ETH zürich

Solid-State Transformers in Future Traction and Smart Grids

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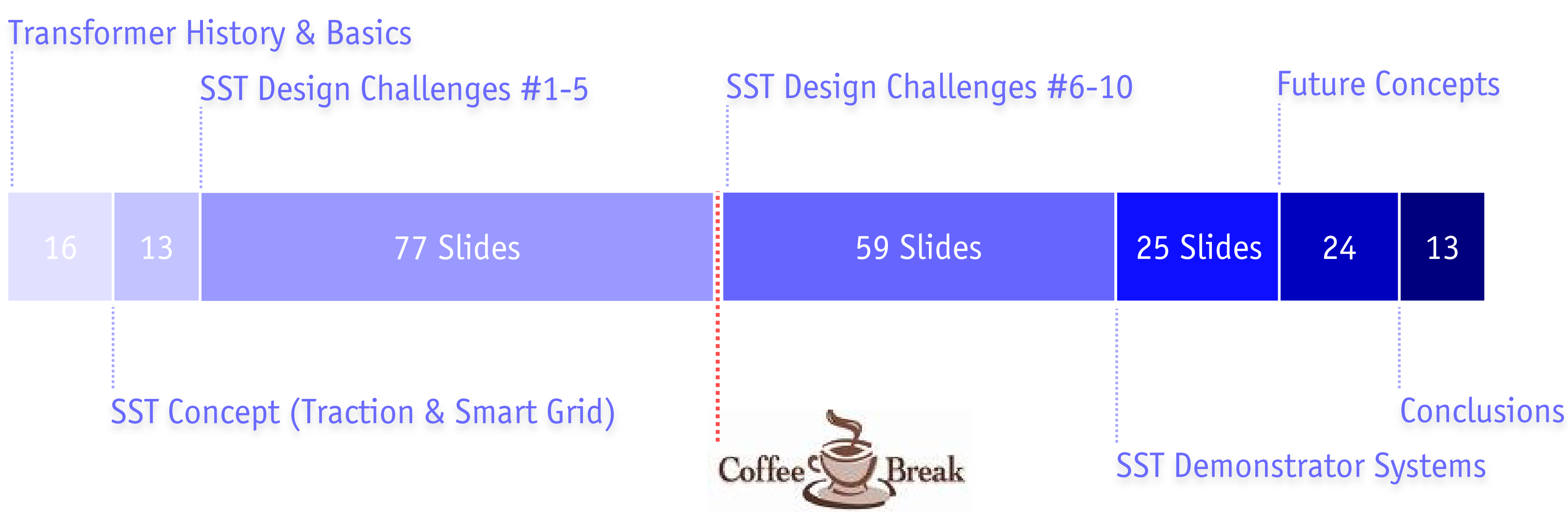
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

PCIM EUROPE

Seminar 9

Agenda


Transformer History & Basics
SST Design Challenges #1-5
SST Design Challenges #6-10
Future Concepts
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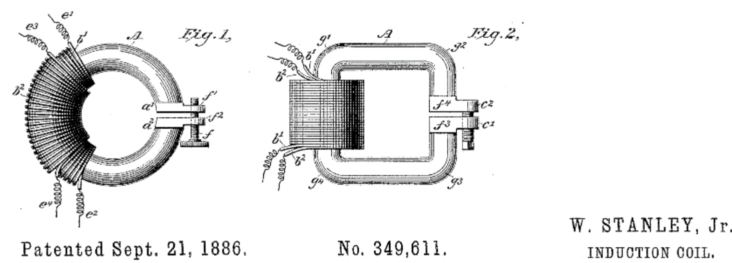
SST Concept (Traction & Smart Grid)
Coffee Break
SST Demonstrator Systems
Conclusions

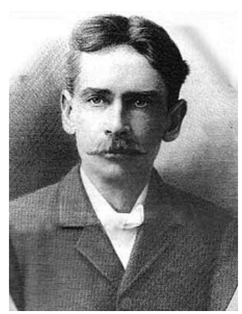
History of Transformers

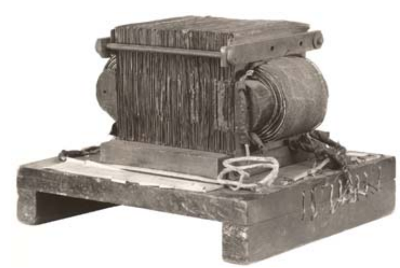
*Low Frequency and
Solid-State Transformers*

► Classical Transformer (XFMR) — History (1)

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







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

► Classical Transformer — History (2)

UNITED STATES PATENT OFFICE.

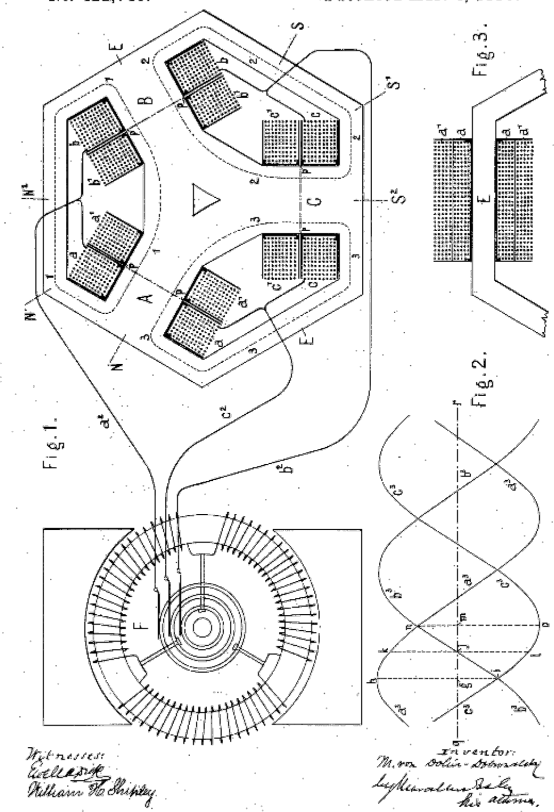
MICHAEL VON DOLIVO-DOBROWOLSKY, OF BERLIN, GERMANY, ASSIGNOR TO THE ALLGEMEINE ELEKTRICITÄTS-GESELLSCHAFT, OF SAME PLACE.

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 (Gen. + XFMR + Transm. + El. Motor + Lamps, 40Hz, 25kV, 175km)

► Valve-Controlled MF Transformer Link DC/AC Converter

■ Isolated Medium Frequency Link DC/AC Converter

Patented Feb. 19, 1929. 1,702,402

UNITED STATES PATENT OFFICE.

LOUIS A. HAZELTINE, OF HOBOKEN, NEW JERSEY.

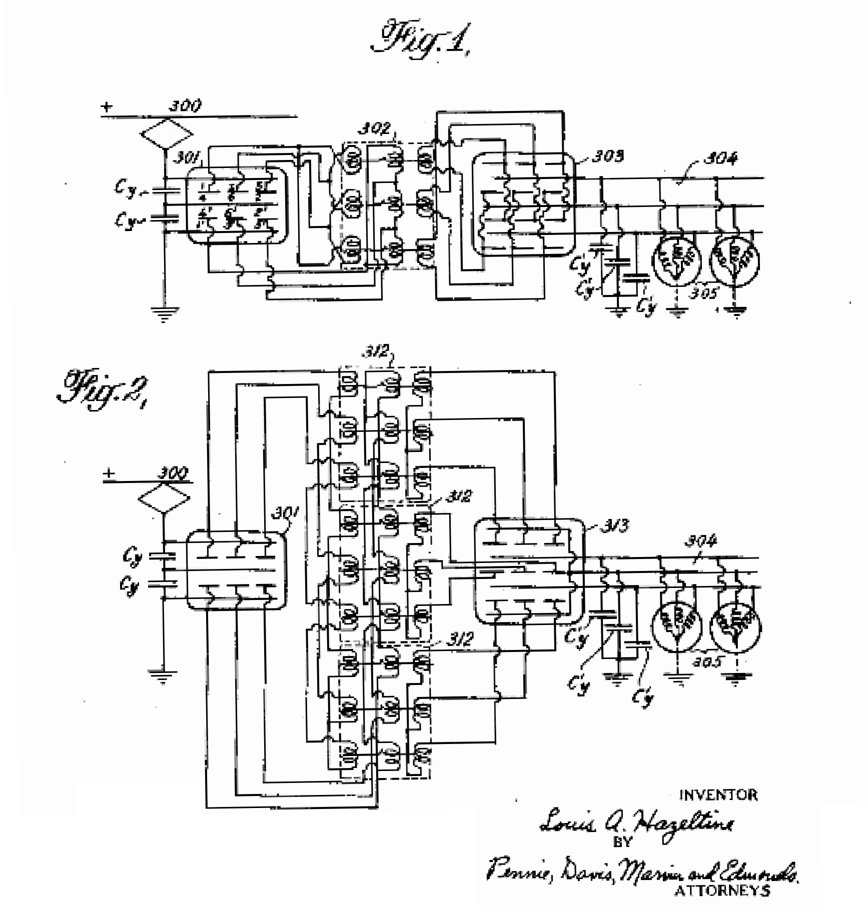
METHOD AND APPARATUS FOR CONVERTING ELECTRIC POWER.

Original application filed July 5, 1923, Serial No. 649,536, and in Great Britain July 4, 1924. Divided and this application filed January 20, 1927. Serial No. 162,237.

1923 !

I claim:

1. A system for operating an alternating-current motor from a source of direct-current power, which comprises a cascade electrostatically controlled valve converter which converts the direct-current power first into high-frequency power and then into low-frequency polyphase power for supply to the motor, two positively connected control commutators for said valve converter, a set of brushes for each of said commutators, and means for driving one set of brushes relatively to the other, the relative motion determining the frequency supplied to the motor.



United States Patent Office

3,517,300
Patented June 23, 1970

1

3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK

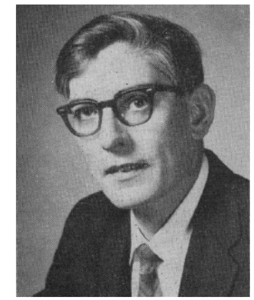
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York

Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims

1968 !

ABSTRACT OF THE DISCLOSURE

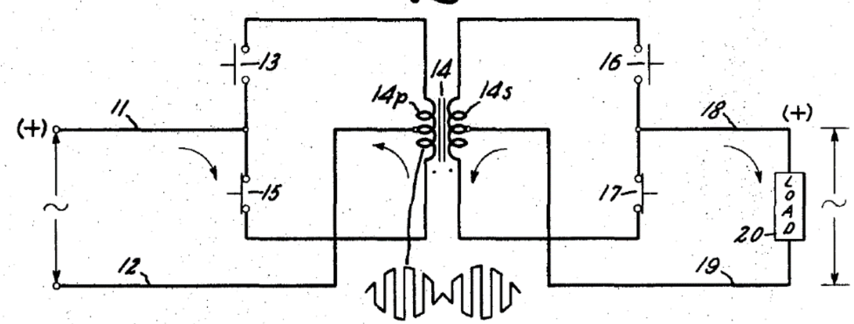
Several single phase solid state power converter circuits have a high frequency transformer link whose windings are connected respectively to the load and to a D-C or low frequency A-C source through inverter configuration switching circuits employing inverse-parallel pairs of controlled turn-off switches (such as transistors or gate turn-off SCR's) as the switching devices. Filter means are connected across the input and output terminals. By synchronously rendering conductive one switching device in each of the primary and secondary side circuits, and alternately rendering conductive another device in each switching circuit, the input potential is converted to a high frequency wave, transformed, and reconstructed at the output terminals. Wide range output voltage control is obtained by phase shifting the turn-on of the switching devices on one side with respect to those on the other side by 0° to 180°, and is used to effect current limiting, current interruption, current regulation, and voltage regulation.



Filed April 16, 1968

Inventor:
William McMurray
by Donald R. Campbell
His Attorney

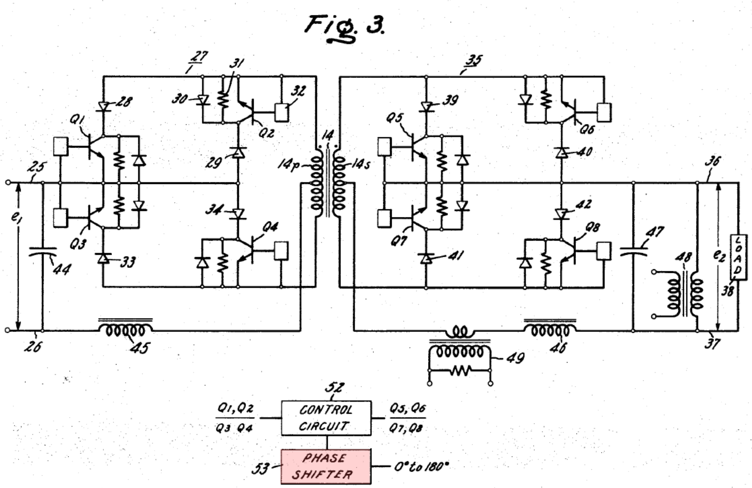
Fig. 1a

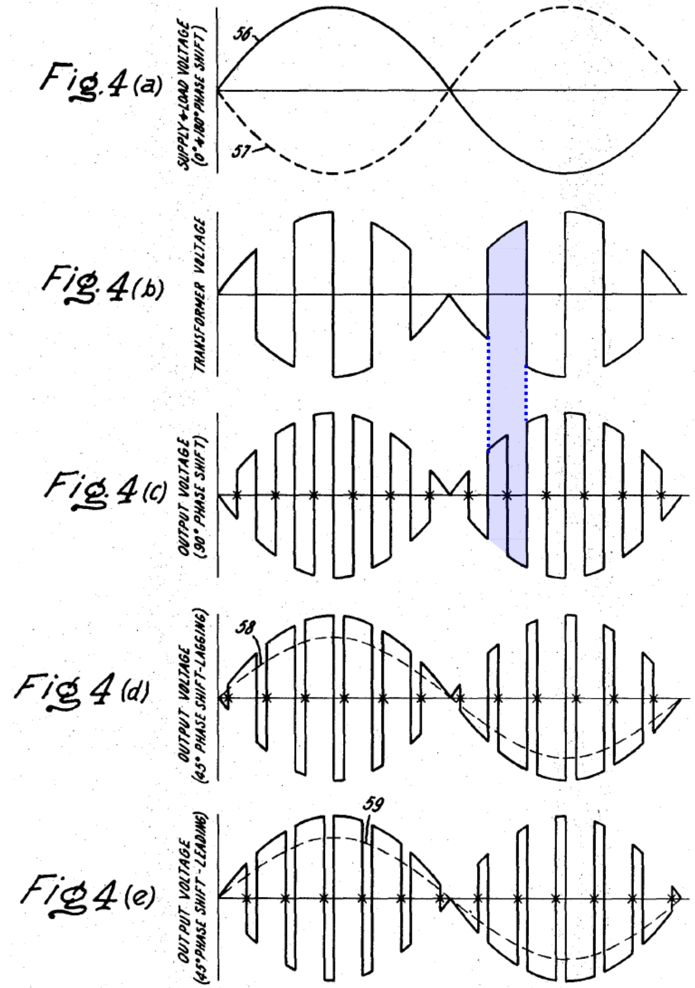


- Electronic Transformer ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption

▶ Electronic Transformer

- Inverse-Paralleled Pairs of Turn-off Switches
- 50% Duty Cycle of Input and Output Stage





- $f_1 = f_2$ → Not Controllable (!)
- Voltage Adjustment by Phase Shift Control (!)

IEEE TRANSACTIONS ON INDUSTRY AND GENERAL APPLICATIONS, VOL. IGA-7 NO. 4, JULY/AUGUST 1971 ← 1971 451

The Thyristor Electronic Transformer: a Power Converter Using a High-Frequency Link

WILLIAM McMURRAY, SENIOR MEMBER, IEEE

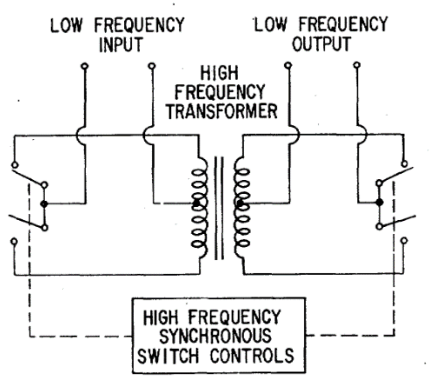


Fig. 1. Principle of electronic transformer.

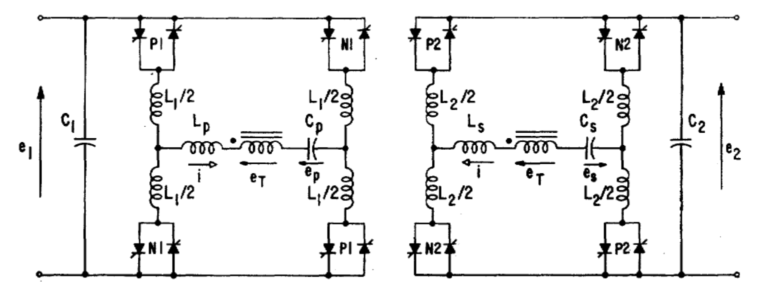


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

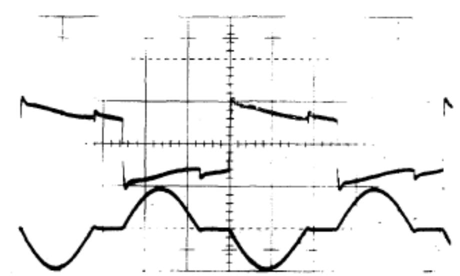


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

- Input / Output Isolation
- "Fixed" Voltage Transfer Ratio (!)
- Current Limitation Feature
- $f \approx f_{res}$ (ZCS) Series Res. Converter

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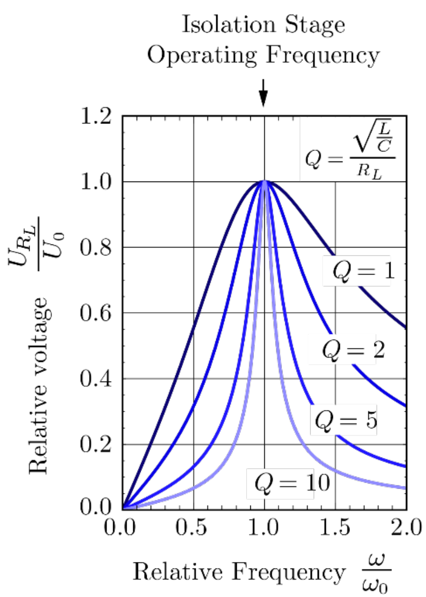

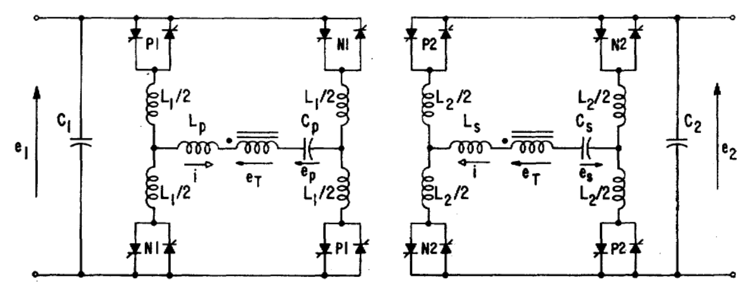

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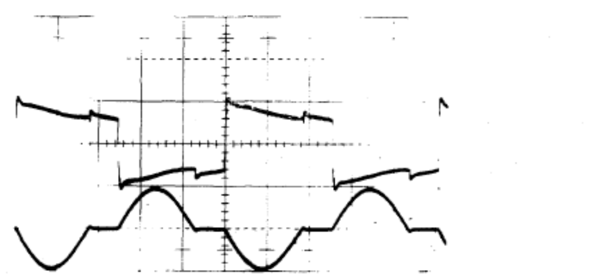

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- Input / Output Isolation
- "Fixed" Voltage Transfer Ratio (!)
- Current Limitation Feature
- $f \approx f_{res}$ (ZCS) Series Res. Converter

United States Patent [19] — **DeDoncker et al.**

[11] **Patent Number: 5,027,264**

[45] **Date of Patent: Jun. 25, 1991** ← 1991

[54] **POWER CONVERSION APPARATUS FOR DC/DC CONVERSION USING DUAL ACTIVE BRIDGES**

[75] Inventors: **Rik W. DeDoncker**, Niskayuna, N.Y.; **Mustansir H. Kheraluwala; Deepakraj M. Divan**, both of Madison, Wis.

[22] Filed: **Sep. 29, 1989**

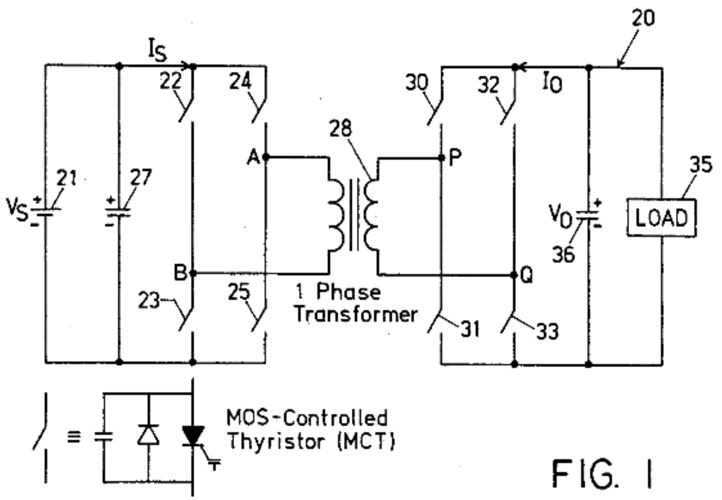


FIG. 1

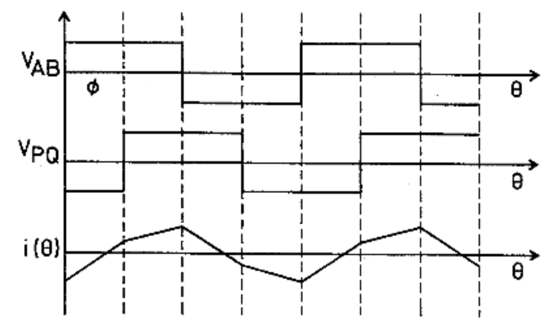


FIG. 2

- Soft Switching in a Certain Load Range
- **Power Flow Control by Phase Shift between Primary & Secondary Voltage**

▶ 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 !**

Record, IEEE Power El
Atlanta, Ga., USA, (16–20
Nienhaus & Bowers, "An
Filter", PESC '78 Record,
Middlebrook et al, "A Ge
Modelling Switching–Conv
'76 Record, pp. 18–31.

Primary Examiner—Willian
Attorney, Agent, or Firm—
St. Amand; W. C. Dauben

[57] **ABST**

OTHER PUBLICATIONS

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

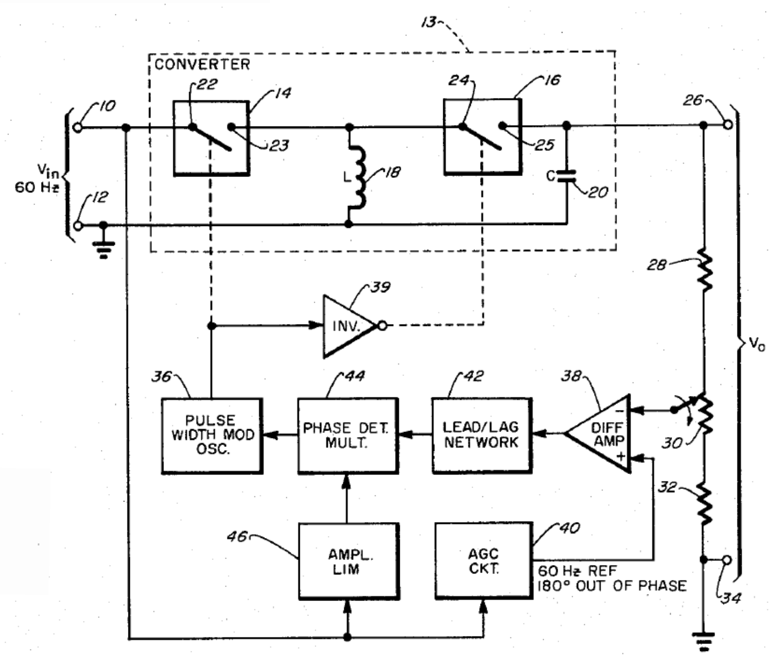
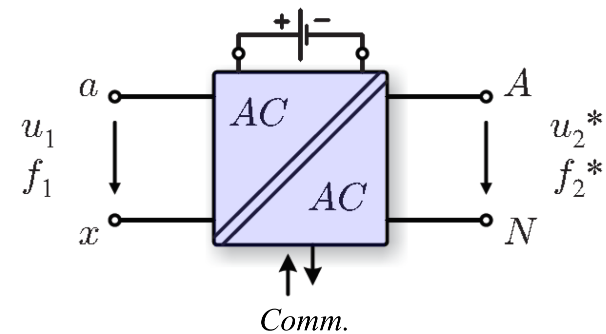
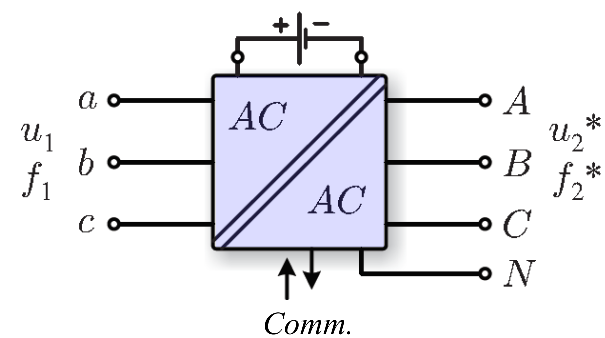


Fig. 1.

- 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.	

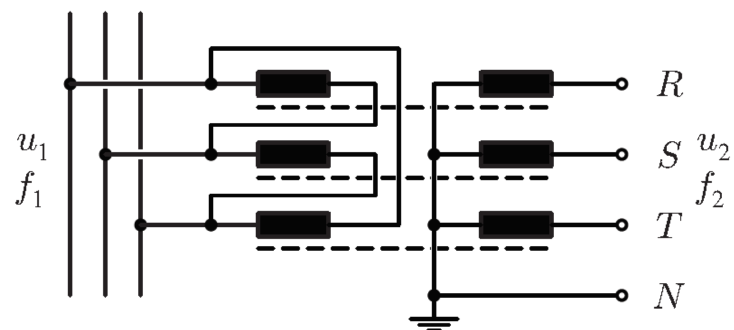
Transformer Basics

▶ Classical Transformer — Basics (1)

- **Magnetic Core Material** * Silicon Steel / Nanocrystalline / Amorphous / Ferrite
- **Winding Material** * Copper or Aluminum
- **Insulation / Cooling** * Mineral Oil or Dry-type

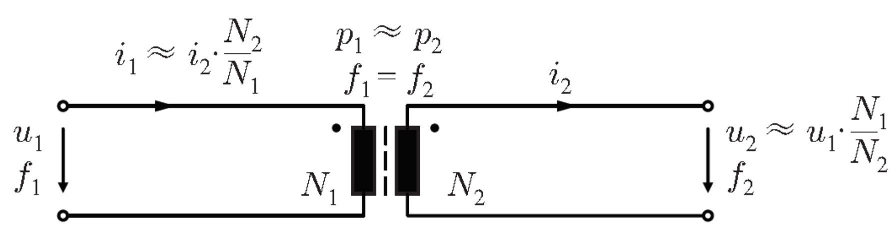
- **Operating Frequency** * **50/60Hz** (El. Grid, Traction) or **16 $^{2}/_{3}$Hz** (Traction)
- **Operating Voltage** * **10kV or 20kV** (6…35kV)
  * **15kV or 20kV** (Traction)
  * 400V

- **Voltage Transfer Ratio** * **Fixed**
- **Current Transfer Ratio** * Fixed
- **Active Power Transfer** * Fixed ($P_1 \approx P_2$)
- **Reactive Power Transfer** * Fixed ($Q_1 \approx Q_2$)
- **Frequency Ratio** * **Fixed ($f_1 = f_2$)**



- **Magnetic Core Cross Section** $$A_{Core} = \frac{1}{\sqrt{2}\pi} \frac{U_1}{\hat{B}_{\max} f} \frac{1}{N_1}$$

- **Winding Window** $$A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$$



▶ Classical Transformer — Basics (2)

- Scaling of Core Losses

$$P_{Core} \propto f_P \left(\frac{\Phi}{A}\right)^2 V$$
$$P_{Core} \propto \left(\frac{1}{l^2}\right)^2 l^3 \propto \frac{1}{l}$$

- Scaling of Winding Losses

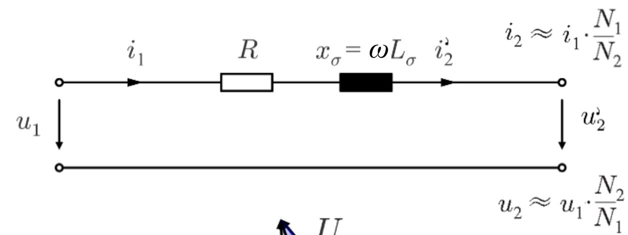
$$P_{Wdg} \propto I^2 R \propto I^2 \frac{l_{Wdg}}{\kappa A_{Wdg}}$$
$$P_{Wdg} \propto \frac{1}{l}$$

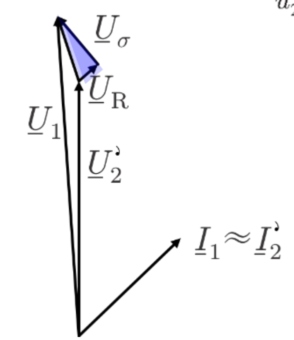
- **Higher Relative Volumes (Lower kVA/m^3) Allow to Achieve Higher Efficiencies**

▶ Classical Transformer — Basics (3)

■ Advantages

- Relatively Inexpensive
- **Highly Robust / Reliable**
- **Highly Efficient (98.5%...99.5% Dep. on Power Rating)**
- Short Circuit Current Limitation





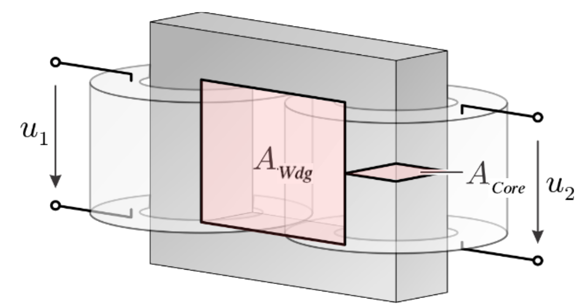
■ Weaknesses

- Voltage Drop Under Load
- Losses at No Load
- Sensitivity to Harmonics
- Sensitivity to DC Offset Load Imbalances
- **Provides No Overload Protection**
- Possible Fire Hazard
- Environmental Concerns

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

- Construction Volume

P_t	...	*Rated Power*
k_w	...	*Window Utilization Factor (Insulation)*
B_{max}	...	*Flux Density Amplitude*
J_{rms}	...	*Winding Current Density (Cooling)*
f	...	*Frequency*



- **Low Frequency → Large Weight / Volume**

▶ Classical Transformer — Basics (4)

■ Advantages

- Relatively Inexpensive
- **Highly Robust / Reliable**
- Highly Efficient (98.5%...99.5% Dep. on Power Rating)
- Short Circuit Current Limitation

Welding Transformer (Zimbabwe) – Source: http://www.africancrisis.org

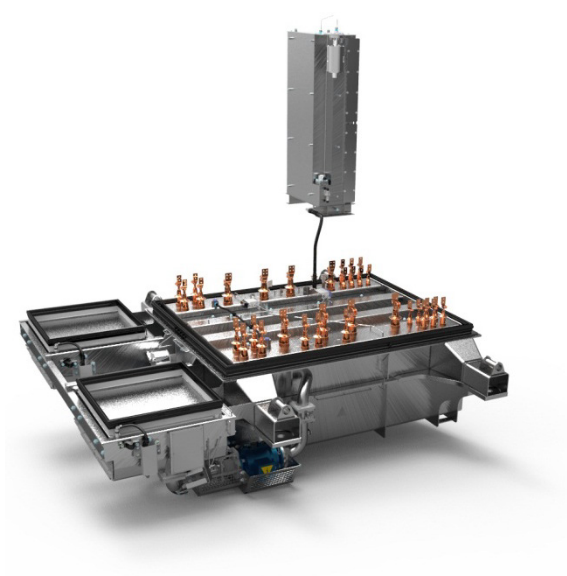
SST Concept

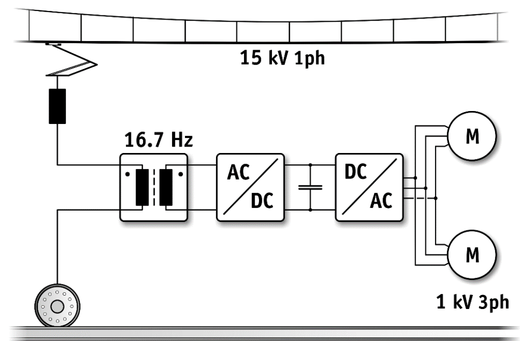
Future Traction Applications
Future Smart Grid Applications

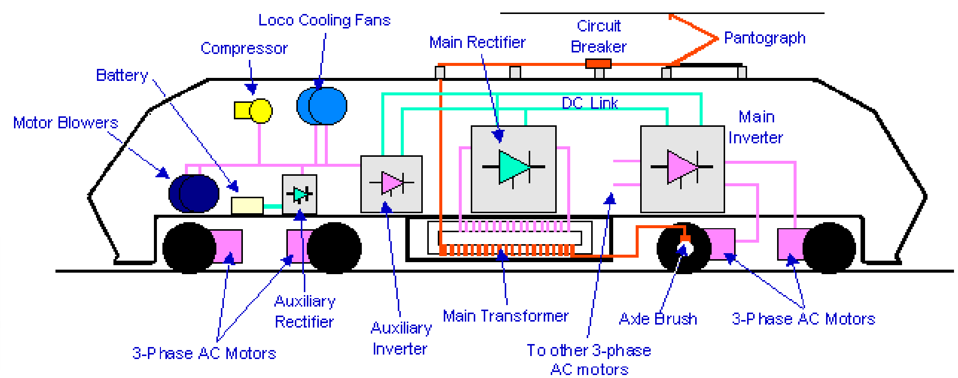
Img.: www.futuretimeline.net

▶ Classical Locomotives

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



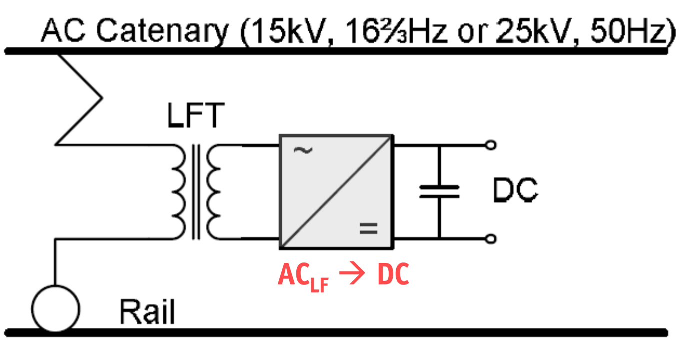




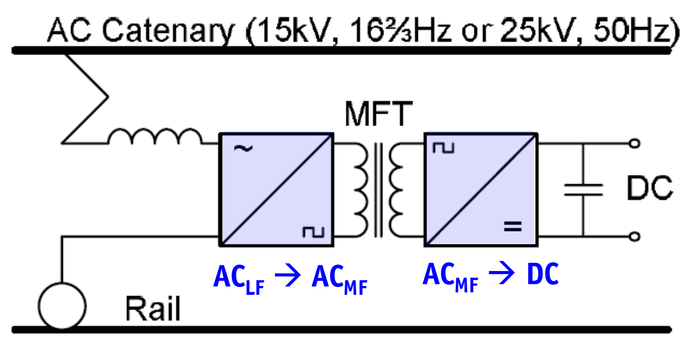
- Transformer **Efficiency** **90...95%** (due to Restr. Vol., 99% typ. for Distr. Transf.)
  Current Density 6 A/mm² (2A/mm² typ. Distribution Transformer)
  Power Density 2...4 kg/kVA

▶ Next Generation Locomotives (1)

- Trends
  - * Distributed Propulsion System → **Weight Reduction** **(pot. Decreases Eff.)**
  - * Energy Efficient Rail Vehicles → **Loss Reduction** **(would Req. Higher Vol.)**
  - * Red. of Mech. Stress on Track → **Mass Reduction** **(pot. Decreases Eff.)**



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

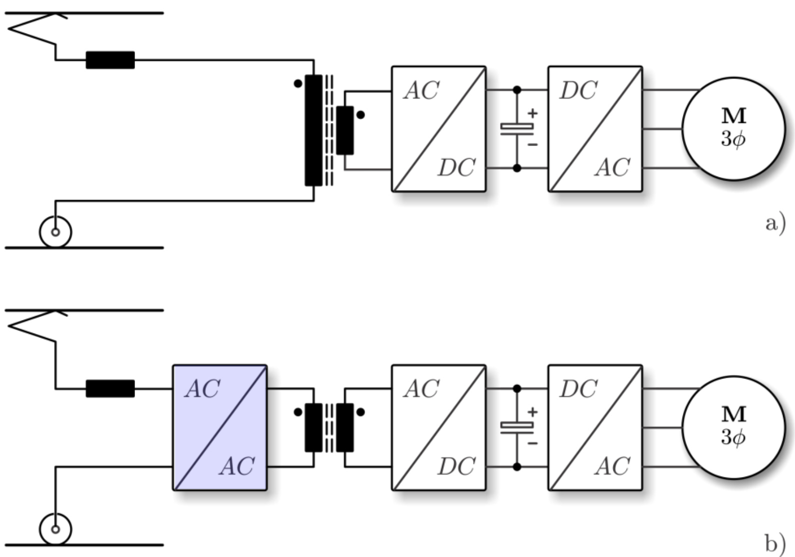


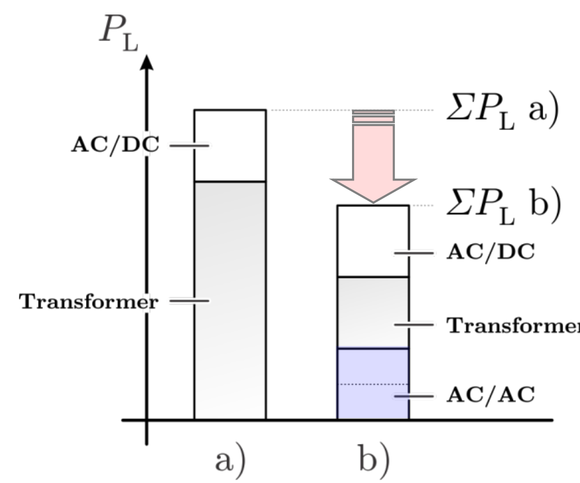
AC-DC conversion with medium frequency transformer (MFT).

- **Replace Low Frequency Transformer by Medium Freq. (MF) Power Electronics Transformer (PET)**
- Medium Freq. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
- El. Syst. of Next Gen. Locom. (1ph. AC/3ph. AC) represents Part of a 3ph. AC/3ph. AC SST for Grid Appl.

▶ Next Generation Locomotives (2)

- Loss Distribution of Conventional & Next Generation Locomotives





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

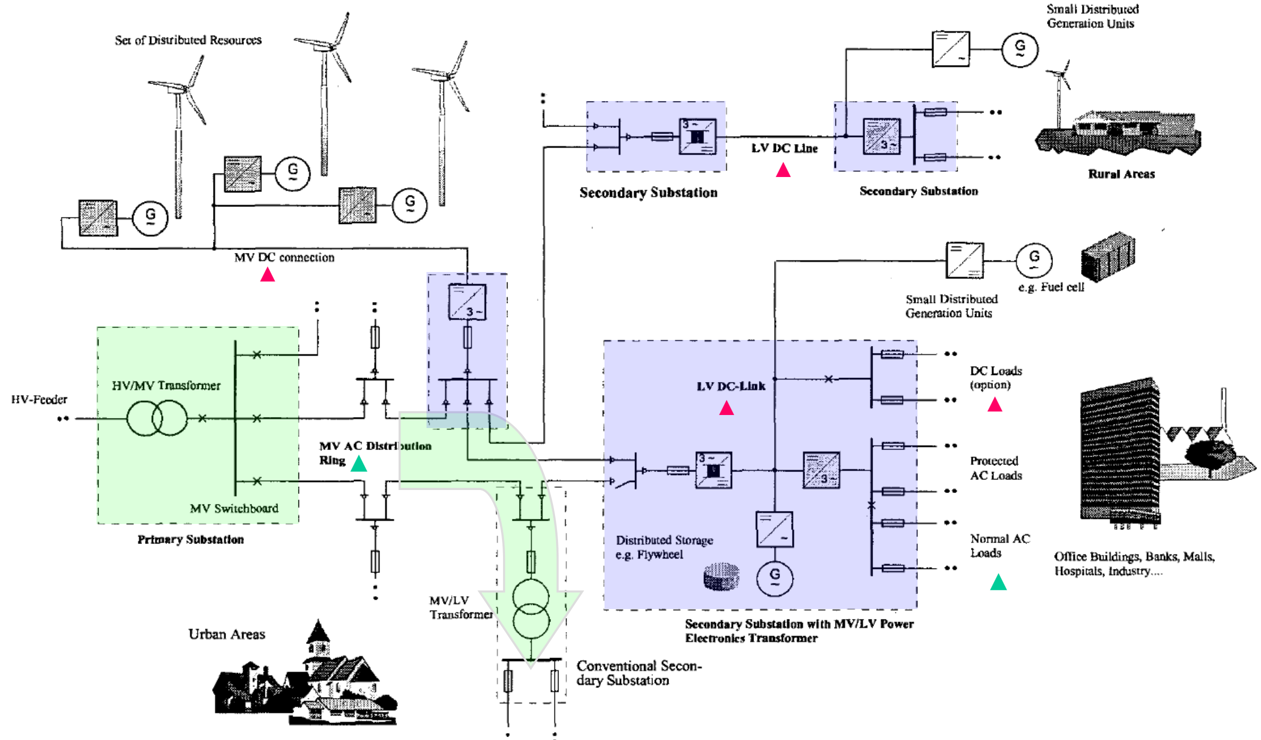
SST Concept

Future Traction Applications
Future Smart Grid Applications

Img.: www.prweb.com

▶ Advanced (High Power Quality) Grid Concept

- Heinemann (2001)



- **MV AC Distribution with DC Subsystems (LV and MV)** and Large Number of Distributed Resources
- MF AC/AC Conv. with DC Link Coupled to **Energy Storage** provide High Power Qual. for Spec. Customers

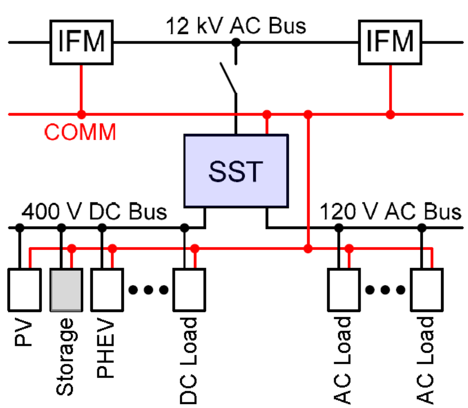
► Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

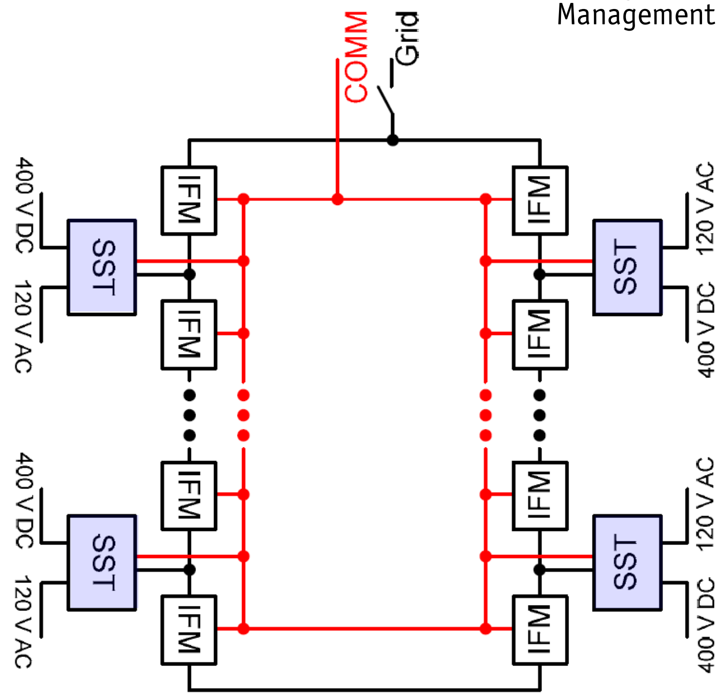
■ Huang et al. (2008)

■ **SST as Enabling Technology for the "Energy Internet"**

- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation

IFM = Intellig. Fault Management





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

▶ Smart Grid Concept

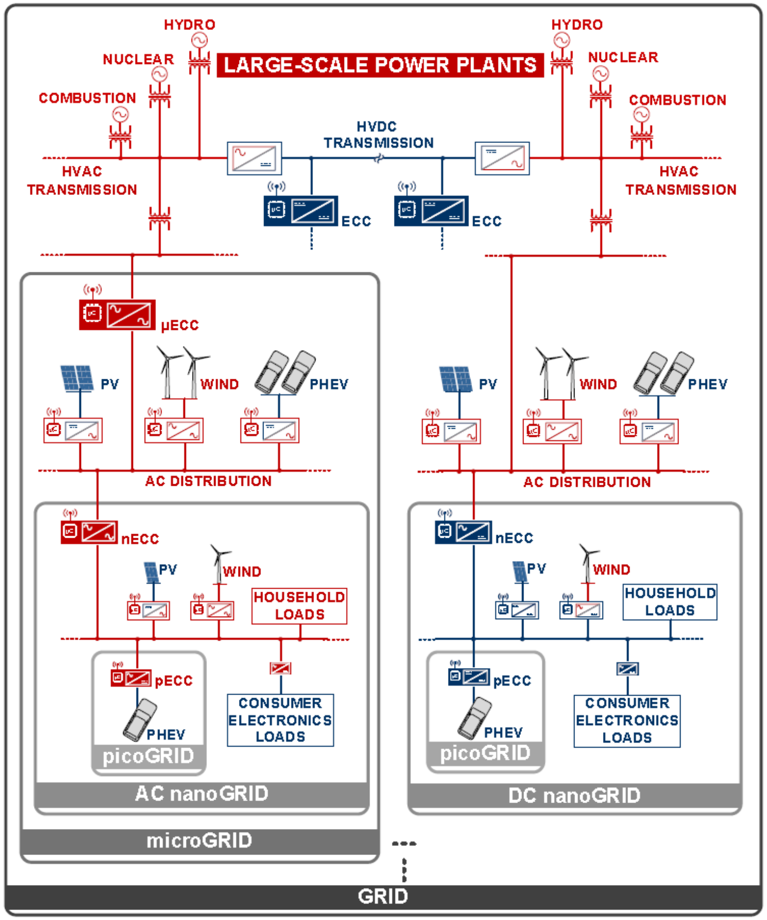
- Borojevic (2010)

- **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**

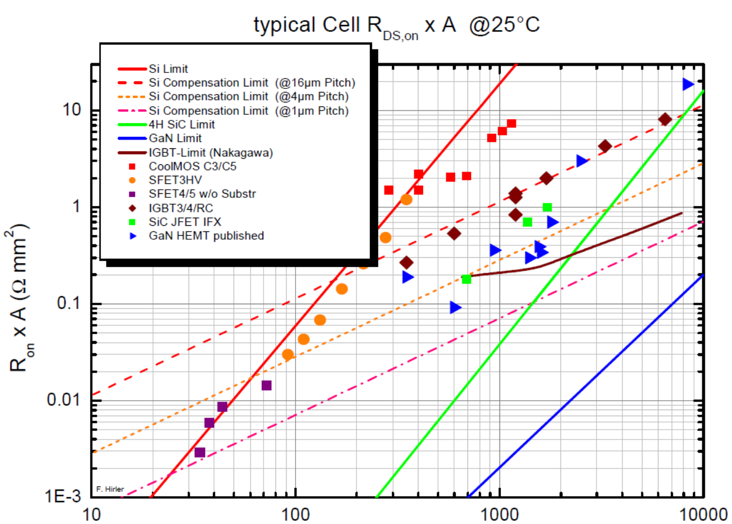
  - Energy Routers
  - Continuous Bidir. Power Flow Control
  - Enable Hierarchical Distr. Grid Control
  - Load / Source / Data Aggregation
  - Up- and Downstream Communic.
  - Intentional / Unintentional Islanding for Up- or Downstream Protection
  - etc.

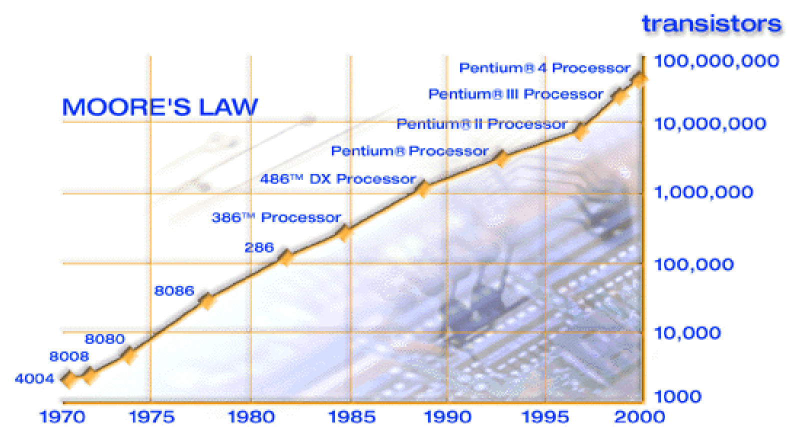


▶ Smart Grid Enablers / Drivers (1)

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

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





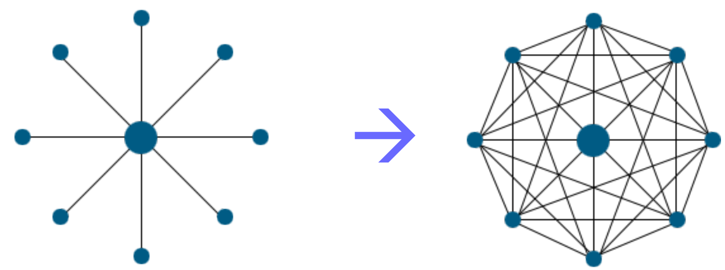
▸ + Advanced packaging (!)

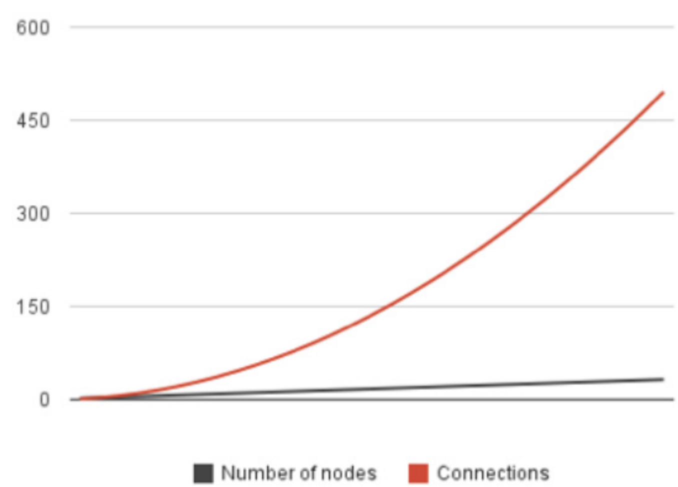
▸ Moore's Law

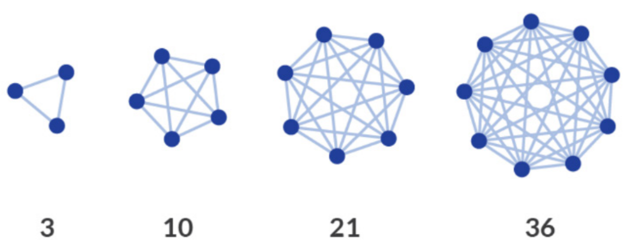
▶ Smart Grid Enablers / Drivers (2)

■ Metcalfe's Law

- Moving from Hub-based Concept to Community Concept Increases Potential Network Value Exponentially (~n(n-1) or ~n log(n))



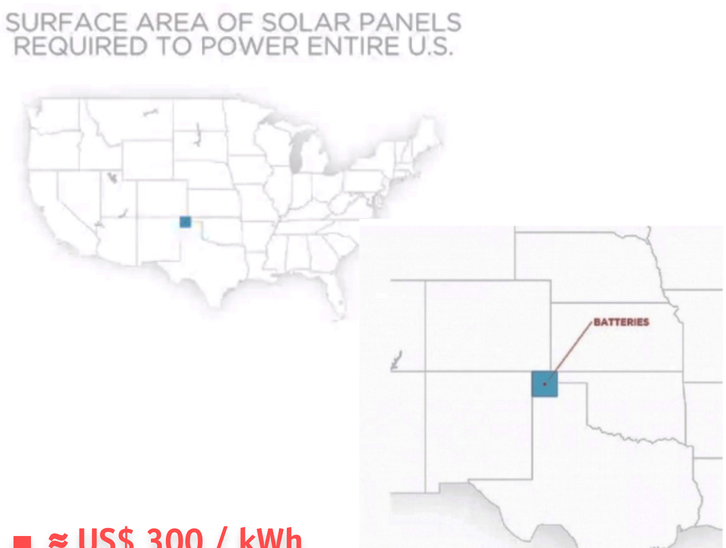




► Smart Grid Enablers / Drivers (3)

- **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+

UL Listed
Outdoor Rated

- ≈ US$ 300 / kWh

▶ SST Functionalities

■ **Protects Load from Power System Disturbance**

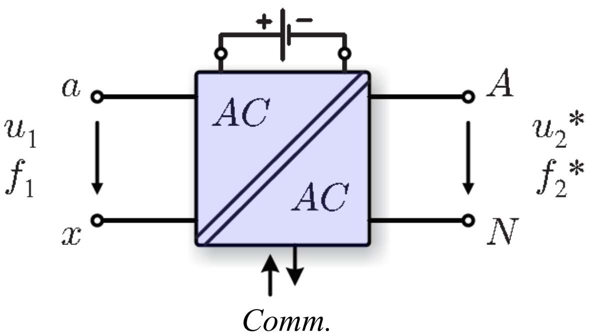
- Voltage Harmonics / Sag Compensation
- Outage Compensation
- Load Voltage Regulation (Load Transients, Harmonics)

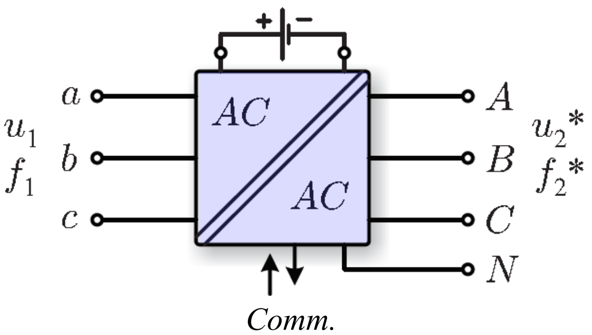
■ **Protects Power System from Load Disturbance**

- Unity Inp. Power Factor Under Reactive Load
- Sinus. Inp. Curr. for Distorted / Non-Lin. Load
- Symmetrizes Load to the Mains
- Protection against Overload & Output Short Circ.

■ **Further Characteristics**

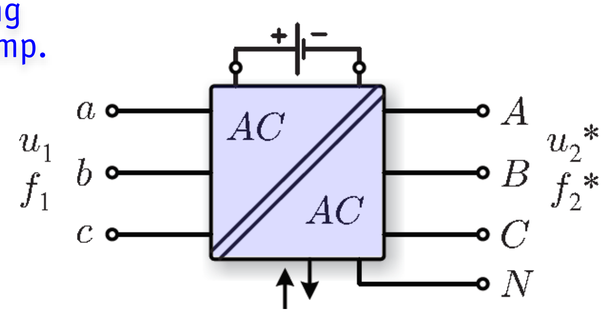
- Operates on Distribution Voltage Level (MV-LV)
- Integrates Energy Storage (Energy Buffer)
- DC Port for DER Connection
- **Medium Frequency Isolation → Low Weight / Volume**
- Definable Output Frequency
- High Efficiency
- No Fire Hazard / Contamination

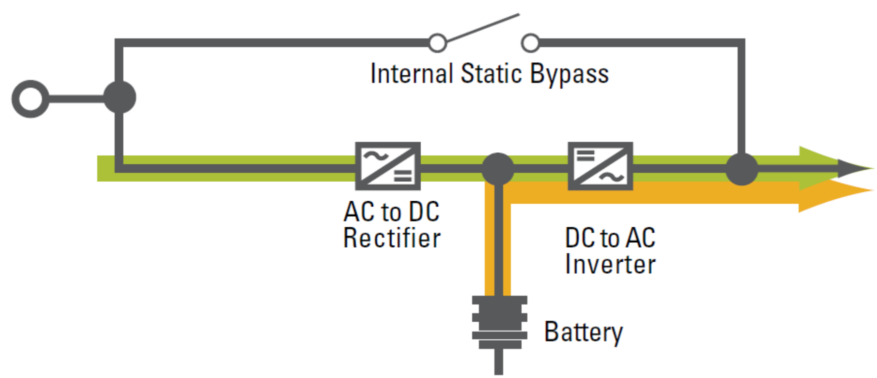




▶ SST vs. Uninterruptible Power Supply

■ **Same Basic Functionality 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.





■ Input Side MV Voltage Connection of SST as Main Difference / Challenge
■ Numerous Topological Options

10 Key Challenges of SST Design

1. *Topology Selection*
2. *Power Semiconductors*
3. *Single-Cell vs. Multi-Cell*
4. *Reliability*
5. *Medium-Freq. Transformer*
6. *Isolation Coordination*
7. *EMI*
8. *Protection*
9. *Control & Communication*
10. *Competing Approaches*

Challenge #1/10

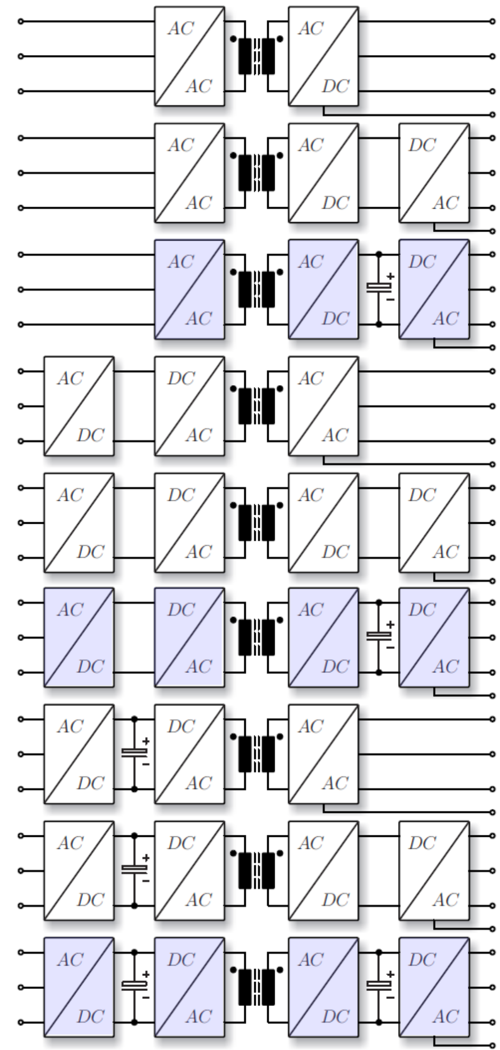
Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Partitioning of Medium Voltage

▶ Basic SST Structures (1)

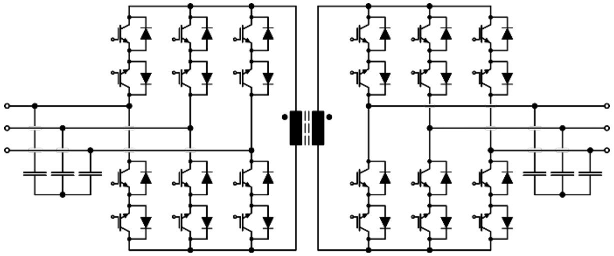
■ 1st Degree of Freedom of Topology Selection ⟶ Partitioning of the AC/AC Power Conversion

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



► Basic SST Structures (1)

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



- DC-Link Based Topologies
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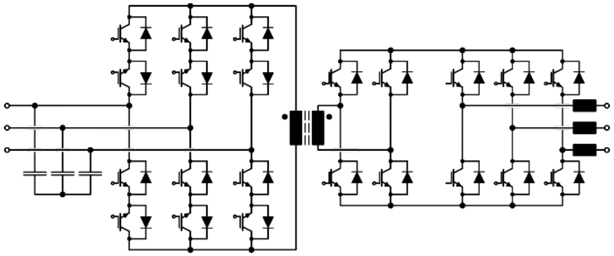
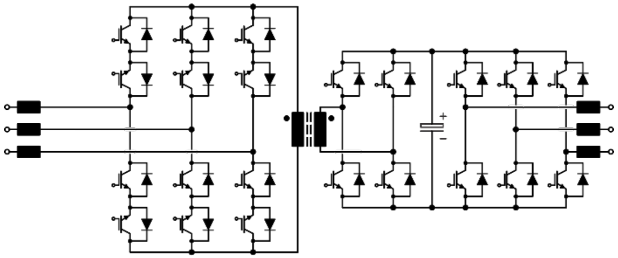
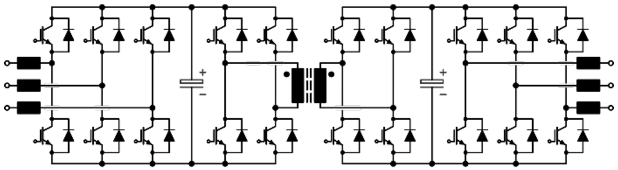
- Hybrid Combinations





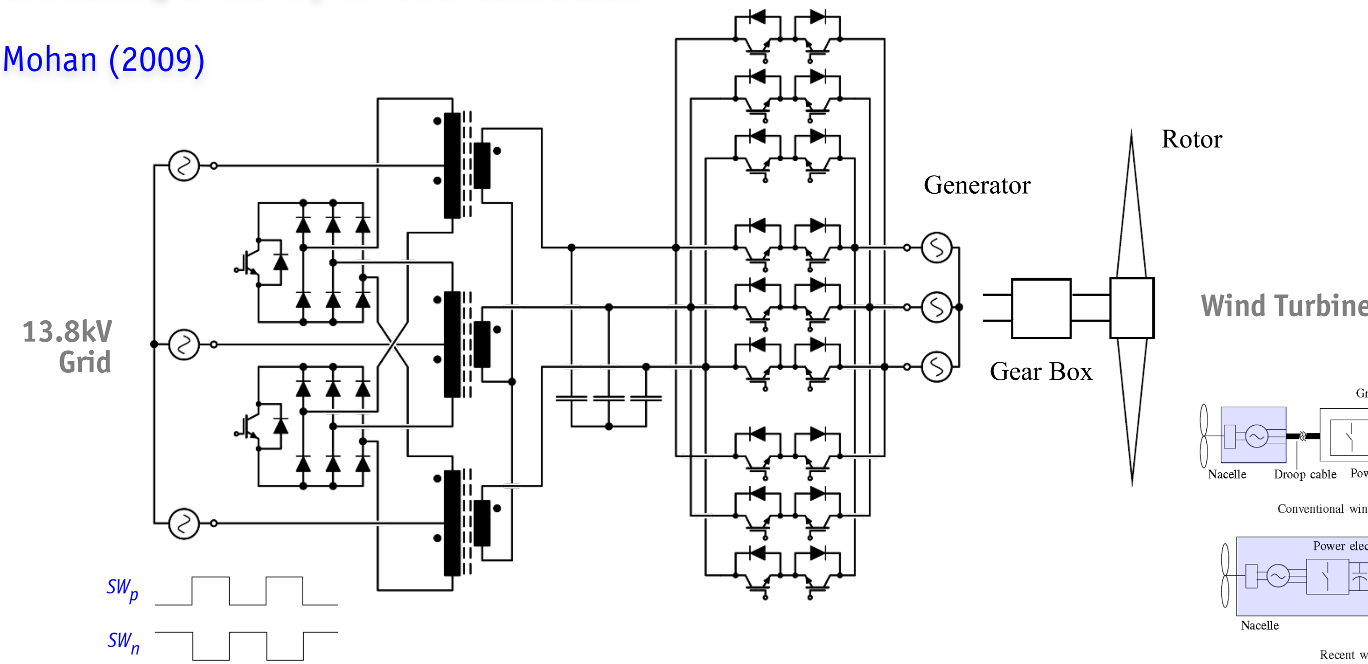
- 1-Stage Matrix-Type Topologies
- 2-Stage with MV DC Link (Connection to HVDC System)
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 3-Stage Power Conversion with MV and LV DC Link

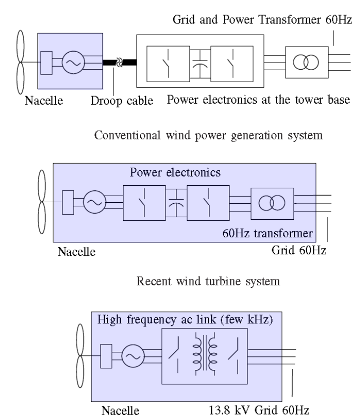


▶ Basic SST Structures (1)

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

  • Mohan (2009)



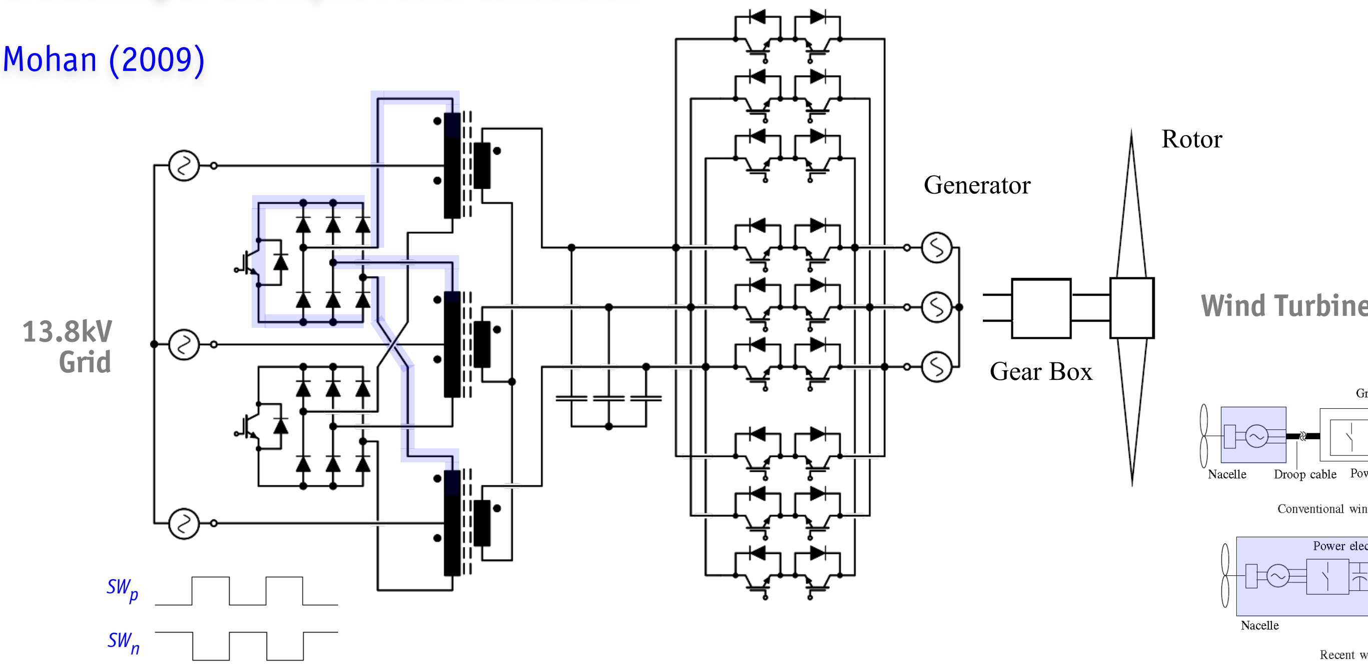


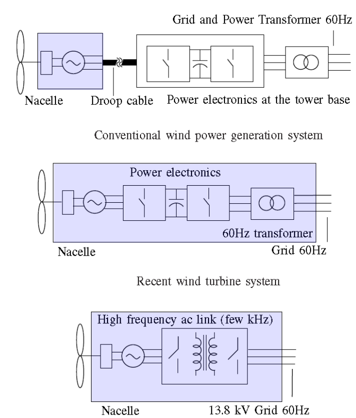
- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency

▶ Basic SST Structures (1)

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

- Mohan (2009)



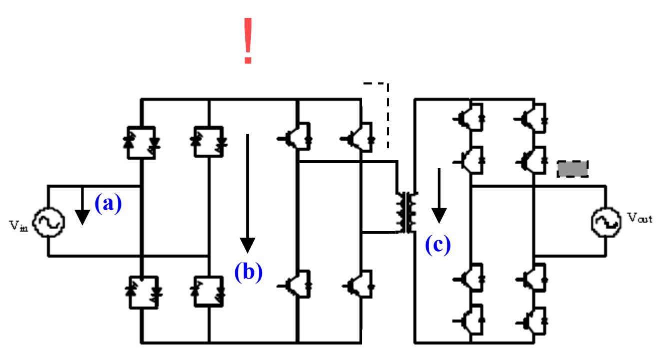


■ Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
■ LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency

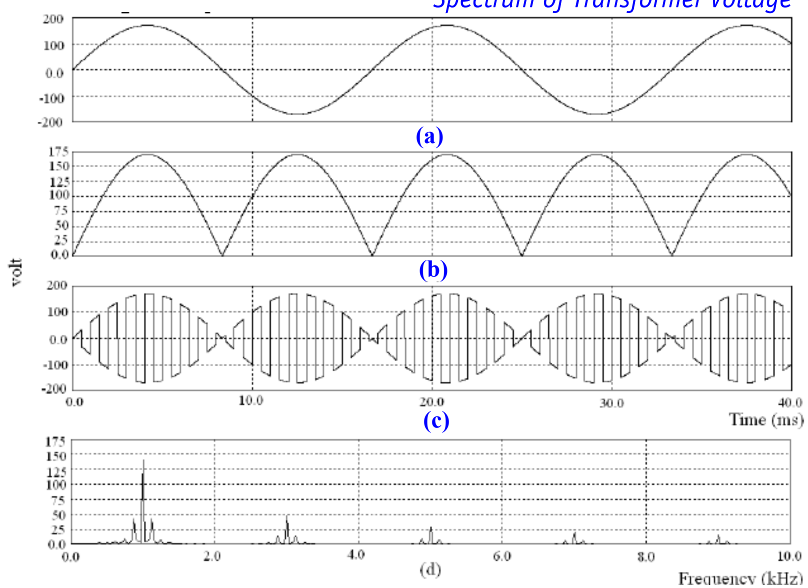
▶ Basic SST Structures (1)

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

- Indirect Matrix-Type 1ph. AC/AC Converter
- Lipo (2010) V-Input, I-Output



AC Input Voltage
Rectifier Output Voltage
Transformer Input Voltage
Spectrum of Transformer Voltage

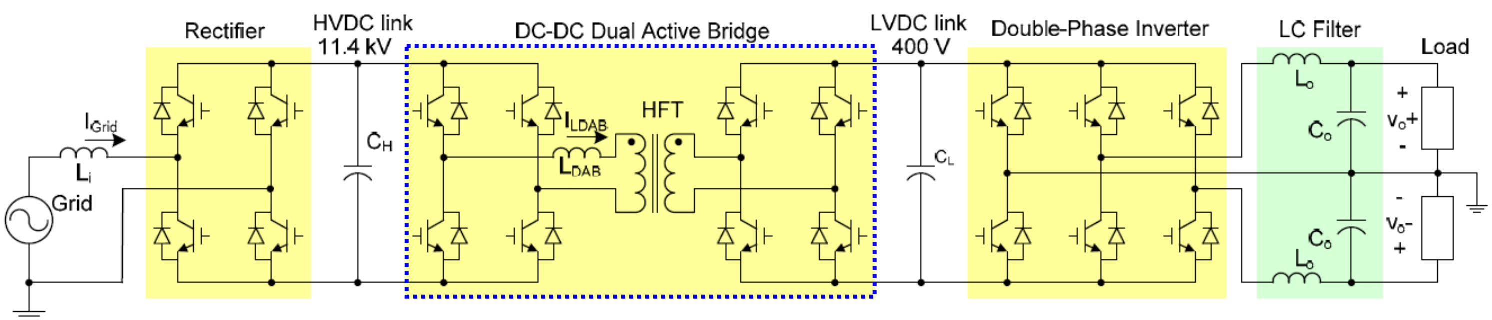


- AC/DC Input Stage (Bidir. Full-Wave Fundamental Frequ. GTO Rect. Bridge, No Output Capacitor)
- Subsequent DC/DC Conversion & DC/AC Conversion (Demodulation, $f_1 = f_2$)
- Output Voltage Control by Phase Shift of Primary and Secondary Side Switches (McMurray)
- Lower Number of HF HV Switches Comp. to Matrix Approach

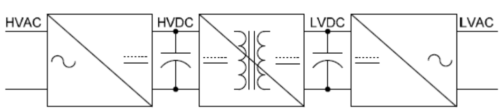
▶ Basic SST Structures (1)

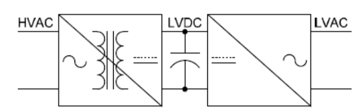
- **1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion**

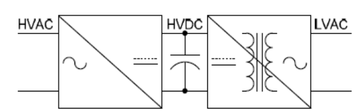
- DC-link-Type (Indirect) 1ph. AC/AC Converter
- **Dual Act. Bridge-Based DC//DC Conv. (Phase Shift Contr. Relates Back to Thyr. Inv. / McMurray)**



(Ayyanar, 2010)







- Alternatives: AC//DC — DC/AC Topologies
  AC/DC — DC//AC Topologies

Challenge #1/10

Topology Selection

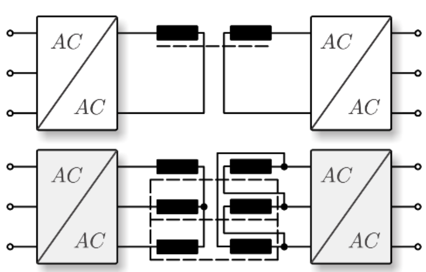
Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Partitioning of Medium Voltage

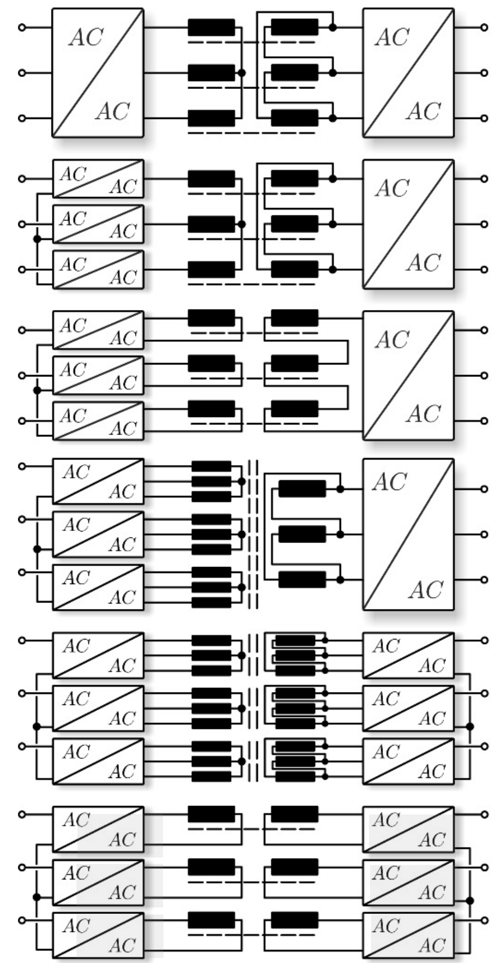
▶ Basic SST Structures (2)

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

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

▾ Phase-Integrated SST

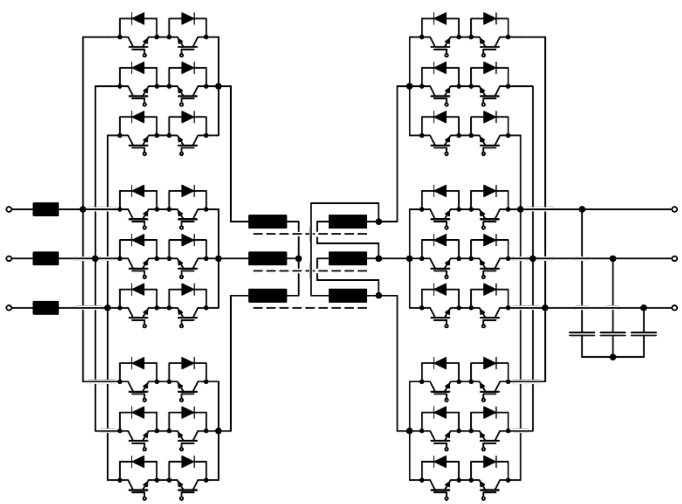




▶ Basic SST Structures (2)

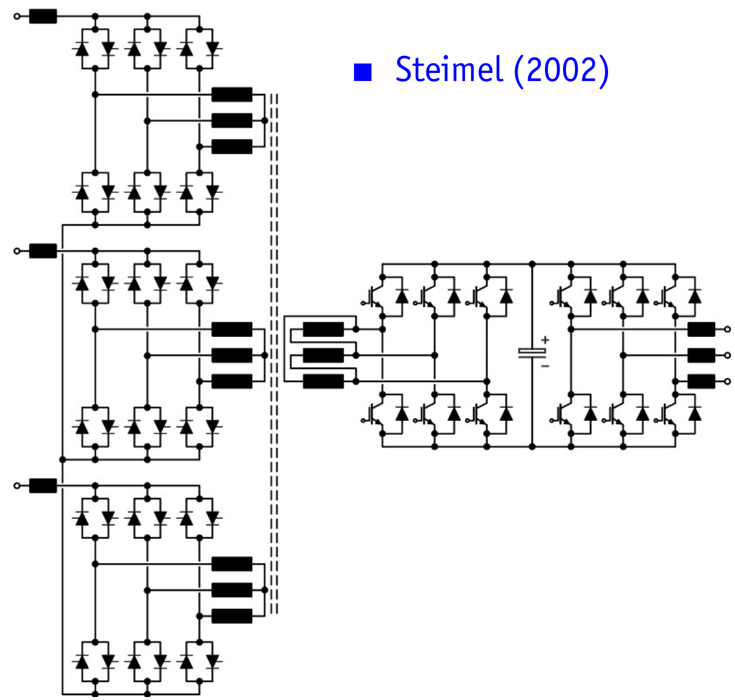
- 2nd Degree of Freedom of Topology Selection → Partial or Full Phase Modularity

- Enjeti (1997)



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

- Steimel (2002)



- Example of Partly Phase-Modular SST

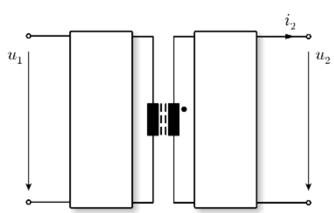
Challenge #1/10
Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
Partitioning of Medium Voltage

► Basic SST Structures (3)

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

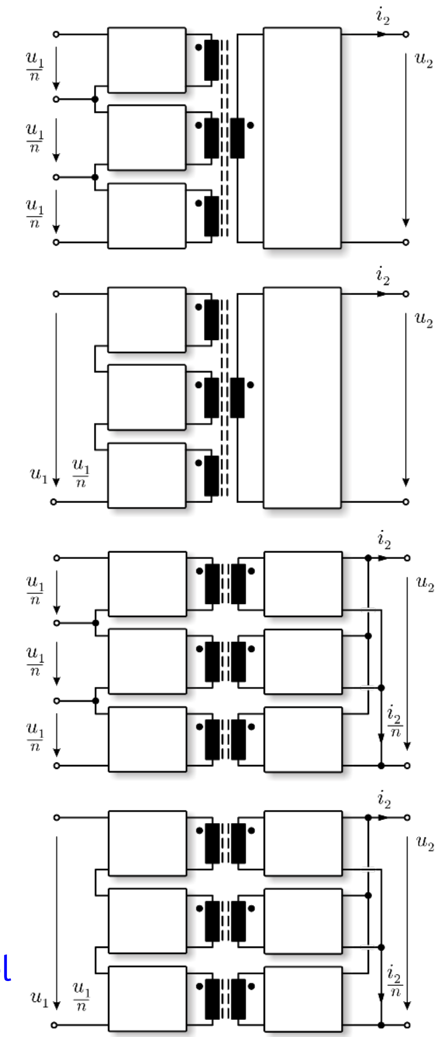
- **Multi-Cell and Multi-Level Approaches:**
  - Low Blocking Voltage Requirement
  - Low Input Voltage / Output Current Harmonics
  - Low Input/Output Filter Requirement



a)

▲ Single-Cell / Two-Level Topology

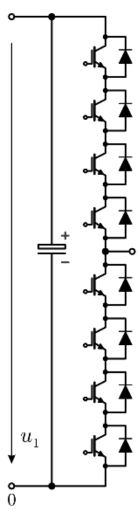
ISOP = Input Series / Output Parallel Topologies



▶ Basic SST Structures (3)

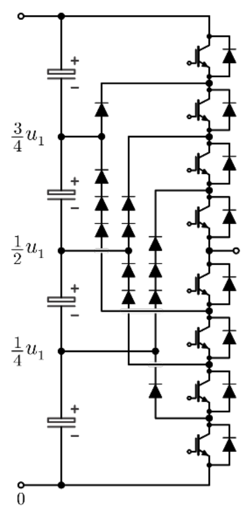
- **3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage**

- **Multi-Cell and Multi-Level Approaches:**

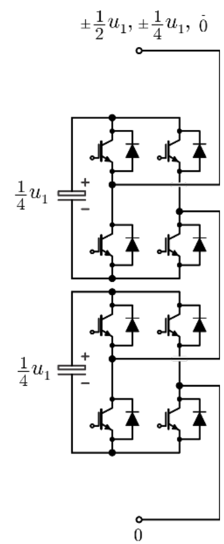


◂ Two-Level Topology

Akagi (1981)

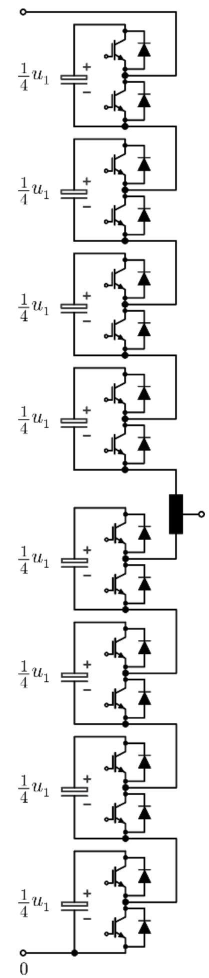


McMurray (1969)



Marquardt

Alesina/ Venturini (1981)

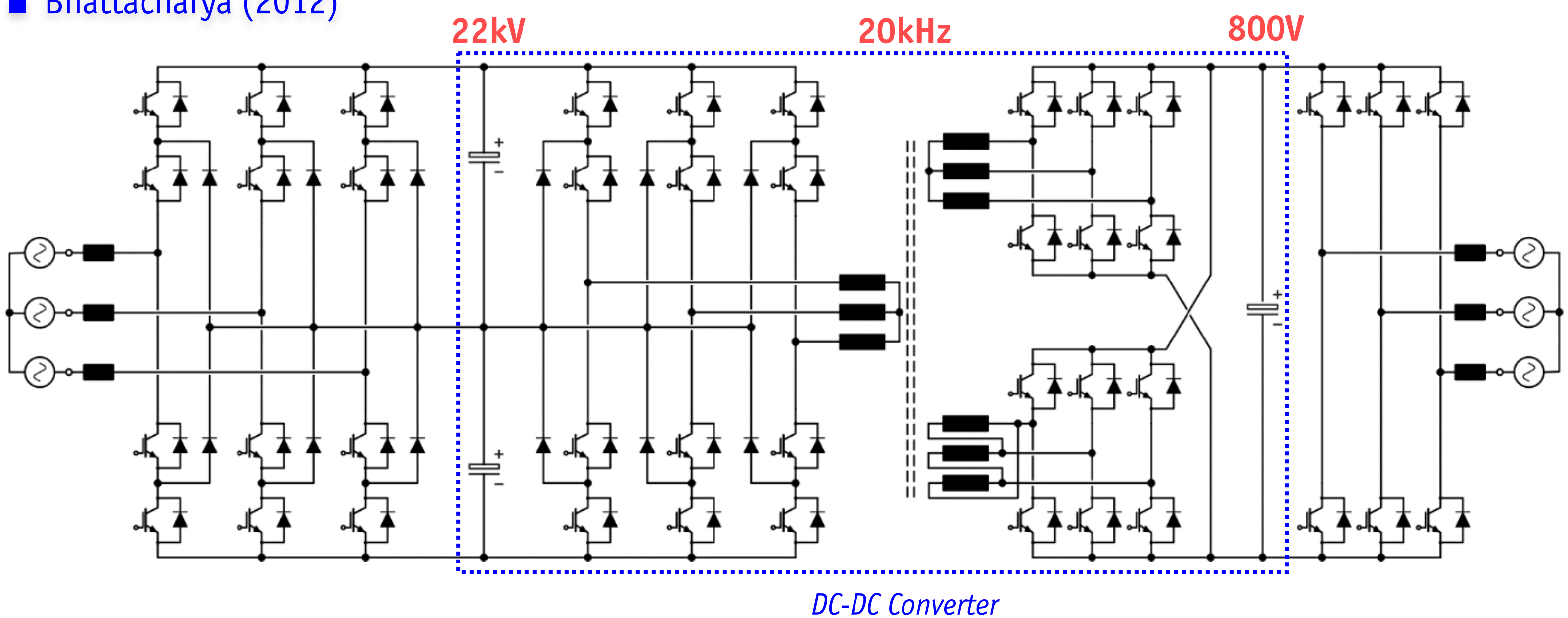


◂ Multi-Level/ Multi-Cell Topologies

▶ Basic SST Structures (3)

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

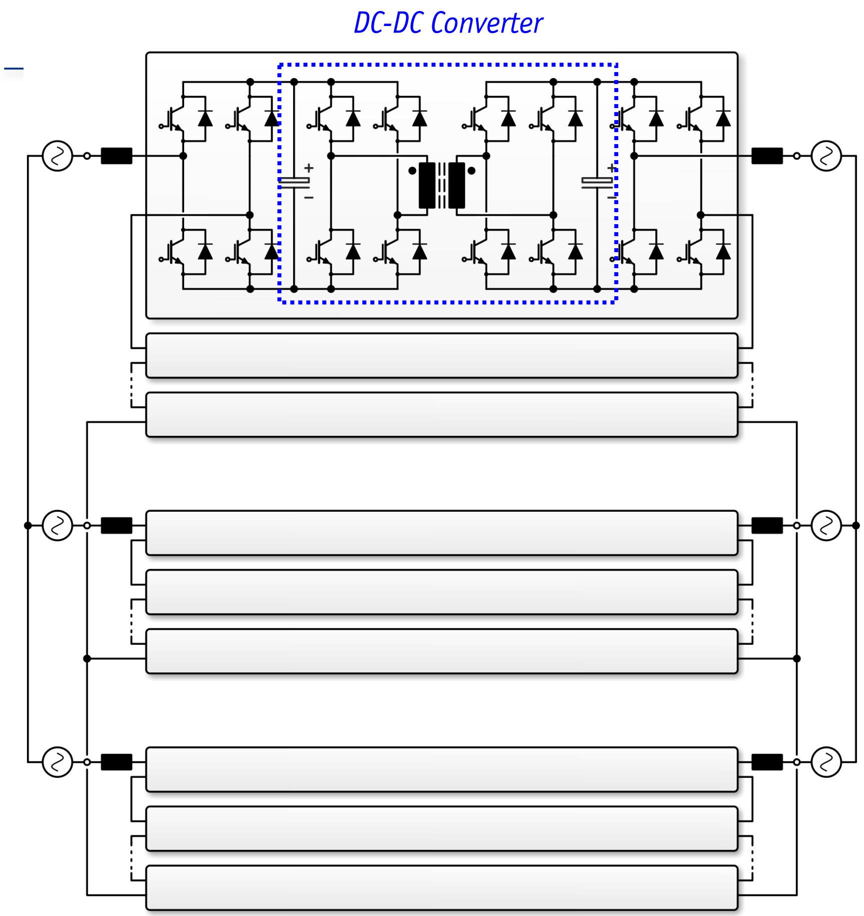
- Bhattacharya (2012)



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

► Basic SST Structures (3)

- 3rd Degree of Freedom of Topology Selection – Partitioning of Medium Voltage
- Akagi (2005)



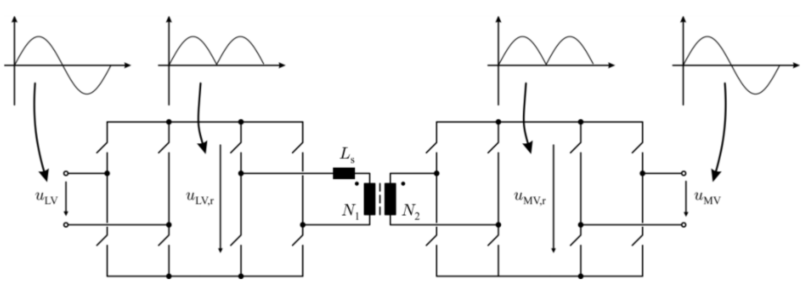
- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control

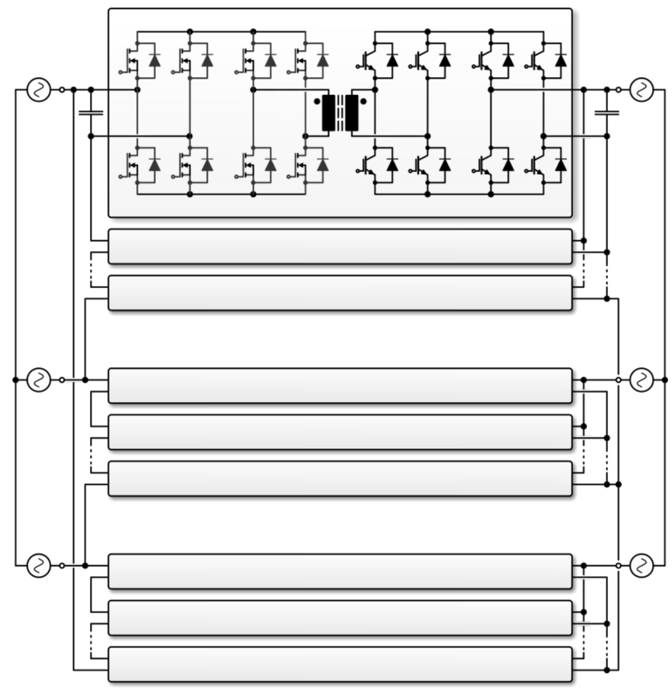
► Basic SST Structures (3)

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

- Das (2011)

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





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

▶ Basic SST Structures (3)

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

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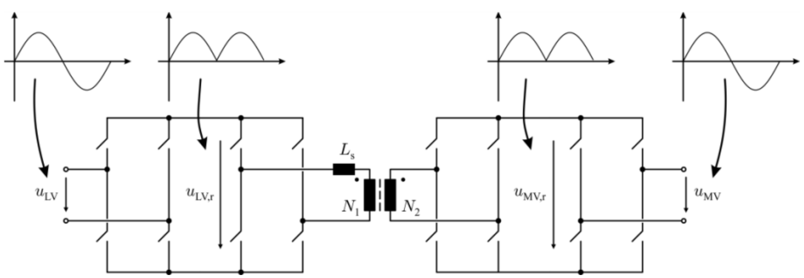
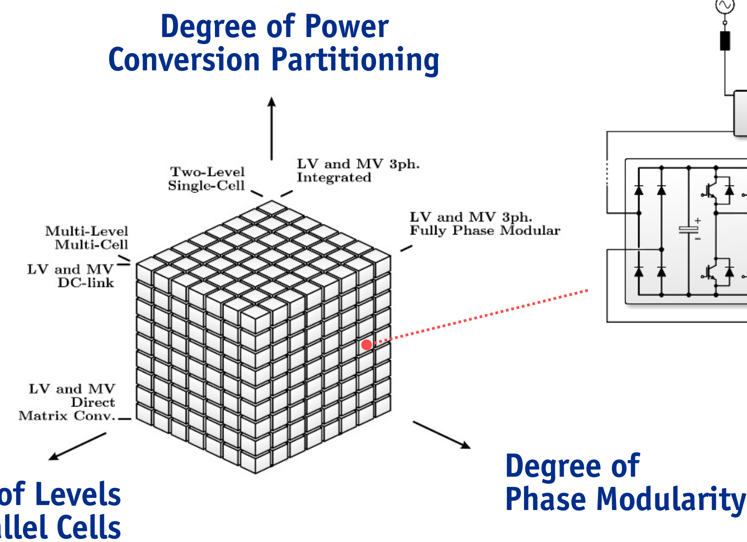
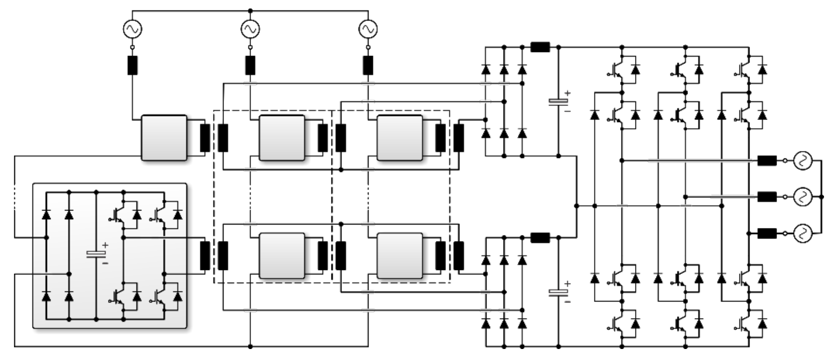


- SiC-Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

▶ Classification of SST Topologies





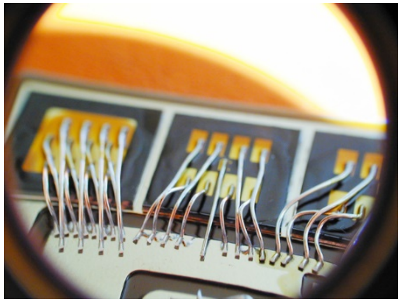
▲ Enjeti (2012)

- **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**

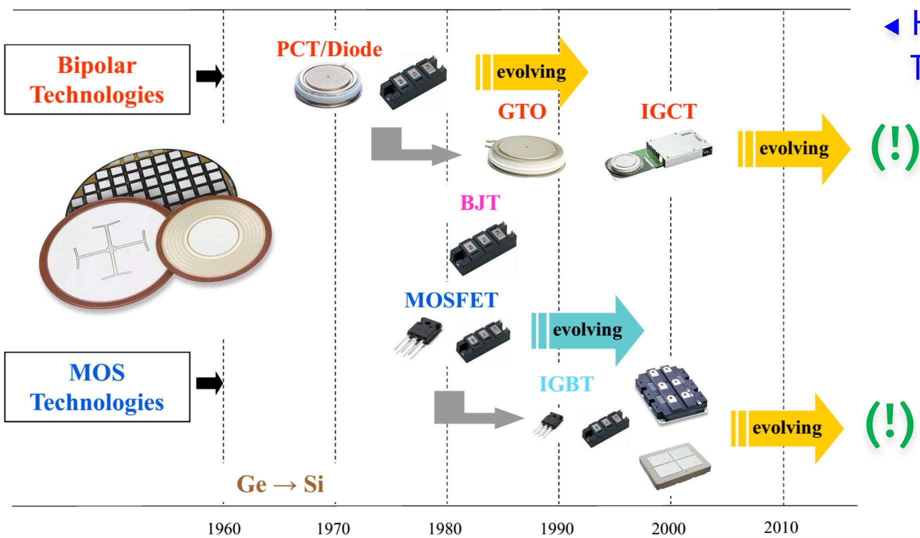
Challenge #2/10

Power Semiconductors



Img.: www.micromat.at

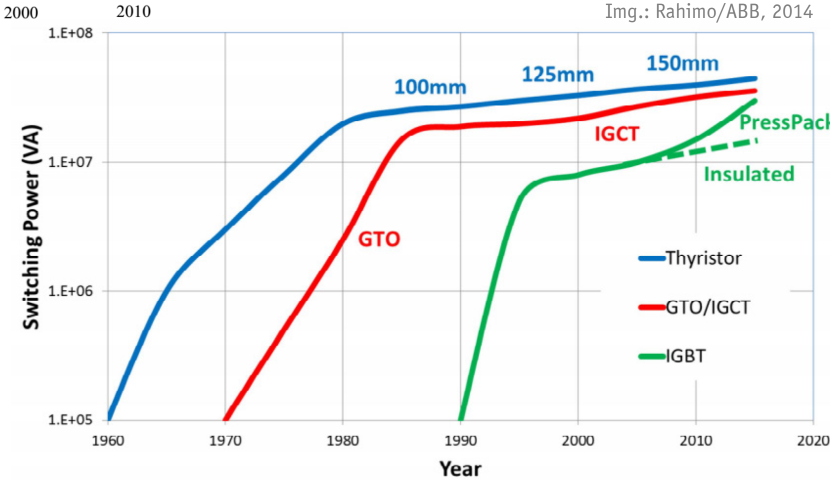
▶ History of Si High-Power Devices



◂ Historical Development of Device Technologies

Img.: Rahimo/ABB, 2014

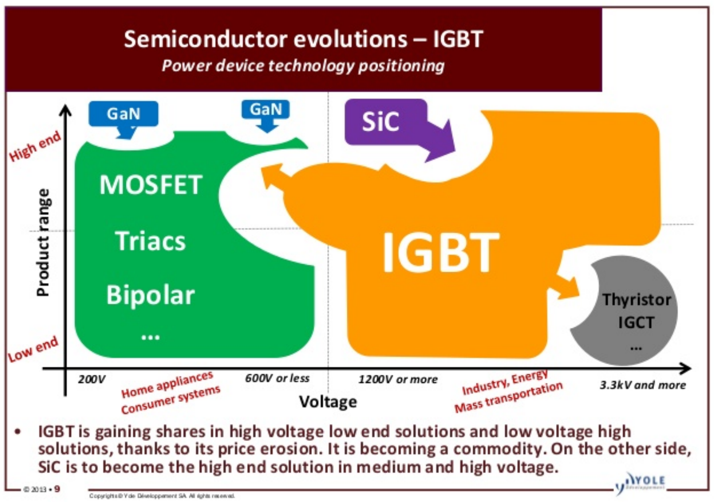
Development of Max. Switching Power ▸



▶ Available Si Power Semiconductors

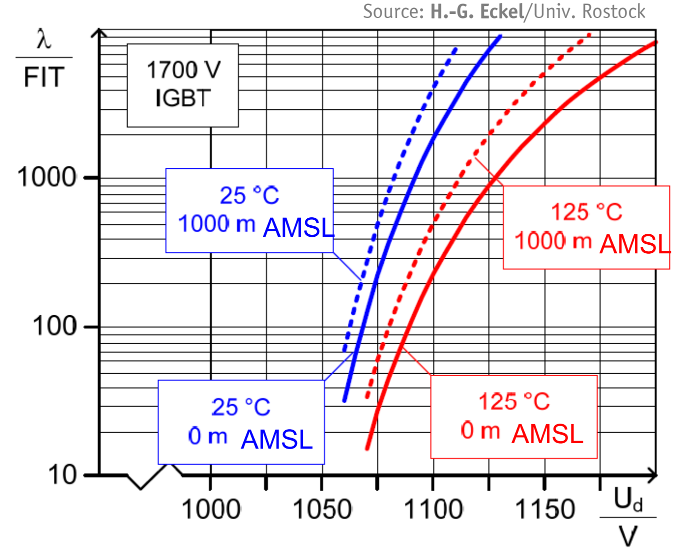
- 1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications

- **Derating** Requirements Due to Cosmic Radiation 1700V Si-IGBTs ⟶ 1000V max. DC Voltage



Img.: Yole Développement.

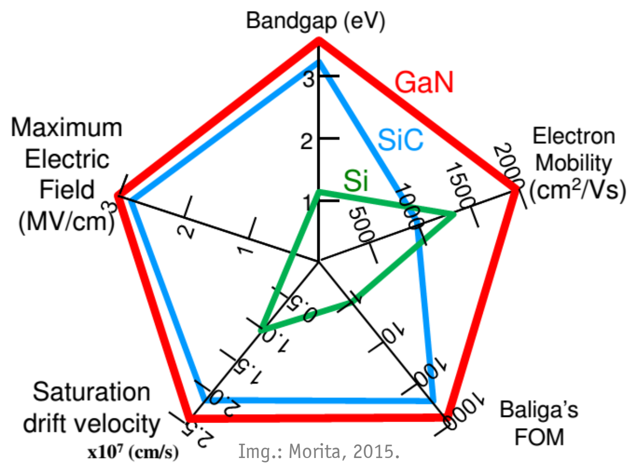
Source: **H.-G. Eckel**/Univ. Rostock



- Blocking Capability Up to 6.5kV
- Proven Heavy-Duty Module Techn. Up to 3.6kA
- **Rel. High Switching Losses**

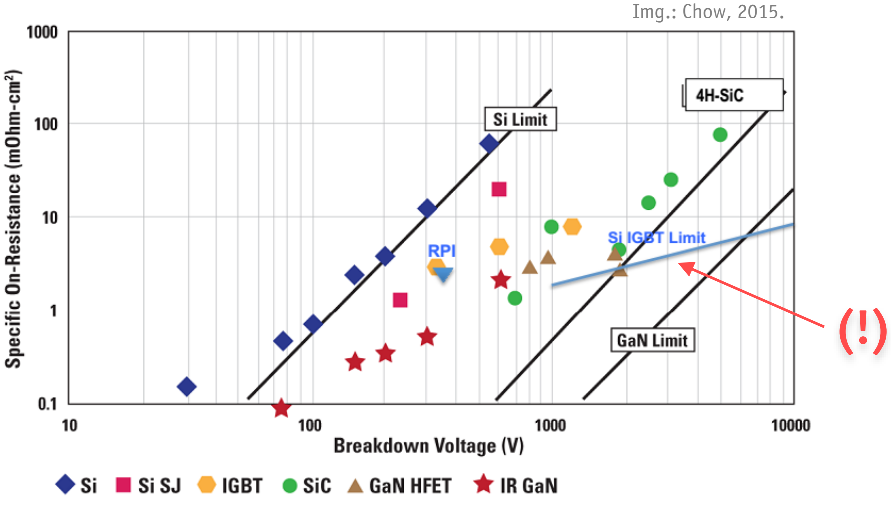
▶ Si vs. WBG (SiC/GaN) Semiconductors

- Superior Material Characteristics than Si



Img.: Morita, 2015.

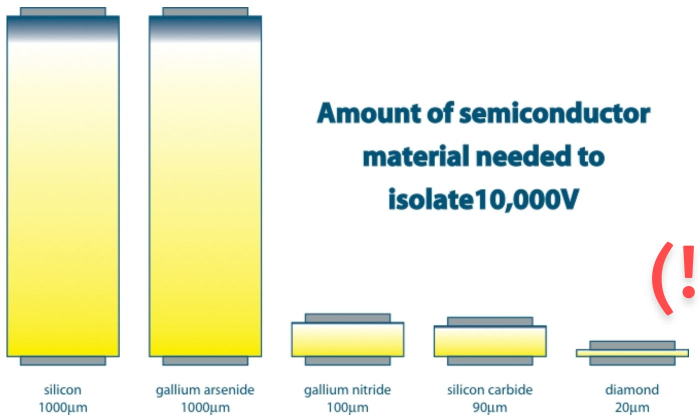
Img.: Chow, 2015.



- SiC More Mature than GaN for HV Applications

- Outlook: SiC **IGBTs** for BV > 10kV

▶ (Far Reaching) Outlook for WBG Semiconductors



Img.: http://www.evincetechnology.com/whydiamond.html

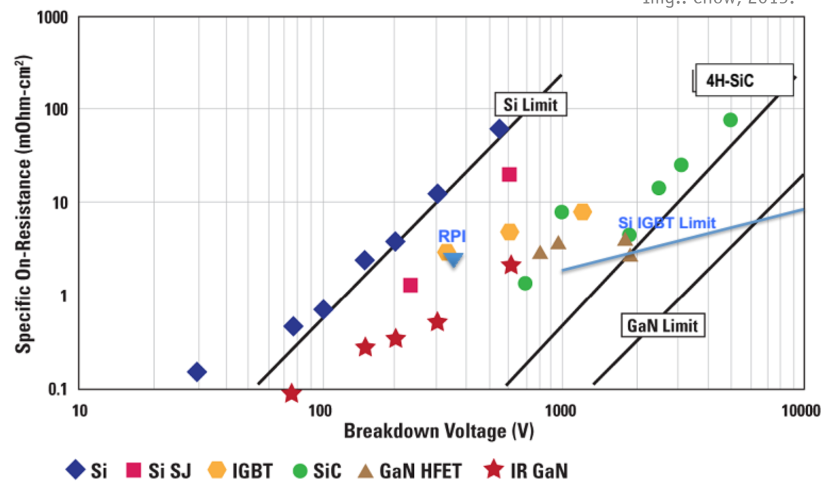
(!)

$$W_\mathrm{D} = 2\frac{BV}{E_\mathrm{crit}}$$

- Specific On-State Resistance vs. Critical Elec. Field Strength

$$R_\mathrm{on,sp} = \frac{4BV^2}{\epsilon\mu_\mathrm{n}E_\mathrm{C}^3}$$

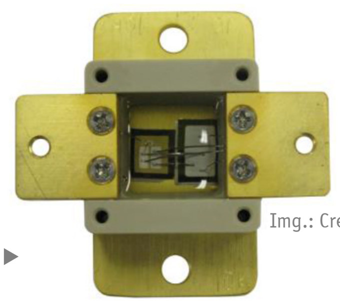
Img.: Chow, 2015.



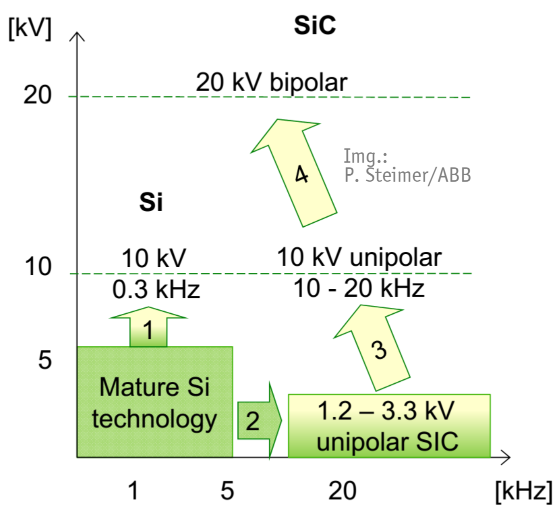
▶ SiC Power Semiconductors

- Lower Switching Losses ▸ Higher f_s, Smaller Passives
- Higher Blocking Voltages ▸ Fewer Devices, Lower Complexity

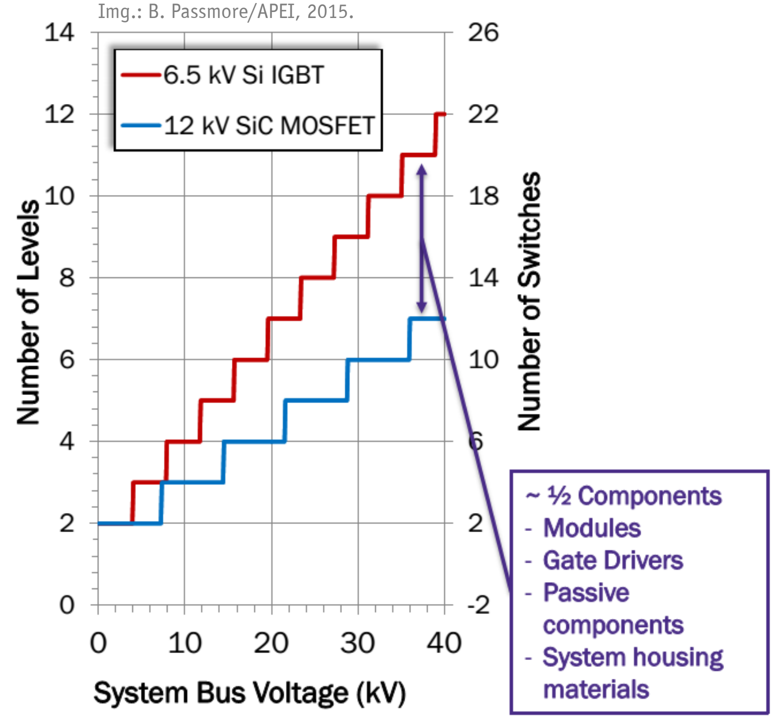
10kV SiC MOSFET ▸



Img.: Cree Inc.



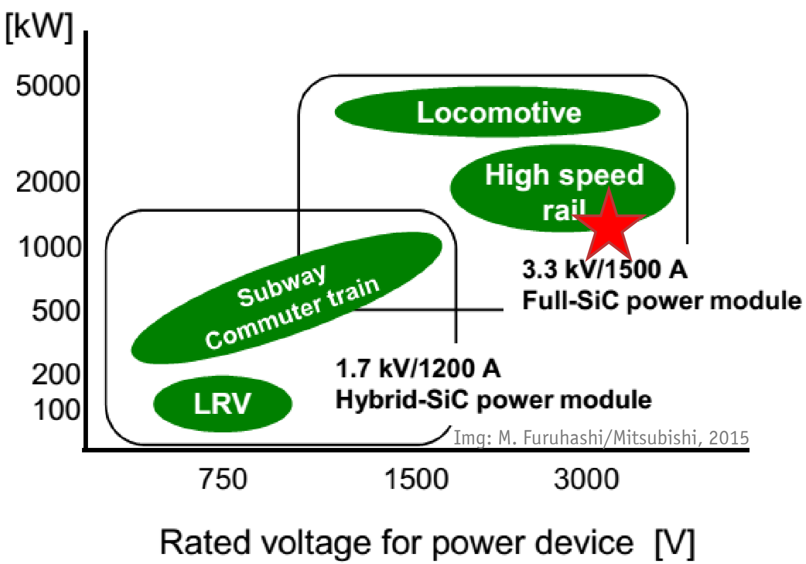
Img.: B. Passmore/APEI, 2015.



▶ SiC Semiconductors Available for High-Power Applications

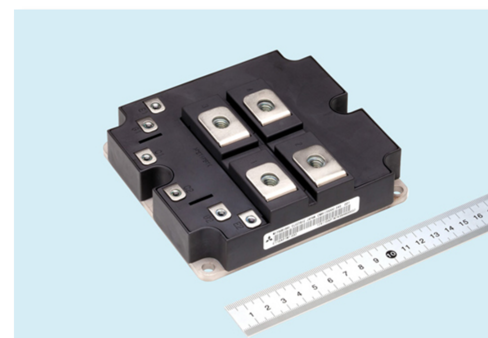
Example: All-SiC Traction Inverter (2014)

- 3.3kV/1.5kA SiC Modules in All-SiC Traction Inverter
- 65% Reduction of Size and Weight
- 55% Loss Reduction



Img: M. Furuhashi/Mitsubishi, 2015

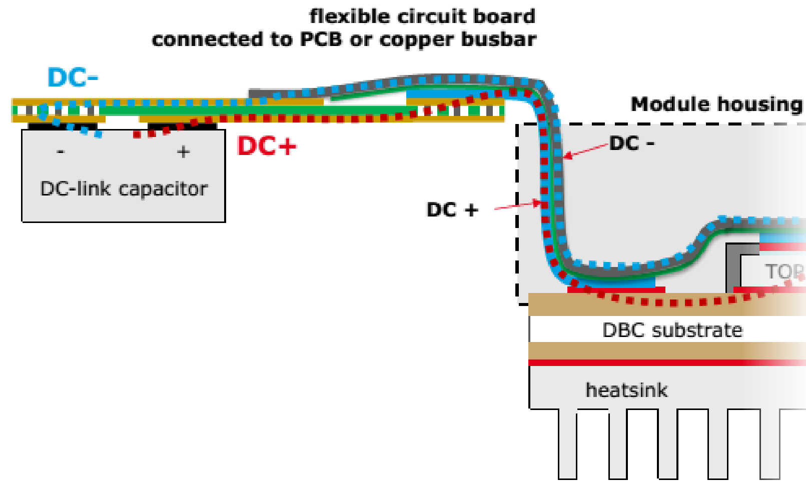
MITSUBISHI ELECTRIC
Changes for the Better
2014



▶ Major WBG Semiconductor Application Challenge: Packaging

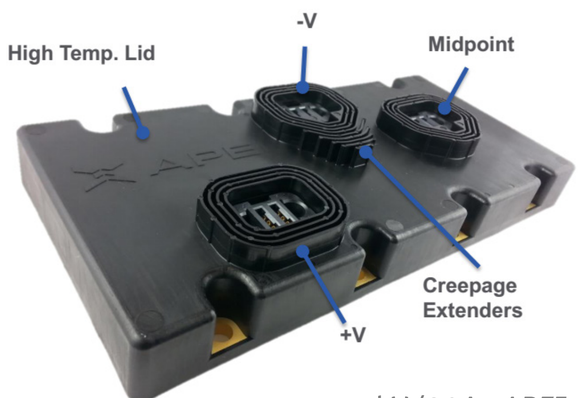
■ Low Inductance for Fast Switching

- < 2nH for 300A Module
- 15 x Lower Than Conventional



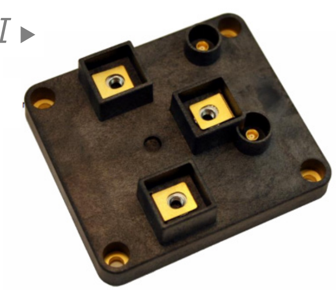
Img.: M. Röblitz/Semikron, 2015

■ Isolation for HV Devices



▲ 15kV/80A, *APEI*

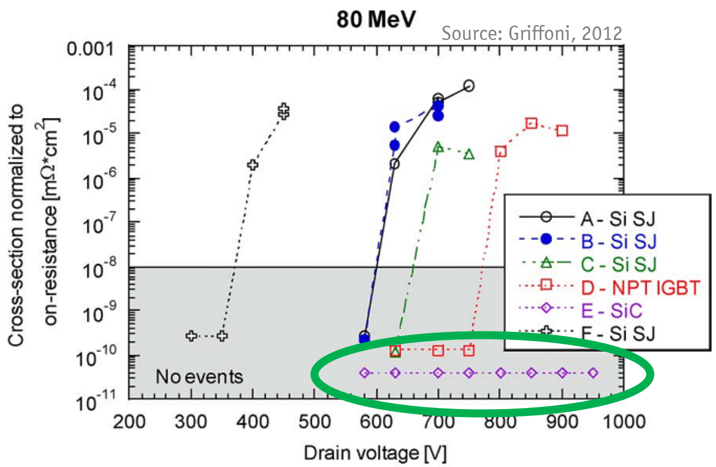
(!)
24kV/30A, **Fully Potted**, *APEI* ▸



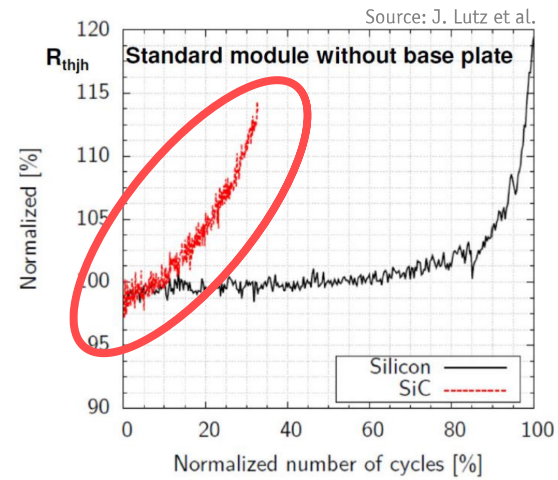
- Isolation of Gate Drives
- dv/dt Capability of Gate Drives

▶ WBG Semiconductor Reliability Considerations

- Cosmic Ray Induced Failures



- Increased Thermo-Mechanical Stress on Interface Materials



▲ Therm. Cycling Perf. (600V SiC Schottky vs. 1200V Si IGBT)

▸ New Packaging Technologies Will Help!

- **Missing Long-Term Field Experience when Compared with Rugged Si Devices**
- Further Research Required

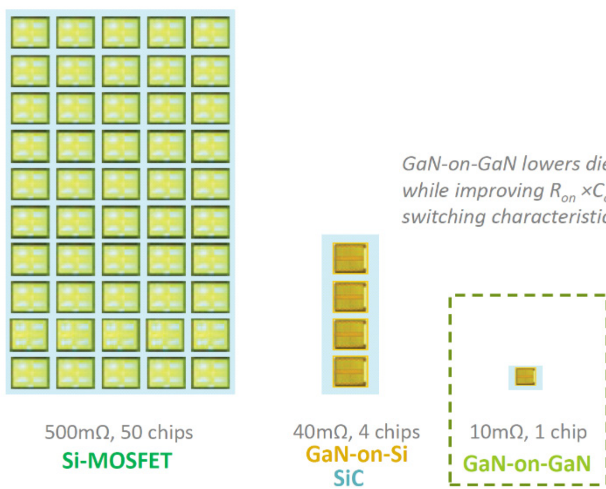
▶ Vertical (!) Power Semiconductors on Bulk GaN Substrates

avogy advancing energy efficiency

■ GaN-on-GaN Means Less Chip Area

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

GaN-on-GaN lowers die cost while improving $R_{on} \times C_{off}$ switching characteristic



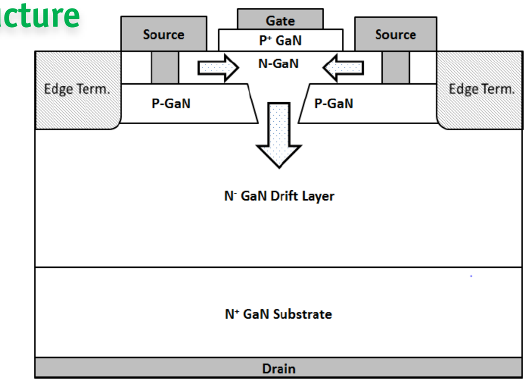
500mΩ, 50 chips
Si-MOSFET

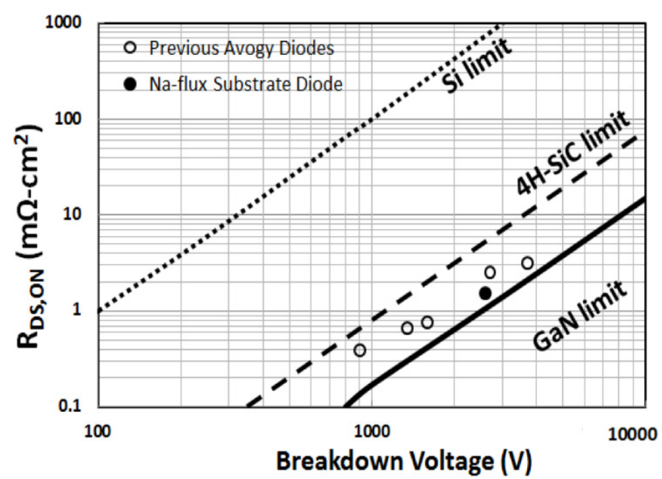
40mΩ, 4 chips
GaN-on-Si
SiC

10mΩ, 1 chip
GaN-on-GaN

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**





Challenge #3/10

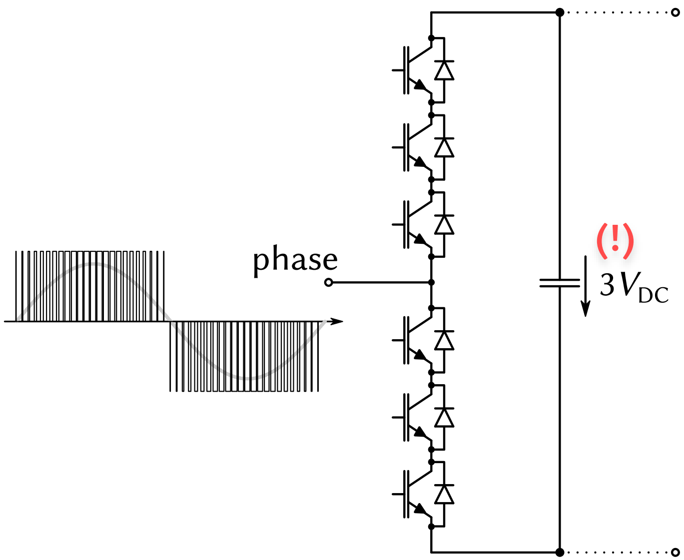
Single Cell vs. Multi Cell

Optimum Number of Levels
DC/DC Conversion
- *DAB*
- *HC-DCM-SRC*

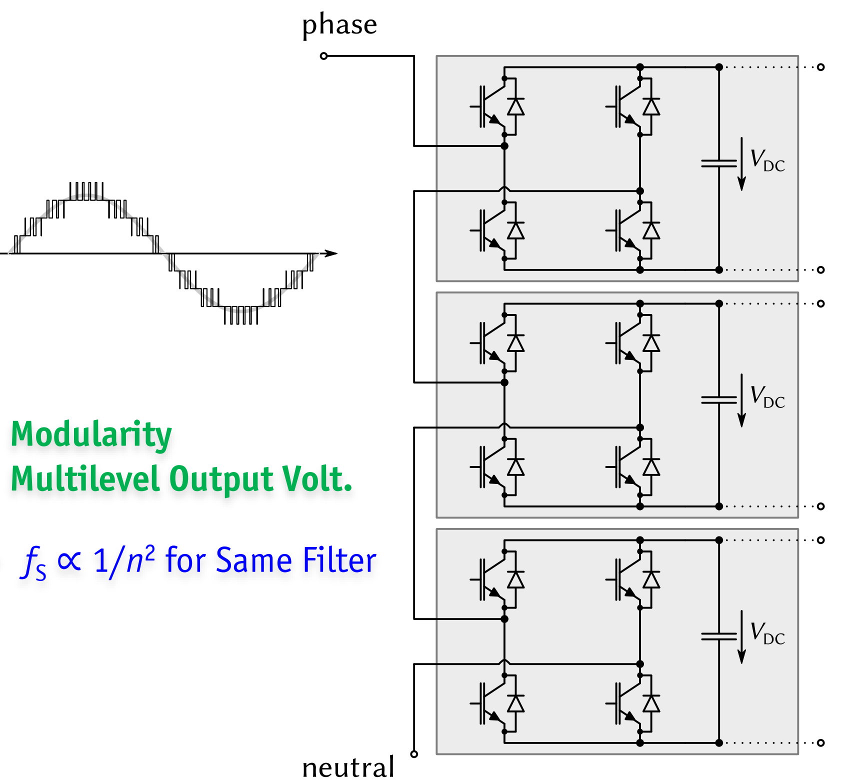
▶ Power Electronics in MV Applications

- Limited Blocking Voltage Capabilities of Si Semiconductors (< 6.5kV)

▸ **Direct Series Connection** **(or HV SiC!)**



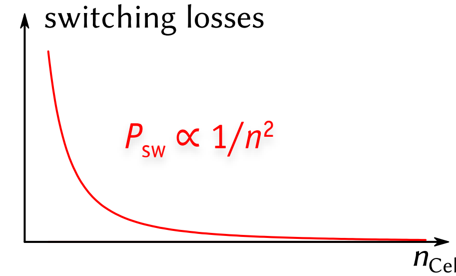
▸ **Cascading of Converter Cells**

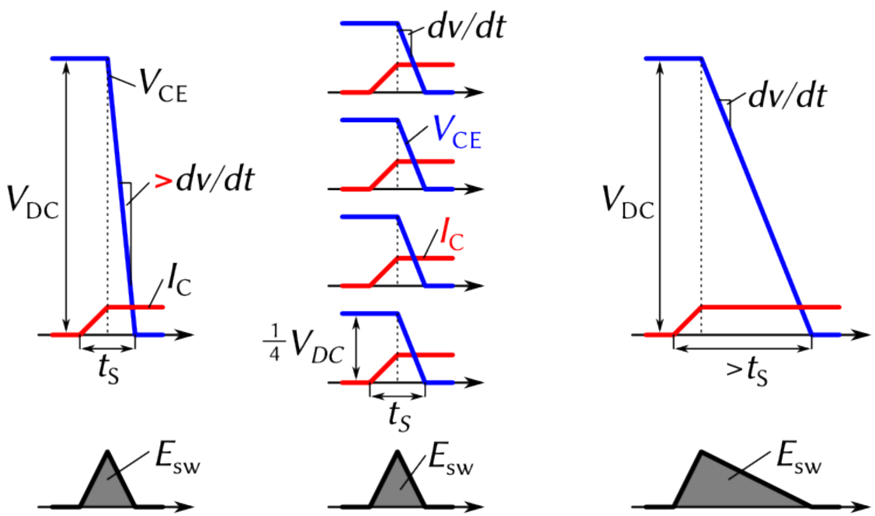


- **Modularity**
- **Multilevel Output Volt.**
  - $f_S \propto 1/n^2$ for Same Filter

▶ Basic Trade-Offs Quantified: Switching Losses

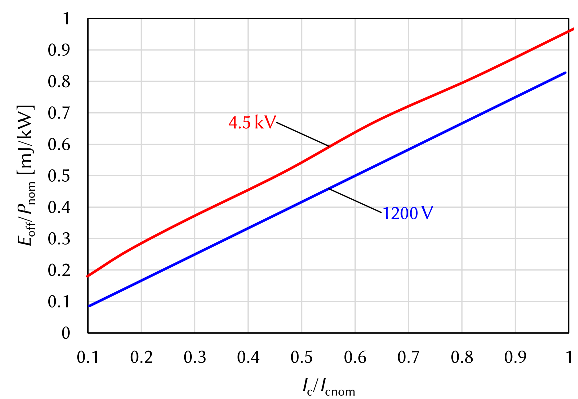
- Cell DC Voltage: $V_{DC} \propto 1/n$
- Switching Frequency for Equal Current Ripple: $f_S \propto 1/n^2$
- n Cells





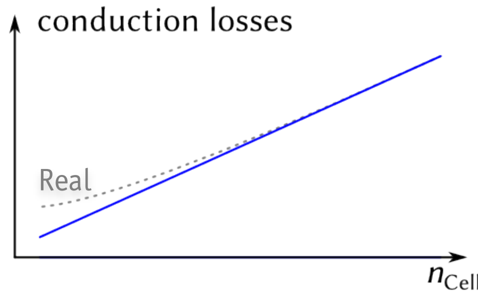
- ▶ Assumed
- ▶ Real → $P_{sw} \propto 1/n^{2\ldots3}$

▼ Normalized IGBT Turn-Off Energies

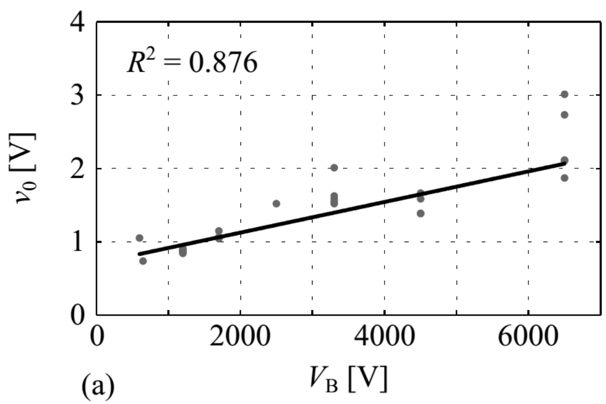


▶ Basic Trade-Offs Quantified: Conduction Losses

- More Cells, More Series Voltage Drops: $P_{\mathrm{cond}} \propto n$



- **Reality:** Voltage Drop Increases with Blocking Voltage Due to Larger Drift Region

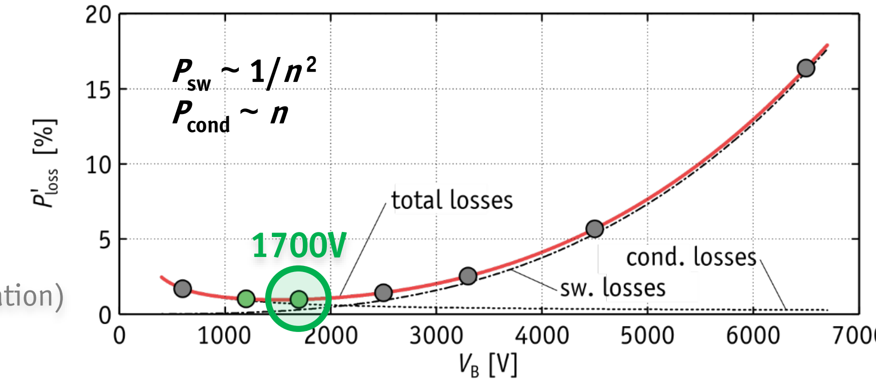


(a)

▶ Loss-Optimal Blocking Voltage Choice

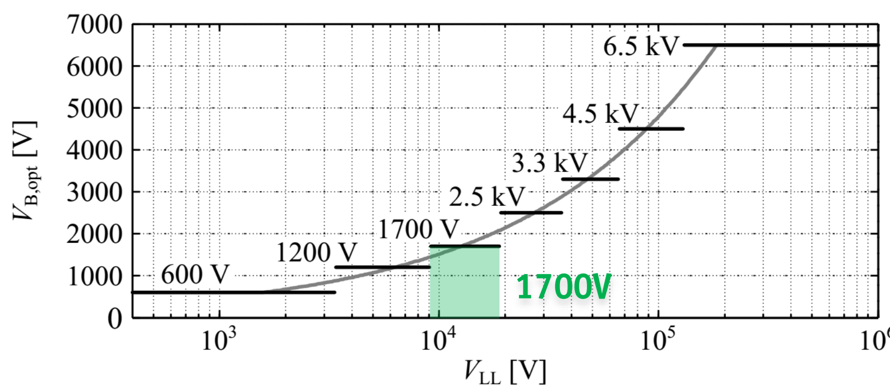
- Semiconductor Blocking Voltage Choice Equivalent to Choice of Number of Cells Choice!

(For a 10kV Grid Application)

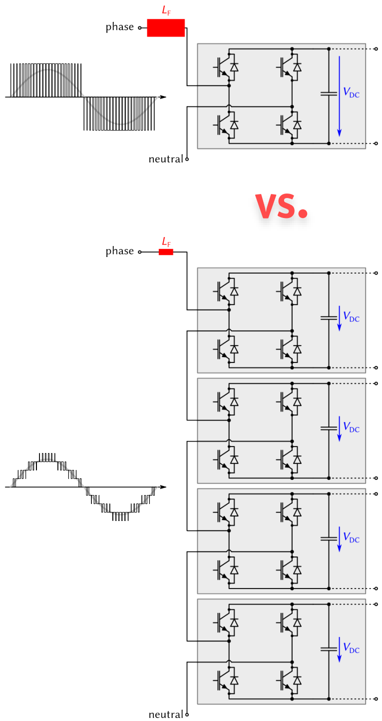


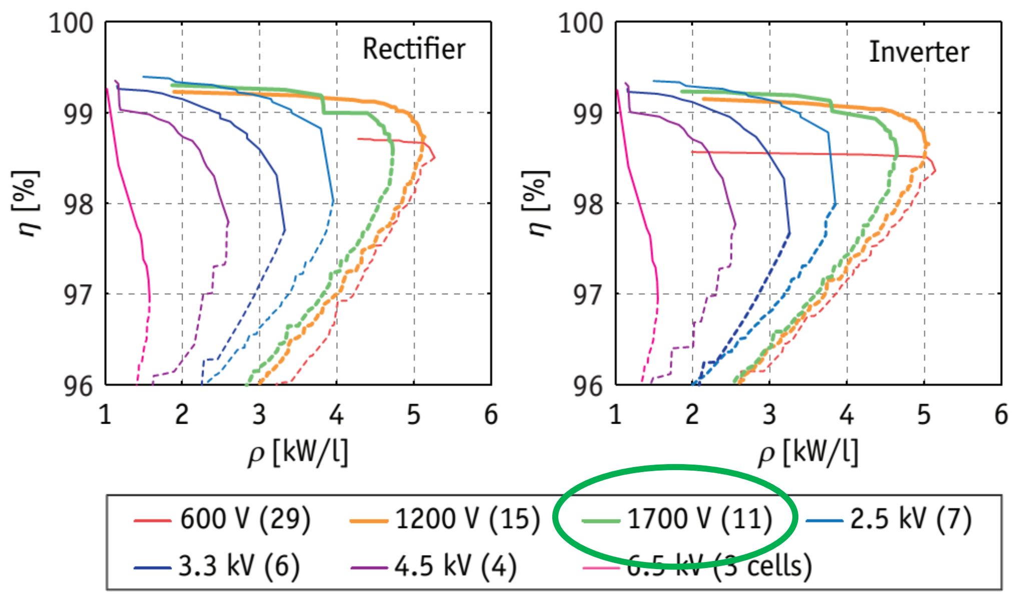
- **There *Is* an Optimum Blocking Voltage**
- 1200V or 1700V Devices Best for 10kV Line-to-Line Voltage Applications

- Optimum Blocking Voltages for Other Grid Voltage Levels



▶ Efficiency vs. Power Density Pareto Front





- **Caution:**
  Minimum Filter Inductance Might be Required from (Application-Dependent) **Protection** Considerations

Challenge #3/10

Single Cell vs. Multi Cell

Optimum Number of Levels

DC/DC Conversion

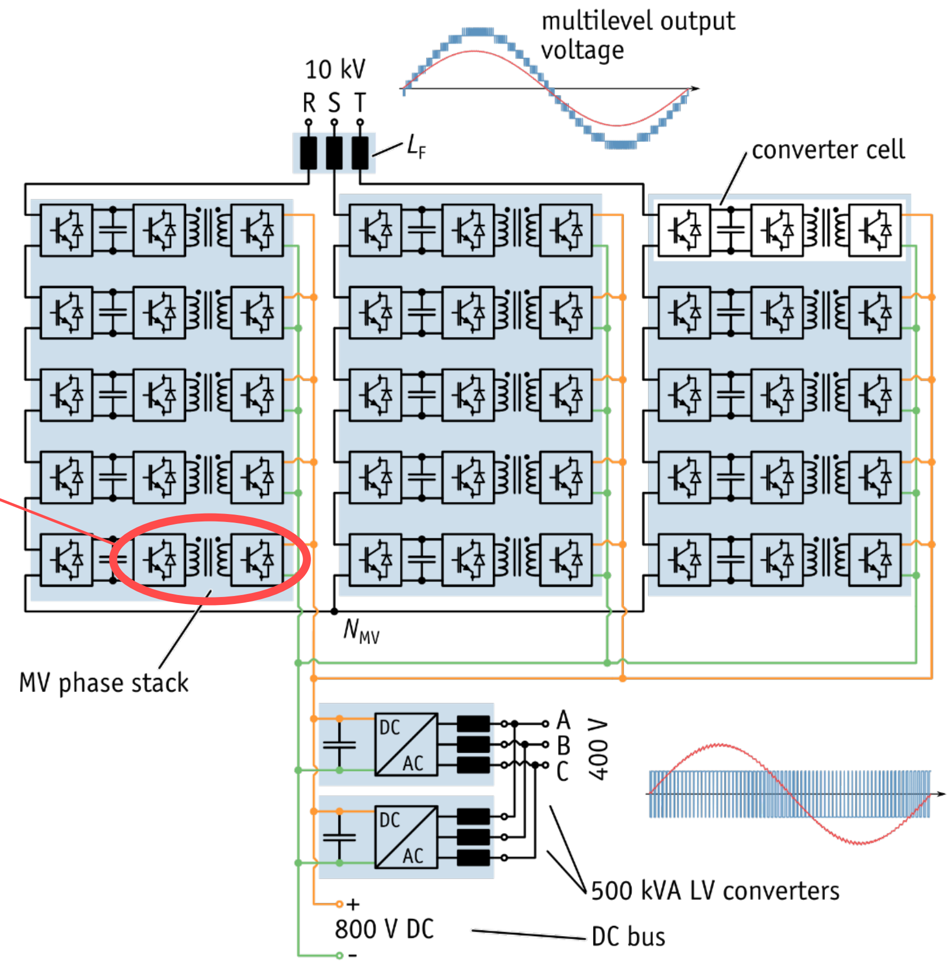
- DAB
- HC-DCM-SRC

▶ Example System: ETH *MEGAlink* Distribution SST

■ Specifications

- 1 MVA
- 10 kV AC to 800 V DC and 400 V AC
- 1700V IGBTs on MV Side

DC/DC Converter



■ Commonly Envisioned Features

- Voltage Scaling & Galvanic Isolation
- Power Flow Control
- Reactive Power Compensation
- Fault Current Limiting
- DC Interface
- …

Challenge #3/10

Single Cell vs. Multi Cell

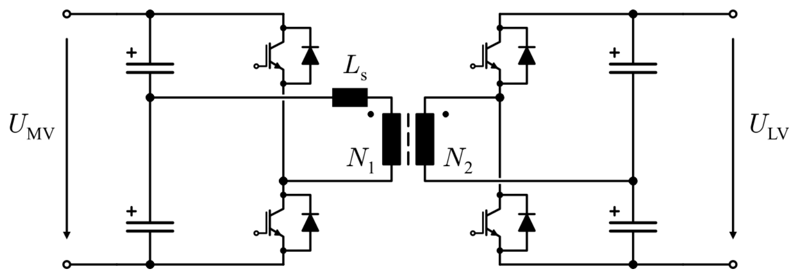
Optimum Number of Levels

DC/DC Conversion

- **DAB**
- HC-DCM-SRC

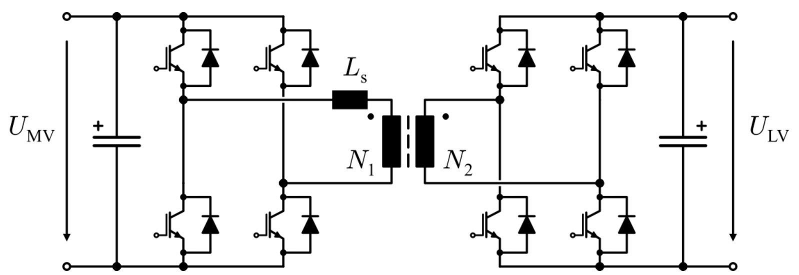
▶ DAB — Common Bridge Configurations

- Half-Bridge



- Two Voltage Levels on Each Side

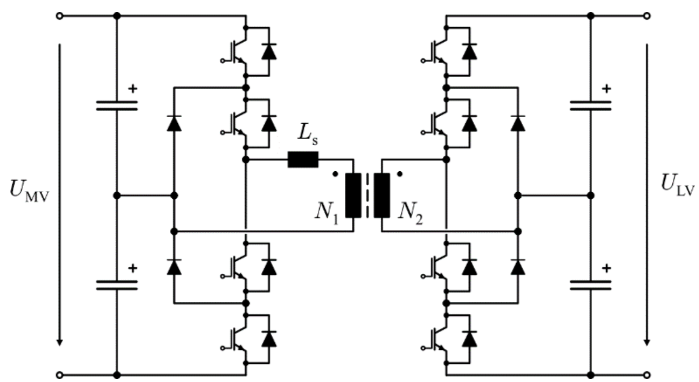
- Full-Bridge



- Three Voltage Levels on Each Side
Additional Freewheeling State

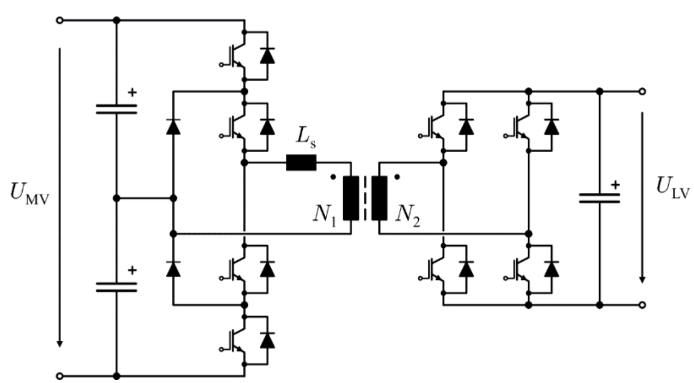
▶ DAB — Common Bridge Configurations

- Neutral Point Clamped (NPC, Multilevel)



- Three Voltage Levels on each Side
- Operation as Voltage Doubler

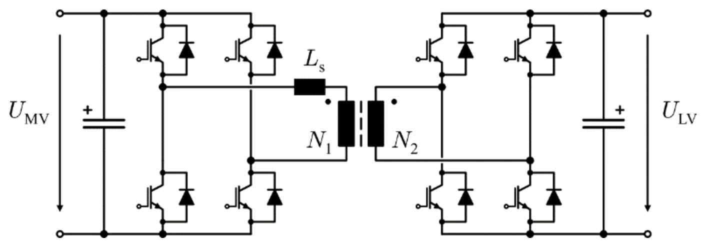
- NPC / Full-Bridge Configuration

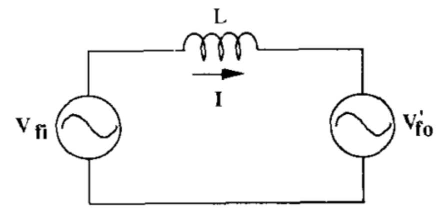


- **Suitable for Higher MV/LV Ratios**

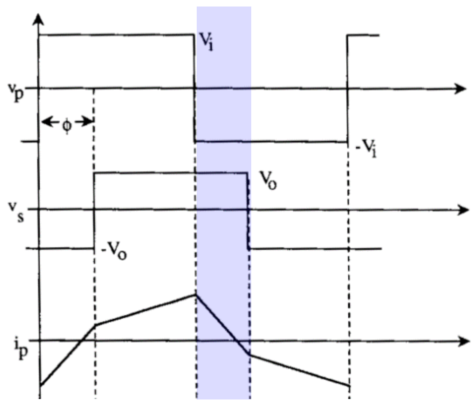
▶ DAB — Phase-Shift Modulation

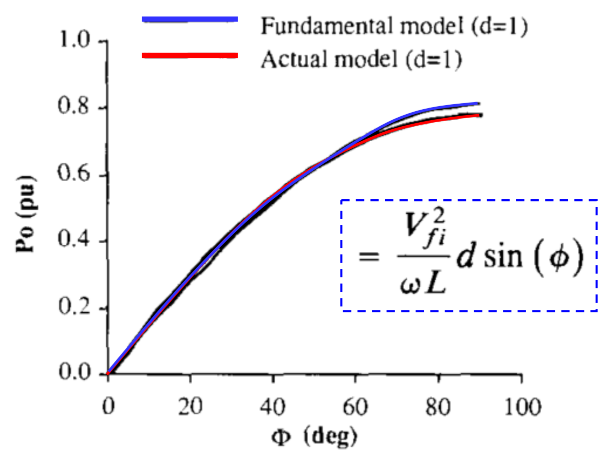
- Power Transfer Controlled through Phase Shift between MV and LV Bridges





Fundamental model of the dual bridge dc/dc converter.

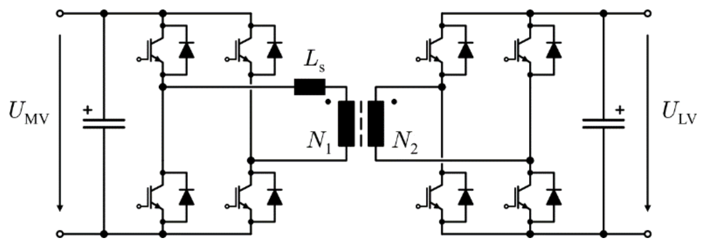


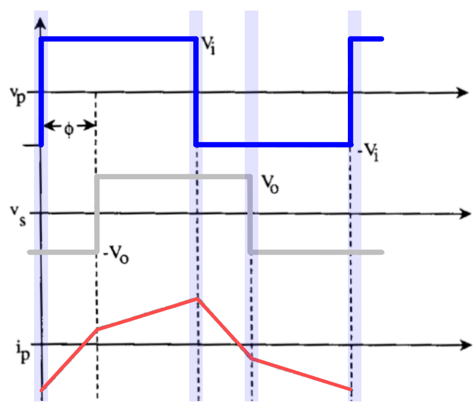


Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

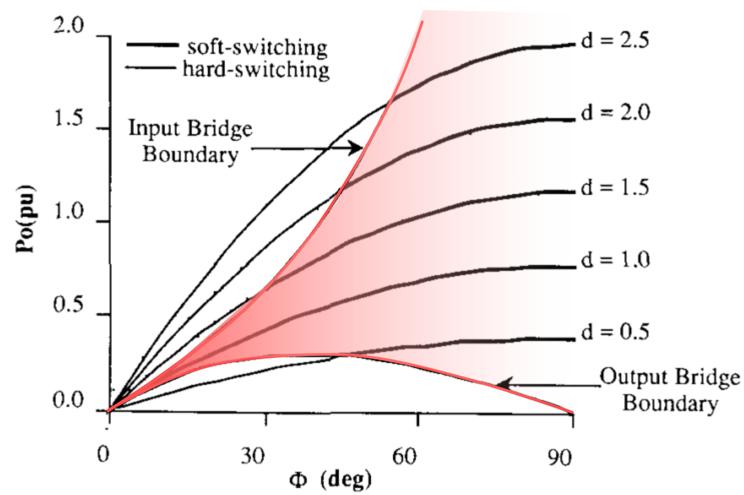
▶ DAB — Phase-Shift Modulation

- All Switching Transitions done in ZVS Conditions (within a Certain Operating Range)



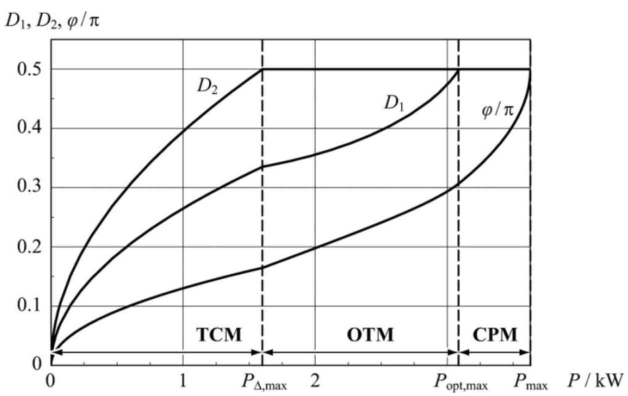


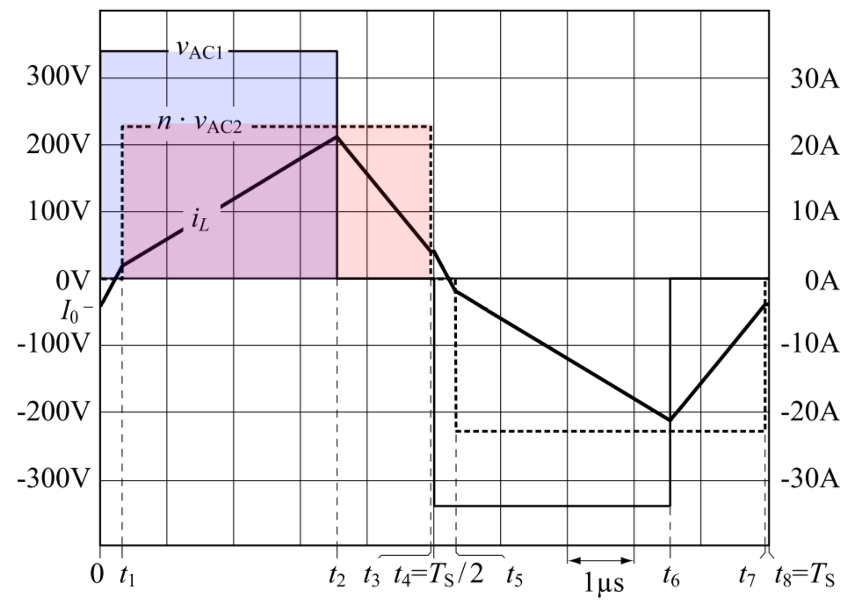
▸ Soft Switching Range



▶ DAB — Phase-Shift / Duty Cycle Modulation

- Additional Degrees of Freedom Can Be Utilized for Optimization
- For Example: Minimization of the RMS Currents through the Transformer (ETH, Krismer, 2012)

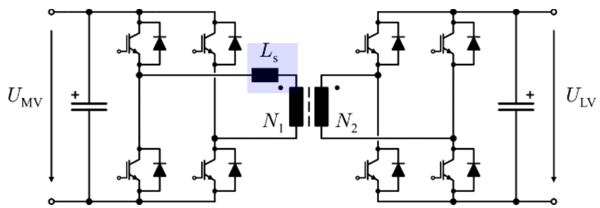


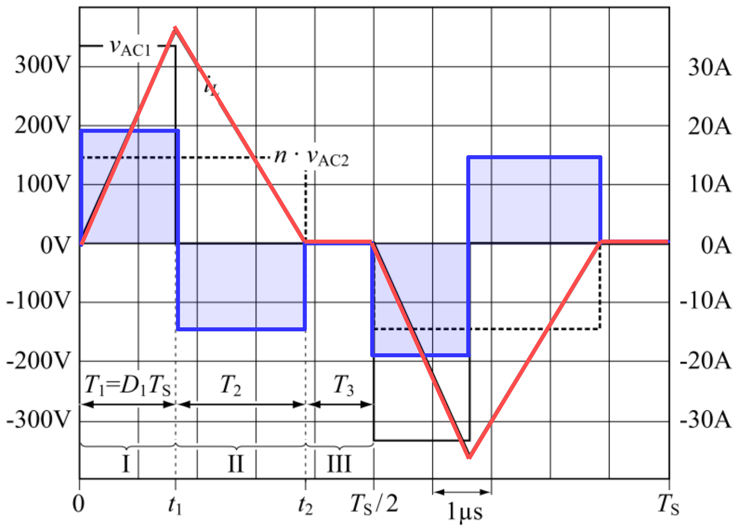


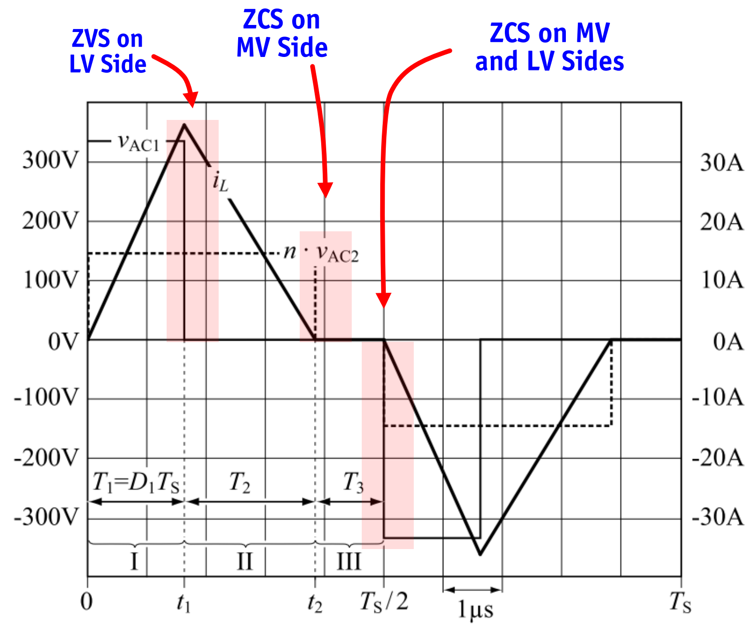
- Not Possible in Half-Bridge Configurations (No Zero Voltage Intervals)

▶ DAB — Triangular Current Mode

■ Duty Cycles and Phase Shift Utilized to Perform Zero Current Switching (ZCS)







▸ ZCS on MV Side (!)

Challenge #3/10

Single Cell vs. Multi Cell

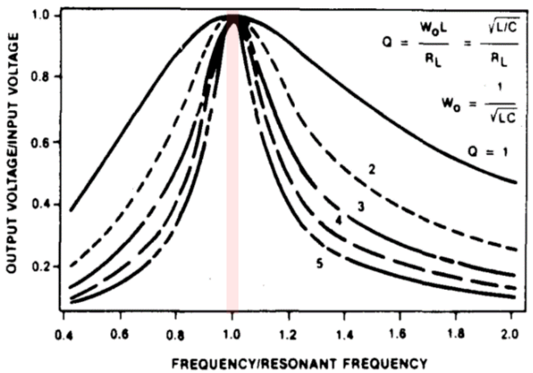
Optimum Number of Levels

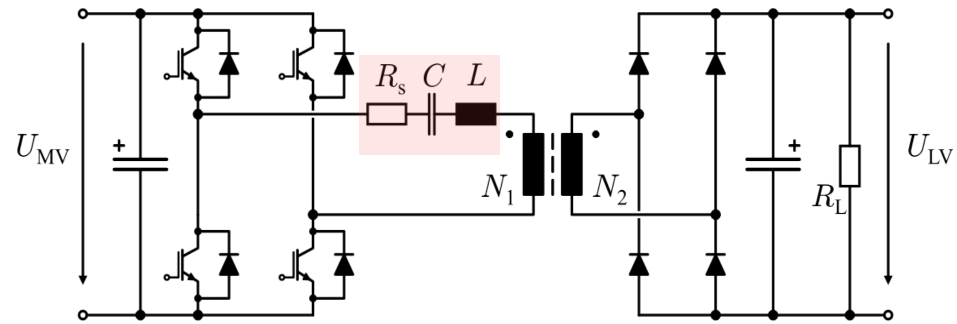
DC/DC Conversion

- DAB
- **HC-DCM-SRC**

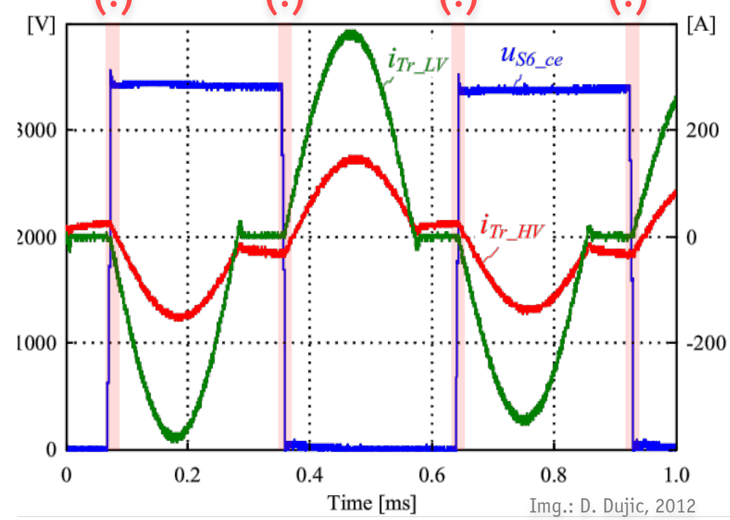
▶ Half-Cycle Discont.-Cond.-Mode Series-Res.-Conv. (HC-DCM-SRC)

- Operating Principle: **Resonant Frequency ≈ Switching Frequency**





- The Input/Output Voltage Ratio is Close to Unity **Independent** of Power Transfer (Steigerwald, 1988)

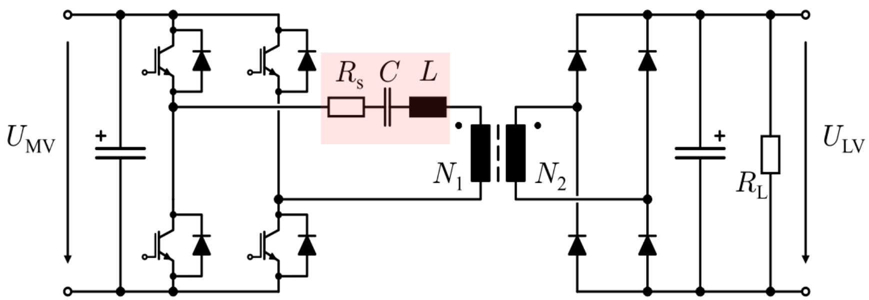


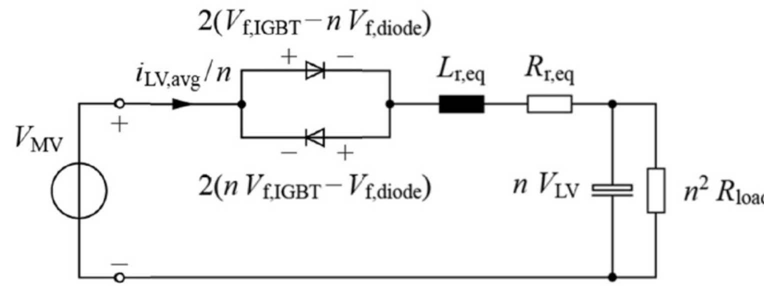
Img.: D. Dujic, 2012

ZCS of All Devices ▸

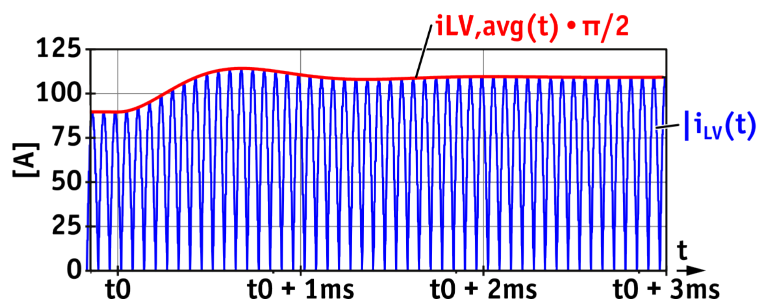
▶ Half-Cycle Discont.-Cond.-Mode Series-Res.-Conv. (HC-DCM-SRC)

■ Equivalent Circuit for Transient Analysis — Esser (1991)





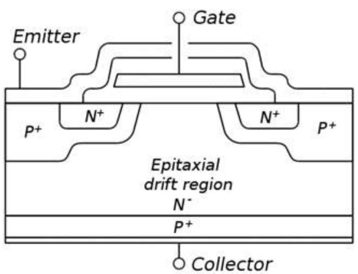
$$L_{r,eq} = \frac{\pi^2}{4} L \qquad R_{r,eq} = \frac{\pi^2}{8} R$$

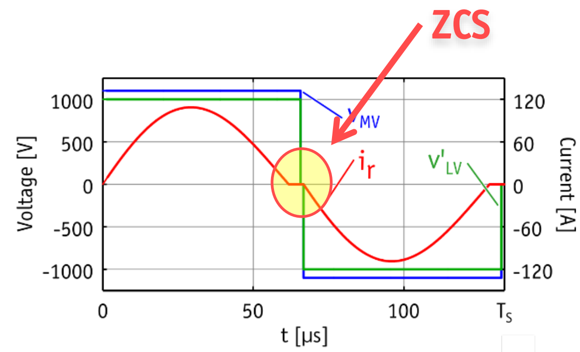


■ **Output Voltage is $V_{LV} \approx V_{MV} \cdot n$ for Any Output Power ⟶ "DC Transformer"**

▶ ZCS Losses in IGBTs – Stored Charge Effects

- Bipolar Device: Free Charges in Drift Region to Modulate Conductivity

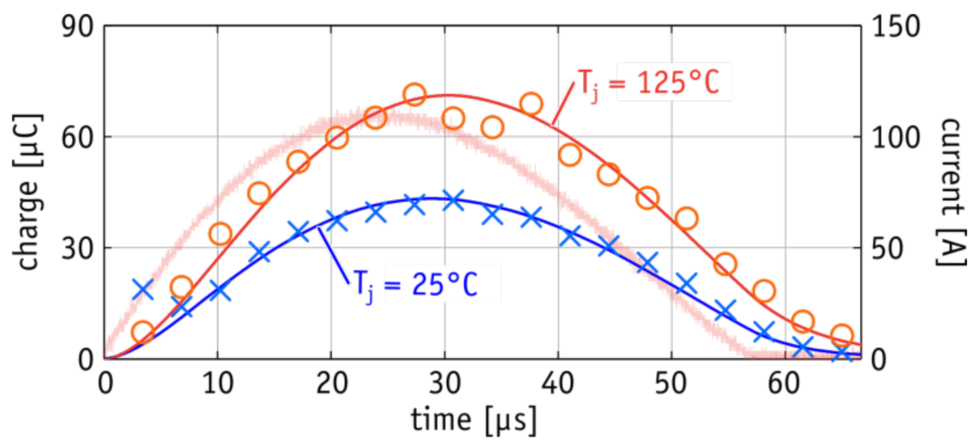




$$\frac{dQ(t)}{dt} = -\frac{Q(t)}{\tau} + k_s \cdot i_s(t)$$

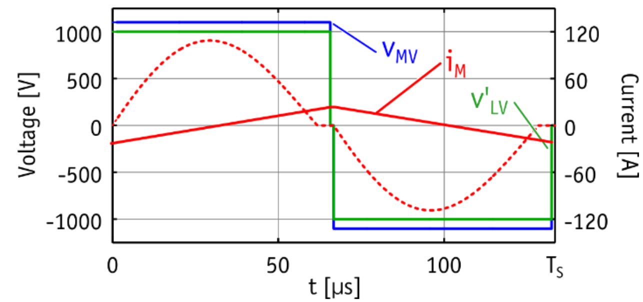
Further Reading
G. Ortiz, H. Uemura, D. Bortis, J. W. Kolar, and **O. Apeldoorn**, "Modeling of Soft-Switching Losses of IGBTs in High-Power High-Efficiency Dual-Active-Bridge DC/DC Converters," *IEEE Trans. Electron Devices*, vol. 60, no. 2, pp. 587–597, Feb. 2013.

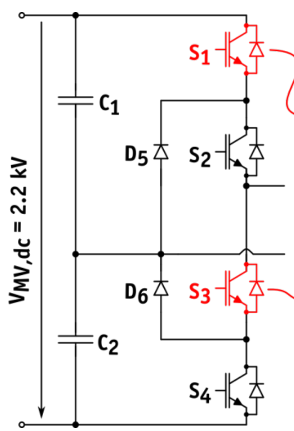
Calculated and Measured Stored ▶ Charge in 1700V/150A IGBT4.

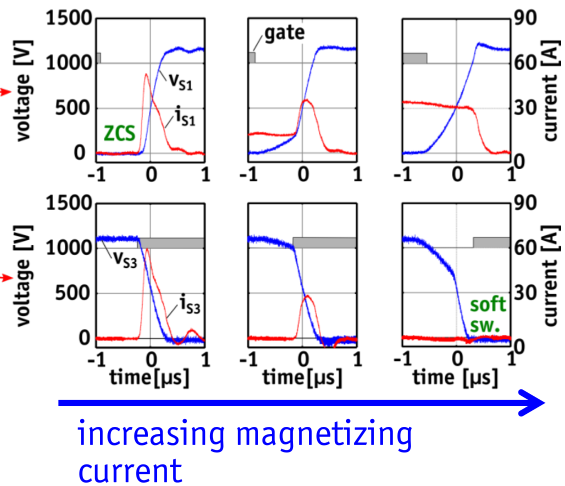


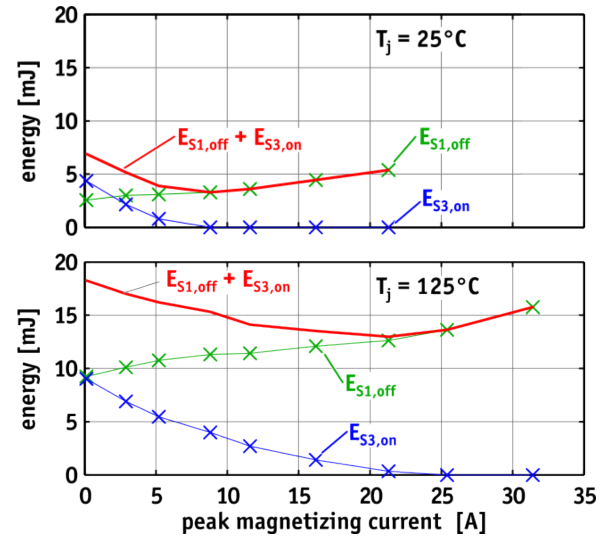
▶ Residual Current Switching – ZVS

- Magnetizing Current Helps Removing Stored Charge From Turning-Off Switch S_1
  - Reduction of Turn-On Losses
  - Increased Turn-Off Losses
- There Is an Optimum!



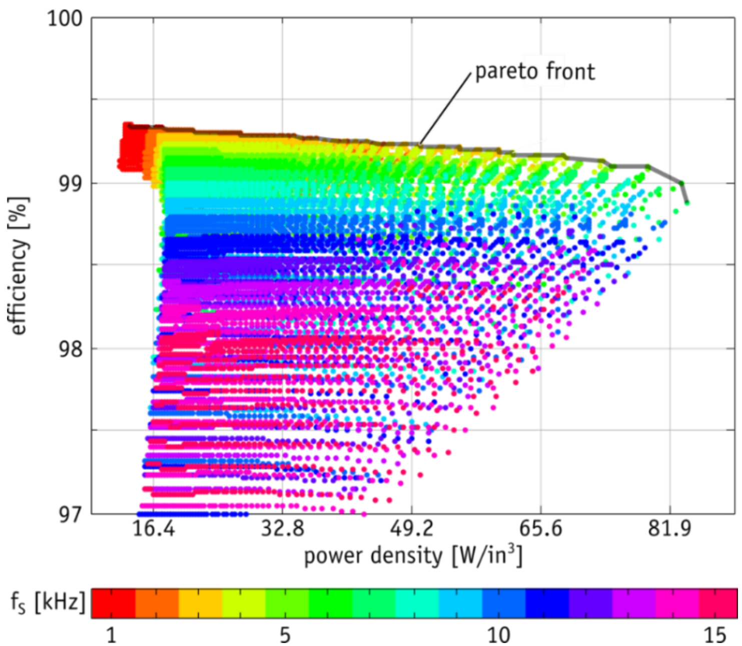




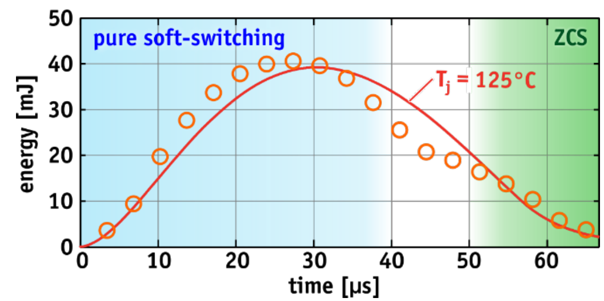


▶ Half-Cycle Discont.-Cond.-Mode Series-Res.-Conv. (HC-DCM-SRC)

- Efficiency / Power Density Optimization → Pareto Front
  - Operating Frequency Used as Free Parameter
  - ZCS Losses Included in the Model



Specs:
80kW
2.2kV ⟶ 800V



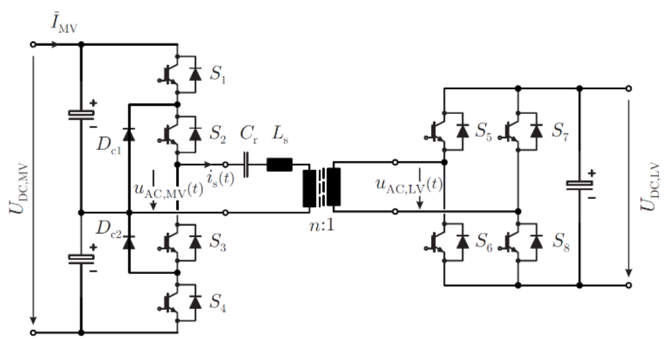
▲ ZCS Loss Modeling and Verification

Further Reading
J. Huber, G. Ortiz, F. Krismer, N. Widmer, and **J. W. Kolar**, "η-ρ pareto optimization of bidirectional half-cycle DC/DC converter with fixed voltage transfer ratio," in *Proc. Applied Power Electronics Conf. (APEC)*, 2013, vol. 1.

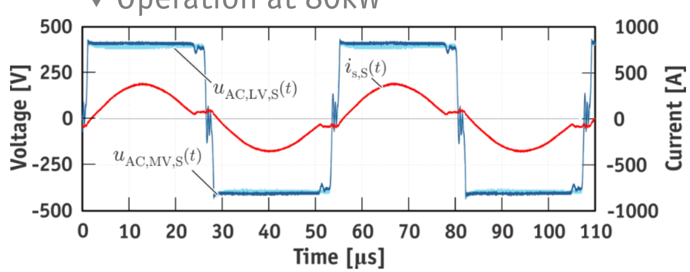
- HC-DCM-SRC Is Capable of Reaching Efficiencies of **99%+**
- The Optimum Frequency at which a 99% Efficiency is Reached is about **7kHz** for the HC-DCM-SRC

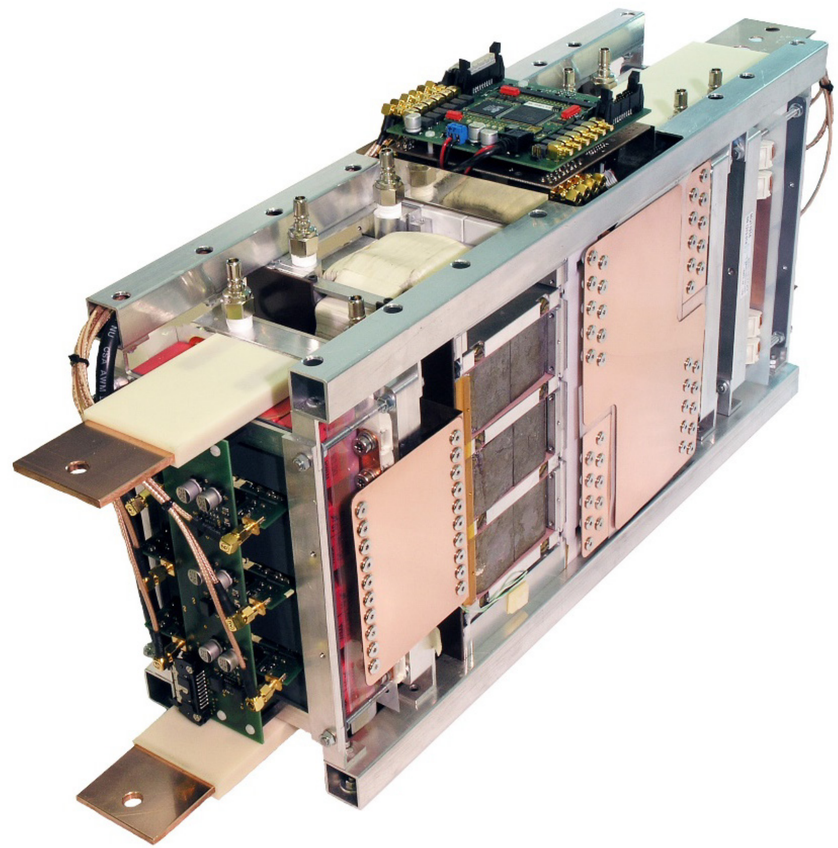
► 166kW / 20kHz HC-DCM-SRC DC-DC Converter Cell

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



▼ Operation at 80kW





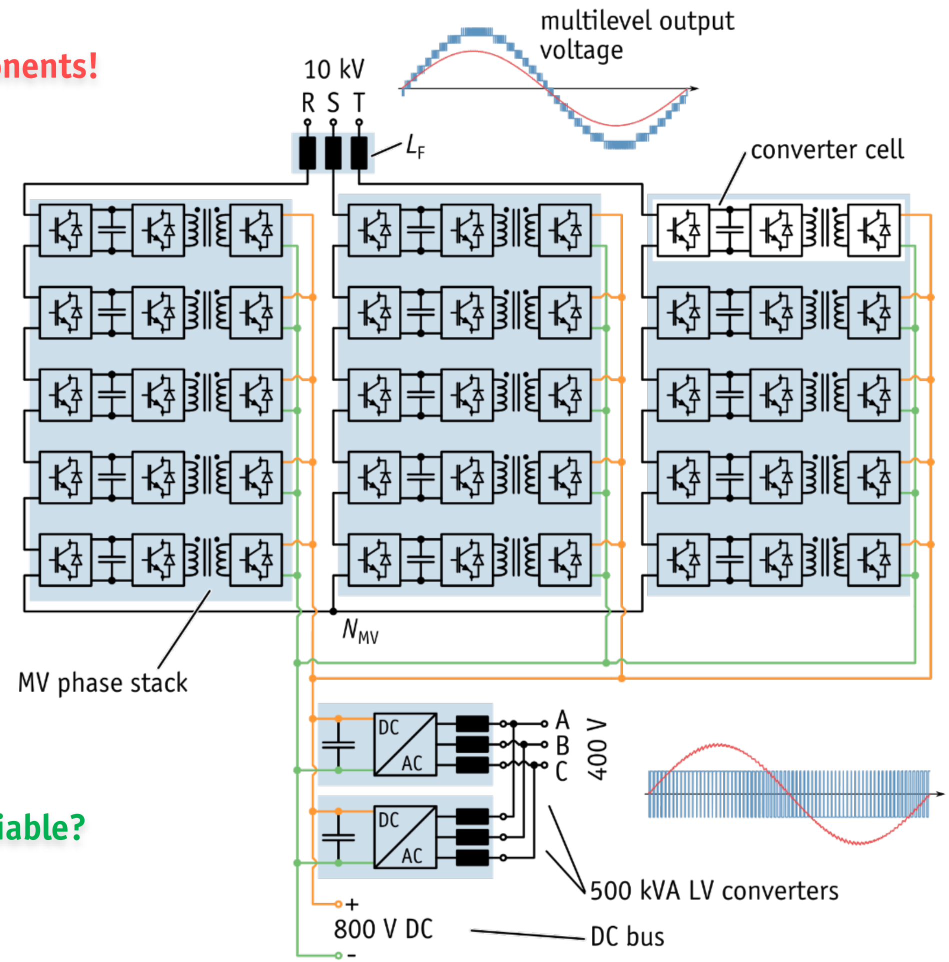
Challenge #4/10

Reliability

Basics of Reliability Modeling
Cell-Level Redundancy
"Reliability Bottlenecks"

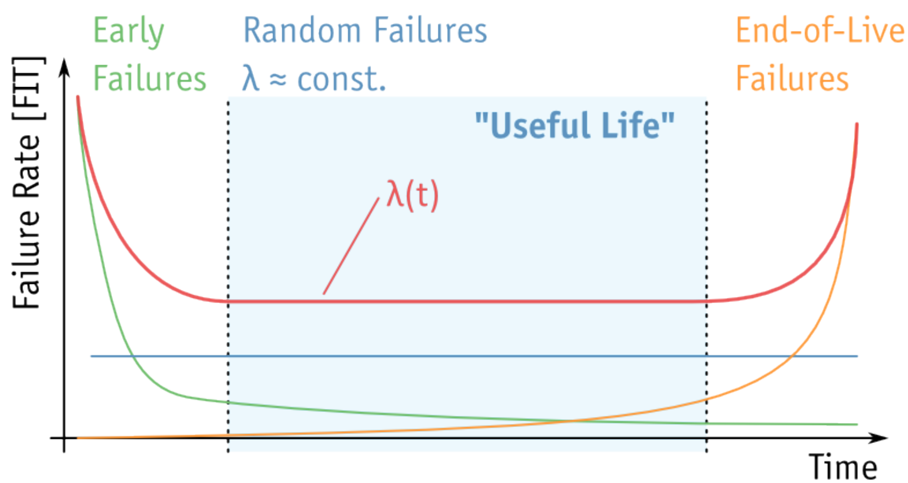
► Example System: ETH *MEGAlink* Distribution SST

- Modular System ► **MANY Components!**



- **Can Such a System Still Be Reliable?**

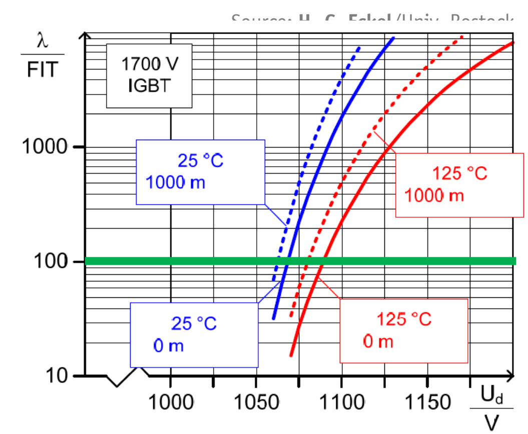
▶ Modeling Reliability: The Failure Rate



◀ *«Bathtub Curve»*

- In General, the **Failure Rate $\lambda(t)$** is a Function of Time

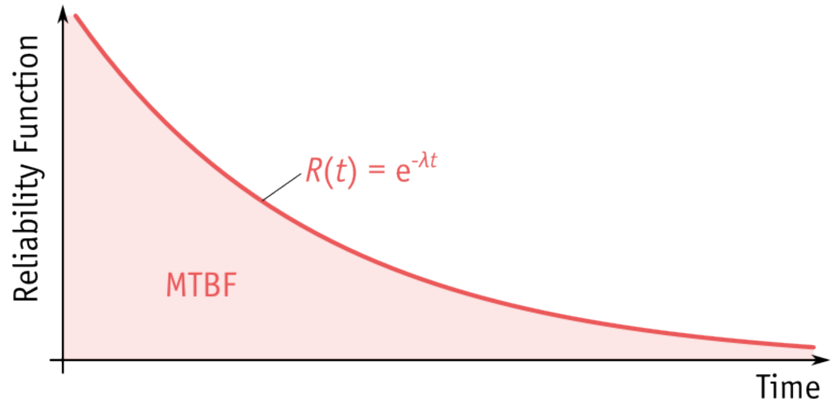
- Here, Only **Useful Life** is Considered
  - Dominated by Random Failure Distribution
  - Constant Failure Rate λ
  - $[\lambda]$ = 1 FIT (1 Fail. in 10^9 h) – Typ. Value for an IGBT Mod.: 100 FIT ▸



- Example **Sources** for Empirical Component Failure Rate Data
  - MIL-HDBK-217F, "Reliability Prediction of Electronic Equipment," 1995.
  - IEC Standard 62380:2004(E), "Reliability Data Handbook," IEC, 2004.
  - Stds. Define Base Failure Rates for Comp. and Factors to Account for Stress Levels (e.g., Temperature)

▶ Modeling Reliability: The Reliability Function

- Expresses Probability of System Being Operational After t Hours
- General Definition: $R(t) = e^{-\int_0^t \lambda(x)dx}$
- During Useful Life $\lambda(t)$ = const. = λ:



- Then: Mean Time Between Failures:

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

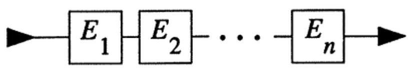
Caution: MTBF is Not the Time Before Which No Failure Occurs – It's All Statistics!

- Average Availability:

$$A = \frac{MTBF}{MTBF + MTTR}$$

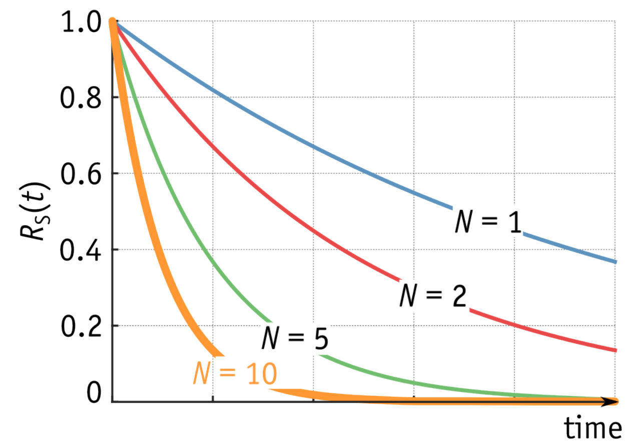
▶ Modeling Reliability: Basic Multi-Element Considerations

■ Series Structure
(e.g. Components of a Single Converter Cell)



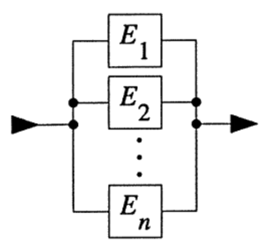
$$\lambda_S = \sum_{i=1}^{n_{\text{comp.}}} \lambda_i$$

(General Assumption: Independent Elements with Equal Failure Rate.)



■ *k*-out-of-*n* Redundancy
(e.g., Redundancy of Cells in a Phase Stack)

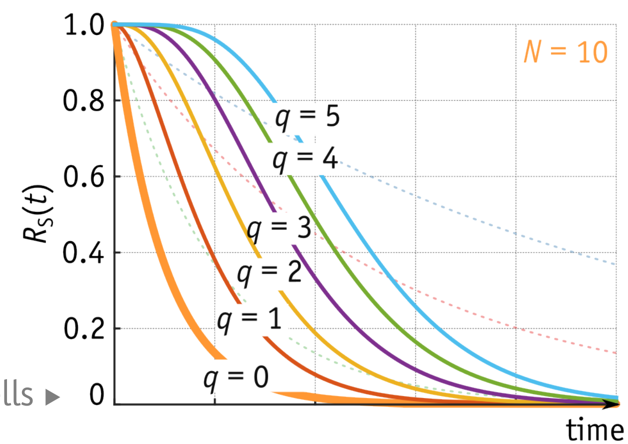
- System is Operational as Long as At Least *k* out of *n* Subsystems (Cells) Are Operational



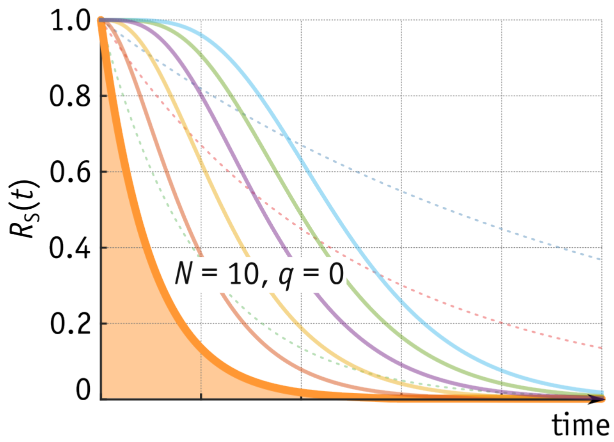
k-out-of-*n*

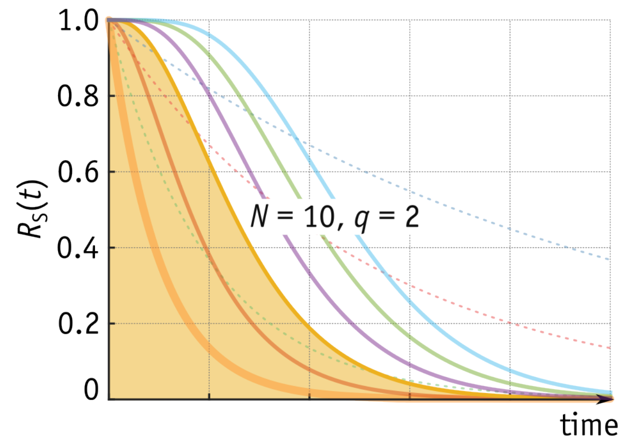
A. Birolini, *Quality and Reliability of Technical Systems*, 2nd ed. Berlin and Heidelberg: Springer, 1997.

Effect of *q* Additional Redundant Cells ▸

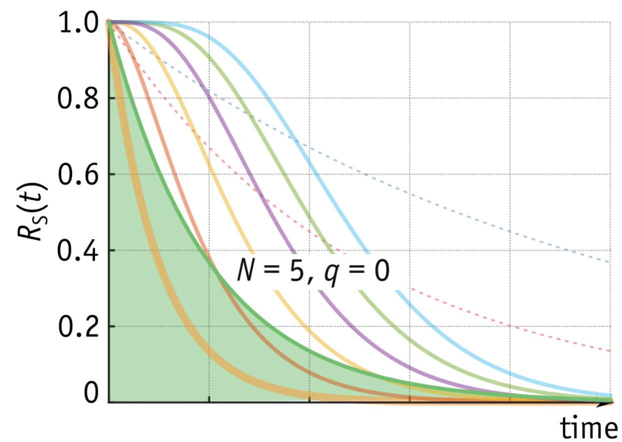


▶ The "Power of Redundancy" (1)





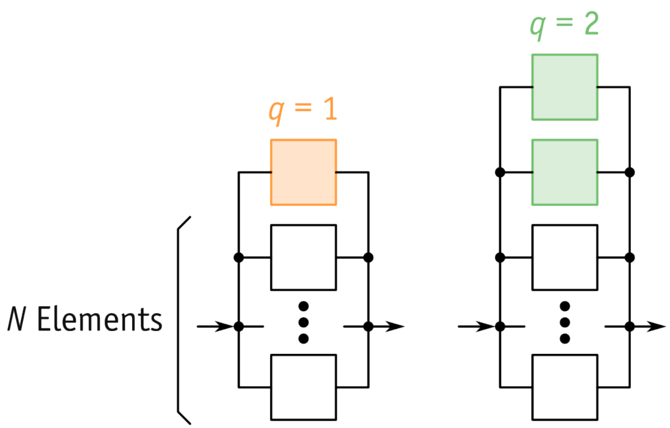
- Remember: $MTBF = \int_0^\infty R(t)dt$
  - Area Below Reliability Function!

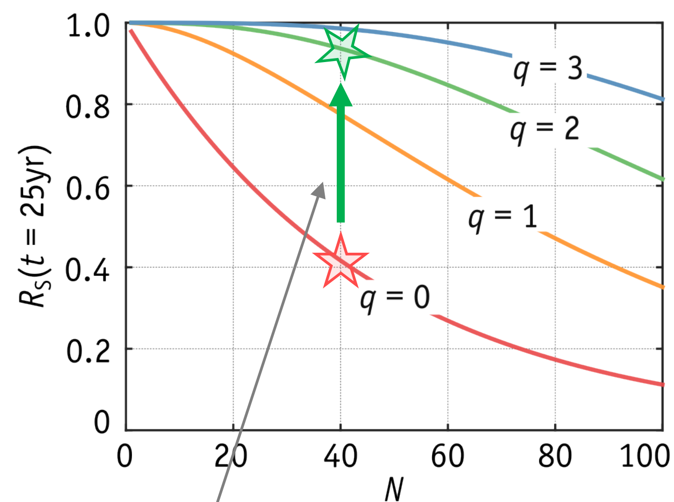


- **Redundancy Can Significantly Improve System Level Reliability**
  - ▸ 10 Elements + 2 Redundant: Reliability Higher than for 5 Elements!

► The "Power of Redundancy" (2)

- Value of Reliability Function at ***t* = 25 years**
  - *N* Elements
  - *q* Additional Redundant Elements



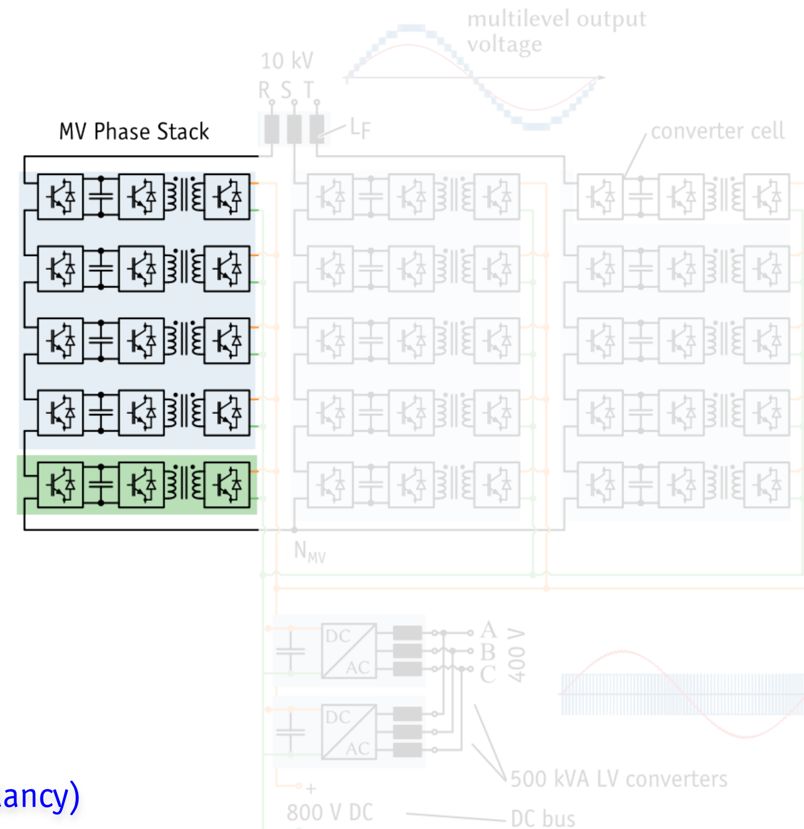


- **Redundancy Can Significantly Improve System Level Reliability**
  - E.g., for *N* = 40: from 40% to >90% with 2 Additional Redundant Cells

▶ Example System: Redundant Cells

- Modular System
  - ▸ **Simple Redundancy of Cells!**

Example:
4-out-of-5 Redundancy ▸



- Basic Assumptions
  - Failure Rate of a Cell: λ_{cell}
  - Failure Rate of Stack: $\lambda_{cell} n_{cell}$ (w/o Redundancy)

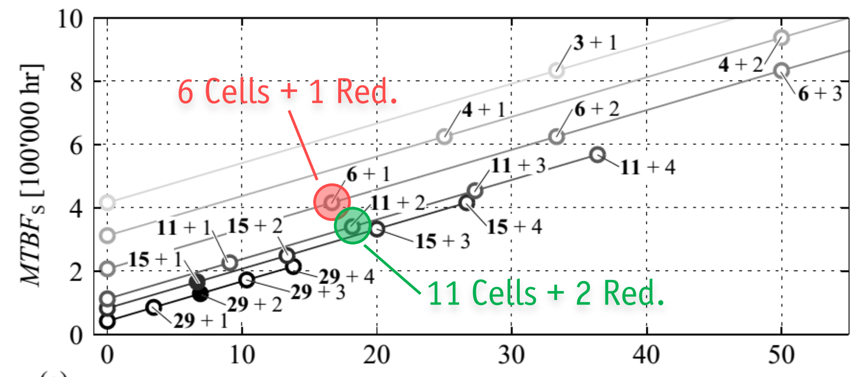
▶ Types of k-out-of-n Cells Redundancy

Note: **Qualitative** Results!

■ Standby Redundancy

- Spare Cell In Ready State, But Not Processing Power
- $\lambda = 0$ For Spare Cell

$$MTBF_S = \frac{n-k+1}{k\lambda_{cell}}$$



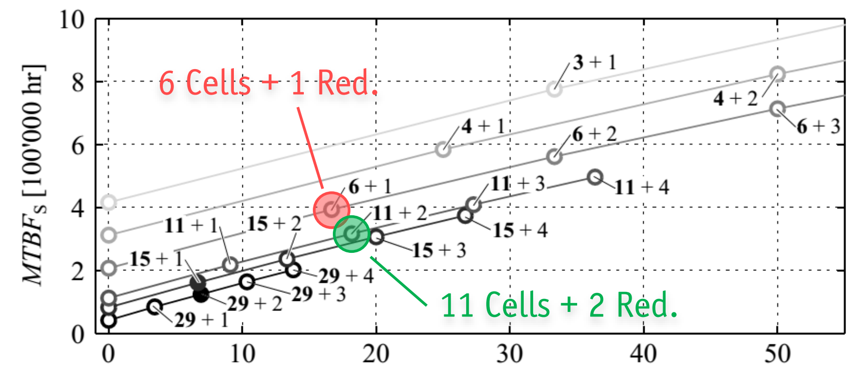
(a)

■ Active Redundancy with Load Sharing

- Spare Cell Processing Power
- Reduced Stress of All Cells Due to Lower Temperatures (and DC Voltages)

$$MTBF_S = \sum_{i=0}^{n-k} \frac{1}{(n-i)\lambda_{cell}\pi_{T,i}}$$

$\pi_{T,i}$: Temperature Stress Factor

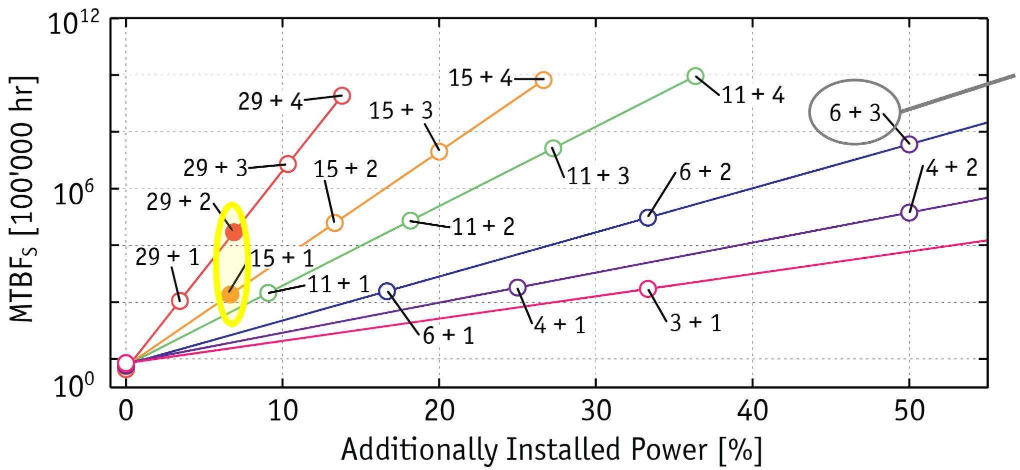


(b)

▶ Reparability

Note: **Qualitative** Results!

- Modularity: Faulty Cell Can Be Replaced On-Site; Possibly Even In a Hot-Swap Operation
  - Example: **Mean Time To Repair** (MTTR) of One Week Assumed



Read "6 Cells Required (Blocking Voltage), Plus 3 Redundant Cells."

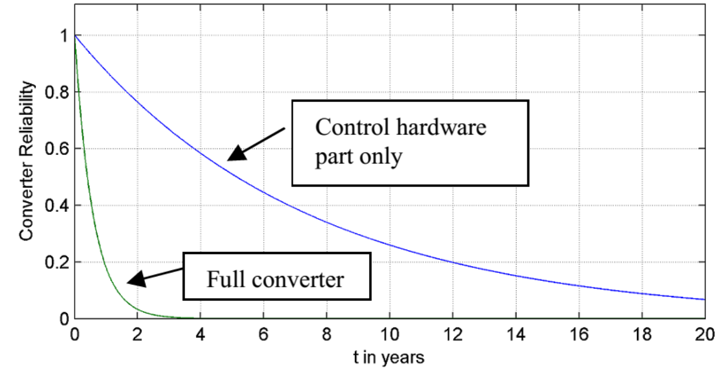
- **Multi-Cell Designs Can Still Be Made Highly Reliable By Adding Redundancy!**
  - Therefore: Reliability Consid. Does not Limit to Choose the ηρ-Optimal Number of Cells
- **Preventive Maintenance** Can Further Improve System Availability

Further Reading
J. E. Huber and **J. W. Kolar**, "Optimum Number of Cascaded Cells for High-Power Medium-Voltage Multilevel Converters," in *Proc. Energy Conversion Congr. and Expo (ECCE USA)*, Denver, CO, USA, Sep. 2013.

▶ Reliability "Bottlenecks" (1)

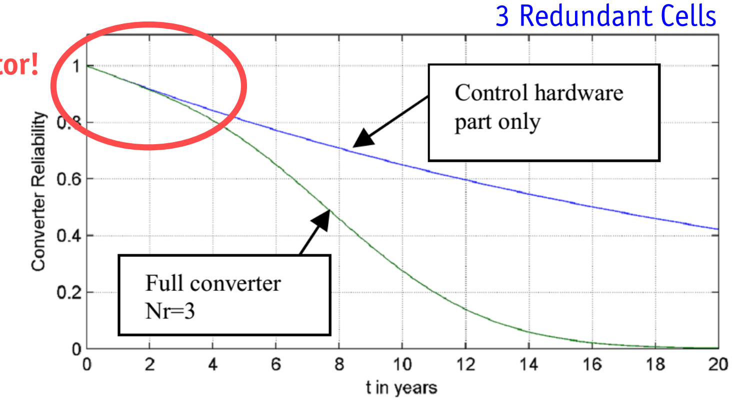
- Reliability Improvement by Means of Cell-Level Redundancy
  - Very Effective
  - But **Limited** by Other Parts of the Converter System
    - Control
    - Auxiliary Supplies
    - Communication
    - Bypass Devices
    - ...

No Redundancy



Control Hardware Becomes Limiting Factor!

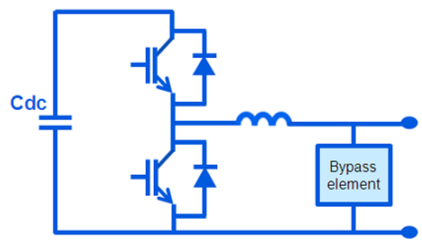
3 Redundant Cells



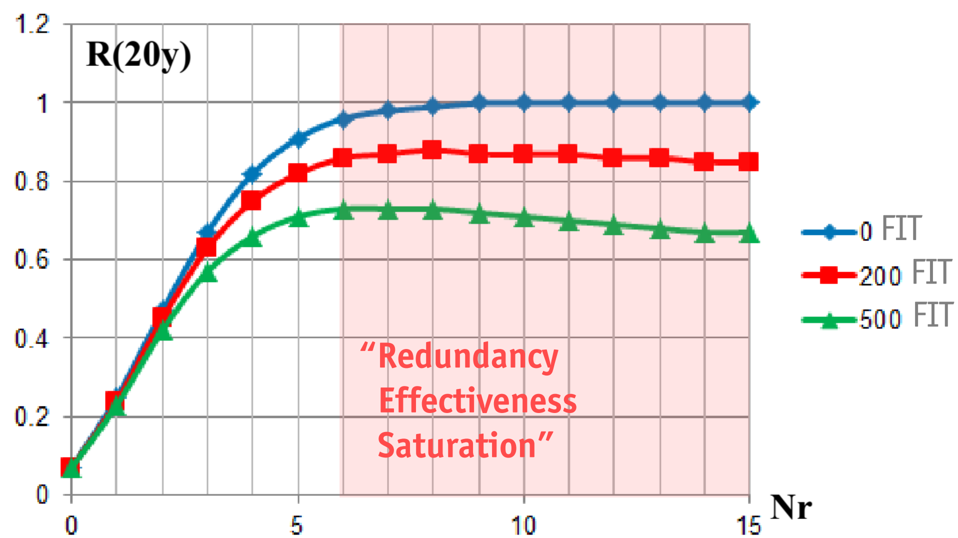
R. Grinberg, **G. Riedel**, **A. Korn**, and **P. Steimer**, "On reliability of medium voltage multilevel converters," in *Proc. Energy Conversion Congr. and Expo. (ECCE USA)*, 2013, pp. 4047–4052.

▶ Reliability “Bottlenecks” (2)

- Non-Ideal Cell Bypassing Device Limits Useful Number of Redundant Cells



Analysis for MMLC Converter



R. Grinberg, G. Riedel, A. Korn, and P. Steimer, “On reliability of medium voltage multilevel converters,” in *Proc. Energy Conversion Congr. and Expo. (ECCE USA)*, 2013, pp. 4047–4052.

Challenge #5/10

MF Transformer Design

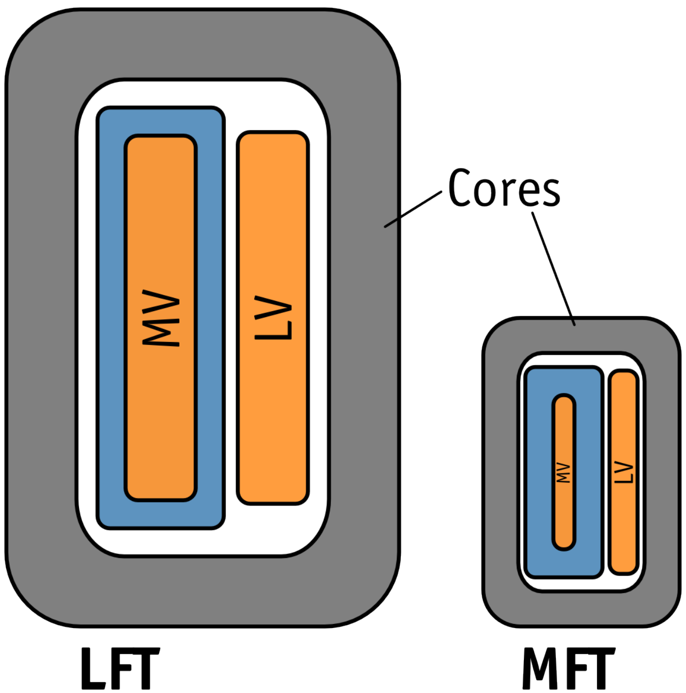
Transformer Types
Litz Wire Issues
Flux Balancing
Noise Emissions

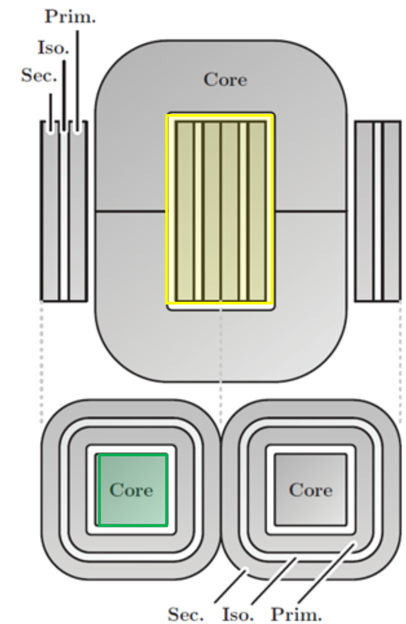
▶ General Challenge of MF Transformers

- Higher Operating Frequency
- Lower Unit Power Rating

$$\boxed{A_{\mathrm{Core}}}\boxed{A_{\mathrm{Wdg}}} = \frac{\sqrt{2}}{\pi}\frac{P_{\mathrm{t}}}{k_{\mathrm{W}} J_{\mathrm{rms}} \hat{B}_{\mathrm{max}} f}$$

- Same Isolation Voltage (!)
- Smaller Active Volume





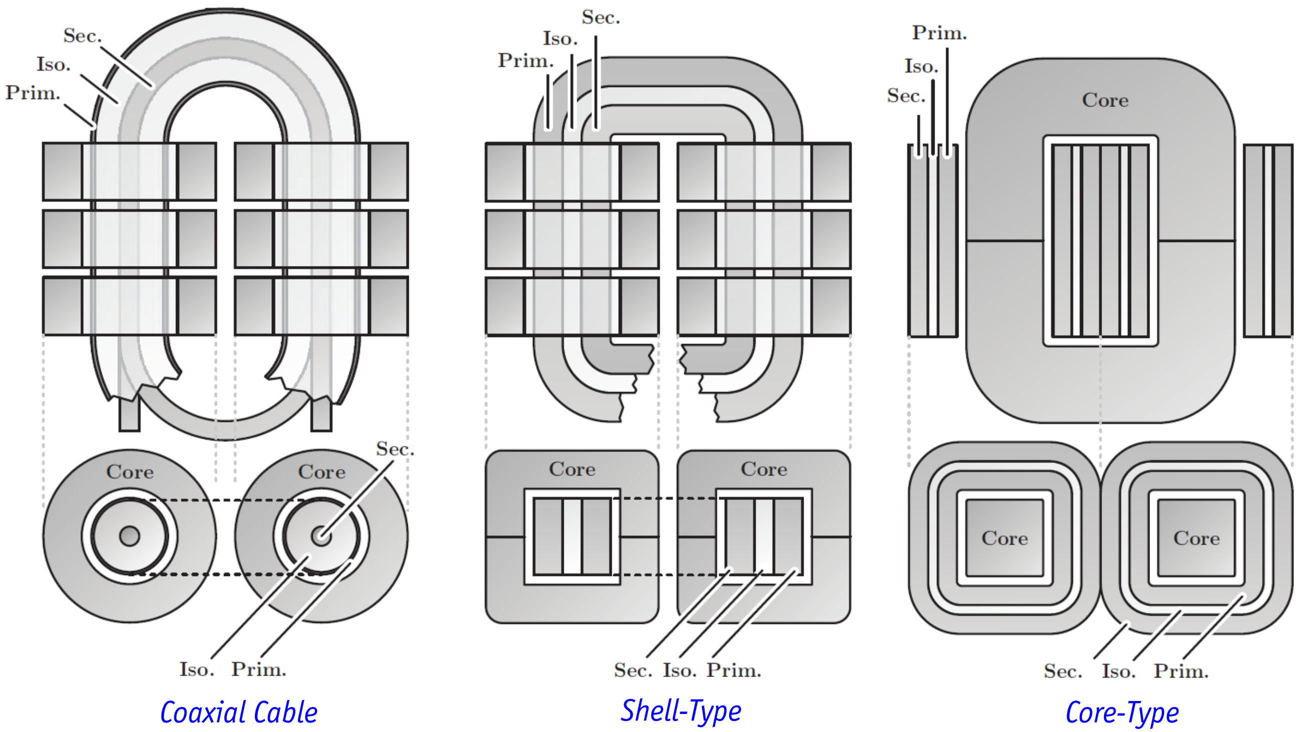
MV Winding Cooling Through Isolators

- Solid Isolators ⟶ Bad Thermal Conductors
- Isolation vs. Cooling Trade-Off

- Oil = Coolant **And** Isolator (!)

▶ MF Transformer Design — Transformer Types

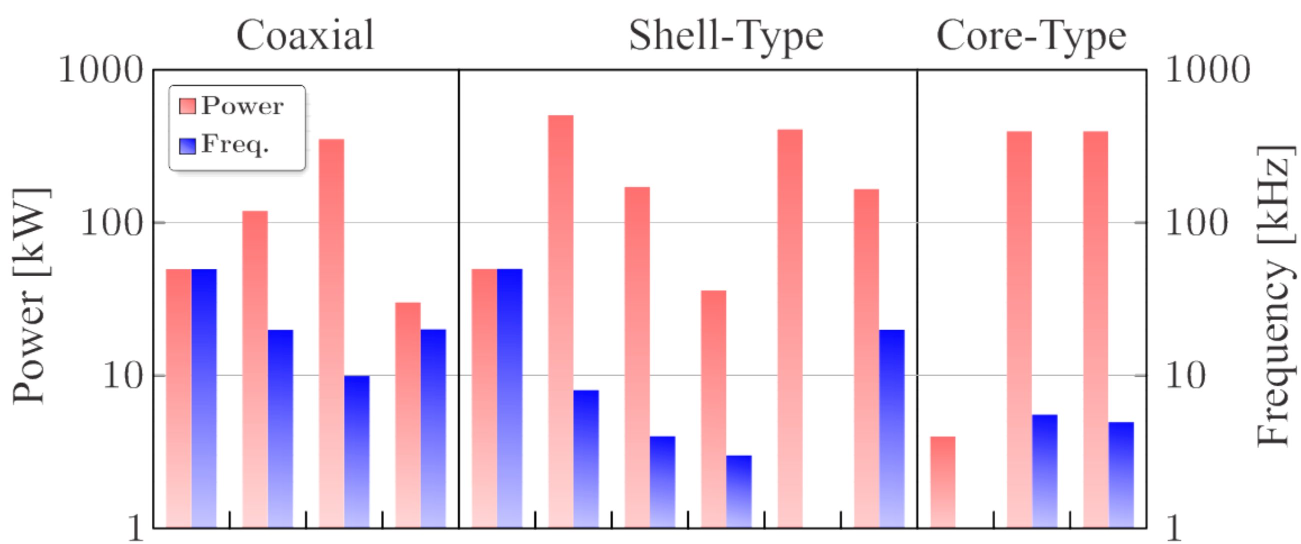
- Main Transformer Types as Found in Literature



- Transformer Construction Types Very Limited by Available Core Shapes in this Dimension Range
- **Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components**

▶ MF Transformer Design — Transformer Types

- Main Transformer Types as Found in Literature



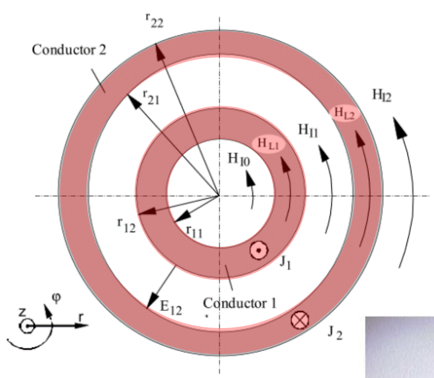
- Transformer Construction Types Very Limited by Available Core Shapes in this Dimension Range
- **Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components**

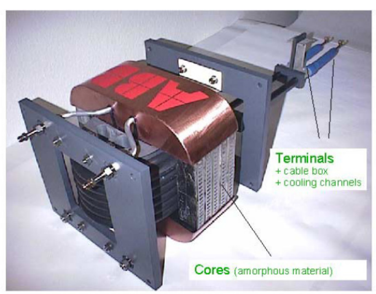
▶ MF Transformer Design — Winding Arrangements

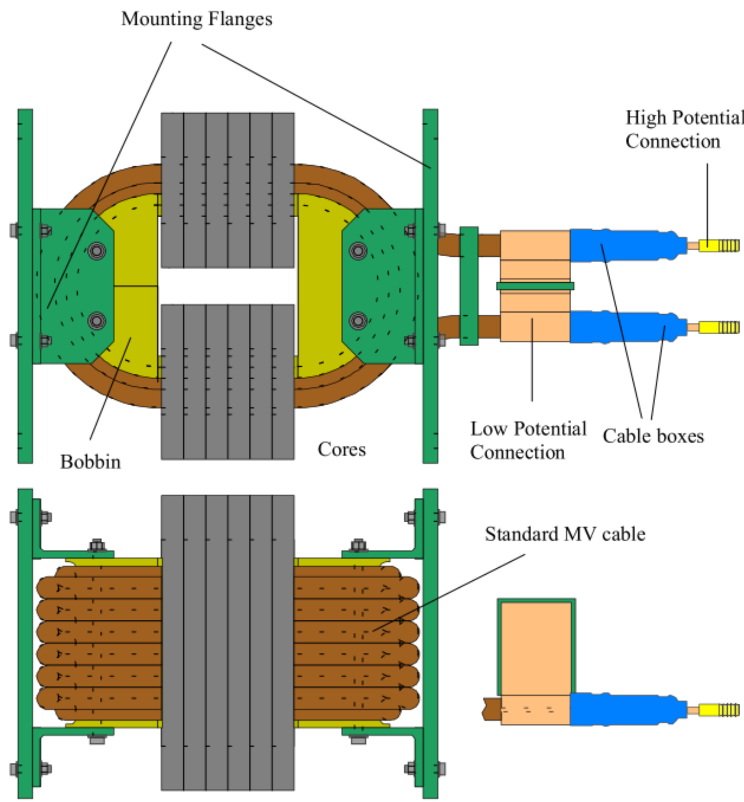
■ Coaxial Cable Winding

- Extremely Low Leakage Inductance
- Reliable Isolation due to Homog. E-Field

- Low Flexibility on Turns Ratio (1:1)
- Complex Terminations





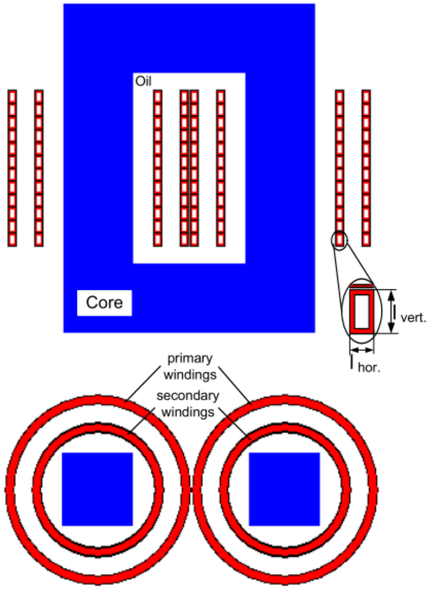


■ Heinemann (ABB, 2002)

► MF Transformer Design — Winding Arrangements

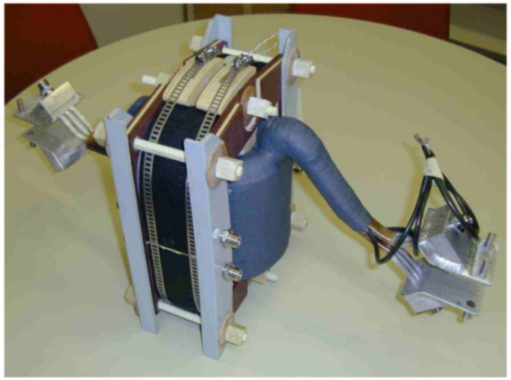
■ Coaxial Windings

- Tunable Leakage Inductance
- More Complex Isolation
- Total Flexibility on Turns Ratio
- Simple Terminations



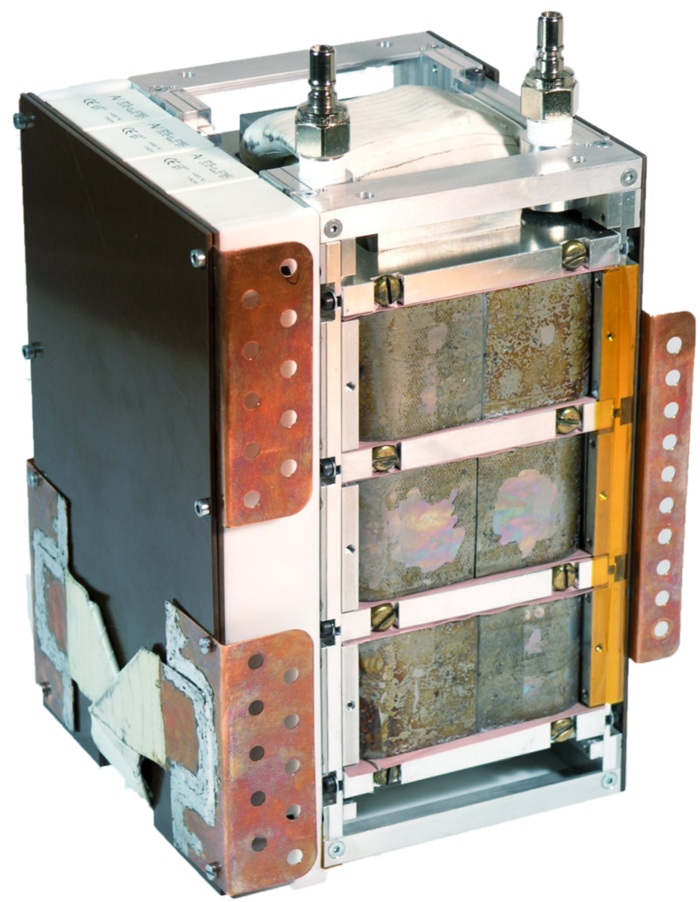
- Hoffmann (2011)

- Steiner (2007)



► ETH *MEGACube*: Water-Cooled Nanocrystalline Transformer

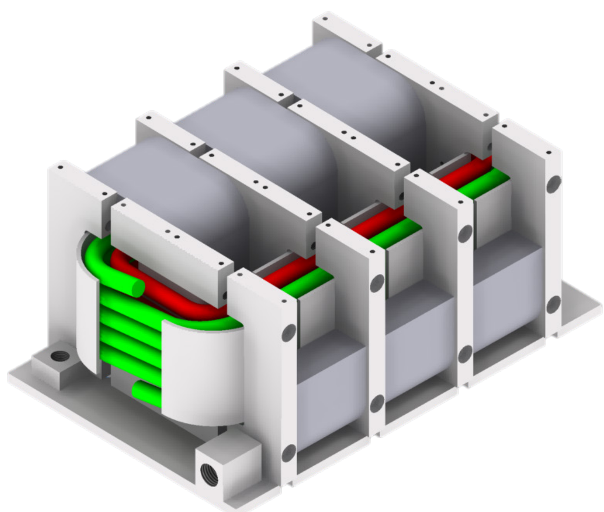
- Power Rating 166kW
- Losses 0.88kW
- Efficiency 99.5%
- **Power Density 45kW/dm^3**

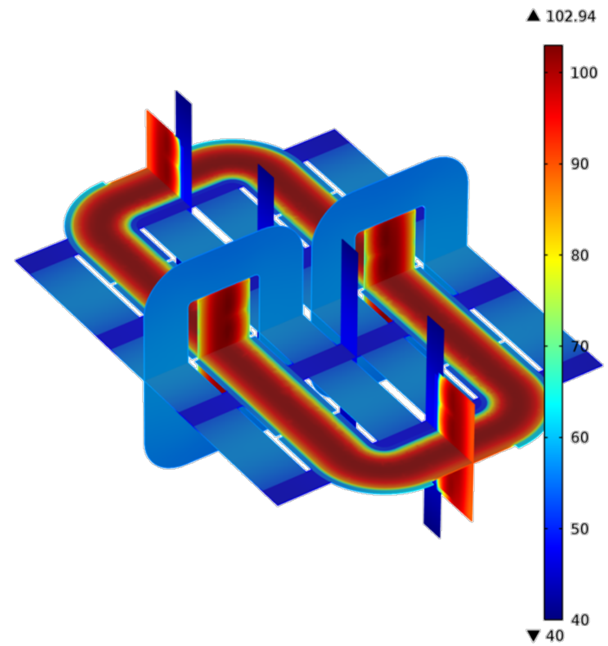


- 166 kW Water-Cooled Nanocrystalline Core Transformer

▶ ETH *MEGACube:* MF Transformer Design — Cold Plates/Water Cooling

- Nanocrystalline 166kW/20kHz Transformer (ETH, Ortiz 2013)



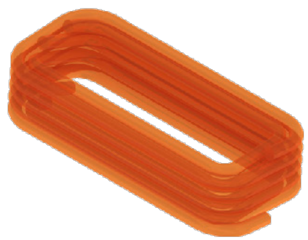


- Combination of **Heat Conducting Plates** and Top/Bottom **Water-Cooled Cold Plates**
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

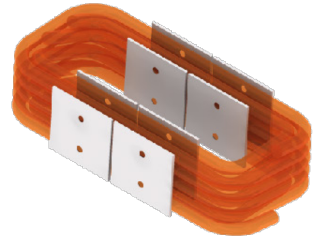
▶ ETH *MEGACube*: MF Transformer Design — Cold Plates/Water Cooling

- Nanocrystalline 166kW/20kHz Transformer (ETH, Ortiz 2013)

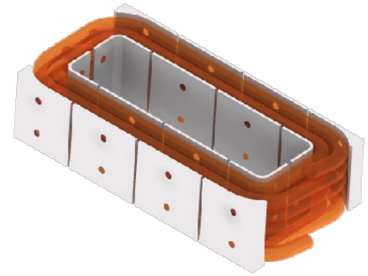
Windings
$\Delta P = 353$ W

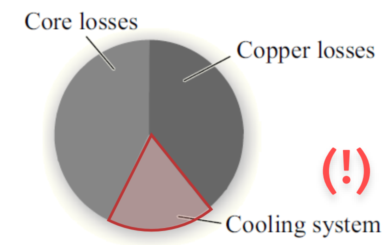


Inner Cooling Plates
$\Delta P = 57$ W

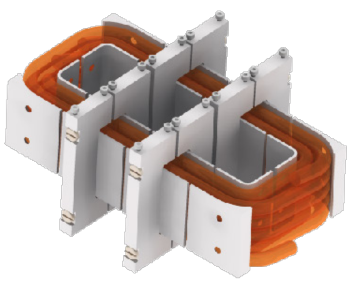


Outer Cooling Plates
$\Delta P = 19$ W

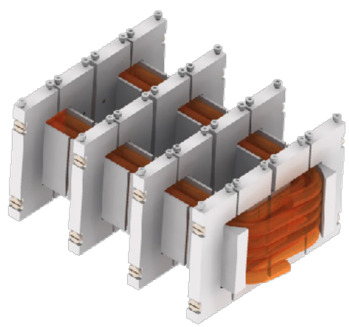




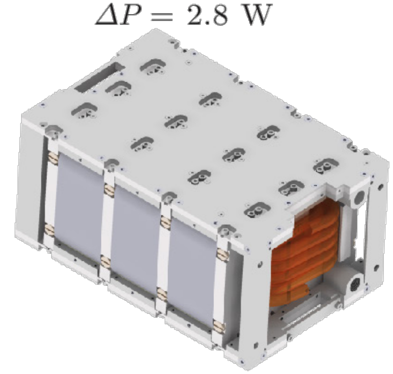
Inner C-Shaped Pieces
$\Delta P = 34$ W

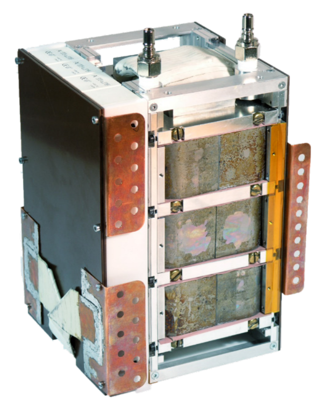


Outer C-Shaped Pieces
$\Delta P = 44$ W



Heat Sinks
$\Delta P = 2.8$ W



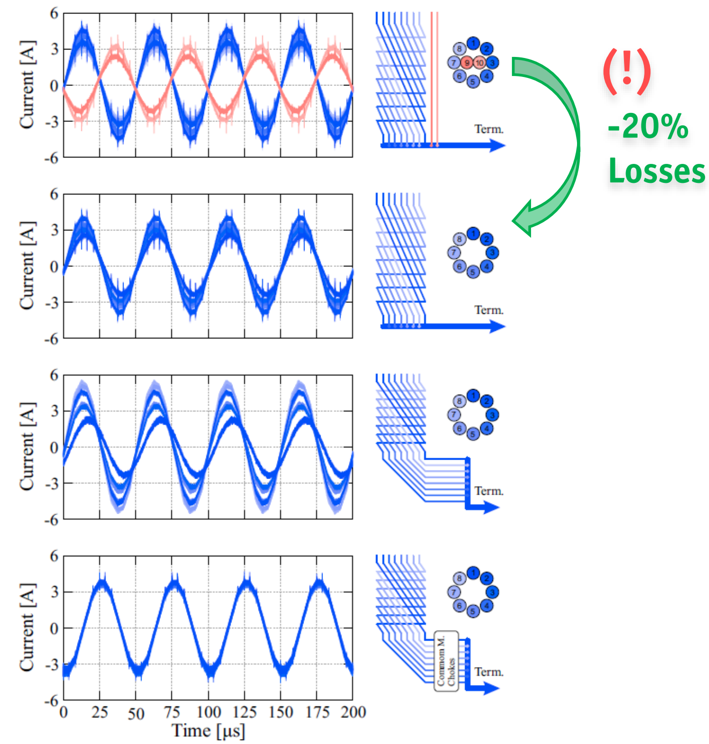


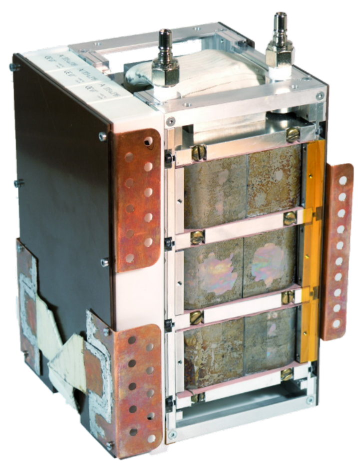
- **Losses Generated in Internal Cooling System Amount to ca. 20% of Total Transformer Losses**

► ETH *MEGACube:* MF Transformer Design – Litz Wire Issues

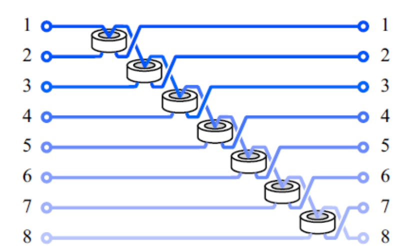
- Case Study: Litz Wire
  with 10 Sub Bundles and 9500 x 71µm Strands in Total

- Unequal Current Sharing Between Sub Bundles
  - **Flawed Interchanging Strategy**
  - Influence of Terminations



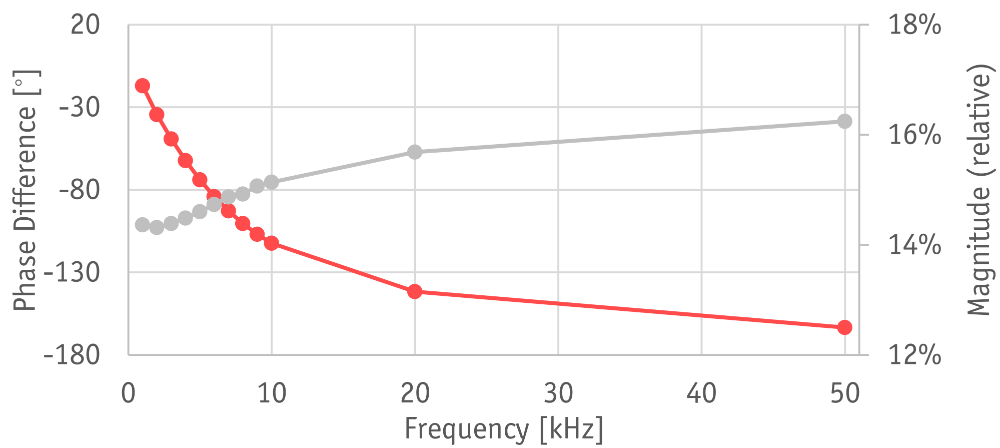


- Common-Mode Chokes for
  Forcing Equal Current Sharing



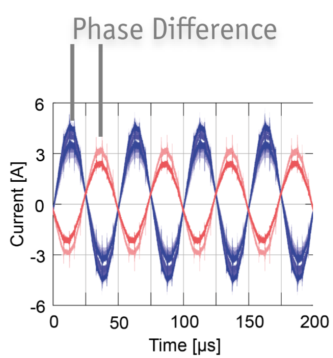
▶ MF Transformer Design — Litz Wire Issues

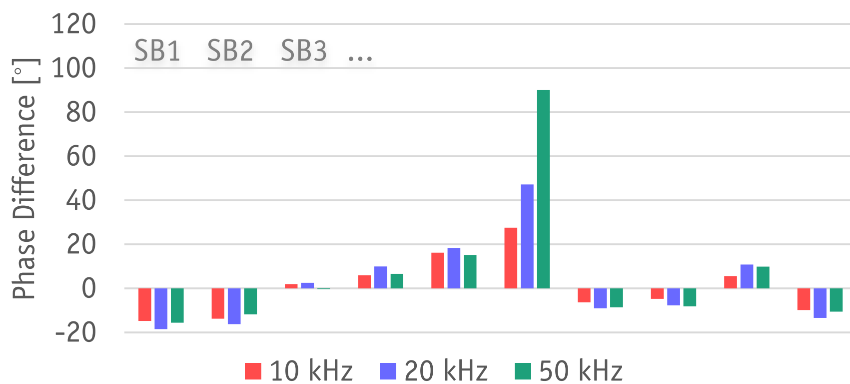
- Flawed Bundle Interchanging Strategy – Two Other Examples from **Different Manufacturer**
  - 700 x 0.2mm, 1000 x 0.2mm
  - 7 Bundles
  - 1 Straight in the Center



- Effect is Frequency Dependent
- **Significant for *f* > A Few kHz**

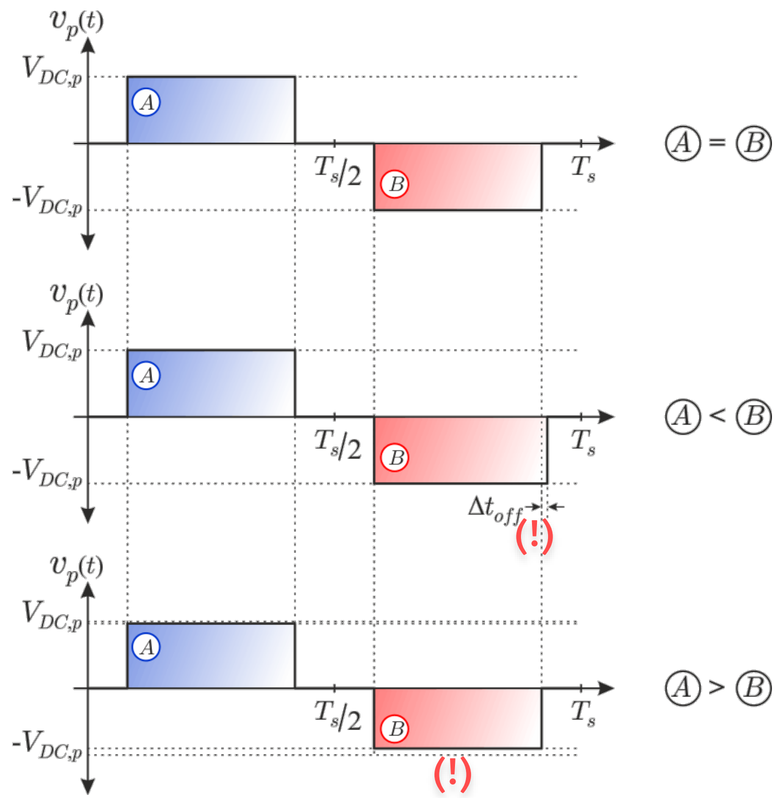
- 1 Bundle Consists of 10 Smaller Sub Bundles – **Same Problem!**





▶ Flux Balancing - DC Magnetization

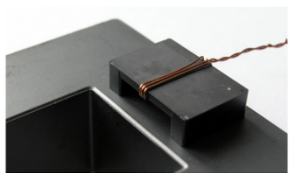
- Higher Losses
- Overcurrents
- Audible Noise

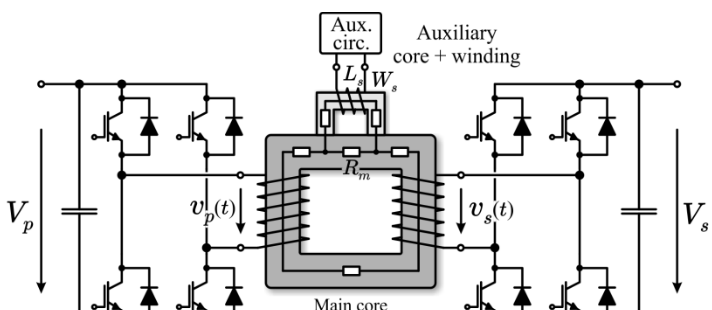


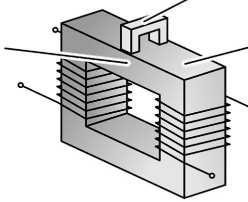
- Diff. Turn-on/Turn-off Times → $A < B$
- Diff. Switch On-Characteristics → $A > B$

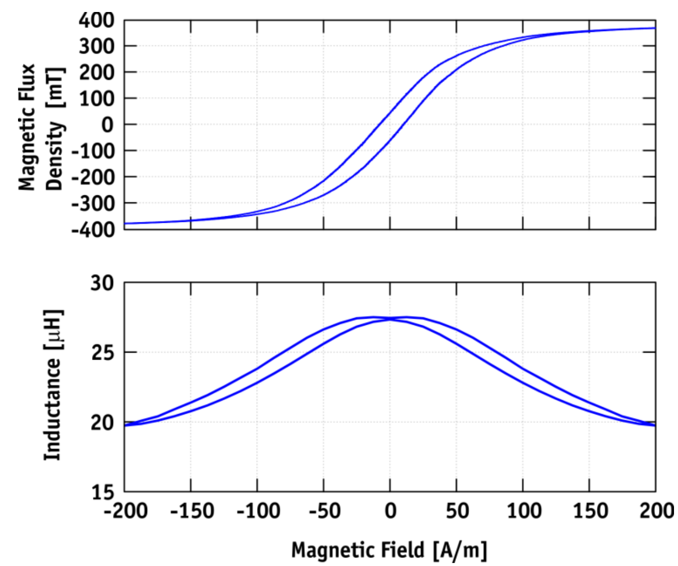
► ETH Flux Density Transducer – The Magnetic Ear

- Shared Magnetic Path between Main and Auxiliary Core
- Change in Inductance on the Auxiliary Core is Related to the Magnetization State



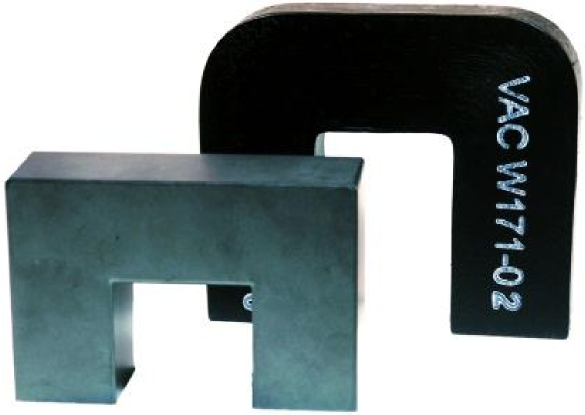






▶ MF Transformer Design — Acoustic Noise Emissions

- Magnetostriction of Core Materials (Zhao, 2011)
  - Nanocrystalline ~ 0ppm
  - Amorphous ~ 27ppm
- Other Influences from Production Processes, Shapes and Assembly Procedures Affect the Emitted Noise



- **Acoustic Noise Emitted at 2·f_s (!)** (w/o DC Magnetization)

Audio Spectrum of *miniLINK* ▸
DC/DC Running at **9.5kHz**

Coffee

Break

Challenge #6/10

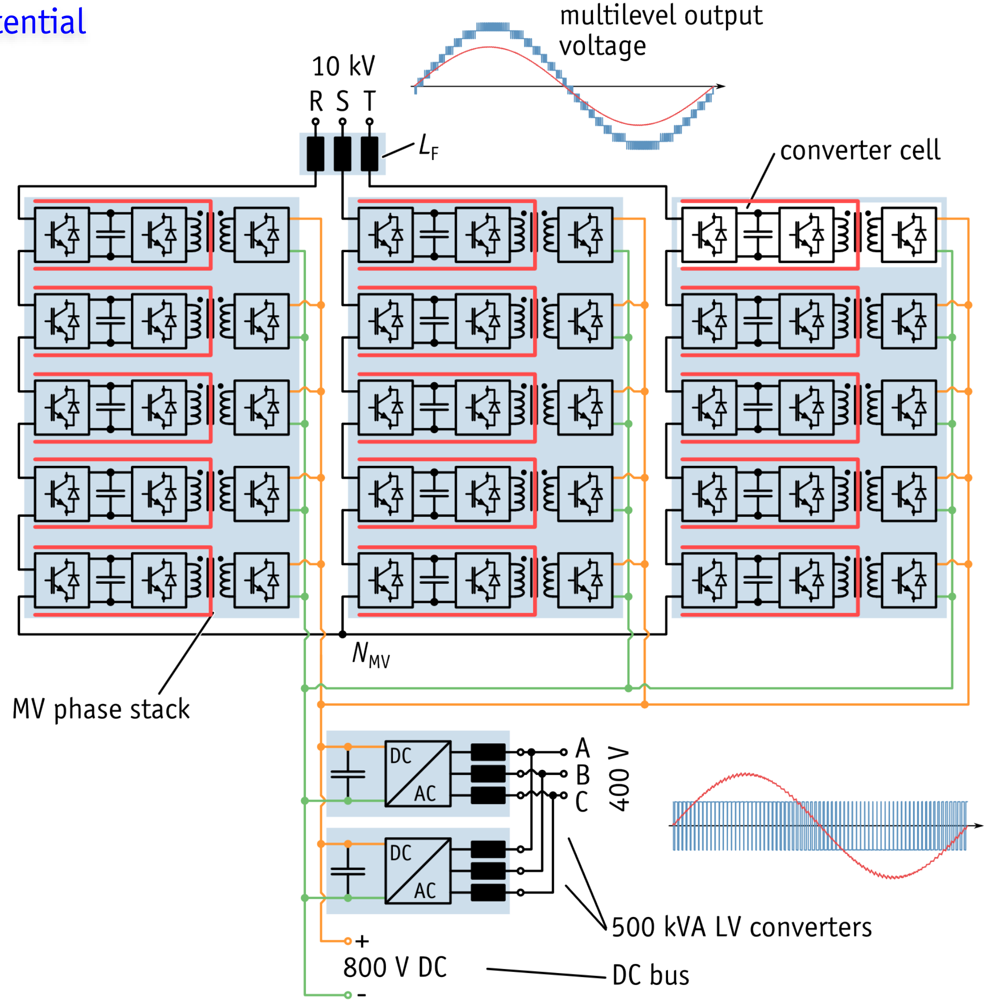
Isolation Coordination

Isolation Barrier Positioning
Mixed-Frequency Stress

► Example System: ETH *MEGAlink* Distribution SST

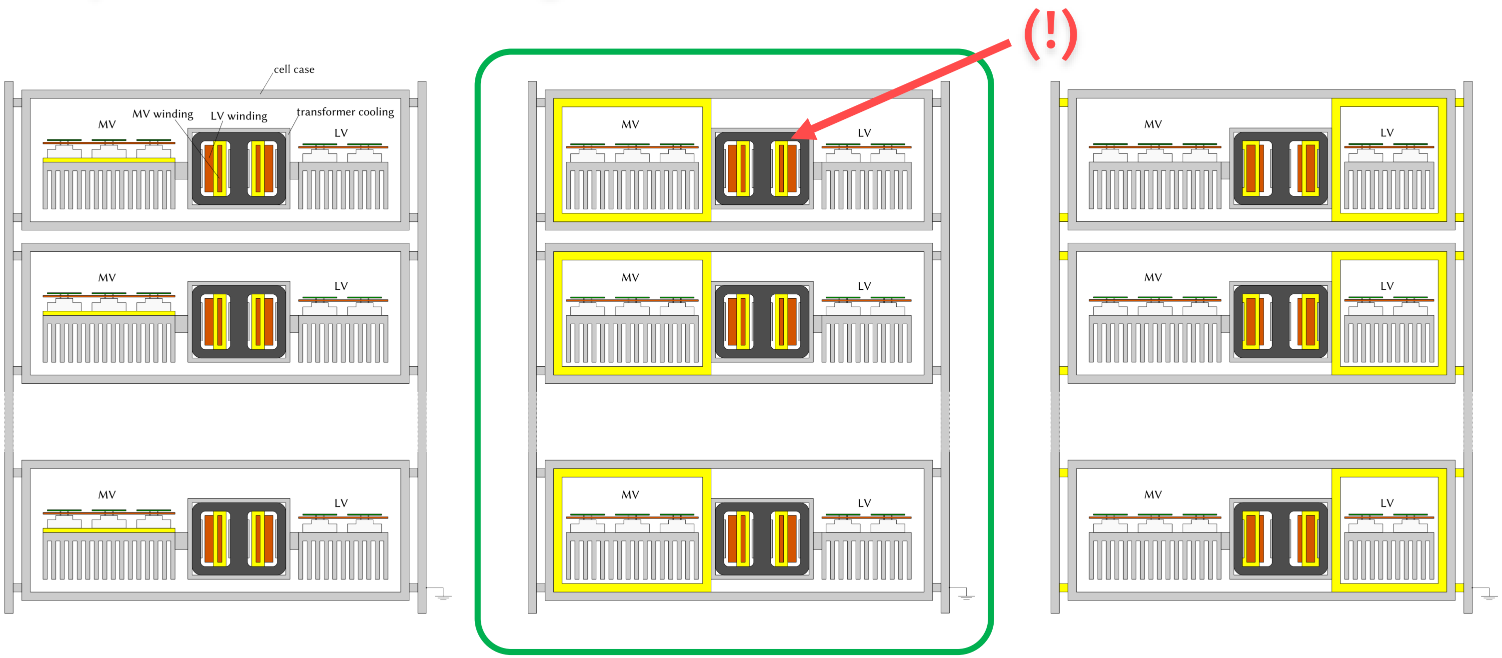
- Cascaded Cells Are On Floating Potential

- Isolation Required
  - Towards Ground
  - Towards Adjacent Cells



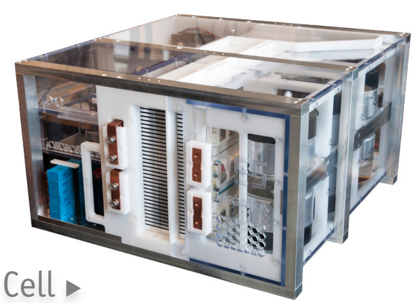
- Isolation Voltage: **10kV** (nom.)

► Options for Positioning of the Isolation Barrier



▲ Feasible Variant

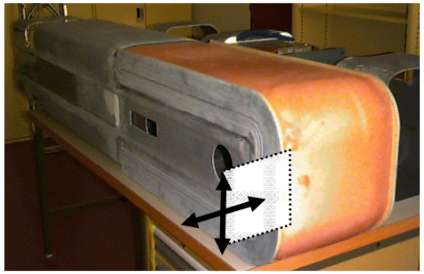
- Transformer Isolation is Critical
- Low Thermal Conductivity of Insulation Material



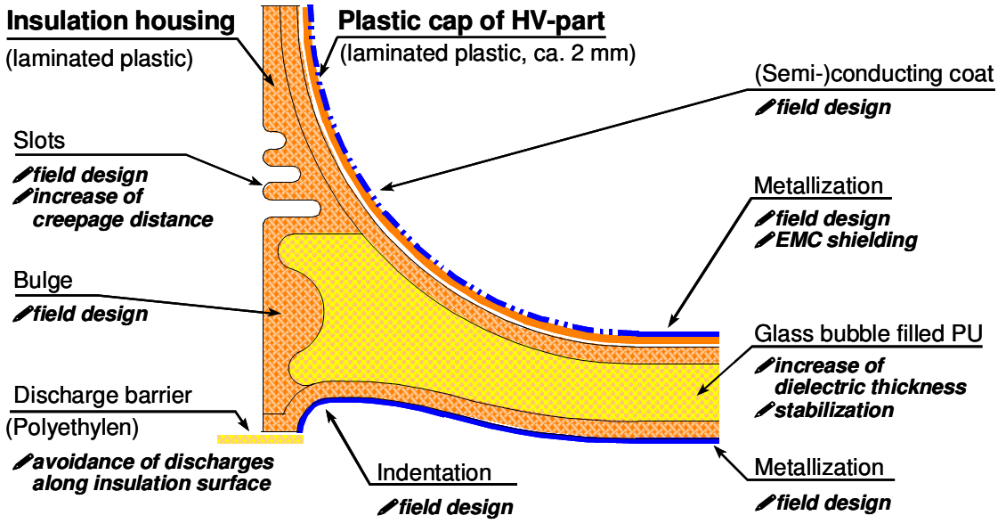
ETH *MEGAlink* Converter Cell ▸

▶ Isolation of Cascaded Cells' MV Part

- Components on MV Potential (e.g., Heat Sink)
- Isolation Towards Cabinet Required
- Field Grading to Avoid Partial Discharges, etc.



Source: Steiner, 2007



Challenge #6/10

Isolation Coordination

Isolation Barrier Positioning

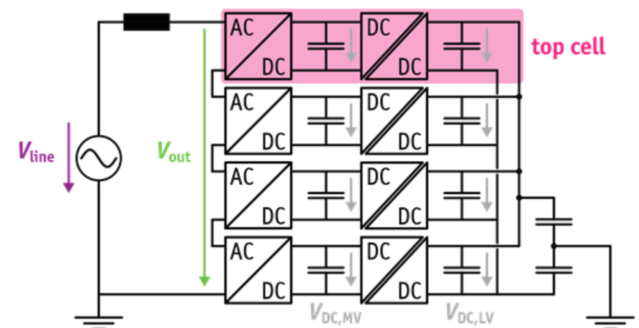
Mixed-Frequency Stress

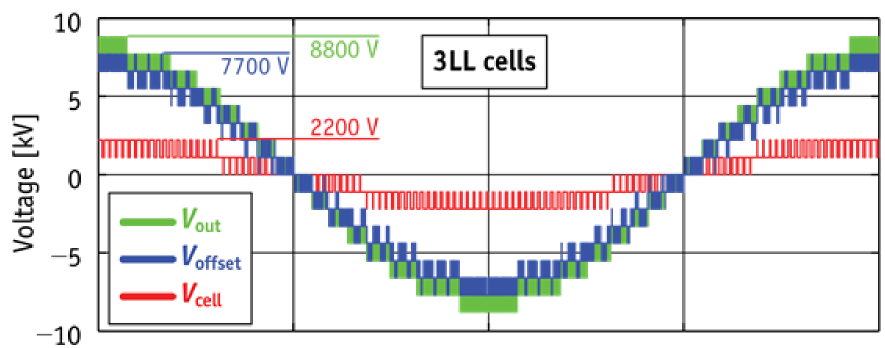
▶ Mixed Frequency Field Stress

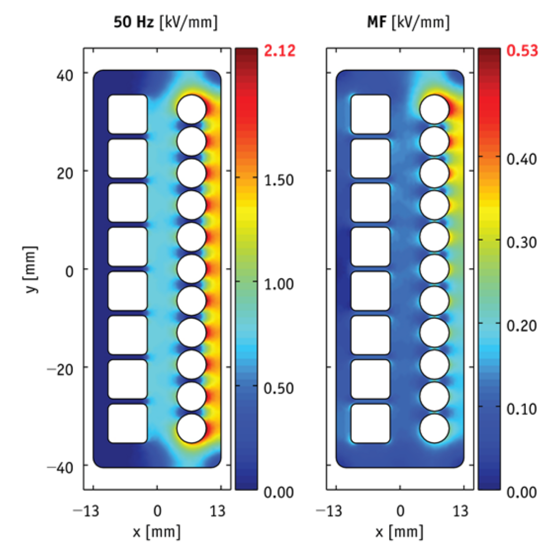
"New" Kind of Electrical Field Stress

- Large DC or Low-Frequency Component
- Smaller Medium-Frequency Component

- Known From Machine Isolation Systems
- Physical Breakdown Mechanisms Still **Unclear**





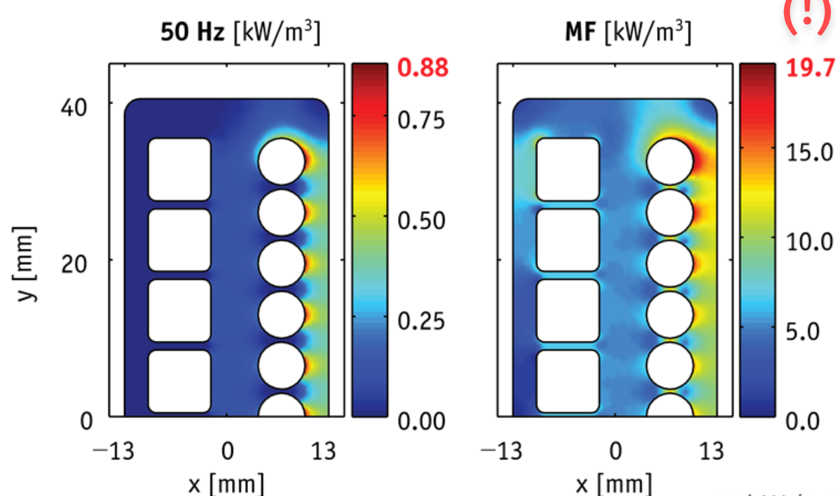


- Highest Stress for Top Cell in Phase Stack
- Highest Stress in Transformer Isolation

▶ Mixed Frequency Field Stress: Dielectric Losses

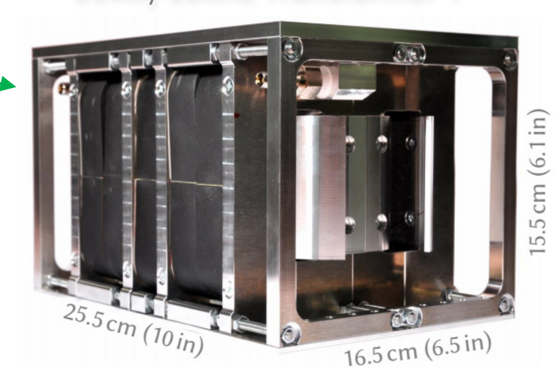
- Dielectric Losses: $P \propto f \cdot E^2$

10kV, 50Hz



1.1kV, 8kHz

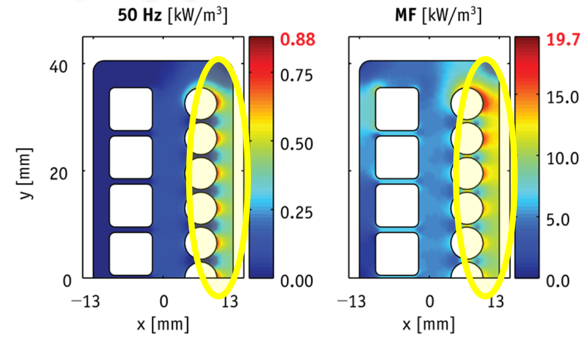
65kW/10kHz Transformer ▼



- Overall Losses Negligible for Efficiency (e.g., 2W)
- But: ▸ Local Thermal Runaway Possible
  ▸ Accelerated Aging?

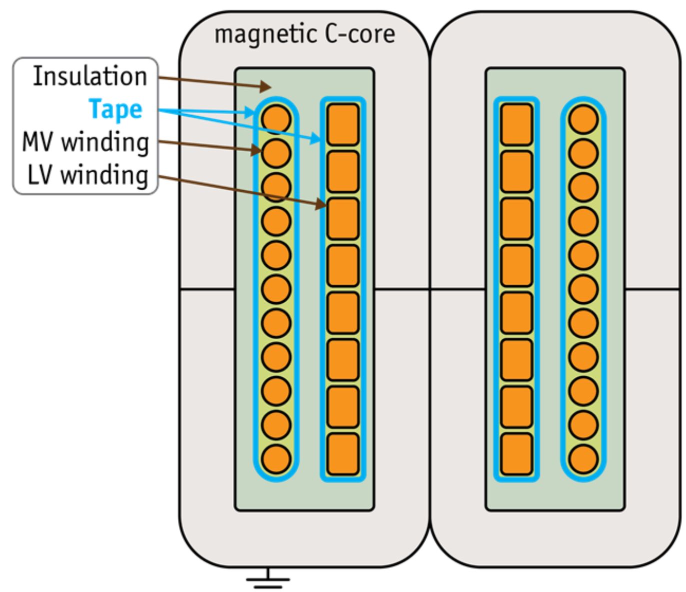
$$P(\vec{x}) \propto f \cdot E(\vec{x})^2$$

▶ Frequency-Dependent Isolation Concept (1)

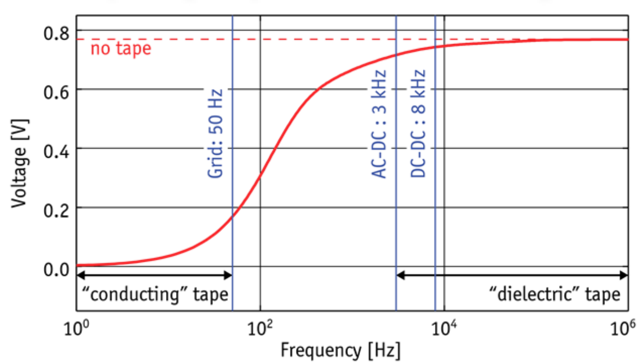


- 50Hz Stress — Common-Mode
- MF Stress — Differential-Mode (Mostly)

- Conductive Field Grading Tape Can Reduce CM Stress
  - But Would Increase DM Stress

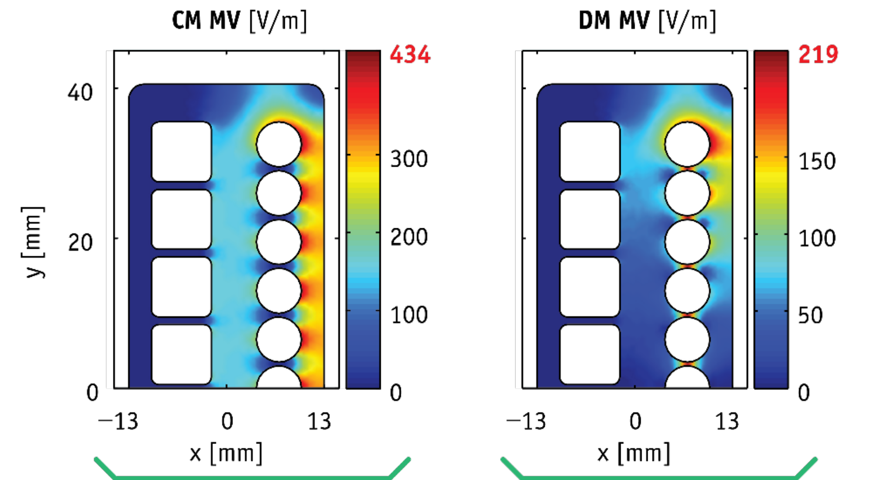


- **Solution: "Semiconducting Tape"**
  - Frequency-Dependent Conductivity

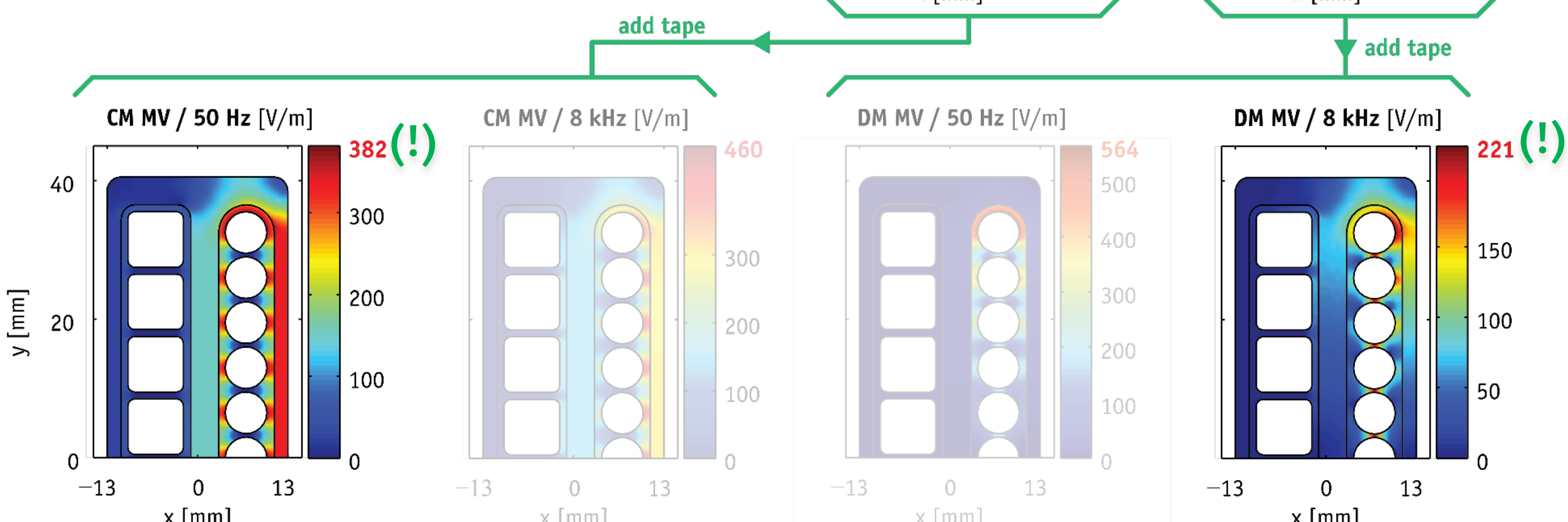


▶ Frequency-Dependent Isolation Concept (2)

- **10% Reduction** of 50Hz (CM) Field Stress
- **No Degradation** of MF (DM) Field Stress



Further Reading
T. Guillod, **J. E. Huber**, **G. Ortiz**, **A. De**, **C. M. Franck**, and **J. W. Kolar**, “Characterization of the Voltage and Electric Field Stresses in Multi-Cell Solid-State Transformers,” in *Proc. Energy Conversion Congr. and Expo (ECCE)*, 2014.



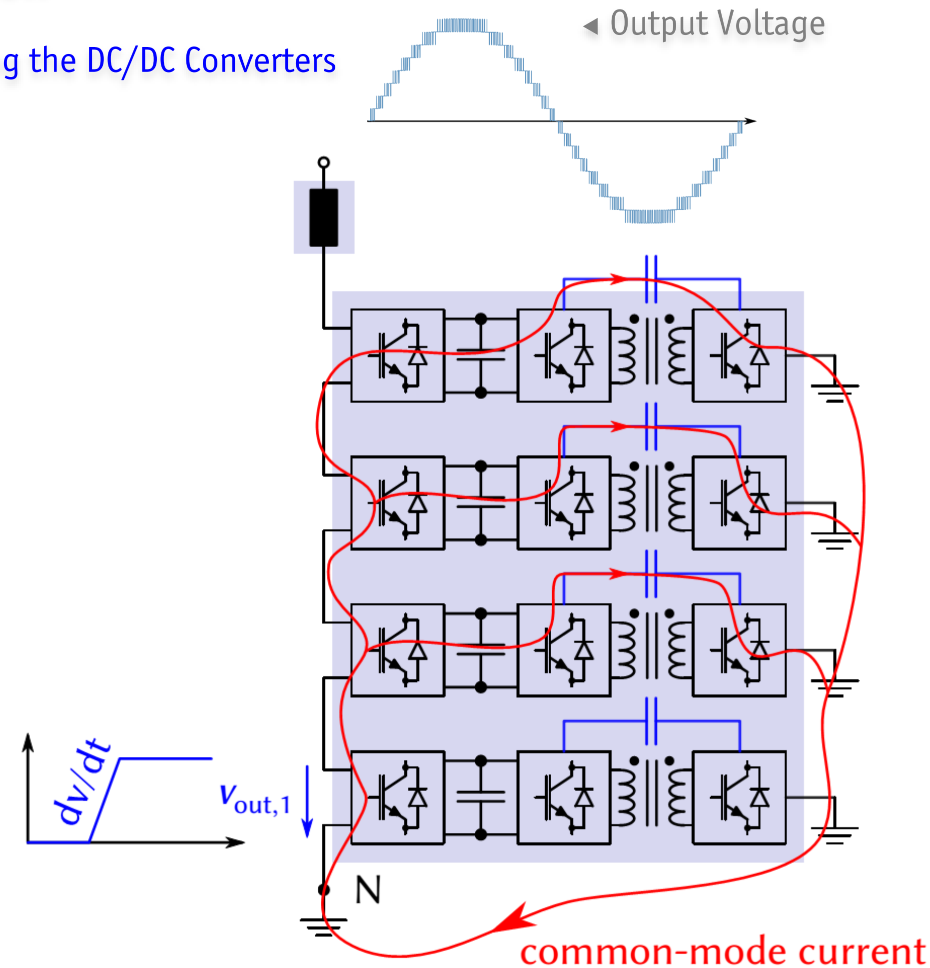
Challenge #7/10

EMI

Common-Mode Ground Currents
EMI Limits

▶ Basic Problem Description

- Considering One Phase Stack Including the DC/DC Converters
- Parasitic Capacitances Between Cells and Ground



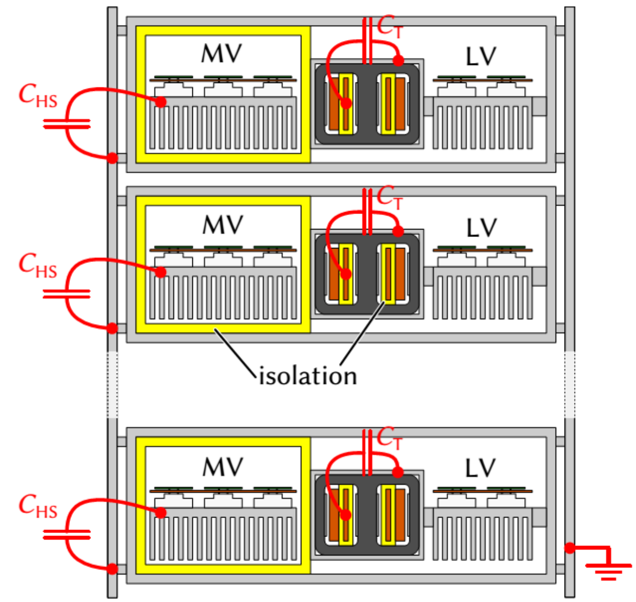
- **Switching Action in One Cell Moves All Cells At Higher Stack Positions In Potential**
- Charging Currents: $i = C\,dv/dt$

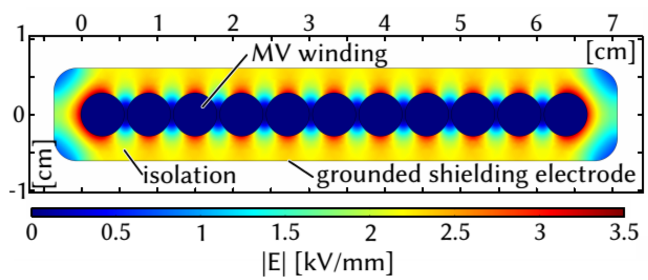
► Origin of Parasitic Capacitances to Ground

- **Heatsink to Housing** (C_{HS})

- **Transformer** (C_T)
  - Medium-Frequency: Small Volume
  - MV Winding Moves with Cell Midpoint
  - Cores and LV Winding are Grounded

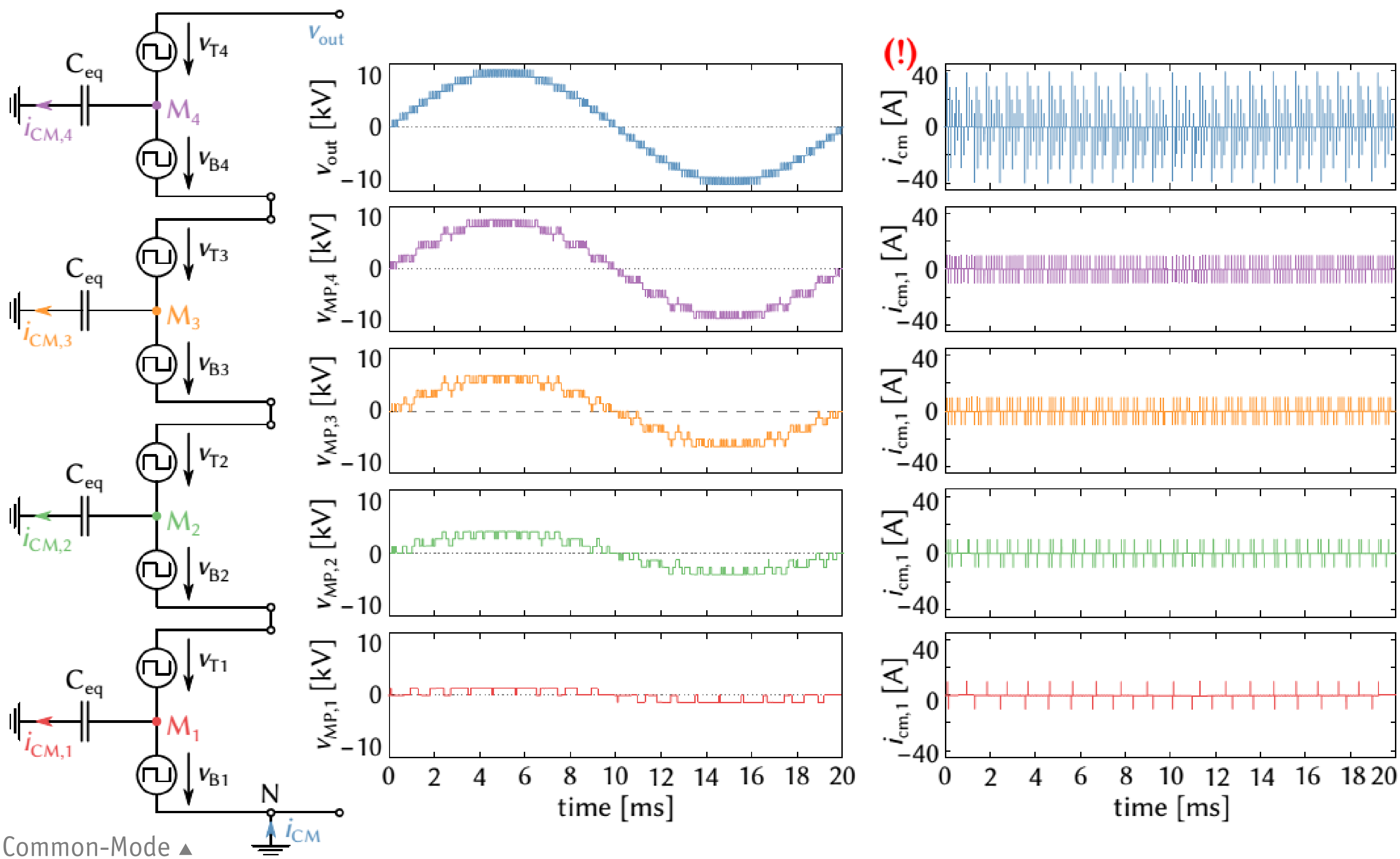
- $C_T \approx$ **650pF >>** C_{HS} (Simulation)





◄ 2D FEM Simulation of Electric Field Distribution in MF Transformer Winding Window

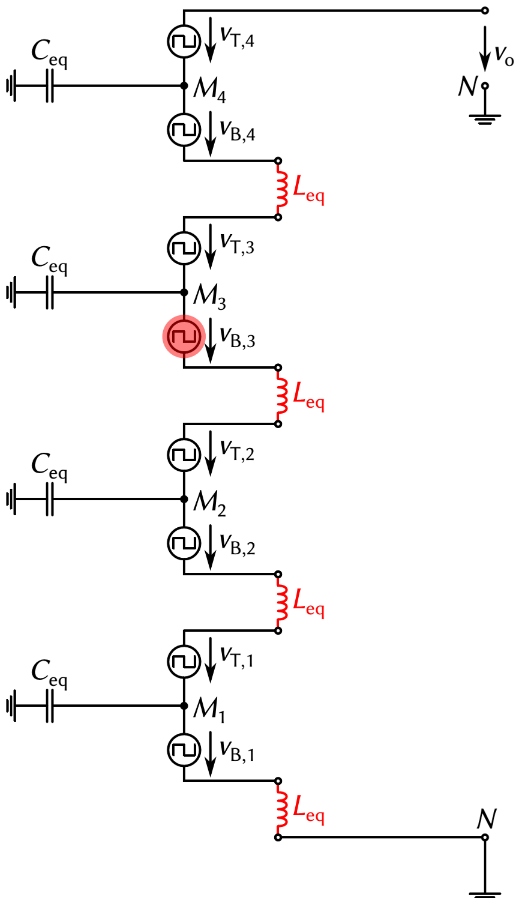
▶ Simulation of Common-Mode Currents

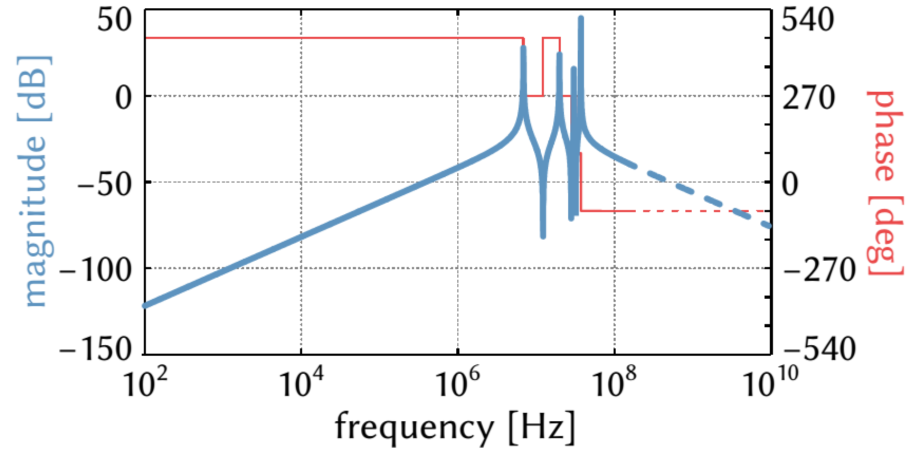


Common-Mode ▲
Eq. Circuit

- Full System Simulation (incl. DC/DC, etc.)
- Cell Switching Freq. 1kHz, dv/dt = 15kV/µs, C_{eq} = 650pF

▶ Reality: Parasitic Inductances Create Resonances!

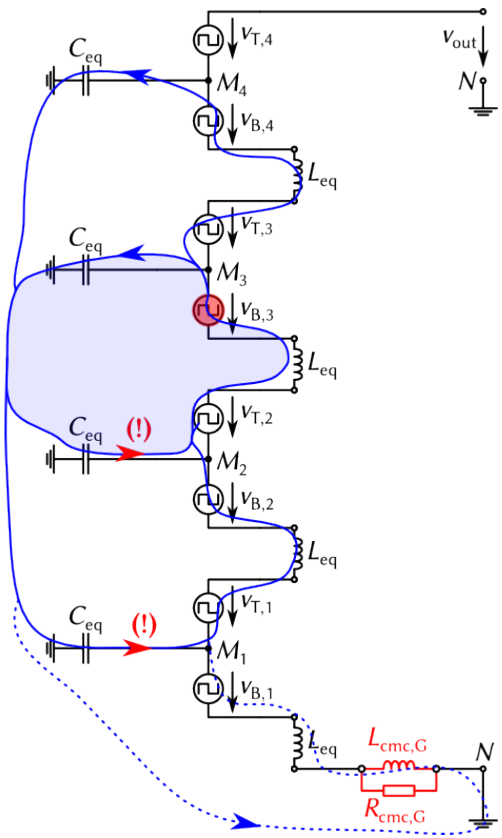


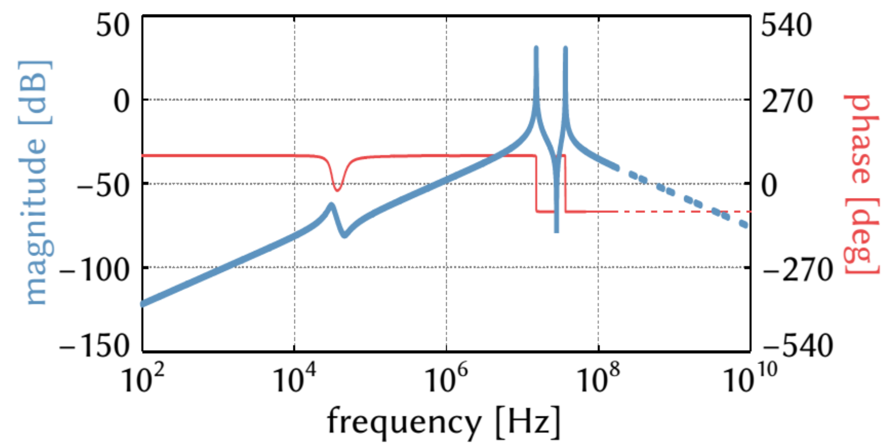


▲ Transfer Function $G(s) = I_{vB,3}(s)/V_{B,3}(s)$

▶ Mitigation: "Global" Common-Mode Choke

- Single Common-Mode Choke Between the Input Terminals of the Phase Stack
- Charging Currents Can Still Flow Through Other Cells' Parasitic Capacitances

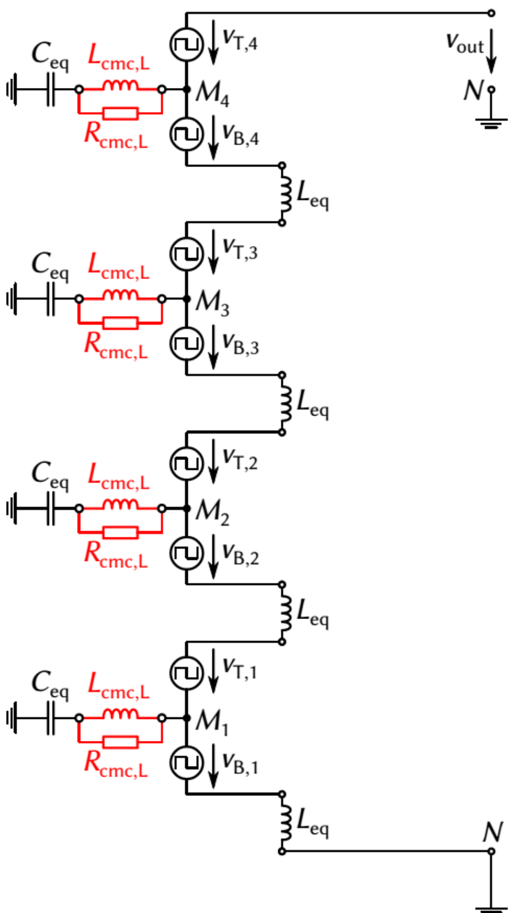




▲ Transfer Function $G(s) = I_{vB,3}(s)/V_{B,3}(s)$ for $L_{cmc,G}$ = 10mH, $R_{cmc,G}$ = 10kΩ

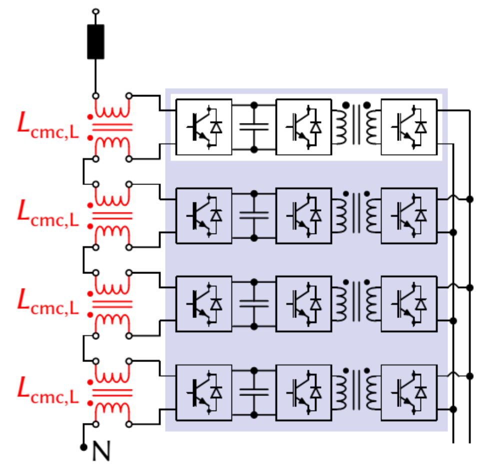
▶ Mitigation: “Local” Common-Mode Chokes

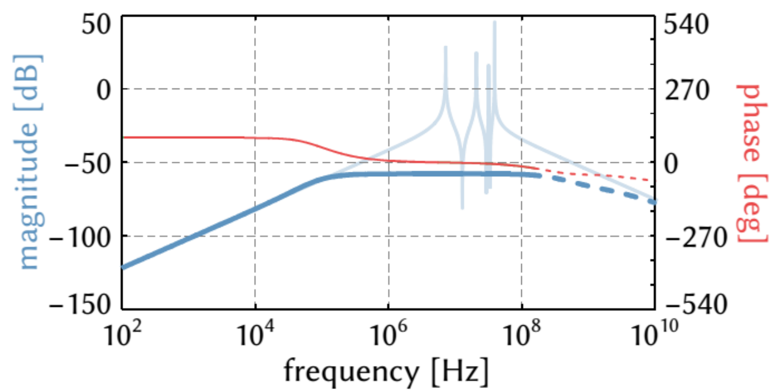
- Common-Mode Chokes at the Input Terminals of **Every Cell**



◂ Equivalent Circuit

Actual Realization ▸





▴ Transfer Function $G(s) = I_{vB,3}(s)/V_{B,3}(s)$ for $L_{cmc,L}$ = 6.2mH, $R_{cmc,G}$ = 1.5kΩ

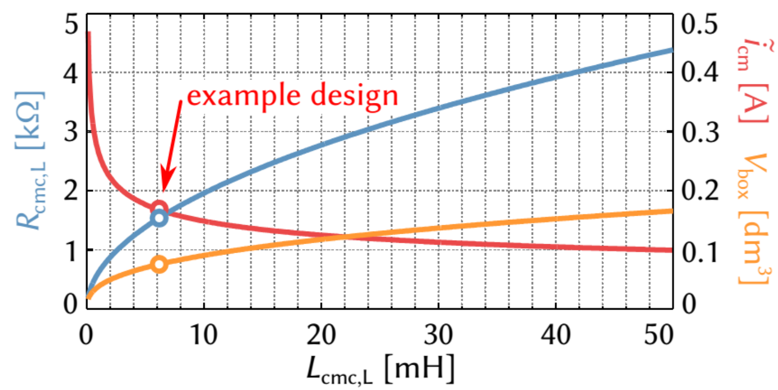
▶ Local Common-Mode Choke Design

Design Procedure

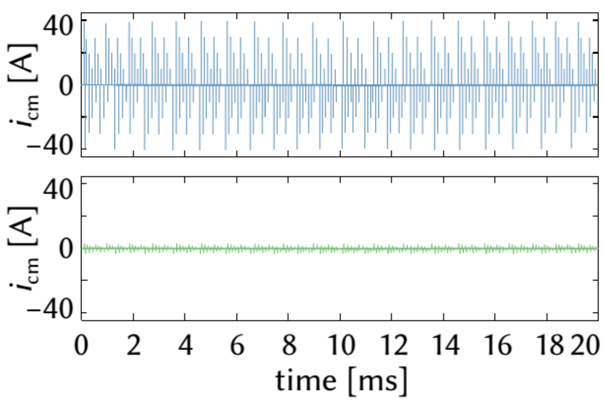
- 2^{nd} order approximation
- L_{cmcL} and R_{cmcL} Chosen To Achive Critical Damping

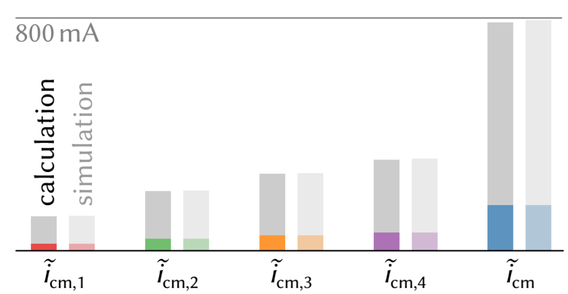
$$\tilde{i}_{cm} = \sqrt{f_s \cdot \frac{5}{8}\frac{C_{eq} V_{dc}^2}{R_{cmc,L}} \cdot \left[\frac{4}{3}N^3 + \frac{2}{3}N\right]} \propto L_{cmc,L}^{-1/4}$$

$$V_{box} = 4 s_h \left(\frac{2\sqrt{L_{cmc,L} C_{eq}}\, V_{dc}\, e^{-1} I_{rms}}{\hat{B} k_w J_{rms} \pi s_h s_r^2 (1-s_r)} \right)^{3/4} \propto L_{cmc,L}^{3/8}$$



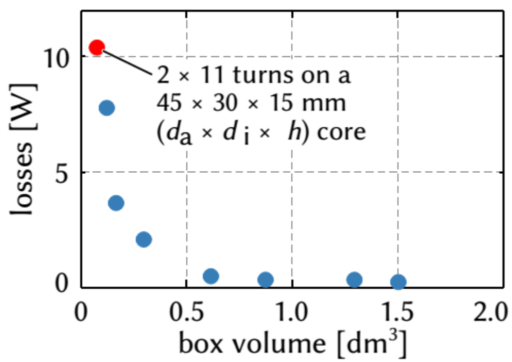
Verification

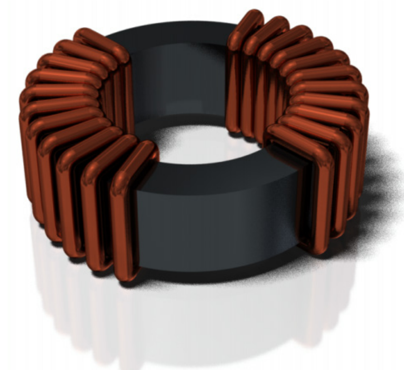




▶ Evaluation of "Local" Common-Mode Choke Concept

- Possible Realizations of 6.2mH/57A_{rms} CMC





- Overall Loss Contribution in 1MVA SST is negligible (< 150W)

Further Issues (!)

- What Are the Limits For Such Common-Mode Ground Currents?
- Impact of LV SiC's **Higher dv/dt ?**

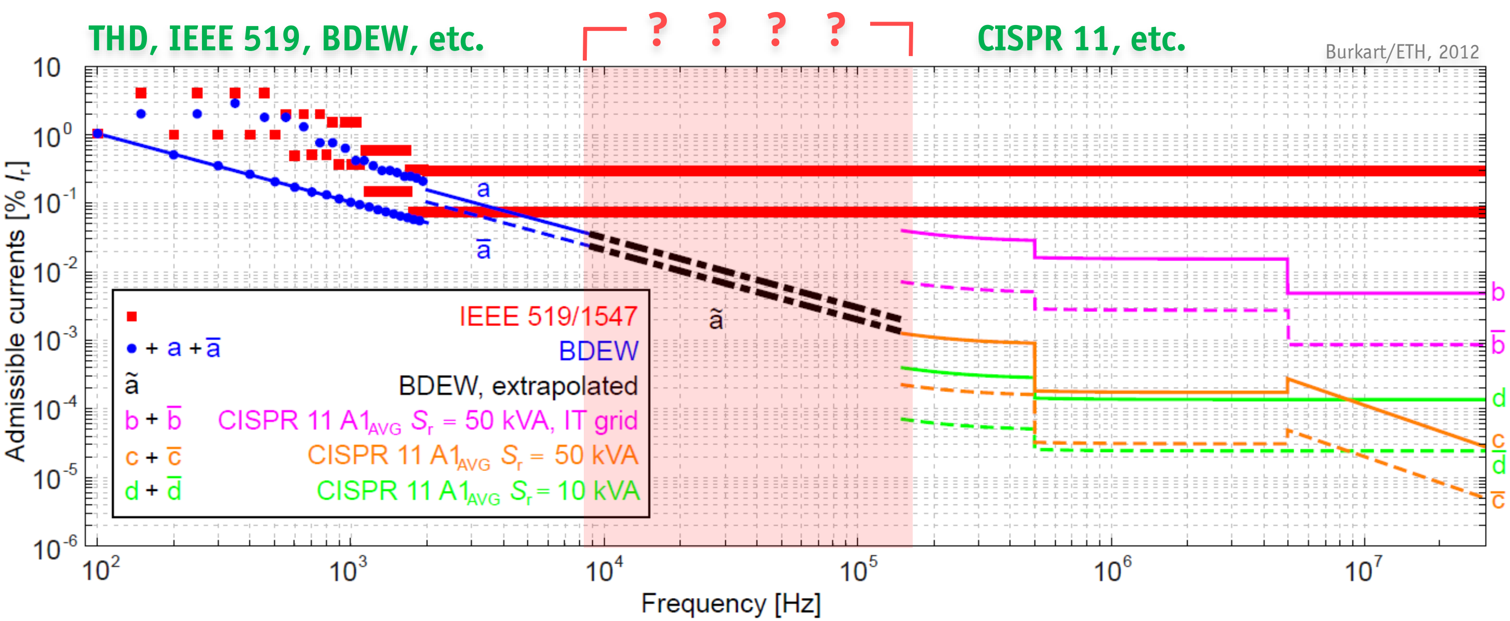
Further Reading
J. E. Huber and **J. W. Kolar**, "Common-Mode Currents in Multi-Cell Solid-State Transformers," in *Proc. IPEC 2014*, Hiroshima, Japan, May 2014.

▶ Grid Harmonics and EMI Standards

■ Medium Voltage Grid Considered Standards

- IEEE 519/1547
- BDEW
- CISPR

■ Requirements on Switching Frequency and EMI Filtering

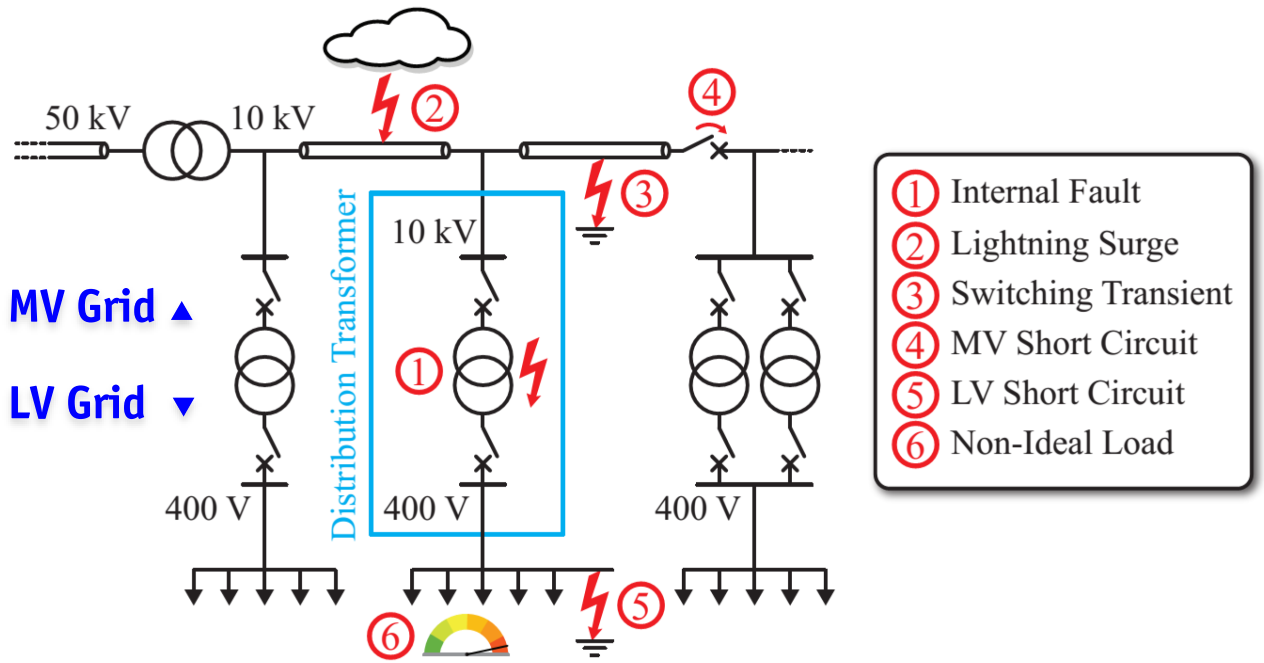


Challenge #8/10

Protection

Protection of the SST
Protection of the Grid
Grid Codes

▶ Possible Fault Situations

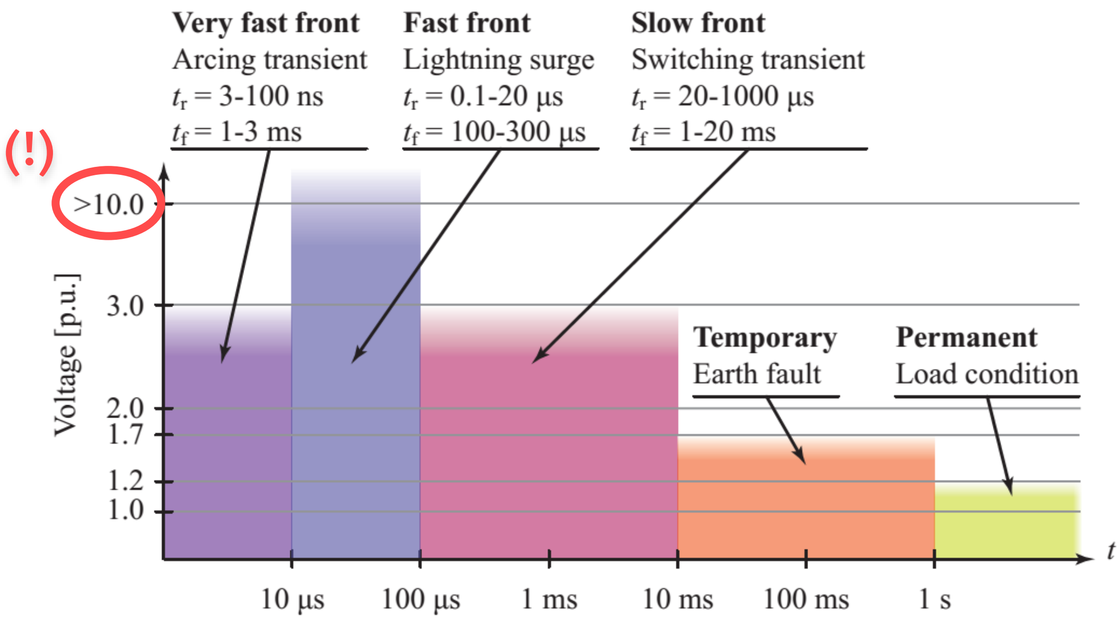


- Protection Scheme Needs to Consider: **Selectivity / Sensitivity / Speed / Safety / Reliability**

  - **Selectivity:** Only Closest Upstream Breaker/Fuse Should Trip to Isolate Faults Quickly
    - Different Trip Current Levels
    - Different Time Delays

▶ Overvoltages

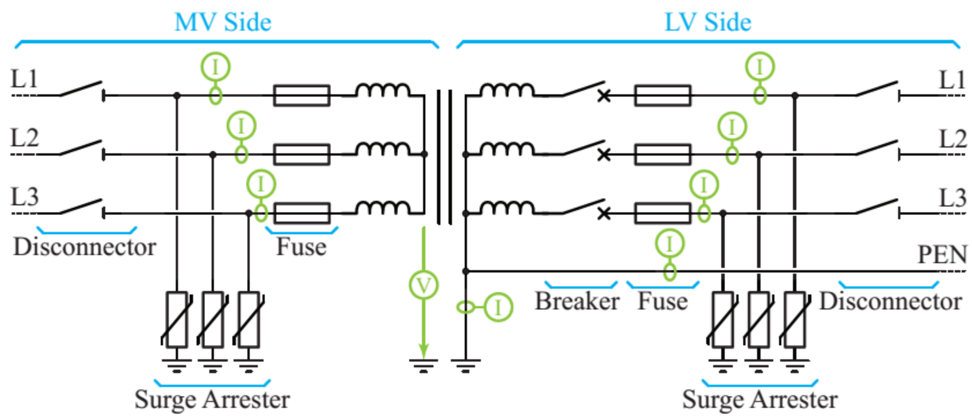
■ Classification of Overvoltage Situations in MV Grids



■ **Fast Protection of Sensitive Power Electronics is Highly Challenging!**

► Typical LFT Protection Scheme

- Overcurrent Protection: Fuses
- Overvoltage Protection: Surge Arresters



Img.: ABB

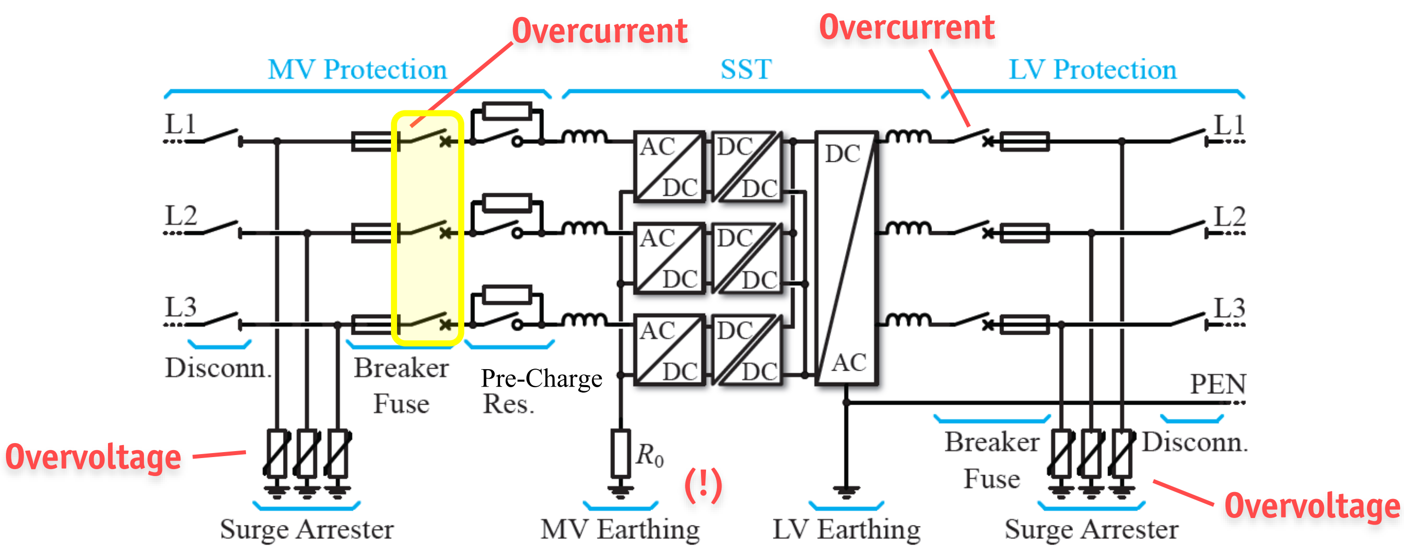
◄ Surge Arresters

LV and MV Fuses ►

Imgs.: http://www.openelectrical.org/

▶ SST Protection Schemes

- Analysis of Fault Cases and Protection Schemes Missing / **Upcoming in ETH Publication**
- Proposed SST Protection Scheme with Minimum Number of Protection Devices



Upcoming Analysis:
T. Guillod, **F. Krismer**, **R. Färber**, **Ch. M. Franck**, and **J. W. Kolar**, "Protection of MV/LV Solid-State Transformer in the Distribution Grid," To Be Published, 2015.

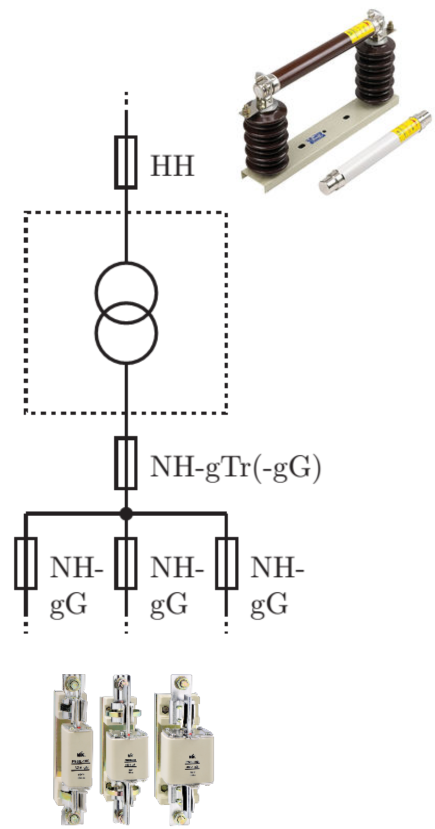
Challenge #8/10

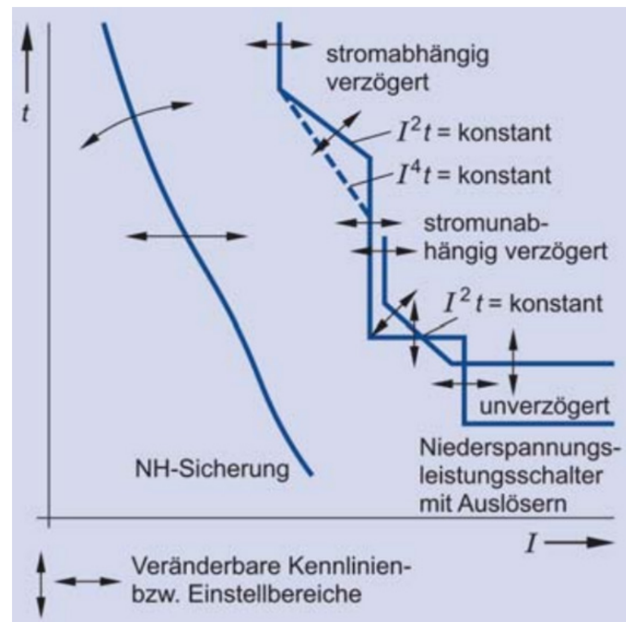
Protection

Protection of the SST
Protection of the Grid
Grid Codes

► Short-Circuit Protection in Distribution Grids

- LFTs Easily Deliver X-Times Rated Current for Tripping Fuses or Breakers

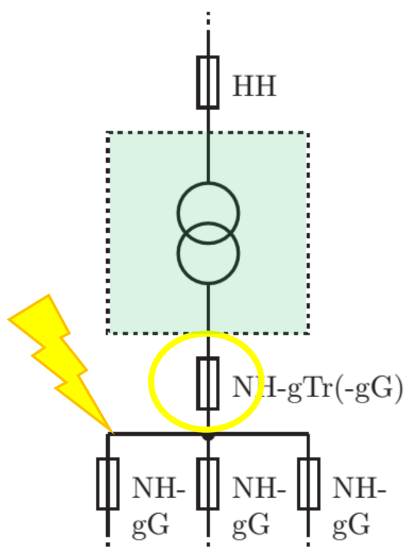


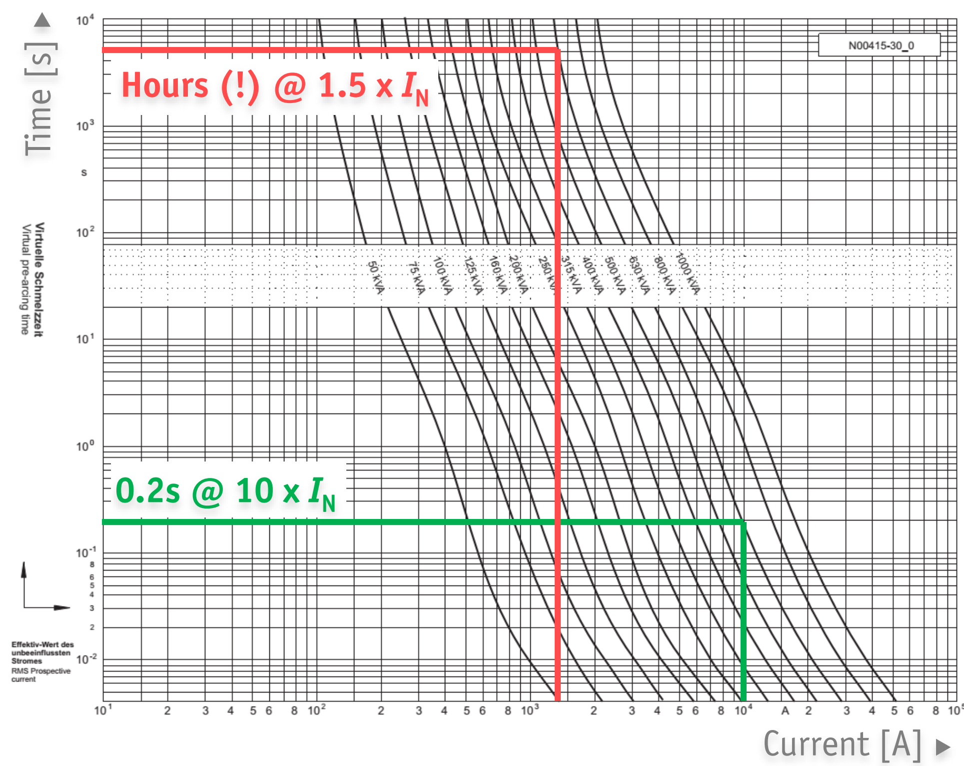


Imgs.: http://www.openelectrical.org/

▶ Tripping of LV Side Fuses

- 400V Fuse for 630kVA Transformer

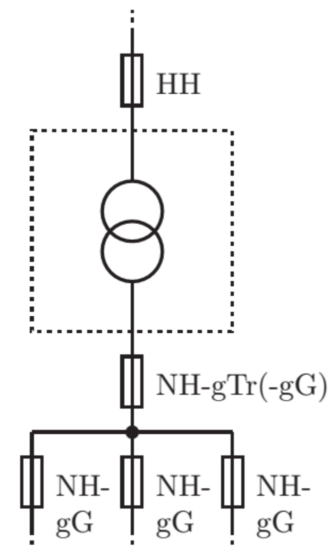


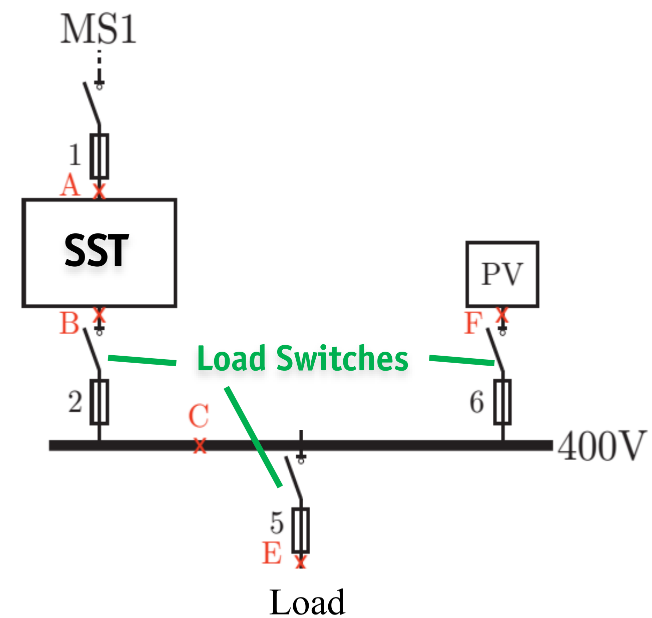


- Very High Short-Circuit Currents Required To Trip Fuses
- Not Possible With Power Electronic Converter (Semiconductors!)

▶ Alternative Protection Schemes

- SST Can **Limit** Its Short-Circuit Current
- **Load Switches** (!= Breakers) Could Be Used To Isolate Faults





- Integration of SST in Existing LV Distribution System Remains Challenging
- **Communication** Between (Protection) Devices Becomes Essential

- **SST Requires a "Smart Grid"**

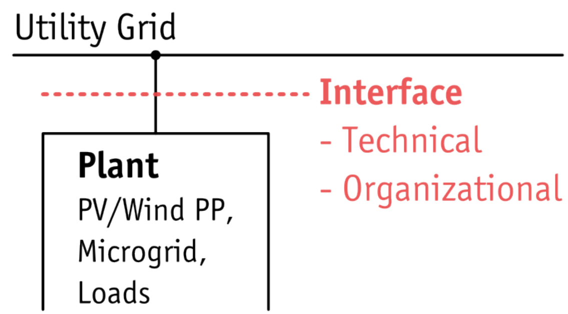
Challenge #8/10

Protection

Protection of the SST
Protection of the Grid
Grid Codes

▶ Purpose of Grid Codes

- General Goal: Ensure Stable Operation of the Grid and High Quality of Supply



Liberalization of Electricity Markets

- Many Agents: Grid Operators, Infrastructure Owners, Energy Producers, Consumers, etc.
- Interactions Involve Many Aspects:
  - **Technical**
  - Organizational (Economical, Legal, etc.)

Distribution Level Grid Codes…

- … Define Minimum Requirements for the Connection To and Operation In the Distribution Grid
- … Regulate Technical Interfaces Between Agents

▶ Distribution Grid Codes

- Focus on Technical Requirements for Equipment Connected to MV or LV Grid

Categorization: Voltage Level

- High Voltage 36…150kV — Transmission
- **Medium Voltage 1… 36kV** — Distribution
- **Low Voltage 0.4… 1kV** — Distribution

SST!

Categorization: Type of Plant

- Consumer (Load)
- Producer (e.g., Distributed Generator)

SST?!

- Technical Parts of Grid Codes May Refer to Other Standards or Documents

	Medium Voltage		Low Voltage
Generator	BDEW EZA MV	IEEE 1547 (IEEE 519)	BDEW EZA LV
		EN 50160	
Consumer	BDEW TAB MV	IEEE 519	BDEW TAB LV

- **Country/Region-Specific!**

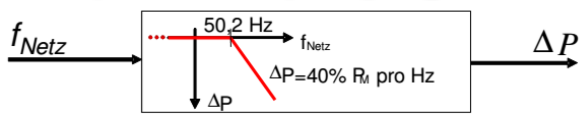
► Examples of Technical Requirements for MV Generating Plants

EMI

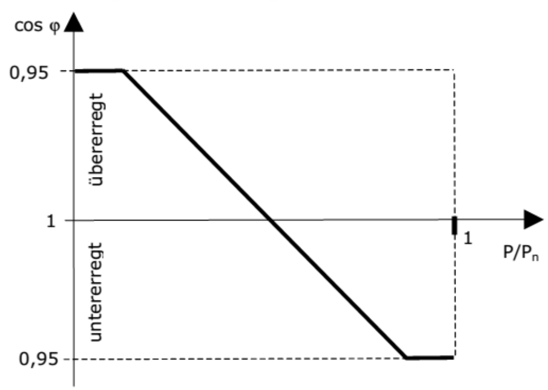
- IEEE 519/1547, BDEW, CISPR, etc.
- Flicker
- Max. Voltage Rise at PCC < 2%
- ...

Normal Operation

- Participation in Frequency Regulation

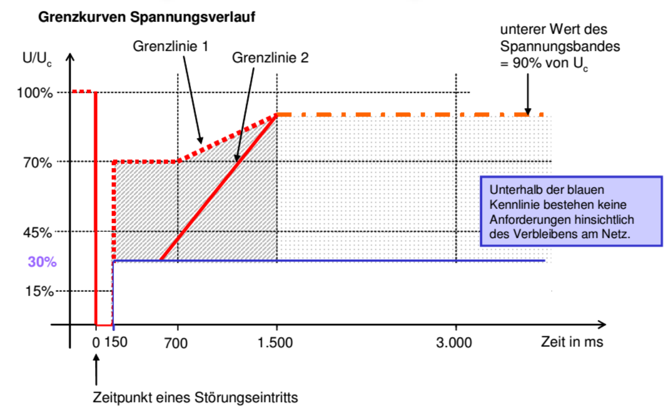


- Provision of Reactive Power According To Grid Operator Requirements



Dynamic Grid Stabilization

- During a Fault
  - No Disconnection (Within Limits)
  - Injecting Reactive Current to Support Grid
  - Islanding Needs To Be Negotiated



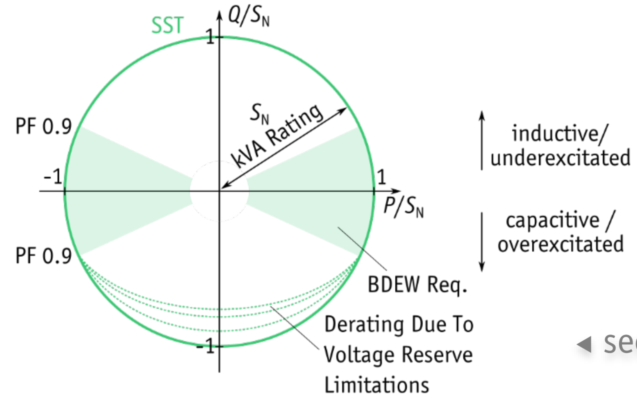
Plant Design Aspects

- Switchgear
- Protection Equipment and Relays
- Communication System
- Star Point Handling
- Auxiliary Supplies
- ...

BDEW, Erzeugungsanlagen am Mittelspannungsnetz, 2008.

▶ What Applies To SSTs?

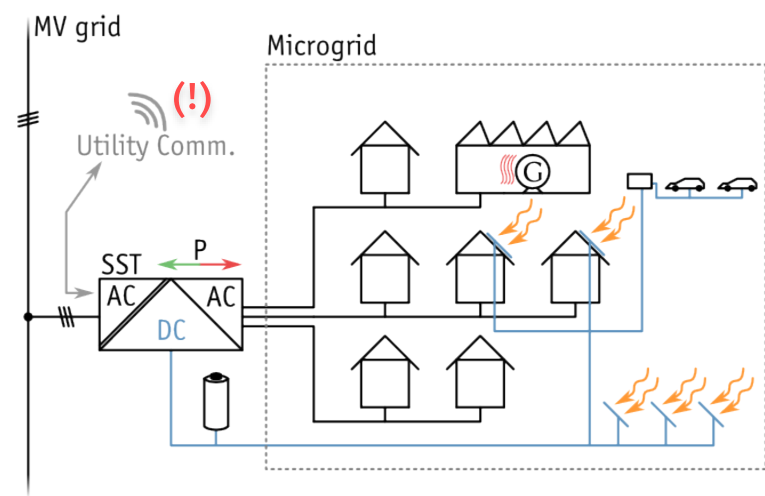
- ✓ EMI Requirements
- ✓ Plant Design
- ✓ Reactive Power – Even More Flexibility:



◂ see FACTS Section

- Dynamic Grid Stabilization
- Frequency Regulation

  - ▸ Storage Required
  - ▸ SST as Manager of "Virtual Power Plant"

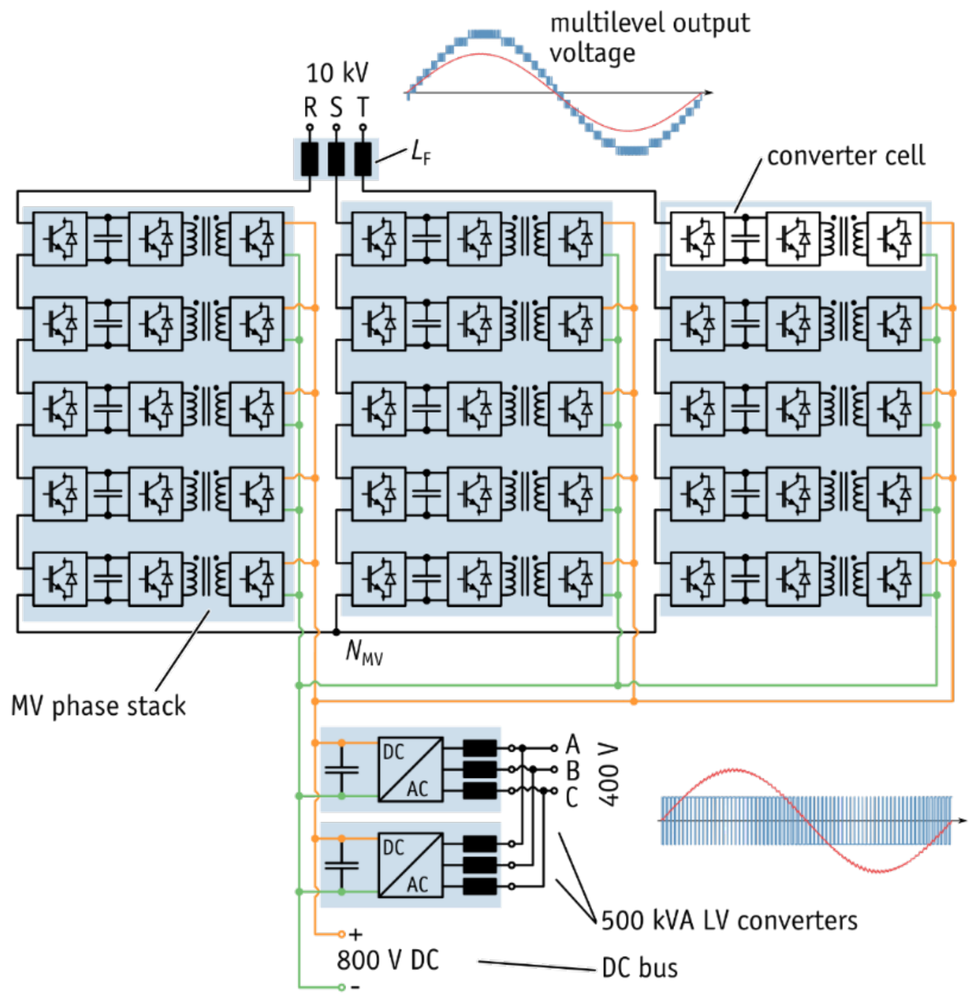


Challenge #9/10
Control & Communication

Smart Grid Integration
Control System Partitioning

▶ How To Realize The Control System?

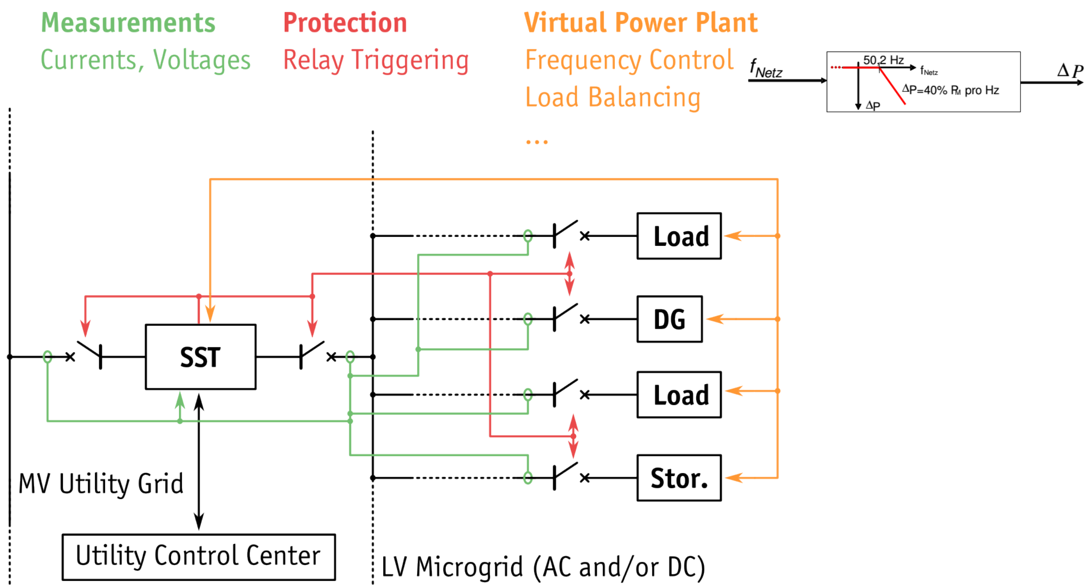
- Complex System with
  Many Functional Units
- Multi-Level SPWM with
  Many Cells on MV Side
- **Smart Grid Integration (!)**



▶ SST Smart Grid Integration

■ SST as "Manager" of a Micro Grid Section

- Novel Protection Schemes
- Micro Grid Can Act as a "Virtual Power Plant"



■ Communication With Other Participants Essential

- Standards
- Reliability

→ **To Be Defined!**

▶ SST Control System Partitioning (1)

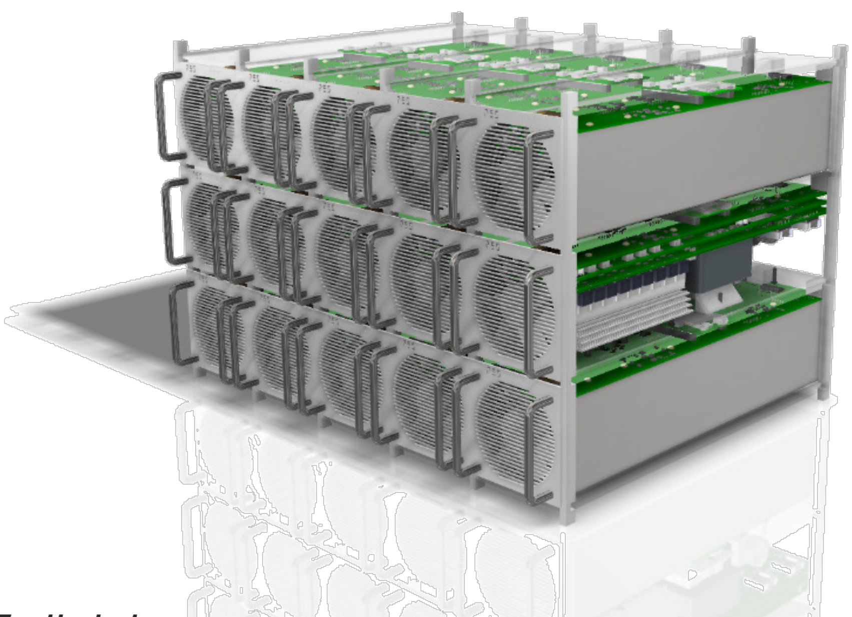
- Very Different Timing Requirements
  - IGBT Protection: us
  - Grid Transients: ms to s
- Several Hierarchical Layers as Feasible Approach
- **How To Test?**

External Ctrl.
- Smart Grid Integration
- Power Flows (P, Q)
- ...

Internal Ctrl.
- Current/Voltage Control
- Redundancy Mgmt.
- ...

(Cell) Internal Ctrl.
- Modulation, Protection
- ...

SST Power Hardware



◂ The *miniLINK*
Lab-Scale Full SST Demonstrator
15kVA, $400V_{AC} \leftrightarrow 800V_{DC} \leftrightarrow 400V_{AC}$

▶ SST Control System Partitioning (2)

MV - Volt. - Cur.

LV - Volt. - Cur.

Battery Management

Central Control Unit (DSP + FPGA)
- Overall Power Flow. Mgmt.
- Current Ref. Generation
- Aux. Units (Breakers, etc.)

SCADA Interface

Smart Grid Integration

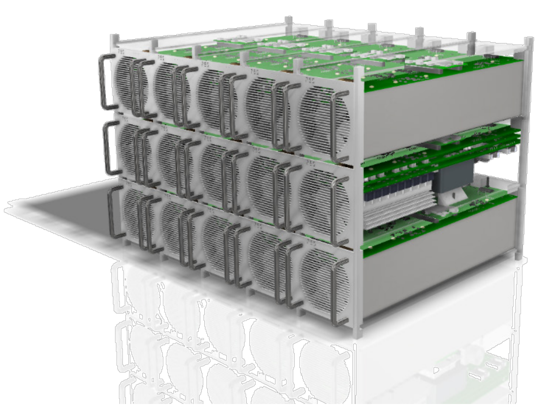
Cascaded MV Inverter
- Time Sync.
- Current Ctrl. & Ref. Gen.
- Redundancy Mgmt.

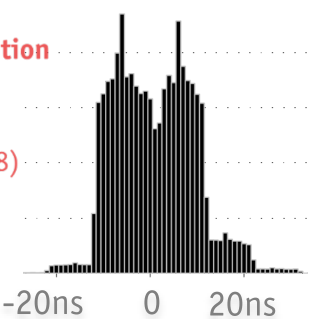
LV Inverter (FPGA)

LV Inverter (FPGA)
- Current Ctrl. & Mod.
- DC Cap. Balancing
- Protection

Cell Ctrl. (FPGA)
- Modulation
- Protection
- DC/DC Ctrl.

Real-Time Communication
- Ethernet-Based
- Fiber Optics
- Time Sync. (IEEE 1588)





◀ Meas. Cell Time Sync. Error **< 20ns**

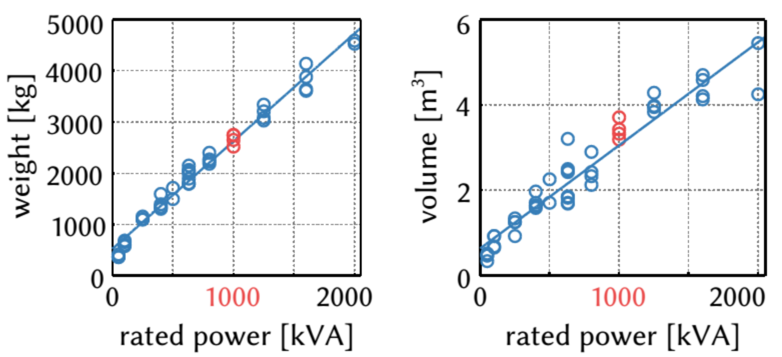
Challenge #10/10

Competing Approaches

SST vs. LFT
SST vs. FACTS

▶ The Competitor: 1000 kVA LF Distribution Transformer

- Standard Off-the-Shelve Products
- Typically Liquid Filled (Oil): Isolation, Cooling

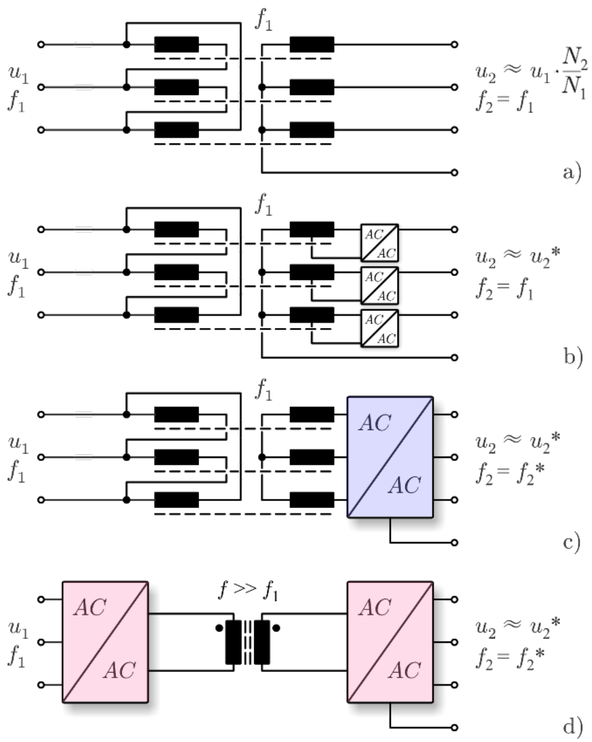


- Averaged Data from Different Manufacturers

	LFT	SST MV	SST LV	SST AC/AC	
efficiency	98.7				%
volume	3.43				m^3
weight	2590				kg
material cost	11.3				kUSD

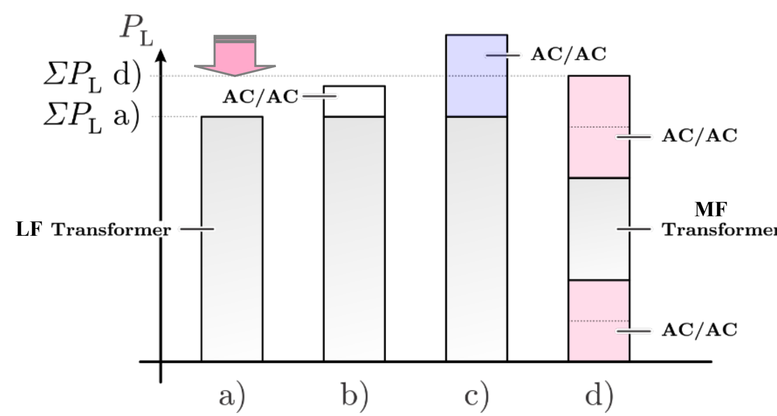
▶ LF Transformer ⟶ SST

■ Efficiency Challenge (Qualitative)



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

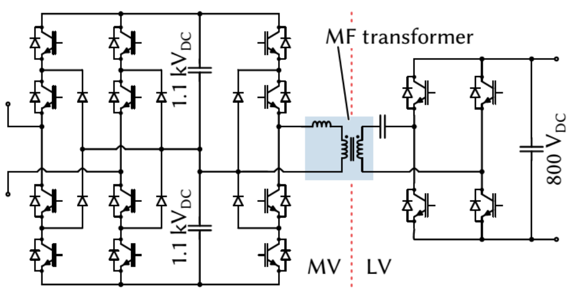
MF Isolation
Active Input & Output Stage (d)

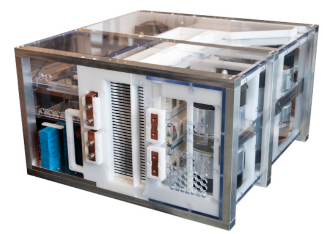


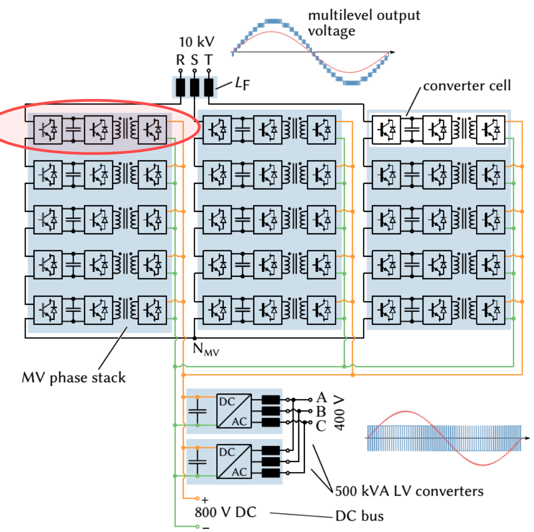
■ Medium Freq. ⟶ Higher Transf. Efficiency Partly Compensates Converter Stage Losses
■ Medium Freq. ⟶ Low Volume, High Control Dynamics

▶ SST vs. LFT Quantified – MV Side Modeling

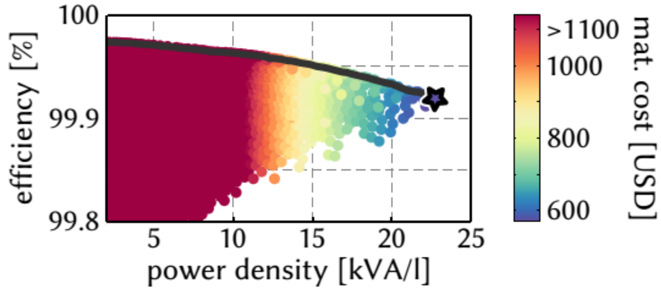
■ Fully Rated Converter Cell Prototype



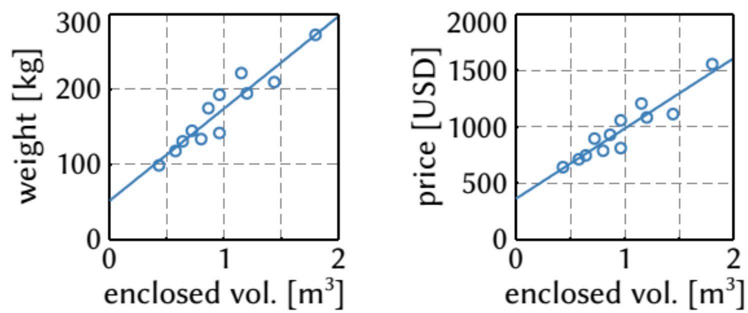




■ Filter Inductor Pareto Optimization



■ Cabinets

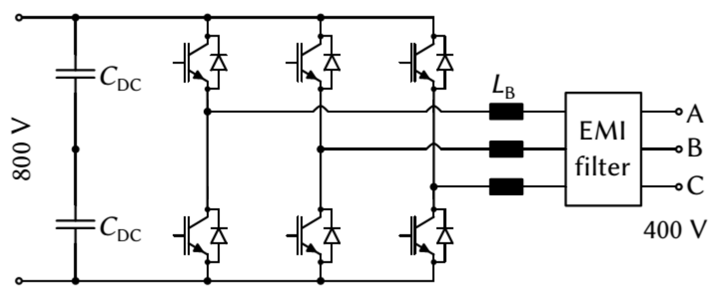


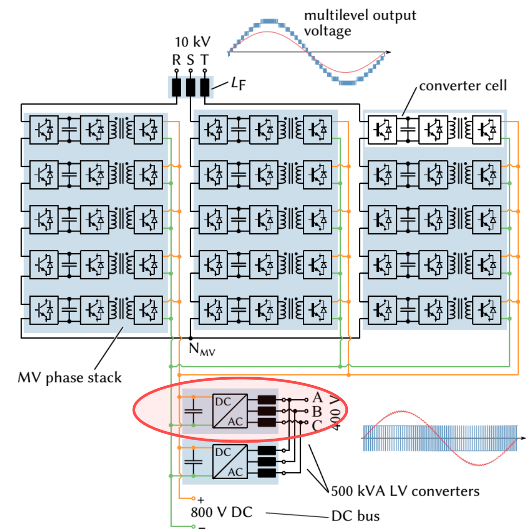
■ Material Costs: High-Volume Component Cost Models

◂ **R. Burkart** and **J. W. Kolar**, "Component cost models for multi-objective optimizations of switched-mode power converters," in *Energy Conversion Congr. and Expo. (ECCE)*, 2013, pp. 2139–2146.

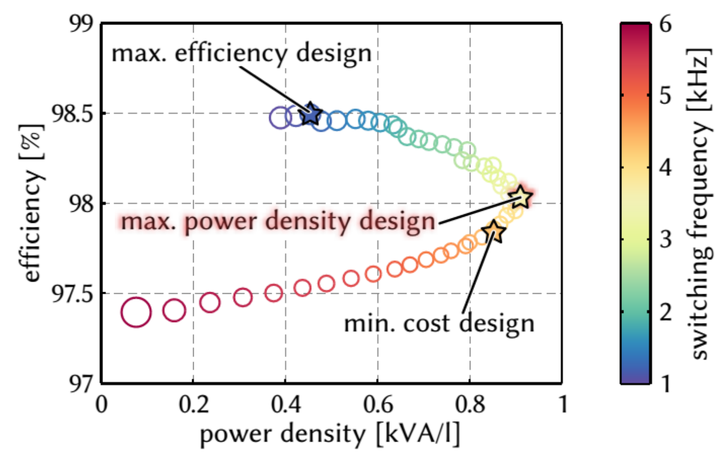
► SST vs. LFT Quantified – LV Side Modeling

■ Basic Pareto Optimization of Standard 500kVA Inverter/Rectifier





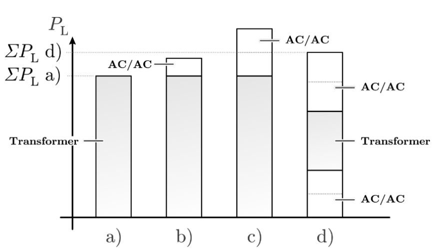
- Calculated Results (Losses, Volumes)
- Good Agreement with Specs of Commercially Available Active Frontend Converter



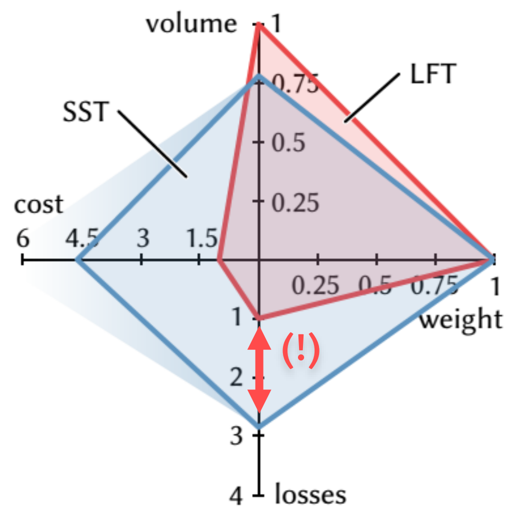
► SST vs. LFT Quantified – AC/AC Conversion

- AC/AC SST = SST MV + 2 SST LV

	LFT	SST MV	SST LV	SST AC/AC	
efficiency	98.7	98.3	98.0	96.3	%
volume	3.43	1.57	1.10	2.67	m^3
weight	2590	1270	1330	2600	kg
material cost	11.3	> 34.1	> 18.6	> 52.7	kUSD

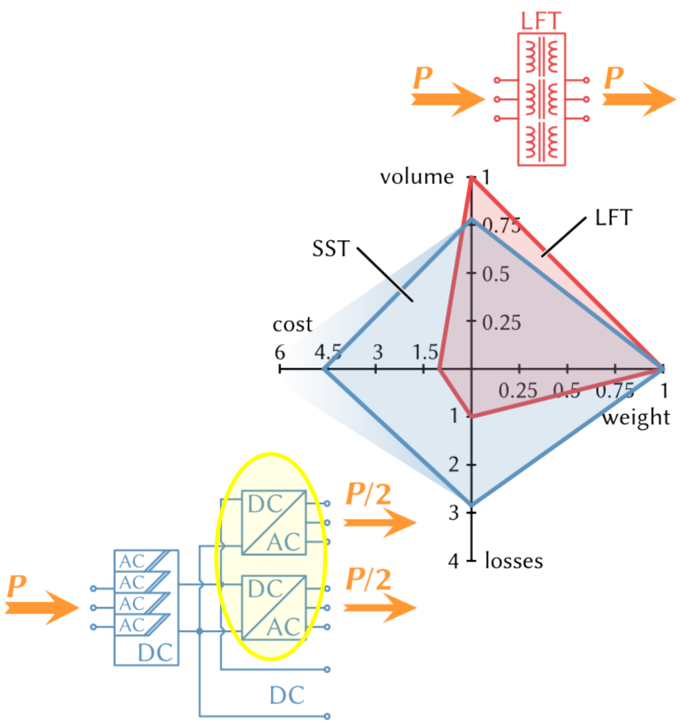


- Efficiency Challenge Confirmed by Quant. Analysis

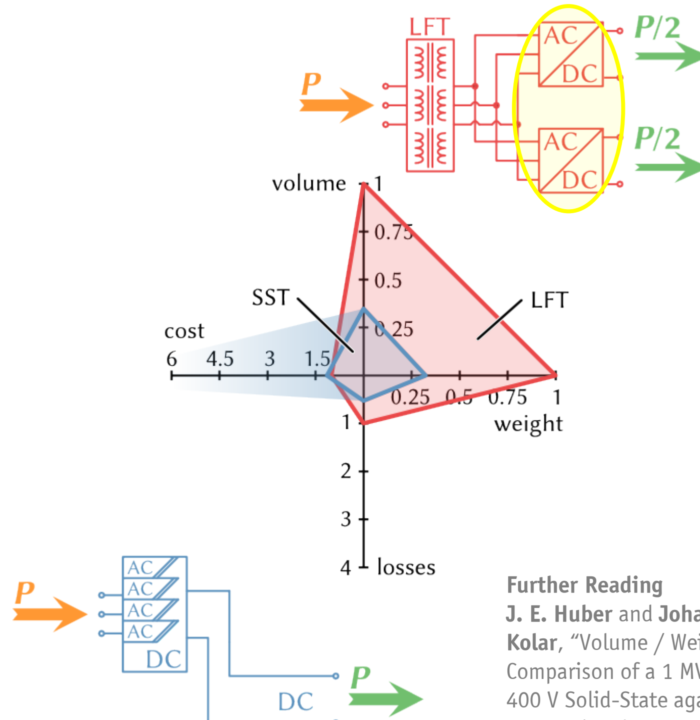


▶ SST vs. LFT Quantified – AC/AC and AC/DC Conversion

- AC/AC Application



- AC/DC Application



Further Reading
J. E. Huber and **Johann W. Kolar**, "Volume / Weight / Cost Comparison of a 1 MVA 10 kV / 400 V Solid-State against a Conventional Low-Frequency Distribution Transformer," in *Proc. Energy Conversion Congr. and Expo (ECCE)*, 2014.

- SSTs Suitable for Future AC/DC Applications With Direct MV Connection

Challenge #10/10

Competing Approaches

SST vs. LFT

SST vs. FACTS

► FACTS – Flexible AC Transmission System

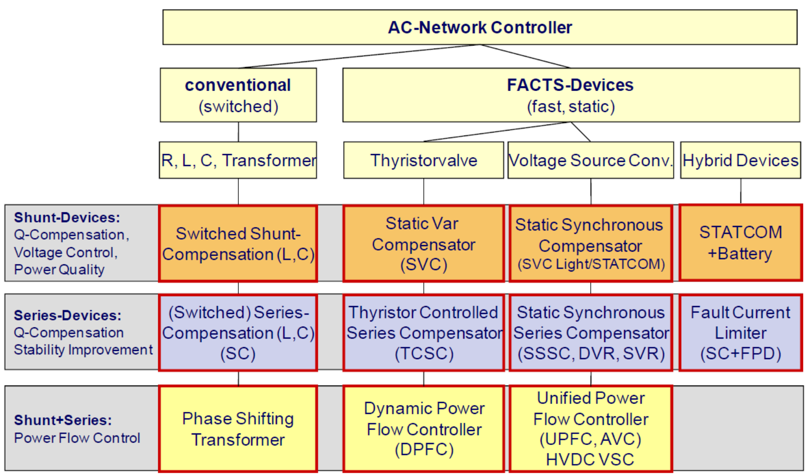
- Goal: Influence Power Flows In Order To Optimally Utilize Transmission Capacities

Without Power Electronics

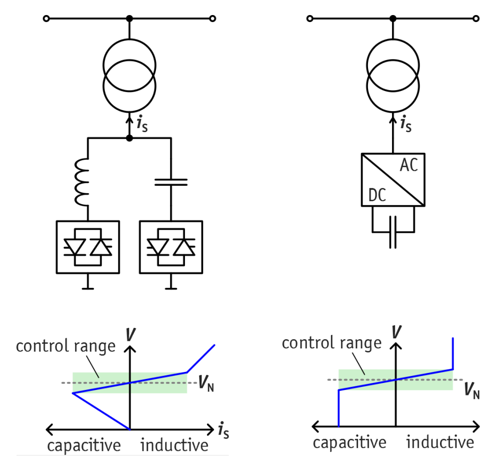
- Static VAr Compensator (Capacitor & Reactor Banks)
- VRDT
- Distribution Voltage Regulators
- Phase Shifting Transformers
- Generator Excitation Settings

With Power Electronics

- STATCOM (Static Synchronous Compensator)
  - Reactive Power Compensation
  - Active Filtering of Harmonics
  - Glitch Compensation
- Active Voltage Regulators
- UPFC (Unified Power Flow Controller)
  - Transmission Level



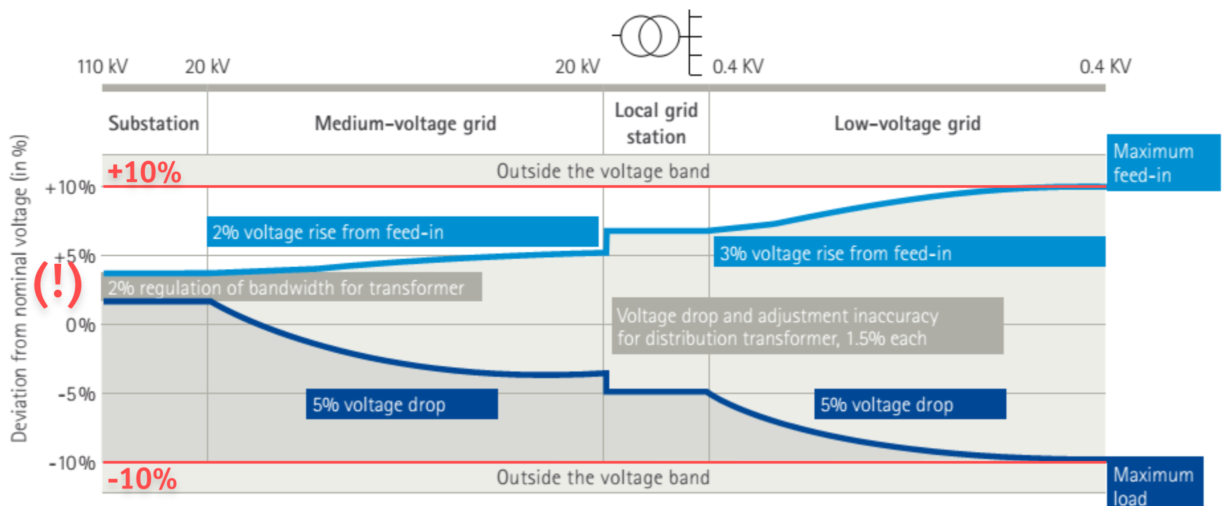
Img.: Ch. Rehtanz/TU Dortmund



► Voltage Band Violations in the Distribution System

- Voltage Band Specified by EN 50160: ±10%

- **Limits** Renewable Power Infeed on LV and MV Level
  - Max. 3% Voltage Increase on LV Level
  - Max. 2% Voltage Increase on LV Level

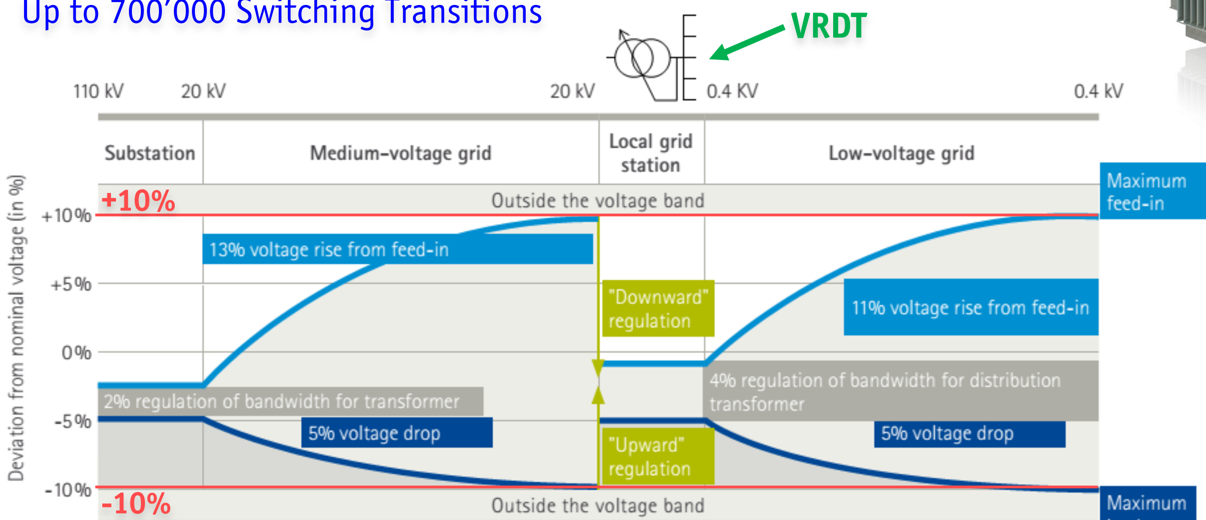


Source: Maschinenfabrik Rheinhausen GRIDCON Brochure

- **Grid Expansion Necessary Even Though Equipment Capacities Are Not Exhausted**
- SST Can Control Voltages – But So Can Voltage Regulation Distribution Transformer (VRDT), etc.

▶ Voltage Regulation Distribution Transformer

- LFT Extended By A Controlled Automatic On-Load Tap Changer
  - Up to 9 Positions, e.g., ±4 x 2.5%
  - Up to 700’000 Switching Transitions

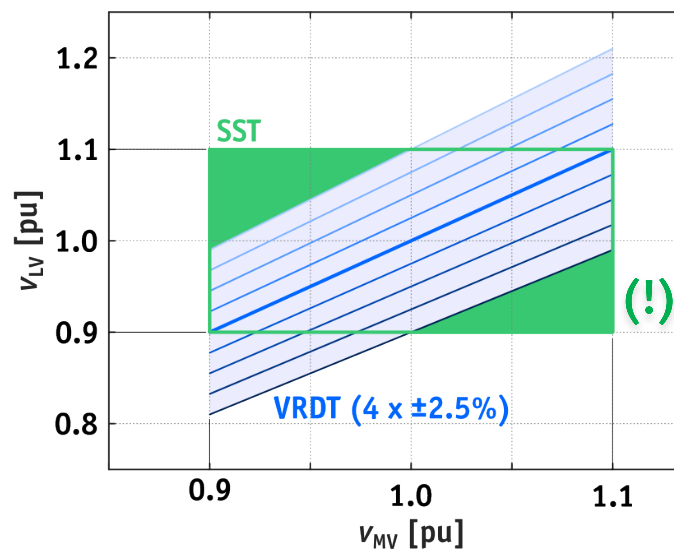


Source: Maschinenfabrik Rheinhausen GRIDCON Brochure

- Max. **11%** Voltage Increase on LV Level
- Max. **13%** Voltage Increase on MV Level

▶ SST vs. Voltage Regulation Distribution Transformer

- SST Control is Continuous and Faster
- SST Control Range Can Be Larger
- SST Transfers only Active Power (Complete Decoupling)

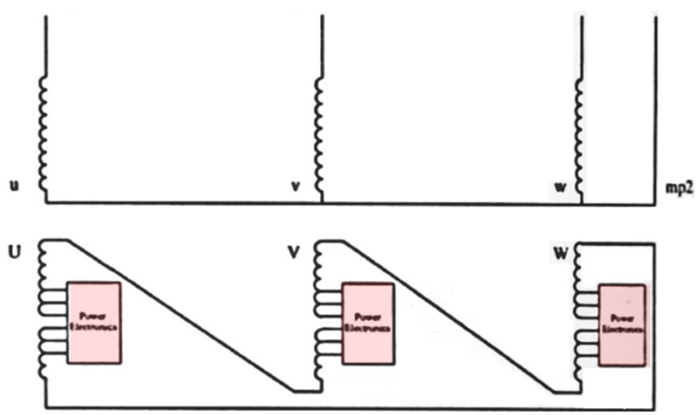


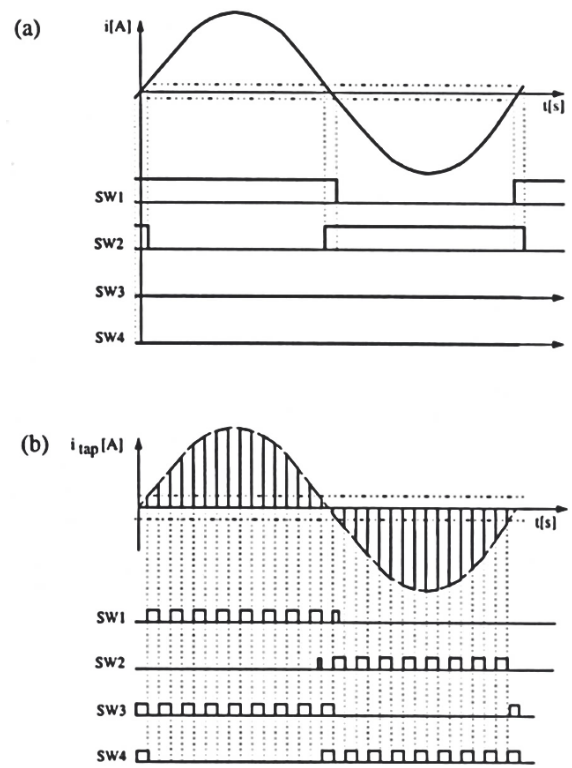
- SST Provides Wider Control Range, ⟶ Interesting in High MV Voltage Situations
- But: Complexity, Costs, Robustness, etc.

► Distribution Transformer with Electronic Tap Changer (1)

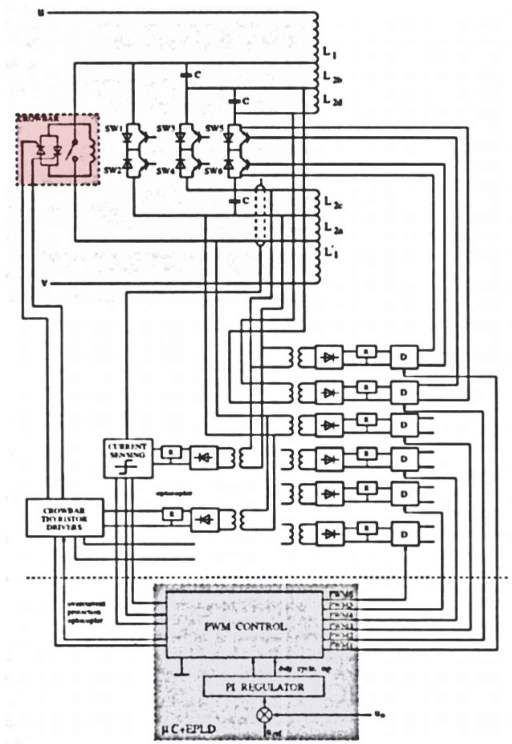
■ P. Bauer (1997)

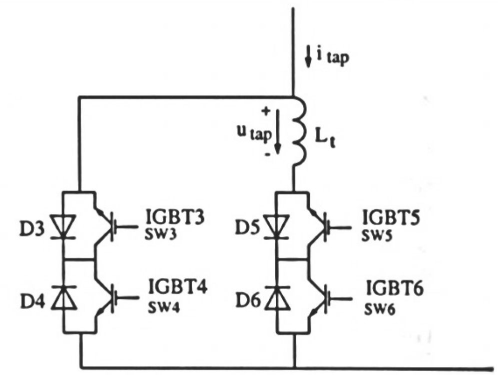
- MV Winding with Power Electronic Switched Tap.
- Two Modes of Operation:
  - Single Tap Position (a)
  - PWM Modulated Tap (b)



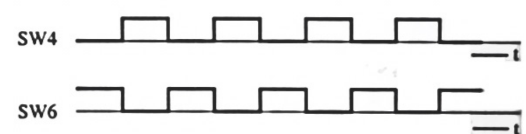


▶ Distribution Transformer with Electronic Tap Changer (2)





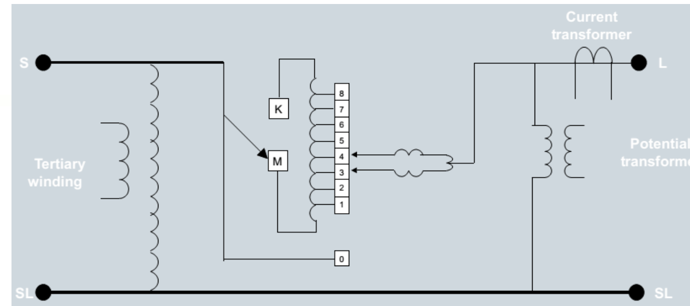
Switching cell of the tap switching.



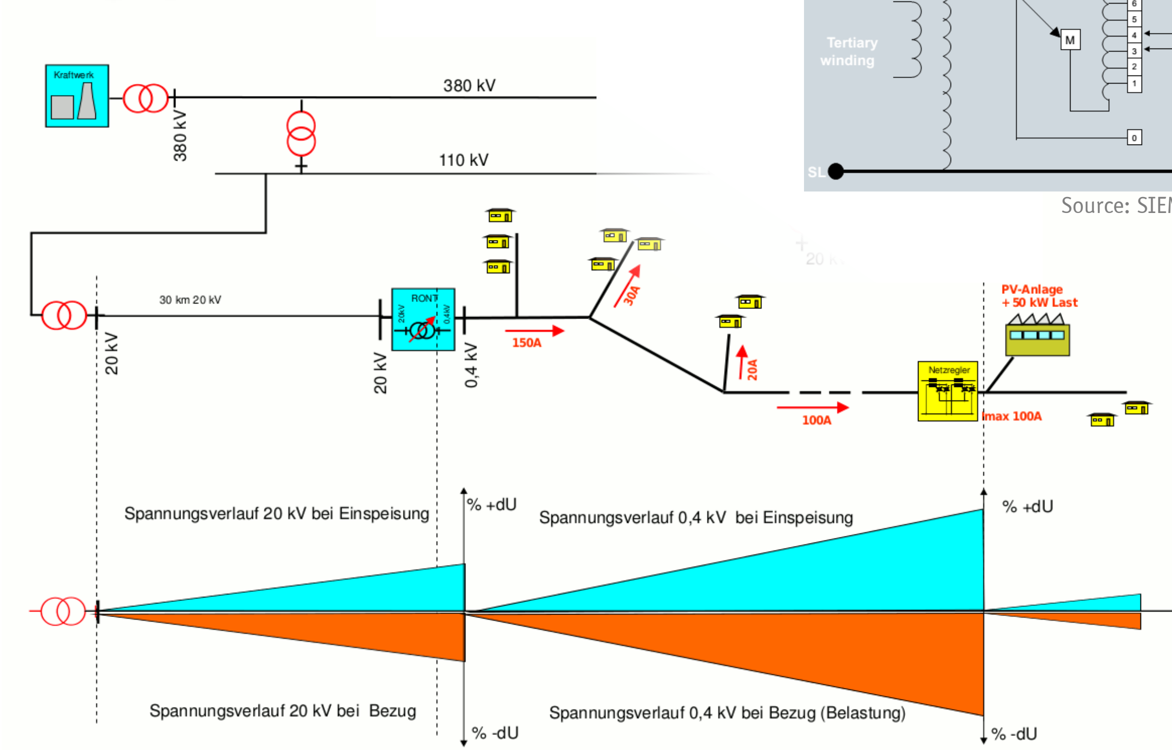
- Electronic Tap Changer — Complex Control Circuit
- **Crowbar for Emergency Ride-Through**
- Commutation Sequence of the 4-Quadrant Switches

▶ Distribution Voltage Regulators

- Available for MV or LV Systems
- Easy **Retrofit** (No Modification of Existing LFT)
- Periodic Placement Along a Feeder Possible
- Voltage Symmetrization



Source: SIEMENS Voltage-Regulator-Catalogue

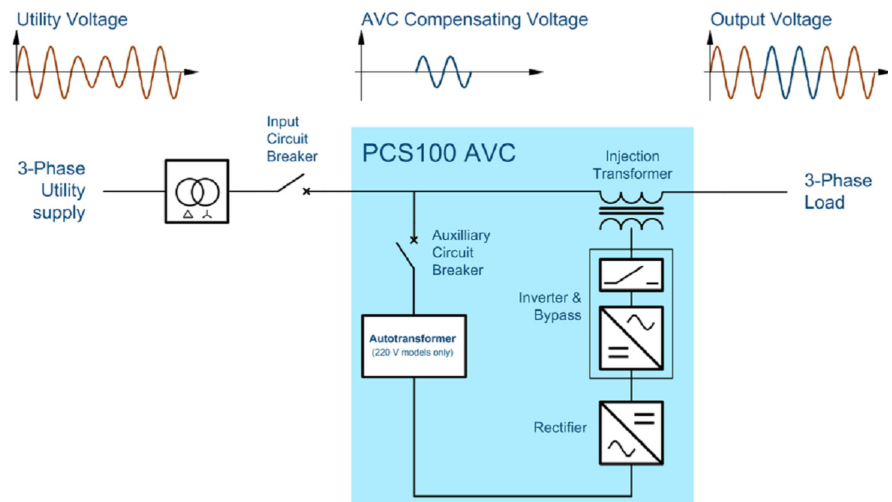


Source: www.walcher.com

► Active Series Voltage Regulators

- Protection of Sensitive Industrial and Commercial Loads from Voltage Disturbances

  - Continuous Voltage Regulation
  - Correction of Voltage Sags, Unbalances, Surges, and Phase Angle Errors
  - Harmonic Filtering
  - Reactive Power Compensation / Power Factor Correction

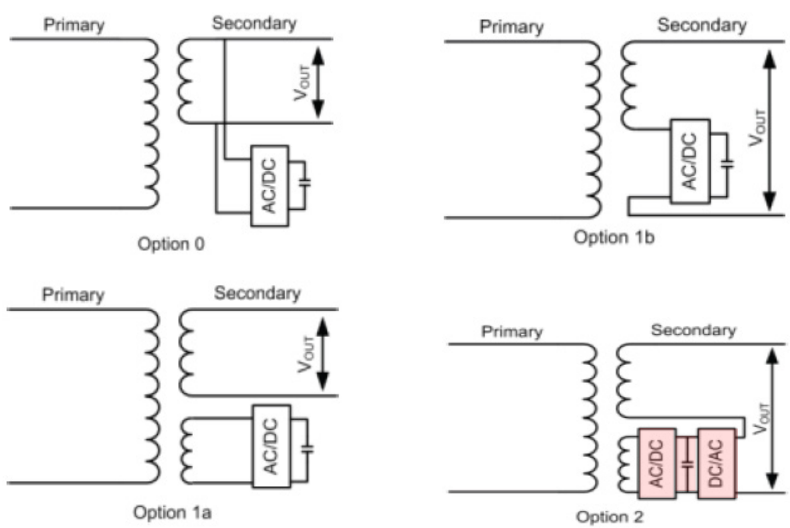


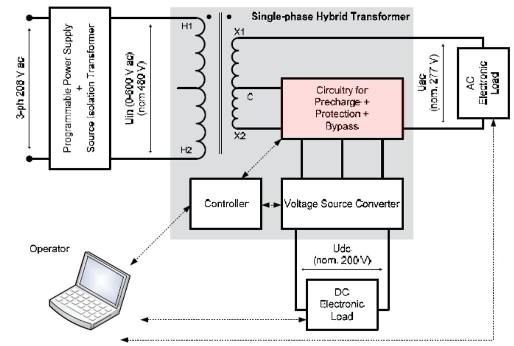
Source: ABB PCS100 Brochure

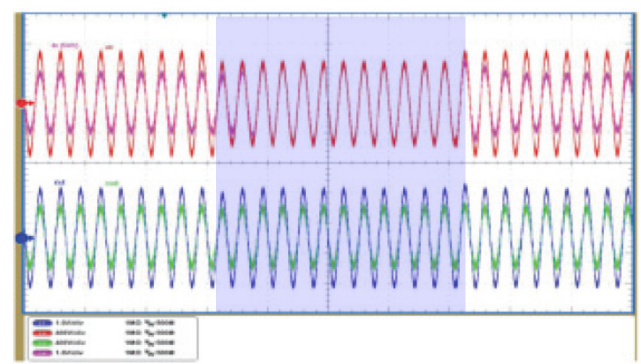
- LFT + AVR = VRDT Functionality!

▶ Combinations of LFT and SST (1)

- Bala (ABB 2012)



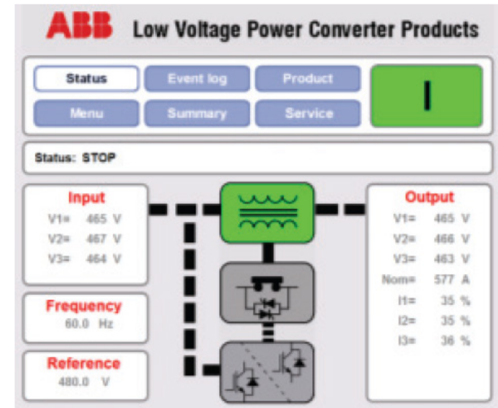


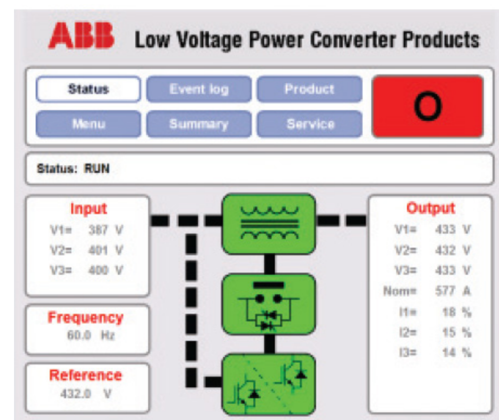


- Reactive Power Compensation (PFC, Active Filter, Flicker Control)
- Available DC Port (Isolated in Option 1a)
- **Option 2: Controlled Output Voltage**

▶ Combinations of LFT and SST (2)

- Bala (ABB, 2012)

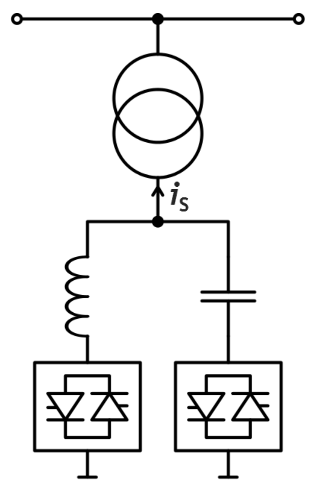


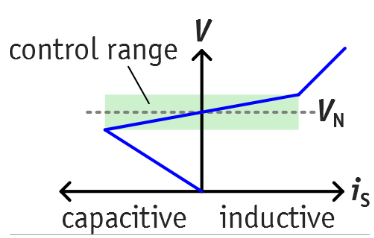


- Commercial Product (ABB)
- Direct Connection of Input to Output (Bypass) or
- Compensation of Inp. Voltage Sag (Contr. Output Voltage)

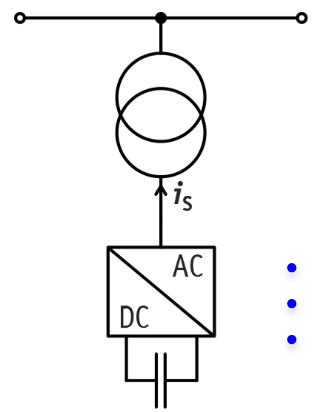
► Reactive Power Compensation / Voltage Regulation

■ Static VAr Compensation

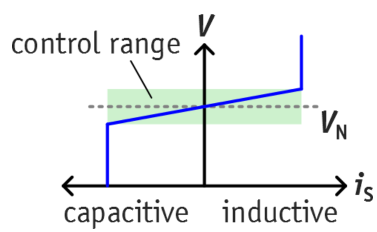




■ STATCOM

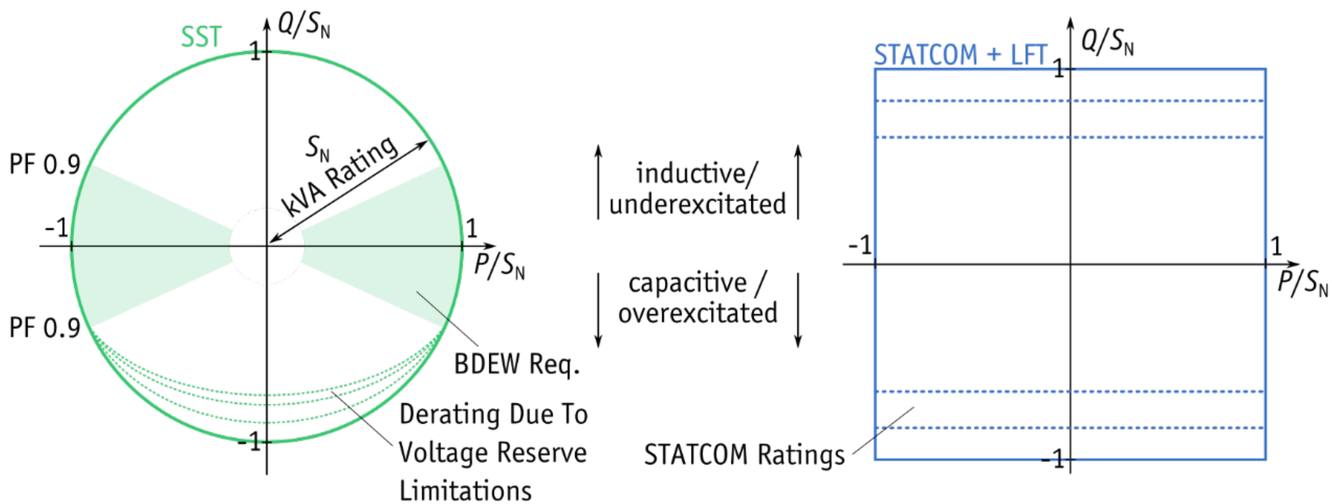


- Power/Voltage Quality Improvement
- Voltage Regulation
- Compensation of Harmonics, Flicker, etc.



► SST vs. LFT + STATCOM

- SST's VAr Capability Depends on Active Power Flow!
  - Or: Max. Active Power Flow Limited By Net Reactive Power Demand of Grid Section!



- SST Provides Complete **Decoupling of Reactive Power Flow** of MV and LV Grid
  - No Propagation of Disturbances
  - Different STATCOM OPs in MV and LV Grid

► SST in Grid Applications

Unique Characteristics
- LV DC Bus Allows Interfacing Local DC Systems
- Complete Decoupling AC Parameters
- Only Active Power Flow Between Grids

Potential Problems
- Costs **!!!**
- Robustness & Reliability
- Efficiency
- Compatibility with Existing Protection Concepts (e.g., Fusing Currents, etc.)

Main Aspects

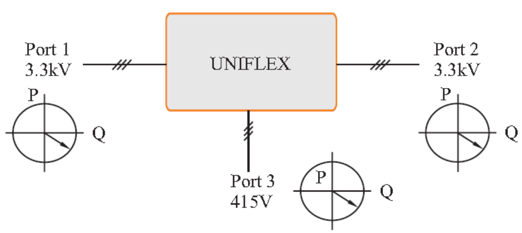
- SSTs Are **Not a 1:1 Replacement** for Conventional Distribution Transformers
- SSTs Can **Integrate Features of Different Components** into a Single Unit

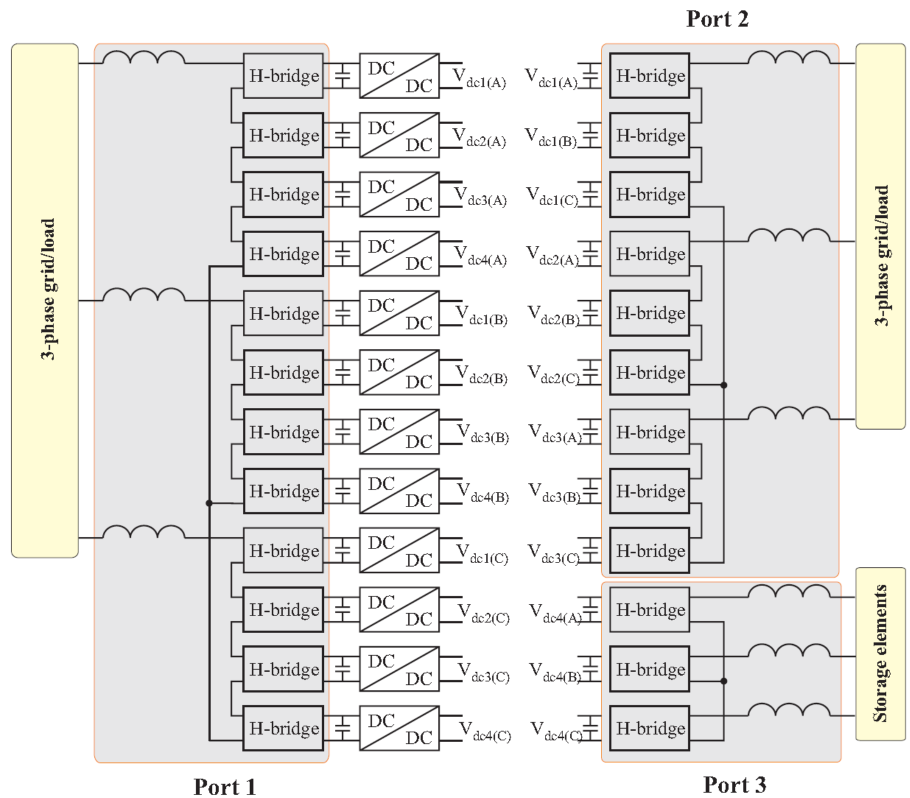
- **Main Potential for SSTs in MV-AC to LV-DC Applications (DC Grids in Plants or Buildings)**

Smart Grid SSTs
Examples

▶ UNIFLEX Project (1)

- EU Project (2009)

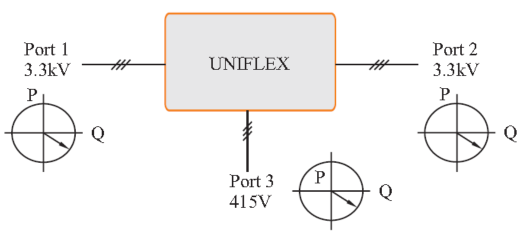


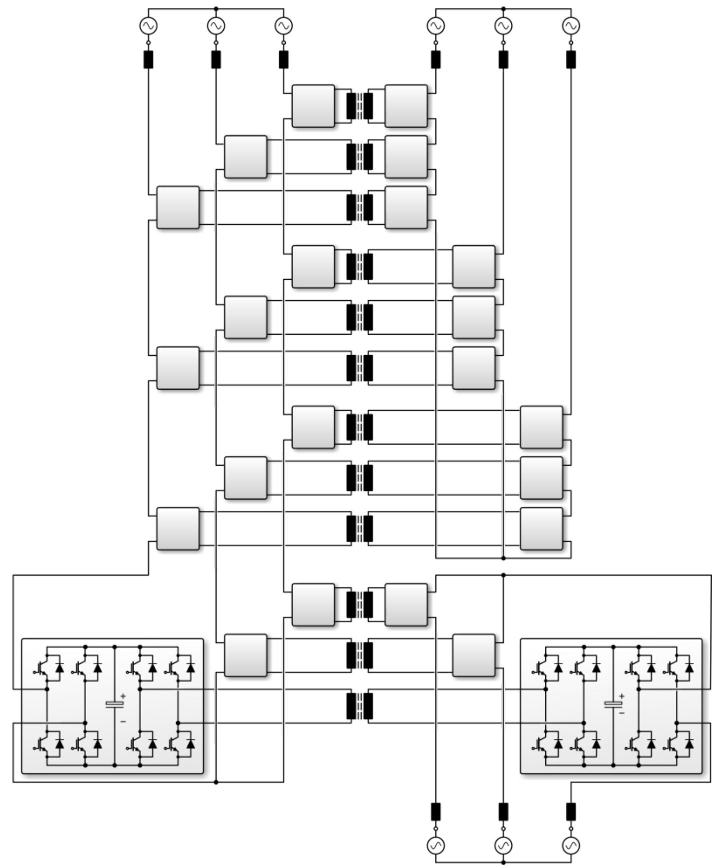


- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- **Cellular 300kVA Demonstrator of 3-Port Topology** for 3.3kV Distr. System & 415V LV Grid Connection

▶ UNIFLEX Project (2)

- EU Project (2009)





- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
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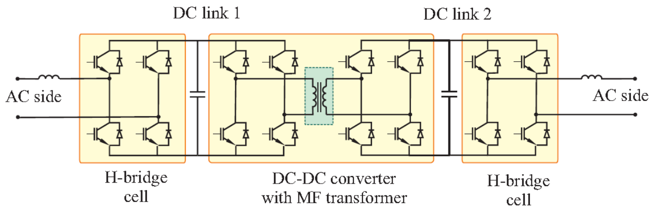
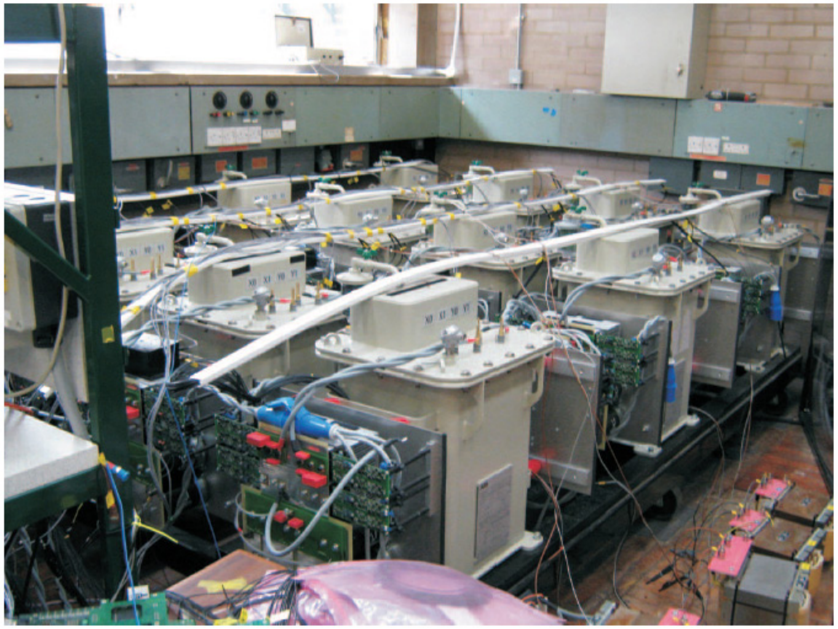


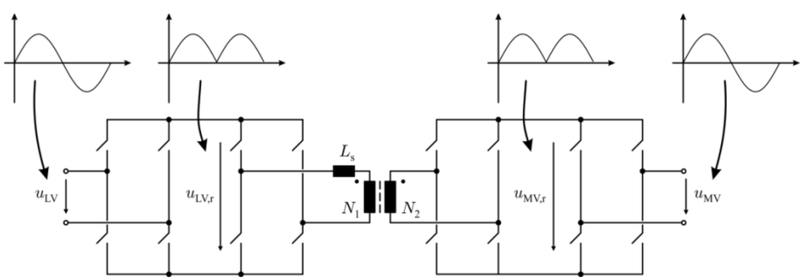


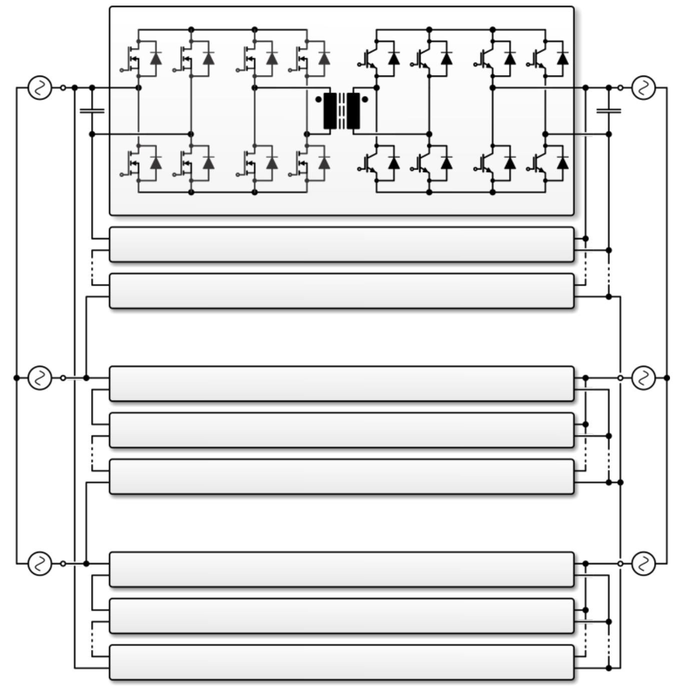
- AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham

► SiC-Enabled Solid State Power Substation (1)

- Das (2011)

- 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/$\sqrt{3}$, Modules in Parallel)



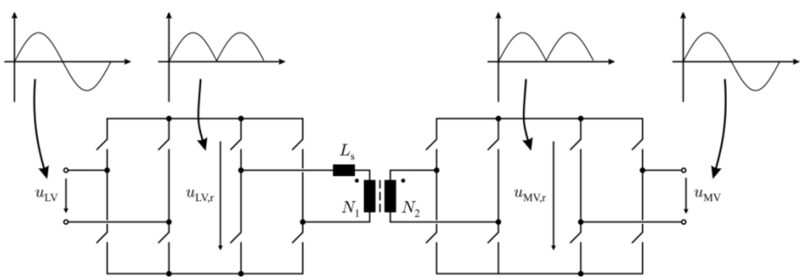


- SiC-Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

▶ SiC-Enabled Solid State Power Substation (2)

- Das (2011)

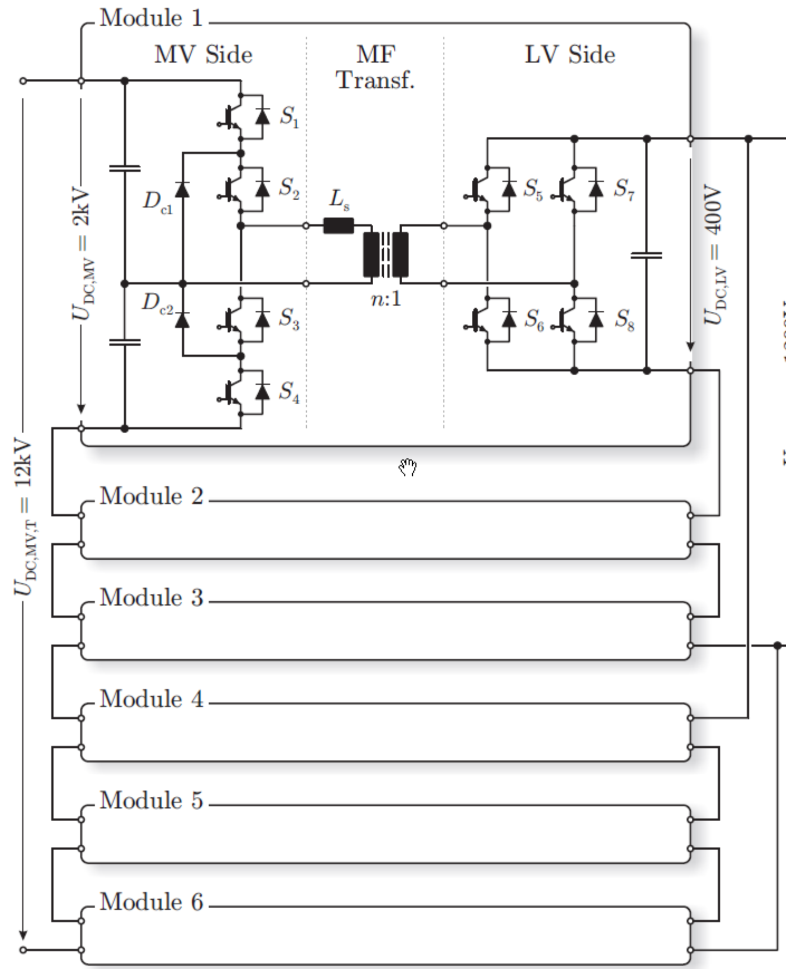
- Fully Phase Modular System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
- MV Δ-Connection (13.8kV$_{\text{l-l}}$, 4 Modules in Series)
- LV Y-Connection (465V/√3, Modules in Parallel)



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

▶ *MEGACube* @ ETH Zurich (1)

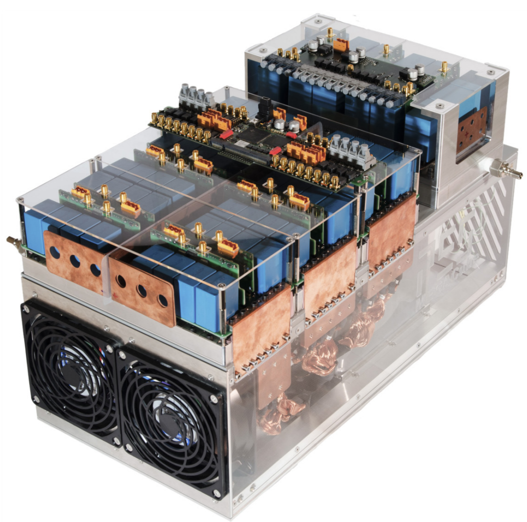
- Total Power 1MW
- Frequency 20kHz
- Efficiency Goal 97%



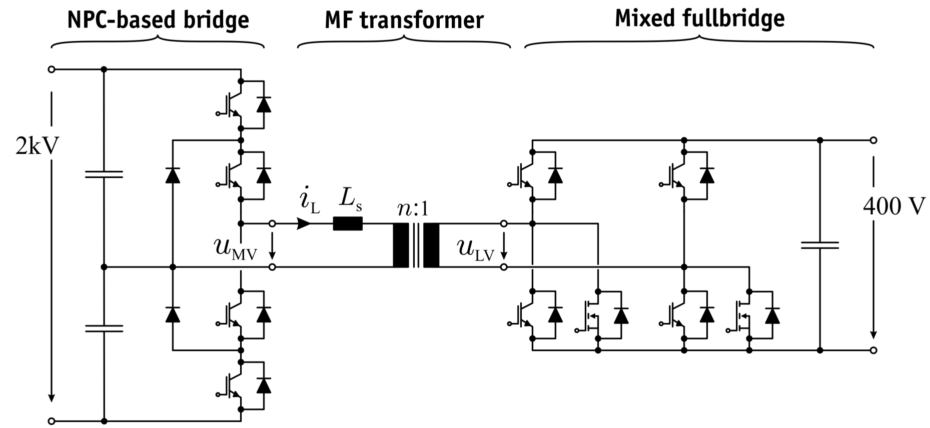
- MV Level 12kV
- LV Level 1.2kV

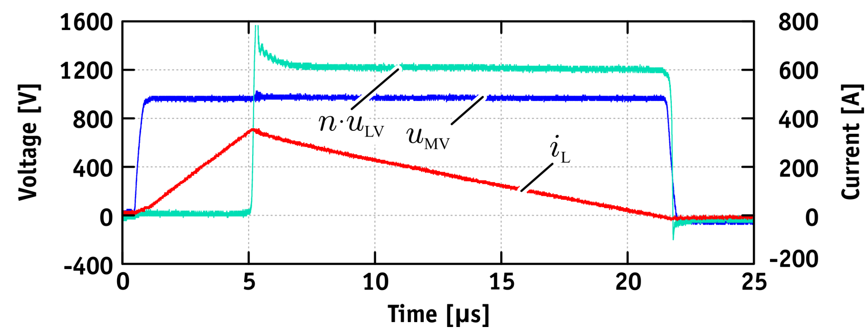
▶ *MEGACube* @ ETH Zurich (2)

- DC-DC Converter Stage
- Module Power 166kW
- Frequency 20kHz
- **Triangular Current Mode Modulation**



▲ 166kW / 20kHz TCM DC-DC Converter (Ortiz, 2014)

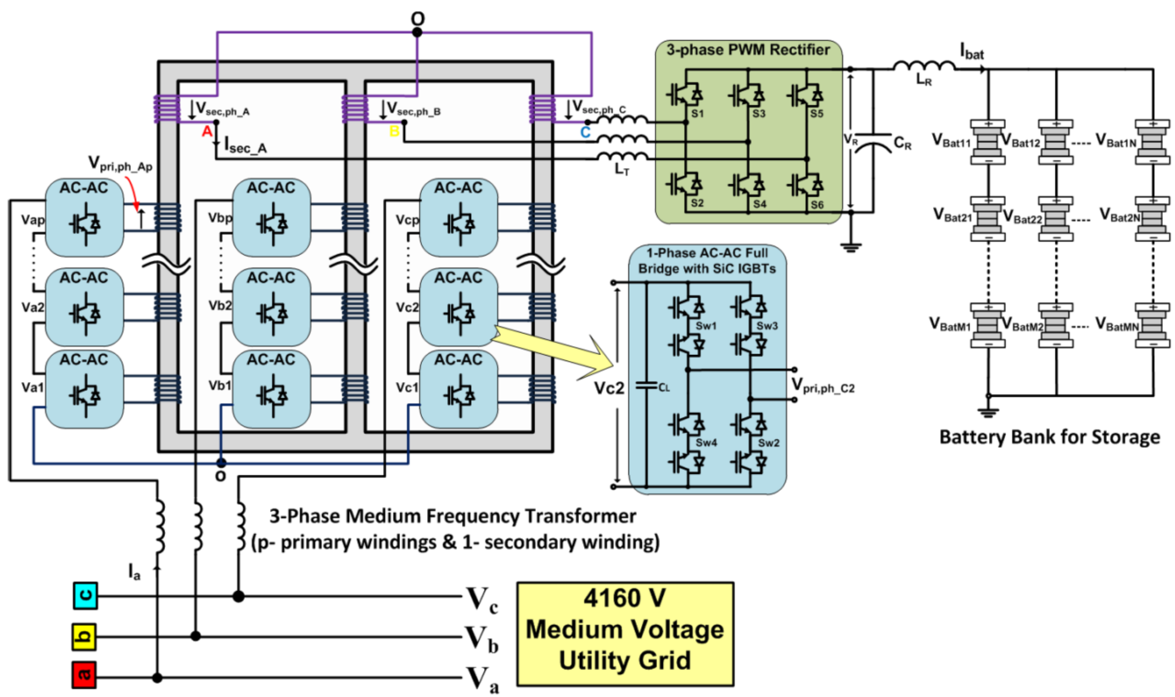




▲ Structure of the 166kW Module and MV Side Waveforms

▶ Matrix-Type SST

- Proposed for Energy Storage Systems (Enjeti, 2012)



- MV Side Series Direct Matrix Structure with Single 3ph. MF Transformer Core
- Single LV Side 2-Level 3ph. Inverter

Traction SSTs
Examples

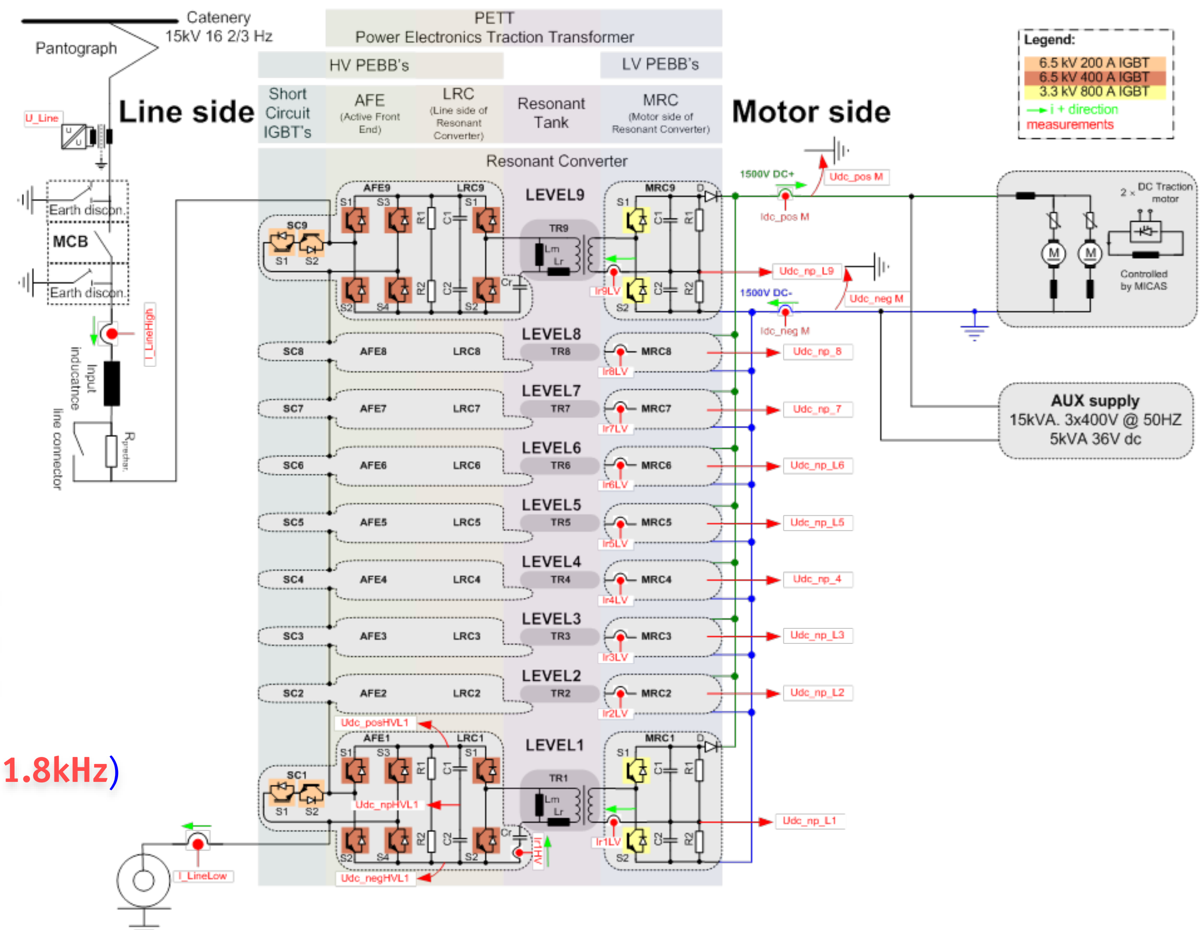
Img.: www.futuretimeline.net

▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages (1)

ABB

- Dujic et al. (2011)

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



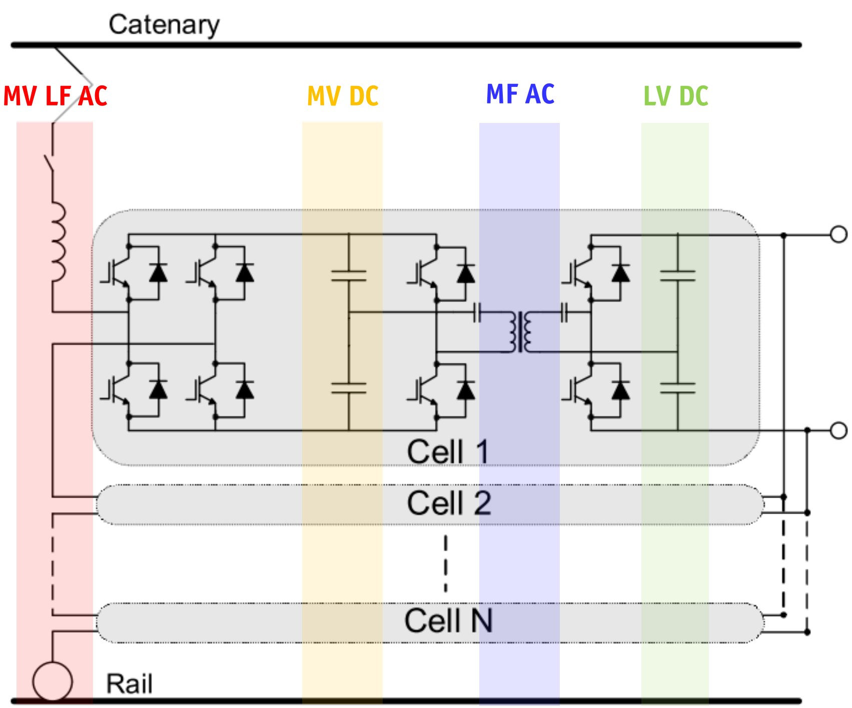
P = 1.2MVA, 1.8MVA pk.
9 Cells (Modular)

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

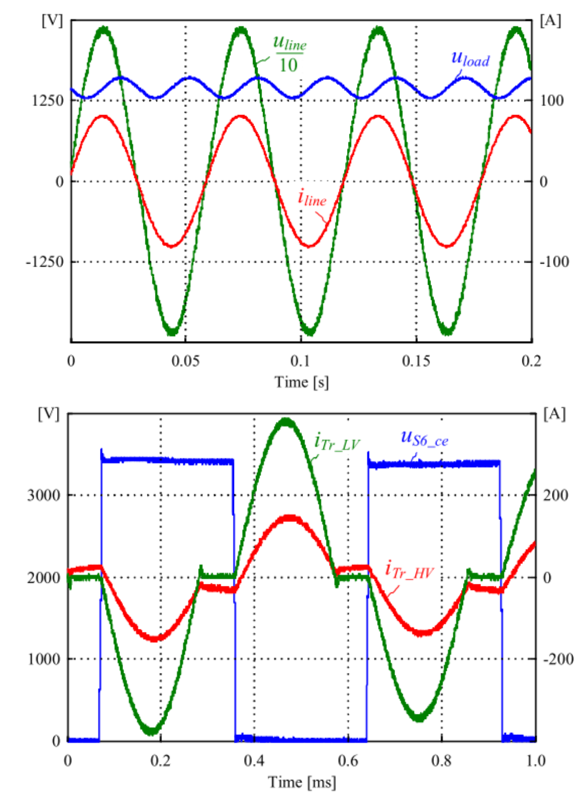
9 x MF Transf. (150kVA, **1.8kHz**)
1 x Input Choke

▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages (2)

- Zhao et al. (ABB, 2011)



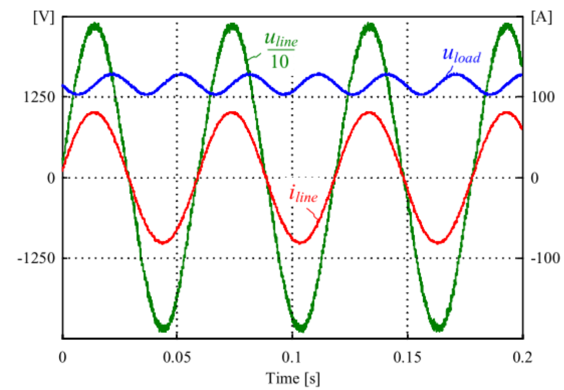
PET topology with cascaded H-bridges and resonant (LLC)DC-DC stages

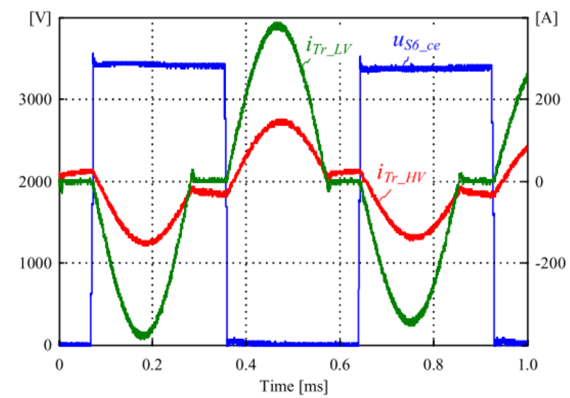


▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages (3)

■ 1.2MVA, 15kV, 16 $^{2}/_{3}$ Hz, 1ph. AC/DC Power Electronic Transformer

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

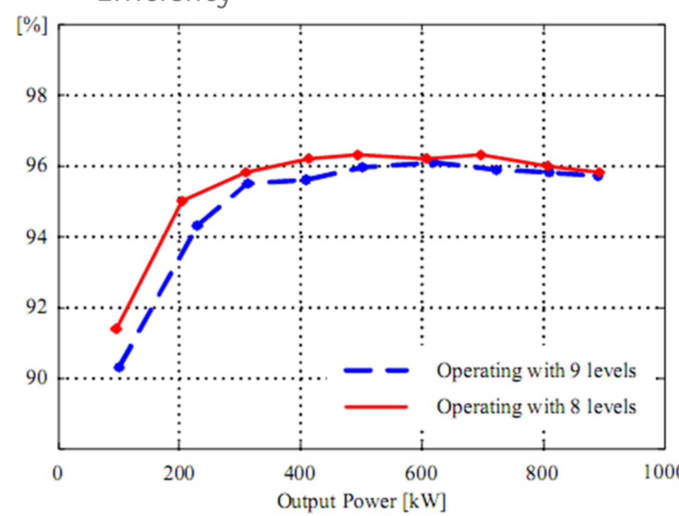




► Cascaded H-Bridges and Resonant LLC DC-DC Stages (4)

- 1.2MVA, 15kV, 16 $^{2}/_{3}$ Hz, 1ph. AC/DC Power Electronic Transformer
  - Cascaded H-Bridge – 9 Cells
  - Resonant LLC DC/DC Converter Stages

▾ Efficiency



► Cascaded H-Bridges and Resonant LLC DC-DC Stages (5)

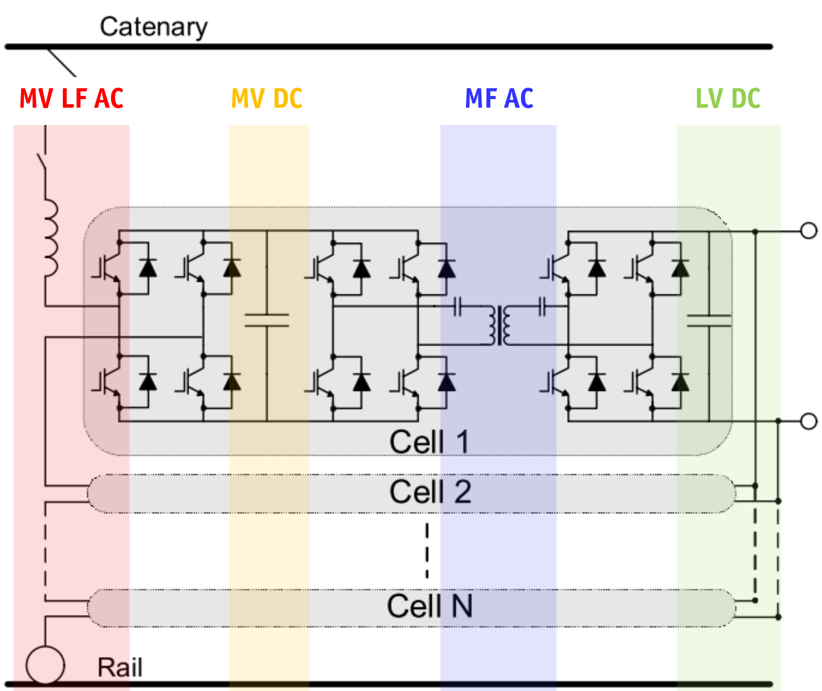
■ 1.2MVA, 15kV, 16 $^2/_3$ Hz, 1ph. AC/DC Power Electronic Transformer

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

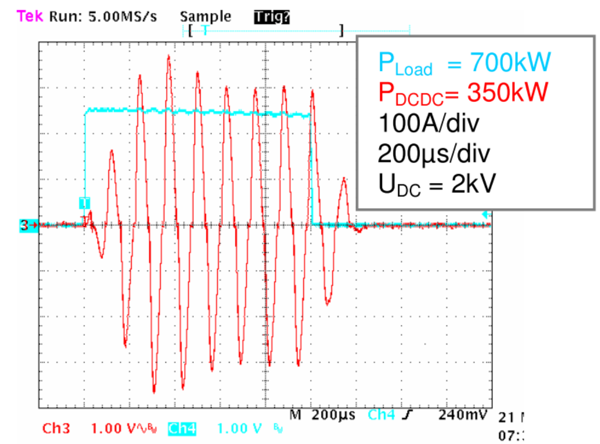
▼ Retrofit of Shunting Locomotive

► Cascaded H-Bridges with Resonant/Non-Resonant DC-DC Stages (1)

- Steiner (Bombardier, 2007)
- Weigel (SIEMENS, 2009)



PET topology with cascaded H-bridges and resonant/non-resonant DC-DC stages.

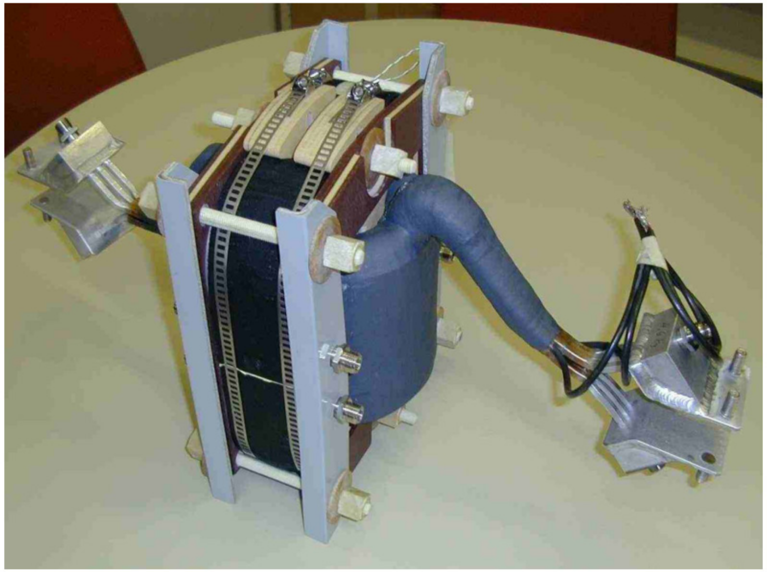


Dynamic behavior of DC-DC converter

► Cascaded H-Bridges with Resonant/Non-Resonant DC-DC Stages (2)

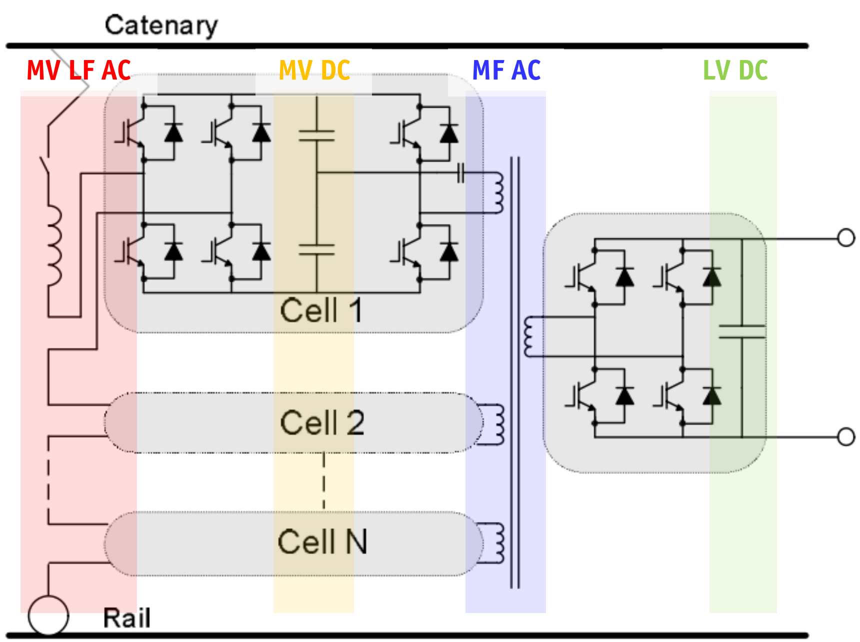
- Weigel (SIEMENS, 2009)
  - Module Power 450kW
  - Frequency 5.6kHz

- Steiner (Bombardier, 2007)
  - Module Power 350kW
  - Frequency 8kHz

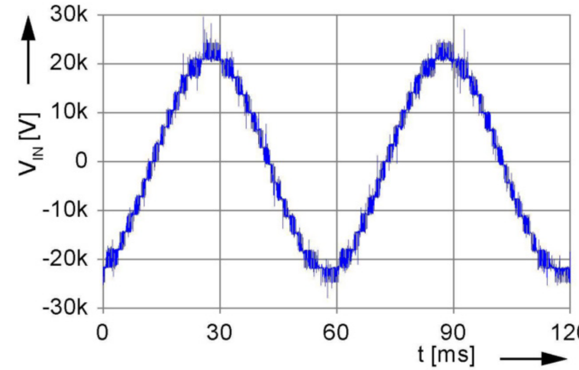


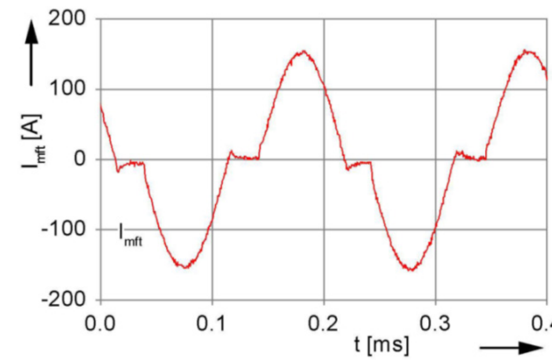
▶ Cascaded H-Bridges with Multi-Winding MF Transformer (1)

- Engel (ALSTOM, 2003)

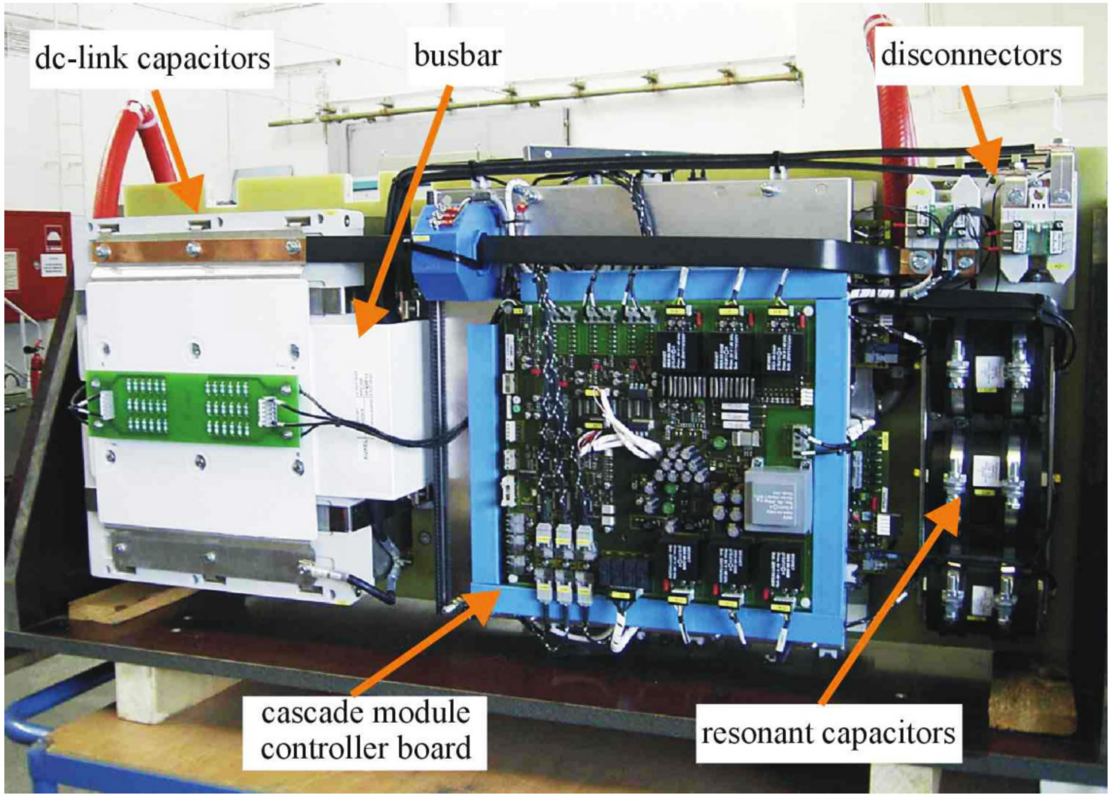


PET topology with cascaded H-bridges and multi-winding MFT





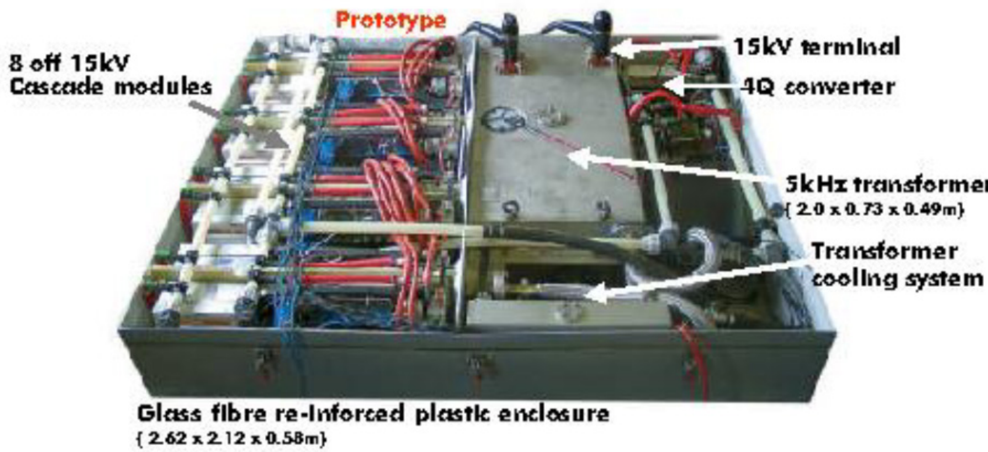
► Cascaded H-Bridges with Multi-Winding MF Transformer (2)



- Engel (ALSTOM, 2003)

- Module Power 180kW
- Frequency 5kHz

► Cascaded H-Bridges with Multi-Winding MF Transformer (3)

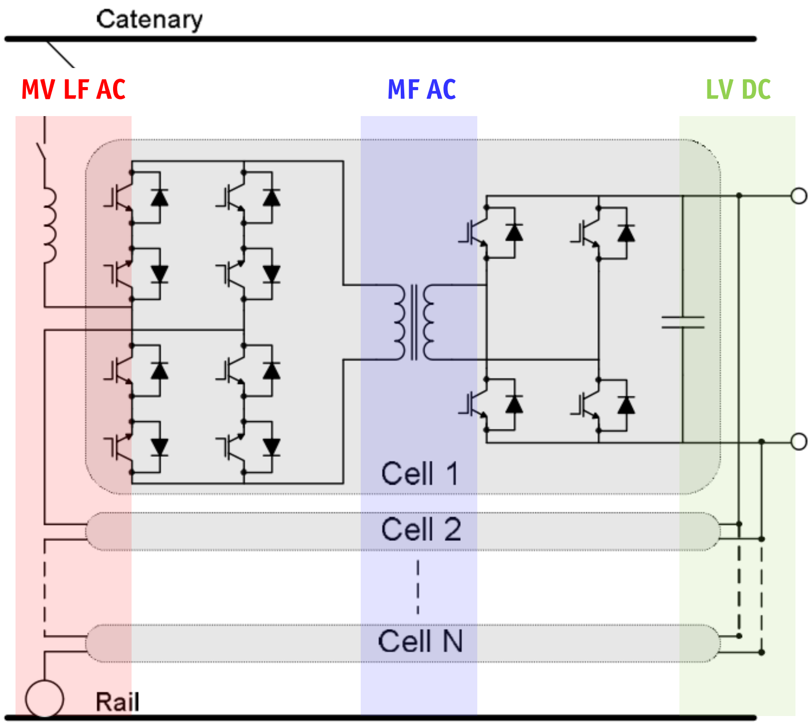


- Taufiq (ALSTOM, 2007)

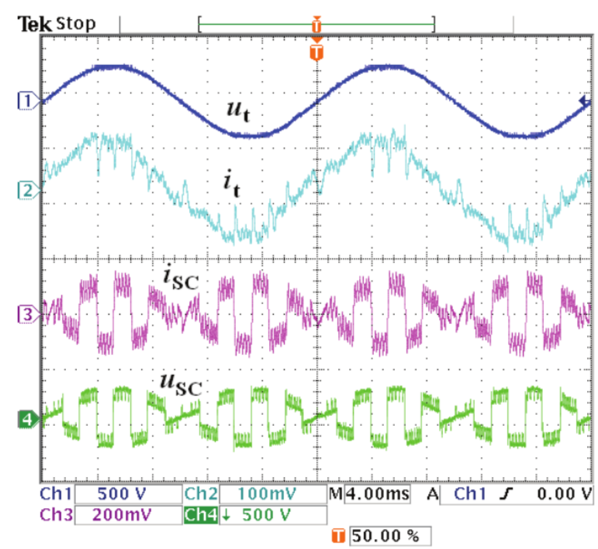
- Module Power 180kW
- Frequency 5kHz

▶ Cascaded VSI Commutated Primary Converter (1)

- Hugo (ABB, 2006)
- Pittermann (2008)

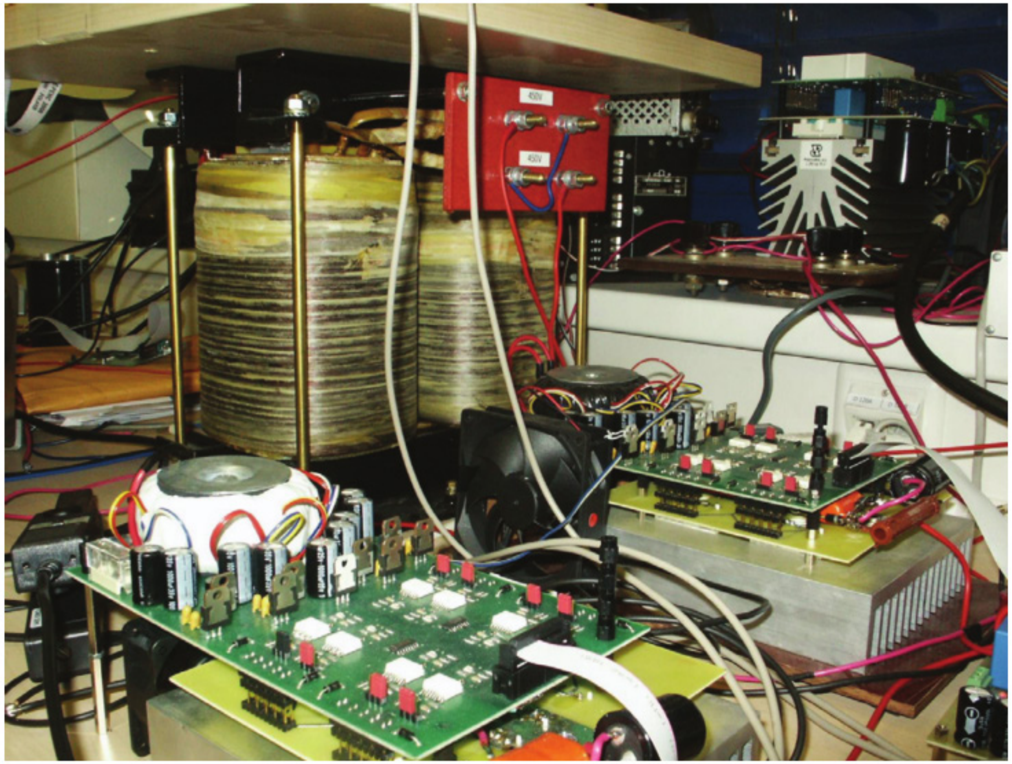


PET topology with cascaded source commutated primary converters



Experiment: steady-state; rectifier mode; load 2 kW; Ch1-u_t, Ch2-i_t: 10A/100mV, Ch3-i_{SC} : 10A/100mV, Ch4- u_{SC}

▶ Cascaded VSI Commutated Primary Converter (2)



- Pittermann (2008)

- Module Power 2kW (downscaled)
- Frequency 800Hz

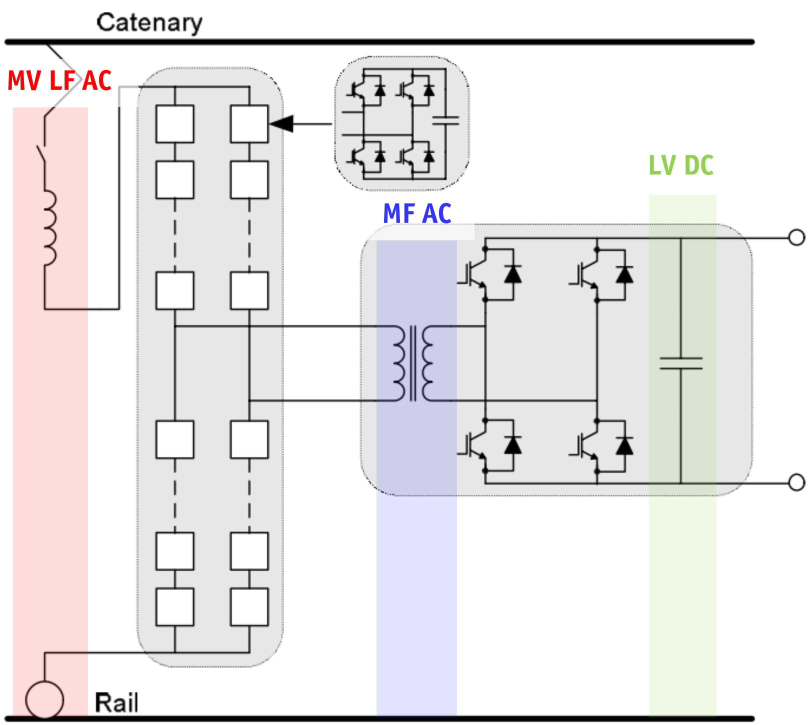
► Cascaded VSI Commutated Primary Converter (3)

- Hugo (ABB, 2006)

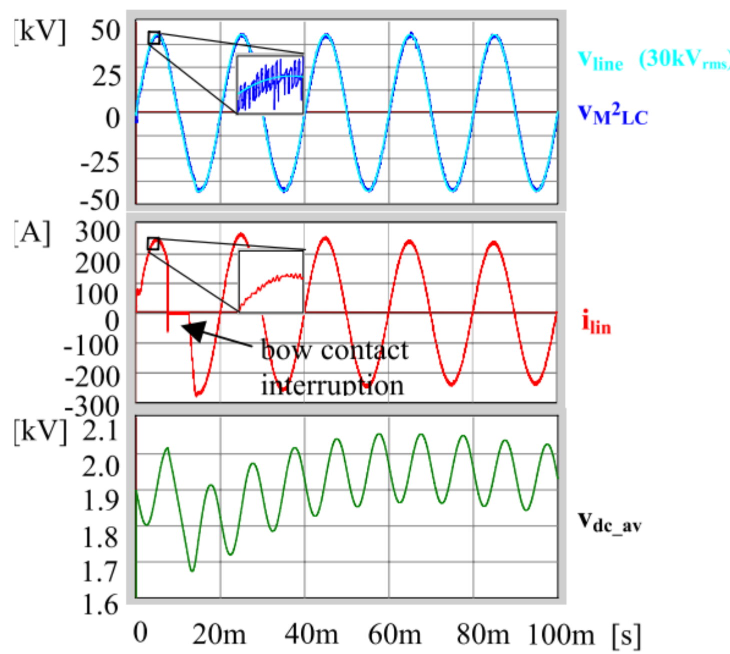
- Total Power 1.2MVA/15kV
- Module Power 75kW
- Frequency 400Hz

► Modular Multilevel Converter (1)

- Marquardt/Glinka (SIEMENS, 2003)



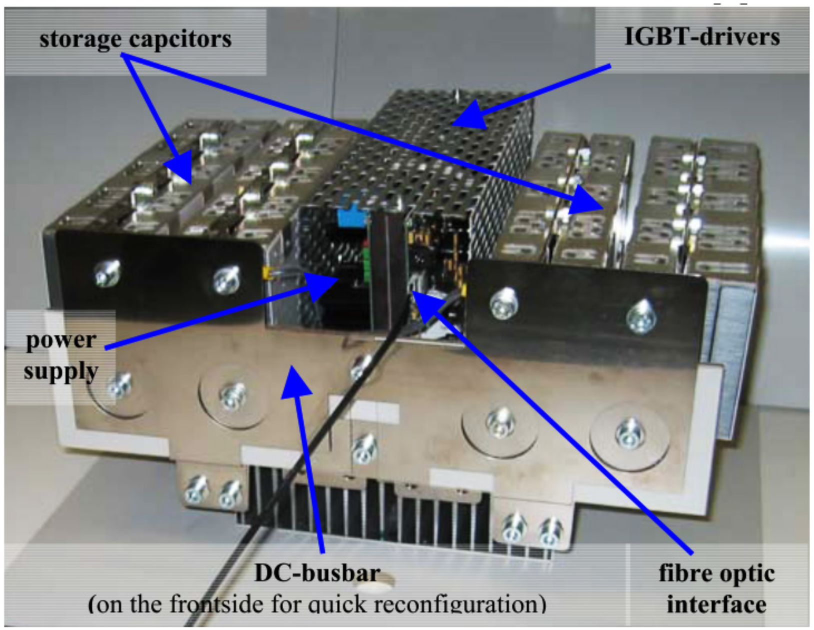
PET topology using M2LC converter



▶ Modular Multilevel Converter (2)

- Marquardt/Glinka (SIEMENS, 2003)

- Module Power 270kW
- Module Frequency 350Hz

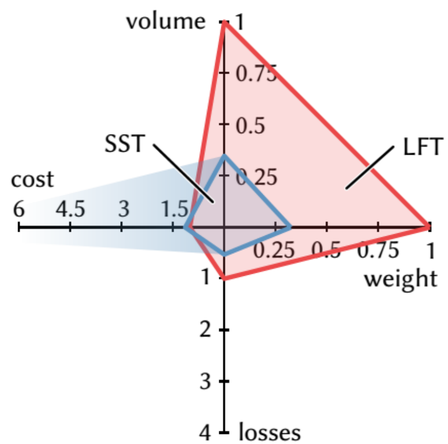


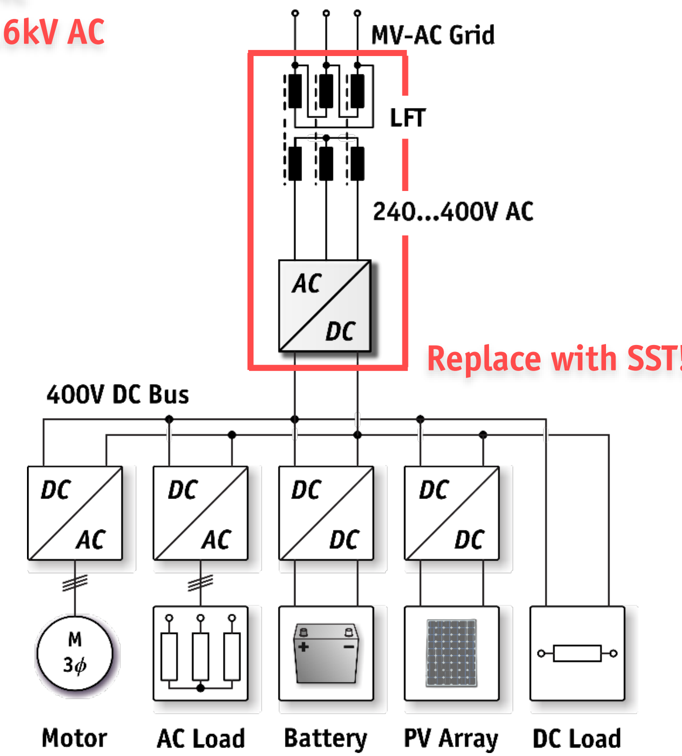
Future Concepts:
Unidirectional SSTs

▶ 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

- SST / LFT Comparison for AC/DC Applications

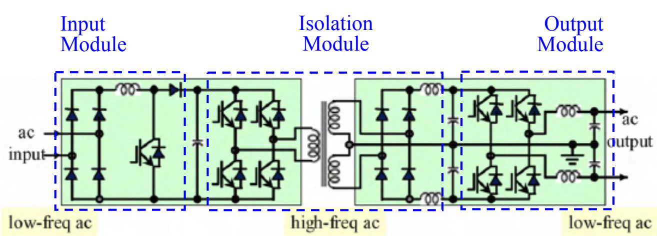


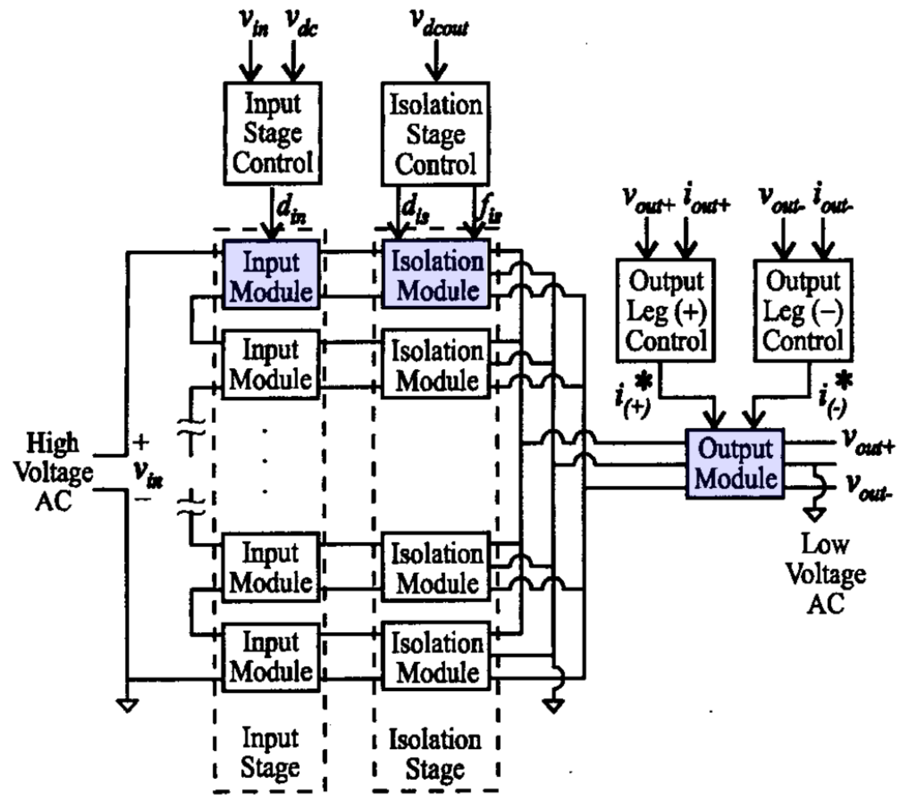


▶ Unidirectional DC-Link Based SST Structure

- Ronan et al. (2000)

- **AC Input** **7.2kV**
- **DC/DC** **1000V/±275V**
- **AC Output** **120V/240V**



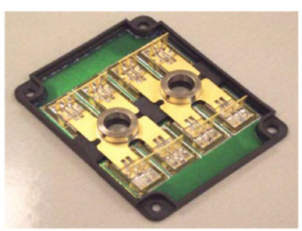


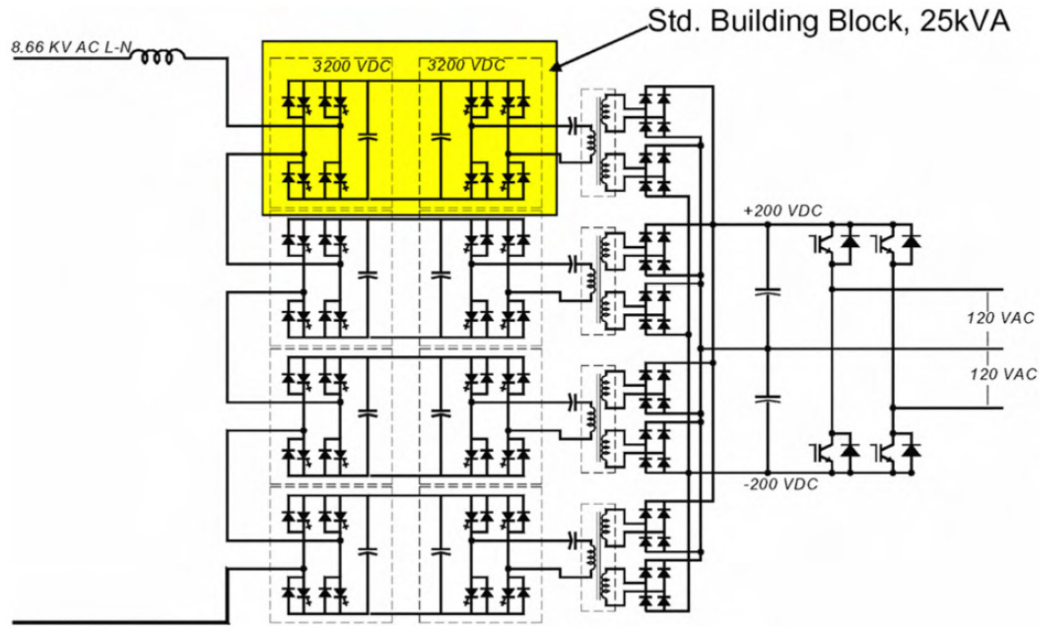
- **ISOP Modular Topology**
- Three-Stage (AC/DC-DC/DC-DC/AC) Approach

► Unidirectional DC-Link Based SST Structure (1)

- EPRI (2009)

- **AC Input** **8.6kV (15kVl-l)**
- **DC/DC** **3.5kV/400V**
- **AC Output** **120V/240V**

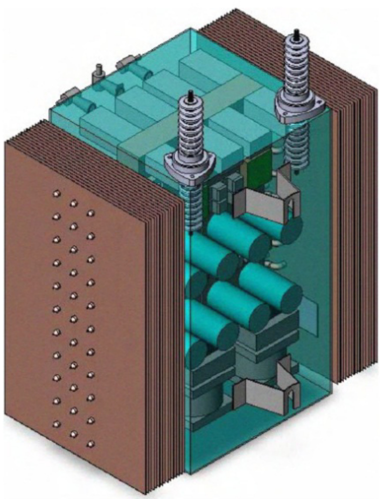


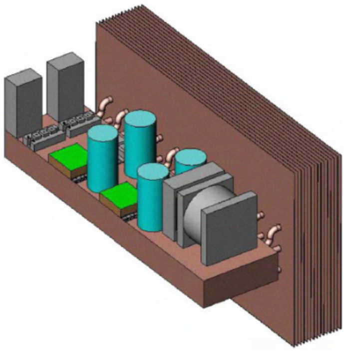


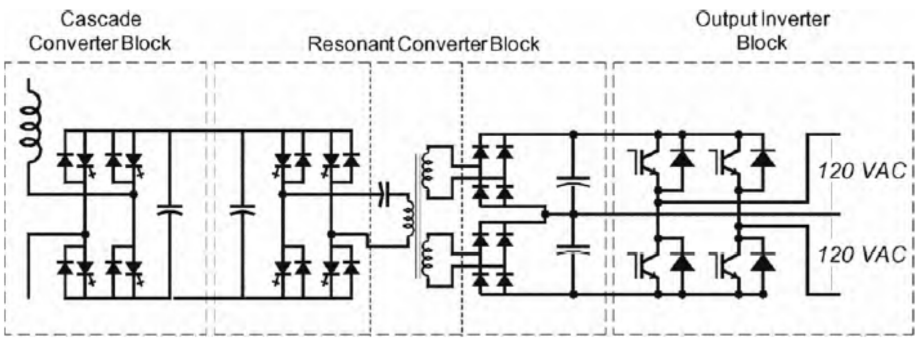
- **100kVA 15kV Class Intelligent Universal Transformer (IUTTM)**
- Development of HV Super GTO (S-GTO) as MV Switching Device / SiC Secondary Diodes
- 20kHz Series Resonant DC/DC Converter Utilizing Transformer Stray Inductance

► Unidirectional DC-Link Based SST Structure (2)

- EPRI (2009)



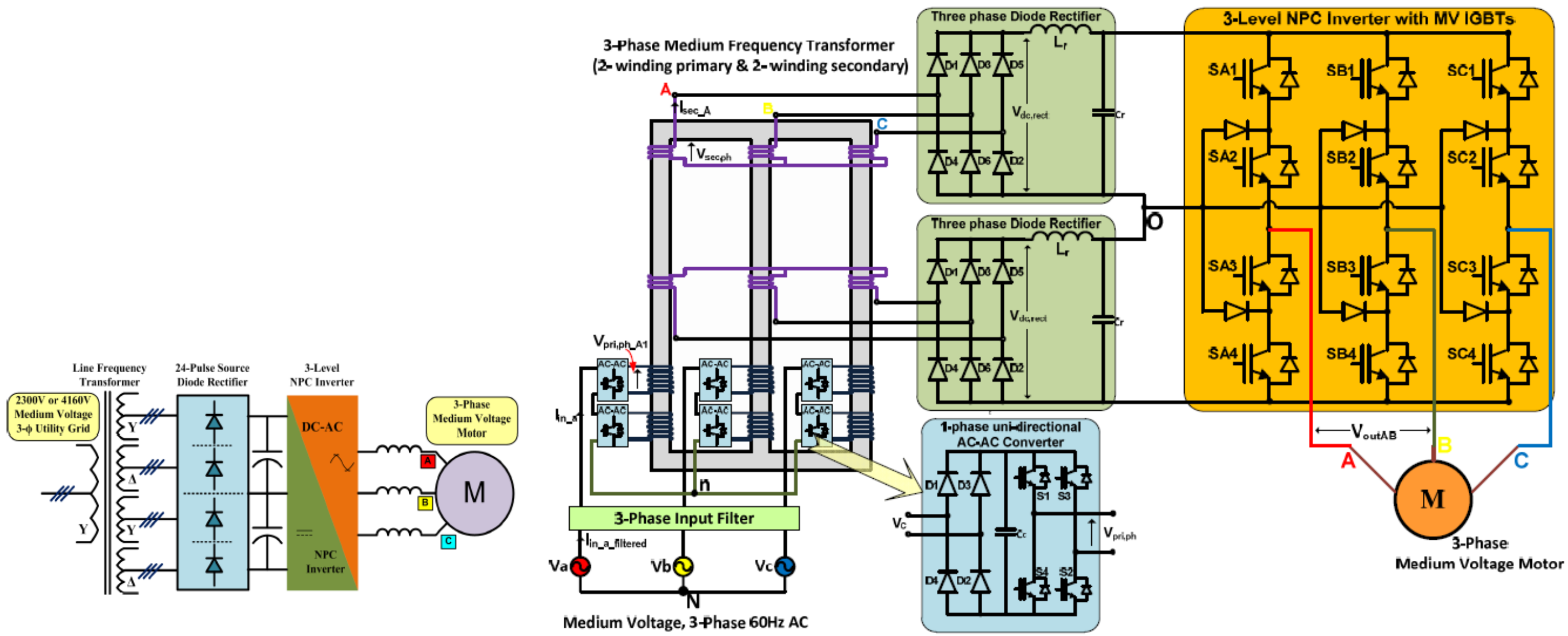




- **Outline of 100kVA (4x25kVA) IUT** (Pole Mount Layout, 35"H 35"W 20"D, 1050 lbs)
- Natural Air Cooling / S-GTO Module (No Wire Bonds, 50kHz Switching Frequency Target)

▶ Unidirectional DC-Link Based SST Structure

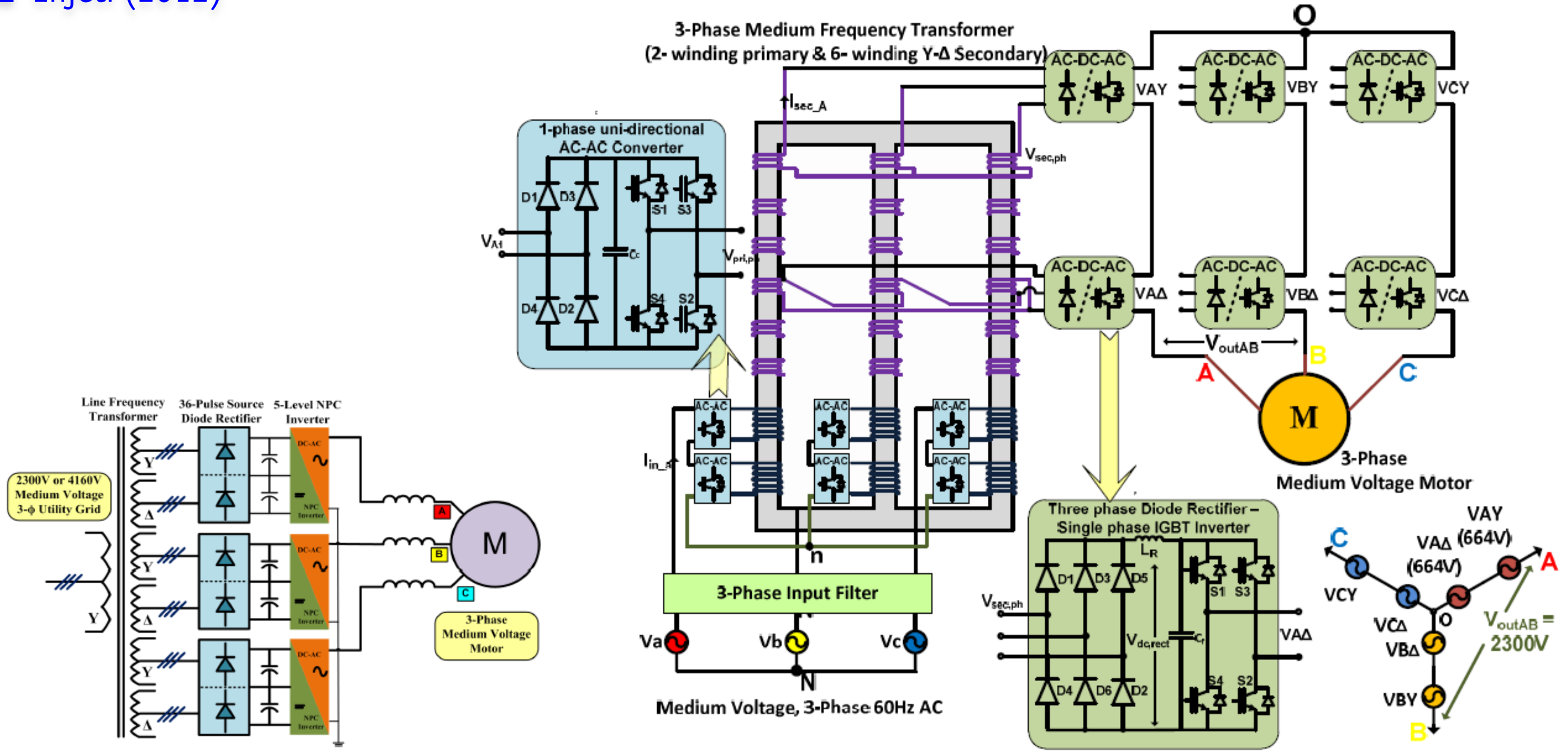
- Enjeti (2012)



- SST Application for MV Adjustable Speed Drive (Unidirectional AC/AC Front End / 3L NPC Inverter)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

▶ Unidirectional DC-Link Based SST Structure

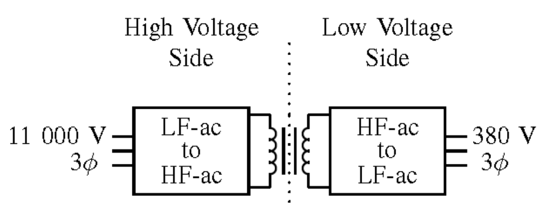
- Enjeti (2012)

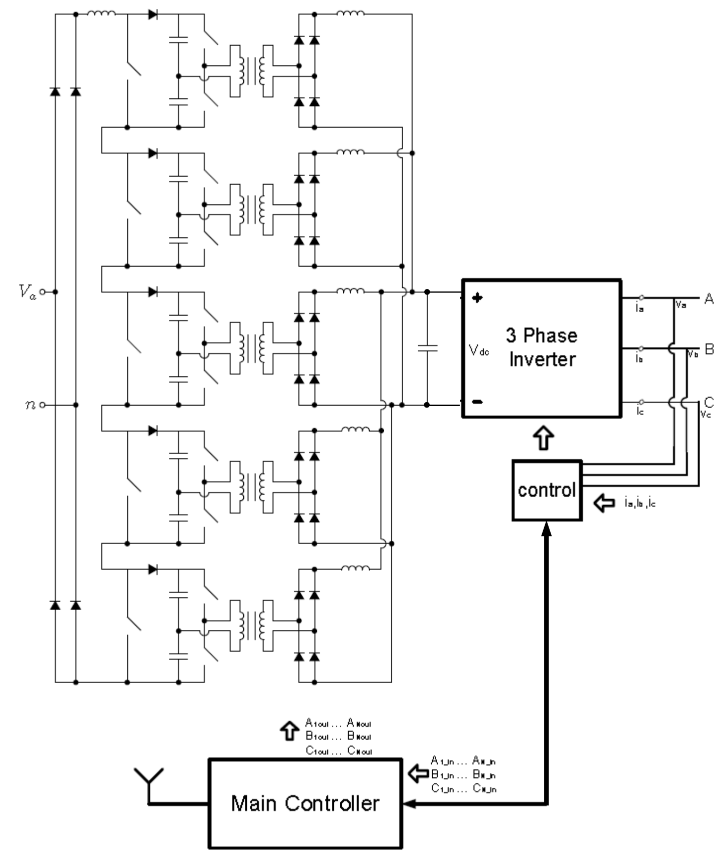


- SST Appl. for MV Adjustable Speed Drive (Unidir. AC/AC Front End / Cascaded 2L 1ph.-Inverters)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

▶ Unidirectional DC-Link Based SST Structure

- van der Merwe (2009)

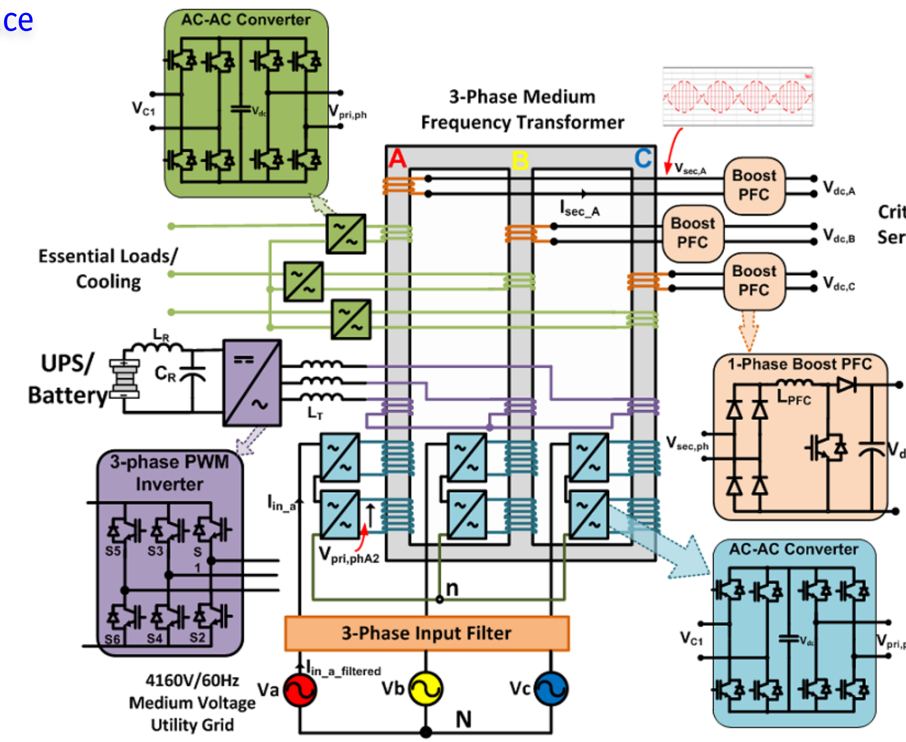




- 5-Level Series Stacked Unidir. Boost Input Stage

► MF Power Distribution Architecture for Data Centers

- Bidirectional AC/AC Grid Interface
- Multi-Winding MF Transformer
- Unidirectional or Bidirectional Loads on Secondaries



Enjeti, 2014

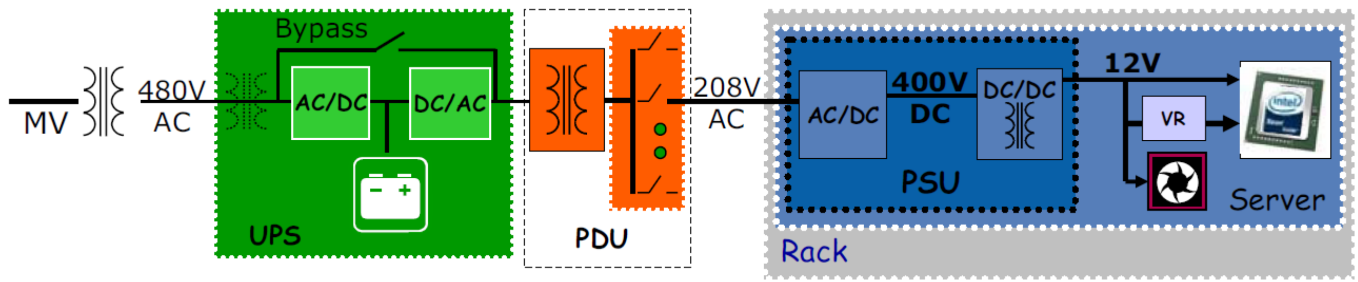
- **Hybrid Uni-/Bidirectional**

► AC vs. Facility-Level DC Telecom Power Supply Systems

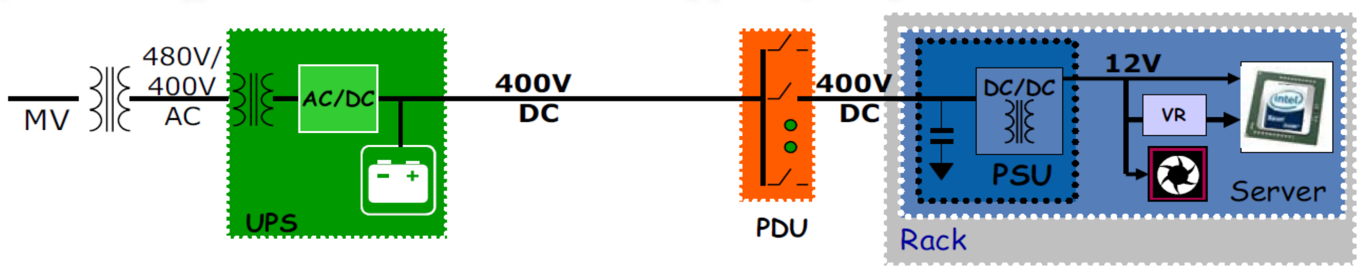
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

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

Source: intel 2007



- Facility-Level 400V$_{DC}$ Distribution → Gain in Efficiency / Complexity



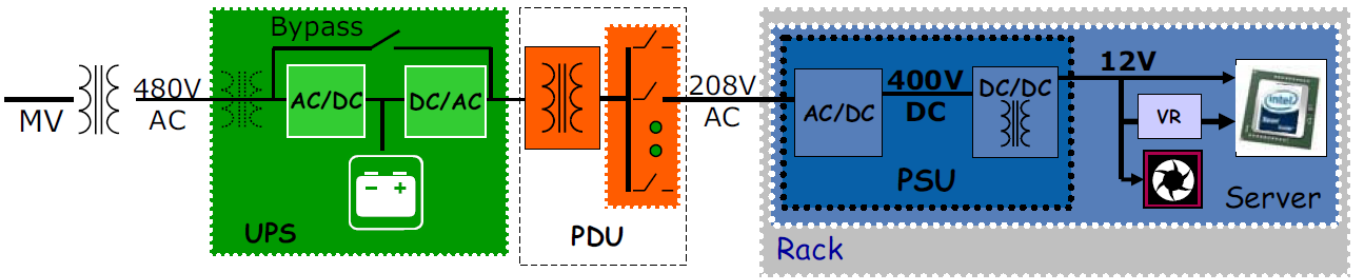
- E.g. ABB / Green DC Data Center (+190V/-190V DC Distribution)

▶ AC vs. Facility-Level DC Telecom Power Supply Systems

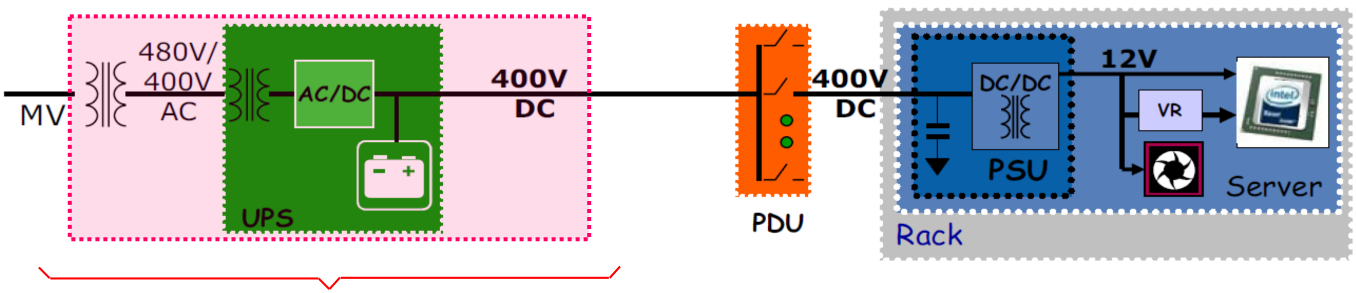
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

- Conventional US $480V_{AC}$ Distribution

Source: intel 2007



- Facility-Level $400V_{DC}$ Distribution ⟶ Gain in Efficiency / Complexity

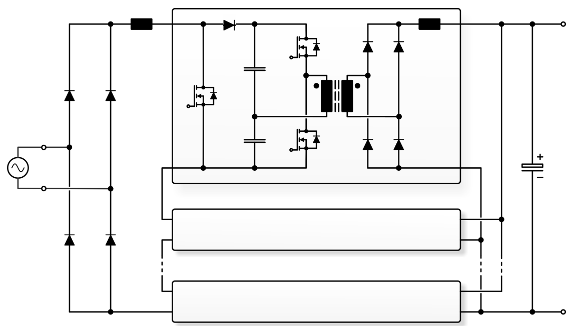


- Future Concept: Direct 6.6kV AC ⟶ 400V DC Conversion (Unidirectional) incl. Isolation

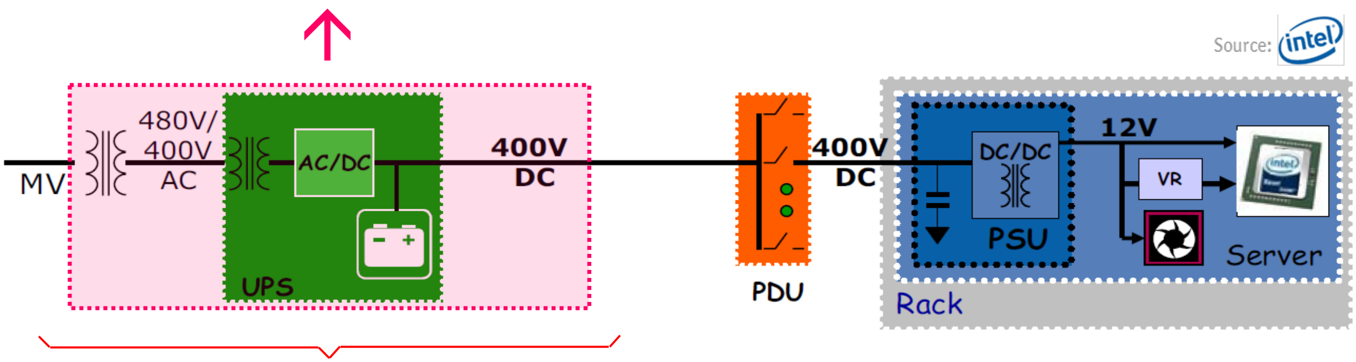
► SST-Based Facility-Level 400V DC Distribution System

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

6.600 V_{AC}



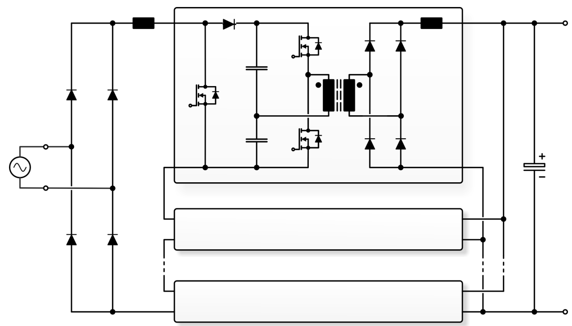
400 V_{DC}



- Future Concept: **Direct 6.6kV AC → 400V DC** Conversion (Unidirectional) incl. Isolation

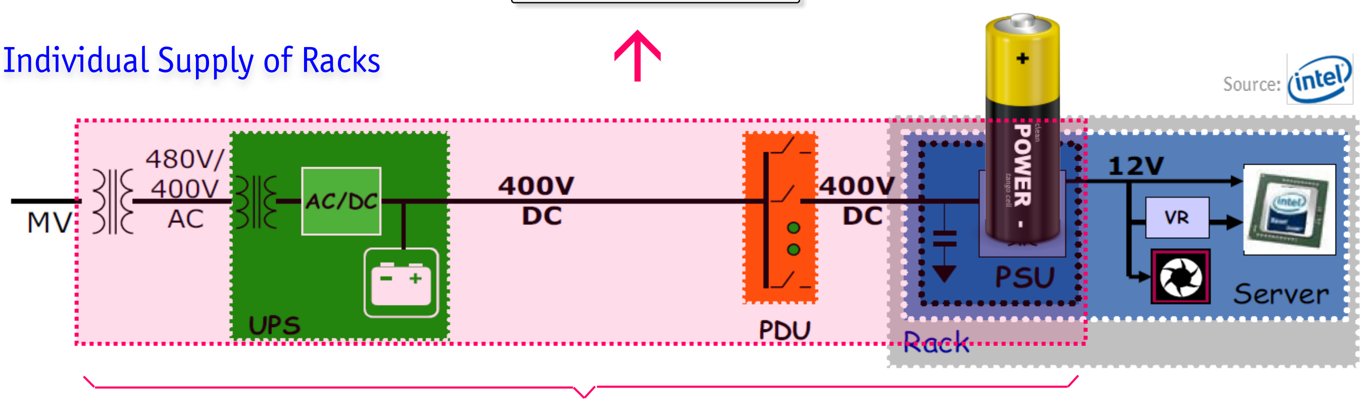
▶ SST-Based Rack-Level 48V DC Power Supply System

6.600 V_{AC}



48 V_{DC}

- Direct / Individual Supply of Racks



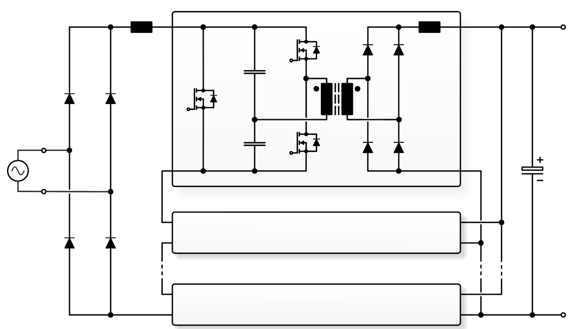
- Future Concept: **Direct 6.6kV AC → 48V DC** Conversion (Unidirectional) **w. Integr. Storage**

► SST-Based Rack-Level 48V DC Power Supply System

- **Reduces Cost** (Losses / Material Effort / Footprint)
- **High Reliability** (Maximum Modularity / Redundancy)

– **Distributed 48V Battery Buffer on Rack Level**

6.600 V_{AC}



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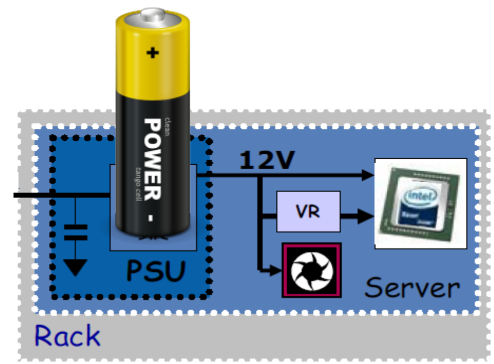
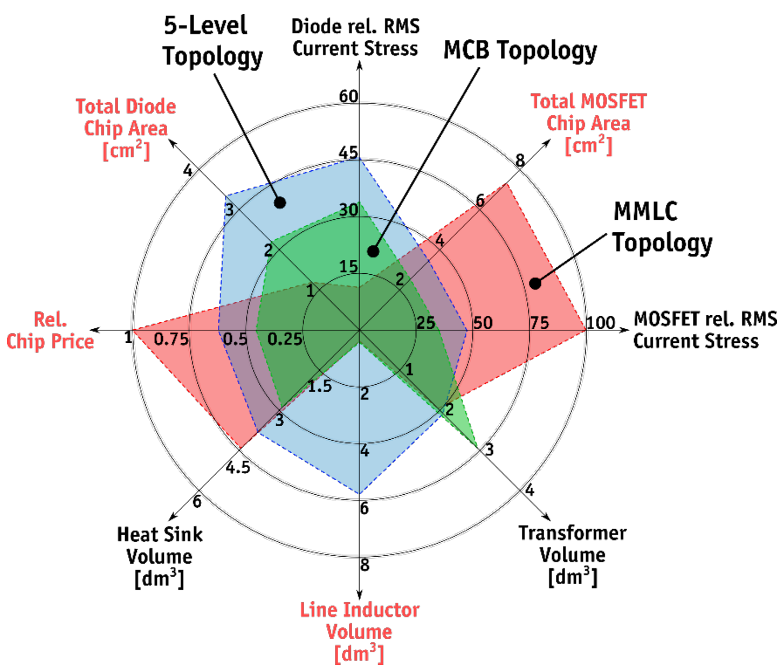
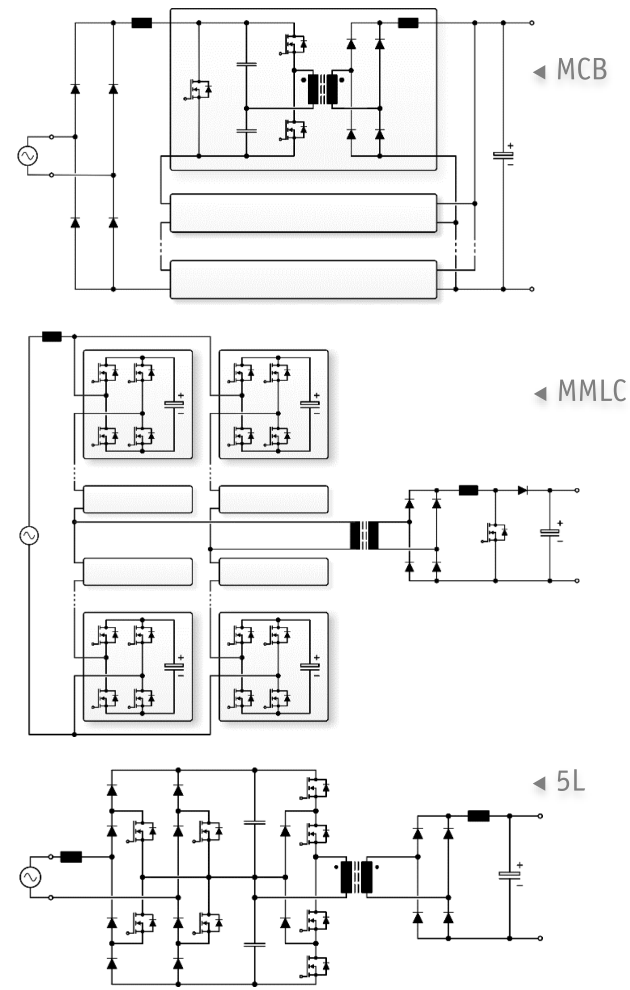


- Future Concept: **Direct 6.6kV AC → 48V DC** Conversion / Unidirectional SST **w. Integr. Storage**

► SST-Based High-Power 400V DC Supplies

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





- Comparative Evaluation Based on Comp. Load Factors

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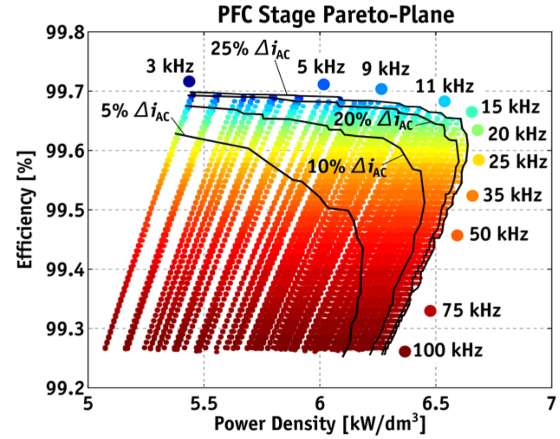
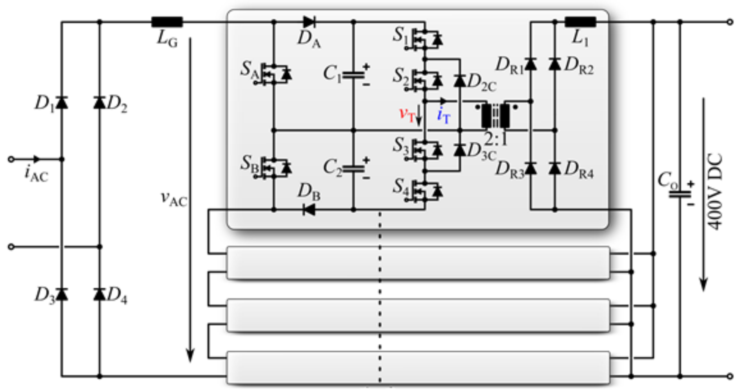
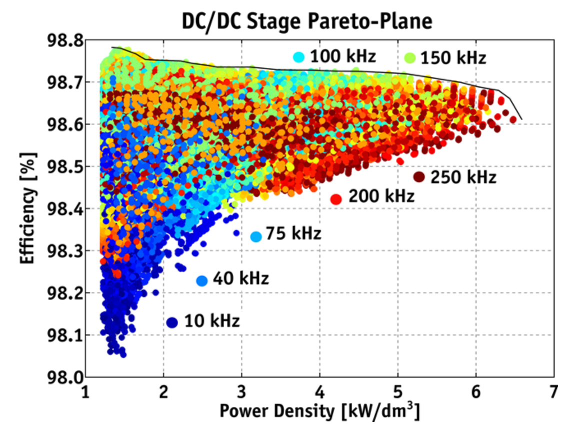


- Overall Multi-Cell Topology Pareto-Optimization





– 25 kHz (200kHz)
– 99.6%
– 6.3 kW/dm³

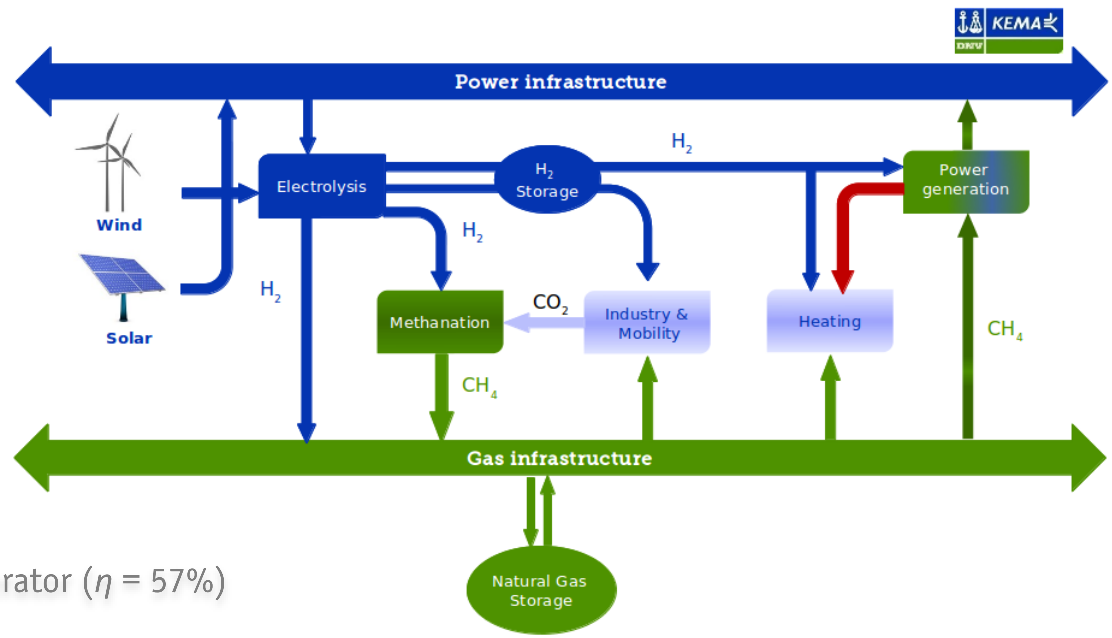
– 200 kHz
– 98.6%
– 6.6 kW/dm³

- Total Efficiency (6.6kV AC → 400V DC) ★ 98.2% @ 3.2 kW/dm³

▶ Other Unidirectional SST Applications: Power-to-Gas

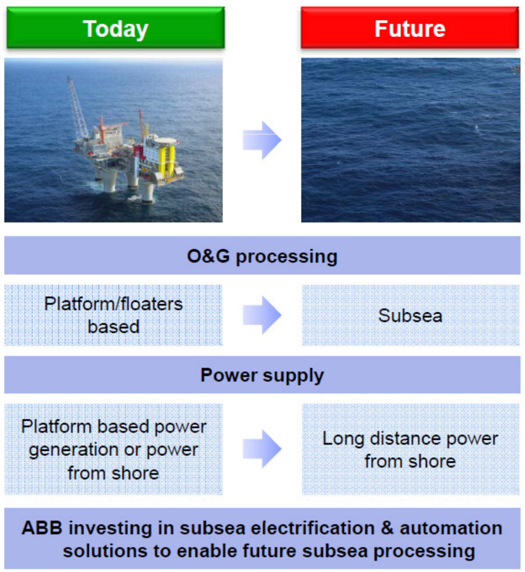
- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into **Hydrogen**
  - ▸ **Fuel-Cell Powered Cars**
  - ▸ **Heating**
- **High-Power @ Low DC Voltage (e.g., 200V)**
- **Very Well Suited for MV-Connected SST-Based Power Supply**

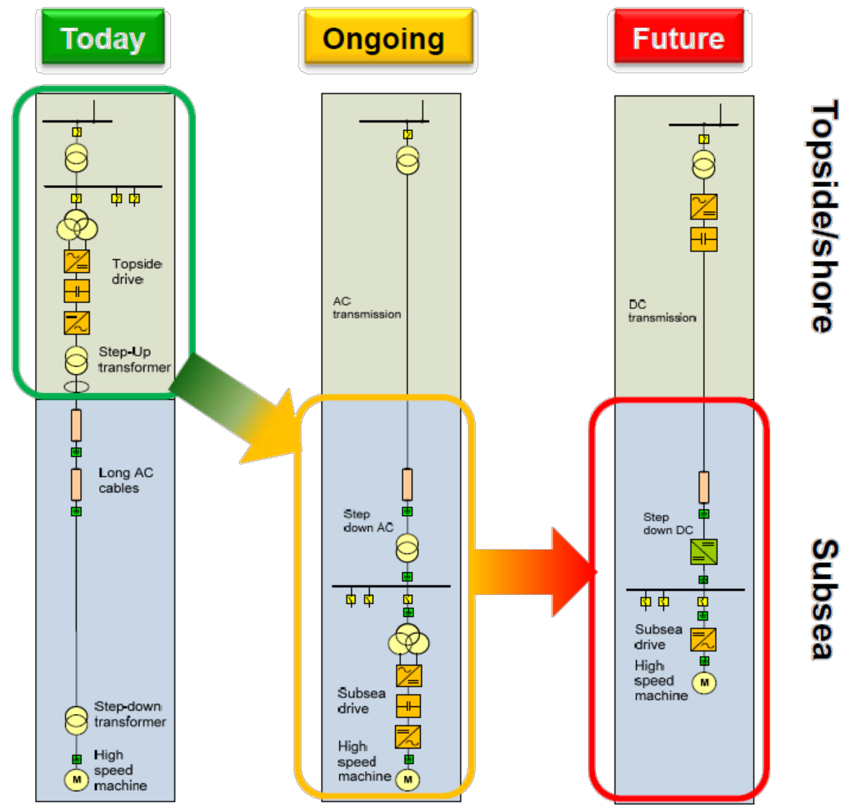
▲ Hydrogenics 100kW H_2-Generator (η = 57%)



▶ Other Unidirectional SST Applications: Oil & Gas Processing

- **Future Subsea Distribution Network** (Devold, ABB, 2012)





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

- **Weight Optimized Power Electronics**

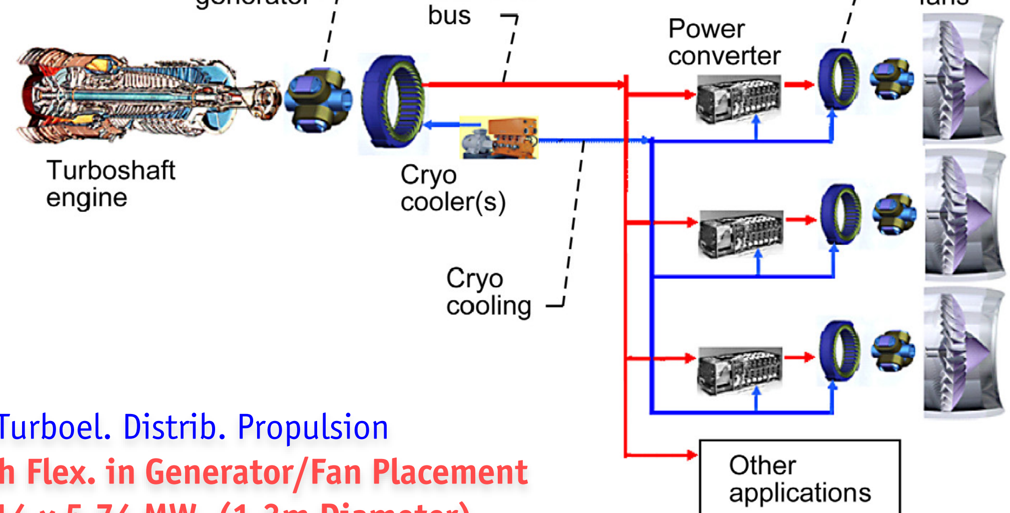
► Future Hybrid or All-Electric Aircraft

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 CO2 Emissions by 75%, NO_x by 90%, Noise Level by 65%**

▶ Future Hybrid Aircraft

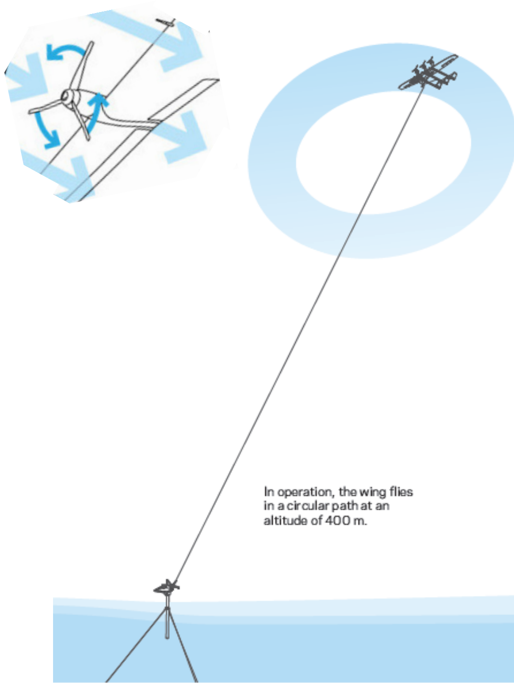
Source: NASA



- 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

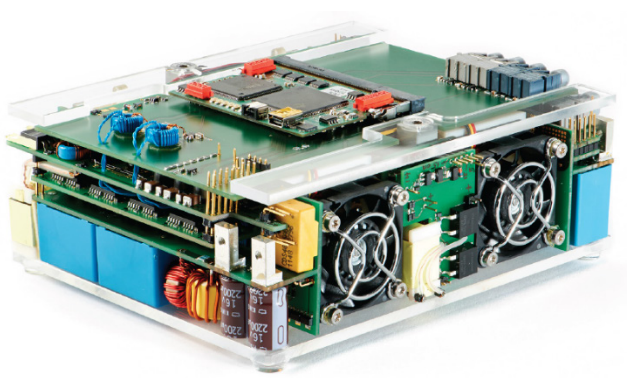


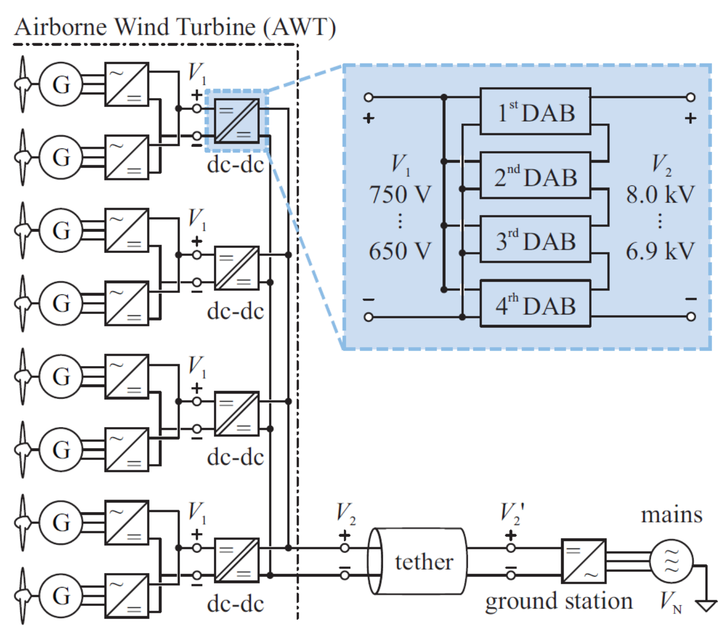
MAKANI POWER

Google X

▶ 100kW Airborne Wind Turbine

- Ultra-Light Weight Multi-Cell **All-SiC Solid-State Transformer** – $8kV_{DC} \longrightarrow 700V_{DC}$
  - **Medium Voltage Port** **1750 … 2000 VDC**
  - **Switching Frequency** **100 kHz**
  - Low Voltage Port 650 … 750 VDC
  - Cell Rated Power 6.25 kW
  - Power Density 5.2 kW/dm³
  - Specific Weight 4.4 kW/kg





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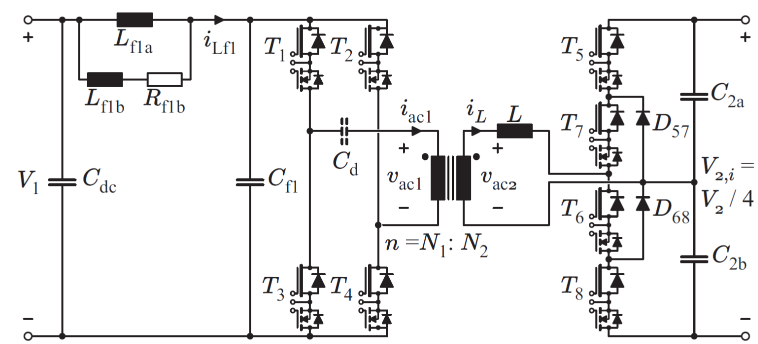
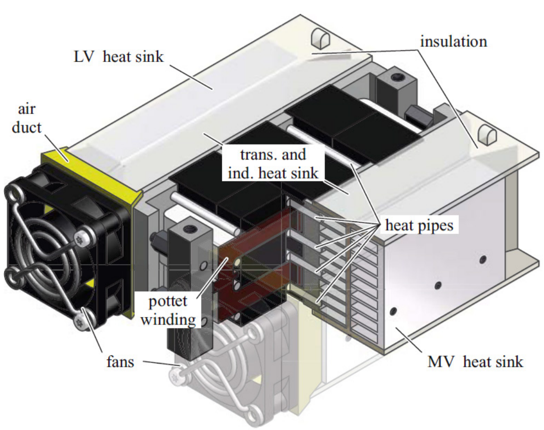
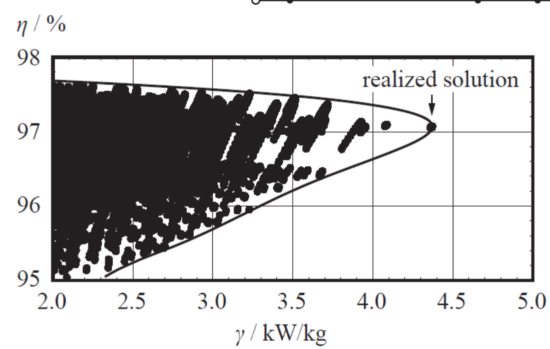
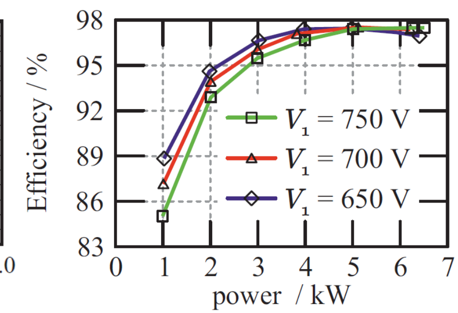




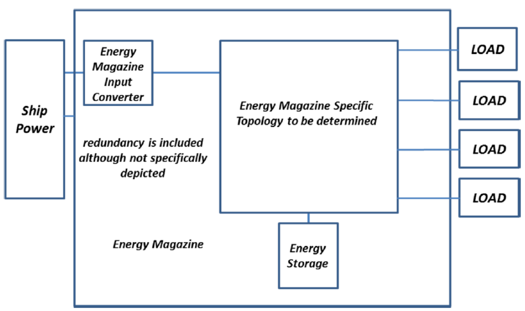




▶ Future Military Applications

- 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

A Few Words on Education...

Img.: www.oln.org

► Education: Smart XXX = Power Electronics + Power Systems + ICT

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

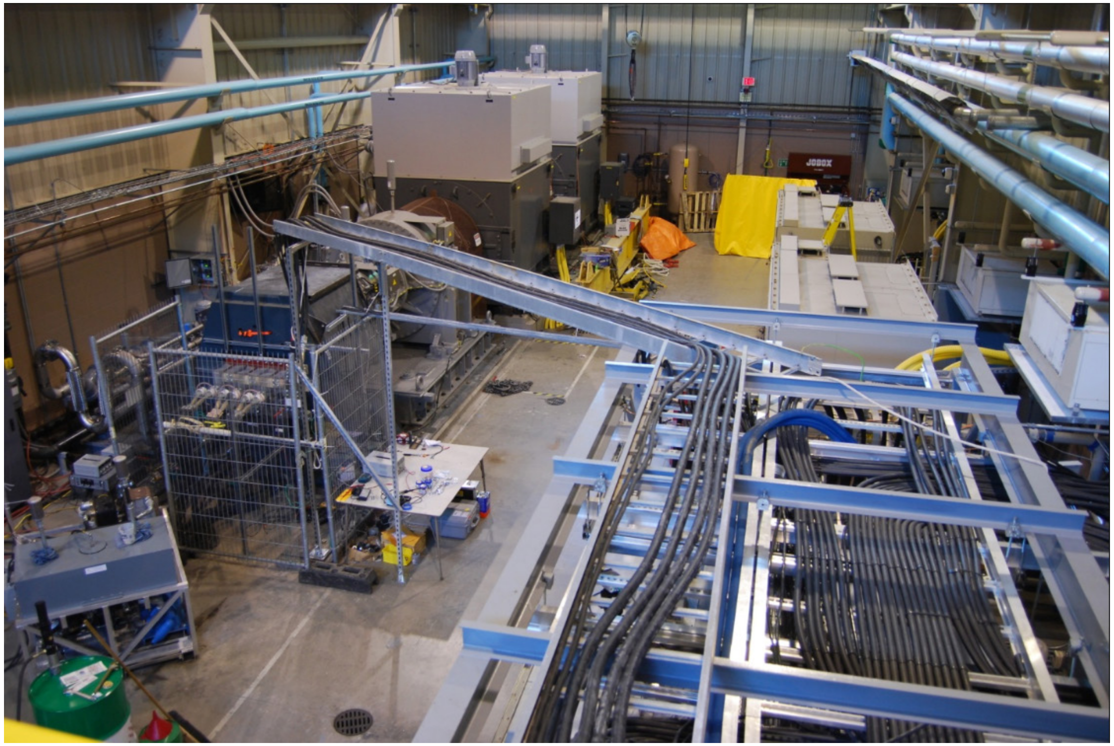
- **Future:**

$$p(t) \rightarrow \int_0^T p(t)dt$$

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

► Education: MV Power Electronics – Test Facility

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

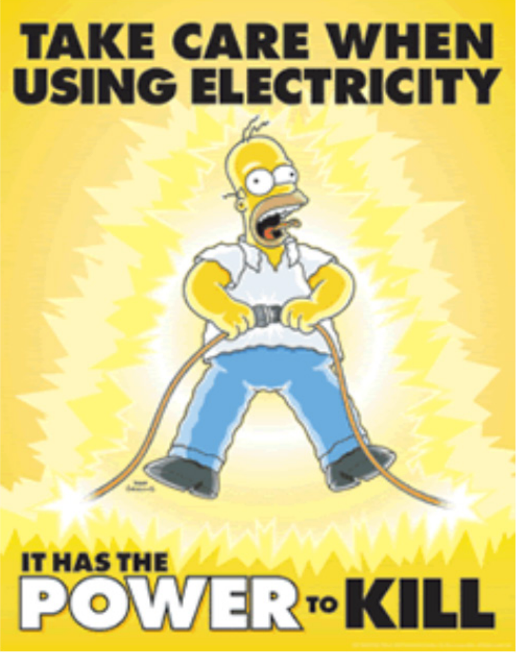


Img.:Center for Advanced Power Systems / Florida State University

- **Large Space Requirement / Considerable Investment (!)**

▶ Education: MV Power Electronics – Safety Issues, etc.

- PhD 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**



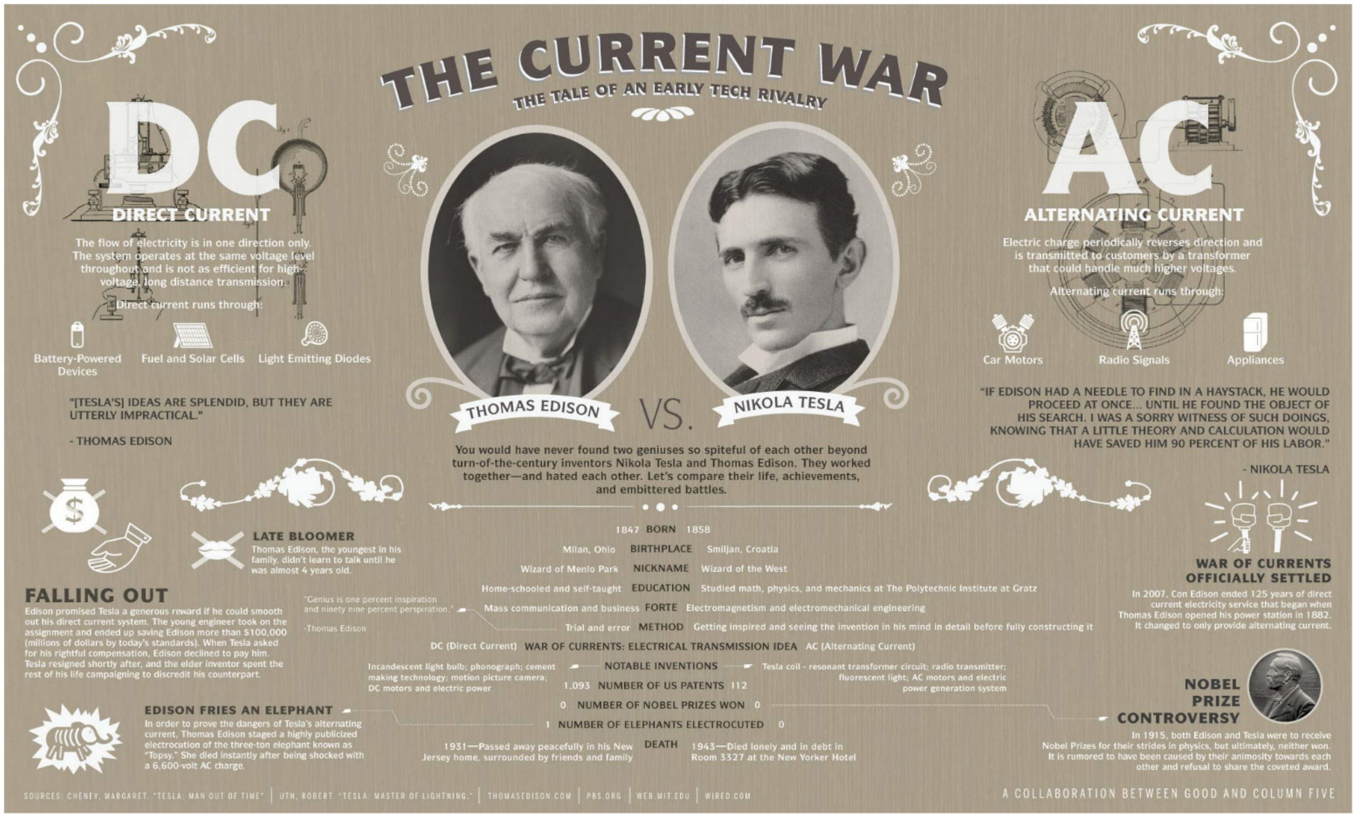
... ESPECIALLY @ **Medium Voltage (!)**

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

Conclusion & Outlook

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 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

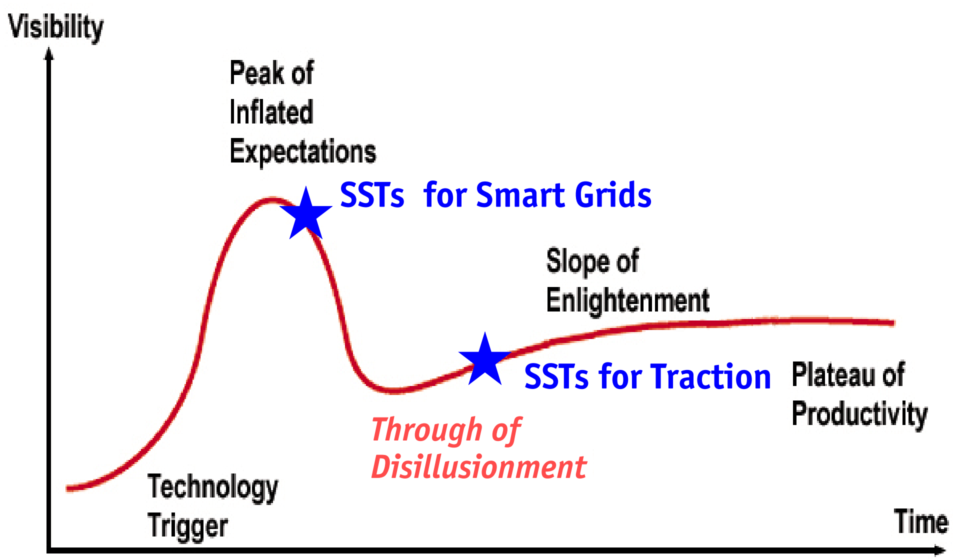
- SST is NOT a 1:1 Replacement for Conv. Distribution Transformers
- SST will NOT Replace All Conv. Distribution Transformers (even in Mid Term Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations

► 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

▶ SST Technology Hype Cycle



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

▶ SST for Grid Applications

SST Research Status

Img.: www.diamond-jewelry-pedia.com

Required for Successful Application

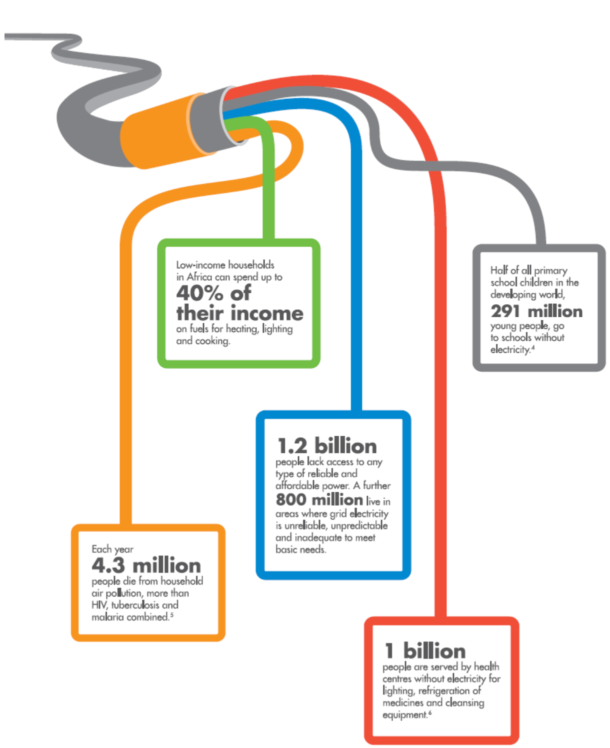
- Huge Multi-Disciplinary Challenges / Opportunities (!)

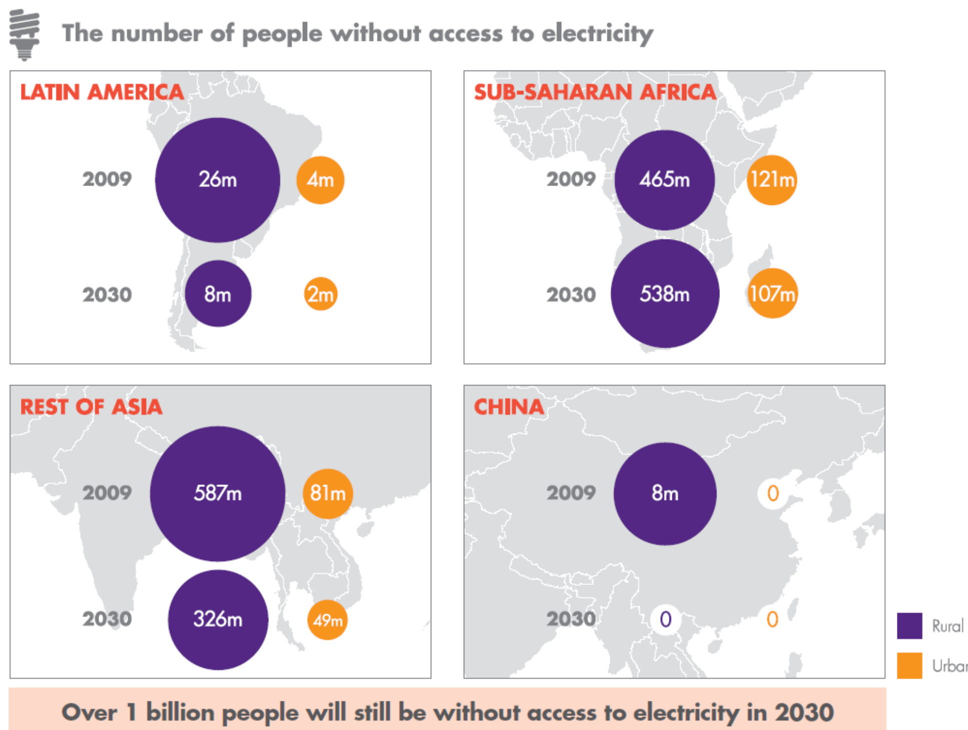
... One Last Comment

Electrification of the Developing World →

► Rural Electrification in the Developing World

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





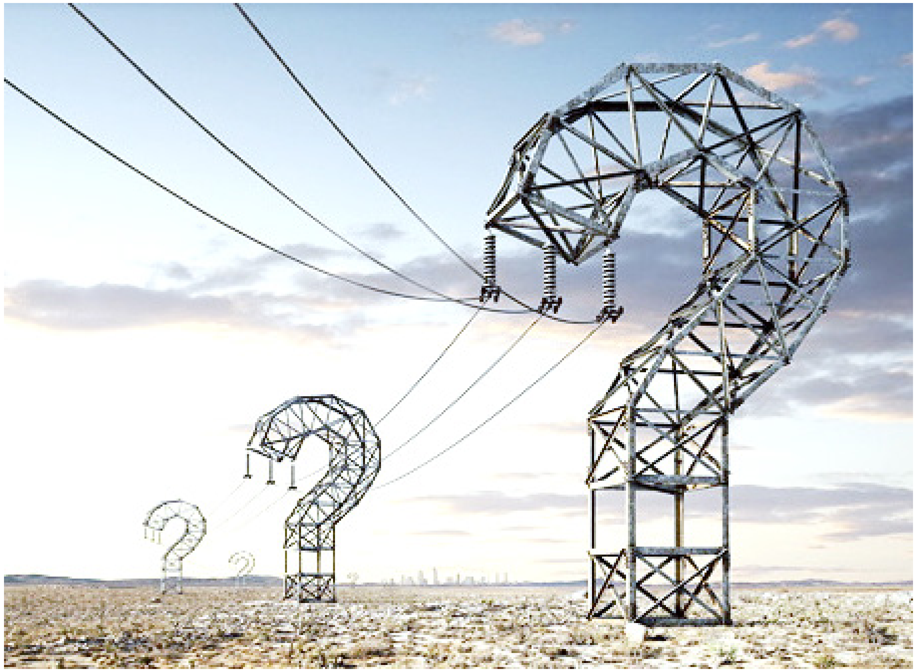
Source: IEA, Dalberg Analysis, IFC

→ Urgent Need for Village-Scale Solar DC Mirogrids, etc.

→ 2 US$ for 2 LED Lights + Mobile-Phone Charging / Household / Month (!)

Thank You!

Questions?



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The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, e.g. for data centers, More-Electric-Aircraft and distributed renewable energy systems, and on Solid-State Transformers for Smart Microgrid Systems. Further main research areas are the realization of ultra-compact and ultra-efficient converter modules employing latest power semiconductor technology (SiC and GaN), micro power electronics and/or Power Supplies on Chip, multi-domain/scale modeling/simulation and multi-objective optimization, physical model-based lifetime prediction, pulsed power, and ultra-high speed and bearingless motors. He has been appointed an IEEE Distinguished Lecturer by the IEEE Power Electronics Society in 2011.

He received 7 IEEE Transactions Prize Paper Awards and 7 IEEE Conference Prize Paper Awards. Furthermore, he received the ETH Zurich Golden Owl Award 2011 for Excellence in Teaching and an Erskine Fellowship from the University of Canterbury, New Zealand, in 2003.

He initiated and/or is the founder/co-founder of 4 spin-off companies targeting ultra-high speed drives, multi-domain/level simulation, ultra-compact/efficient converter systems and pulsed power/electronic energy processing. In 2006, the European Power Supplies Manufacturers Association (EPSMA) awarded the Power Electronics Systems Laboratory of ETH Zurich as the leading academic research institution in Power Electronics in Europe.

Dr. Kolar is a Fellow of the IEEE and a Member of the IEEJ and of International Steering Committees and Technical Program Committees of numerous international conferences in the field (e.g. Director of the Power Quality Branch of the International Conference on Power Conversion and Intelligent Motion). He is the founding Chairman of the IEEE PELS Austria and Switzerland Chapter and Chairman of the Education Chapter of the EPE Association. From 1997 through 2000 he has been serving as an Associate Editor of the IEEE Transactions on Industrial Electronics and since 2001 as an Associate Editor of the IEEE Transactions on Power Electronics. Since 2002 he also is an Associate Editor of the Journal of Power Electronics of the Korean Institute of Power Electronics and a member of the Editorial Advisory Board of the IEEJ Transactions on Electrical and Electronic Engineering.

Authors

Jonas E. Huber (S´10) received his M.Sc. (with distinction) degree from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2012, after studying electrical engineering with focus on power electronics, drive systems, and high voltage technology. He worked on a new modulation concept for the modular multilevel converter during an industry internship with ABB Switzerland as part of his master studies, before he designed and constructed a 100 kW/20 kHz back-to-back test bench for a medium frequency transformer in the scope of his master thesis, which was carried out at the Power Electronic Systems Laboratory, ETH Zurich. In 2012, he then joined the Power Electronic Systems Laboratory, ETH Zurich, as a PhD student, where his main research interests are in the area of solid-state transformers for smart grid applications, focusing on the analysis, optimization, and design of high-power multi-cell converter systems, reliability considerations, control strategies, and grid integration aspects, among others. He has authored five papers published at international IEEE conferences.