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Long Beach California
March 20-24, 2016
Professional Education Seminar 6

Solid-State Transformers
Key Design Challenges, Applicability, and Future Concepts

Johann W. Kolar, Jonas E. Huber

Power Electronic Systems Laboratory
ETH Zurich, Switzerland

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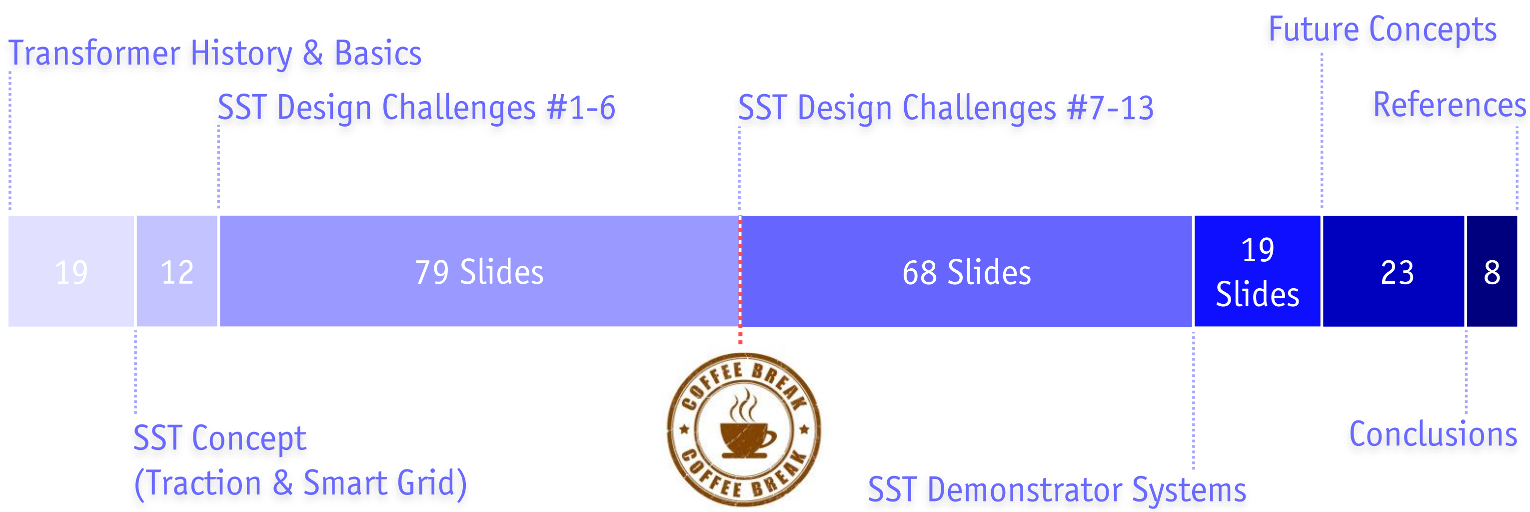
www.pes.ee.ethz.ch

Agenda



Contact Information
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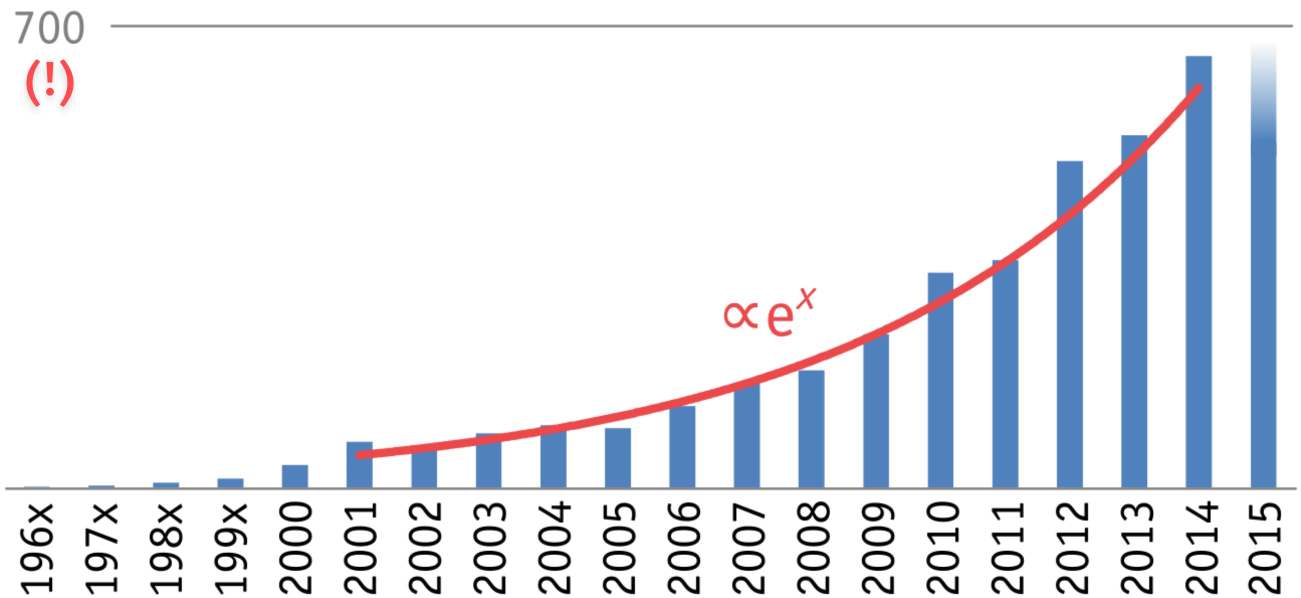
ETH Zurich
Power Electronic Systems Lab
Physikstrasse 3
8092 Zürich
Switzerland

History of Transformers

*Low Frequency and
Solid-State Transformers*

▶ The Solid-State Transformer Hype

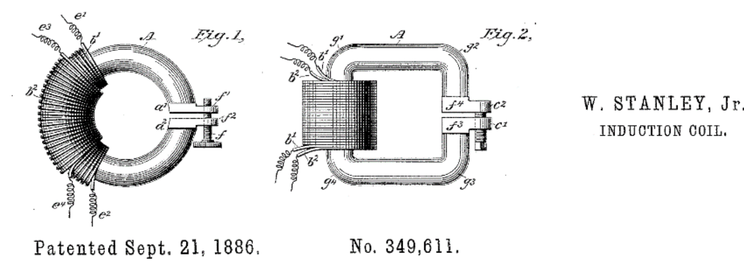
- **Evolution of # of SST Publications Per Year:**

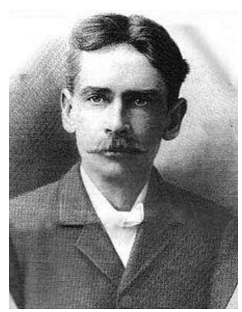


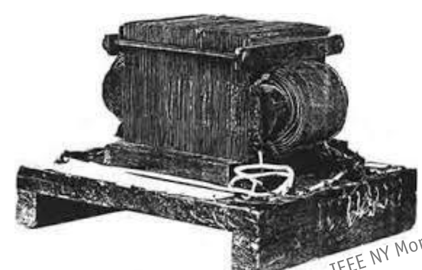
- **How To Keep An Overview?**
  - Identify Origin and Evolution of Key Concepts
  - Narrow Down Feasible Solutions by Identifying Core Requirements, e.g., Modularity

▶ 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)







Img. Src.: IEEE NY Monitor

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

[Stanley1886]

▶ Classical Transformer — History (2)

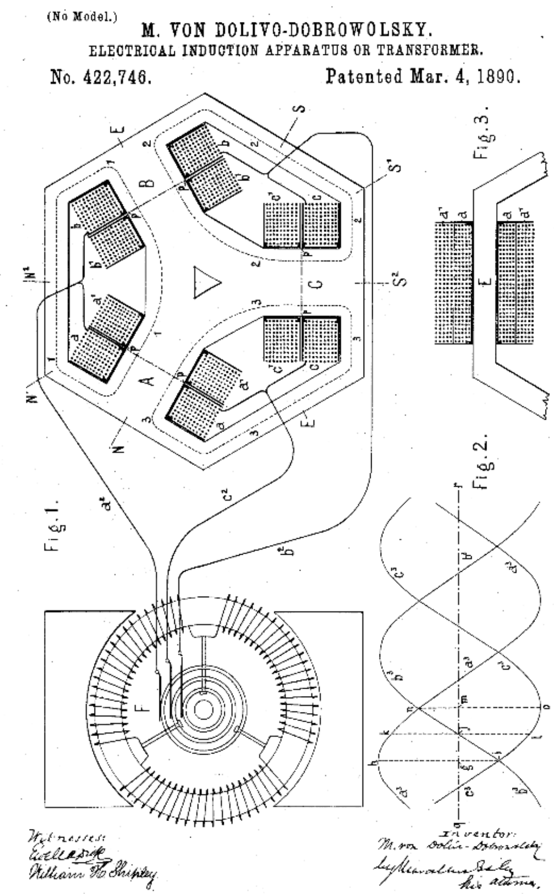
UNITED STATES PATENT OFFICE.

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.)



- 1889 Dobrovolsky → 3-Phase Transformer
- 1891 1st Complete AC System (Gen. + XFMR + Transm. + El. Motor + Lamps, 40Hz, 25kV, 175km)

[Dobrovolski1890]

▶ 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.

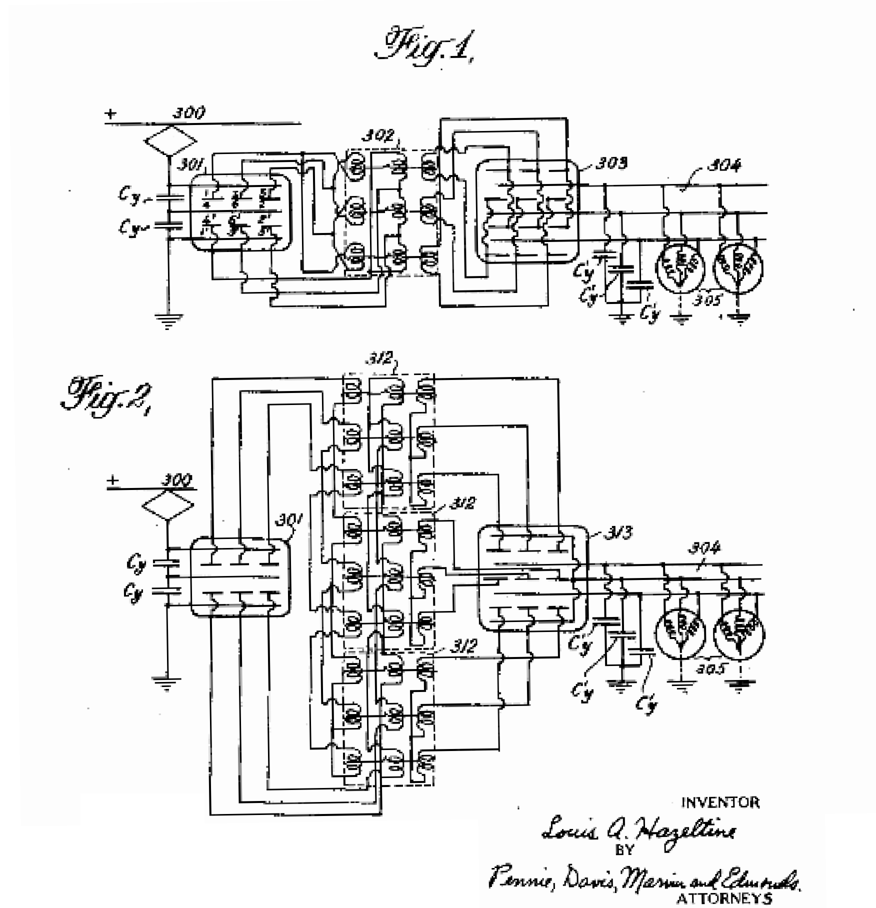
METHOD AND APPARATUS FOR CONVERTING ELECTRIC POWER.

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.



[Hazeltine1923]

United States Patent Office

3,517,300
Patented June 23, 1970

1

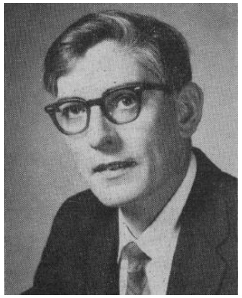
3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York
Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims

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.

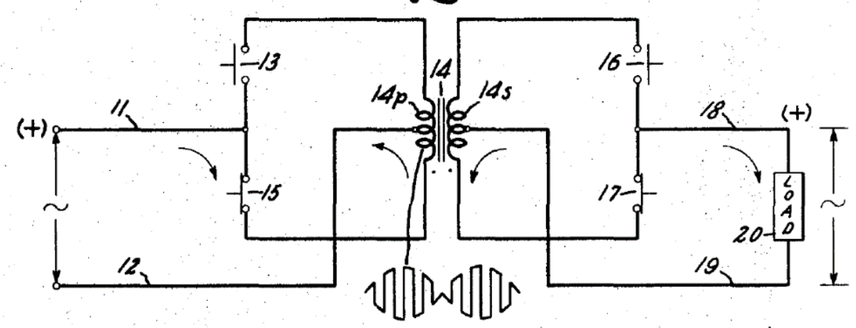
1968 !

Filed April 16, 1968



Inventor: William McMurray
by Donald R. Campbell
His Attorney

Fig. 1a

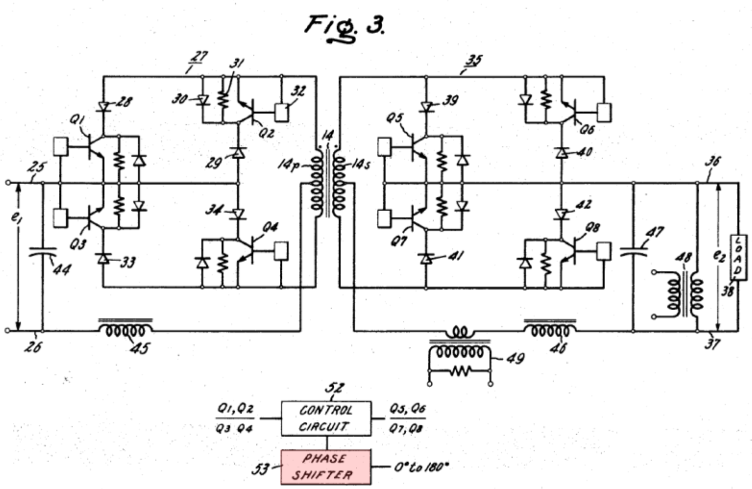


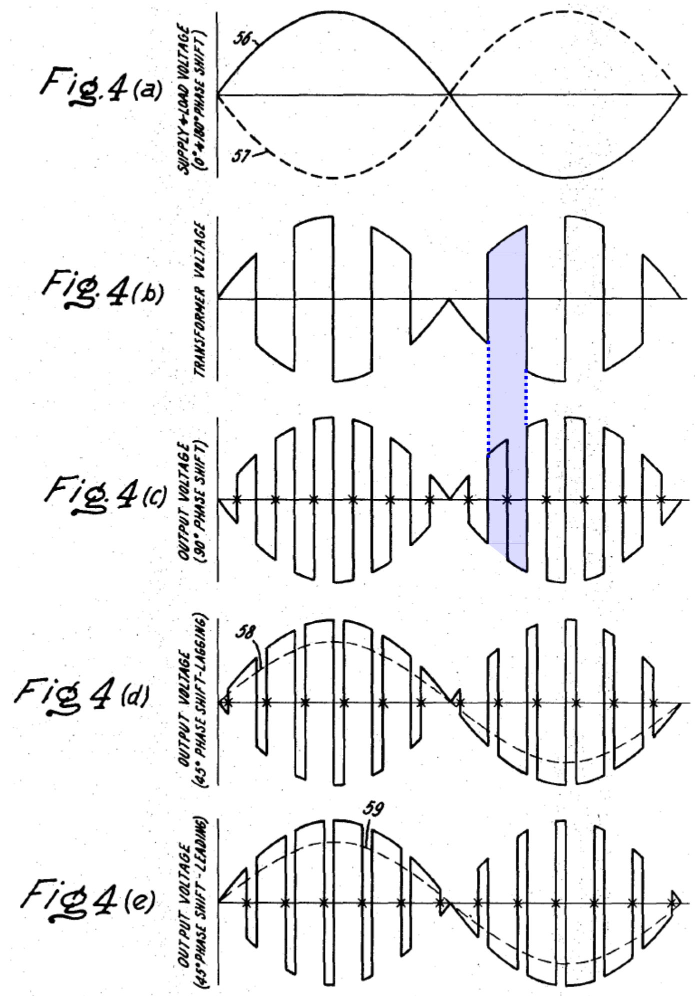
- Electronic Transformer ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption

[McMurray1968]

▶ Electronic Transformer

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





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

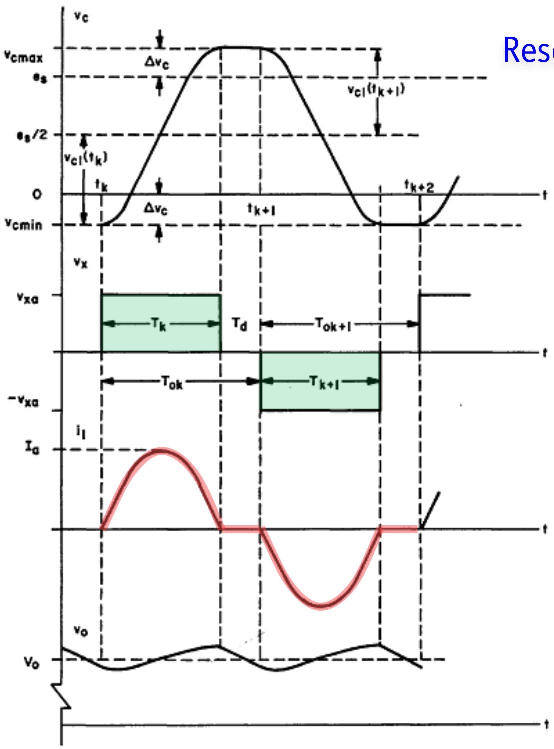
[McMurray1968]

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS AND CONTROL INSTRUMENTATION VOL. IECI-17, NO. 3, MAY 1970 **1970 (!)**

A Method of Resonant Current Pulse Modulation for Power Converters

Img.: ewh.ieee.org

FRANCIS C. SCHWARZ, SENIOR MEMBER, IEEE



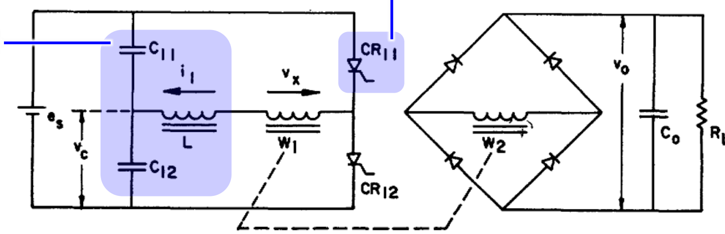
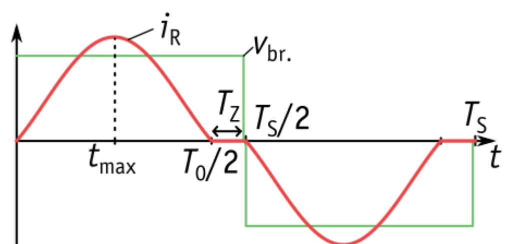


Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

◀ **Discontinuous Conduction Mode (!)** ▶



[Schwarz1970]

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

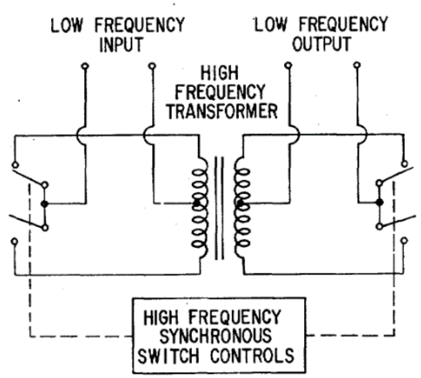


Fig. 1. Principle of electronic transformer.

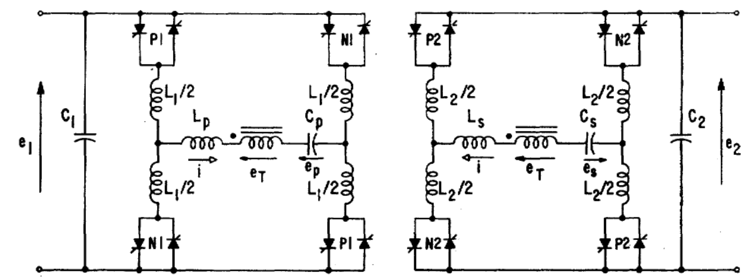


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

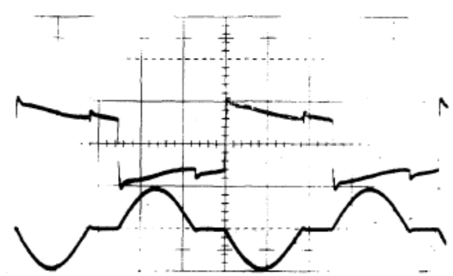


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

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

[McMurray1971]

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

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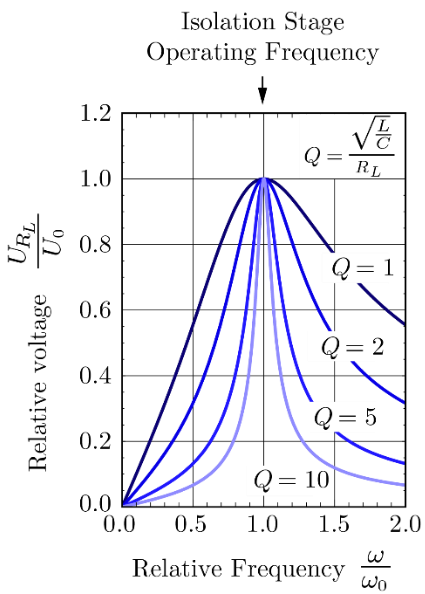

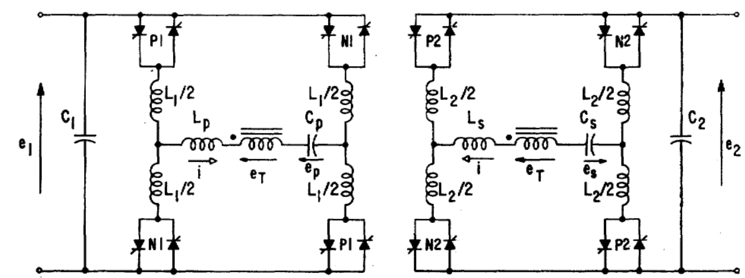

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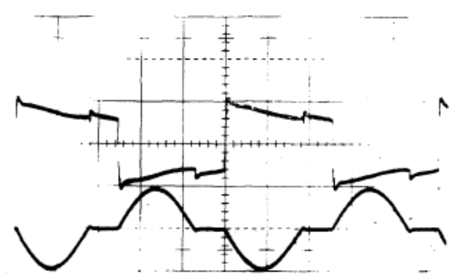


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

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

[McMurray1971]

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**

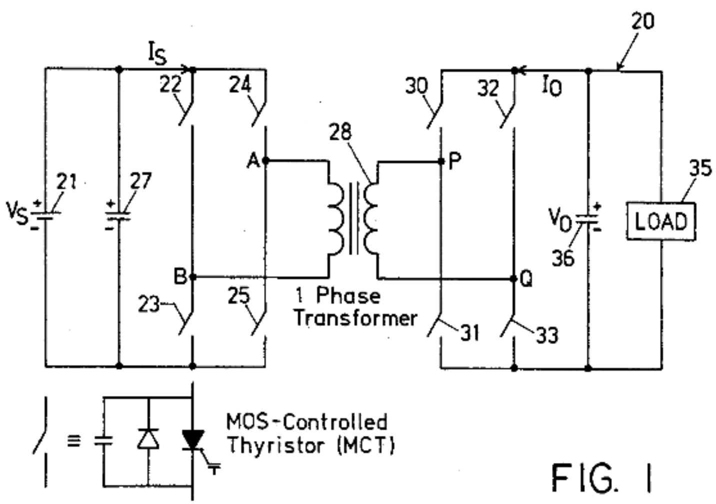


FIG. 1

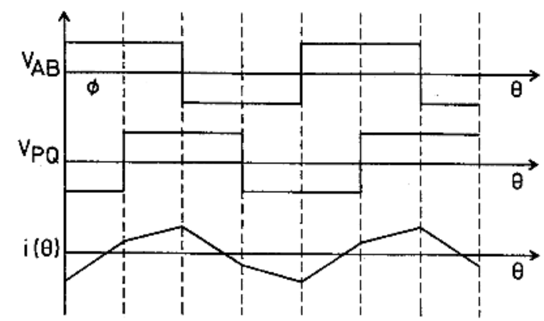


FIG. 2

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

[DeDoncker1989]

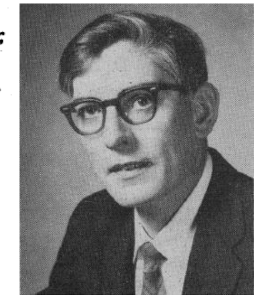
United States Patent

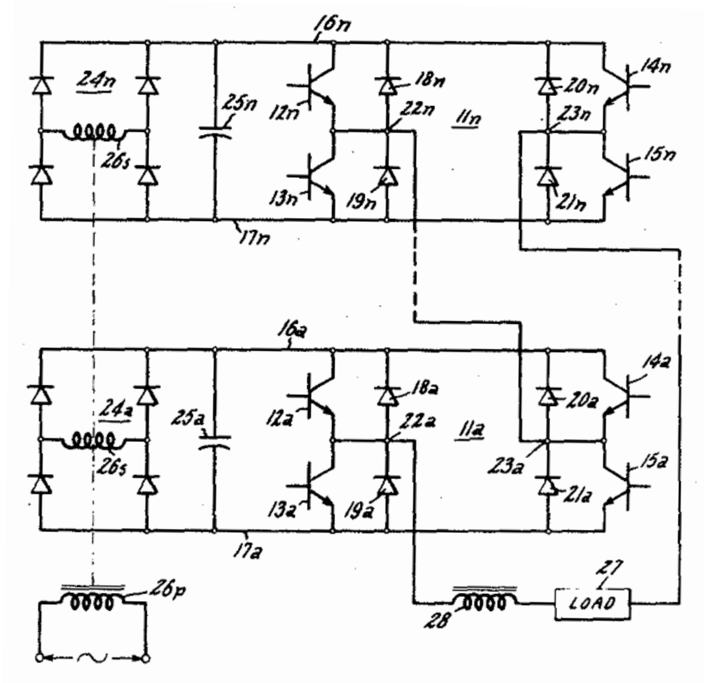
[11] 3,581,212

[54] **FAST RESPONSE STEPPED-WAVE SWITCHING POWER CONVERTER CIRCUIT**

[72] Inventor **William McMurray**
Schenectady, N.Y.
[21] Appl. No. **846,354**
[22] Filed **July 31, 1969** ← 1969!
[45] Patented **May 25, 1971**
[73] Assignee **General Electric Company**

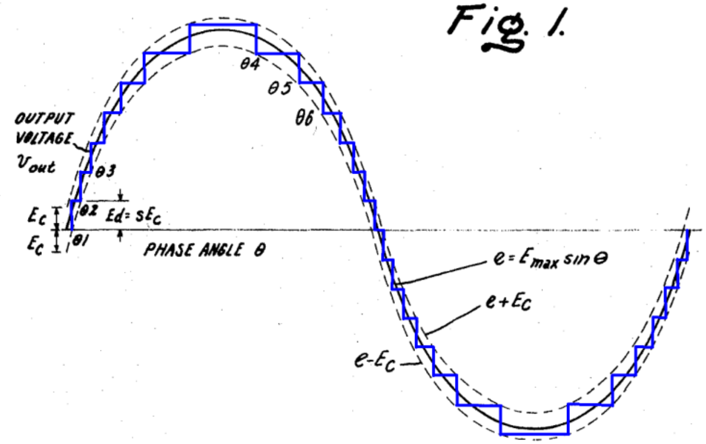
Inventor:
William McMurray,
by Donald R. Campbell
His Attorney.





- Cascading of Converter Cells
- Multilevel Output Voltage

Fig. 1.



▶ 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

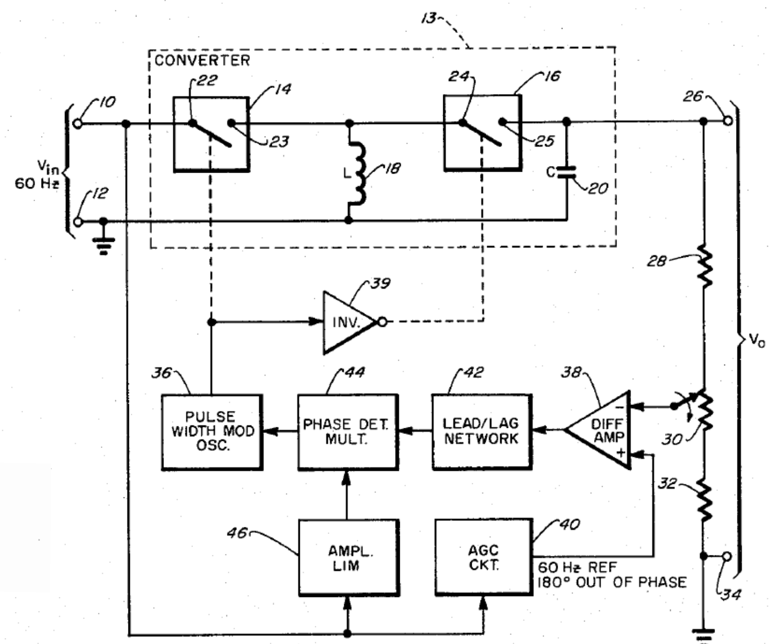
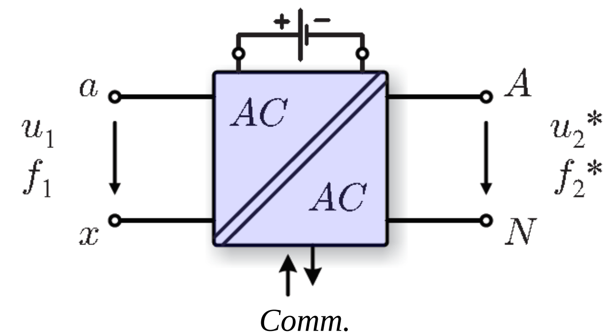


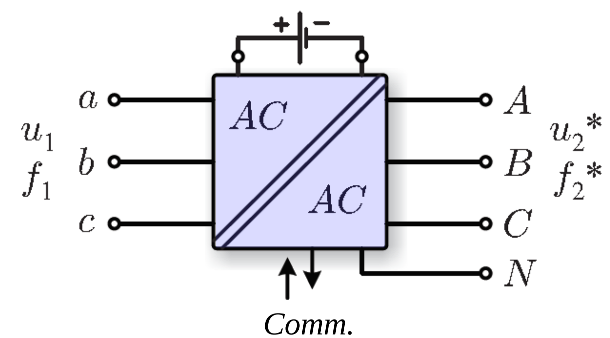
Fig. 1.

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

[Brooks1980]

▶ 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

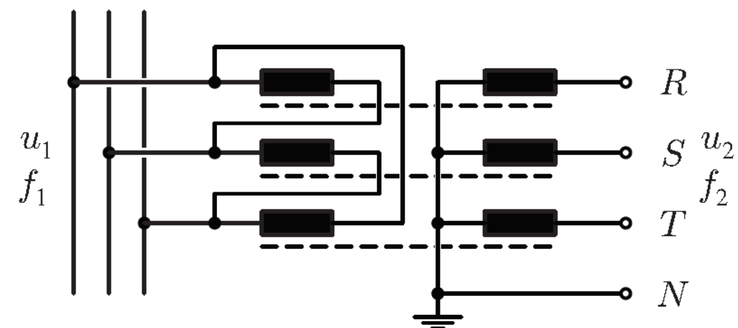

Img.: http://www.hieco-electric.com

▶ Classical Transformer — Basics (1)

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

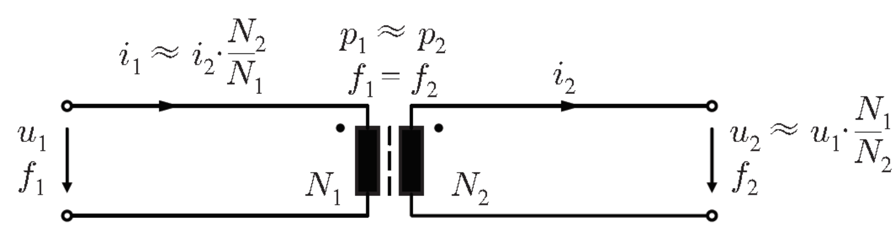
- **Operating Frequency** — 50/60Hz (El. Grid, Traction) or $16^2/_3$Hz (Traction)
- **Operating Voltage**
  - 10kV or 20kV (6…35kV)
  - 15kV or 20kV (Traction)
  - 400V

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

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



▶ Classical Transformer — Basics (2)

- **Scaling of Core Losses**

$$P_{\mathrm{Core}} \propto f_{\mathrm{P}} \left(\frac{\Phi}{A}\right)^2 V$$

$$P_{\mathrm{Core}} \propto \left(\frac{1}{l^2}\right)^2 l^3 \propto \frac{1}{l}$$

- **Scaling of Winding Losses**

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

$$P_{\mathrm{Wdg}} \propto \frac{1}{l}$$

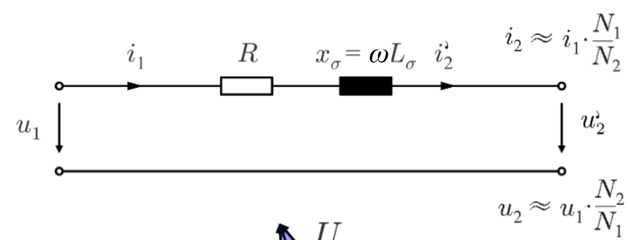
Img.: http://www.hieco-electric.com

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

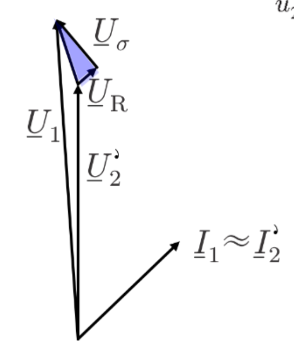
▶ Classical Transformer — Basics (3)

■ Advantages

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



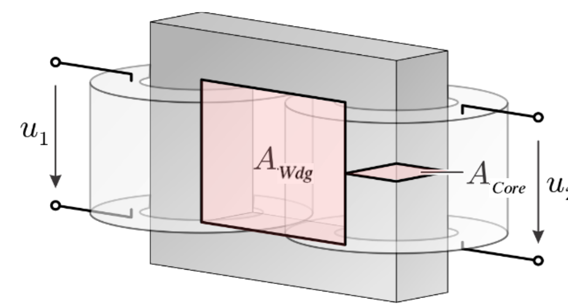
■ Weaknesses



- 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

- Construction Volume: $$A_{\text{Core}}A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$ ↑ ↑ ↑

  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

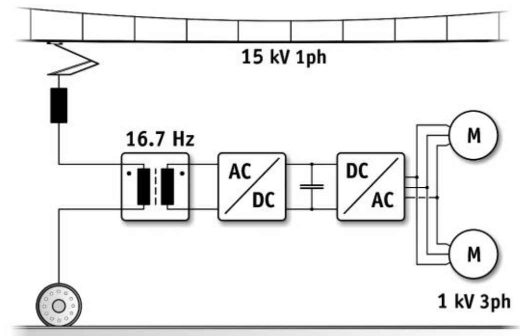
Future Traction Applications

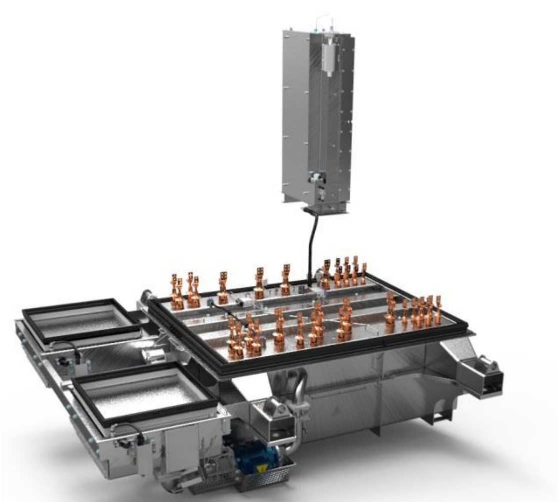
Future Smart Grid Applications

Yuyang / 123RF Stock Photo

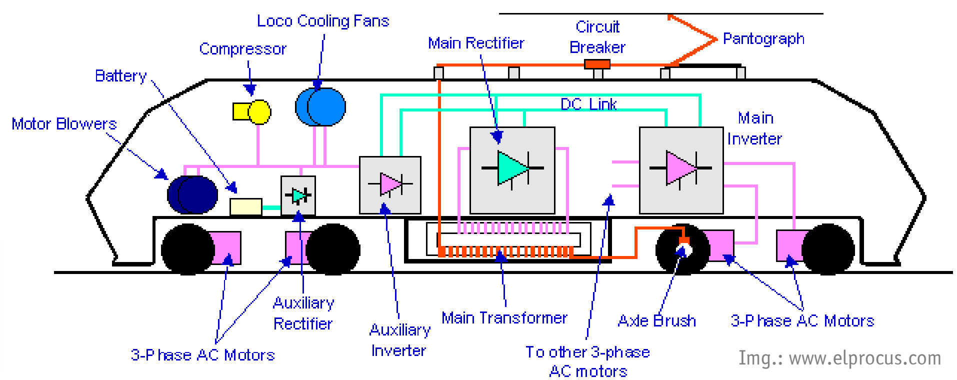
▶ Classical Locomotives

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





Img.: www.abb.com



Img.: www.elprocus.com

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	

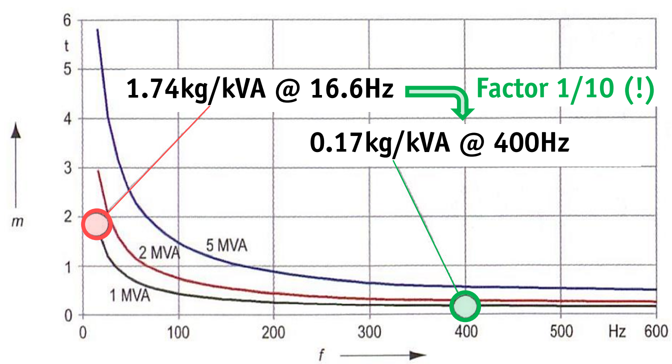
▶ Development Vectors for Modern Traction Systems

- **Distributed Propulsion** → **Volume Constraints**
- **Low-Floor Vehicles** → **Weight Constraints** (Roof Mounting)
- **High-Speed Traction** → **Weight Constraints** (Higher Power at Same Max. Axle Load Limit)

- **Development Potential of Conventional Technology is Exhausted**
  - Materials
  - Cooling Technologies

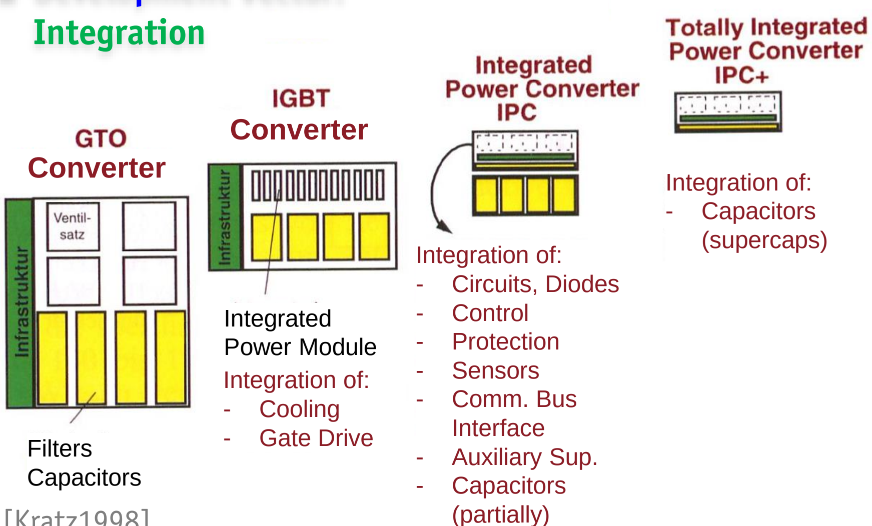
▶ **LFT Limits:**
Further Volume/Weight Reduction
→ **Lower Efficiency**

- **Development Vector:**
Higher Transformer Freq.



[Victor2005]

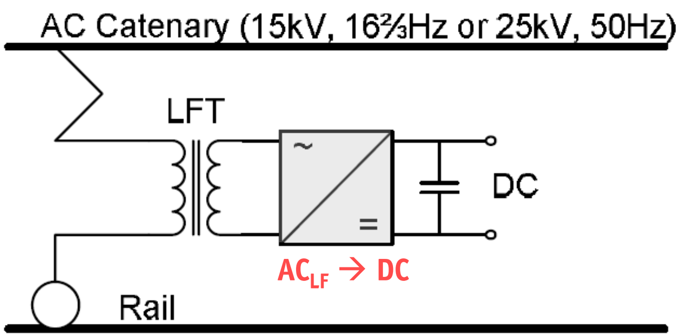
- **Development Vector:**
Integration



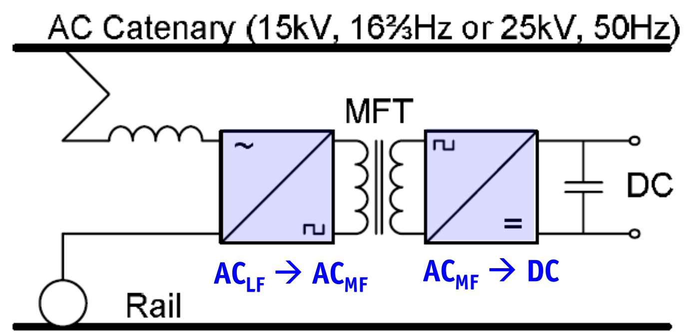
[Kratz1998]

▶ 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).



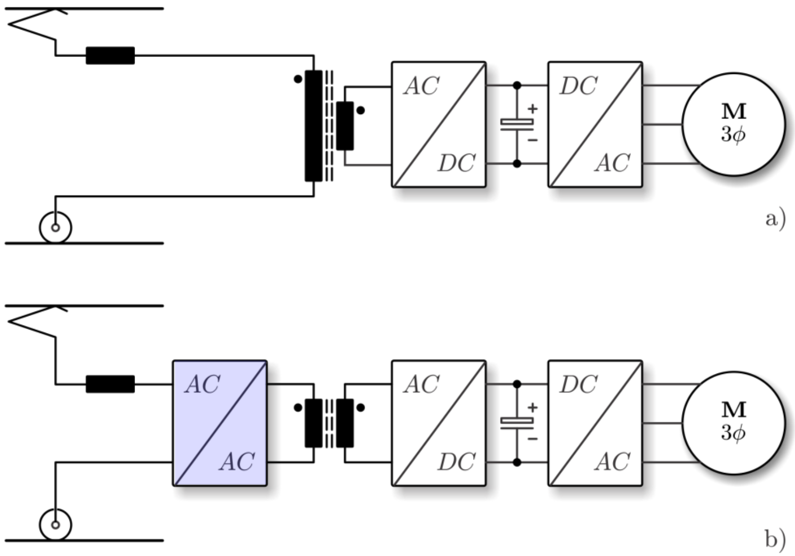
AC-DC conversion with medium frequency transformer (MFT).

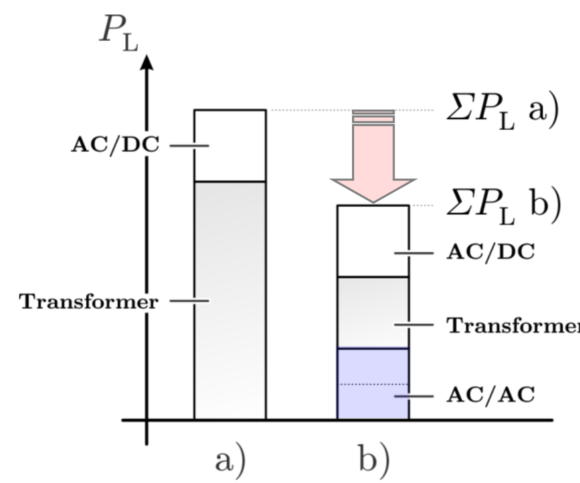
Img.: [Dujic2011]

- **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**

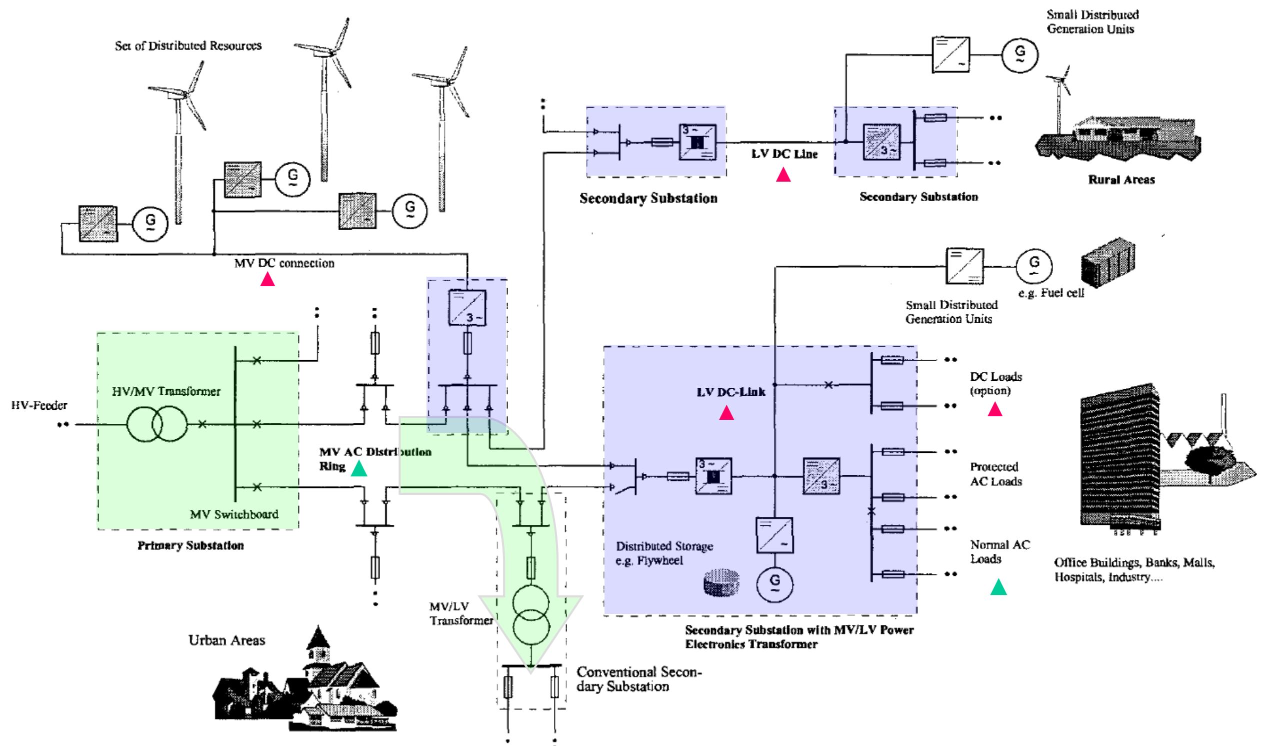
SST Concept

Future Traction Applications
Future Smart Grid Applications

Img.: http://www4.in.tum.de/lehre/seminare/SS12/sesgs/

▶ 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

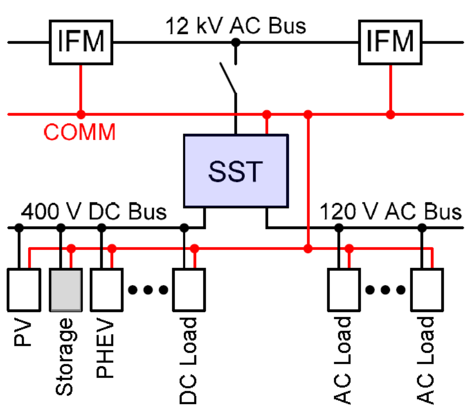
[Heinemann2001]

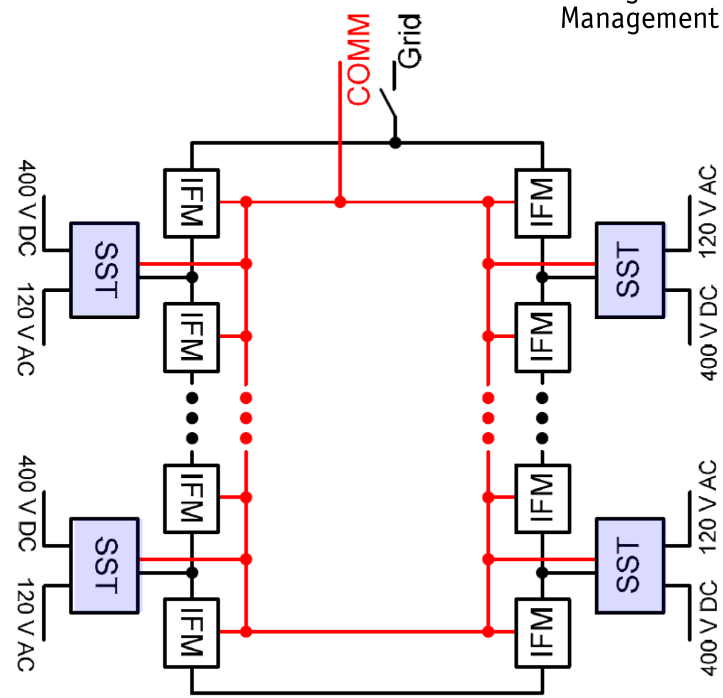
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) System

- **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.

[Huang2009, Huang2011]
Figs.: [Falcones2010]

▶ Smart Grid Concept

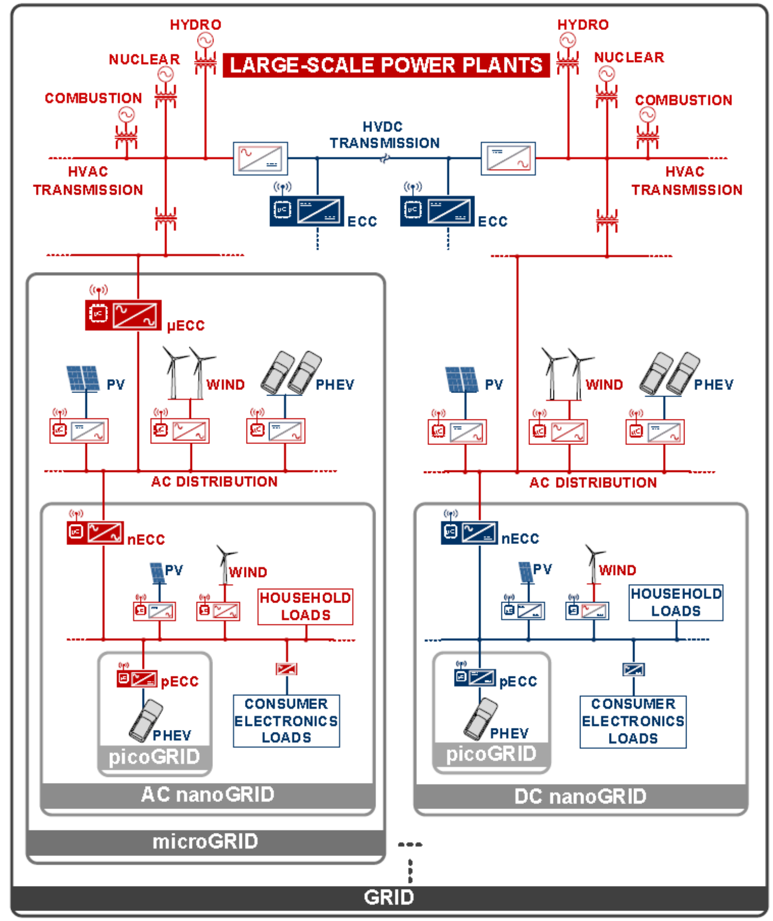
■ **Boroyevich (2010)**

■ **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.



[Boroyevich2010]

SST Functionalities

Protects Load from Power System Disturbance

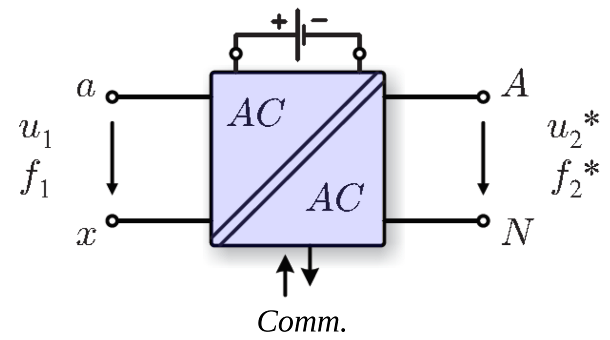
- Voltage Harmonics / Sag Compensation
- Outage Compensation
- Load Voltage Regulation (Load Transients, Harmonics)

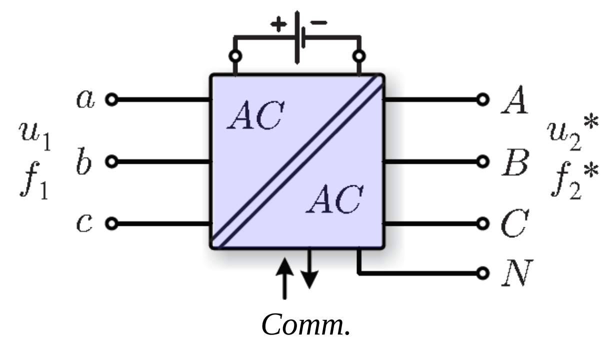
Protects Power System from Load Disturbance

- 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 (1-ph. AC, 3-ph. AC, DC)
- High Efficiency
- No Fire Hazard / Contamination
- Supervisory Control / Status Monitoring Interface





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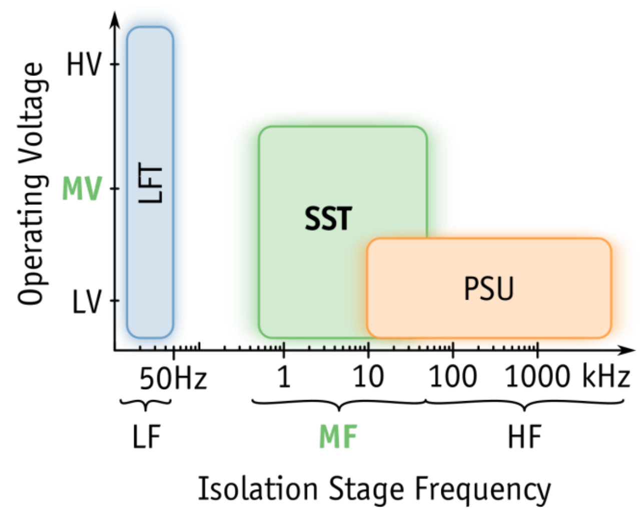
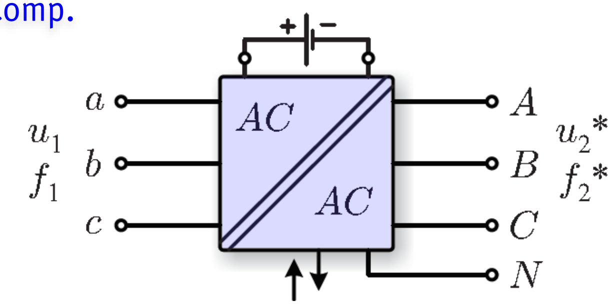
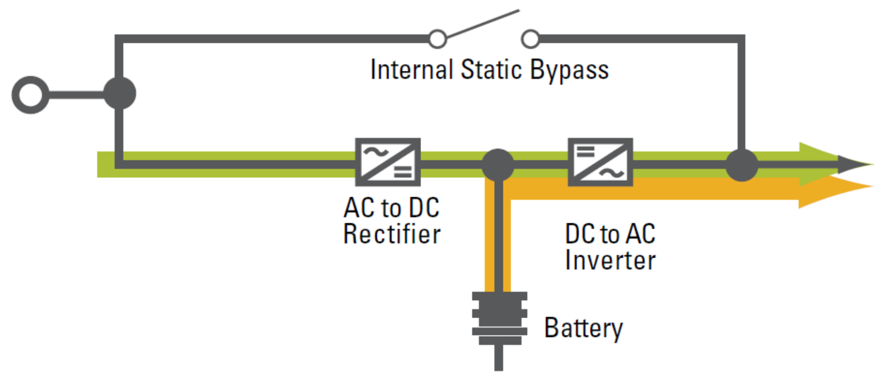


▶ Remark: AC/AC SST vs. Uninterruptible Power Supply

- **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**

13 Key Challenges of SST Design

1. *Topology Selection*
2. *Power Semiconductors*
3. *Optimum Number of Levels*
4. *Reliability*
5. *MF Isolated Power Converters*
6. *Medium-Freq. Transformer*
7. *Isolation Coordination*
8. *EMI*
9. *Protection*
10. *Control & Communication*
11. *Competing Approaches*
12. *Construction of Modular Conv.*
13. *Testing*

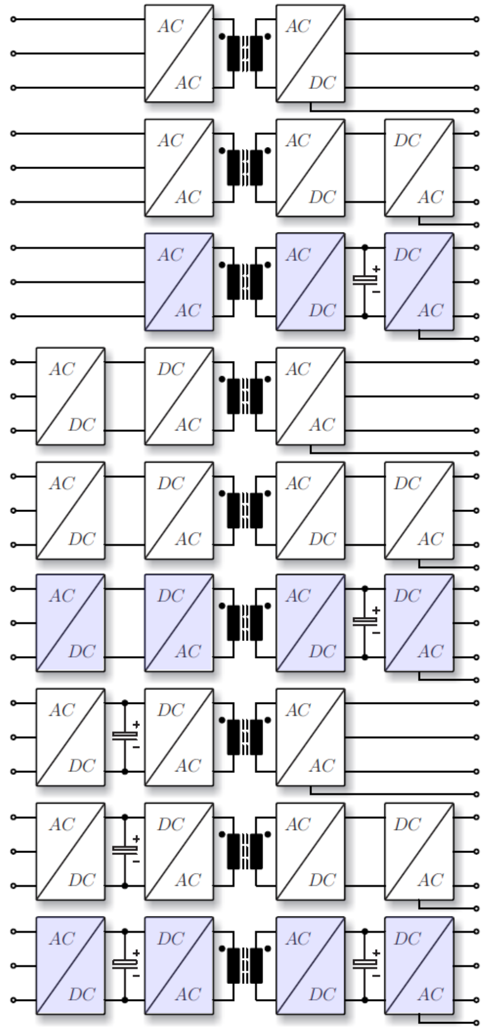
Challenge #1/13
Topology Selection

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

▶ 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



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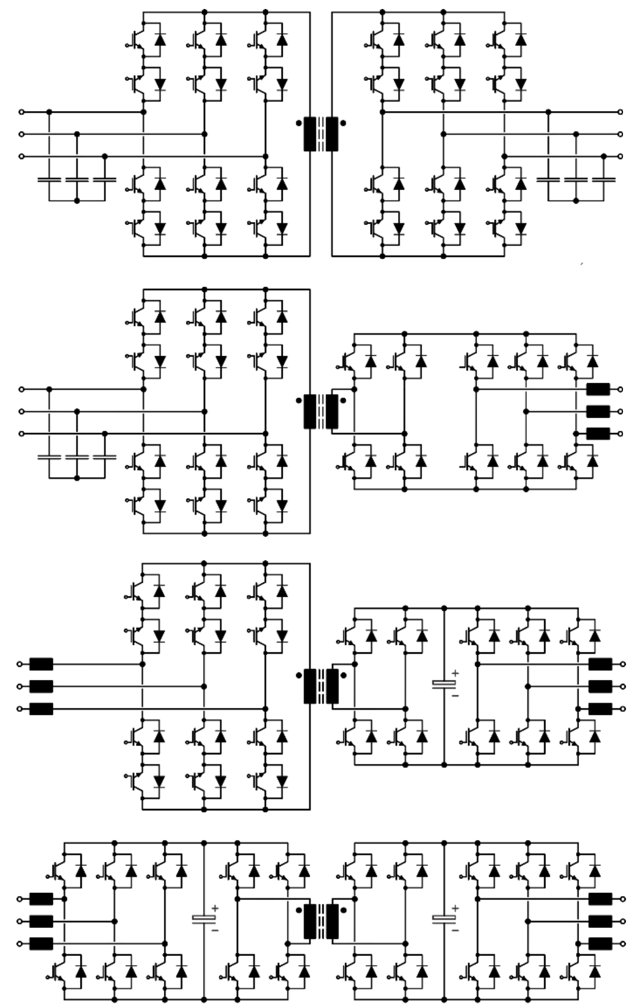
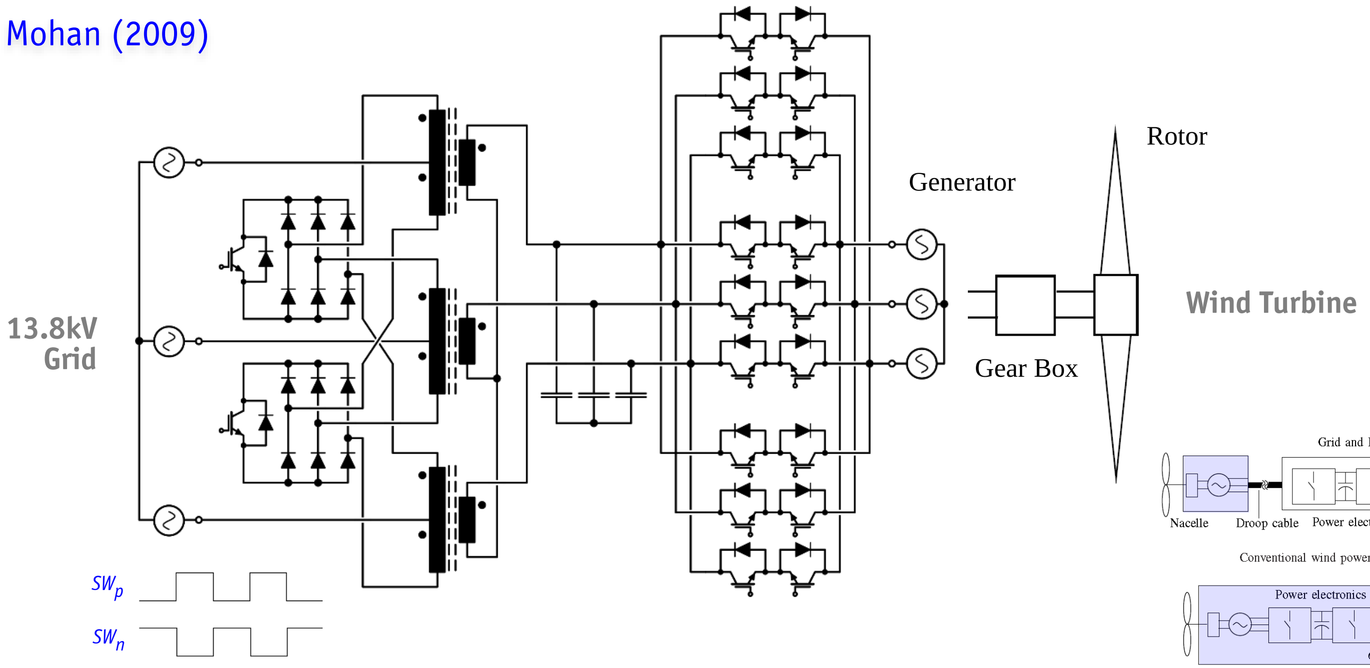


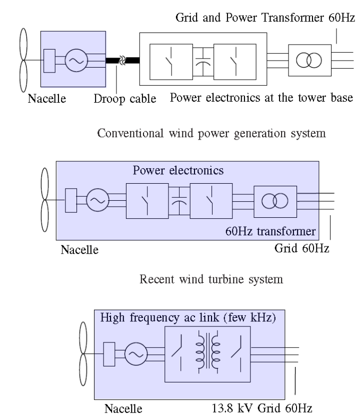
  - 1-Stage Matrix-Type Topologies
  - 2-Stage with MV DC Link (Connection to HVDC System)
  - 2-Stage with LV DC Link **(Connection of Energy Storage)**
  - 3-Stage Power Conversion with MV and LV DC Link

▶ 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

[Gupta2009]

▶ Basic SST Structures (1)

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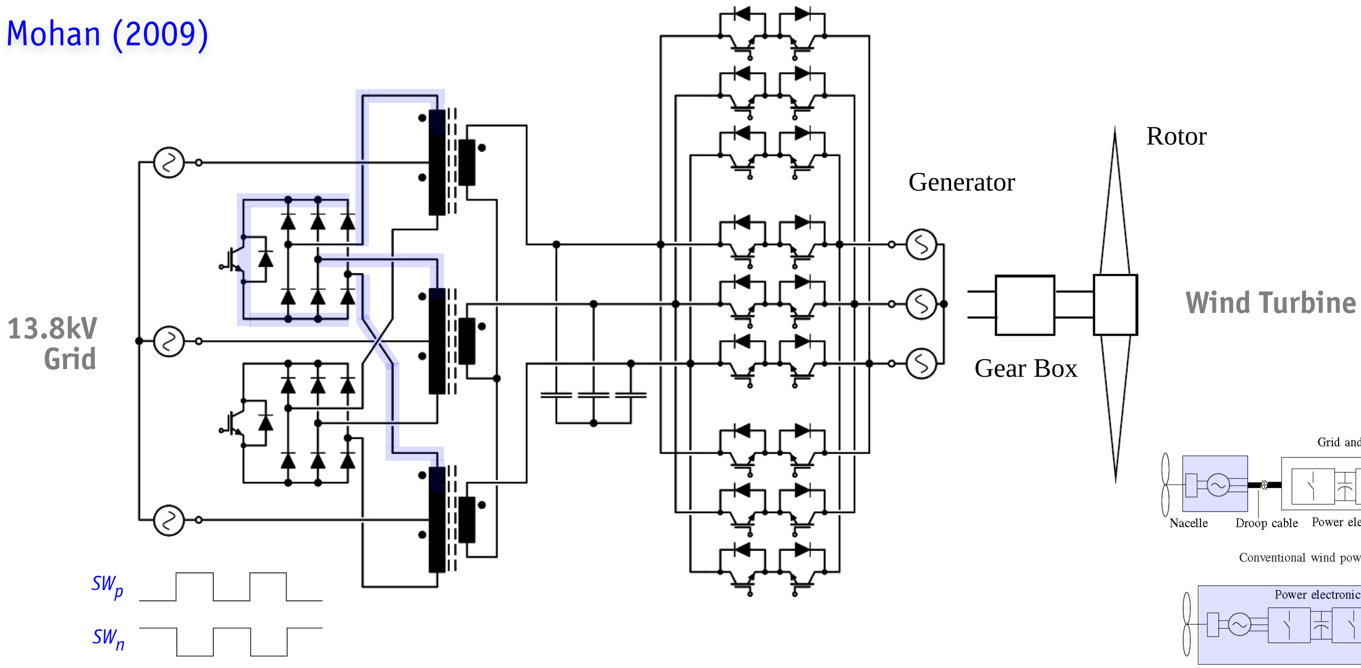

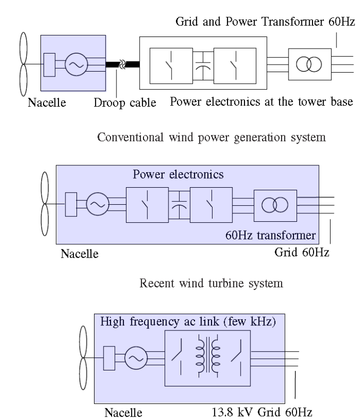

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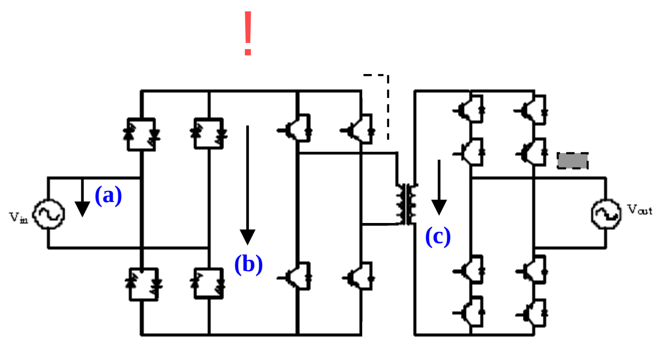
[Gupta2009]

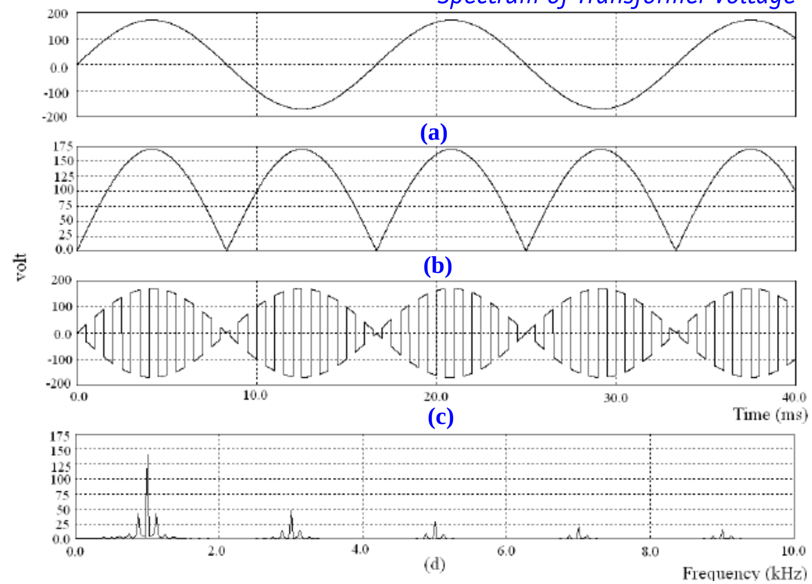
▶ Basic SST Structures (1)

- 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



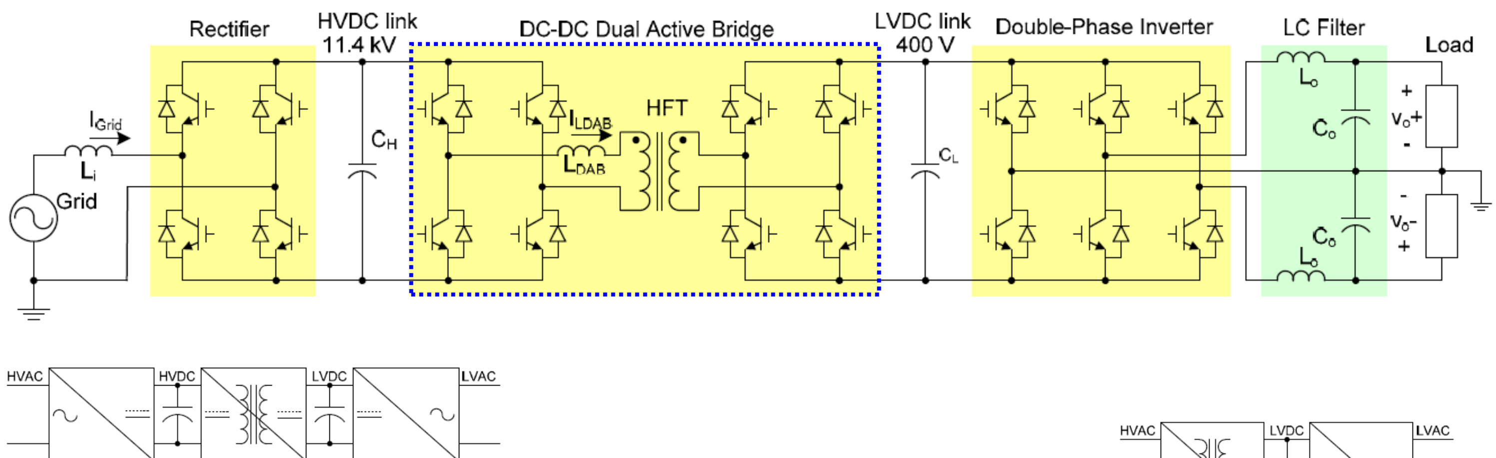
- AC/DC Input Stage (Bidir. Full-Wave Fundamental Frequ. GTO Rect. Bridge, No Output Capacitor)
- Subsequent DC/DC Conversion & DC/AC Conversion (Demodulation, $f_1 = f_2$)
- Output Voltage Control by Phase Shift of Primary and Secondary Side Switches (McMurray)
- Lower Number of HF HV Switches Comp.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

[Abedini2010]

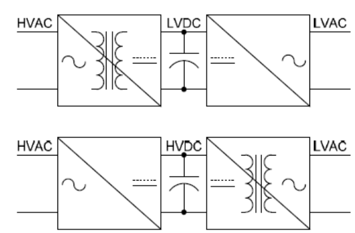
▶ Basic SST Structures (1)

- 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)



- Alternatives: AC//DC – DC/AC Topologies
  AC/DC – DC//AC Topologies



[Falcones2010]

Challenge #1/13

Topology Selection

Partitioning of AC/AC Power Conv.

Partial or Full Phase Modularity

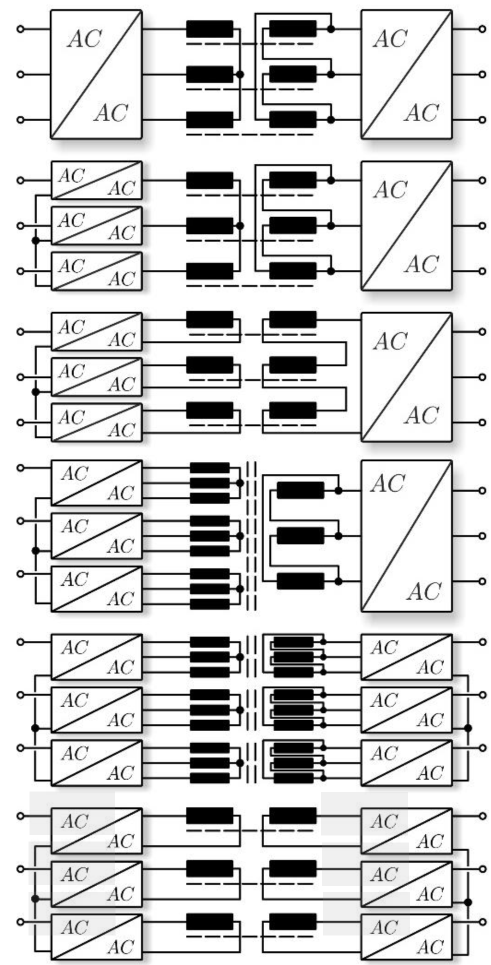
Partitioning of Medium Voltage

Classification of SST Topologies

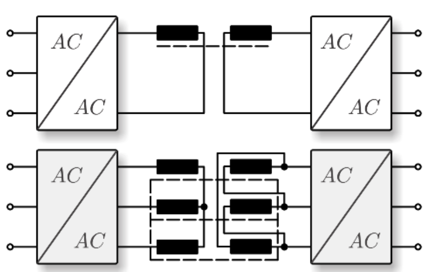
▶ Basic SST Structures (2)

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

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



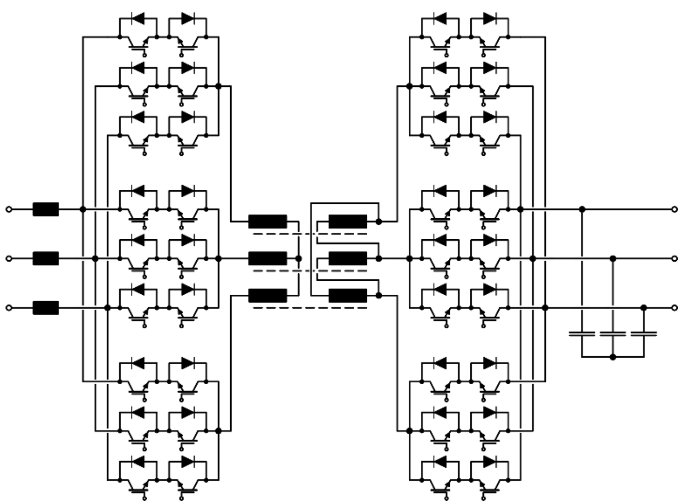
▼ Phase-Integrated SST



▶ Basic SST Structures (2)

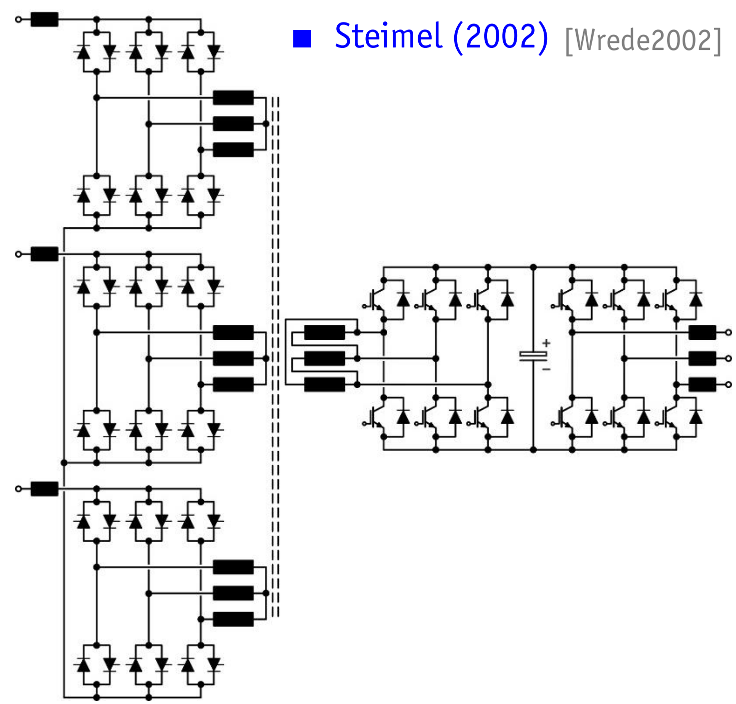
- 2nd Degree of Freedom of Topology Selection
  → Partial or Full Phase Modularity

- Enjeti (1997) [Kang1999]



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

- Steimel (2002) [Wrede2002]



- Example of Partly Phase-Modular SST

Challenge #1/13

Topology Selection

Partitioning of AC/AC Power Conv.
Partial or Full Phase Modularity
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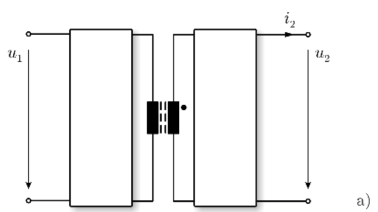
Classification of SST Topologies

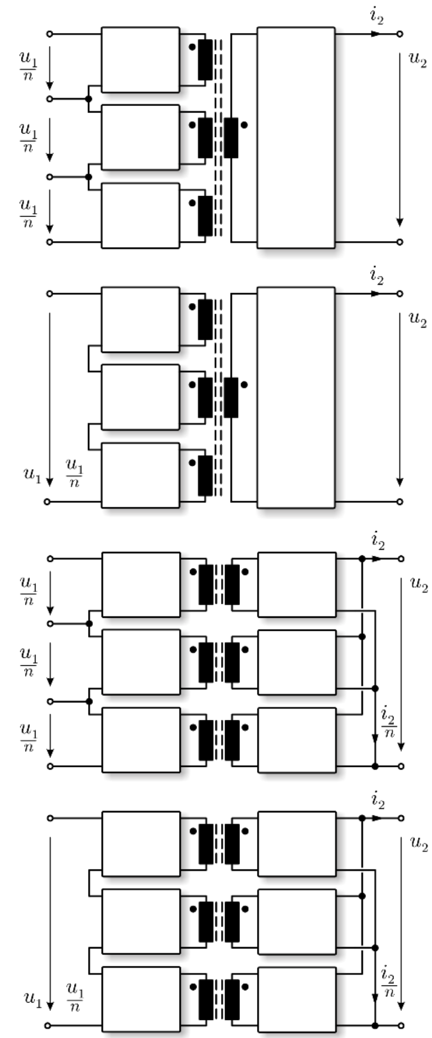
▶ Basic SST Structures (3)

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

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



▲ Single-Cell / Two-Level Topology



ISOP = Input Series / Output Parallel Topologies

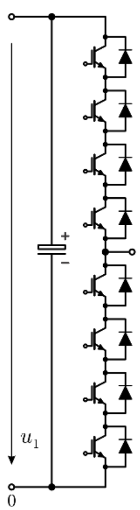
▶ Basic SST Structures (3)

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

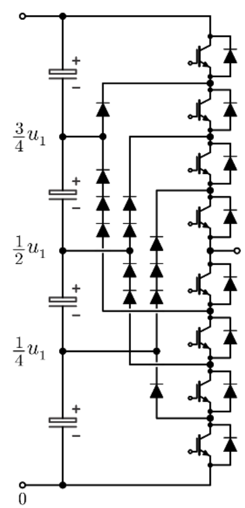
- Multi-Cell and Multi-Level Approaches

Multi-Level/Multi-Cell Topologies ▶

◀ Two-Level Topology

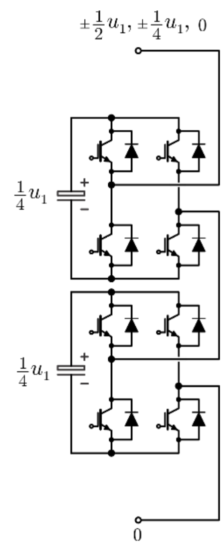


Akagi (1981)



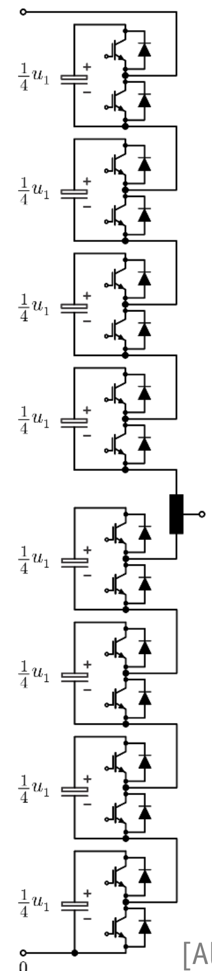
[Nabae1981]

McMurray (1969)



[McMurray1969]

Marquardt

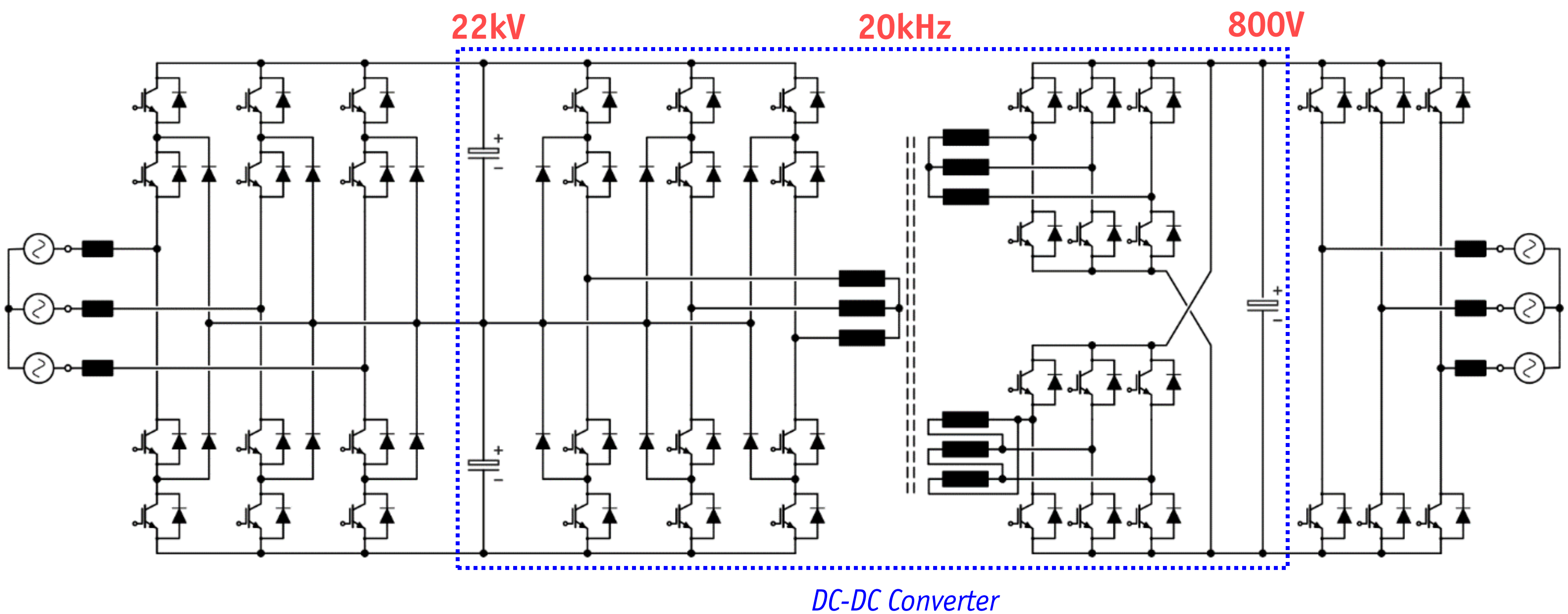


[Alesina1981]
[Marquardt2002]
[Lesnicar2003]

▶ Basic SST Structures (3)

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

- Bhattacharya (2012)



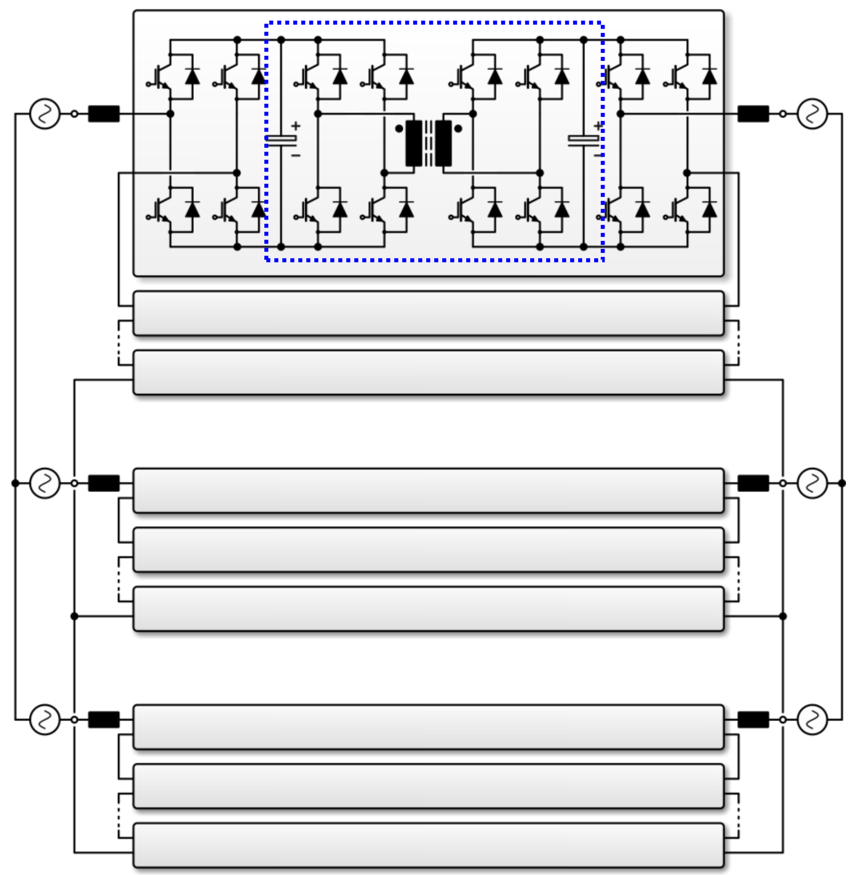
- 13.8kV → 480V
- 15kV SiC-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype

[Tripathi2012]

▶ Basic SST Structures (3)

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

- Akagi (2005)



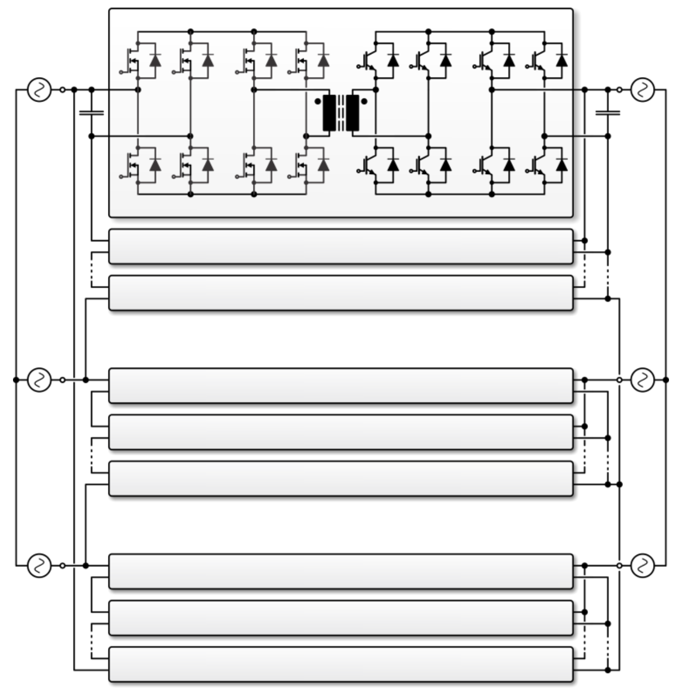
- **Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs**
- Combination of Clustered Balancing Control with Individual Balancing Control

[Inoue2007]

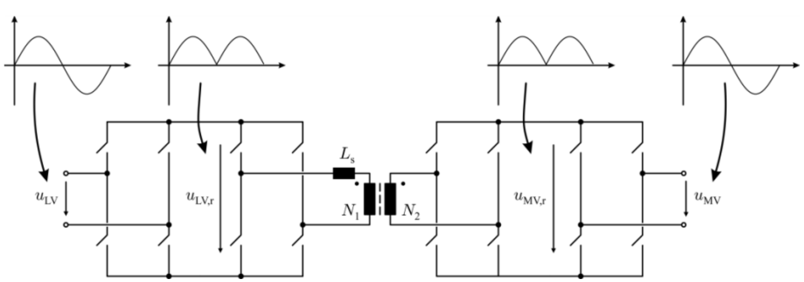
▶ Basic SST Structures (3)

- 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$_{l\text{-}l}$, 4 Modules in Series)**
- **LV Y-Connection (465V/√3, Modules in Parallel)**



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

[Das2011]

▶ Basic SST Structures (3)

- 3rd Degree of Freedom of Topology Selection
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- Das (2011)

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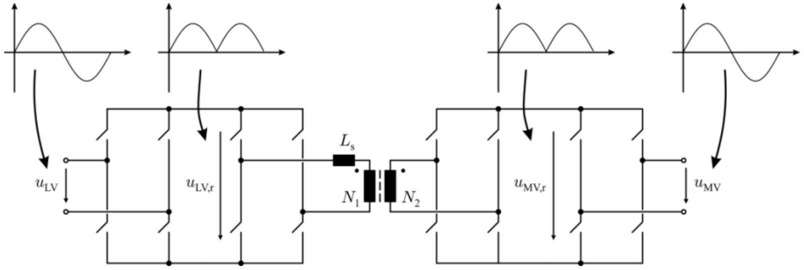

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[Das2011]

Challenge #1/13

Topology Selection

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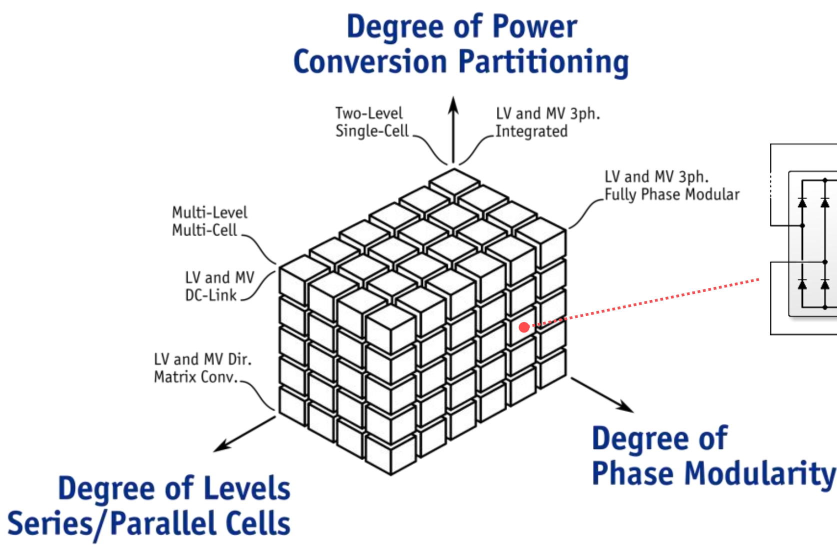
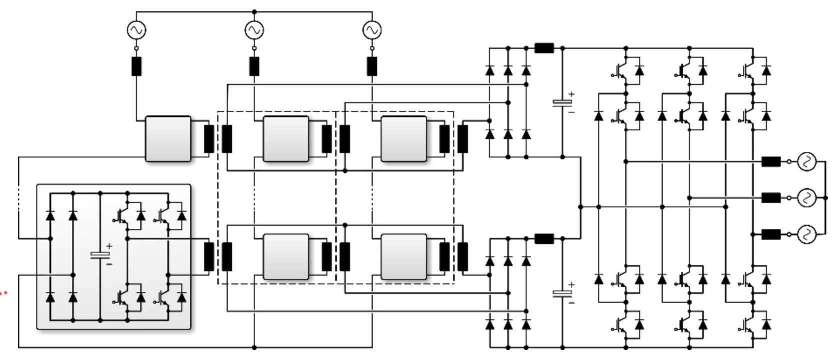
Partial or Full Phase Modularity
Partitioning of Medium Voltage
Classification of SST Topologies

▶ Classification of SST Topologies





▲ Enjeti (2012)
[Krishnamoorthy2012]

- 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 Voltage into Lower Partial Voltages → Multi-Level/Cell Approaches

▶ Partitioning of AC/DC PFC Functionality

■ Required Functionality

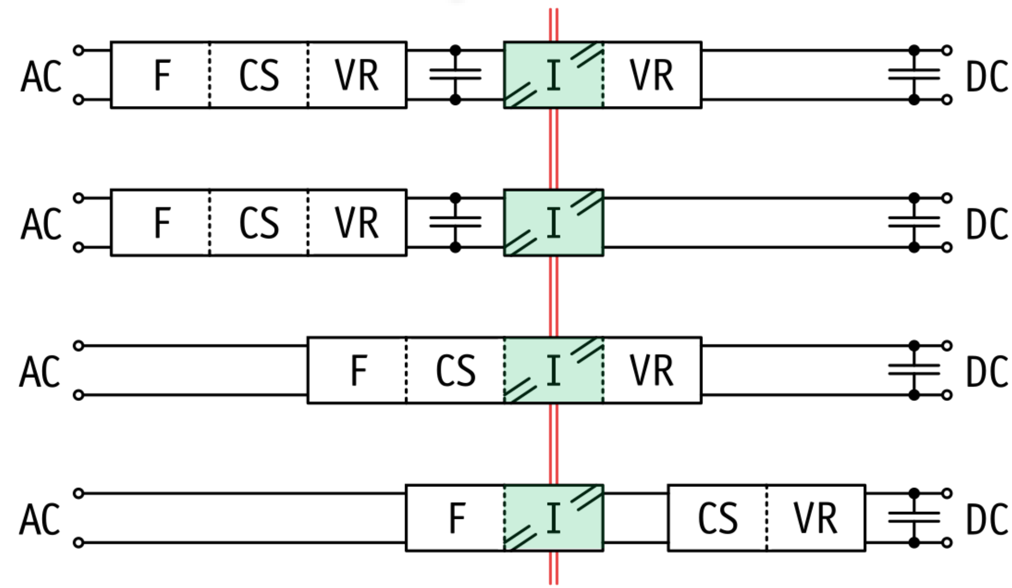
- **F:** Folding of the AC Voltage Into a |AC| Voltage
- **CS:** Input Current Shaping
- **I:** Galvanic Isolation & Voltage Scaling
- **VR:** Output Voltage Regulation

■ Isolated PFC Task Partitioning Variants:

Isolated Back End (IBE) ▶
→ Broadly Analyzed and Employed in SSTs

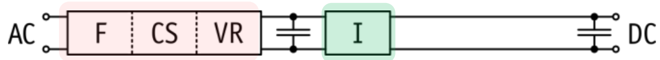
Fully Integrated ▶

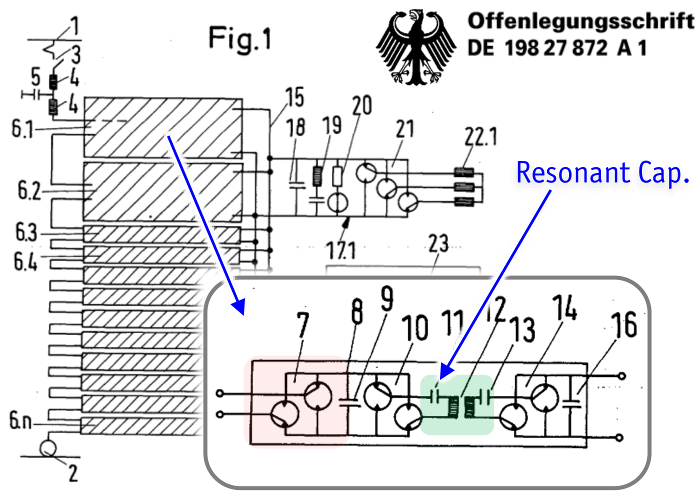
Isolated Front End (IFE) ▶
→ Less Common, Interesting Alternative



▶ IBE and IFE in SST Applications (1)

■ Isolated Back End



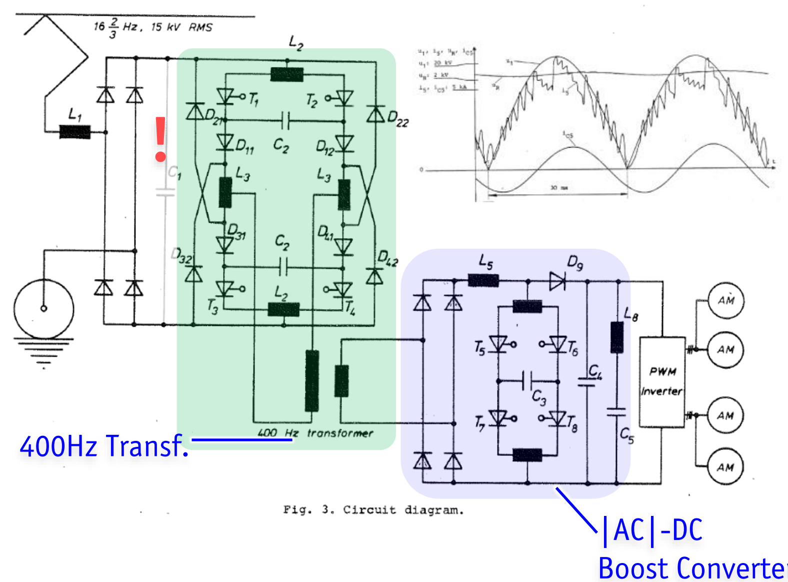


- Steiner, 1996 → Traction Applications
- **Primary Side** Active Rectification
- ISOP System Structure

- Soft-Switched Isolation Stage (HC-DCM Series Resonant Conv.)

[Steiner1998], [Steiner2000]

■ Isolated Front End (1)



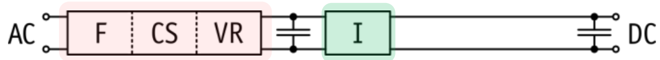
- Weiss,1985 (!) → Traction Applications
- **Secondary Side** |AC|-DC Boost Converter for Sinusoidal Current Shaping and Volt. Reg.
- Hard-Switched Isolation Stage

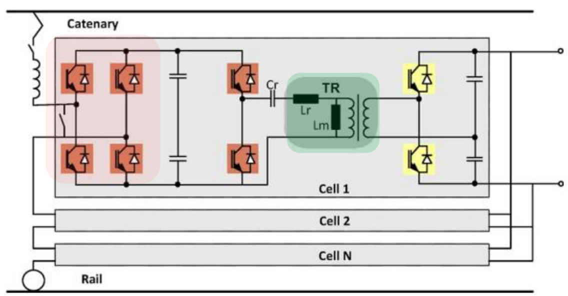
- Han, 2014 → Ext. to Resonant & Modular Concept

[Weiss1985], [Han2014]

▶ IBE and IFE in SST Applications (2)

■ Isolated Back End

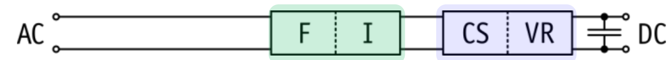


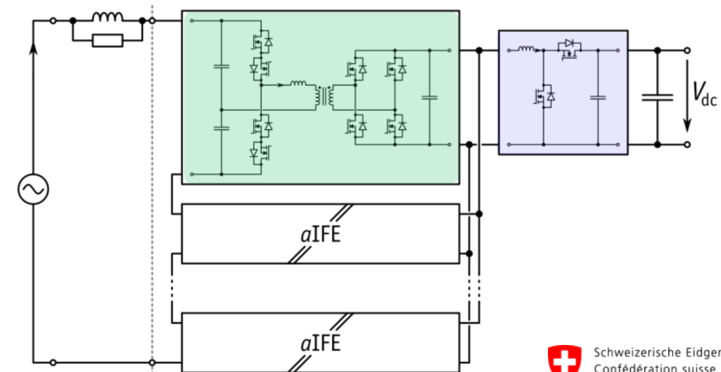


- Developed Into **Fully Functional Traction SST** by ABB (Dujic, Zhao, et al.), ca. 2011-2014
- Soft-Switched Isolation Stage (HC-DCM Series Resonant Conv.)

[Dujic2013] & [Zhao2014]

■ Isolated Front End (2)





Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

- ETH, 2015, in the Scope of 70 NRP Energy Turnaround National Research Programme

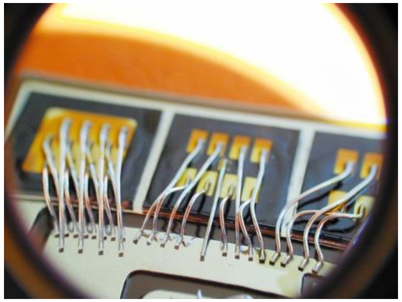
▶ "Swiss SST" (S^3T)

- All-SiC, Full ZVS Realization
- Simplified Input Stage
- Further Configurations: 3-Ph., AC/AC, etc.
- Soft-Switched Isolation Stage (HC-DCM Series Resonant Conv.)

ETH / [Kolar2016], [Huber2016a]

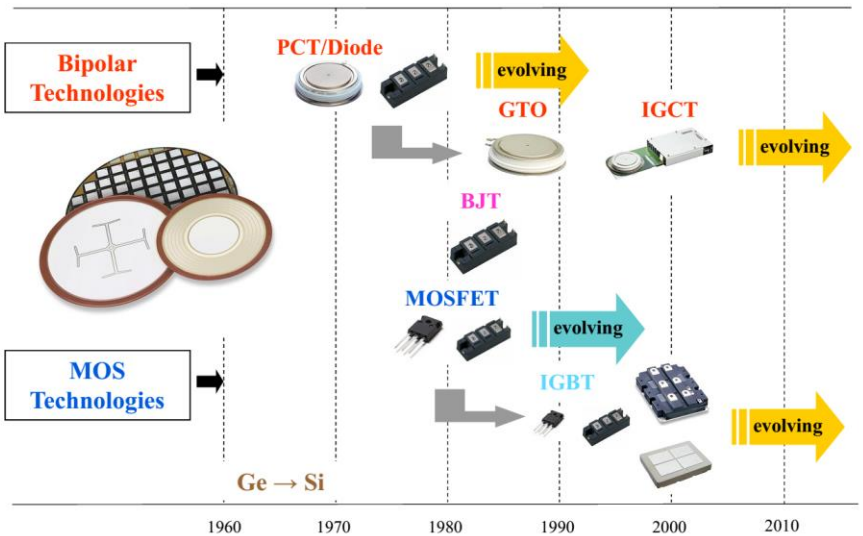
Challenge #2/12

Power Semiconductors



Img.: www.micromat.at

▶ History of Silicon (Si) High-Power Devices



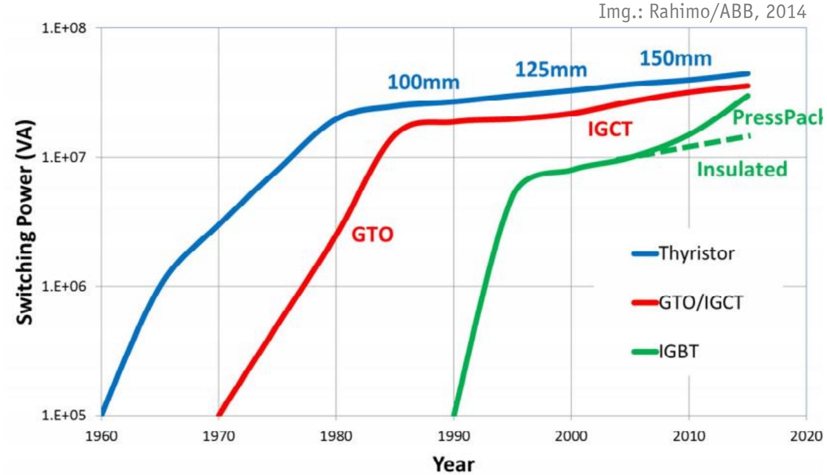
◀ Historical Development of Device Technologies

(!) → Bi-Mode IGCT(BGCT) [Rahimo2009]

(!) → Wide Band Gap SCs (**SiC**)
→ Bi-Mode IGBT (BIGT) [Vemulapati2012]

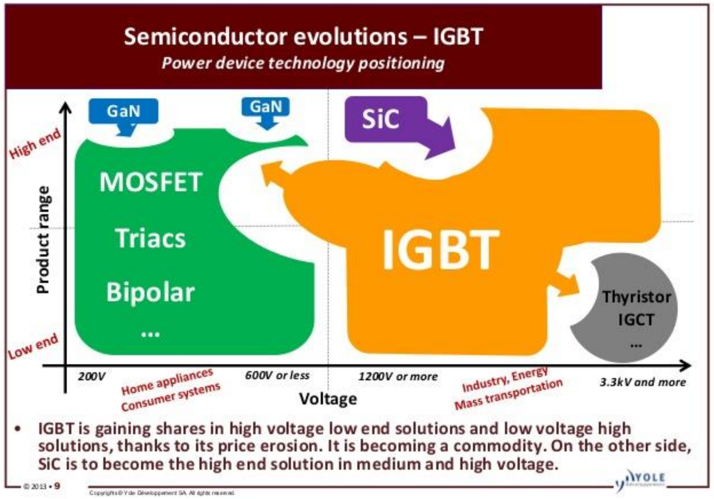
Development of Max. Switching Power ▶

Img.: Rahimo/ABB, 2014



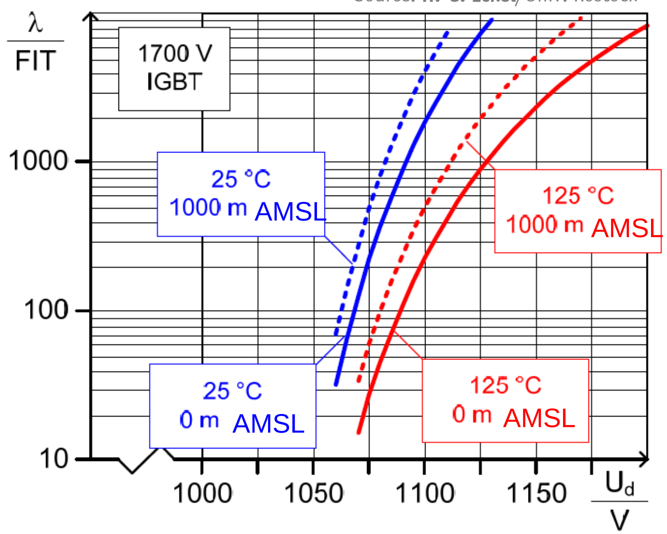
▶ Available Si Power Semiconductors

- **1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications**
- Derating Requirements Due to Cosmic Radiation 1700V Si-IGBTs → 1000V max. DC Voltage



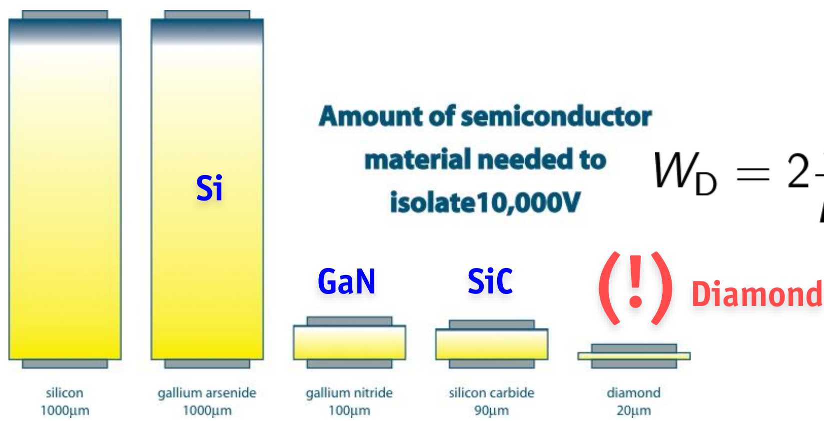
Img.: Yole Développement.

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



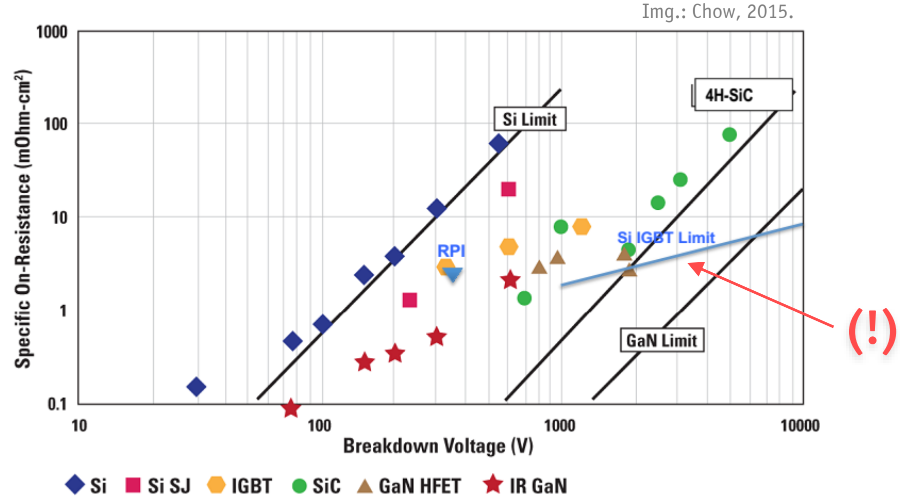
Img.: http://www.evincetechnology.com/whydiamond.html

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

■ **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.



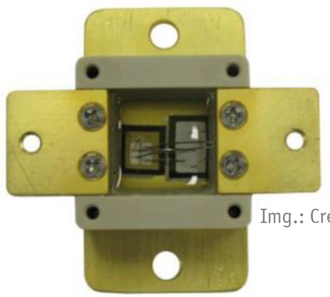
■ **SiC More Mature than GaN for HV Applications**

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

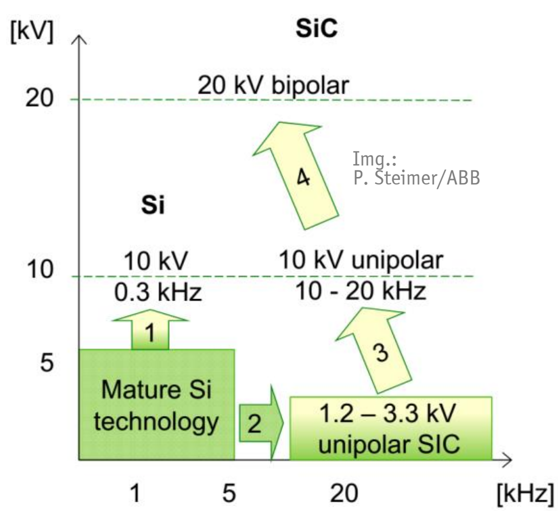
▶ SiC Power Semiconductors

- **Lower Switching Losses** → **Higher f_s** → **Smaller Passives**
- **Higher Blocking Voltages** → **Fewer Devices** → **Lower Complexity**

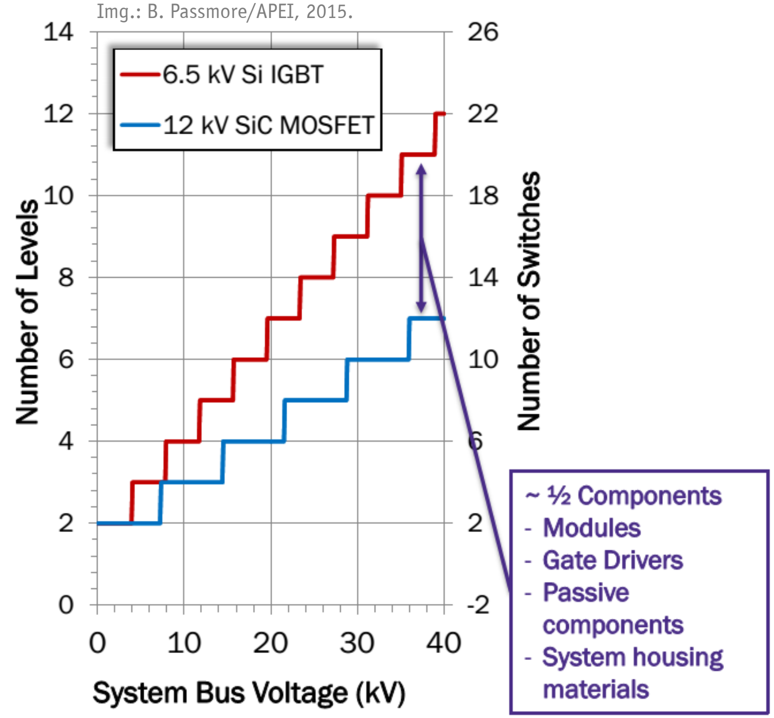
10kV SiC MOSFET ▶



Img.: Cree Inc.



Img.: B. Passmore/APEI, 2015.

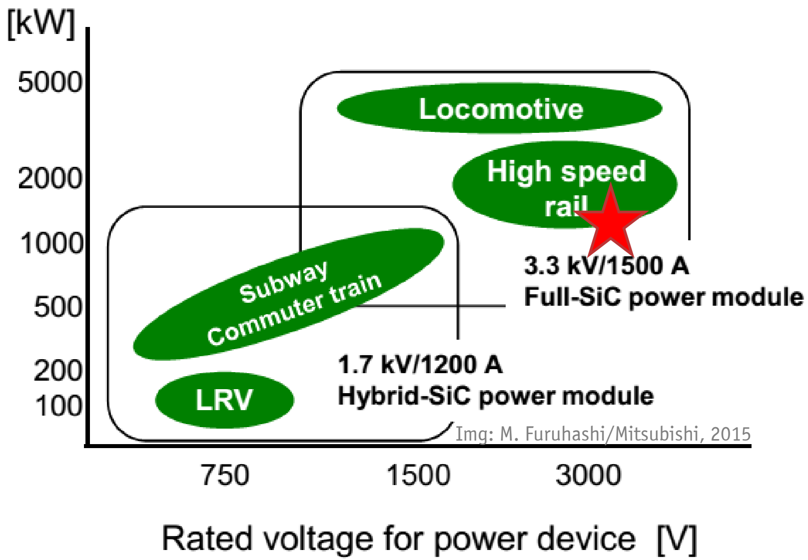


▶ SiC Semiconductors Available for High-Power Applications

■ Example: All-SiC Traction Inverter (2014)

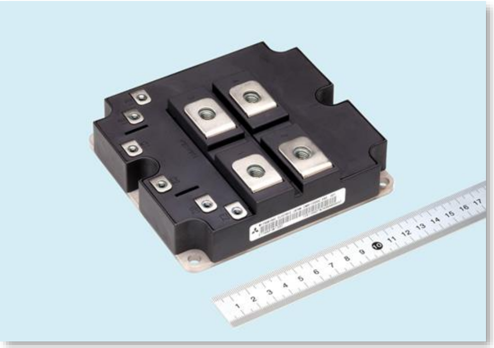
- 3.3kV/1.5kA SiC Modules in All-SiC Traction Inverter

- 65% Reduction of Size and Weight
- 55% Loss Reduction



Img: M. Furuhashi/Mitsubishi, 2015

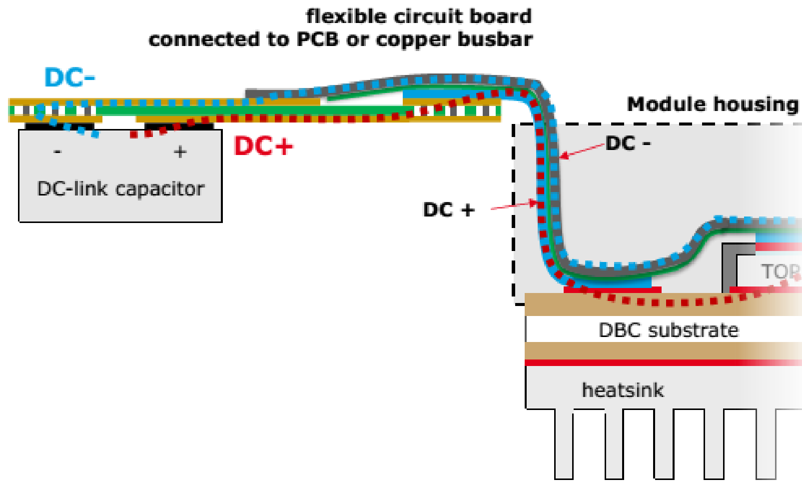
▲ MITSUBISHI ELECTRIC *Changes for the Better* 2014 ▼



▶ Major WBG Semiconductor Application Challenge: Packaging

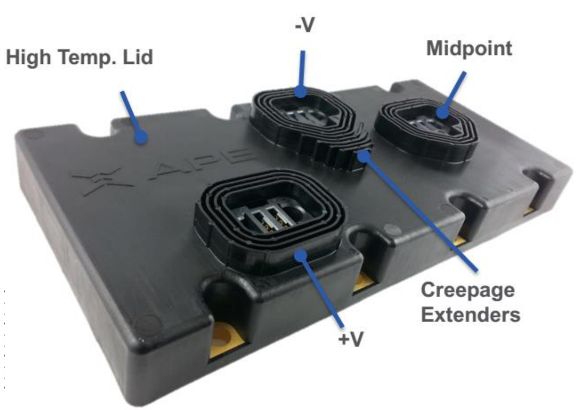
■ **Low Inductance for Fast Switching**

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



Img.: M. Röblitz/Semikron, 2015

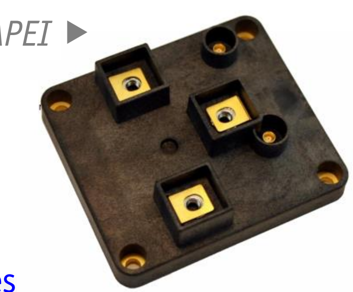
■ **Isolation for HV Devices**



▲ 15kV/80A, *APEI*

(!)

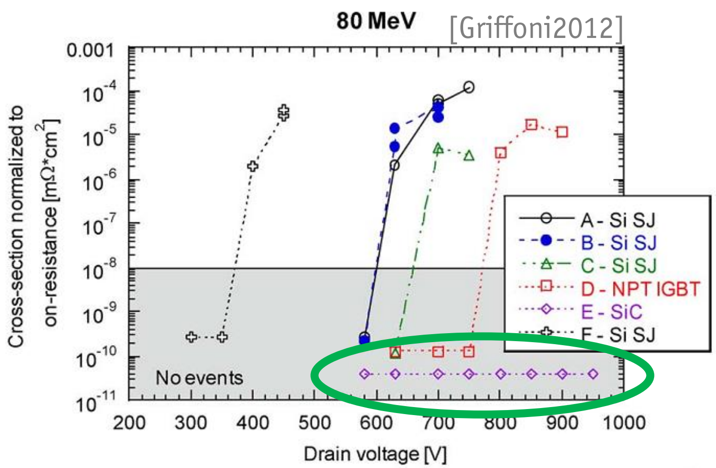
24 kV/30 A, **Fully Potted**, *APEI* ▶



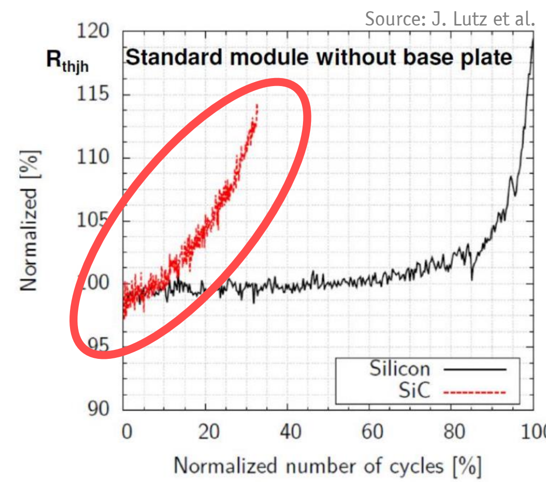
- Isolation of Gate Drives
- dv/dt Capability of Gate Drives

▶ 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)

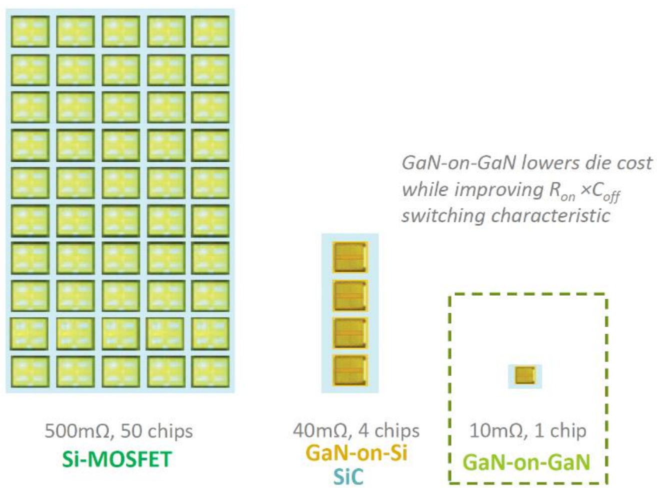
▶ New Packaging Technologies Will Help!

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

▶ Vertical (!) Power Semiconductors on Bulk GaN Substrates

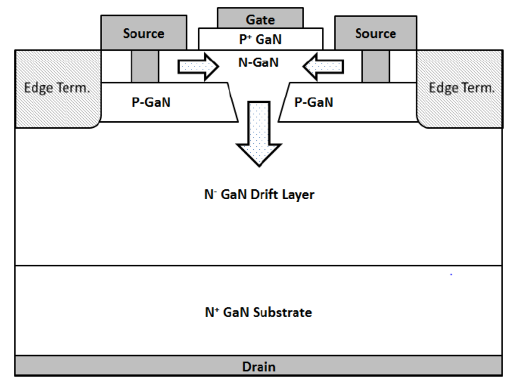
■ GaN-on-GaN Means Less Chip Area

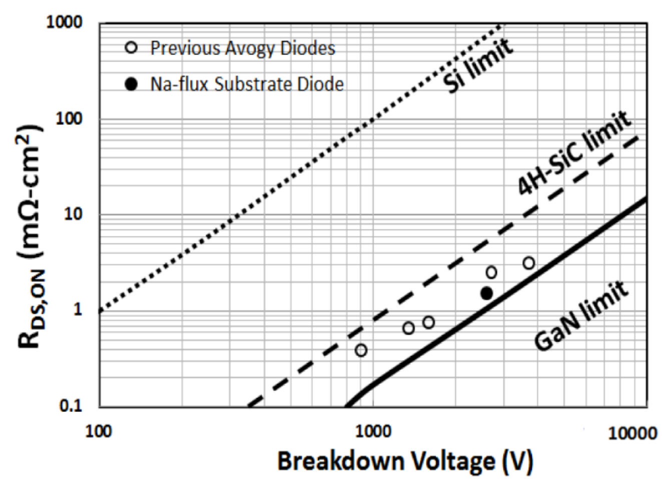
For a given on-resistance (R_{on}) of 10mΩ:



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

▶ Vertical FET Structure





Challenge #3/13

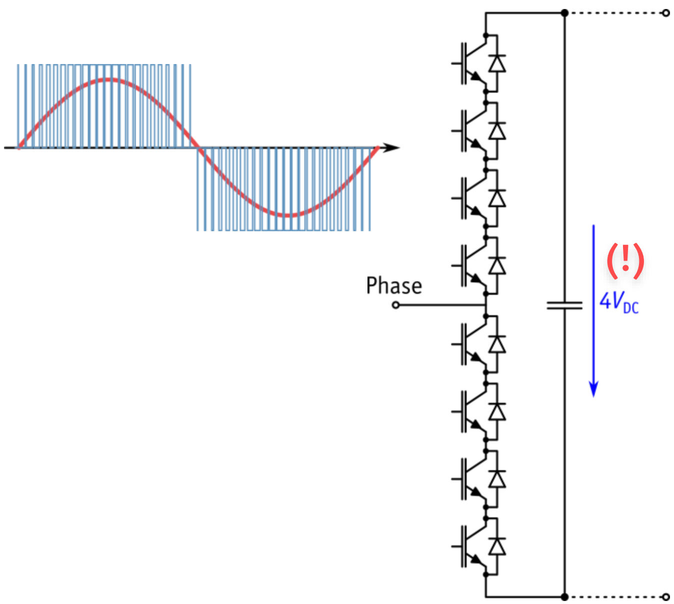
Optimum Number of Levels

Optimum Number of Levels
Single Cell with HV SiC

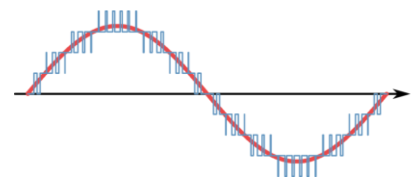
▶ Power Electronics in MV Applications

■ Limited Blocking Voltage Capabilities of Si IGBTs (< 6.5kV)

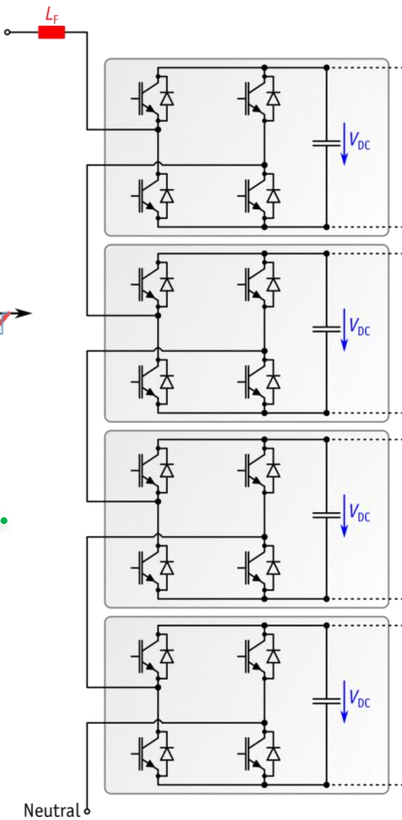
- Direct Series Connection (or HV SiC!)



- Cascading of Converter Cells

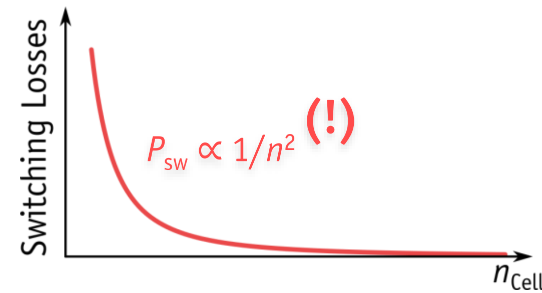


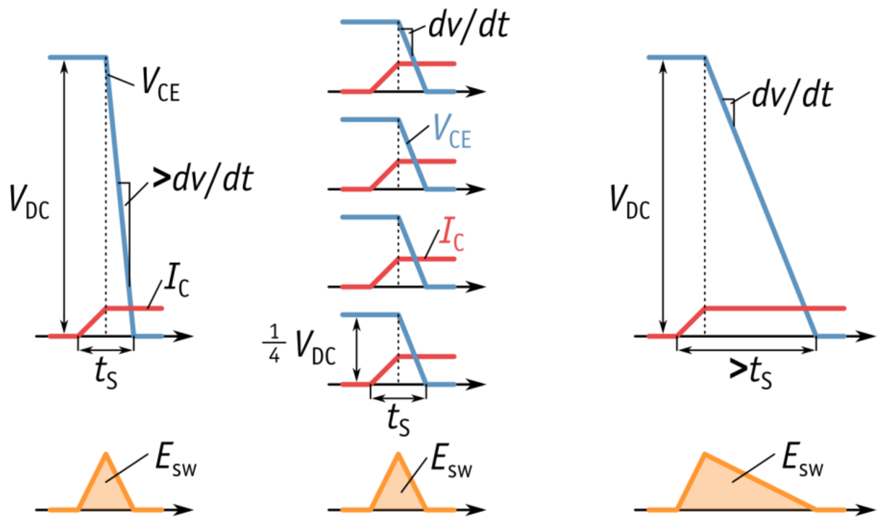
■ Modularity
■ Multilevel Output Volt.
  - $f_S \propto 1/n^2$ for Same Filter



▶ 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**

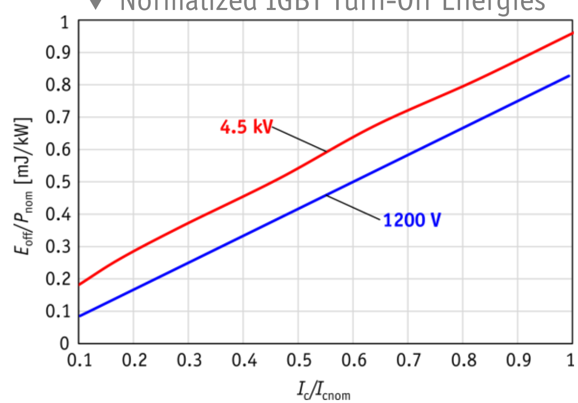




▶ Assumed

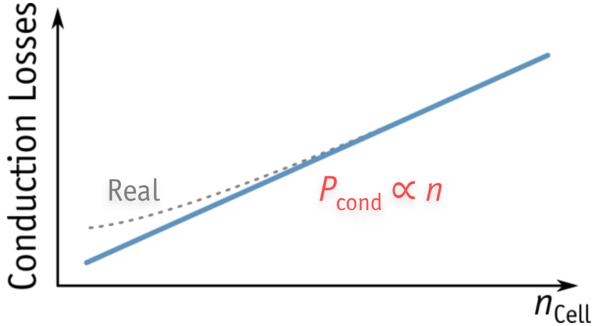
▶ Real ⟶ $P_{sw} \propto 1/n^{2...3}$

▼ Normalized IGBT Turn-Off Energies

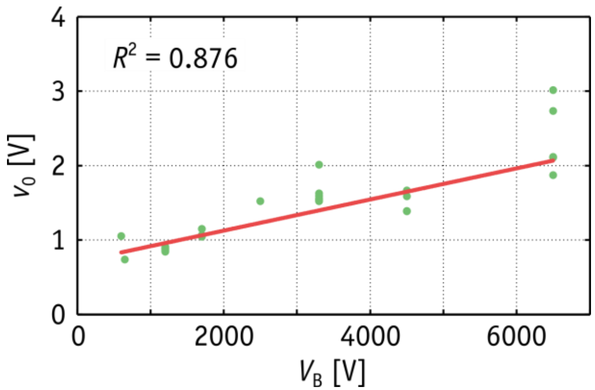


▶ Basic Trade-Offs Quantified: Conduction Losses

- **More Cells, More Series Voltage Drops (IGBTs):**



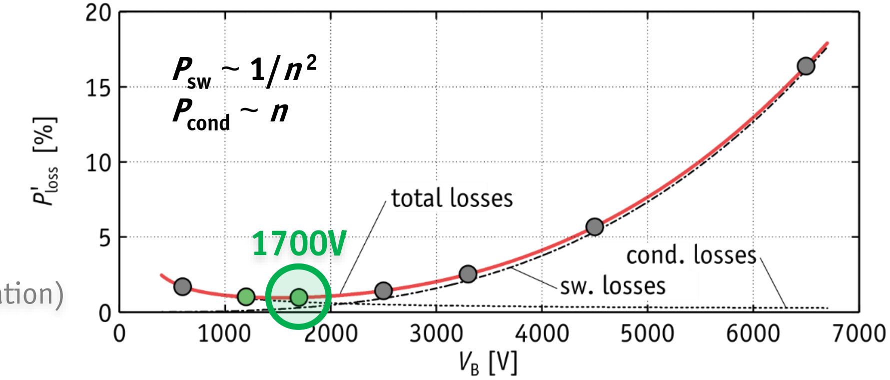
- **Reality: Voltage Drop Increases with Blocking Voltage Due to Larger Drift Region**



▶ Loss-Optimal Blocking Voltage Choice

■ **Semiconductor Blocking Voltage Choice Equivalent to Choice of Number of Cells Choice!**

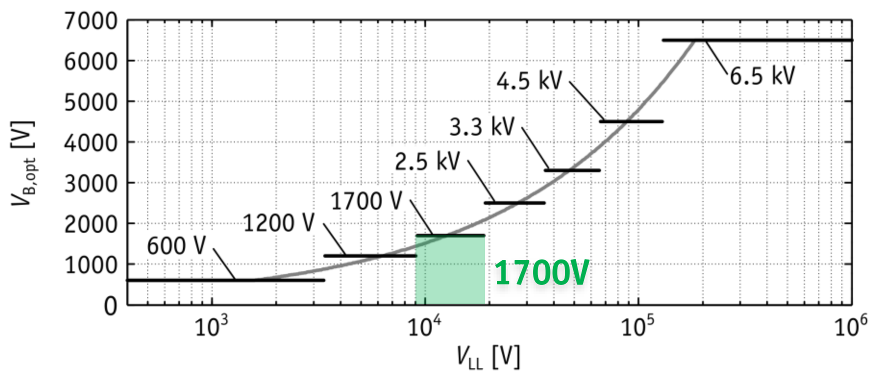
(For a 10kV Grid Application)



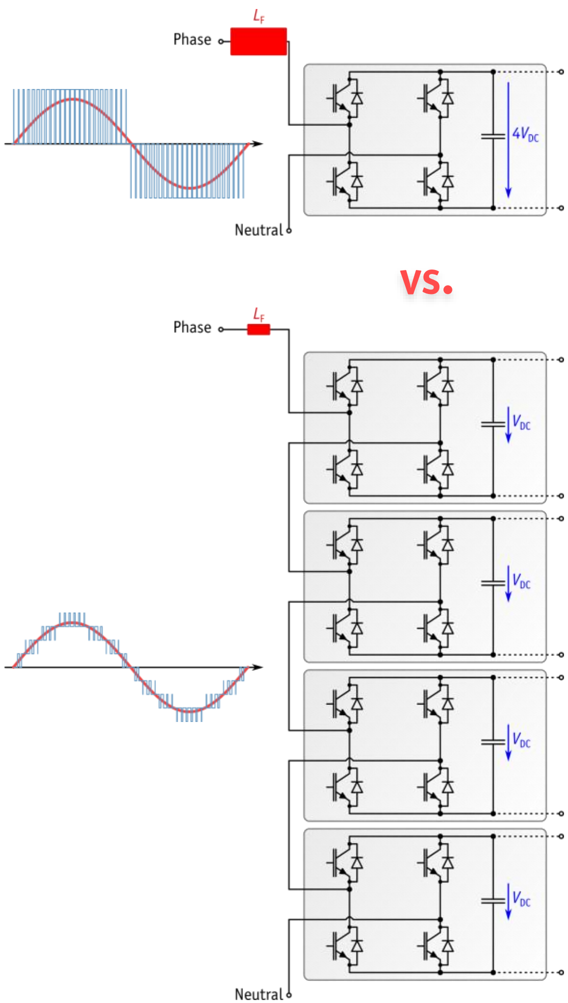
▶ **There *Is* an Optimum Blocking Voltage**

▶ **1200V or 1700V Devices Best for 10kV Line-to-Line Voltage Applications**

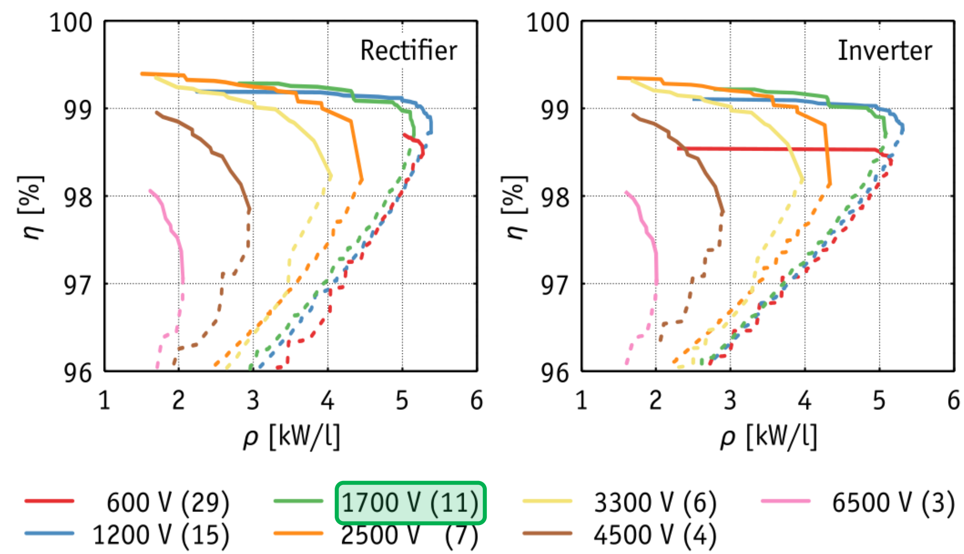
■ **Optimum Blocking Voltages for Other Grid Voltage Levels**



▶ Efficiency vs. Power Density Pareto Front



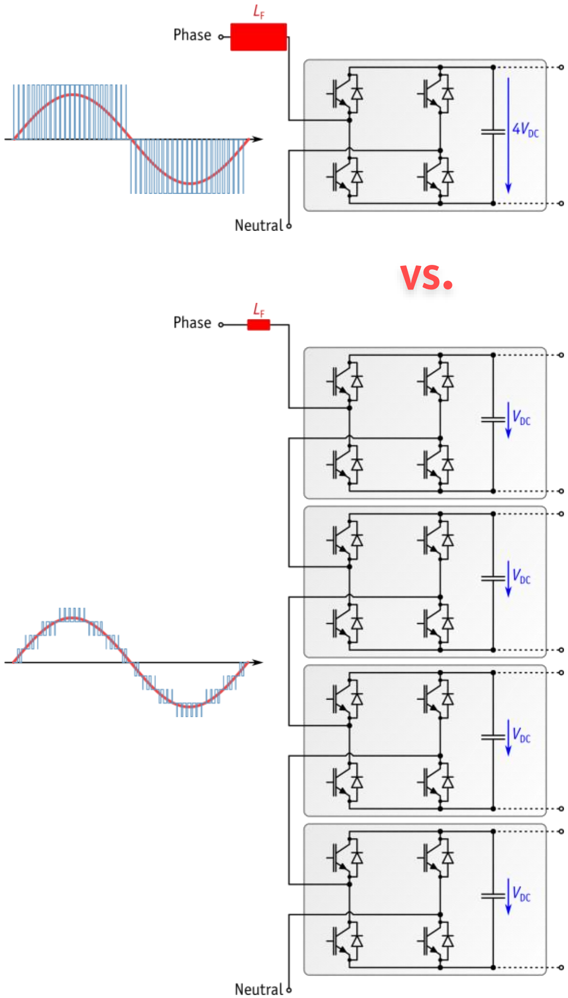
■ **Heavy-Duty Silicon IGBT Modules Considered: Max. 6.5kV < 10kV**



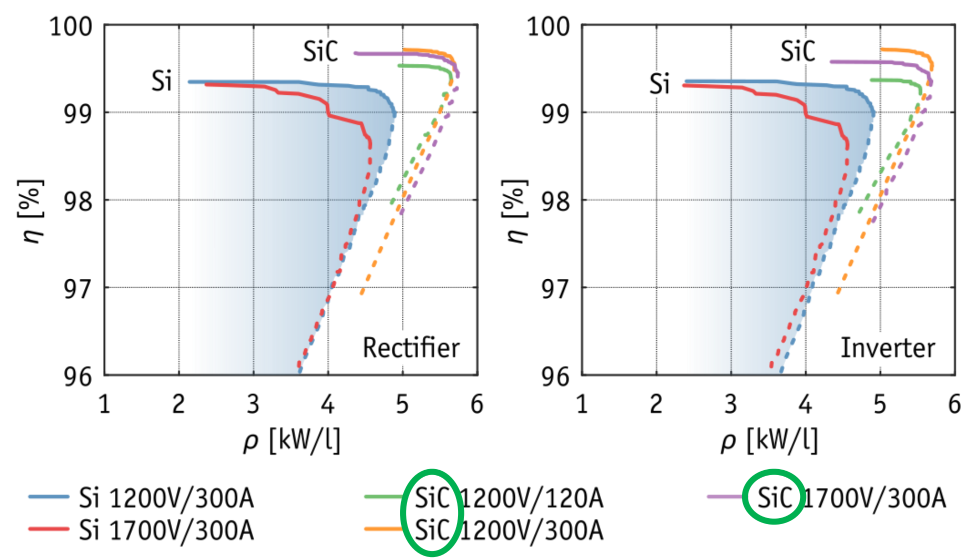
■ **Caution:** Minimum Filter Inductance Might be Required from Application-Dependent **Protection Considerations**

Further Reading: ETH / [Huber2013b]

► Efficiency vs. Power Density Pareto Front



■ **1200V and 1700V SiC FET Power Modules for Comparison**



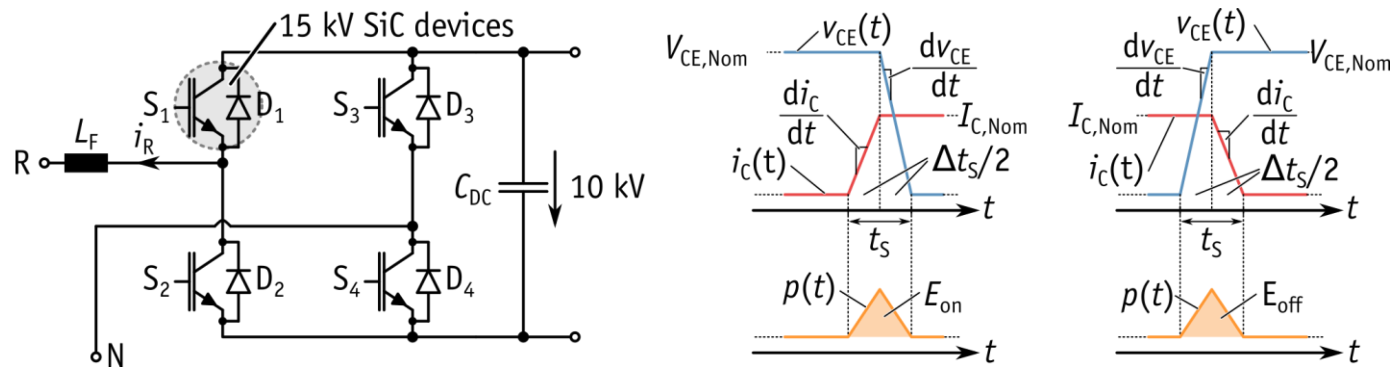
■ **Caution:** Minimum Filter Inductance Might be Required from Application-Dependent **Protection Considerations**

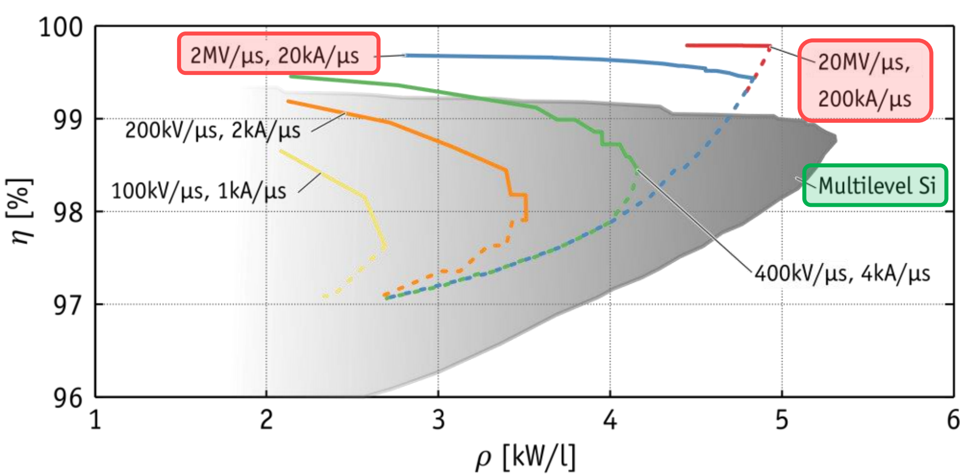
■ **Future: Higher Efficiency With LV SiC Power Modules**

Further Reading: ETH / [Huber2013b]

▶ Outlook: Comparison With Single-Cell Based on HV-SiC

- **Remember: $f_S \propto 1/n^2$**
  → Fast Switching Transitions Required To Avoid Excessive Switching Losses





- **Very Fast Switching Transitions**
  - High dv/dt → CM Disturbances
  - High di/dt → Overvoltages

▶ **Multilevel Solutions With LV (!) SiC Seem More Promising!**

▶ **Further Analysis Required...**

Further Reading: ETH / [Huber2013b]

Challenge #4/13

Reliability

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

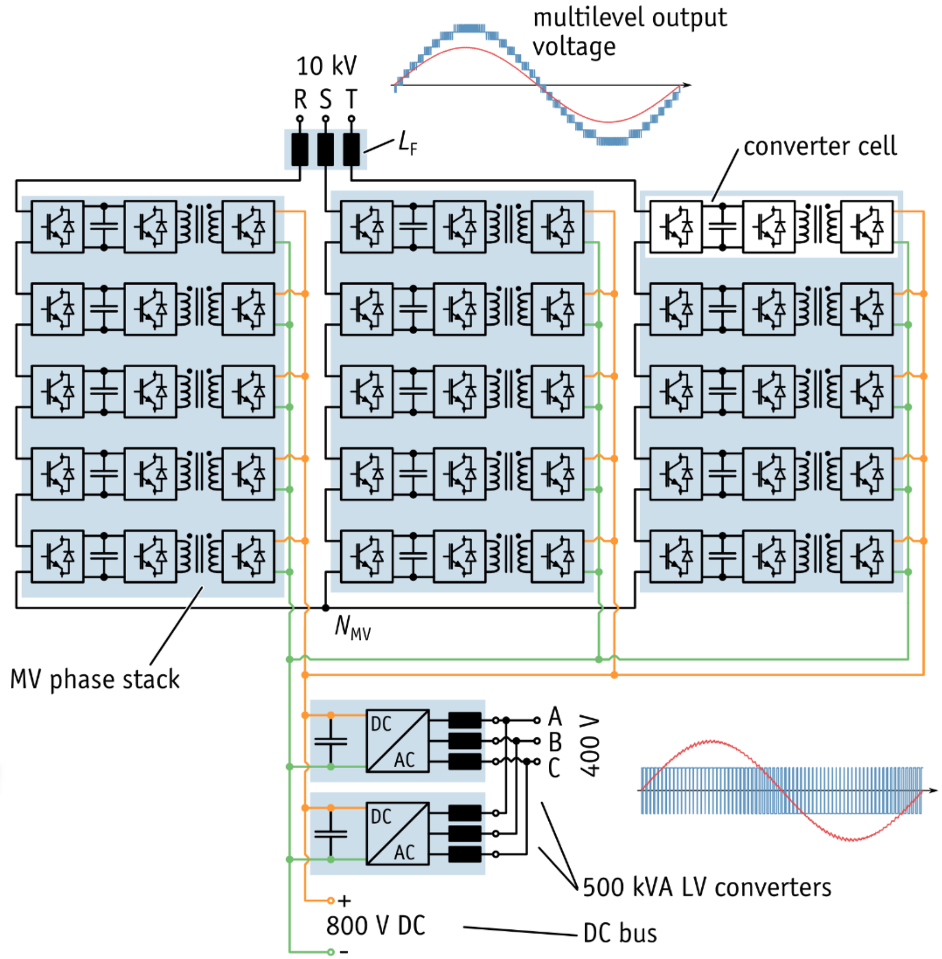
▶ Example System: ETH *MEGAlink* Distribution SST

■ Specifications

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

■ Commonly Envisioned Features

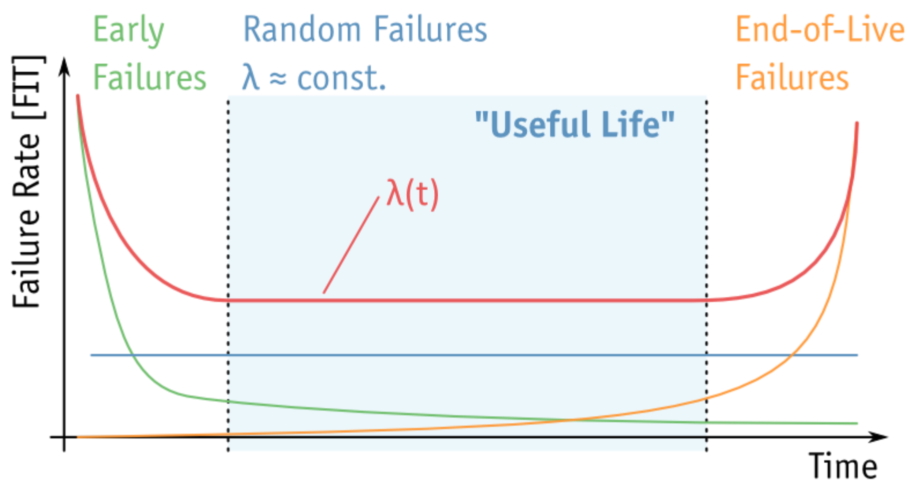
- Voltage Scaling & Galvanic Isol.
- Power Flow Control
- Reactive Power Compensation
- Fault Current Limiting
- DC Interface
- ...



■ Modular System → MANY Components!

▶ Can Such a System Still Be Reliable?

▶ Modeling Reliability: The Failure Rate

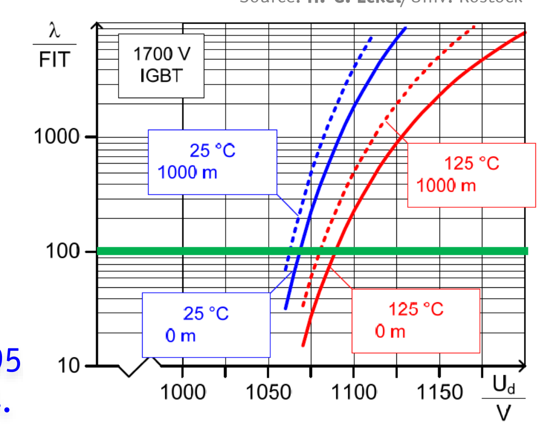


◀ *«Bathtub Curve»*

- **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 ▶

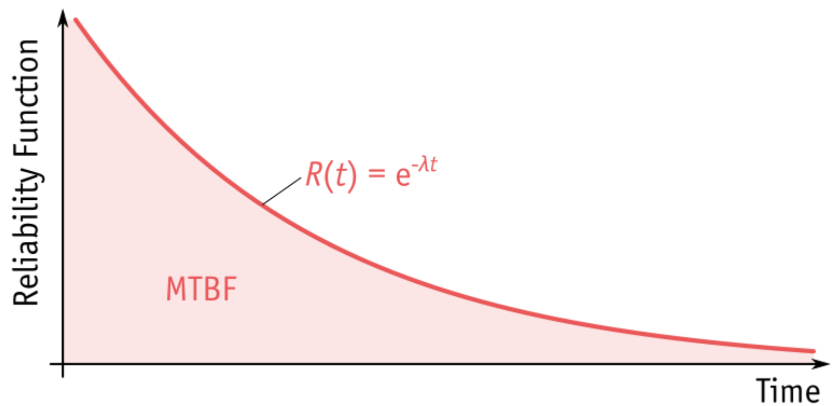
Source: **H.-G. Eckel**/Univ. Rostock



- **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:** $$R(t) = \mathrm{e}^{-\int_0^t \lambda(x)dx}$$
- **During Useful Life: $\lambda(t)$ = const. = λ:**



- **Then: Mean Time Between Failures:** $$MTBF = \int_0^\infty R(t)dt = \int_0^\infty \mathrm{e}^{-\lambda t}dt = \frac{1}{\lambda}$$

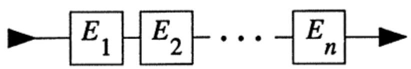
Caution: MTBF is Not the Time Before Which No Failure Occurs – It's All Statistics!

- **Average Availability:** $$A = \frac{MTBF}{MTBF + MTTR}$$

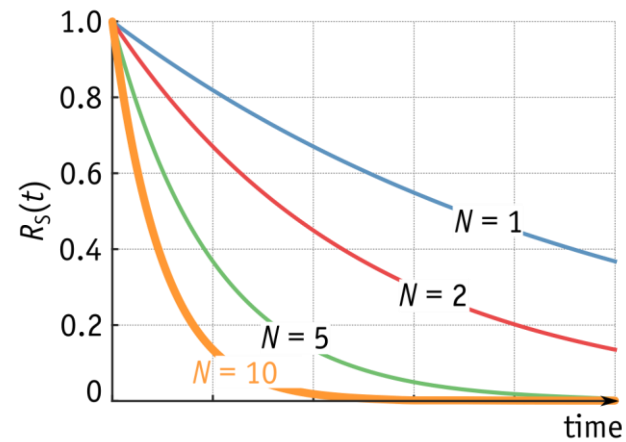
Textbook: [Birolini1997]

▶ Modeling Reliability: Basic Multi-Element Considerations

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



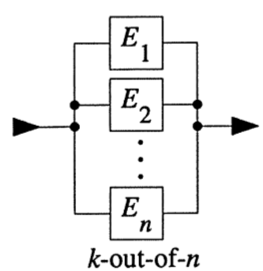
$$\lambda_S = \sum_{i=1}^{n_{\text{comp.}}} \lambda_i$$



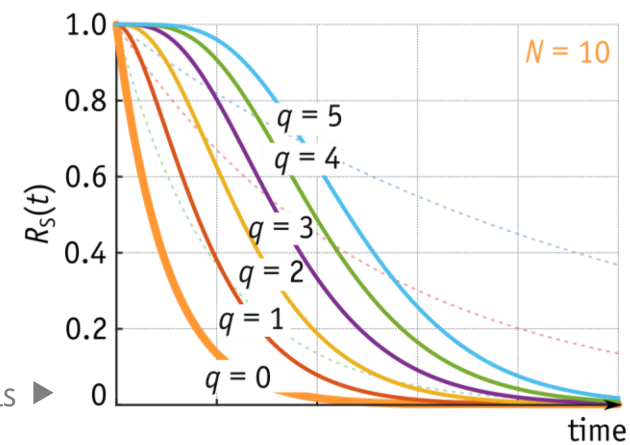
(General Assumption: Independent Elements with Equal Failure Rate.)

■ *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* Sub-systems (Cells) Are Operational

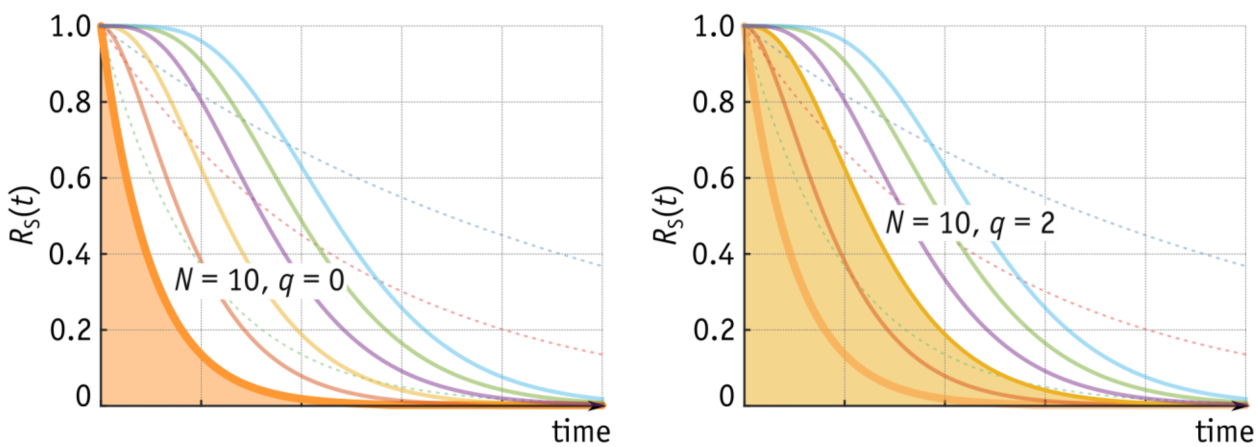


Effect of *q* Additional Redundant Cells ▶



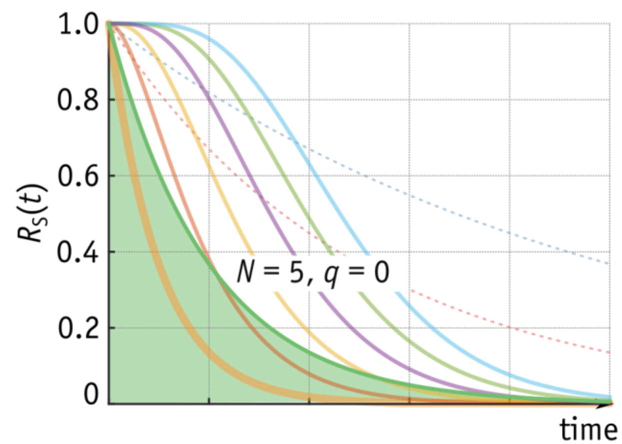
Textbook: [Birolini1997]

▶ The "Power of Redundancy" (1)



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

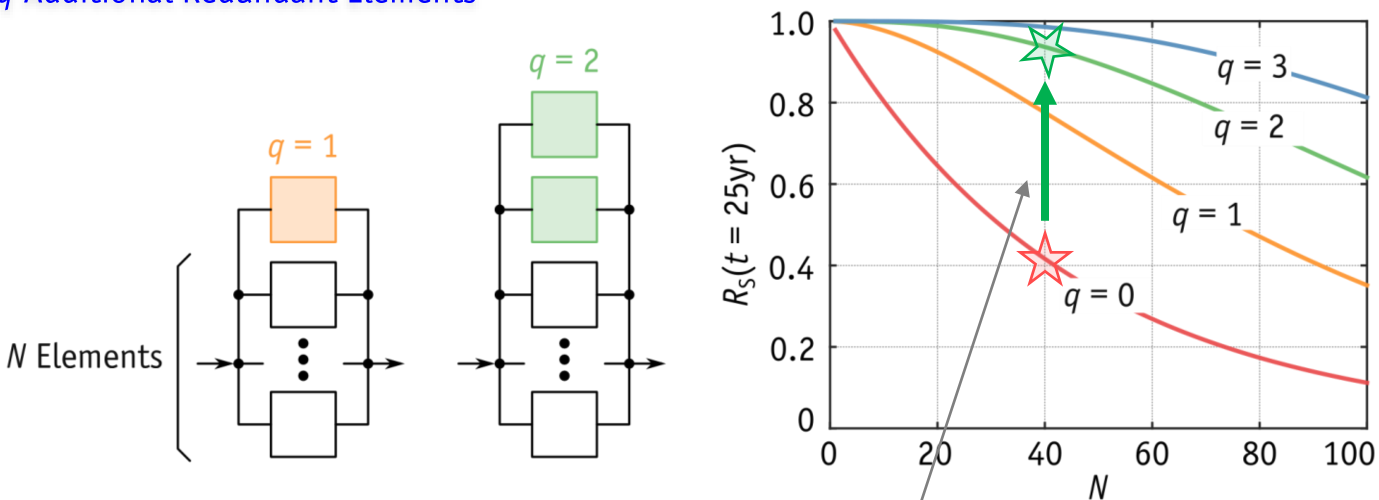
- **Redundancy Can Significantly Improve System Level Reliability**
  - 10 Elements + 2 Redundant: Reliability Higher than for 5 Elements!



▶ The "Power of Redundancy" (2)

■ Value of Reliability Function at t = 25 years

- N Elements
- q Additional Redundant Elements



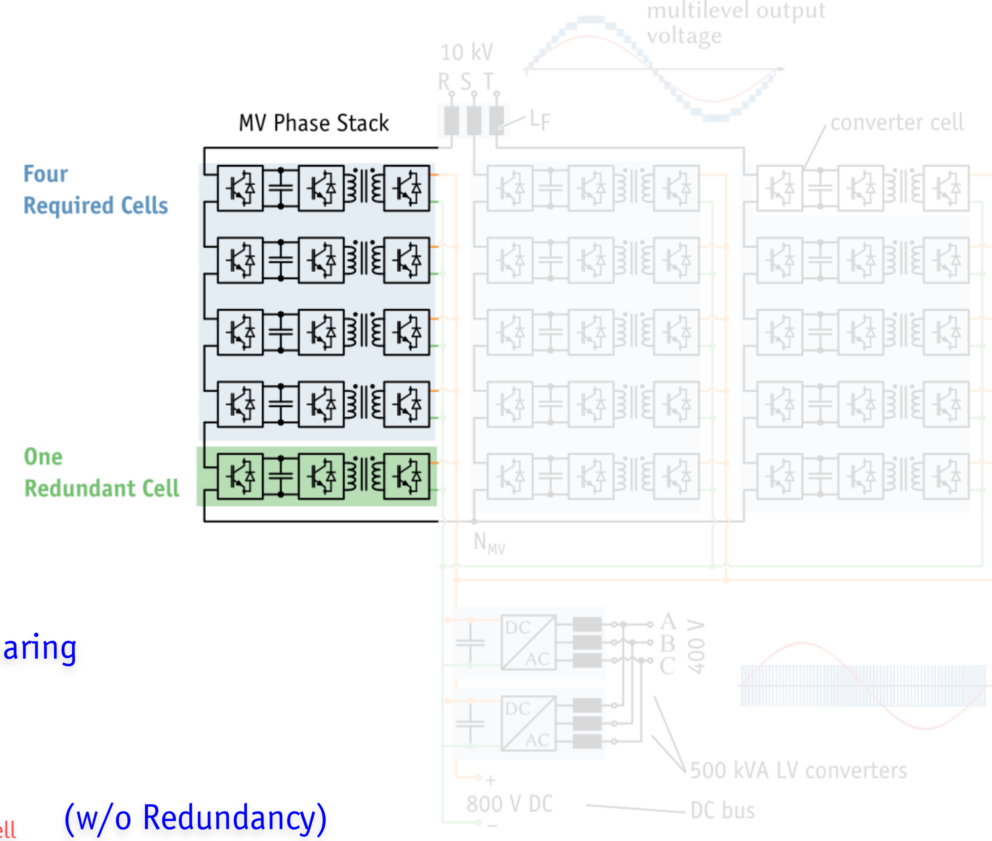
■ Redundancy Can Significantly Improve System Level Reliability

- E.g., for N = 40: from 40% to > 90% with 2 Additional Redundant Cells

Example System: Cell Redundancy

- **Modular System**
  - **Simple Implementation of Cell Redundancy!**

Example:
4-out-of-5 Redundancy



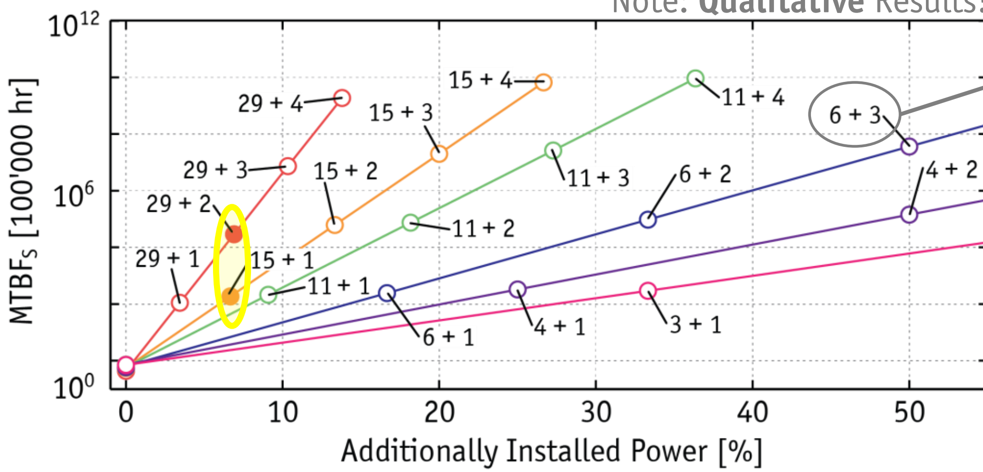
- **Redundancy Concepts**
  - Standby Redundancy
  - Active Redundancy with Load Sharing

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

► Example System: Cell Redundancy and Reparability

- **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

Note: **Qualitative** Results!



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

- **Multi-Cell Designs Can Still Be Made Highly Reliable By Adding Redundancy!**
  - Therefore: Reliability Considerations Do not Prevent the Choice of the $\eta\rho$-Optimal Number of Cells
- **Preventive Maintenance Can Further Improve System Availability**

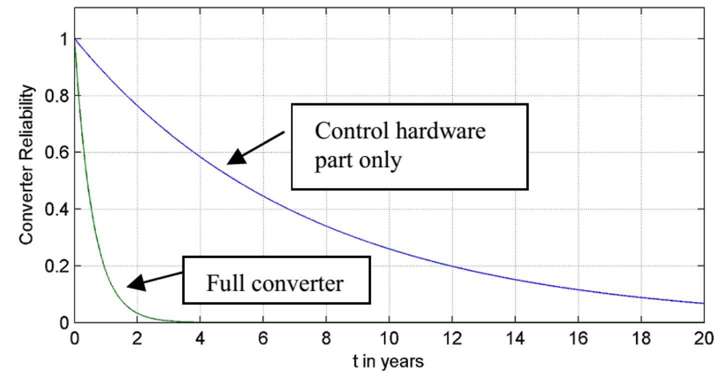
Further Reading:
ETH / [Huber2013b]

▶ Reliability “Bottlenecks” (1)

■ **Reliability Improvement by Means of Cell-Level Redundancy**

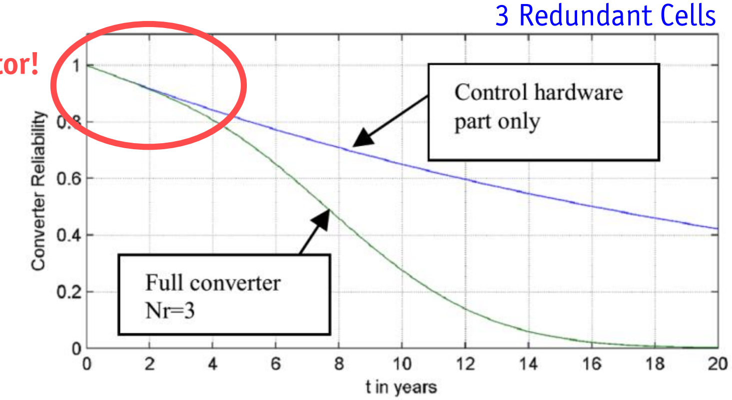
- Very Effective
- But **Limited** by Other Parts of the Converter System
  - Control
  - Auxiliary Supplies
  - Communication
  - Bypass Devices
  - ...

No Redundancy



Control Hardware Becomes Limiting Factor!

3 Redundant Cells

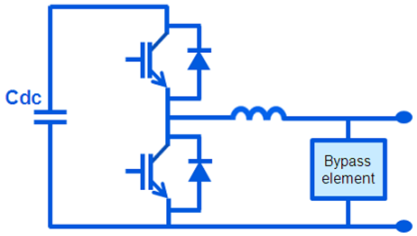


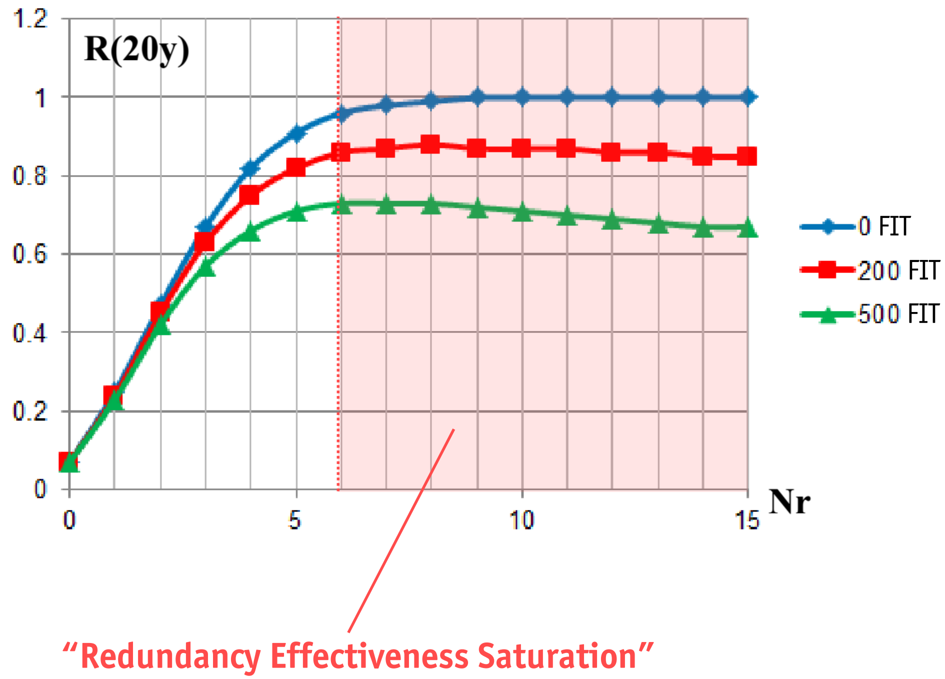
[Grinberg2013]

▶ Reliability "Bottlenecks" (2)

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

- Analysis for MMLC Converter





[Grinberg2013]

▶ Reliability Considerations for SST Design

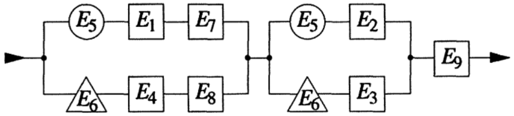
- **Remember: Conventional Transformers are Highly Reliable and Robust**
  - Copper, Iron and Oil

vs.

  - High # of Semiconductors, Gate Drives, Measurement and Control Electronics, Cooling Systems, ... (!)

Welding Transformer
Source: http://www.africancrisis.org

- **Very High Reliability Requirement for Grid and Traction Equipment**
- **Include Reliability Considerations Early in the SST Design Process**
  - Reliability Block Diagrams
  - Design for Reliability Approach [Wang2013]
  - Etc.



Textbook: [Birolini1997]

Challenge #5/13

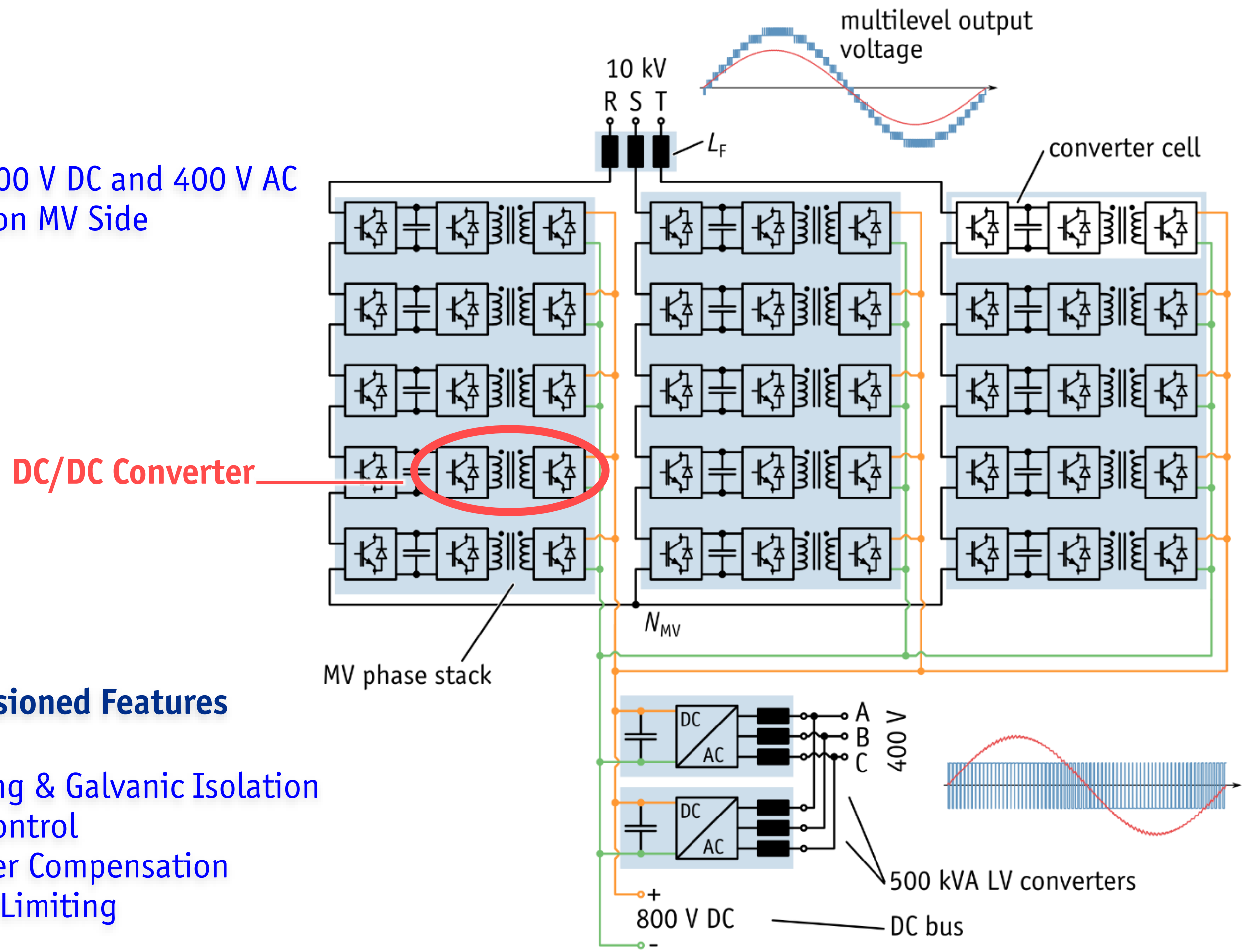
MF Isolated Power Converters

Dual Active Bridge
HC-DCM Series Resonant Converter

▶ 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

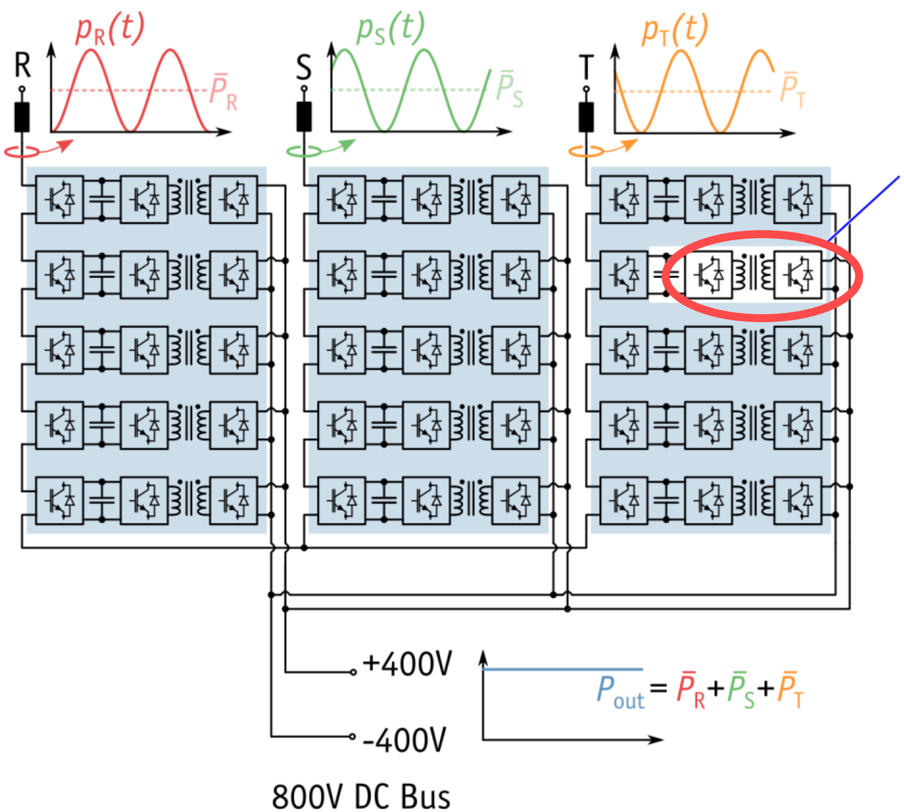


■ Commonly Envisioned Features

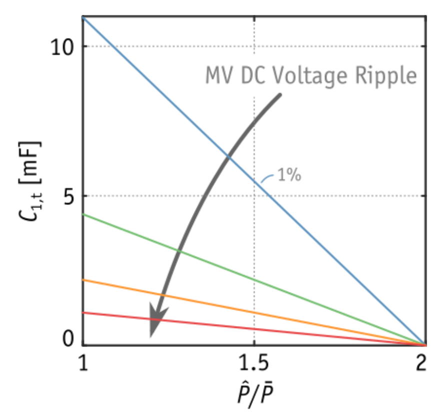
- Voltage Scaling & Galvanic Isolation
- Power Flow Control
- Reactive Power Compensation
- Fault Current Limiting
- DC Interface
- ...

▶ Power Flows in Phase-Modular Solid-State Transformers

- **MV: 100 Hz (120 Hz) Power Fluctuation in Single-Phase Systems**



- **Converter Cell = ARU + Isol. DC/DC**
  - DC/DC: Fixed Voltage Transfer Ratio
- **DC/DC Power Flow Options**



- Transmission ⟷ Buffering of Single-Phase Power Fluctuation
- RMS Losses ⟷ Capacitor Volume

- **LV: Constant Power Behavior of Three-Phase Systems**

Challenge #4/13

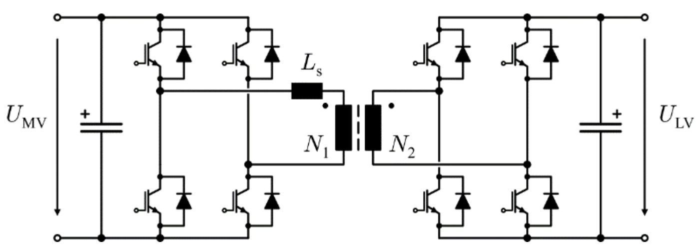
MF Isolated Power Converters

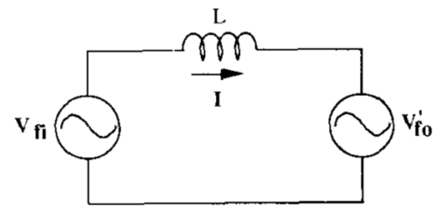
Dual Active Bridge

HC-DCM Series Resonant Converter

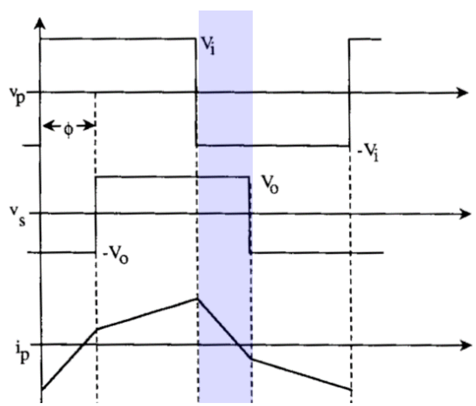
▶ Phase-Shift Modulation

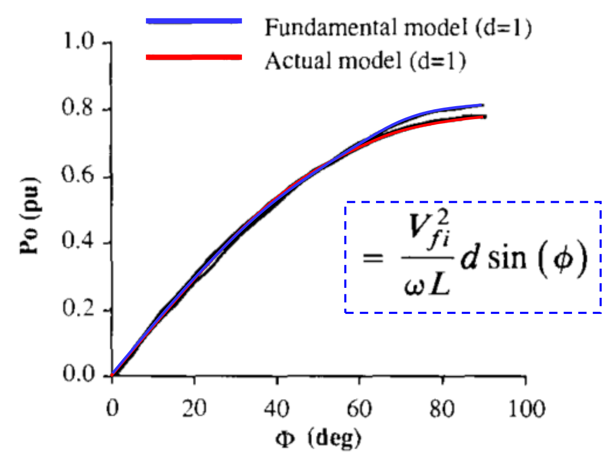
■ Power Transfer Controlled through Phase Shift between MV and LV Bridges





Fundamental model of the dual bridge dc/dc converter.



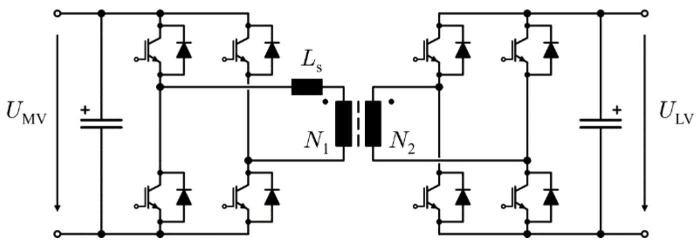


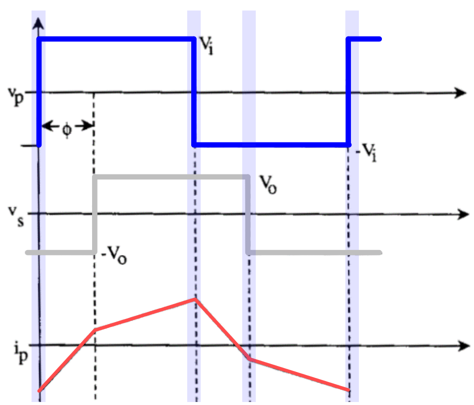
Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

[DeDoncker1989]

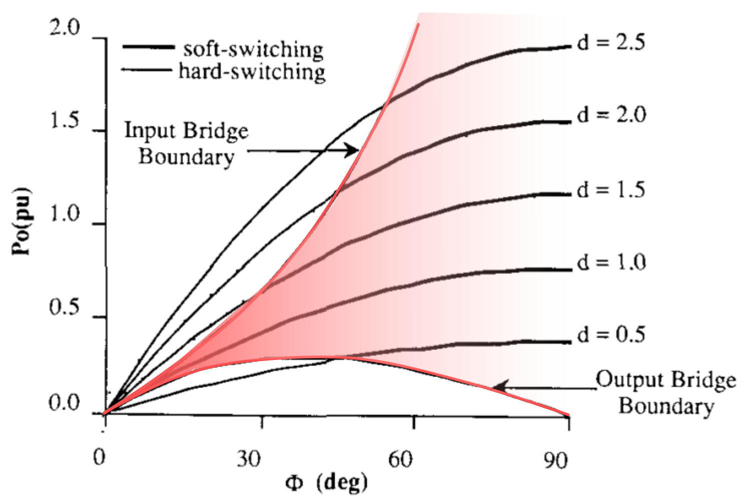
▶ Phase-Shift Modulation (2)

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



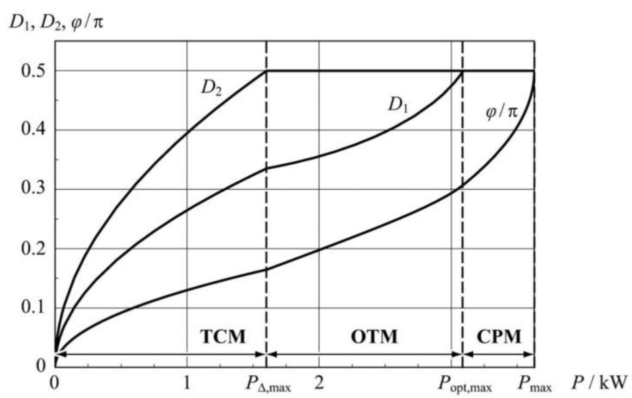


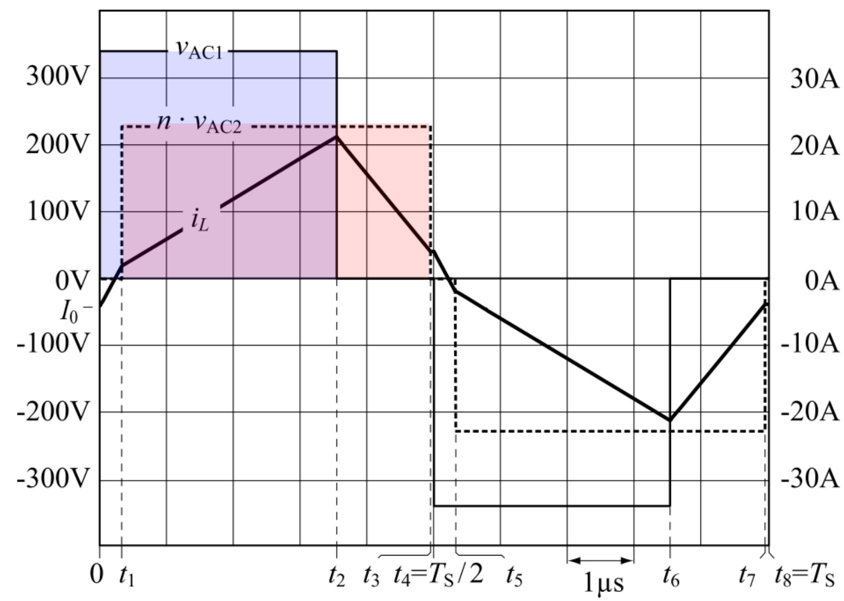
▶ Soft Switching Range



▶ 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)



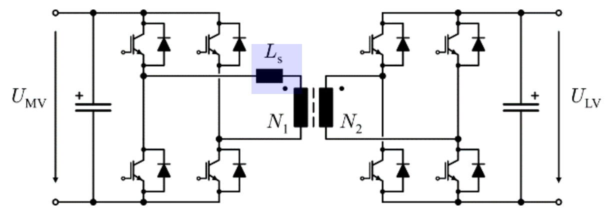


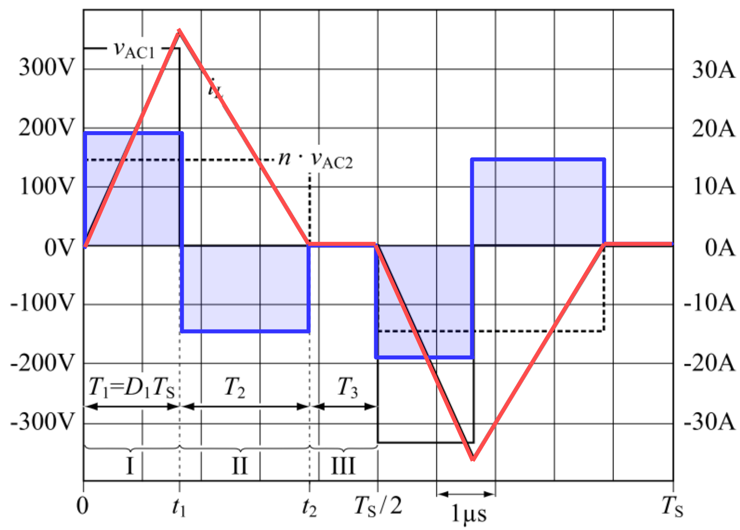
- Not Possible in Half-Bridge Configurations (No Zero Voltage Intervals)

[Krismer2012]

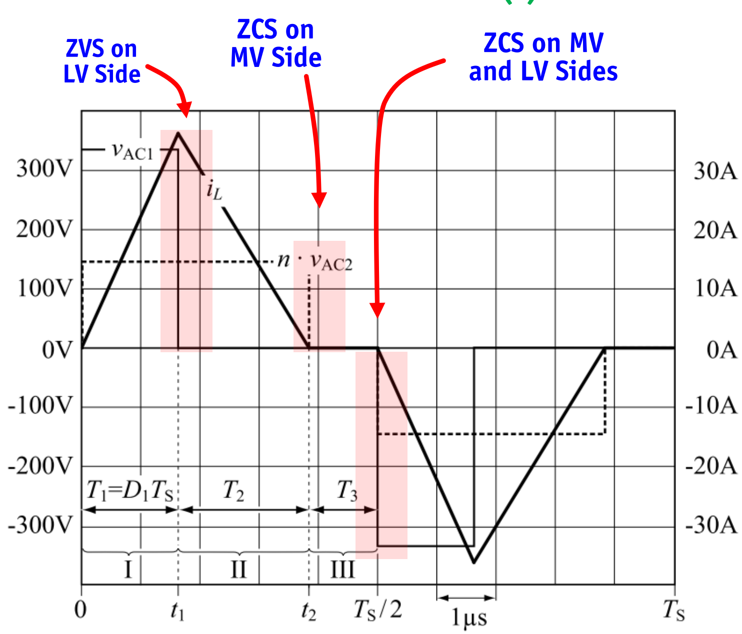
▶ Triangular Current Mode

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



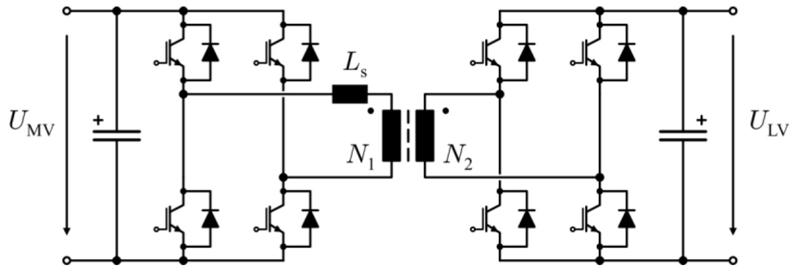


▶ ZCS on MV Side (!)



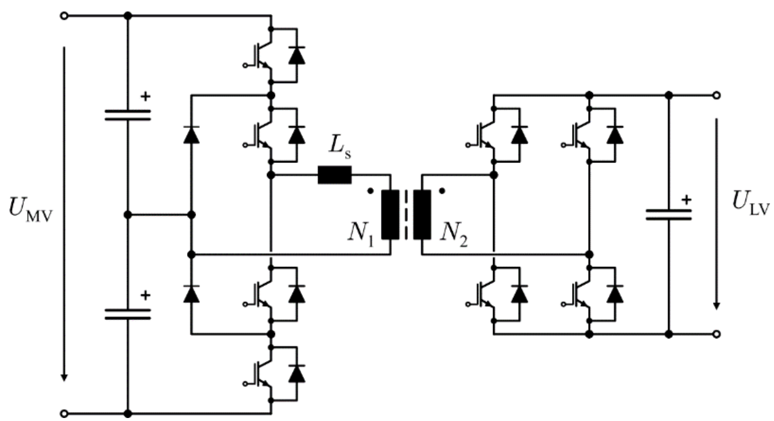
▶ Common Bridge Configurations

■ Full-Bridge



- Three Voltage Levels on Each Side

■ NPC / Full-Bridge Configuration



- Suitable for Higher MV/LV Ratios

■ Other Configurations Possible (Half-Bridge / Half-Bridge, etc.)

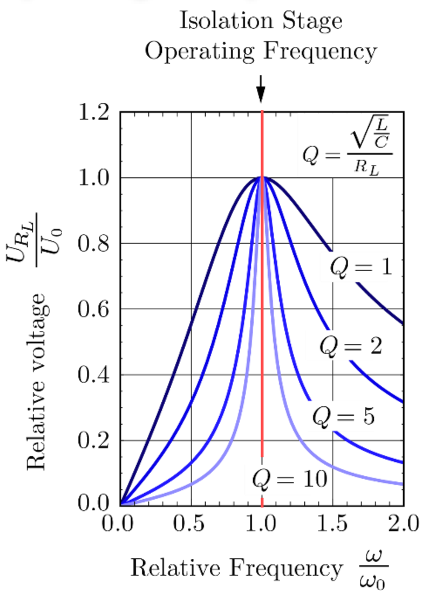
Challenge #5/13

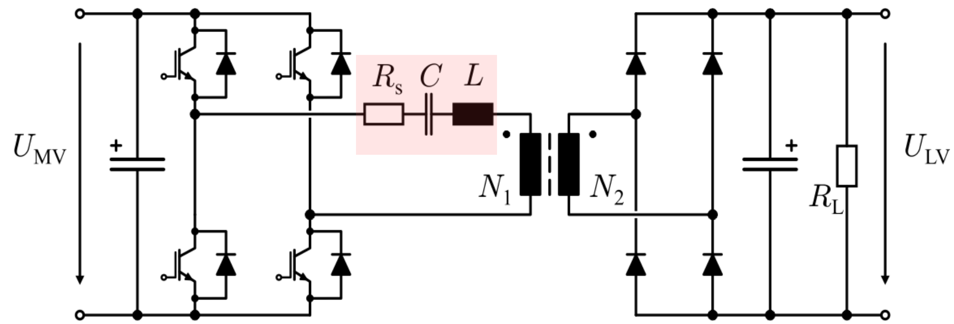
MF Isolated Power Converters

Dual Active Bridge
HC-DCM Series Resonant Converter

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

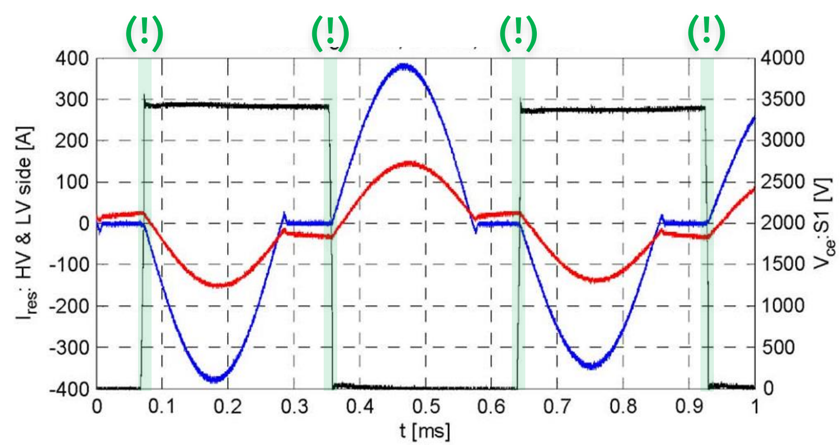
- **Operating Principle:** Resonant Frequency ≈ Switching Frequency





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

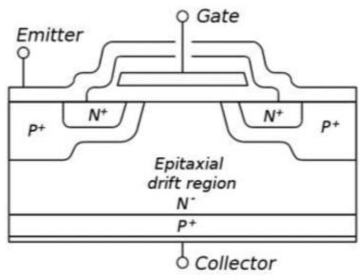
ZCS of All Devices ▶

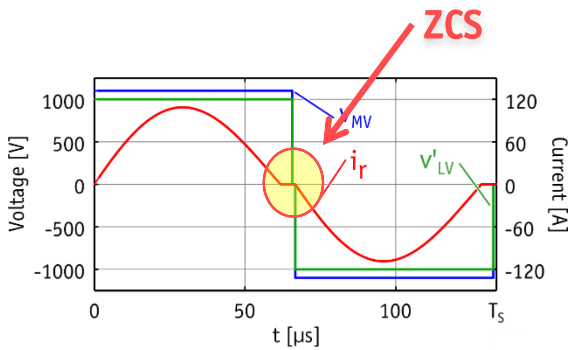


Img.: [Zhao2014]

► ZCS Losses in IGBTs – Stored Charge Effects

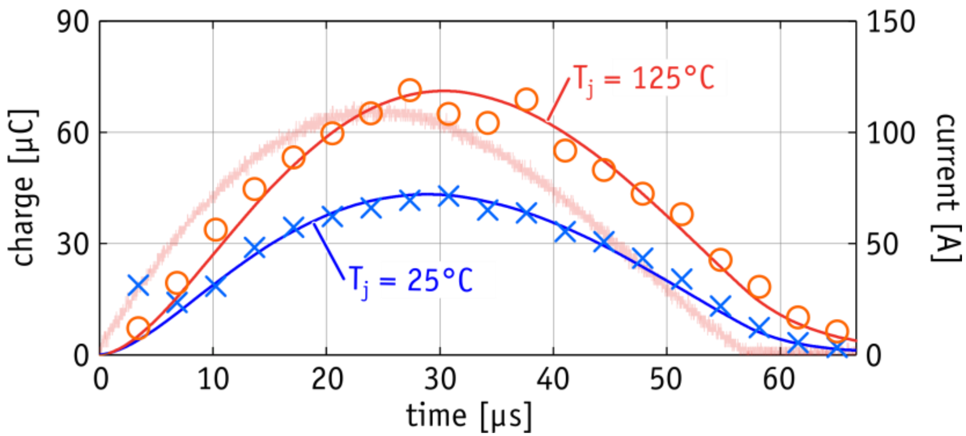
- **Bipolar Device: Free Charges in Drift Region to Modulate Conductivity**





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

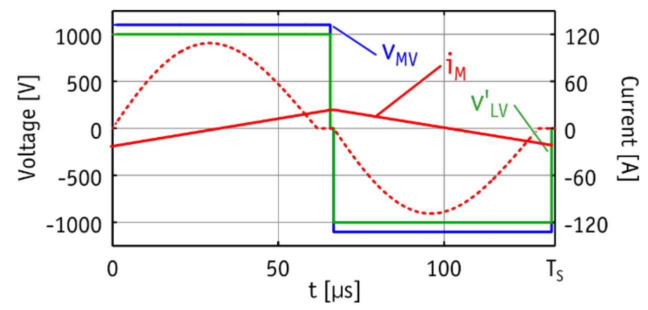
Calculated and Measured Stored Charge in 1700V/150A IGBT4. ▶

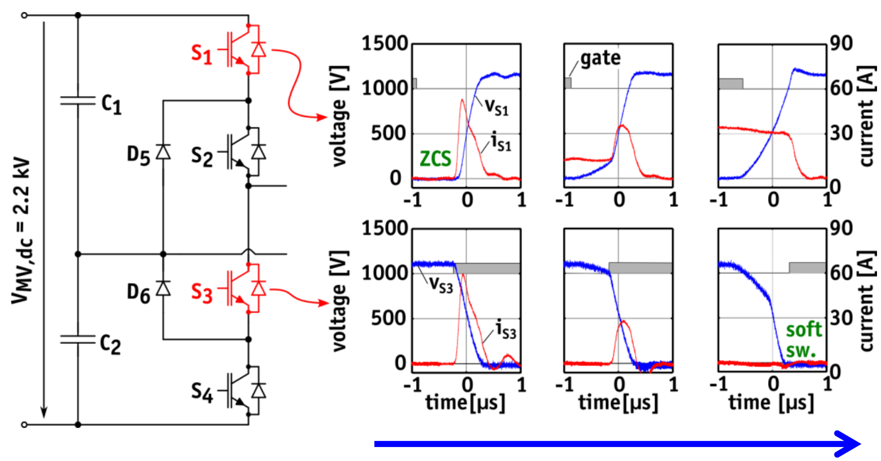


[Ortiz2012], [Huber2013a]

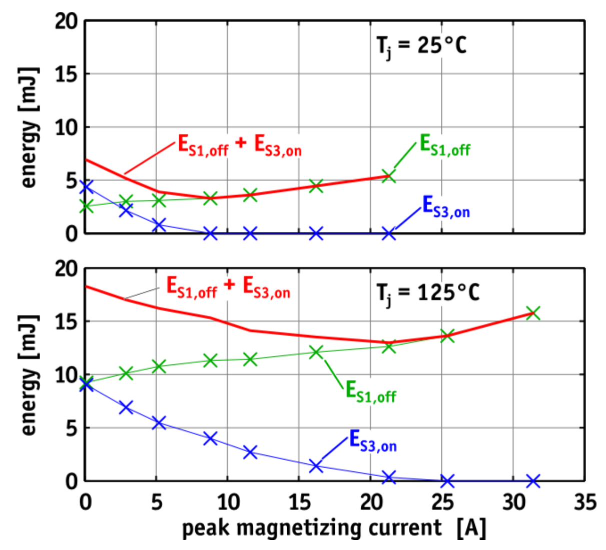
▶ Residual Current Switching – ZVS

- **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!**



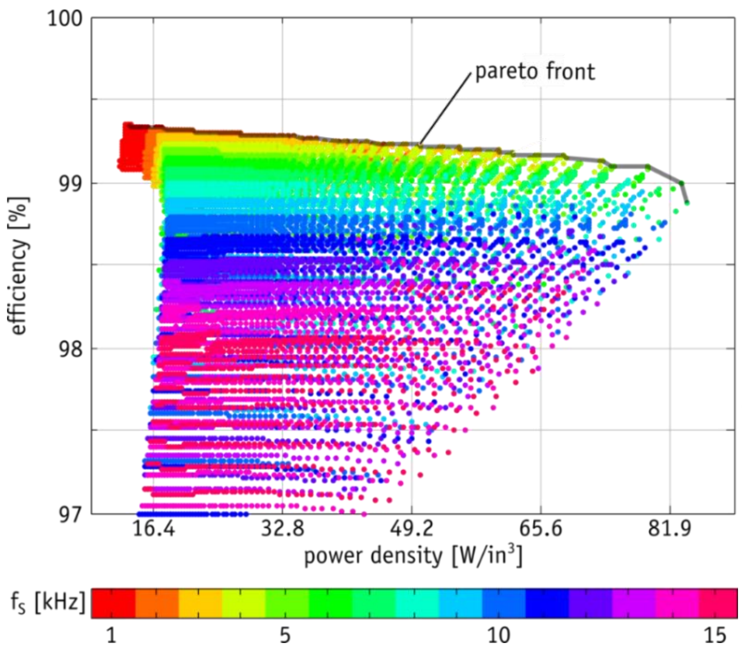


Increasing Magnetizing Current

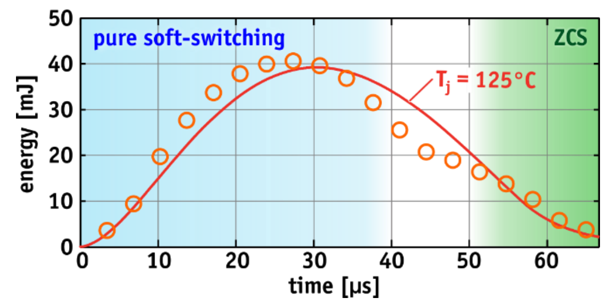


▶ Pareto Optimization of HC-DCM SRC

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



Specs:
80kW
2.2kV → 800V



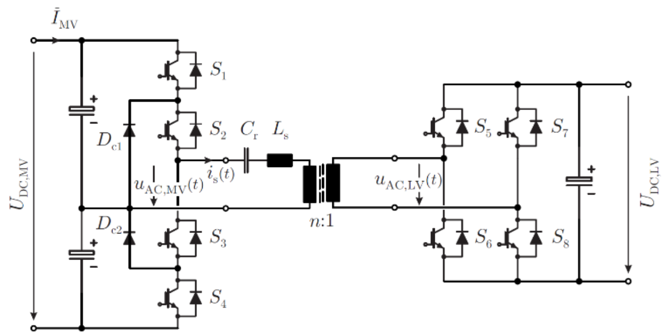
▲ ZCS Loss Modeling and Verification

- **HC-DCM-SRC Is Capable of Reaching Efficiencies of 99%+**
- **The Optimum Frequency at which a 99% Efficiency is Reached is about 7kHz (with Si IGBTs)**

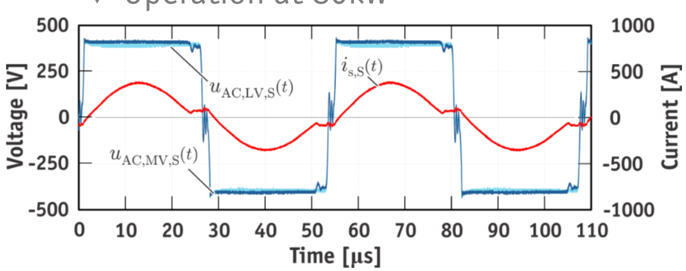
Further Reading: ETH / [Huber2013a]

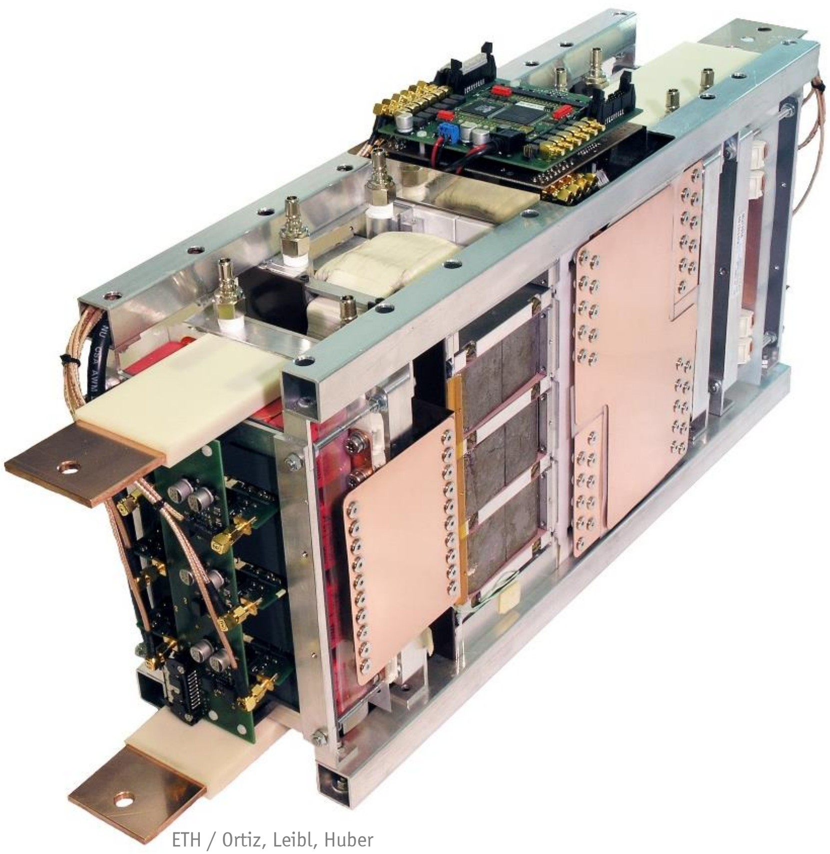
▶ 166kW / 20kHz HC-DCM-SRC DC-DC Converter Cell

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



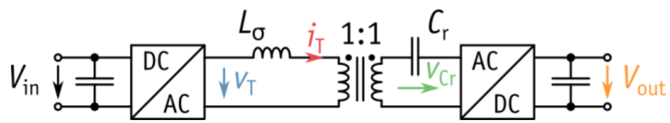
▼ Operation at 80kW





ETH / Ortiz, Leibl, Huber

▶ HC-DCM SRC Operating Principle



- Source Bridge → Actively Switched Only
- Sink Bridge → Operated Passively (Diodes)

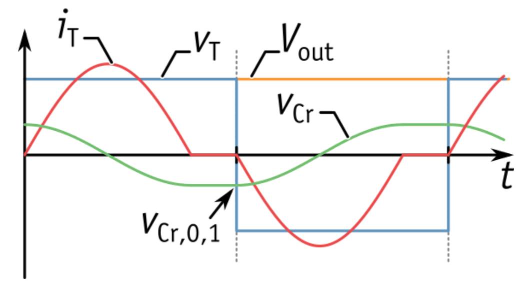
- **Ideal (Lossless Components)** →
  → Steady State: $V_{out} = V_{in}$

- **Real**
  → Steady State: $V_{out} \approx V_{in}$
  (Deviation Due to Losses)

  → Tight Coupling of DC Input and Output Voltages

- **Steady State 1**

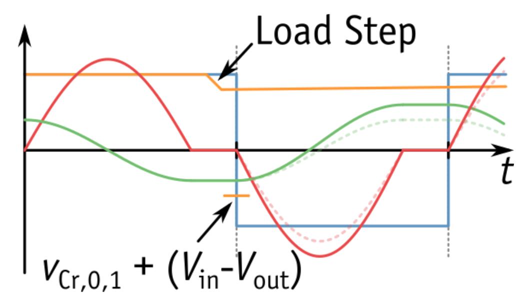
$$\hat{\imath}_{T,1} = \frac{\hat{v}_{Cr,0,1}}{Z_0}$$
$$V_{out} = V_{in}$$



- **Disturbance**

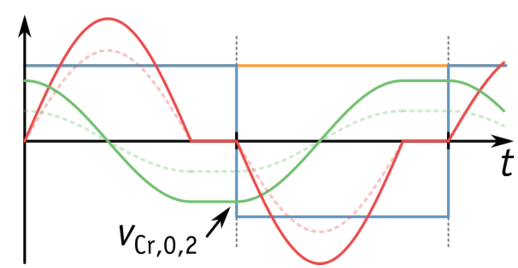
$$V_{out} \neq V_{in}$$

→ Add. Excit. Volt.



- **Steady State 2**

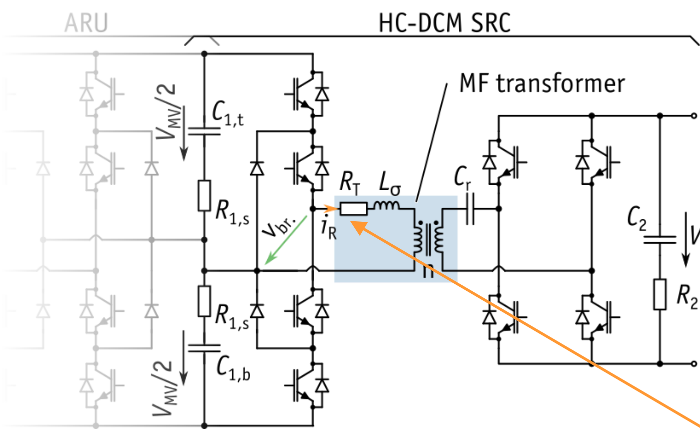
$$\hat{\imath}_{T,2} = \frac{\hat{v}_{Cr,0,2}}{Z_0}$$
$$V_{out} = V_{in}$$



▶ **Acts as "DC Transformer" with Certain Dynamics!**

▶ **No Control Possible/Required!**

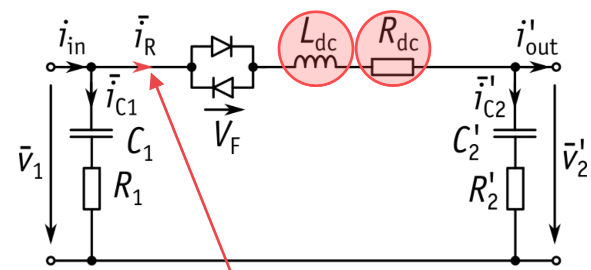
▶ HC-DCM SRC Dynamic Modeling of Terminal Behavior

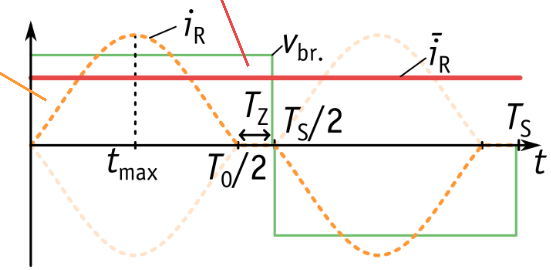


[Esser1991]

■ **Dynamic Equivalent Circuit** [Steiner2000]

- Modeling of Terminal Behavior
- Based on Local Average Current, $\bar{i}_R$
- (MV-Referred)





■ **How to Choose Eq. Circ. Element Values?**

- R_{dc} (Equal RMS Losses):

$$\bar{i}_R^2 R_{dc} \stackrel{!}{=} \tilde{i}_R^2 R_{total} \quad \Rightarrow \quad R_{dc} = \frac{\tilde{i}_R^2}{\bar{i}_R^2} R_{total} = \beta^2 R_{total}$$

- L_{dc} (Equal Stored Energy):

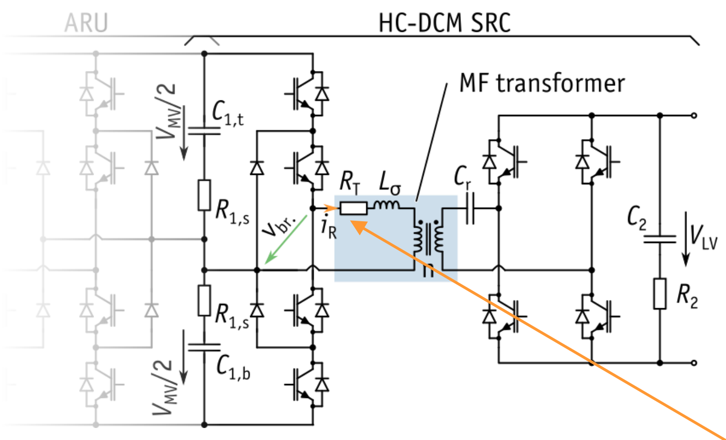
$$\bar{i}_R^2 L_{dc} \stackrel{!}{=} \hat{i}_R^2 L_\sigma \quad \Rightarrow \quad L_{dc} = \frac{\hat{i}_R^2}{\bar{i}_R^2} L_\sigma = \alpha^2 L_\sigma$$

- For Piecewise Sinusoidal Current:

$$\alpha = \frac{\pi}{2} \cdot \frac{f_0}{f_s} \qquad \beta^2 = \frac{\pi^2}{8} \cdot \frac{f_0}{f_s}$$

Further Reading: ETH / [Huber2015]

▶ HC-DCM SRC Dynamic Modeling of Terminal Behavior



[Esser1991]

■ **Dynamic Equivalent Circuit** [Steiner2000]

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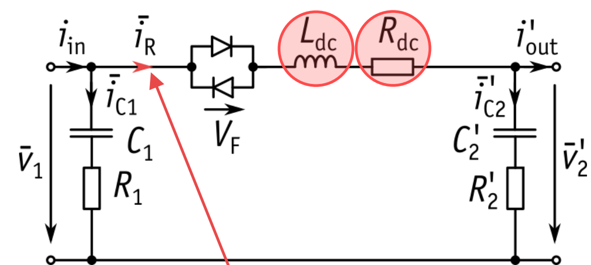
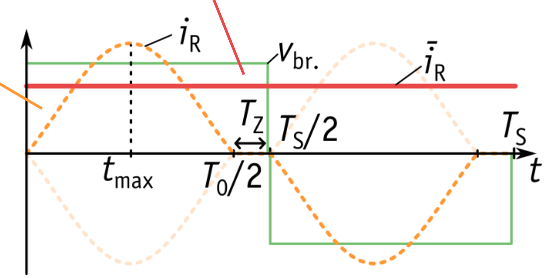
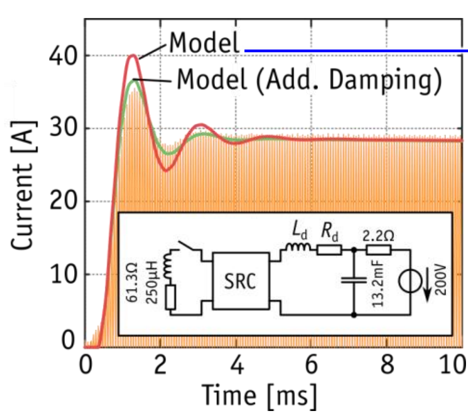
- (MV-Referred)





■ **Model vs. Measurement:**



$$\alpha := \frac{\hat{i}_R}{\bar{i}_R}$$

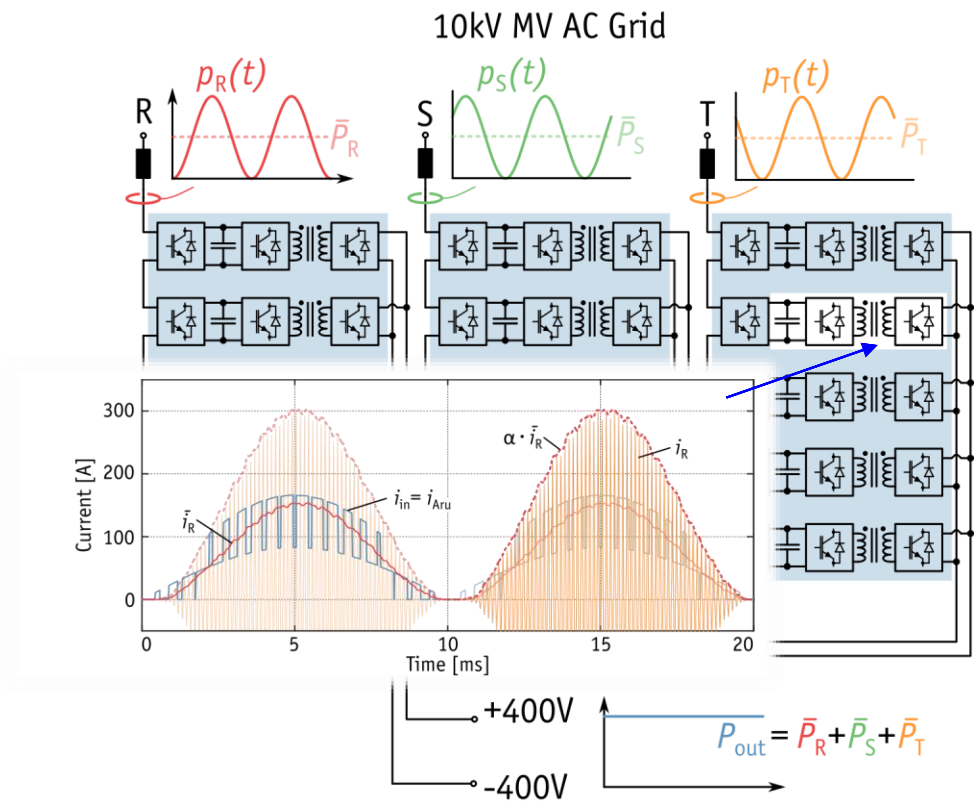
- For Piecewise Sinusoidal Current:

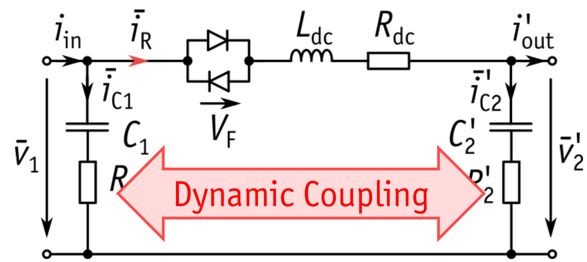
$$\alpha = \frac{\pi}{2} \cdot \frac{f_0}{f_s} \qquad \beta^2 = \frac{\pi^2}{8} \cdot \frac{f_0}{f_s}$$

Further Reading: ETH / [Huber2015]

► Again: Power Flows in Phase-Modular SSTs

- **MV: 100 Hz (120 Hz) Power Fluctuation in Single-Phase Systems**





- **HC-DCM SRC Dynamics**
  - MV DC Volt.: 100 Hz Fluct.
  - LV DC Volt.: Constant

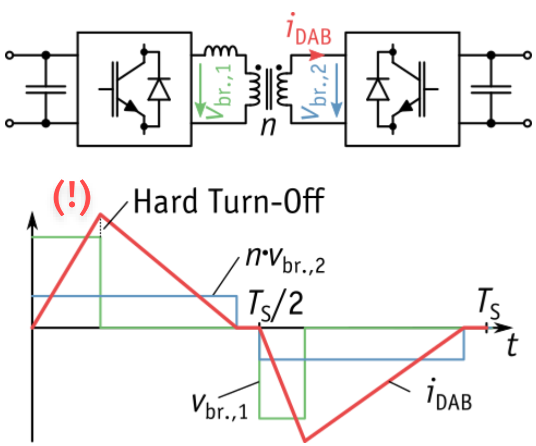
- **Transmission of Full Single-Phase Power Fluctuation!**
  - Higher RMS Current (23%)
  - Appropriate Dimensioning

- **LV: Constant Power Behavior of Three-Phase Systems**

Further Reading: ETH / [Huber2015]

▶ Realization Options for DC/DC Converters in SST Cells

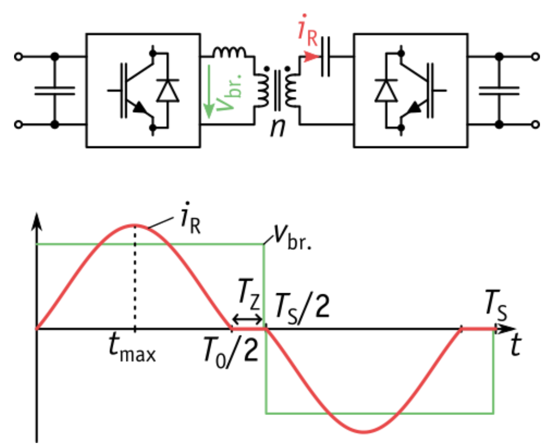
- **Dual Active Bridge**
  (DAB)



- **Can (Must!) Be Fully Controlled**
  - Arbitrary Choice in Losses ↔ Capacitor Volume Trade-Off

- **Switching at Peak Current (Losses!)**

- **Half-Cycle Discontinuous-Conduction-Mode SRC**
  (HC-DCM SRC)



- **Zero-Current Switching (ZCS!)**
- **Zero-Current Interval, T_z: Optimization Param.**
  (Conduction ↔ Switching Losses)

- **Can Not (Must Not!) Be Controlled (!)**

▶ **Predominant Solution in Multi-Cell SSTs!**

Challenge #6/13

MF Transformer Design

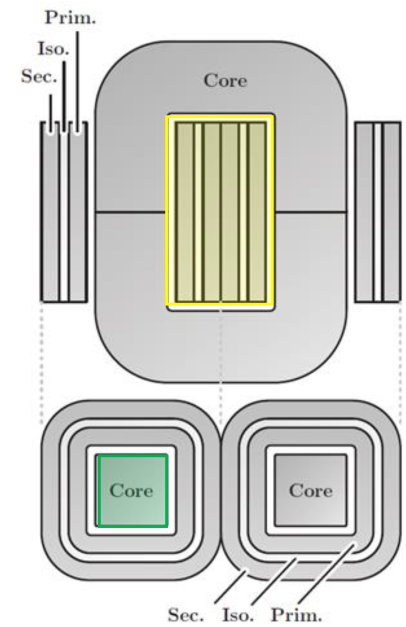
Transformer Types
Litz Wire Issues

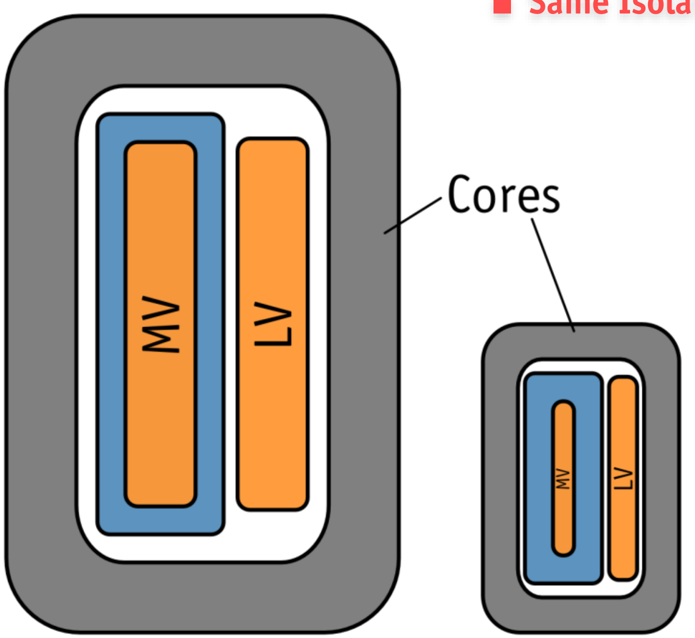
▶ General Challenge of MF Transformers

- Higher Operating Frequency
- Lower Unit Power Rating

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

- Smaller Active Volume
- Same Isolation Voltage (!)





LFT MFT

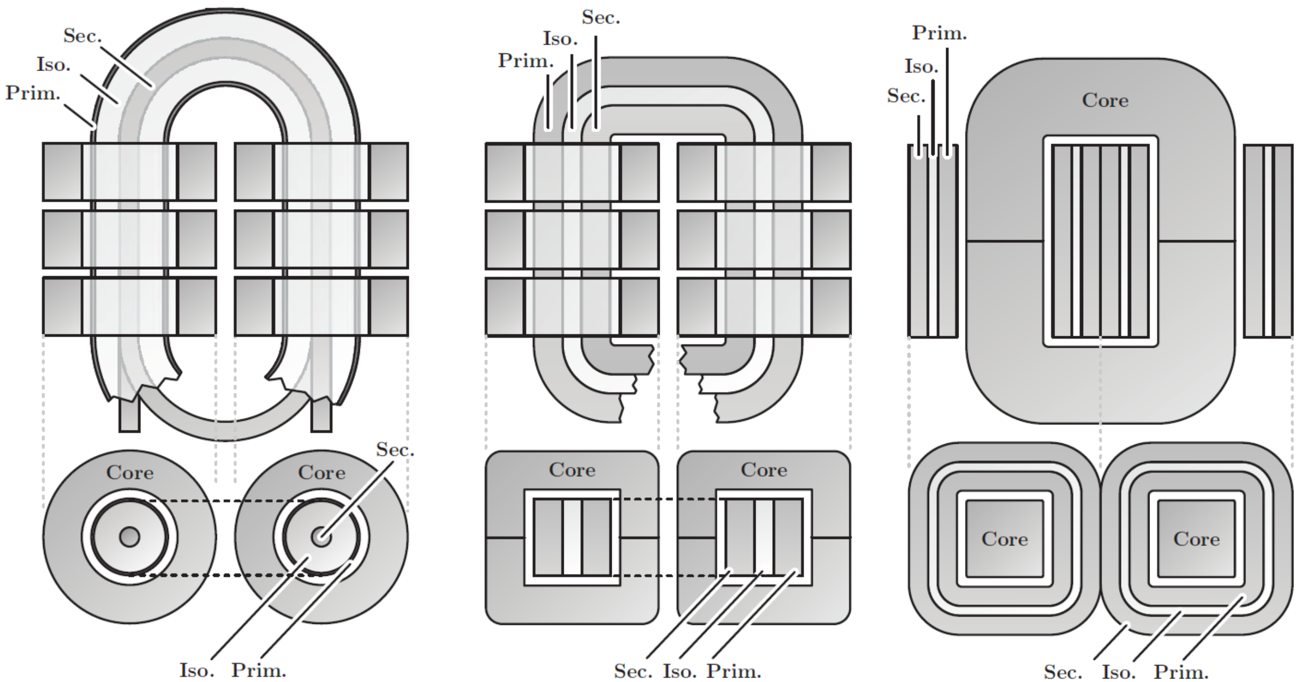
MV Winding Cooling Through Isolators

- 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



Coaxial Cable *Shell-Type* *Core-Type*

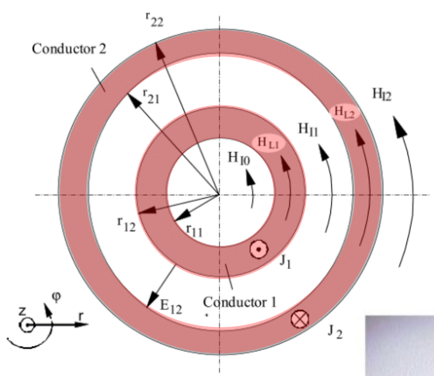
- ■ **Transformer Construction Types Very Limited by Available Core Shapes in this Dimension Range**
- ■ **Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components**

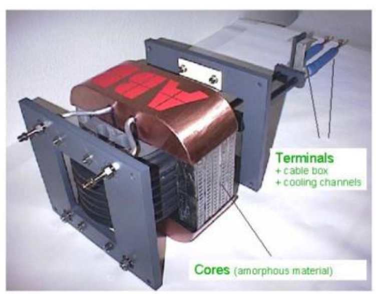
▶ MF Transformer Design – Winding Arrangements

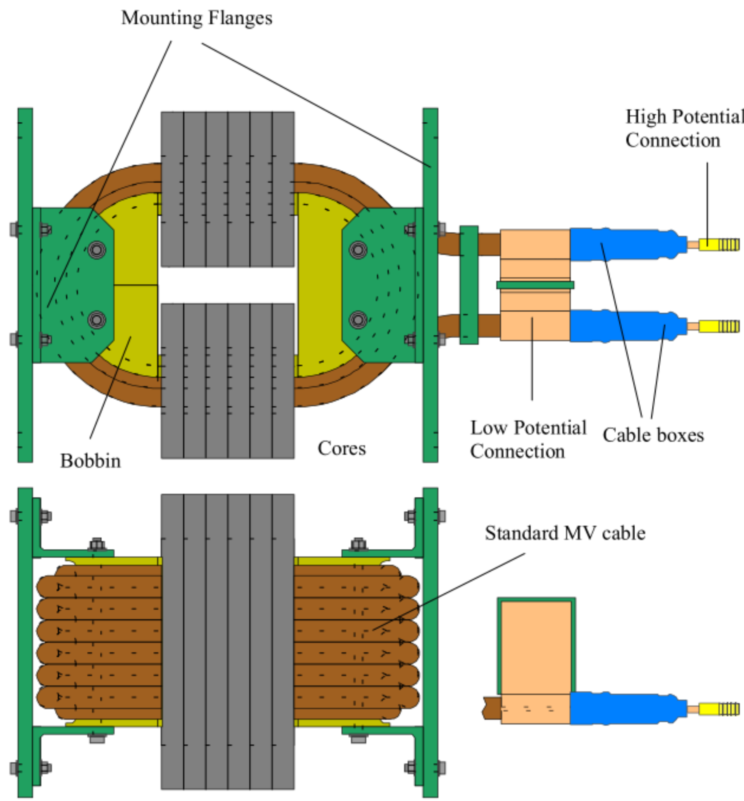
■ Coaxial Cable Winding

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

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







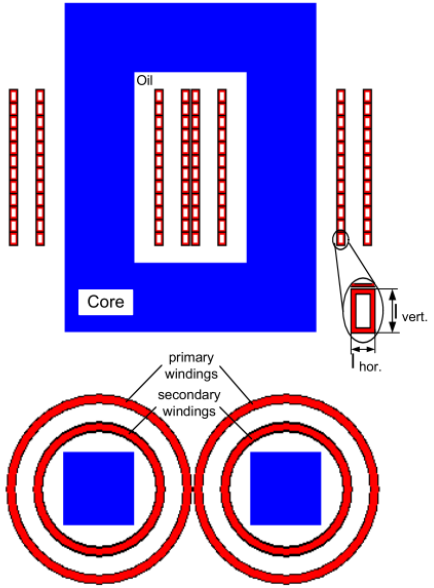
■ Heinemann (ABB, 2002)

[Heinemann2002]

▶ MF Transformer Design – Winding Arrangements

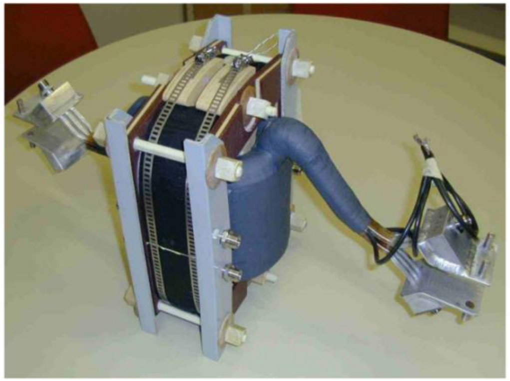
■ Coaxial Windings

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



- Hoffmann (2011)
  [Hoffmann2011]

- Steiner (2007)
  [Steiner2007]

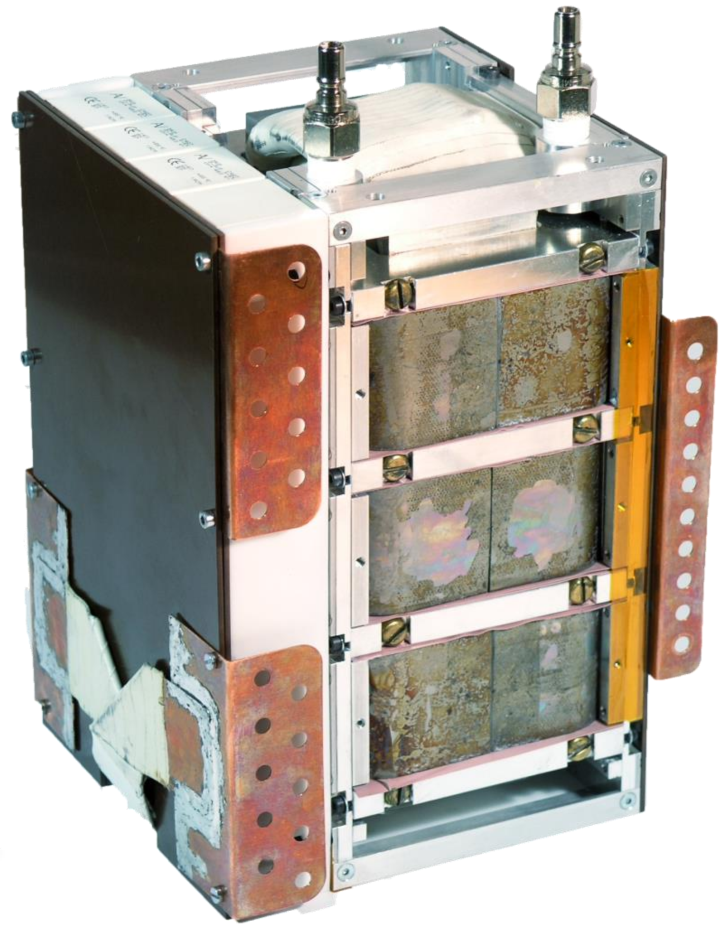


► ETH *MEGACube:* Water-Cooled Nanocrystalline Transformer

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

■ ETH / Ortiz, Leibl (2013)

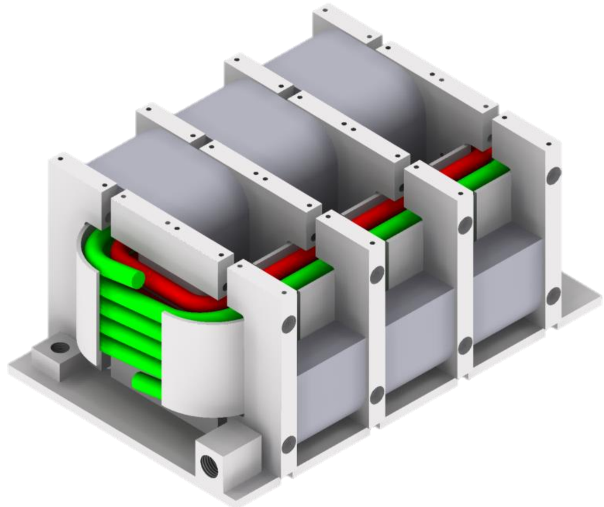
166kW / 20kHz Water-Cooled
Nanocrystalline Core Transformer ▶

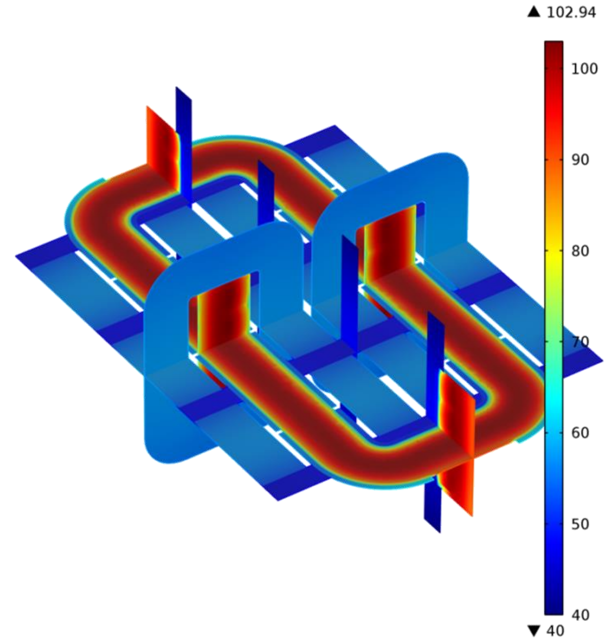


ETH / [Ortiz2013b]

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

- Nanocrystalline 166kW/20kHz Transformer



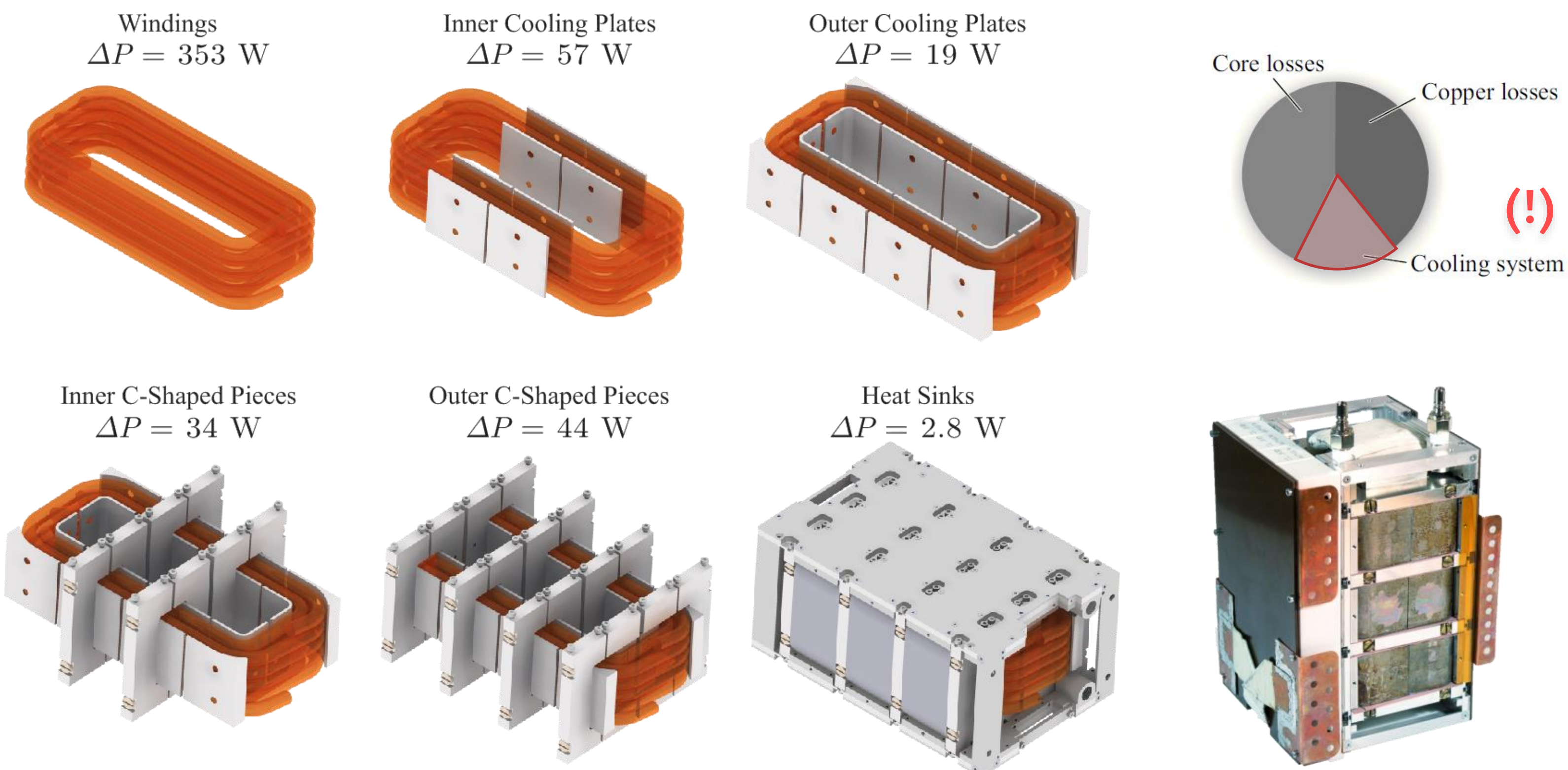


- Combination of Heat Conducting Plates and Top/Bottom Water-Cooled Cold Plates
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

ETH/ [Ortiz2013b]

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

- **Nanocrystalline 166kW/20kHz Transformer**



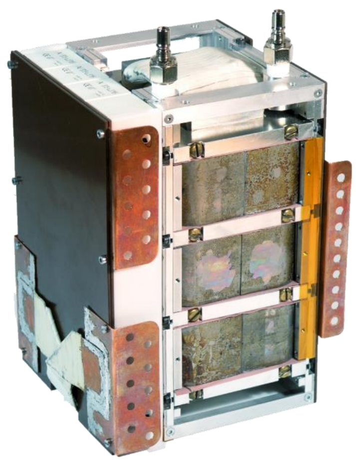
- Losses Generated in Internal Cooling System Amount to **ca. 20% of Total Transformer Losses**

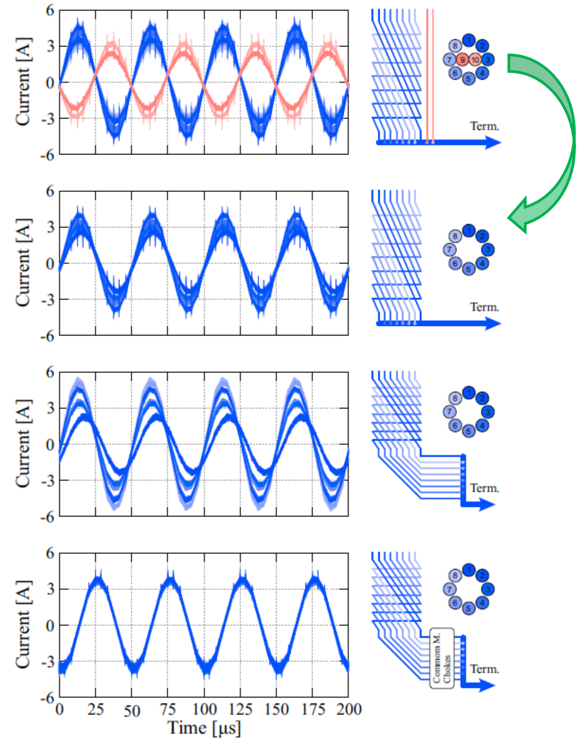
ETH/ [Ortiz2013b]

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

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

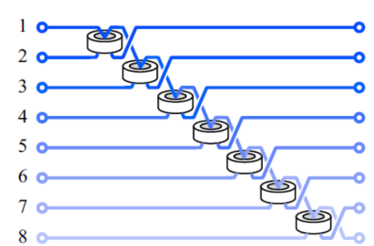
- **Unequal Current Sharing Between Sub Bundles**
  - **Flawed Interchanging Strategy**
  - Influence of Terminations





(!)
-20% Losses

- **Common-Mode Chokes for Forcing Equal Current Sharing**



ETH/ [Ortiz2013b]

Coffee

Break

Challenge #7 /13

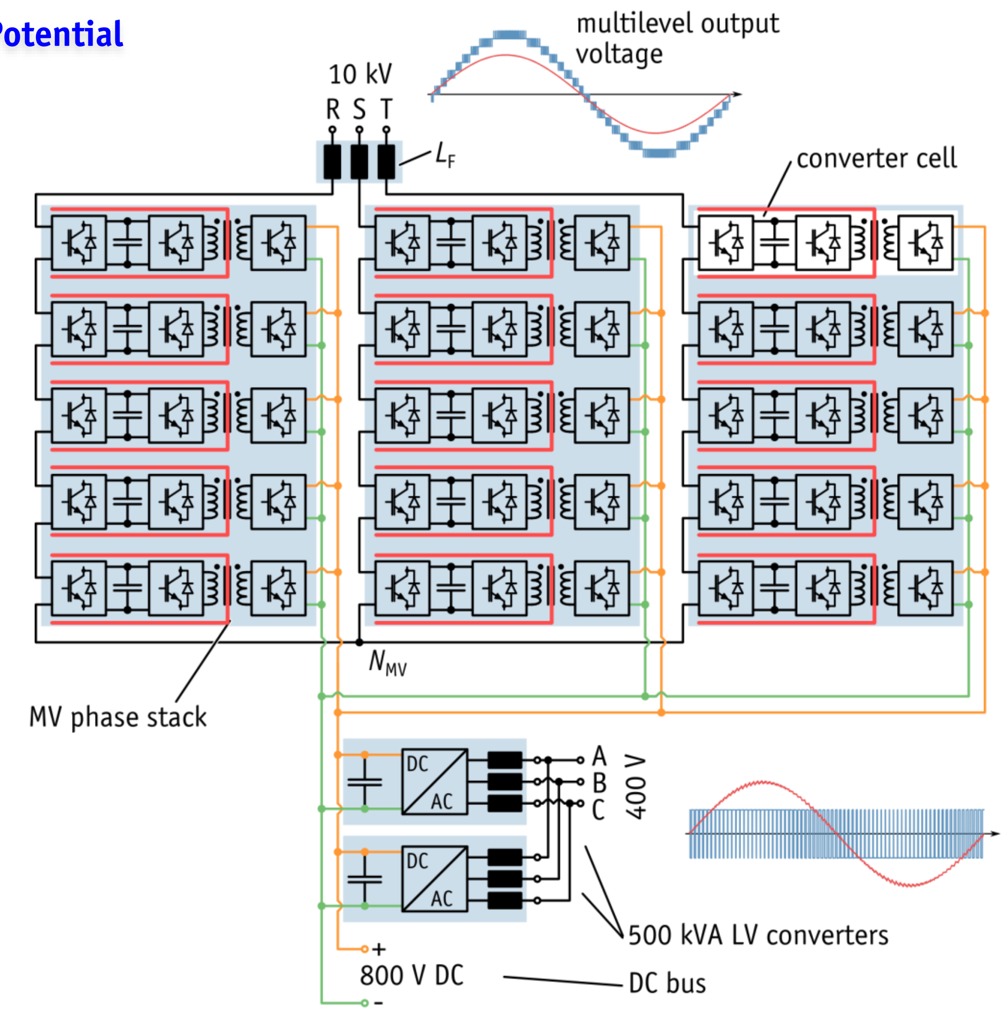
Isolation Coordination

Isolation Barrier Positioning
Mixed-Frequency Stress

► Example System: ETH *MEGAlink* Distribution SST

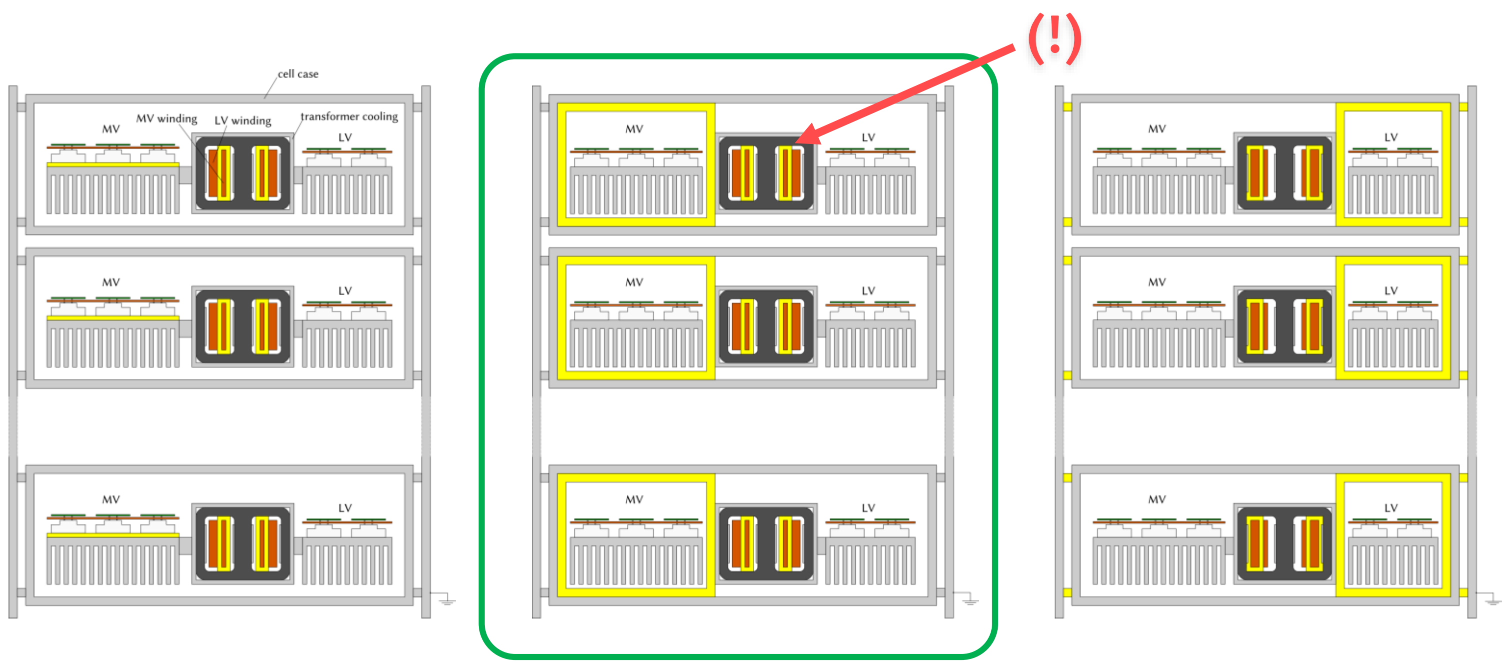
■ **Cascaded Cells Are On Floating Potential**

■ **Isolation Required**
- Towards Ground
- Towards Adjacent Cells



■ **Isolation Voltage: 10kV (nom.)**

▶ Options for Positioning of the Isolation Barrier



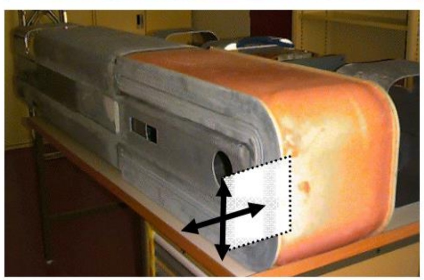
▲ Feasible Variant

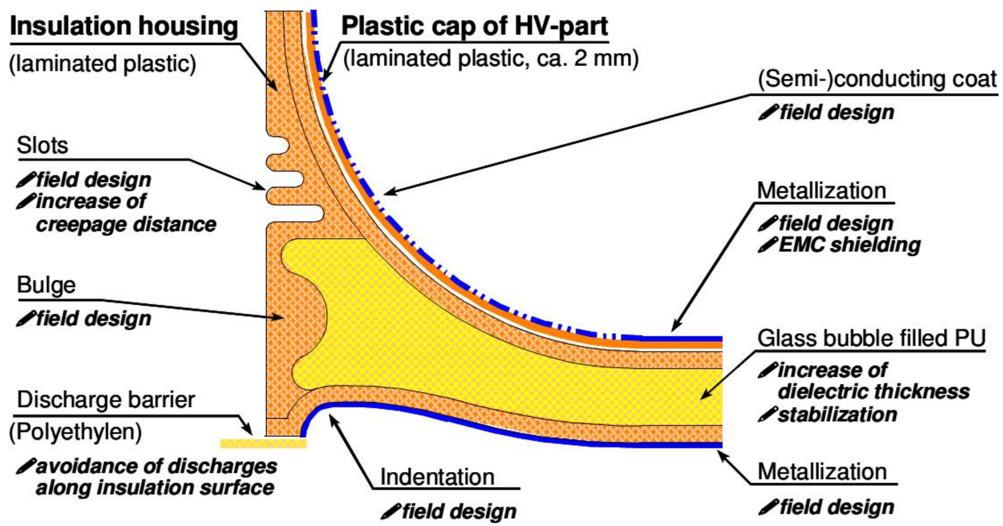
- Transformer Isolation is Critical
- Low Thermal Conductivity of Insulation Material

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.





[Steiner2007]

Challenge #7/13

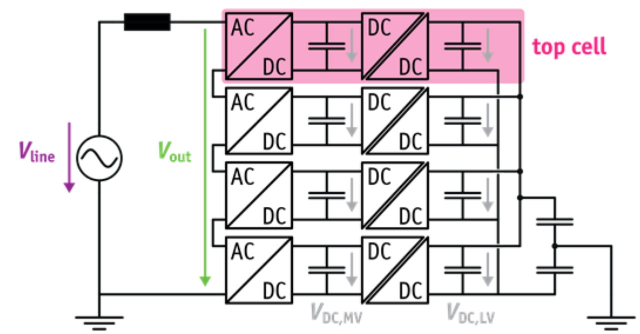
Isolation Coordination

Isolation Barrier Positioning

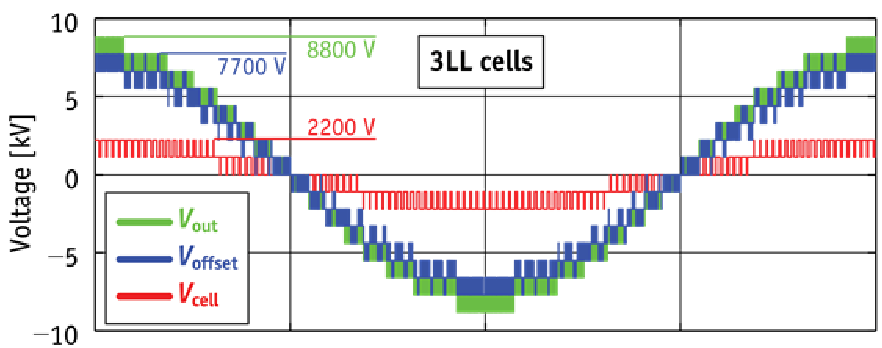
Mixed-Frequency Stress

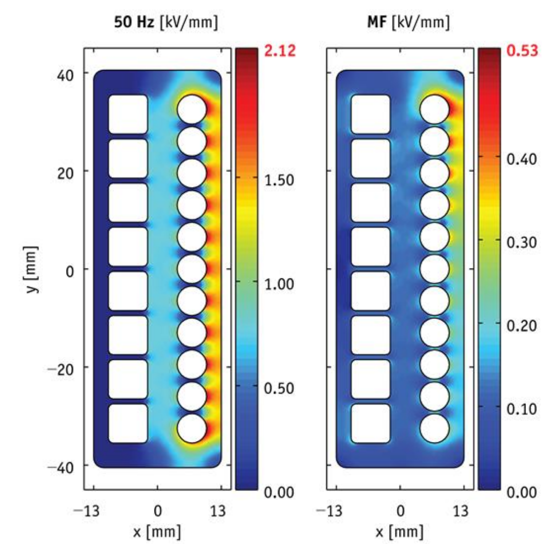
▶ Mixed Frequency Field Stress

- "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



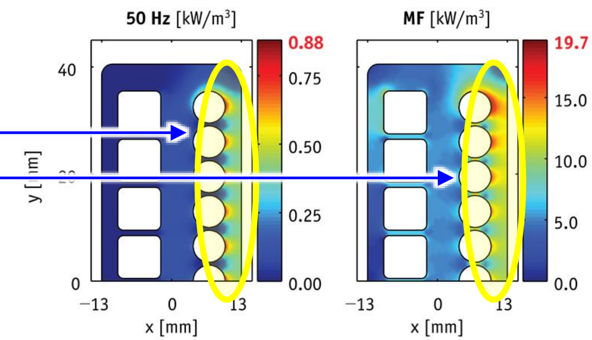


- Highest Stress for Top Cell in Phase Stack
- Highest Stress in Transformer Isolation

ETH / [Guillod2014]

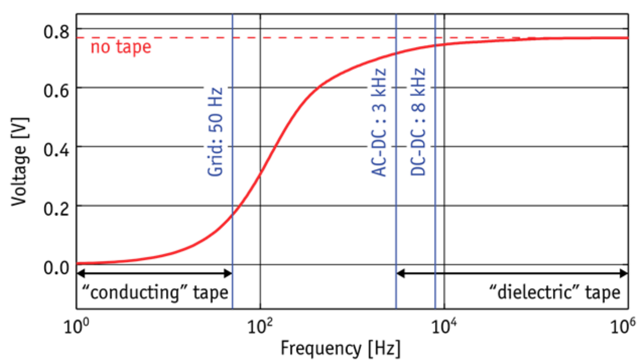
▶ Frequency-Dependent Isolation Concept

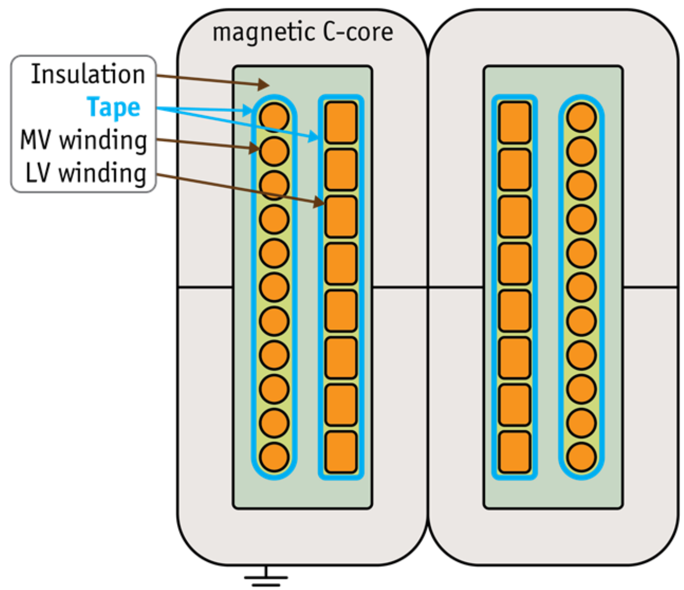
- 50Hz Stress — Common-Mode
- MF Stress — Differential-Mode (Mostly)



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

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





Further Reading: ETH / [Guillod2014]

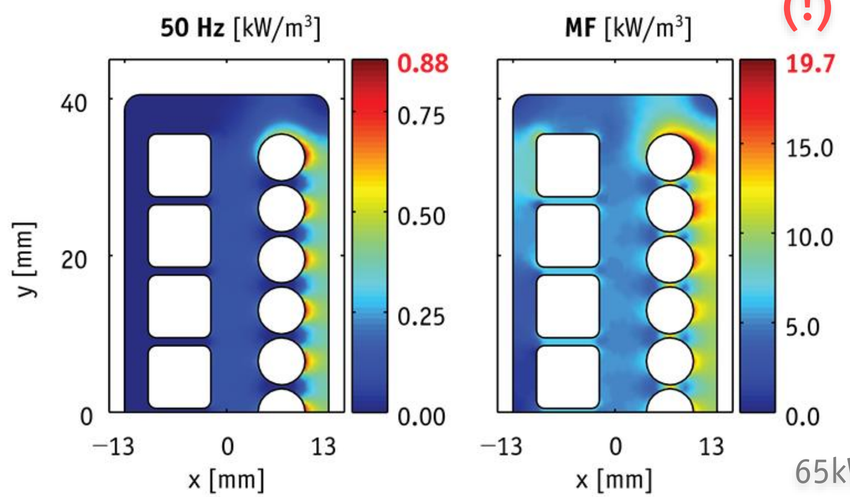
▶ Mixed Frequency Field Stress: Dielectric Losses (1)

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

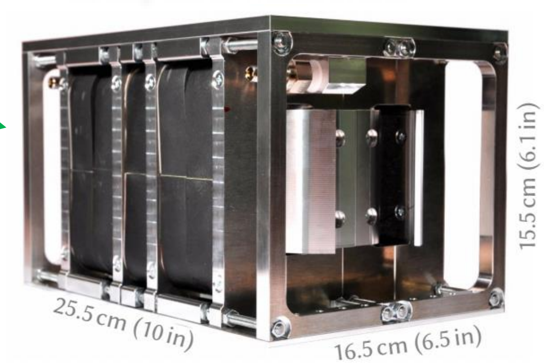
10kV, 50Hz

(!)

1.1kV, 8kHz



65kW/8kHz Transformer ▼



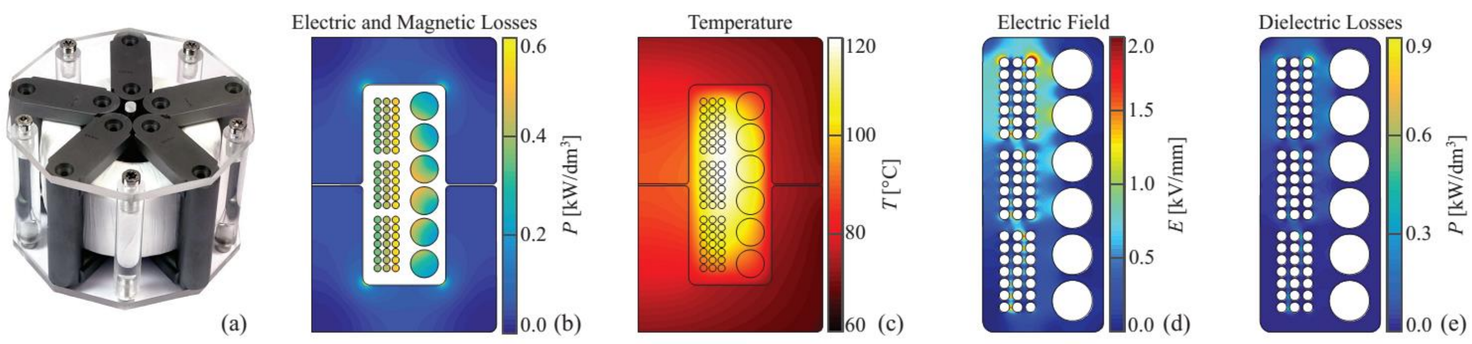
ETH / [Guillod2014]

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

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

▶ Mixed Frequency Field Stress: Dielectric Losses (2)

- **Strong Dependence on Switching Frequency**
- **Example: HV-SiC DC/DC Converter:**
  - 25kW
  - 8kV
  - 50kHz ← (!)



- **Dielectric Losses with Epoxy Isolation: 16% of Total Transformer Losses**
  → Reduced Efficiency
  → Increased Hot-Spot Temperature
- **Careful Choice of Isolation Material is Essential (Field Strength/Thermal Cond./Dielectric Losses)**

Further Reading: Upcoming ETH Pub. by T. Guillod.

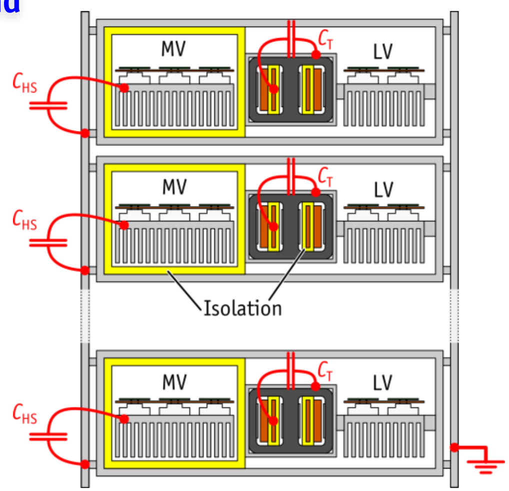
Challenge #8/13

EMI

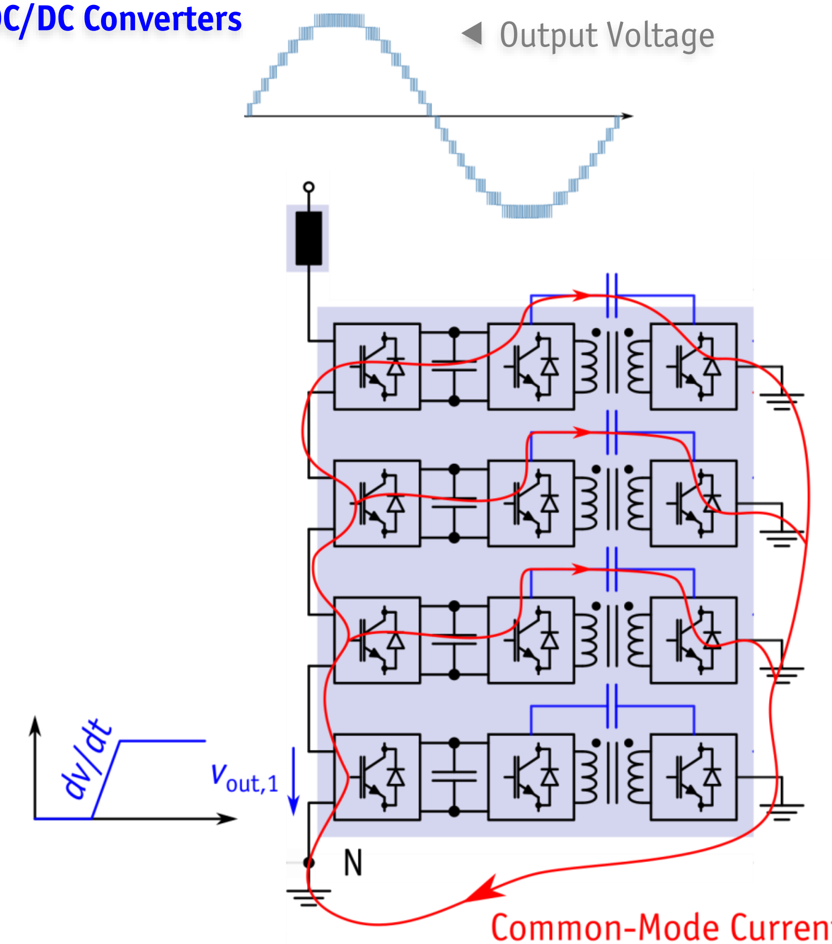
Common-Mode Ground Currents
EMI Limits

▶ Basic Problem Description

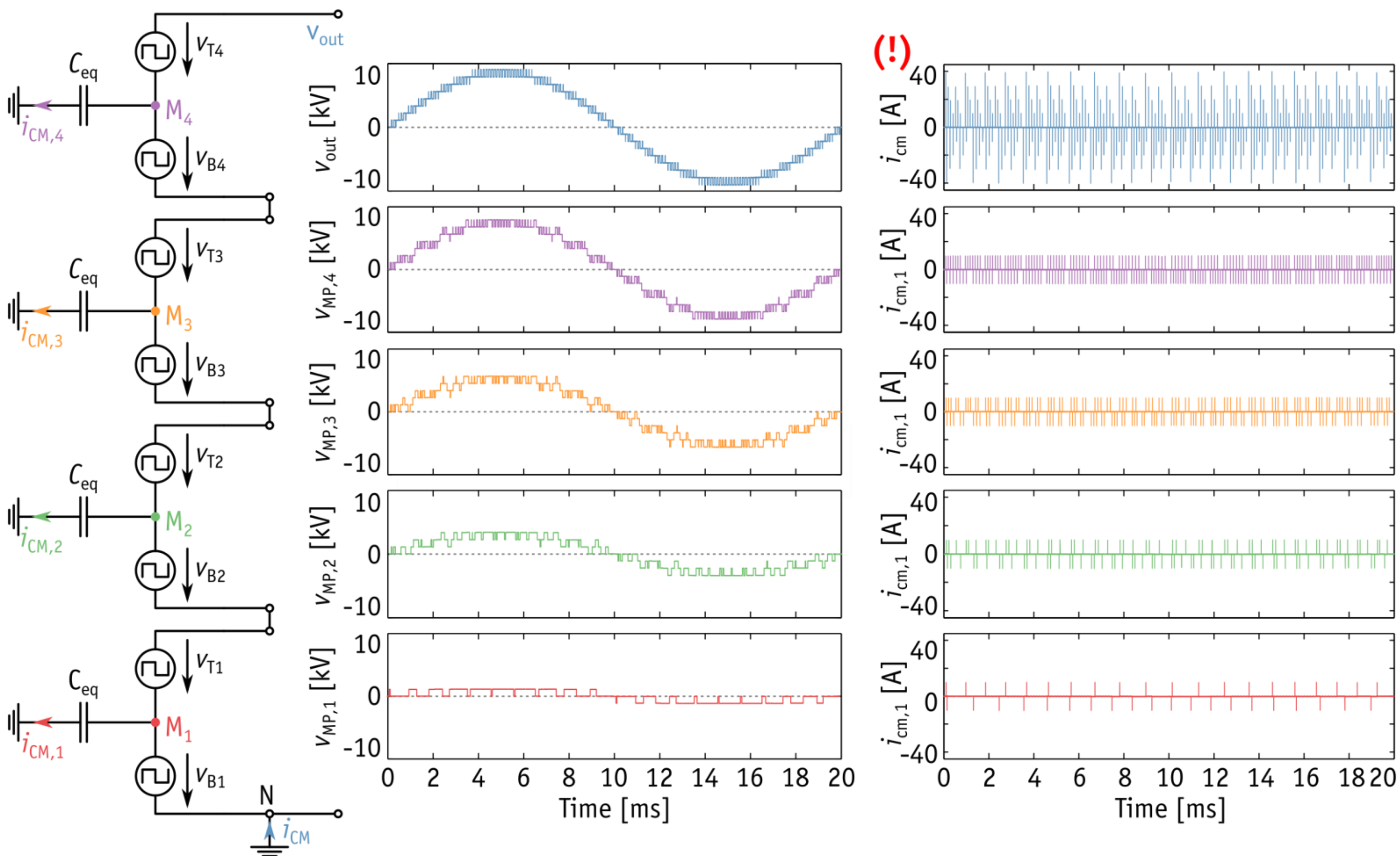
- Considering One Phase Stack Including the DC/DC Converters
- Parasitic Capacitances Between Cells and Ground



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



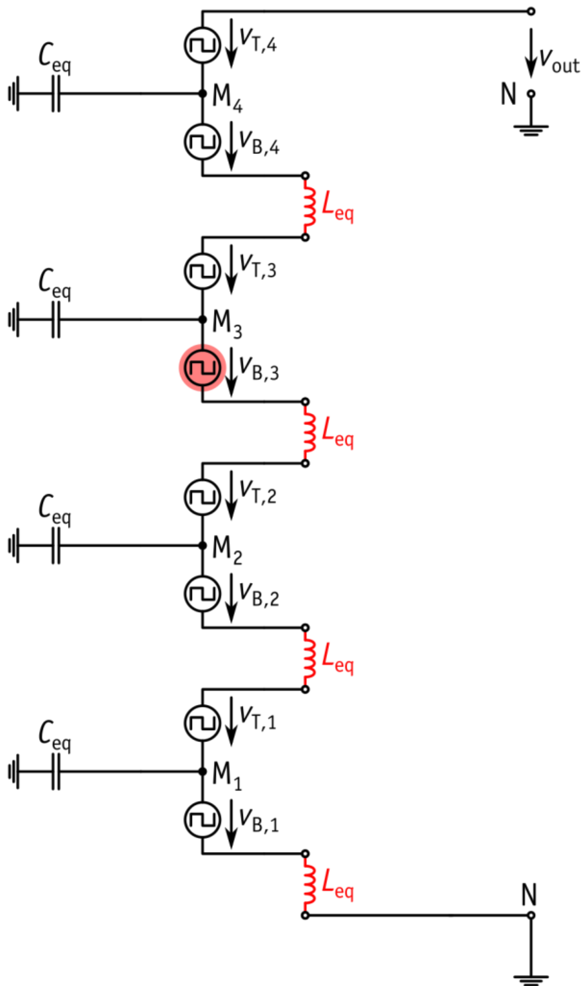
► Simulation of Common-Mode Currents

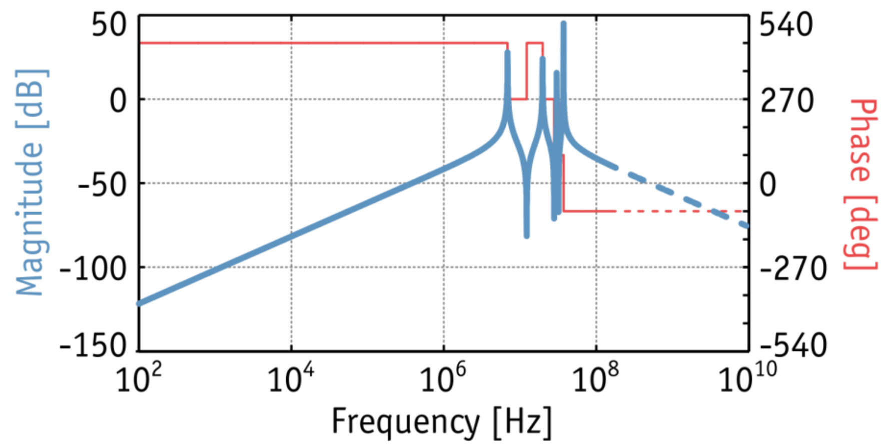


▲ Common-Mode Eq. Circuit

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

► Reality: Parasitic Inductances Create Resonances!

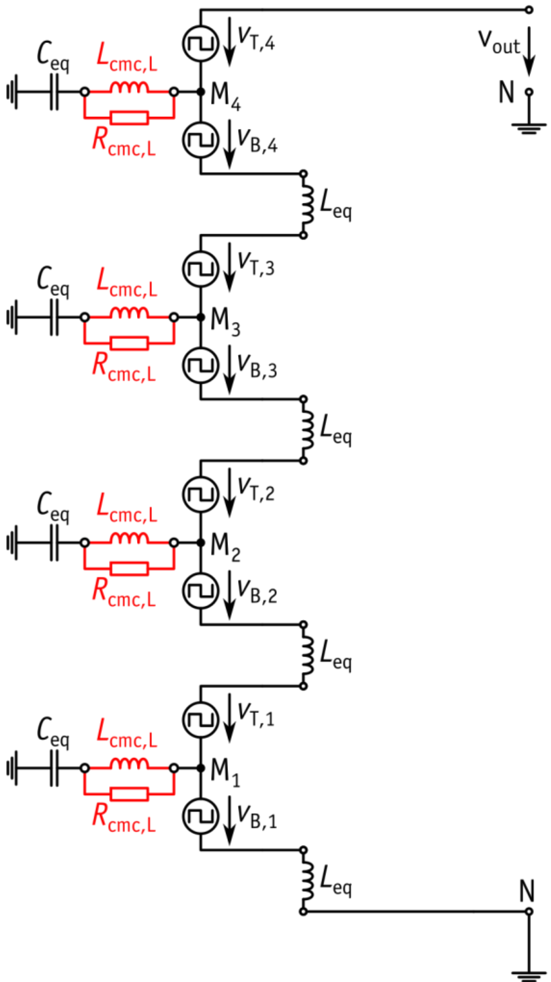




▲ Transfer Function $G(s) = I_{vB,3}(s)/V_{B,3}(s)$

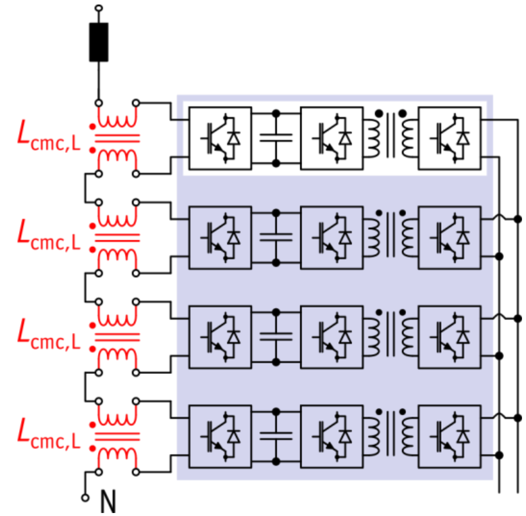
▶ Mitigation: "Local" Common-Mode Chokes

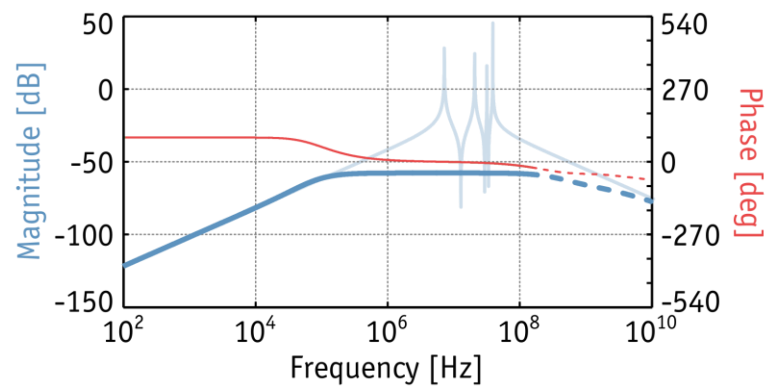
■ Common-Mode Chokes at the Input Terminals of Every Cell



◄ Equivalent Circuit

Actual Realization ►



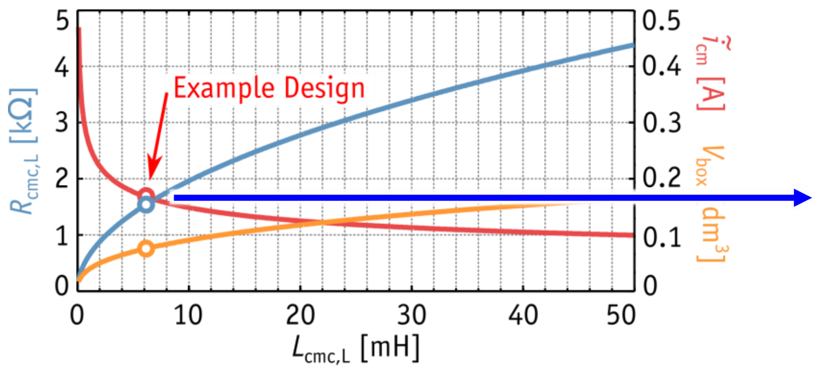


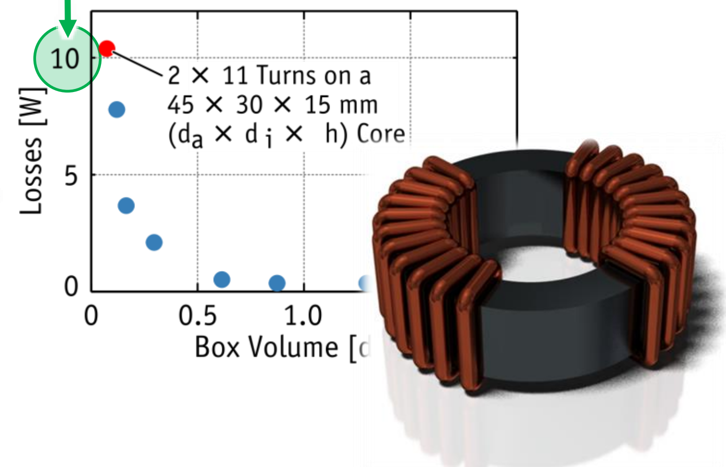
▲ Transfer Function $G(s) = I_{vB,3}(s)/V_{B,3}(s)$ for $L_{cmc,L} = 6.2\text{mH}$, $R_{cmc,G} = 1.5\text{k}\Omega$

▶ Local Common-Mode Choke Design

■ **Design Procedure** → 6.2mH/57A_{rms} CMC

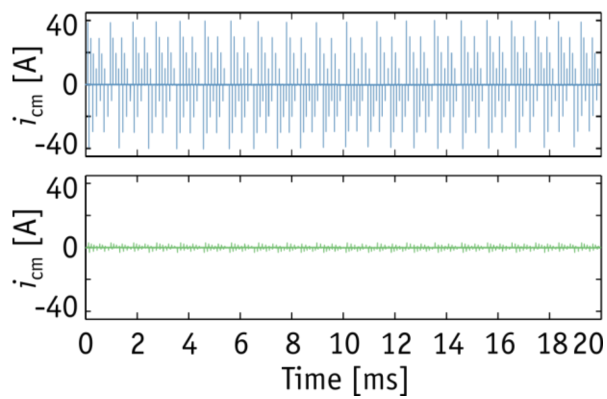
Negligible Total Losses (< 150W) in 1MVA SST

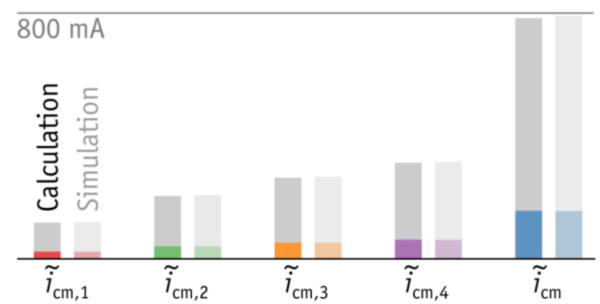




■ **Verification**

- W/o CMC:
- With CMC:





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

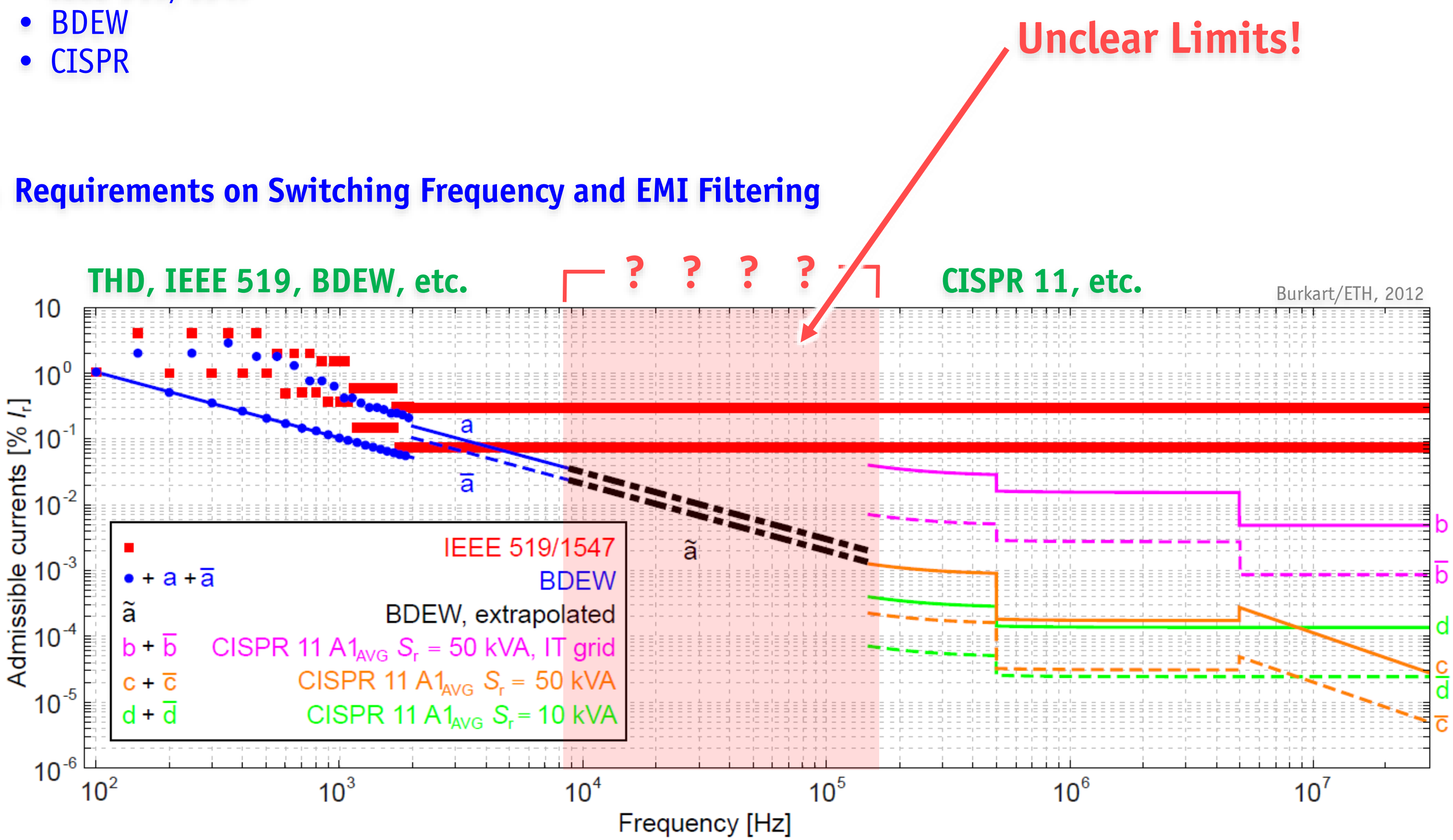
Further Reading: ETH / [Huber2014a]

▶ Grid Harmonics and EMI Standards

■ Medium Voltage Grid Considered Standards

- IEEE 519/1547
- BDEW
- CISPR

■ Requirements on Switching Frequency and EMI Filtering



ETH / [Burkart2012]

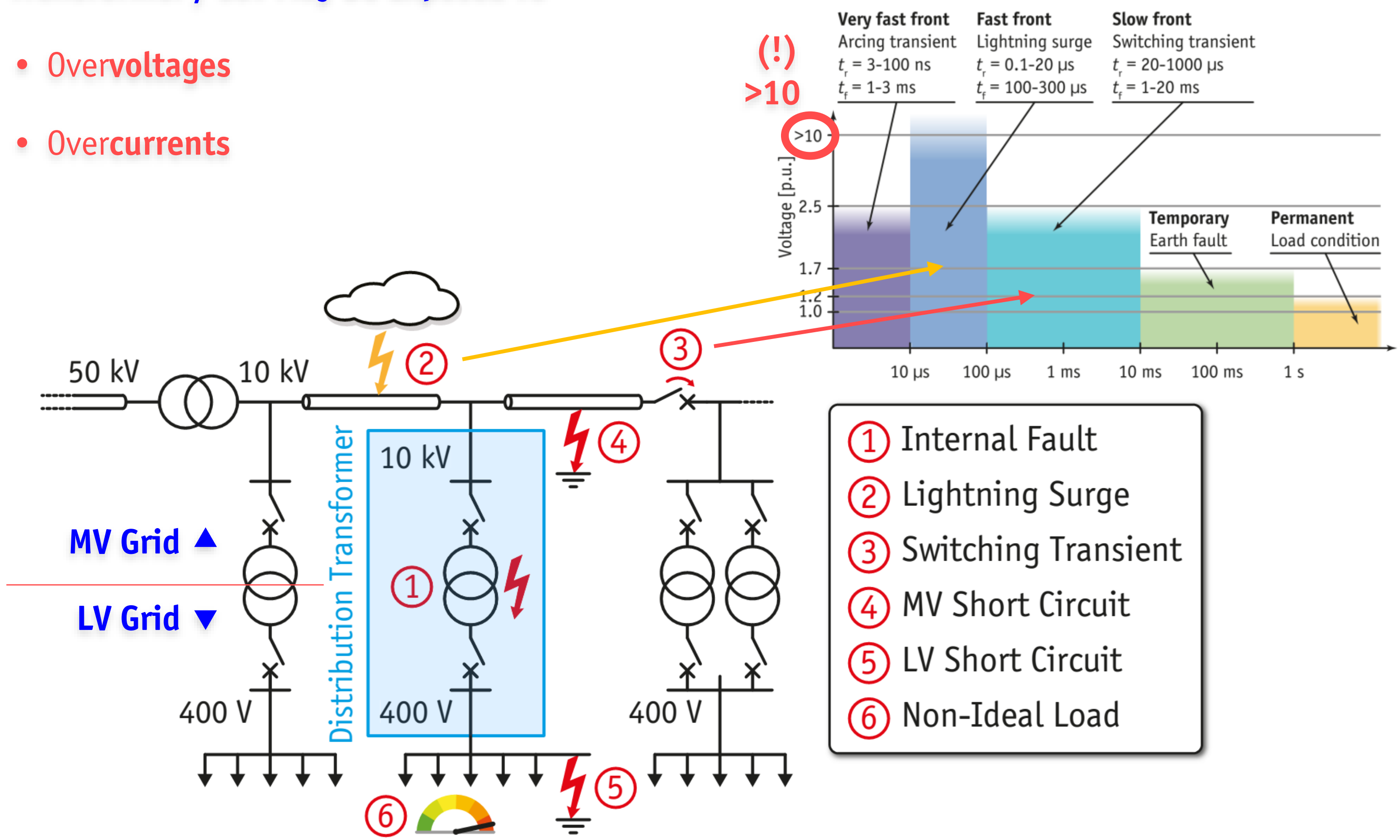
Challenge #9/13

Protection

Protection of the SST
Protection of the Grid
Grid Codes

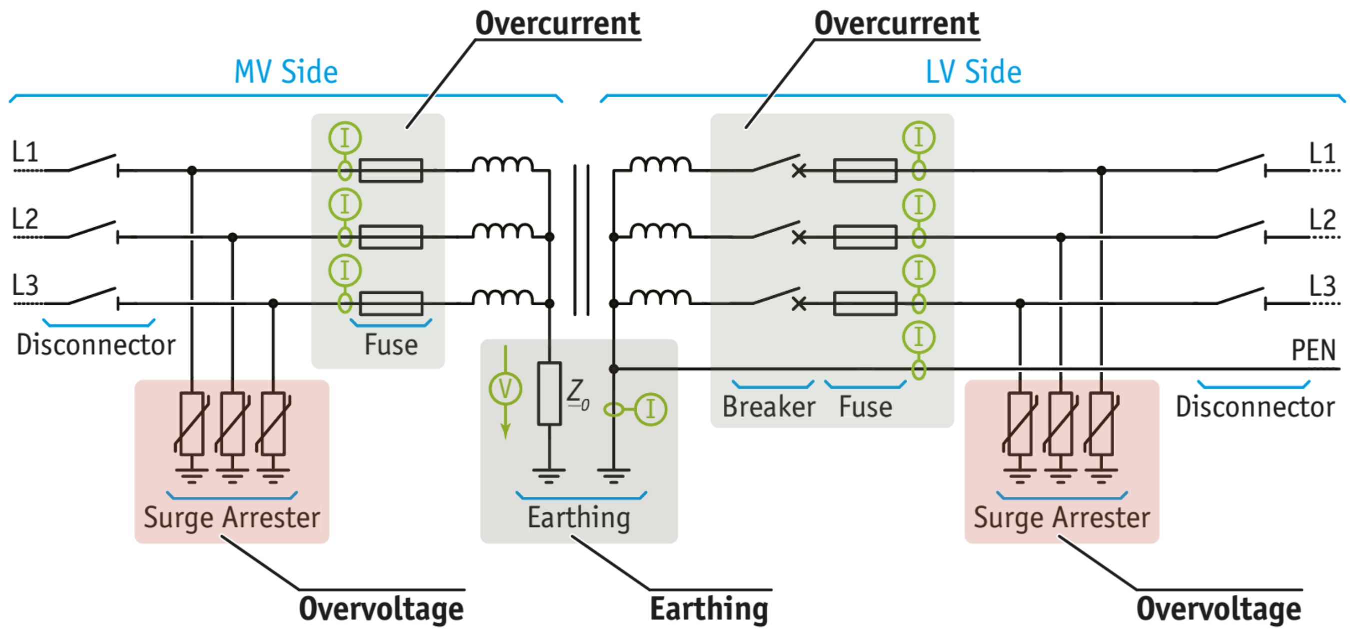
Possible Fault Situations

- **Transformer / SST May Be Exposed To**
  - Over**voltages**
  - Over**currents**



ETH / [Guillod2015]

▶ Typical LFT Protection Scheme



▶ Trade-Off Betw. Over-voltages and Overcurrents

Img.: ABB

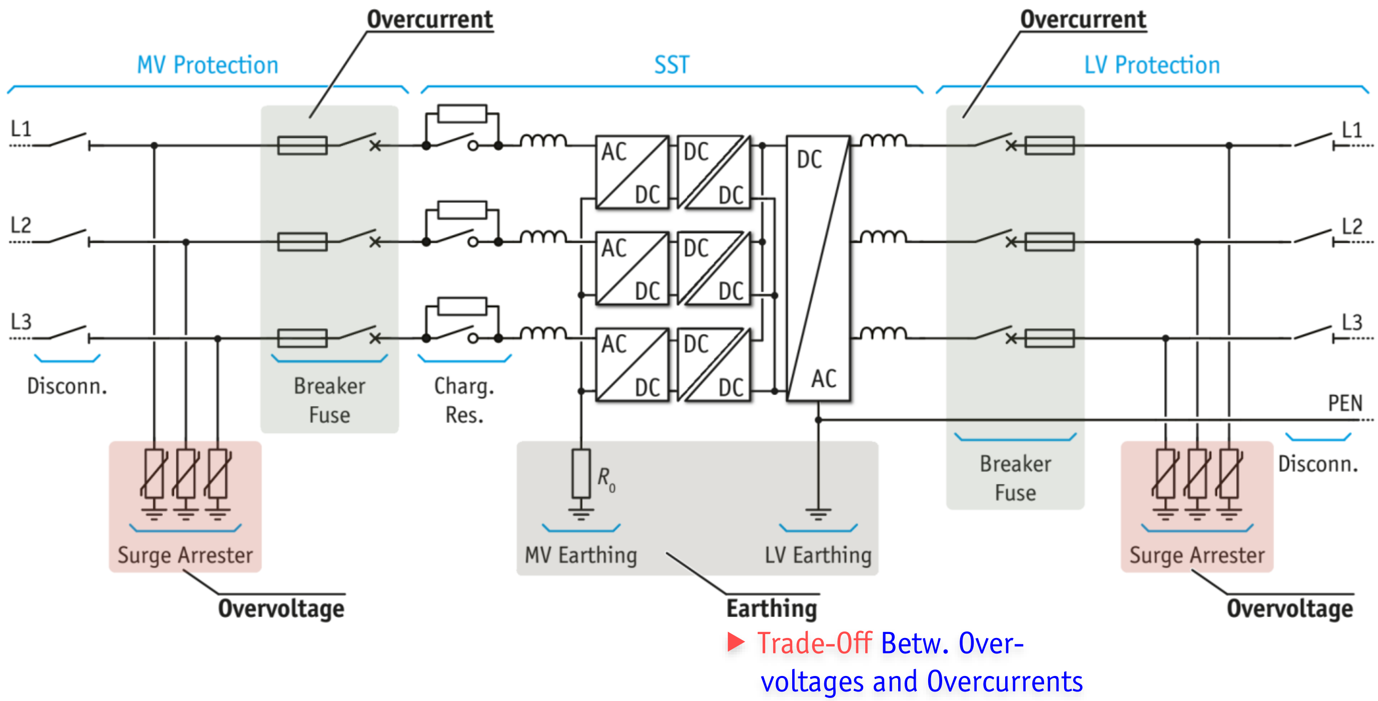
◀ Surge Arresters

LV and MV Fuses ▶

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

ETH / [Guillod2015]

▶ Proposed SST Protection Scheme

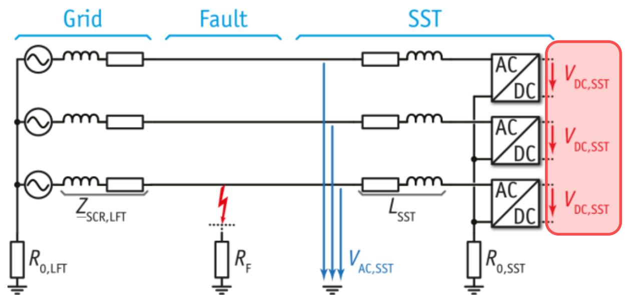


- **Similar to LFT Protection Concept**
- **But: SST Is Less Robust Than LFT → SST Design Needs To Consider Protection, esp. on MV Side!**

ETH / [Guillod2015]

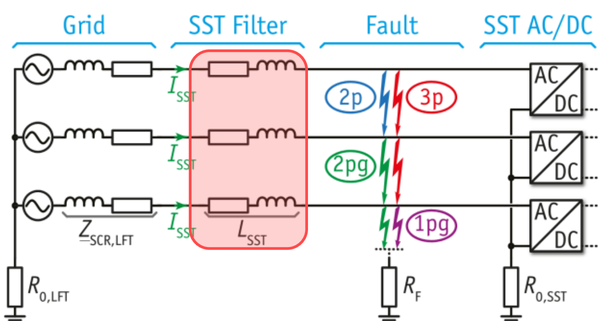
▶ MV Side SST Protection (1)

■ Grid Short Circuit



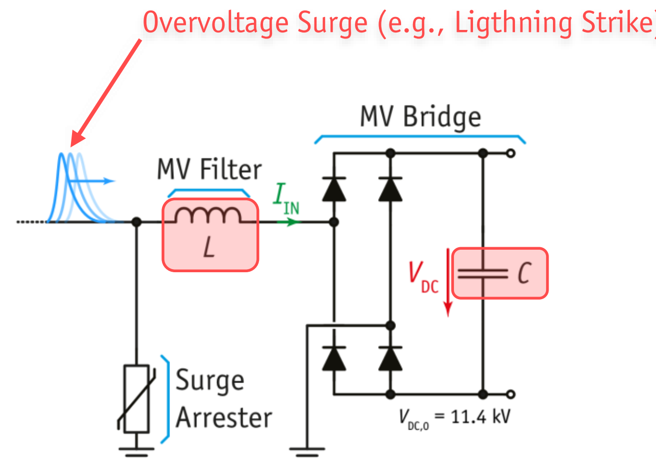
- Phase-To-Phase Voltage (!) Must Be Blocked → DC Capacitor Ratings!

■ SST Short circuit



- Current Limiting: Filter Inductor > 8% (SCR > 10%)

■ Overvoltage Protection



- Arrester Clamping Voltage Is Still High
- Earthing Scheme: Lower Stress if Unearthed

- Filter Inductor > 8% to Limit Current
- DC Link Size Large Enough to Absorb Energy

Further Reading: ETH / [Guillod2015]

MV Side SST Protection (2)

Resulting Requirements (Selection)

- DC Link Energy — One Half-Period At Rated Power
- DC Link Overvoltage — 1.7 x AC Peak
- SC Overcurrent Cap. (ms) — 5 x Rated Current

- **Filter Inductor** — **min. 8% pu** (SCR > 8%)

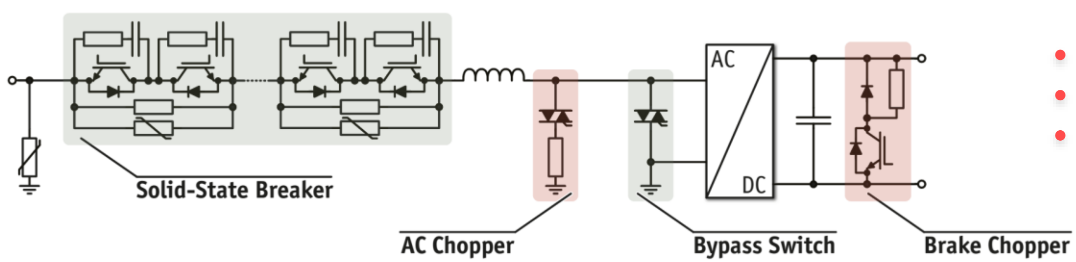
Critical for Low Power SSTs: $L_F = 8\% \cdot \frac{V_B^2}{2\pi f \cdot P_N}$

- Creation of Safe Environments to Protect Several SSTs at Once → **"Swarm Protection"**

Protection vs. Control Bandwidth Trade-Off: Large Filter Inductor Limits Control Bandwidth

→ Key SST Features Compromised (Active Filtering, Harmonic Compensation, etc.)

Advanced Protection Concepts (e. g., Solid-State Protection)



- Reliability?
- Cost?
- Losses?

Further Reading: ETH / [Guillod2015]

Challenge #9/13

Protection

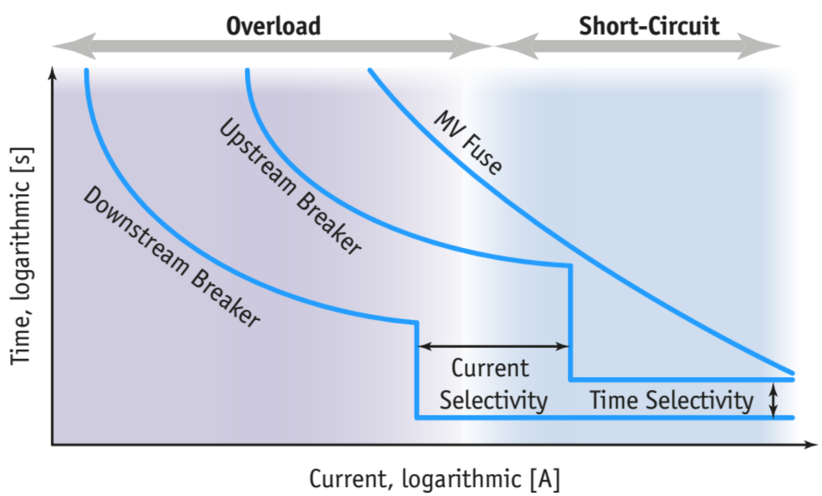
Protection of the SST

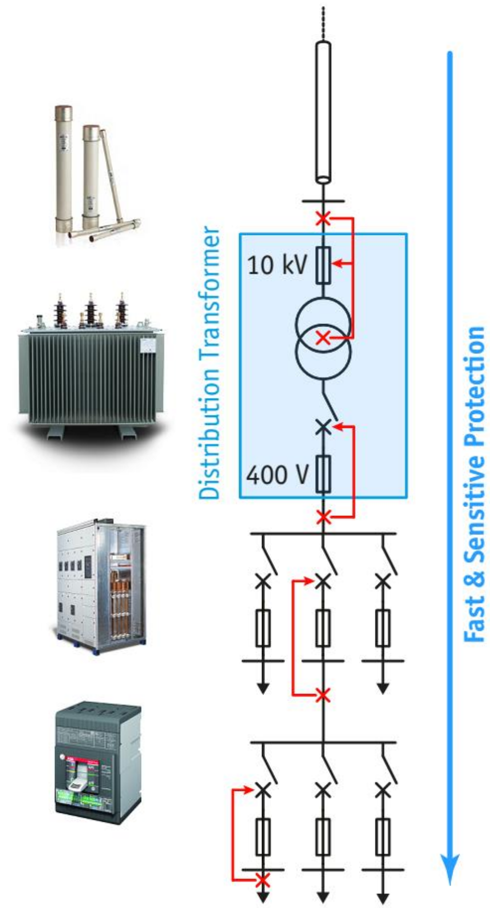
Protection of the Grid

Grid Codes

▶ Grid Protection Schemes

- **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



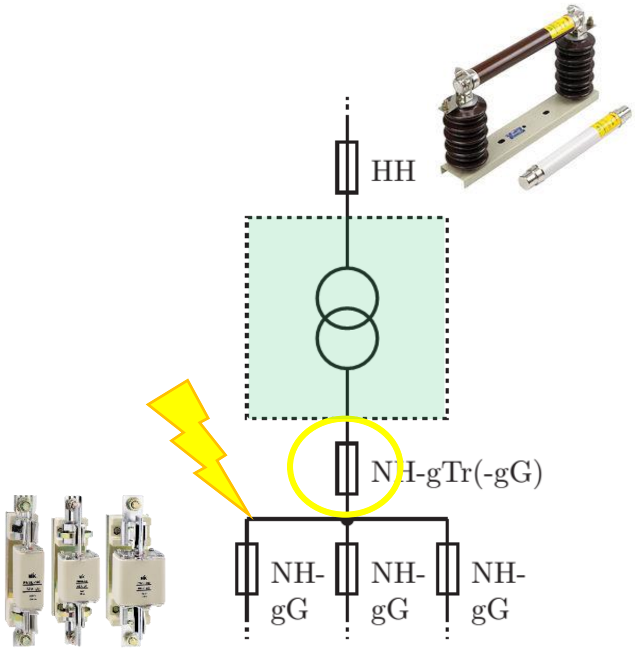


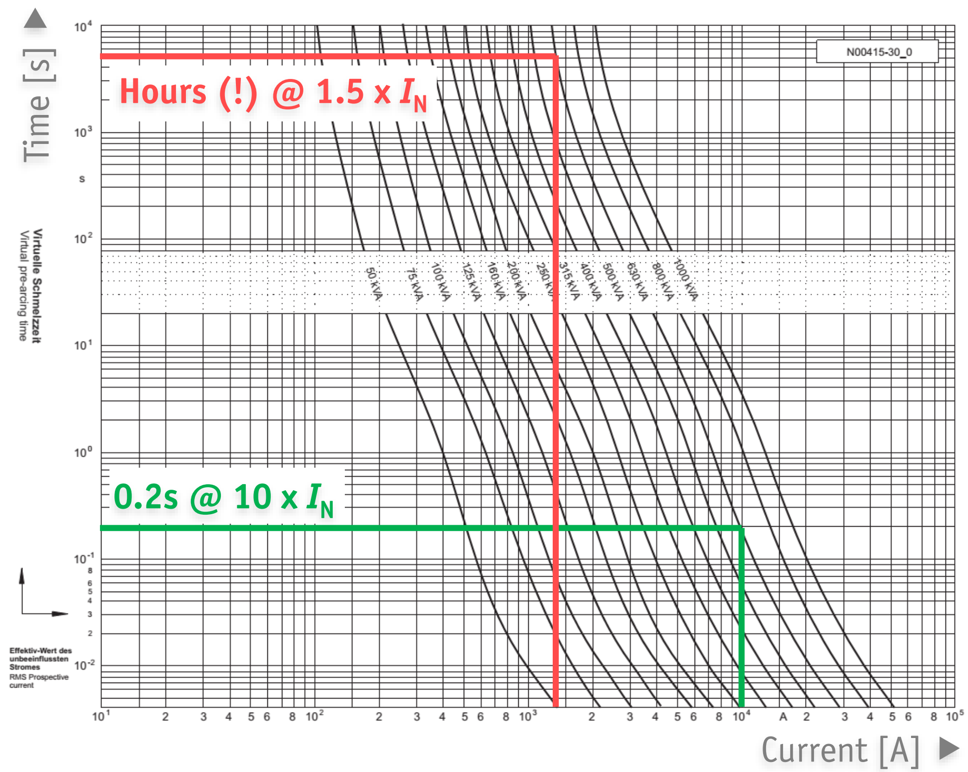
- **LFTs Easily Deliver X-Times Rated Current for Tripping Fuses or Breakers**

Imgs.: ETH / [Guillod2015]

▶ Tripping of LV Side Fuses

- **Example: 400V Fuse for 630kVA Transformer**

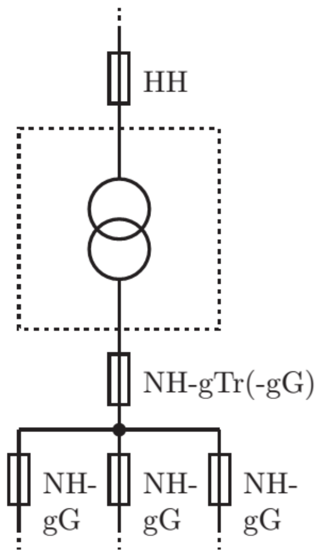


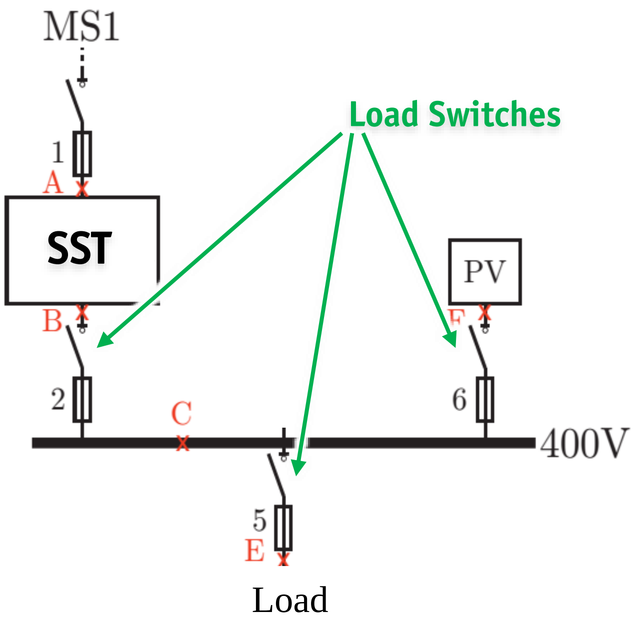


- **Very High Short-Circuit Currents Required To Trip Fuses → No Problem for LFT!**
- **But Not Possible With Power Electronic Converter (Semiconductors!)**

▶ 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" → Coordination of Protection Relays

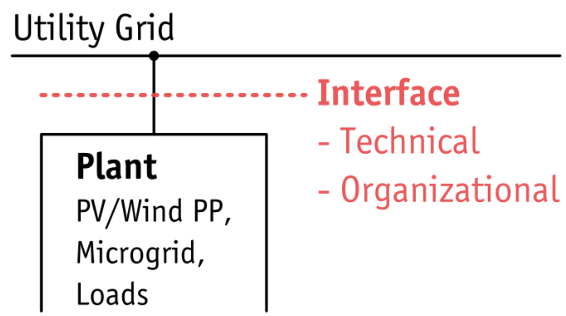
Challenge #9/13

Protection

Protection of the SST
Protection of the Grid
Grid Codes

► Purpose of Grid Codes

- **General Goal:**
  Ensuring 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 ... 150 kV — Transmission
- **Medium Voltage 1 ... 36 kV**
- **Low Voltage 0.4 ... 1 kV**

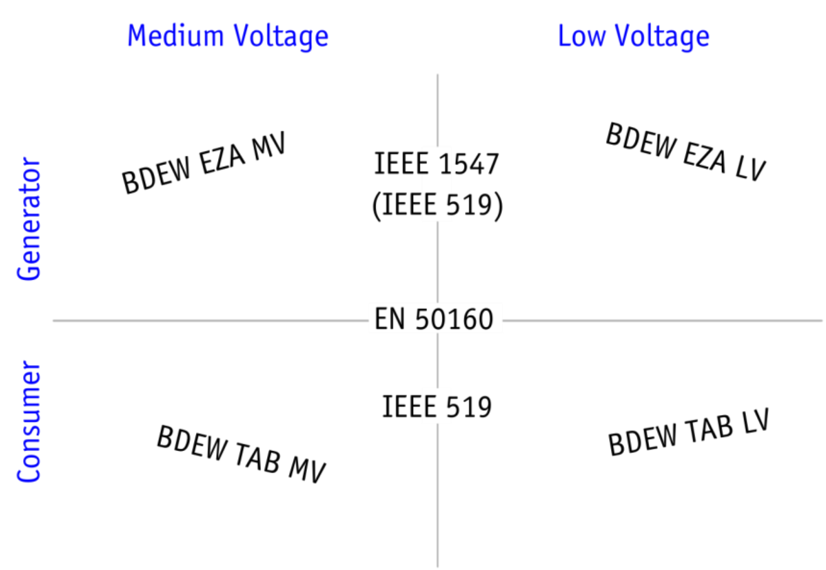
(Medium and Low Voltage: Distribution) SST!

Categorization: Type of Plant

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

SST?!

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

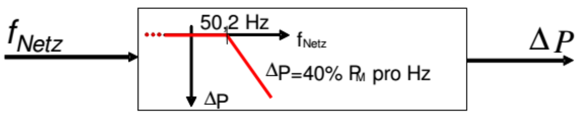


■ Country/Region-Specific!

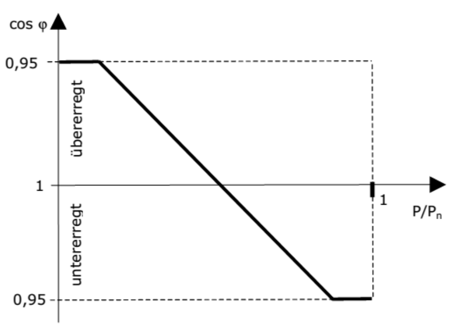
▶ Examples of Technical Requirements for MV Generating Plants

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

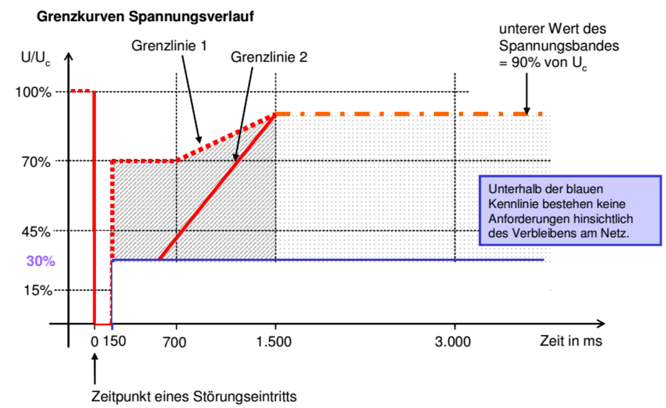
■ Normal Operation
- Participation in Frequency Regulation



- Provision of Reactive Power According To Grid Operator Requirements



■ Dynamic Grid Stabilization
- During a Fault
- No Disconnection (Within Limits)
- Reactive Current Injection to Support the Grid
- Islanding Needs to be Negotiated



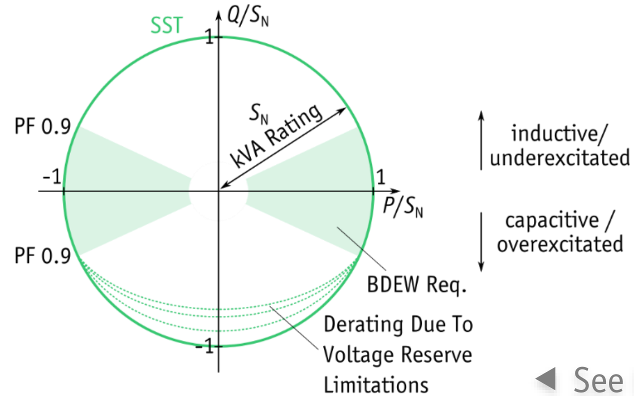
■ Plant Design Aspects
- Switchgear
- Protection Equipment and Relays
- Communication System
- Star Point Handling
- Auxiliary Supplies

Source: [BDEW2008]

▶ SSTs Operate Within a Complex Regulatory Framework!

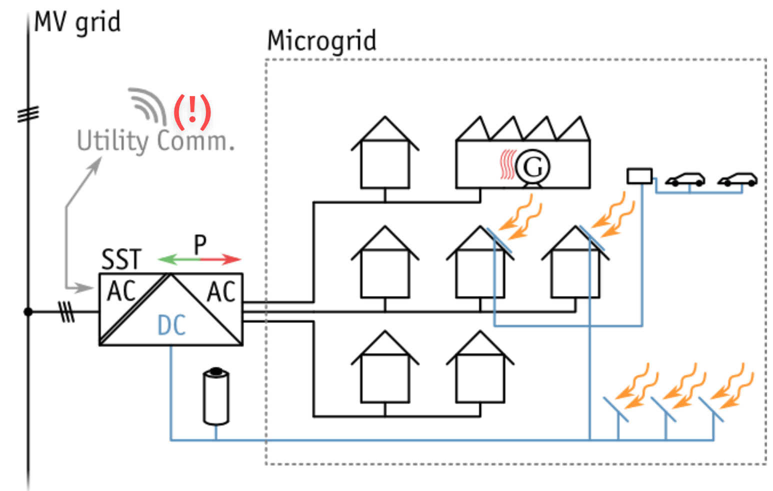
▶ What Applies to SSTs?

- ✓ 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"

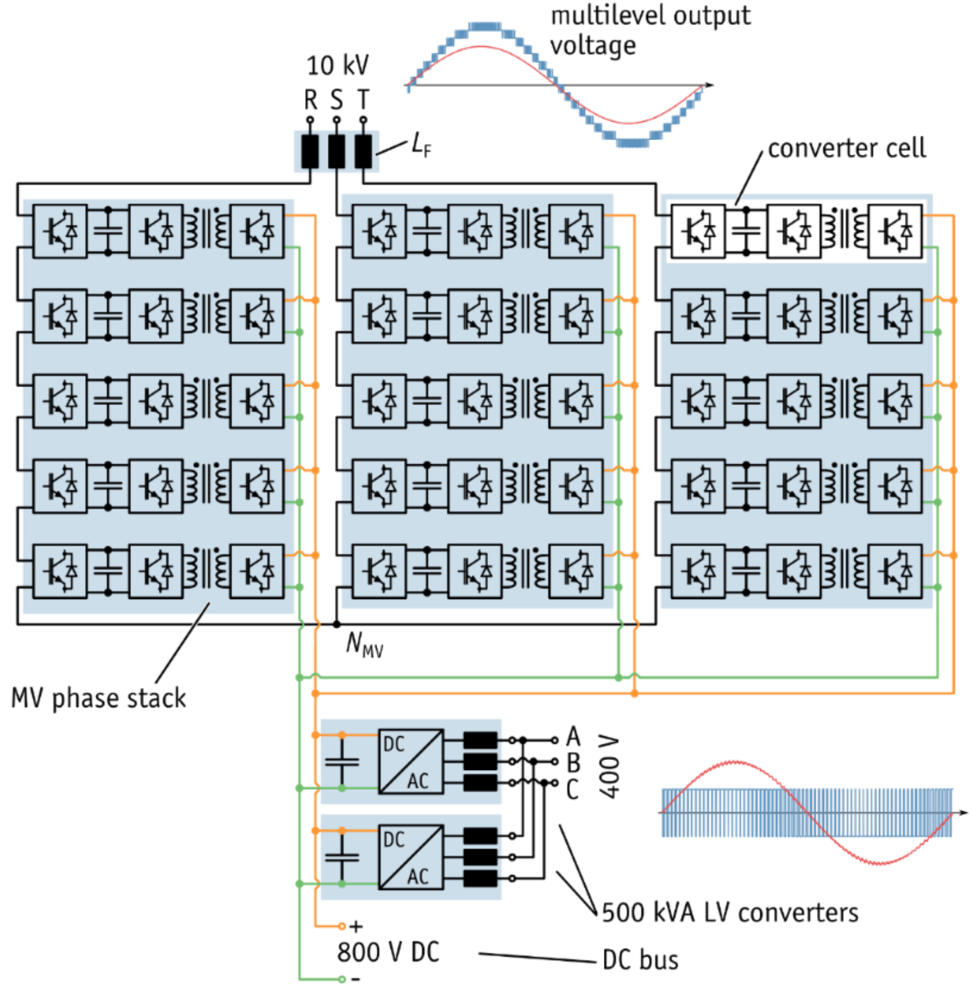


Challenge #10/13
Control & Communication

Smart Grid Integration
Control System Partitioning

► How To Realize The Control System?

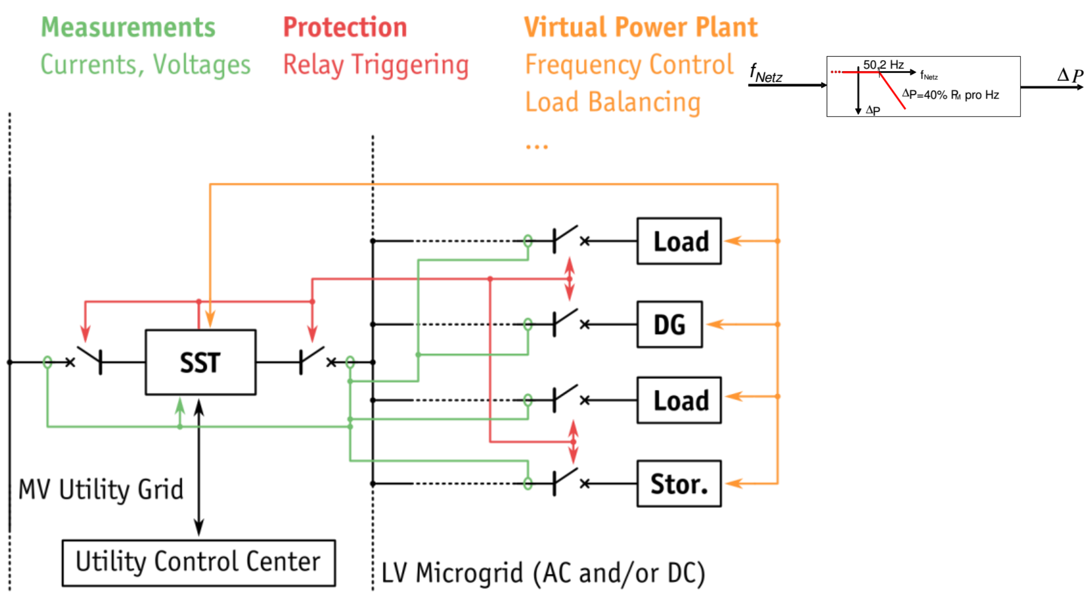
- Complex System with Many Functional Units
- Multi-Level SPWM with Many Cells on MV Side
- Smart Grid Integration (!)



▶ 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 Is 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)
- ...

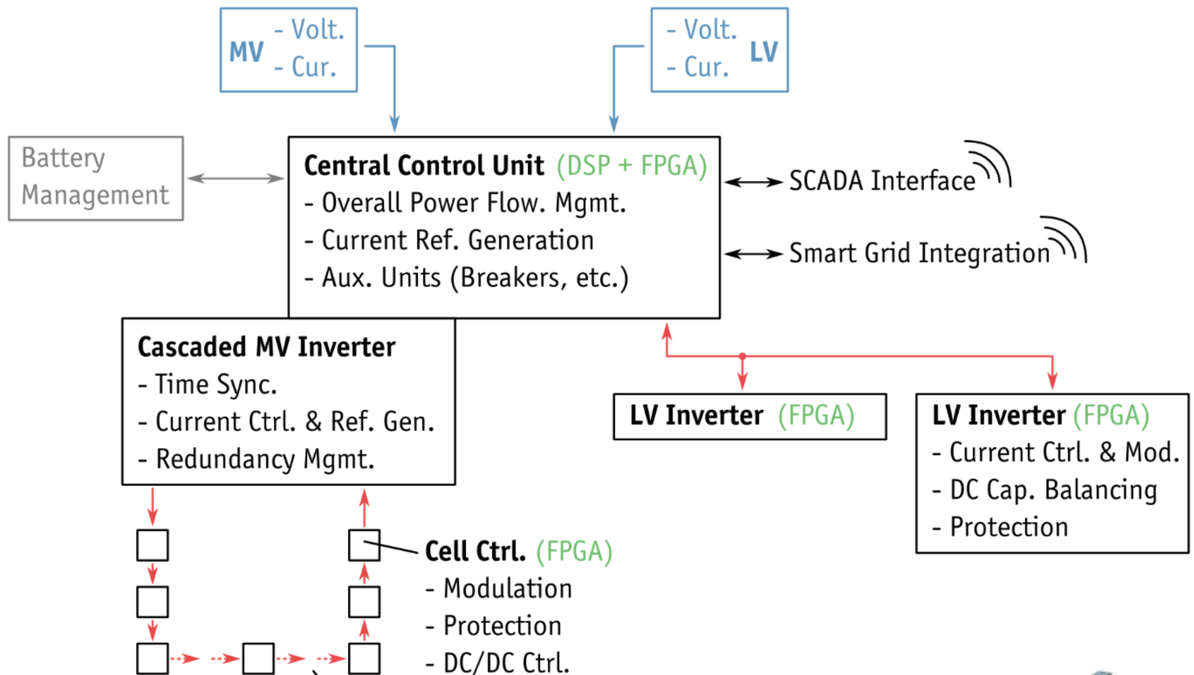
Internal Ctrl.
- Current/Voltage Control
- Redundancy Mgmt.
- ...

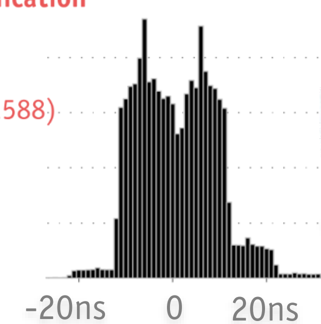
(Cell) Internal Ctrl.
- Modulation, Protection
- ...

SST Power Hardware

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

▶ SST Control System Partitioning (2)





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

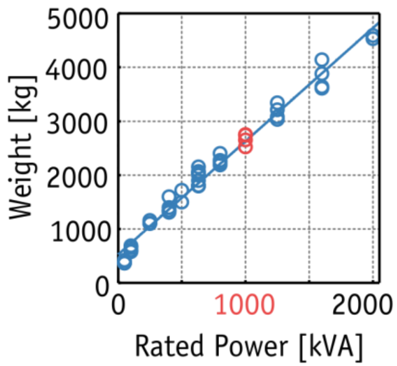
Challenge #11/13

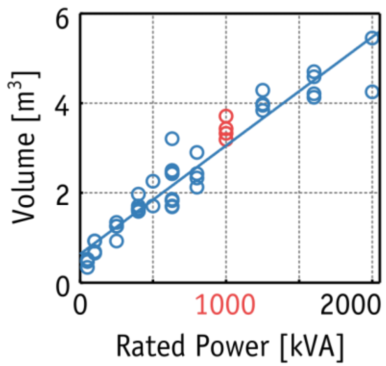
Competing Approaches

SST vs. LFT
SST vs. FACTS

▶ The Competitor: 1000 kVA LF Distribution Transformer

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





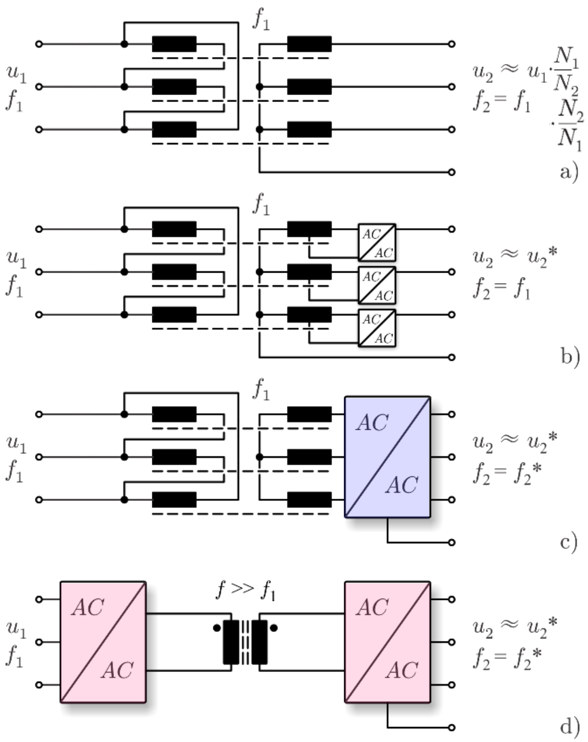
Source: ABB

- 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

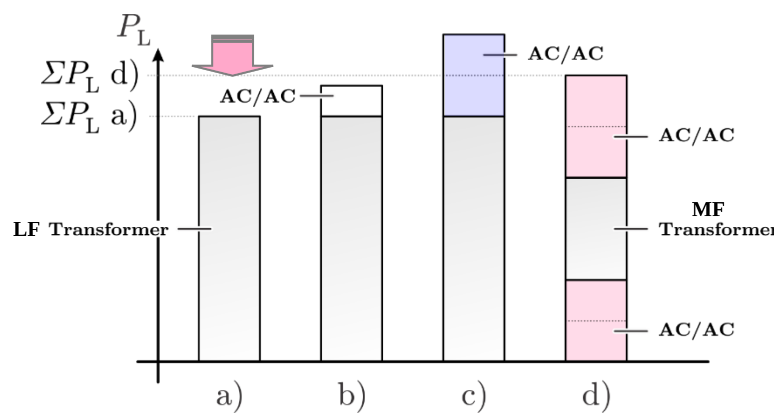
▶ LF Transformer → SST

■ Efficiency Challenge (Qualitative)



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

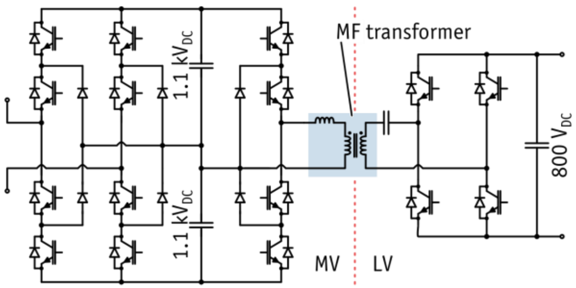
MF Isolation
Active Input & Output Stage (d)

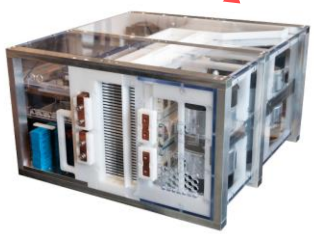


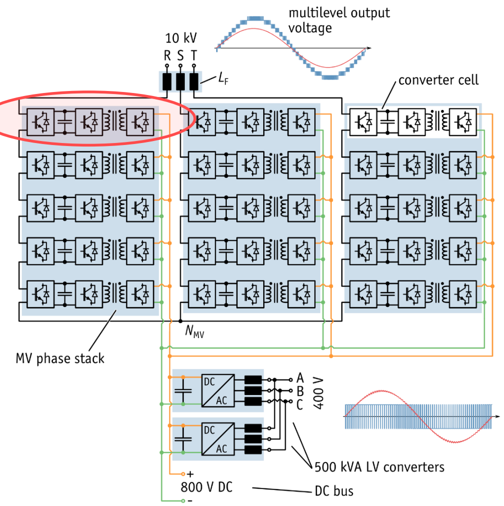
■ Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses
■ Medium Freq. → Low Volume, High Control Dynamics

▶ SST vs. LFT Quantified – MV Side Modeling

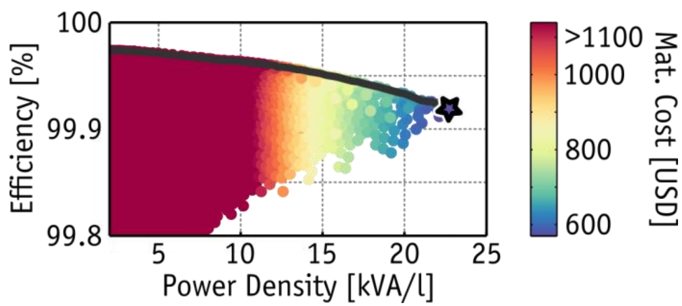
■ Fully Rated Converter Cell Prototype



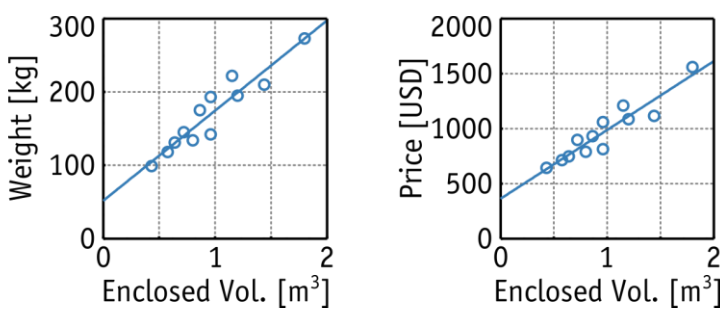




■ Filter Inductor Pareto Optimization



■ Cabinets

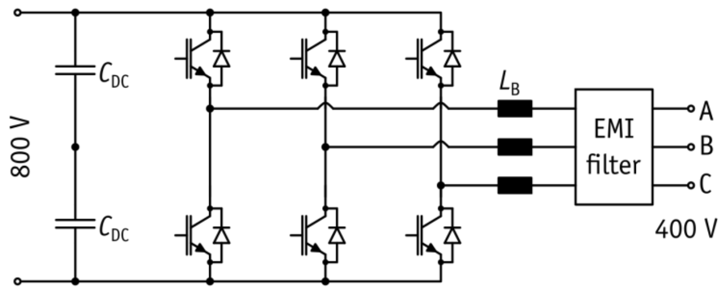


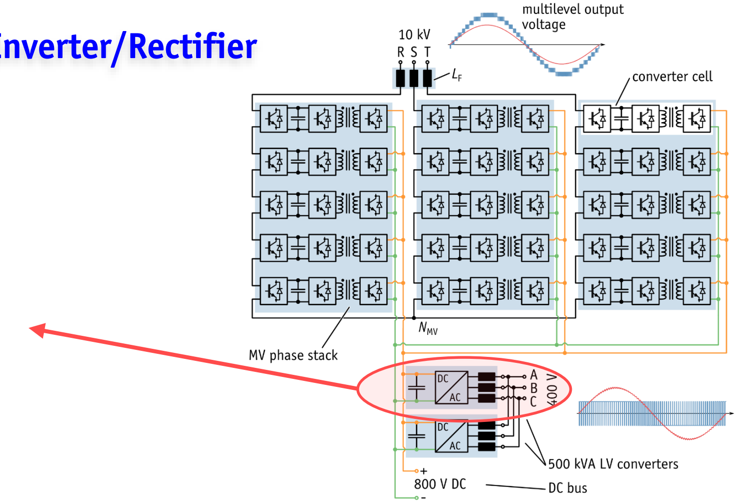
■ Material Costs: High-Volume Component Cost Models

[Burkart2012]

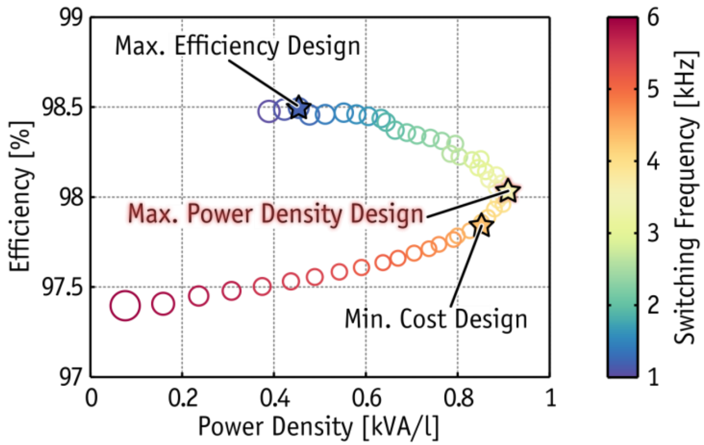
► SST vs. LFT Quantified – LV Side Modeling

■ Basic Pareto Optimization of Standard 500kVA Inverter/Rectifier





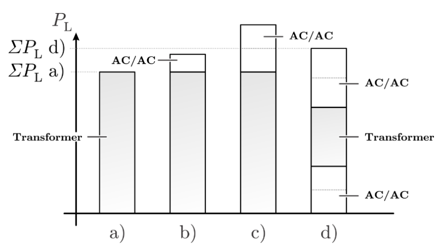
- Calculated Results (Losses, Volumes)
- Good Agreement with Specs of Commercially Available Active Frontend Converter



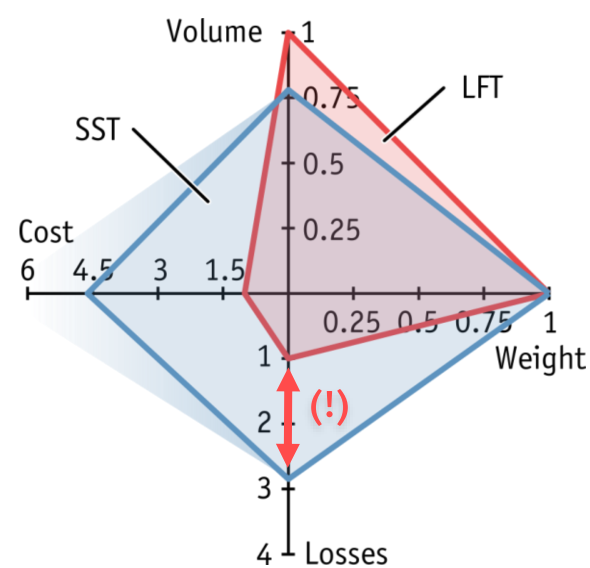
▶ SST vs. LFT Quantified – AC/AC Conversion

- 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

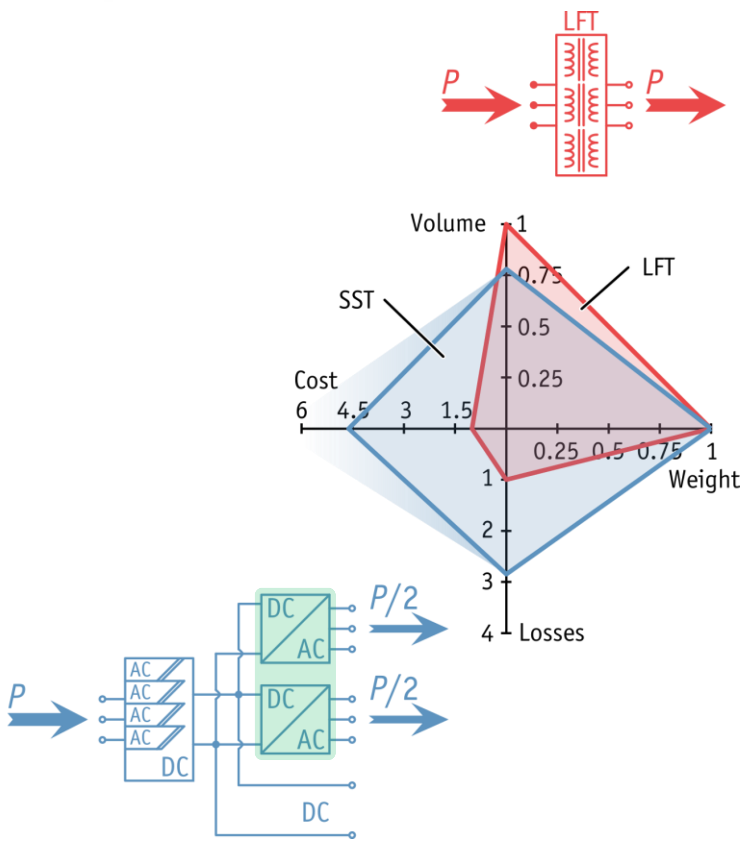


- **Efficiency Challenge Confirmed by Quantitative Analysis**

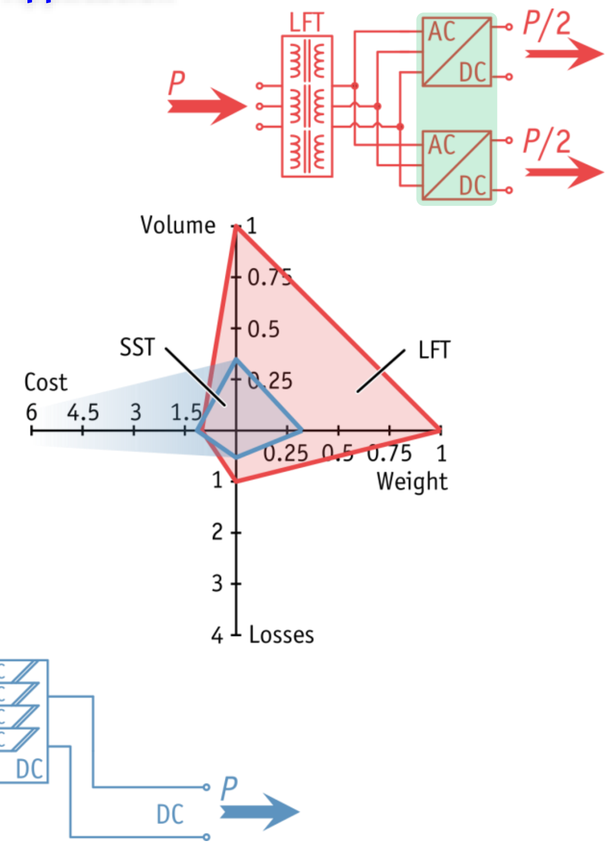


▶ SST vs. LFT Quantified – AC/AC and AC/DC Conversion

- AC/AC Application



- AC/DC Application



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

Further Reading: ETH / [Huber2014b]

Challenge #11/13

Competing Approaches

SST vs. LFT

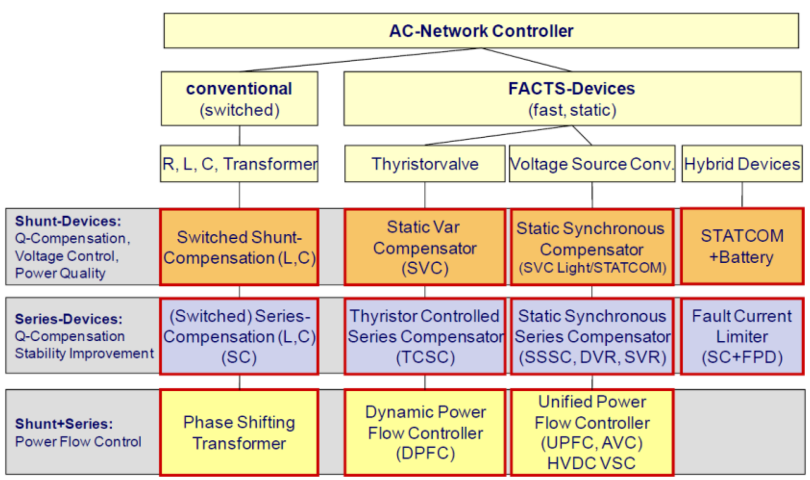
SST vs. FACTS

▶ FACTS – Flexible AC Transmission System

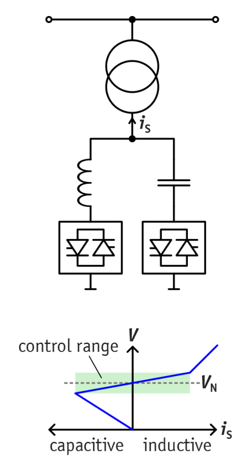
- **Goal: Influence Power Flows In Order To Optimally Utilize Transmission Capacities**

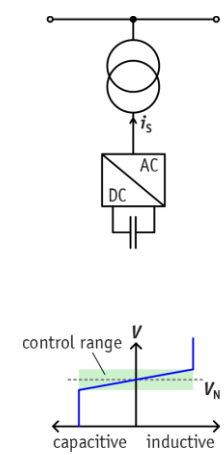
Without Power Electronics
- **Static VAr Compensator (Capacitor & Reactor Banks)**
- **VRDT**
- **Distribution Voltage Regulators**
- **Phase Shifting Transformers**
- **Generator Excitation Settings**

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

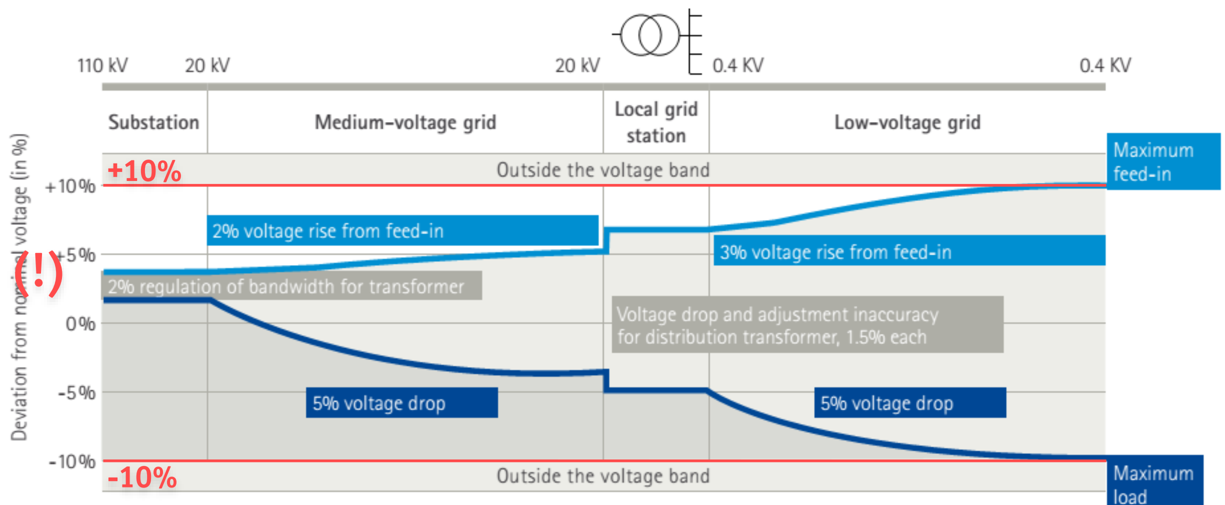




▶ Voltage Band Violations in the Distribution System

■ **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



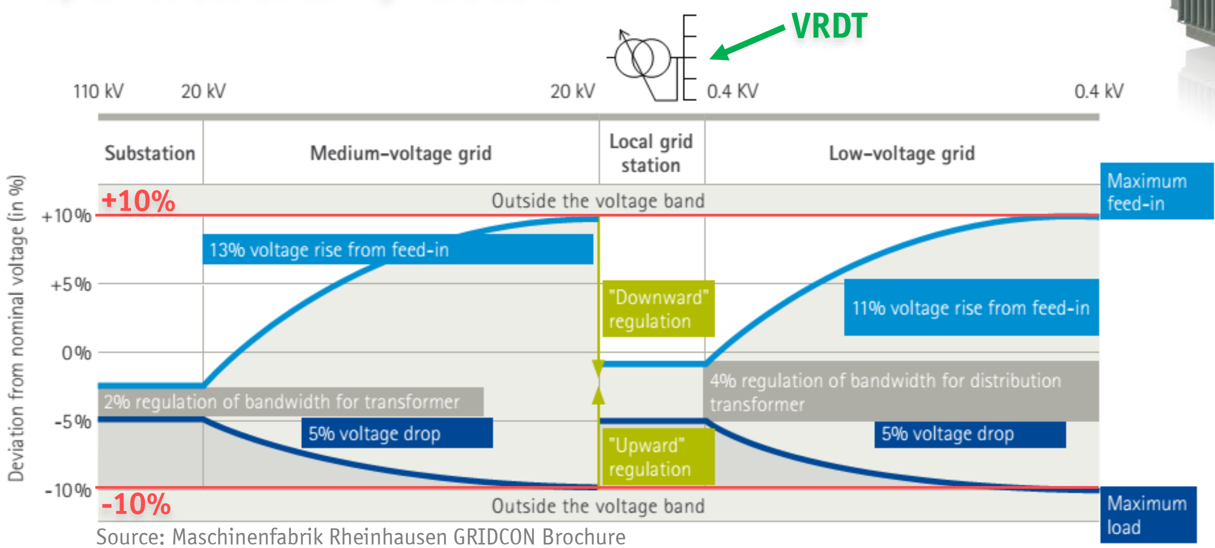
Source: Maschinenfabrik Rheinhausen GRIDCON Brochure

■ **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

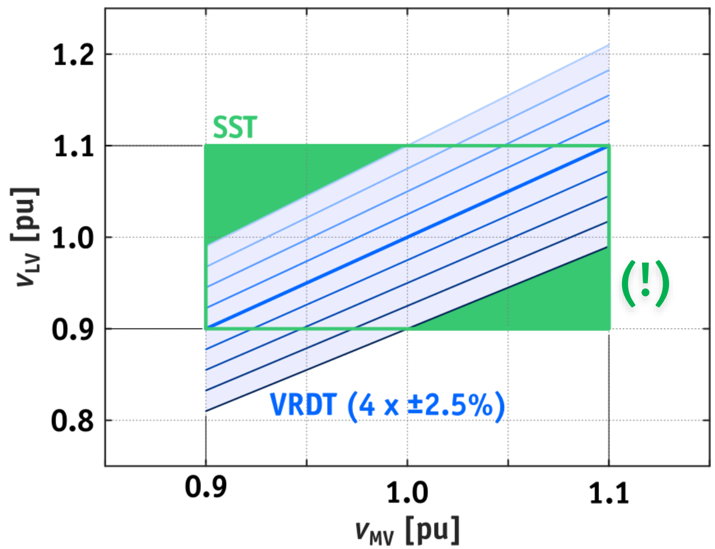


Source: Maschinenfabrik Rheinhausen GRIDCON Brochure

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

▶ SST vs. Voltage Regulation Distribution Transformer

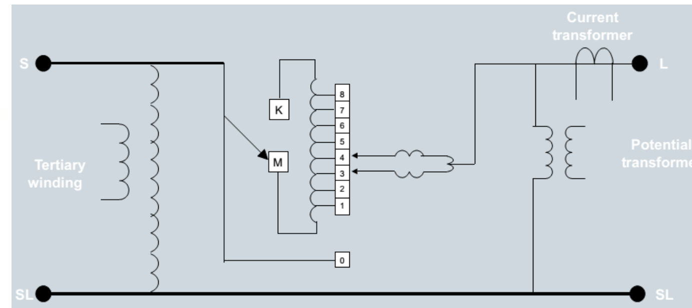
- SST Control is Continuous and Faster
- SST Control Range Can Be Larger
- SST Transfers only Active Power (Complete Decoupling)



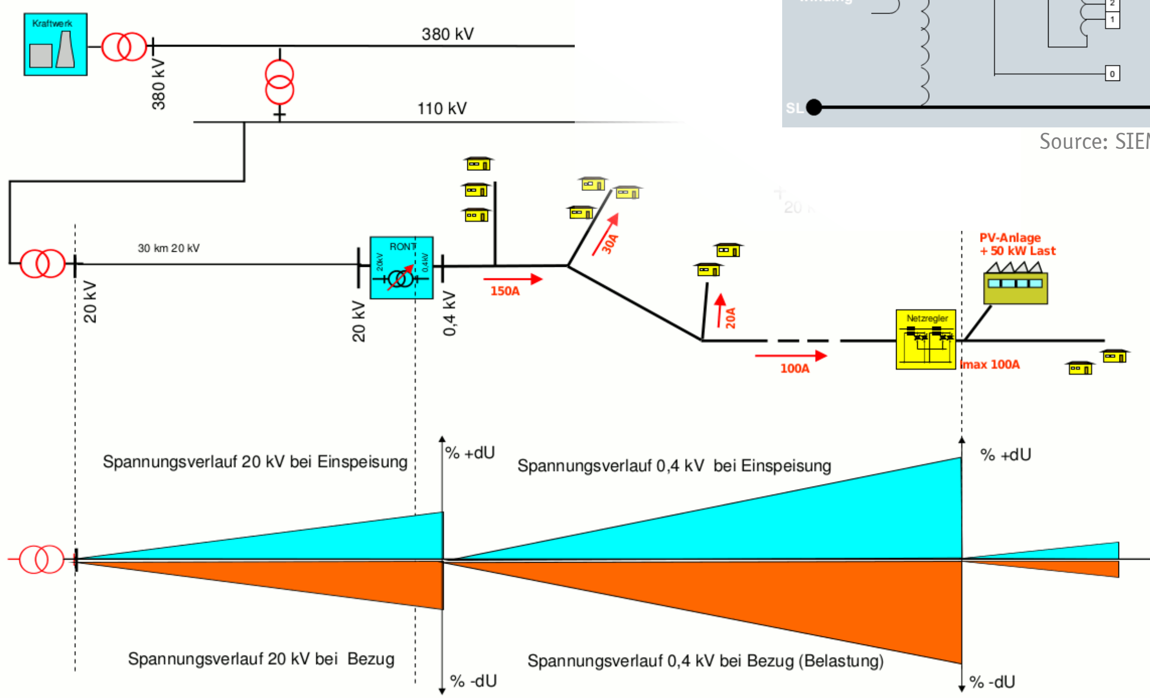
- SST Provides Wider Control Range → Interesting in High MV Voltage Situations
- But: Complexity, Costs, Robustness, etc.

▶ Distribution 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

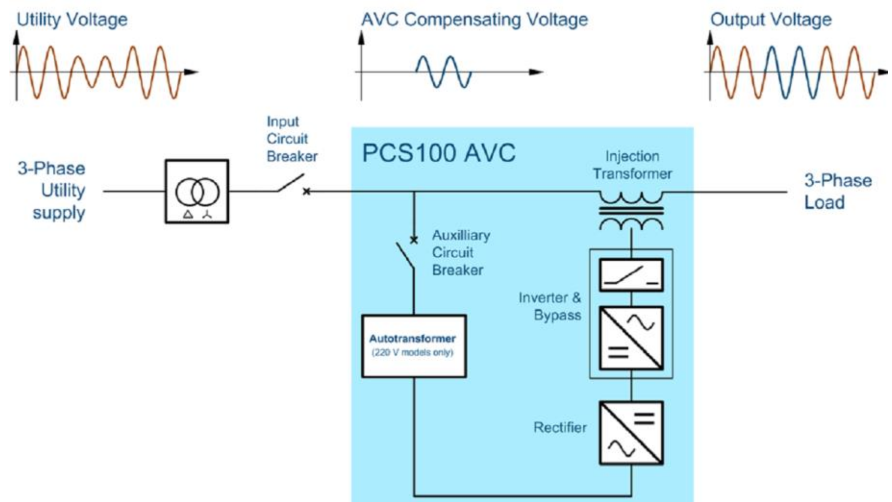


Source: www.walcher.com

▶ 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

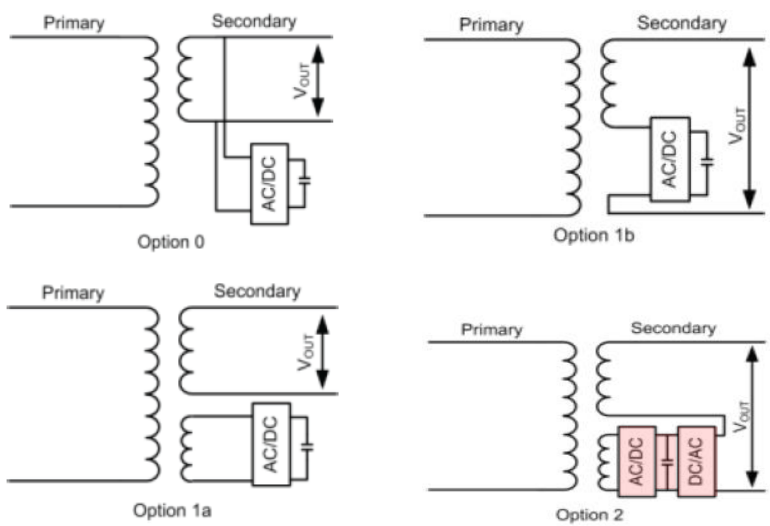


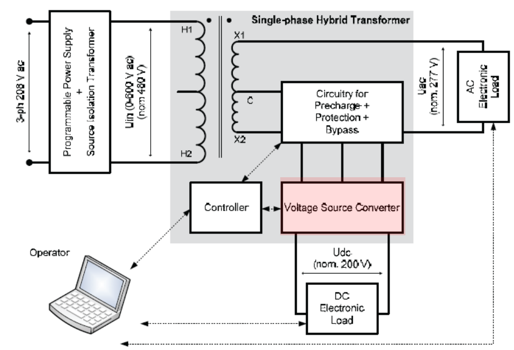
Source: ABB PCS100 Brochure

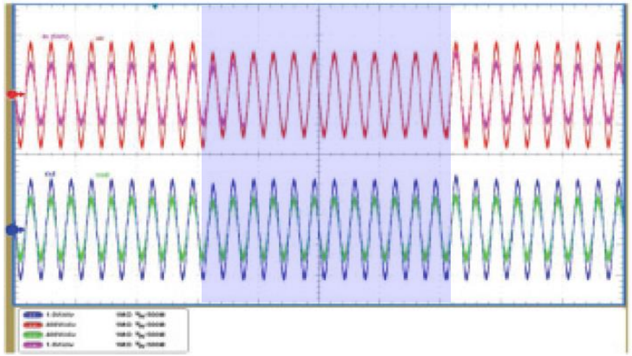
■ LFT + AVR = VRDT Functionality!

▶ Combinations of LFT and SST (1)

- Bala (ABB 2012)





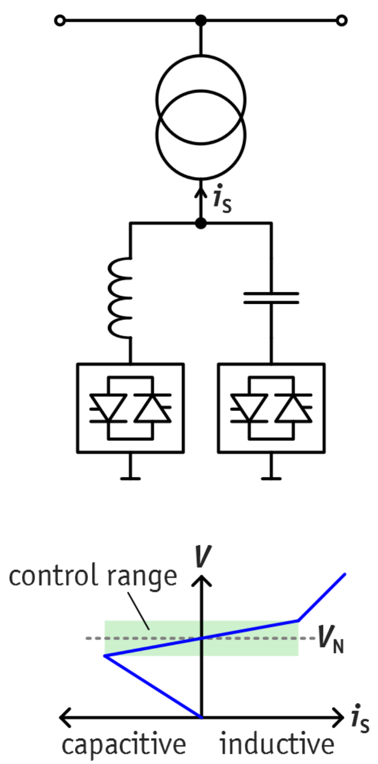


- **Reactive Power Compensation (PFC, Active Filter, Flicker Control)**
- **Available DC Port (Isolated in Option 1a)**
- **Option 2: Controlled Output Voltage**

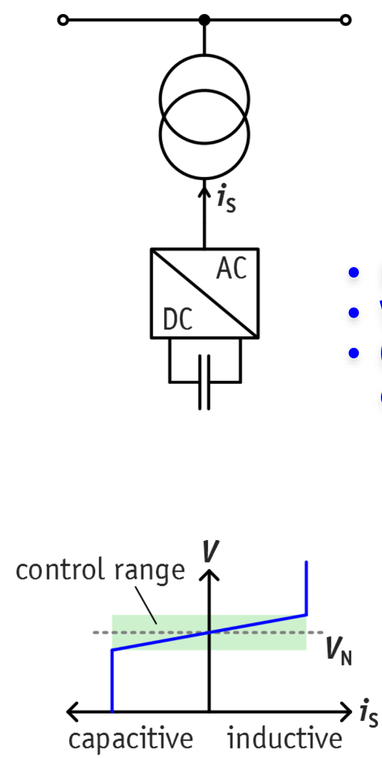
[Bala2012]

▶ Reactive Power Compensation / Voltage Regulation

■ Static VAr Compensation



■ STATCOM

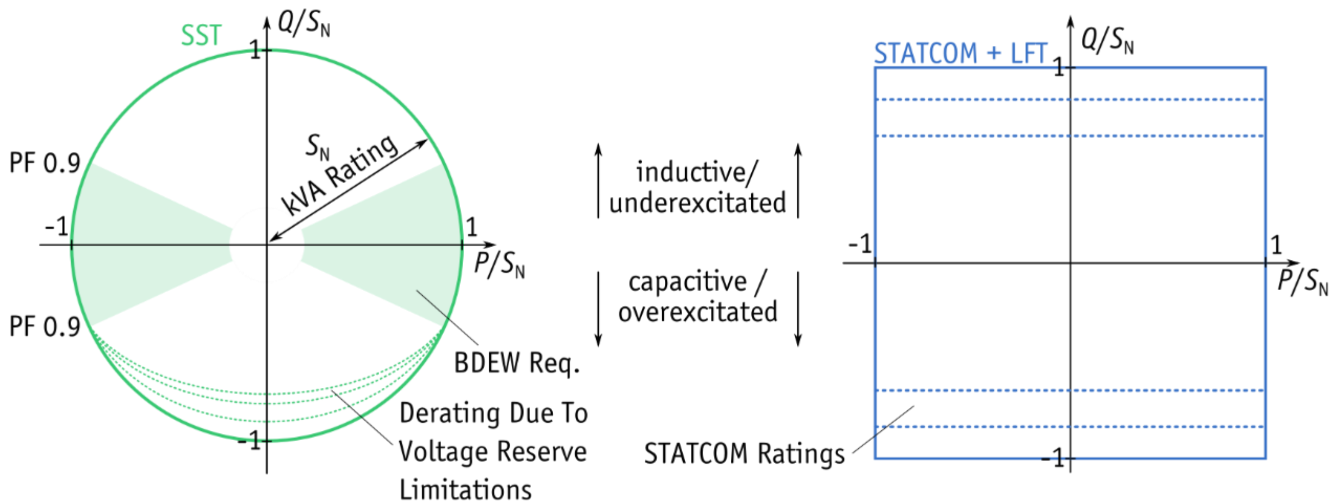


- Power/Voltage Quality Improvement
- Voltage Regulation
- Compensation of Harmonics, Flicker, etc.

▶ 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)**

Img.: Wenger SA, www.wenger.ch

Challenge #12/13

Construction of Modular Converter Systems

From Conceptualization to Realization

► From Conceptualization to Realization (1)

■ Actual Realization of a Modular MV Converter Systems → Complex Task

- Isolation Coordination
- Cooling
- Control & Communication
- Hot-Swap
- Auxiliary Supply
- Mechanical Assembly
- etc., etc.

PCIM Europe 2015, 19 – 21 May 2015, Nuremberg, Germany

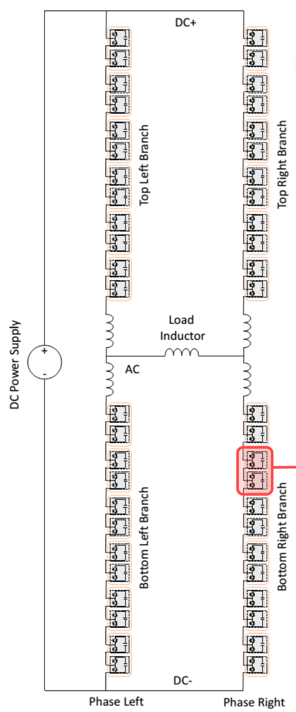
Integration Technologies for a Fully Modular and Hot-Swappable MV Multi-Level Concept Converter

Didier Cottet, Wim van der Merwe, Francesco Agostini, Gernot Riedel, Nikolaos Oikonomou, Andrea Rüetschi, Tobias Geyer, Thomas Gradinger, Rudi Velthuis, Bernhard Wunsch, David Baumann, Willi Gerig, Franz Wildner, Vinoth Sundaramoorthy, Enea Bianda, Franz Zurfluh, Richard Bloch, Daniele Angelosante, Dacfey Dzung, ABB Switzerland Ltd., Corporate Research, 5405 Baden-Dättwil, Switzerland
Tormod Wien, Anne Elisabeth Vallestad, Dalimir Orfanus, Reidar Indergaard, Harald Vefling, Arne Heggelund, ABB Norway Ltd., Corporate Research, 1375 Billingstad, Norway
Jonathan Bradshaw, DPS Ltd., Auckland 1010, New Zealand
Contact: didier.cottet@ch.abb.com

> 25 Authors (!)

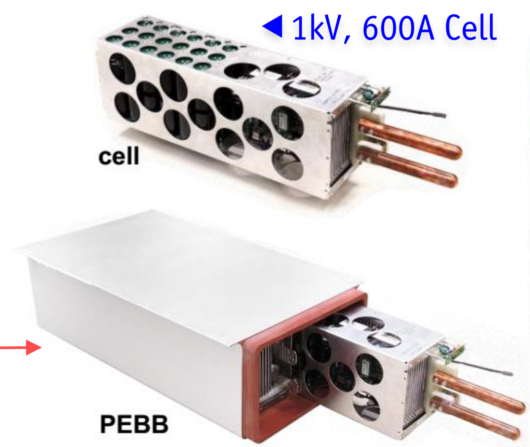
[Cottet2015a]
[Cottet2015b]

■ Example: MV Modular Multilevel Converter Presented by ABB (2015)



◄ 2 Single-Phase MMC in Back-to-Back Configuration

◄ 1kV, 600A Cell



◄ 48 Cells

Imgs.: W. van der Merwe

▶ From Conceptualization to Realization (2)

■ Actual Realization of a Modular MV Converter Systems → Complex Task

- Isolation Coordination
- Cooling
- Control & Communication
- Hot-Swap
- Auxiliary Supply
- Mechanical Assembly
- etc., etc.

PCIM Europe 2015, 19 – 21 May 2015, Nuremberg, Germany

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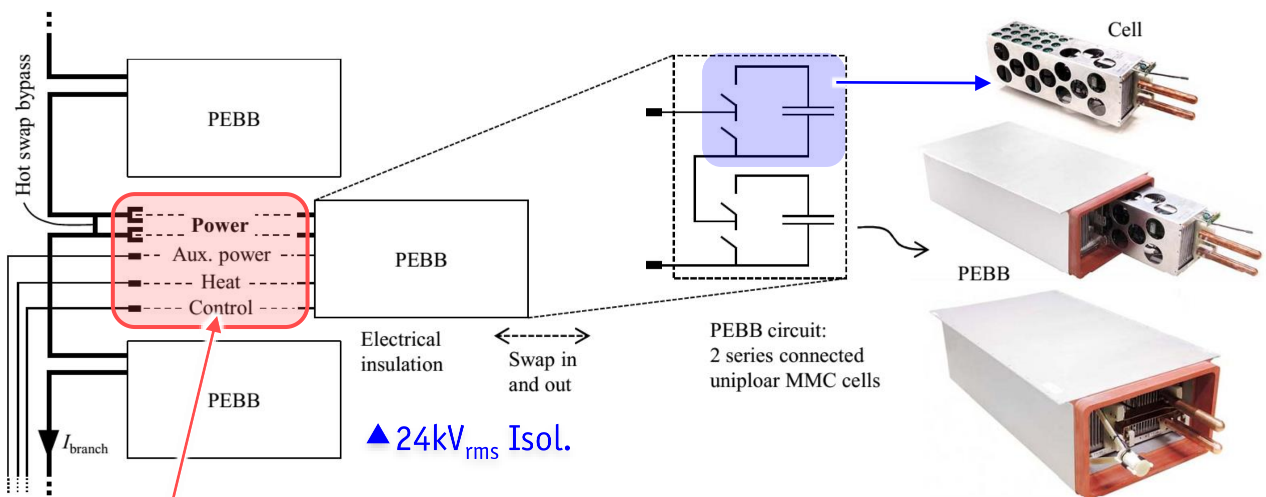
■ Example: MV Modular Multilevel Converter Presented by ABB (2015)

[Cottet2015a]
[Cottet2015b]

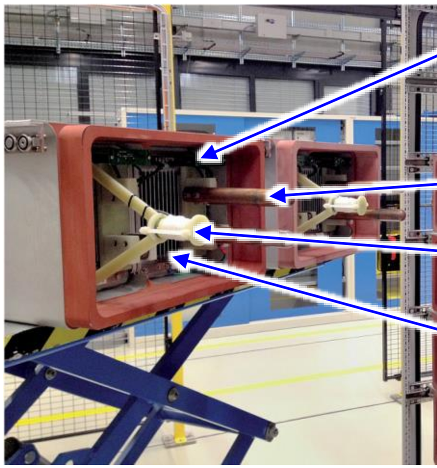


Interface

▶ Modularity: Hot-Swapping at 24kV

■ **Example: MV Modular Multilevel Converter Presented by ABB (2015)** [Cottet2015a], [Cottet2015b]

■ **All Interfaces Affected**



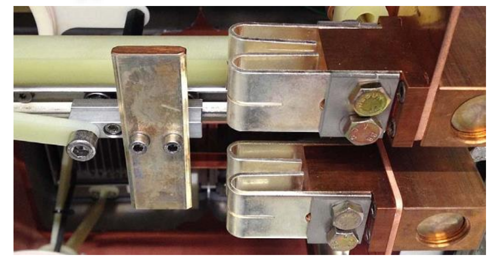
Communication (Wireless Optical)

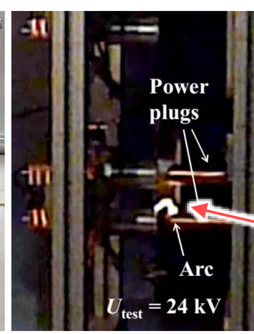
Power

Auxiliary (IPT)

Cooling (Air)

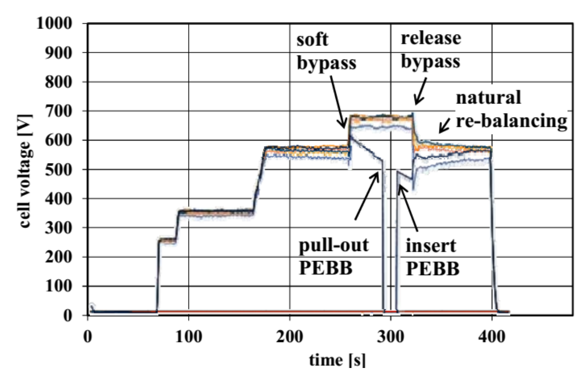
▼ Bypass Switch





◀ Lab Test ▶

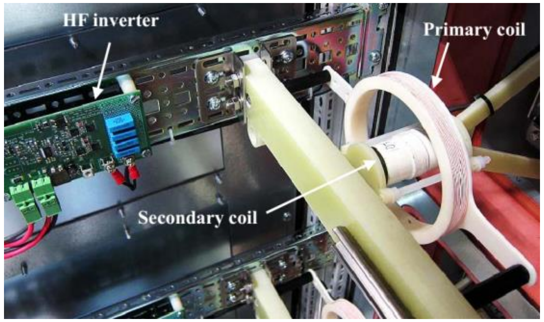
24kV Sw. Arc



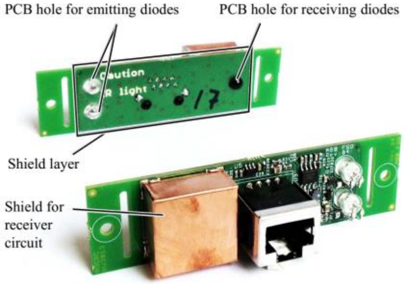
▶ Advanced Integration Technologies

- **Example: MV Modular Multilevel Converter Presented by ABB (2015)** [Cottet2015a], [Cottet2015b]

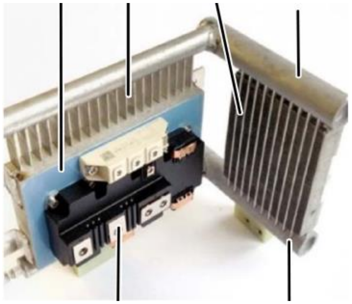
- Integration Technology:
  IPT for Auxiliary Power Supply



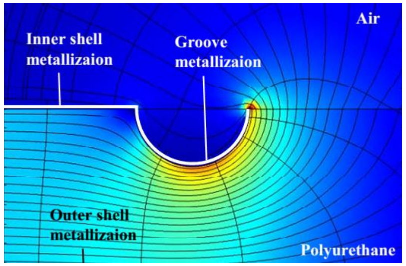
- Integration Technology:
  Wireless Optical EtherCAT Comm.

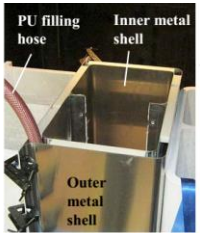


- Integration Technology:
  Two-Phase Cooling



- Integration Technology:
  Solid Isolation of PEBBs





→ **Actually Building an SST is a Multi-Disciplinary, Highly Complex Task!**

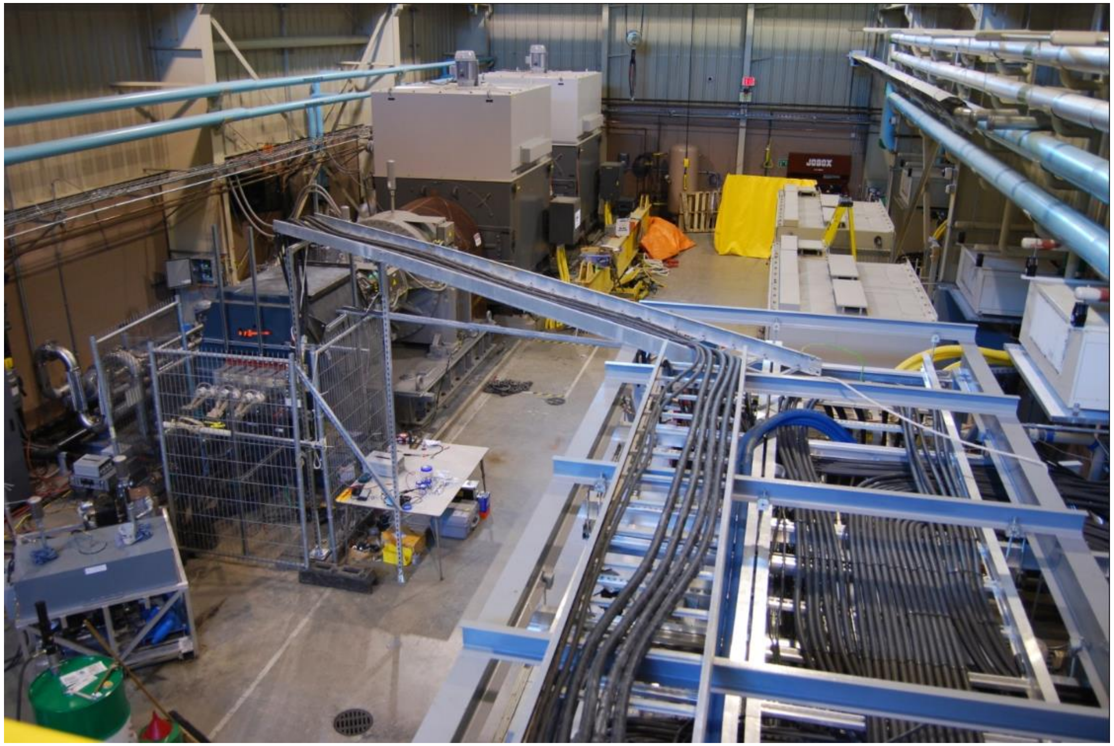
Challenge #13/13

Testing of MV Converters

...and a Few Words on Education

▶ Infrastructure (1)

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

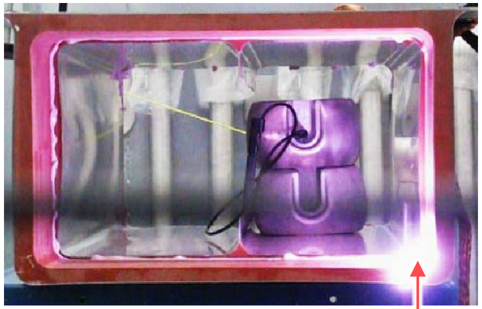


Img.:Center for Advanced Power Systems / Florida State University

- Large Space Requirement / Considerable Investment (!)

▶ Infrastructure (2): Examples

■ Medium-Voltage and High-Voltage Testing Facilities & Experience

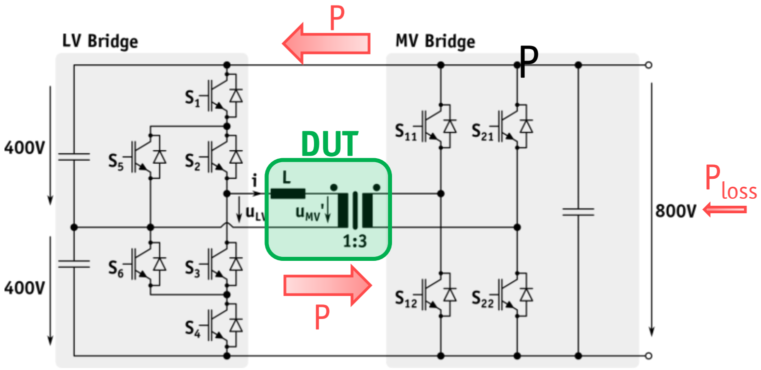
Imgs.: [Cottet2015b]

Img.: High Voltage Lab, ETH Zurich]

■ Source/Sink for 100s of kW

Img.: electrical-engineering-portal.com

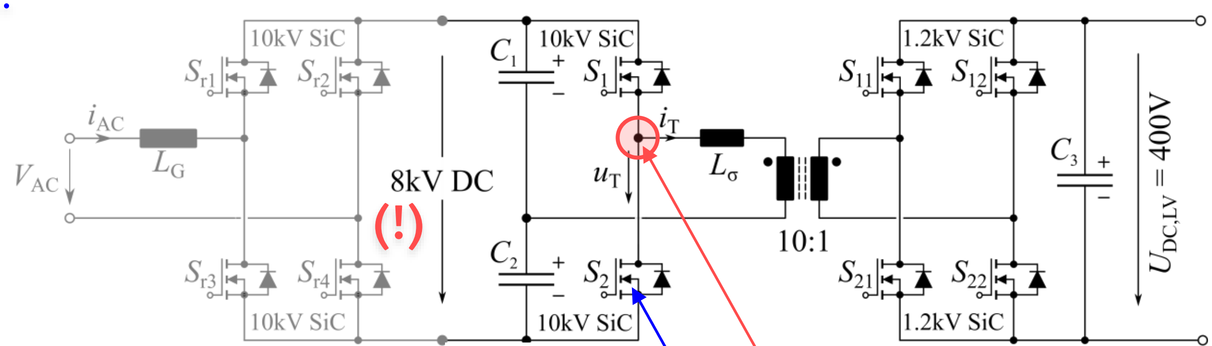
■ Or Back-To-Back Testing Concepts → Complexity



▶ Measurement Equipment

■ E.g., Switching Loss Measurements of HV SiC Devices

- Voltage Range vs. Accuracy/Resolution
- Skew
- Disturbances
- …

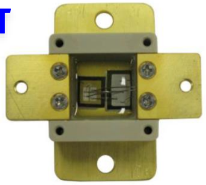


Switch Node: 8kV at 50kHz (!)

■ Special High-Voltage Measurement Eq.

Img.: www.Tektronix.com

10kV SiC FET



Img.: Cree Inc.

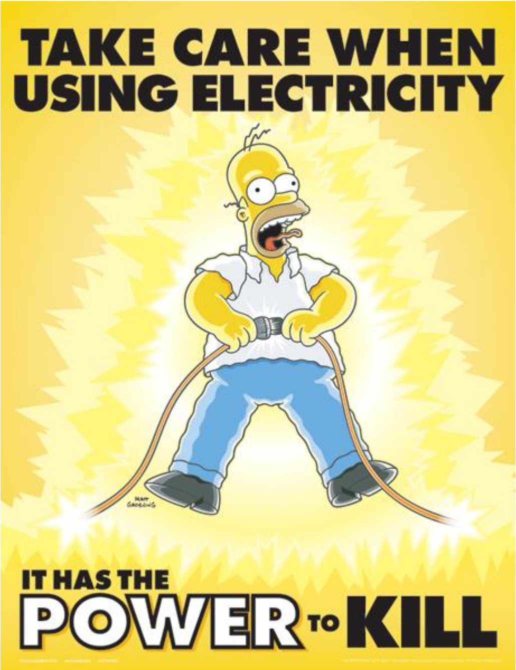
Circuit: ETH / [Rothmund2015]

A Few Words on Education...

eyeidea / 123RF Stock Photo

► 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



Source: www.safetyposters.com

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

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

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

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

alphaspirit / 123RF Stock Photo

- **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

13 Key Challenges

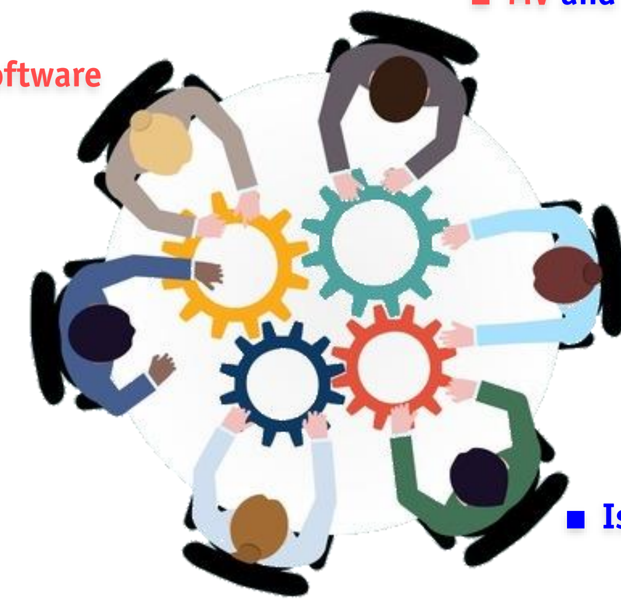
Core Competencies

1. *Topology Selection*
2. *Power Semiconductors*
3. *Optimum Number of Levels*
4. *Reliability*
5. *MF Isolated Power Converters*
6. *Medium-Freq. Transformer*
7. *Isolation Coordination*
8. *EMI*
9. *Protection*
10. *Control & Communication*
11. *Competing Approaches*
12. *Construction of Modular Conv.*
13. *Testing*

▶ Core Competencies for SST Design

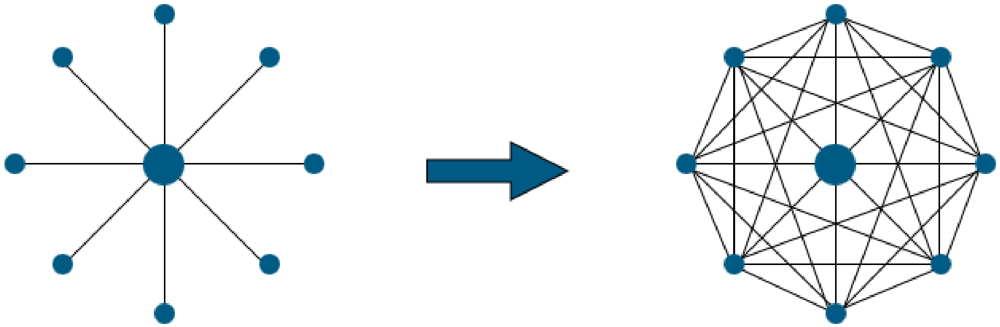
- The 13+ Challenges Need To Be Addressed By a TEAM

- MV and LV Power Electronics
- Digital Control & Software
- Transformers & Magnetics
- Mechanical Construction
- Isolation Coordination
- ...



▶ Developing and Actually Building an SST is a Multi-Disciplinary, Highly Complex Task!

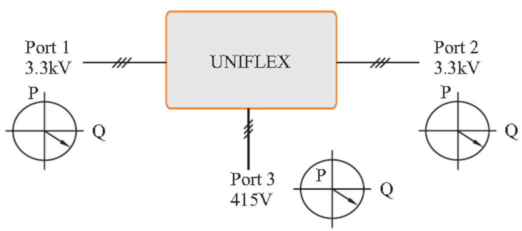
Examples of SSTs for Smart Grids

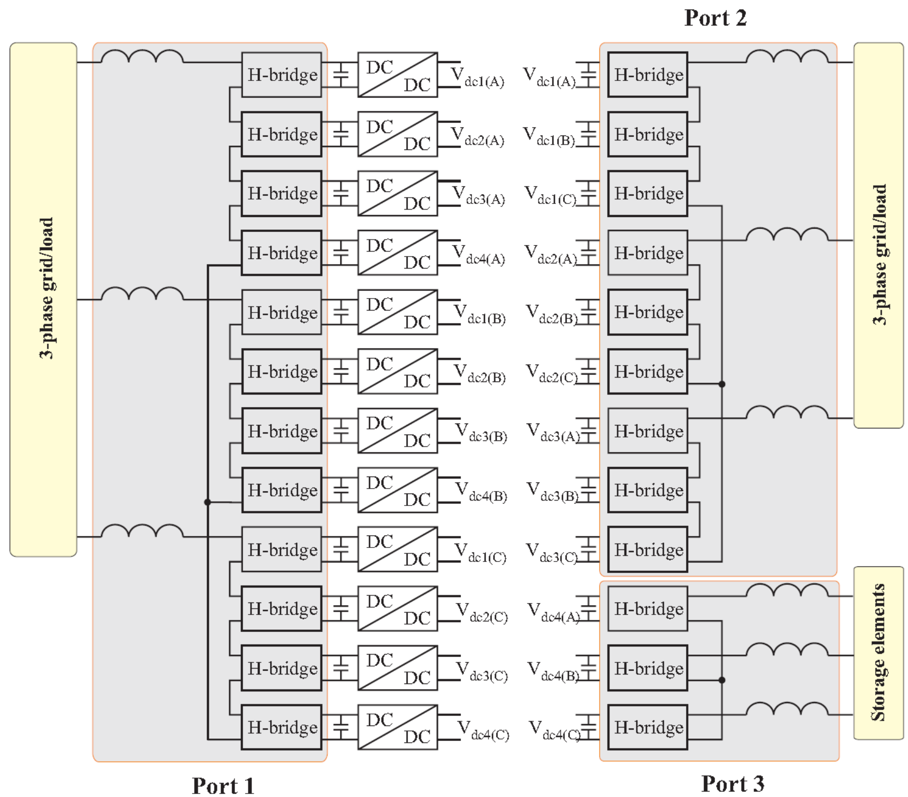


Img.: M. Simmons / www.forbes.com

▶ UNIFLEX Project (1)

- EU Project (2009)



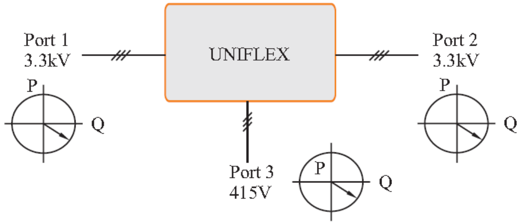


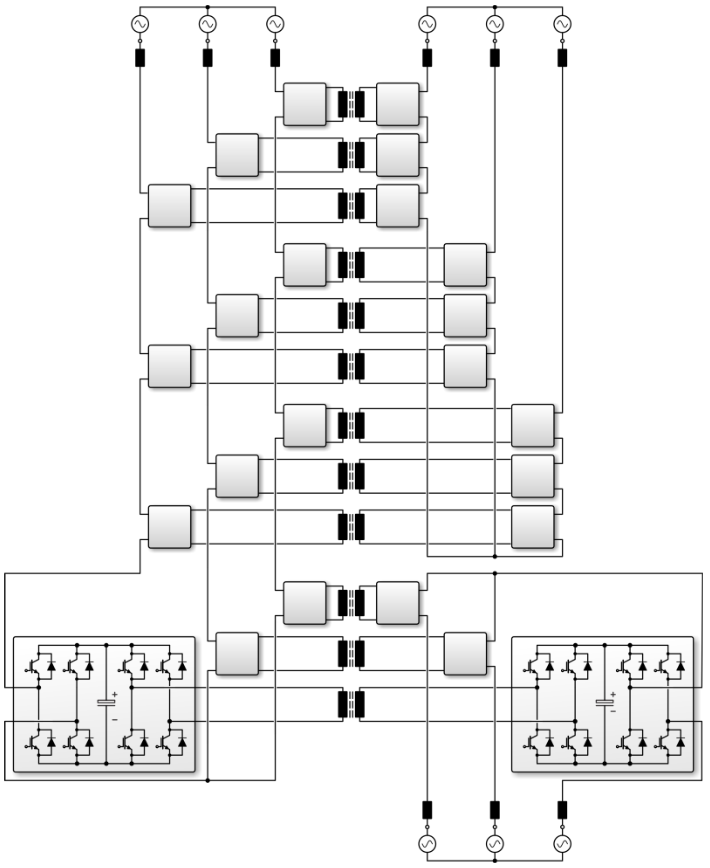
- **Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids**
- **Cellular 300kVA Demonstrator of 3-Port Topology for 3.3kV Distr. System & 415V LV Grid Connection**

[Watson2009]

▶ UNIFLEX Project (2)

- EU Project (2009)



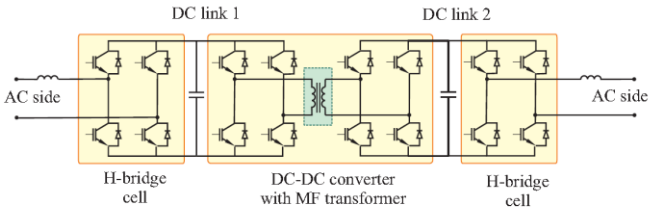


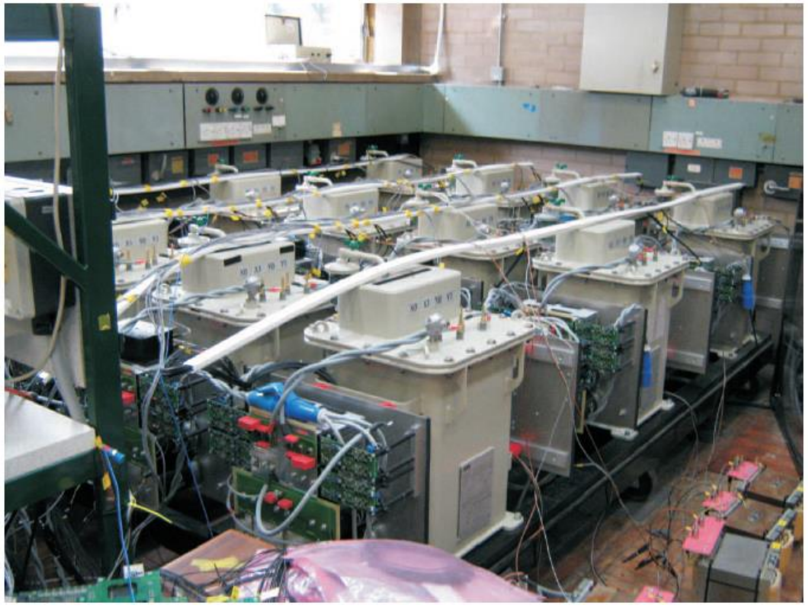
- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- Cellular 300kVA Demonstrator of 3-Port Topology for 3.3kV Distr. System & 415V LV Grid Connection

[Watson2009]

▶ UNIFLEX Project (3)

- EU Project (2009)





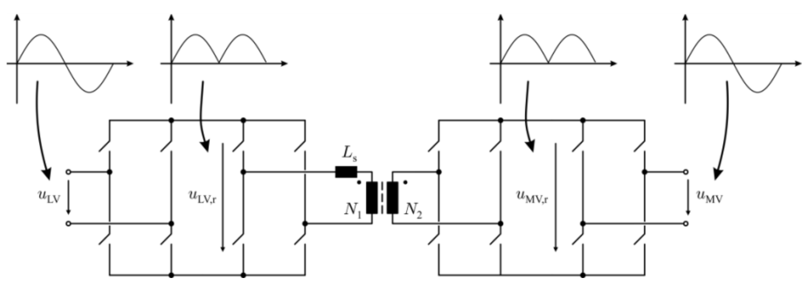
- **AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham**

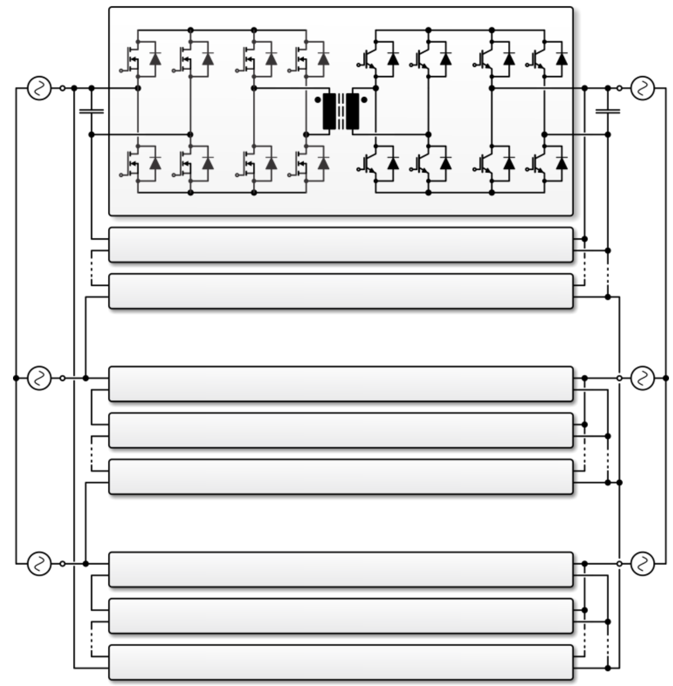
[Watson2009]

▶ 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)**

[Das2011]

► SiC-Enabled Solid State Power Substation (1)

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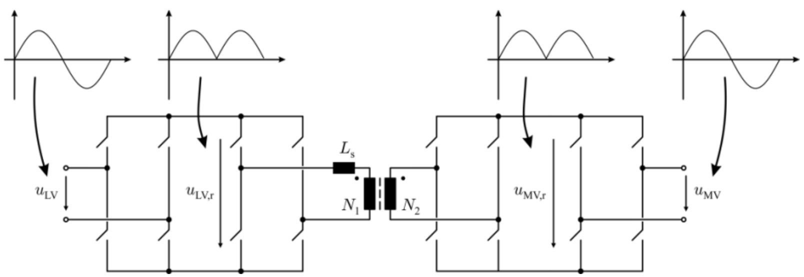
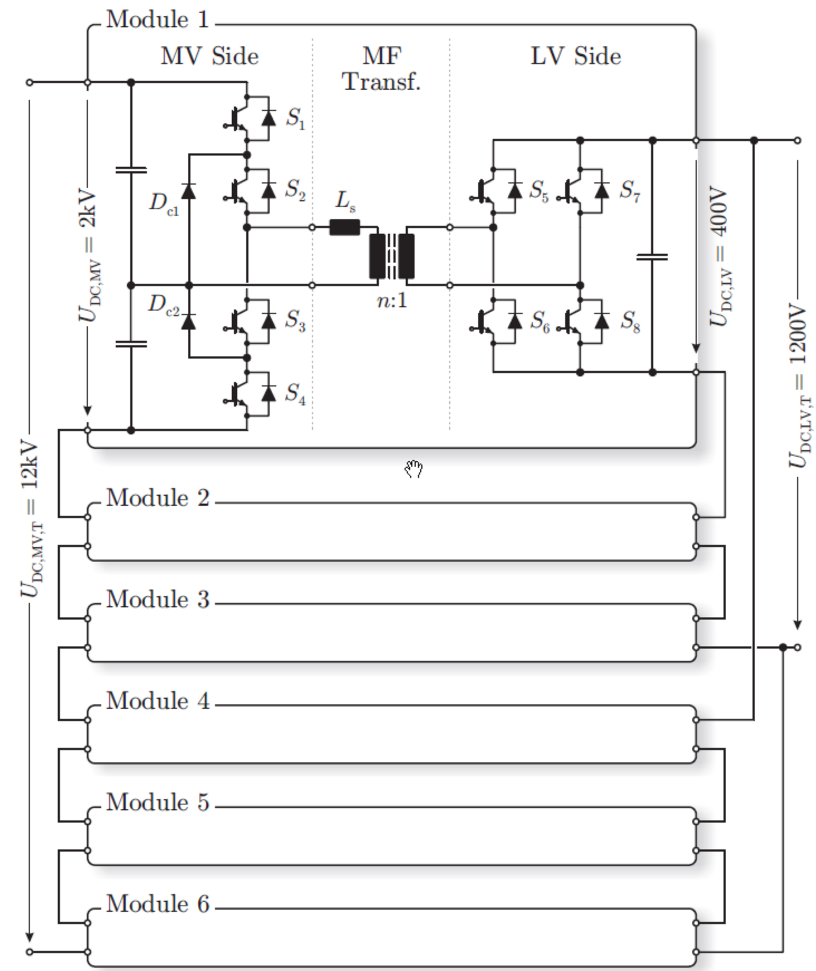


- **SiC-Enabled 20kHz/1MVA "Solid State Power Substation"**
- **97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)**

[Das2011]

▶ MEGACube @ ETH Zurich (1)

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

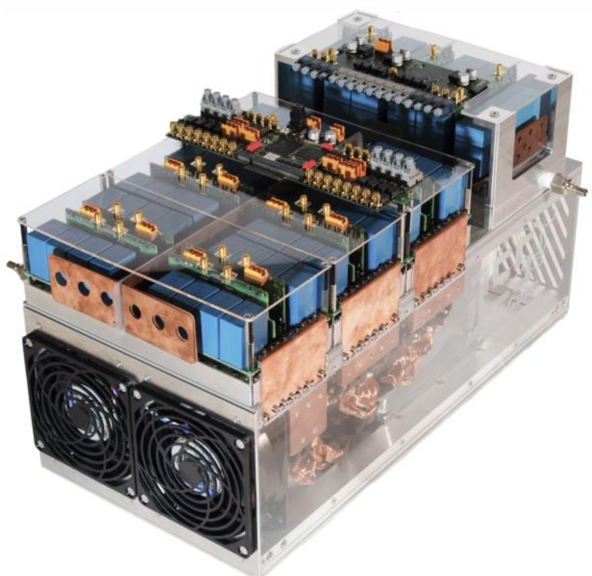


- MV Level 12.0 kV
- LV Level 1.2 kV

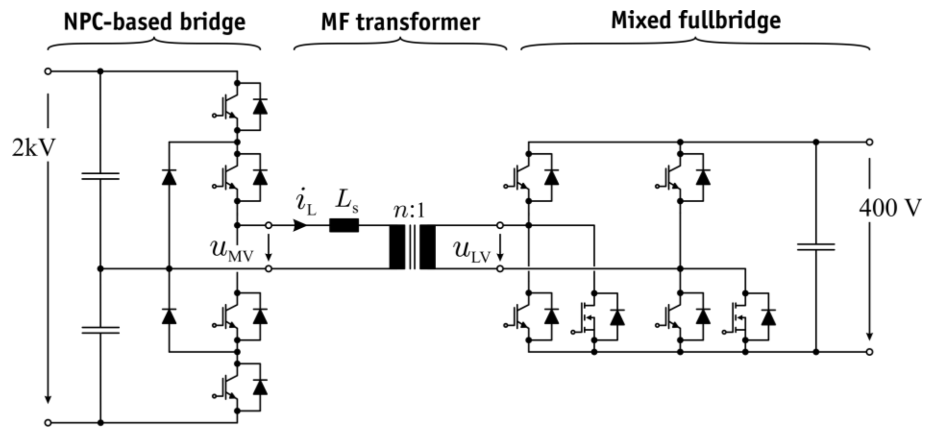
[Ortiz2010], [Ortiz2013c]

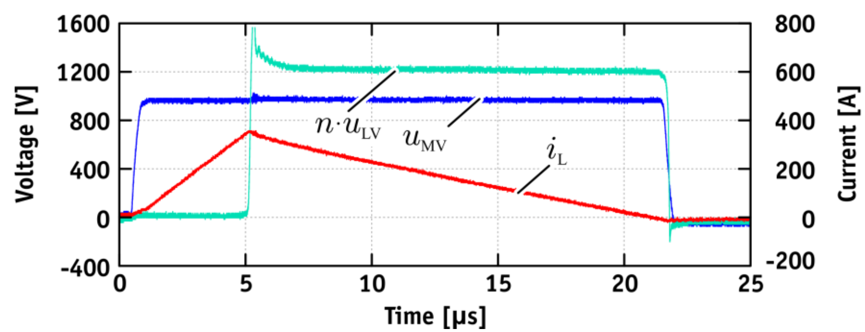
▶ MEGACube @ ETH Zurich (2)

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



▲ 166kW / 20kHz TCM DC-DC Converter (Ortiz, 2013)





▲ Structure of the 166kW Module and MV Side Waveforms

[Ortiz2013c]

Traction SSTs
Examples

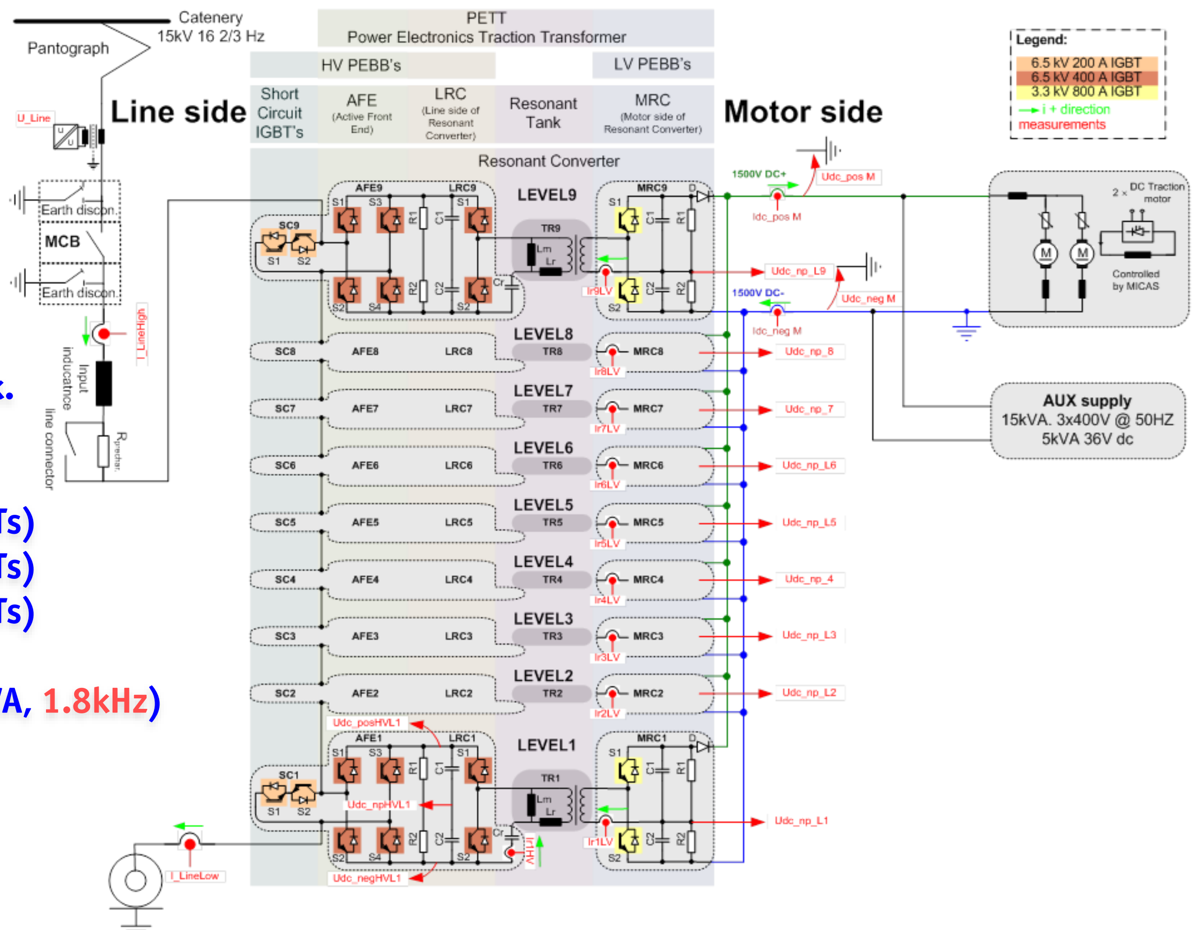
Img.: www.futuretimeline.net

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

ABB PETT

- Dujic et al. (2011)

- Steiner (1996)
- 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)

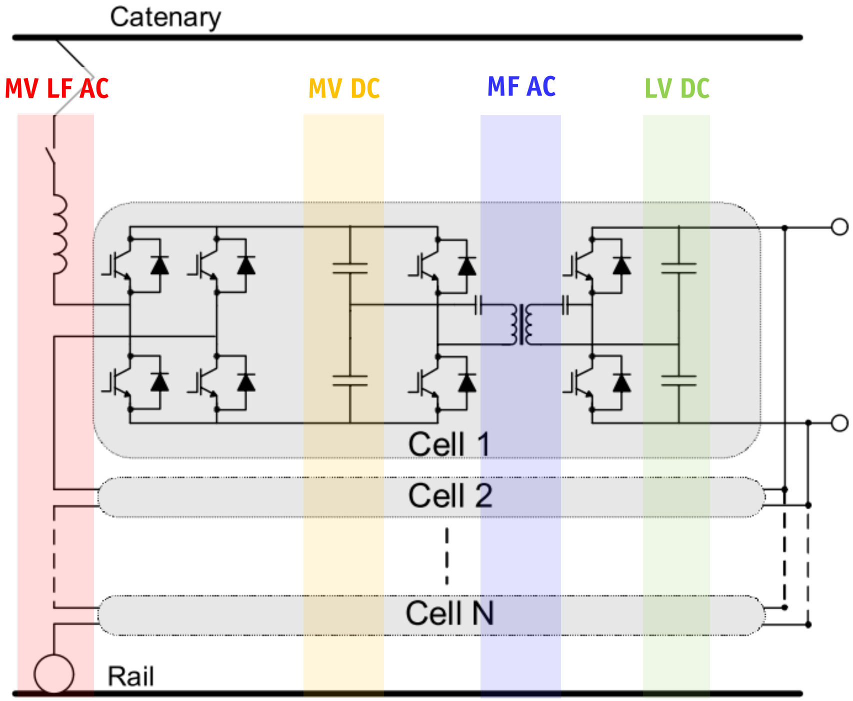
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

[Dujic2013] & [Zhao2014]

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

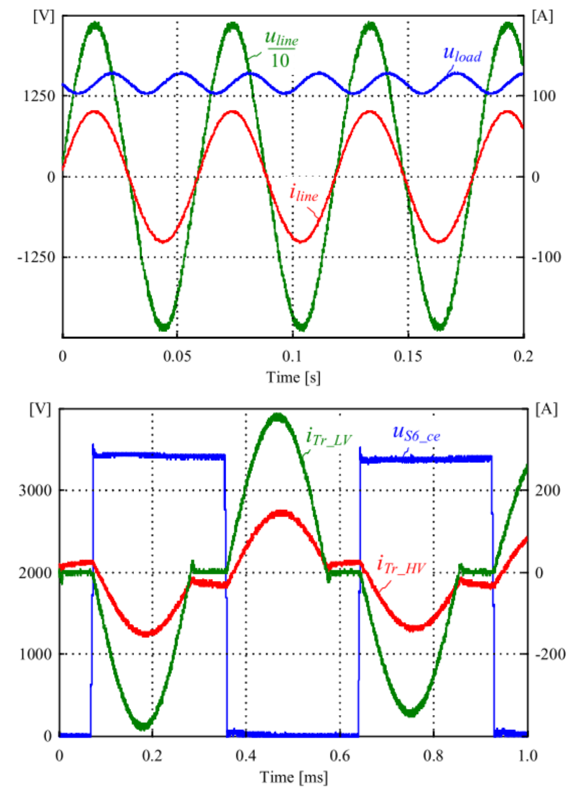
■ 1.2MVA, 15kV, 16 $^2/_3$ Hz, 1ph. AC/DC Power Electronic Transformer (PETT)

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



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

Img.: [Dujic2011]

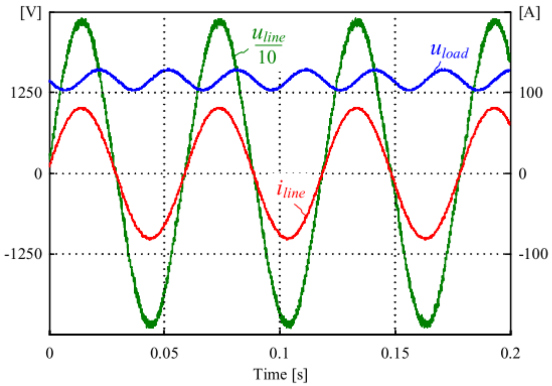


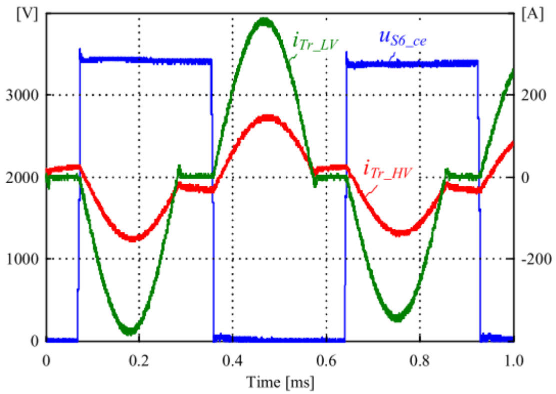
[Dujic2013] & [Zhao2014]

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

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

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





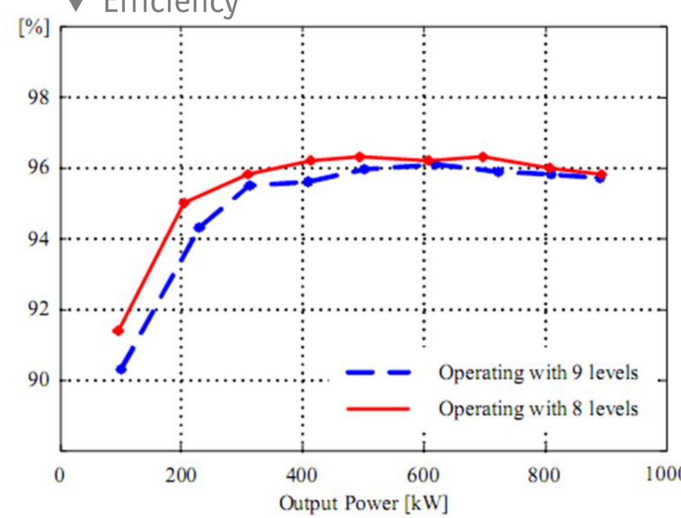
[Dujic2013] & [Zhao2014]

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

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

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

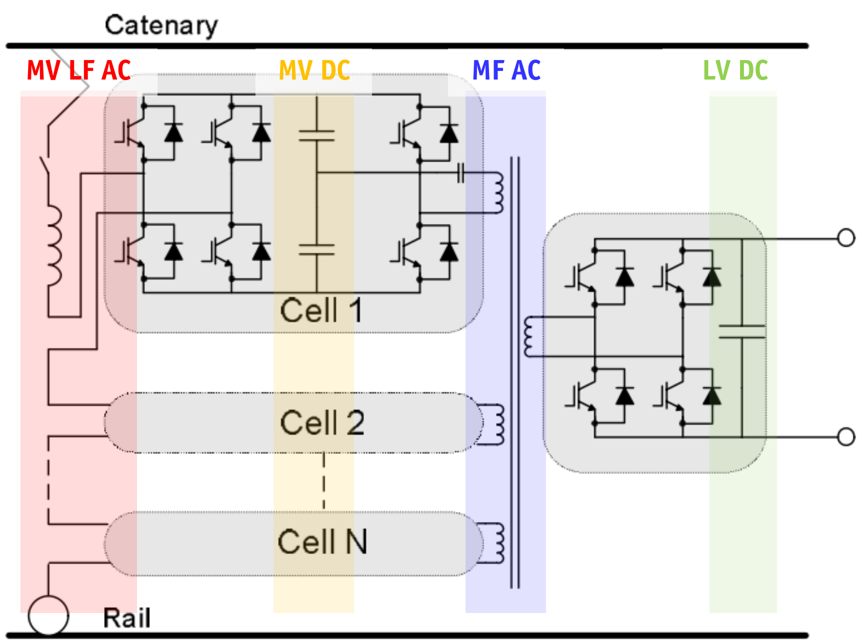
▼ Efficiency



[Dujic2013] & [Zhao2014]

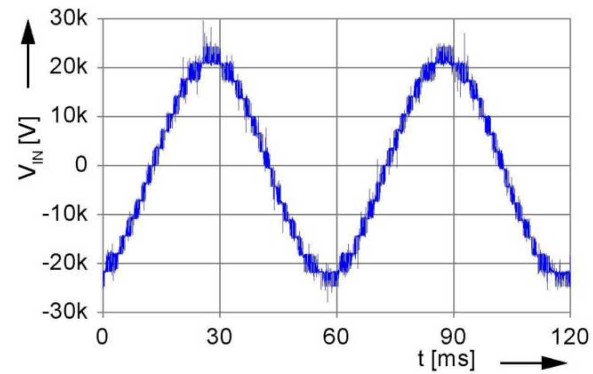
▶ Cascaded H-Bridges with Multi-Winding MF Transformer (1)

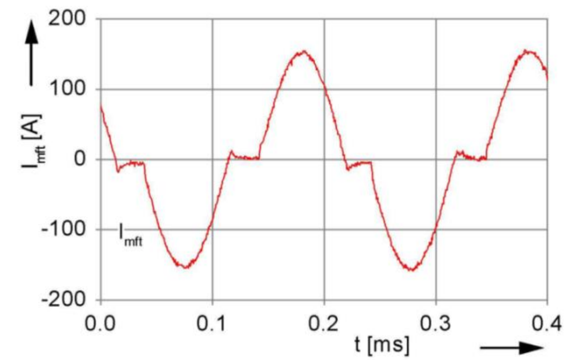
- ALSTOM e-Transformer (Engel, 2003)



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

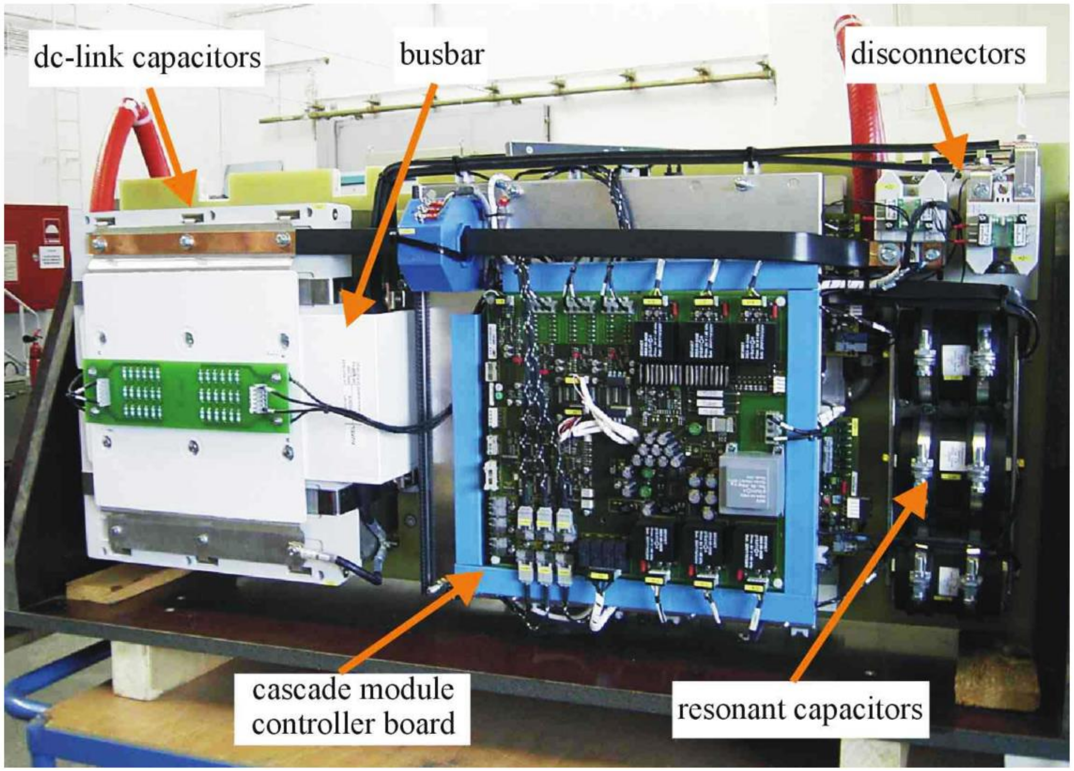
Img.: [Dujic2011]





[Engel2003]

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

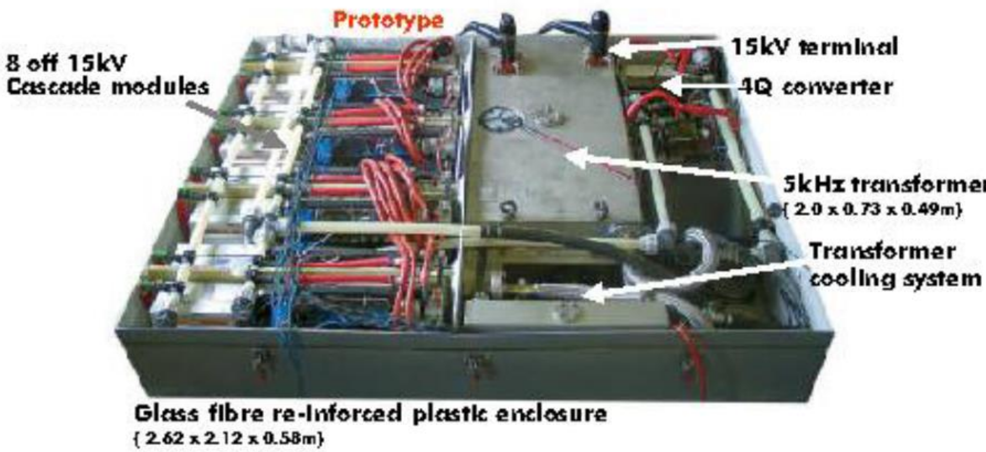


■ **ALSTOM e-Transformer**

- Module Power 180 kW
- Frequency 5 kHz

[Engel2003]

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



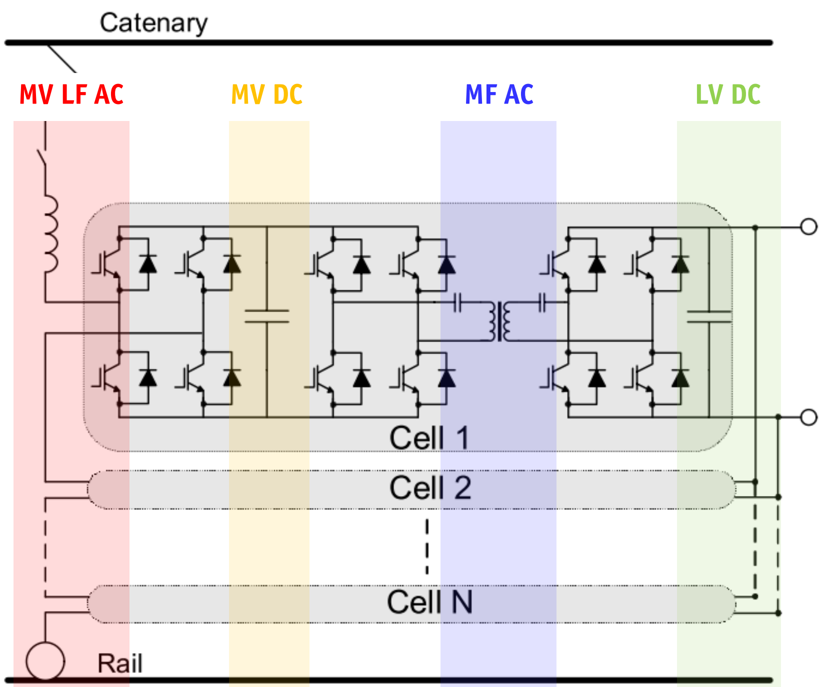
■ ALSTOM e-Transformer

- Module Power 180 kW
- Frequency 5 kHz

[Engel2003], [Taufiq2007]

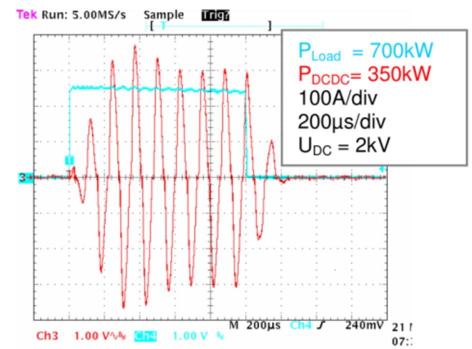
▶ Cascaded H-Bridges with Resonant/Non-Resonant DC-DC Stages (1)

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

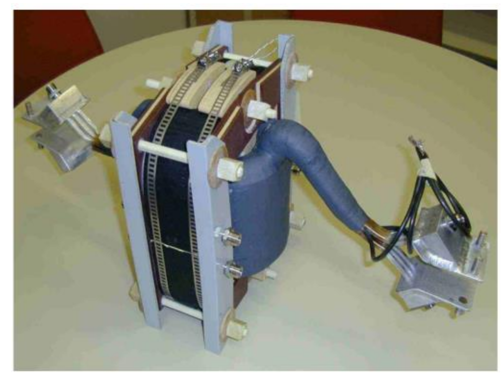


PET topology with cascaded H-bridges and resonant/non-resonant DC-DC stages.

Img.: [Dujic2011]



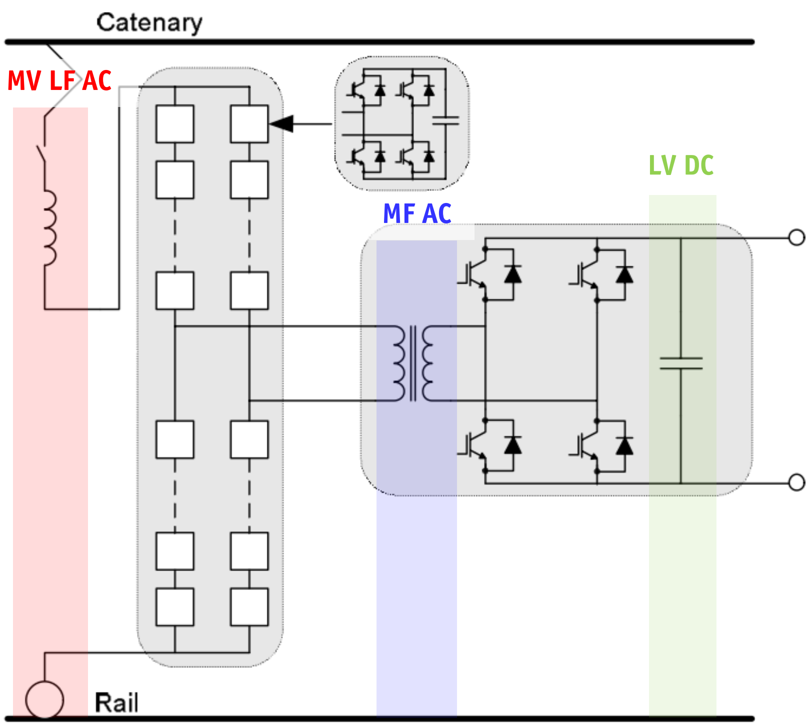
Dynamic behavior of DC-DC converter



[Steiner2007]

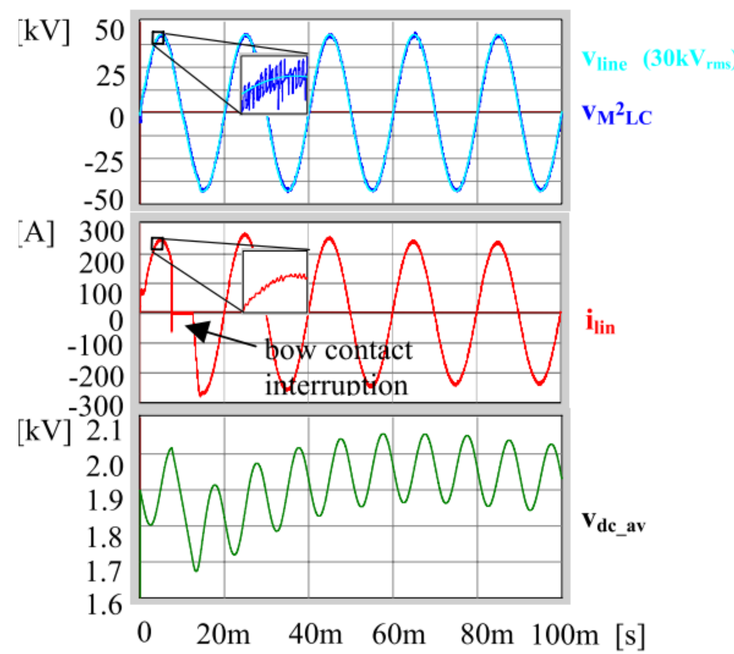
▶ Modular Multilevel Converter (1)

■ **Marquardt/Glinka (SIEMENS, 2003)**



PET topology using M2LC converter

Img.: [Dujic2011]

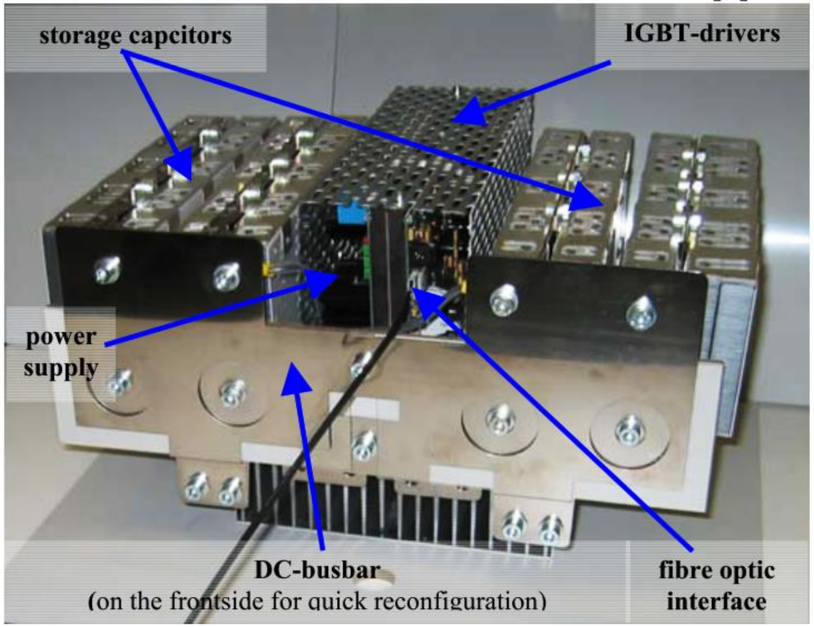


[Glinka2003]

▶ Modular Multilevel Converter (2)

■ Marquardt/Glinka (SIEMENS, 2003)

- Module Power 270 kW
- Frequency 350 Hz



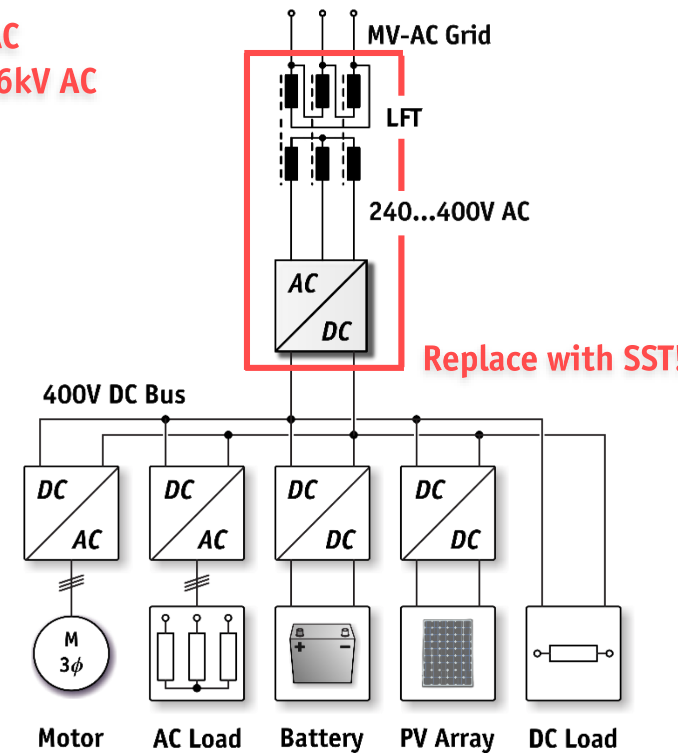
[Glinka2003]

Future Concepts and Applications

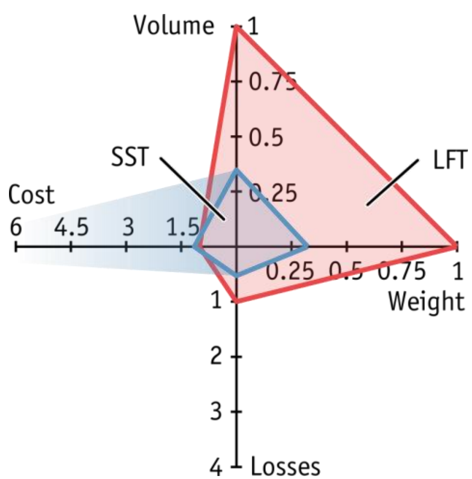
scanrail / 123RF Stock Photo

▶ 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

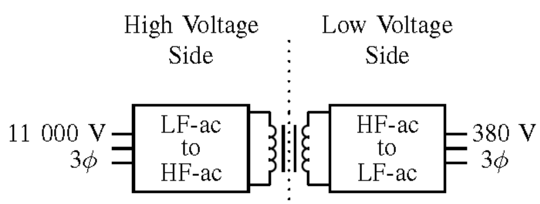


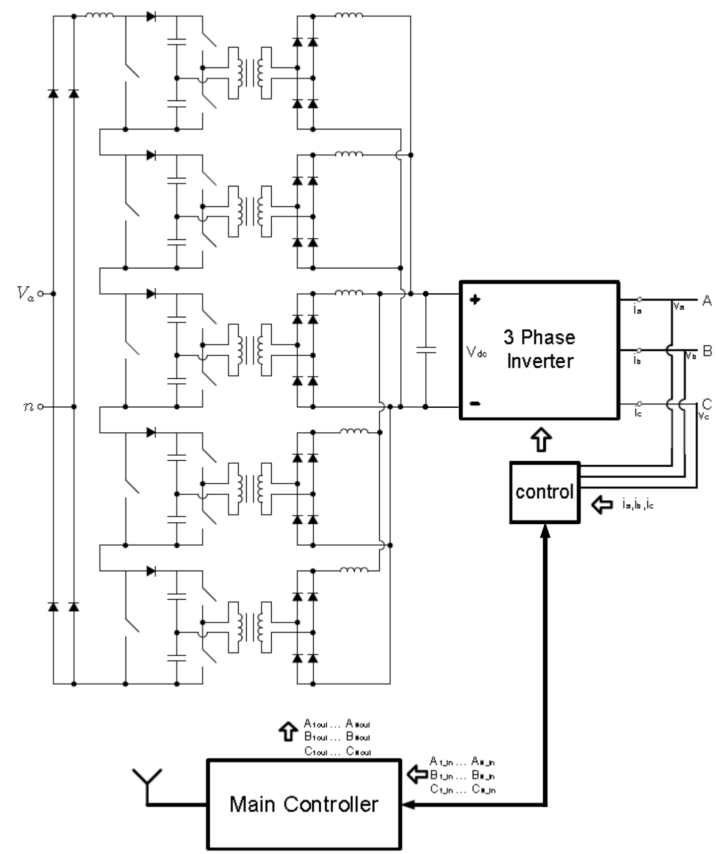
- SST / LFT Comparison for AC/DC Applications



▶ Unidirectional DC-Link Based SST Structure

- van der Merwe (2009)





- **5-Level Series Stacked Unidir. Boost Input Stage**

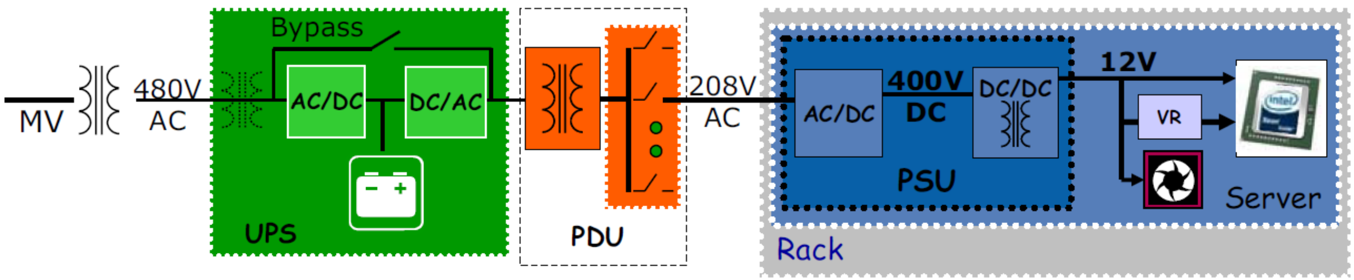
[VanDerMerwe2009a] & [VanDerMerwe2009b]

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

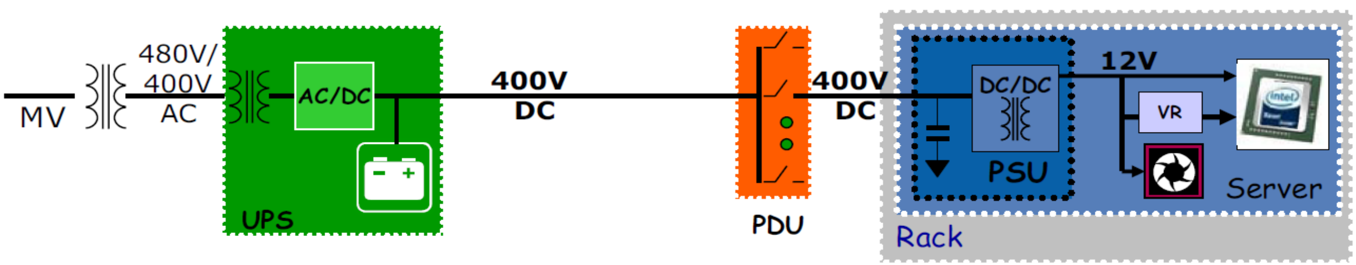
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

- Conventional US $480V_{AC}$ Distribution

Img.: intel 2007



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



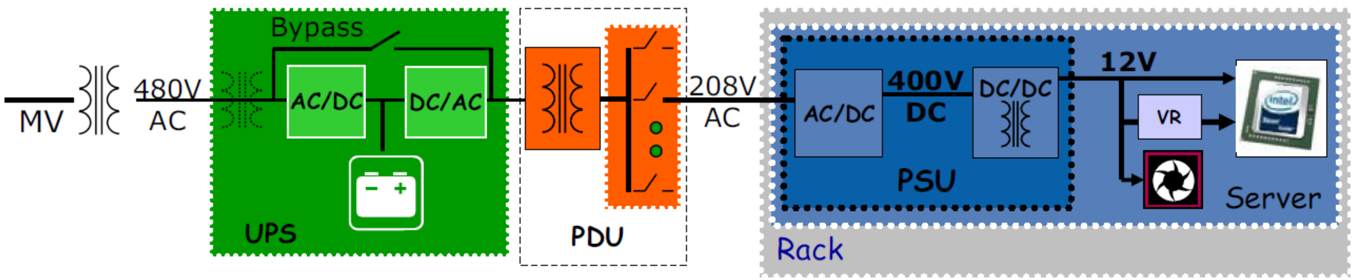
- E.g. ABB / Green DC Data Center (+190V/-190V DC Distribution)

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

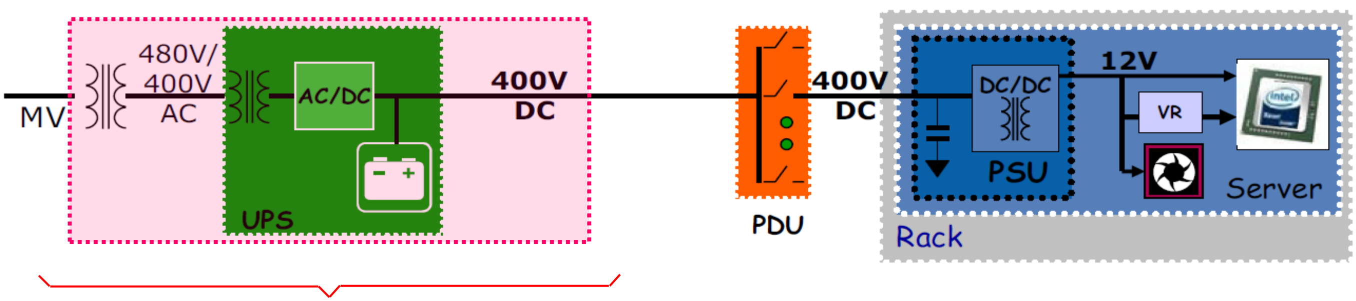
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

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

Img.: intel 2007



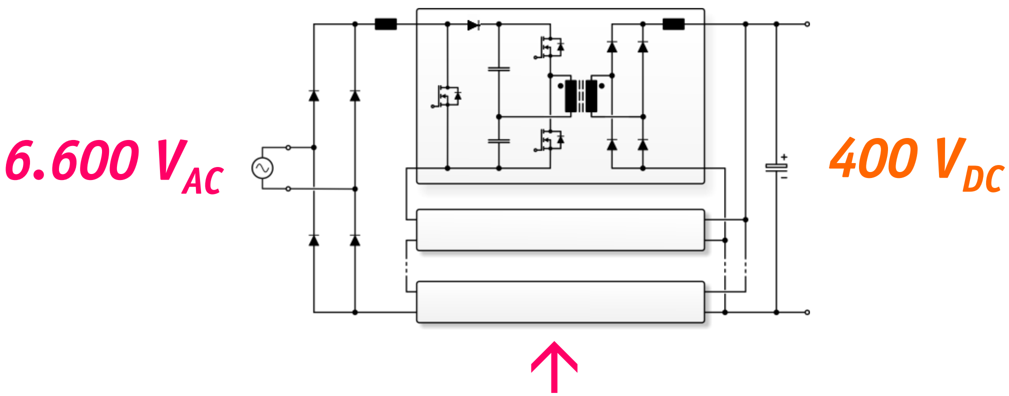
- Facility-Level 400V$_{DC}$ Distribution → Gain in Efficiency / Complexity



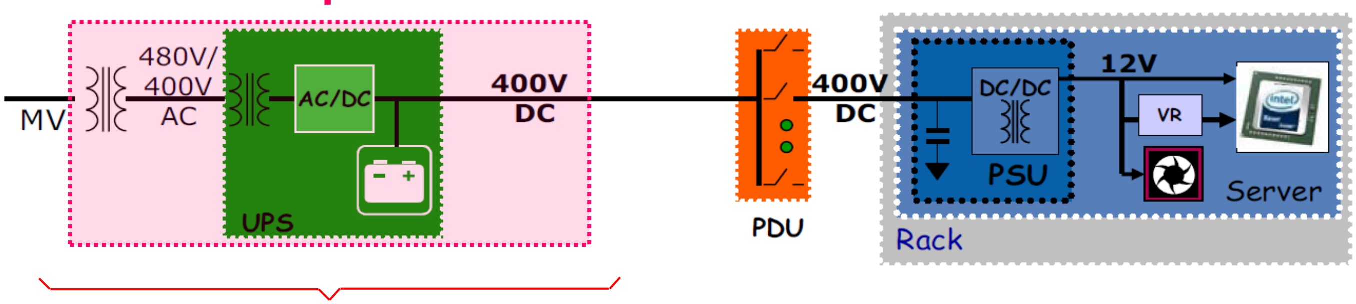
- Future Concept: Direct 6.6kV AC → 400V DC Conversion (Unidirectional) incl. Isolation

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

- Reduces Losses & Footprint
- Improves Reliability & Power Quality



Img.: intel 2007

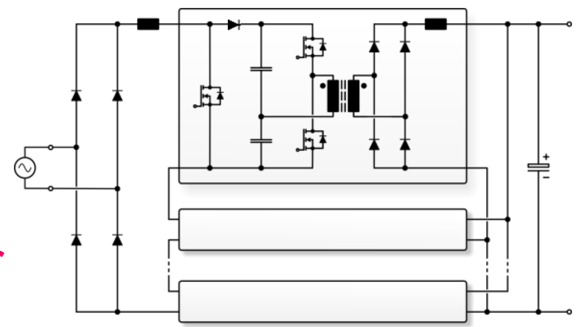


- Future Concept: Direct 6.6kV AC → 400V DC Conversion (Unidirectional) incl. Isolation

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

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

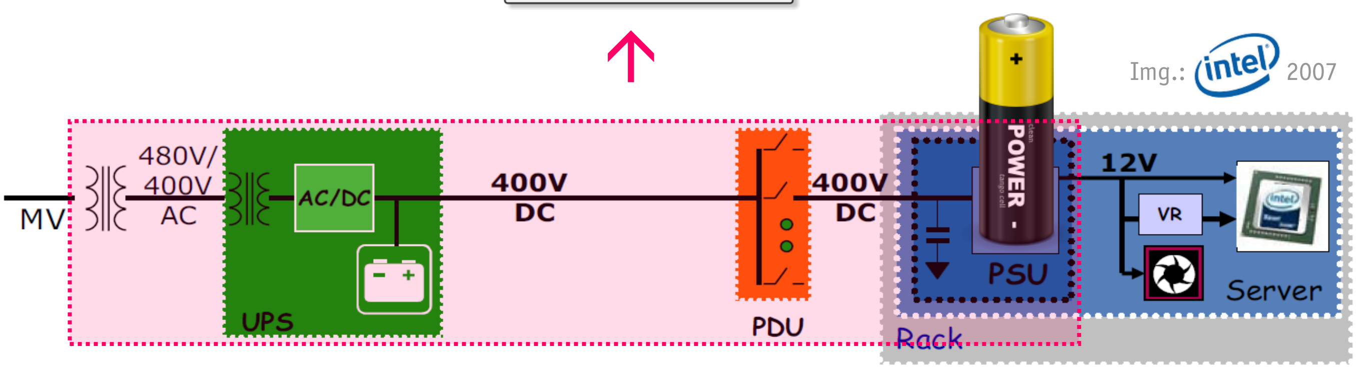
6.600 V_{AC}



48 V_{DC}

- Distributed 48V Battery Buffer on Rack Level

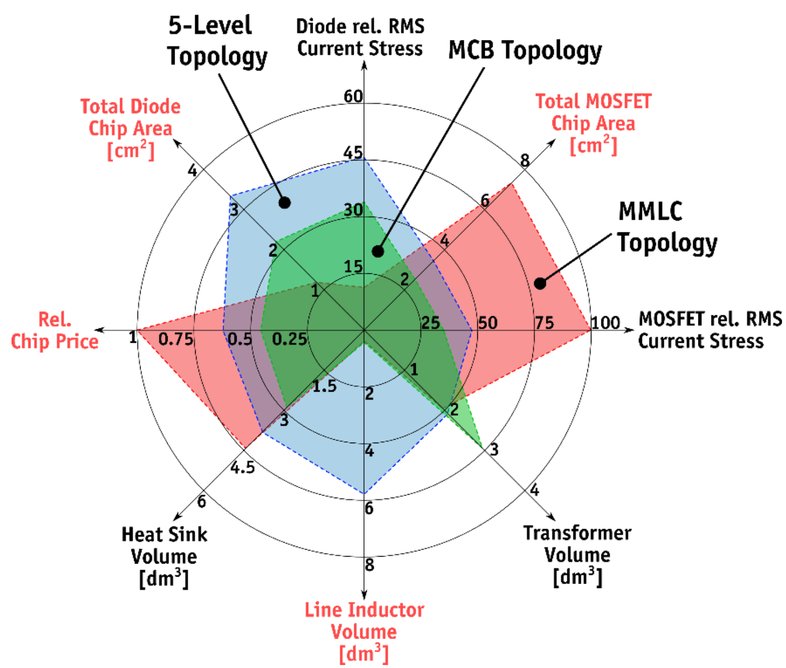
Img.: intel 2007

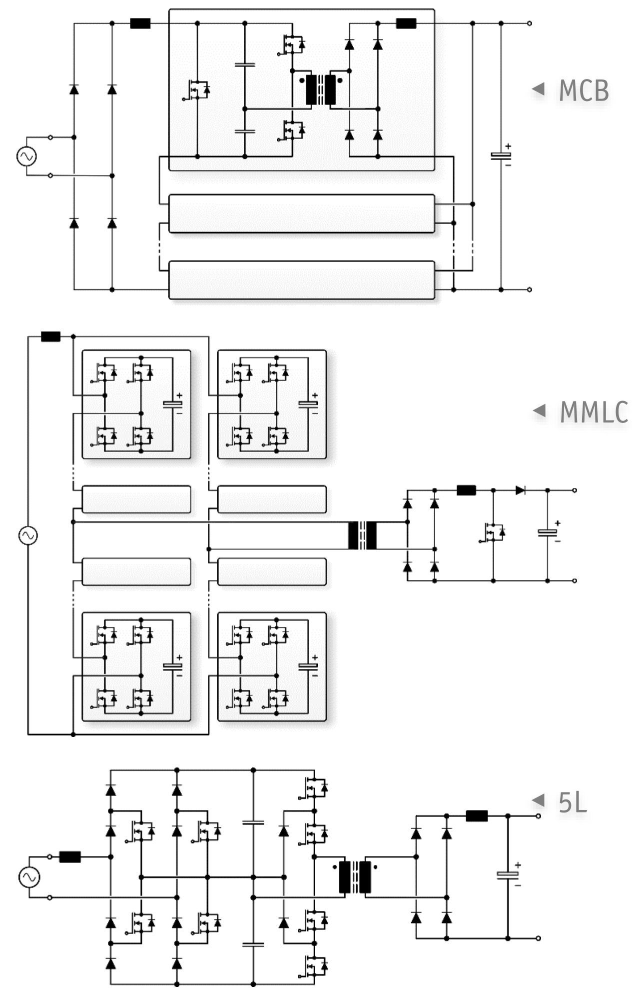


- Future Concept: Direct 6.6kV AC → 48V DC Conversion / Unidirectional SST w. Integr. Storage

▶ SST-Based High-Power 400V DC Supplies

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



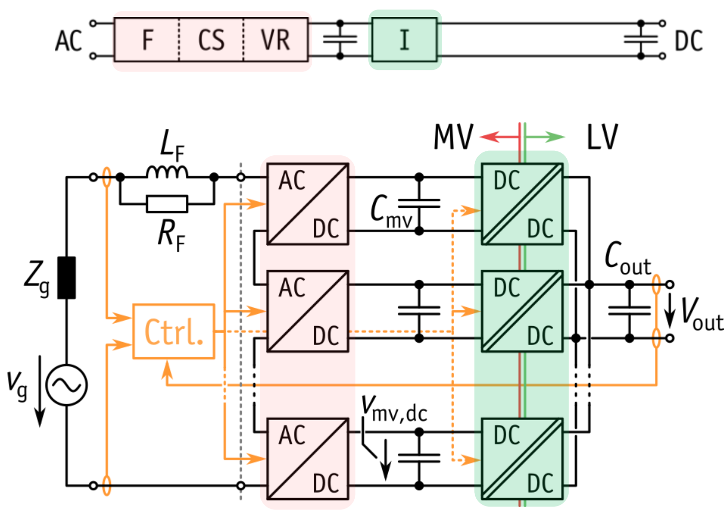


- Comparative Evaluation Based on Comp. Load Factors

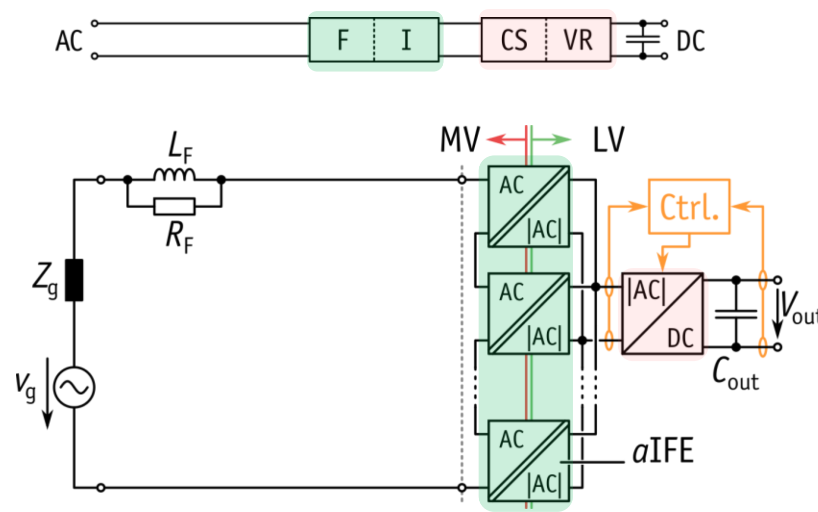
ETH / [Rothmund2014]

▶ S³T (1) – Remember: IBE vs. IFE

■ Isolated Back End



■ Isolated Front End



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

■ Typical Multi-Cell SST Topology

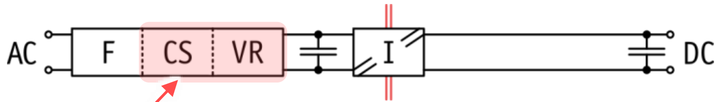
- Two-Stage Approaches with Intermediate Floating DC Buffer Cap.
- Autonomous **DC-DC** Isolation Back End (*a*IBE)

■ Swiss SST (S³T)

70 NRP **Energy Turnaround** National Research Programme

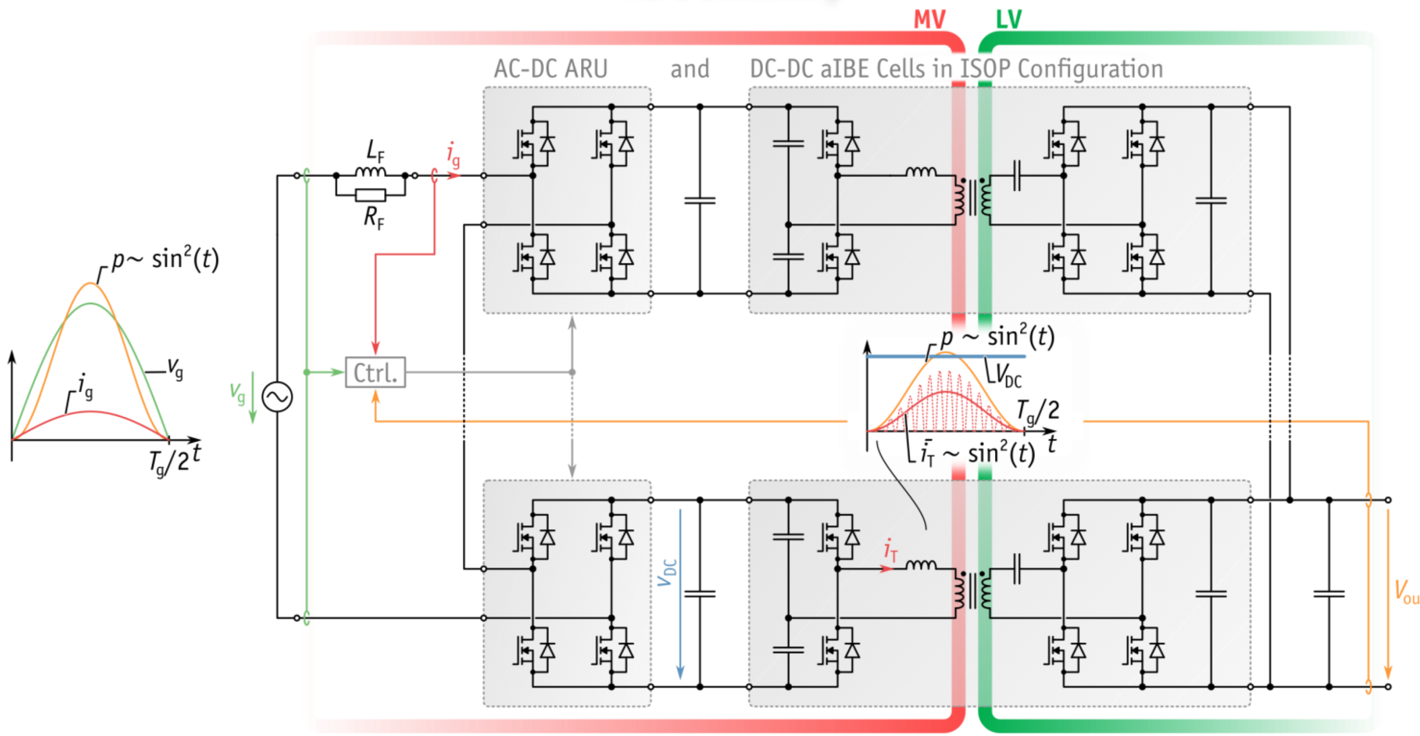
- 25kW, 6.6kV AC (line-line) To 400V DC
- 5 Cascaded Cells
- All-SiC Realization
- Autonomous **AC-|AC|** Isolation Front End (*a*IFE)

▶ S^3T (2) – IBE Example System

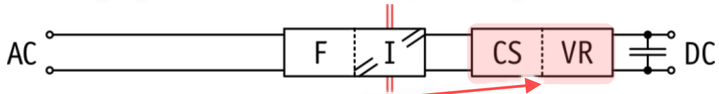


MV Side Control Stage

- **(Cascaded) AC/DC Boost (ARU)**
  - Approx. Const. MV DC Volt.
    - Transf. Cur. Envelope ∝ $\sin^2(t)$
    - DC Buffer Caps.
  - Total Blocking Volt. Ca. 1.2 x $v_{g,Pk}$
  - Complexity (MV Side Meas. & Contr.)
  - Hard Switching

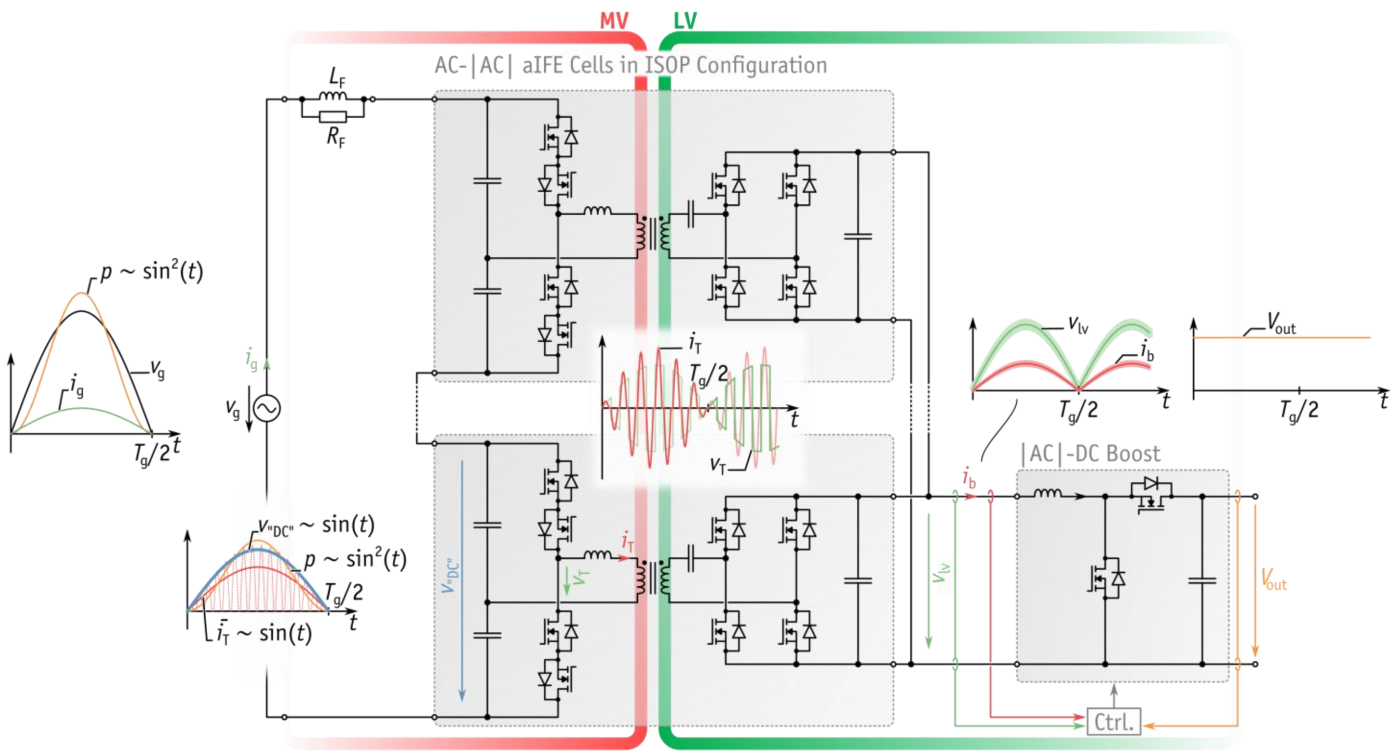


▶ S^3T (3) – IFE Example System: The Swiss SST (S^3T)



Back Side

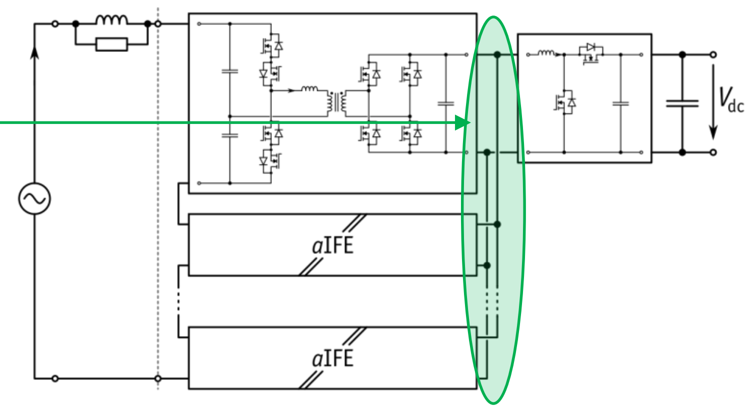
■ **(Interleaved) |AC|-DC Boost**
- MV "DC" Volt. ∝ sin(t)
  - **Transf. Cur. Envelope ∝ sin (t)**
    → Larger SiC Area, More Copper
    → Less Core Mat.
- Lower Total MV Block. Volt.
- Low MV Side Complexity and Smaller Floating Assembly
- Full ZVS Possible



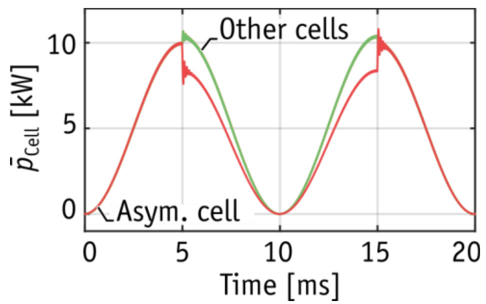
▶ S³T (4) – ISOP: Balancing & Load Sharing

- ***a*IFE Tightly Couples Its Terminal Voltages**
  - All Cells Share Common LV Bus Voltage

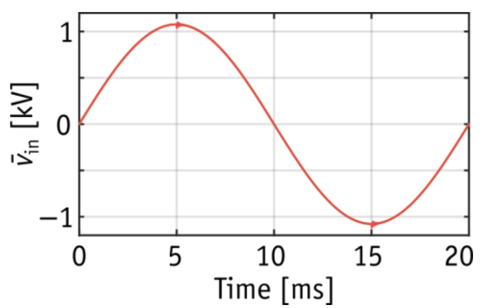
    → **MV Side Voltage Sharing is Ensured!**



- **Example:**
  - Add. Load (10% nominal) On MV Side of One Cell



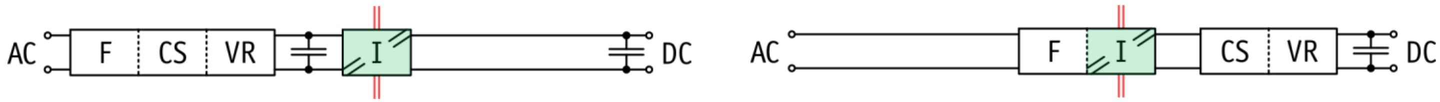
→ **Redistribution of Power Transfer**



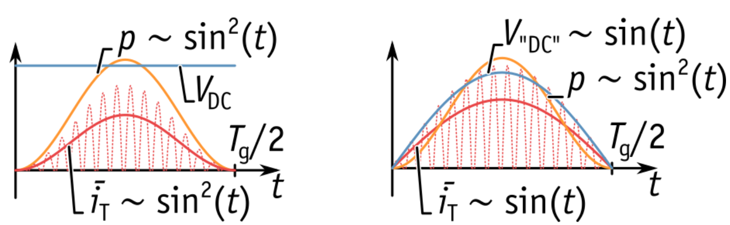
→ **Voltage Sharing Ensured**

- **Also Simulated w/o Problems for Primary Resonant Capacitance Tolerances (20%)**

▶ S³T (5) – Comparative Evaluation of IBE and IFE Concept



Key Differences	IBE	IFE	IFE Features...
■ Control Stage (Boost) Location	MV Side	LV Side	→ Low MV Side Complexity (No Contr., Meas., Smaller Mech. Assem., etc.) → Lower Total MV Blocking Voltage (5 Instead of 6 Casc. Cells for 6.6kV) → No DC Buffering Per Cell (3-ph) → Possibly Full ZVS of Contr. Stage → Limitation To cos$\varphi \approx 1$ (Bidirectional) → Higher SRC LV Side Cur. (Lower Volt.)
■ Transf. Volt. Envelope	Const. → $\tilde{I}_T$	$\propto \sin(t)$ → $1.44 \cdot \tilde{I}_T$	→ Higher Copper Usage } Ca. 2...3x (!) → Higher SiC Area Usage } → Lower Transf. Core Mat. Usage



▶ S³T (6) – (Preliminary) Conclusions on IBE vs. IFE

- **Isolated Back End Main Advantage:**
  Lower RMS Currents → Lower Semic. Area
- **Isolated Front End Main Advantage:**
  Lower MV Side Complexity

▶ Complexity vs. SiC Area Requirement Trade-Off

Img.: scanrail / 123RF Stock Photo

▶ **IFE Concept (S3T) Has Potential for SST Appl. with Lower Power Ratings**
→ Higher Contrib. of Meas. And Control Electron. To Costs

- **Comparative Evaluation is Work in Progress:**
  - Grid Filter Requirements
  - Control Stage Sw. Losses
  - Full Multi-Objective Optimization
  - ...

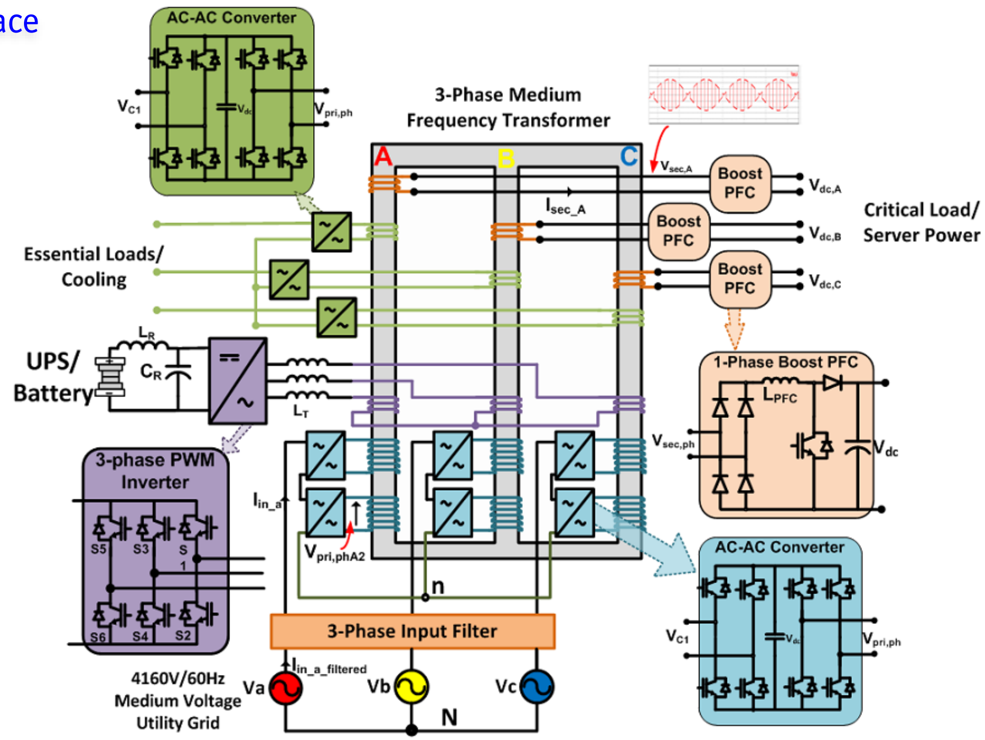
S³T Research Status

Img.: U. Kils / Wikimedia.org

Further Reading: ETH / [Kolar2016], [Huber2016a]

▶ MF Power Distribution Architecture for Data Centers

- Enjeti, 2014
  - Bidirectional AC/AC Grid Interface
  - Multi-Winding MF Transformer
  - Unidirectional or Bidirectional Loads on Secondaries



- **Hybrid Uni-/Bidirectional**

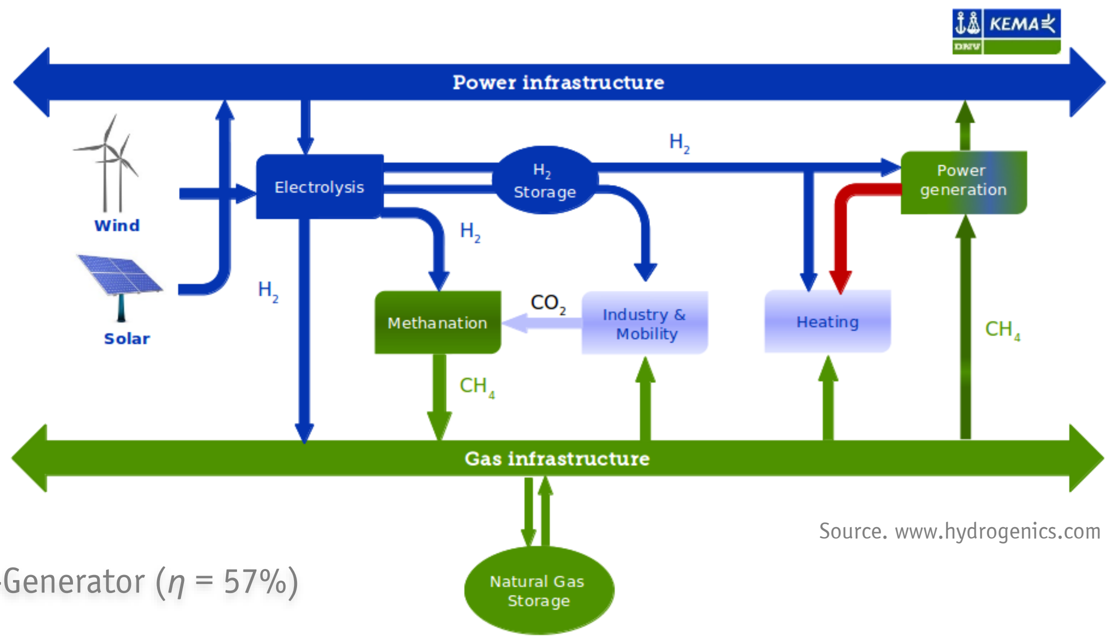
[Hafez2014]

▶ Other Unidirectional SST Applications: Power-to-Gas

- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen

- High-Power @ Low DC Voltage (e.g., 200V) → Fuel-Cell Powered Cars
- Very Well Suited for MV-Connected SST-Based Power Supply → Heating

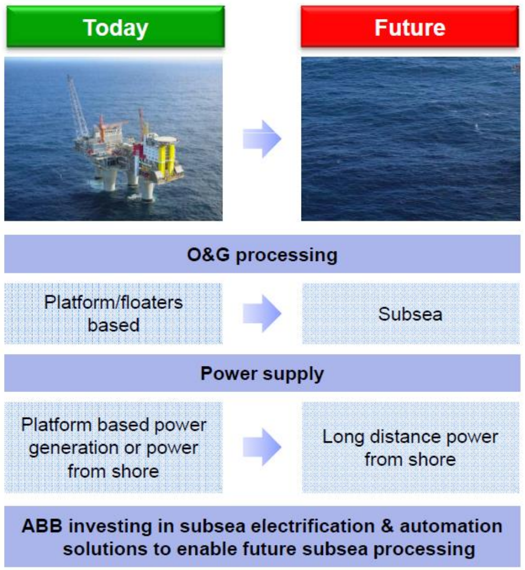
▲ Hydrogenics 100kW H_2-Generator (η = 57%)

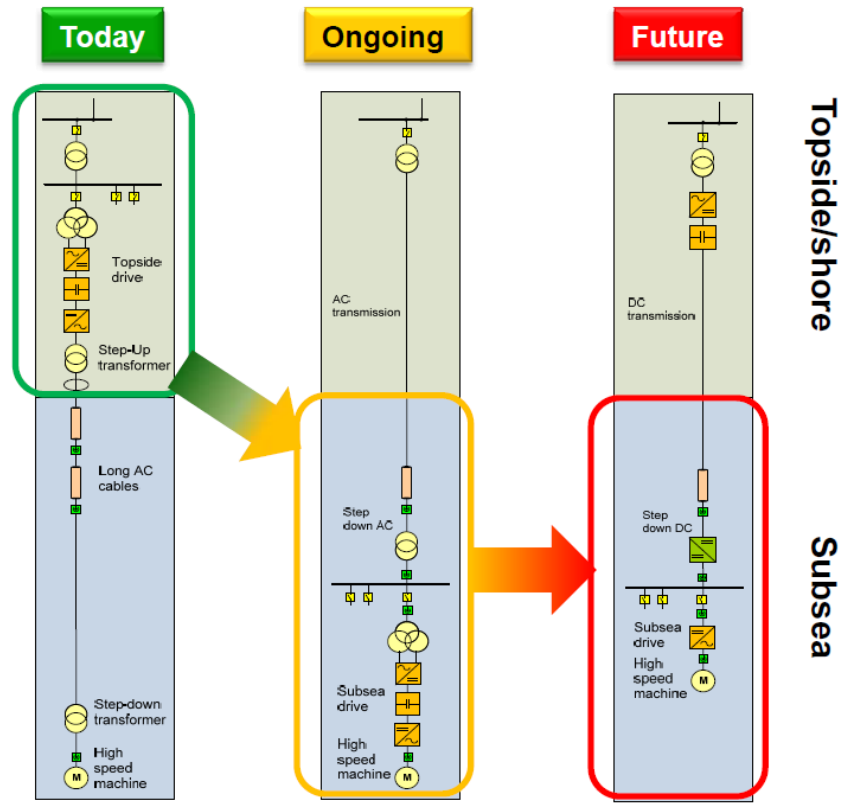


Source. www.hydrogenics.com

► 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

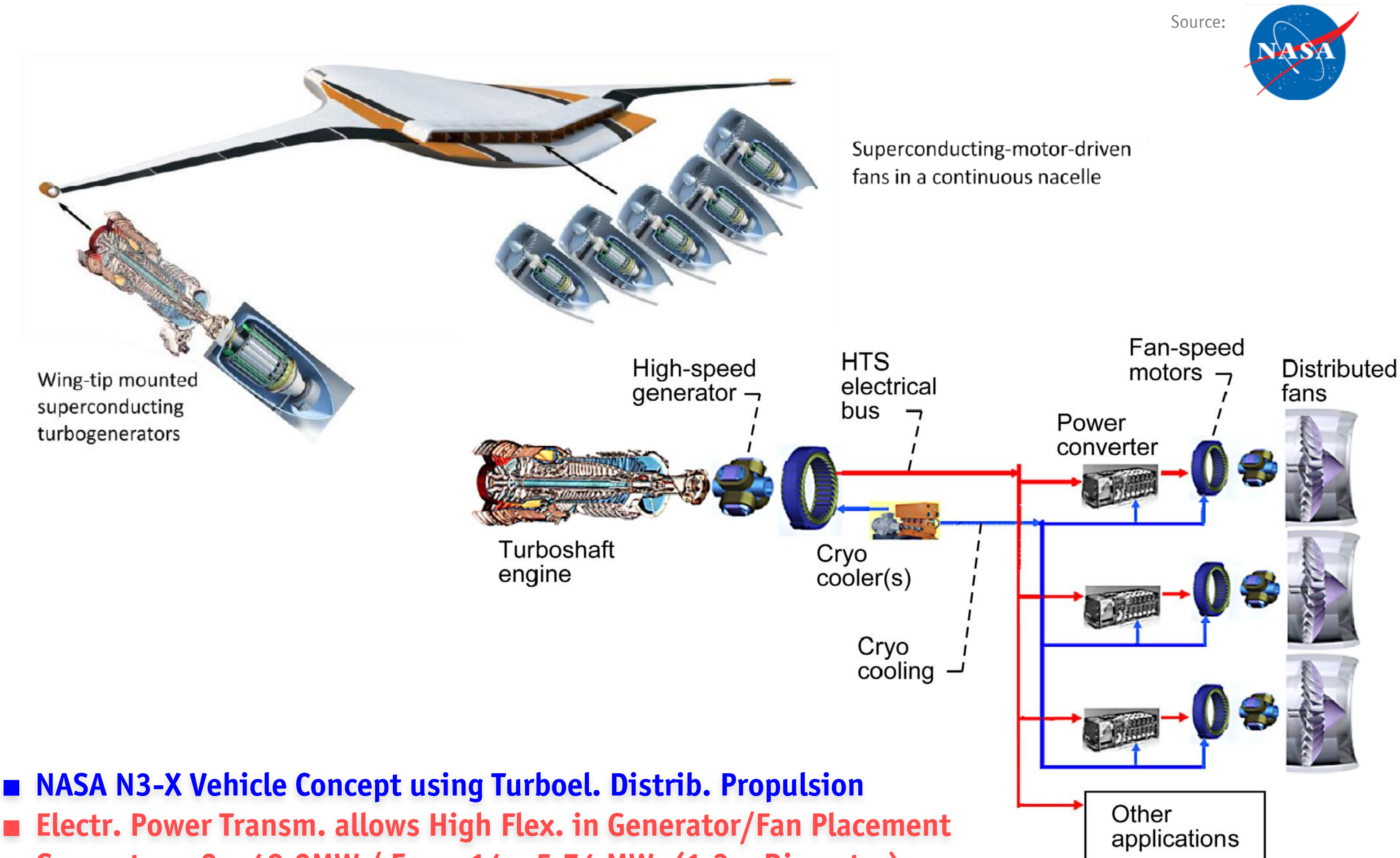
- Weight Optimized Power Electronics

► 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%

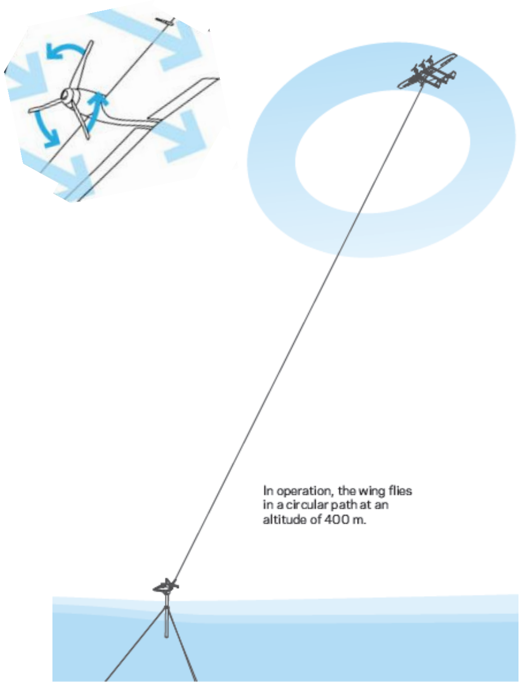
▶ Future Hybrid Aircraft



- 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

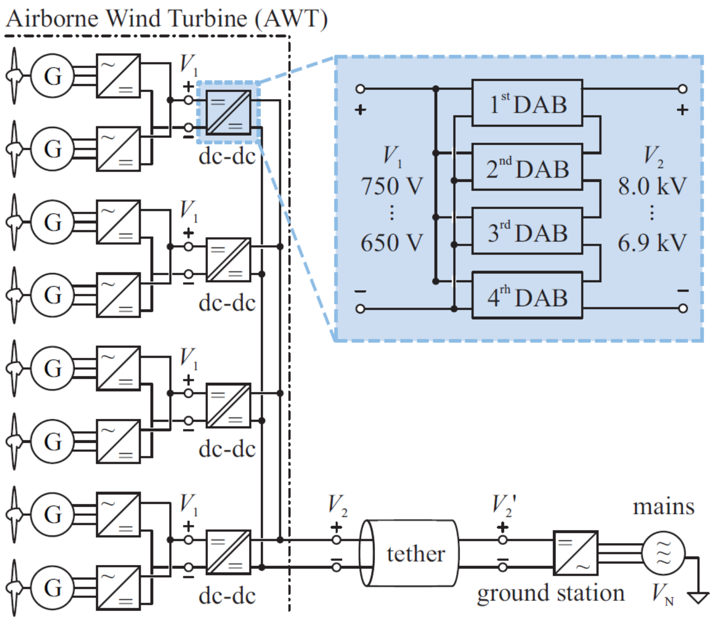


MAKANI POWER Google X

▶ 100kW Airborne Wind Turbine (1)

■ **Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer – 8kV$_{DC}$ → 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/dm^3
• Specific Weight	4.4	kW/kg



ETH / [Gammeter2014]

▶ 100kW Airborne Wind Turbine (2)

■ **Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer – 8kV$_{DC}$ → 700V$_{DC}$**

• Medium Voltage Port	1750 ... 2000	VDC
• Switching Frequency	100	kHz
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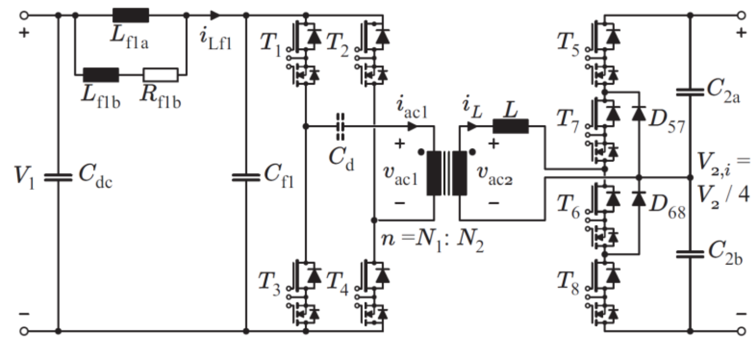
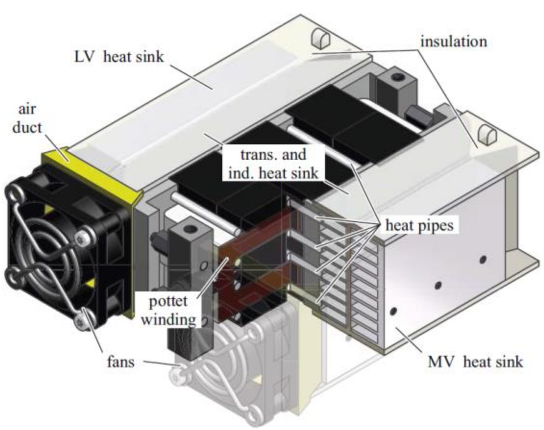
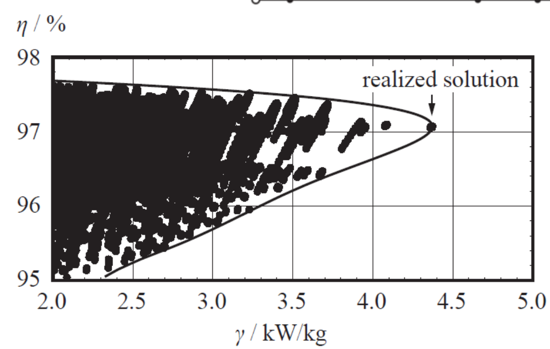
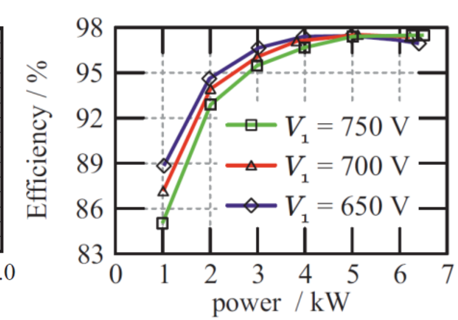




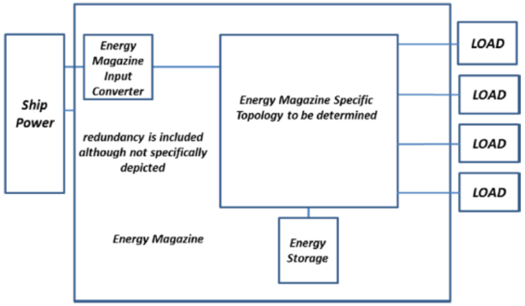




ETH / [Gammeter2014]

▶ Future Military Applications

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



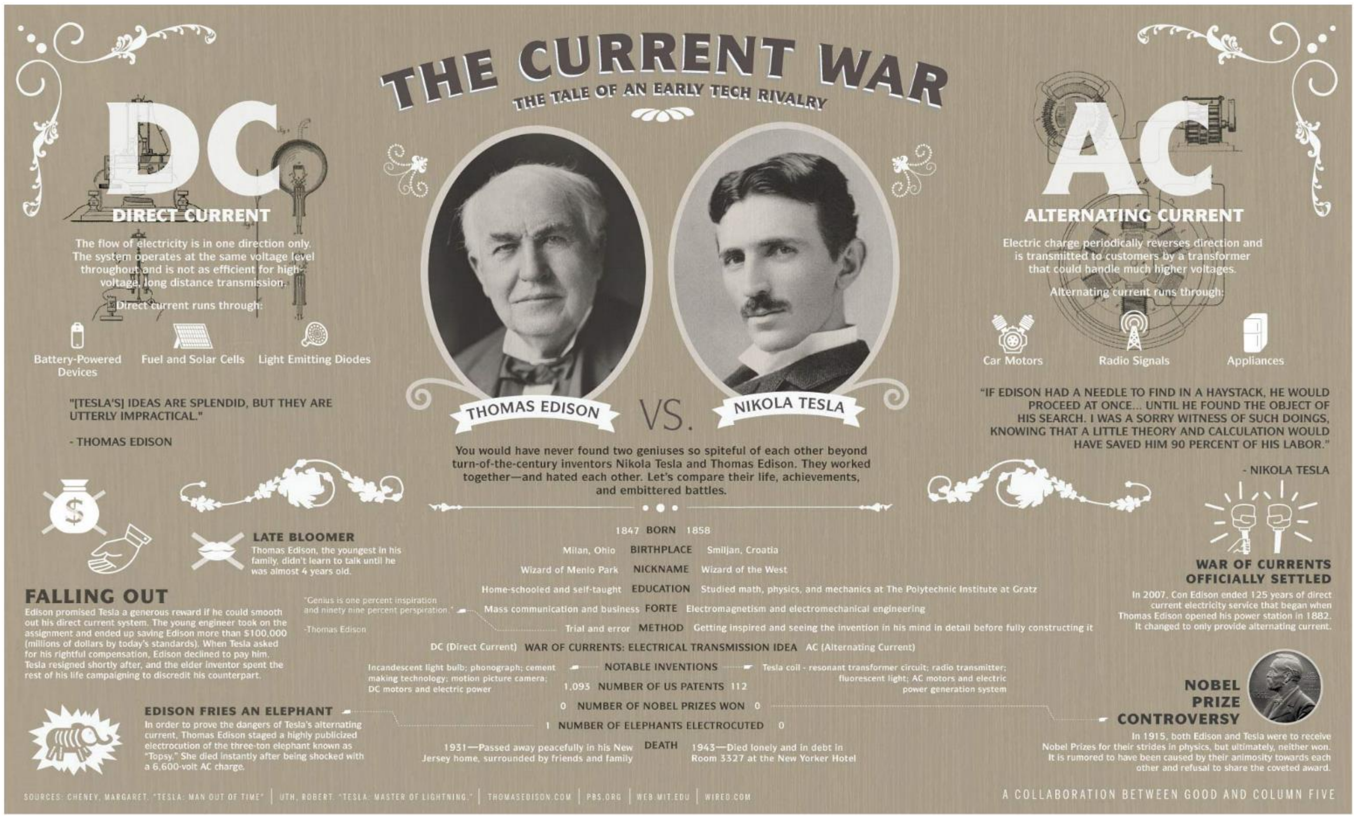
Source: General Dynamics

- **"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**

Conclusion & Outlook

SST Evaluation / Application Areas
Future Research Areas

▶ SST Ends the "War of Currents"



Source: Column Five, http://magazine.good.is

- No "Revenge" of T.A. Edison, but Future "Synergy" of AC and DC Systems!

▶ Key Messages #1/3

■ Basic SST Limitations

- Efficiency (Rel. High Losses of 2-4%)
- High Costs (Cost-Performance Adv. still to be Clarified)
- Limited Weight/ Volume Reduction vs. Conv. Transf. (Factor 2-3)
- **Limited Overload Capability**
- **Limited Overvoltage Tolerance**
- **(Reliability)**

■ Potential Application Areas

▶ MV Grid/Load-Connected AC/DC and DC/DC Converter Systems
▶ Volume/Weight Limited Systems where 2-4% of Losses Could be Tolerated

- **Traction Vehicles**
- **MV Distribution Grid Interface**
  * DC Micgrogrids (e.g., Datacenters)
  * Renewable Energy (e.g., DC Collecting Grid for PV, Wind; Power-to-Gas)
  * High Power Battery Charging (E-Mobility)
  * More Electric Ships
  * etc.
- **Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)**
- **Temporary Replacement of Conv. Distribution Transformer**
- **Military Applications**

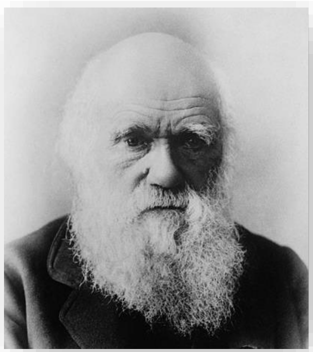
Img.: Marina Gallud / 123RF Stock Photo

▶ Key Messages #2/3

■ Advantageous Circuit Approaches

▶ Fully Modular Concepts

- Resonant Isolated Back End Topology (ABB)
- Resonant Isolated Front End Topology (Swiss SST)



"It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change."

Charles Darwin

- Redundancy (!)
- Scalability (Voltage / Power)
- Natural Voltage / Current Balancing
- Economy of Scale

▶ Alternatives

- Single Transformer Solutions (MMLC-Based)
- HV-SiC Based Solutions (SiC NPC-MV-Interface)

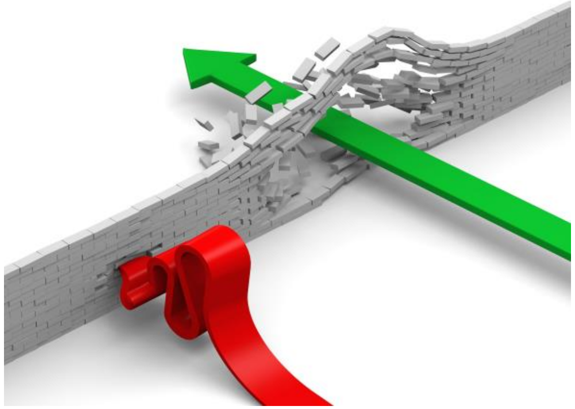
▶ Key Messages #3/3

- Main Research Challenges

  - Multi-Level vs. Two-Level Topologies with HV SiC Switches
  - Low-Inductance MV Power Semiconductor Package
  - Mixed-Frequ./Voltage Stress on Insul. Materials
  - Low-Loss High-Current MF Interconnections / Terminals
  - Thermal Management (Air and H_2O Cooling, avoiding Oil)
  - SST Protection
  - SST Monitoring
  - SST Redundancy (Power & (!) Control Circuit)
  - SST vs. FACTS (Flexible AC Transmission Systems)
  - System-Oriented Analysis → Clarify System-Level Benefits (Balancing the Low Eff. Drawback)

- SST Design for Production → Multi-Disciplinary Challenge

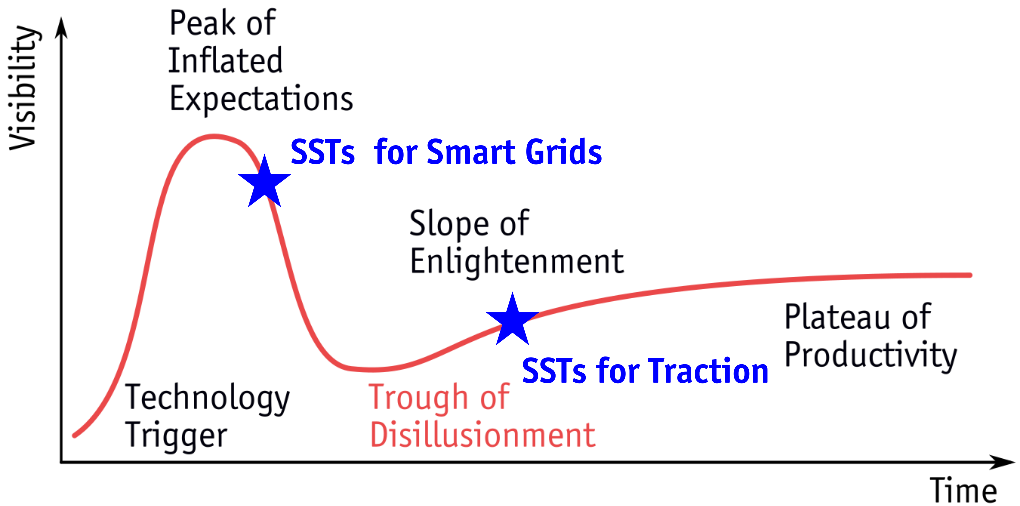
▶ Required Competences
  - MV (High) Power Electronics incl. Testing
  - Digital Signal Processing (DSP & FPGA)
  - MF High Power Magnetics
  - Isolation Coordination / Materials
  - Power Systems
  - etc.



Tomas Griger / 123RF Stock Photo

▶ 50/60Hz XFRM Design Knowledge is NOT (!) Sufficient

► 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 (!)

Thank You!

Questions?

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- *Daniel Rothmund*

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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.

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