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Solid-State Transformers — The Slope of Enlightenment

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
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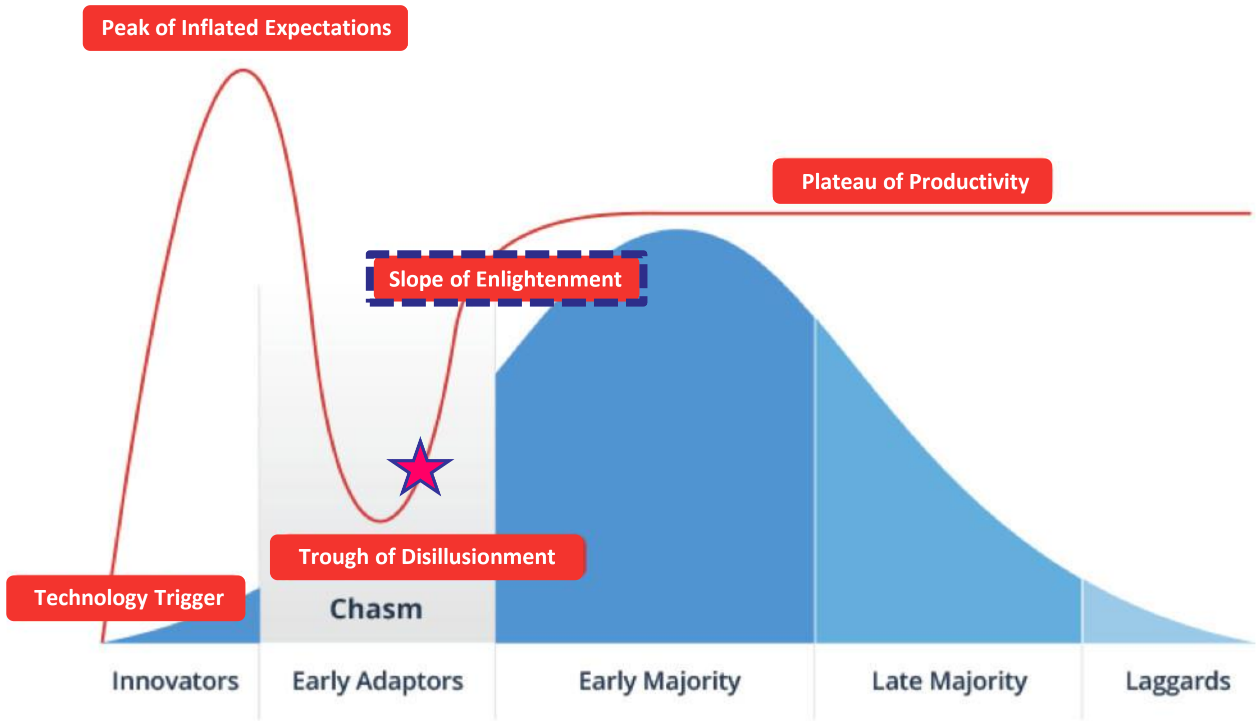
Gartner Hype Cycle (1)

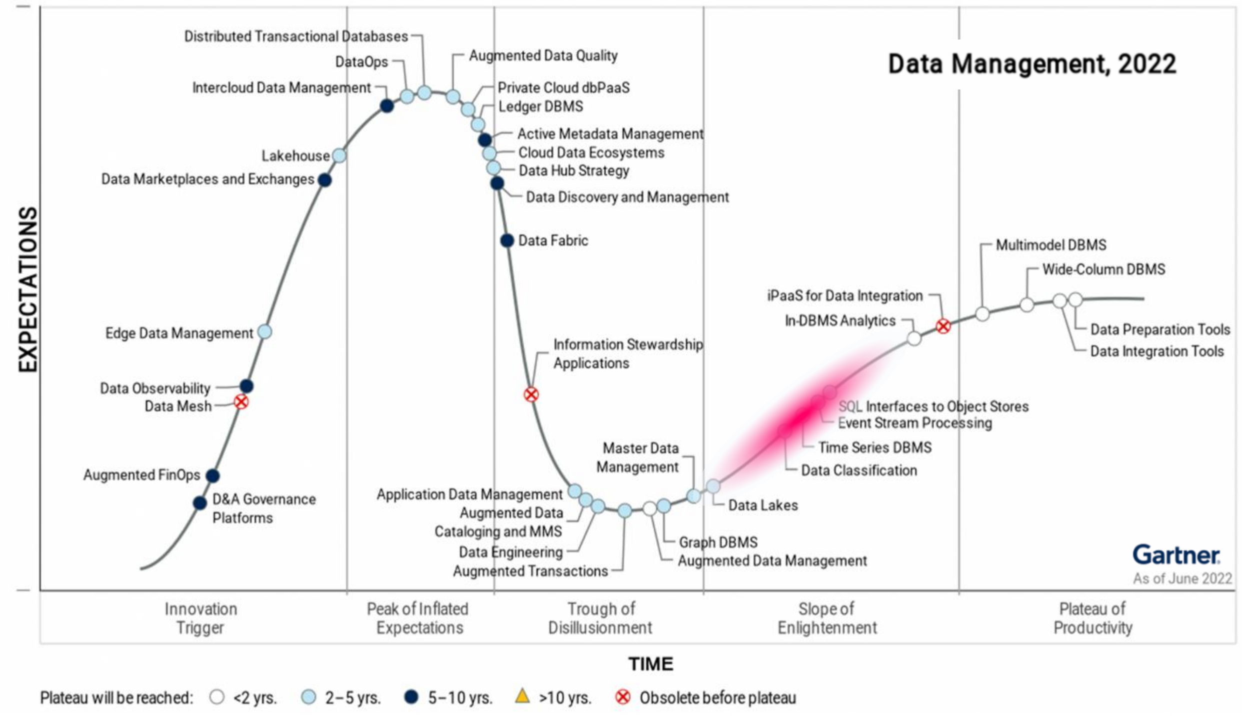
- Graphical Representation of Technology Perception / Acceptance / Maturity



- Peak of Inflated Expectations → Early Publicity / Success Stories
- Trough of Disillusionment → Implementations Fail to Deliver
- Slope of Enlightenment → Benefits Start to Crystallize

Gartner Hype Cycle (2)

- Graphical Representation of Technology Perception / Acceptance / Maturity



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Outline

- ► *Introduction*

- ► *SST Motivation / Concepts*
- ► *Full-Scale Demonstrator Systems*
- ► *Performance Evaluation*

- ► *Outlook*

Acknowledgement

P. Czyz
T. Guillod
G. Ortiz
D. Rothmund

Introduction

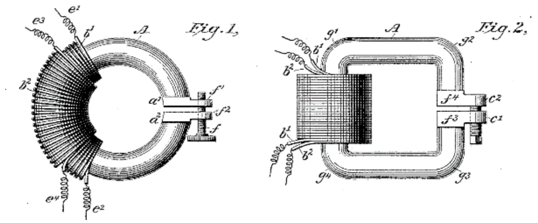
Classical Transformer
SST Motivation in Traction & Smart Grids
SST Topologies

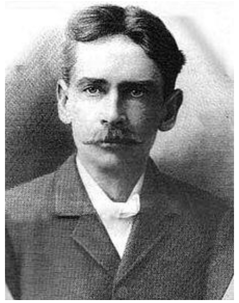
Classical Transformer — History

— 1830	Henry/Faraday	→	Property of Induction
— 1878	Ganz Company (Hungary)	→	Toroidal Transformer (AC Incandescent Syst.)
— 1880	Ferranti	→	Early Transformer
— 1882	Gaulard & Gibbs	→	Linear Shape XFMR (1884, 2kV, 40km)
— 1884	Blathy/Zipernowski/Deri	→	Toroidal XFMR (Inverse Type)

Europe

USA





— 1885 Stanley & (Westinghouse) → Easy Manufact. XFMR (1st Full AC Distr. Syst.)

Classical Transformer — Basics

■ Characteristics

- Voltage Transf. Ratio — Fixed
- Current Transf. Ratio — Fixed
- Active Power Transf. — Fixed ($P_1 \approx P_2$)
- React. Power Transf. — Fixed ($Q_1 \approx Q_2$)
- Frequency Ratio — Fixed ($f_1 = f_2$)

Source: www.faceofmalawi.com

■ Weaknesses

- Voltage Drop Under Load
- Not Directly Controllable
- Losses at No Load
- Large Weight/Volume @ Low Frequency

■ Advantages

- Inexpensive
- Highly Robust / Reliable
- Highly Efficient
- Passive Short Circuit Current Limitation

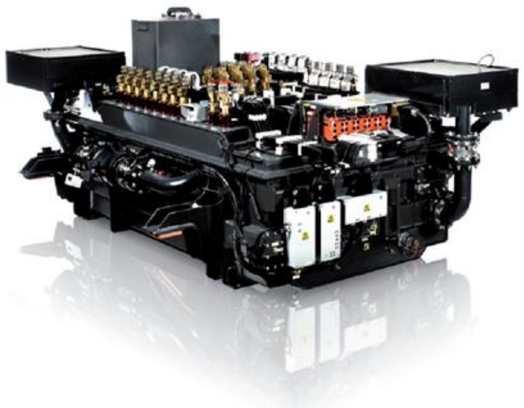
SST Motivation

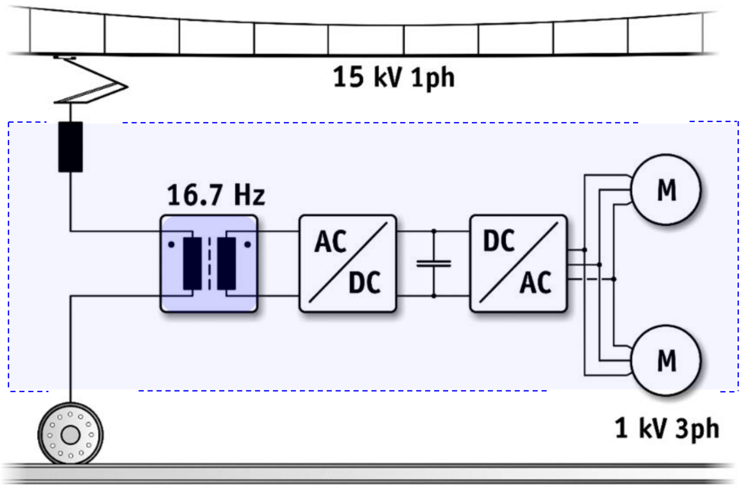
Next Generation Traction Vehicles

Classical Locomotives

— Catenary Voltage 15 kV or 25 kV
— Frequency $16^2/_3$ Hz or 50 Hz
— Power Level 1...10 MW typ.

Source: www.abb.com





- Transformer
  - Efficiency 90...95% (Due to Restr. Vol., 99% typ. for Distr. Transf.)
  - Current Density 6 A/mm² (2 A/mm² typ. Distribution Transformer)
  - Power Density 2...4 kg/kVA

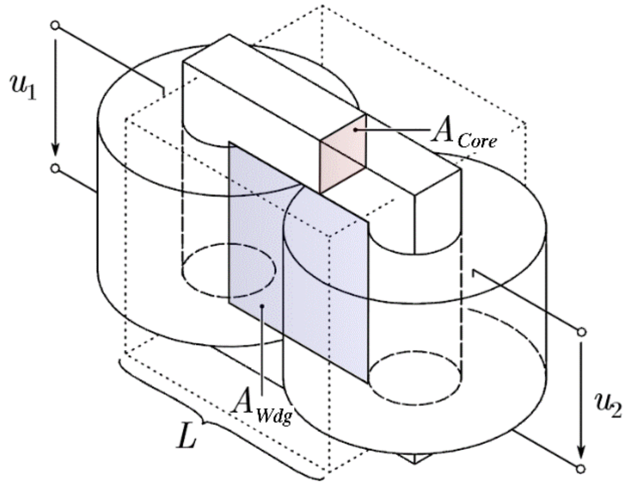
Classical Transformer — Scaling Law

- **Magnetic Core Cross Section** $$A_{Core} = \frac{1}{\sqrt{2}\pi} \frac{U_1}{\hat{B}_{max} f} \frac{1}{N_1}$$
- **Winding Window** $$A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$$
- **Construction Volume**

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

↑ ↑ ↑

P_t .... Rated Power
k_W .... Window Utilization Factor
B_{max} .. Flux Density Amplitude
J_{rms}... Winding Current Density
f ..... Frequency

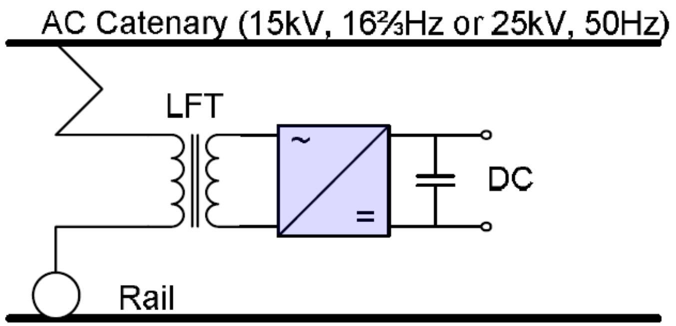


- Low Frequency → Large Weight / Volume
- Trade-off → Volume vs. Efficiency

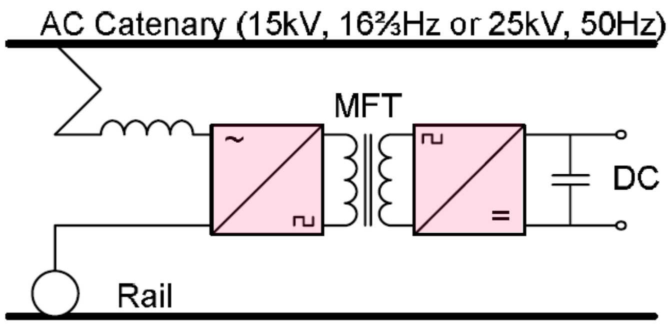
Next Generation Locomotives (1)

- **Trends**
  - — Distributed Propulsion System → Volume Reduction (Decreases Efficiency)
  - — Energy Efficient Rail Vehicles → Loss Reduction (Requires Higher Volume)
  - — Red. of Mech. Stress on Track → Mass Reduction

Source: ABB



Conventional AC-DC conversion with a line frequency transformer (LFT).

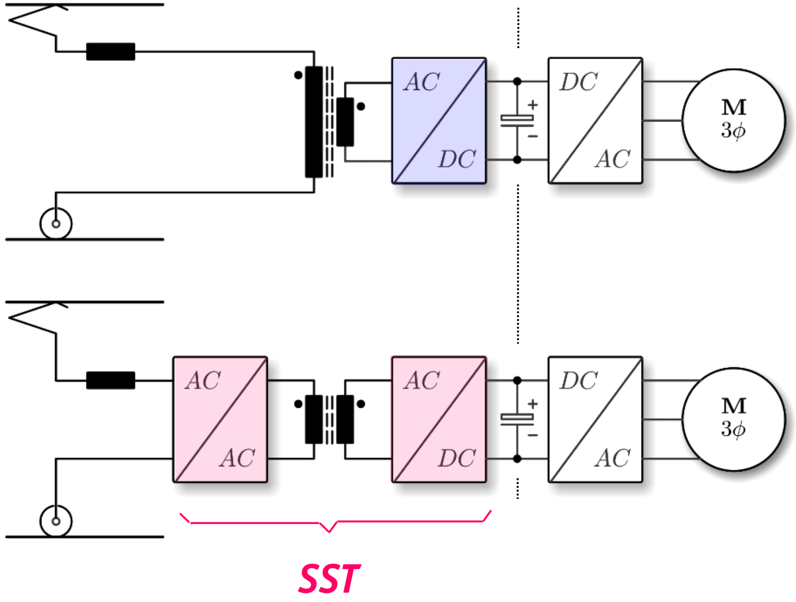


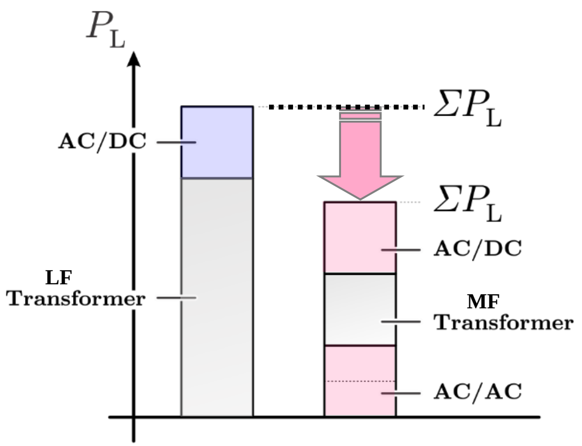
AC-DC conversion with medium frequency transformer (MFT).

- Replace LF Transformer with *MF Transformer & Power Electronics Interface* → *"Solid-State Transformer"*
- Medium-Frequency Allows *Reduction of Volume & Losses*

Next Generation Locomotives (2)

■ Loss Distribution of Conventional & Next Generation Locomotives





● Medium Frequency Provides Degree of Freedom → Reduction of Volume & Losses (!)

Future Smart EE Distribution

Source: TU Munich

Classical Transformer — History

UNITED STATES PATENT OFFICE.

MICHAEL VON DOLIVO-DOBROWOLSKY, OF BERLIN, GERMANY, ASSIGNOR TO THE ALLGEMEINE ELEKTRICITÄTS-GESELLSCHAFT, OF SAME PLACE.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

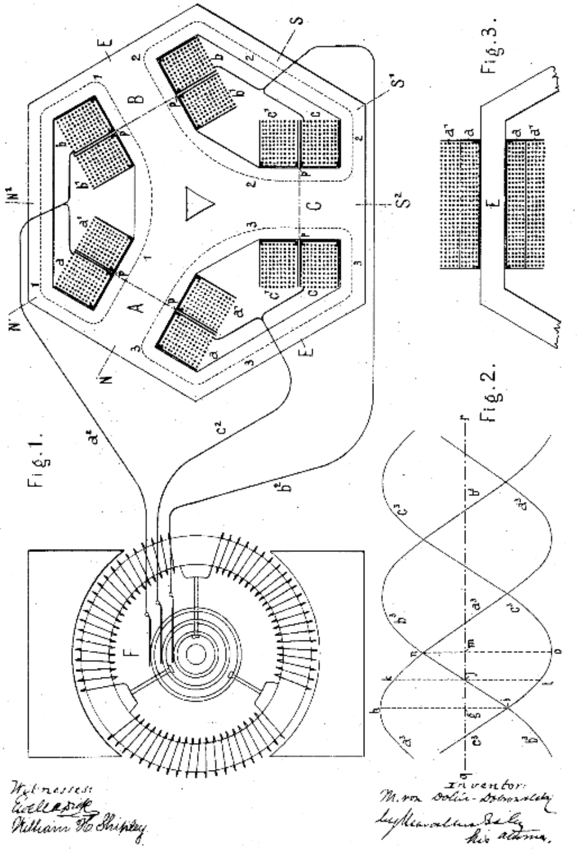
SPECIFICATION forming part of Letters Patent No. 422,746, dated March 4, 1890.

Application filed January 8, 1890. Serial No. 336,290. (No model.)

(No Model.) M. VON DOLIVO-DOBROWOLSKY.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

No. 422,746. Patented Mar. 4, 1890.

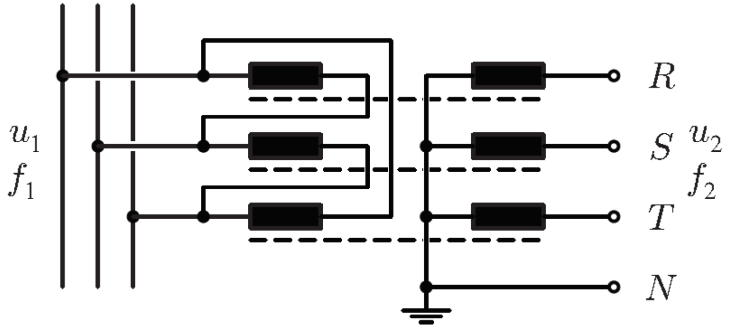


1889 — Dobrovolski → 3-Phase Transformer

1891 — 1st Complete AC System (Generator - XFRM - Transmission – XFRM - Motor & Lamps, 40 Hz, 25 kV, 200 kW, 175 km)

Classical Transformer

— Magnetic Core Material	Silicon Steel / Nanocrystalline / Amorphous
— Winding Material	Copper or Aluminium
— Insulation/Cooling	Mineral Oil or Dry-Type
— Operating Frequency	50/60Hz (El. Grid, Traction)
— Operating Voltage	10kV or 20 kV (6…35kV) 400V



Vacuum Cast Coil Dry-Type
Distribution Transformer

- 1 MVA – 12kV/400V @ 2600kg
- 0.5% / 1% Losses @ No / Rated Load
- Not Directly Controllable
- Sensitivity to Harmonics & DC Offsets

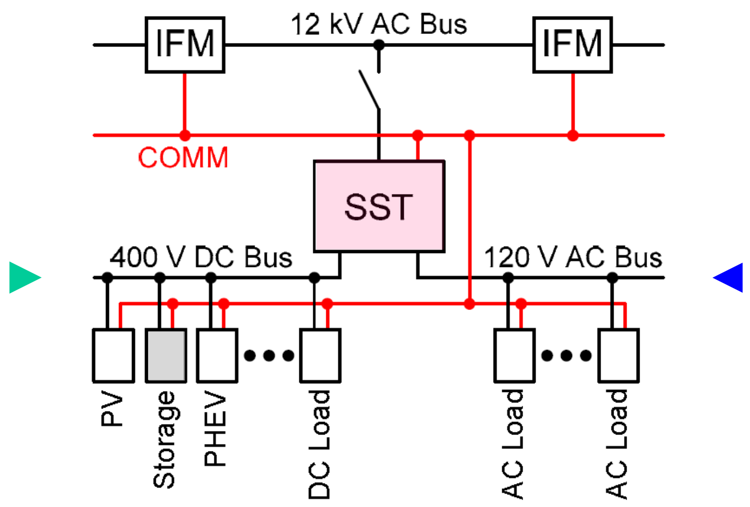
Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

- SST as Enabling Technology for the "Energy Internet"

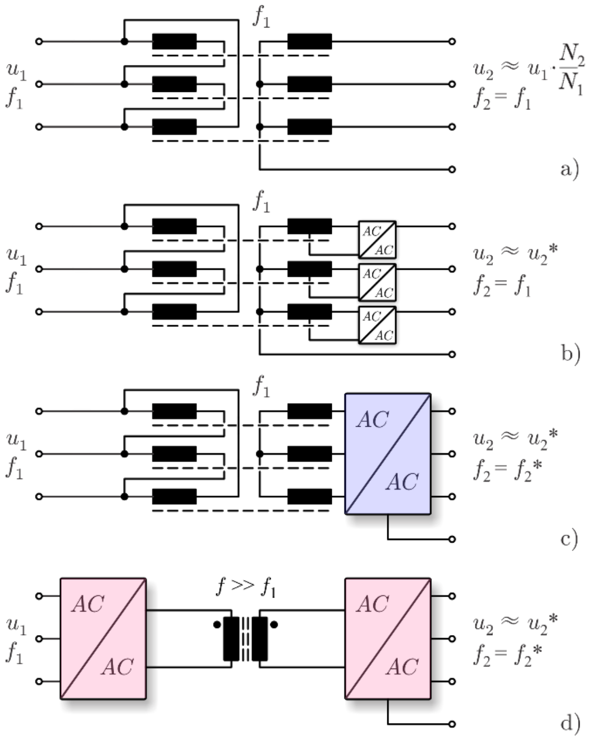
- Full Control of the Power Flow
- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Protects Power Syst. From Load Disturbances
- Protects Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.
- etc.

IFM = Intellig. Fault Management



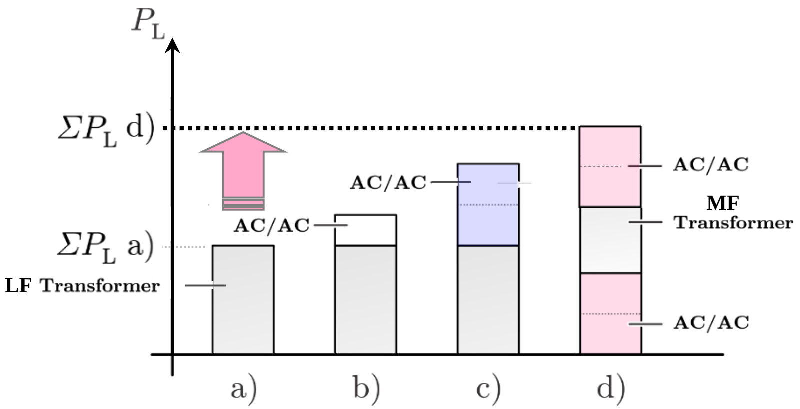
- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Control

Trade-Off — Controllability vs. Efficiency



LF Isolation
Purely Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

MF Isolation
Active Input & Output Stage (d)

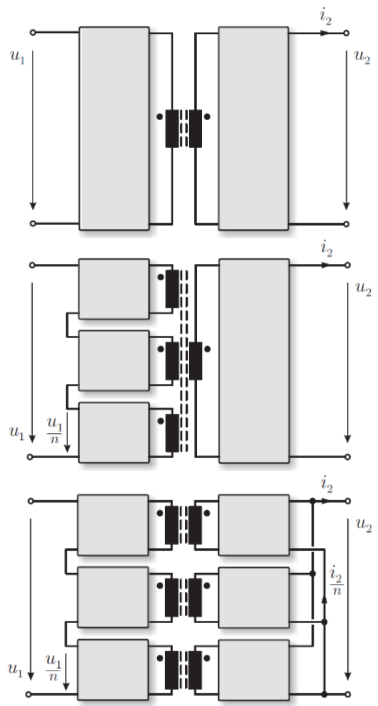


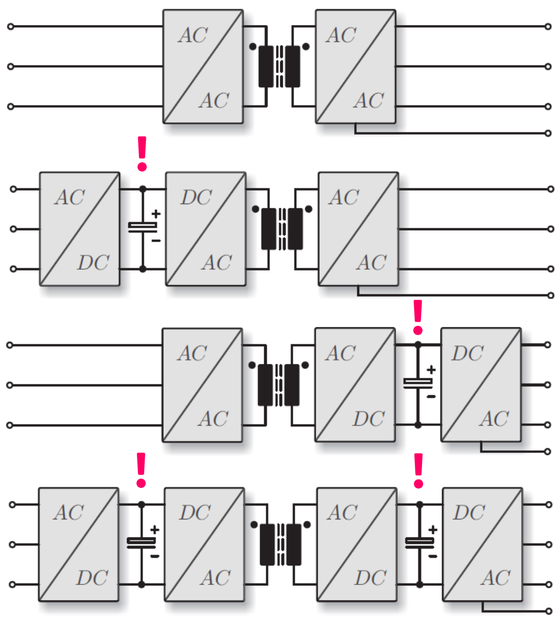
- Lower Efficiency of SST Compared to "Grid-Type" Passive Transformer
- Medium Freq. → Higher Transf. Efficiency only Partly Compensates Converter Stage Losses

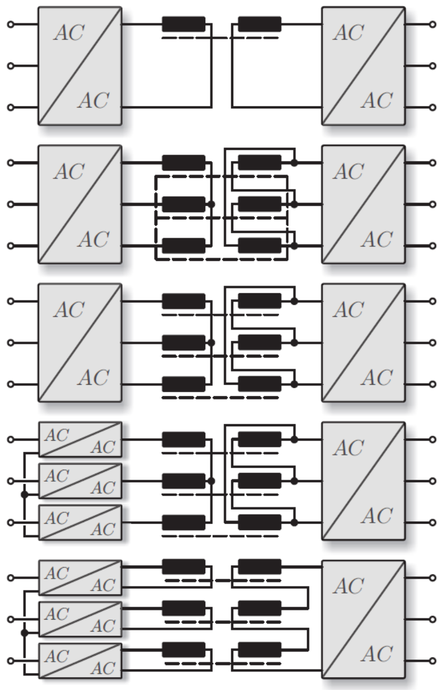
Derivation of MV → LV SST Topologies

Classification of SST Topologies (1)

- Number of Levels Series/Parallel Cells
- Degree of Power Conversion Partitioning
- Degree of Phase-Modularity

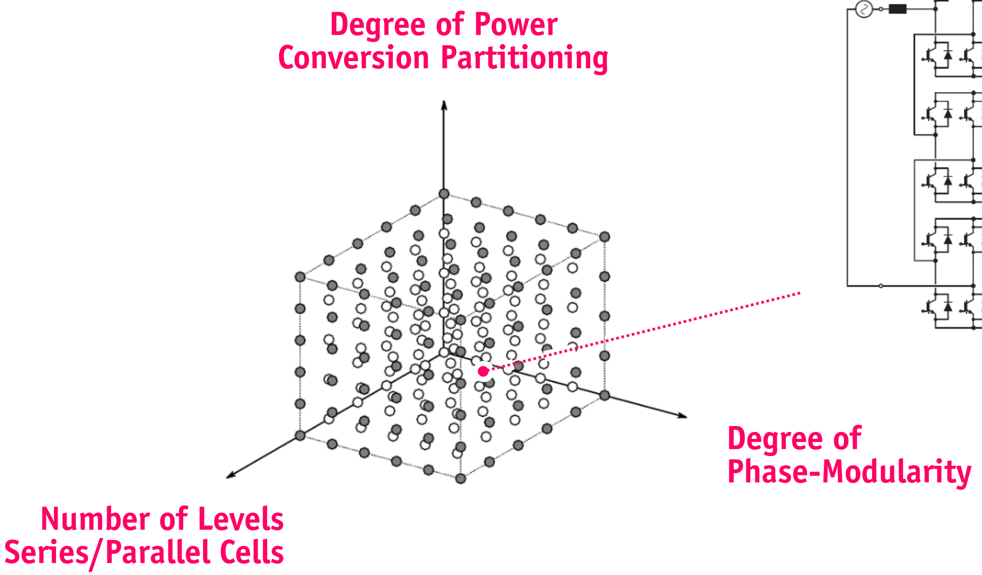


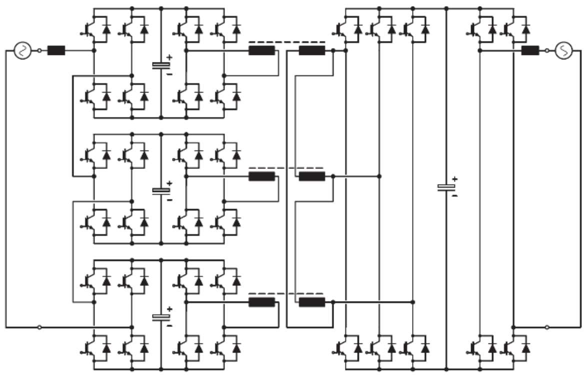




- 3-Dimensional Topology Selection Space

Classification of SST Topologies (2)





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

— Partitioning of Power Conversion → Matrix & DC-Link Topologies
— Splitting of 3ph. System into Individual Phases → Phase Modularity
— Splitting of Medium Operating Voltage into Lower Partial Voltages → Multi-Level/Cell Approaches

Power Electronic Systems Laboratory

Full-Scale Industrial SSTs for Future Traction Applications

1-Φ AC-DC Conversion
DC/DC Conversion

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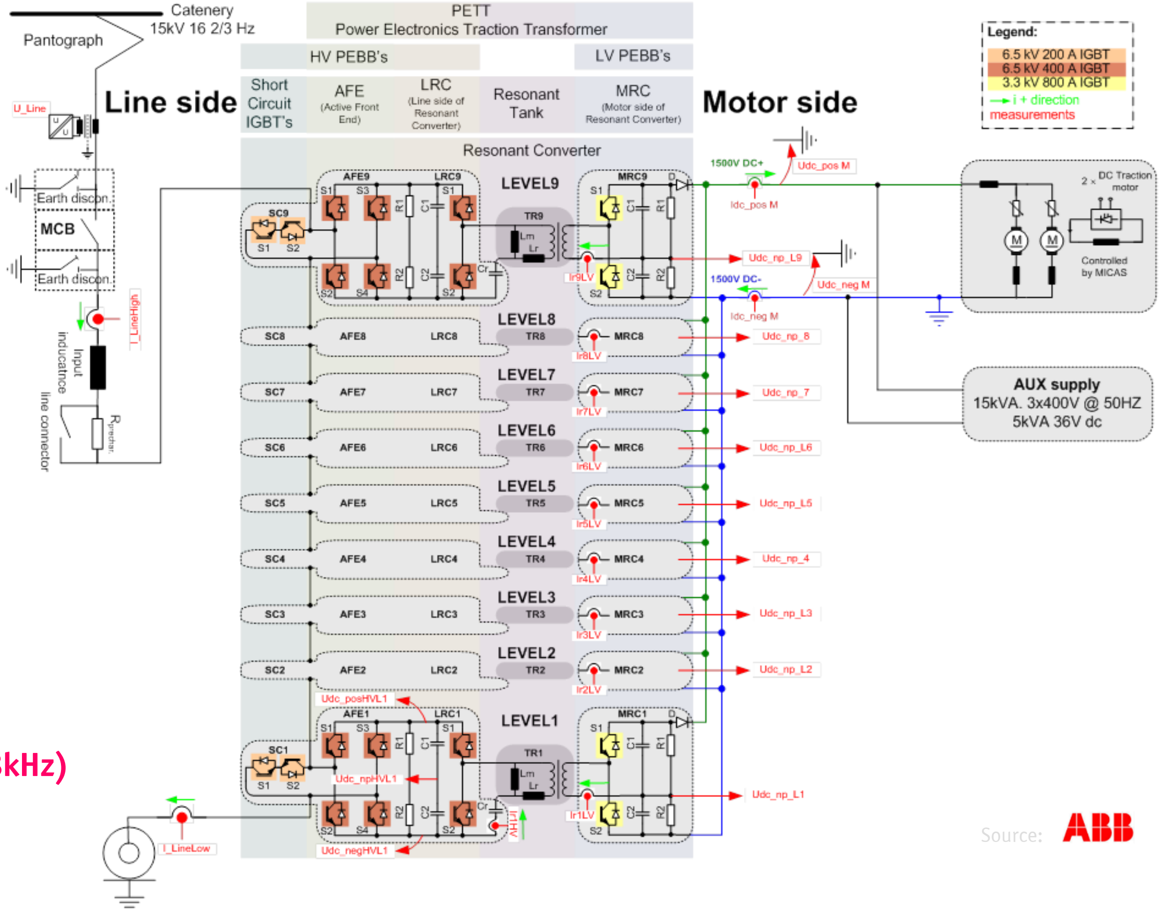
1.2 MVA 1-Φ AC/DC Power Electronic Transformer

- Dujic et al. (2011)

- Heinemann (2002)
- Steiner/Stemmler (1997)
- Schibli/Rufer (1996)



Source: ABB

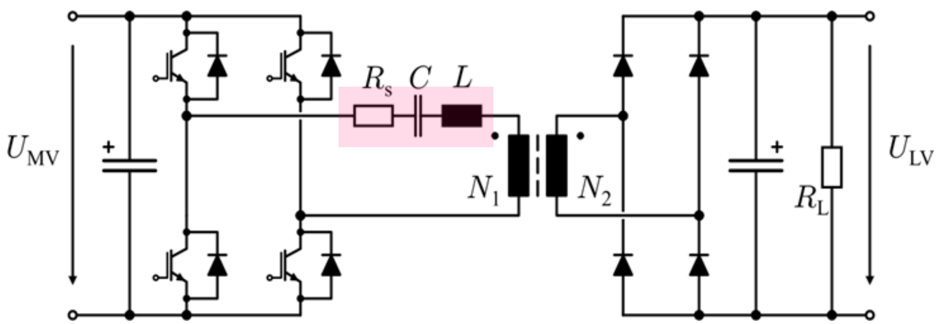
P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

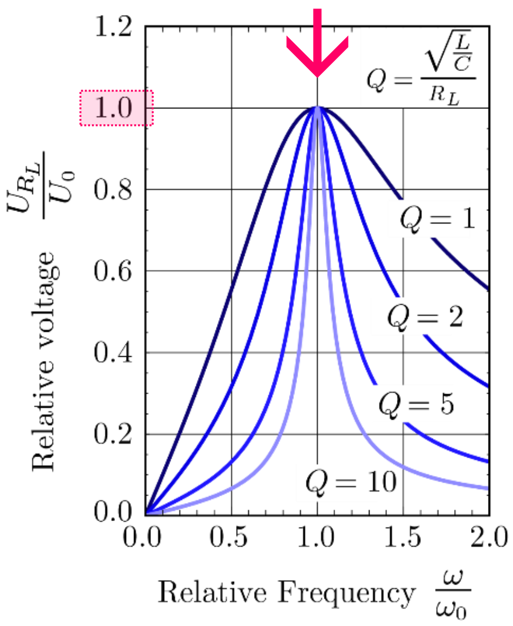
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

DCX — "DC Transformer"

- $f_S \approx$ Resonant Frequency → "Unity Gain" ($U_2/U_1=N_2/N_1$)
- Fixed Voltage Transfer Ratio Independent of Transferred Power (!)
- Power Flow Level & Direction Self-Adjusting
- No Controllability / No Need for Control
- ZVS/ZCS of All Devices

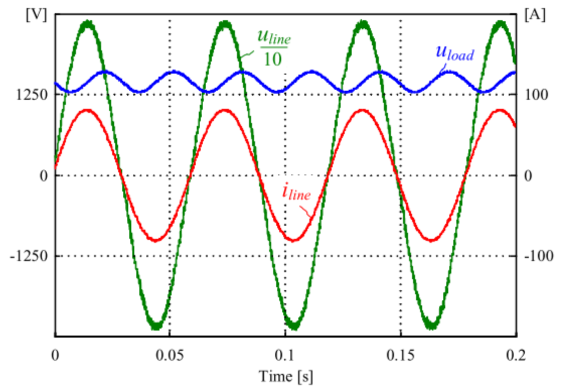


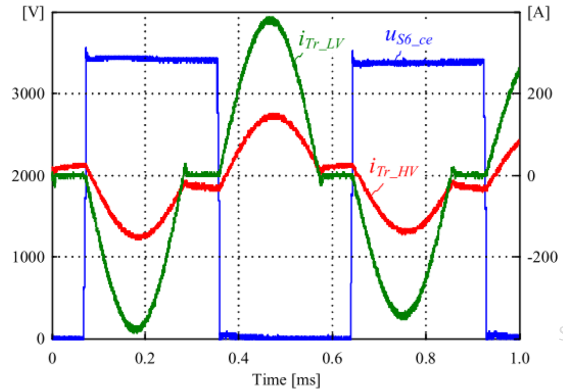


1.2 MVA 1-Φ AC/DC Power Electronic Transformer

- Cascaded H-Bridges – 9 Cells
- Resonant LLC "DC-Transformer" DC/DC Converter Stages

★ η = 96%





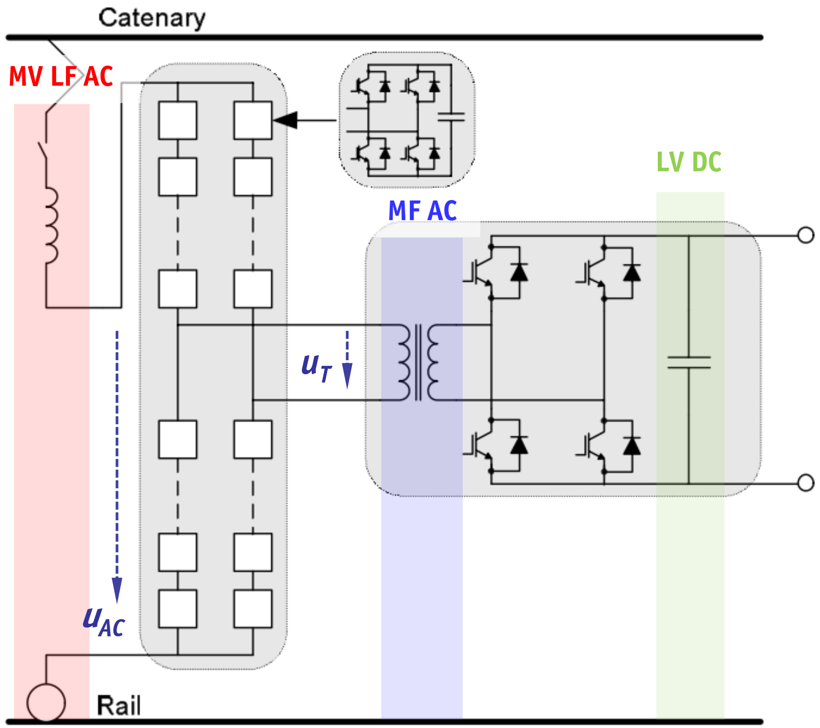
Source: ABB

- Same Overall Volume as a Conventional System
- Future Development Targets Half Volume

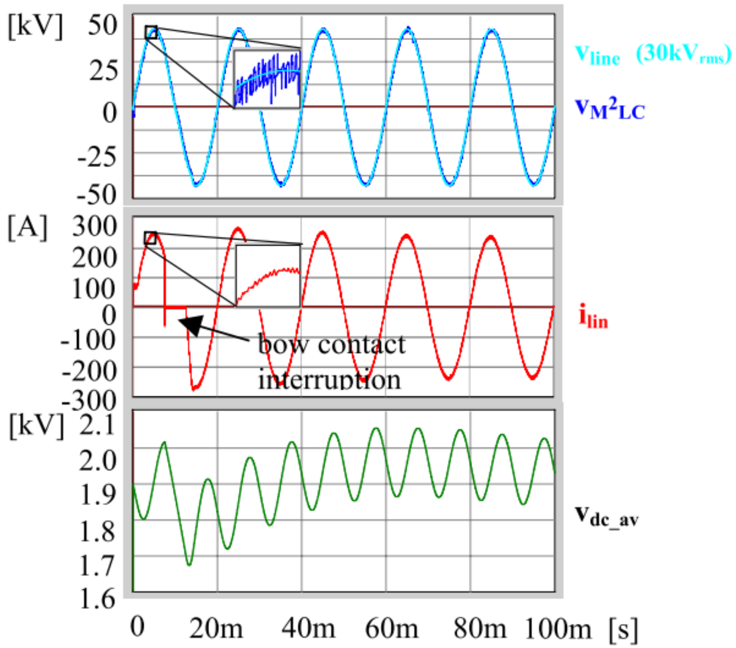
1-Φ AC/DC SST — Modular Multi-Level Converter Approach

- Highly Modular / Scalable
- Single Transformer w/ Full Isolation Voltage Rating
- Redundancy of Lifetime-Critical Power Semiconductors
- High Semiconductor & Cell Voltage Control Effort

SIEMENS
- Marquardt/Glinka (2003)



Source: Zhao / Dujic (ABB / 2011)

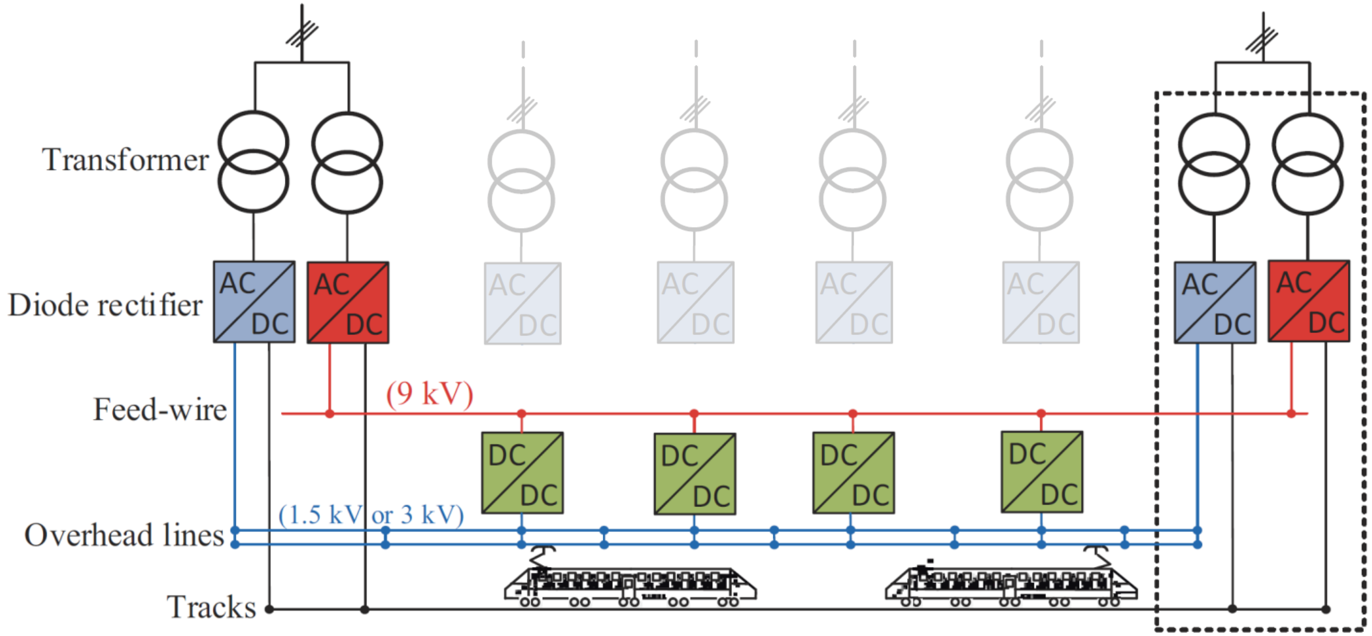


- AC/AC Front-End Features Independent Generation of u_T and u_{AC}

DC Traction Applications

Future DC-Railway DC/DC-SST Application (1)

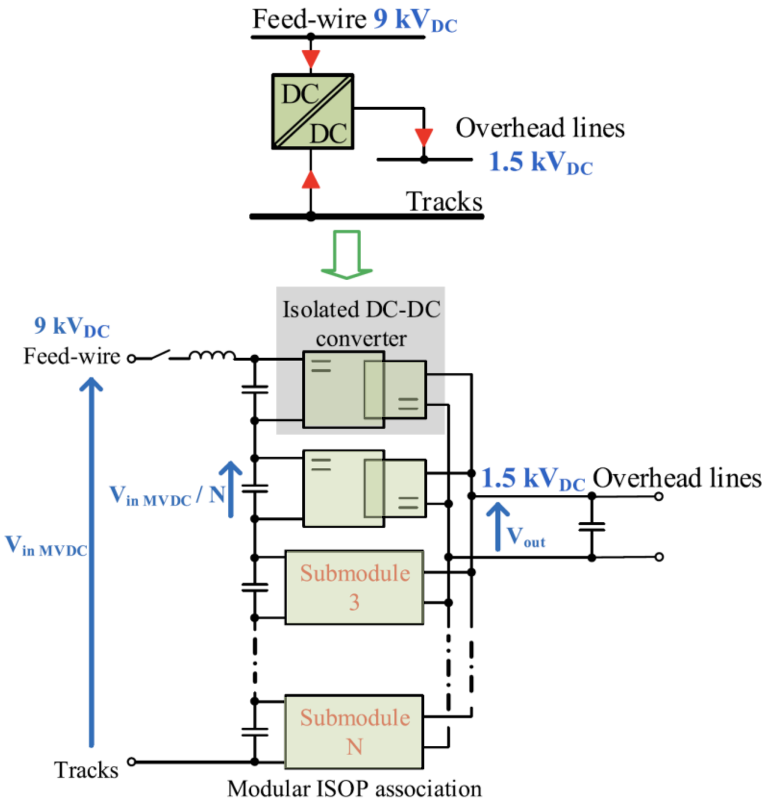
- Increase in Regional & Freight Traffic → Higher Power Demands
- 9 kV DC-Bus Extension of Current 1.5 kV | 3 kV SNCF DC System (1000 mm²)

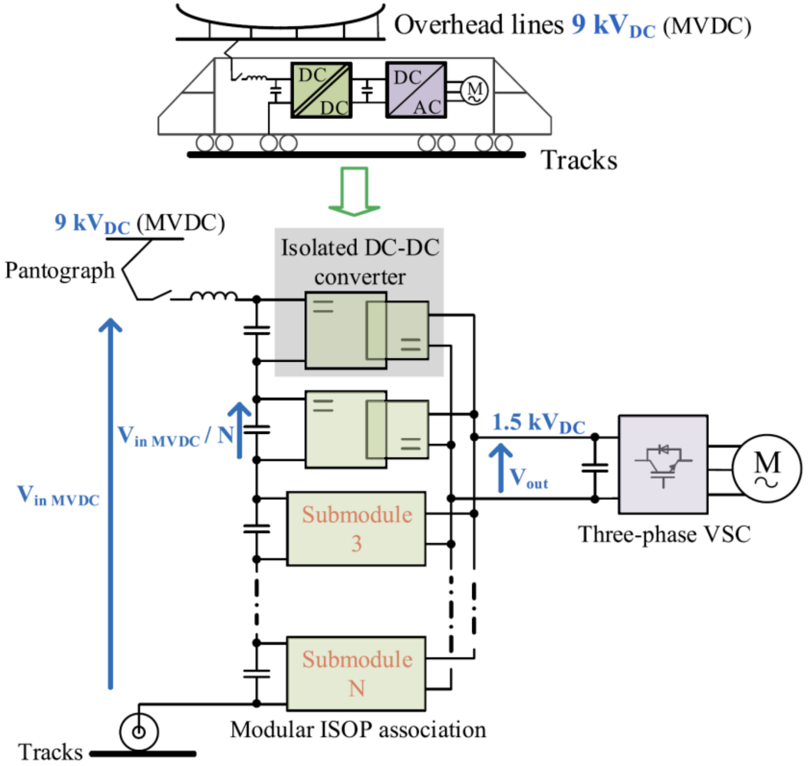


- DC/DC SSTs Instead of New AC/DC Substations → Lower Realization Effort | Higher Eff.
- Potential 9 kV DC-Interface to Renewable Energy / Energy Storage / HVDC Lines etc.

Future DC-Railway DC/DC-SST Application (2)

- Increase in Regional & Freight Traffic → Higher Power Demands
- 9 kV DC-Bus Extension of Current 1.5 kV | 3 kV SNCF DC System (1000 mm²)



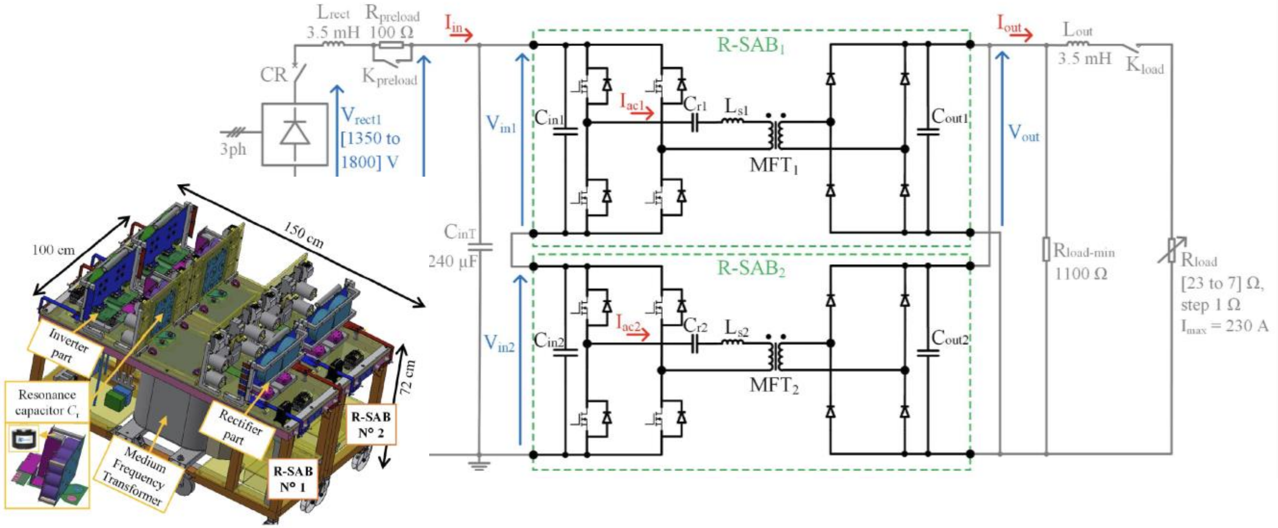


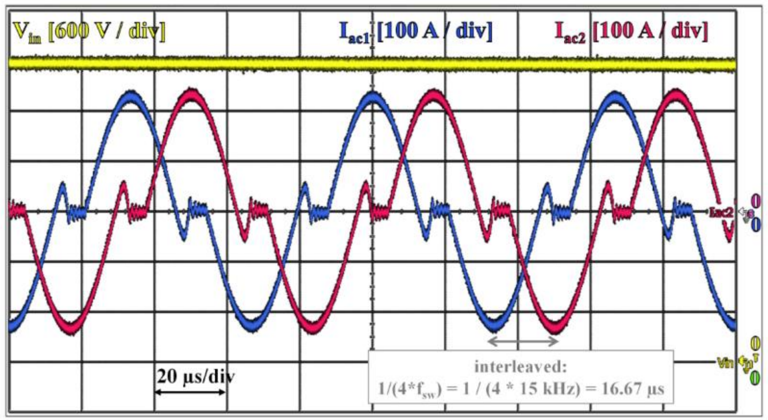
- Future Elimination of 1.5kV Overhead Lines → Onboard 9 kV/1.5 kV DC/DC Conversion

Future DC-Railway DC/DC-SST Application (3)

- 3.3kV / 750A SiC MOSFETs | 400kVA 1:1 Water-Cooled Nanocryst. Core Oil-Tank MFT | f_{sw}= 15kHz
- 2-Stage ISOP Demonstrator System — 600kW | 3.6kV/1.8kV DC/DC Conversion | $\rho\approx$ 0.6 kW/dm³

★ η = 99% peak

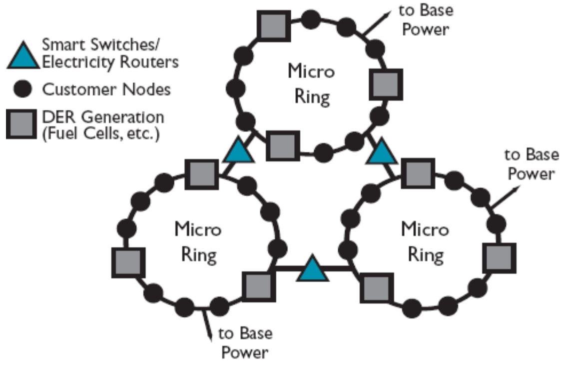




- DCX-Type ISOP Converter Stages
- Natural Voltage & Current Sharing Experimentally Confirmed
- Interleaving — 4x 15kHz = 60kHz Output Voltage Ripple

Smart Grid SSTs Applications

3-Φ AC-AC Conversion

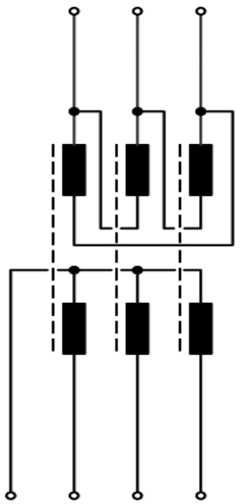


Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

Isolated-Back-End ISOP 3-Φ AC/AC SST Topology

- ETH Zurich MEGA-Link Project
- Input Series Output Parallel CHBs — ISOP Topology

S_N = 1 MVA
U_{MV} = 10 kV
U_{LV} = 400 V



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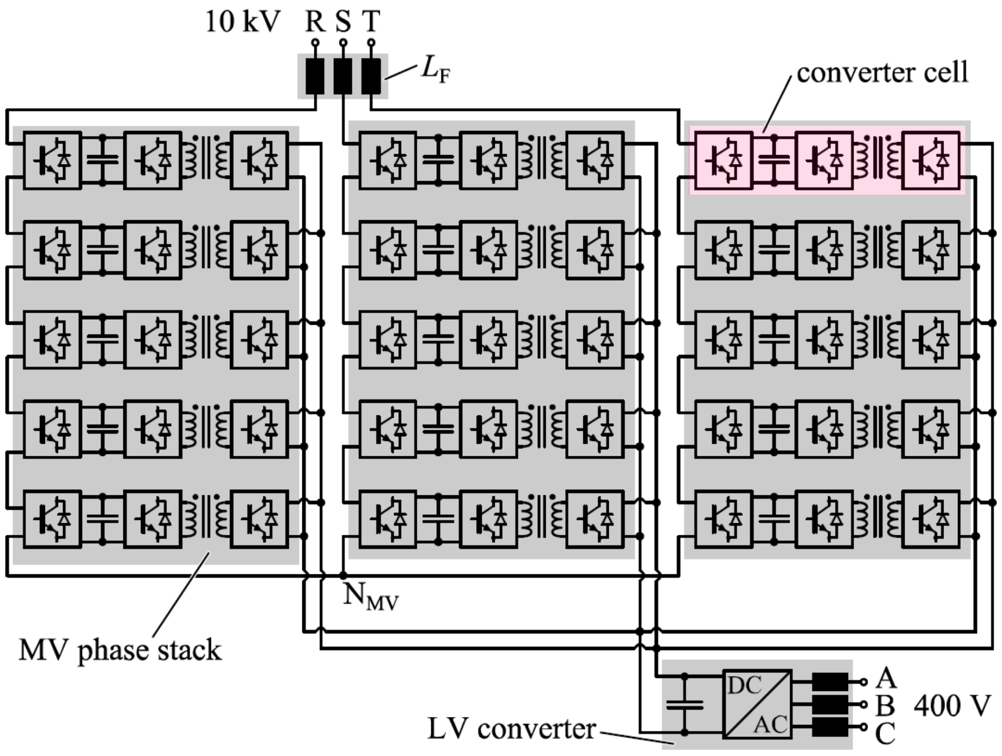
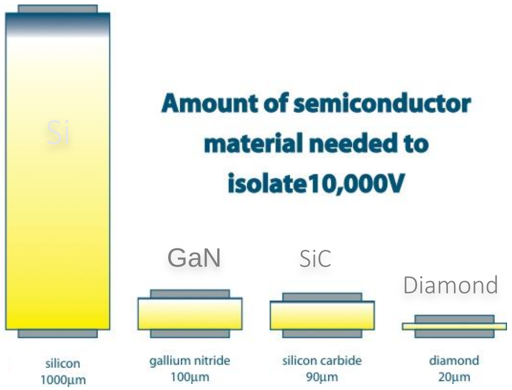


- Si-IGBT-Based Realization
- 2-Level Inverter on LV Output Side
- DC-Transformer DC/DC Conversion Stages

Medium Voltage SiC Power MOSFETs / IGBTs

- SiC MOSFETs
- Low Conduction Losses
- High Efficiency

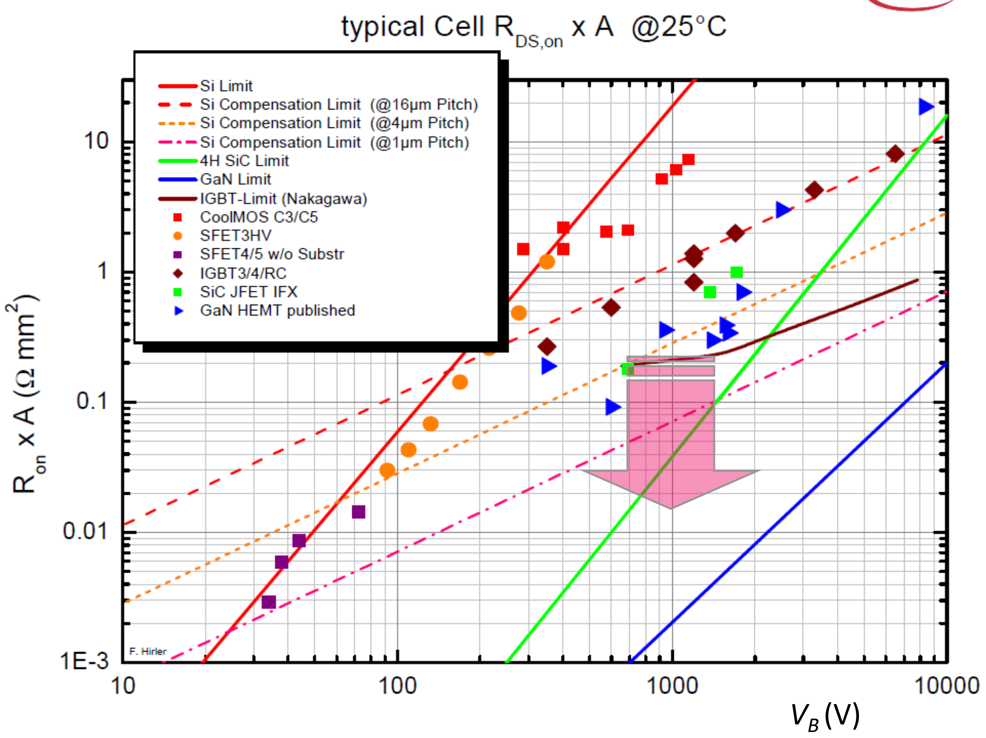
Source: www.evincetechnology.com



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

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

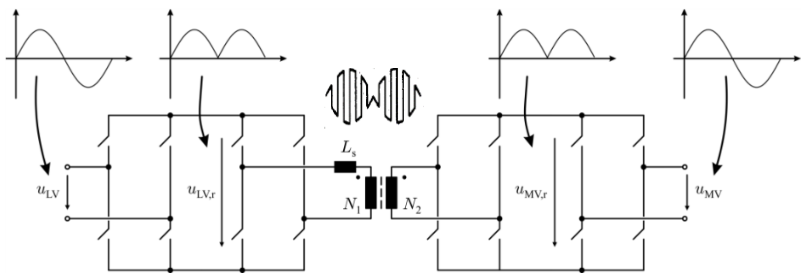
Source: Infineon

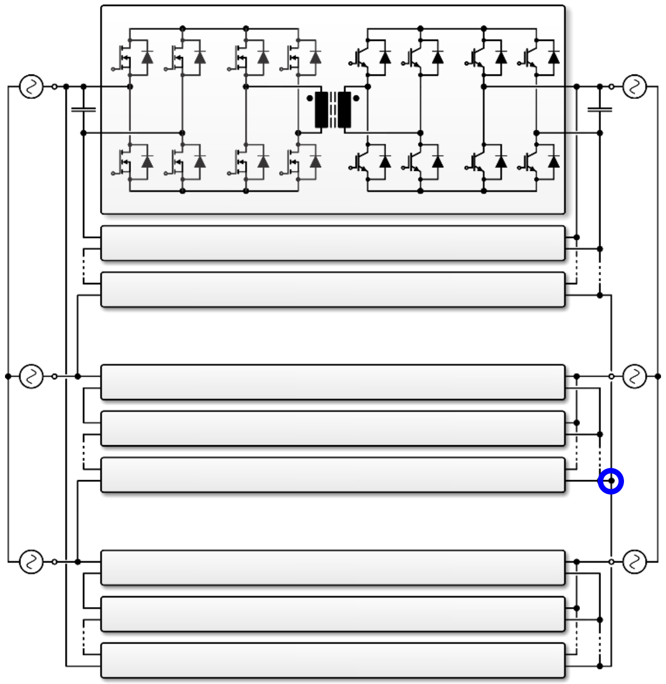


- High Voltage Unipolar (!) Devices → Excellent Sw. Performance / High Power Density

SiC-Enabled Solid-State Power Substation (1)

- 10 kV SiC-Enabled 1MVA @ f_{sw}= 20 kHz
- MV Δ-Connection (13.8kV$_{LL}$, 4 Modules in Series)
- LV Y-Connection (265V, All Modules in Parallel)

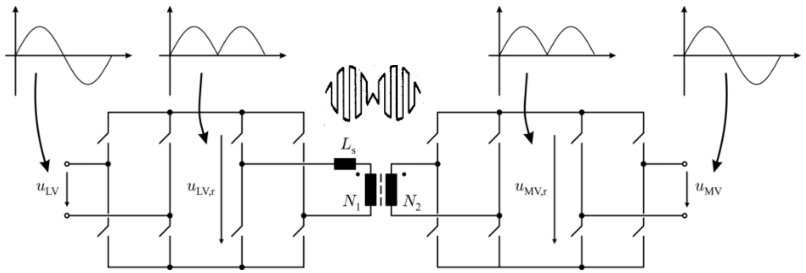




- Fully Phase-Modular ISOP Topology
- Indirect Matrix Converter Modules — $f_1 = f_2$
- 97% Efficiency @ Full Load | 1/3rd Weight | 50% Volume Reduction (Comp. to 60 Hz)

SiC-Enabled Solid-State Power Substation (2)

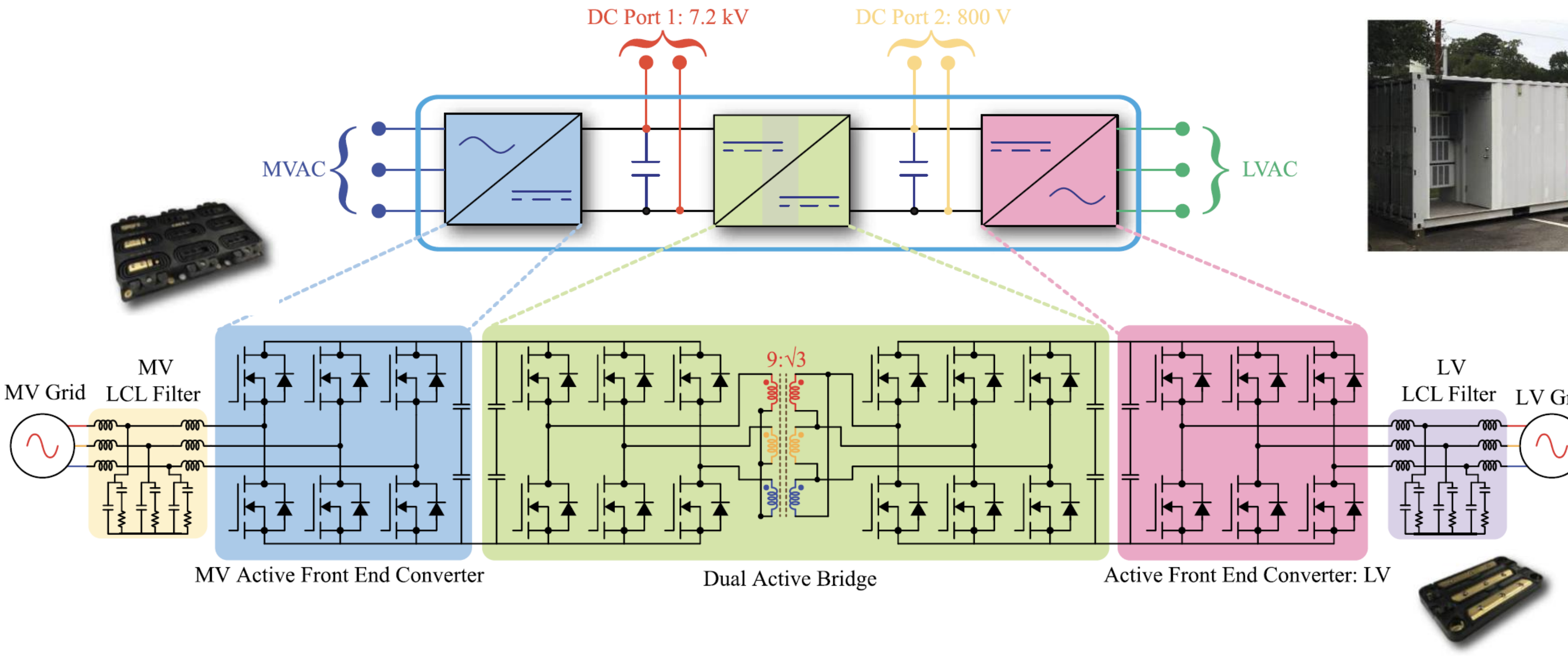
- 10 kV SiC-Enabled 1 MVA @ f_{sw} = 20 kHz
- MV Δ-Connection (13.8kV$_{LL}$, 4 Modules in Series)
- LV Y-Connection (265V, All Modules in Parallel)



- Fully Phase-Modular ISOP Topology
- Indirect Matrix Converter Modules — $f_1 = f_2$
- 97% Efficiency @ Full Load | 1/3rd Weight | 50% Volume Reduction (Comp. to 60 Hz)

2-Level Mobile Utility Support 3-Φ AC/AC SST

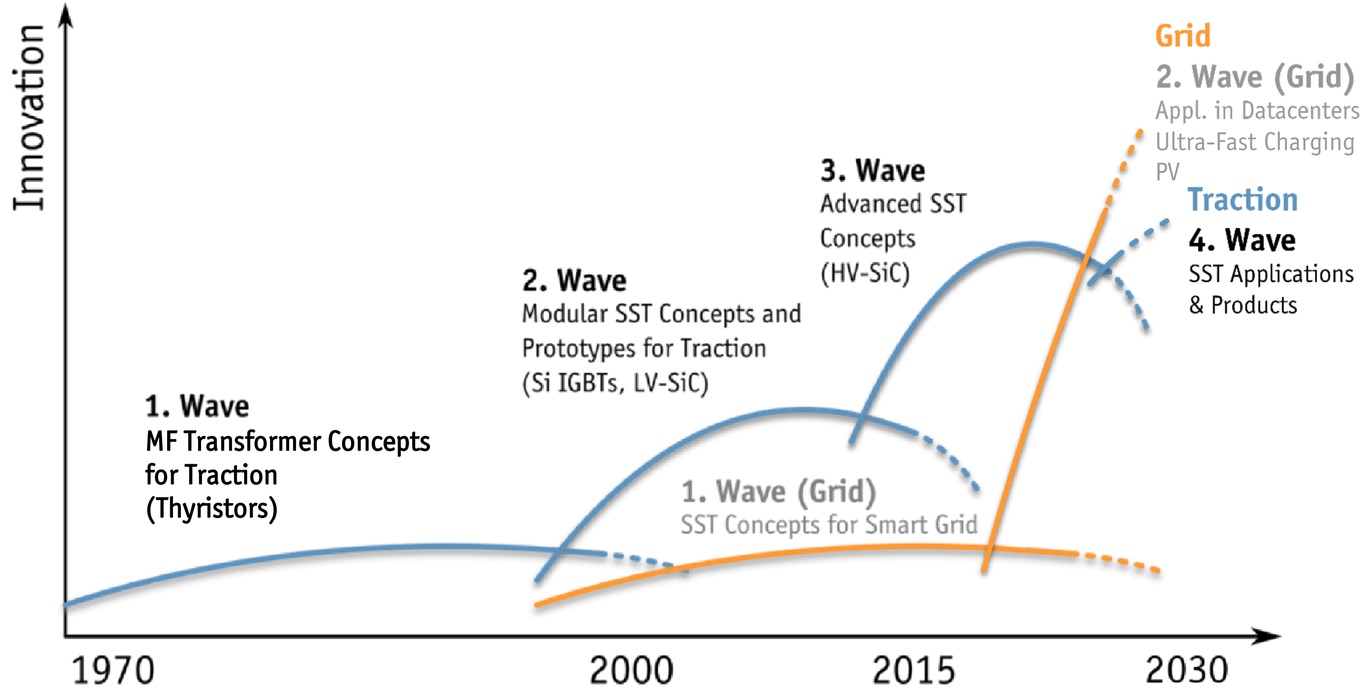
- Mobile Utility Support Equipment (MUSE-SST) Placed in Mobile Container
- MV and LV DC-Links Facilitate Integration of Renewables / Energy Storage
- 100kW | 4.16 kV — 7.2 kV_{DC} — 800 V_{DC} — 480 V



Source: NC STATE UNIVERSITY

- 10kV Gen-3 Extra High Voltage (XHV) & 1.2 kV SiC MOSFET Half-Bridge Modules
- Thermosyphon Air Cooling | MV Power Block — 0.2 kW/dm³ | 0.6 kW/kg | $\eta \approx 95.5\%$ @ f_{sw} = 10 kHz / 3.5 kV_{DC} / 35 kW

SST Development Cycles



- Development Cycles Reaching Over Decades — Matched to "Product" Life Cycle

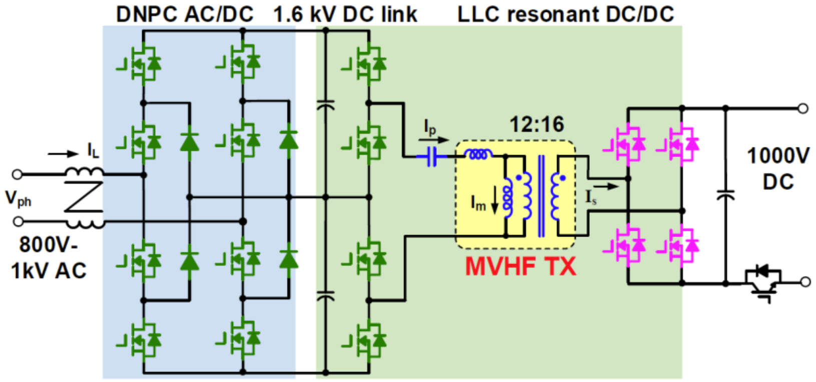
Ultra-Fast Multi-Port EV Charging Stations

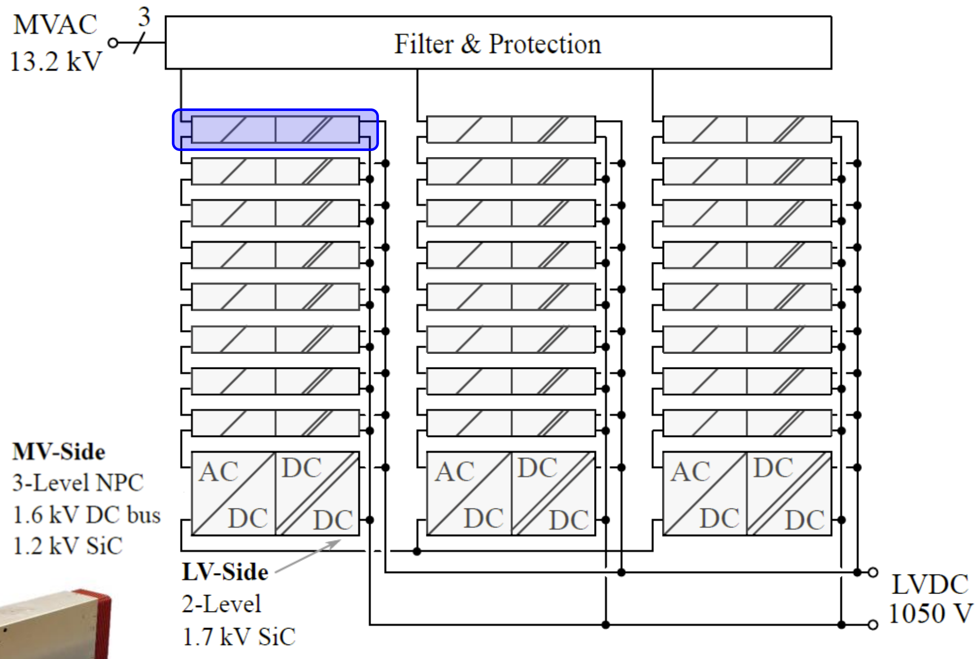
3-Φ AC-DC Conversion

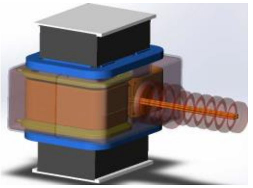
3-Φ 13.2kV / 400kW SST-Based EV Charger

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

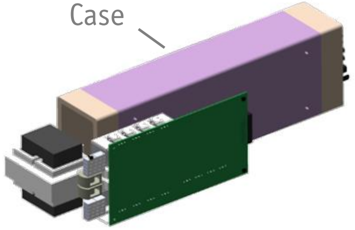
DELTA
Source: Ch. Zhu, 2021







Isolation Case

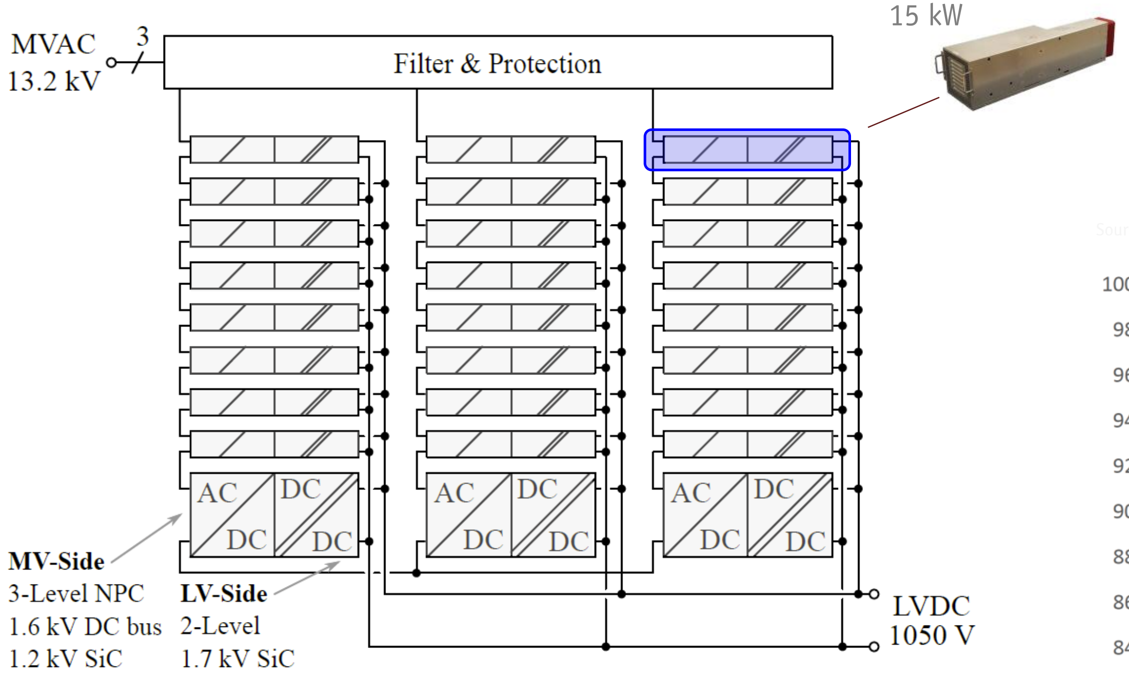


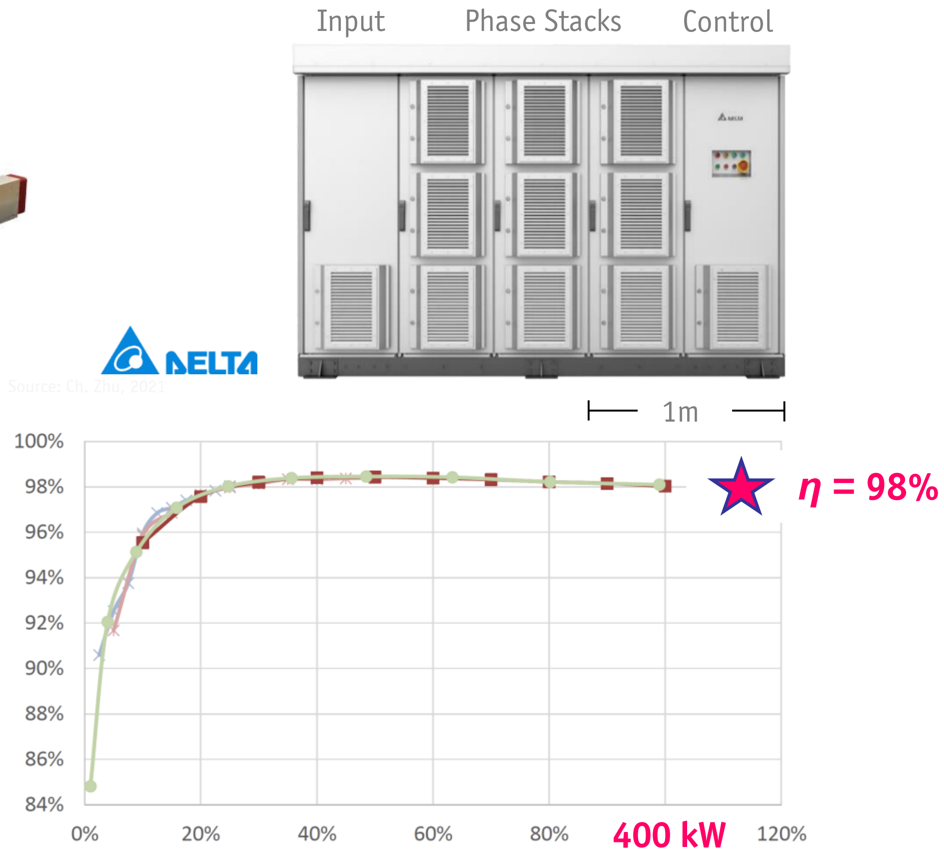
Grounded Housing

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

3-Φ 13.2kV / 400kW SST-Based EV Charger

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



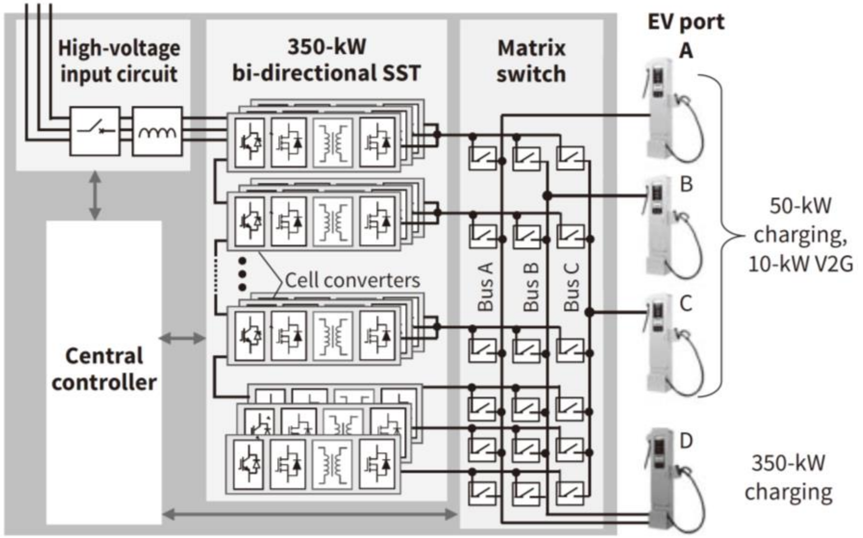


- 3000 kgs Weight | 3100 x 1300 x 2100 mm Outer Dimensions
- Power Density → 0.05kW/dm³ (System) | ≈ 0.5 kW/dm³ (Cells) | ≈ 8.5 kW/dm³ (MFT)

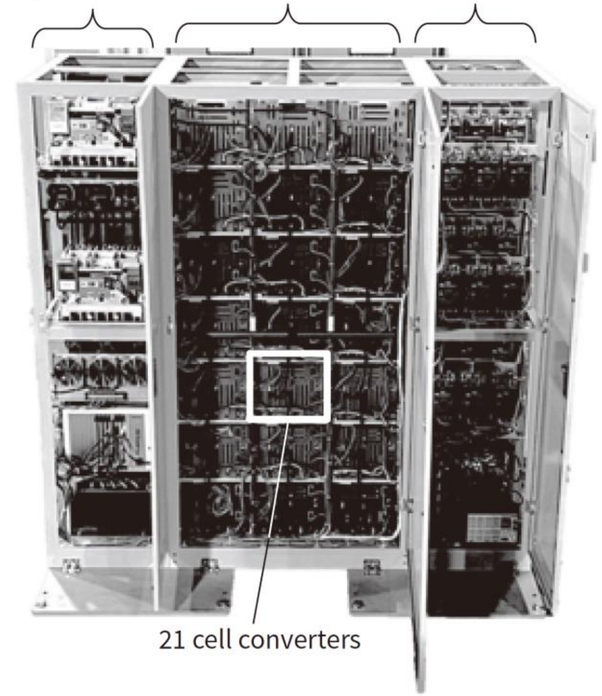
3-Φ 6.6kV / 350kW SST-Based Multi-Port EV Charger

- 3x7 = 21 Cells | 5kHz 1.7kV Si-IGBT AC/DC Stage | 50kHz 1.7kV SiC 1050V/400V DC/DC Converter
- Matrix Switch Output for 21x 17kW → 1x 350kW Charging Port Config. & Cascaded Cell Balancing
- Forced Air Cooling

≈ 2000 x 1000 x 2000 mm



Source: HITACHI



- Power Density → 0.09kW/dm³ (System) | ≈ 0.18 kW/dm³ (SST/Cells incl. Isol.)
- -40% Footprint / -70% Weight vs. LFT-Based Solution / 83% Lower Transf. Volume

3-Φ 6.6kV / 350kW SST-Based Multi-Port EV Charger

- 3x7 = 21 Cells | 5kHz 1.7kV Si-IGBT AC/DC Stage | 50kHz 1.7kV SiC 1050V/400V DC/DC Converter
- Matrix Switch Output for 21x 17kW → 1x 350kW Charging Port Config. & Cascaded Cell Balancing
- Forced Air Cooling

Source: HITACHI

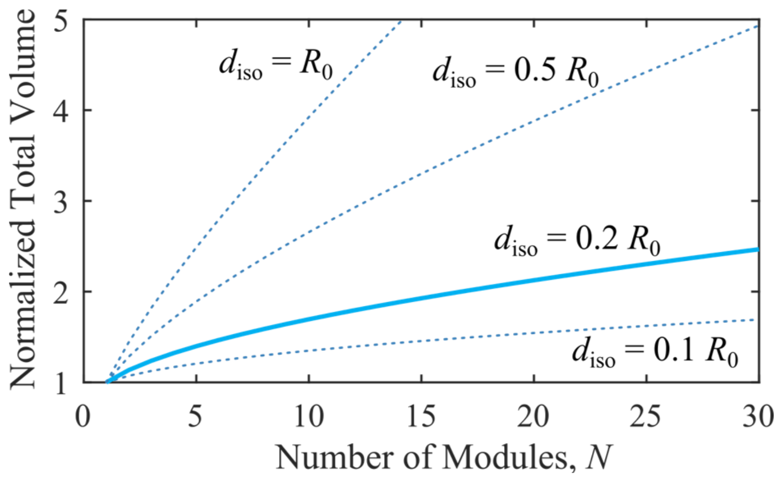
- Power Density → 0.09kW/dm³ (System) | ≈ 0.18 kW/dm³ (SST/Cells incl. Isol.)
- -40% Footprint / -70% Weight vs. LFT-Based Solution / ≈80% Lower Transf. Volume

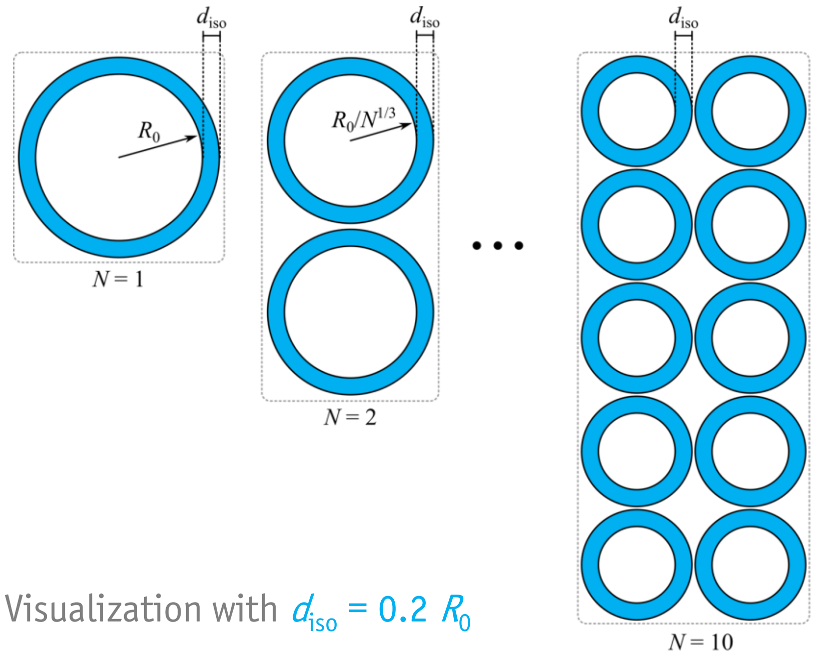
Modularization Penalty

- Highly (!) Simplified Consideration

— Power P Processed in Sphere with Radius R_0
— Modularization Assuming const. P/V [W/in^3]
— Const. Isolation / Overhead Distance d_{iso}

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





2-D Visualization with d_{iso} = 0.2 R_0

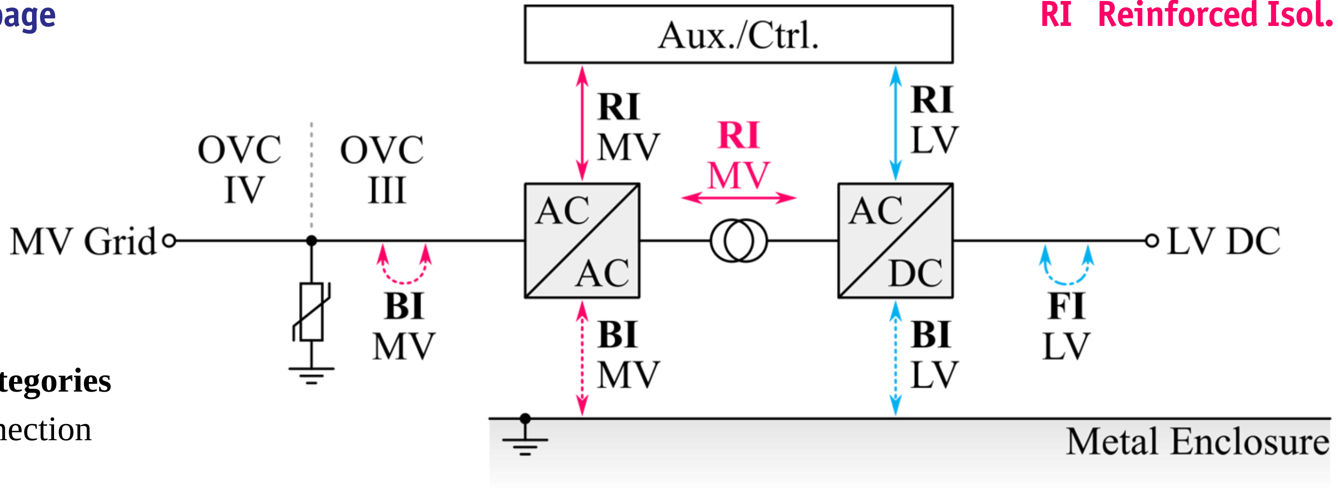
- High Number of Modules → Massive Reduction of Overall Power Density
- Add. Overhead → Input & Output Filters | Protection Equipment | Mech. Assembly | Cabinets etc.

Isolation Coordination

- Decisive Voltage Class (DVC) of MV Side Circuitry — DVC-D (> 1 kV AC or > 1.5 kV DC)
- "Safe Isolation" Towards Circuits w/ Other DVC / RI Required for Direct Contact
- BI Towards Touchable Grounded Parts Sufficient / BI or FI Between Circuits w/ same DVC

13.2 kV Grid
RI MV — 100 kV BIL (Lightning Imp.)
220 mm Clearance / Creepage

FI Functional Isol.
BI Basic Isol.
RI Reinforced Isol.



OVC	Overvoltage Categories
OVC IV	Direct Grid Connection
OVC III	Surge Protection

Schweizer Norm
Norme Suisse
Norma Svizzera

EN IEC 62477-2

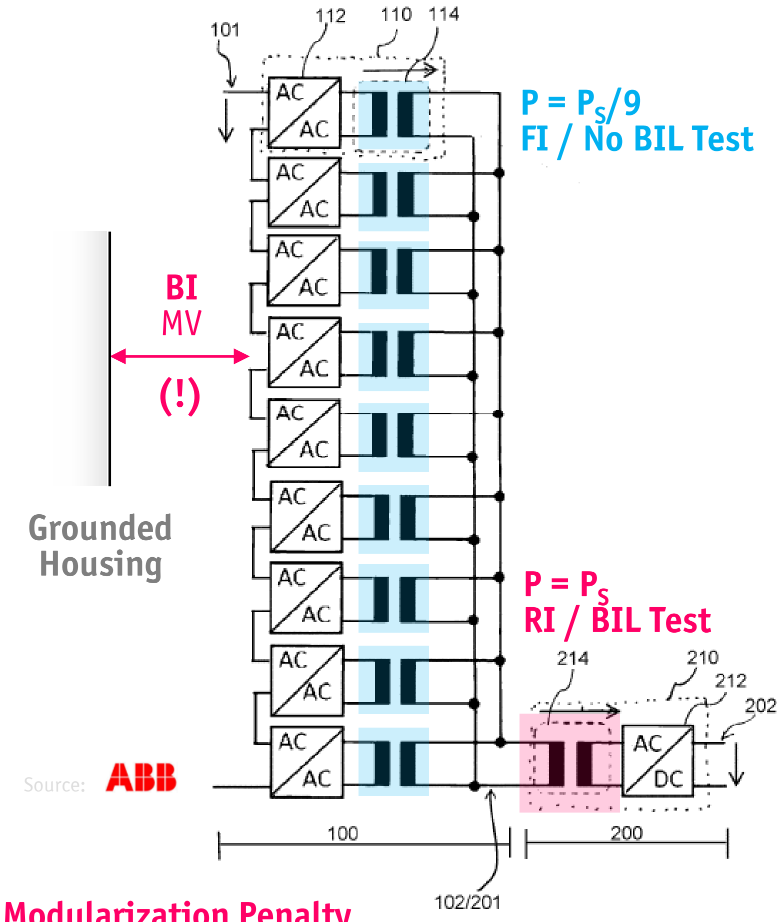
Safety requirements for power electronic converter systems and equipment - Part 2: Power electronic converters from 1 000 V AC or 1 500 V DC up to 36 kV AC or 54 kV DC

- Simplified Example Only
- Applicable Standards Must be Considered in Full Detail!

Remark System-Level Perspective

- 2-Stage Transformer Approach
- 1st Stage Isolation for Nominal Voltage (PD Tests)
- 2nd Stage Isolation for BIL

- More Compact Realiz. of 1st Stage MFTs, e.g., w/o Bushings
- BI Requirement for MV Electronics to Housing Remains

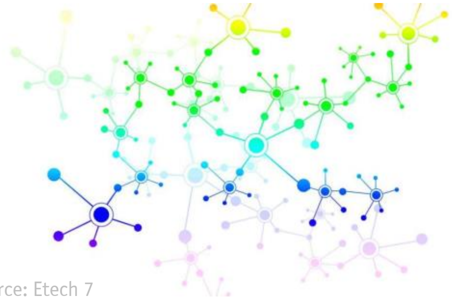


- Design DOF / Separate Optimization
- Especially Interesting for Lower Voltage / Power → Reduced Modularization Penalty

Power Electronic Systems Laboratory

Datacenter Power Supply

High-Power
3-Φ AC-DC SST
Systems



Source: Etech 7

ETH zürich

IEEE Power Electronics Society
SOUTHERN POWER ELECTRONICS CONFERENCE
SPEC

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

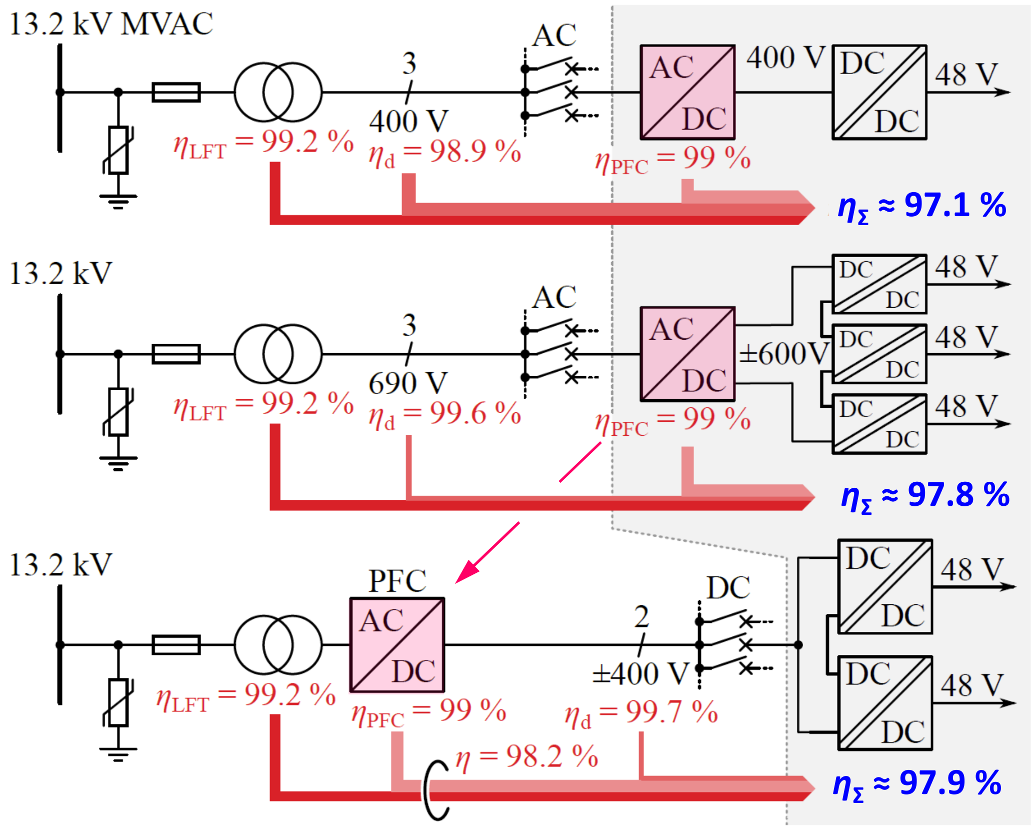
Since 2006
Running Costs >
Initial Costs

Source: Facebook

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

Comparison of AC and DC Power Distribution

- State-of-the-Art 400V AC
- 690V AC
- ± 400V DC

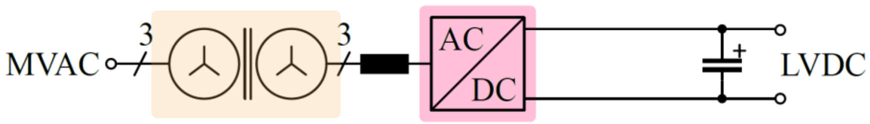


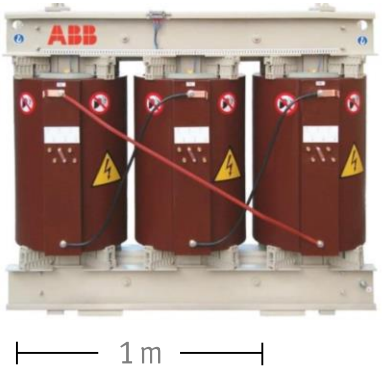
- η_Σ Similar to 690V AC Distribution

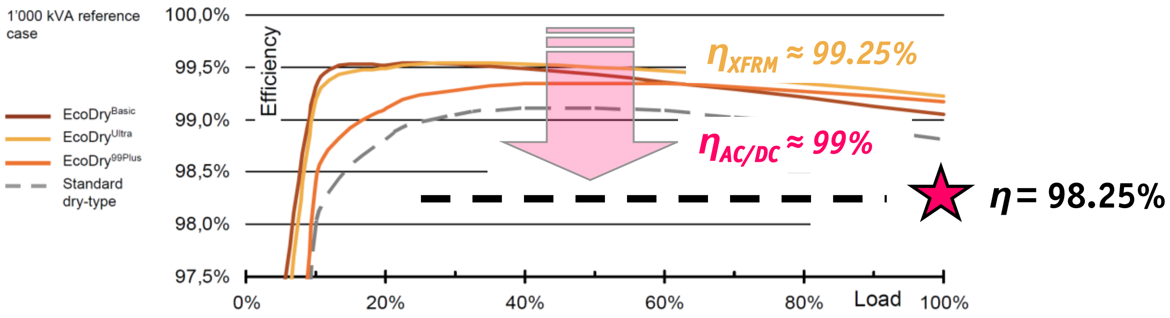
- Centralized PFC Rectifier Stage / DC Distribution — Minor Efficiency Gain (!) / Adv. for Integr. of RES & FCs

Dry-Type LFT Technology & SiC PFC Rectifier

- 400kVA EcoDry^{TM} High-Efficiency Transformer
- Vacuum Cast Coils → No Fire Hazard
- Amorphous Metal Core → Low No-Load Losses
- High Overvoltage / Overload Capability



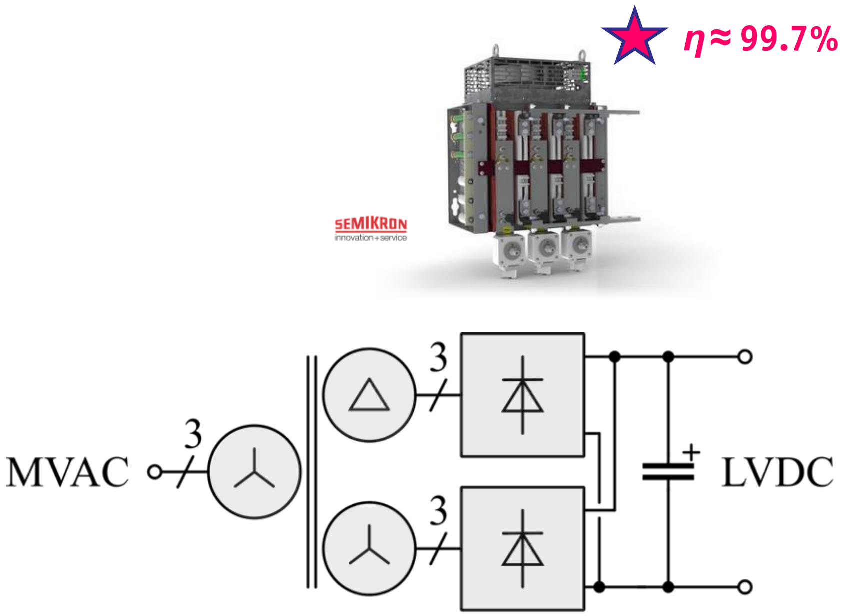


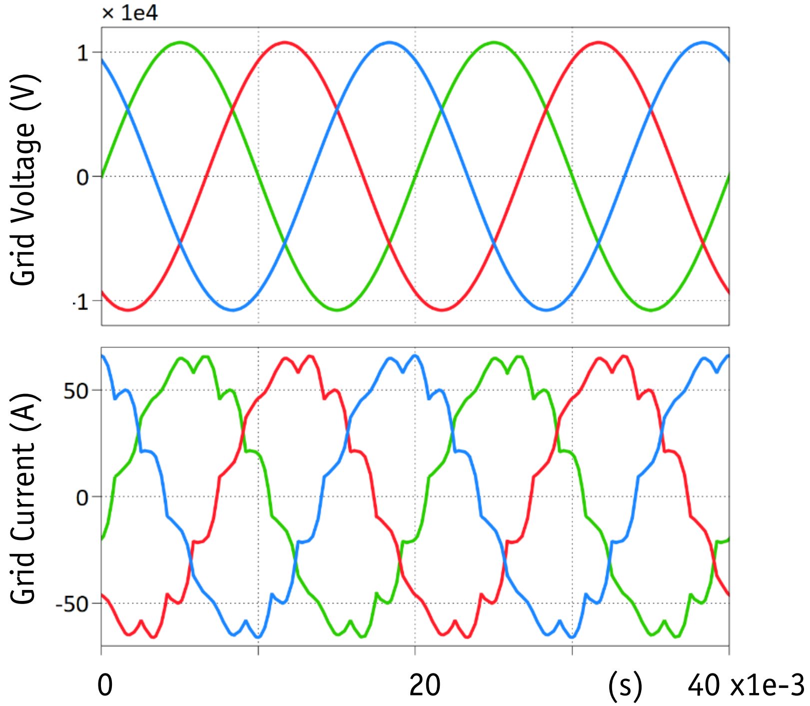


- Utilizing Proven LV SiC MOSFETs in AC/DC Stage → $\eta_{AC/DC}$ = 99+ % Efficiency
- Full Functionality — Reactive Power Gen. | Bidir. Power Flow | Scalability to Higher MVAC-Levels
- No DC Fault Current Limit (!)

3-Φ 12-Pulse / Multi-Pulse 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





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

Comparative Evaluation — Efficiency

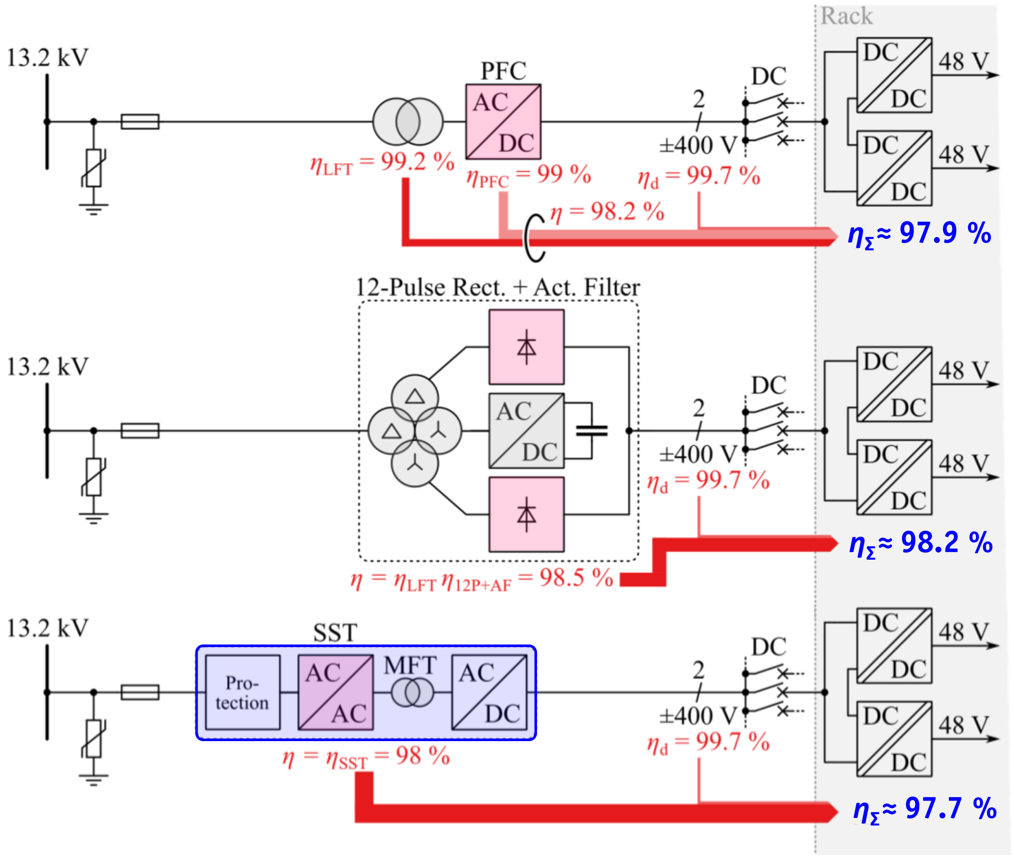
■ ± 400V DC Power Distribution — Fuel Cell Back-Up Power / PV Integration etc.

— Central PFC Rectifier on LV-Side

— No Switch-Mode PFC / Partial-Power Active Filter

— Central PFC on MV-Side

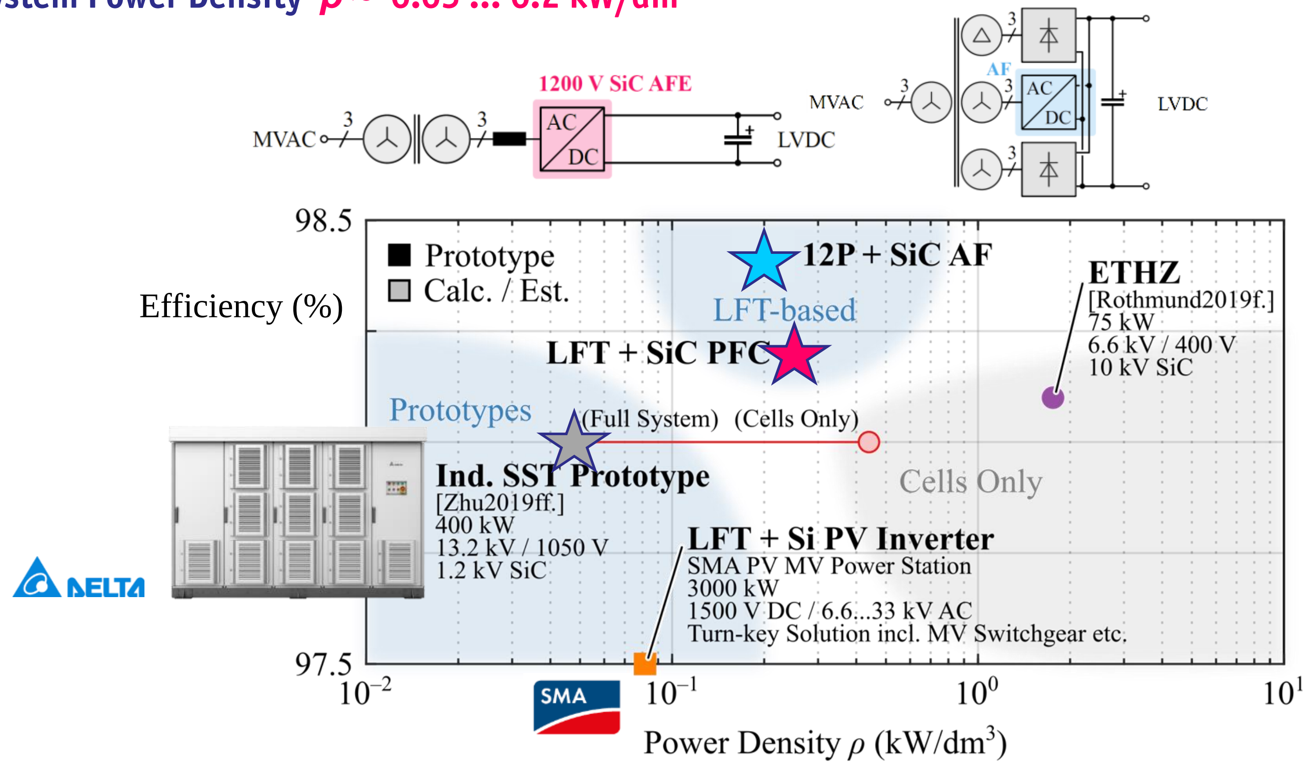
Future Solid-State Transformer Based MV Interface



● 12-Pulse + Active Filter → Highest Efficiency & Robustness @ Reduced Functionality

Comparative Evaluation — Efficiency & Power Density

- Industrial AC/DC SST → NO Efficiency / Volume Advantage Compared to LFT + SiC AC/DC Conv.
- Efficiency of Industrial Prototypes $\eta \approx 98\%$
- Full System Power Density $\rho \approx$ 0.05 … 0.2 kW/dm³

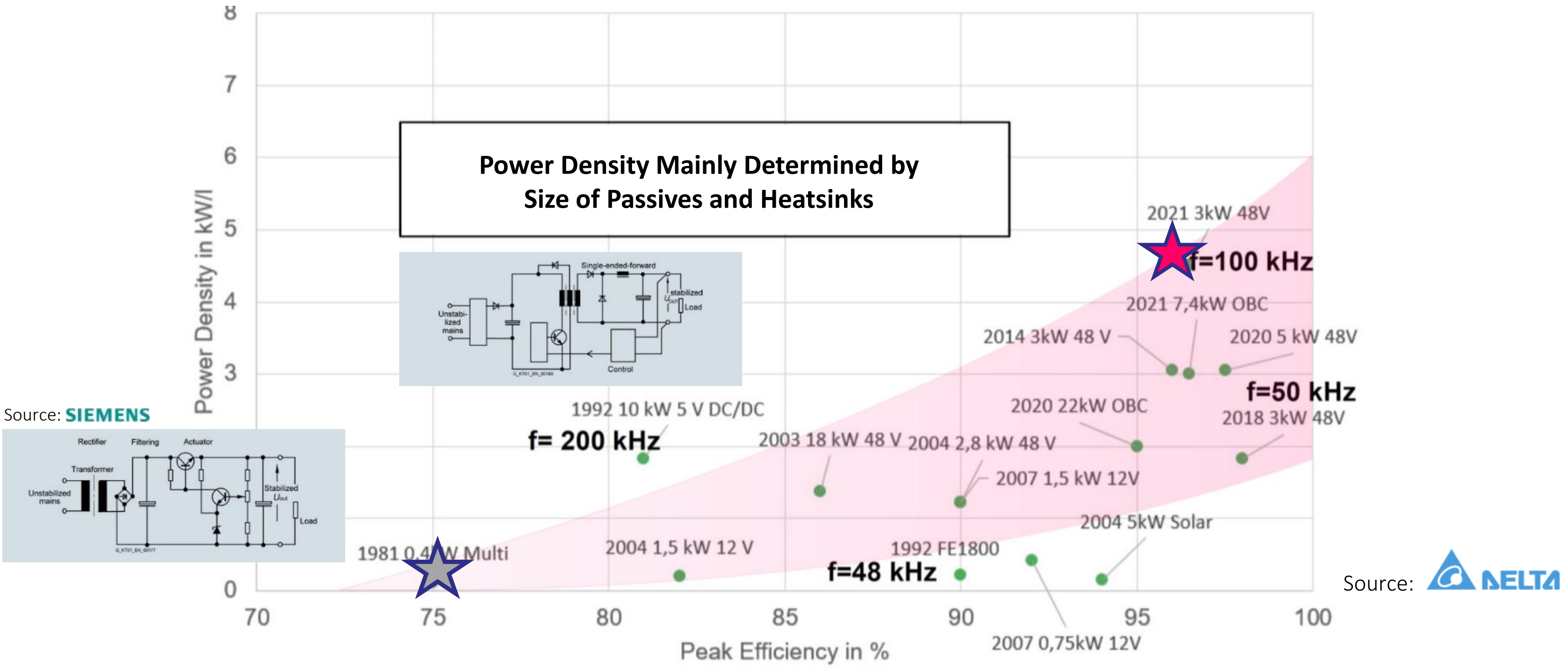


- Dry-Type LFT-Based Systems → Voltage Scalability & Robustness
- 12-Pulse Rect. & Act. Filter → Low Complexity @ Reduced Functionality

Conclusion

LV Low-Power SMPS Efficiency / Power Density 1981 — 2021

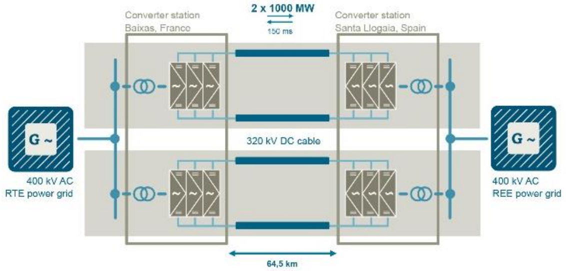
- 1981 — Large Volume Line-Frequ. Isolation/Voltage Step-Down | Diode Rectifier | Low Eff. Linear Stabilization
- 2021 — PFC Rectifier Front-End | High-Frequ. Isolated DC/DC Converter



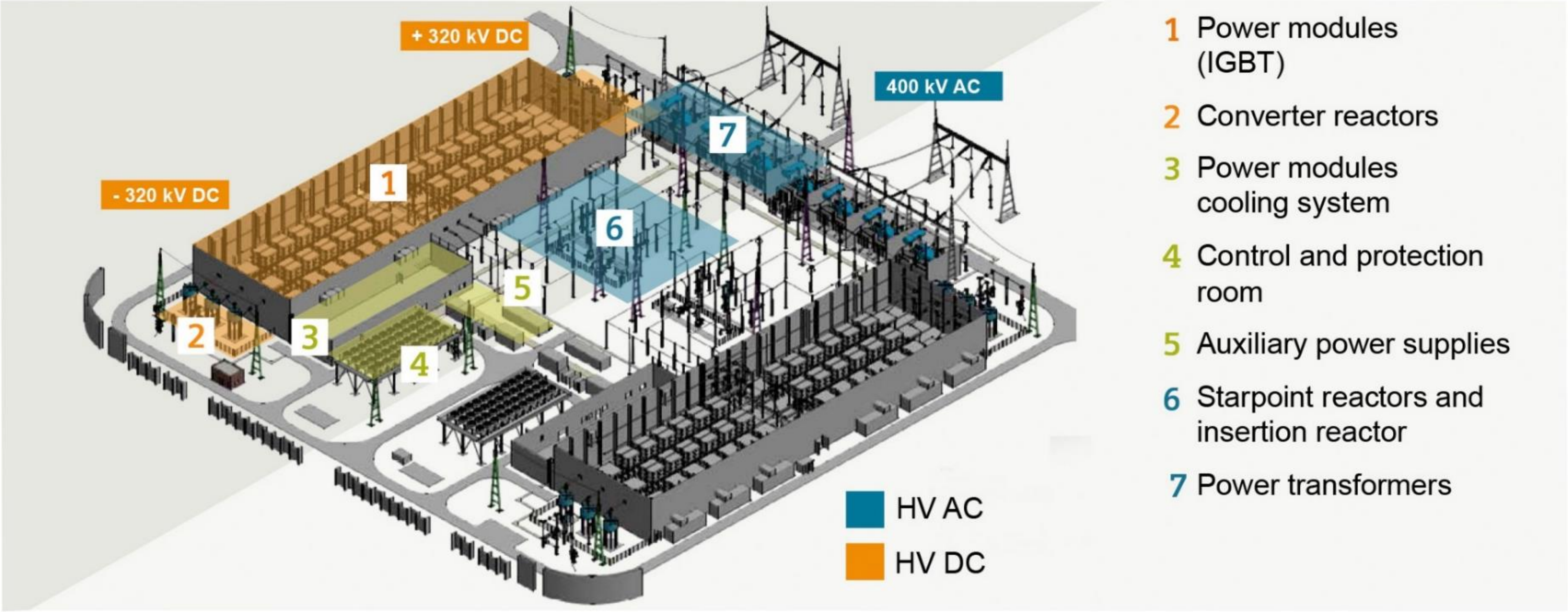
- Power Density AND Eff. Improvement | Line-Frequ. → High-Frequ. Conv. & Linear → Sw.-Mode Regulation

Remark HVDC Converter Station (1)

- 2 x 1 GW / ± 320 kV HVDC Link btw. France & Spain



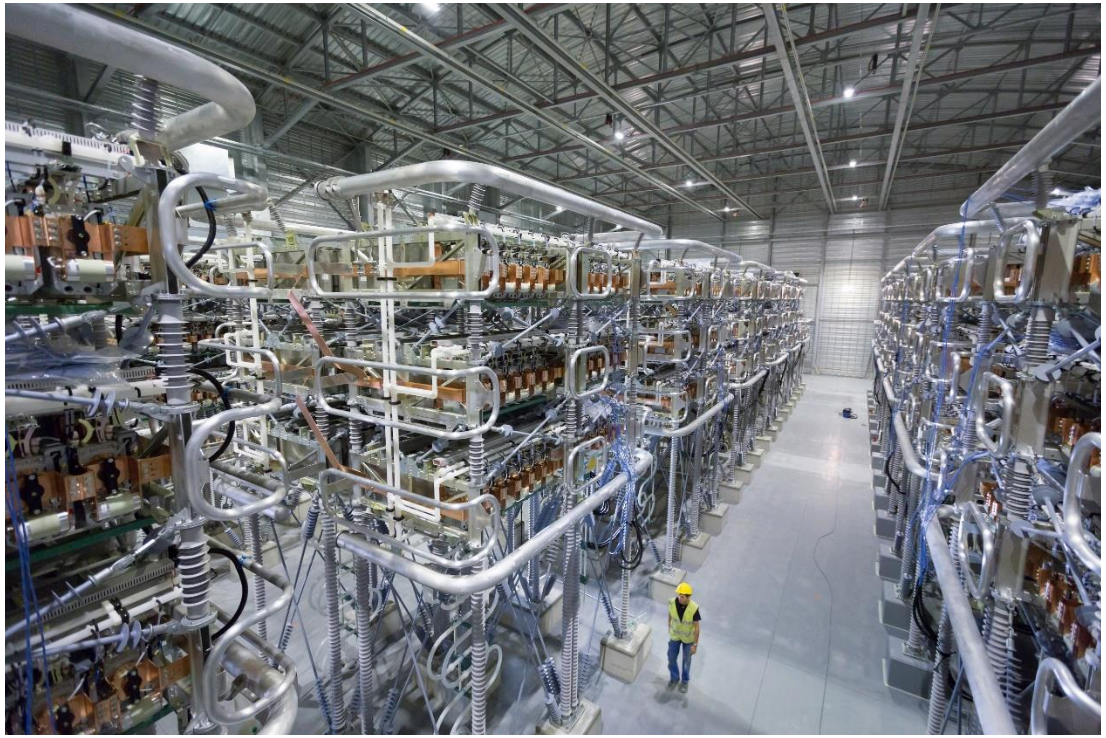
Source: SIEMENS



- Isolation Clearances (!) Largely Determine Space Requirement | Low LFT Volume Contribution (!)

Remark HVDC Converter Station (2)

- 2 x 1 GW / ± 320 kV HVDC Link btw. France & Spain

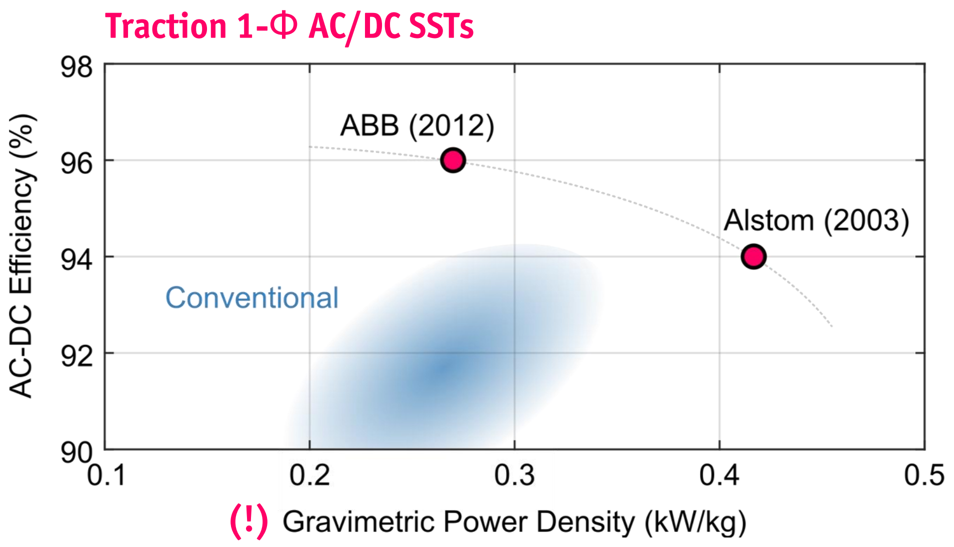


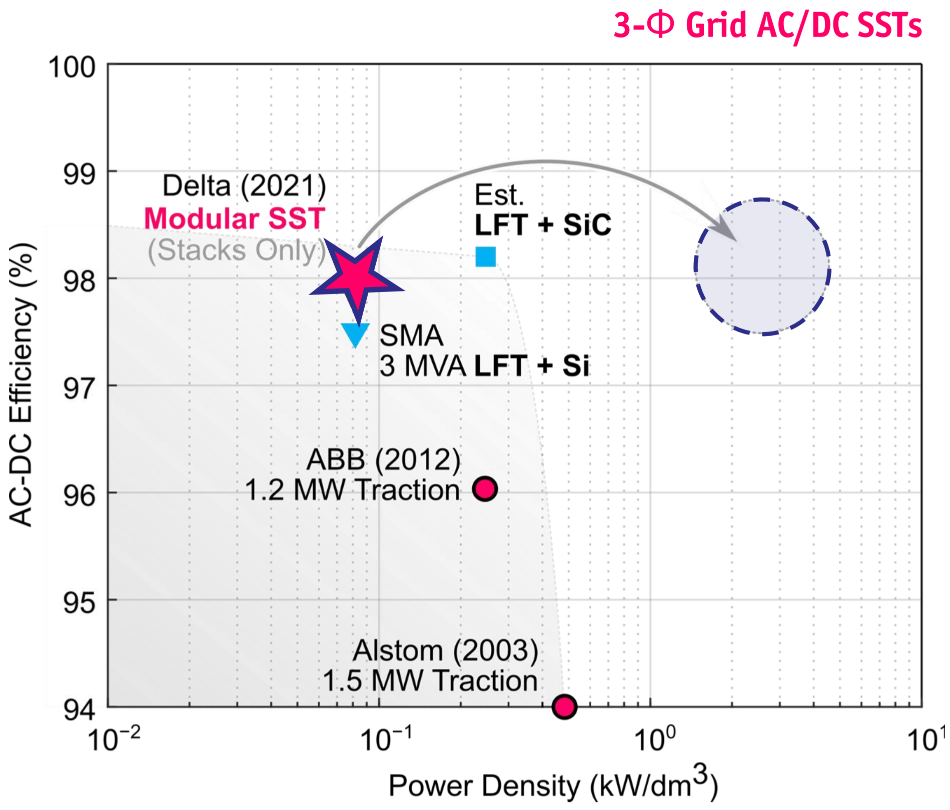
Source: SIEMENS

- Isolation Clearances (!) Largely Determine Space Requirement | Low LFT Volume Contribution (!)

Status Quo — Traction & Grid AC/DC SSTs

- Traction → Clear Improvements in Efficiency / Power Density > 10 Years Ago
- Grid → Recently Built 1st Full Industrial Demonstrators w/o Efficiency / Power Density Advantage



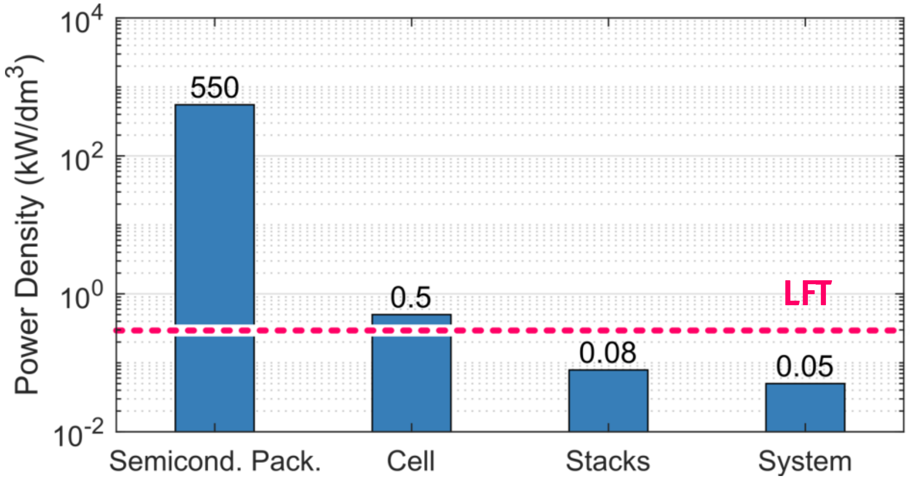


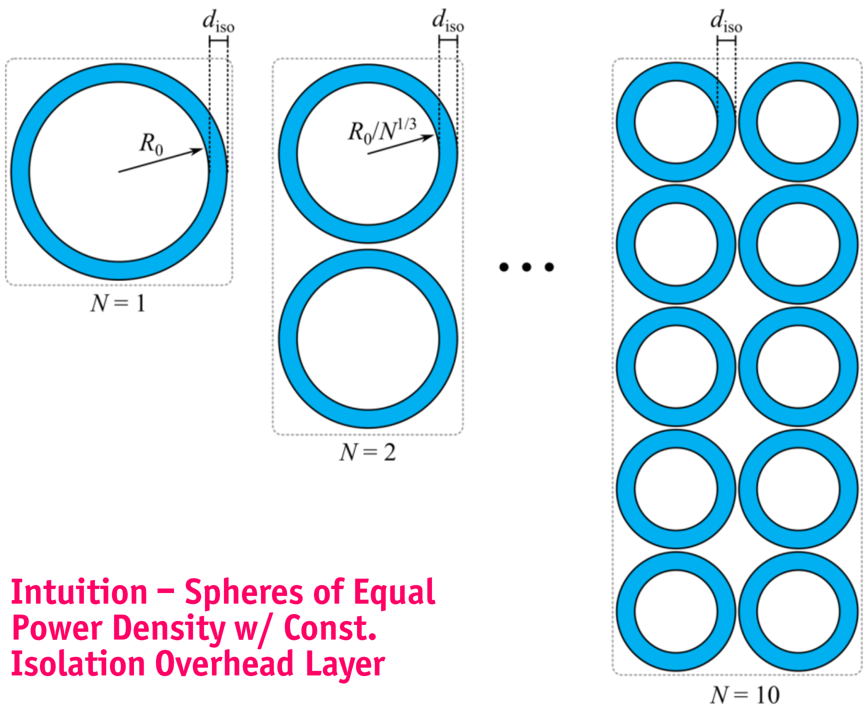
- Full-Scale Industry Demonstrators Complying with All Relevant Regulations & Standards

Grid AC/DC SST Challenges (1)

- Massive Reduction of Power Density from Cell to Full System → Modularization Penalty

Power Module → System



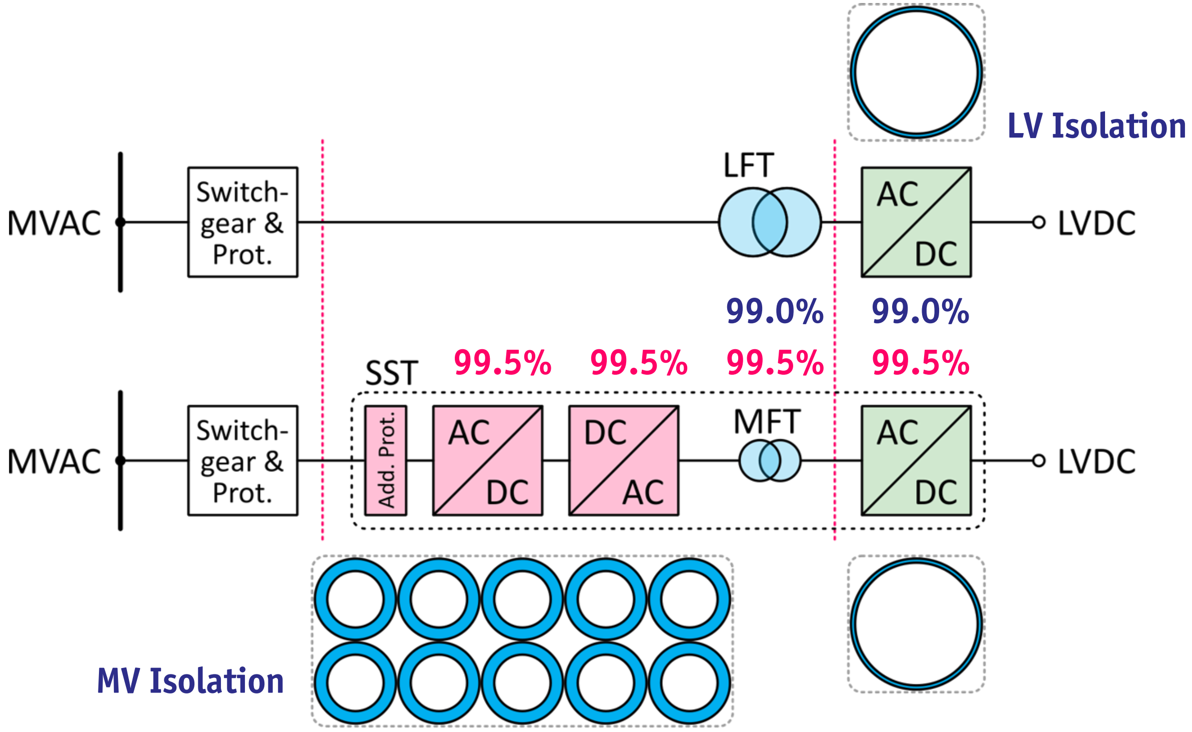


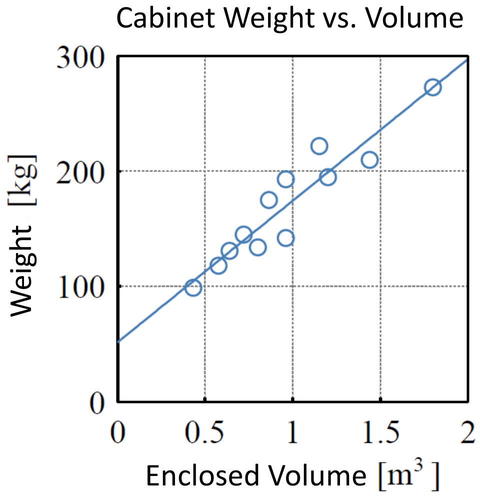
Intuition – Spheres of Equal Power Density w/ Const. Isolation Overhead Layer

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

Grid AC/DC SST Challenges (2)

- PFC Functionality on MV-Side → Modularization Penalty & Add. Protection
- Target Efficiency of 98% → 2% Loss Budget for 4 Conversion Stages vs. 2 Stages for LFT-Based Concept

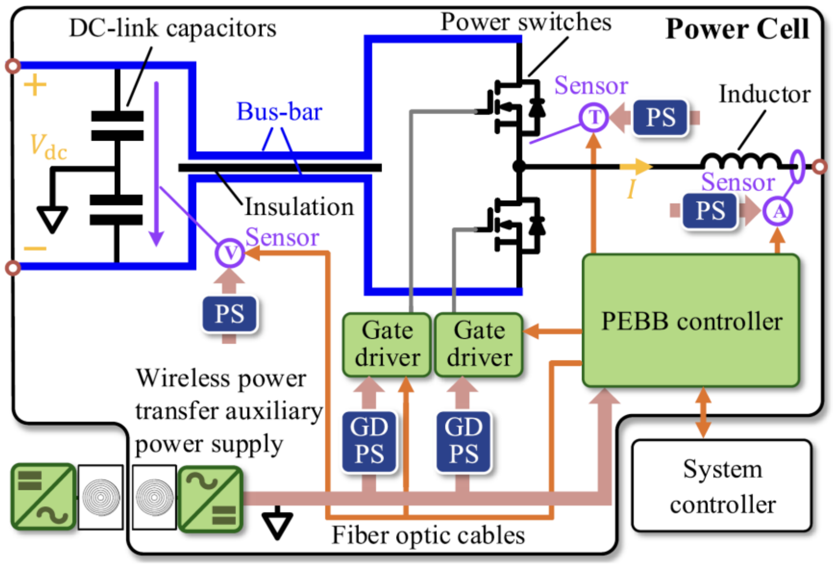


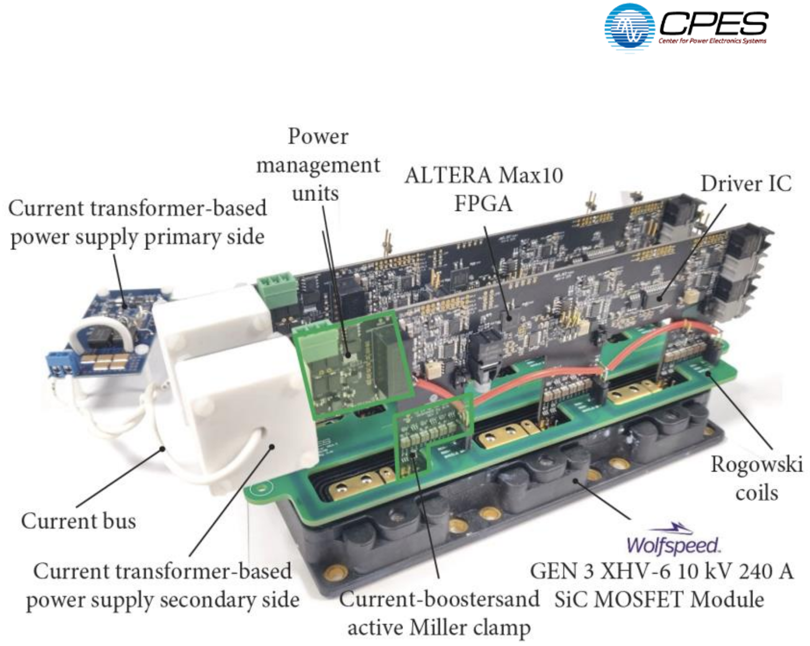


- Modularization Penalty — Larger Cabinets / Heavier Weight etc.
- MV-Side Power Electronics Overhead — Protection, Connectors, Access for Maintenance etc.

10kV SiC Power-Cell w/ Integrated Output Inductor

- 250kW Half-Bridge Power-Cell (HB-PEEB)
- 10kV/240A SiC MOSFET Modules (4200kW/dm^3) | 6kV DC-Link
- $\eta \approx 99.3\%$ @ f_{sw} = 10 kHz for D = 0.5 Power Circulation
- $\rho \approx 12$ kW/dm^3

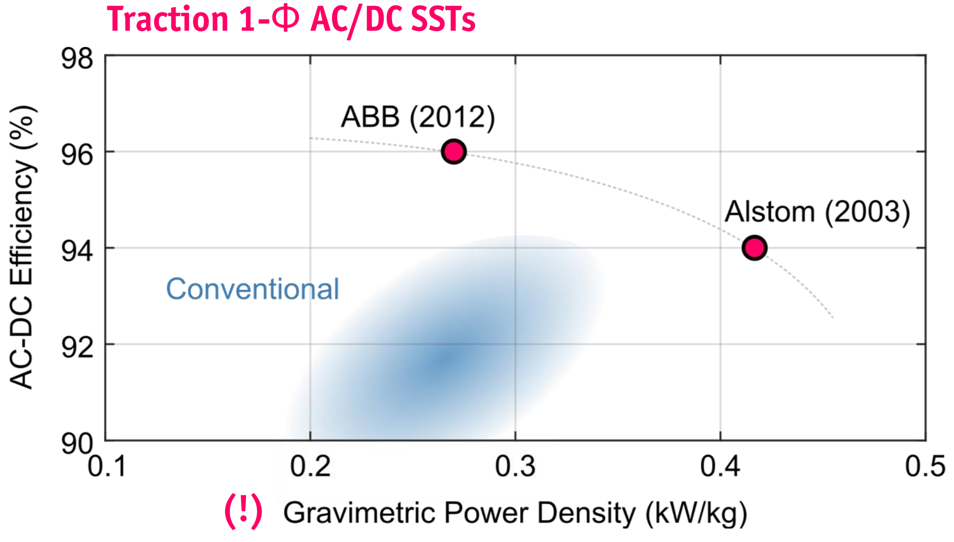


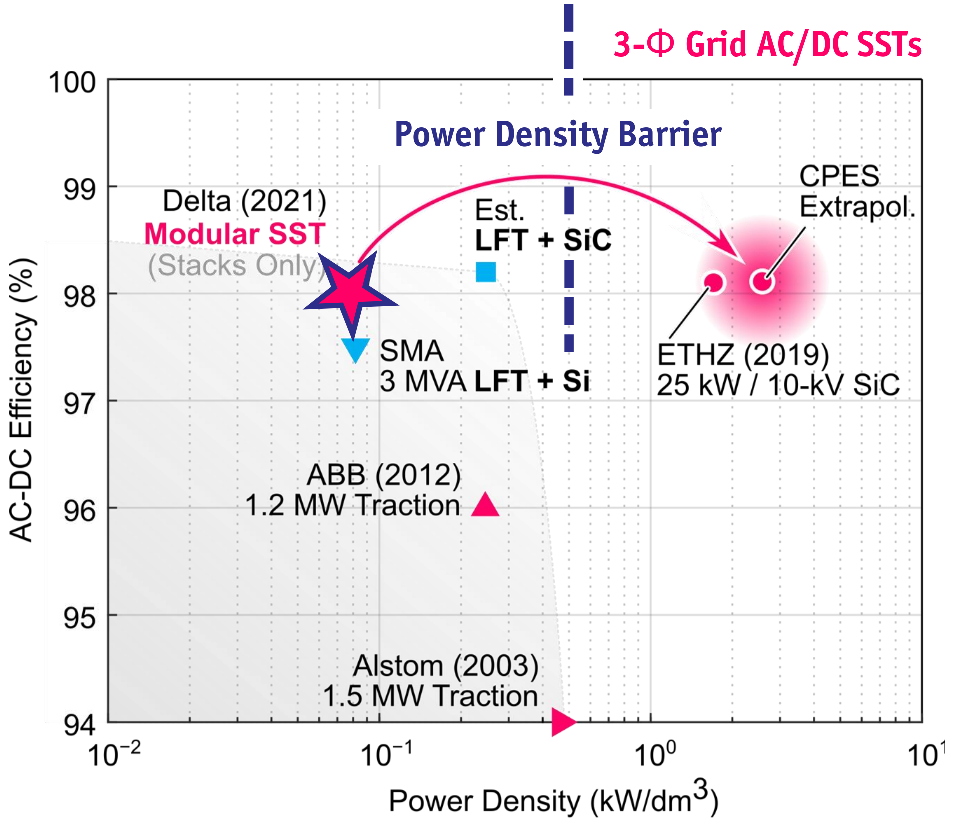


- Multi-Layer PCB DC-Bus | Gate Driver for 100V/ns Sw. Speed | PCB Rogowski Coil Sw. Curr. Sensing / Protection
- Local Controller & Voltage/Current Sensors | Wireless Aux. Supply | Curr. Loop GD supply | Temp. Sensing etc.

Next.-Gen. SSTs — Improvement Potential

- 10 kV SiC and/or MMC Topology Might Facilitate to Overcome the Power Density Barrier
- AC/DC Efficiencies >98% Remain Difficult to Attain
- Future Research Focus on NEW Aspects
  — SST DC-Side Fault Protection & Ride-Through
  — Grid-Side Overvoltage Protection
  — $$$ Learning Curve
  — Etc.





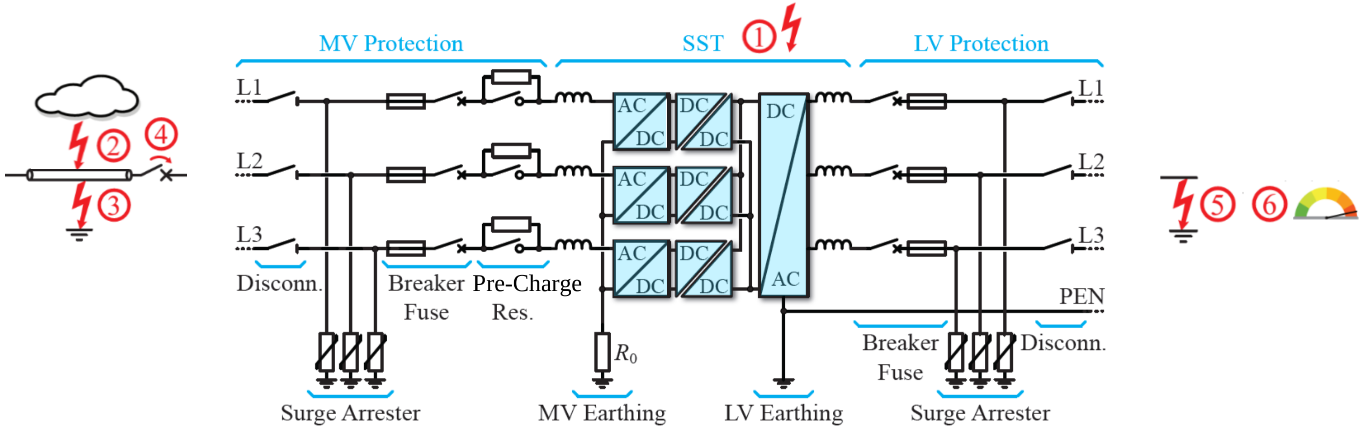
- Full-Scale Demonstrators Complying with All Relevant Regulations Mandatory for Realistic Assessment

Grid AC/DC SST Challenges (3)

- SST Fault Behavior & Stresses (Line-to-Line, Line-to-Gnd, Short Circuits, etc.)
- Fault Handling Schemes / Fault Ride-Through / Grid Code Compliance

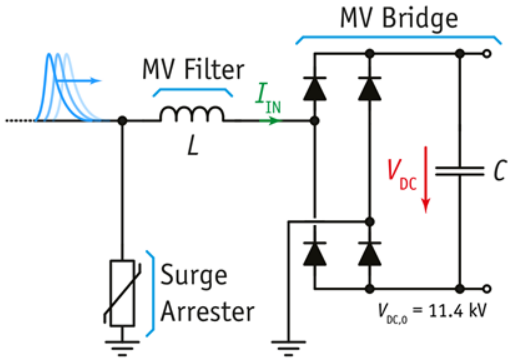
- **SST Protection Scheme**

(1) Internal Fault
(2) Lightning Surge
(3) Switching Transient
(4) MV Short Circuit
(5) LV Short Circuit
(6) Non-Ideal Load



- **Overvoltage Protection (Lightning Strike)**

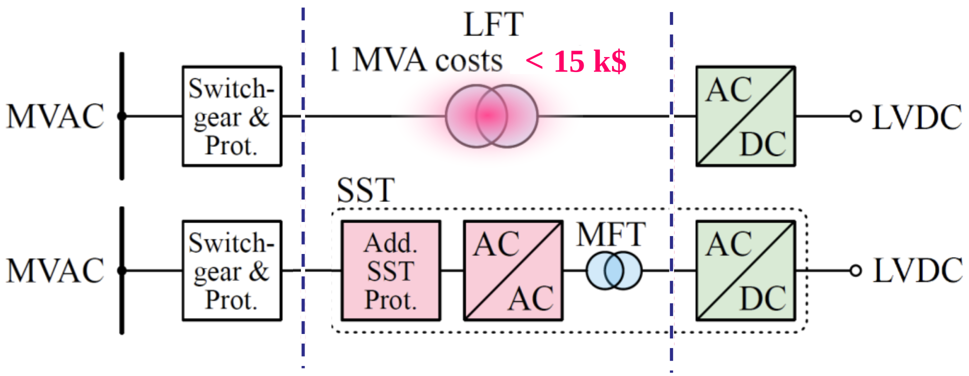
High Arrester Clamping Voltage
AC Inductor > 8% for Current Limitation
Sufficient DC-Link Capacitance
Sufficient Semicond. Blocking Capability
Grounding – Lower Stress if Unearthed

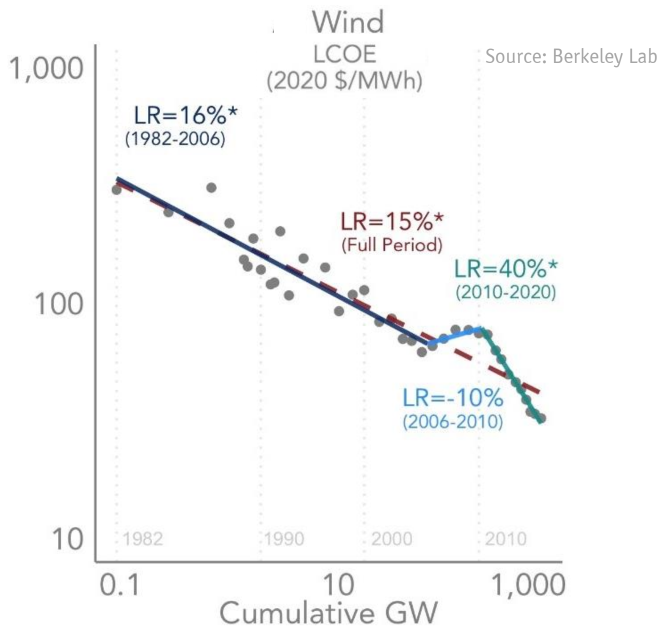


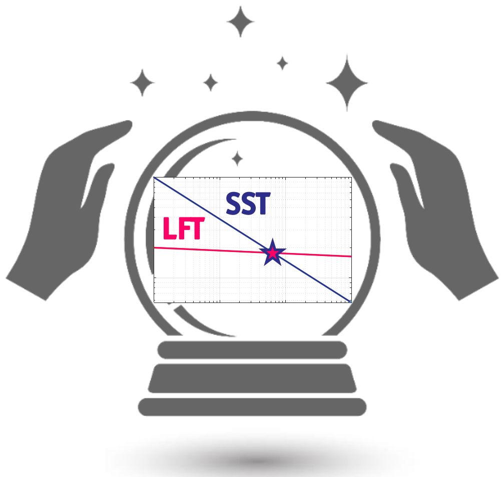
- Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed / Safety / Reliability

Outlook — SST Technology Learning Curve

- Learning Rate → Cost Reduction for Each Doubling of the Cumulative Production / Accumulated Experience
- Used for Prediction of Future Costs of a Technology (e.g. PV or Wind "Grid Parity") → Long Term Strategies





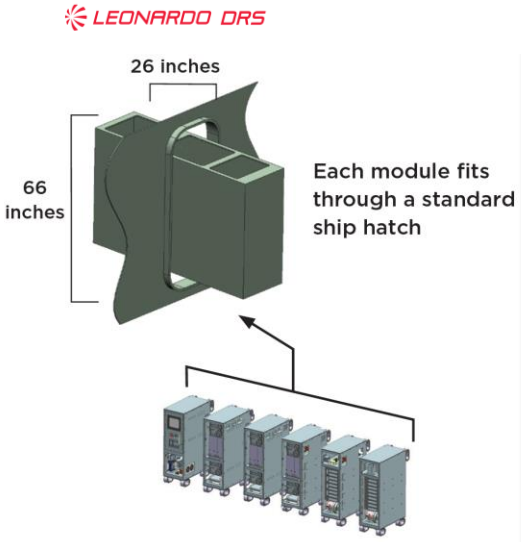


- Typ. Empirical Learning Rates of 15...25% → Dramatic Cost Reduction Over Longer Timespan
- 15 k$ Budget for 1MVA SST MV Power Electronics & MFT ≈ 10 k$/1MVA Power Converter → 10 $/kW (!)

Remark Future Combat Ships

- MV Cellular DC Power Distribution — 6kV DC/DC SST for Size & Weight Reduction

Source: General Dynamics



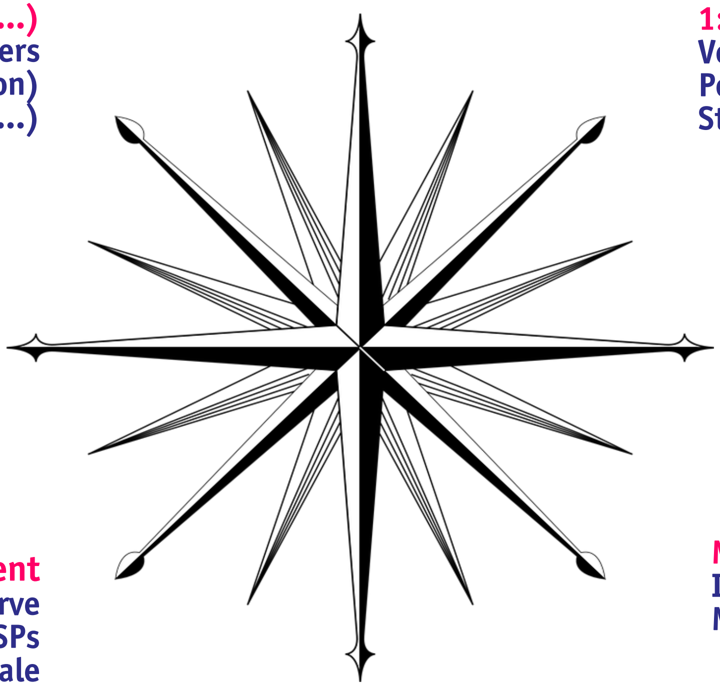
- "Energy Magazine" as Extension of Electric Power System / Individual Load Power Conditioning
- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements

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

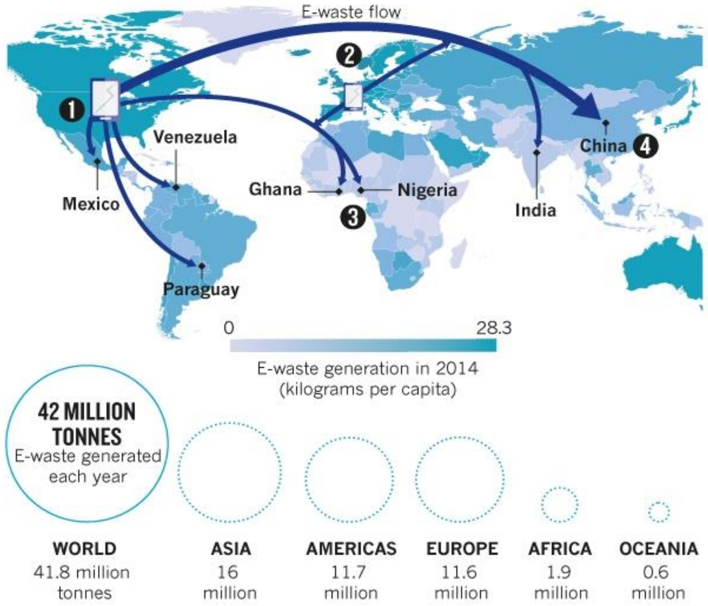
Materials
Insulation Materials
Mixed-Frequ. Insulation Stress Testing

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

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

Remark Increasing E-Waste Problem

- 53´000´000 Tons of Electronic Waste Produced Worldwide in 2019 → 74´000´000 Tons in 2030
- Increasingly Complex Constructions → No Repair or Recycling



Source: nature

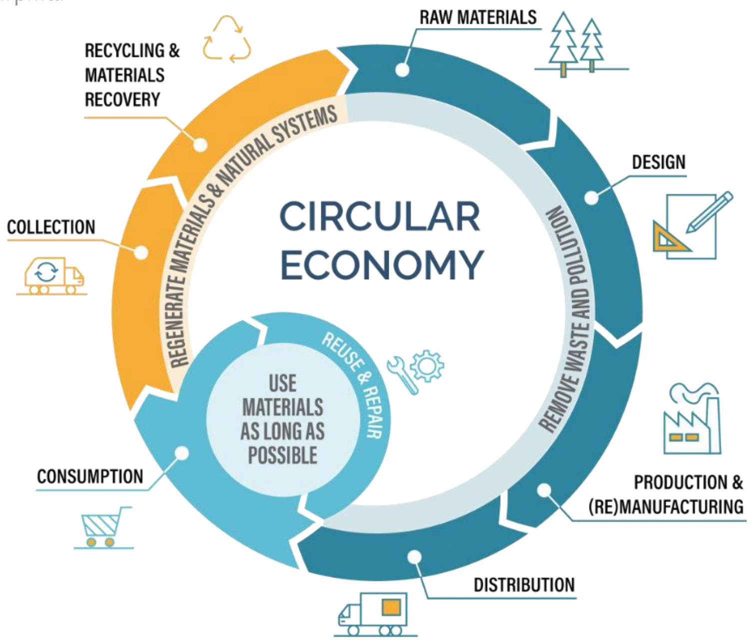
Source: Green IT Solution

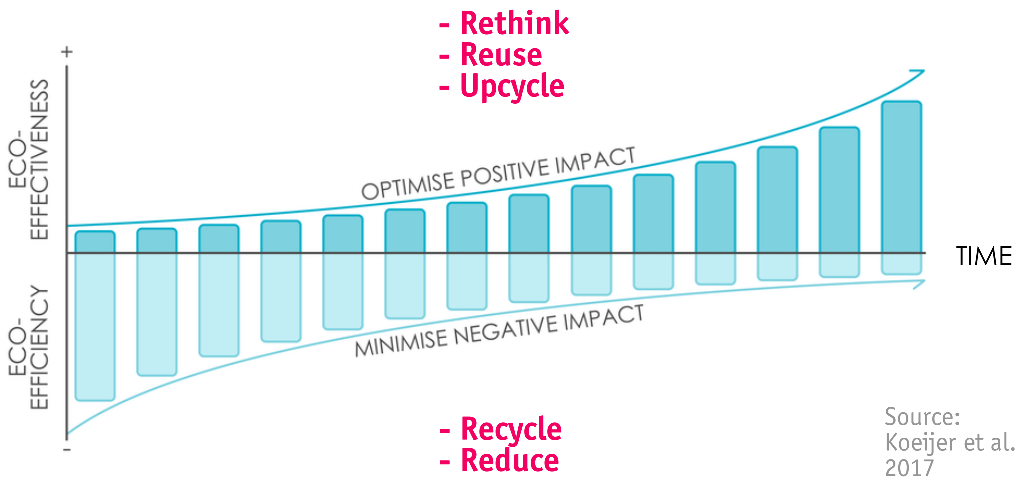
- Growing Global E-Waste Streams → Upcoming Regulations

Remark Cradle-to-Cradle

- "Linear" Economy / Take-Make-Dispose → "Circular" Economy / Perpetual Flow of Resources
- Resources Returned into the Product Cycle at the End of Use

Source: https://circularphiladelphia.org



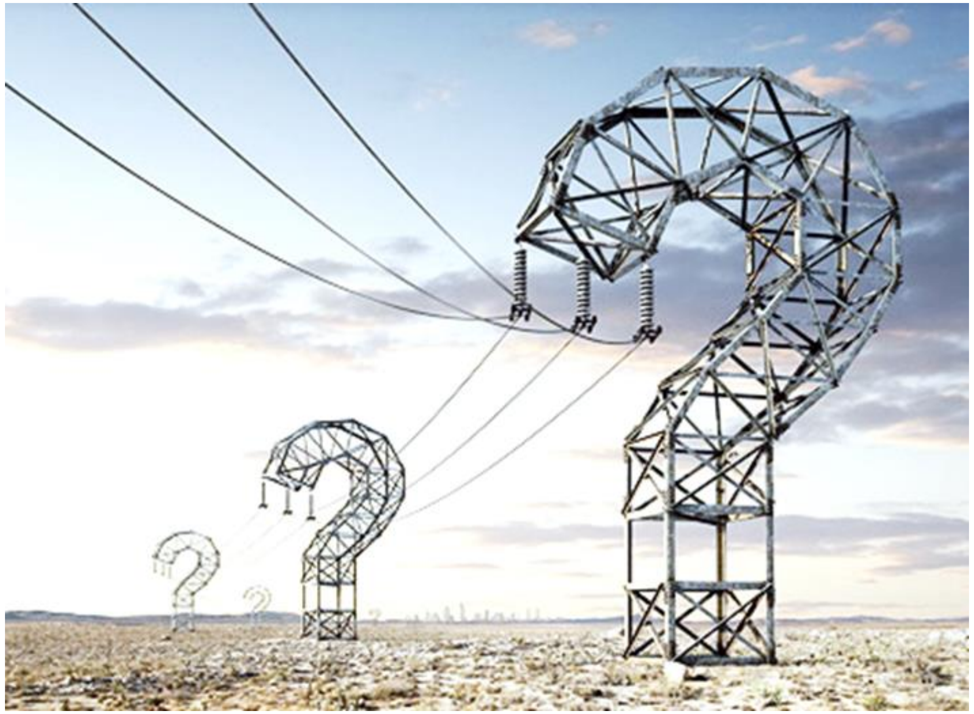


Source: Koeijer et al. 2017

- Decoupling of Economic Growth & Use of Resources (!)

Thank you!

Source: P. Aylward



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