Research Challenges and Future Perspectives of Solid-State Transformers

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Outline

- Smart Grid
- SST Functionalities
- 10 Key SST Realization/Application Challenges
- Future Perspectives
- Conclusions

▶ Smart Grid Concept

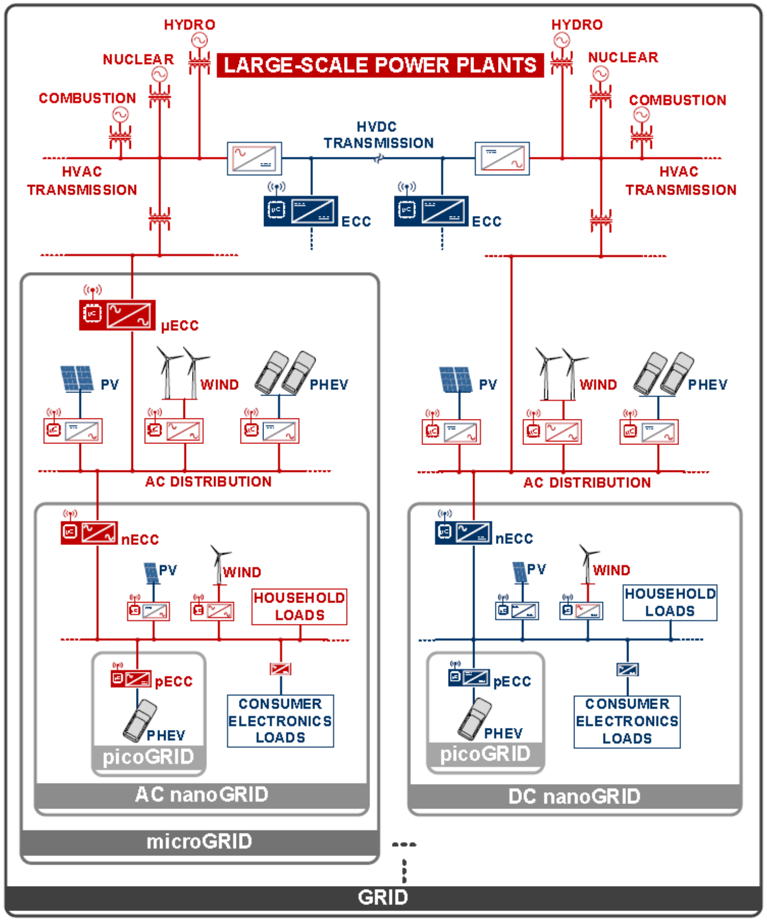
- Borojevic (2010)

● Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids

- Distr. Syst. of Contr. Conv. Interfaces
- Source / Load / Power Distrib. Conv.
- Picogrid-Nanogid-Microgrid-Grid Structure
- Subgrid Seen as Single Electr. Load/Source
- ECCs provide Dyn. Decoupling
- Subgrid Dispatchable by Grid Utility Operator
- Integr. of Ren. Energy Sources

● ECC = Energy Control Center

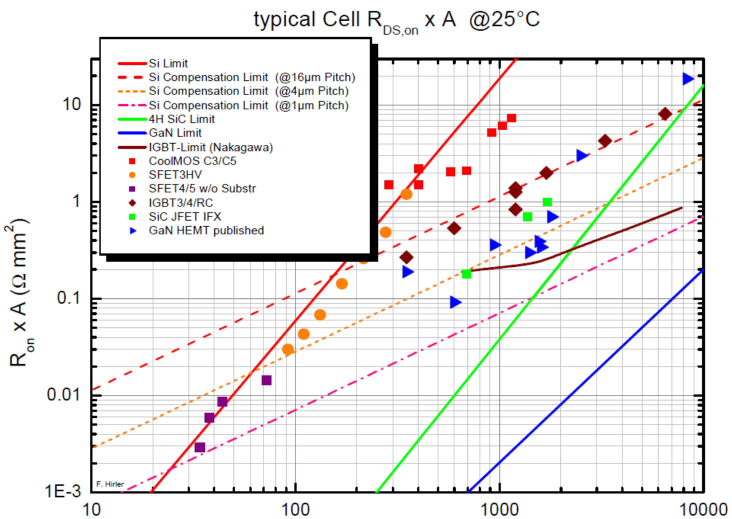
- Energy Routers
- Continuous Bidir. Power Flow Control
- Enable Hierarchical Distr. Grid Control
- Load / Source / Data Aggregation
- Up- and Downstream Communic.
- Intentional / Unintentional Islanding
  for Up- or Downstream Protection
- etc.

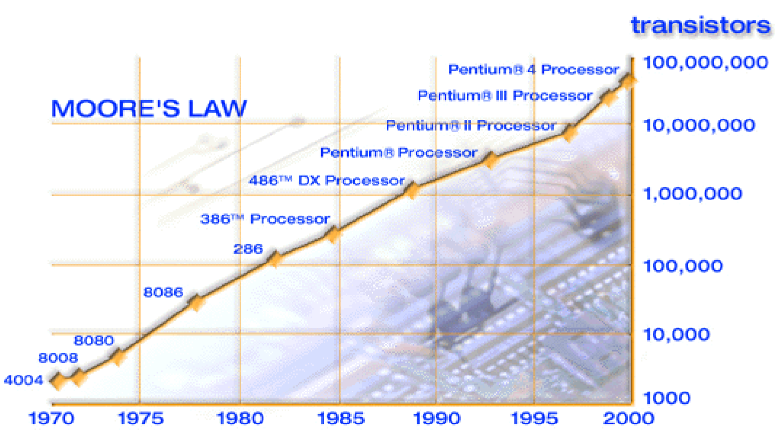


▶ Smart Grid Enablers / Drivers (1)

... besides CO_2 Reduction / Ren. Energy Integration etc.

- WBG Semiconductor Technology → Higher Efficiency, Lower Complexity
- Microelectronics → More Computing Power





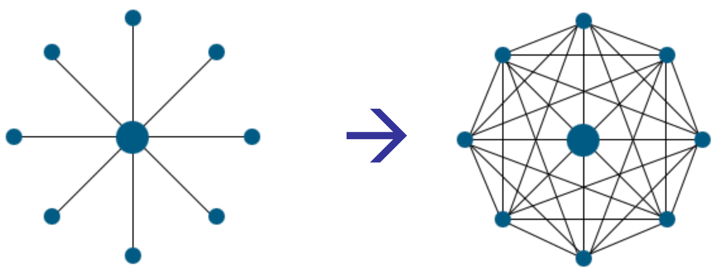
→ + Advanced Packaging (!)

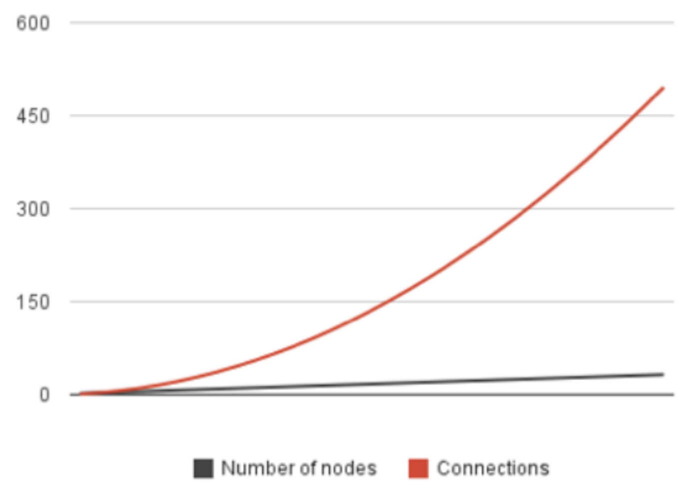
→ Moore's Law

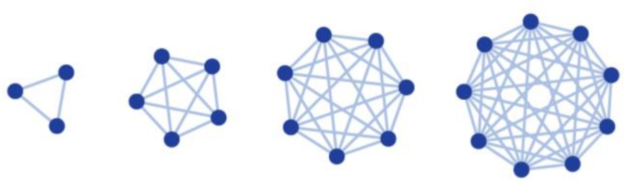
Smart Grid Enablers / Drivers (2)

Metcalfe's Law

– Moving form Hub-Based Concept to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))



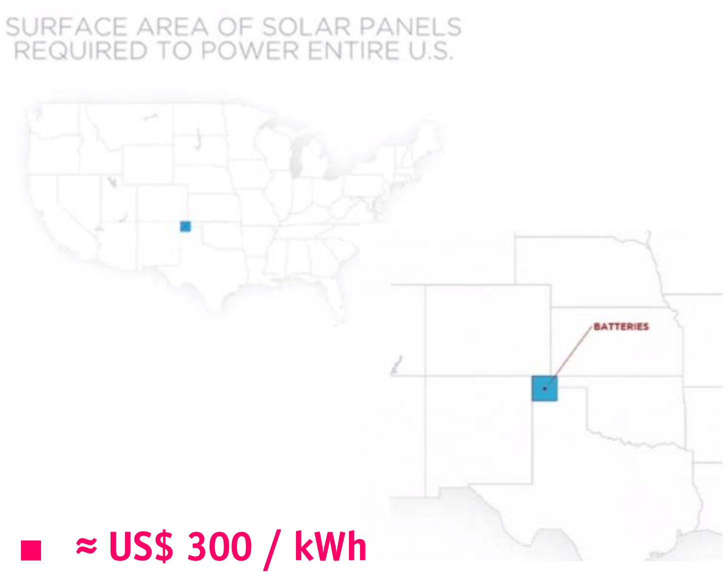


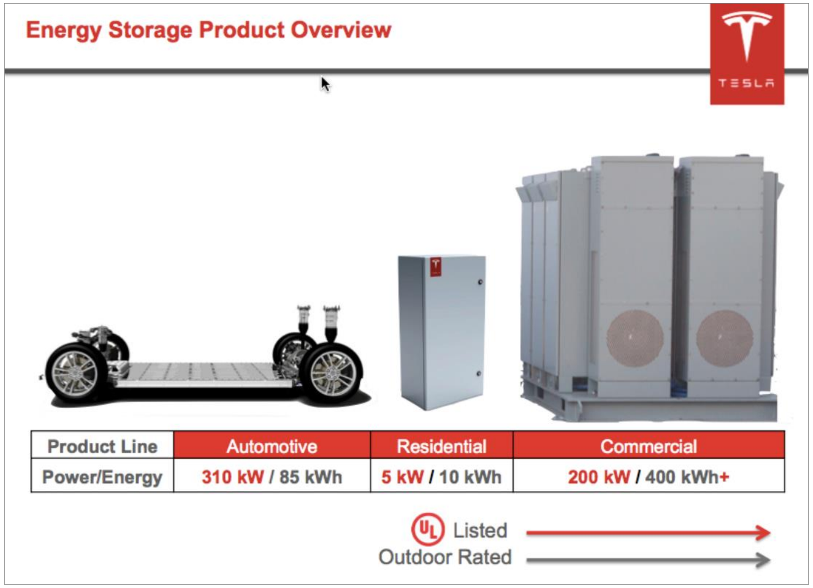


▶ Smart Grid Enablers / Drivers (3)

- Battery Technology

- TESLA Announces „The Beginning of the End For Fossil Fuels“
- Plans to Invest US$ 4-5 Billion in US Gigafactory until 2020
- Scalable up to Several MWh´s





Product Line	Automotive	Residential	Commercial
Power/Energy	310 kW / 85 kWh	5 kW / 10 kWh	200 kW / 400 kWh+

- ≈ US$ 300 / kWh

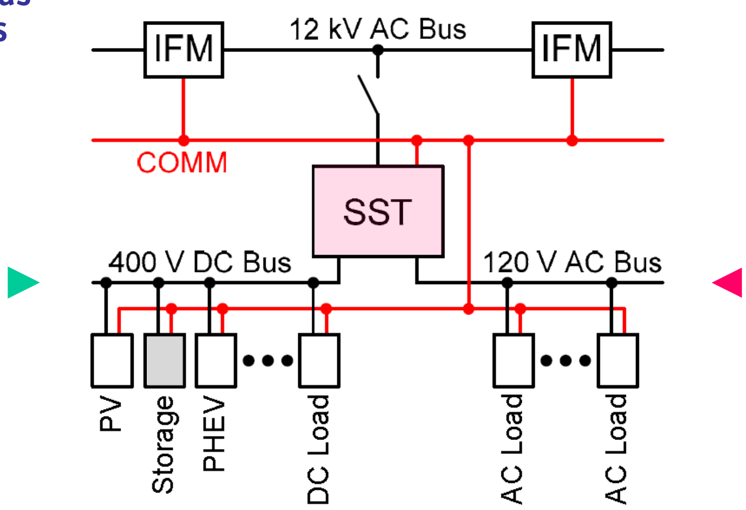
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

- **Solid State Transformer (SST)** as Enabling Technology for the **"Energy Internet"**

- Full Control of Active/Reactive/Harmonic Power Flow
- Integr. of Distributed Energy Resources
- Integr. of Distributed E-Storage + Intellig. Loads
- Protects Power System From Load Disturbances
- Protects Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.
- etc.

IFM = Intellig. Fault Management



- **Medium Frequency Isolation** → Low Weight / Volume
- **Bidirectional Flow of Power & Information** / High Bandw. Comm. → Distrib. / Local Auton. Cntrl

▶ Terminology (1)

United States Patent [19] [11] **4,347,474**
Brooks et al. [45] **Aug. 31, 1982**

[54] **SOLID STATE REGULATED POWER TRANSFORMER WITH WAVEFORM CONDITIONING CAPABILITY**

[75] Inventors: **James L. Brooks**, Oxnard; **Roger I. Staab**, Camarillo, both of Calif.; **James C. Bowers; Harry A. Nienhaus**, both of Tampa, Fla.

[73] Assignee: **The United States of America as represented by the Secretary of the Navy, Washington, D.C.**

[21] Appl. No.: **188,419**

[22] Filed: **Sep. 18 1980** ← **1980 !**

OTHER PUBLICATIONS

Bowers et al, "A Solid State Transformer", PESC '80

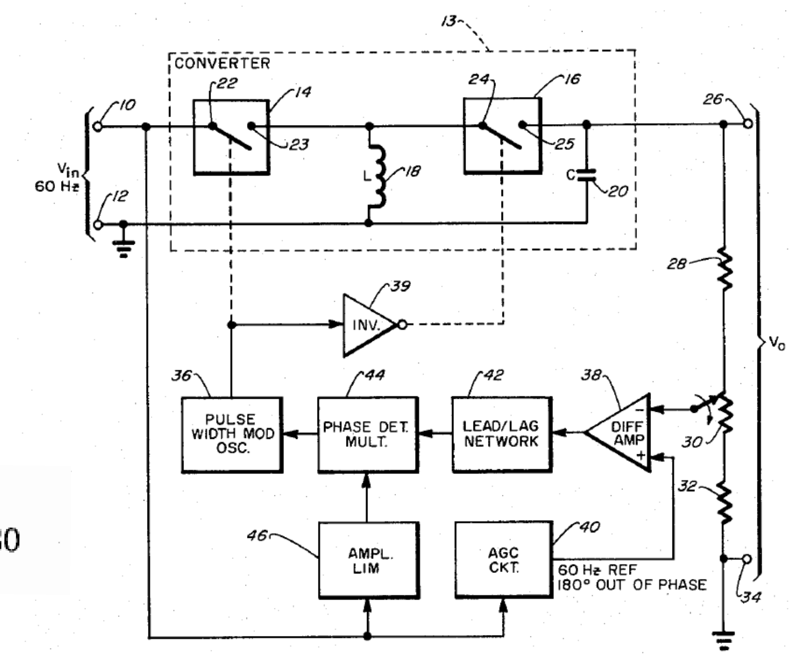
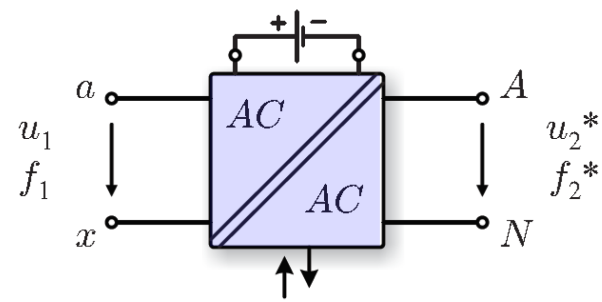


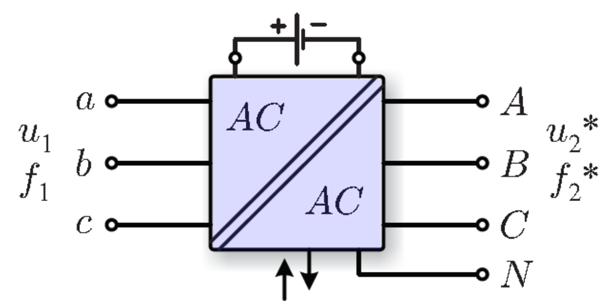
Fig. 1.

- No Isolation (!)
- "Transformer" with Dyn. Adjustable Turns Ratio

▶ Terminology (2)



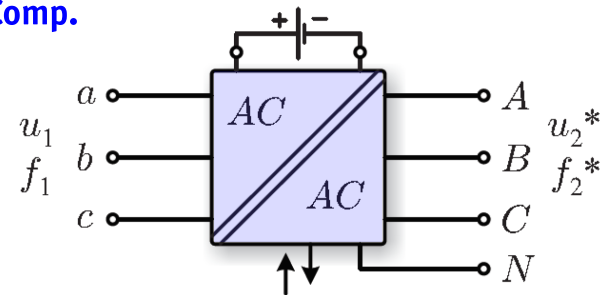
McMurray	Electronic Transformer (1968)
Brooks	Solid-State Transformer (SST, 1980)
EPRI	Intelligent Universal Transformer (IUT™)
ABB	Power Electronics Transformer (PET)
Borojevic	Energy Control Center (ECC)
Wang	Energy Router
etc.	



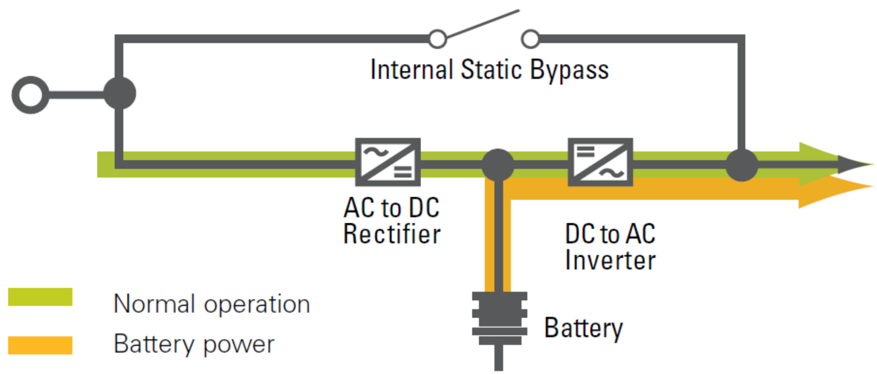
▶ SST vs. Uninterruptible Power Supply

■ **Same Basic Functionalities of SST and Double-Conversion UPS**

- **High Quality of Load Power Supply**
- **Possible Ext. to Input Side Active Filtering**
- **Possible Ext. to Input Reactive Power Comp.**



Source: EATON Corp.



■ **Input Side MV Voltage Connection of SST as Main Difference / Challenge**

■ **Numerous Topological Options**

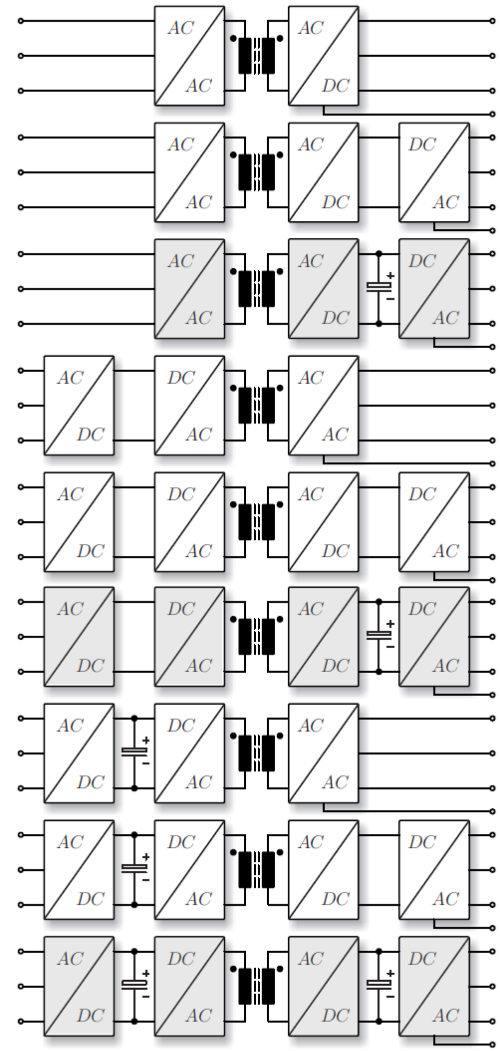
Challenge #1/10

Creation of MV→LV SST Topologies

▶ Basic SST Structures (1)

- 1^{st} Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion

* DC-Link Based Topologies
* Direct/Indirect Matrix Converters
* Hybrid Combinations



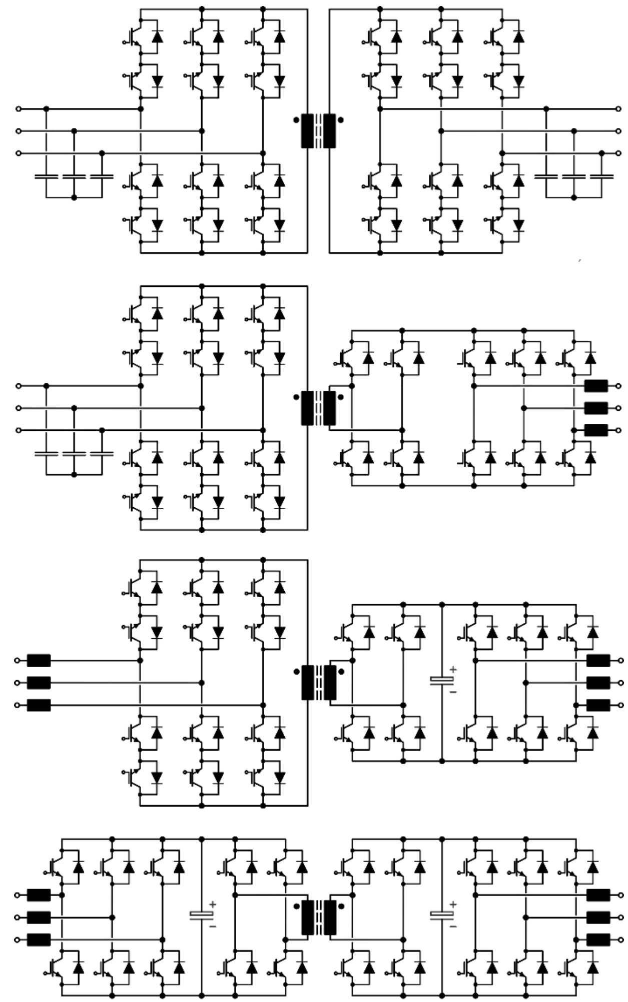
- 1-Stage Matrix-Type Topologies
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 2-Stage with MV DC Link (Connection to HVDC System)
- 3-Stage Power Conversion with MV and LV DC Link

- Only Concepts Featuring MF Isolation Considered

▶ Basic SST Structures (1)

■ 1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion

* DC-Link Based Topologies
* Direct/Indirect Matrix Converters
* Hybrid Combinations

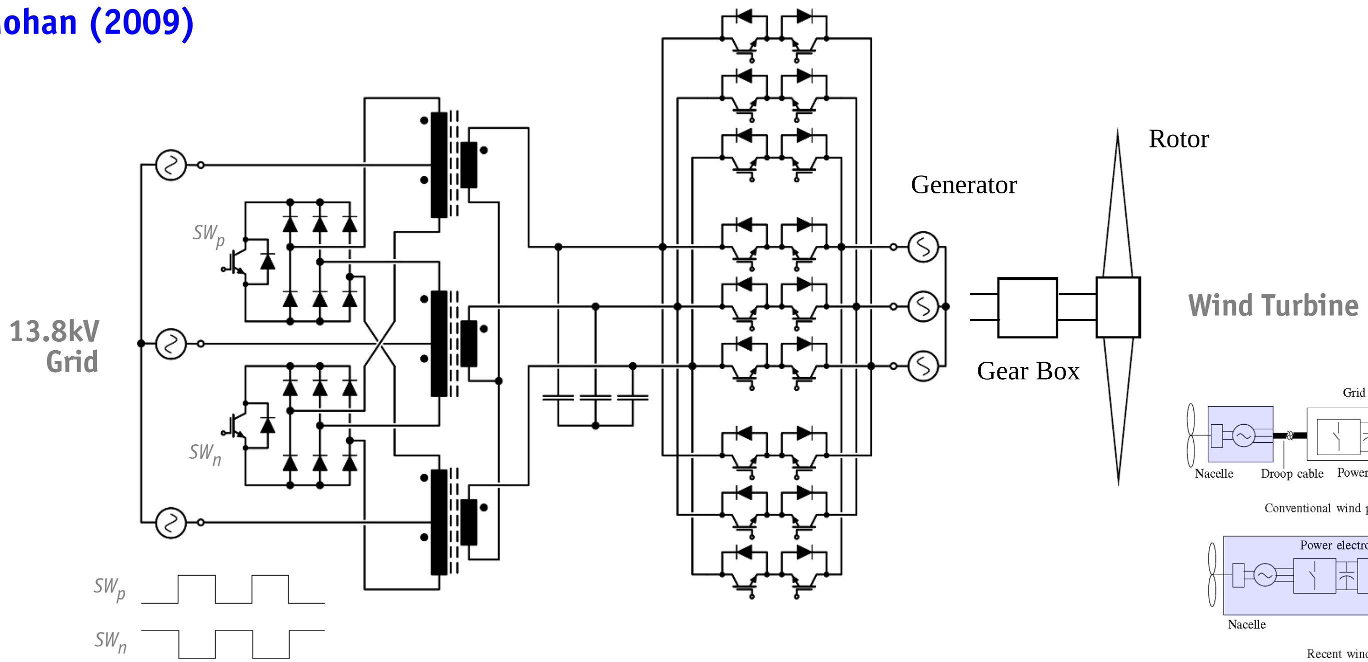


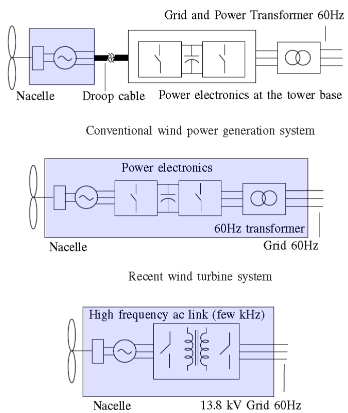
● 1-Stage Matrix-Type Topologies
● 2-Stage with LV DC Link (Connection of Energy Storage)
● 3-Stage Power Conversion with MV and LV DC Link

▶ Basic SST Structures (1)

■ 1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion

\- Mohan (2009)



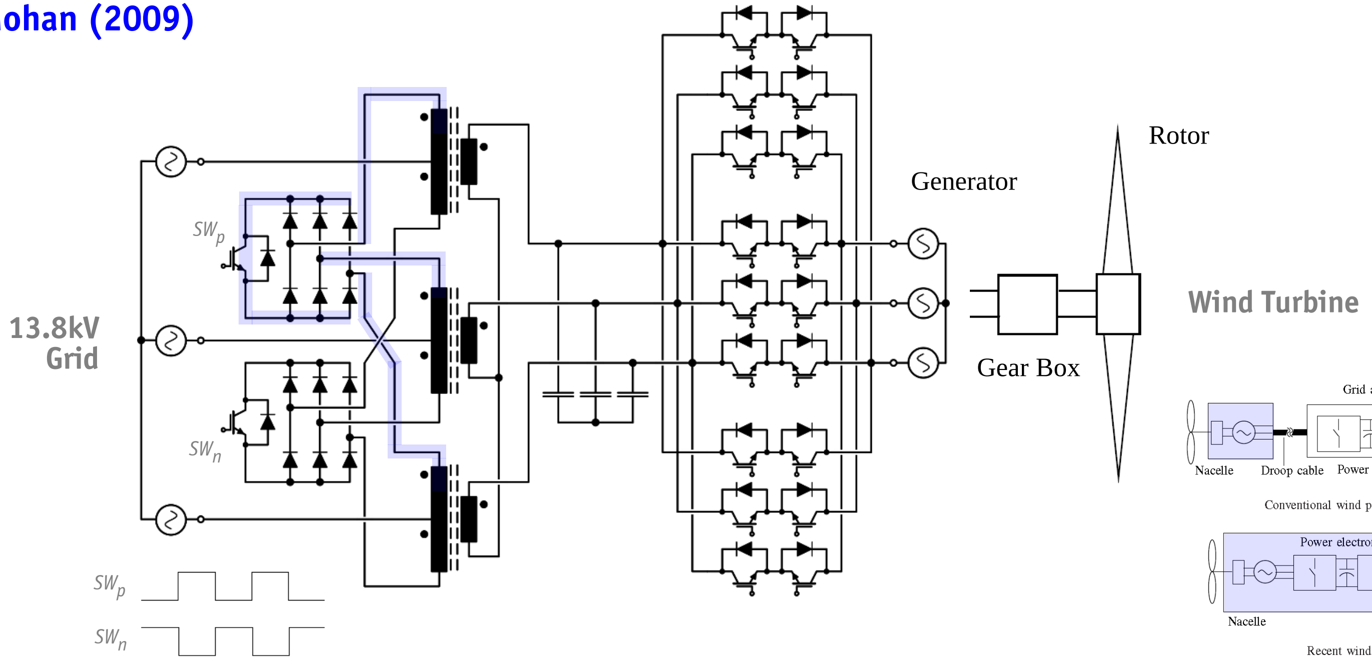


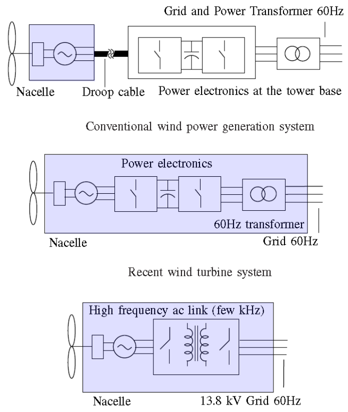
- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency

▶ Basic SST Structures (1)

- **1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion**

- Mohan (2009)



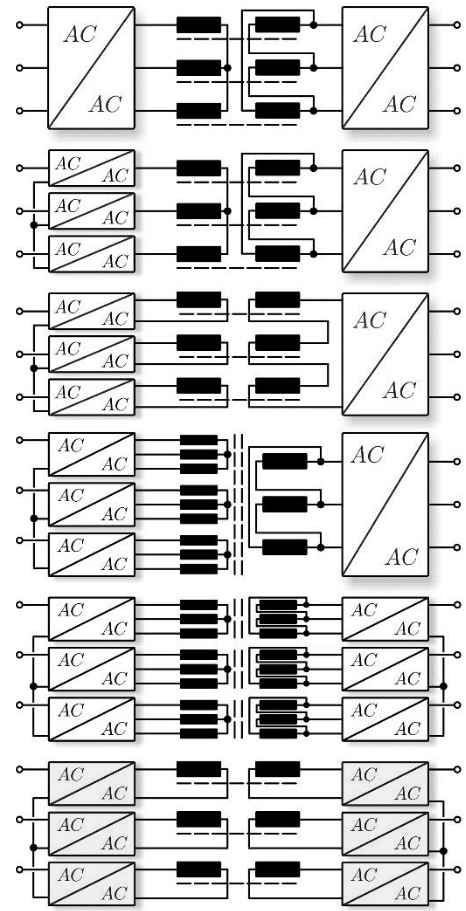


- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency

▶ Basic SST Structures (2)

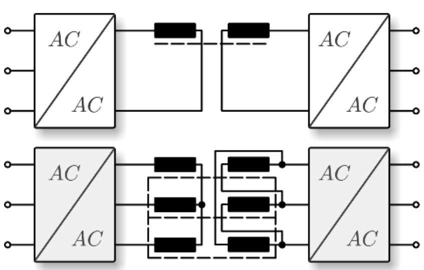
- **2nd Degree of Freedom of Topology Selection → Partial or Full Phase Modularity**

* **Phase-Modularity of Electric Circuit**
* **Phase-Modularity of Magnetic Circuit**



* Possibility of Cross-Coupling of Input and Output Phases (UNIFLEX)

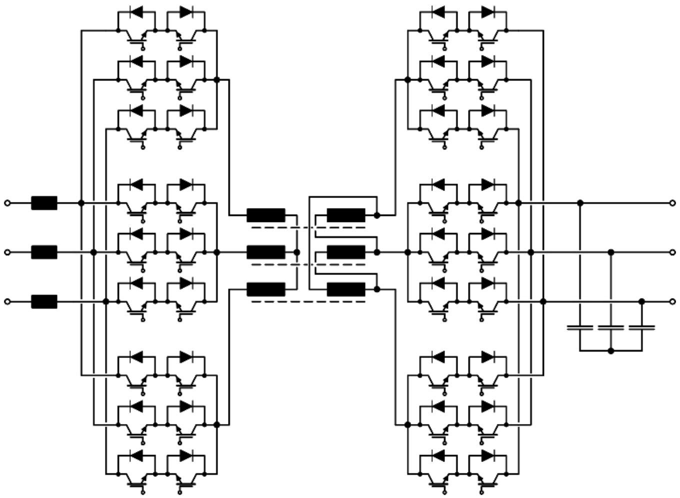
* Phase-Integrated SST



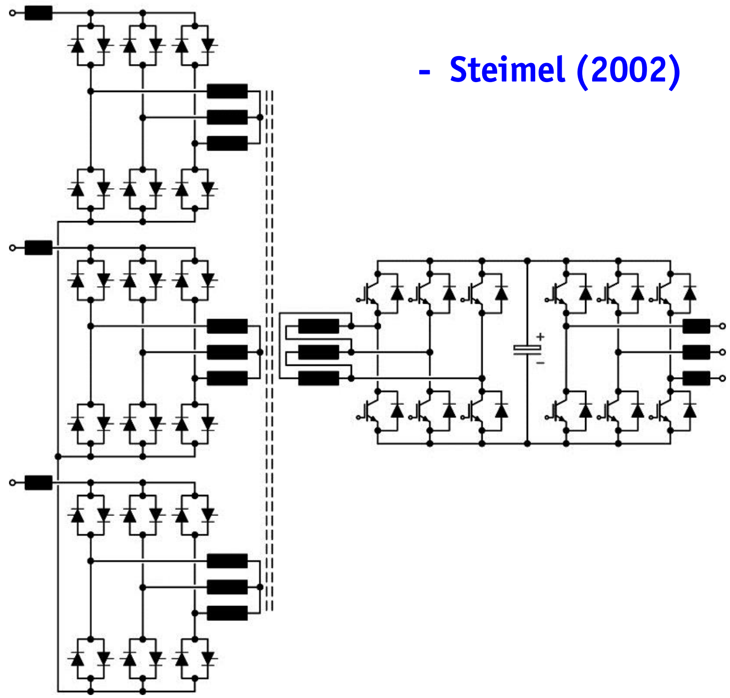
▶ Basic SST Structures (2)

■ 2nd Degree of Freedom of Topology Selection → Partial or Full Phase Modularity

- Enjeti (1997)



- Steimel (2002)

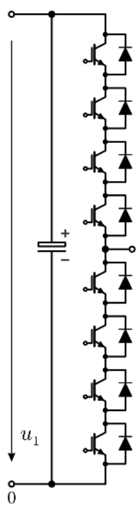


- Example of Three-Phase Integrated (Matrix) Converter & Magn. Phase-Modular Transf.
- Example of Partly Phase-Modular SST

▶ Basic SST Structures (3)

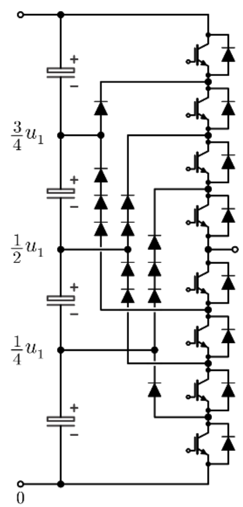
- 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

- Multi-Cell and Multi-Level Approaches

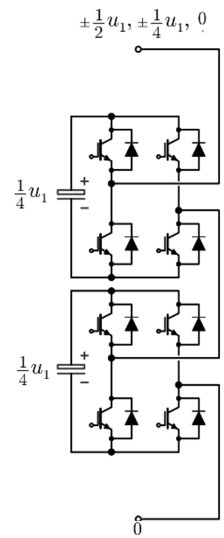


* Two-Level Topology

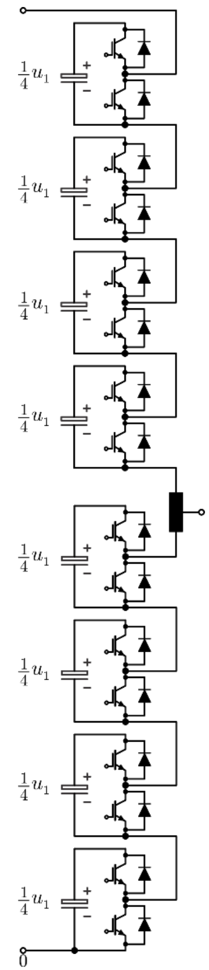
Akagi (1981)



McMurray (1969)



Marquardt

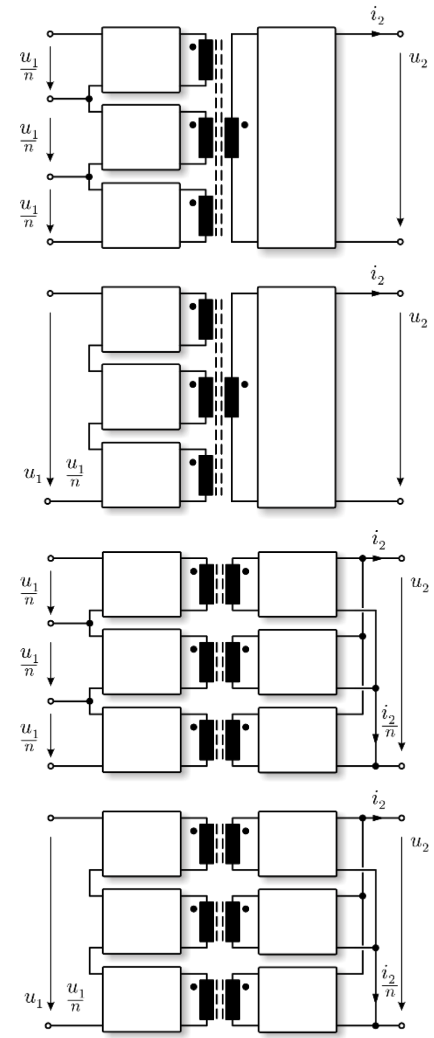


Alesina/ Venturini (1981)

* Multi-Level/ Multi-Cell Topologies

▶ Basic SST Structures (3)

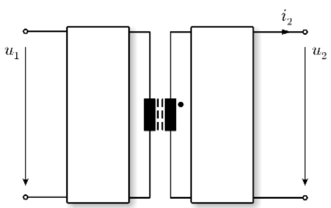
- 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage



- Multi-Cell and Multi-Level Approaches

- Low Blocking Voltage Requirement
- Low Input Voltage / Output Current Harmonics
- Low Input/Output Filter Requirement

* Single-Cell / Two-Level Topology

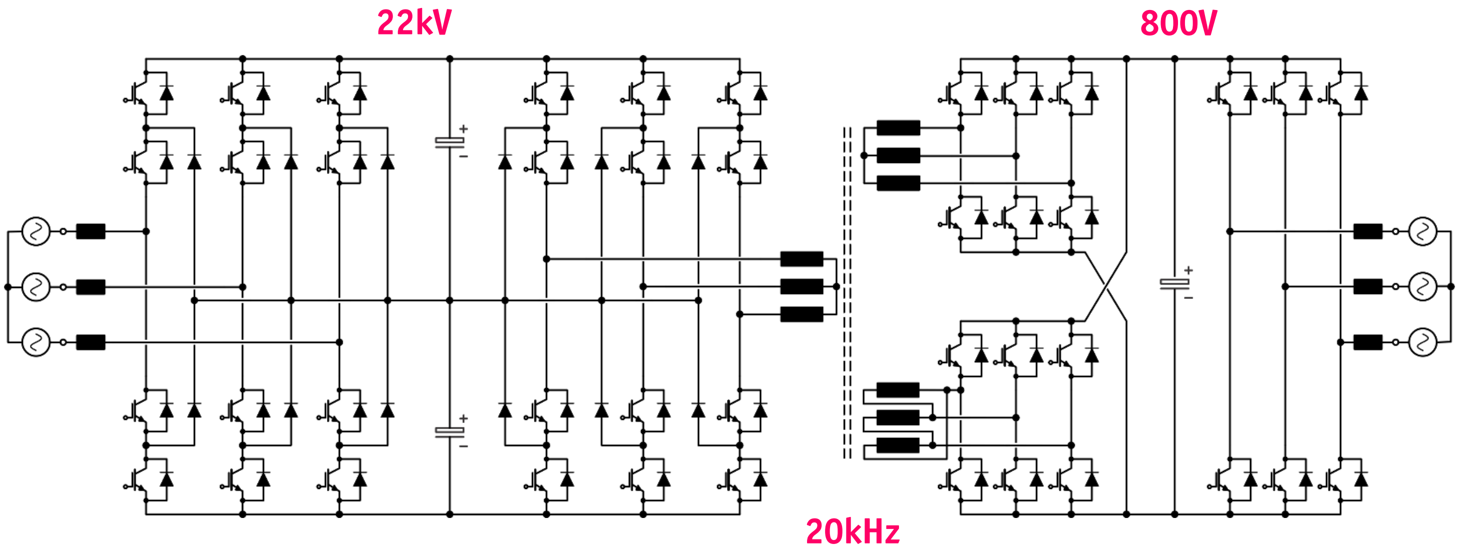


a)

ISOP = Input Series / Output Parallel Topologies

▶ Basic SST Structures (3)

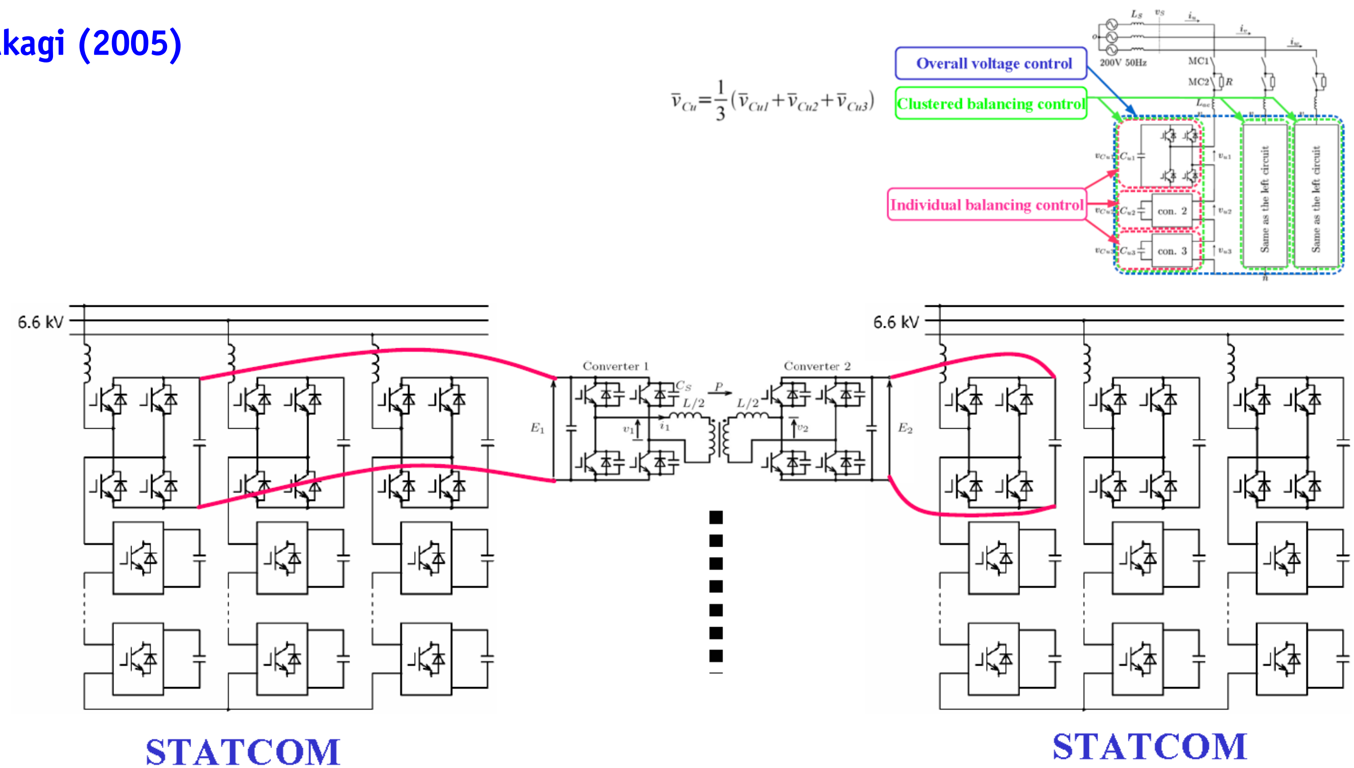
- Bhattacharya (2012)



- 13.8kV → 480V
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype

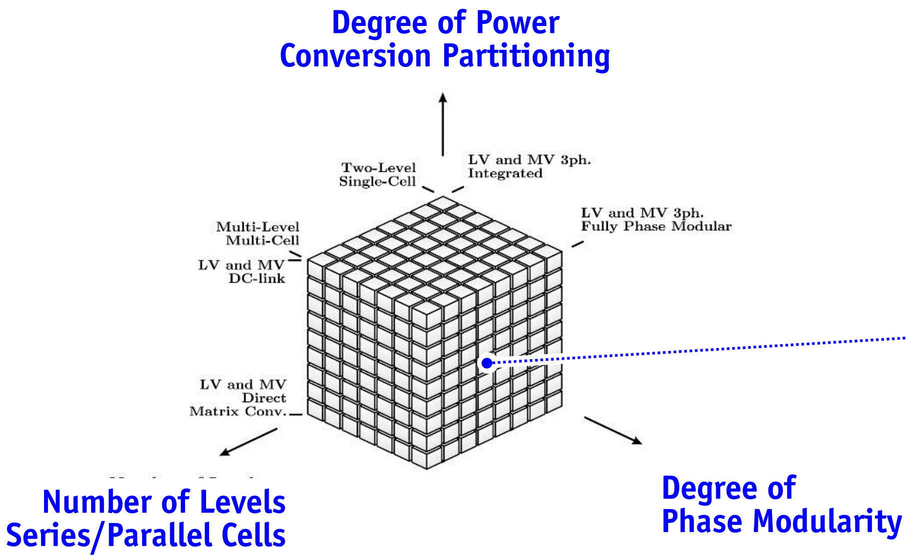
▶ Basic SST Structures (3)

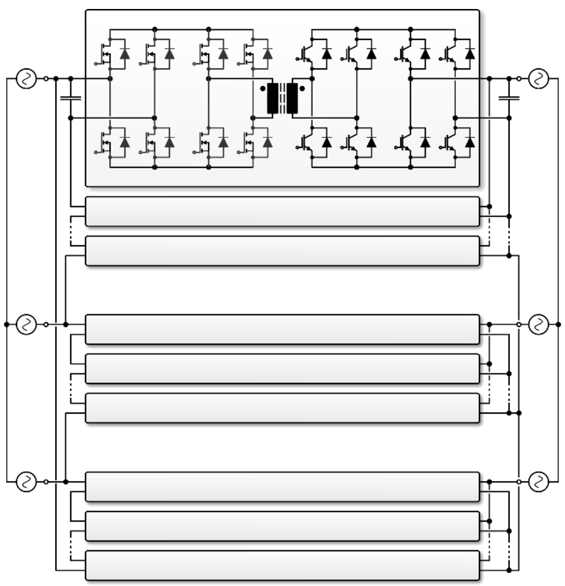
- Akagi (2005)



- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control

▶ Classification of SST Topologies





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

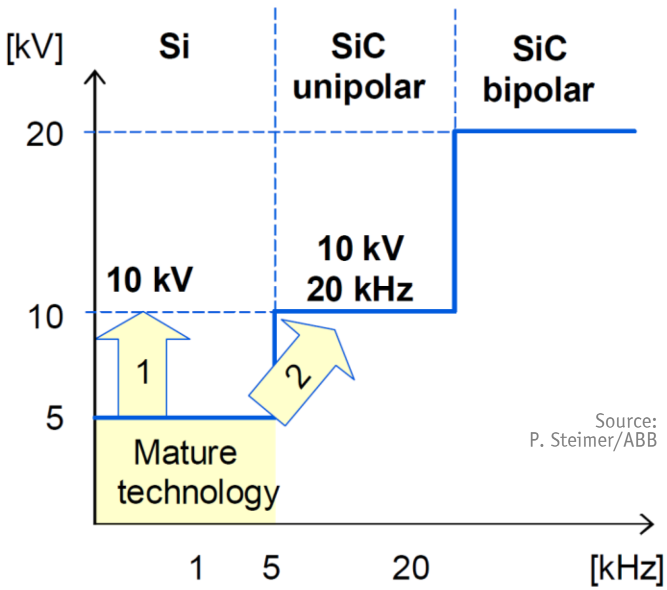
* Partitioning of Power Conversion → Matrix & DC-Link Topologies
* Splitting of 3ph. System into Individual Phases → Phase Modularity
* Splitting of Medium Operating Voltage into Lower Partial Voltages → Multi-Level/Cell Approaches

Challenge #2/10

Availability / Selection of Power Semiconductors

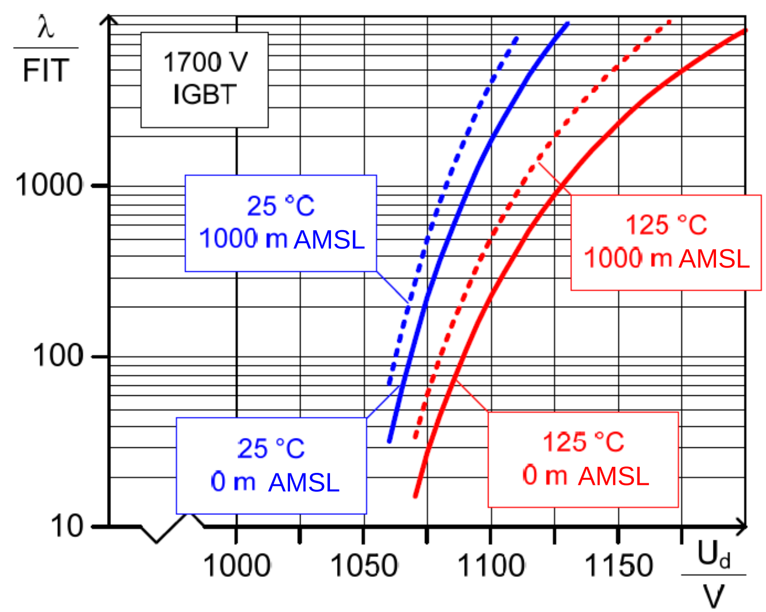
▶ Available Si Power Semiconductors

- **1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications**



- **Derating Requirement due to Cosmic Radiation 1700V Si-IGBTs → 1000V max. DC Voltage**

Source: H.-G. Eckel/Univ. Rostock

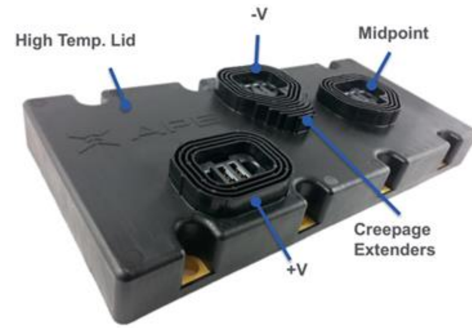


■ **Multi-Level Converters for High Grid Voltages / High Reactive Power Injection**

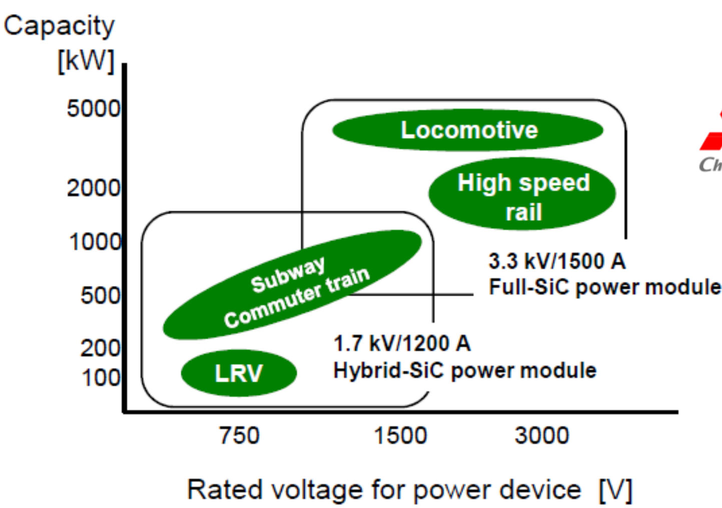
▶ Available SiC Power Semiconductors

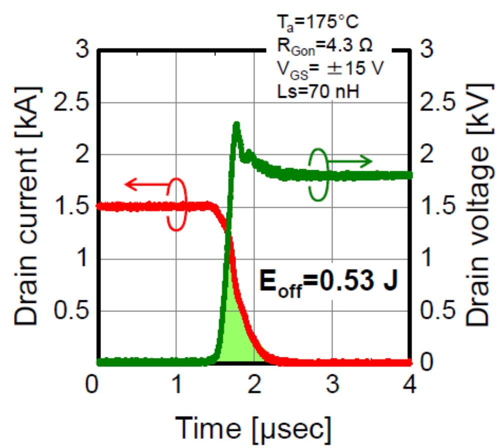
- **10kV / 10A SiC MOSFET and Antiparallel SiC Schottky Diode**

- **15kV / 80A Low-Ind. High-Temp. Package**



■ **High Current 3.3kV / 1.7kV / 1.2 kV Power Modules Available (Mitsubishi, ROHM, etc.)**



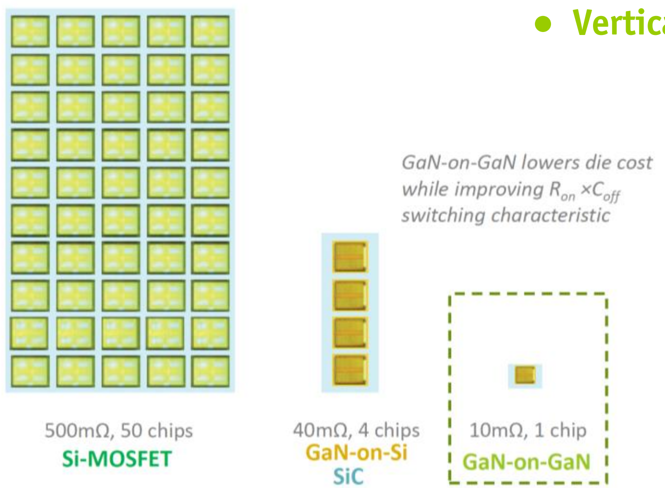


▶ Vertical (!) Power Semiconductors on Bulk GaN Substrates

avogy advancing energy efficiency

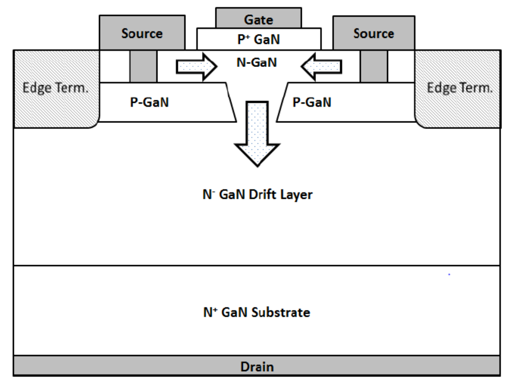
■ GaN-on-GaN Means Less Chip Area

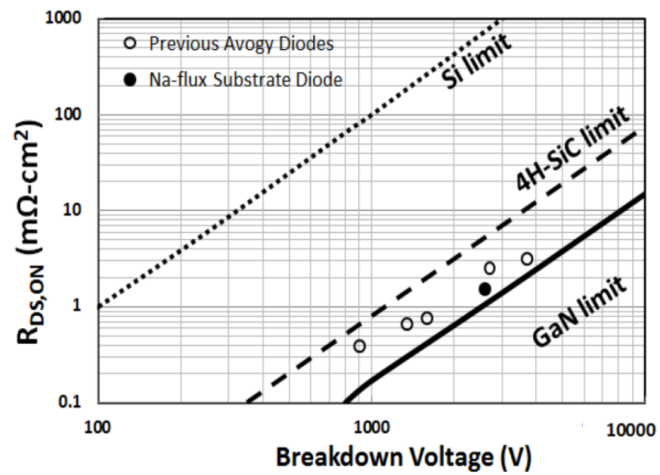
For a given on-resistance (R_{on}) of 10mΩ:



Breakdown Voltage (V)	Doping(cm-3)	Drift Length (μm)
600	4.8×10^{16}	3.7
1200	2.4×10^{16}	7.3
1800	1.6×10^{16}	10.9
2400	1.2×10^{16}	14.6
3200	0.9×10^{16}	19.4
4800	0.6×10^{16}	29.1
5600	0.5×10^{16}	34.0

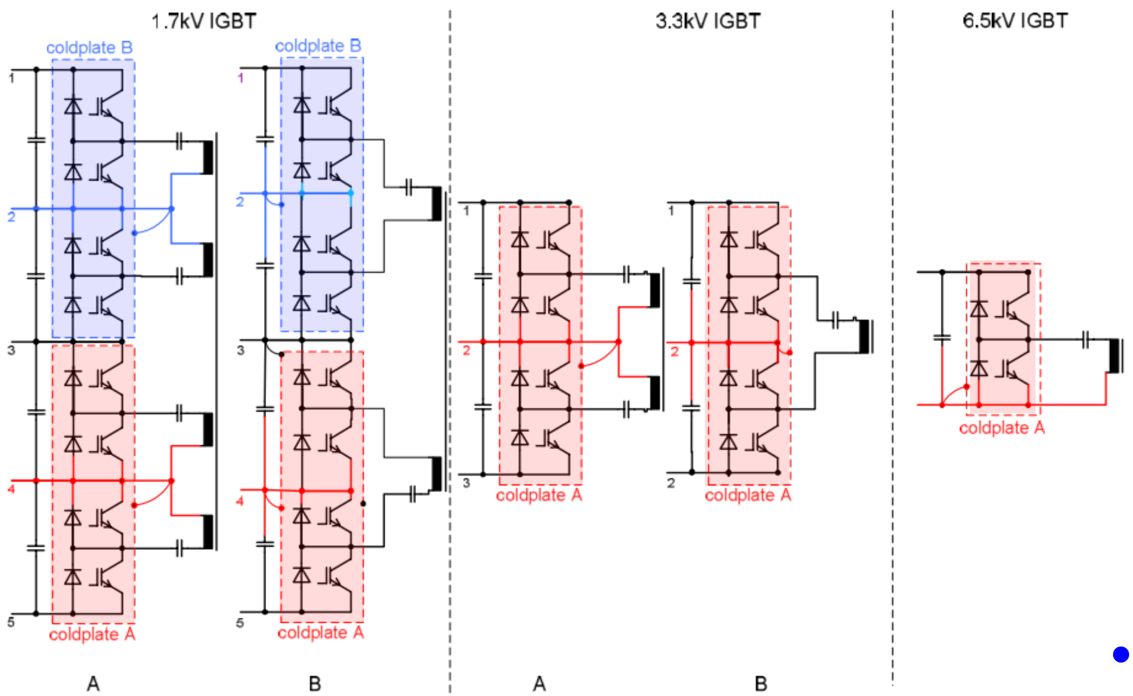
- Vertical FET Structure





▶ Semiconductor Cooling and Isolation

- **1.7kV IGBTs → Semiconductor Modules on Coldplates/Heatsinks Connected to Different Potentials (CM Voltage Problems)**
- **3.3kV or 6.5kV IGBTs → Isolation Provided by the Modules' Substrate, No Splitting of the Cooling System Necessary.**

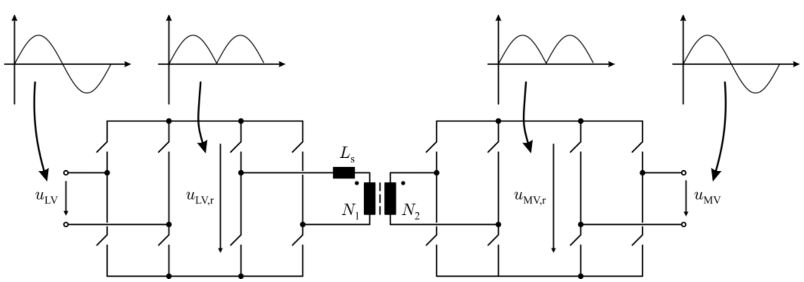


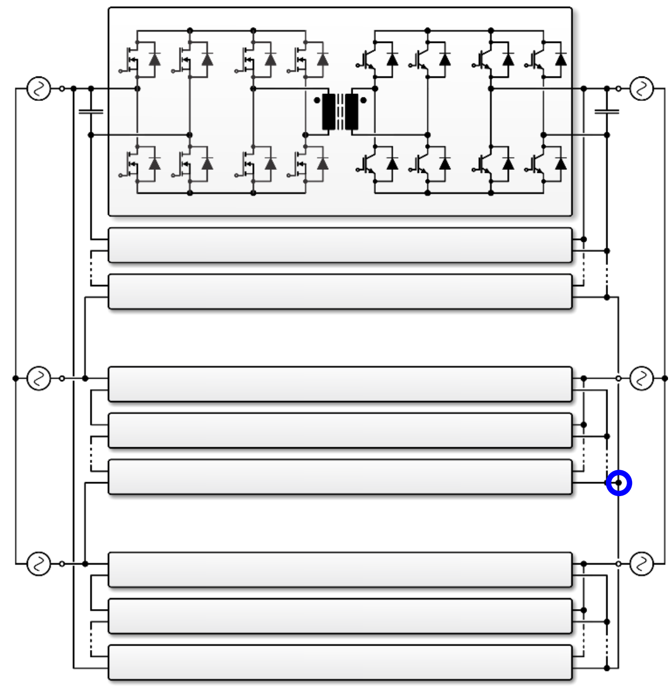
- **Hoffmann (2009)**

▶ SiC-Enabled Solid-State Power Substation

- Das et al. (2011)
- Lipo (2010)
- Weiss (1985 for Traction Appl.)

- Fully Phase Modular System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
- MV Δ-Connection (13.8kV$_{l\text{-}l}$, 4 Modules in Series)
- LV Y-Connection (465V/√3, Modules in Parallel)





- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

► SiC-Enabled Solid-State Power Substation

- Das (2011)

- Fully Phase Modular System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
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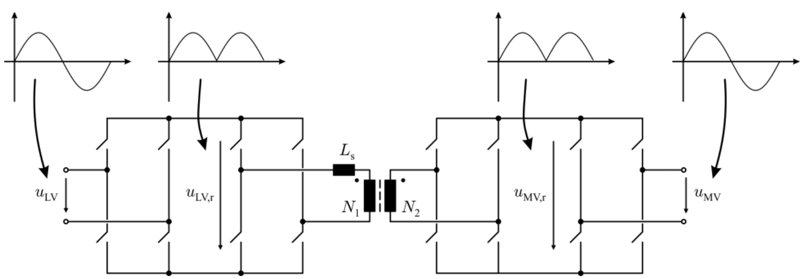


- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

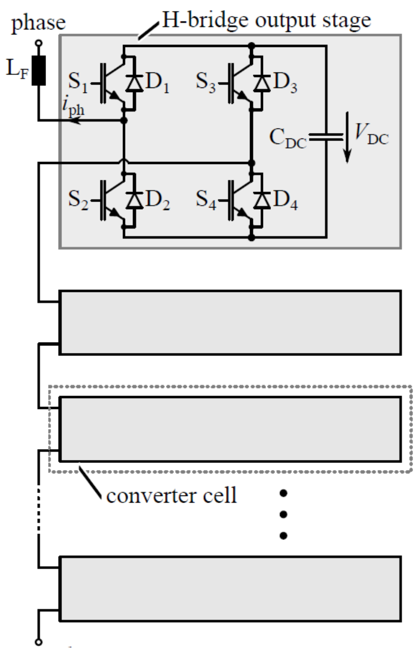
Challenge #3/10

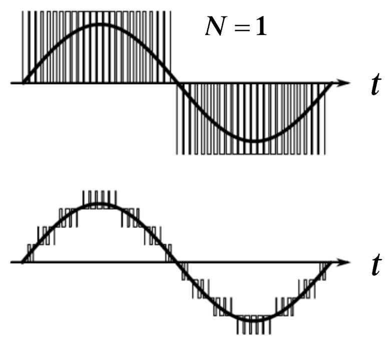
Single-Cell vs. Multi-Cell Converter Concepts

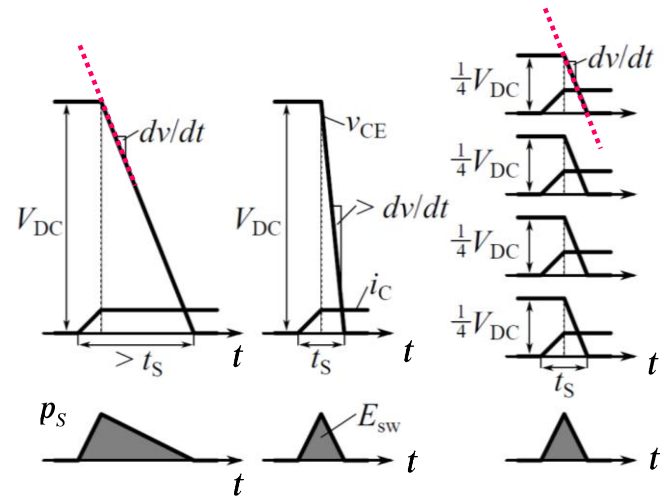
- *Losses*
- *Reliability*

► Scaling of Multi-Cell Converters

■ Interleaved Series Connection Dramatically Reduces Switching Losses







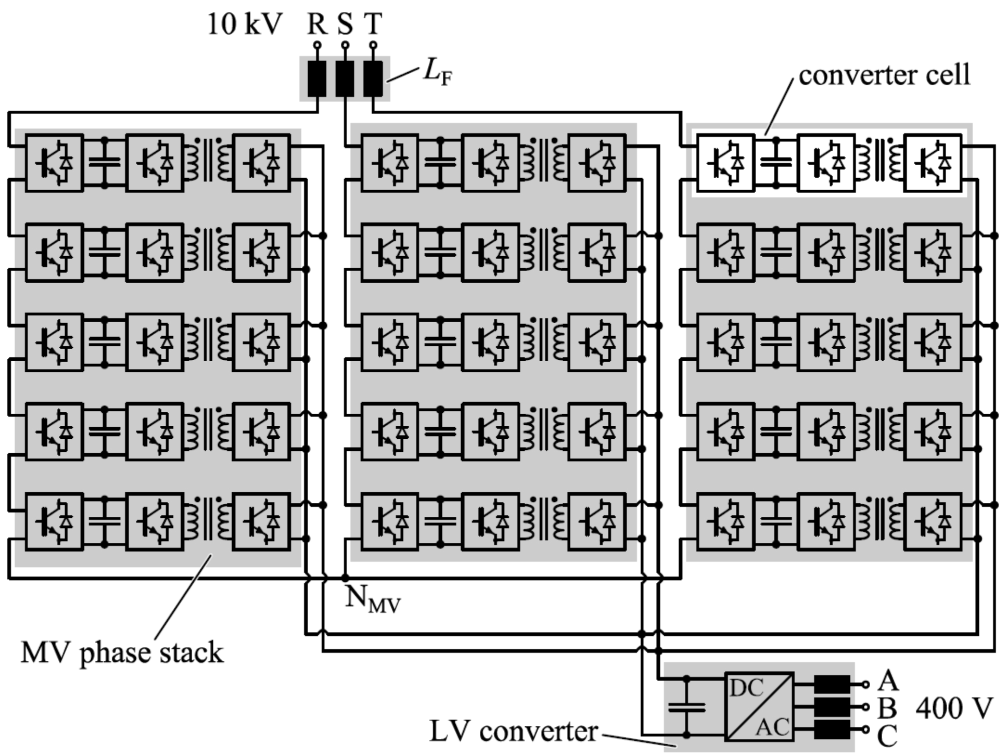
– Scaling of Switching Losses for Equal $\Delta i/I$ and dv/dt

$$P_{S,N} \approx P_{S,N=1} \cdot \left(\frac{1}{2N^2} \dots \frac{1}{N^3}\right)$$

■ Converter Cells Could Operate at VERY Low Switching Frequency (e.g. 5kHz)
■ Harmonics Cancellation instead of Filtering → Minimization of Filter Components

▶ MEGALink @ ETH Zürich

S_N = 630kVA
U_{LV} = 400 V
U_{MV} = 10kV

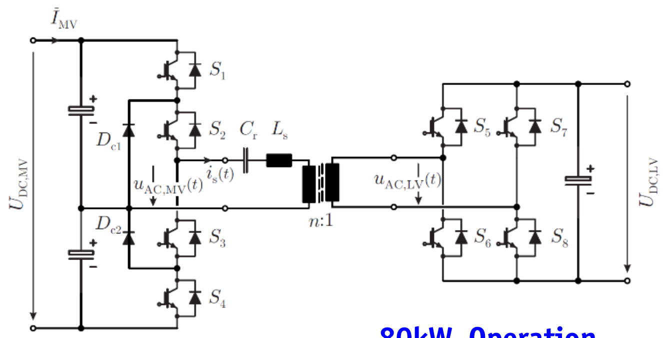


- 2-Level Inverter on LV Side / HC-DCM-SRC DC-DC Conversion / Cascaded H-Bridge MV Structure

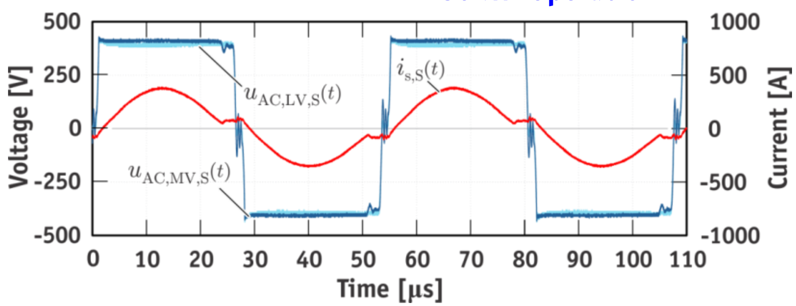
▶ 166kW / 20kHz DC-DC Converter Cell

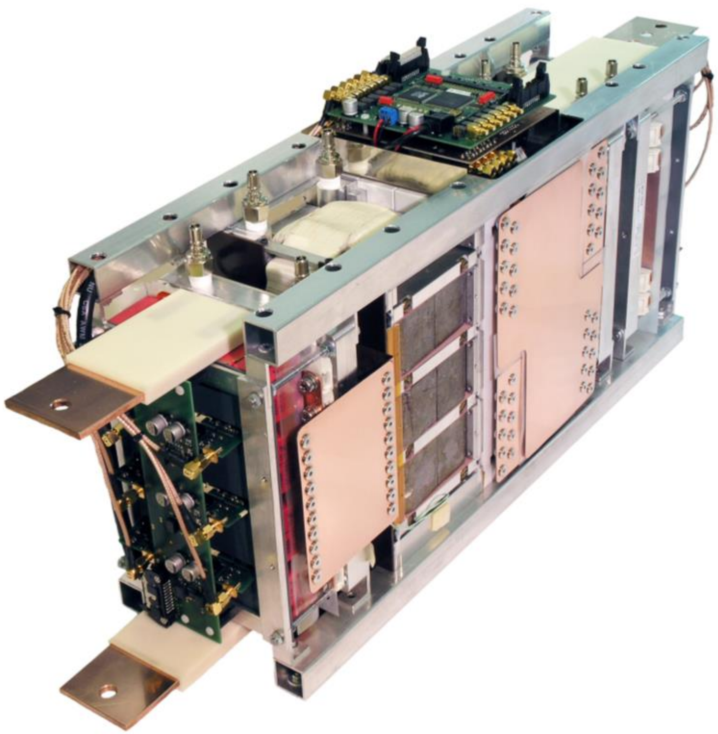
- **Half-Cycle DCM Series Resonant DC-DC Converter**

- **Medium-Voltage Side 2kV**
- **Low-Voltage Side 400V**



80kW Operation

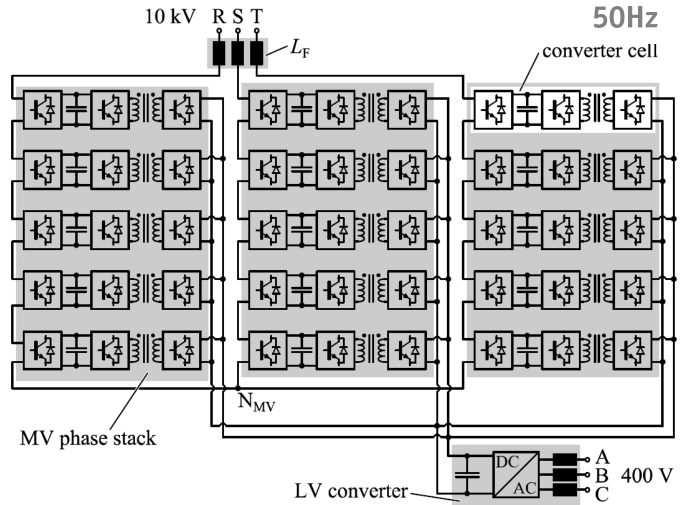




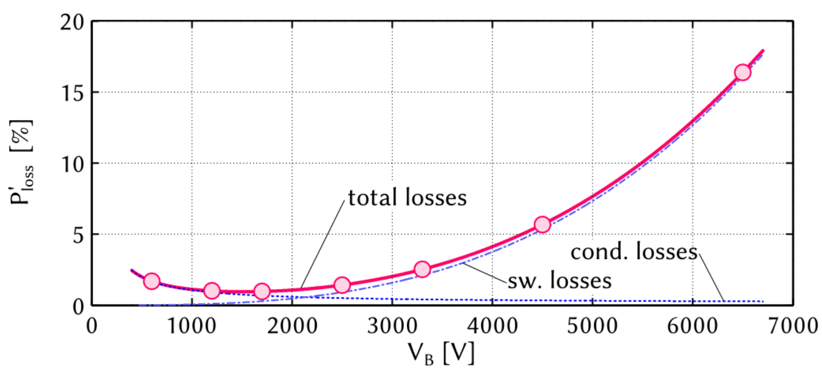
▶ Optimum Number of Converter Cells

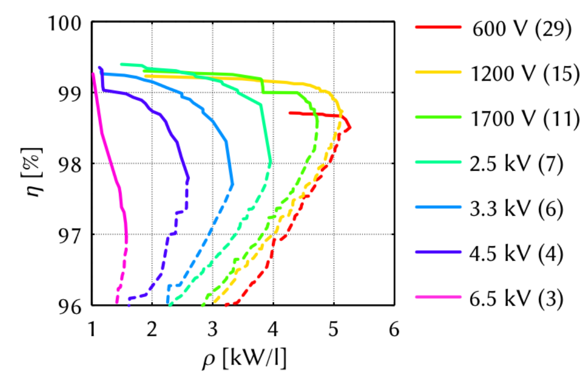
- **Trade-Off** High Number of Levels → High Conduction Losses/ Low Cell Switchng Frequ./Losses (also because of Device Char.)

1 MVA
10kV → 400V
50Hz



- Opt. Device Voltage Rating for Given MV Level
- ηρ-Pareto Opt. (Compliance to IEEE 519)





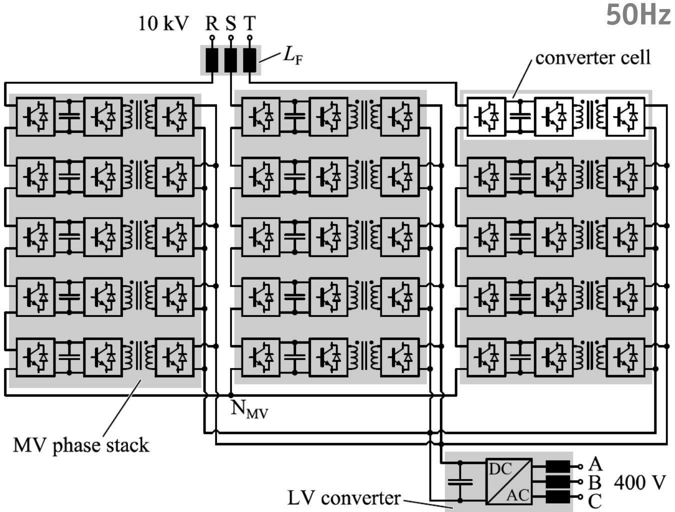
- 1200V … 1700V Power Semiconductors best suited for 10kV Mains → No Advantage of SiC (!)

▶ Optimum Number of Converter Cells

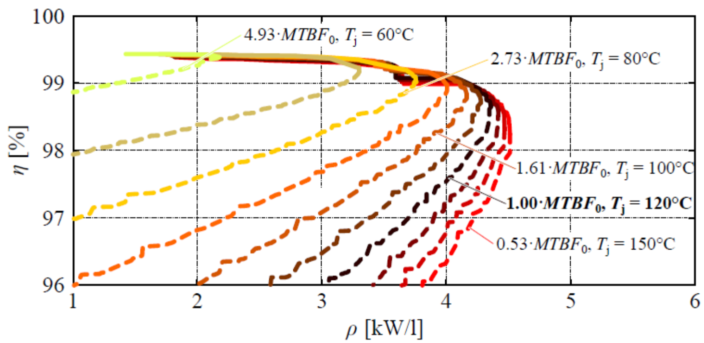
1 MVA
10kV → 400V
50Hz

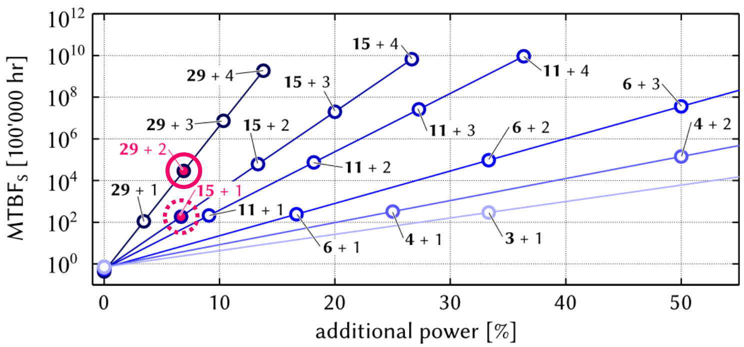
- Trade-Off → Mean-Time-to-Failure vs. Efficiency / Power Density

- Influence of
  * FIT Rate (Voltage Utilization)
  * Junction Temperature
  * Number of Redundant Cells



No Redundancy
1700V IGBTs, 60% Utilized





- High MTBF also for Large Number of Cells (Repairable) / Lower Total Spare Cell Power Rating

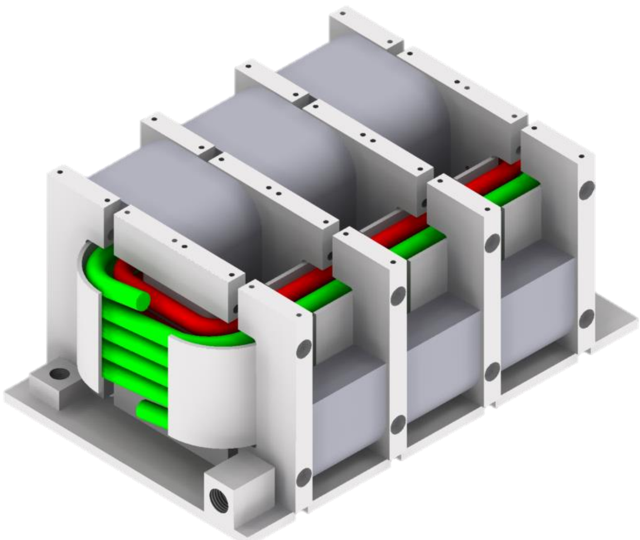
Challenge #4/10

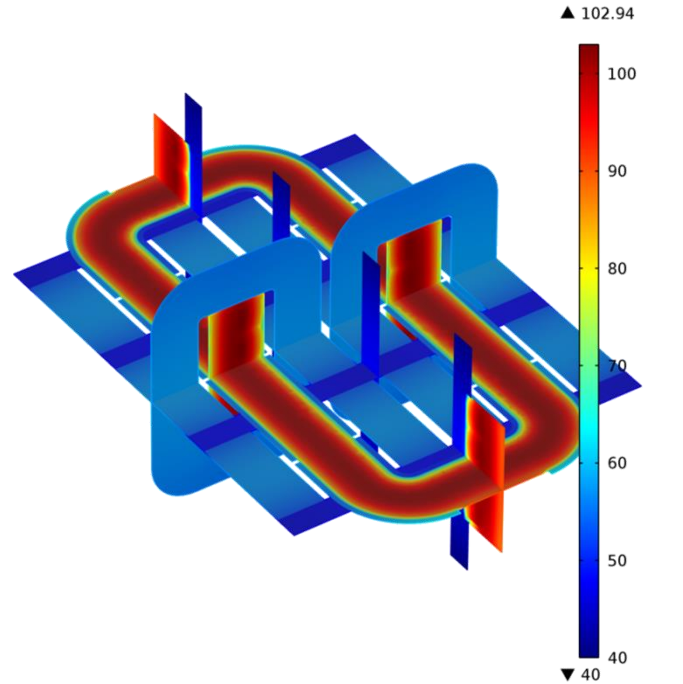
Medium-Frequency Transformer Design

- *Heat Management*
- *Isolation*

▶ MF Transformer Design – Cold Plates/ Water Cooling

■ Nanocrystalline 160kW/20kHz Transformer (ETH, Ortiz 2013)





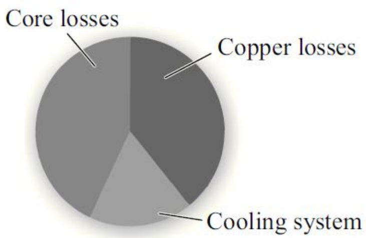
- Combination of Heat Conducting Plates and Top/Bottom Water-cooled Cold Plates
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

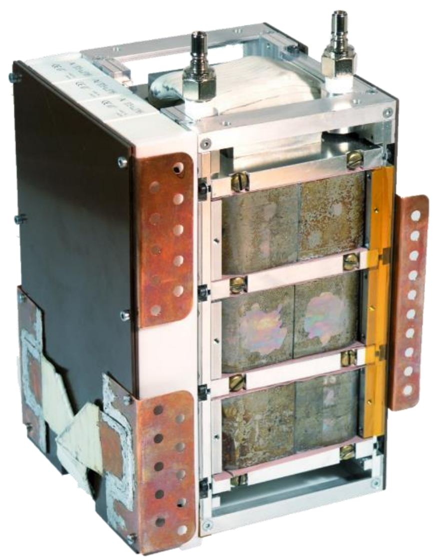
▶ Water-Cooled 20kHz Transformer

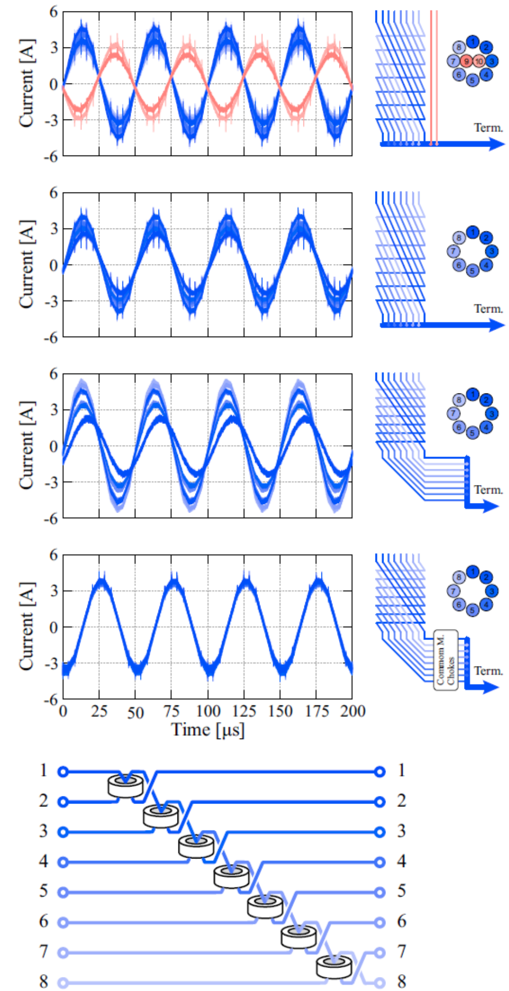
- Power Rating 166kW
- Efficiency 99.5%
- Power Density 32 kW/dm^3

- Nanocrystalline Cores with 0.1mm Airgaps between Parallel Cores for Equal Flux Partitioning

- Litz Wire (10 Bundles) with CM Chokes for Equal Current Partitioning



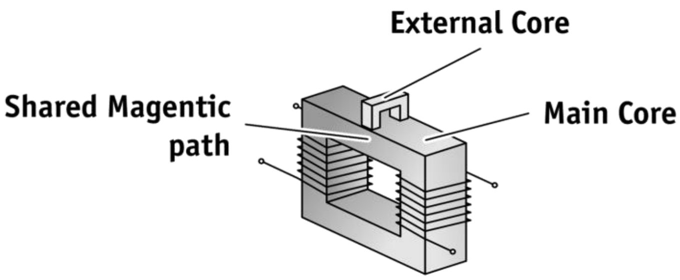


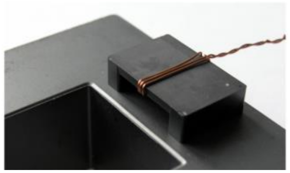


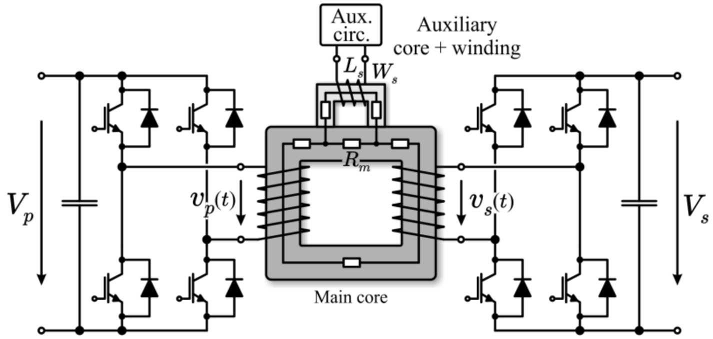
▶ Transformer Core Flux Density Measurement

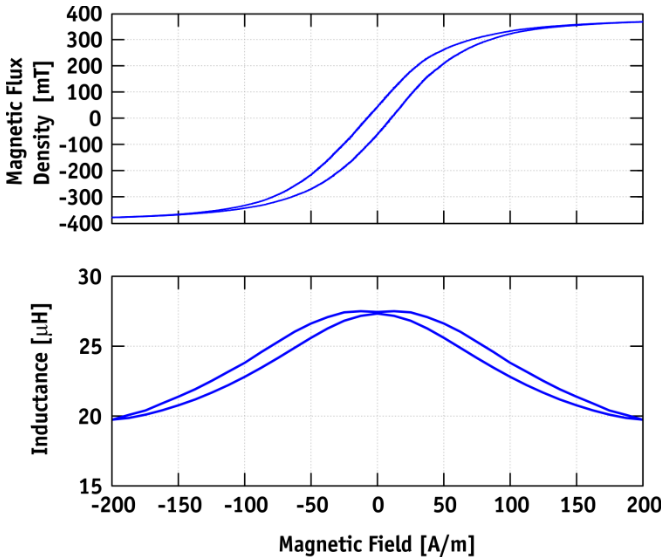
■ "Magnetic Ear"

- Auxiliary Core Inductance Related to Main Core Magnetization State
- Enables Closed Loop Transformer Flux Balancing





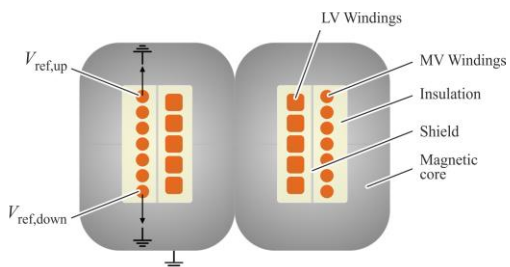


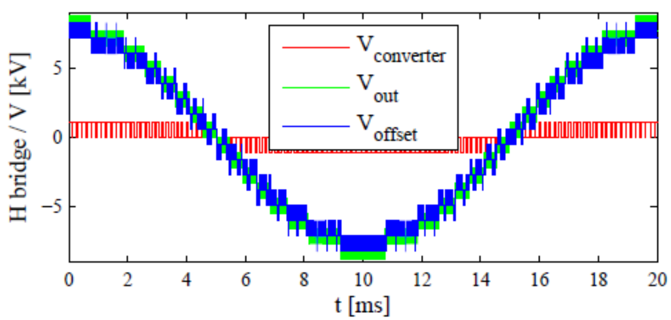


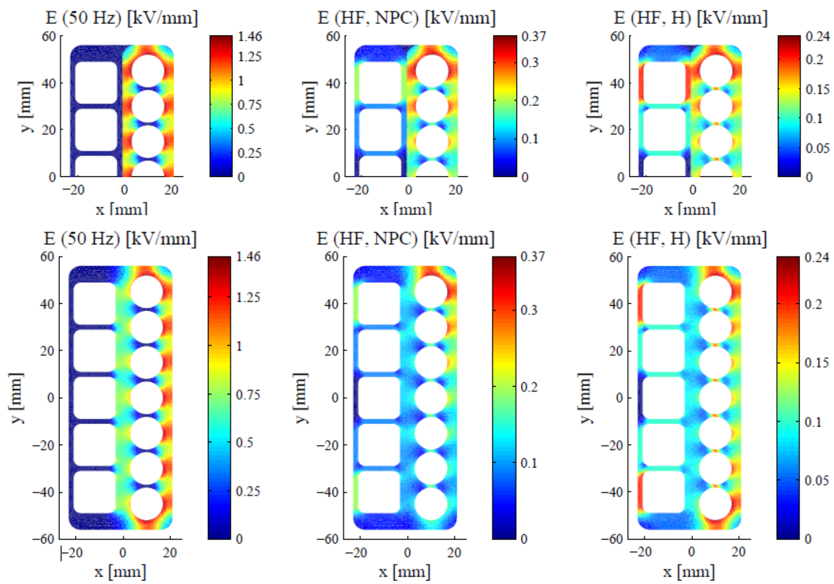
Voltage and E-Field Stresses in SSTs

- Mixed-Frequency (LF + Switching Frequency) Voltage Stress on Isolation
- Unequal Dynamic Voltage Distribution
- Potentially Accelerated Aging (!)

RMS Electric Field
LF, NPC-Cells, H-Cells
Bottom: w/o Shield
Top: With Shield







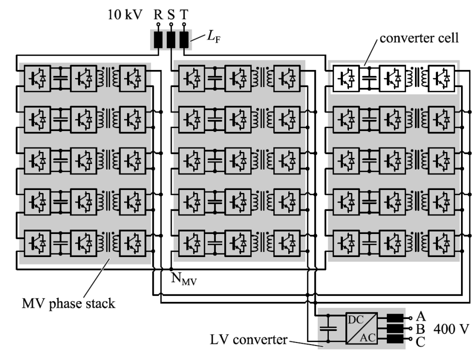
- Neglectable Dielectric Losses
- Specific Test Setup Required for Insulation Material Testing

Challenge #5/10

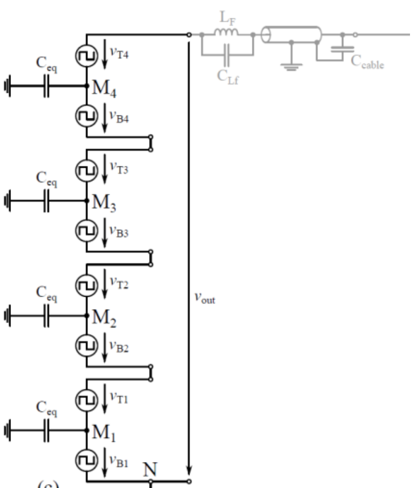
SST Noise Emissions /EMI

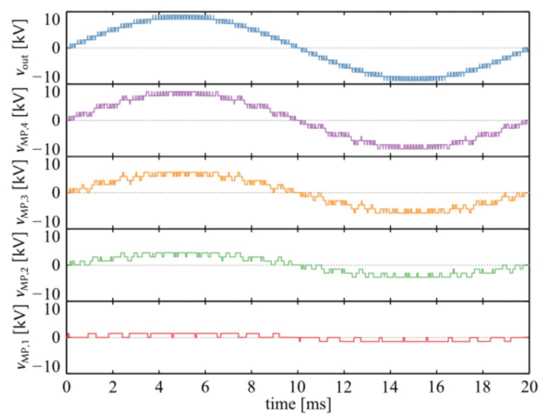
▶ Common-Mode Currents of Cascaded H-Bridge SSTs

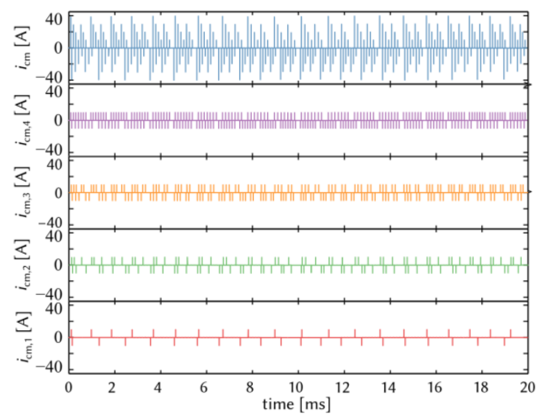
- Switching Actions of a Cell *i* Changes the Ground Potential of Cells *i*, *i*+1,... *N*
- CM Currents through Ground Capacitances



- Example
  1MVA
  10kV Input
  400V Output
  1kHz/Cell
  $C_{eq} \approx 650$pF







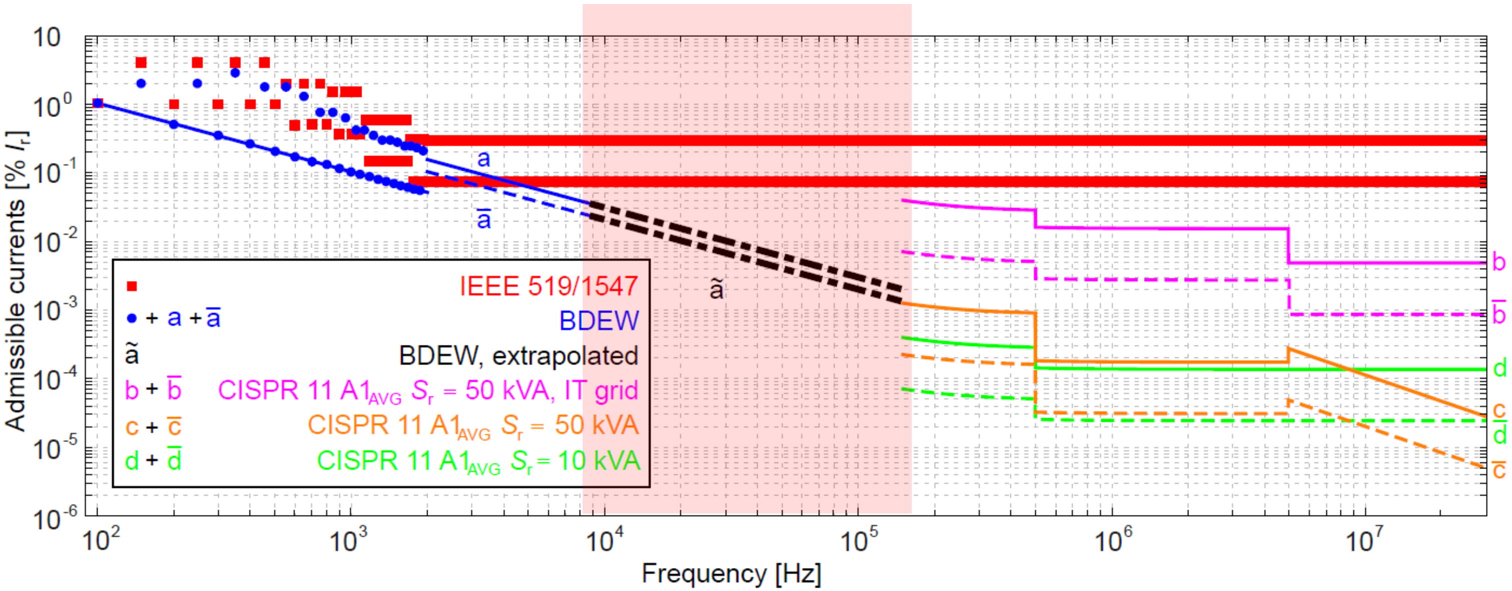
- 6.2mH  at the Input of Each Cell for Limiting i_{CM}

dv/dt=15kV/µs

▶ Grid Harmonics and EMI Standards

- **Medium Voltage Grid Considered Standards (Burkart, 2012)**
  - IEEE 519/1547
  - BDEW
  - CISPR

- **Requirements on Switching Frequency and EMI Filtering**



Challenge #6/10

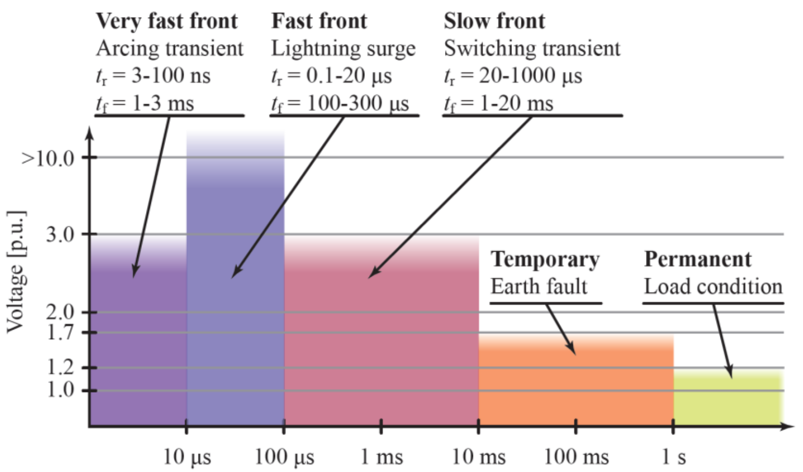
Mains ← SST → Load
Protection / Grid Codes

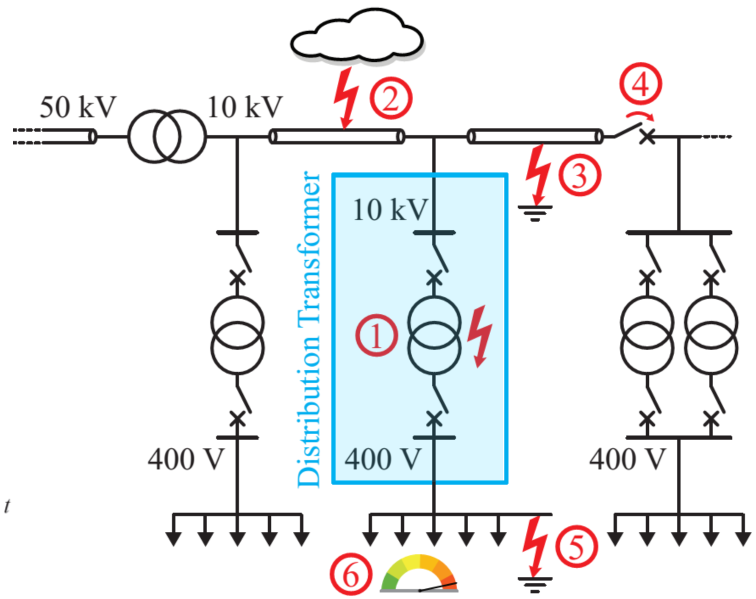
▶ Potential Faults of MV/LV Distribution-Type SSTs

- Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids
- SST more Appropriate for Local Industrial MV Grids

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

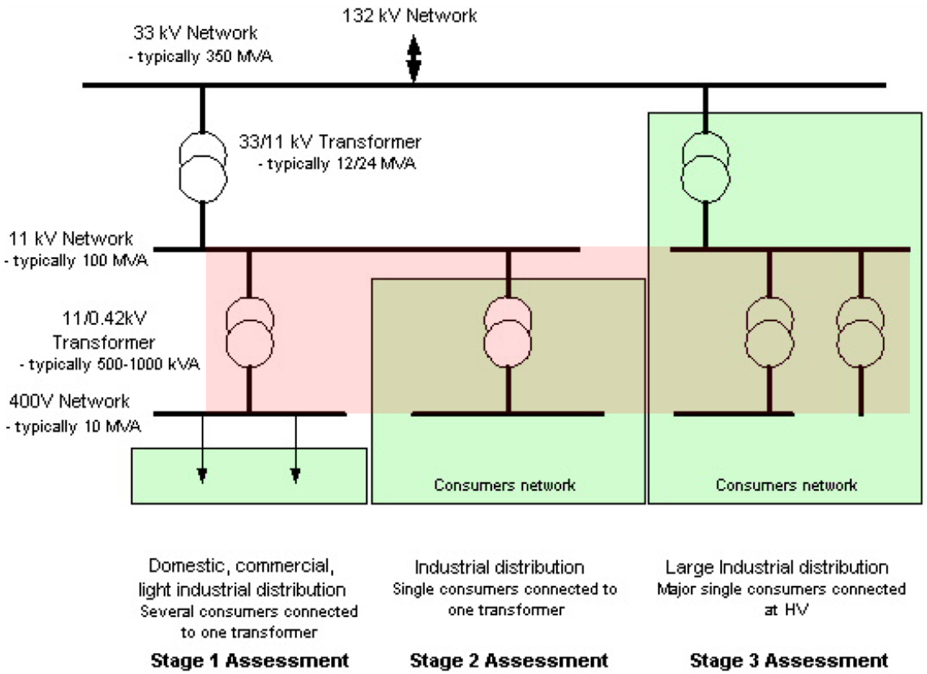
- Conv. MV Grid Time-Voltage Characteristic





▶ Current Ratings – Overcurrent Requirements

- Low-Frequ. XFRM must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)
- Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)
- Power Electronics: Very Short Time Constants !

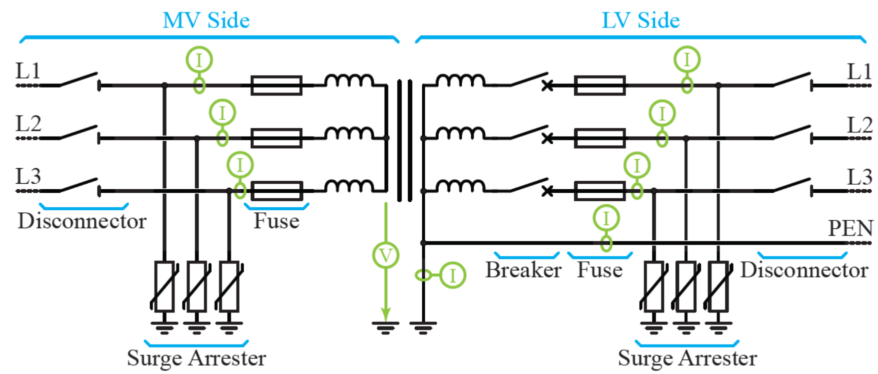


■ SST is NOT (!) a 1:1 Replacement for a Conventional Low-Frequency XFRM

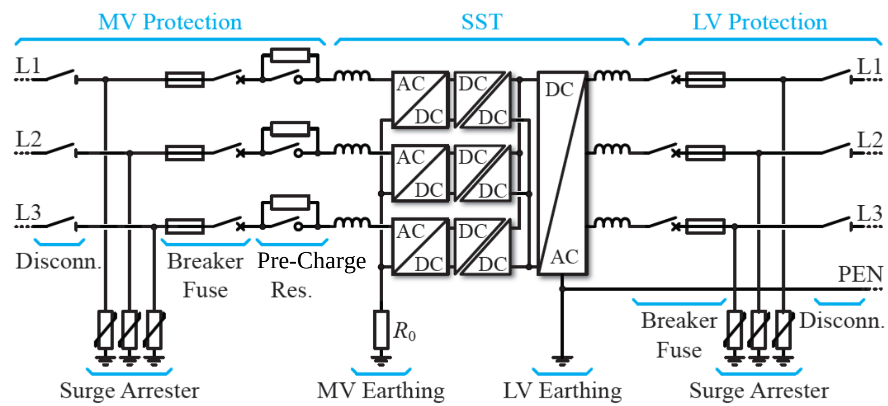
▶ Protection of LF-XFRM vs. SST Protection

■ **Missing Analysis of SST Faults (Line-to-Line, Line-to-Gnd, S.C., etc.) and Protection Schemes**

- **Typical LF-XFRM Protection (Fuses, Surge Arresters)**



- **Proposed SST Protection Scheme with Minimum # of Protection Devices**



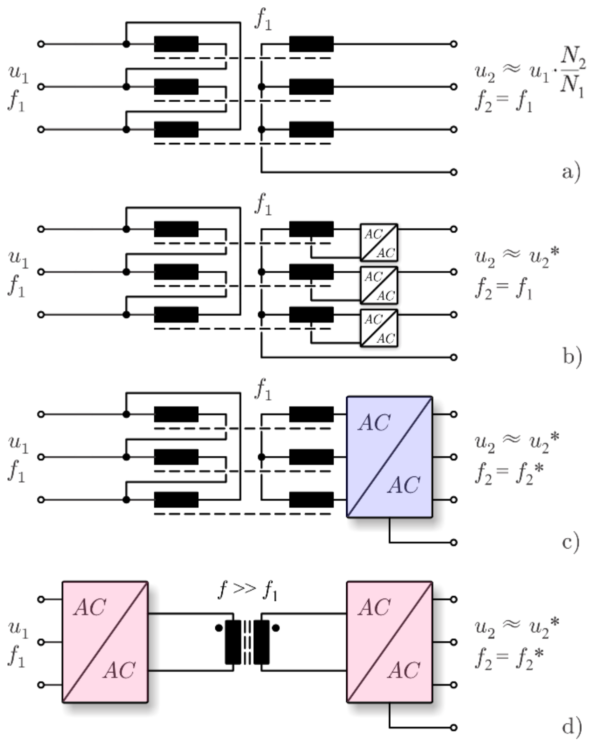
■ **Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed /Safety /Reliability**

Challenge #7/10

*SST Efficiency / Size / Costs vs.
Low-Frequency XFRM-Based Solution*

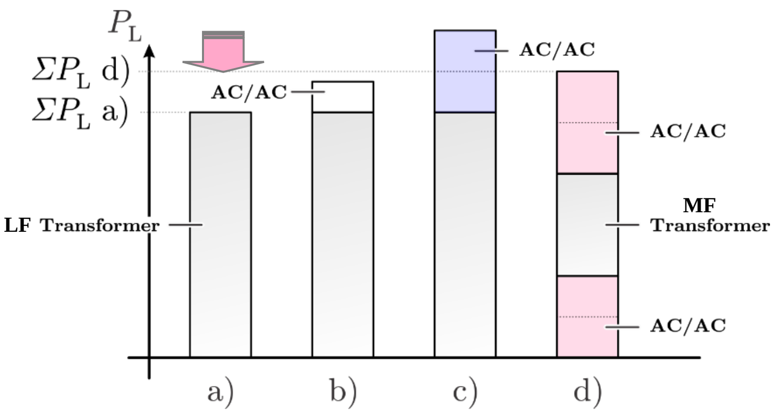
▶ Passive Transformer → SST

- Efficiency Challenge



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

MF Isolation
Active Input & Output Stage (d)

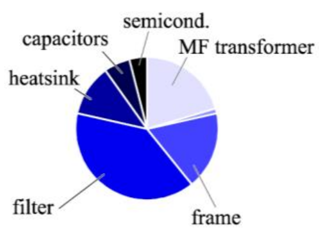


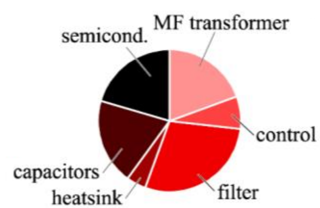
- **Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses**
- **Medium Freq. → Low Volume, High Control Dynamics**

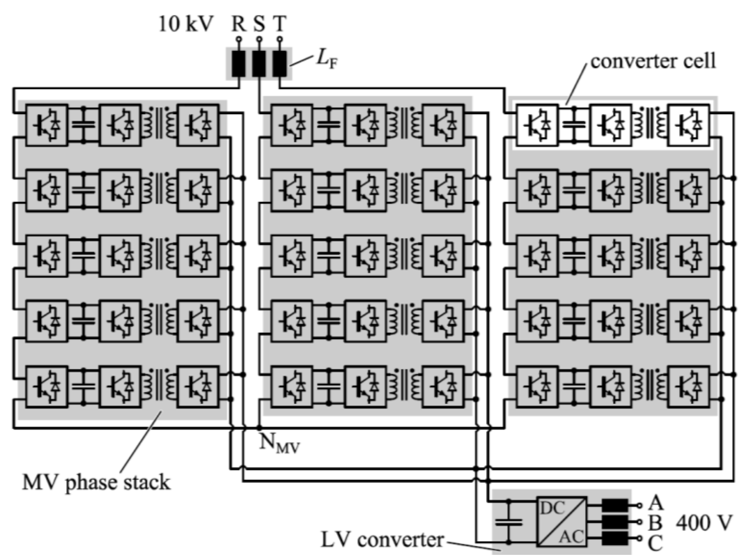
▶ Efficiency Advantage of Direct MV AC – LV DC Conversion

- **Comparison to LF Transformer & Series Connected PFC Rectifier (1MVA)**

  – **MV AC/DC Stage Weight (Top) and Costs (Bottom) Breakdown**







CHARACTERISTIC PERFORMANCE INDICES FOR 1000 kVA LFTS AND SSTS IN AC/AC OR AC/DC APPLICATIONS.

	AC/AC			AC/DC		
	LFT	factor	SST	LFT	factor	SST
losses [W/kVA]	13.0	×2.75	35.7	30.9	×0.58	17.9
costs [USD/kVA]	16.2	×4.75	77.0	43.9	×1.12	49.3
volume [l/kVA]	3.43	×0.57	1.96	3.64	×0.48	1.75
weight [kg/kVA]	2.59	×0.89	2.30	3.63	×0.35	1.26

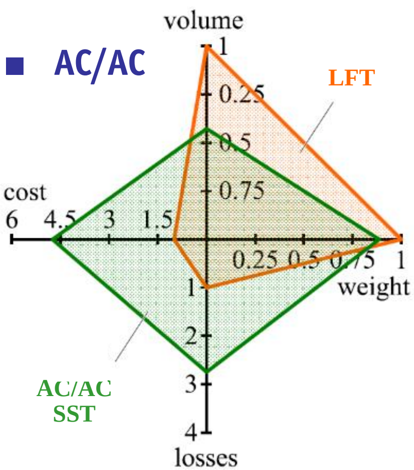
PERFORMANCE CHARACTERISTICS OVERVIEW.

	SST MV	SST LV	SST	LFT
efficiency	98.2 %	98.2 %	96.5 %	98.7 %
volume	1.751 m^3	0.211 m^3	1.962 m^3	3.427 m^3
weight	1262 kg	1036 kg	2298 kg	2591 kg
cost	49.3 kUSD	27.7 kUSD	77.0 kUSD	16 kUSD

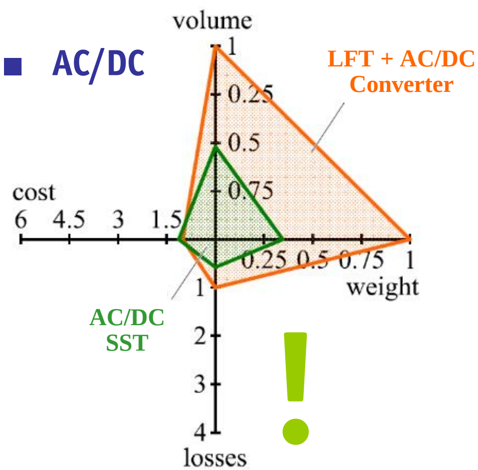
▶ SST vs. LF Transformer + AC/DC Converter

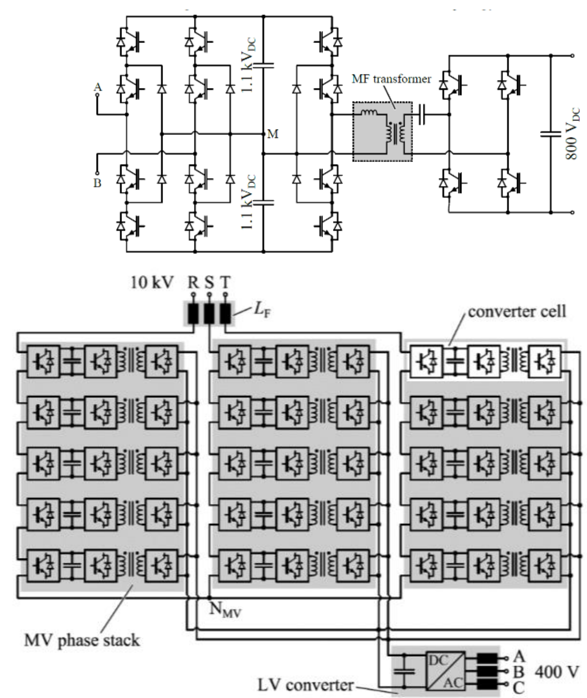
- Specifications: 1MVA, 10kV Input, 400V Output, 1700V IGBTs (1kHz/8kHz/4kHz)
- LF Transformer: 98.7 %, 16.2 kUSD, 2600kg (5700lb)

■ AC/AC



■ AC/DC





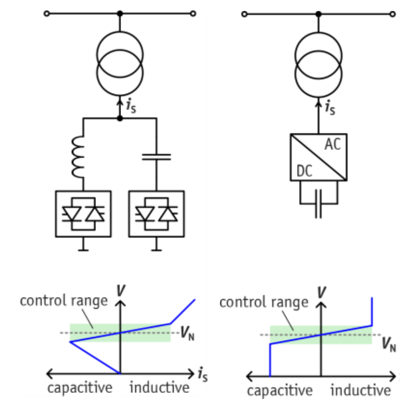
■ Clear Efficiency/Volume/Weight Advantage of SST for DC Output (98.2%)
■ Weakness of AC/AC SST vs. Simple LF Transformer (98.7%) - 5 x Costs, 2.5 x Losses

Challenge #8/10

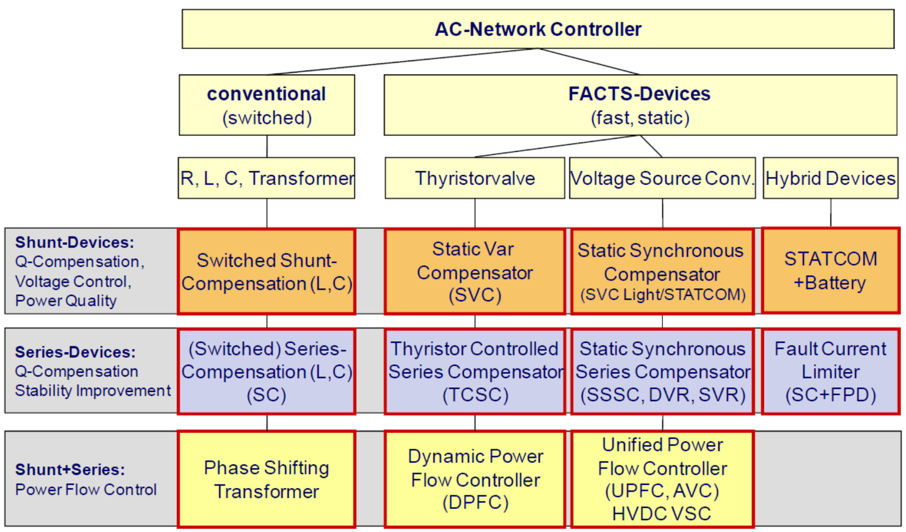
SST vs. FACTS

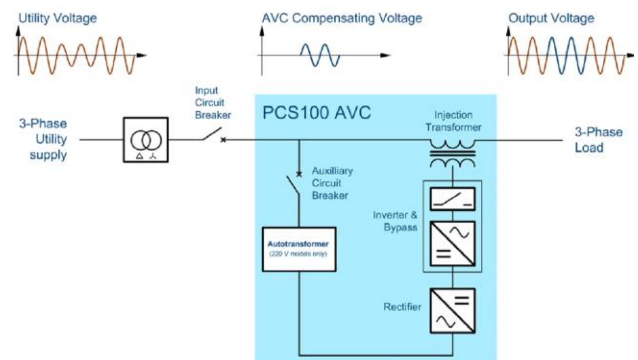
▶ Power Electronics for Flexible AC Transmission (FACTS)

- **Improvement of Voltage Quality / Power Flow Control**
- **Hybrid SSTs as Compromise between FACTS & Full-SST**



Source:
Ch. Rehtanz/TU Dortmund





- **Missing Contr. Concepts for Stable Operation of Low-Inertia Future Grids (for FACTS and SSTs)**
- **Performance/Cost/Reliability Adv./Disadv. of SST and FACTS Still to be Clarified (!)**

Challenge #9/10

Multi-Disciplinary Education

▶ Smart XXX = Power Electronics + Power Systems + ICT

- **Today:** Gap in Mutual Understanding Between the Disciplines

- **Future:**

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

— Power Conversion → Energy Management / Distribution
— Converter Stability → System Stability (Autonom. Cntrl of Distributed Converters)
— Cap. Filtering → Energy Storage & Demand Side Management
— Costs / Efficiency → Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency

► Example: US NSF/NAE-Sponsored Faculty/Industry Workshop

NATIONAL ACADEMY OF ENGINEERING

- Organized by University of Minnesota / Ned Mohan — www.cusp.umn.edu
- Reforming Electric Energy Systems Curric. in the USA — Emphasis on Sustainability

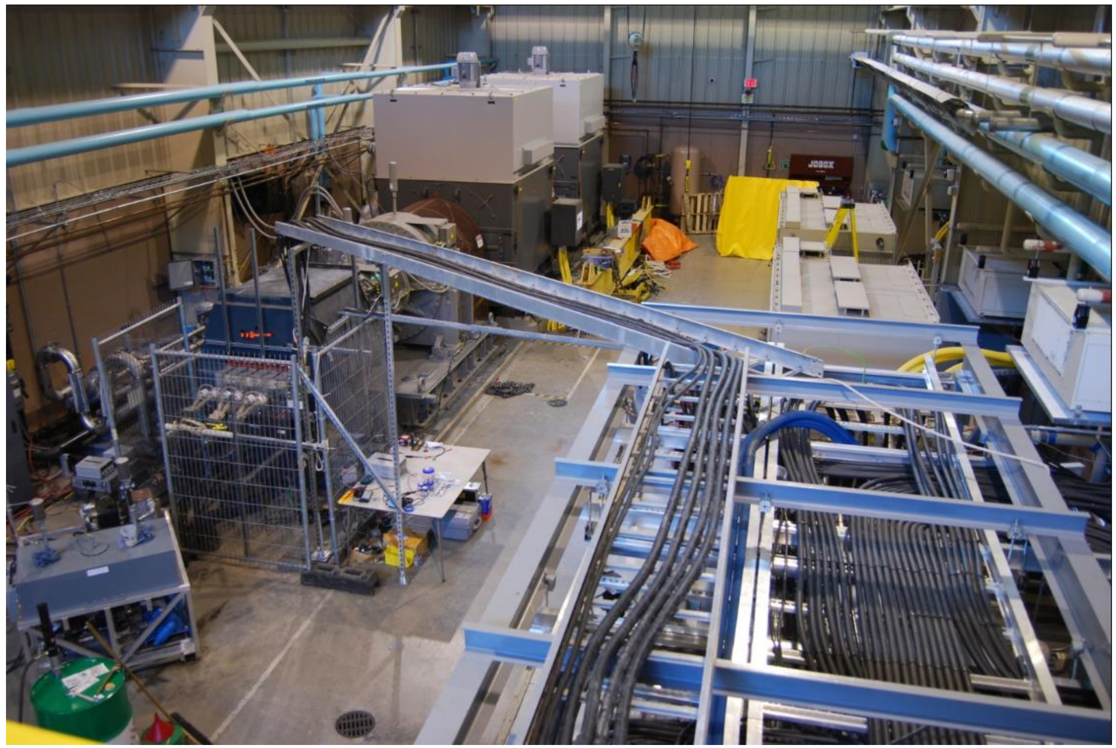
Challenge #10/10

University Medium-Voltage Power Electronics

▶ MV Power Electronics – Test Facility

- Significant Planning and Realization Effort
- Power Supply / Cooling / Control / Simulation (integrated)

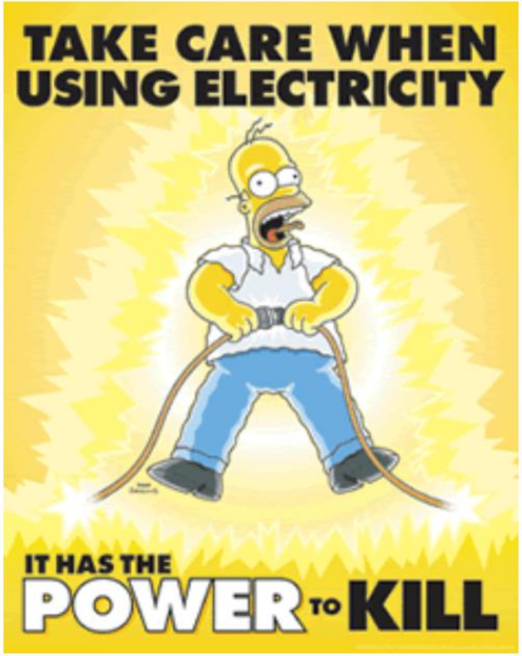
Source: Center for Advanced Power Systems / Florida State University



- Large Space Requirement / Considerable Investment (!)

▶ MV Power Electronics – Safety Issues etc.

- Ph.D. Students are Missing Practical Experience / Underestimate the Risk
- High Power Density Power Electronics Differs from Conv. HV Equipment
- Very Careful Training / Remaining Question of Responsibility



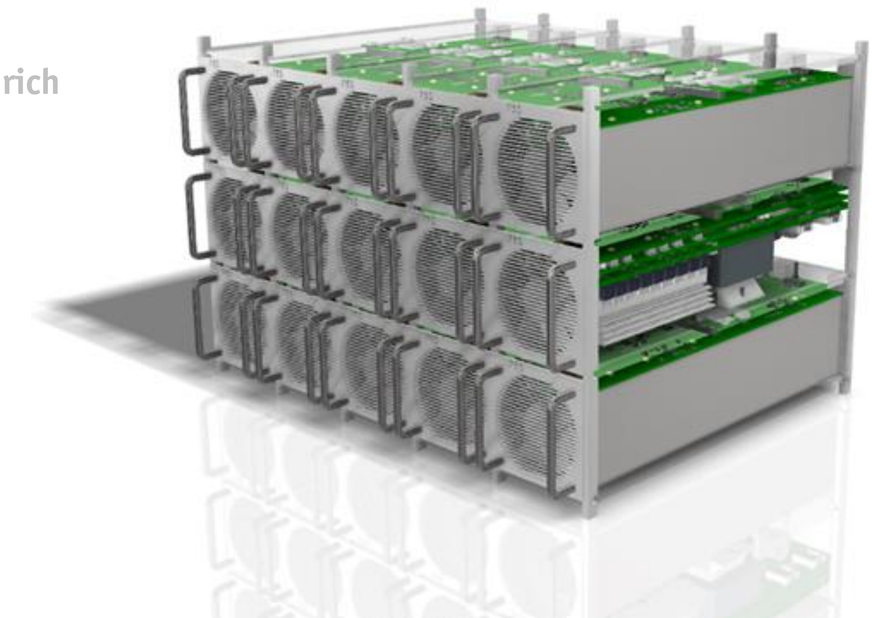
… ESPECIALLY @ Medium Voltage (!)

- High Costs / Long Manufacturing Time of Test Setups
- Complicated Testing Due to Safety Procedures → Lower # of Publications / Time

► Alternative – Scaled Demonstrator Systems

- Full Functionality at Relatively Safe Power and Voltage Levels

- E.g.: SST Demonstrator @ ETH Zurich
  $400V_{AC}$ - $800V_{DC}$ - $400V_{AC}$
  15kVA



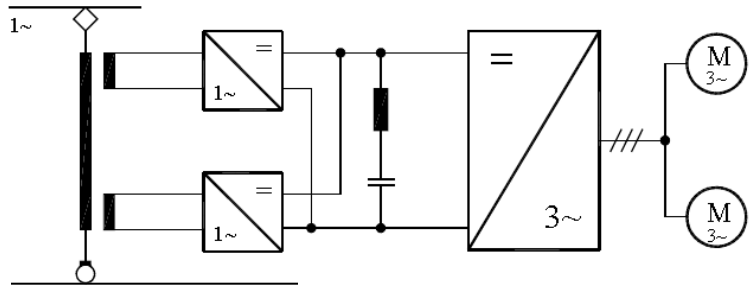
- Allows Analysis of All Basic Functionalities / Testing of Control Hardware
- No Testing Concerning Parasitics / Isolation Stresses / Efficiency etc.
- Question of Full Simulation vs. Scaled Demonstration

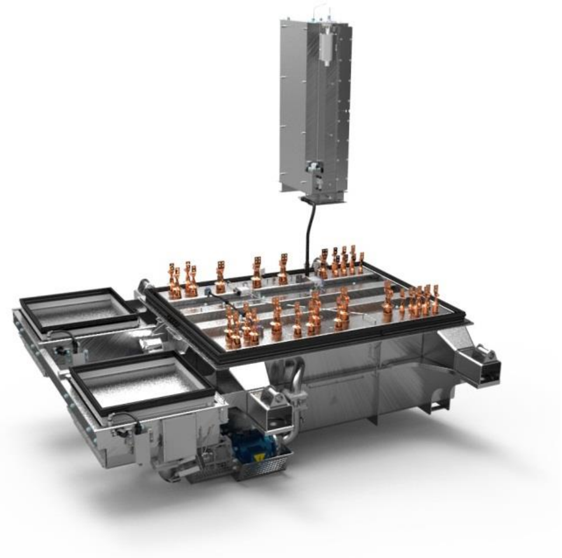
Near Future SST Applications

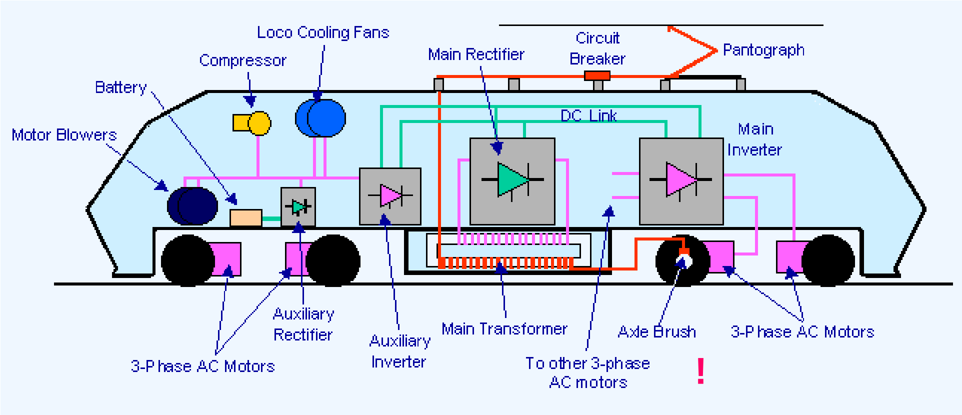
Next Generation Locomotives
Direct MV_{AC} → LV_{DC} Power Supply →

▶ Classical Locomotives

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







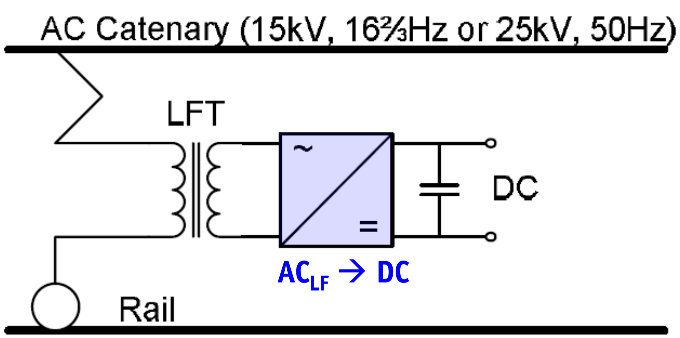
- **Transformer:**

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

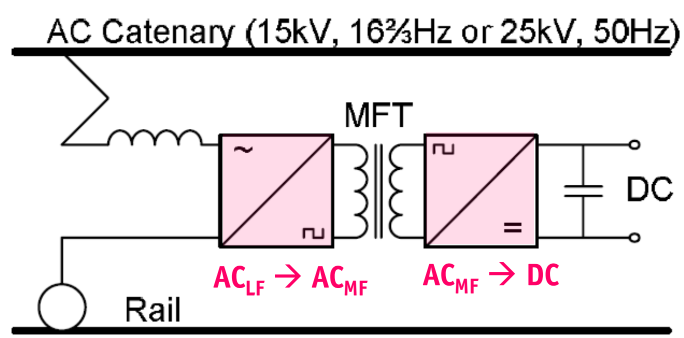
▶ Next Generation Locomotives

- 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).

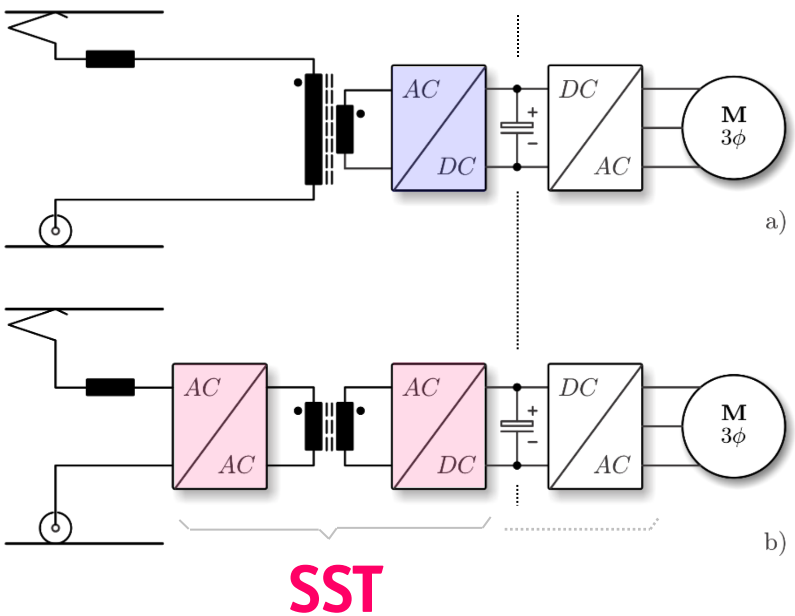


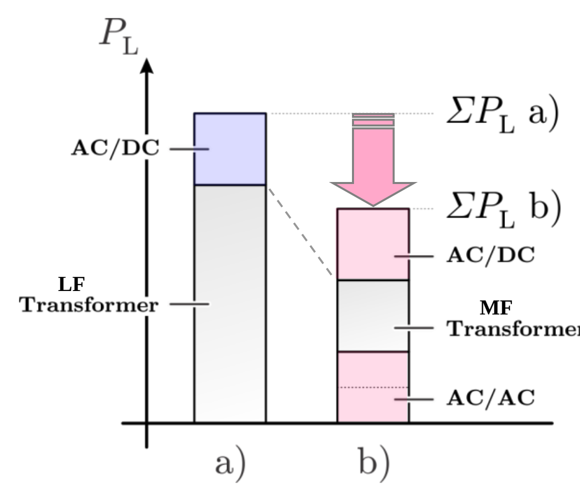
AC-DC conversion with medium frequency transformer (MFT).

- Replace LF Transformer by *Medium Frequency* Power Electronics Transformer → **SST**
- *Medium Frequency* Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives





- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

▶ 1ph. AC/DC Power Electronic Transformer - PET

ABB

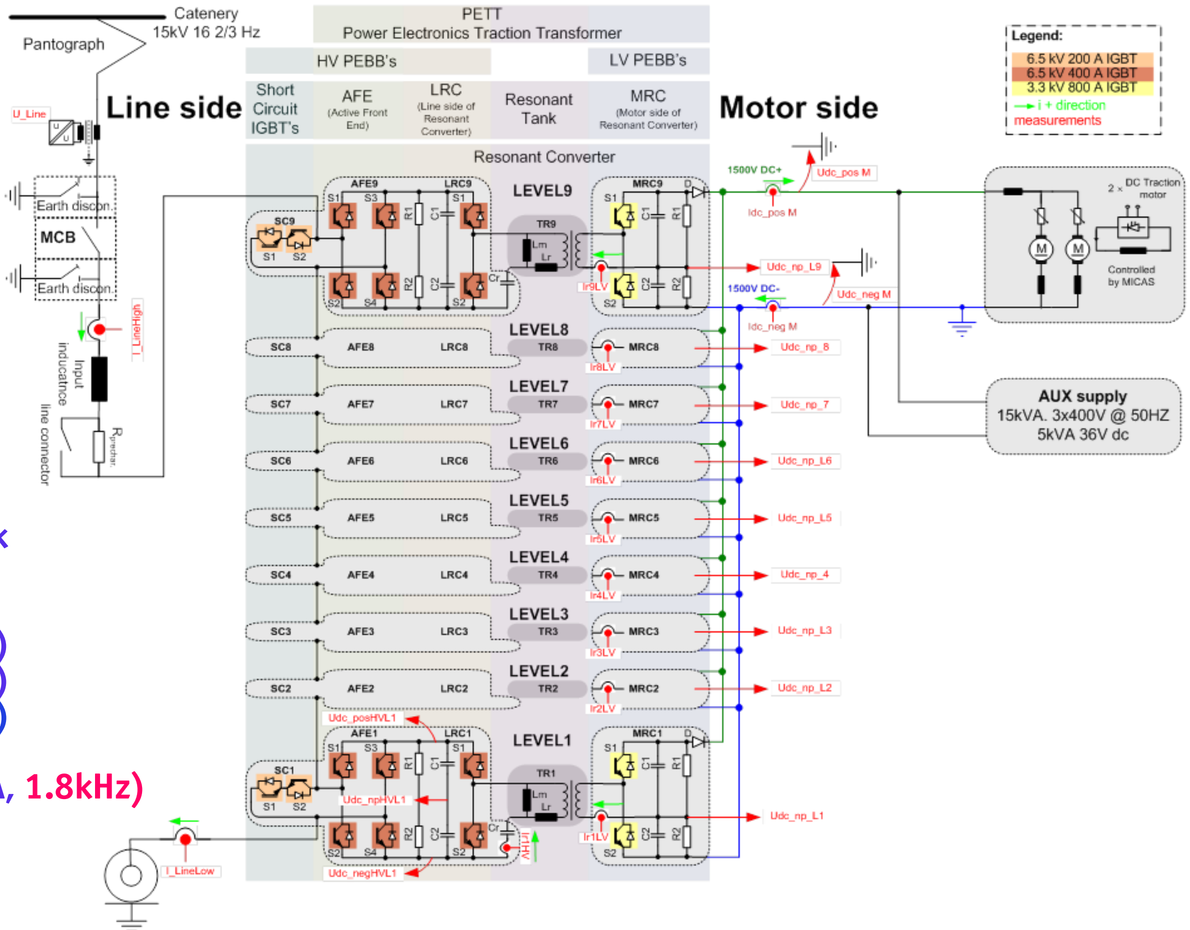
- Dujic et al. (2011)

- Rufer (1996)
- Steiner (1997)
- Heinemann (2002)

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

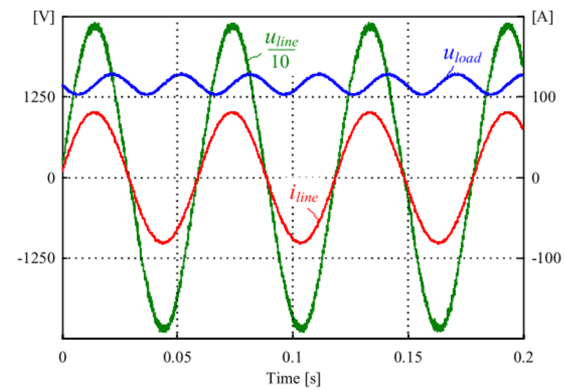
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

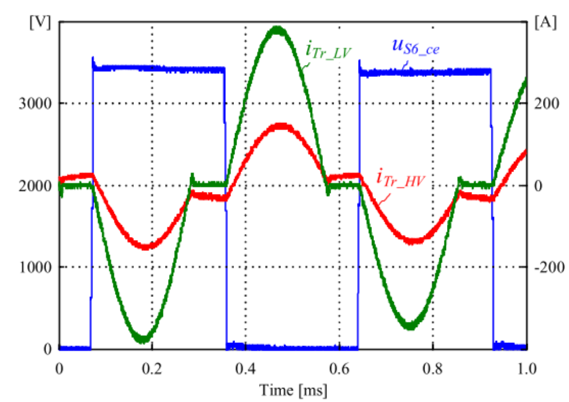
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke



▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

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

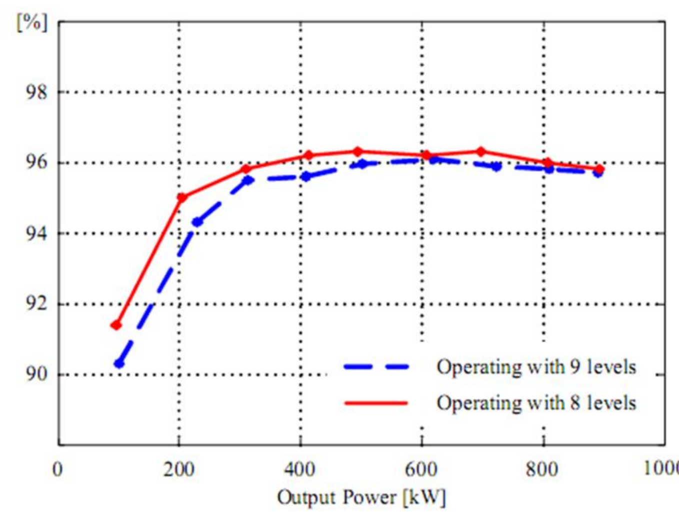




▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

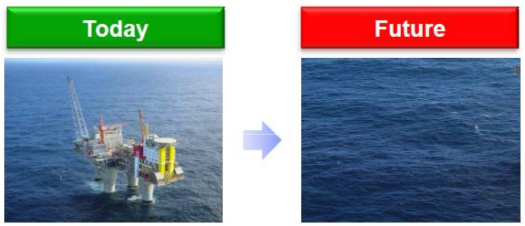
- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages

Efficiency



▶ Future Subsea Distribution Network – O&G Processing

- Devold (ABB 2012)



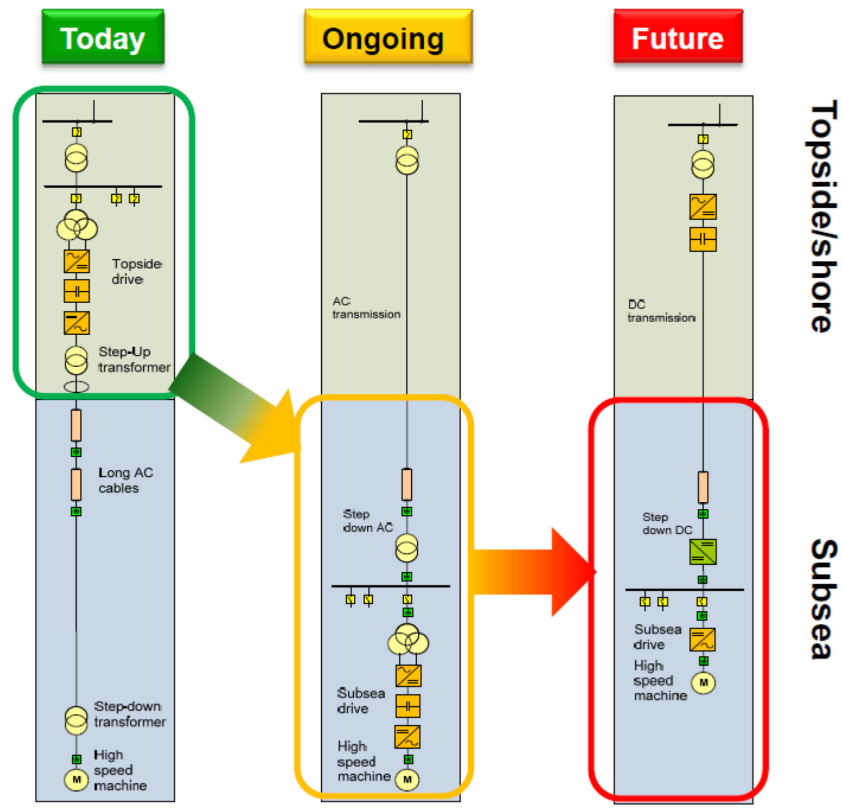
O&G processing

Today	Future
Platform/floaters based	Subsea

Power supply

Today	Future
Platform based power generation or power from shore	Long distance power from shore

ABB investing in subsea electrification & automation solutions to enable future subsea processing



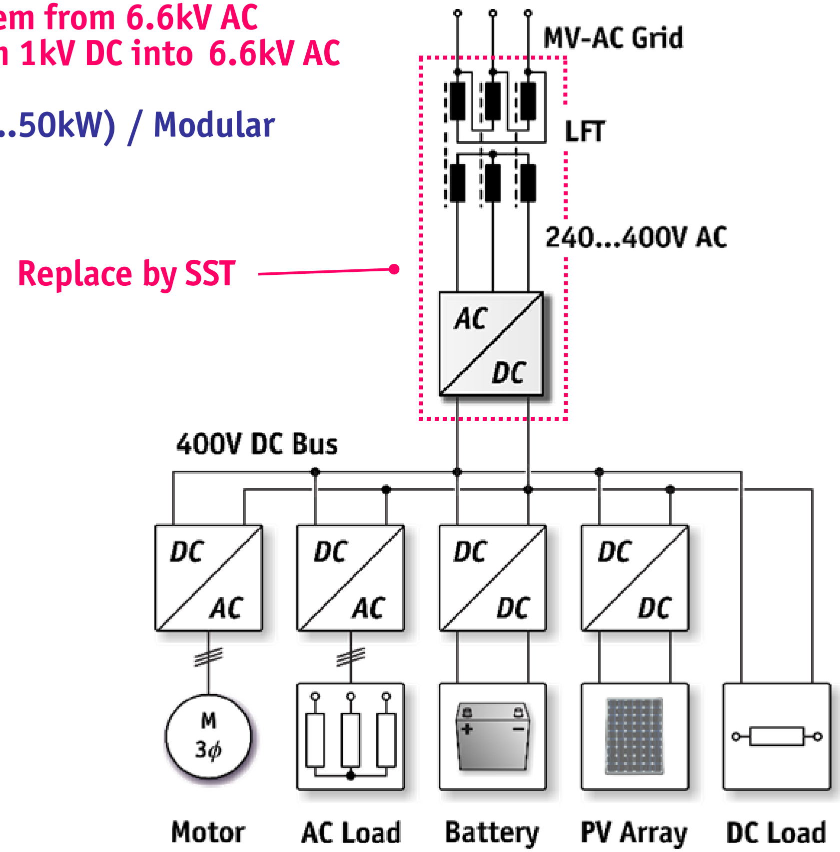
- **Transmission Over DC, No Platforms/Floaters**
- **Longer Distances Possible**
- **Subsea O&G Processing**

- **Weight Optimized Power Electronics**

▶ Unidirectional SST Topologies

- Direct Supply of 400V/48V DC System from 6.6kV AC
- Direct PV Energy Regeneration from 1kV DC into 6.6kV AC

- Even for Relatively Low Power (25...50kW) / Modular
- All-SiC Realization (50kHz XFMR)



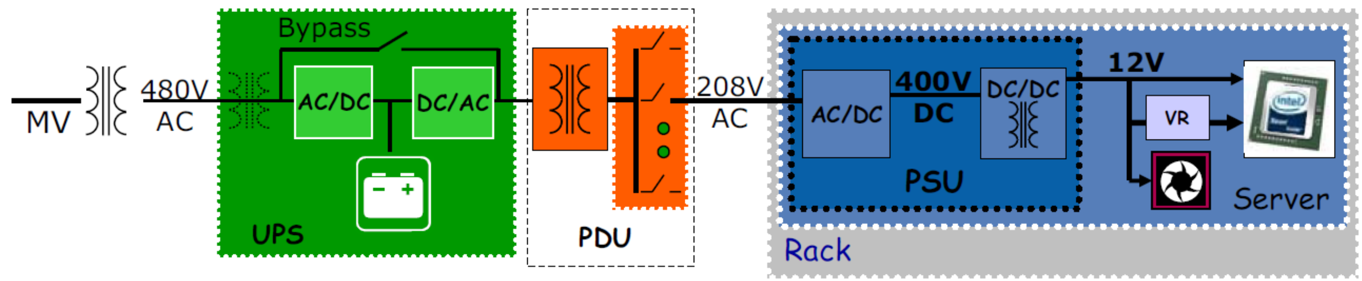
- Comparative Evaluation of SST Topologies based on Comp. Load Factors

▶ AC vs. Facility-Level DC Systems for Datacenters

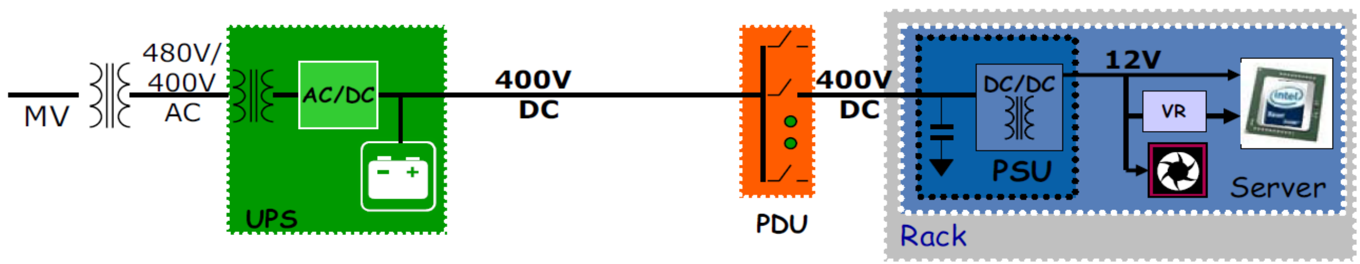
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US 480V$_{AC}$ Distribution

Source: intel 2007



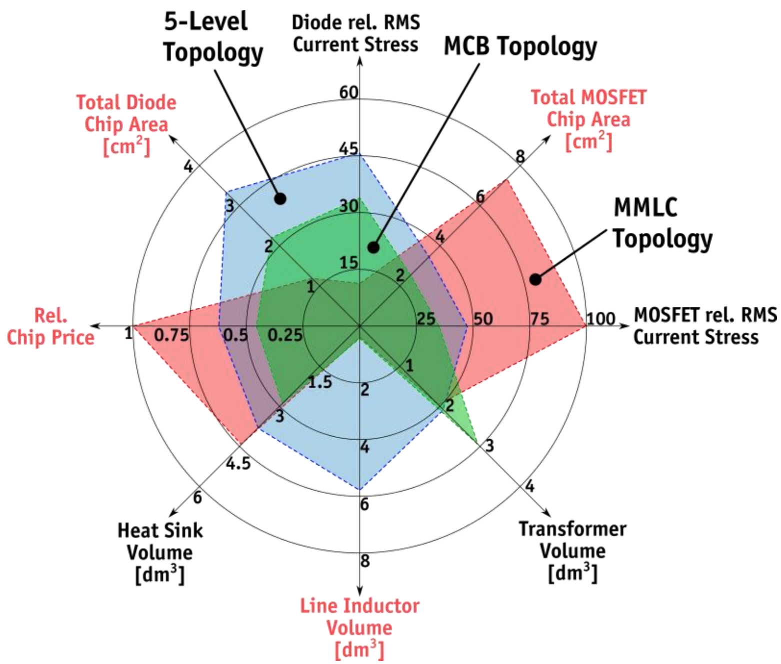
— Facility-Level 400 V$_{DC}$ Distribution

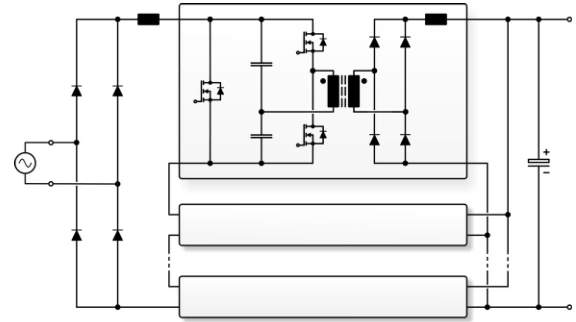


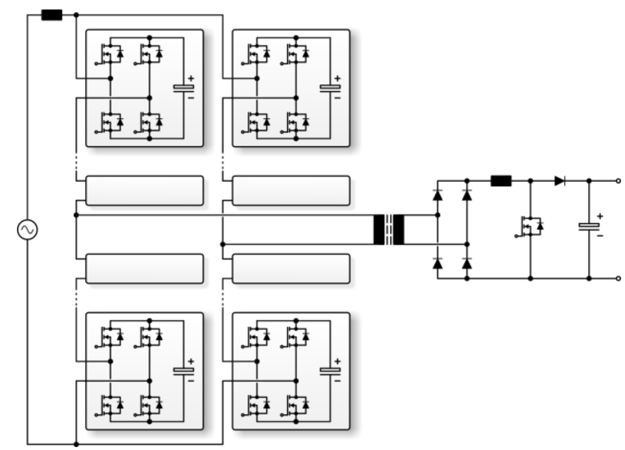
- Future Concept: Direct 6.6kV AC → 400V DC Conversion / Unidirectional SST

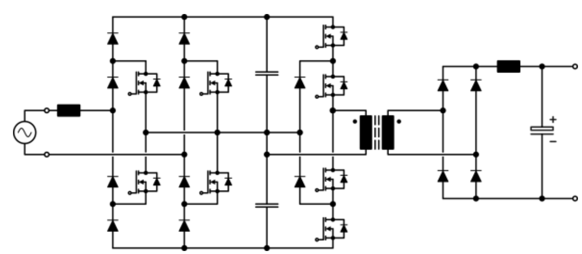
▶ Unidirectional SST Topologies

- Direct Supply of 400V DC System from 6.6kV AC
- All-SiC Realization (50kHz XFMR)
- $P =$ 25kW









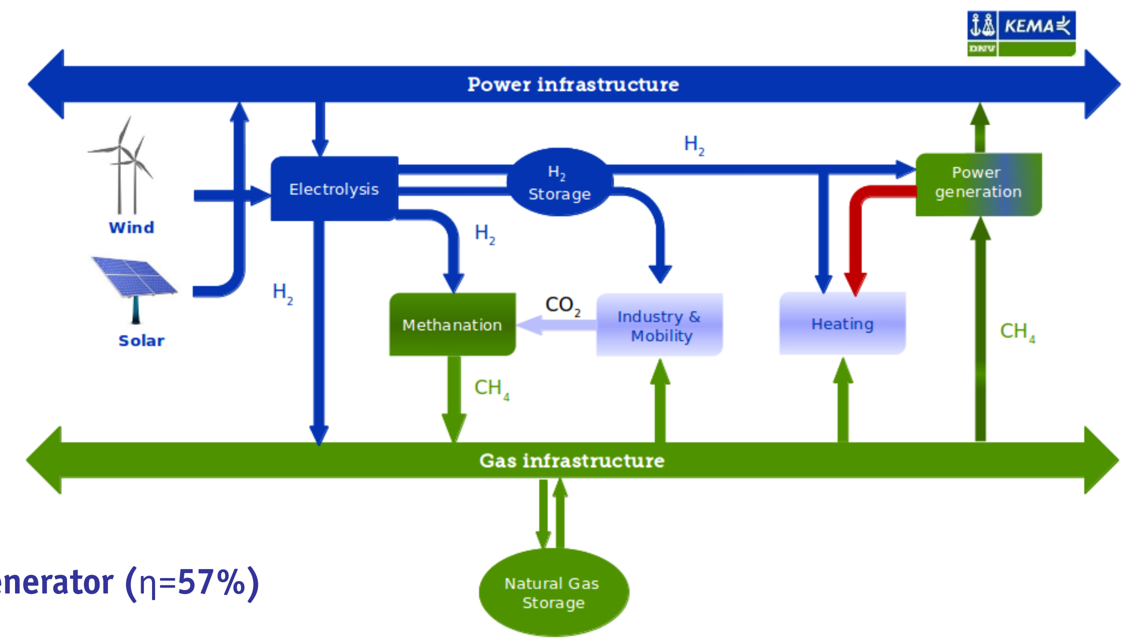
- Comparative Evaluation based on Comp. Load Factors

▶ Power-to-Gas

- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen
  → Fuel-Cell Powered Cars
  → Heating

- High-Power @ Low DC Voltage (e.g. 220V)
- Very Well Suited for MV-Connected SST-Based Power Supply

– Hydrogenics 100 kW H_2-Generator (η=57%)



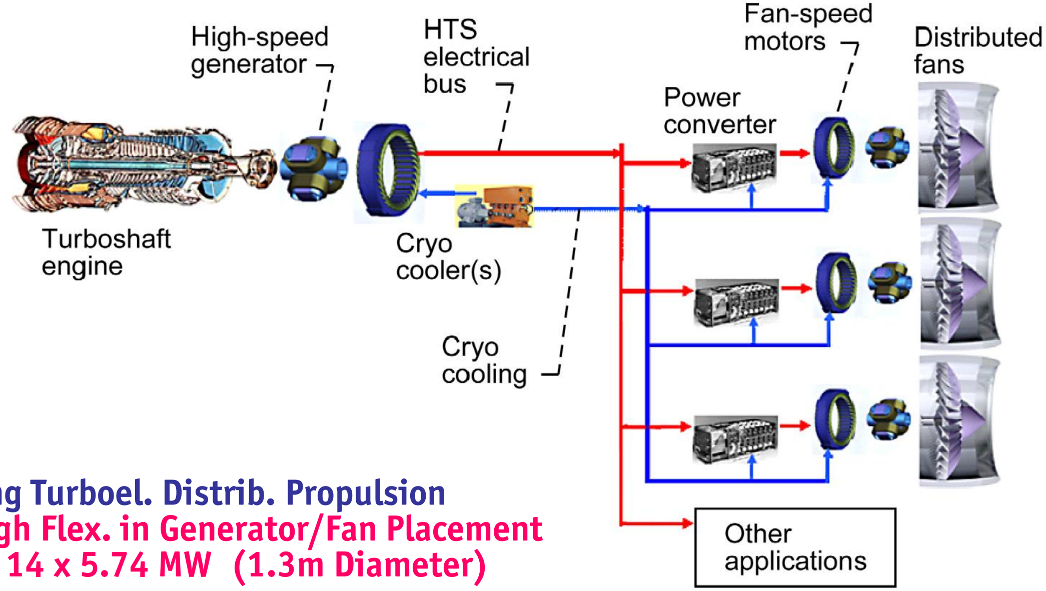
► Future Hybrid or All-Electric Aircraft (1)

Source: EADS

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- Until 2050: Cut CO_2 Emissions by 75%, NO_x by 90%, Noise Level by 65%

▶ Future Hybrid or All-Electric Aircraft (2)

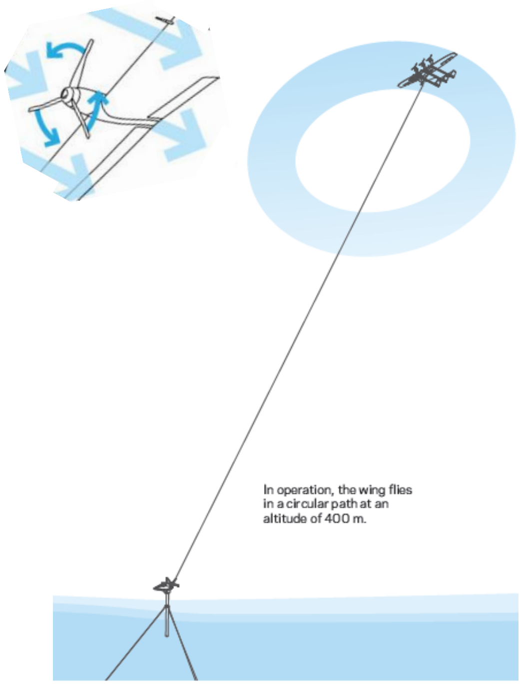
Source: NASA



- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

▶ Airborne Wind Turbines

- **Power Kite Equipped with Turbine / Generator / Power Electronics**
- **Power Transmitted to Ground Electrically**
- **Minimum of Mechanically Supporting Parts**



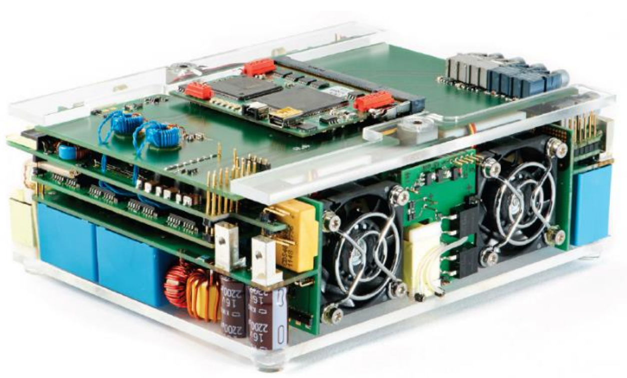
MAKANI POWER

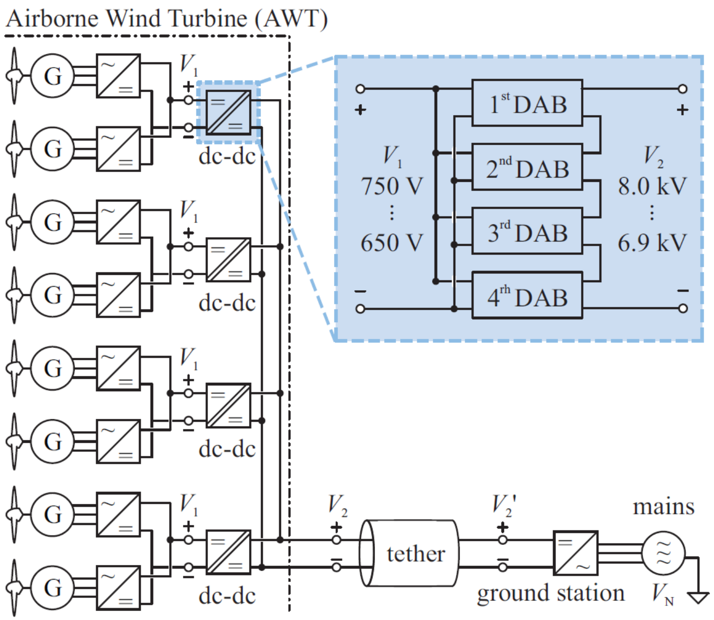
Google X

▶ 100kW Airborne Wind Turbine

■ Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer - $8kV_{DC} \rightarrow 700V_{DC}$

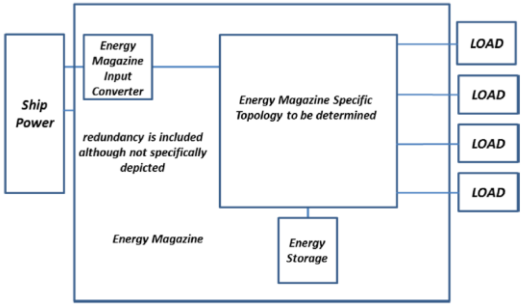
– Medium Voltage Port	1750 ... 2000 V_{DC}
– Switching Frequency	100 kHz
– Low Voltage Port	650 ... 750 V_{DC}
– Cell Rated Power	6.25 kW
– Power Density	5.2kW/dm^3
– Specific Weight	4.4kW/kg





▶ Future Military Applications

■ **MV Cellular DC Power Distribution on Future Combat Ships etc.**



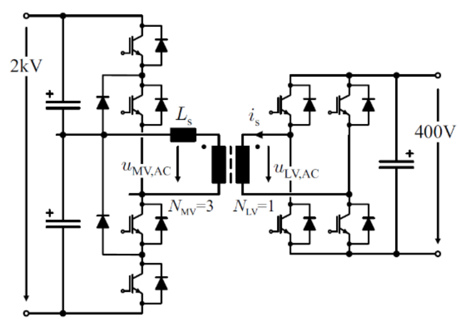
Source: General Dynamics

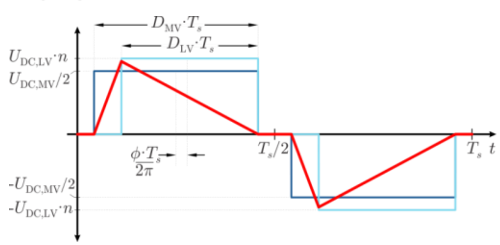
- ▶ "Energy Magazine" as Extension of Electric Power System / Individual Load Power Conditioning
- ▶ Bidirectional Power Flow for Advanced Weapon Load Demand
- ▶ Extreme Energy and Power Density Requirements

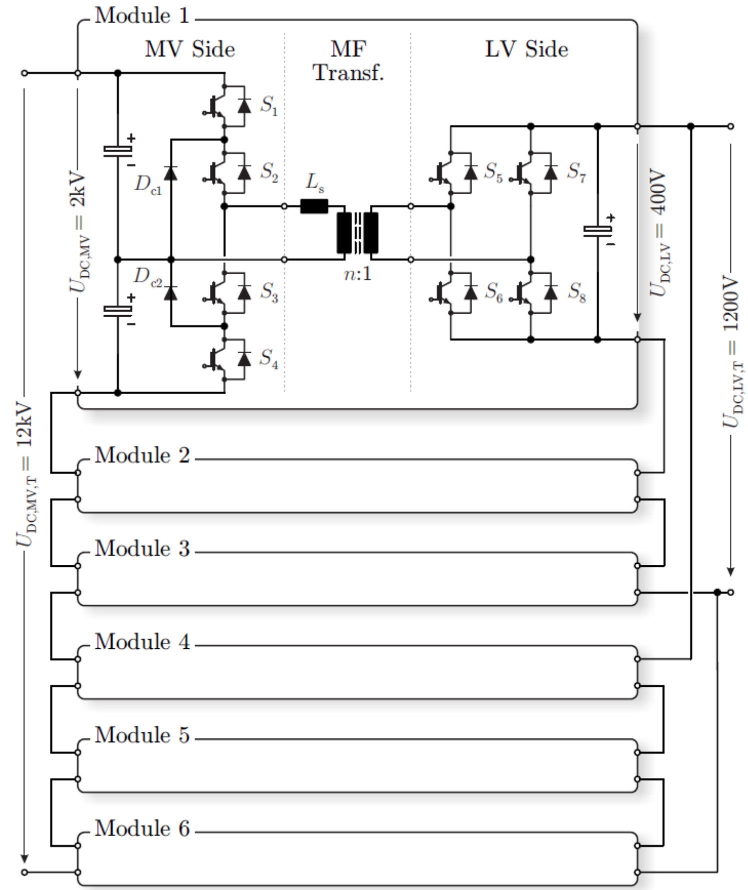
▶ MV→LV DCDC Conversion

- Rated Power 1MW (MEGA Cube)
- Frequency 20kHz
- Input Voltage $12kV_{DC}$
- Output Voltage $1.2kV_{DC}$

- Efficiency Goal 97%







■ ISOP Topology – 6/2x3 - Input / Output

MV – LV DCDC Conversion

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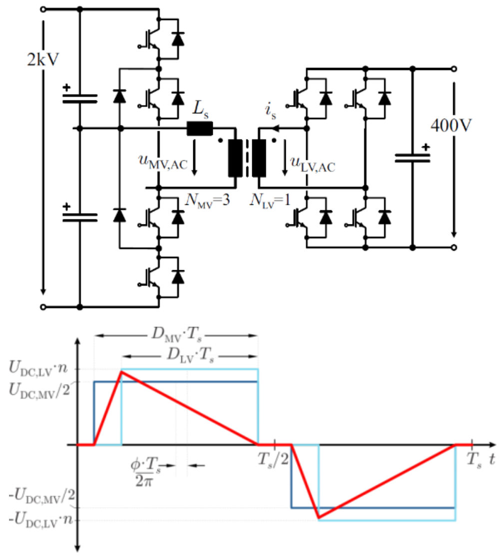
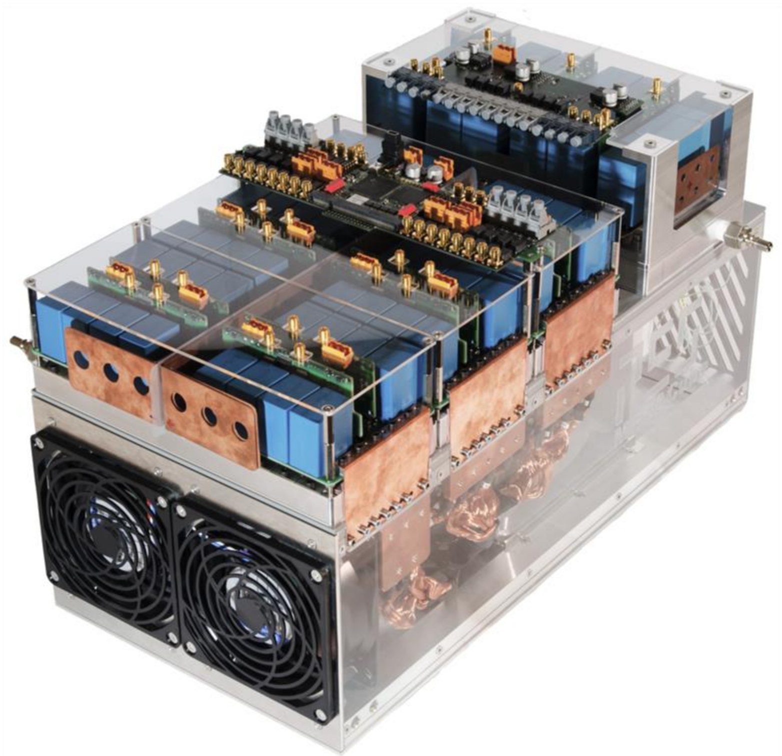


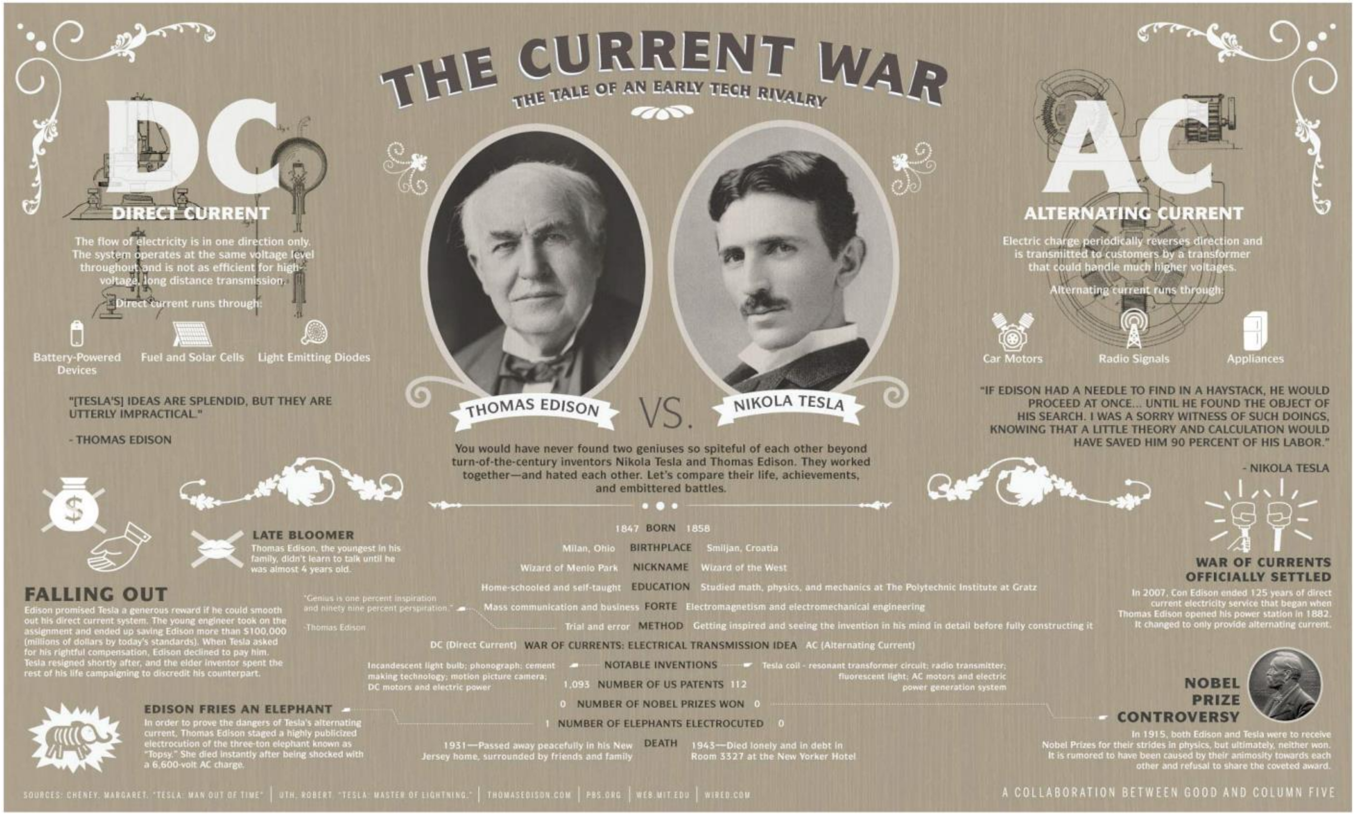


- ISOP Topology – 6/2x3 - Input / Output

Conclusions

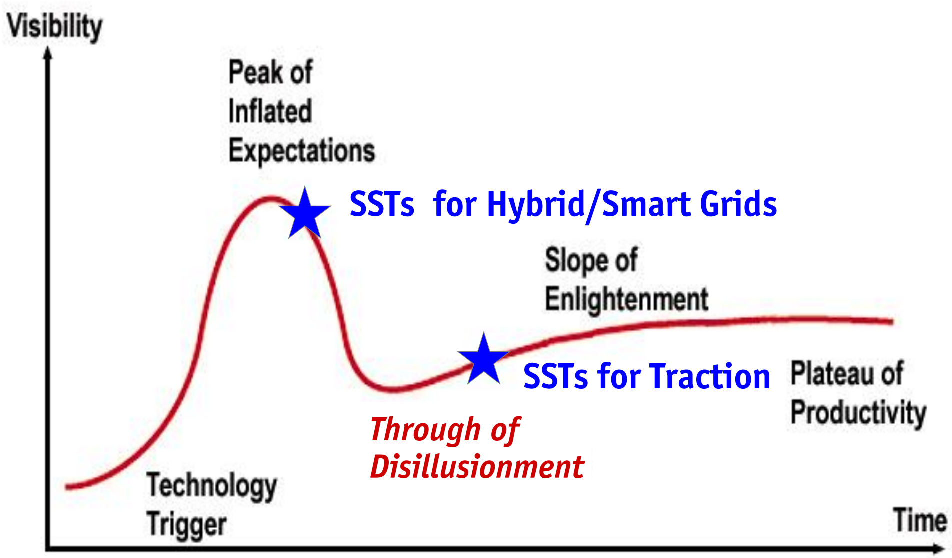
SST Evaluation / Application Areas
Future Research Areas

▶ SST Ends the “War of Currents”



■ No “Revenge” of T.A. Edison but Future “Synergy” of AC and DC Systems !

▶ SST Technology Hype Cycle



- Different States of Development of SSTs for
  - Traction Applications
  - Hybrid / Smart Grid Applications

▶ SST for Grid Applications

Source: www.diamond-jewelry-pedia.com

SST Research Status

Required for Successful Application

■ Huge *Multi-Disciplinary* Challenges / Opportunities (!)

▶ SST Limitations – Application Areas

■ SST Limitations

- Efficiency (Rel. High Losses 2-6%)
- High Costs (Cost-Performance Ratio still to be Clarified)
- Limited Volume Reduction vs. Conv. Transf. (Factor 2-3)
- Limited Overload Capability
- (Reliability)

■ Potential Application Areas

- Traction Vehicles
- UPS Functionality with MV Connection
- Temporary Replacement of Conv. Distribution Transformer
- Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
- Military Applications

▶ Applications for Volume/Weight Limited Systems where 2-4 % of Losses Could be Accepted

▶ Overall Summary

- SST is NOT a 1:1 Replacement for Conv. Distribution Transformers
- SST will NOT Replace All Conv. Distribution Transformers (even in Mid Term Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations

→ SST Requires a Certain Application Environment (until Smart Grid is Fully Realized)
→ SST Preferably Used in LOCAL Fully SMART EEnergy Systems

@ Generation End (e.g. Nacelle of Windmills)
@ Load End - Micro- or Nanogrids (incl. Locomotives, Ships etc.)

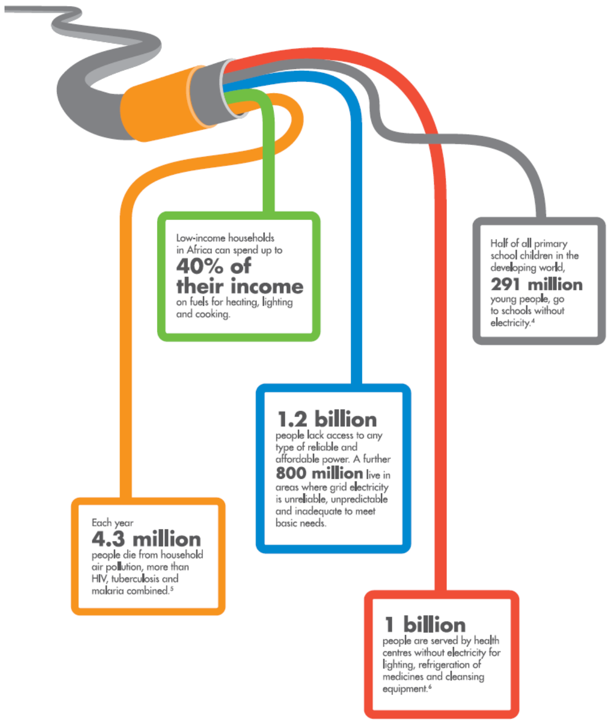
- Environments with Pervasive Power Electronics for Energy Flow Control (No Protection Relays etc.) →
- Environments which Could be Designed for SST Application
- (Unidirectional) Medium Voltage Coupling of DC Distribution Systems

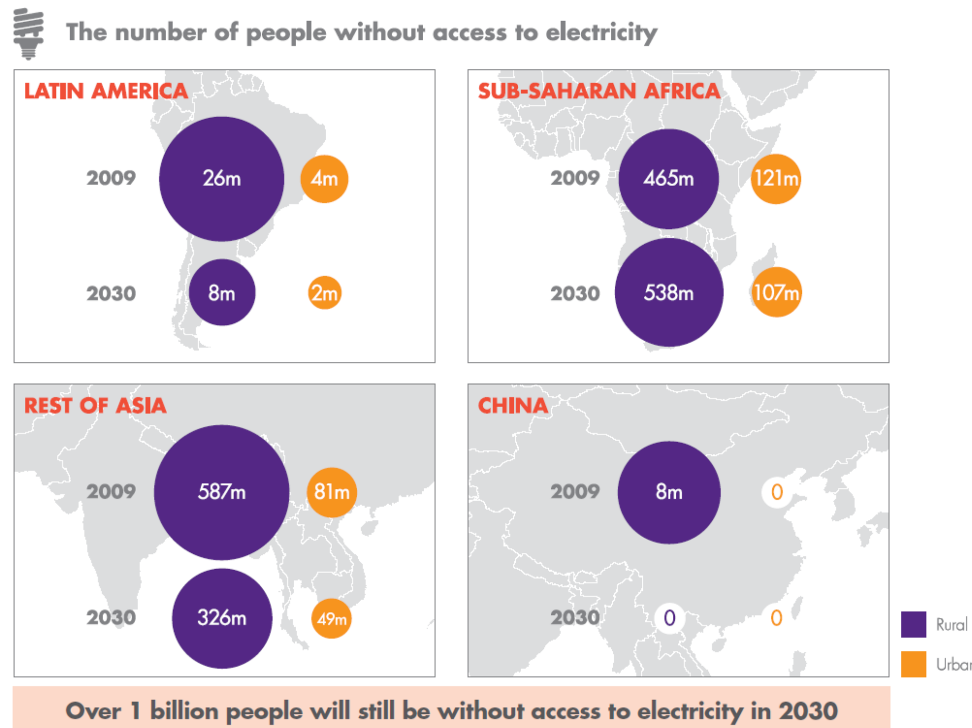
… One Last Comment

Electrification of the Developing World →

Rural Electrification in the Developing World

2 Billion "Bottom-of-the-Pyramid People" are Lacking Access to Clean Energy





Source: IEA, Dalberg Analysis, IFC

→ Urgent Need for Village-Scale Solar DC Mirogrids etc.
→ 2 US$ for 2 LED Lights + Mobile-Phone Charging / Household / Month (!)

Thank You!

Questions ?