3-Φ AC/DC Solid-State Transformer Concepts for Next-Generation AI Datacenters

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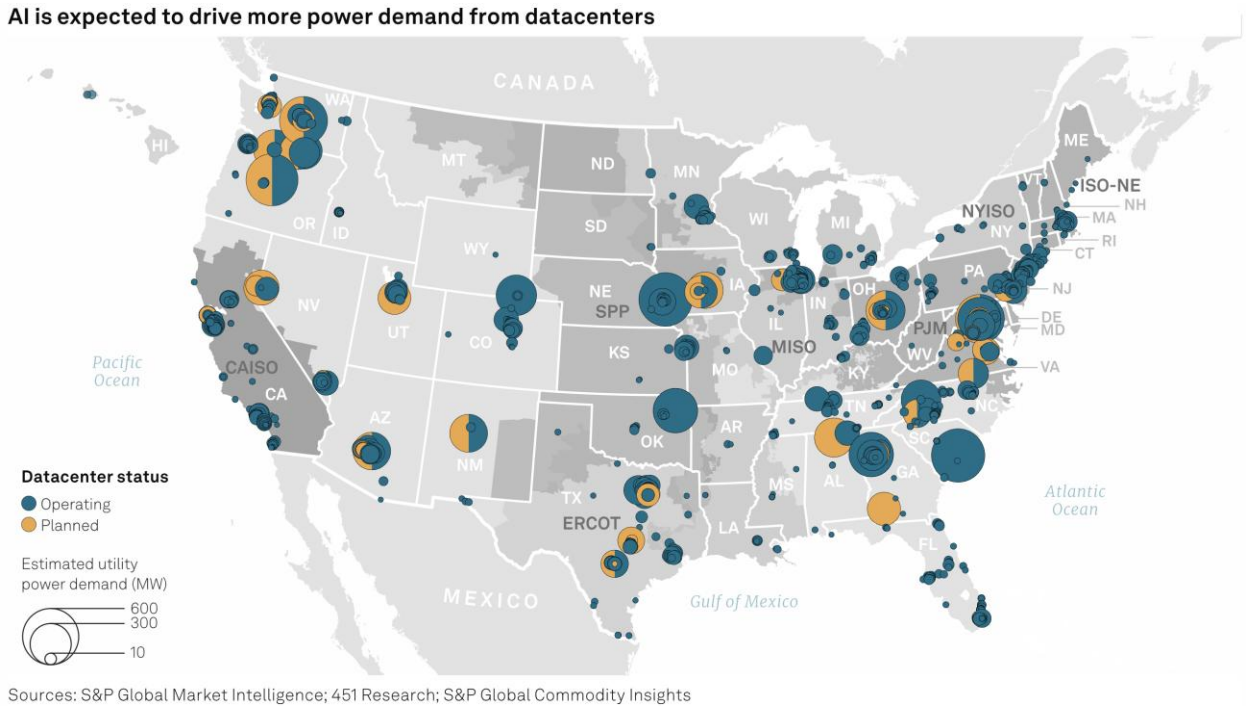
Outline

- *Introduction*
- *Two-Stage AC/DC SST Concepts*
- *Quasi-Single-Stage Topologies*
- *Single-Stage/Matrix-Type SSTs*
- *Outlook*

Future Gigawatt-Scale Datacenters

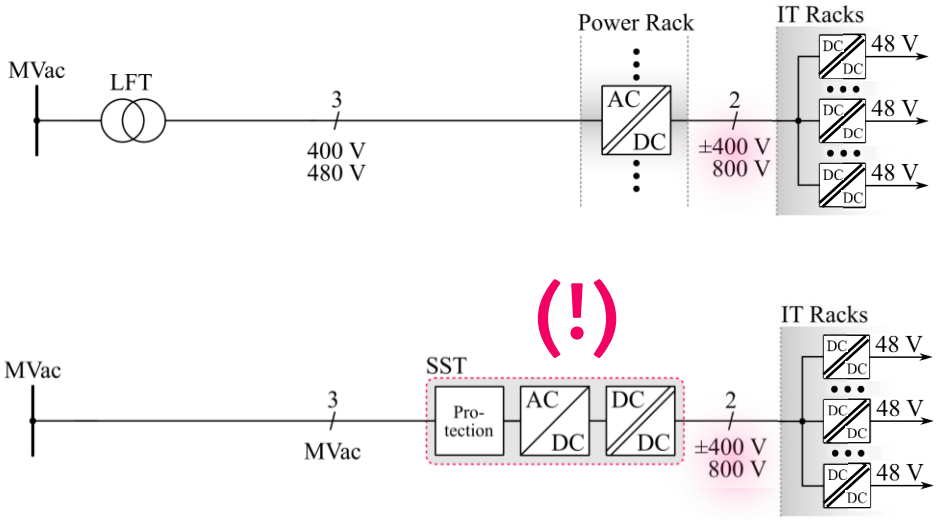
- *«Explosion» of AI — Hyperscale Datacenters Providing Massive Scalable Cloud Services*
- *Gigawatt Power Levels — ≈7…12% of US Electricity in 2028 / 35…65 GW (≈4% in 2023)*

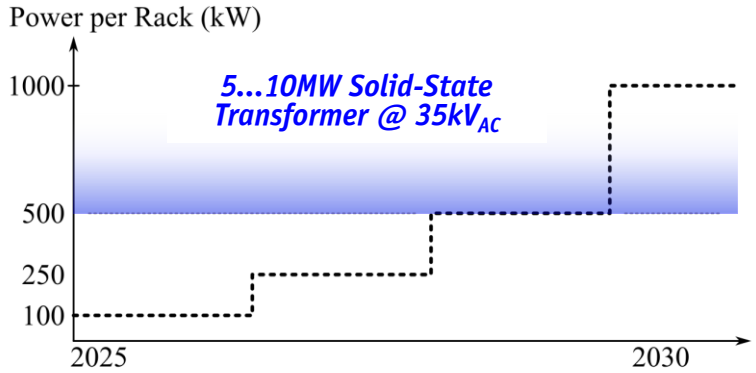


- *Plans for 2.5 … 6 … 11 Gigawatt Campuses Co-Located w/ Nuclear Power Plants (!)*
- *Collaboration w/ Utilities — Datacenters as Responsive Loads for Balancing Solar & Wind Power*

Future 3-Φ Medium-Voltage AC/800V DC Power Supply

- *Near Term — 3-Φ 400V_{AC} or 480V_{AC} or 600V_{AC} Supply & AC/DC Power Racks / Side Cars incl. Battery Buffer Units*
- *Mid Term — Medium-Voltage AC Distribution & AC/DC Solid-State Transformers (SSTs) Replacing Power Racks*

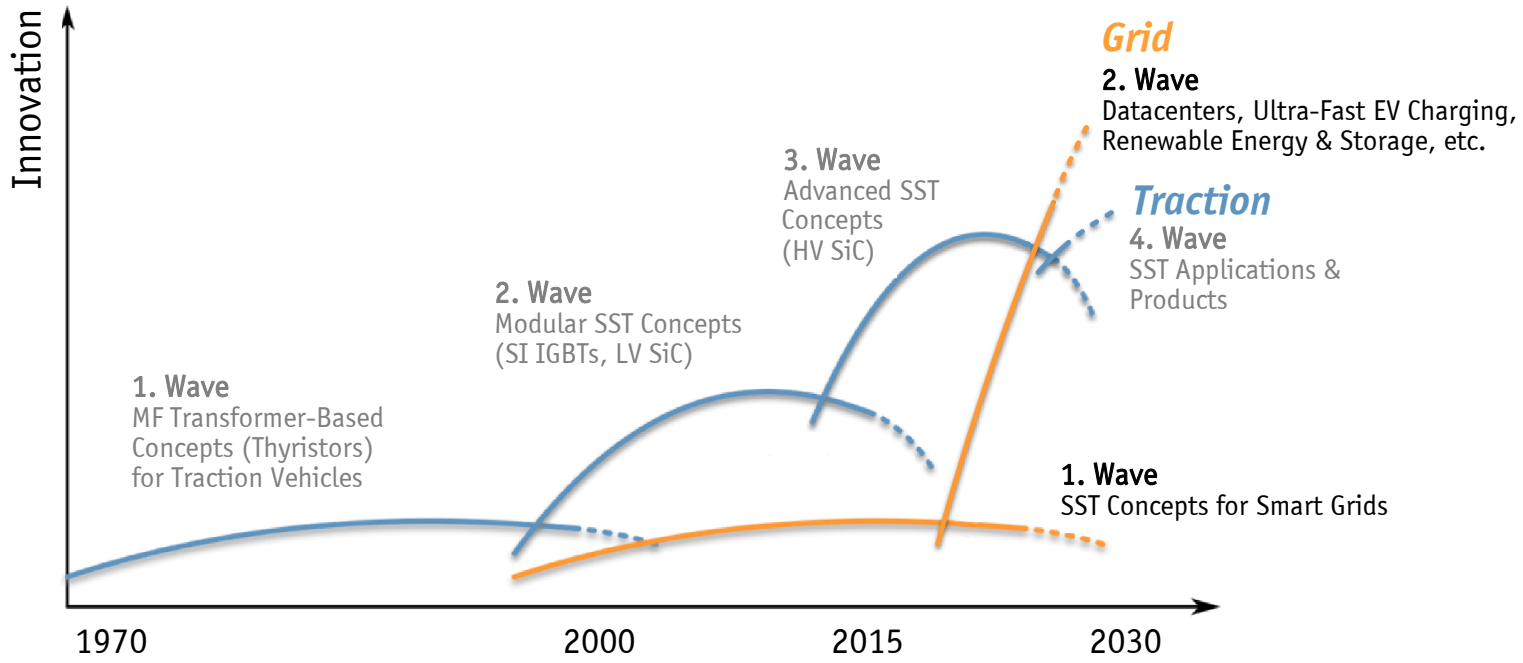




- *IT Rack Power Levels Expected to Reach 1MW by 2030 / ±400V_{DC} or 800V_{DC} or ±750V_{DC} Replacing 54V_{DC} In-Rack Bus*
- *Medium-Voltage AC Supplied SSTs Feature Lower Busbar Cross Sections & Lower Distribution Losses*

Remark SST Development Cycles

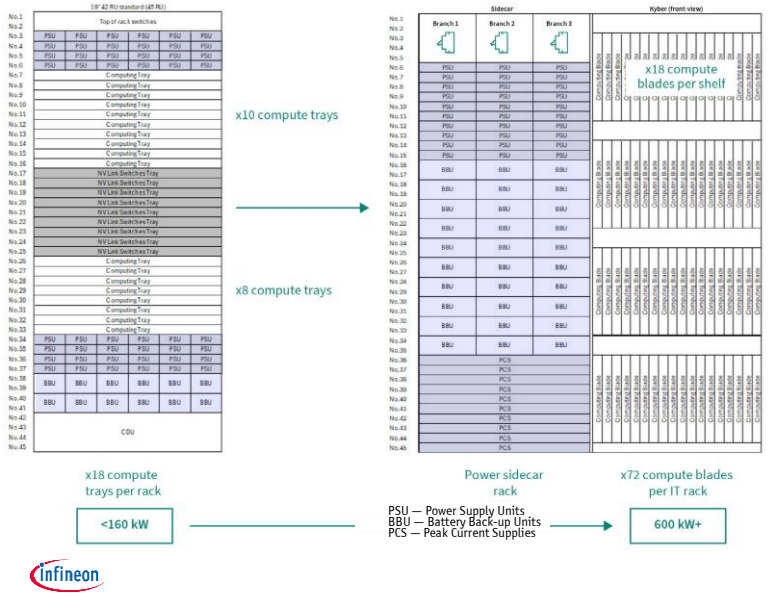
- *Traction — Higher Efficiency / Low Volume & Mass*
- *Smart Grid — Grid Controllability / Renewables & Storage Integration / Ancillary Services*
- *EV Charging — High Power Density / Integrated Buffer Storage / Renewables Integration*
- *Datacenters — Direct MVAC–LVDC Interface / Elimination of Conversion Stages / High Efficiency*



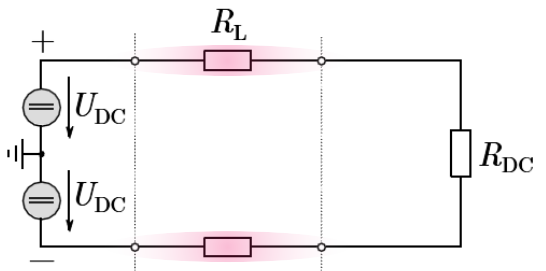
- *Development Cycles Spanning Decades — Governed by Product Life Cycles*
- *Replacement / Expansion of Legacy Systems — Complex Multi-Objective Decisions*

$54V_{DC} \rightarrow 800V_{DC}$ Rack-Level Power Distribution

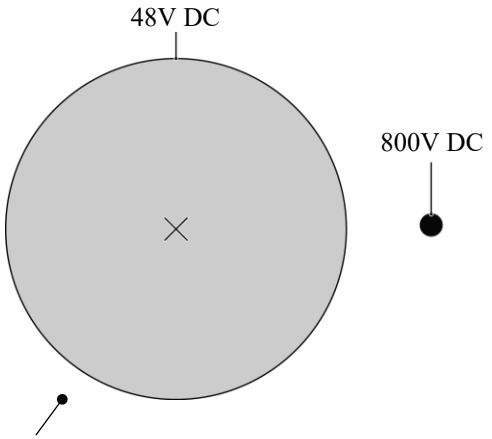
- *Quadratic(!) Dependency of Losses on Voltage Level*
- *Higher Voltage Allows Massive Reduction of Conductor Cross Section / No Bulky Busbars / Low Raw Material Effort*



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



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



Conductor Cross Sections A_{Cu} for Same Losses

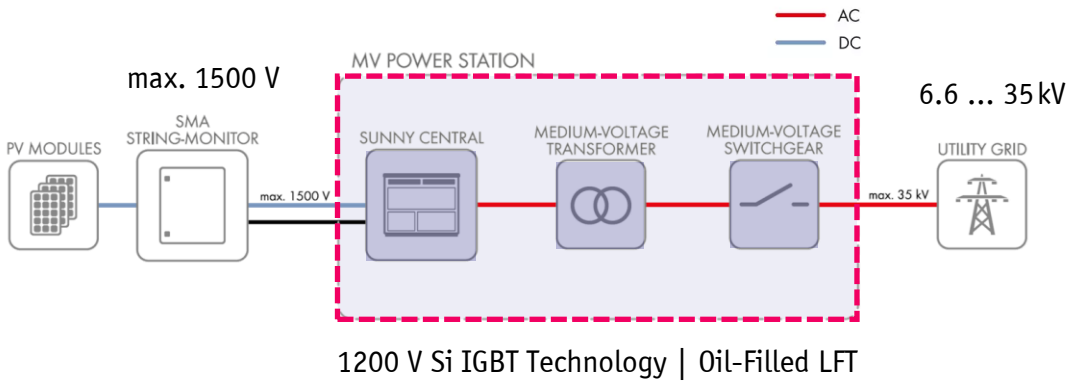
- *Next-Generation AI Workloads — $54V_{DC}$ In-Rack Distribution Replaced by $800V_{DC}$ & Separation of Power & Compute*
- *Traditional $54V_{DC}$ System Would Require Over 200 kg of Copper to Power a 1MW Rack*

State-of-the-Art

LFT-Based Utility-Scale PV Inverter
SST-Based High-Power EV Charging

LFT-Based 3-Φ MV AC/800V DC Power Supply

- *SOTA Turnkey Power Station for Utility-Scale PV Power Plants in 20 ft Container (6.1 m x 2.6 m x 2.4 m)*
- *3 MVA Low-Voltage Si IGBT Inverter | 50Hz Transformer (LFT) | MV Switchgear | etc. — 0.08 MW/m³*

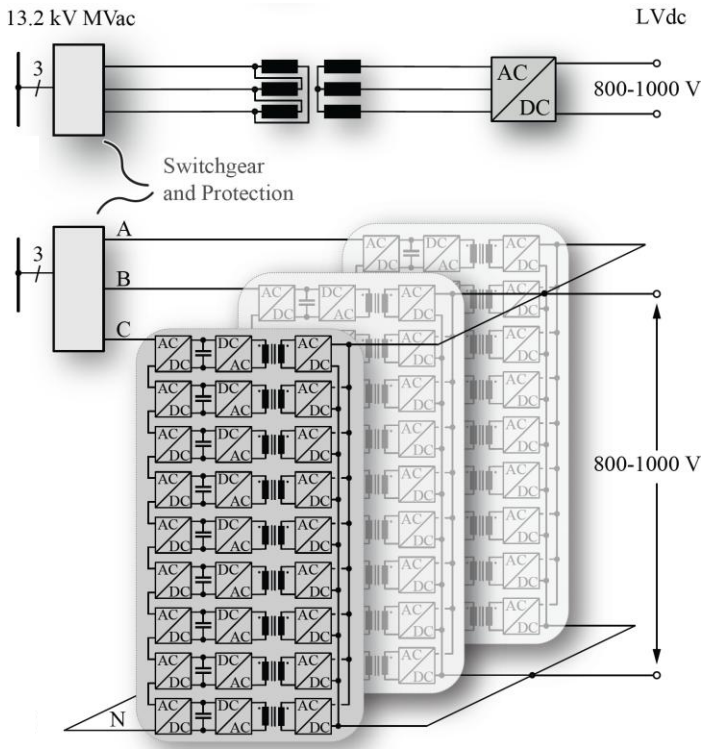


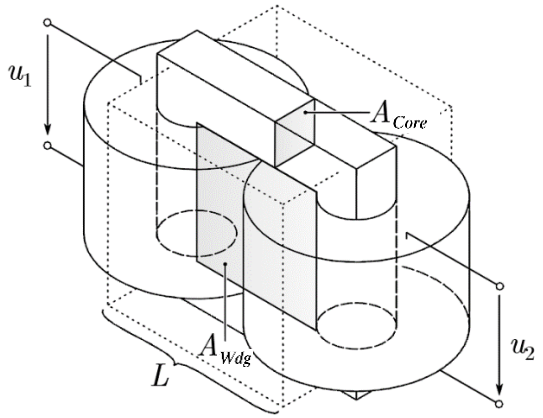
1200 V Si IGBT Technology | Oil-Filled LFT

- *98.5% CEC Inverter Efficiency / 99% Transformer Efficiency (EcoDesign, Oil-Filled)*
- *97.5% Overall Efficiency / Improvements for Si IGBTs → SiC MOSFETs & Dry Type LFT → 98+%*

LFT-Based vs. SST-Based 3-Φ MV AC/800V DC Supply

- *Conventional Realization w/ 50Hz Transformer (LFT) & Low-Voltage AC/DC Converter*
- *Fully-Modular Solid-State-Transformers (SST) w/ HF-Isolation Stages in ISOP Arrangement*



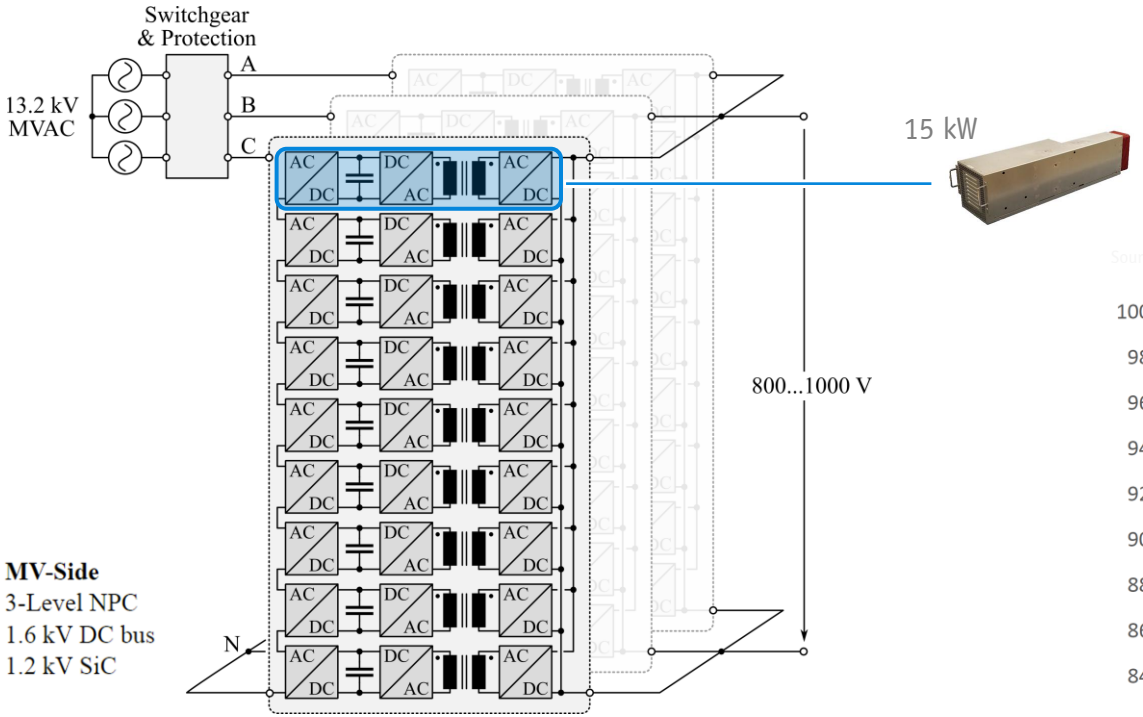


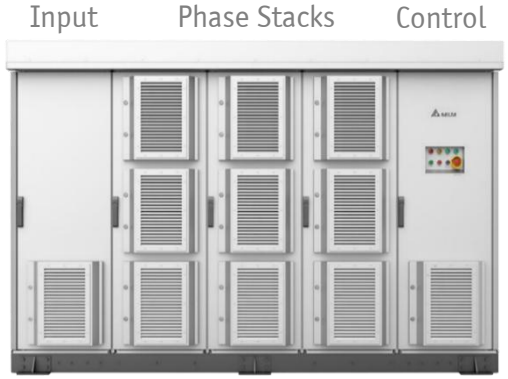
$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{\mathrm{rms}} \hat{B}_{\max} f} \sim L^4 \qquad \frac{P_t}{L^3} \sim L.f$$

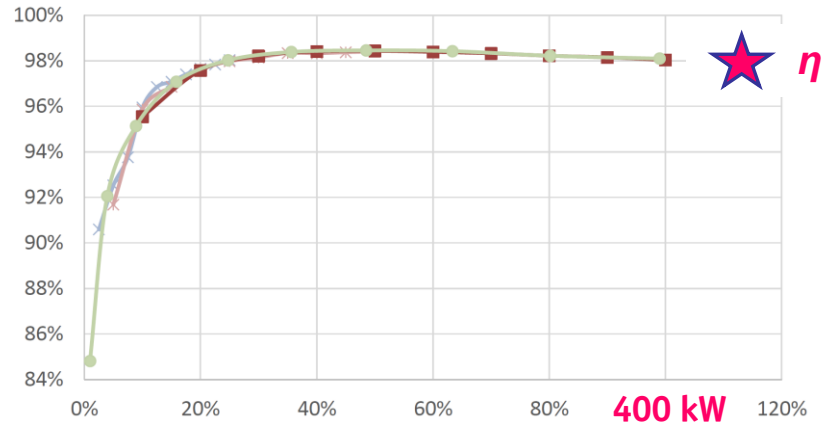
- *LFTs — Excessive 100+ Weeks Delivery Time of 50/60Hz Transformers*
- *MFTs — Lower Raw Material Effort / Lower Raw Material Costs / Lower CO_2 Footprint*

400kW 3-Φ 13.2kV$_{AC}$/800V$_{DC}$ SST — Gen #1 1/2

- *Industrial SST Prototype (US DOE Project 2018 - 2021)*
- *3 x 9 = 27 AC/DC — DC/DC Cells → 438 Switches*
- *Forced-Air Cooling*





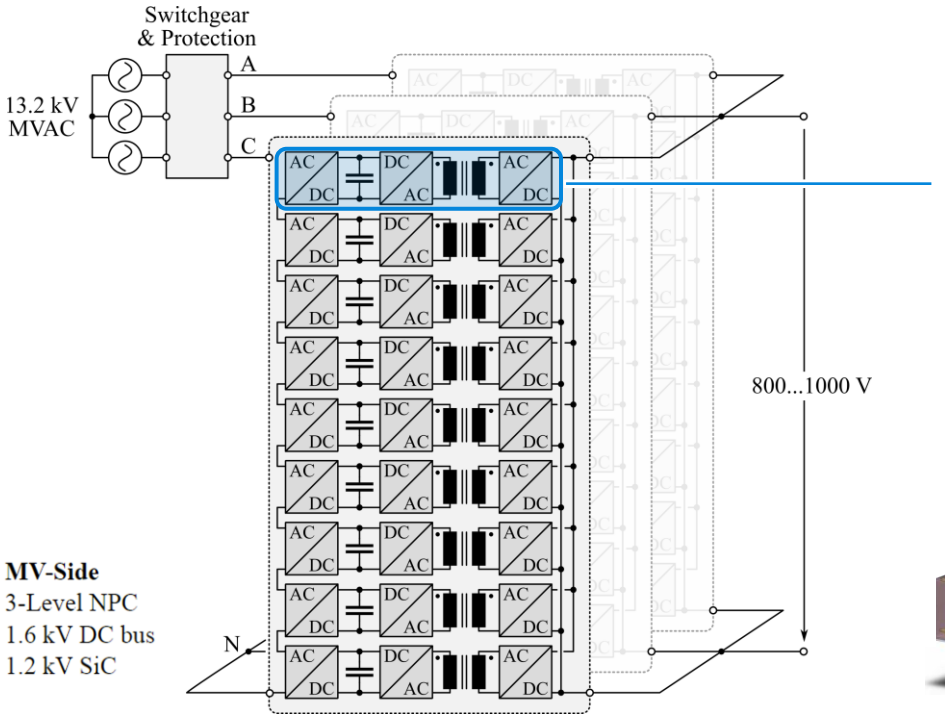


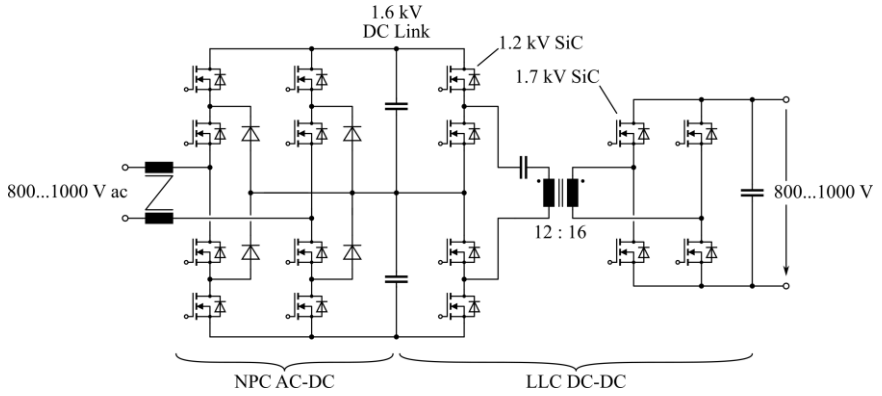
- *3000 kg Weight | 3100 x 1300 x 2100 mm Outer Dimensions*
- *Power Density → 0.05 kW/dm³ (System) | ≈ 0.5 kW/dm³ (Cells) | ≈ 8.5 kW/dm³ (MFT)*

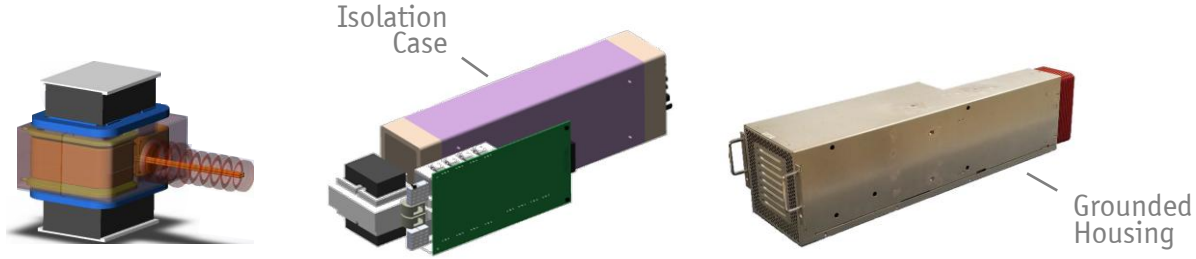
400kW 3-Φ 13.2kV$_{AC}$/800V$_{DC}$ SST — Gen #1 2/2

- *Industrial SST Prototype (US DOE Project 2018 - 2021)*
- *3 x 9 = 27 AC/DC — DC/DC Cells → 438 Switches*
- *Forced-Air Cooling*

Source: Ch. Zhu, 2021







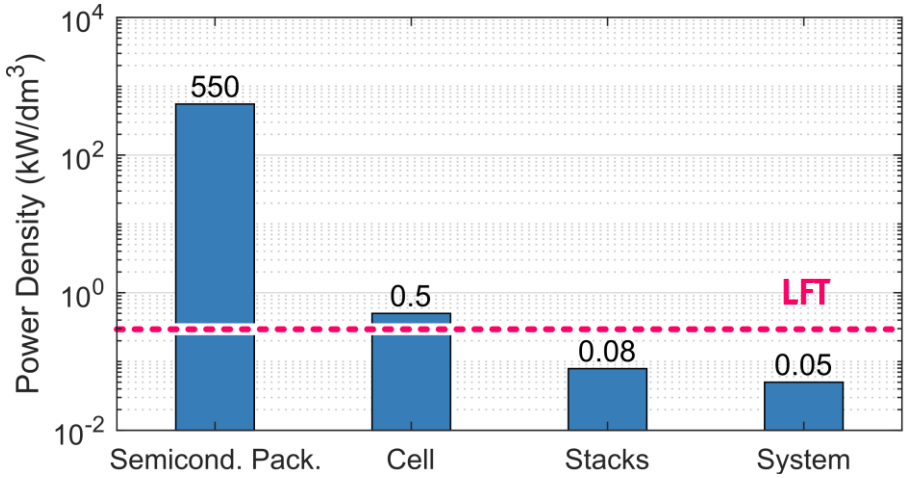
- *15 kW Cells (≈ 0.5 kW/dm³) / All-SiC Realization | 100+ kHz MFT (≈ 8.5 kW/dm³ w/o Bushing !)*

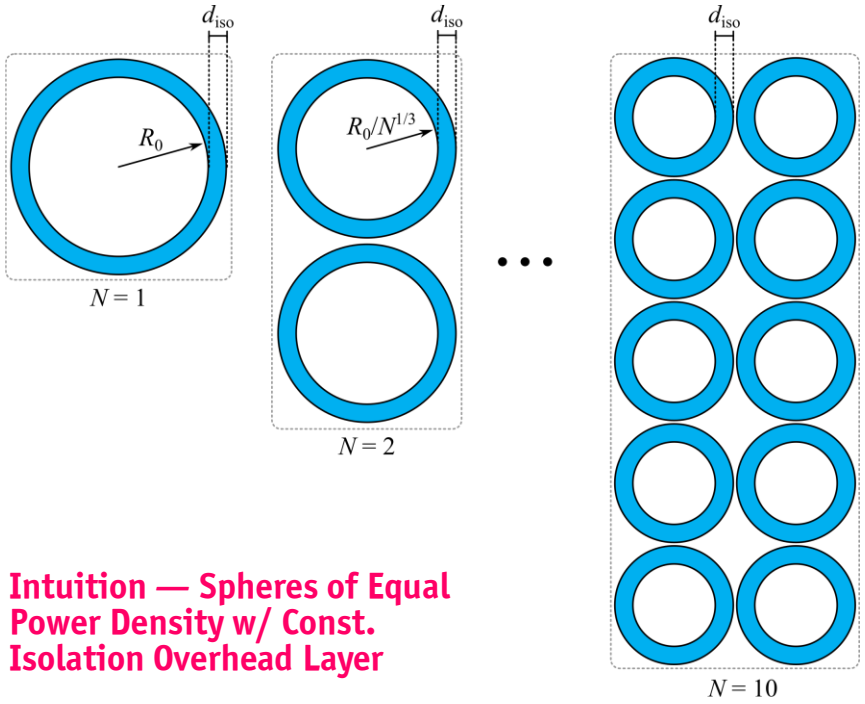
Penalty of Full Modularization

- *Massive Reduction of Power Density from Cell to Full System → «Modularization Penalty»*
- *Accumulation of Isolation Distances AND Transformer Scaling (!)*

$$\frac{P_t}{L^3} \sim L.f$$

Power Module → System — DELTA Gen. #1



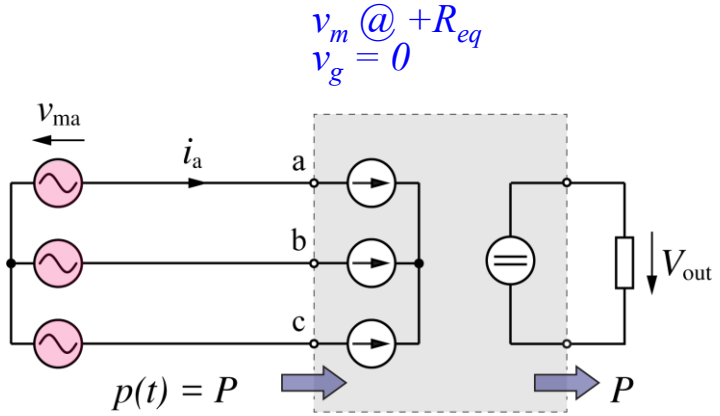


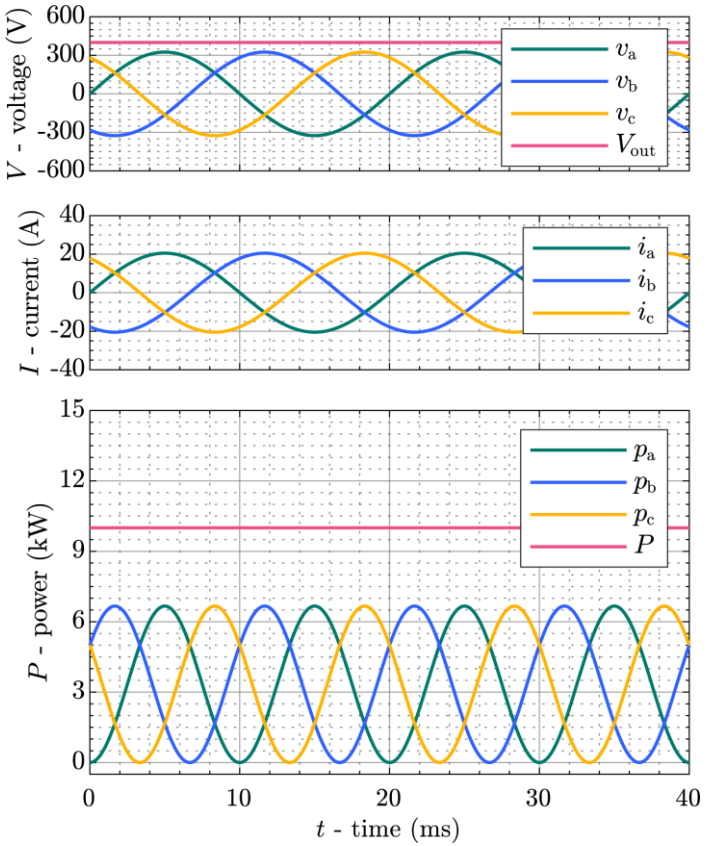
Intuition — Spheres of Equal Power Density w/ Const. Isolation Overhead Layer

- *Future 10+kV SiC Devices → Lower Number of Cells for Given Medium-Voltage Level*

Penalty of 3x 1-Φ AC/DC Conversion Power Pulsation

- *Symmetric 3-Φ Sinusoidal AC Mains*
- *Symmetric 3-Φ Sinusoidal Input Currents*
- *Ohmic Mains Behavior*

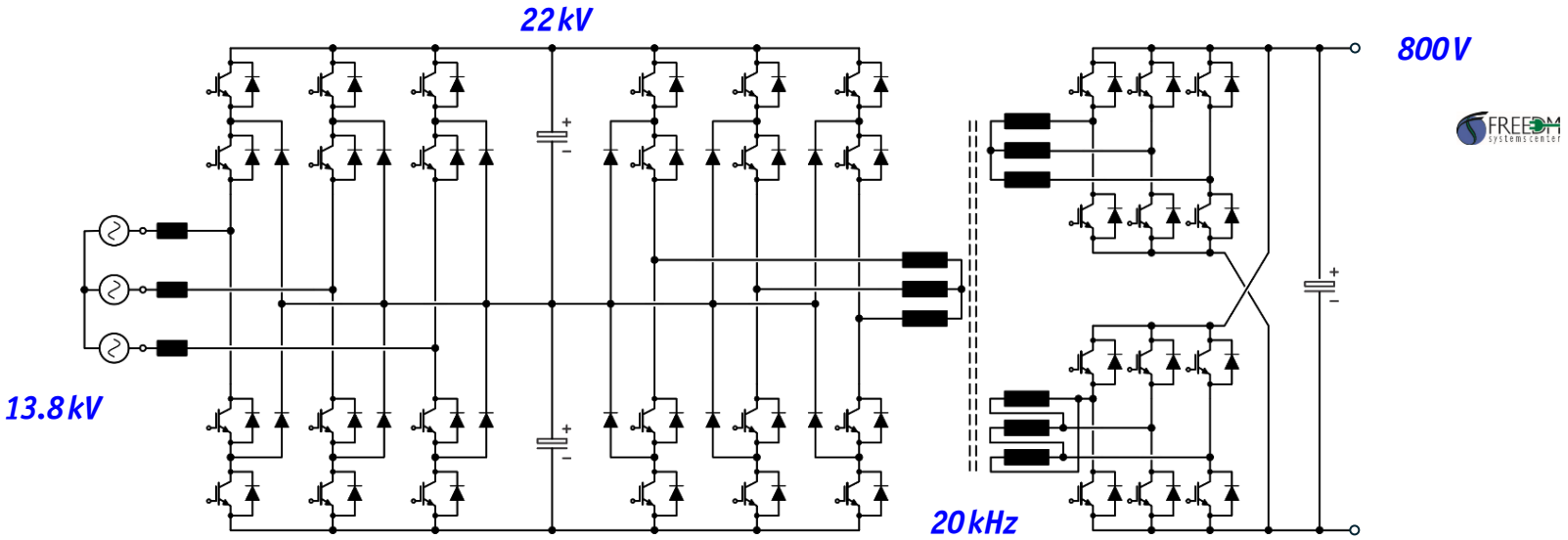




- *2x Mains-Frequency Input Power Pulsation in Individual Phase Units — DC-Link Buffer Capacitors*
- *Constant Overall 3-Φ Instantaneous Power*

Remark Two-Stage Monolithic 3-Φ AC/DC SST

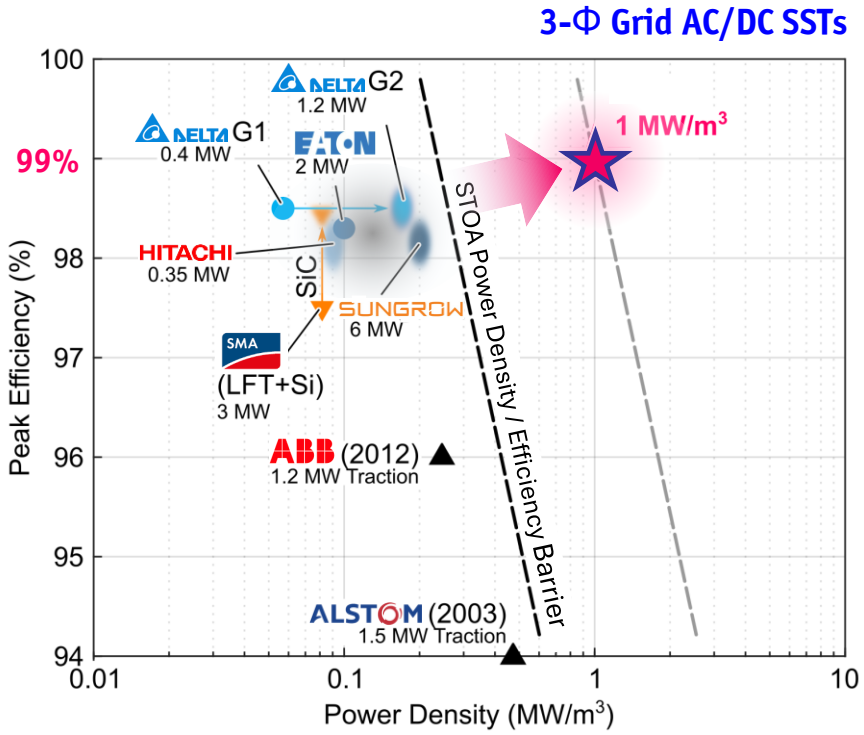
- *Non-Modular Approach / Standard Converter Topology / Low Complexity / Single-MFT*
- *15kV SiC IGBTs / 1200V SiC MOSFETs — Operation @ 13.8kV AC Mains → 800V DC*



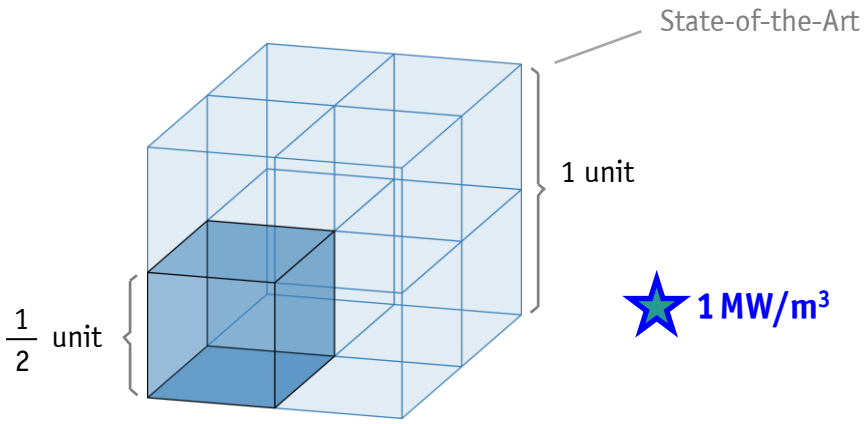
- *No Redundancy (!) — Would Require Series Connection of Power Semiconductors (!)*
- *Not Scalable to Higher Grid Voltages*

Two-Stage AC/DC SST Power Density/Efficiency Barrier

- *State-of-the-Art SST Performance Comparable to LFT-Based Solution (!)*
- *Power Densities of Typ. ≈0.15 MW/m³ | Efficiencies of 98...98.5%*



→ *Next Generation Single-Stage SST*



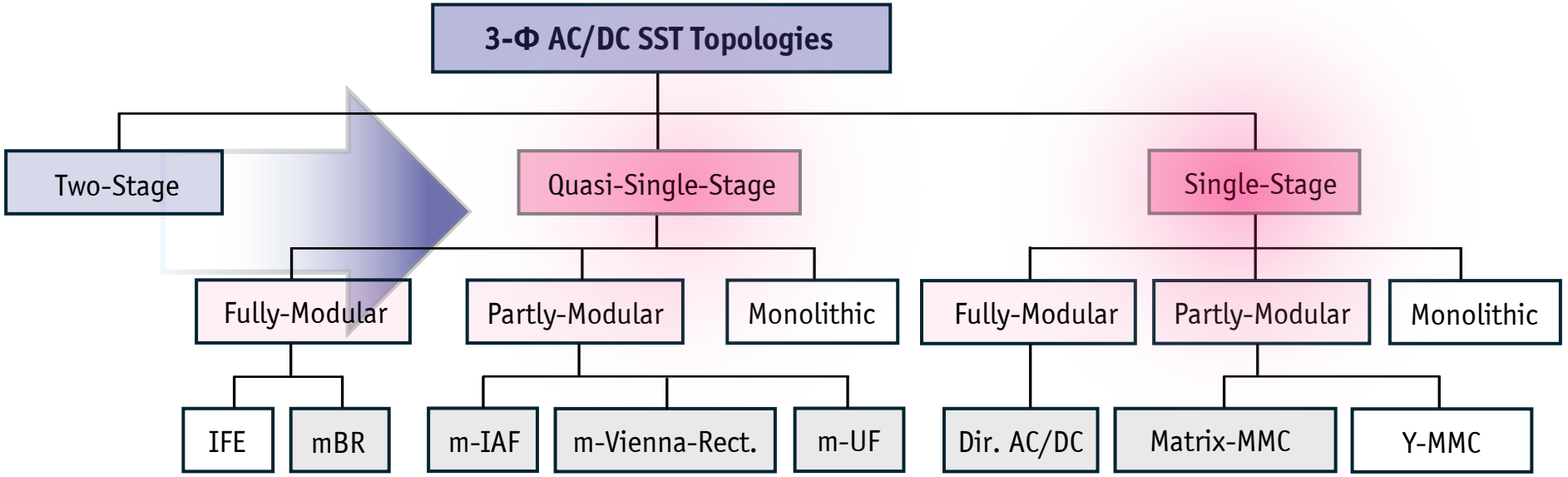
- *Next-Generation SSTs — Power Density x5...10 @ -30% Losses*
- *Full-Scale Demonstrators Complying with All Relevant Regulations Mandatory for Realistic Assessment*

Classification of SST Topologies

Two-Stage / Quasi-Single-Stage / Single-Stage
Fully-Modular/Partly-Modular / Monolithic

Next-Generation Ultra-Compact 3-Φ AC/DC SST Concepts

- *Two-Stage AC/DC-DC/DC → Quasi-Single-Stage OR Single-Stage AC/DC Conversion*
- *Fully-Modular Topology → Partly-Modular OR Monolithic Structure / Transformer Scaling Advantage*
- *Si IGBTs → SiC MOSFETs*

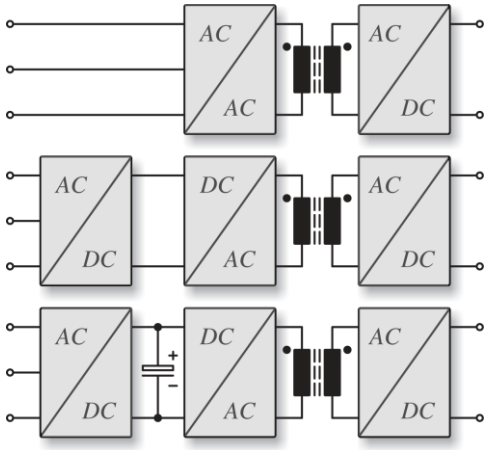


- *99% AC/DC Power Conversion Efficiency / 30% Loss Reduction Comp. to SOTA*
- *1MW/m³ Power Density / Factor 5...10 Increase in Compactness Comp. to SOTA*

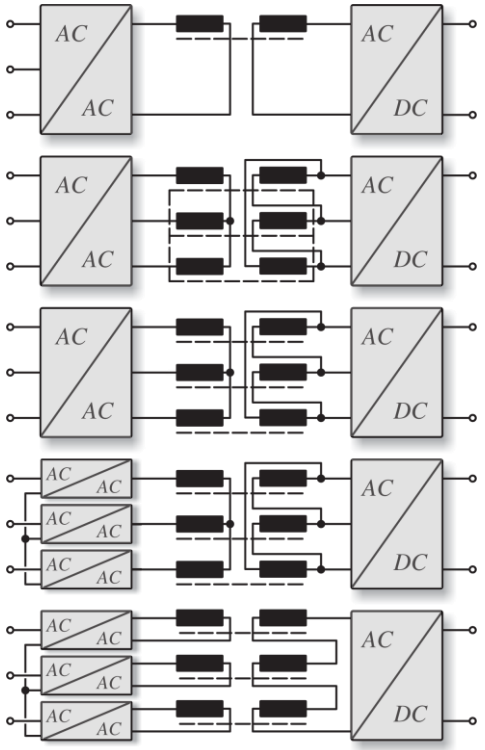
Modularity Categories
- 3-Φ Phase-Modularity
- Phase-String Modularity

3-Φ AC/DC Power Conversion Partitioning 1/2

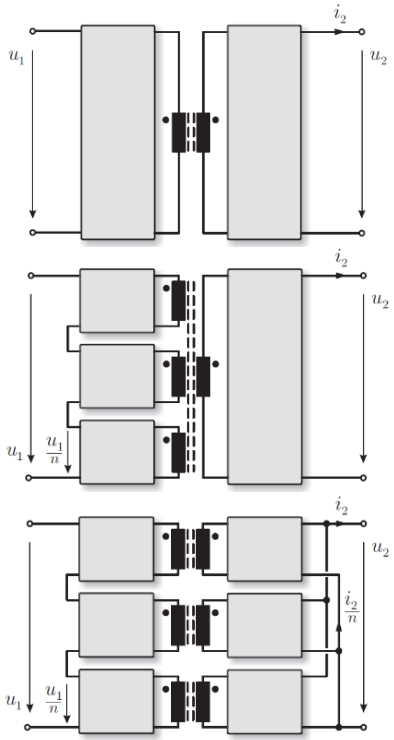
- *Degree of AC/DC Power Conversion Partitioning*



- *Degree of Phase Modularity*



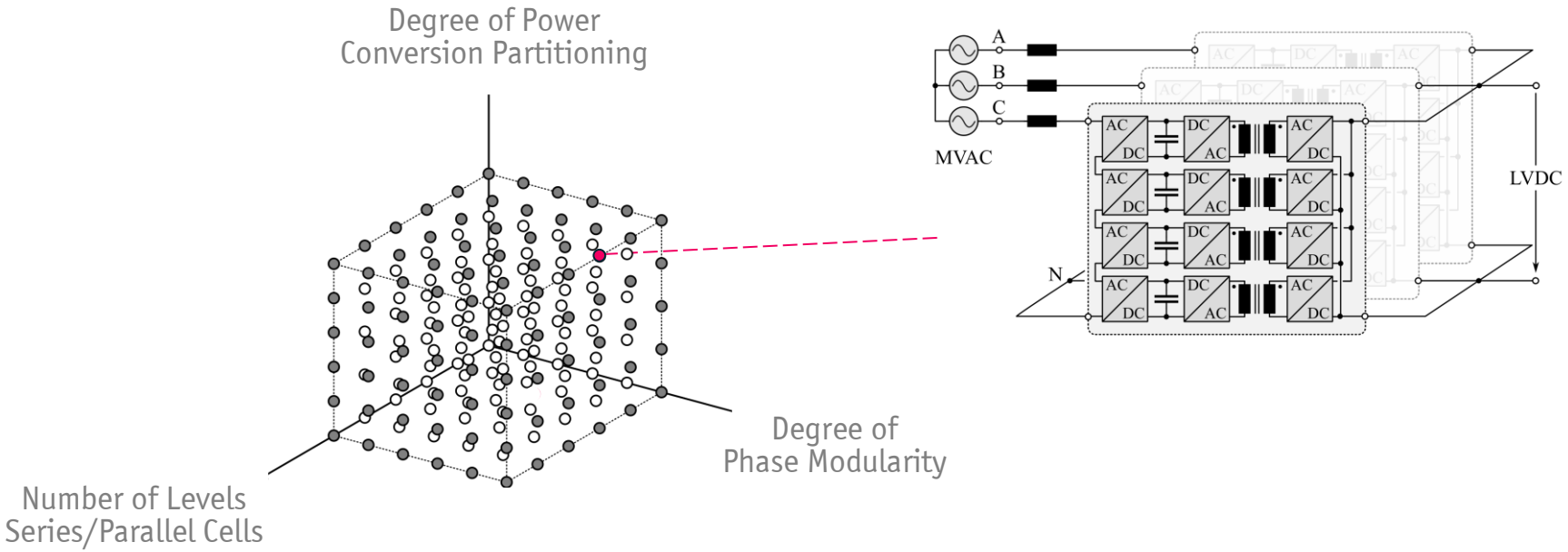
- *Number of Levels Series/Parallel Cells*



- *3-Dimensional Topology Selection Space (!)*

3-Φ AC/DC Power Conversion Partitioning 2/2

- *Partitioning of AC/DC Power Conversion* → *DC-Link & Matrix-Type Topologies*
- *Splitting of 3-Φ Systems into Individual Phases* → *Phase Modularity (Electric &/or Magnetic)*
- *Splitting of Operating Voltage / Current* → *Multi-Level/Cell ISOP Approaches*



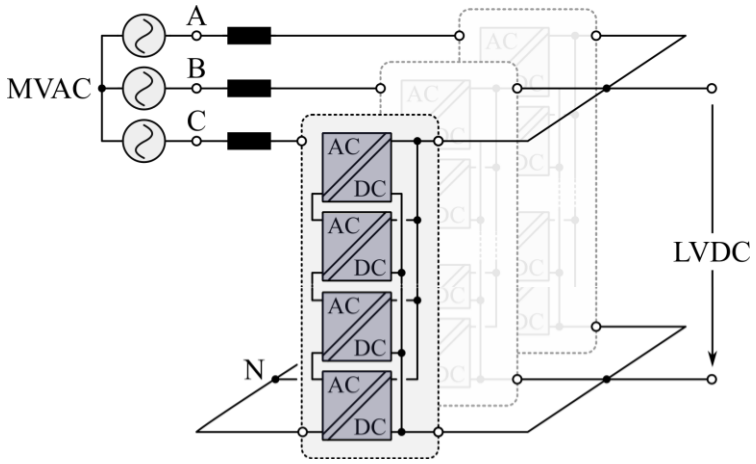
- *Extremely (!) Large Number of Possible Topologies*

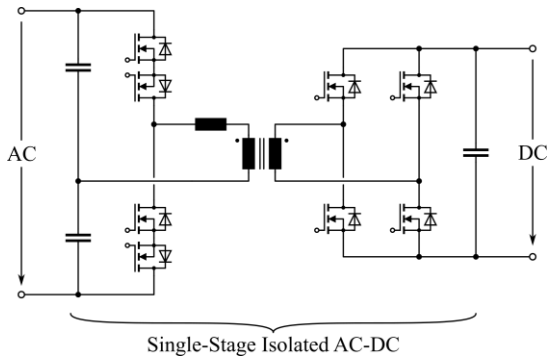
Single-Stage SST Topologies
Matrix-Type SST Concepts

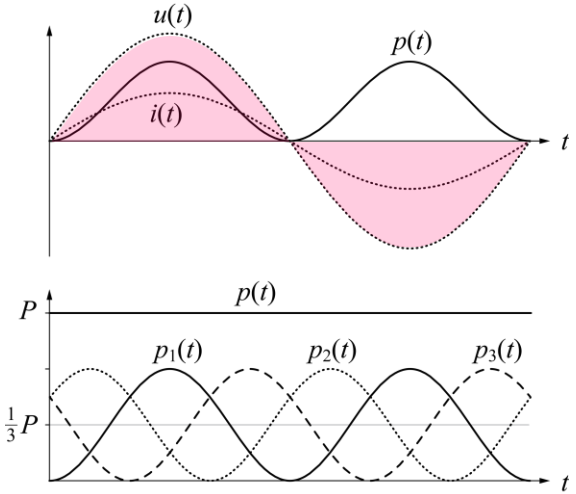
Single-Stage Fully-Modular 3-Φ AC/DC SST Topology

- *AC-Switch-Based Dual-Active-Bridge-Type or Resonant AC/DC Converter Sub-Modules*
- *Half-Bridge Primary Minimizes Number of MV-Side Switches / Full-Bridge Secondary Provides Higher Controllability*

ETH Zurich
Jauch/Biela
2012



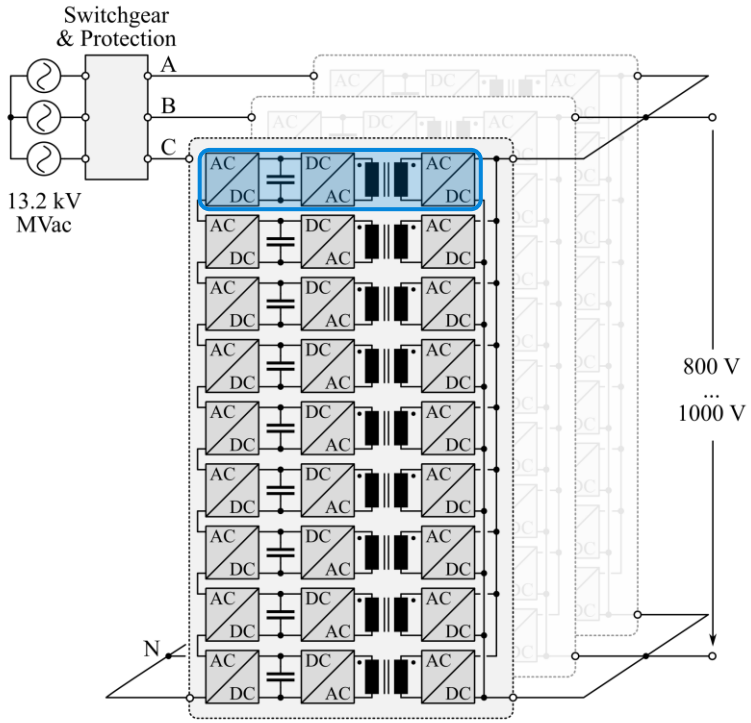


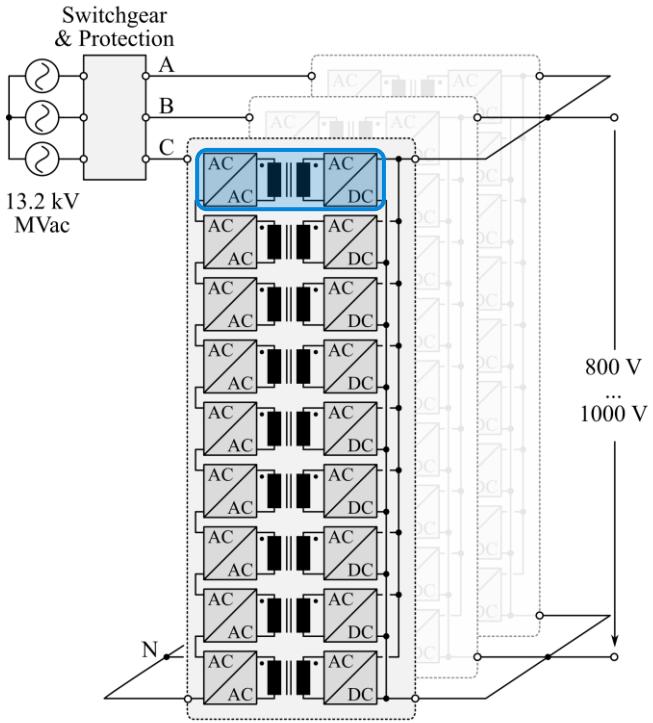


- *2x Grid Frequency Power Fluctuation / Peak Phase Power of 2/3 (!) Total 3-Φ Power / Rel. High Comp. Stresses*
- *120° «Interleaving» of Phases Results in Constant Overall Power Flow — No DC-Side Storage Required (!)*

Remark Single-Stage vs. Two-Stage 3-Φ AC/DC SST

- *Functional Separation vs. Functional Integration of AC Power Factor Correction and DC/DC Conversion*
- *DC-Link Energy Buffer vs. Direct Processing of 2x Mains-Frequency Pulsating Power*



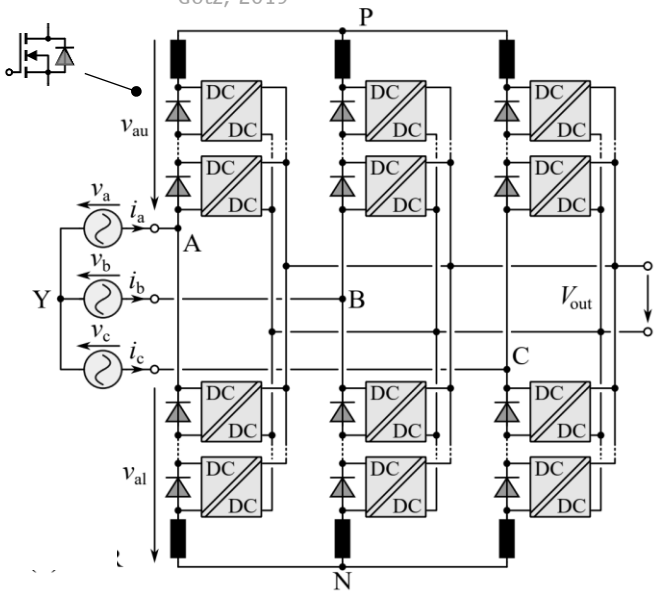


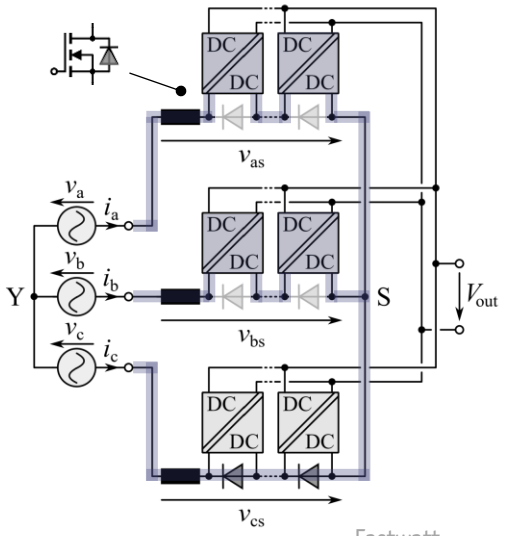
- *Implementation of Single-Stage AC/DC Power Conversion Limited by Availability of AC-Switches*

Single-Stage Modularized 3-Φ Bridge Rectifier SST

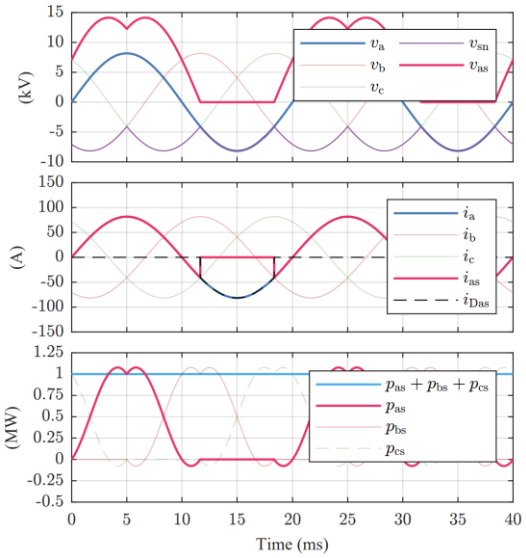
- *Voltages Across Blocking Diodes Used as Unipolar Supply of DC/DC Stages*
- *DC/DC Stage Operating Intervals Defined by the Mains Line-to-Line Voltages / Relatively Low Utilization*

Porsche
Götz, 2019





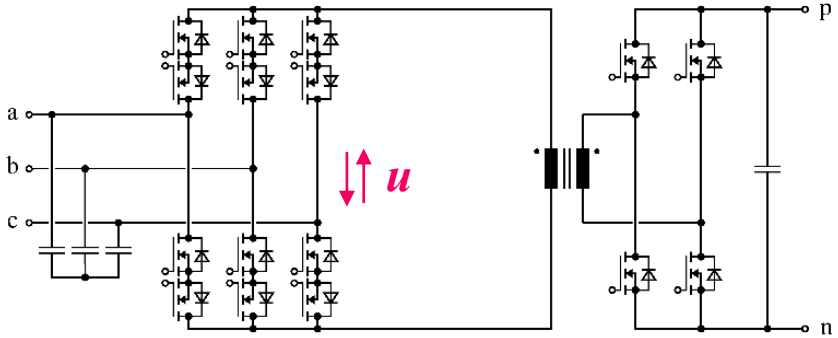
Fastwatt
Raju, 2023

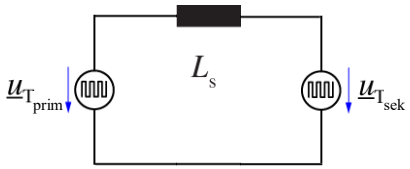


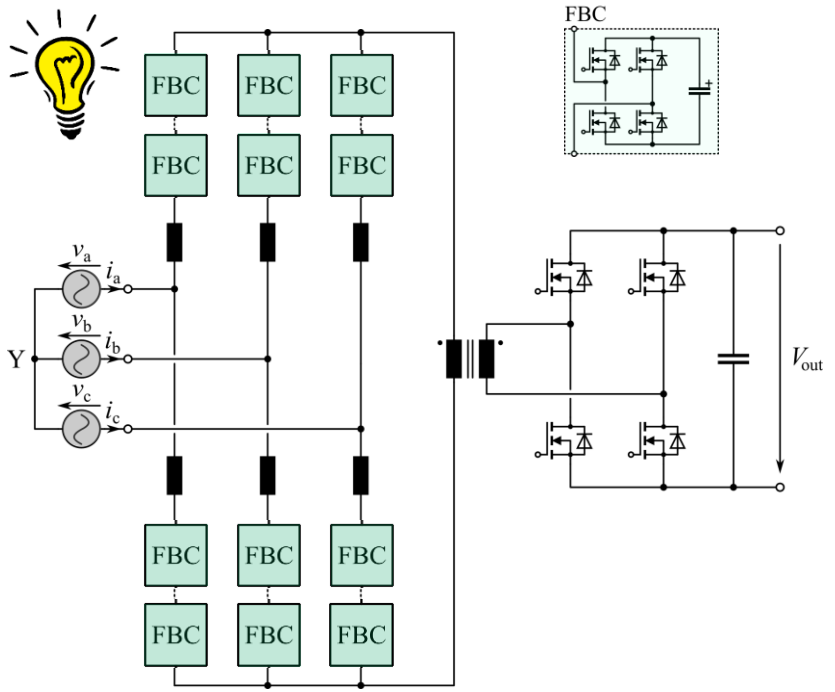
- *Antiparallel Switches for Extension to Bidirectional Power Transfer*
- *Defined Voltage Sharing of Series Connected Diodes BUT Voltage Rating Defined by Line-to-Line Voltage*

Single-Stage MMLC-Based Matrix-Type 3-Φ AC/DC SST

- *AC-Switches Replaced w/ Full-Bridge Cells Utilizing Unipolar Power Semiconductors / Voltage Scalability*
- *Modularity / Redundancy Limited to Power Semiconductors / Critical Components*



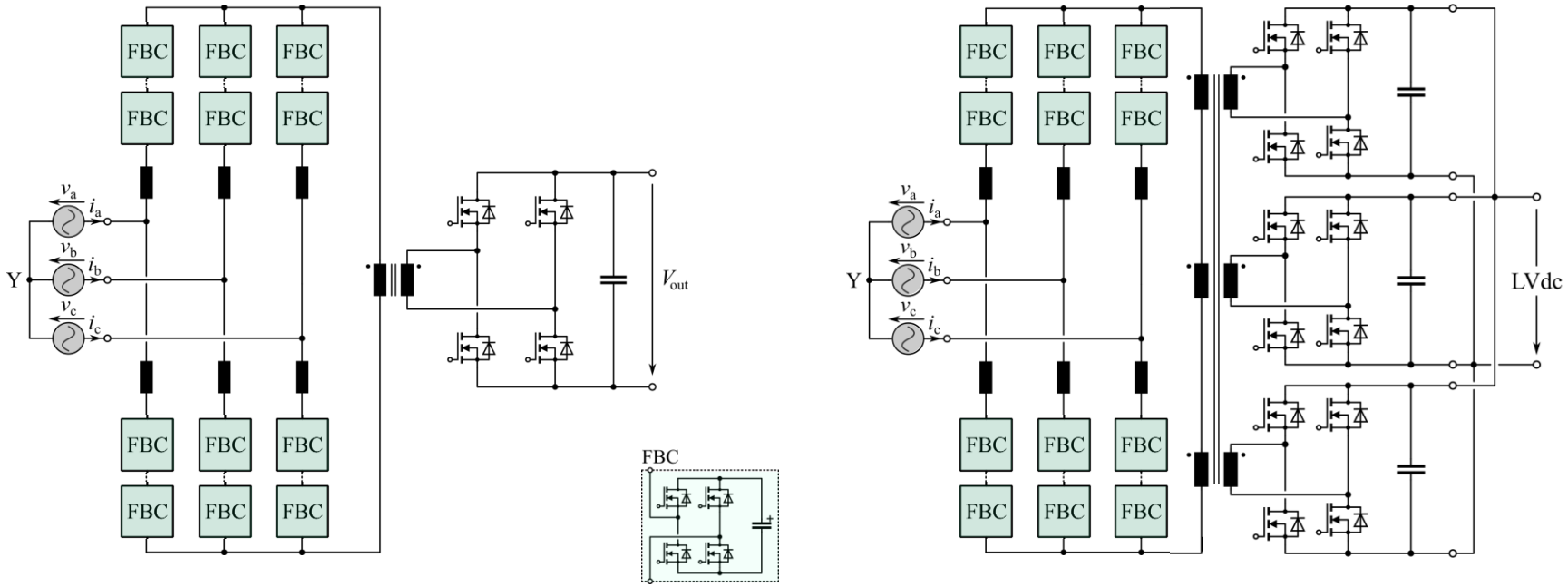




- *Dual-Active-Bridge-Type Operation / No «Transformer Modularization Penalty» (!)*
- *Output-Side Current Splitting to Parallel Branches — Matrix Transformer Concepts*

Single-Stage MMLC-Based Matrix-Type 3-Φ AC/DC SST

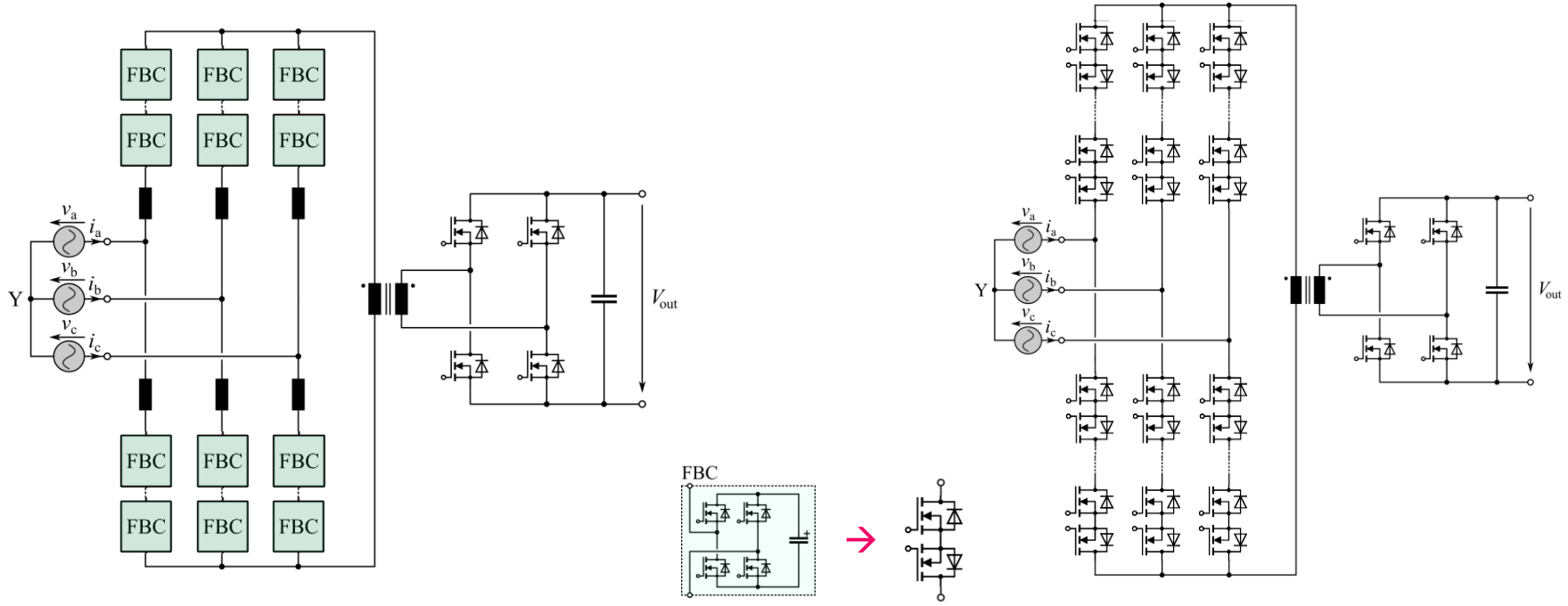
- *Matrix-Type SST — Single-Transformer / Modularity & Redundancy Limited to Lifetime-Critical Components*
- *Application of Multi-Winding Single-Core Transformer Concepts / Splitting of High Output Currents*



- *Modular-Multilevel-Converter-(MMLC)-Type Full-Bridge-Cells as Temporary Substitute of AC-Switches*
- *Realization Effort / Protection / Handling of SST-Internal Failures & Redundancy / etc. Still to be Clarified*

Single-Stage MMLC-Based Matrix-Type 3-Φ AC/DC SST

- *Matrix-Type SST — Single-Transformer / Modularity & Redundancy Limited to Lifetime-Critical Components*
- *Application of High Blocking Voltage (Monolithic) Bidirectional SiC MOSFET-Type or IGBT-Type Switches*



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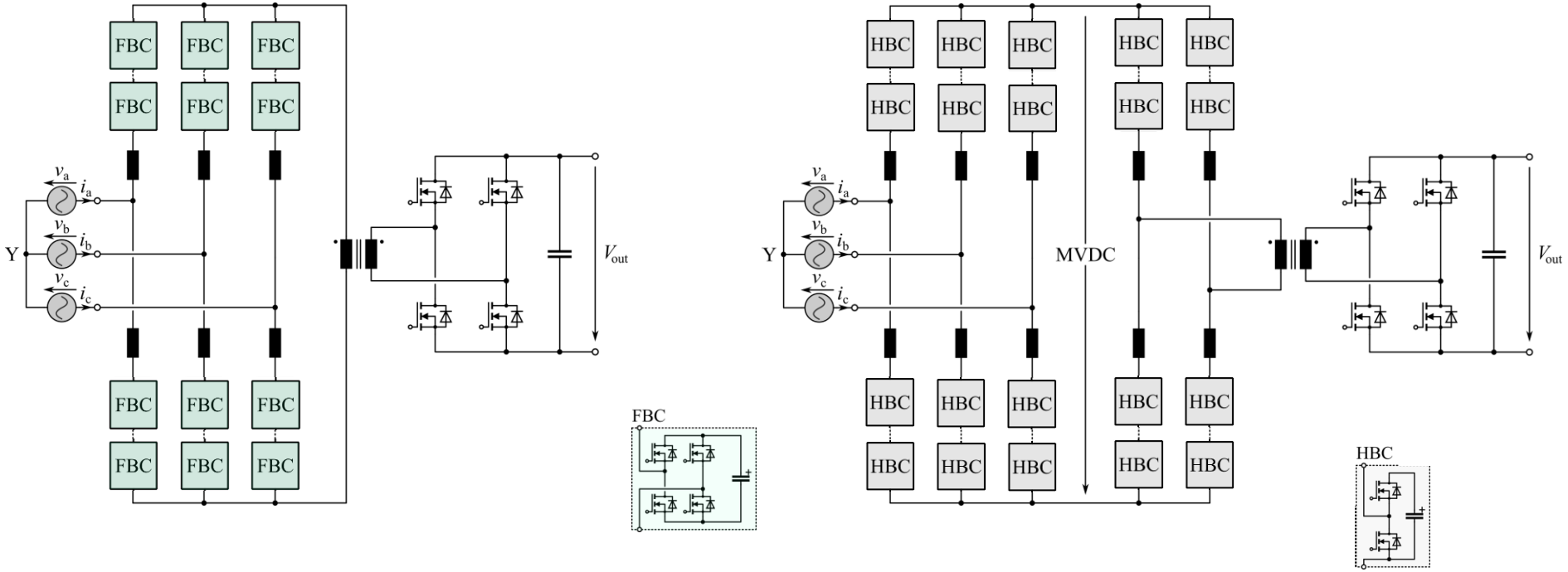
Direct & Indirect Matrix-Type 3-Φ AC/DC SST 1/2

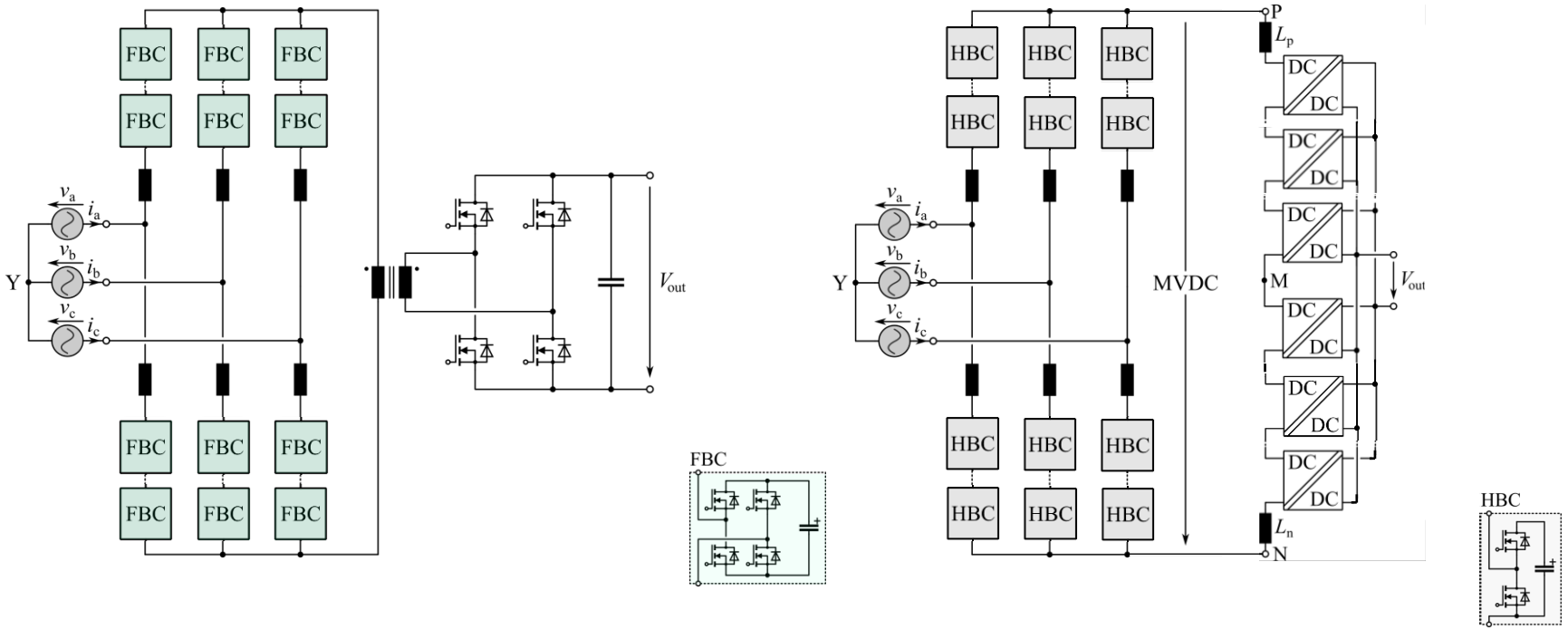
- *Indirect Approach Features Higher Control Flexibility & Higher Transformer Utilization*
- *Overhead / Underground Coupling of High-Power Front-End to Multiple ±10...20kV$_{DC}$/±800V$_{DC}$ DCX-Stages*



- *Comparative Evaluation of Power Semiconductor Stresses / Protection / Reliability etc. Still to Be Clarified*

Direct & Indirect Matrix-Type 3-Φ AC/DC SST 2/2

- *Indirect Approach Features Higher Control Flexibility & Higher Transformer Utilization*
- *Overhead / Underground Coupling of High-Power Front-End to Multiple ±10...20kV$_{DC}$/±800V$_{DC}$ DCX-Stages*

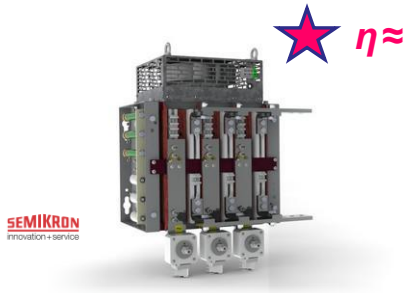


- *Comparative Evaluation of Power Semiconductor Stresses / Protection / Reliability etc. Still to Be Clarified*

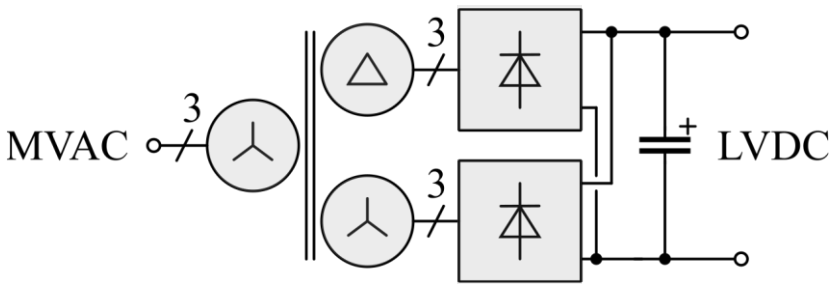
Hybrid Quasi-Single-Stage Partly-Modular SST Concepts

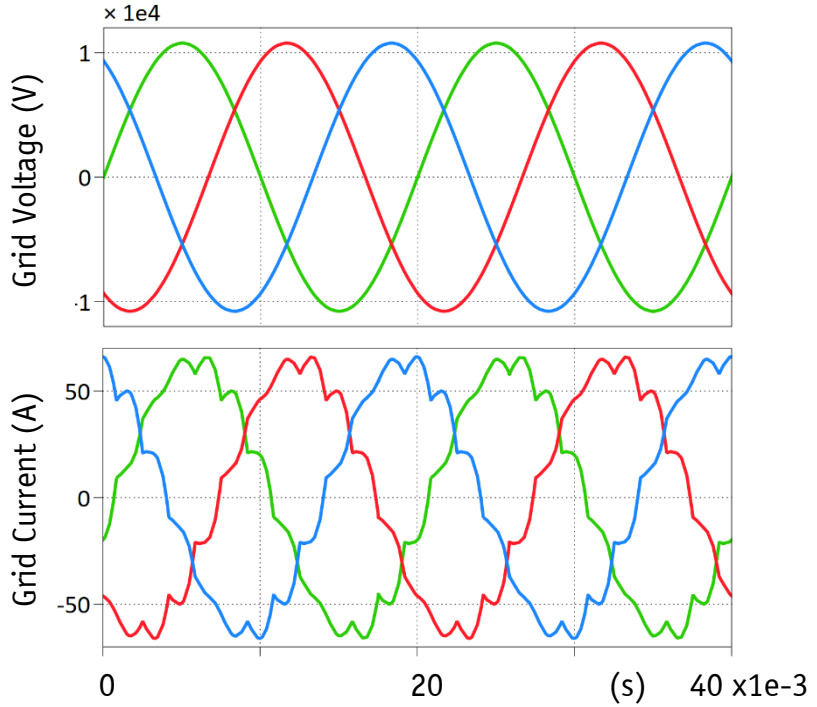
12-Pulse / Multi-Pulse 3-Φ Diode Rectifier

- *No Explicit PFC Stage (!) → Passive Realization of PFC with Phase-Shifting Transformer / No Inductors*
- *Low Complexity | High Robustness | Long Lifetime*
- *18-Pulse, 24-Pulse For High Power Levels*
- *4 kW/dm³ Rectifier Stage / Air Cooling*



★ $\eta \approx 99.7\%$

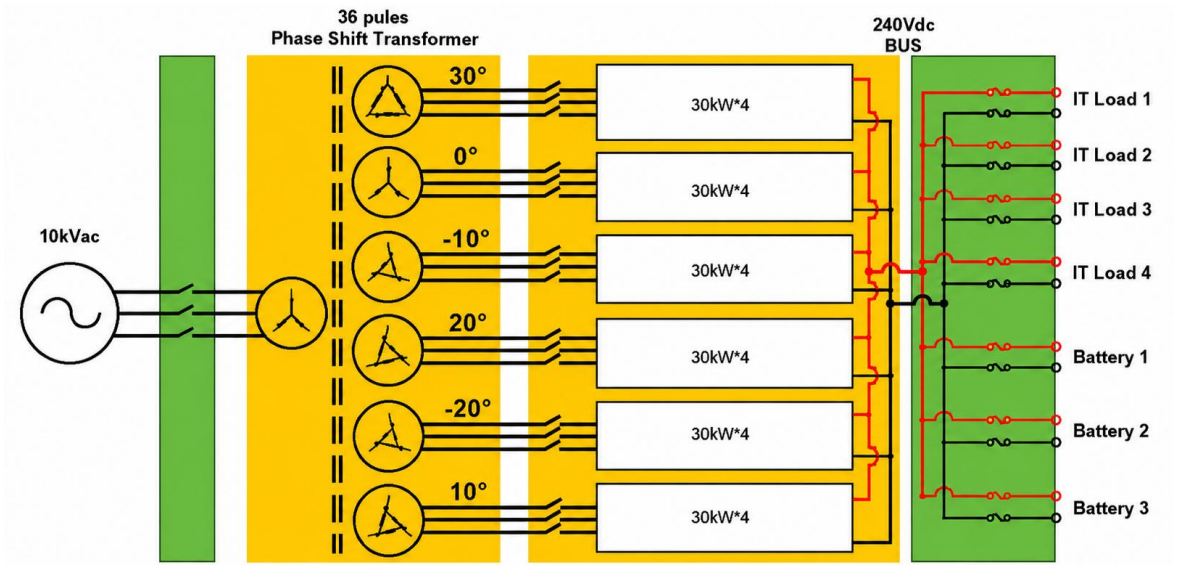




- *Unidirectional*
- *No Active Output Voltage Control (Tap-Changer)*
- *Remaining Current Distortion / Reactive Power Consumption*

Remark "Panama" Datacenter Power Supply

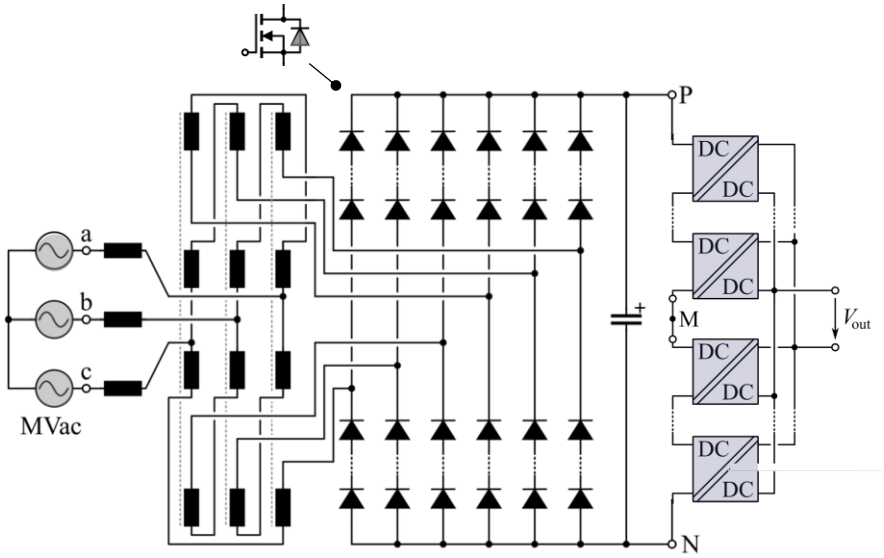
- *$10kV_{AC}$ Medium-Voltage Input Stage Directly Supplying a $240V_{DC}$ Bus (Alibaba, or $336V_{DC}$)*
- *36-Pulse Diode (!) Rectifier Topology / Low S.C. Current per Load Output / Scalable Beyond 2.5MW*
- *98.5% Efficiency & Ultra-High Reliability / 50% Smaller Installation Footprint / 20% Lower Investment $$$*

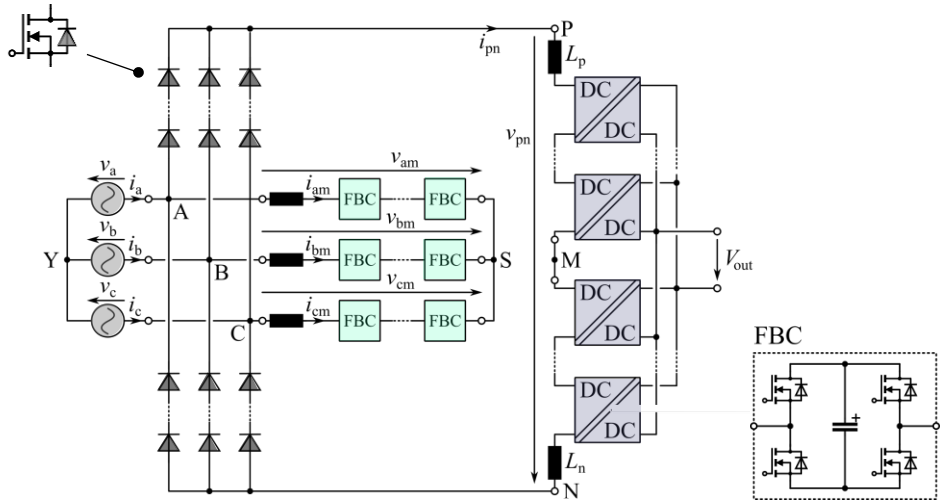


- *Input Stage Topology Analogous to SIEMENS ROBICON MV Variable-Frequency Drives (2.4–13.8kVAC, 50/60Hz)*
- *SuperX AI Technology Ltd — "Panama"-800VDC End-to-End Solution (Employs Phase-Shift Transformers)*

Hybrid Quasi-Single-Stage 3-Φ AC/DC SSTs

- *12-Pulse Line Interphase Transformer Rectifier OR 6-Pulse Diode Rectifier & AC-Connected MMLC-Type Active Filter*
- *Alternative Central Diode Rectifier & Local ±10...20kV$_{DC}$ / ±800V$_{DC}$ DC/DC-SSTs*



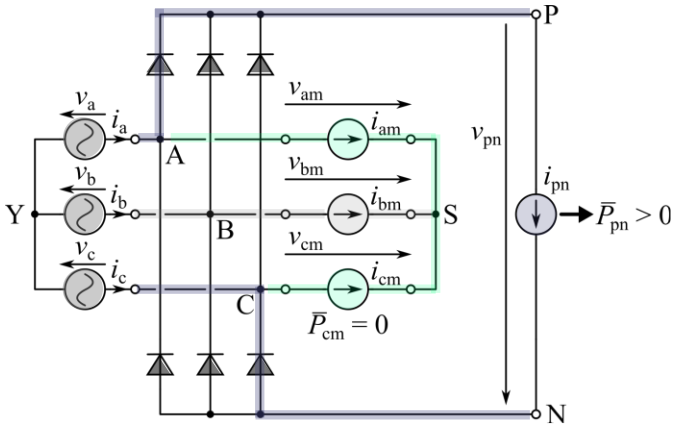


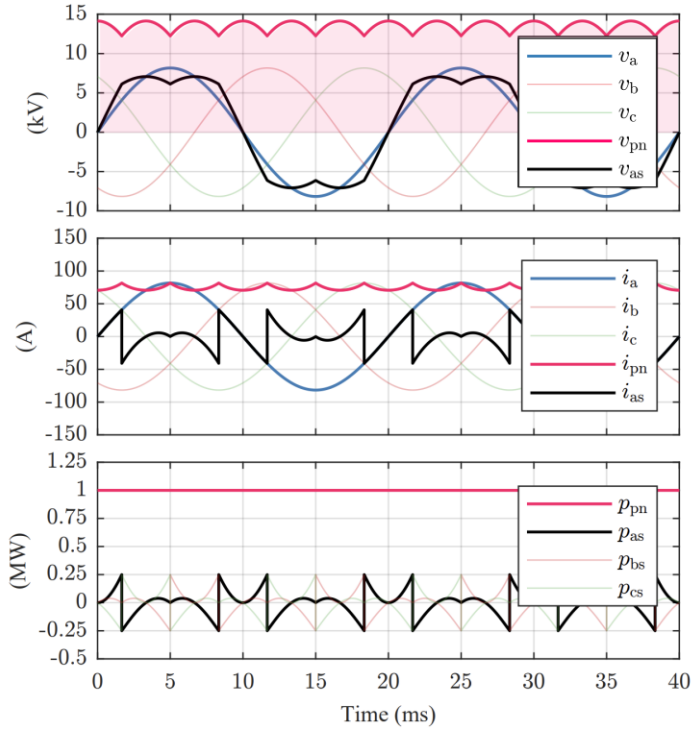
Source: EP 3905480A1, 2020
DE 3826524C2, 1988

- *Uncontrolled DC Voltage Level w/ 12-Pulse or 6-Pulse Ripple*
- *Overall Realization Effort / Protection / Handling of SST-Internal Failures & Redundancy / etc. Still to be Clarified*

3-Φ Diode-Bridge & Active-Filter Front-End

- *Operation @ 10kV$_{Line\text{-}to_line}$ AC-Mains & 1MW*
- *Characteristic Waveforms*

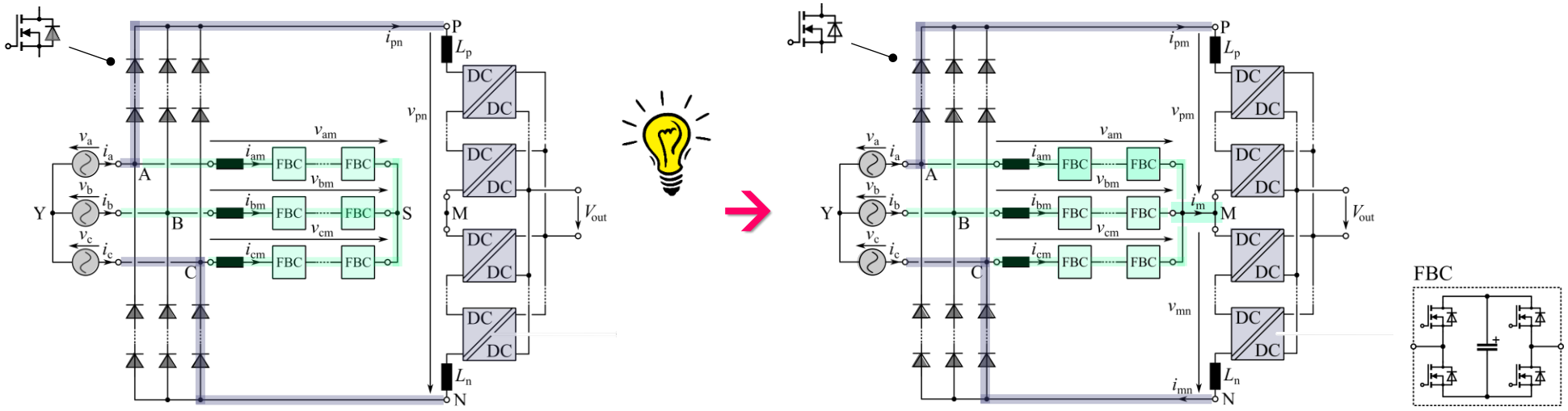




- *Possible Limitation of AF Operation to Phases w/ Max. & Min. Voltage / 2-out-of-3 Filter Branches (!)*
- *Saving of AF Sw. Losses But Higher AF String Voltages*

Modularized 3-Φ VIENNA-Rectifier-Type SST

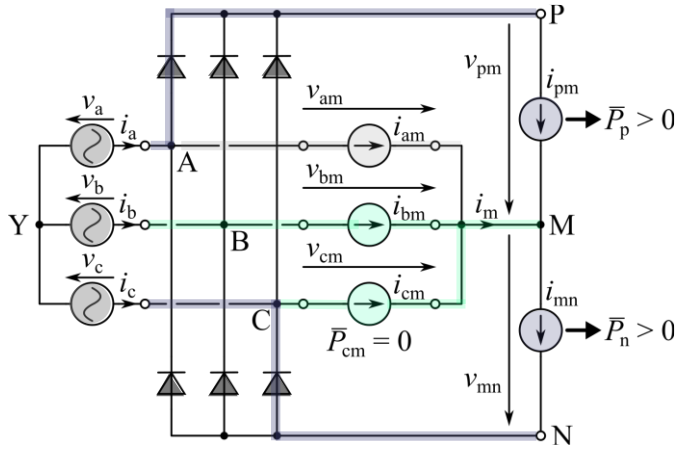
- *Active Filter Star-Point Connected to DC Output Voltage Midpoint*
- *Modularized VIENNA Rectifier Topology (mVR)*

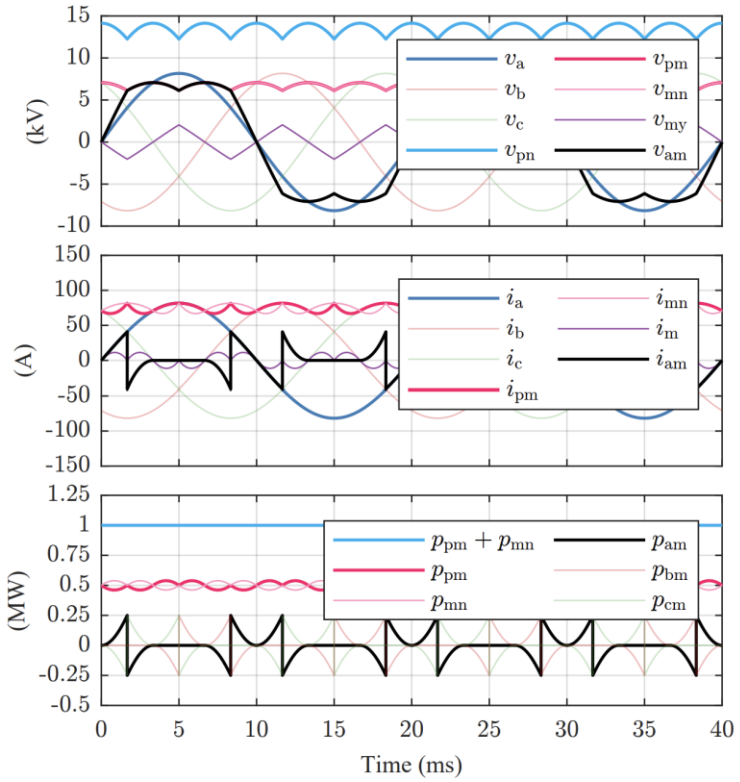


- *Active Balancing of Upper & Lower DC/DC SST String Voltages*
- *Full-Bridge-Cell-(FBC)-String Voltages Defined by Half Mains Line-to-Line Voltage Amplitude*

3-Φ VIENNA-Rectifier-Type AC/DC SST

- *Operation @ 10kV$_{Line\text{-}to_line}$ AC-Mains & 1MW*
- *Characteristic Waveforms*

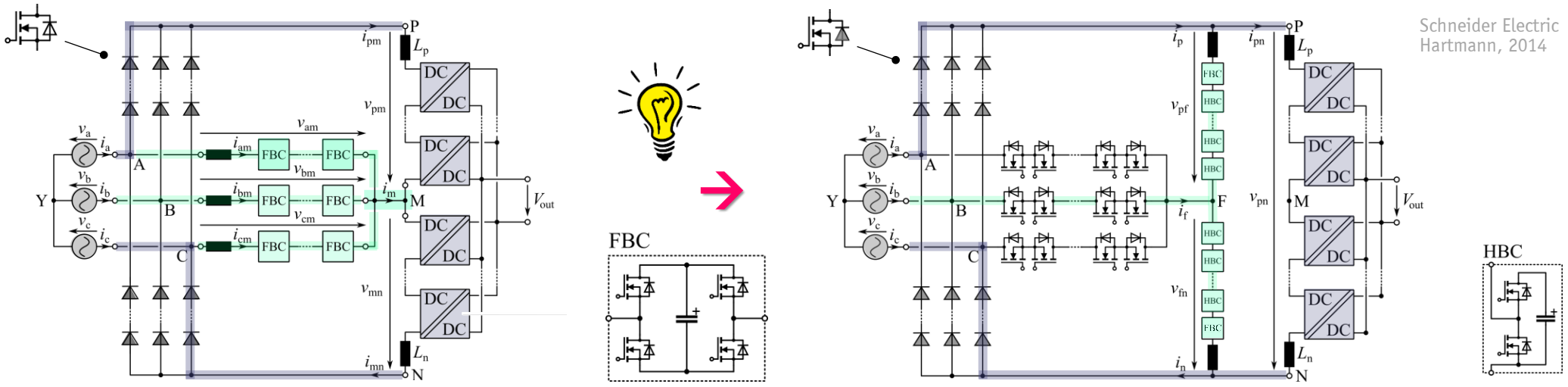




- *3/3 Act. Filter Operation / All 3 Filter Branches Active / Avg. $i_m = 0$ / $i_{pm} = i_{mn}$*
- *Low Sw. Loss 2/3 Operation Utilizes Midpoint Connection to Allow i_m / Decouple i_{pm} and i_{mn}*

3-Φ Diode-Bridge & Integrated Active Filter SST

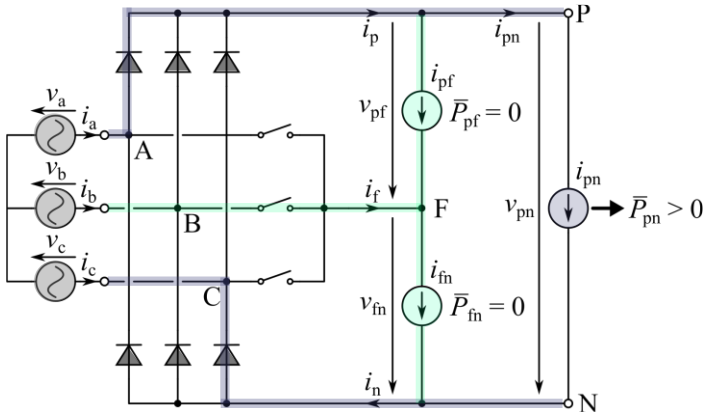
- *AC-Connected Active Filter (AF) w/ Full-Bridge Cells Shifted to Diode-Bridge DC Output / Half-Bridge Cells AF (!)*
- *Phase Selector Switches / Injection of Current into Phase of Not Conducting Diode Branch*

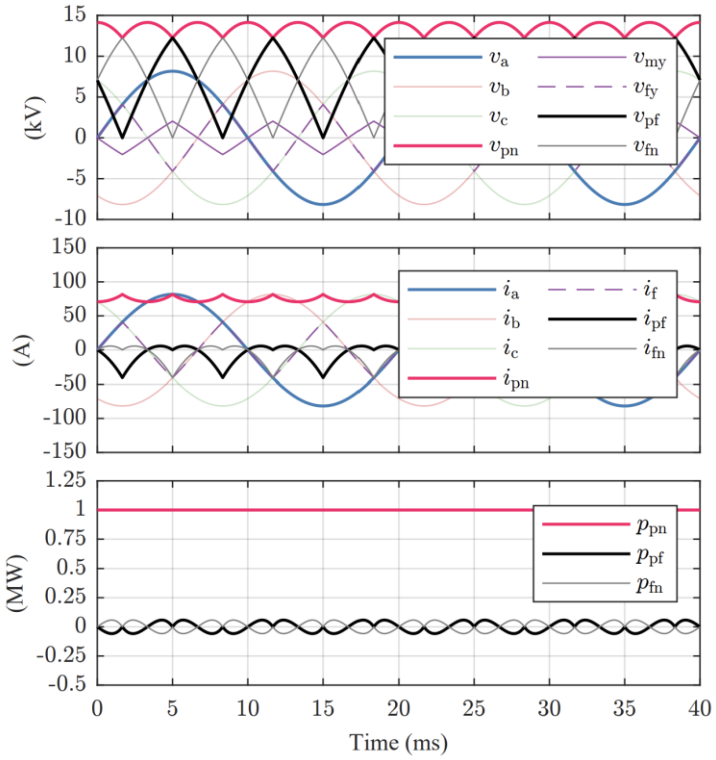


- *Lower Complexity Compared to AC-Side Active Filter / mVR*
- *Mains Frequency Commutation of Current Injector Switches / Blocking Voltage Balancing Requirement*

3-Φ Diode-Bridge & Integrated Active Filter SST

- *Operation @ 10kV$_{Line\text{-}to_line}$ AC-Mains & 1MW*
- *Characteristic Waveforms*

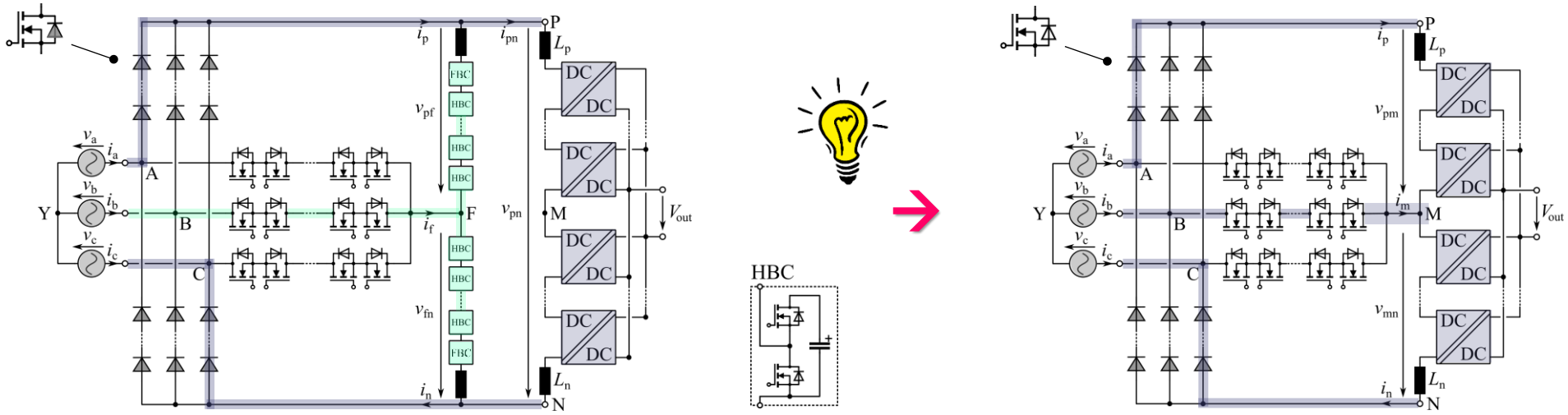




- *Max. Voltage of √3/2 Grid Line-to-Line Voltage Amplitude Across Upper and Lower Filter String*
- *Low Voltage Values v_{pf} & v_{fn} @ High Values of Currents i_{pf} & i_{fn} — Low Power Rating of Filter String*

Unfolder-Front-End 3-Φ AC/DC SST

- *Combination of Integrated Active Filter & DC/DC Converter Functionality*
- *Difference of Upper & Lower DC/DC Conv. String Currents Injected into Phase with Blocking Diode Branch*

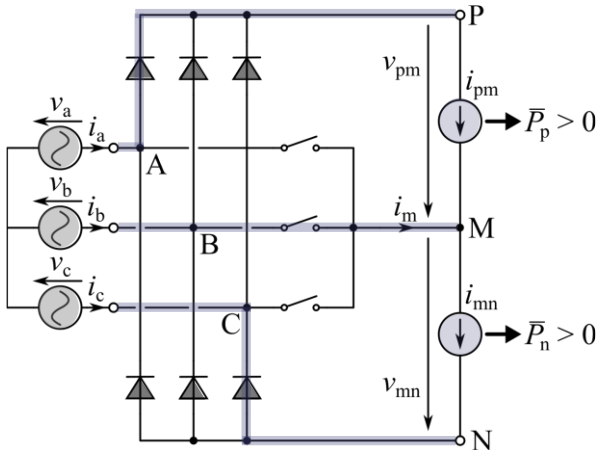


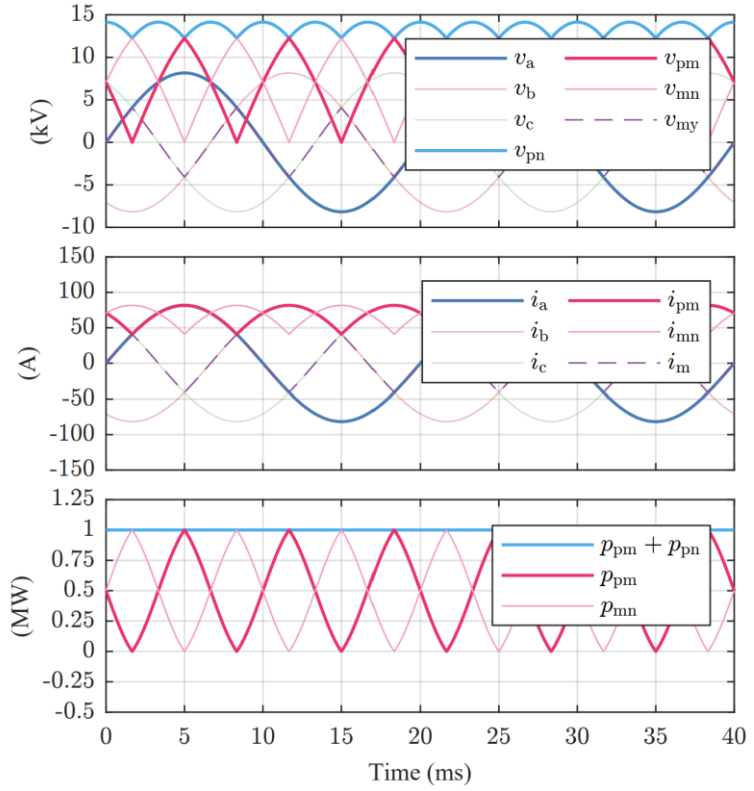
Utah State Univ.
Chen et al., 2017

- *Lower Complexity Compared to Integrated Active Filter Diode-Bridge Rectifier*
- *Large Voltage & Power Fluctuations of the DC/DC Converters Strings / Rel. Low DC/DC Stage Utilization*

Unfolder-Front-End 3-Φ AC/DC SST

- *Operation @ 10kV$_{Line\text{-}to_line}$ AC-Mains & 1MW*
- *Characteristic Waveforms*



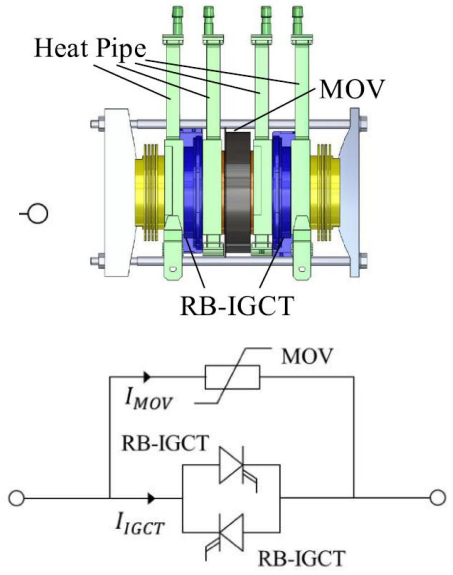


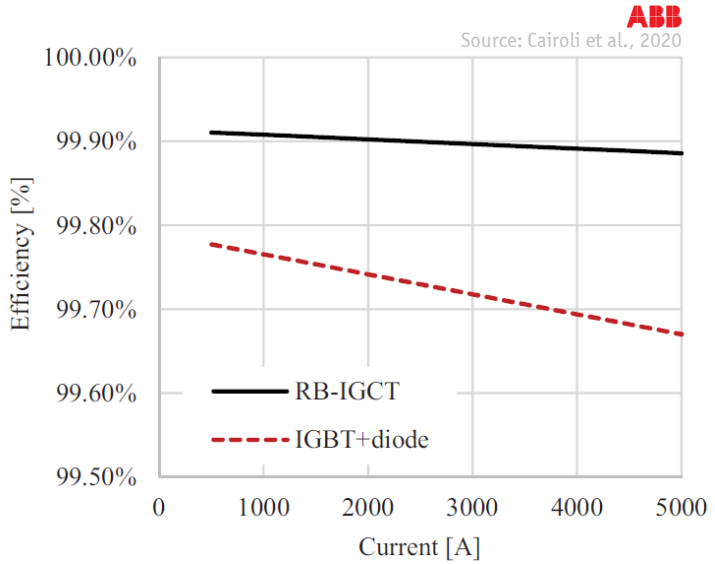
- *Voltages v_{pm} & v_{fm} of DC//DC Conv. Strings Varying Btw 0...√3/2 Line-to-Line Voltage Amplitude*
- *Power Processed by DC//DC Conv. Strings Fluctuates Btw 0...$P_{nominal}$*

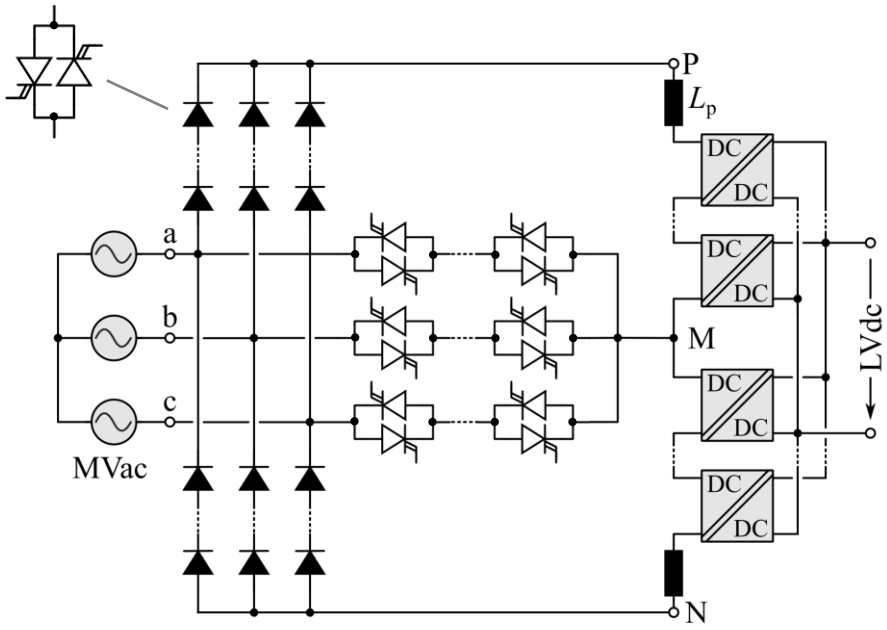
Reverse-Blocking IGCTs
Si-MOSFET & Cascaded SiC JFETs

Reverse-Blocking-IGCT Injection Switches

- *IGCT — Thyristor w/ Integrated Low-Inductance Gate Drive Enabling Fast Turn-Off and High-Power Switching*
- *RB IGCTs — Full Forward & Full Reverse Blocking Capability / Typ. Used in Curr. Source Converters & DC SSCBs*



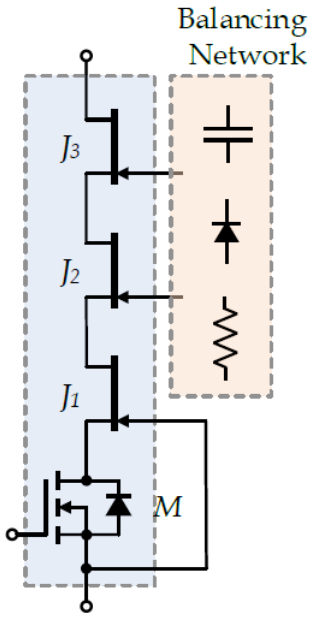


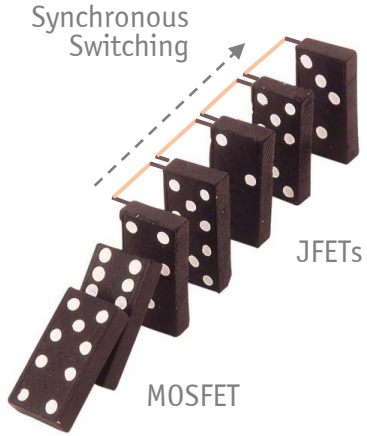


- *Specific Device Designs for Very Low On-State Losses – 0.9V@1kA for 2.5kV Blocking Voltage / High Turn-Off Currents*
- *Field Failure Rate (FIT) of GCT & Gate Unit Below 100 FIT — Future SiC ETO Devices up to 22kV*

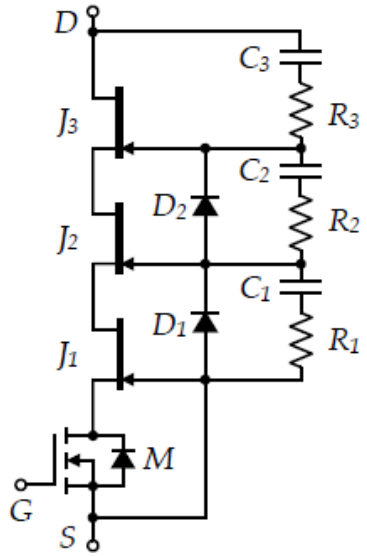
SiC Super-Cascode Injection Switches

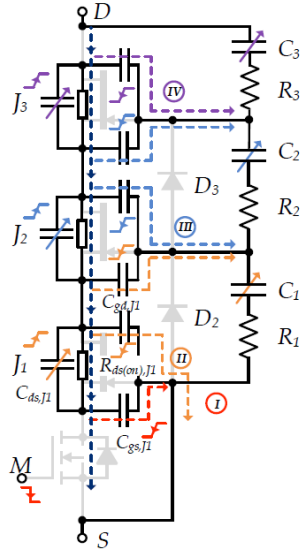
- *Cascode Configuration — LV Si-MOSFET & Normally-ON SiC JFET / Linear ON-Resistance Scaling (!) / Low $$$*
- *Supercascode — Series JFETs Enable High Blocking Voltage / Passive Dynamic & Static Voltage Balancing*

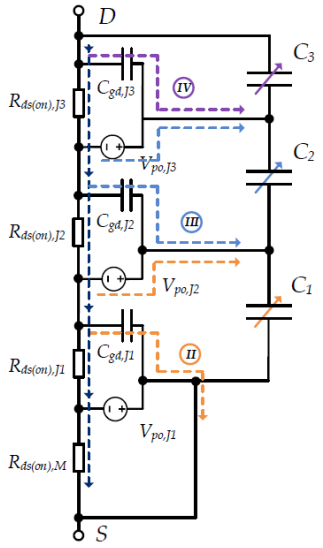




Source: L. Gill et al., 2021, Sandia National Labs





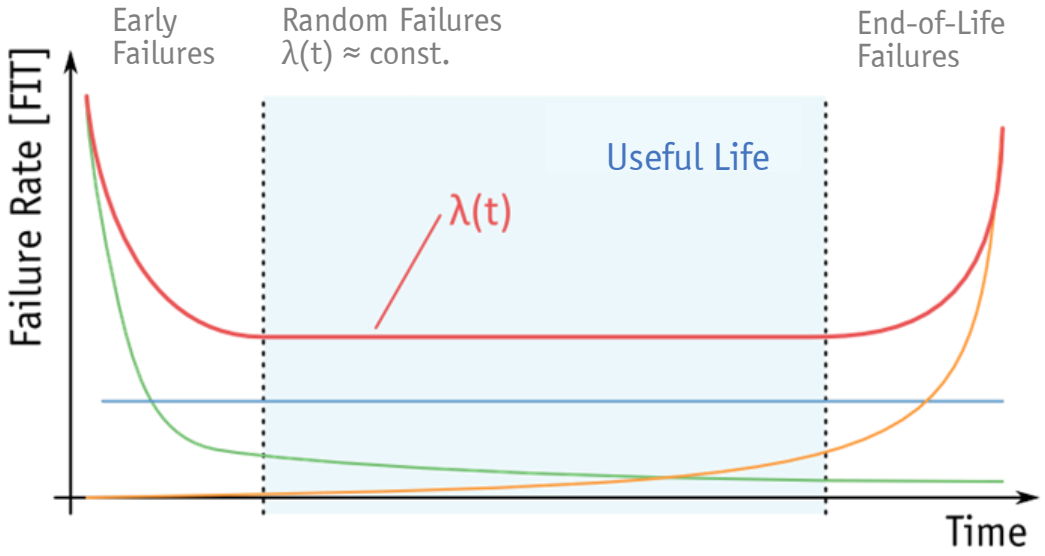


- *Different Balancing Network Topologies — RC Snubbers & Avalanche Diodes / Challenging Design Due to Parasitics*
- *Integration in Power Module Enables Controlled Parasitics / Consistent Switching Characteristics*

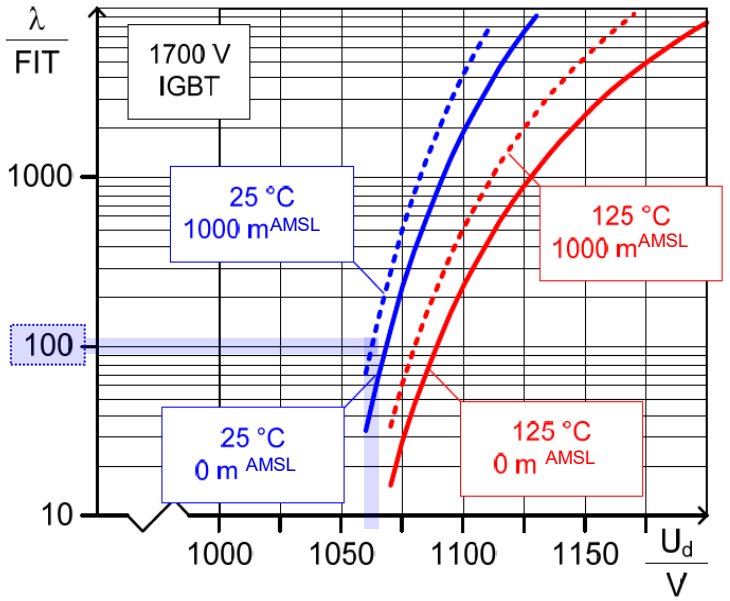
Reliability for k-out-of-n Redundancy

Redundancy in Multi-Cell Converter Systems 1/3

- *Failure Rate λ(t) is a Function of Time – „Bathtub Curve“*
- *Useful Life Dominated by Random Failures (e.g. Cosmic Rays) → λ(t) = const.*
- *[λ] = 1 FIT (1 Failure in 10^9 h)*
- *Typ. Value for IGBTs: 100 FIT*



Source: H.-G. Eckel
Univ. Rostock



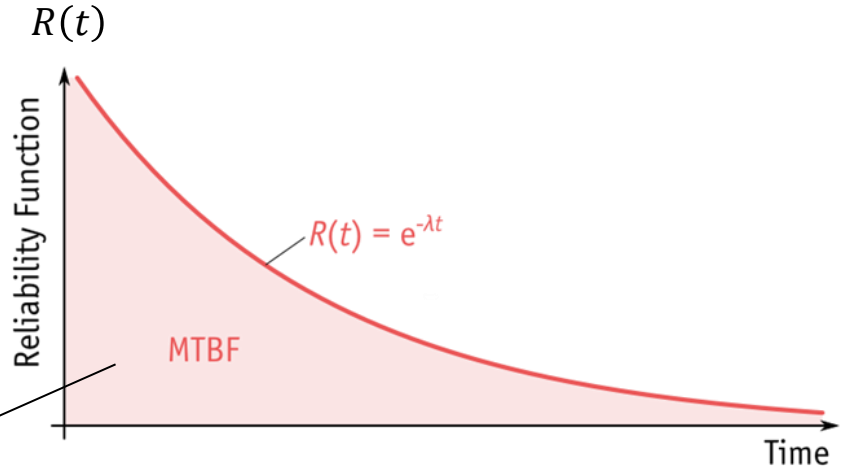
- *Sources for Empirical Component Failure Rate Data — MIL-HDBK-217F, IEC Standard 62380, etc.*

Redundancy in Multi-Cell Converter Systems 2/3

- ***Reliability Function — Probability of System being Operational after Time t***

$$R(t) = e^{-\int_0^t \lambda(x)dx} = e^{-\lambda t}$$

$\lambda(t) = const.$

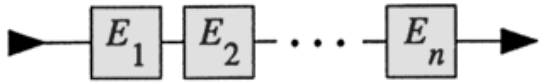


- ***Mean Time Between Failures***

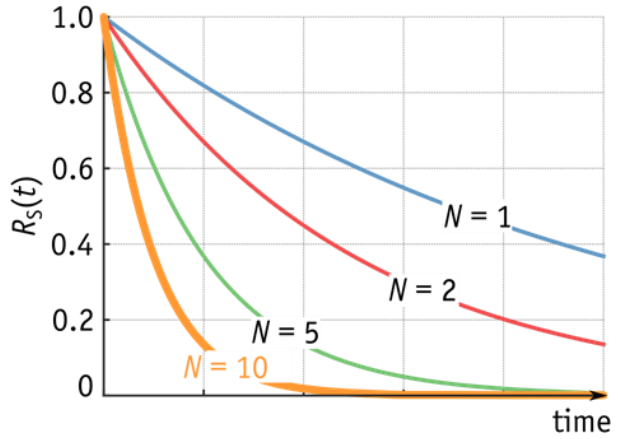
$$\text{MTBF} = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}\,dt = \frac{1}{\lambda}$$

- ***Series Structure***

$$\lambda_S = \sum_{i=1}^{n} \lambda_i$$



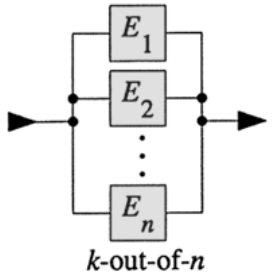
Independent Cells
with Equal Failure Rate

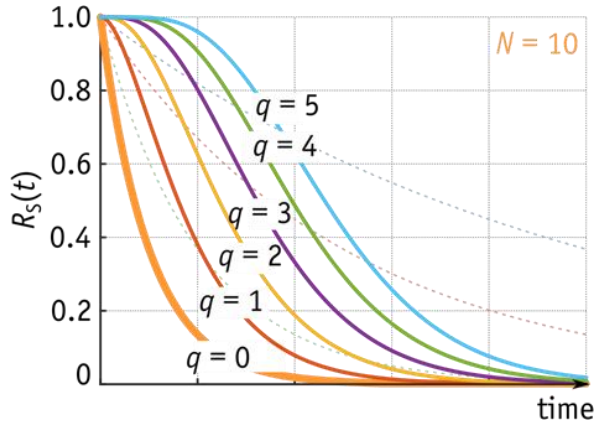


Redundancy in Multi-Cell Converter Systems 3/3

- *k-out-of-n Redundancy*
  Redundancy of Cells in Phase Stack

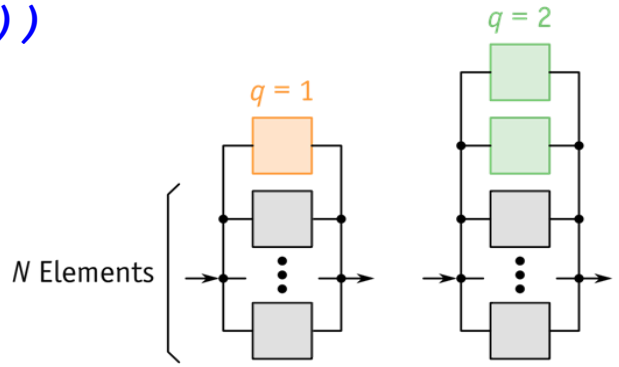
  System is Operational as
  Long as at Least k-out-of-n
  Subsystems are Working

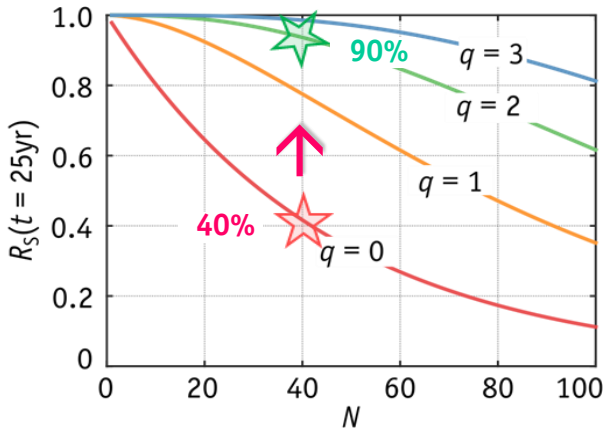




- *Effect of q Redundant Cells on*
  $R_S(t)$ and/or MTBF (Area below $R_S(t)$)

Independent Cells
with Equal Failure Rate

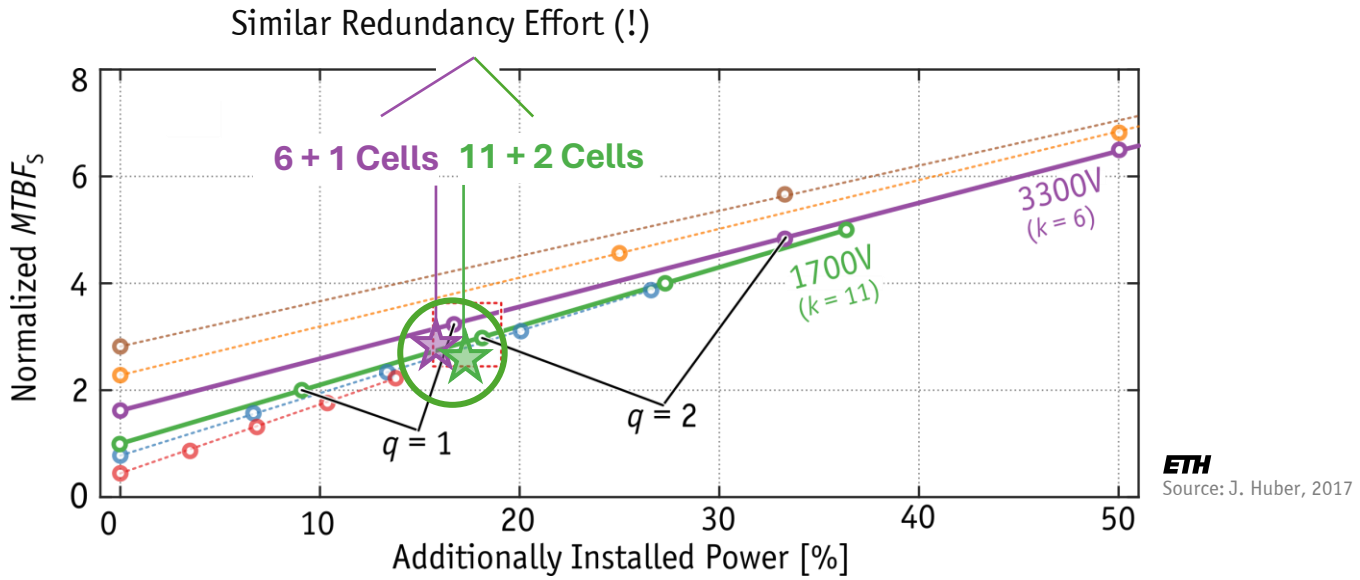




- *Redundancy Significantly Improves System-Level Reliability (!)*

Cost of Redundancy

- *Redundant Cells — Additionally Installed But Unused Power Processing Capability (Standby)*
- *Example: Phase Stacks with Same Total DC Voltage & Different Number of Cells*



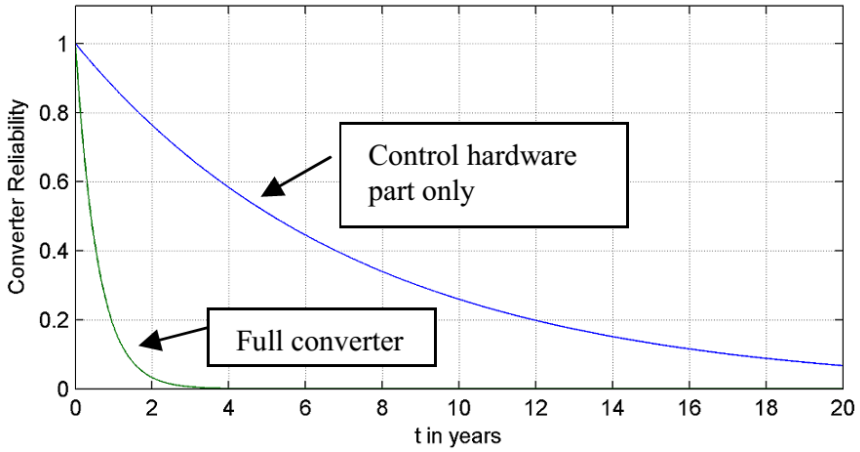
ETH
Source: J. Huber, 2017

- *Similar Added Power Capability → Similar Normalized MTBFs*
- *Simplified Consideration / Beware Overheads and Reliability Bottlenecks – Control System etc. (!)*

Reliability "Bottlenecks"

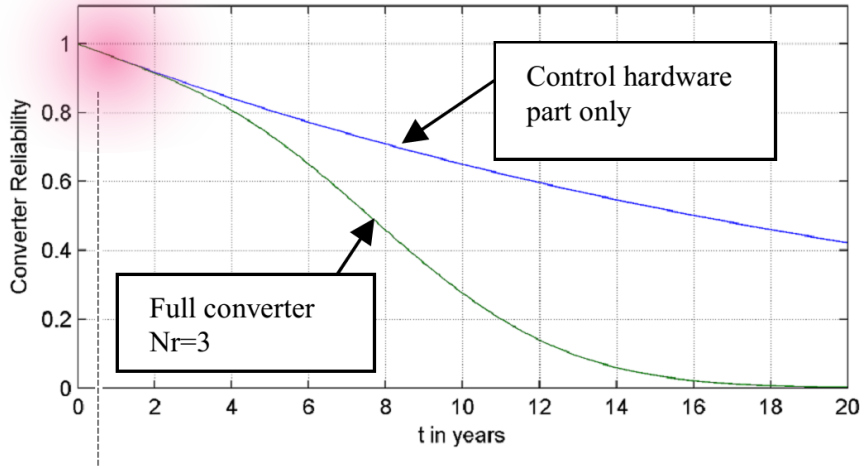
- *Very Effective Reliability Improvement by Means of Cell-Level Redundancy — Too Good to Be True?*

No Redundancy



3 Redundant Cells

Source: Grinberg, 2013



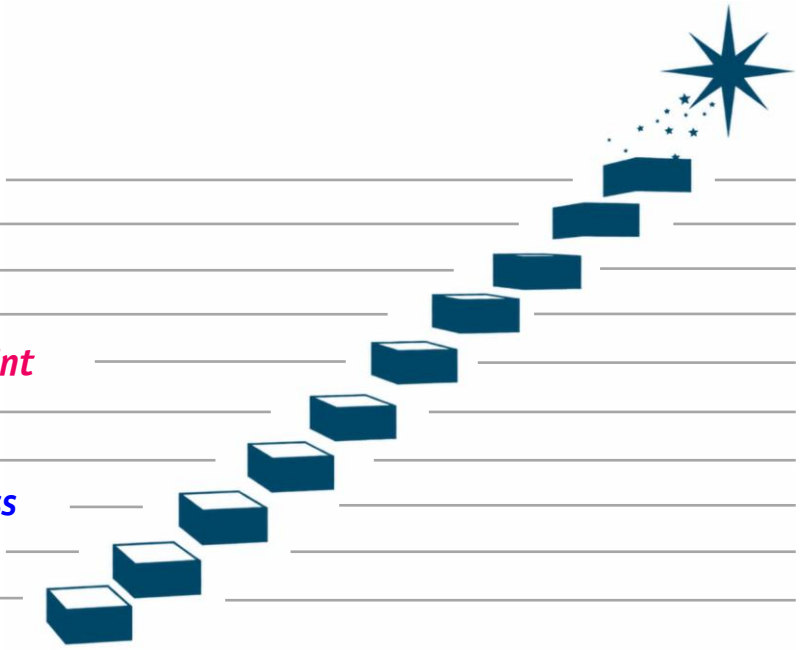
Control Hardware Becomes Limiting Factor (!)

- *Redundancy Effectiveness Limited by Other (Non-Redundant) Parts of the Converter System (!)*
- *Control / Auxiliary Supplies / Communication Systems / Bypass Devices / etc.*

Conclusion

Short-Term Datacenter SST Priorities

- *Major Innovation Step #1 — $54V_{DC}$ → $800V_{DC}$ / Higher Efficiency @ High Power*
- *Major Innovation Step #2 — Elimination of AC/DC-Stage of UPS / Higher Efficiency*
- *SST vs. LFT-Based-Solution — Functionally Largely Equivalent / Availability? / 99% SST Efficiency?*

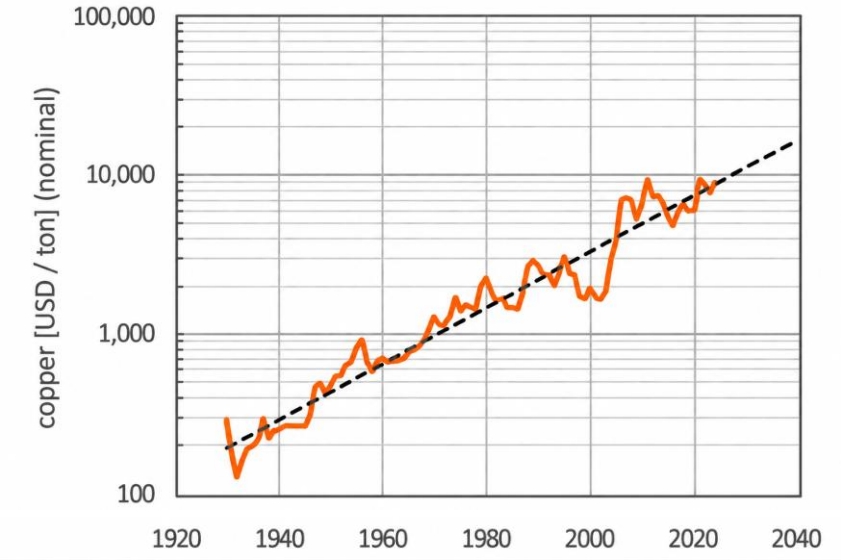


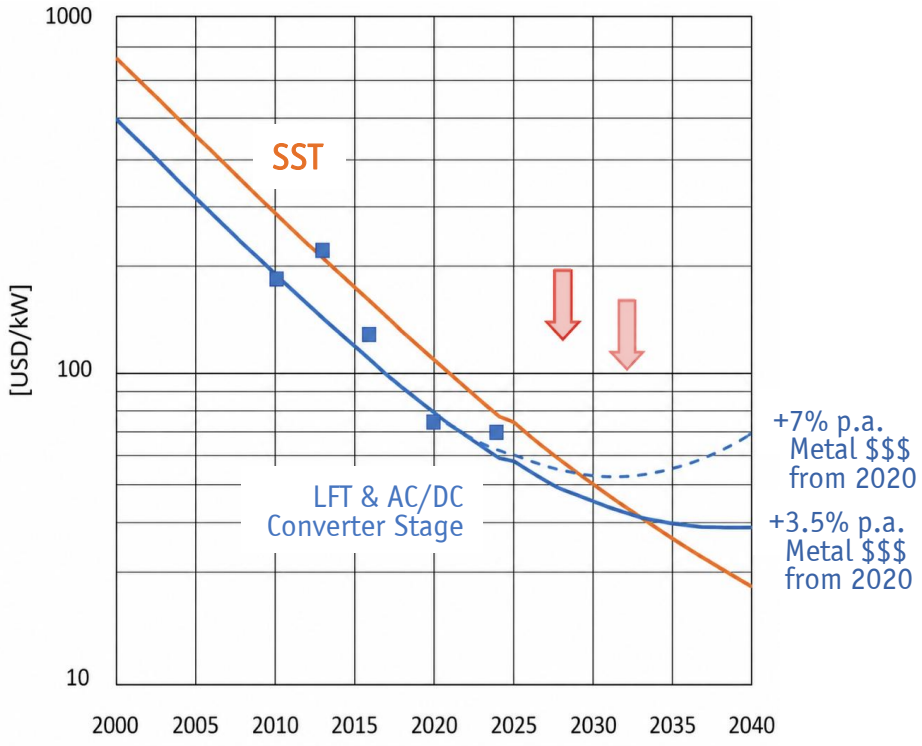
1. System Availability	Redundancy / Modularity* / Maintainability
2. Time-to-Power	Factory-Tested Blocks / Modularity
3. Efficiency	OPEX (Life Cycle Costs)
4. CAPEX	Economy of Scale / Modularity
5. Power Density / Footprint	Future White Space Installation
6. Voltage Scalability	10kV / 13.8kV / 34.5kV Grids
7. Standardization	Voltage / Power / Protection (!)
8. Supply Chain Robustness	Multi-Source Components
9. Multi-Functional Use	Grid Services etc.
10. Sustainability	Design for Circularity

- ** Large # of Modules / High Redundancy → Same Availability as for Low # of Modules @ Same Cost*
- *Complex Multi-Objective Decision Processes / Main Criteria Currently NOT Considered in Academic Research (!)*

Potential Cost Benefits of SSTs over LFT-Based Solutions

- *Calculation of Price Trends (Nominal USD) Based on International Energy Agency (IEA) Data*
- *LV AC/DC Converter — Based on Grid-Scale PV | -11% p.a. | ≈60 USD/kW*
- *LFT — +3.5% p.a. $$$ of Metals Since 1920 | 10 USD/kAV*
- *SST Power Electronics $$$ — 1.5x LV AC/DC Converter*
- *MFT $$$ — Constant @ 15 USD/kVA*

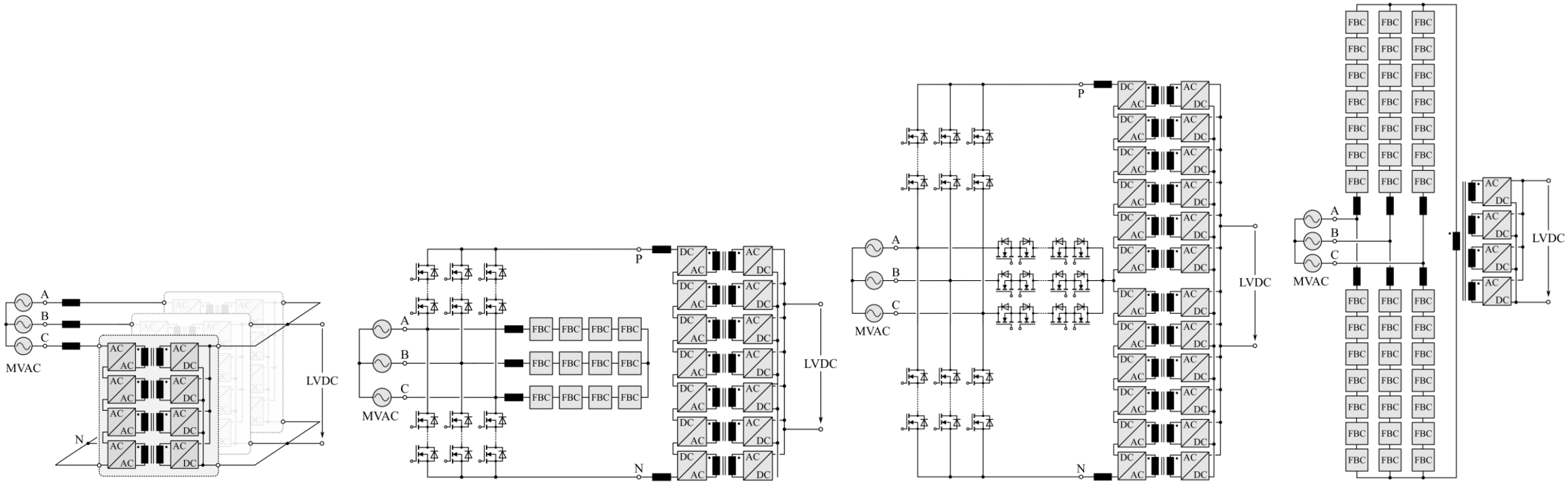




- *LFT & Multi-Pulse Rectifier — Availability & Cost-Optimized Near-Term Solution*
- *MVAC–800 VDC SST — Integration / Density / Functionality-Optimized Longer-Term Solution*

Next-Generation 3-Φ AC/DC SST Research Scope 2/3

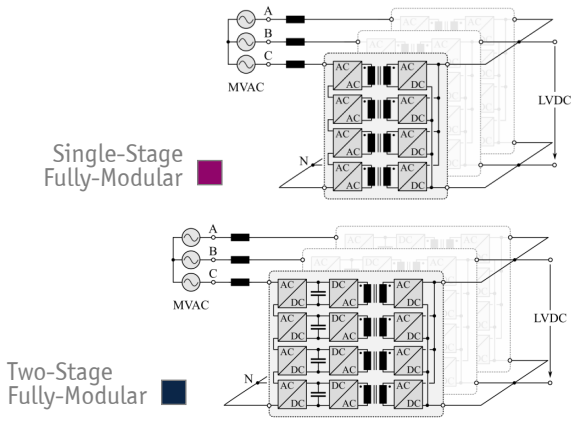
- *Fully-Modular Single-Stage — High Modularity | Requires AC-Switches | Design for 3x P_{pk}=2/3P_{out}@100Hz & 3x P_{avg}=1/3P_{out}*
- *Partly-Modular Quasi-Single-Stage — Unfolder-Type Front-End | Design for 2x P_{pk}=P_{out}@150Hz & 2x P_{avg}=1/2P_{out}*
- *Single-Stage Matrix-Type — Redundancy Limited to Sw. Stages | High Transformer Utilization | Limited Modularity*

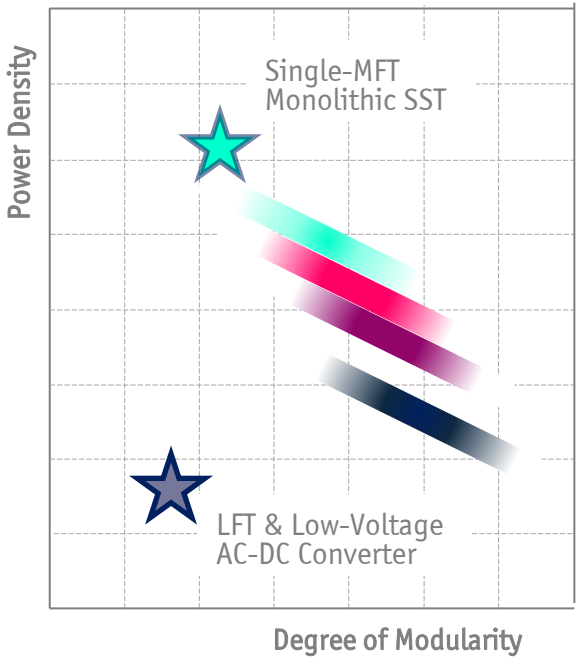


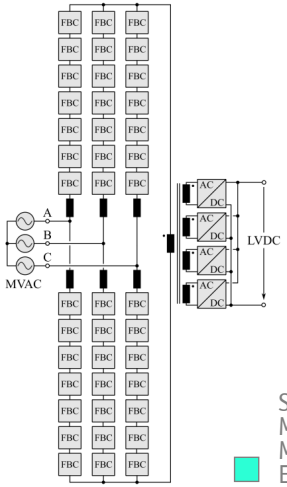
- *Comparative Evaluation incl. mB6AF — Diode-Bridge Rectifier Front-End & Active Filter Common to Several SST Units*
- *Overall Realization Effort / Protection / Handling of SST-Internal Failures & Redundancy / etc. Must be Clarified*

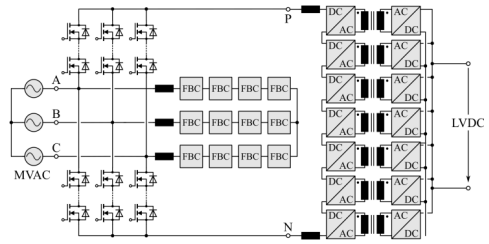
Power Density / Modularity Trade-Off

- *Transformer Scaling Law — Favors Single-Transformer Over Multiple Transformers*
- *Processing of Pulsating Power @ 100Hz or 150Hz vs. Constant Power Flow*
- *Modularization Penalty — Accumulation of Isolation Distances*





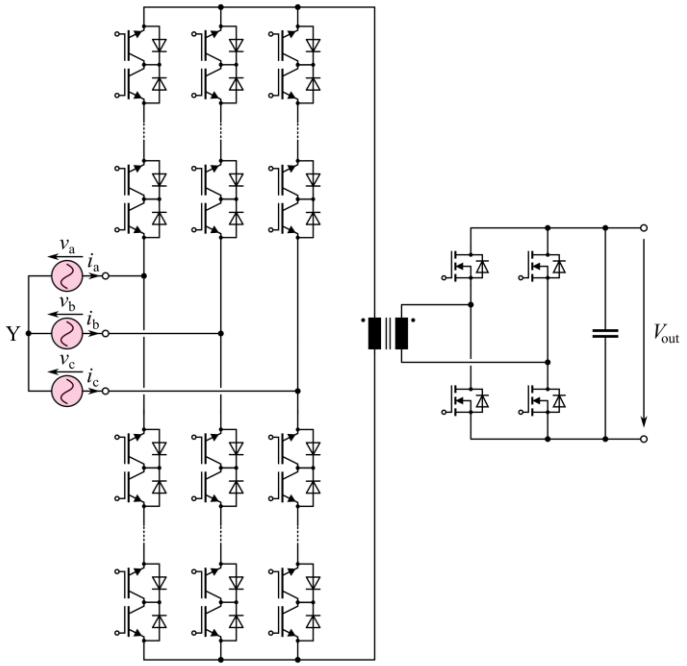


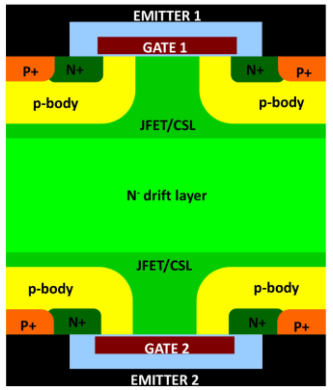


- *"Zero-Order" Engineering Estimate Shown Above — Requires Rigorous Validation Through Future Research (!)*

Next-Generation 3-Φ AC/DC SST Research Scope 3/3

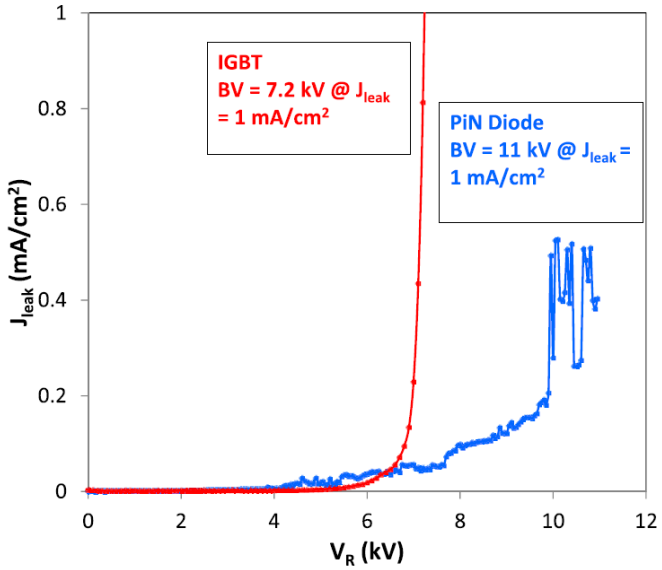
- *Monolithic Bi-Directional SiC IGBT w/ Double-Sided Lithography Process on Free-Standing n⁻ Wafers*
- *MOS-Cells on Both Sides of Lightly Doped Drift Region / Cond. & Sw. Loss Infl. of Back-Side Gate Volt. Bias*
- *Challenging Packaging & Cooling*





Blocking Voltage

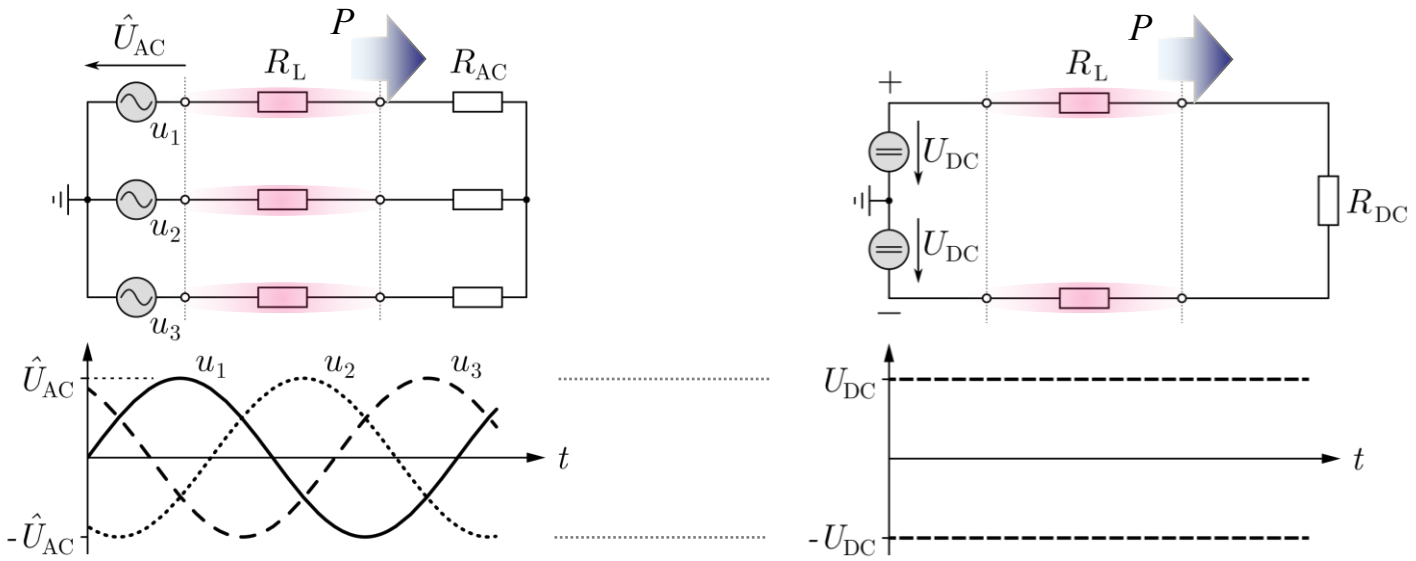
Source: RPI, S. Chowdhury et al. IEEE TED, 2017



- *15kV BD-IGBT | Measured Blocking Capability of 7.2 kV – Epi Layer Defects etc.*
- *Shared Drift Region → "True" Monolithic Bidirectional Switch (TM-BDS)*

Remark DC vs. 3-Φ AC Power Distribution

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



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

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

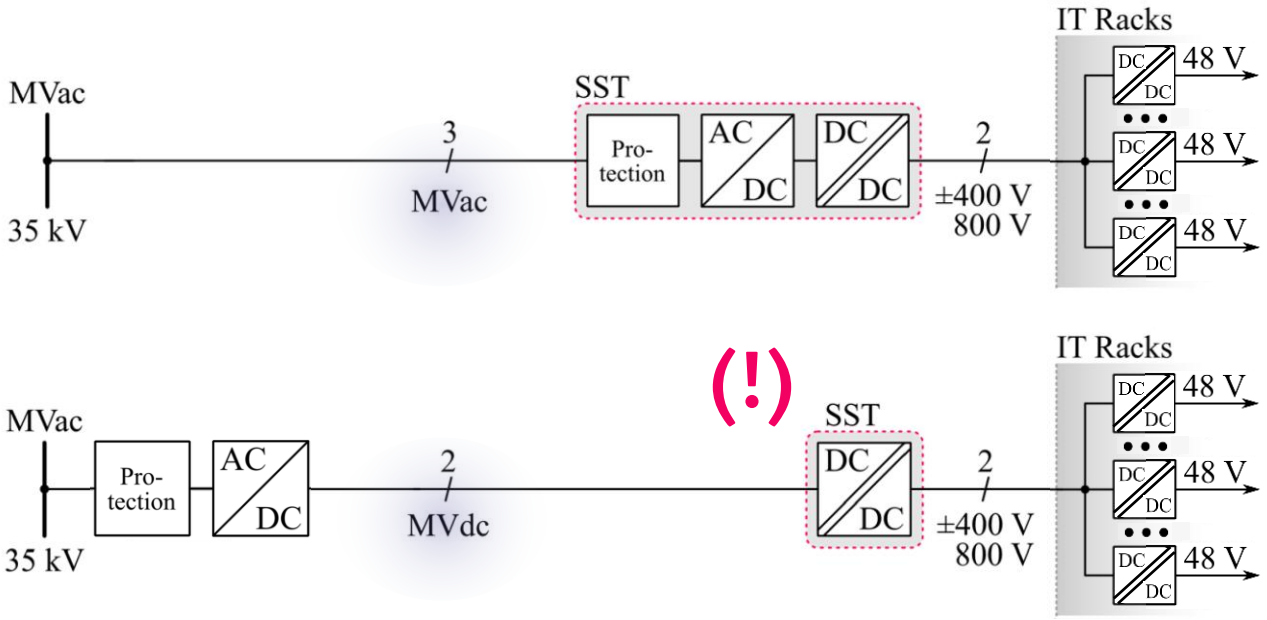
$$\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2} \cdot (\frac{U_{AC}}{U_{DC}})^2 \Big|_{U_{DC}=\hat{U}_{AC}=\sqrt{2}\,U_{AC}} = 0.75$$

U_{AC} ... RMS Phase Voltage

- *Central MVAC Rectification & Local High-Power Density/Efficiency MVDC/LVDC SSTs*

Future MVDC vs. 3-Φ MVAC Power Distribution

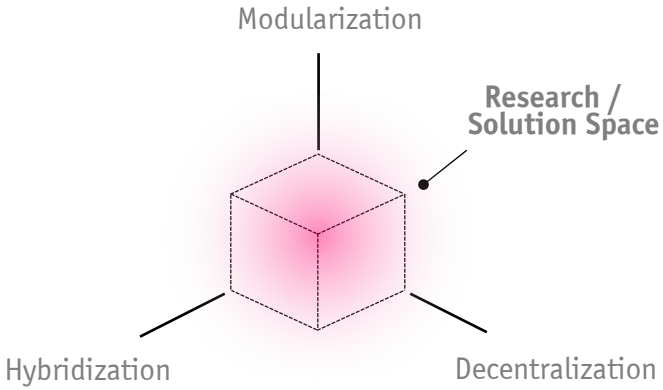
- *DC Voltage → Max. Utilization of Isolation Voltage → Lower Losses & Less Conductor Material (!)*
- *Central MVAC Rectification & Local High-Power Density High-Efficiency Low-Complexity MVDC/LVDC SSTs*

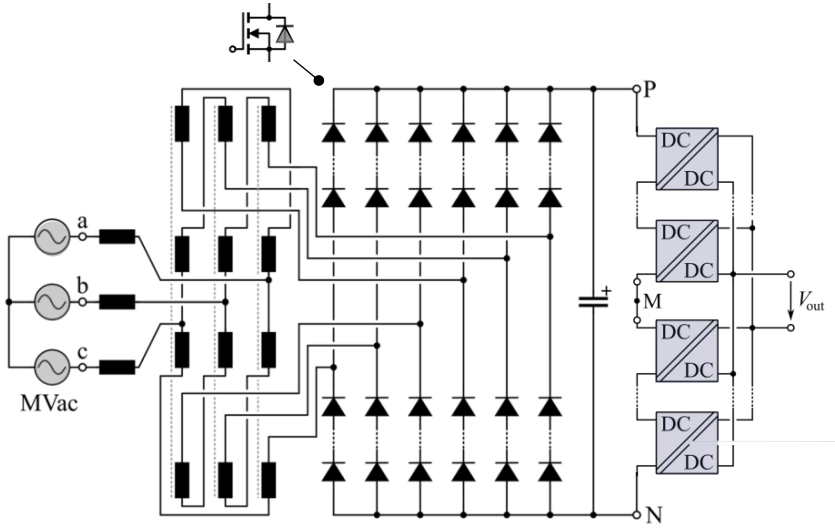


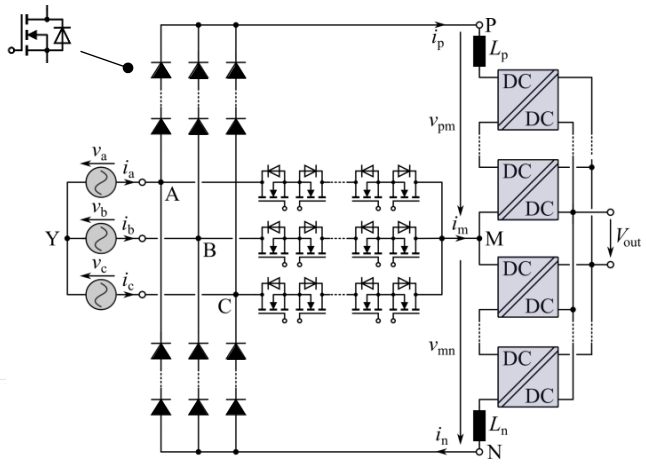
- *Analysis of SST Current-Limiting Capabilities / DC Solid-State Circuit Breaker Concepts*
- *MVDC Grid Stability Analysis incl. Local Power/Energy Buffer Concepts*

Next-Generation 3-Φ AC/DC SST Research Scope 1/3

- *Category #1 – Novel SST Concepts (Degree of Modularization & Hybridization)*
- *Category #2 – Distribution Architecture (Degree of Decentralization & Voltage Level & Protection) / ±10 kVDC, 500 Hz AC?*







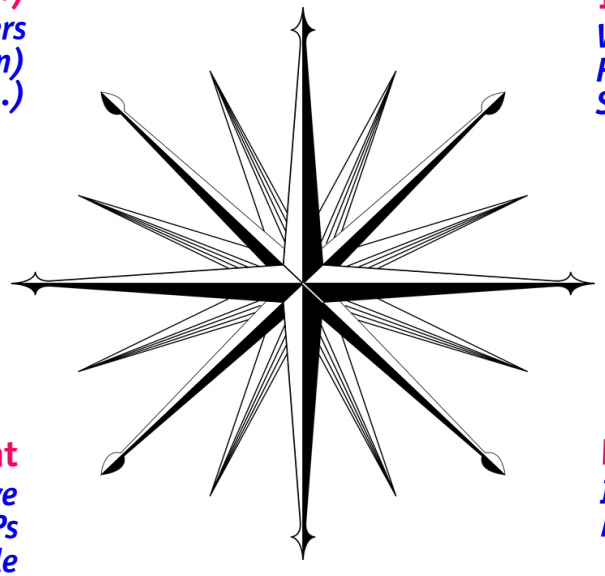
Source: EP 3905480A1, 2020
DE 3826524C2, 1988

- *Keep All Converter Strings Active All Time*
- *Aim for High Utilization / Avoid Processing of 2x f_{Mains} Power and/or Fluctuating Voltage*

Research Vectors

More Compact Realization
Modularity / Hatchability /Transportability
SiC Medium-Voltage PEBBs
Separation of Safety Protection & Funct. Isol.

System Studies (TCO, LCA, ...)
High-Power EV Charging & Datacenters
MVDC Grids (Collector Grids, Traction)
Special Applications (Naval, Aircraft, ...)



1:1 Demonstrators for Full Assessment
Voltage → 10+ kV
Power → 1+ MW
Std. Compliance (BIL, Prot.) → 50+ kV

Alternative Concepts
Local MFAC Distribution
Optimization of LFT-Based Solutions / Hybrid Multi-Pulse Rect.

Protection & Robustness
MV AC & DC Protection / Fault Curr. Lim. Schemes
Grid-Code Compliance (e.g. IEEE 1547)
Modularity / Redundancy / Mean-Time-to-Repair
Design for 20+ Years Lifetime

Business Model Development
Clarification of SST Learning Curve
Demonstration of SST USPs
Modularity / Economy of Scale
Standardization

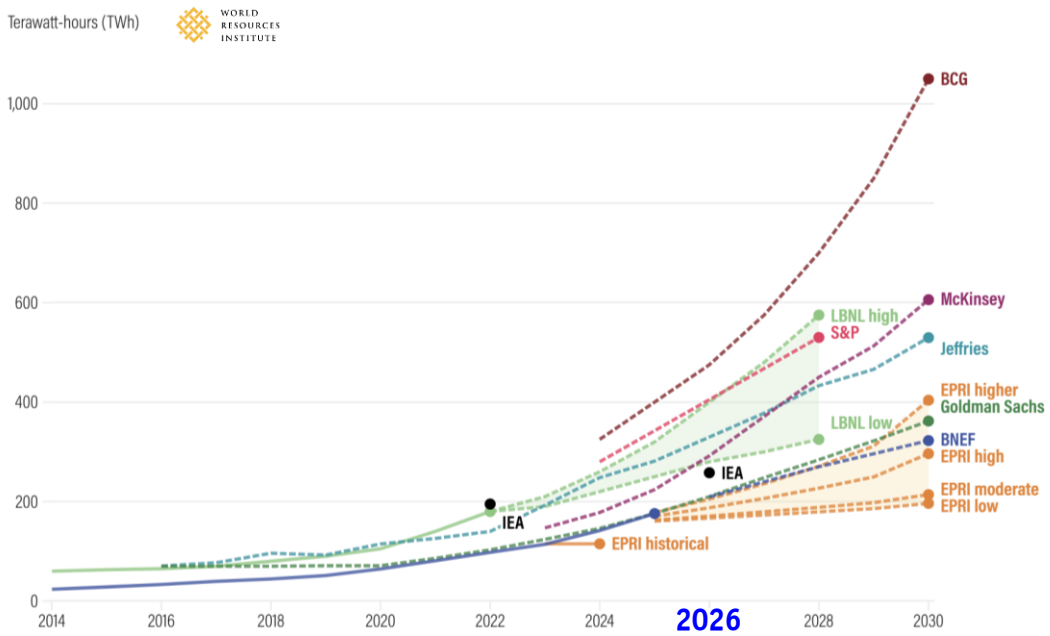
Materials
Insulation Materials
Mixed-Frequ. Insulation Stress Testing

Circular Economy & Sustainability
New/Future KPIs: Longevity / Repair / Re-Use / Recycle

... Focus on Topology | Modulation | Control | Efficiency | Power Density is Far Too Limited (!)

Remark Overbuilding & Overspending (?)

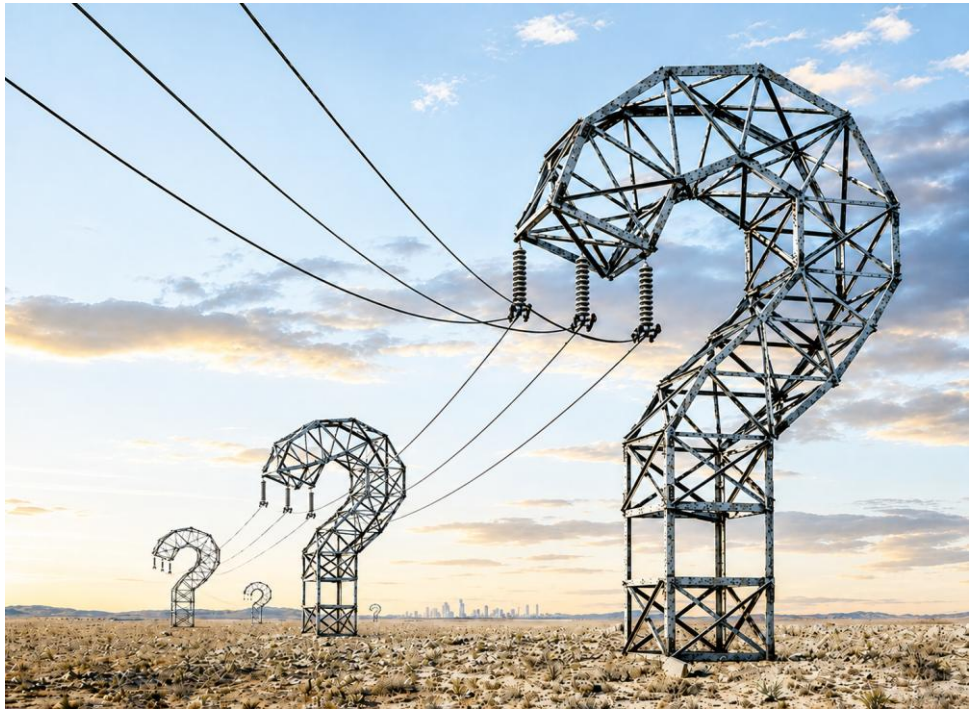
- *Extreme Variations in Projections of US Datacenter Consumption in 2030 (!)*
- *200 TWh...1000 TWh → 5 ... 25% of US Electricity Consumption*



- *Technology Leaps — Hardware/Software/Cooling/Optical Computing Promise Massive Efficiency Gains*
- *"Rather Risk Misspending x 100 Billion USD Than Be Late to Superintelligence" (M. Zuckerberg)*

Thank you!

Source: P. Aylward



Further Reading — https://ams.ee.ethz.ch/publications.html