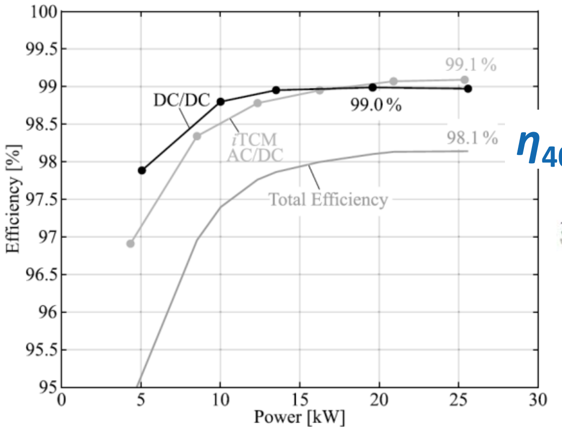


η_{48V} = 96 %

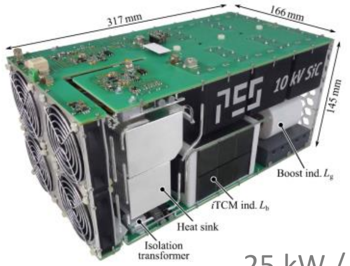
Y. Kashihara et al., “An isolated medium-voltage AC/DC power supply based on multil-cell converter topology,” in *Proc. APEC* 2017, doi: 10.1109/APEC.2017.7931002.

ETH Zürich, 2019

- 3.8 kV (l-n) | 25 kW | **400 V DC**
- 10 kV SiC single cell | 3.5 kW/dm^3



η_{400V} = 98.1 %



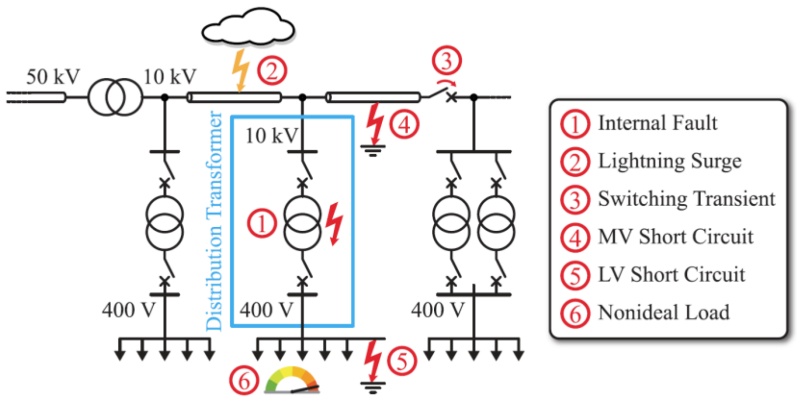
25 kW / 7 kV PFC stage

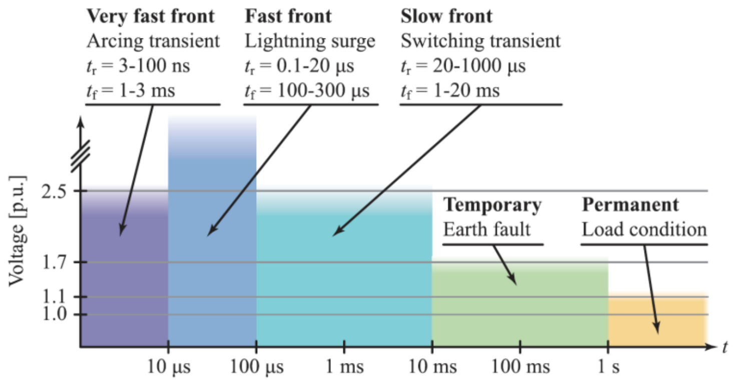
D. Rothmund et al., “99% efficient 10 kV SiC-based 7 kV/400 V DC transformer for future data centers,” *IEEE Trans. Emerg. Sel. Topics Power Electron.*, 2019, doi: 10.1109/JESTPE.2018.2886139.

- **Large Overhead!**
  - MV protection equipment & MV switchgear (disconnectors, grounding switches, …)
  - Central LFT needed unless incoming MV level is distributed (typ. >> 2.4 kV)

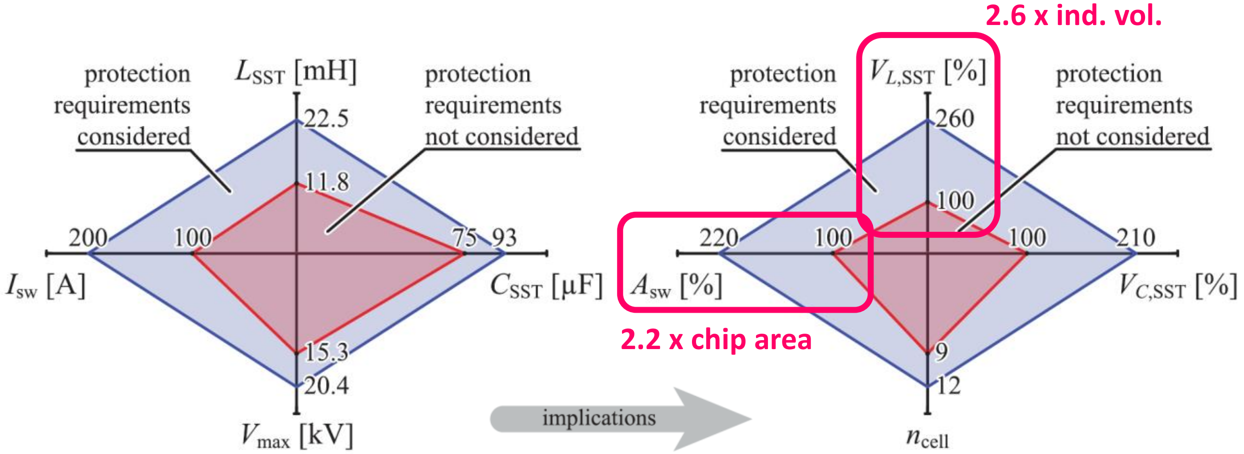
Remark: Protection of SSTs

- **Harsh MV grid realities: Surges, overvoltages, short-circuit faults, …**





- **Example: 1 MVA @ 10 kV**
  - f_{sw} = 1 kHz
  - 9 cells → 12 cells
  - Si IGBTs 1700V/100A → 1700V/200 A
  - L_{sst} from IEEE 519→ L_{sst} from SCR = 7%



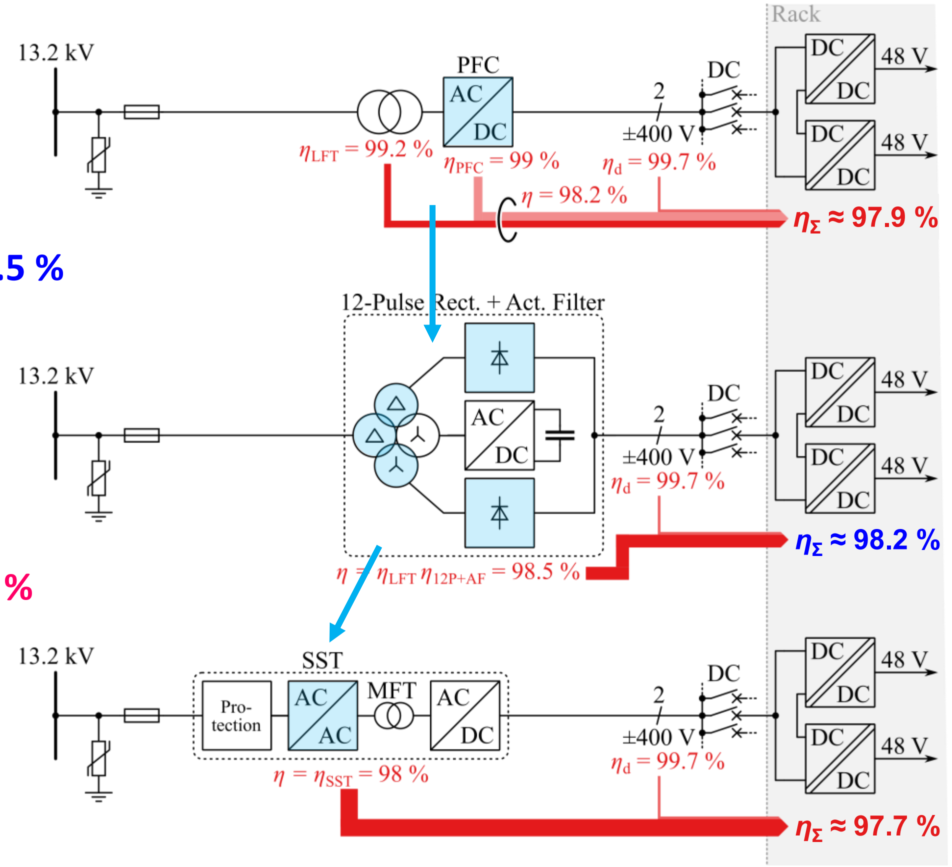
- **Protection requirements → Significant impact on MV-side power electronics dimensioning!**

Source: T. Guillod et al., "Protection of MV converters in the grid: the case of MV/LV solid-state transformers," *IEEE Trans. Emerg. Sel. Topics Power Electron*, 2017.

Comparative Evaluation of MVAC-LVDC Interfaces

Efficiency

- LFT + SiC PFC: $\eta \approx 98.2$ %
- 12-Pulse + AF: $\eta \approx 98.5$ %
- Industrial SST: $\eta \approx 98$ %



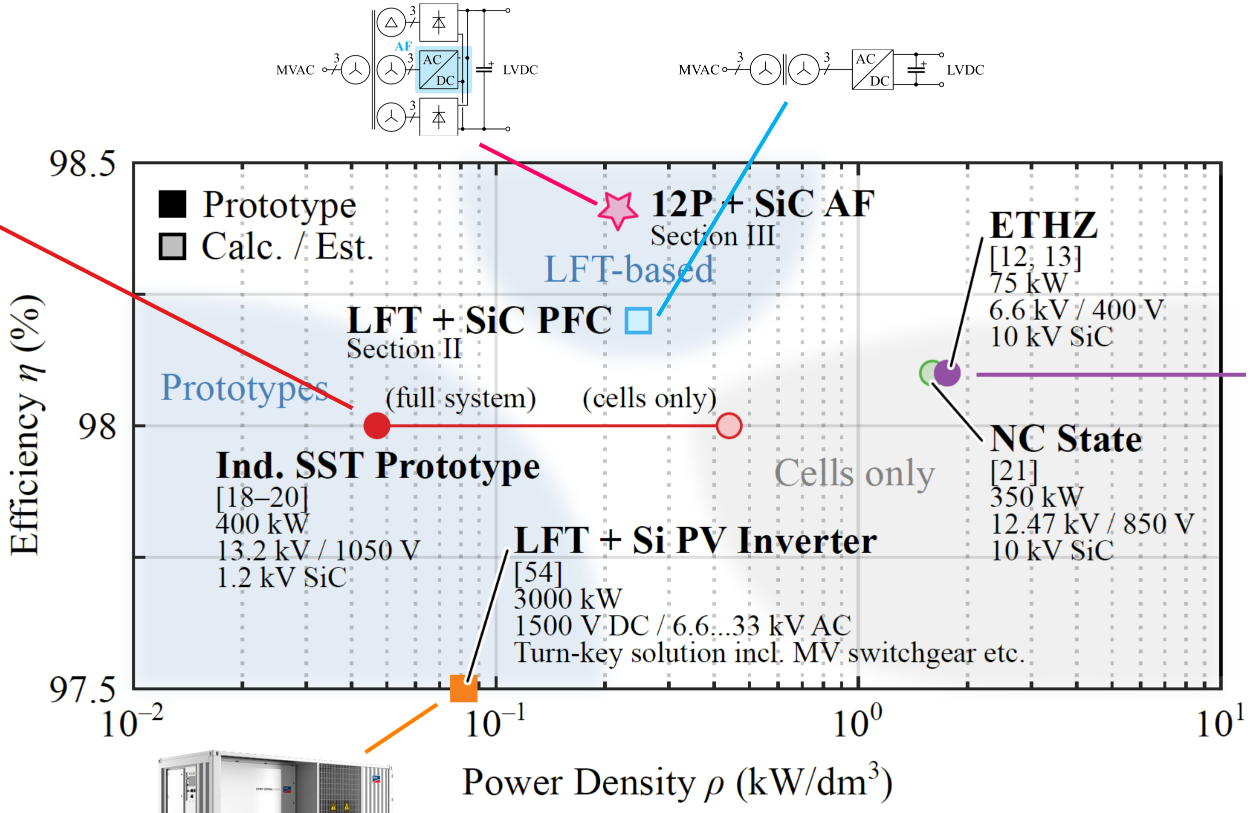
- Central PFC on LV-side
- No switch-mode PFC
- Active filter / partial-power proc.
- Central PFC on MV-side

- 12-Pulse + AF → Highest efficiency & robustness vs. reduced functionality

Efficiency & Power Density

- **Industrial MVAC-LVDC SSTs** → **No volume / efficiency / functionality advantage over LFT + LV SiC PFC**
- **LFT-based solutions** → **Robustness & Scalability**
- **12-Pulse rectifier + act. filter** → **Low complexity | Reduced functionality**

400 kVA LFT
Shown for comparison

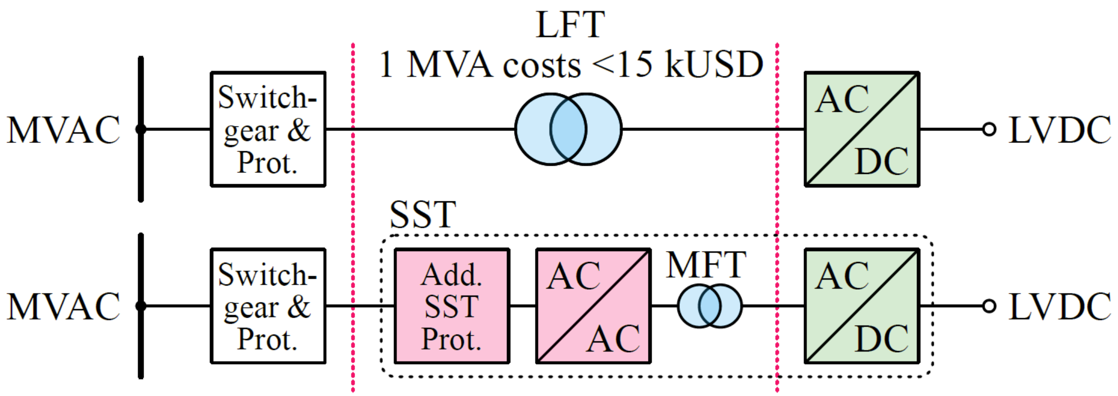


10 kV SiC
Not industrialized

[12, 13]	Rothmund et al., 2019
[18-20]	Zhu et al., 2019-2021
[21]	Liang et al., 2019
[54]	SMA, 2018

Realization Cost (CAPEX)

- **High-efficiency (Ecodesign) LFTs cost < 15 kUSD/MVA**
- MMC-based SST: Similar LV-side power electronics → Similar cost
- MFT smaller but likely higher USD/kVA (e.g., Litz wire vs. solid copper, etc.)



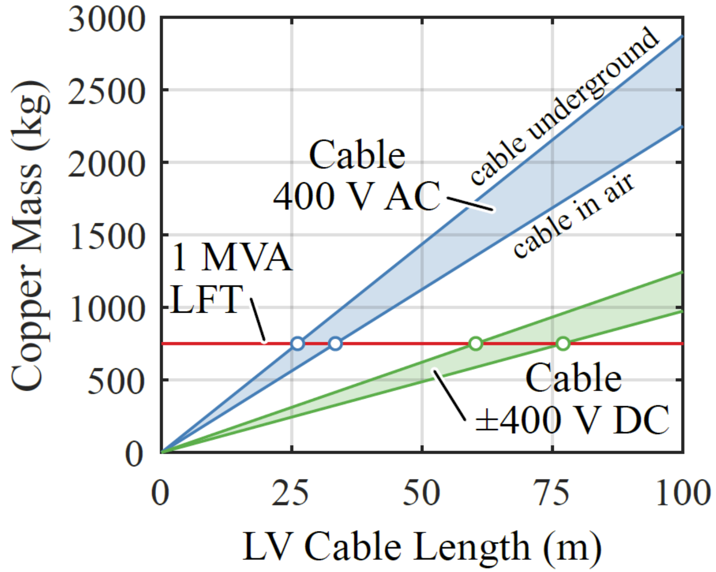
- **Budget for SST's MV-side PE incl. additional protection < 15 kUSD/MVA**

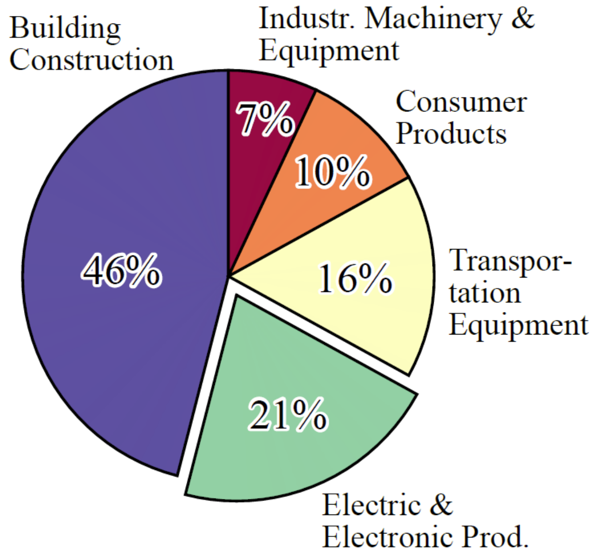
- State of the art
  - Automotive LV DC-AC inverters: 3 USD/kW (U.S. Drive Roadmap R&D target for 2025)
  - Grid-connected PV DC-AC inverters: 30…55 USD/kW (Fraunhofer, 2022)

- **SST cost drivers: MFT, MV-level isolation coordination, assembly, communication systems, …**

Ecological Aspects / Resource Usage

- LV distribution busbars / cables dominate the installed copper mass
- 40+ vs. 10 years typ. lifetime of LFTs vs. SSTs
- Recyclability advantage of LFTs & high-power single units (such as diode/thyristor rectifiers)



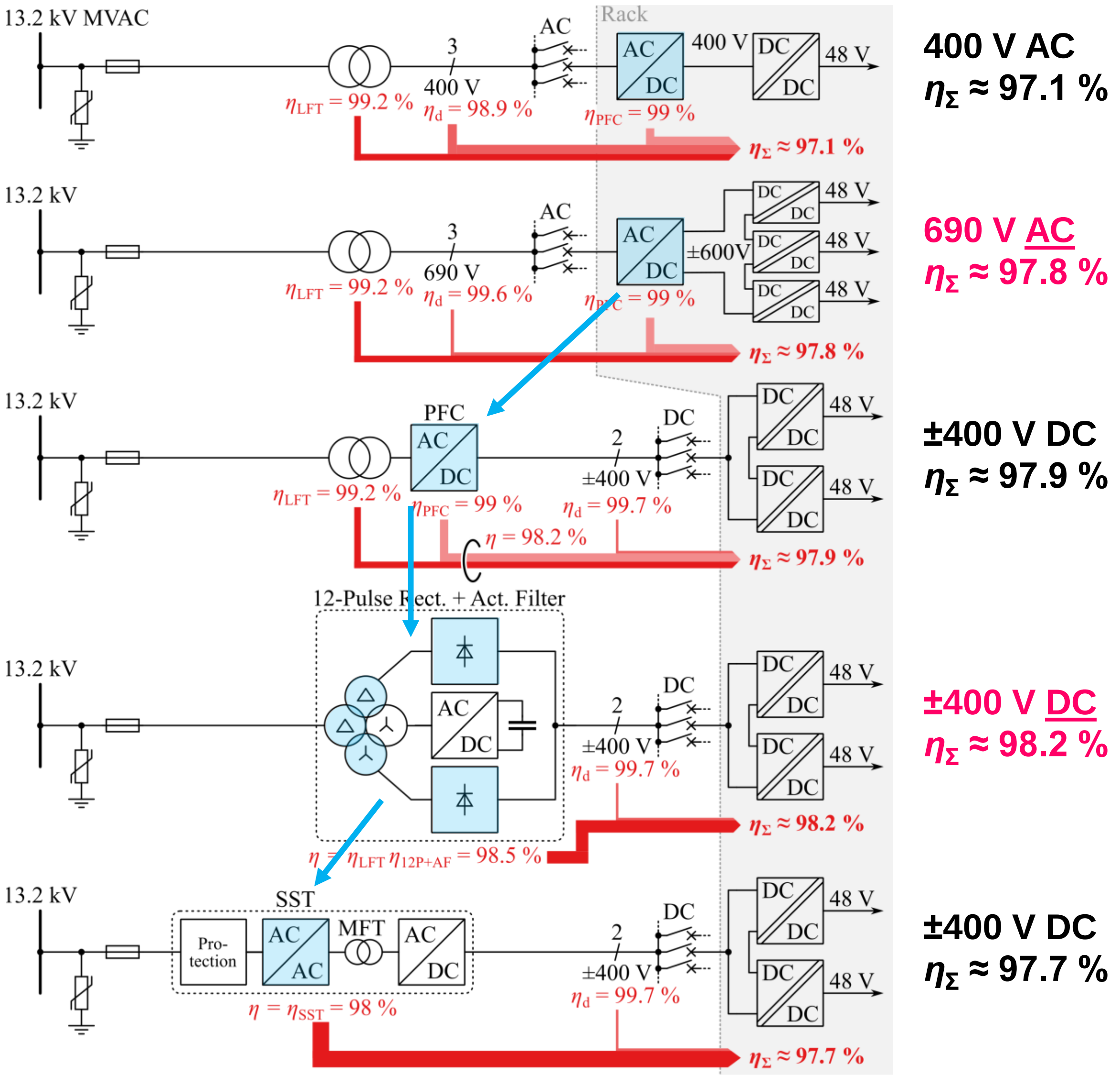


Copper usage by sector in the U.S. (2021)
U.S. Geological Survey

- Global copper usage dominated by other sectors
- Life-cycle assessments—cradle-to-grave / cradle-to-cradle—still missing!

Conclusion

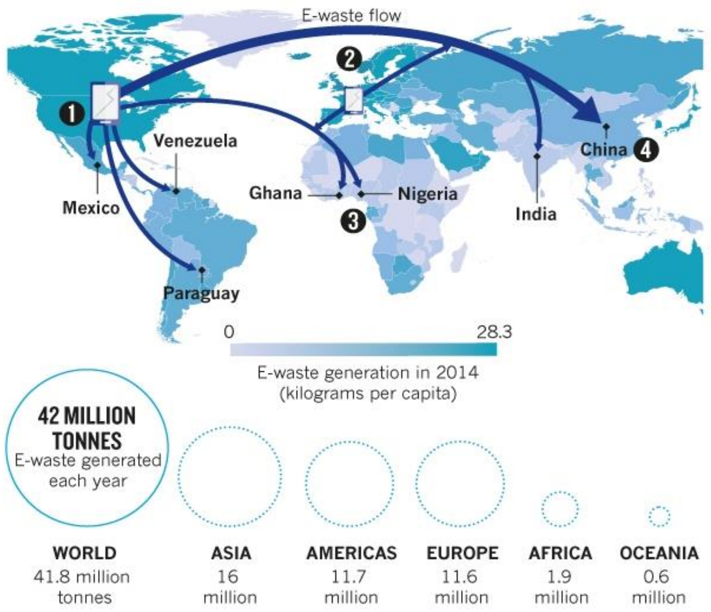
- **690 V AC competitive with ±400 V DC**
  - Add. considerations on integration of renewables, fuel-cell backup power, grid services, etc.
- **LFT + LV SiC PFC**
  - Full functionality, scalability, high robustness
- **12-Pulse rectifier & act. filter**
  - Low complexity, **high efficiency**, scalability
  - **High robustness, long lifetime, good recyclability**
  - Reduced functionality (unidir., no act. DC volt. ctrl.)
- **SST w/o clear advantages**
  - High complexity even for MMC-based designs
  - Modularity / economies of scale / protection / …
  - → Need for future research!



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

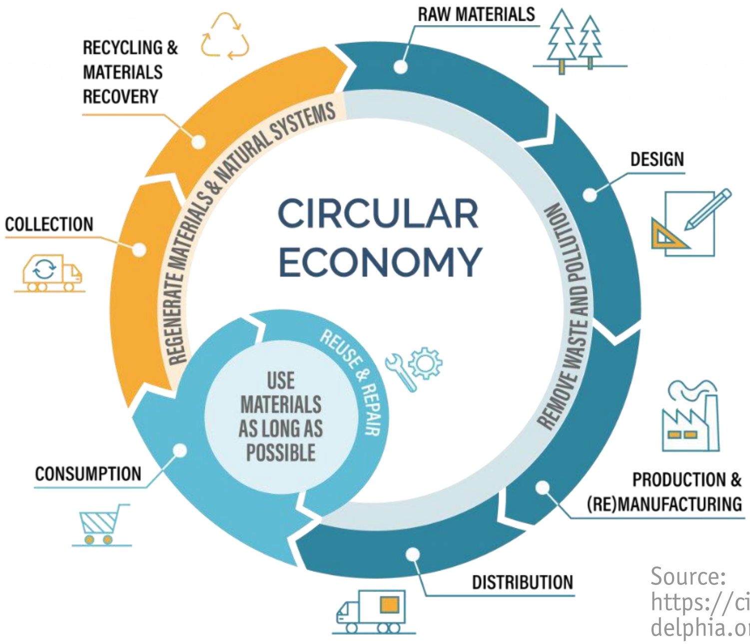
Source: Green IT Solution



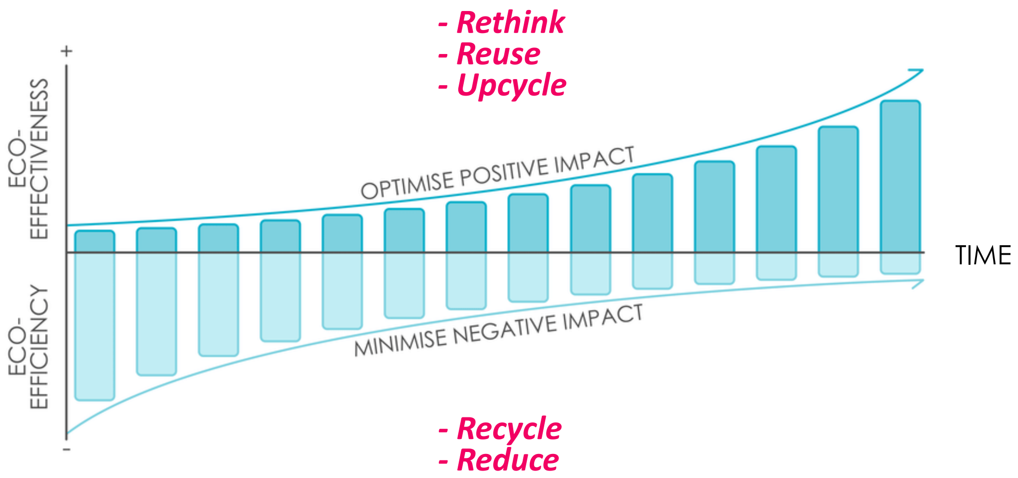
- Growing global E-waste streams → Increasing attention of the public / Upcoming regulations

Remark Cradle-to-Cradle (C2C) Design Concept

- "Linear" economy / Take-make-dispose → "Circular" economy / Perpetual flow & maintained value of resources
- Resources returned into the product cycle at the end of use / Generation of waste minimized
- Maximized use of pure and non-toxic reusable materials



Source: https://circularphiladelphia.org



- Decoupling of economic growth & use of resources
- Measures covering the entire lifecycle → Design | Manufacturing | Consumption | Repair | Reuse | Recycling

Thank You!

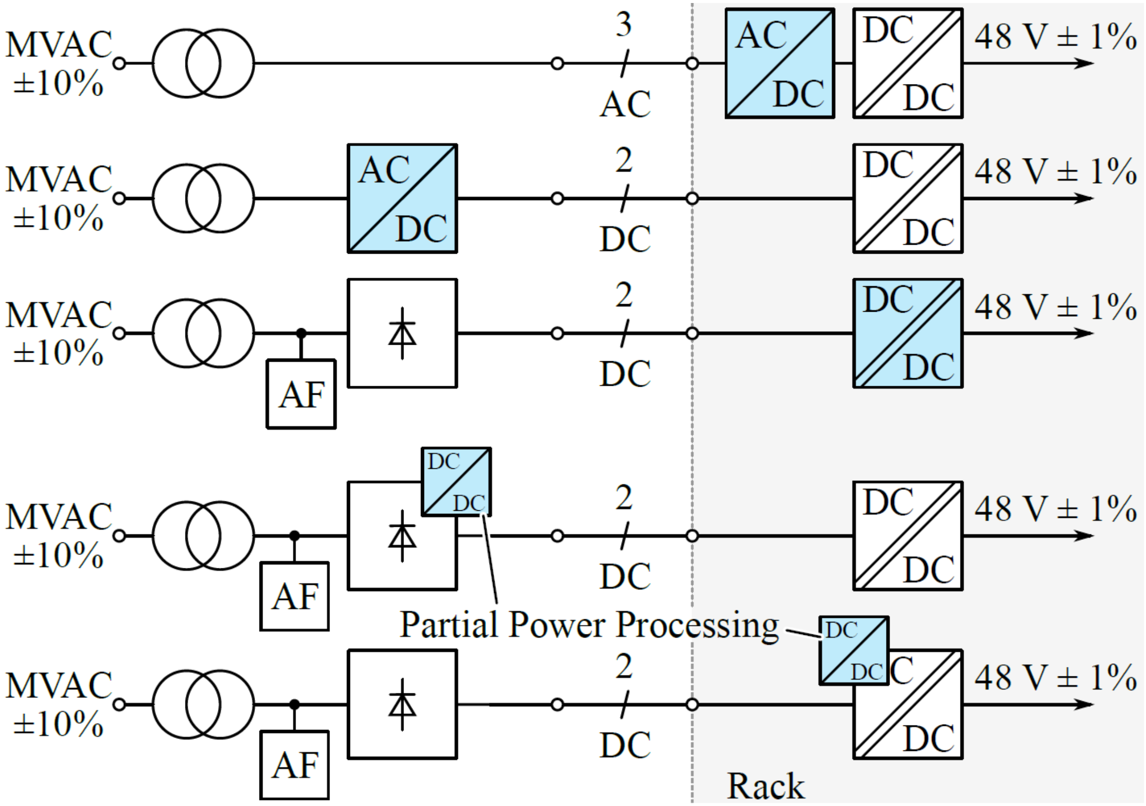
- **Q & A**
  - Contact: huber@lem.ee.ethz.ch

Further Reading:
J. Huber, P. Wallmeier, R. Pieper, F. Schafmeister, and J. W. Kolar, "Comparative evaluation of MVAC-LVDC SST and hybrid transformer concepts for future datacenters," *Proc. Int. Power Electron. Conf. (IPEC/ECCE Asia),* Himeji, Japan, May 2022. [Download]

Backup

DC Voltage Control

- Grid voltage varies ±10% (EN 50160) | Stable 48 V DC for IT equipment needed



- One converter stage must provide regulation capability!