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IEEE PEMC
INDUSTRY ACADEMIA
TECHNOLOGY BRIDGE
Tutorial No. 1

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

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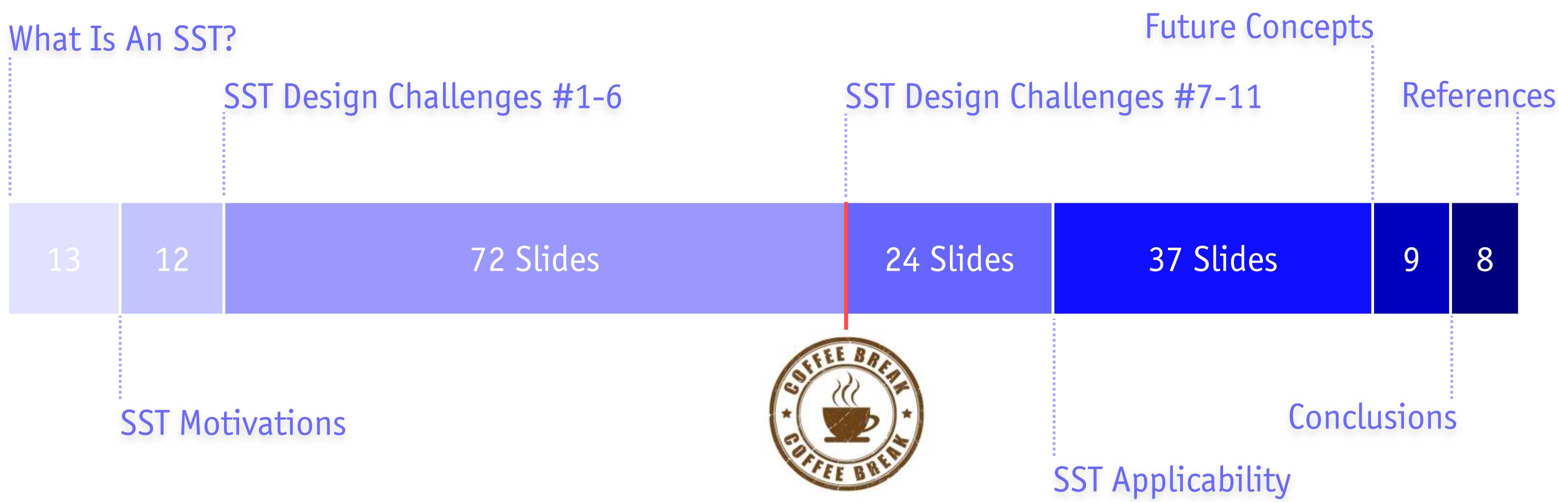
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

Agenda



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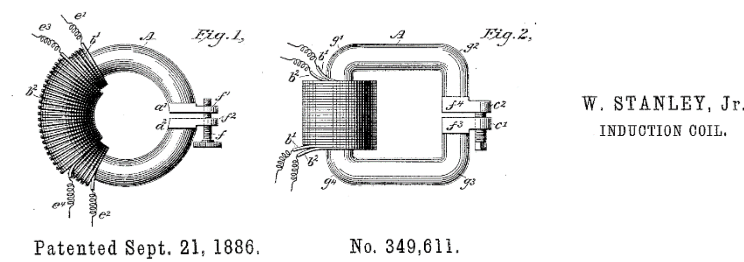
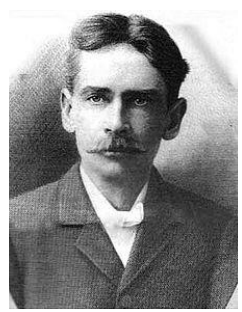
What Is a SST?

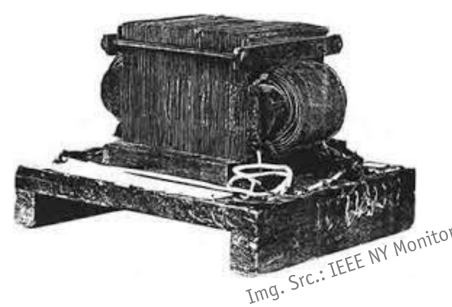
Transformer History and Basics
SST Definition

▶ Classical Transformer — History (1)

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







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

[Stanley1886]

▶ Classical Transformer — History (2)

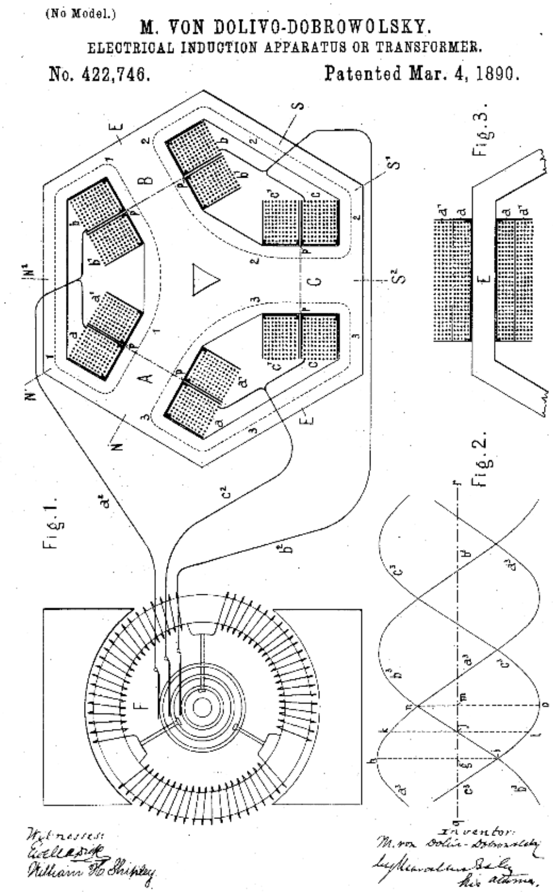
UNITED STATES PATENT OFFICE.

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)

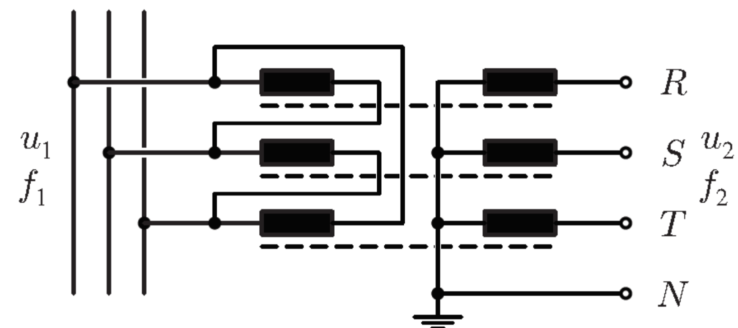
[Dobrovolski1890]

▶ Classical Transformer — Basics

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

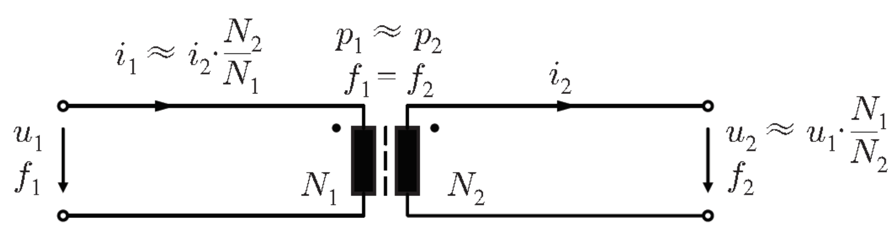
- **Operating Frequency** — • 50/60Hz (El. Grid, Traction) or $16^2/_3$Hz (Traction)
- **Operating Voltage** — • 10kV or 20kV (6…35kV)
  • 15kV or 20kV (Traction)
  • 400V

- **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 ($f_1 = f_2$)

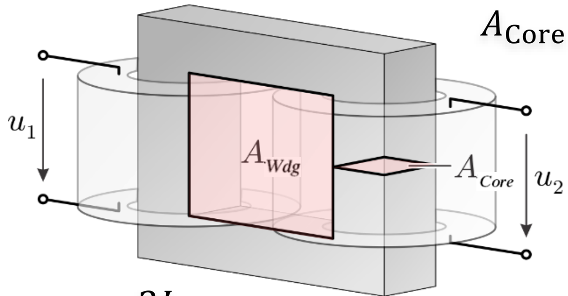


- **Magnetic Core Cross Section** $$A_{\text{Core}} = \frac{1}{\sqrt{2}\pi} \frac{U_1}{\hat{B}_{\max} f} \frac{1}{N_1}$$

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



▶ Transformer Scaling Laws (1)

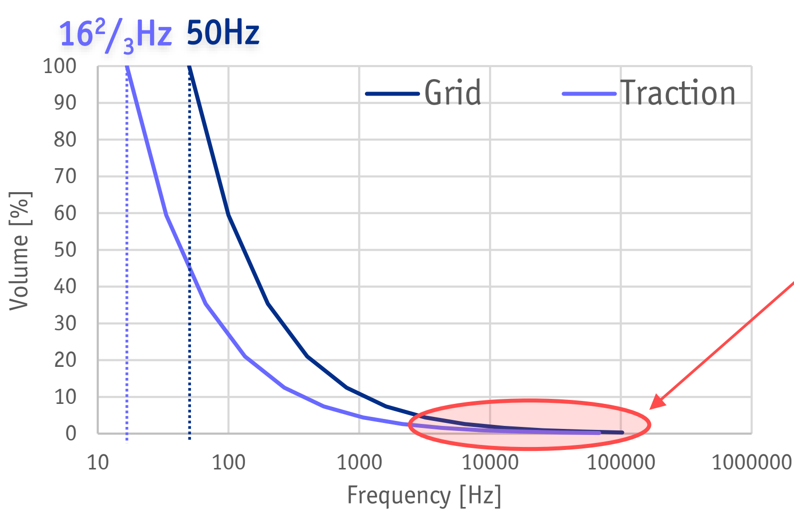


$$A_{\mathrm{Core}} = \frac{1}{\sqrt{2}\pi}\frac{U_1}{\hat{B}_{\max} f}\frac{1}{N_1}$$

$$A_{\mathrm{Wdg}} = \frac{2I_1}{k_{\mathrm{W}} J_{\mathrm{rms}}} N_1$$

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

- **Volume:** $V \propto \left(A_{\mathrm{Core}} A_{\mathrm{Wdg}}\right)^{\frac{3}{4}} \propto \frac{1}{f^{3/4}}$



- **Caution: Too Optimistic!**
  - Constant Isolation Material Thickness
  - Lower Fill Factor (k_{W}) because of Litz Wires

- Gain of Frequency Increase Depends on Grid Frequency

▶ Transformer Scaling Laws (2)

- **Scaling of Core Losses**

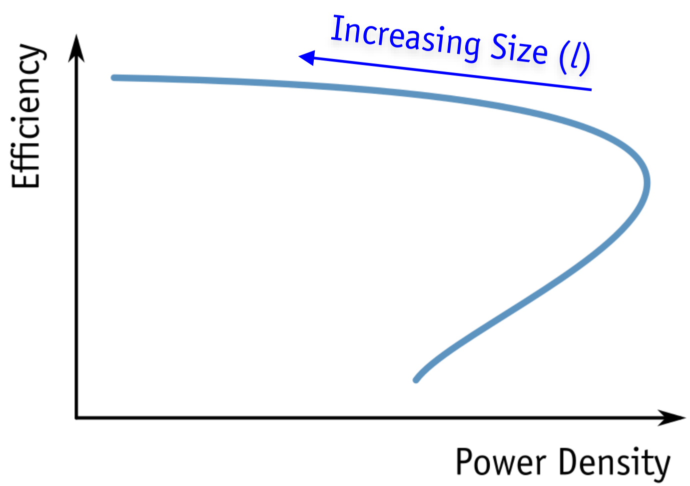
$$P_{\mathrm{Core}} \propto f_{\mathrm{P}} \left(\frac{\Phi}{A}\right)^2 V$$

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

- **Scaling of Winding Losses**

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

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



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

▶ Classical Transformer — Summary (1)

■ Advantages

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

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

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

▶ Classical Transformer — Summary (2)

■ Advantages

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

Source: http://www.africancrisis.org

What Is a SST?

Transformer History and Basics

SST Definition

United States Patent Office

3,517,300
Patented June 23, 1970

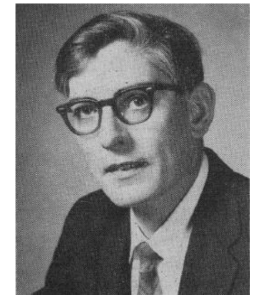
1

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

1968 !

ABSTRACT OF THE DISCLOSURE

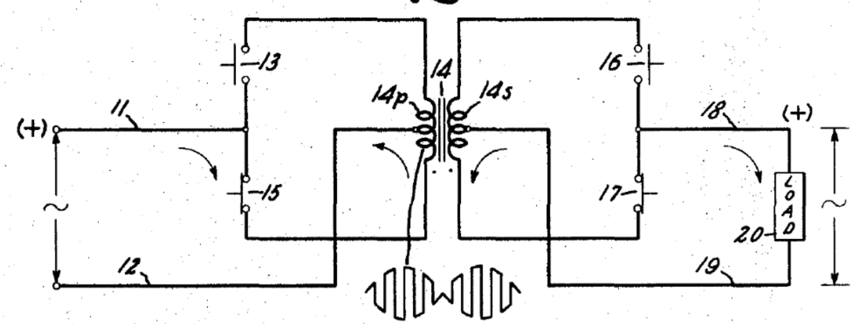
Several single phase solid state power converter circuits have a high frequency transformer link whose windings are connected respectively to the load and to a D-C or low frequency A-C source through inverter configuration switching circuits employing inverse-parallel pairs of controlled turn-off switches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



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

Filed April 16, 1968

Fig. 1a

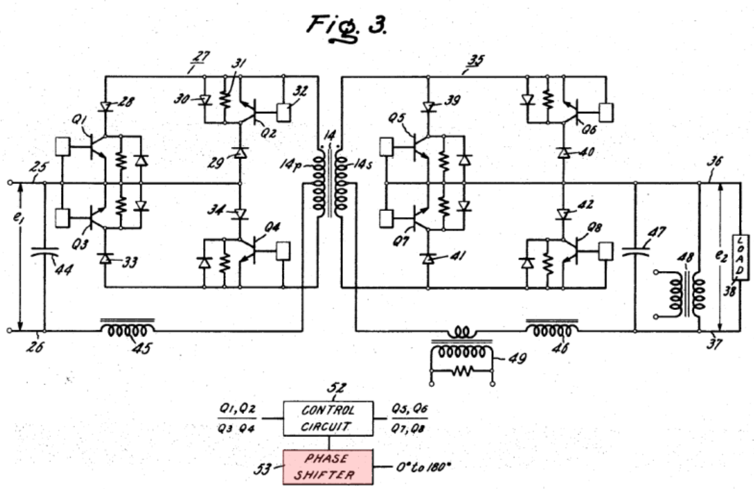


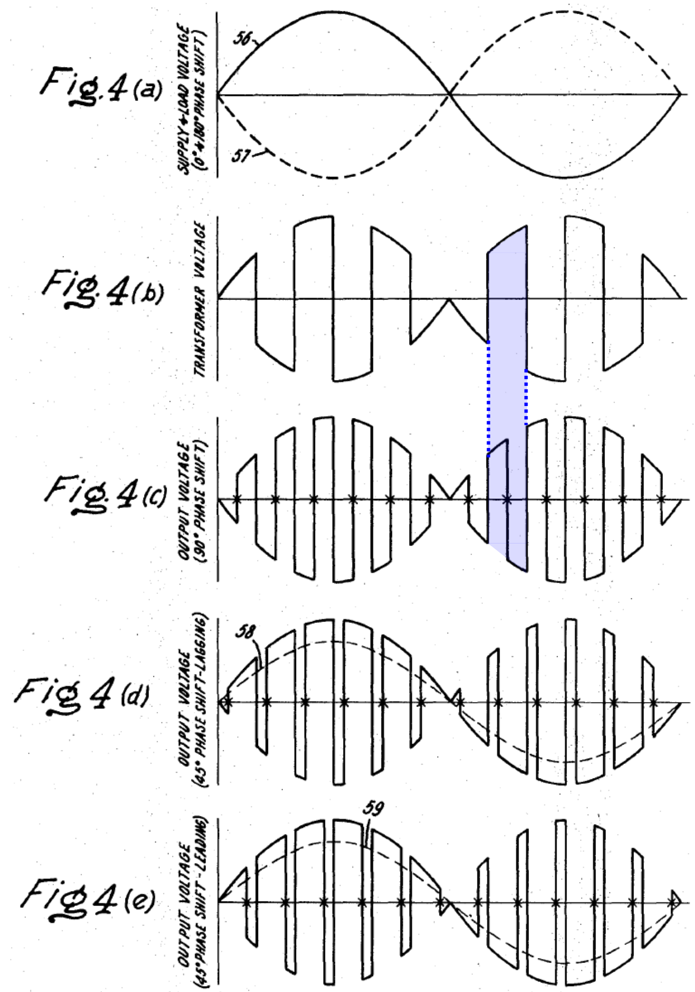
- **Electronic Transformer ($f_1 = f_2$)**
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption

[McMurray1968]

▶ Electronic Transformer

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



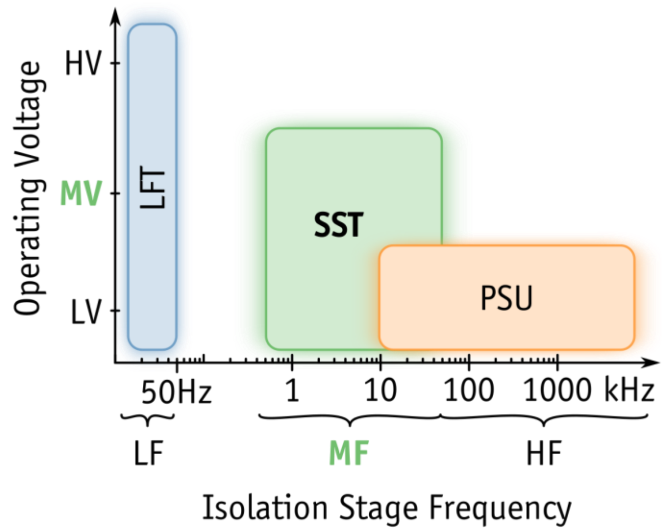


- $f_1 = f_2 \rightarrow$ Not Controllable (!)
- Voltage Adjustment by Phase Shift Control (!)

[McMurray1968]

▶ What is a Solid-State Transformer (SST)?

- **Power Electronics Interface**
- **Medium Voltage** Connection
- **Medium Frequency** Isolation Stage
- Communication Link



- **I/O Quantities**
  - DC/DC
  - AC/DC
  - AC_{f1}/AC_{f1}
  - AC_{f1}/AC_{f2}
  - 1ph, 3ph, var. *f*, etc.
  - MV/LV, MV/MV

- **Terminology**

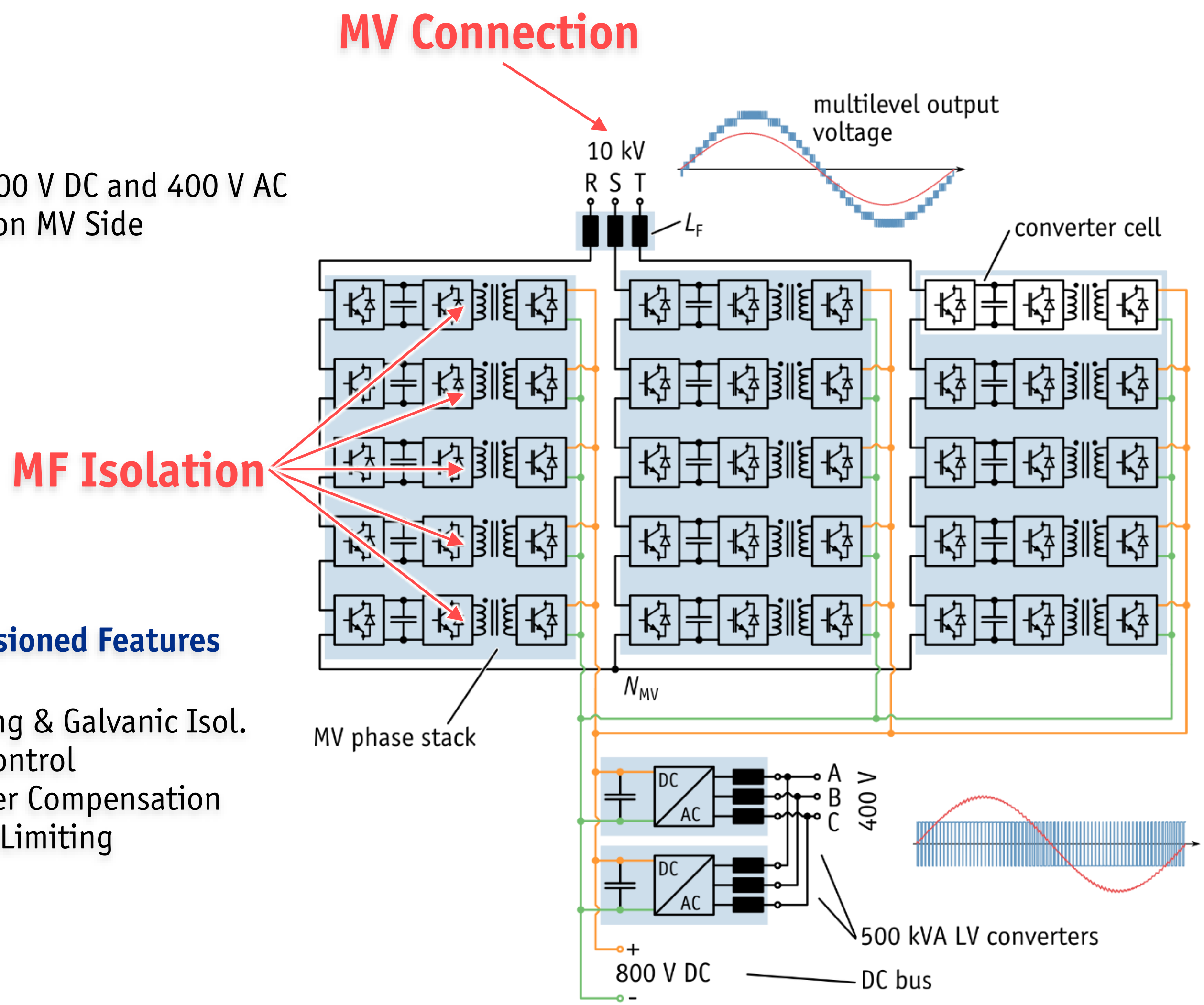
McMurray	Electronic Transformer (1968)
Brooks	**Solid-State Transformer (SST, 1980)**
EPRI	Intelligent Universal Transformer (IUT)
ABB	Power Electronics Transformer (PET)
Borojevic	Energy Control Center (ECC)
Wang	Energy Router
etc.	

[Brooks1980]

▶ Example SST System: ETH *MEGAlink* SST Concept

■ **Specifications**

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

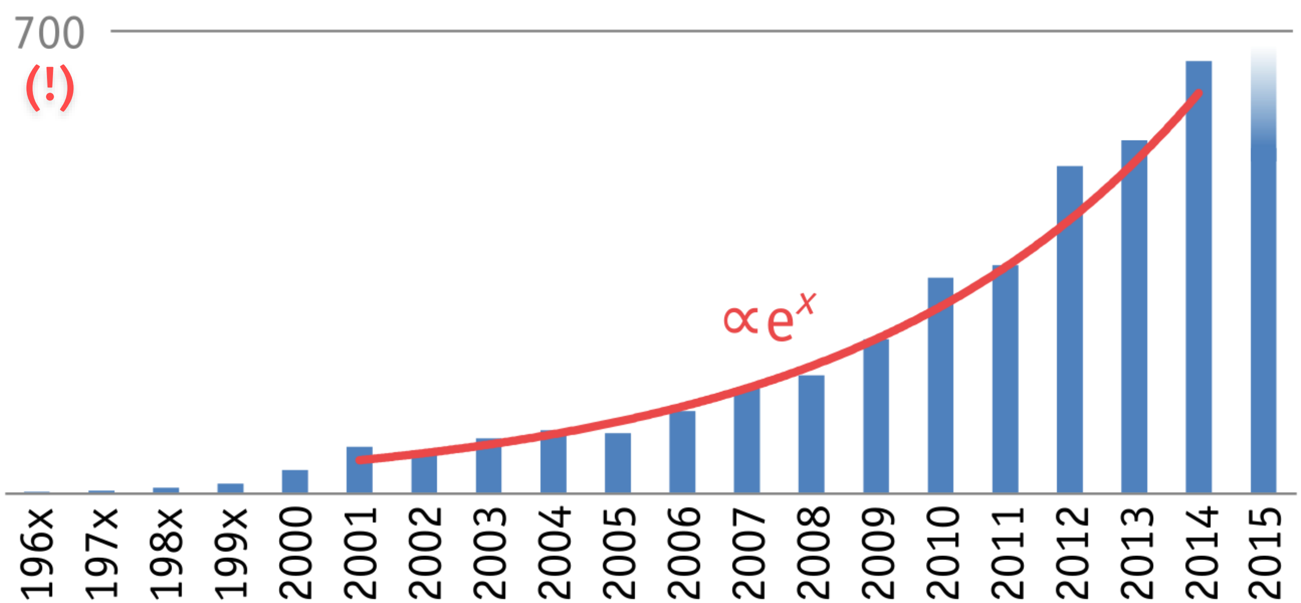


■ **Commonly Envisioned Features**

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

▶ The Solid-State Transformer Hype

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



Google Scholar Hits for Query: ("solid-state transformer") OR ("electronic transformer") OR ("Intelligent Universal Transformer") OR ("Power Electronic Transformer") OR ("Power Electronics Transformer")

■ How To Keep An Overview?

- Identify Origin and Evolution of Key Concepts
- Narrow Down Feasible Solutions by Identifying Core Requirements, e.g., Modularity

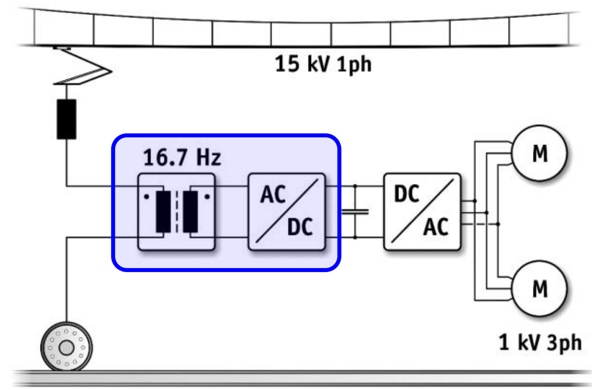
SST Concept Motivations

Traction → Weight & Volume
Smart Grid → Controllability
DC-DC Conversion

▶ Classical Locomotives (1)

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

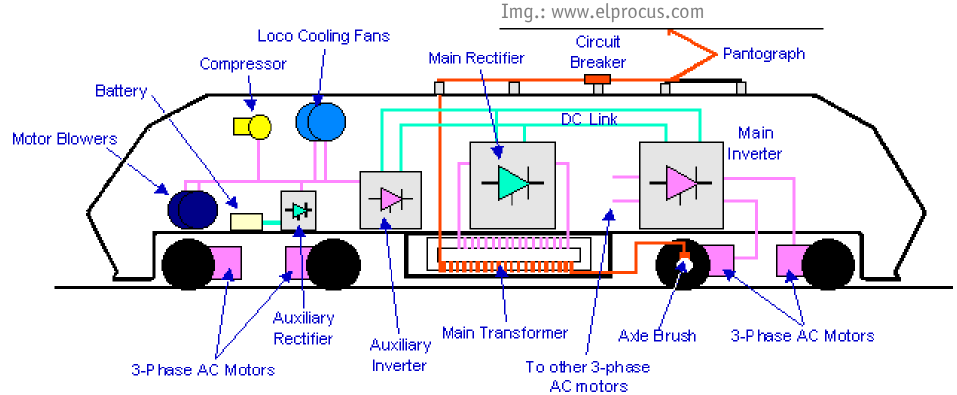
- Isolated **AC/DC** Conversion (!)
- Volume & Weight Constraints



Img.: www.abb.com

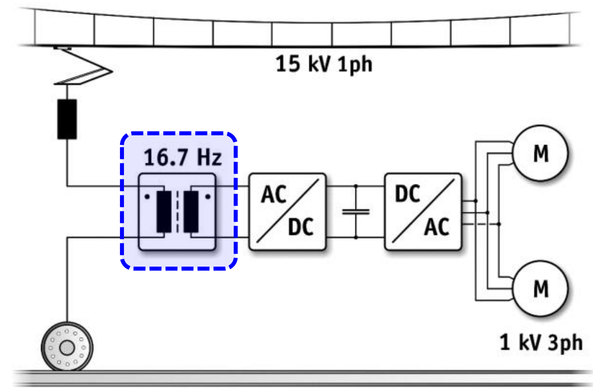
▲ Main Transformer

Img.: www.elprocus.com



▶ Classical Locomotives (2)

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



- Isolated **AC/DC** Conversion (!)
- Volume & Weight Constraints

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

Img.: www.abb.com

→ Volume/Weight Reduction By Increasing J_{rms}

Efficiency	90...95%	(99% Typ. for Distr. Transf.)
Current Density	6 A/mm²	(2A/mm² Typ. for Distr. Transf.)
Power Density	2...4 kg/kVA	

▶ Next Generation Traction Systems

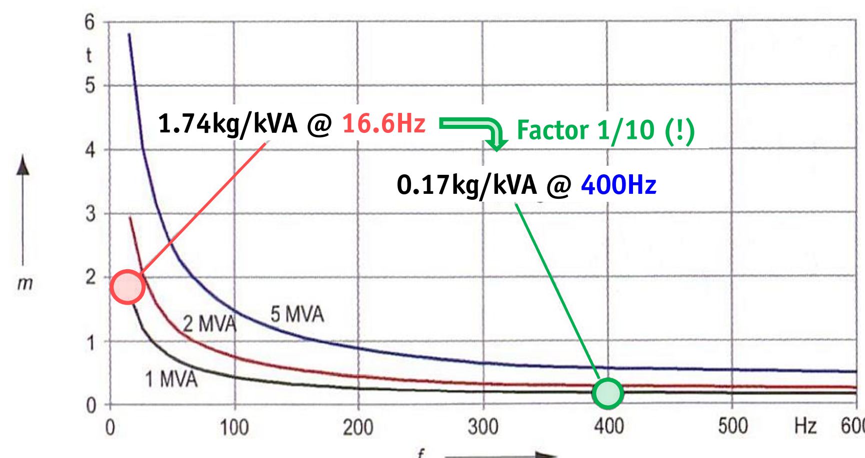
■ It's Getting Tougher!

- Distributed Propulsion → Volume Constraints (Space for Add. Seats)
- Low-Floor Vehicles → Weight Constraints (Roof Mounting)
- High-Speed Trains → Weight Constraints (Higher Power at Same Max. Axle Load Limit)
- Impr. Energy Efficiency → Loss Constraints (No Further Increase of J_{rms}, etc.)

■ What Degrees of Freedom Are Left?

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

$$V \propto (A_{Core}A_{Wdg})^{\frac{3}{4}} \propto \frac{1}{f^{3/4}}$$

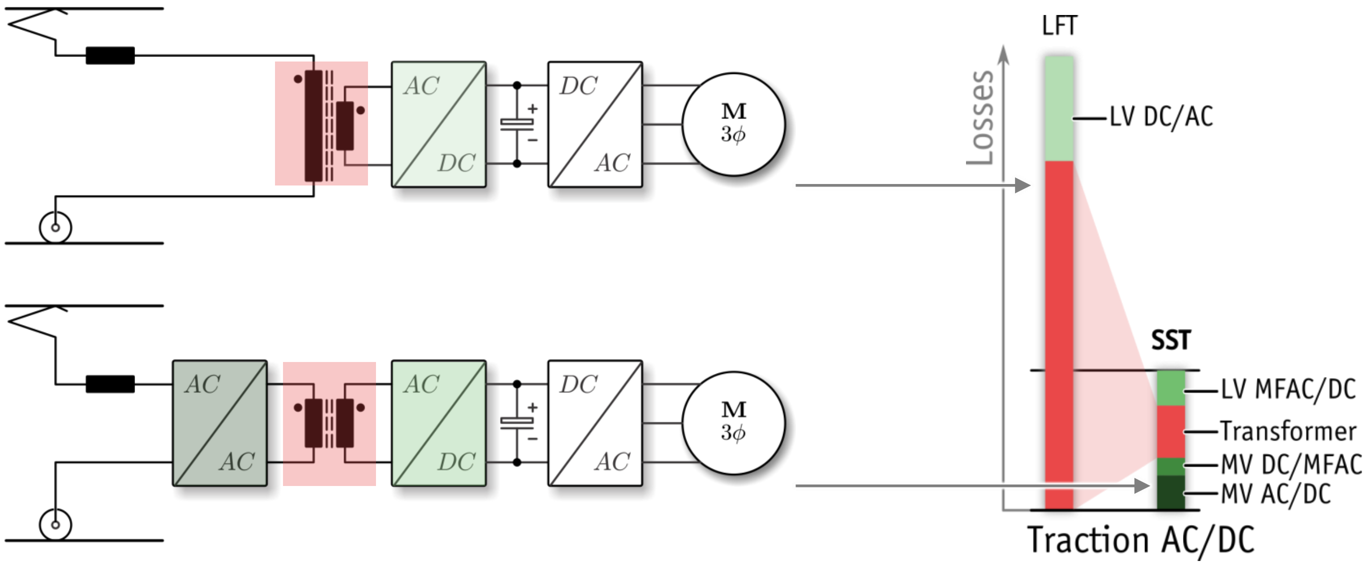


→ Frequency as DOF to Reduce Weight & Volume!

[Victor2005]
[Hazeltine1923]

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives



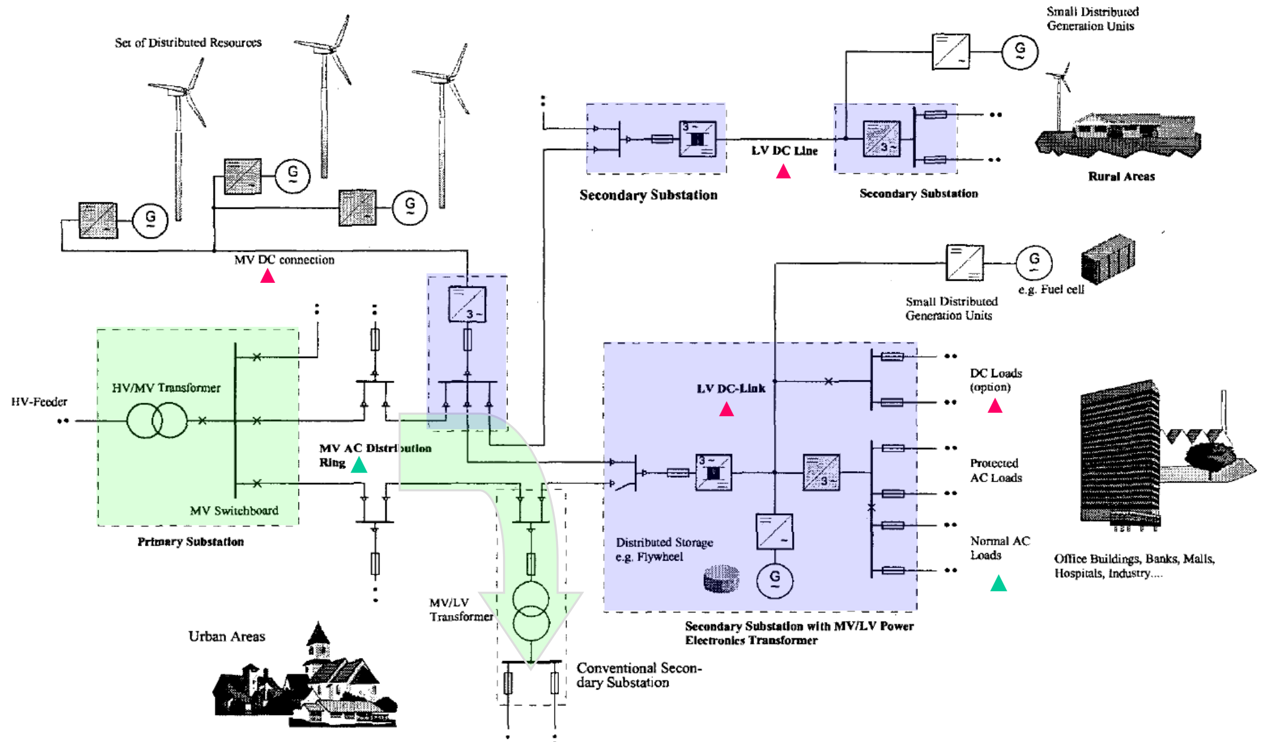
- Medium Freq. Provides Degree of Freedom → **Allows Loss Reduction AND Volume Reduction**

SST Concept Motivations

Traction → Weight & Volume
Smart Grid → Controllability
DC-DC Conversion

▶ 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]

▶ Smart Grid Concept

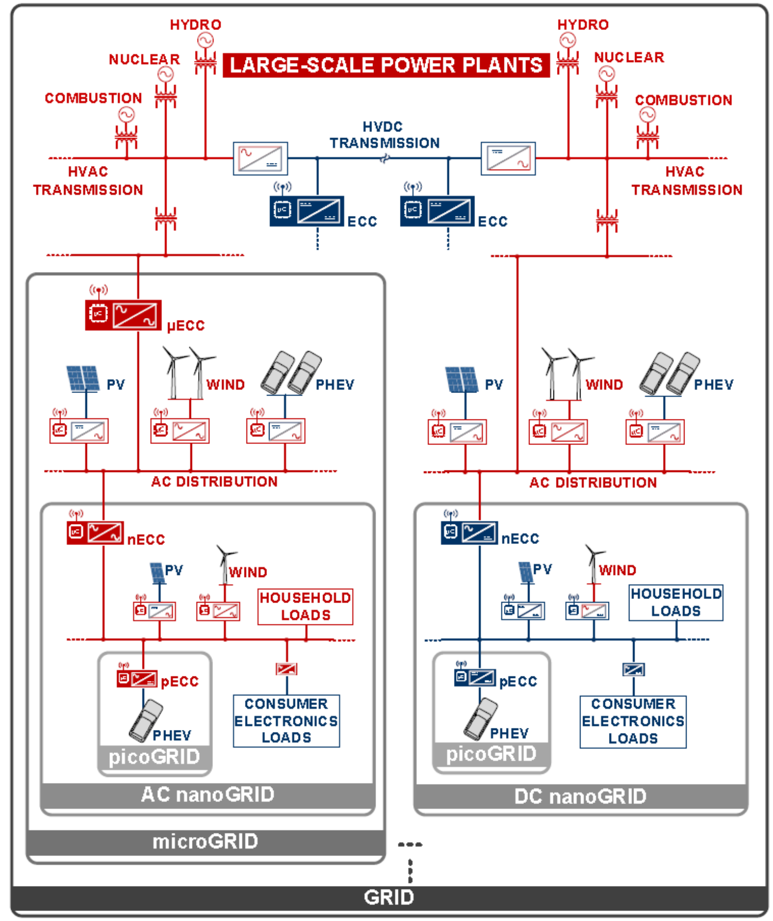
- Boroyevich (2010)

- **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.



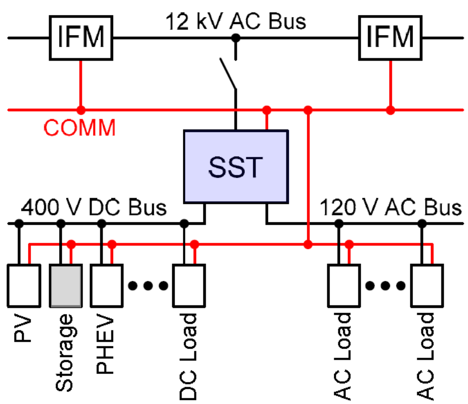
[Boroyevich2010]

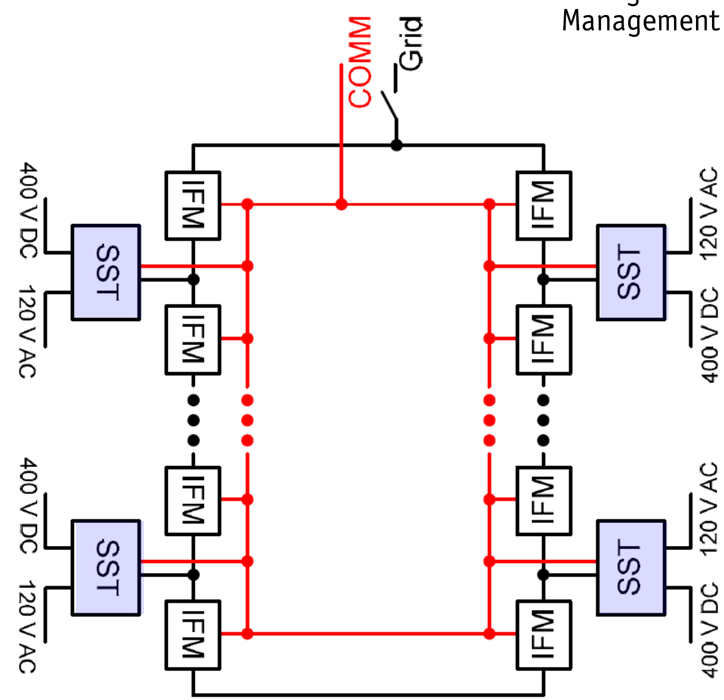
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) System

- 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





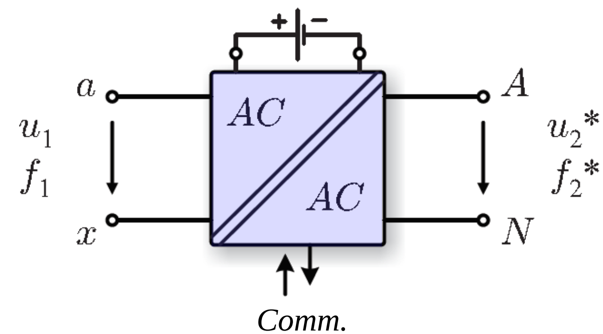
- **Bidirectional Flow of Power & Information** / High Bandw. Comm. → Distrib. / Local Autonom. Ctrl.

[Huang2009, Huang2011], Figs.: [Falcones2010]

▶ SST Functionalities

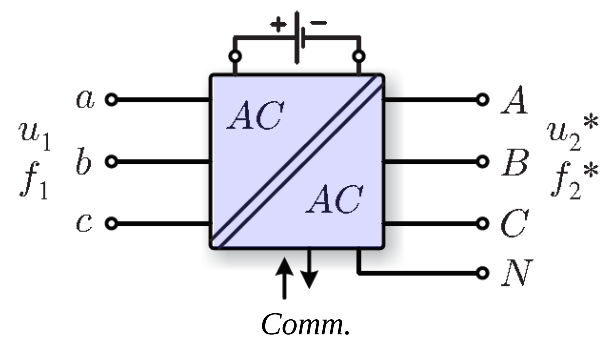
■ Protects Load from Power System Disturbance

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



■ Protects Power System from Load Disturbance

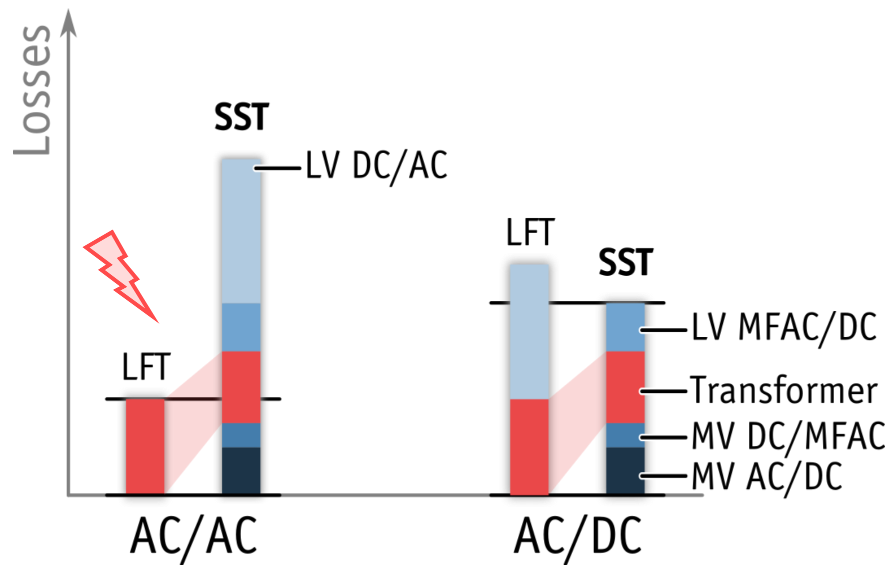
- Unity Inp. Power Factor Under Reactive Load
- Sinus. Inp. Curr. for Distorted / Non-Lin. Load
- Symmetrizes Load to the Mains
- Protection against Overload & Output Short Circ.



■ 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

► "Efficiency Challenge" (Qualitative)



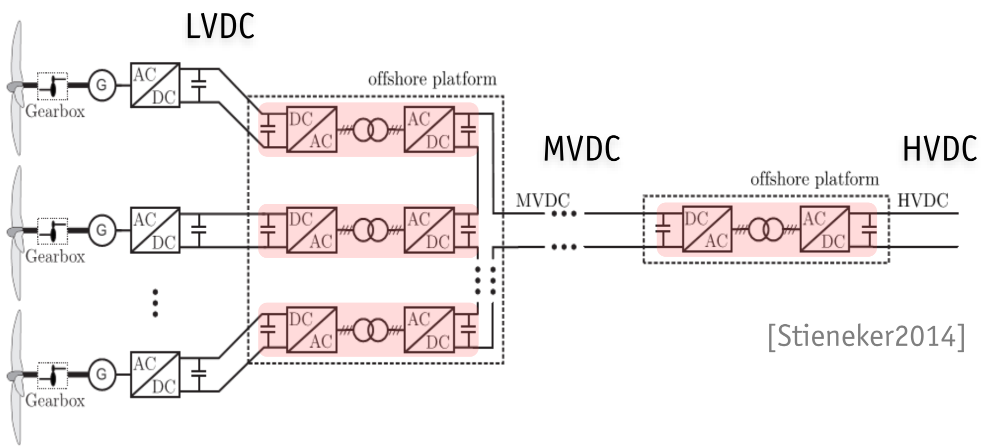
■ SSTs in Grid Applications – A Skeptic's View

- **Efficiency** of LFT for AC/AC Very Hard To Attain
- Weight/Volume Typically Not an Issue In Stationary Grid Applications
- Robustness, Reliability?
- Cost?

SST Concept Motivations

Traction → Weight & Volume
Smart Grid → Controllability
DC-DC Conversion

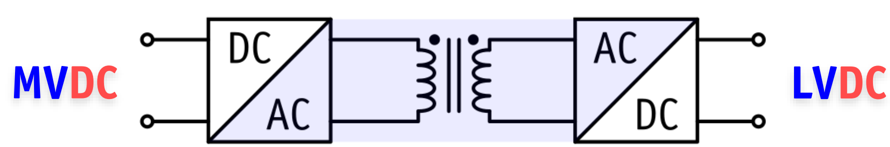
▶ Isolated DC-DC Applications



■ Examples

- In-Building DC Microgrids
- DC Collection Grids (Wind, PV)
- Future DC Grids in General

- DC Systems With Galvanic Separation Requirements → Isolated DC-DC Conversion = SST!
- Not Limited to MV Connection (Overlap With PSUs)



- **Transformer Operating Frequency Can Be Freely Chosen!**

11 Key Challenges of SST Design

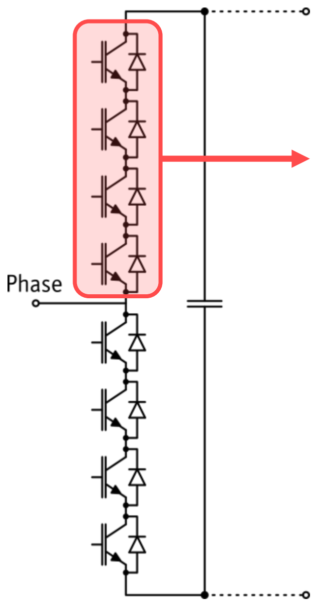
1. *Handling of Medium Voltage*
2. *Topology Selection*
3. *Reliability*
4. *MF Isolated Power Converters*
5. *MF Transformer Design*
6. *Isolation Coordination*
7. *EMI*
8. *Protection*
9. *Control*
10. *Construction of Modular Conv.*
11. *Testing of MV Converters*

Challenge #1/11
Handling of Medium Voltage

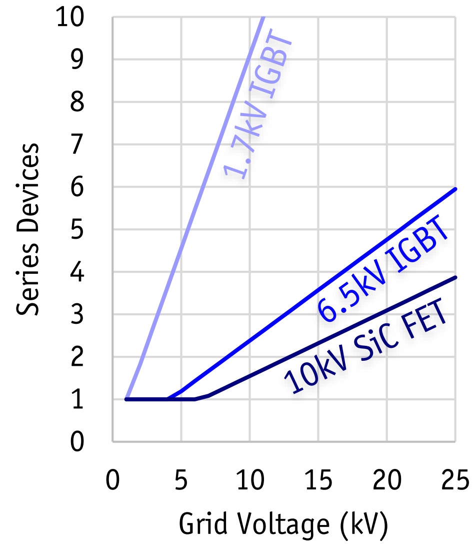
Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook

► Interfacing Medium Voltage With Power Electronics

- Limited Blocking Voltages of Available Semiconductors
  - **6.5kV** for Si IGBTs
  - **10-15kV** for SiC FETs (Prototype Devices Only)
- Feasible Blocking Voltage Utilization: Only 50-70% (Cosmic Ray Induced Failures)



- **A Single Device Is Often Not Sufficient!**



Mod. Index.: 0.8
Blocking Voltage Utilization: 0.66

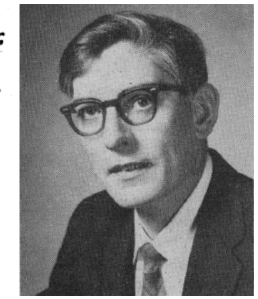
United States Patent

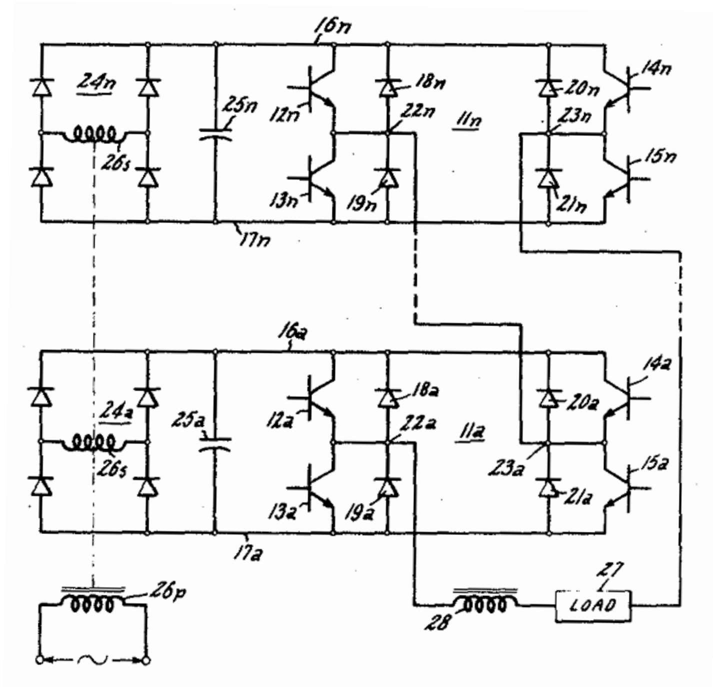
[11] 3,581,212

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

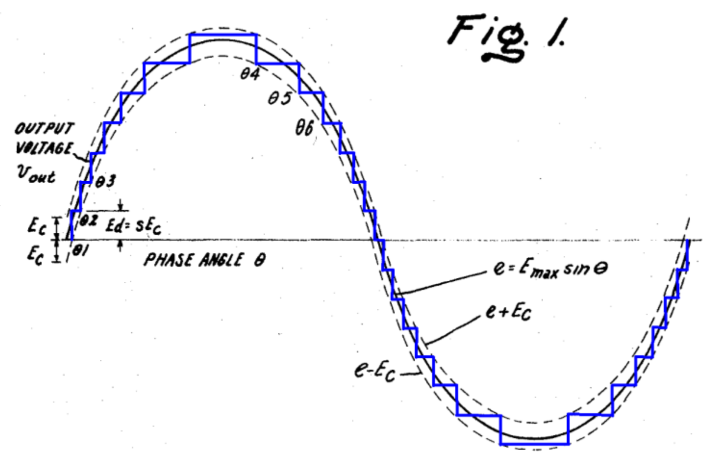
[72] Inventor **William McMurray**
Schenectady, N.Y.
[21] Appl. No. **846,354**
[22] Filed **July 31, 1969** ← **1969 !**
[45] Patented **May 25, 1971**
[73] Assignee **General Electric Company**

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





- Cascading of Converter Cells
- **Multilevel Output Voltage**



[McMurray1969]

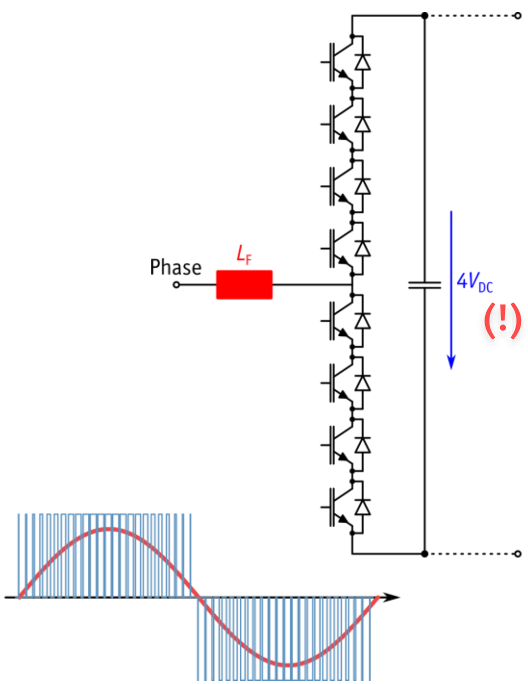
► Cascaded Converter Cells Instead of Direct Series Connection

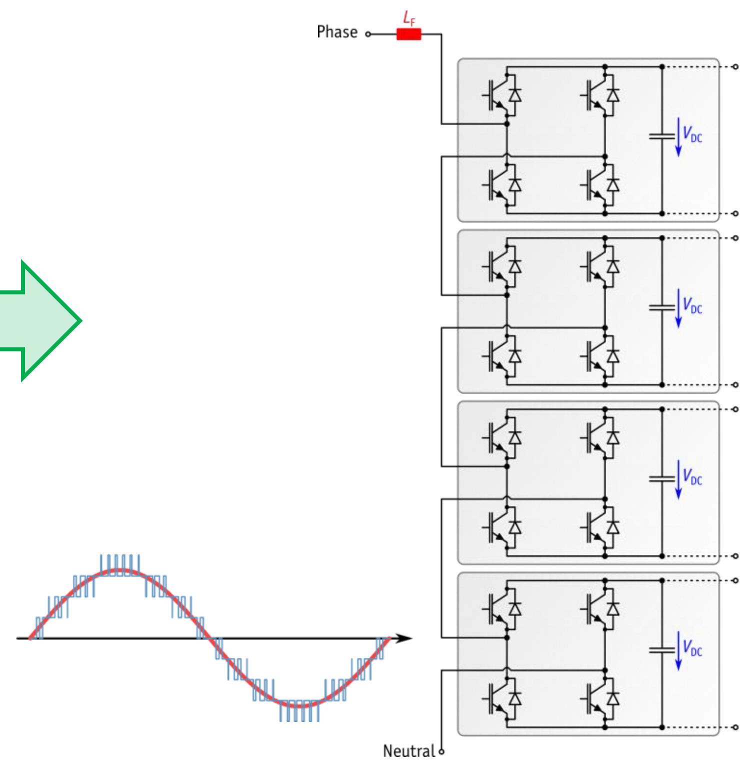
■ Direct Series Connection is Suboptimal

- Voltage Sharing (Static and Dynamic)
- Switching Synchronization
- No Add. Benefit of Multiple Switches

■ **Added Value: Multiple Converter *Cells***

- Modularity, Redundancy
- Multilevel Output Voltage Waveform
  → $f_S \propto 1/N_{Cell}^2$ for Same Filter Inductor





Challenge #1/11

Handling of Medium Voltage

Multi-Cell Approaches

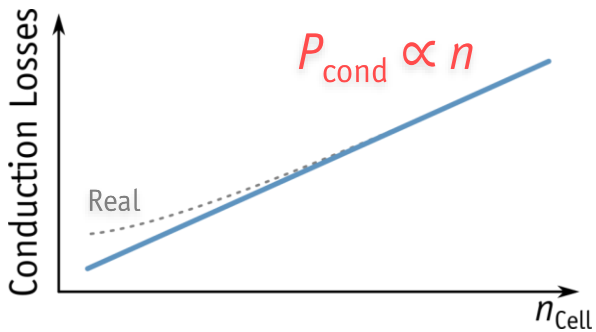
Optimum Blocking Voltage

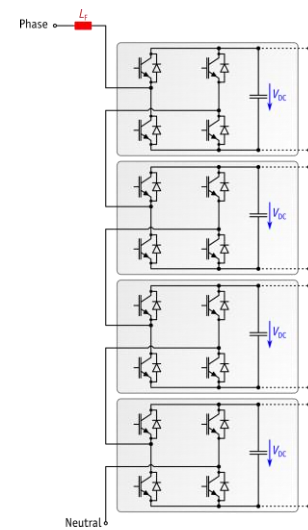
Single-Cell Approaches

Outlook

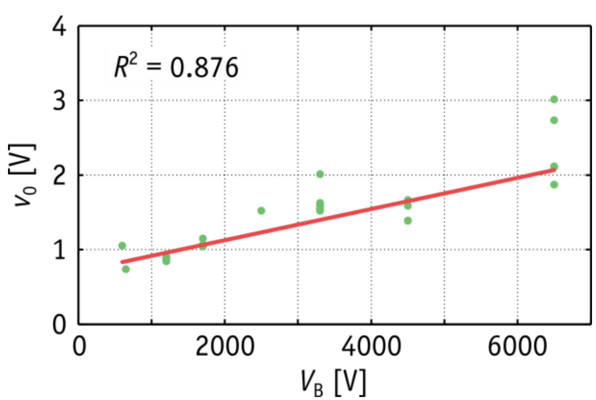
▶ Basic Trade-Offs: Conduction Losses

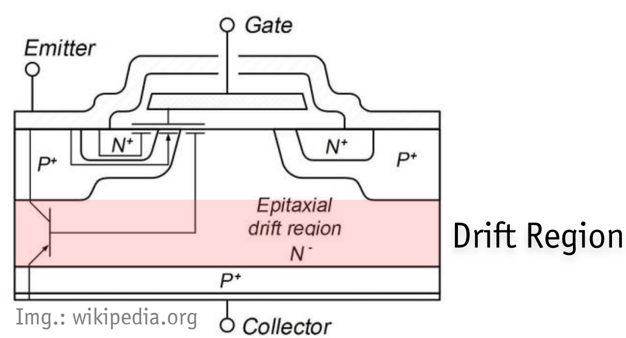
- More Cells, More Series Voltage Drops (**IGBTs**):





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

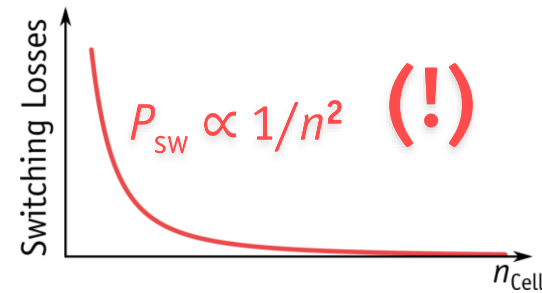




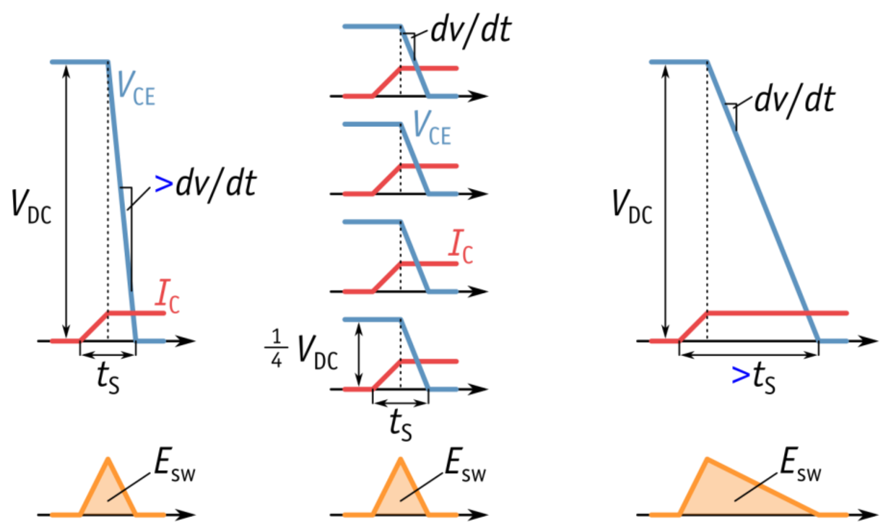
Img.: wikipedia.org

Basic Trade-Offs: Switching Losses

- For Equal Current Ripple in Equal Filter Inductors
  - Switching Frequency (per Cell): $f_S \propto 1/n^2$
  - Cell DC Voltage: $V_{DC} \propto 1/n$
  - But: Number of Cells: $\propto n$



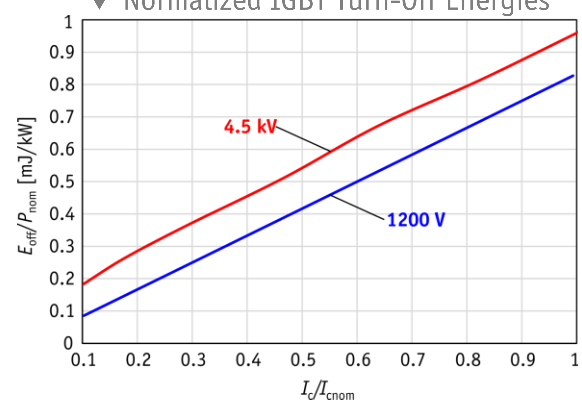
Switching Loss Modeling (Qualitative)



► Assumed

► Reality →
$P_{sw} \propto 1/n^{2...3}$

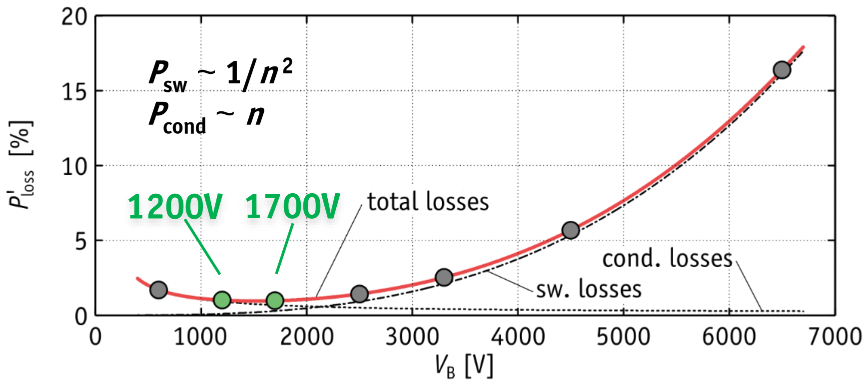
▼ Normalized IGBT Turn-Off Energies



▶ Loss-Optimal Blocking Voltage Choice

■ For Equal Current Ripple in Equal Filter Inductors

- 10kV Grid Voltage ▶ **There *Is* an Optimum Blocking Voltage**

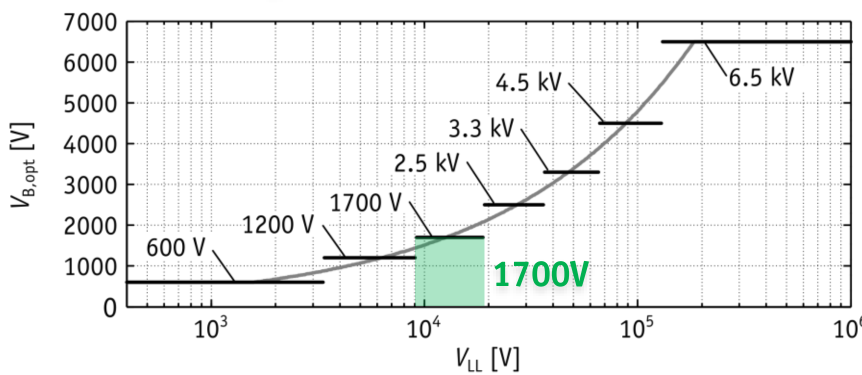


■ Optimum Blocking Voltage

⇕

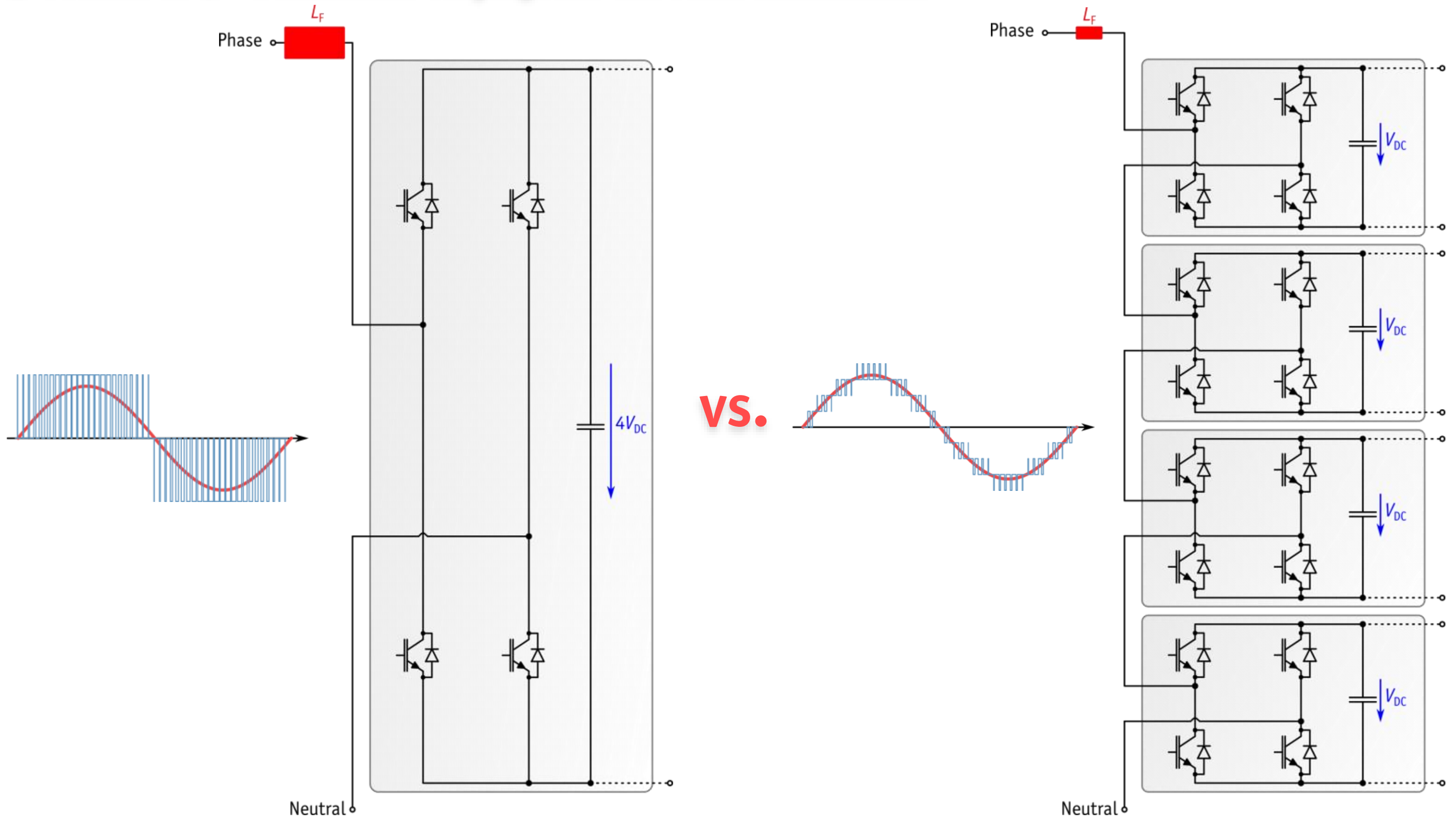
■ Optimum Number of Cascaded Cells

- Other Grid Voltages



► Optimal (Efficiency & Power Density!) Blocking Voltage (1)

■ **Volume as 2nd Dimension: Varying Also the Filter Inductance!**

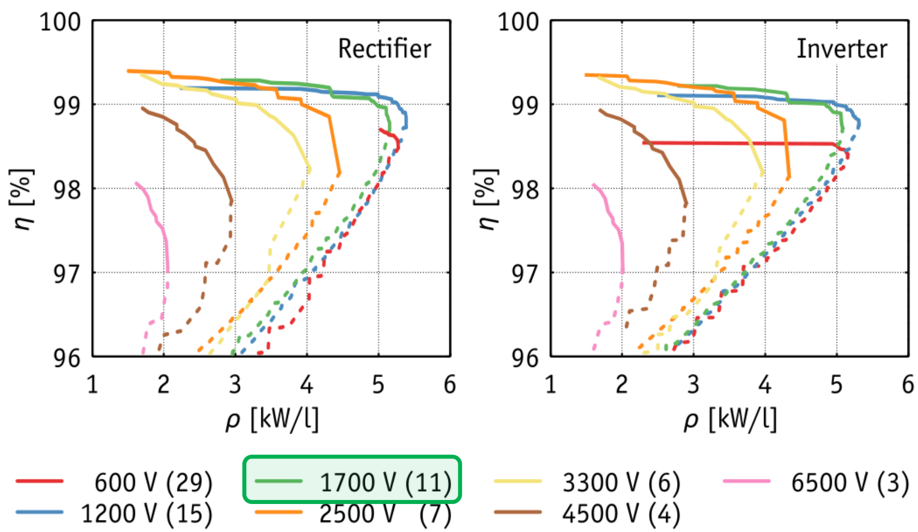


■ Modeling of Component Losses and Volumes (Inductor, Heatsinks, Capacitors, IGBTs, etc.)

▶ Optimal (Efficiency & Power Density!) Blocking Voltage (2)

■ **Volume as 2nd Dimension: Varying Also the Filter Inductance!**

■ Component Losses and Volumes (Inductor, Heatsinks, Capacitors, IGBTs, etc.)

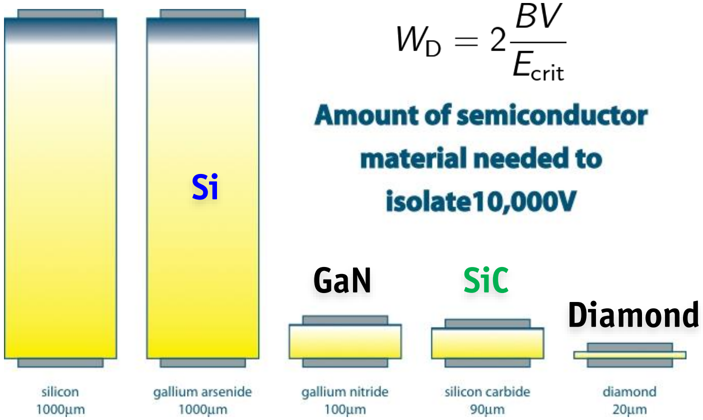


■ **Caution:** Minimum Filter Inductance Might be Defined By Application-Dependent **Protection Considerations**

Further Reading: ETH / [Huber2016b]

▶ Enter Silicon Carbide: Si vs. WBG (SiC/GaN) Semiconductors

$$W_D = 2\frac{BV}{E_{crit}}$$



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

- Specific On-State Resistance

$$R_{on,sp} = \frac{4BV^2}{\epsilon\mu_n E_C^3}$$

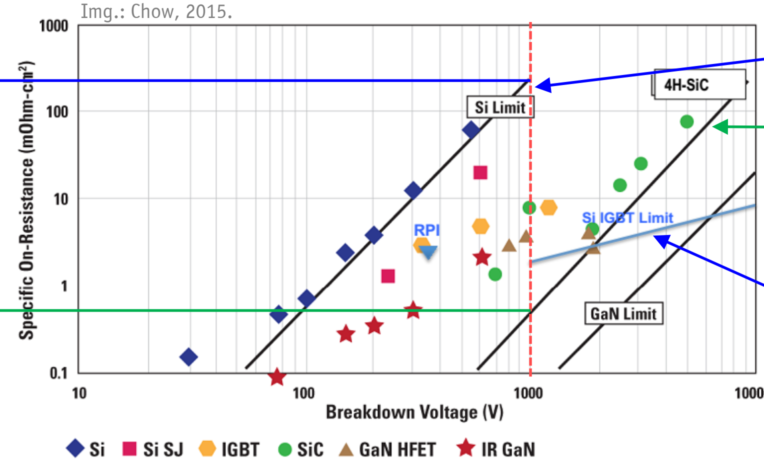
Blocking Voltage (BV^2)
Critical Electric Field (E_C^3)

- E_C in SiC ca. 9x Larger Than in Si
- **Lower $R_{on,sp}$ For Given Blocking Voltage**

Img.: Chow, 2015.

300 mΩ cm²

0.6 mΩ cm²



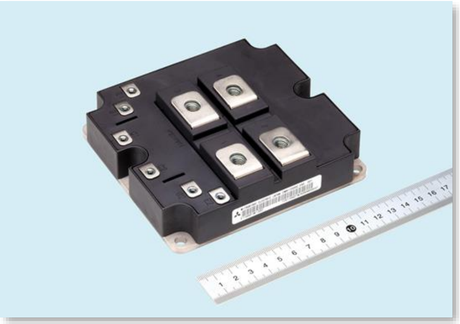
Unipolar Si Limit

Unipolar 4H-SiC Limit

Bipolar Si (!) Limit
But: Bipolar → Sw. Losses!

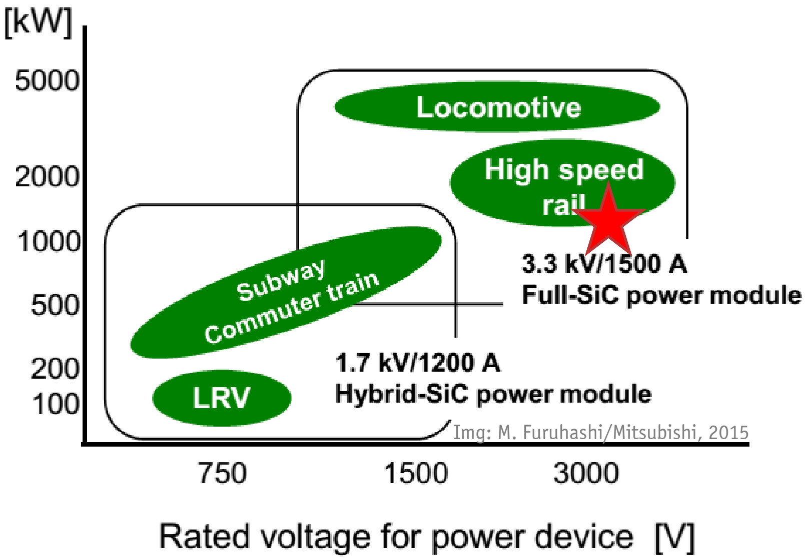
▶ Example: All-SiC Traction Inverter

- Mitsubishi 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

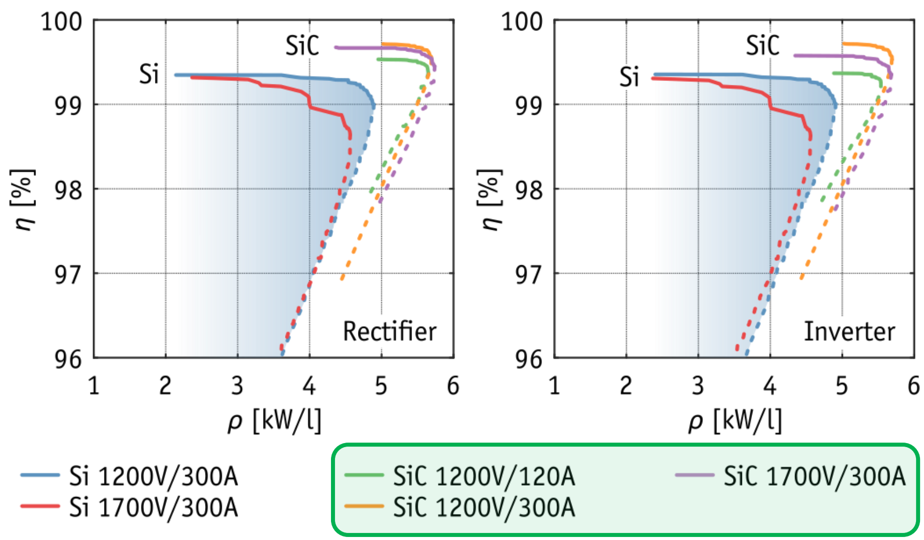
▲ MITSUBISHI ELECTRIC *Changes for the Better* 2014



Img: M. Furuhashi/Mitsubishi, 2015

▶ Optimal (Efficiency & Power Density!) Blocking Voltage with SiC

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



Wolfspeed 1200V/5mΩ ▼

- **Caution:** Minimum Filter Inductance Might be Defined By Application-Dependent **Protection Considerations**

- **Si IGBT → SiC Transition Yields Significant Benefits!**

Further Reading: ETH / [Huber2016b]

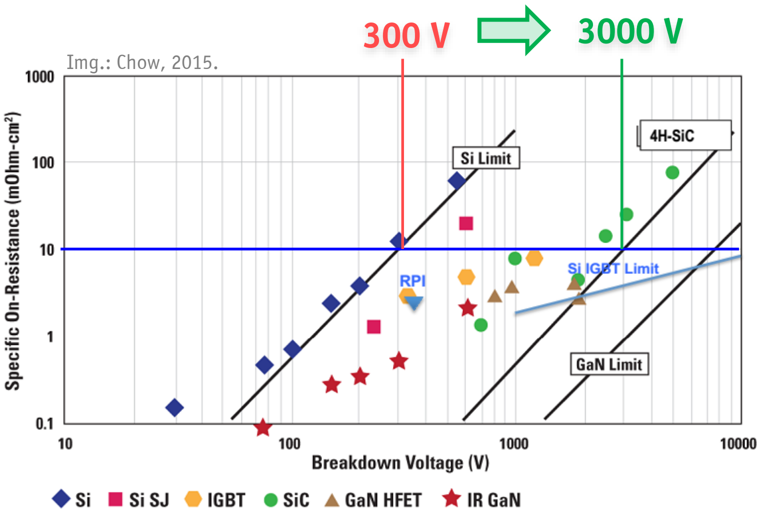
Challenge #1/11
Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook

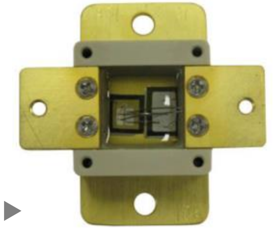
▶ Enter HV SiC Power Semiconductors

- E_C in SiC ca. 9x Larger Than in Si
- Lower $R_{on,sp}$ For Given Blocking Voltage

- **Or: Higher Blocking Voltage for Given $R_{on,sp}$**



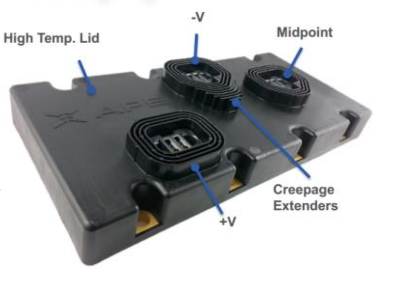
- 10…15kV Prototype Devices Are Available



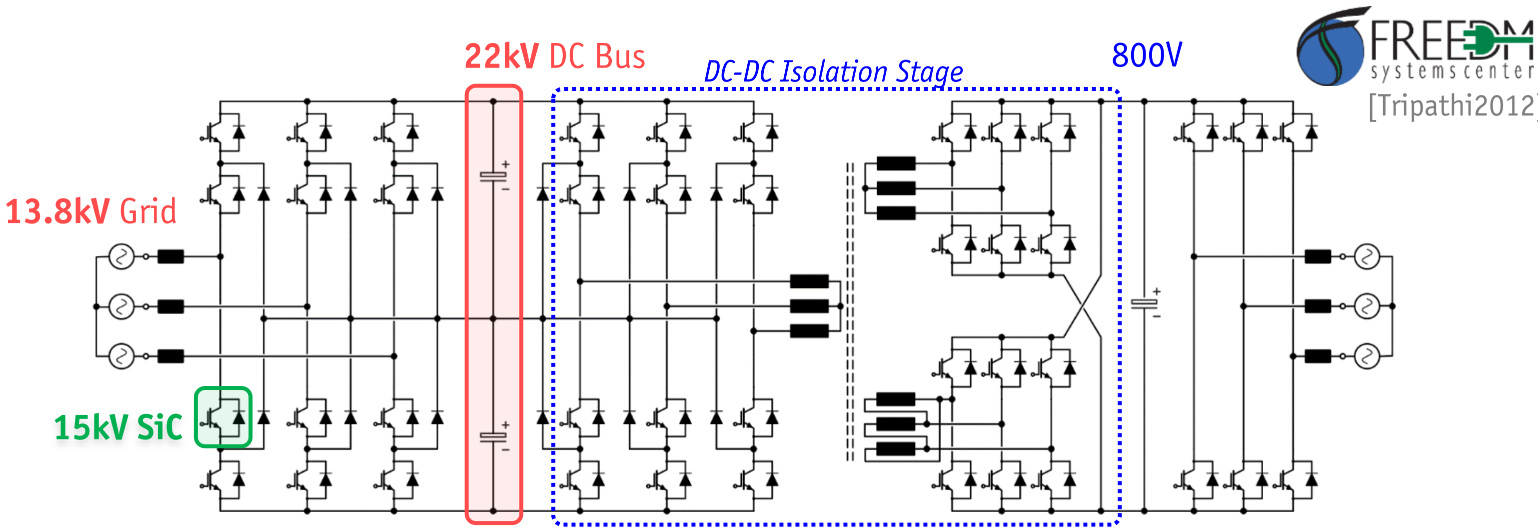
10kV SiC MOSFET ▶
(Wolfspeed)

- Challenging HV Packaging

15kV/80A Package ▶
(Wolfspeed)



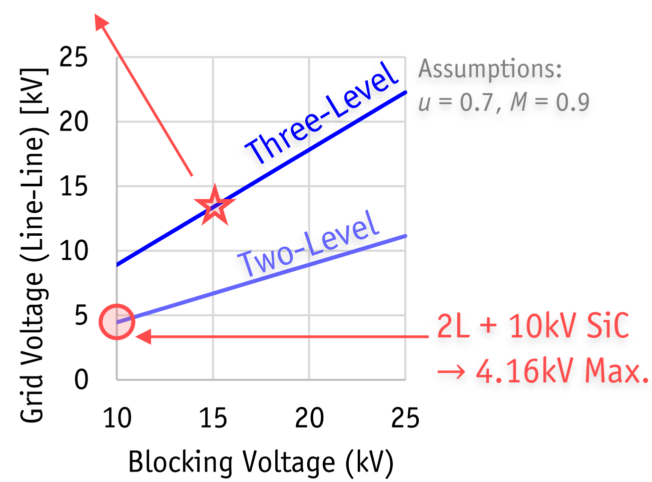
▶ Single-Cell Approach: The Positive Aspects



- Standard Inverter Topologies Can Be Employed (Two-Level, Three-Level)
- Comparably Low System Complexity

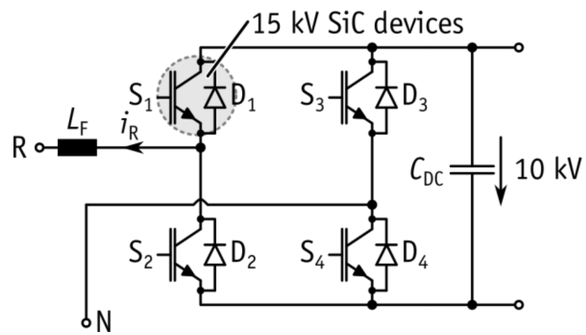
- **Three-Phase Inverter Stage**
  → Constant Power Flow In Isolation Stage (!)

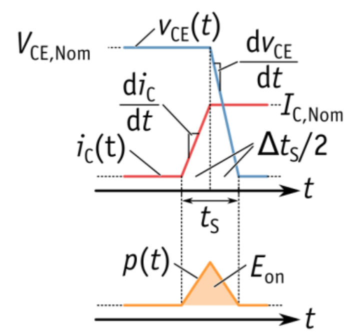
- Max. Feasible Grid Voltages Limited By Blocking Voltages



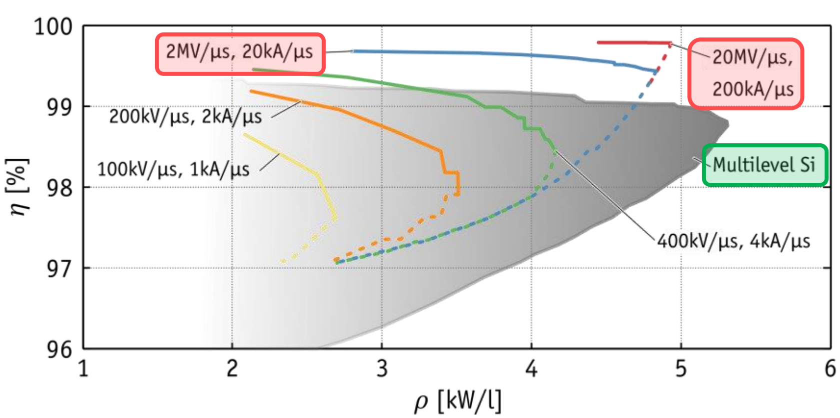
▶ Single-Cell Approach: The Challenging Aspects

- Low Number of Levels → Remember: $f_S \propto 1/n^2$
- High Switching Frequency and/or Large Filter Inductor





- "Virtual" Devices By Adapting t_S (and thus di/dt and dv/dt)
- Pareto Optimization for Two-Level, Single-Phase (!) System



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

  Further Reading: ETH / [Huber2016b]

- Implementation of Redundancy?

Challenge #1/11

Handling of Medium Voltage

Multi-Cell Approaches
Optimum Blocking Voltage
Single-Cell Approaches
Outlook

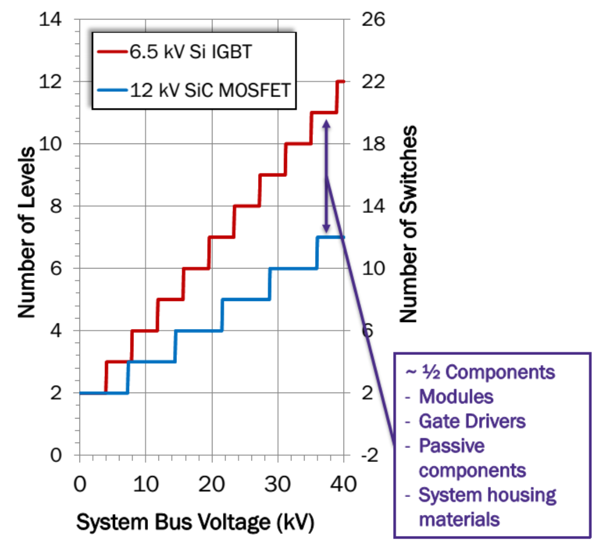
▶ Outlook: Single-Cell vs. Multi-Cell

■ Strategies for Handling Medium Voltage Connection

- Multi-Cell Approach
  - \+ LV Devices, Multilevel Waveforms, Redundancy, "Divide et Impera"
  - \- Complexity, Phase-Modular Topologies
- Single-Cell Approach
  - \+ Simplification of Converter Structure, Three-Phase Topologies
  - \- Max. Grid Volt. Limited, 2L/3L w. Fast Switching Trans.

■ The Best of Both Worlds?

- **FEWER-Cells Approach**
  - Higher DC Voltage per Cell
  - Less Cells, Lower Complexity
  - Multilevel Waveforms
  - Redundancy



Img: [Passmore2015]

■ Suitable Choice Depends on Application Voltage and Power Levels

■ Careful Choice/Optimization of Blocking Voltage for Multi-Cell Systems

Challenge #2/11
Topology Selection

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

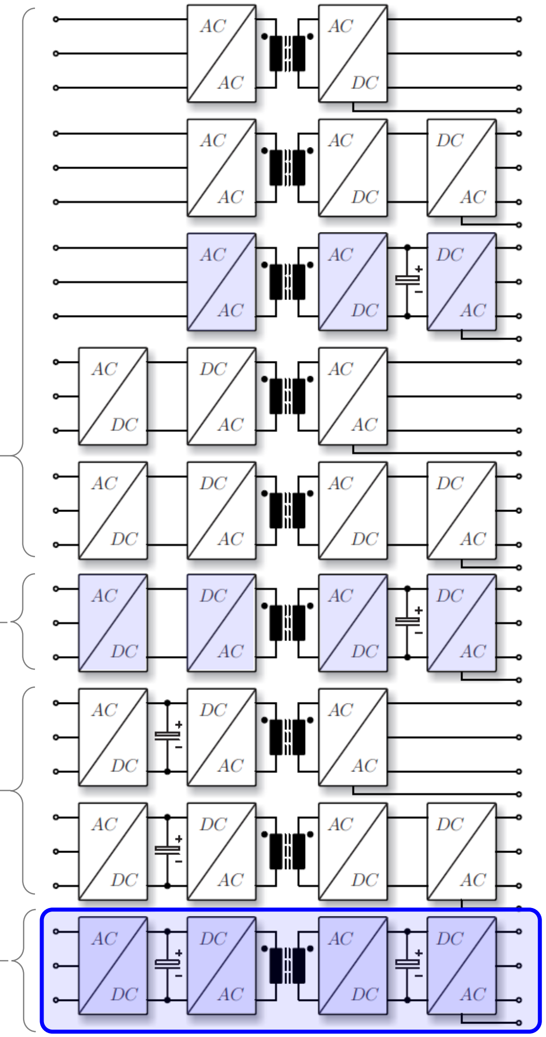
Conclusion: Main SST Topologies

▶ Partitioning of the AC/AC Power Conversion

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

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

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



▶ Partitioning of the AC/AC Power Conversion

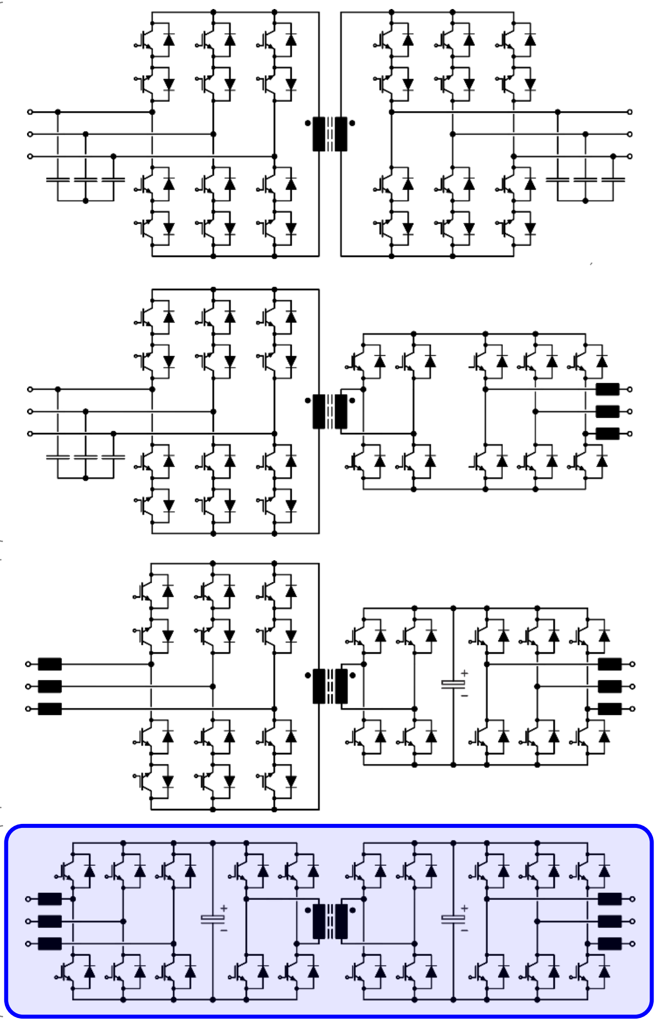
- **1st Degree of Freedom of Topology Selection**
  → Partitioning of the AC/AC Power Conversion

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

  - 1-Stage Matrix-Type Topologies

  - 2-Stage with LV DC Link (Connection of Energy Storage)

  - **3-Stage Power Conversion with MV and LV DC Link**
    → Requires HV Devices (!)



Challenge #2/11
Topology Selection

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

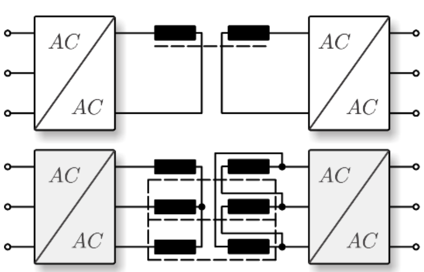
Conclusion: Main SST Topologies

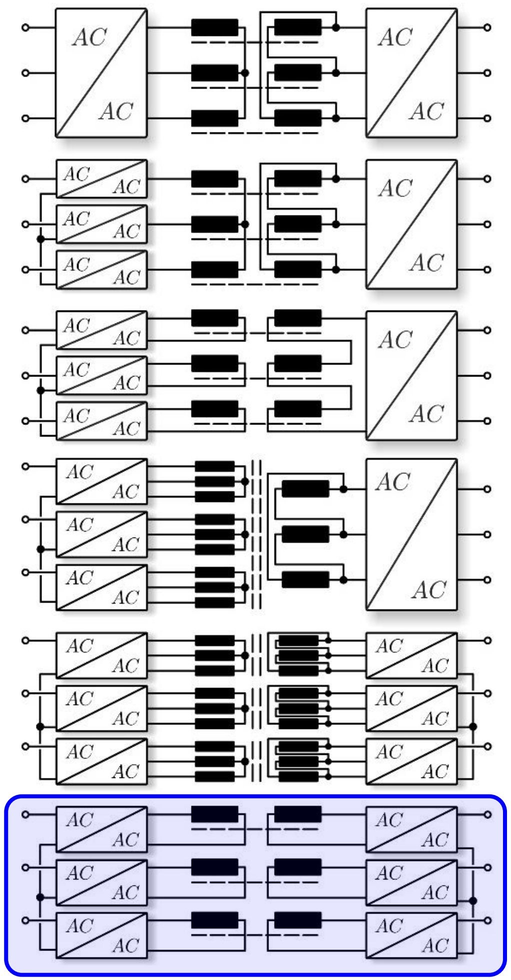
▶ Partial or Full Phase Modularity

■ 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

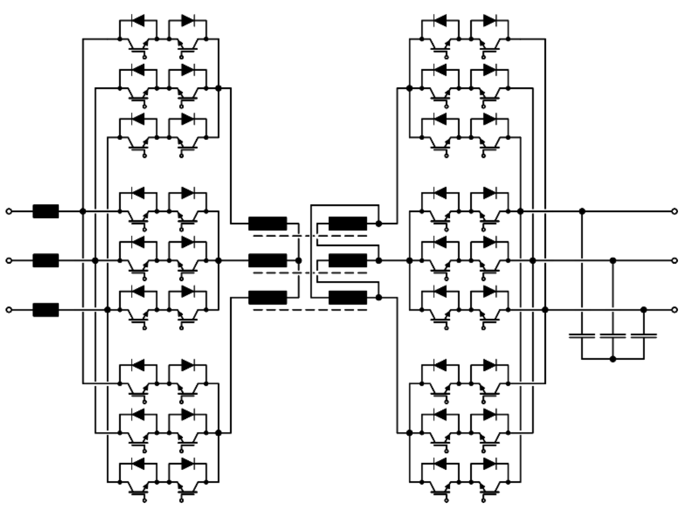




▶ Partial or Full Phase Modularity: Examples

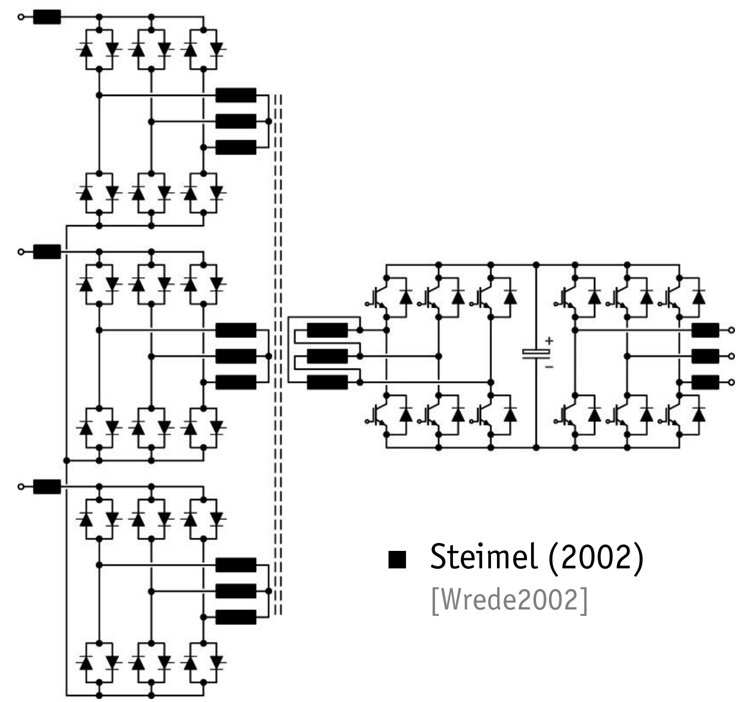
■ 2nd Degree of Freedom of Topology Selection
→ Partial or Full Phase Modularity

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



■ Enjeti (1997)
[Kang1999]

- Example of Partly Phase-Modular SST



■ Steimel (2002)
[Wrede2002]

▶ Partitioning of Single-Phase AC/DC PFC Functionality

■ Required Functionality

- **F**: **F**olding of the AC Voltage Into a |AC| Voltage
- **CS**: Input **C**urrent **S**haping
- **I**: Galvanic **I**solation & Voltage Scaling
- **VR**: Output **V**oltage **R**egulation

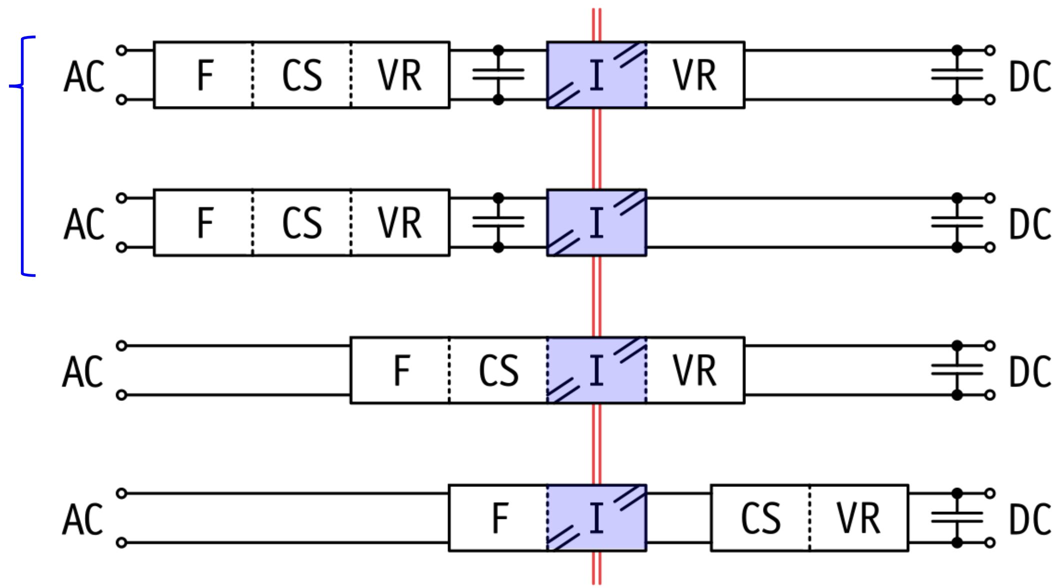
One Phase of Phase-Modular 3ph-SST
→ Single-Phase System!

■ Isolated PFC Task Partitioning Variants

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

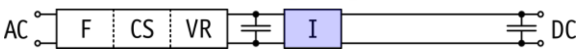
Fully Integrated ▶

Isolated Front End (IFE) ▶
→ Less Common Alternative

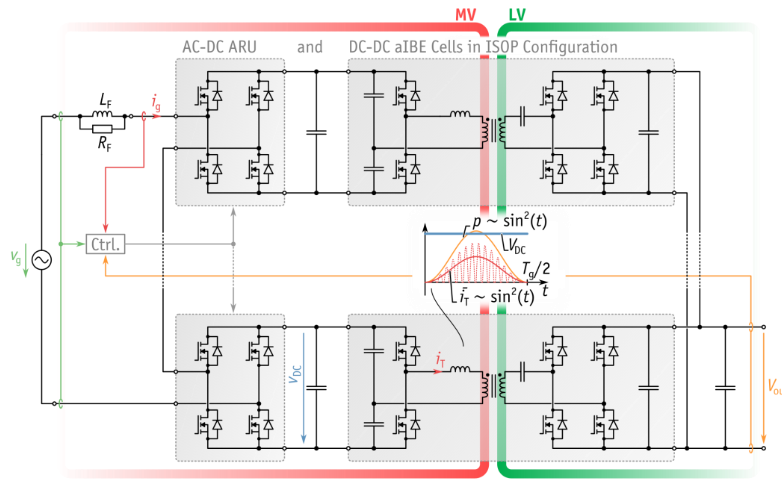


▶ Examples of Multi-Cell AC/DC SST Topologies

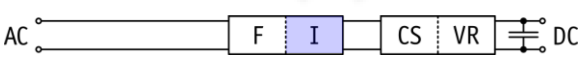
■ **Isolated Back End (IBE)**



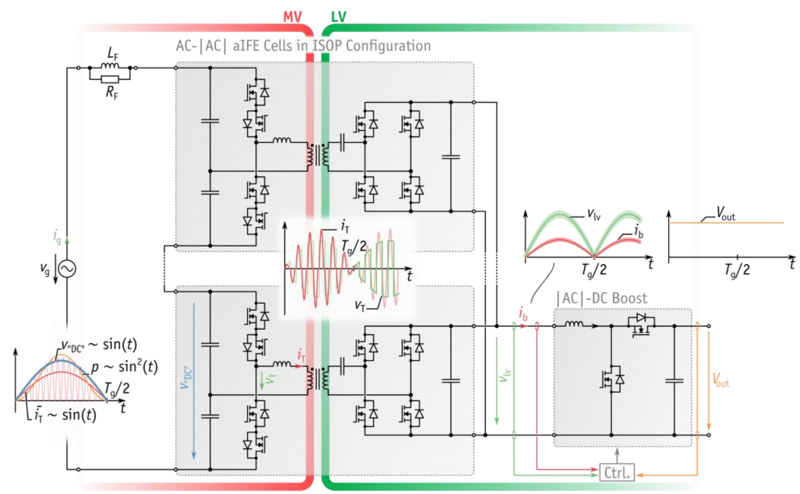
[Steiner1998], [Steiner2000]
[Dujic2013], [Zhao2014]



■ **Isolated Front End (IFE)**



[Weiss1985], [Han2014],
[Kolar2016], [Huber2016a]



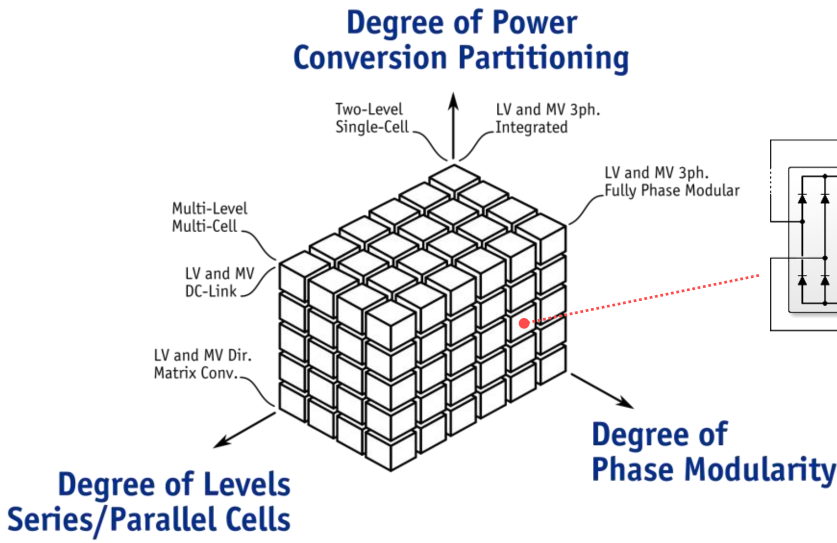
Challenge #2/11

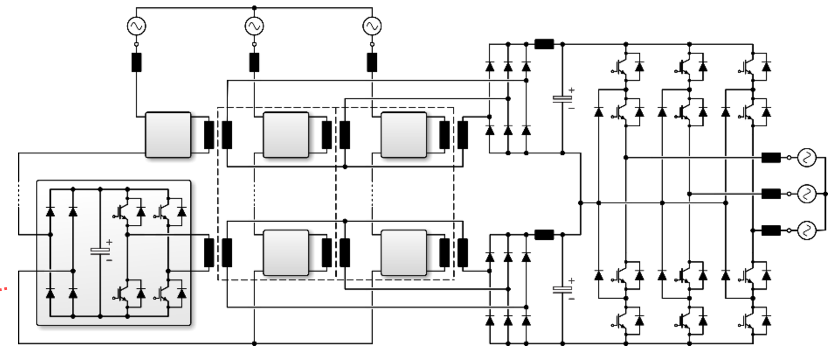
Topology Selection

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

Conclusion: Main SST Topologies

▶ Classification of SST Topologies





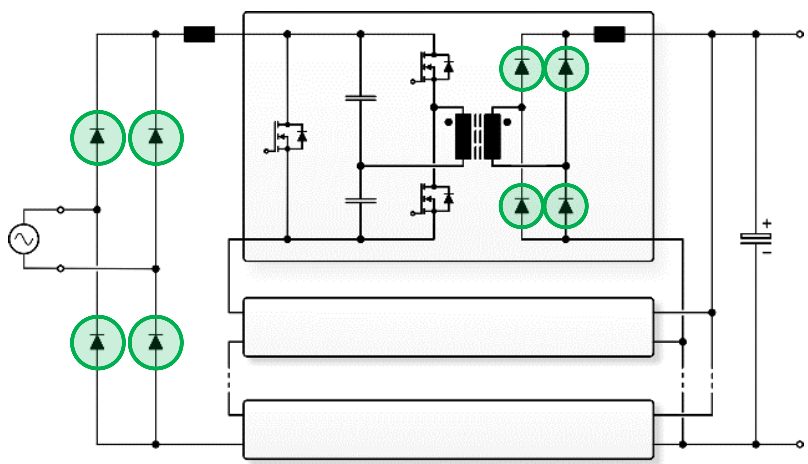
▲ Enjeti (2012)
[Krishnamoorthy2012]

- **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

▶ Side Note: Unidirectional SSTs

- Simplification of Topologies for Unidirectional Power Flow
- SST As **MV-Connected Power Supply**



- Example Topology: **Unidirectional** Multi-Cell Boost Topology

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

[VanDerMerwe2009a]
[VanDerMerwe2009b]
ETH / [Rothmund2014]

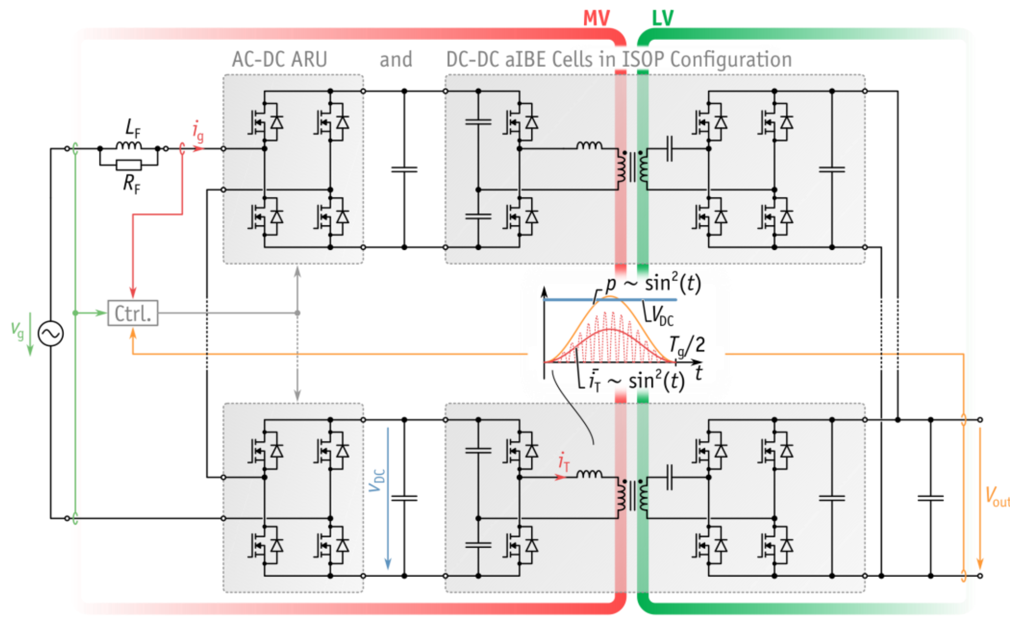
Challenge #2/11
Topology Selection

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

Conclusion: Main SST Topologies

▶ Main SST Topologies (1)

- Multi-Cell Topologies
  - **Isolated Back End**
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)
- Single-Cell Topologies



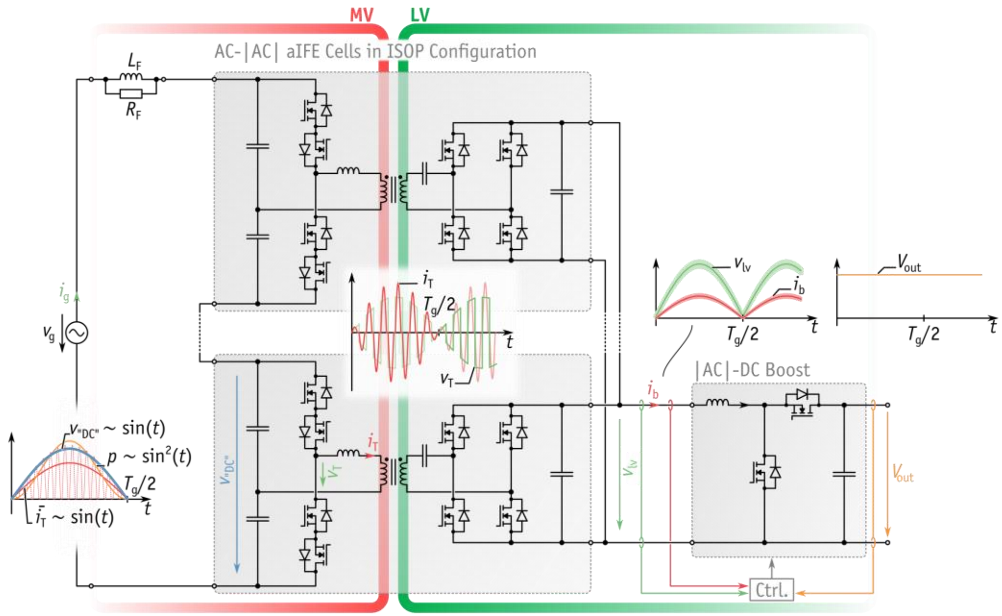
- Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, NPC Cells, DC-DC Converter Type, Unidirectionality, etc.)

[Steiner1998]
[Steiner2000]
[Dujic2013]
[Zhao2014]

▶ Main SST Topologies (2)

- Multi-Cell Topologies
  - Isolated Back End
  - **Isolated Front End**
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies



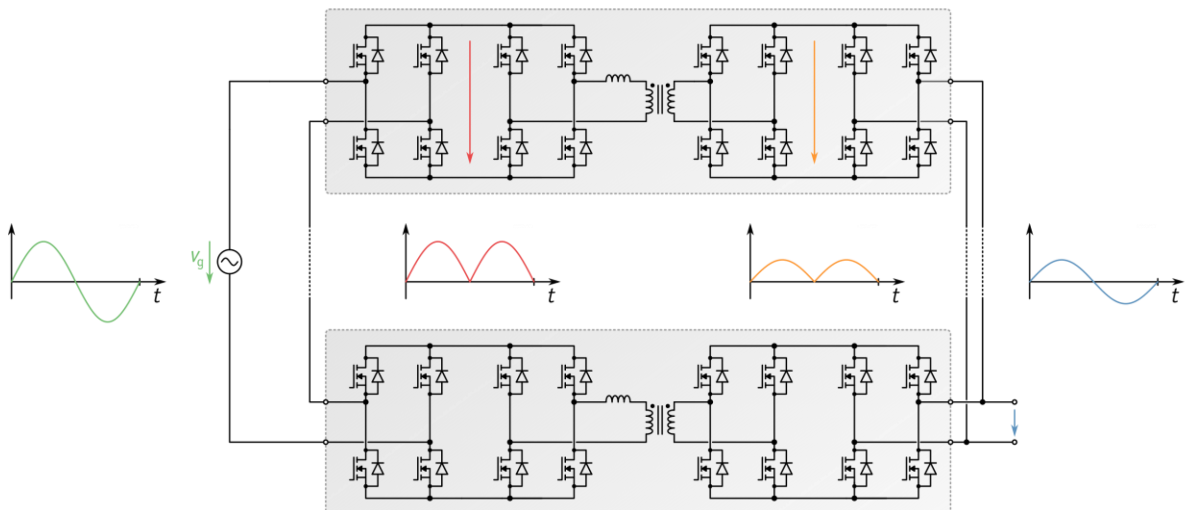
- Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, NPC Cells, Unidirectionality, etc.)

[Weiss1985]
[Han2014]
[Kolar2016]
[Huber2016a]

▶ Main SST Topologies (3)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - **Matrix-Type (AC/AC)**
  - Modular-Multi-Level (M2LC)

- Single-Cell Topologies

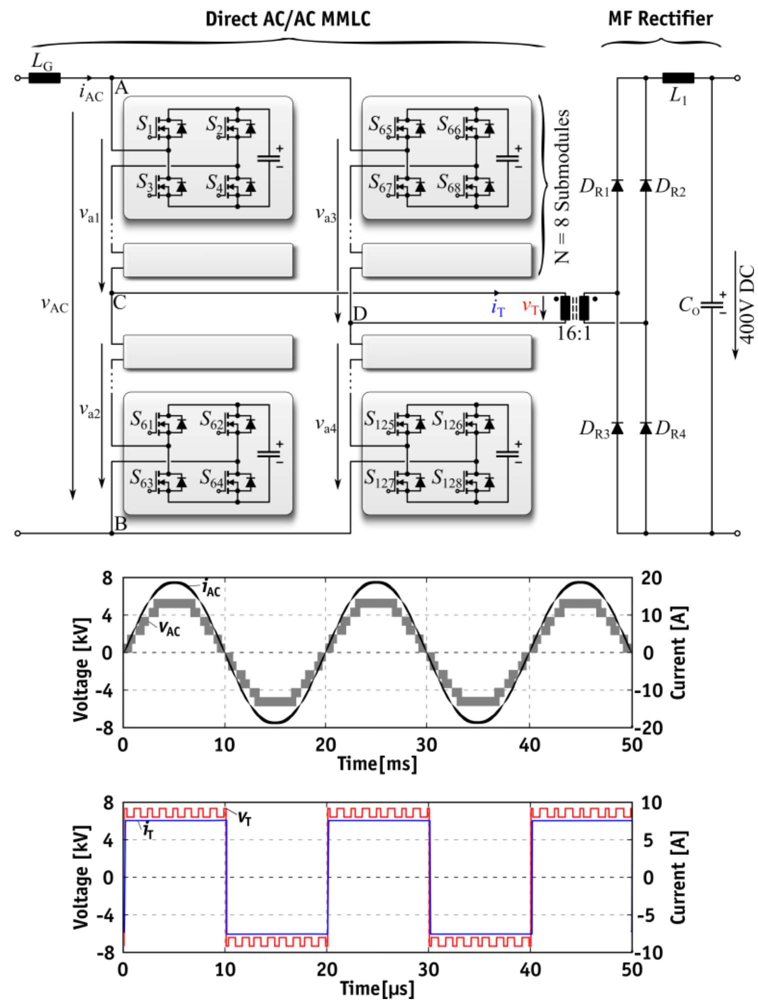


- Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, NPC Cells, Unidirectionality, etc.)

[Das2011]

▶ Main SST Topologies (4)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - **Modular-Multi-Level (M2LC)**
- Single-Cell Topologies



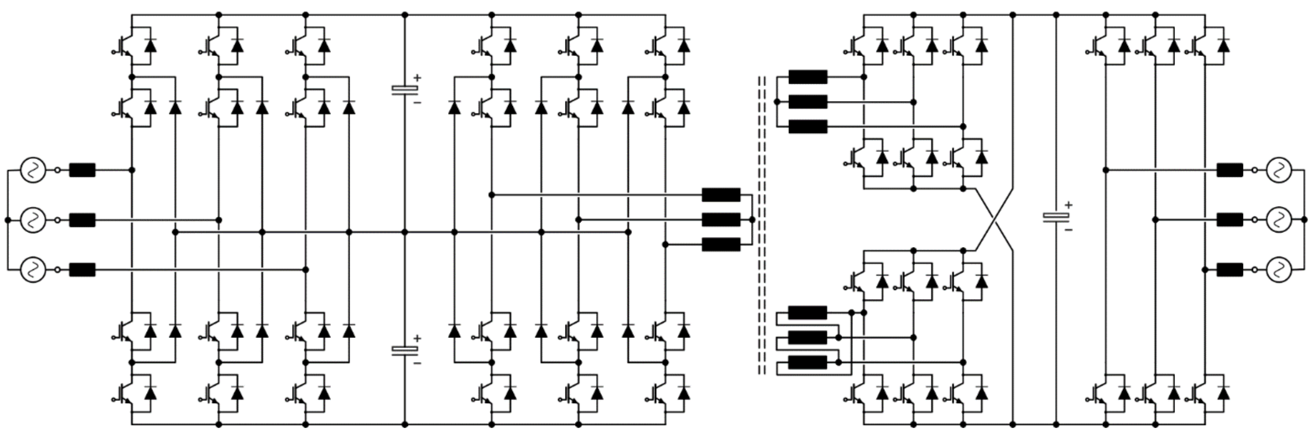
- Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, Bidirectionality, etc.)

[Glinka2003], Img.: ETH / [Rothmund2014]

▶ Main SST Topologies (5)

- Multi-Cell Topologies
  - Isolated Back End
  - Isolated Front End
  - Matrix-Type (AC/AC)
  - Modular-Multi-Level (M2LC)

- **Single-Cell Topologies**

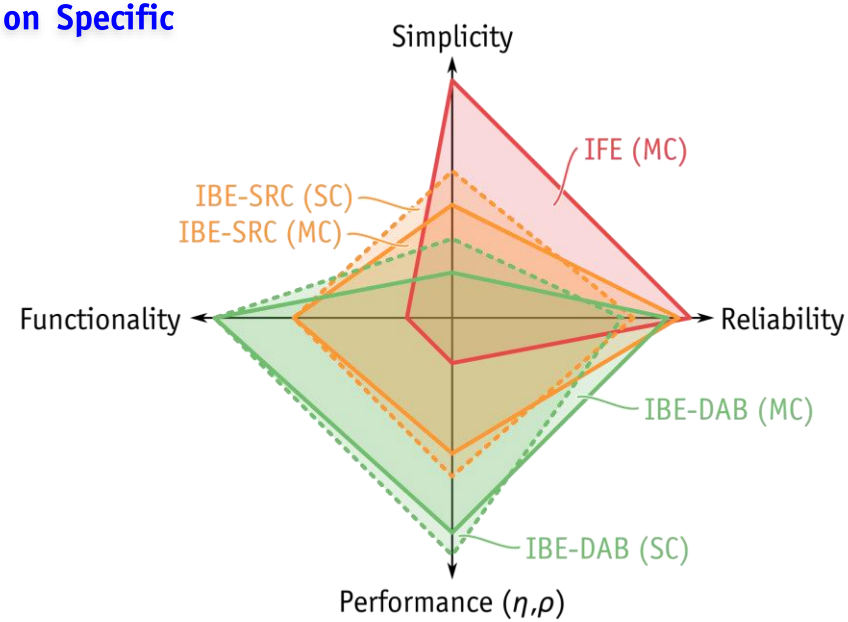


- Note: Specific Realizations May Vary
  (e.g., DC-DC Converter Type, Unidirectionality, etc.)

[Tripathi2012]

► SST Topologies Summary & Outlook

- High Number of Possible SST Topologies
  → **Optimum Topology Choice Depends on Specific Application Requirements!**



- **Trends And Outlook**
  - LV SiC Devices
  - **HV SiC Devices / Single-Stage SSTs**
  - Reliability Considerations Are Highly Important

Challenge #3/11

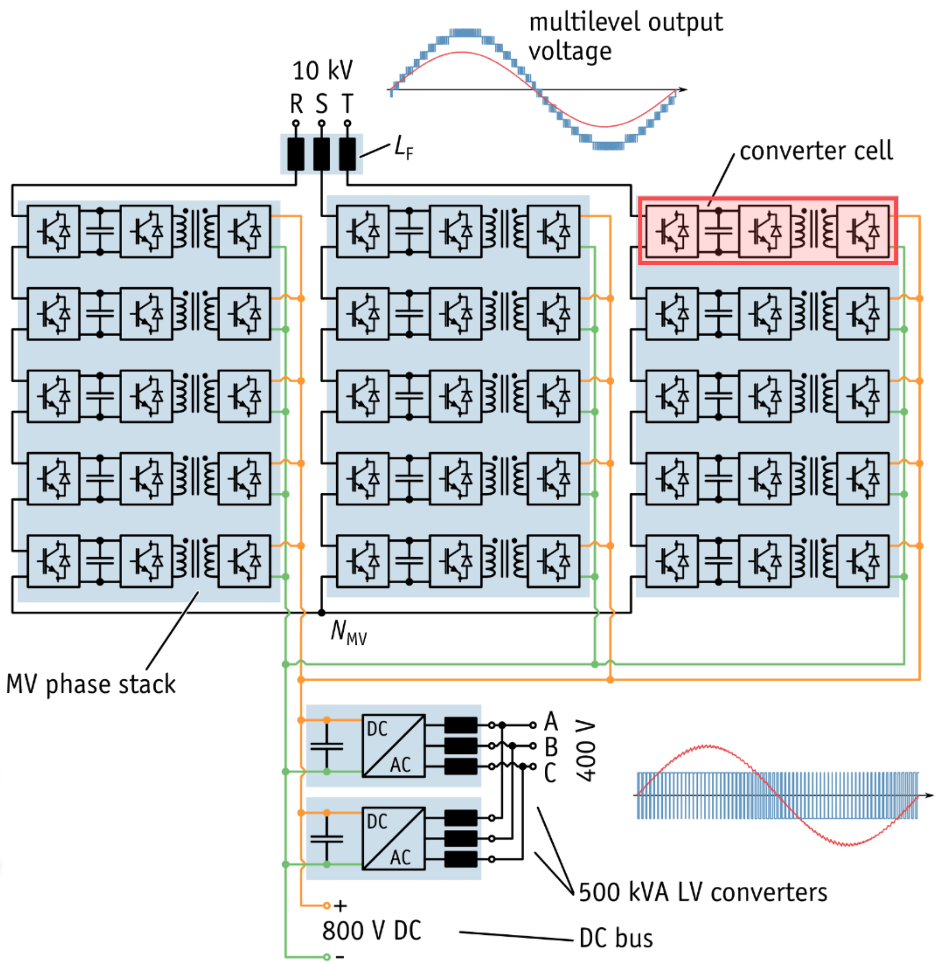
Reliability

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



■ Modular System → MANY Components!

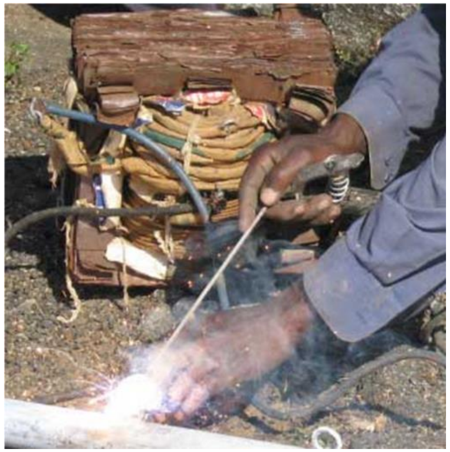
→ Can Such a System Still Be Reliable?

▶ Reliability Considerations for SST Design

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

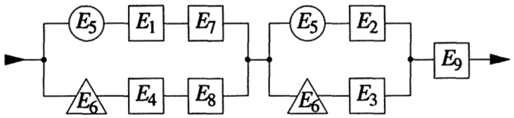
  vs.

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



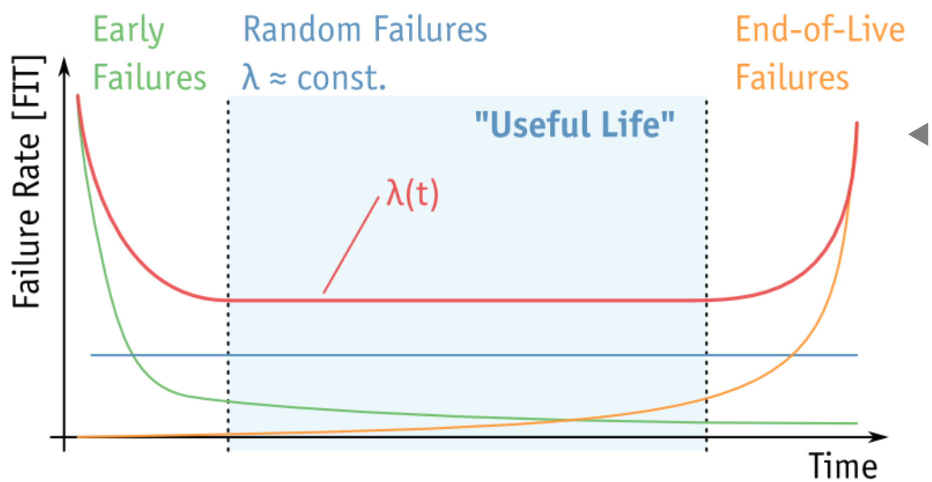
Source: http://www.africancrisis.org

- **Very High Reliability Requirements 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]

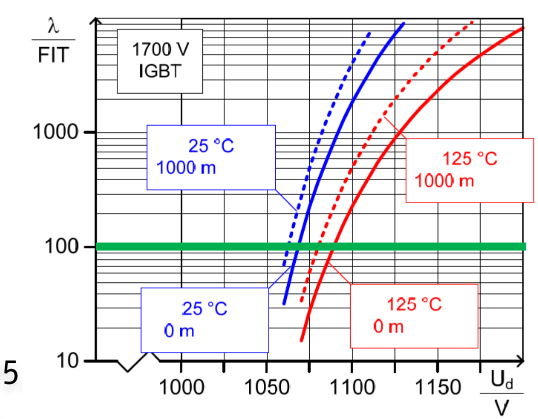
▶ Modeling Reliability: The Failure Rate



◄ «Bathtub Curve»

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

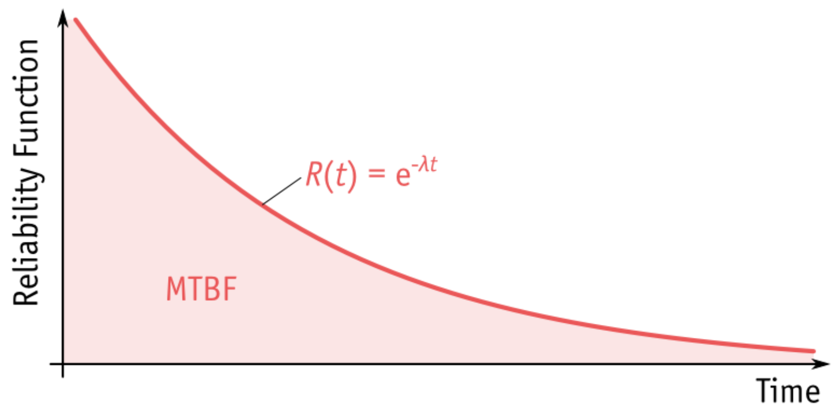
- **Here, Only Useful Life is Considered**
  - Dominated by Random Failure Distribution
  - Constant Failure Rate λ
  - $[\lambda]$ = 1 FIT (1 Fail. in 10^9 h) – Typ. Value for an IGBT Mod.: 100 FIT ▶



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

▶ Modeling Reliability: The Reliability Function

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



- 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!

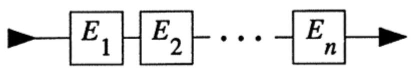
- Average Availability: $$A = \frac{MTBF}{MTBF + MTTR}$$

Textbook: [Birolini1997]

▶ Modeling Reliability: Basic Multi-Element Considerations

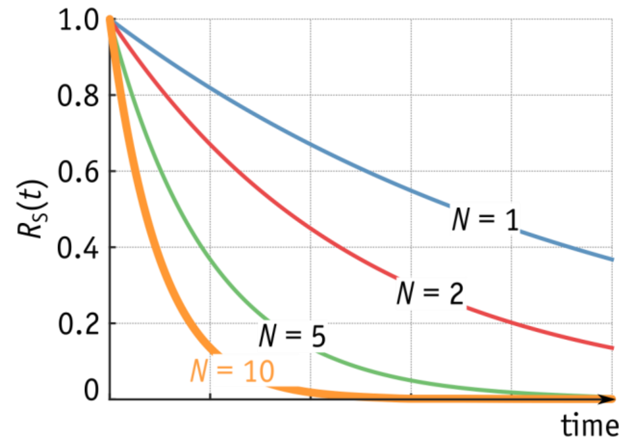
■ Series Structure

(e.g. Components of a Single Converter Cell)



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

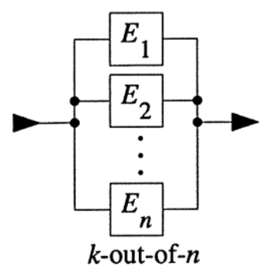
(General Assumption: Independent Elements with Equal Failure Rate.)



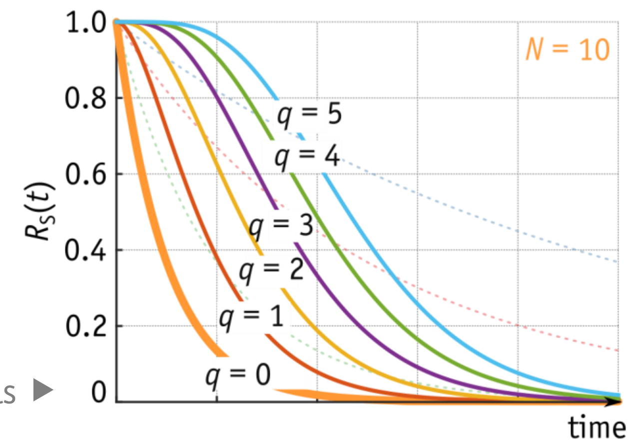
■ *k*-out-of-*n* Redundancy

(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

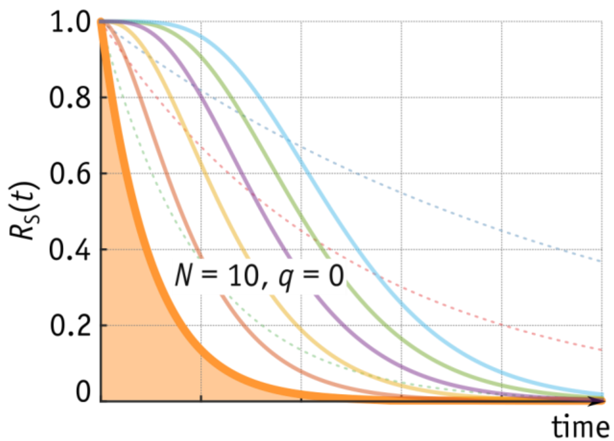


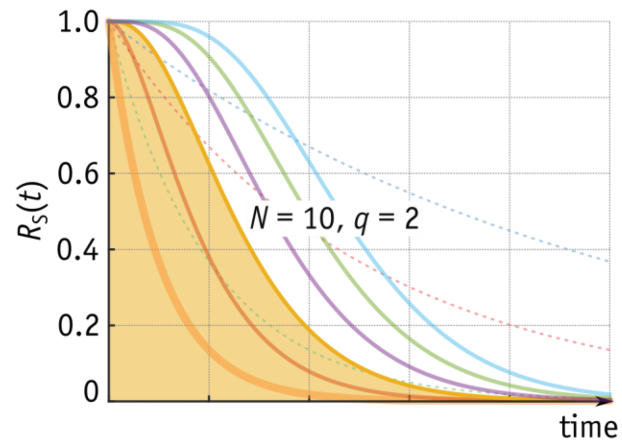
Effect of *q* Additional Redundant Cells ▶



Textbook: [Birolini1997]

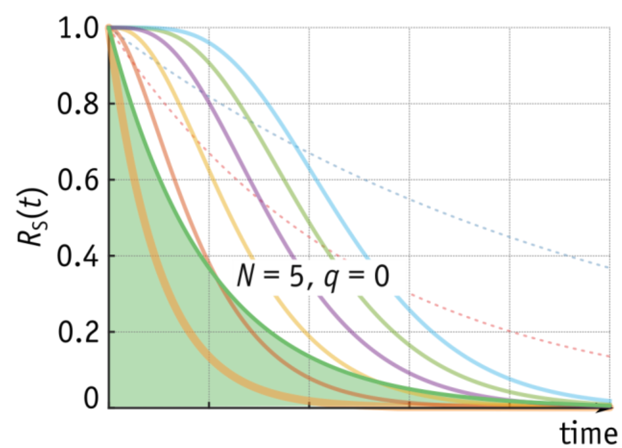
▶ The "Power of Redundancy" (1)





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

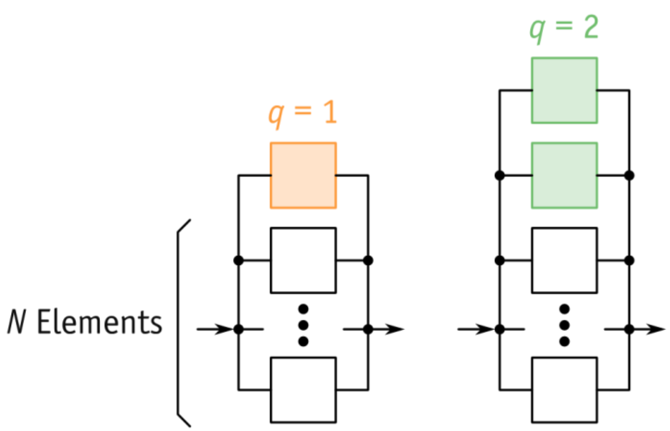
- **Redundancy Can Significantly Improve System Level Reliability**
  - 10 Elements + 2 Redundant: Reliability Higher than for 5 Elements!

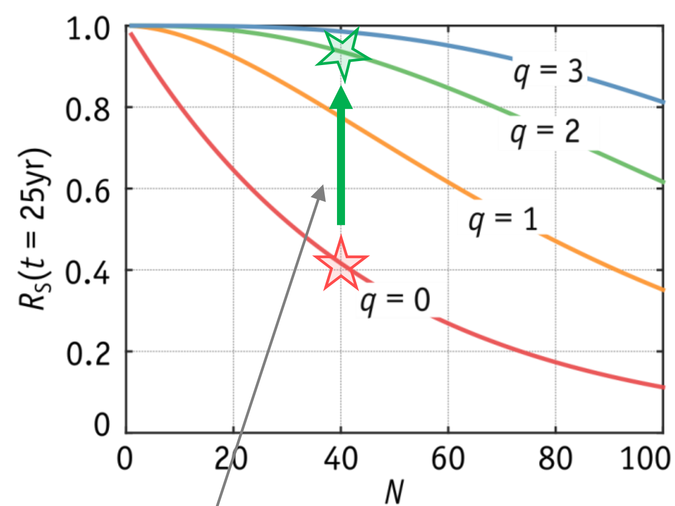


▶ The "Power of Redundancy" (2)

■ **Value of Reliability Function at t = 25 Years**
(Probability That System Is Operational After 25 Years)

- N Elements
- q Additional Redundant Elements





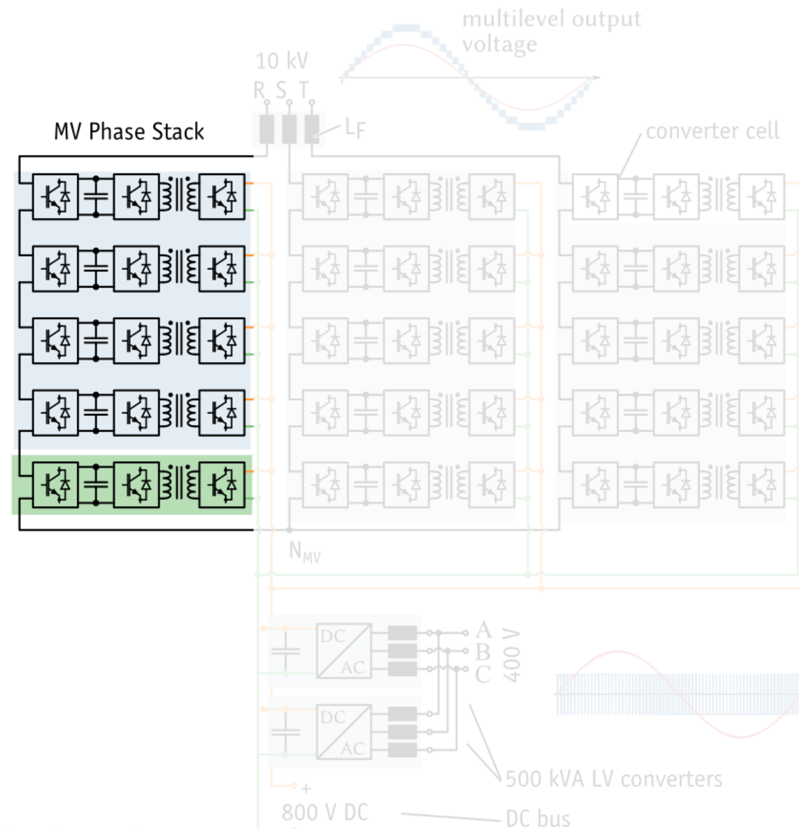
■ **Redundancy Can Significantly Improve System Level Reliability**

- 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 ▶

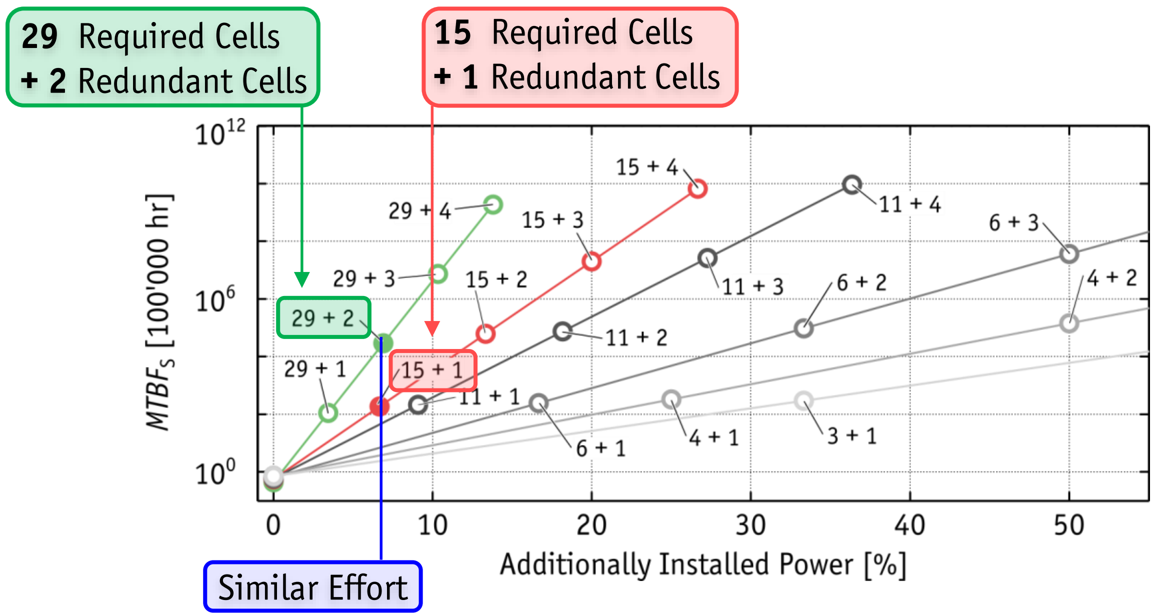


- **Redundancy Concepts**
  - Standby Redundancy
  - Active Redundancy with Load Sharing

- **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

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



- **Multi-Cell Designs Can Be Made Highly Reliable By Adding Redundancy!**
- Preventive Maintenance Can Further Improve System Availability

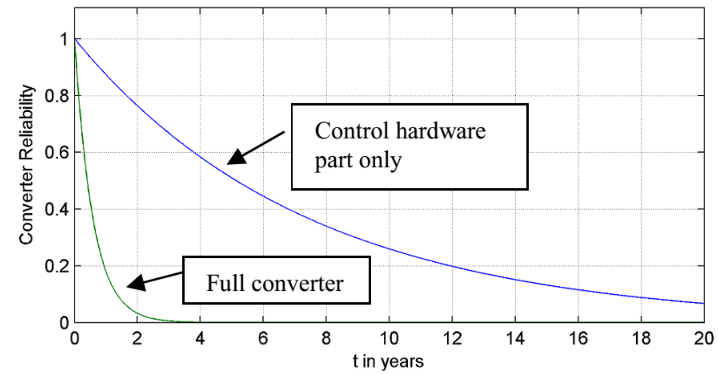
Note 1: 50% Of Cell FIT Rate Is Assumed To Be Proportional To Blocking Voltage
Note 2: Absolute MTBFS Values Depend on FIT Rate Assumptions; Relative Results Stay The Same

Further Reading:
ETH / [Huber2016b]

▶ Reliability "Bottlenecks"

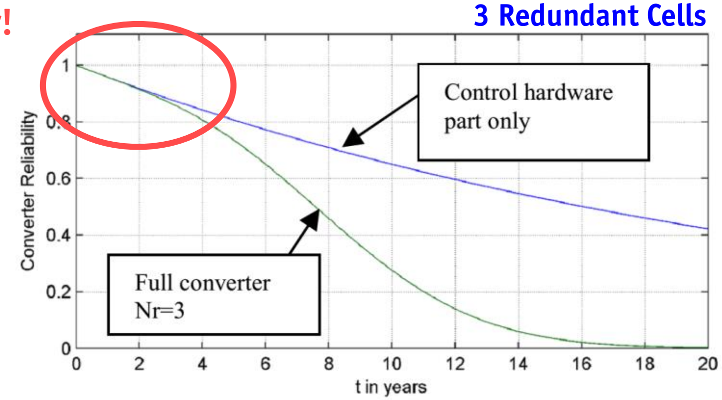
- Reliability Improvement by Means of Cell-Level Redundancy Is
  - Very Effective

No Redundancy



Control Hardware Becomes Limiting Factor!

3 Redundant Cells



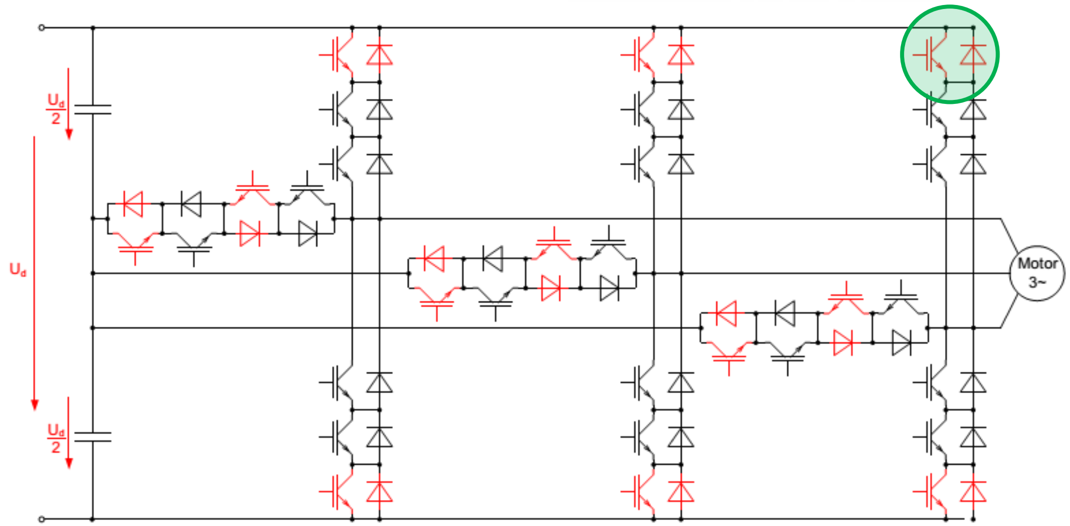
- **But Limited by Other Parts of the Converter System**
  - Control
  - Auxiliary Supplies
  - Communication
  - Bypass Devices
  - ...

[Grinberg2013]

▶ Redundancy In Single-Cell Systems

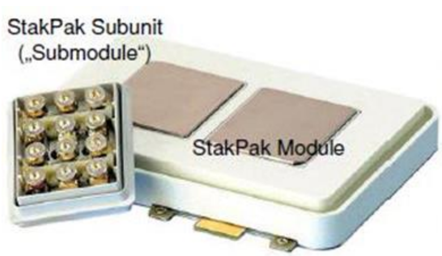
- Example: MV Motor Drive

Redundant Series Devices



Img.: M. Hiller, KIT

▲ Press-Pack NPC Phase Module (Converteam GmbH)



Img: powerguru.org

- **Fail-To-Short Behavior Required!**
- Only Feasible With IGBT Press Pack Modules

[Hiller2016]

Challenge #4/11

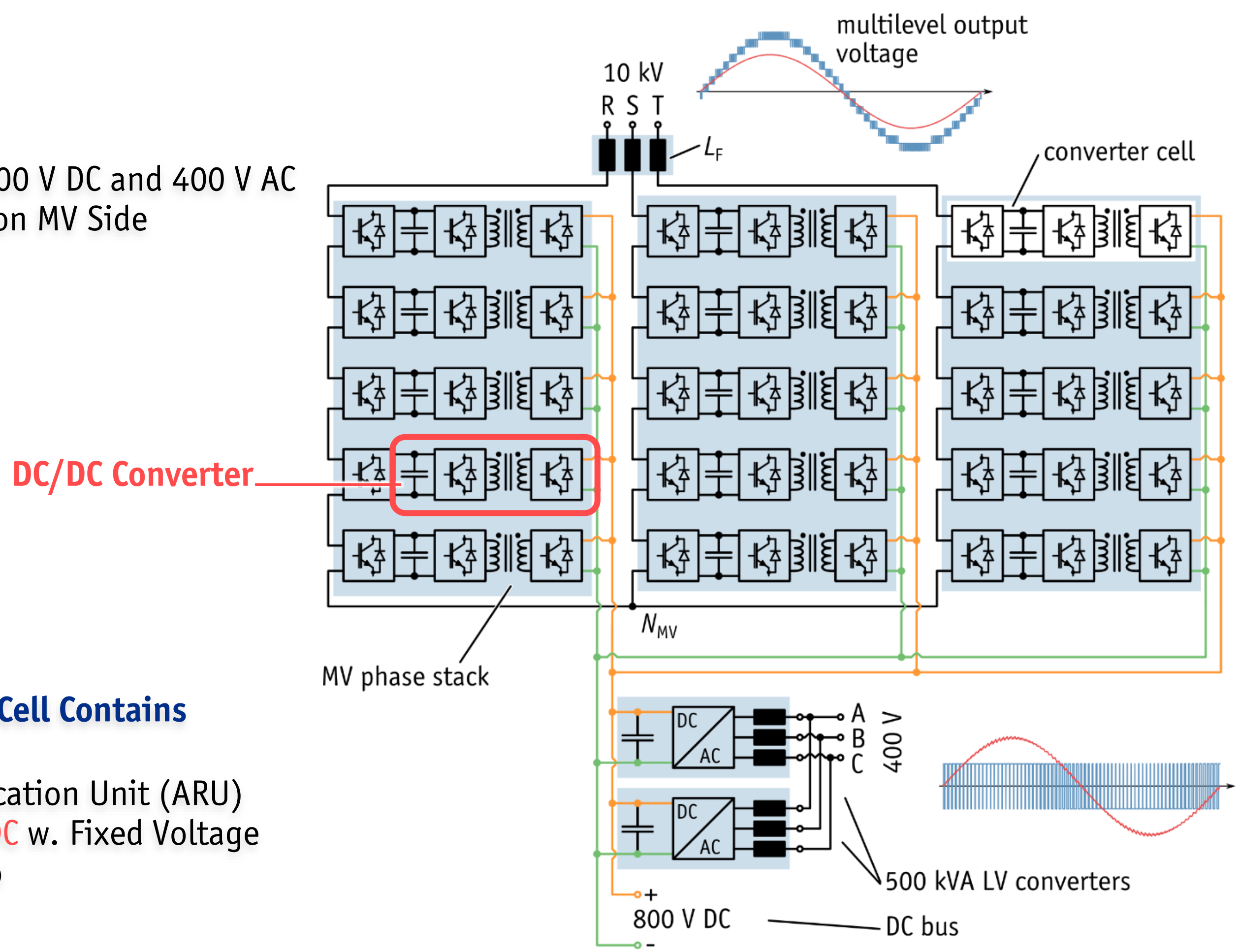
MF Isolated Power Converters

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

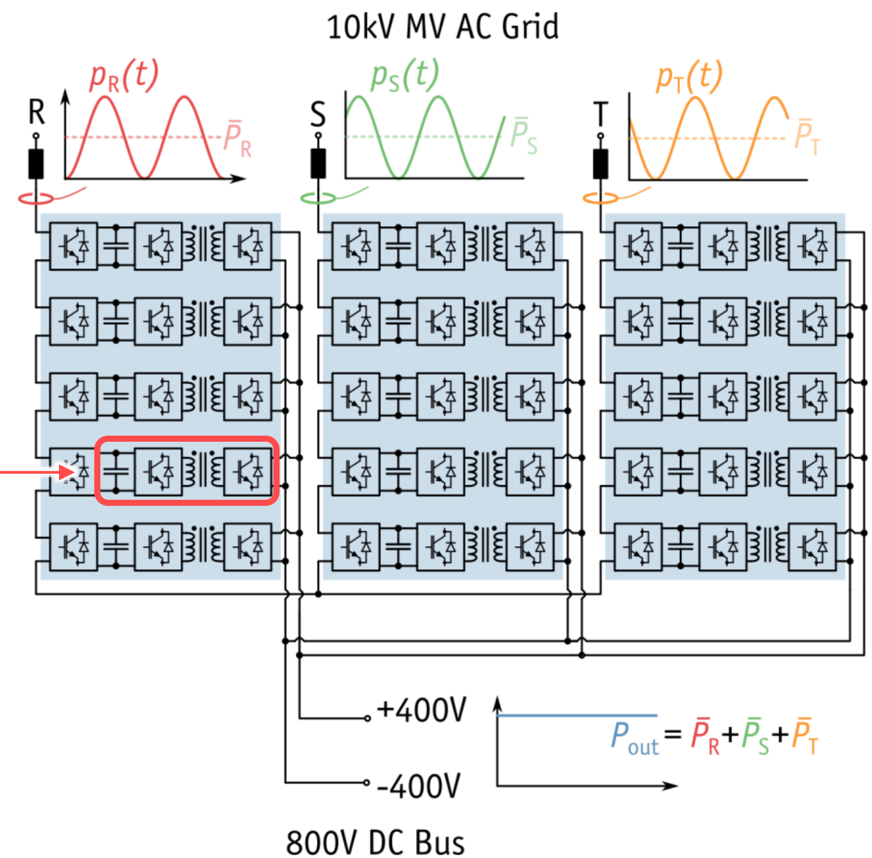


■ Each Converter Cell Contains

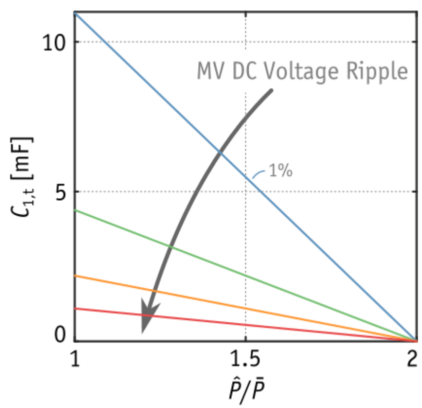
- Active Rectification Unit (ARU)
- Isolated DC/DC w. Fixed Voltage Transfer Ratio

▶ Power Flows in Phase-Modular Solid-State Transformers

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



- **DC/DC Converter Power Flow**
  How To Handle The Single-Phase Power Fluctuation?



Buffering ⟷ Transmission
Capacitor Vol. ⟷ RMS Currents

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

Challenge #4/11

MF Isolated Power Converters

Dual Active Bridge

HC-DCM Series Resonant Converter

United States Patent [19]

DeDoncker et al.

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

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

1991

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

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

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

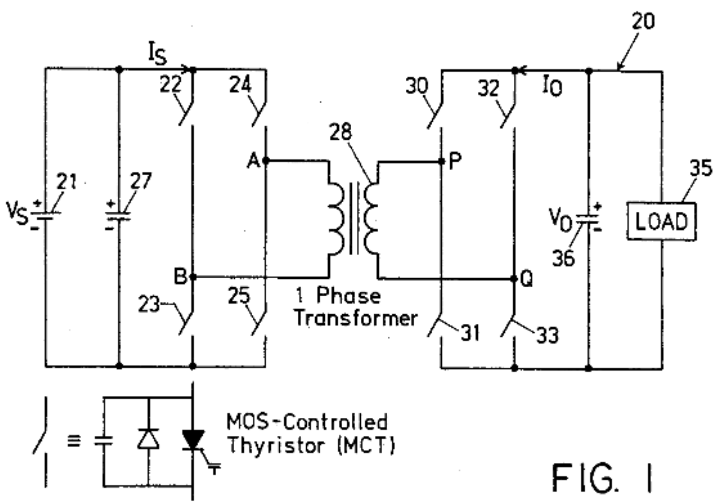


FIG. 1

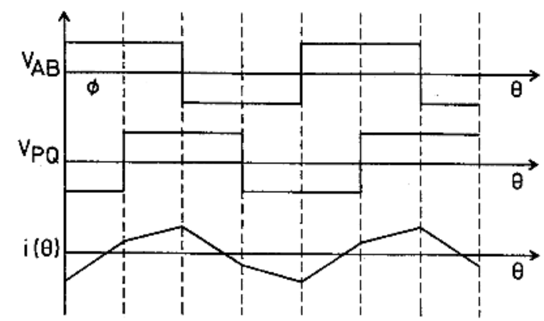


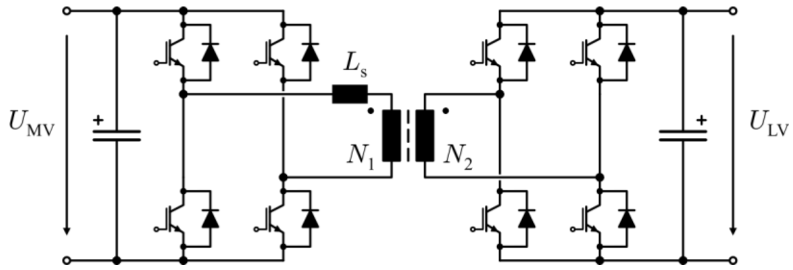
FIG. 2

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

[DeDoncker1989]

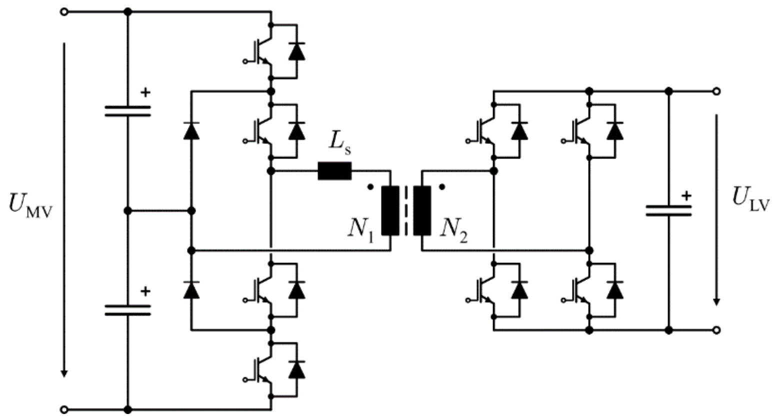
▶ Common Bridge Configurations

■ Full-Bridge



• Three Voltage Levels on Each Side

■ NPC / Full-Bridge Configuration

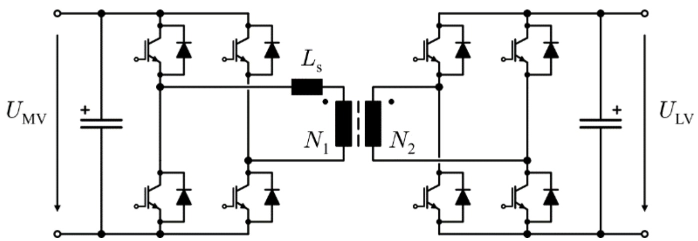


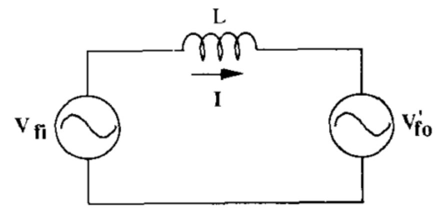
• **Suitable for Higher MV/LV Ratios**

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

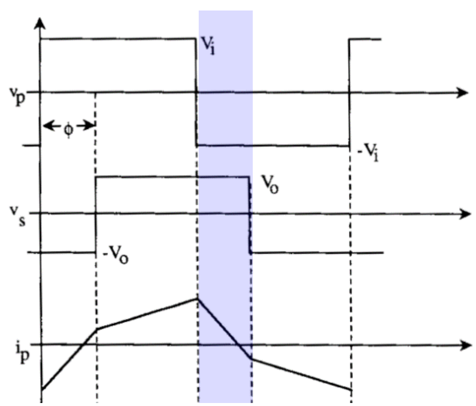
▶ Phase-Shift Modulation (1)

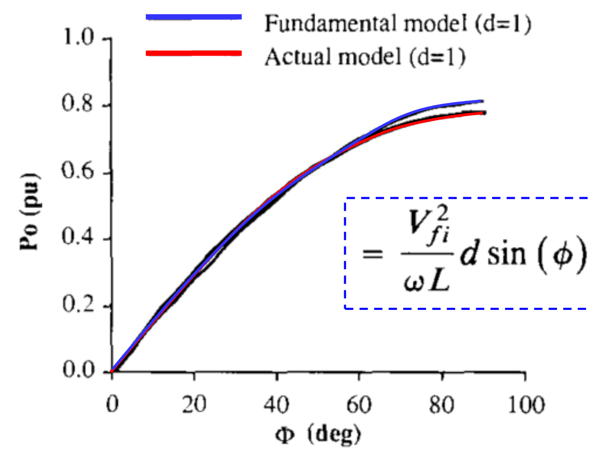
- **Power Transfer Controlled** Through Phase Shift Between MV and LV Bridges





Fundamental model of the dual bridge dc/dc converter.



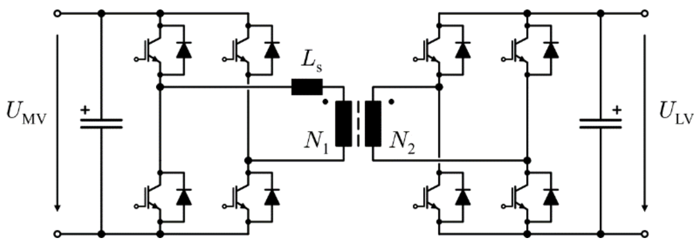


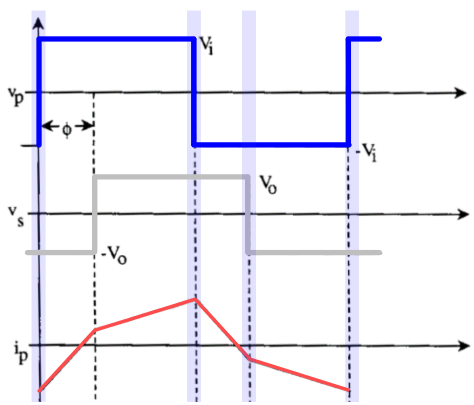
Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

[DeDoncker1989]

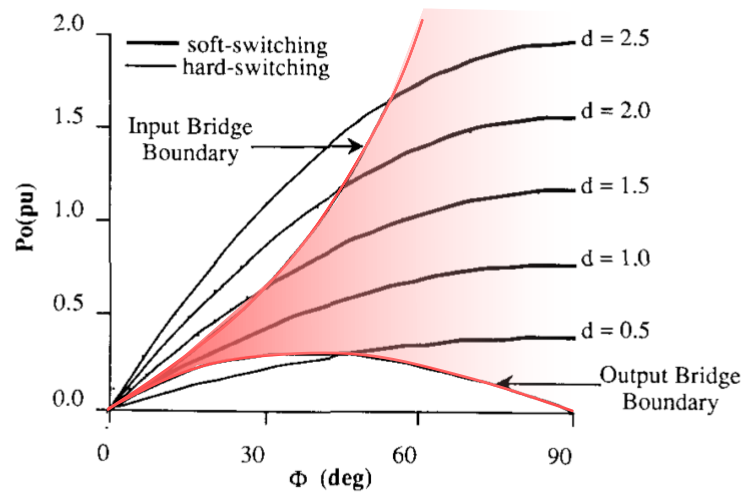
▶ Phase-Shift Modulation (2)

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



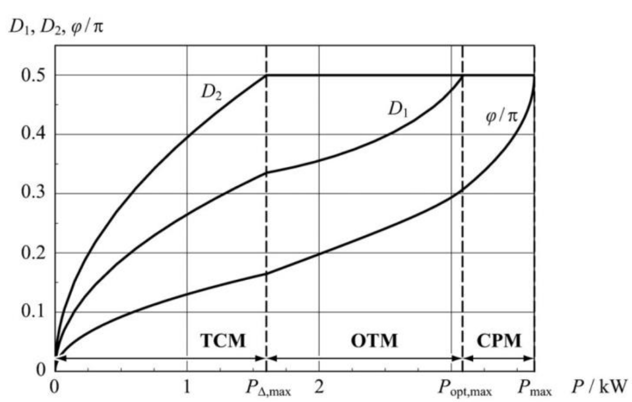


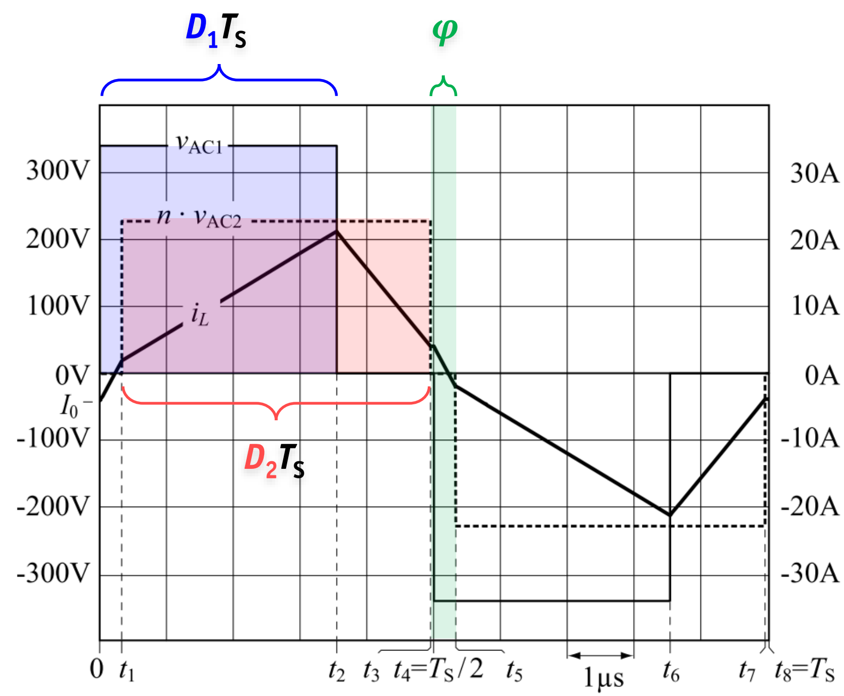
▶ Soft Switching Range



▶ Phase-Shift / Duty Cycle Modulation

- **Additional Degrees of Freedom** Can Be Utilized for Optimization
- For Example: Minimization of the RMS Currents through the Transformer





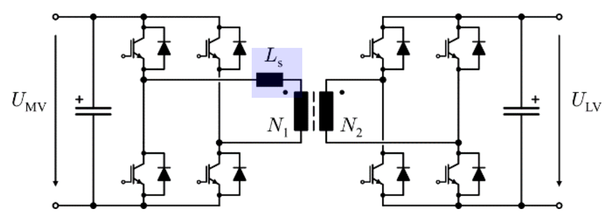
- Not Possible in Half-Bridge Configurations (No Zero Voltage Intervals)

[Krismer2012]

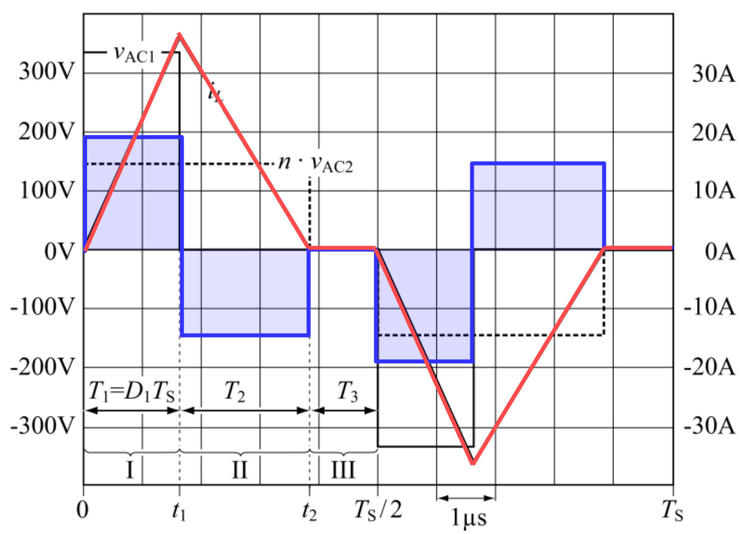
▶ Triangular Current Modulation

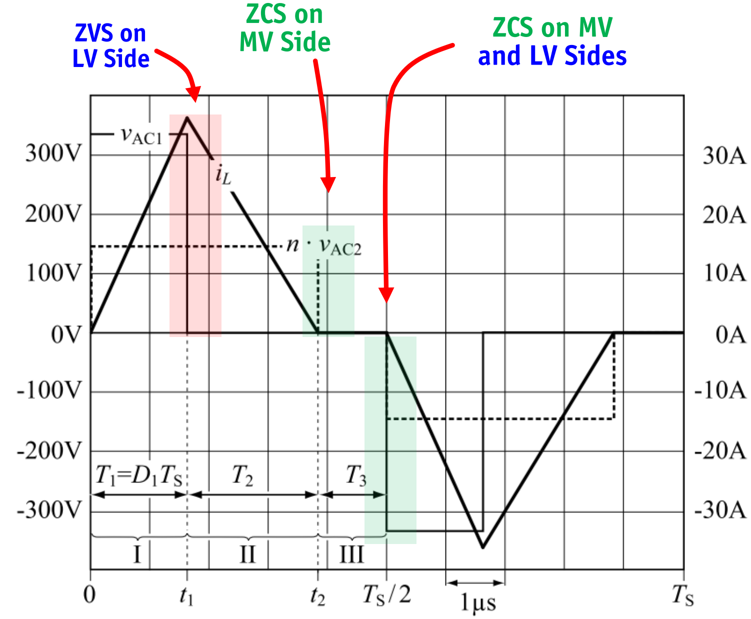
■ Duty Cycles and Phase Shift Utilized to Perform **Zero Current Switching (ZCS)**

▶ HV IGBT Switching Loss Reduction



▶ **ZCS on MV Side (!)**





Challenge #4/11

MF Isolated Power Converters

Dual Active Bridge

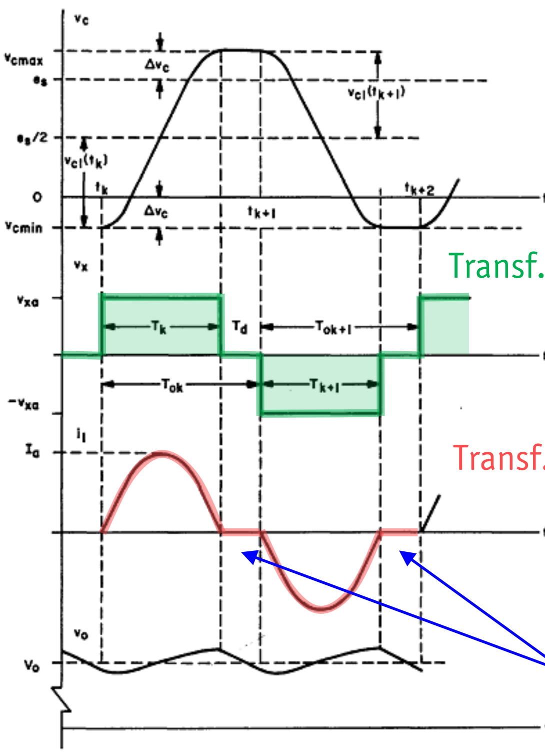
HC-DCM Series Resonant Converter

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



Transf. Voltage

Transf. Current

Discontinuous Conduction Mode (!)

Resonant Tank

Thyristor-based

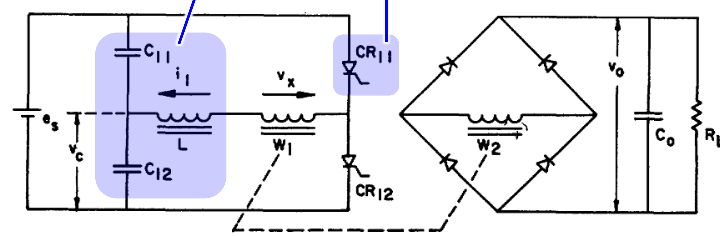
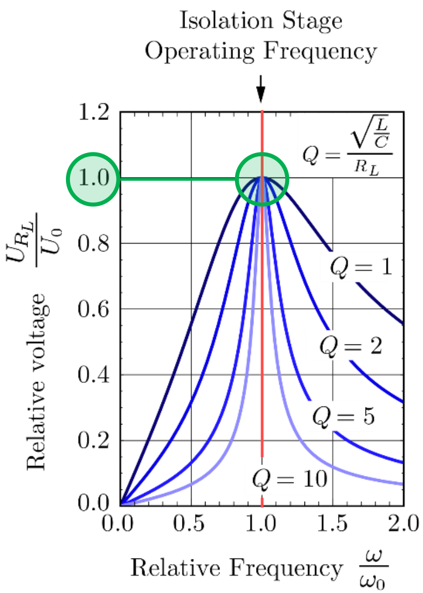


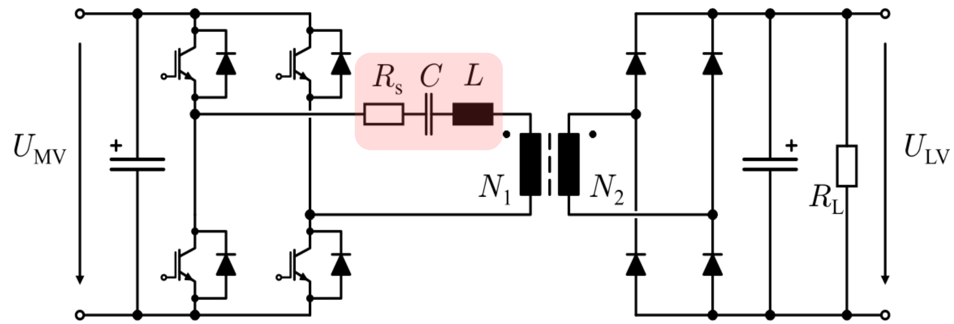
Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

[Schwarz1970]
[McMurray1971]

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

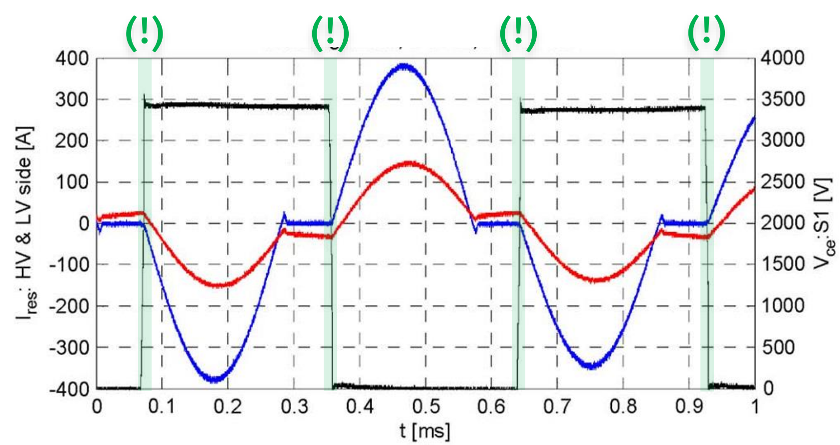
- Operating Principle: **Resonance Frequency ≈ Switching Frequency → Unity Gain**





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

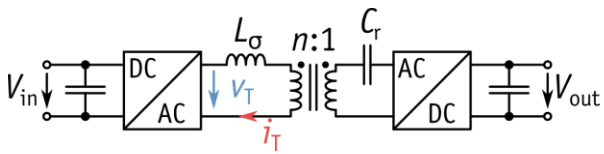
ZCS of All Devices ▶

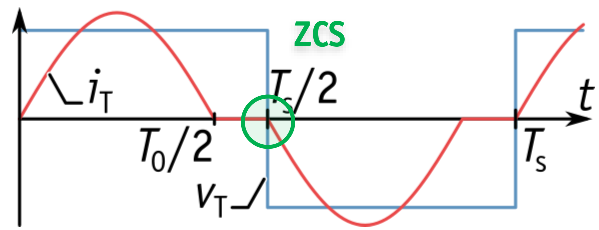


Img.: [Zhao2014]

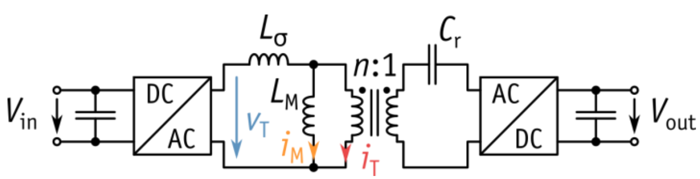
▶ HC-DCM SRC Switching Transitions

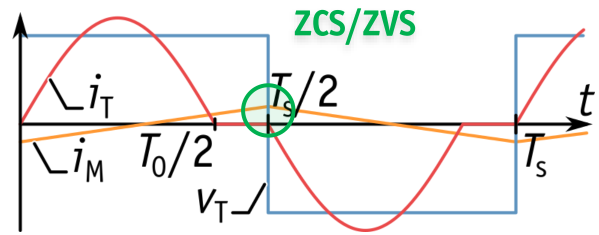
- **Zero Current Switching (ZCS) For All Transitions**

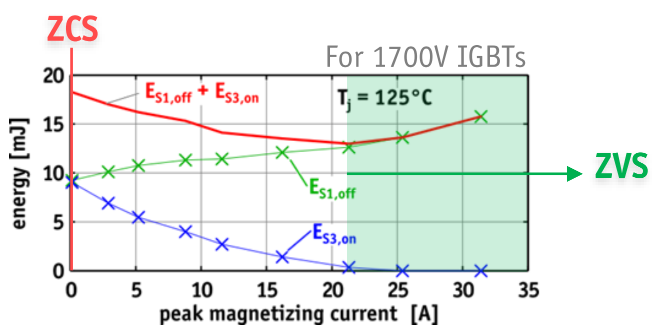




- **Load-Independent Zero Voltage Switching (ZVS)**
  Using The Magnetizing Current



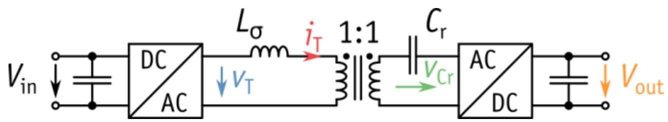




- Loss Optimization With Magnetizing Current and Interlock Time
- Example: 1700V IGBT

Further Reading: ETH / [Huber2013a]
ETH / [Ortiz2013a]

▶ HC-DCM SRC: "DC Transformer" Behavior



- Source Bridge → Actively Switched Only
- Sink Bridge → Passive Operation (Diodes)

■ **Ideal** (Lossless Components) →

→ Steady State: $V_{out} = V_{in}$

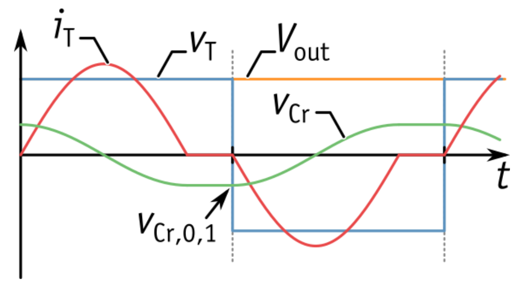
■ **Real**

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

→ **Tight Coupling of DC Input and Output Voltages**

■ Steady State 1

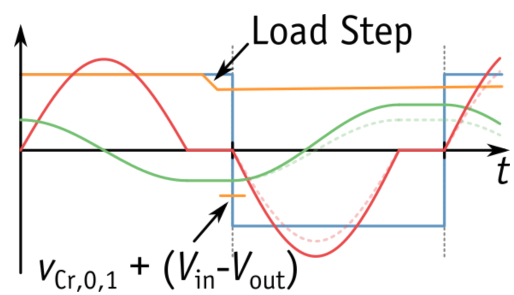
$$\hat{i}_{T,1} = \frac{\hat{v}_{Cr,0,1}}{Z_0}$$
$$V_{out} = V_{in}$$



■ **Disturbance**

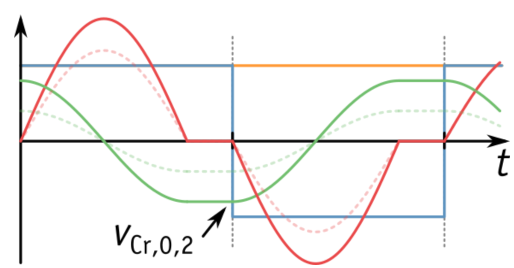
$V_{out} \neq V_{in}$

→ **Add. Excit. Volt.**



■ Steady State 2

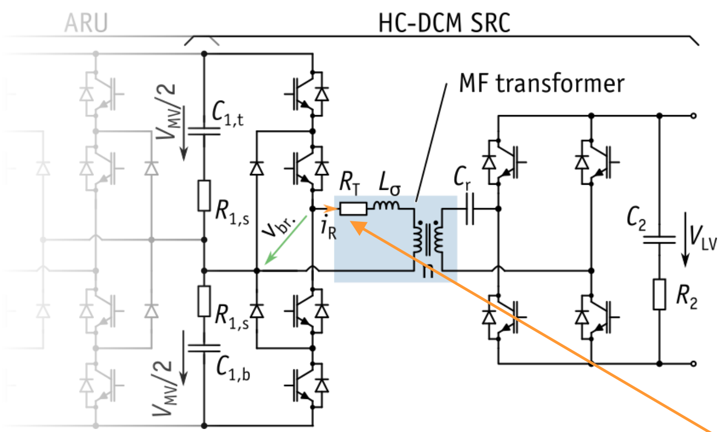
$$\hat{i}_{T,2} = \frac{\hat{v}_{Cr,0,2}}{Z_0}$$
$$V_{out} = V_{in}$$



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

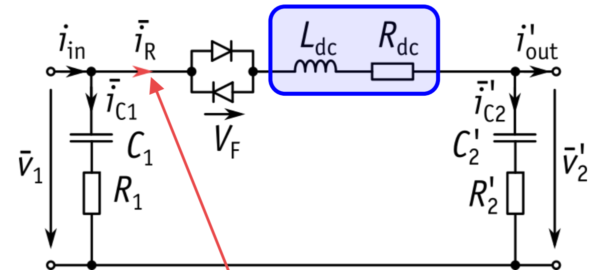
▶ **No Control Possible/Required!**

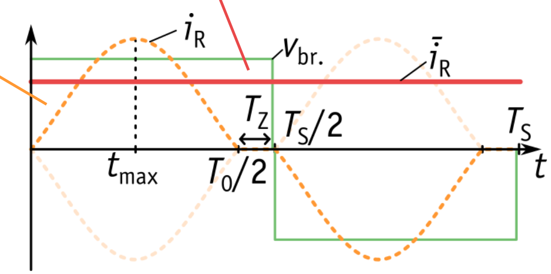
▶ HC-DCM SRC Dynamic Modeling of Terminal Behavior



■ Dynamic Equivalent Circuit

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





■ How to Choose Eq. Circ. Element Values?

- $\boldsymbol{R_{dc}}$ (Equal RMS Losses):

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

- $\boldsymbol{L_{dc}}$ (Equal Stored Energy):

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

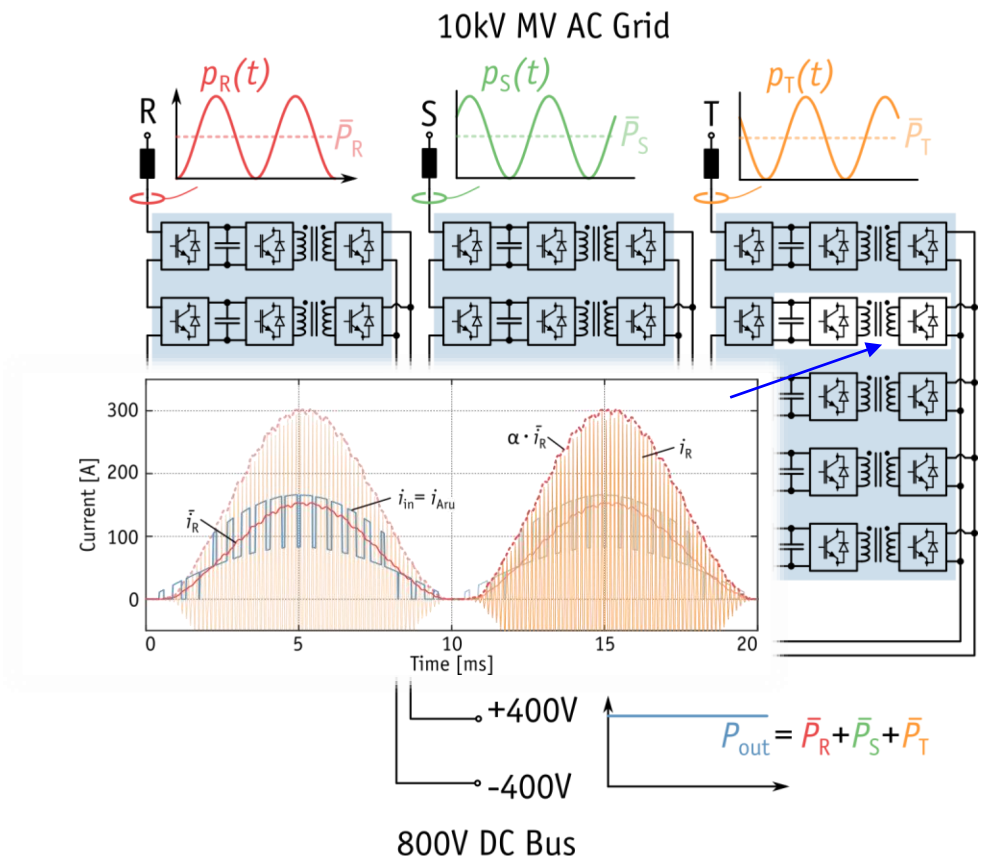
- For Piecewise Sinusoidal Current:

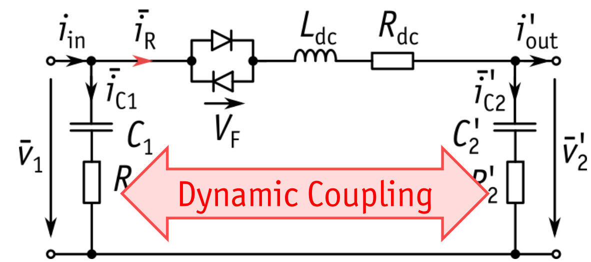
$$\alpha = \frac{\pi}{2} \cdot \frac{f_0}{f_s} \qquad \beta^2 = \frac{\pi^2}{8} \cdot \frac{f_0}{f_s}$$

Further Reading: [Esser1991], [Steiner2000], 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

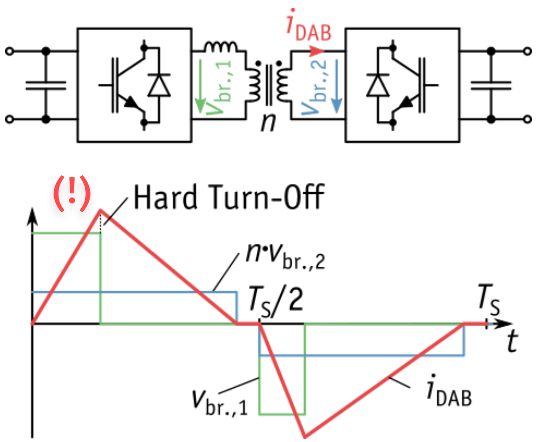
→ **Transmission of Full Single-Phase Power Fluctuation!**
  - Higher RMS Current (23%) in Transformer and DC-DC Switches
  - Appropriate Dimensioning

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

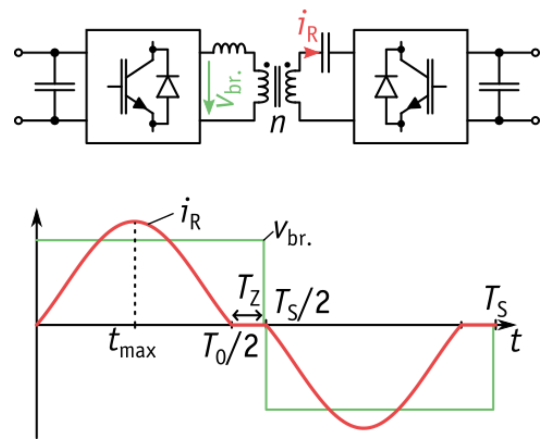
Further Reading: ETH / [Huber2015]

▶ Realization Options for DC/DC Converters in SST Cells

■ **Dual Active Bridge (DAB)**



■ **Half-Cycle Discont.-Conduction-Mode SRC (HC-DCM SRC)**



■ **Can (Must!) Be Fully Controlled**

- Arbitrary Choice in Losses ↔ Capacitor Volume Trade-Off
- Potentially Lower RMS Currents

■ **Does Not Have To (Can Not!) Be Controlled (!)**

- Reduces Complexity in Multi-Cell Systems
- Ensures MV Side Voltage Balancing

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

Challenge #5/11

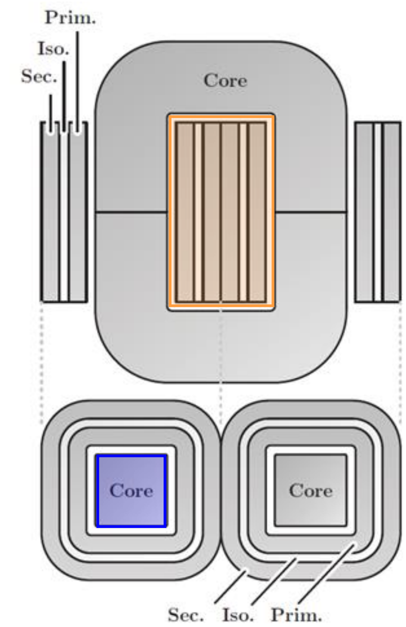
MF Transformer Design

Transformer Types
Litz Wire Issues

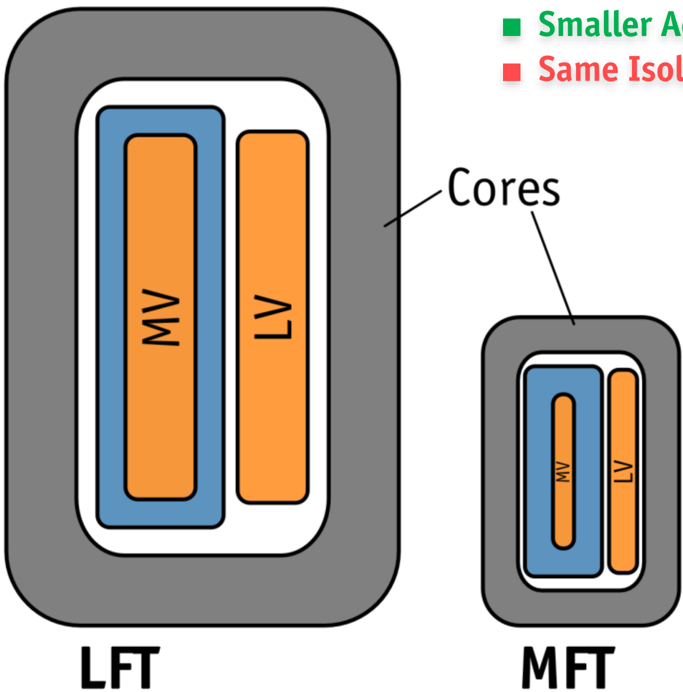
General Challenge of MF Transformers

- Higher Operating Frequency
- Lower Unit Power Rating

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



- Smaller Active Volume
- Same Isolation Voltage (!)



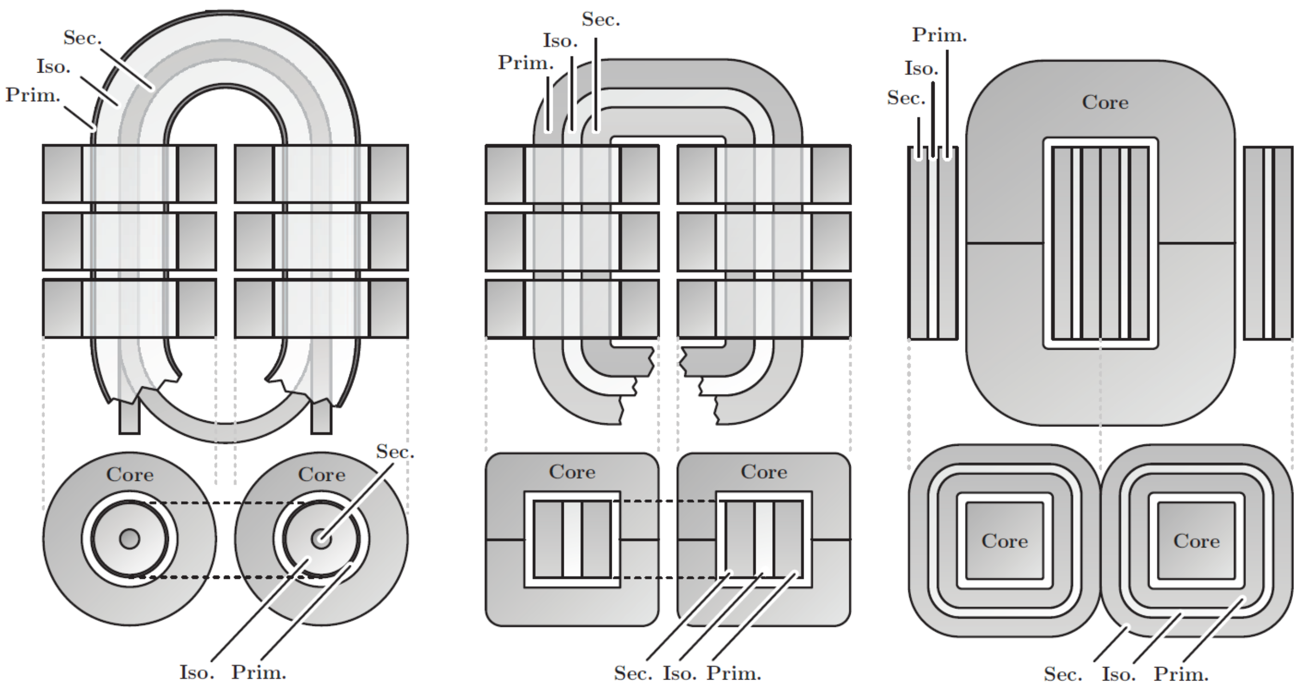
MV Winding Cooling Through Isolators

- 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**

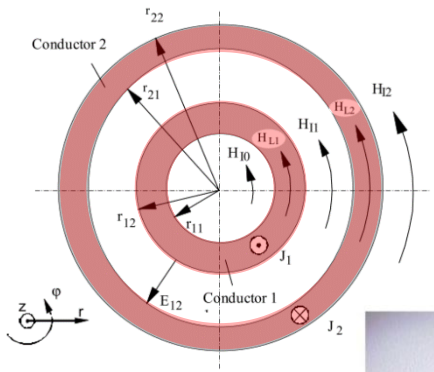
- Transformer Construction Types Very Limited by Available Core Shapes in this Dimension Range
- Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components

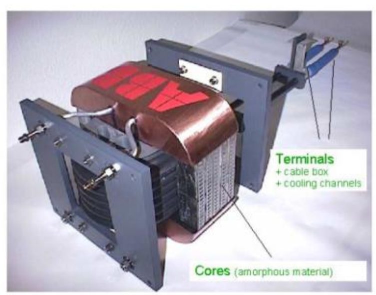
▶ MF Transformer Examples (1)

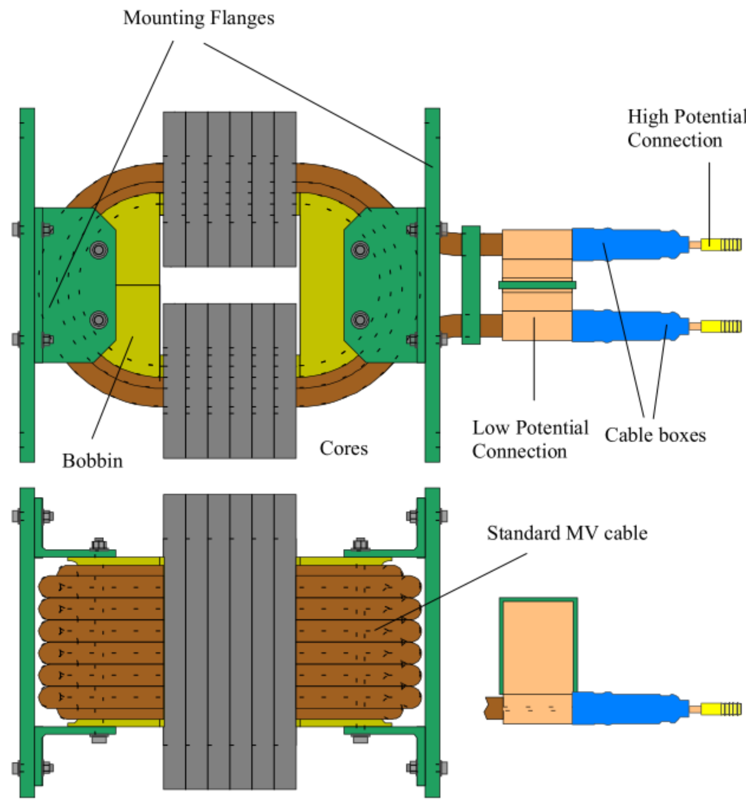
■ Coaxial Cable Winding

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

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





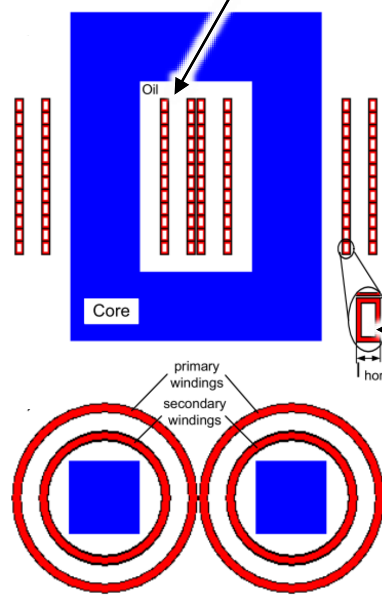


- Heinemann (ABB, 2002)
  [Heinemann2002]

▶ MF Transformer Examples (2)

■ Coaxial Windings – Core Type

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

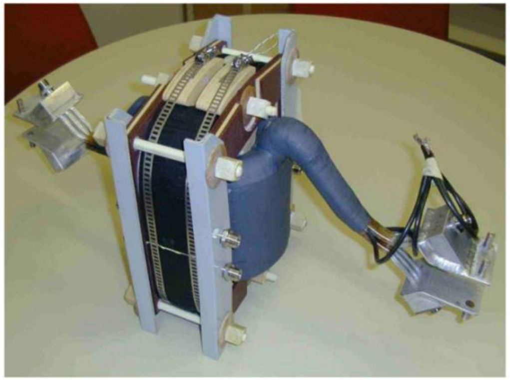


- Hoffmann (2011)
  [Hoffmann2011]

▶ MF Transformer Examples (3)

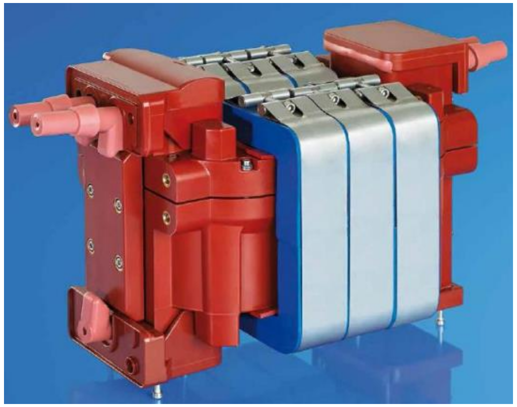
■ Coaxial Windings – Shell Type

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



- 8kHz, 350kW
- Water Cooling (Hollow Conductors)
- Isolation for 33kV

- Steiner (2007)
  [Steiner2007]



- 8kHz, 450kW, 50kg
- Efficiency: 99.7%
- Dry-Type / Liquid Isol. (34.5kV)

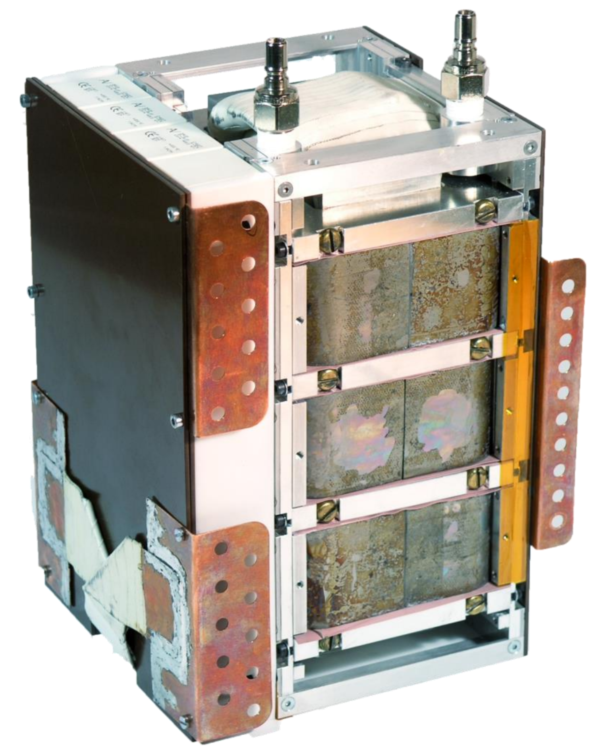
- STS (2014)
  www.sts-trafo.com

▶ ETH *MEGACube:* Water-Cooled Nanocrystalline Core Transformer

■ Power Rating	166	kW
■ Losses	0.88	kW
■ Efficiency	99.5	% (Meas.)
■ **Power Density**	**32.7**	**kW/dm^3**

- ETH / Ortiz, Leibl (2013)

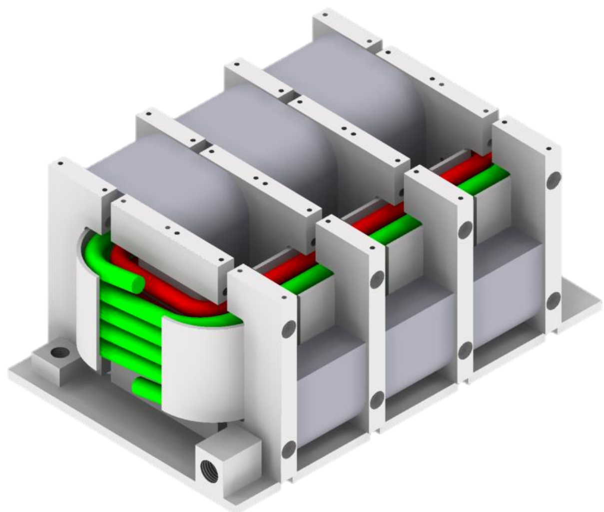
166kW / 20kHz Water-Cooled
Nanocrystalline Core Transformer ▶

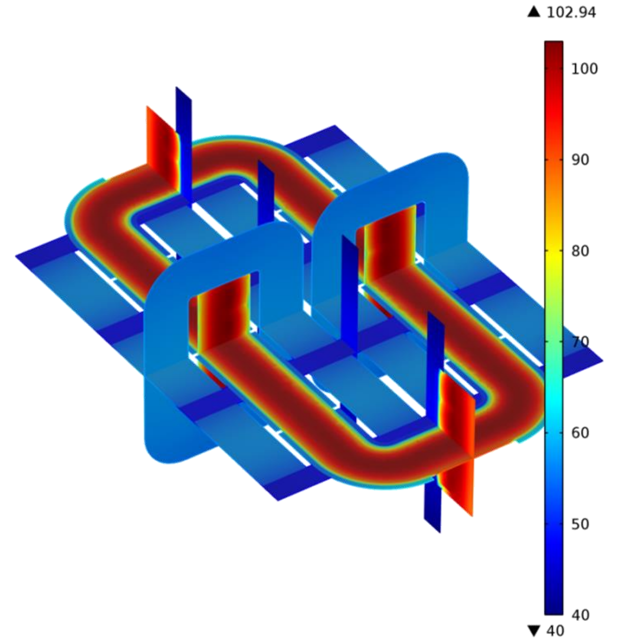


ETH / [Ortiz2013b]

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

- Nanocrystalline 166kW/20kHz Transformer



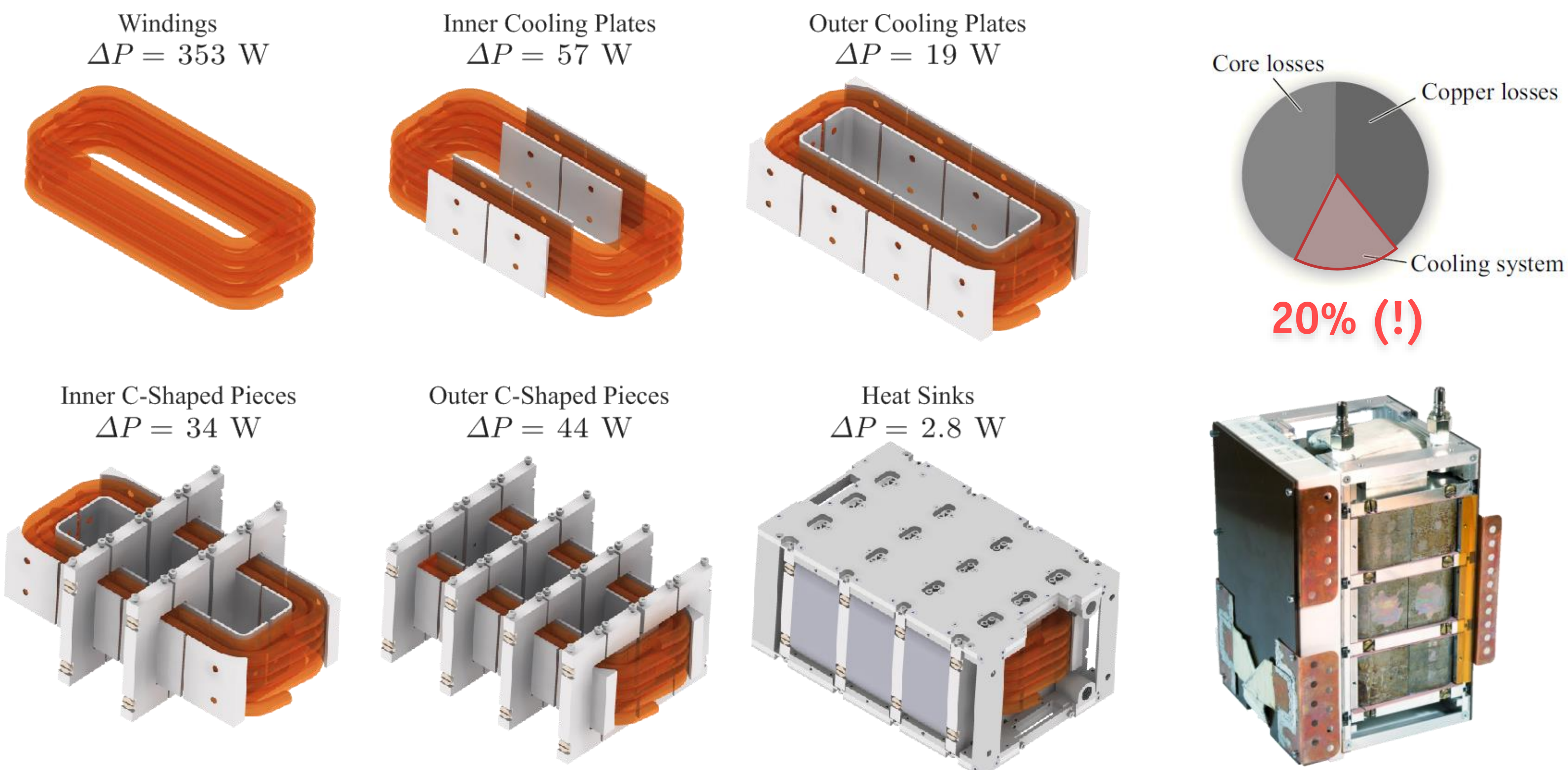


- Combination of **Heat Conducting Plates** and Top/Bottom **Water-Cooled Cold Plates**
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

ETH / [Ortiz2013b]

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

- Nanocrystalline 166kW/20kHz Transformer



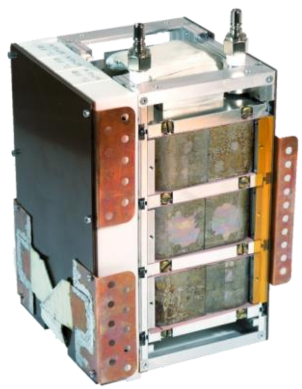
- Losses Generated in Internal Cooling System Amount to ca. 20% of Total Transformer Losses

ETH / [Ortiz2013b]

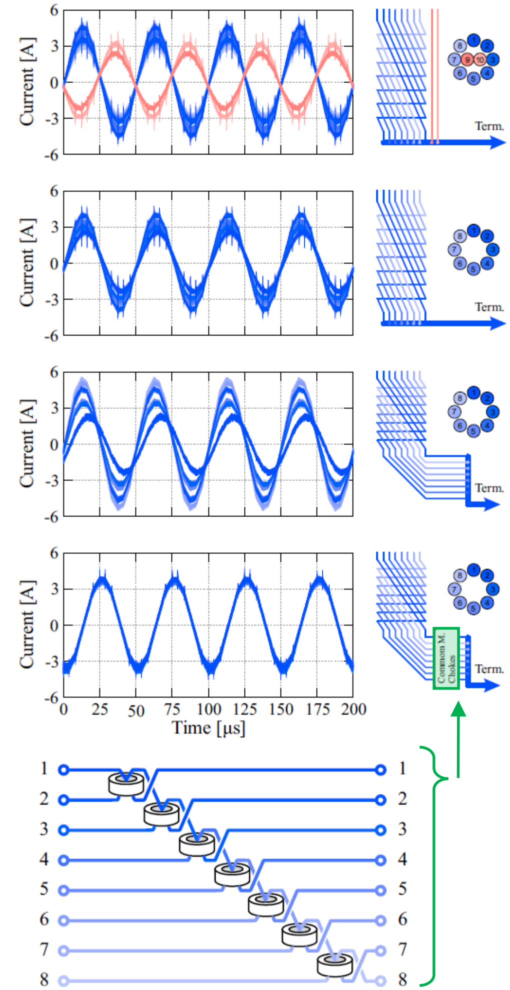
▶ Anecdote: Litz Wire Issues

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

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



- Common-Mode Chokes for Forcing Equal Current Sharing



(!)
-20% Losses

ETH / [Ortiz2013b]

Coffee

Break

Challenge #6/11

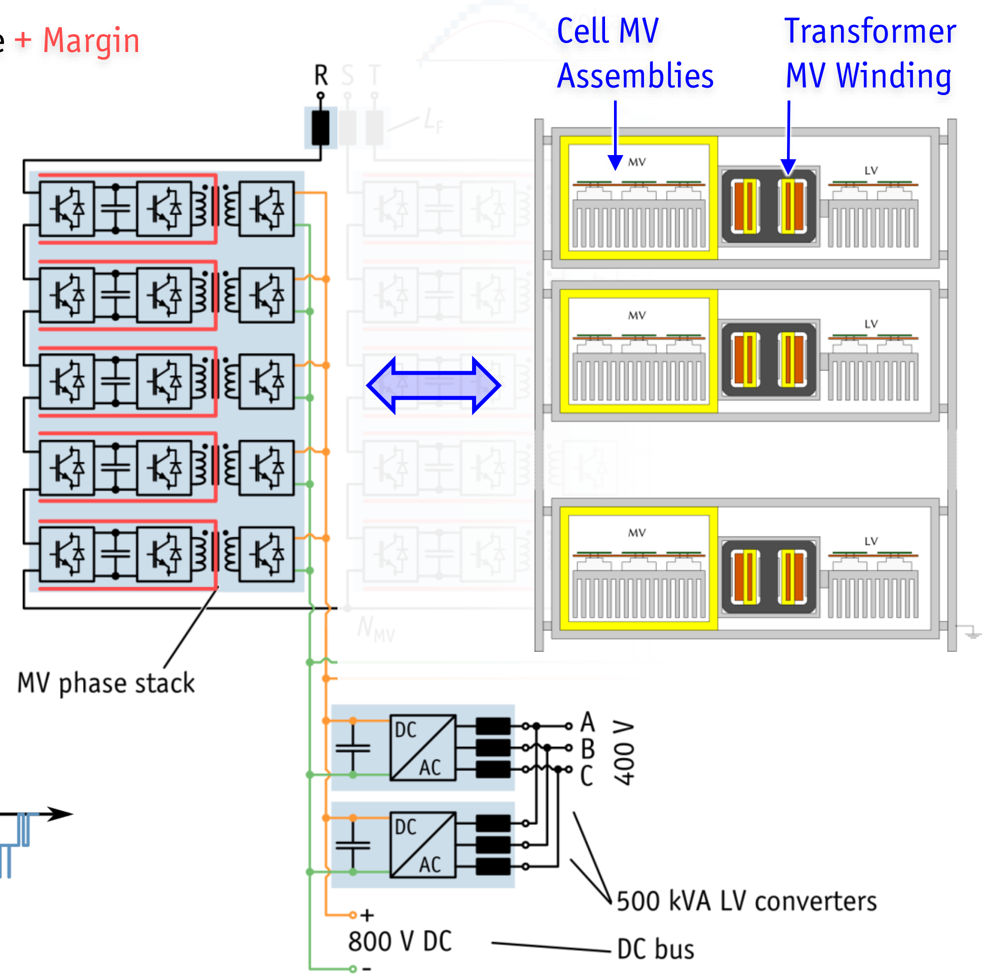
Isolation Coordination

Isolation Barrier Positioning
Mixed-Frequency Stress

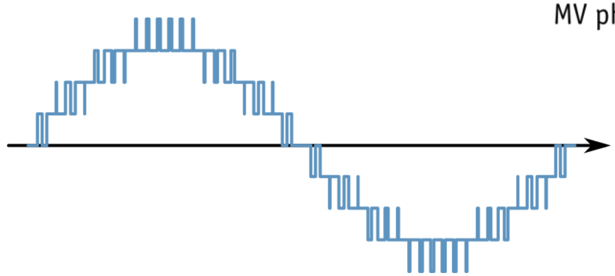
▶ Isolation Barriers In A Multi-Cell SST

- Cascaded Cells Are On **Floating Potentials**
  - Isolation Voltage = Grid Voltage + Margin
    → I.e., Many kV!

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

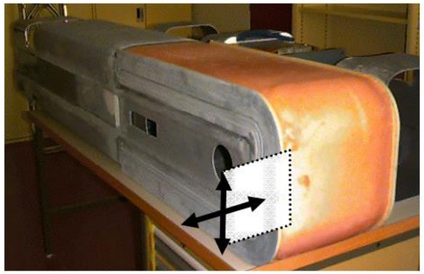


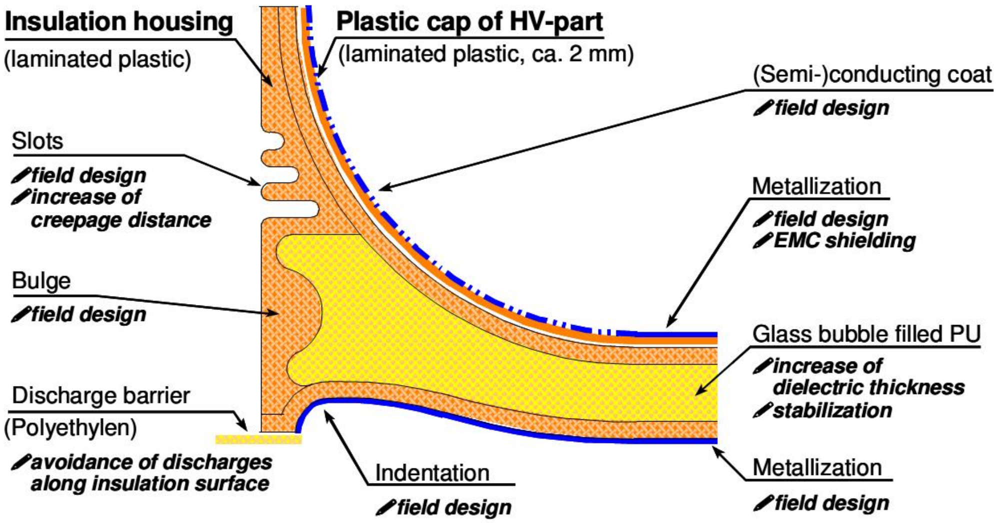
▼ Typical Isolation Voltage (Qualitative)



▶ Example: Isolation Coordination 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 #6/11

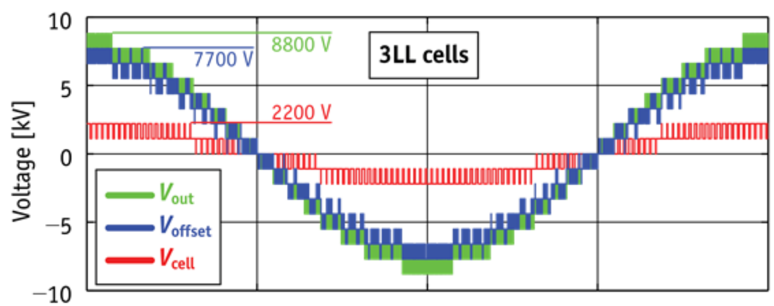
Isolation Coordination

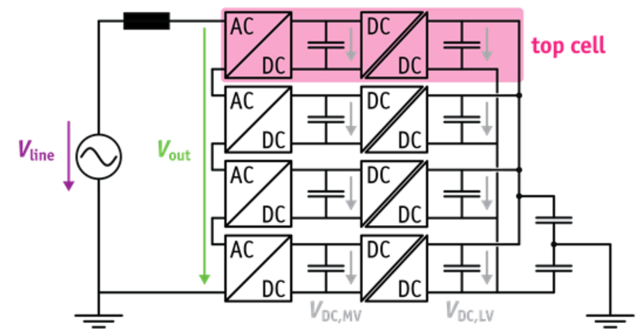
Isolation Barrier Positioning

Mixed-Frequency Stress

▶ Mixed-Frequency Electrical Field Stress

- **Combined Electrical Field Stress**
  - Large DC or Low-Frequency Component
  - Smaller Medium-Frequency Component

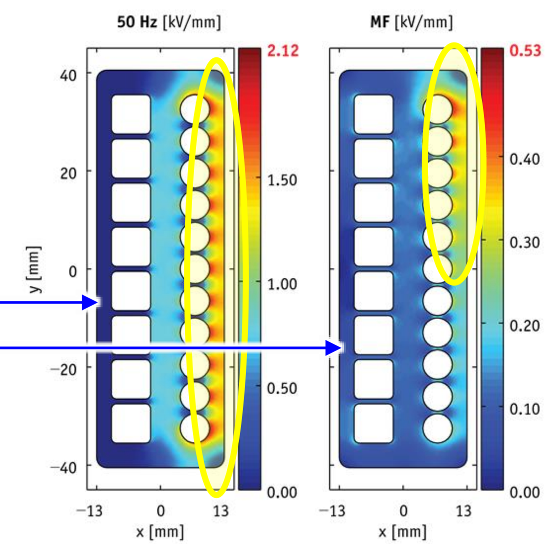




- Known From Machine Isolation Systems
- Physical Breakdown & Ageing Mechanisms Are **Unclear**

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

→ Degree of Freedom To Optimize Isolation System!



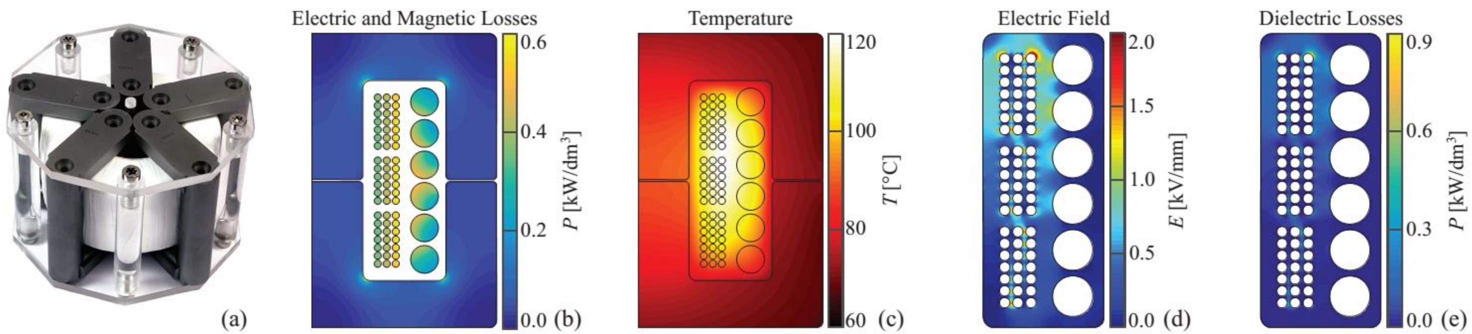
Further Reading: ETH / [Guillod2014]

▶ Mixed-Frequency Electrical Field Stress: Dielectric Losses

- Dielectric Losses Depend on the Frequency $P(\vec{x}) \propto f \cdot E(\vec{x})^2$

  Danger of Local Hotspots

- Example: HV-SiC DC/DC Converter:
  - 25kW
  - 8kV
  - 50kHz ← (!)



- **Dielectric Losses In Epoxy Isolation: 16% of Total Transformer Losses**
  → **Reduced Efficiency**
  → **Increased Hot-Spot Temperature**
  → Accelerated Aging (?)

- Careful Choice of Isolation Material is Essential (Field Strength/Thermal Cond./Dielectric Losses)

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

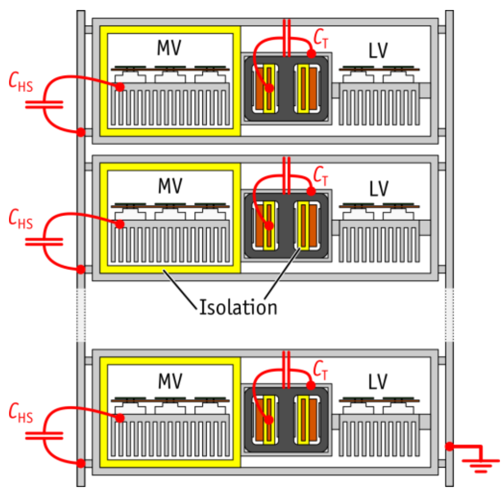
Challenge #7 /11

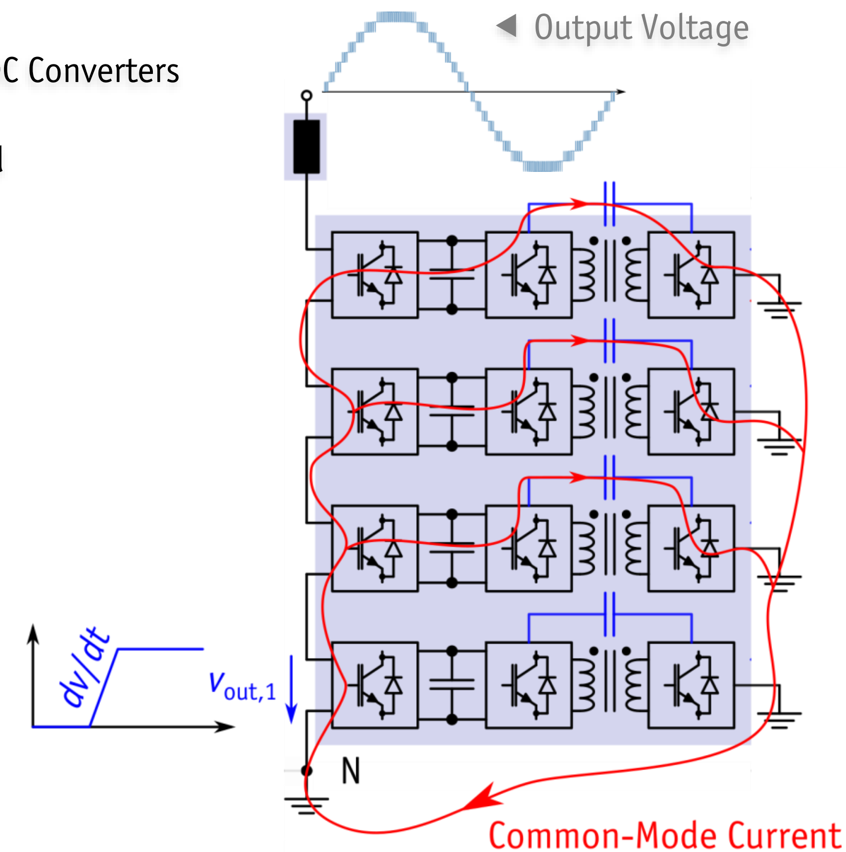
EMI

Common-Mode Ground Currents
EMI Limits

▶ CM Ground Currents: Basic Problem Description

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

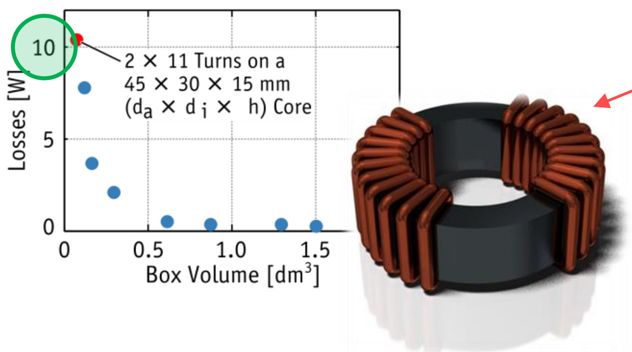


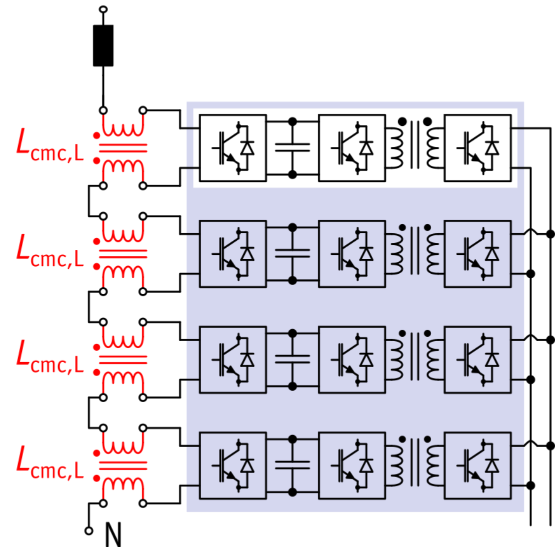


- **Switching Action in One Cell Moves All Cells At Higher Stack Positions In Potential**
- Charging Currents: $i = C\, dv/dt$
- **CM Oscillations** With Parasitic Inductances!

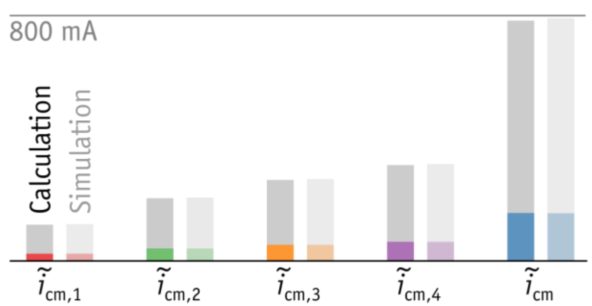
▶ CM Ground Currents: Countermeasure

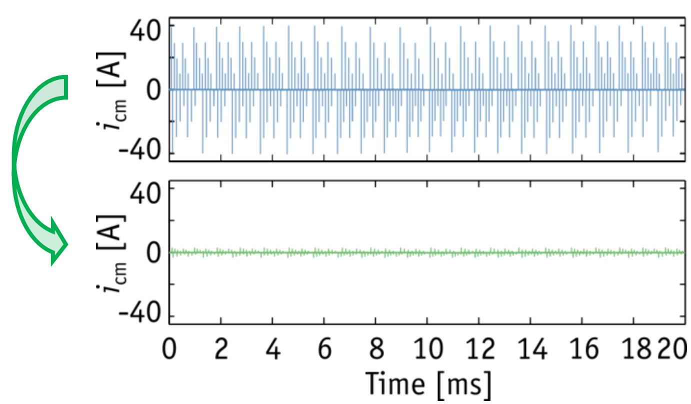
- Placing **Common-Mode Chokes At Cells' AC Inputs**
  - Low Effort (Losses, Volume)





- Simulations With/Without CM Chockes





- Outlook: Higher *dv/dt* With **SiC!?**

Further Reading: ETH / [Huber2014a]

Challenge #7/11

EMI

Common-Mode Ground Currents

EMI Limits

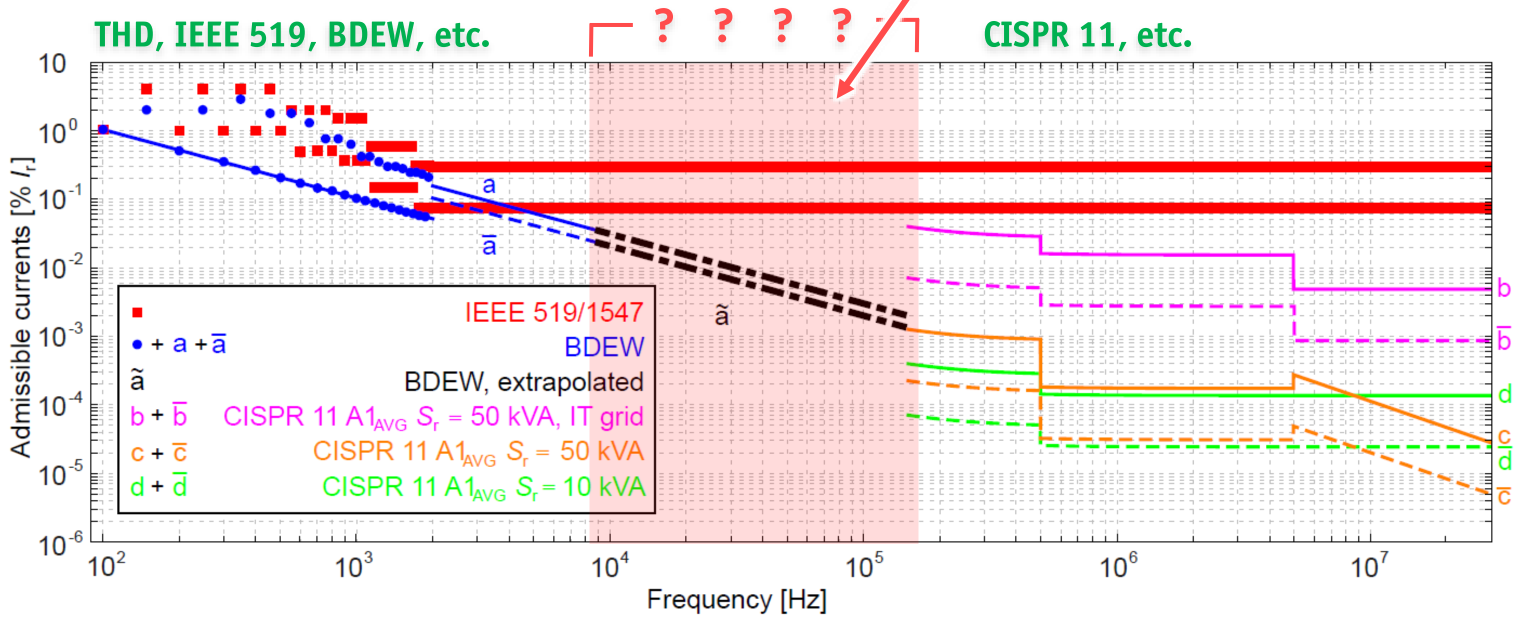
▶ Grid Harmonics and EMI Standards

- Medium Voltage Grid Considered Standards
  - IEEE 519/1547
  - BDEW
  - CISPR (?)

- Limits for CM Ground Currents?
- Limits for HF Noise?

Unclear Limits!

- Requirements on Switching Frequency and EMI Filtering



ETH / [Burkart2012]

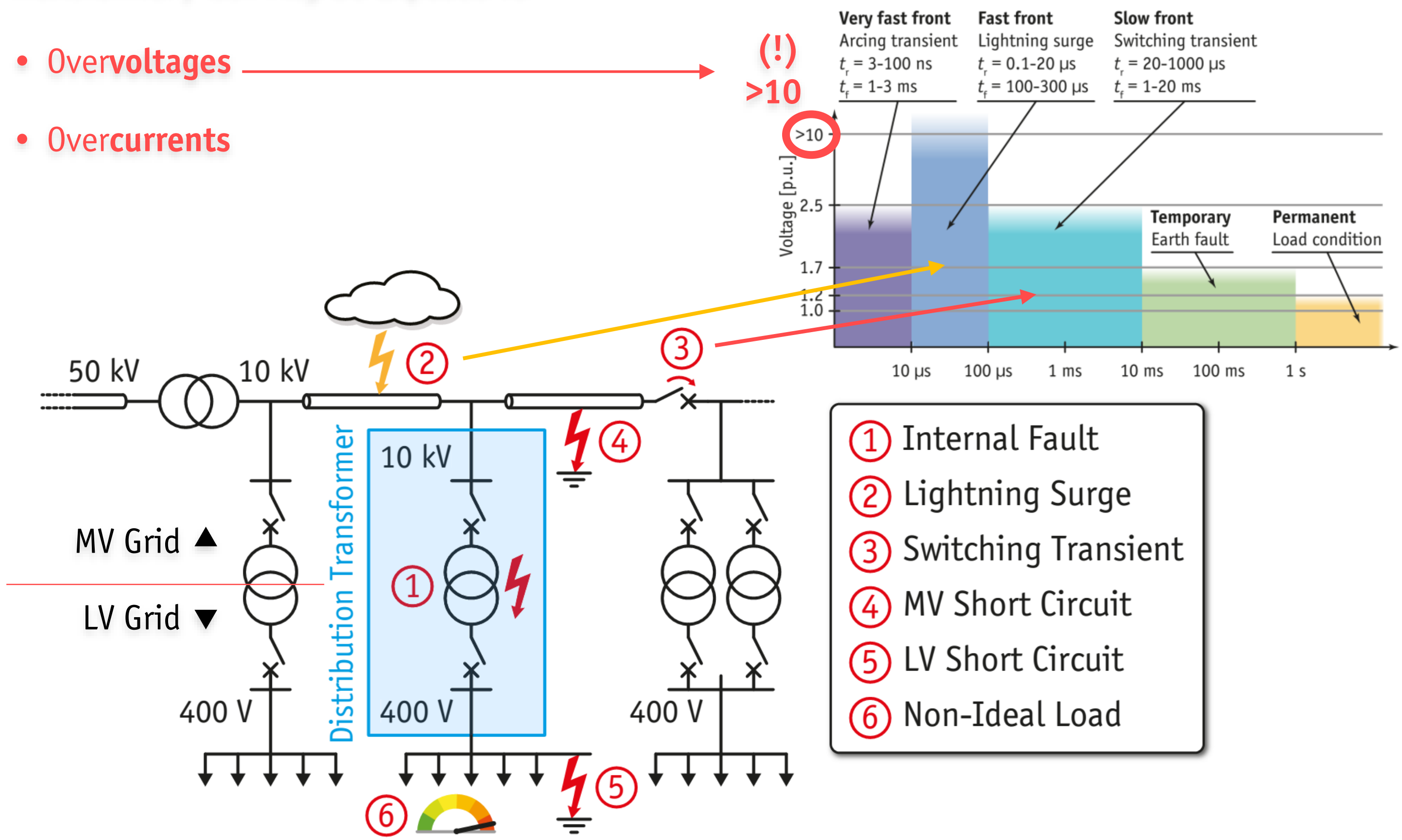
Challenge #8/11

Protection

Protection of the SST

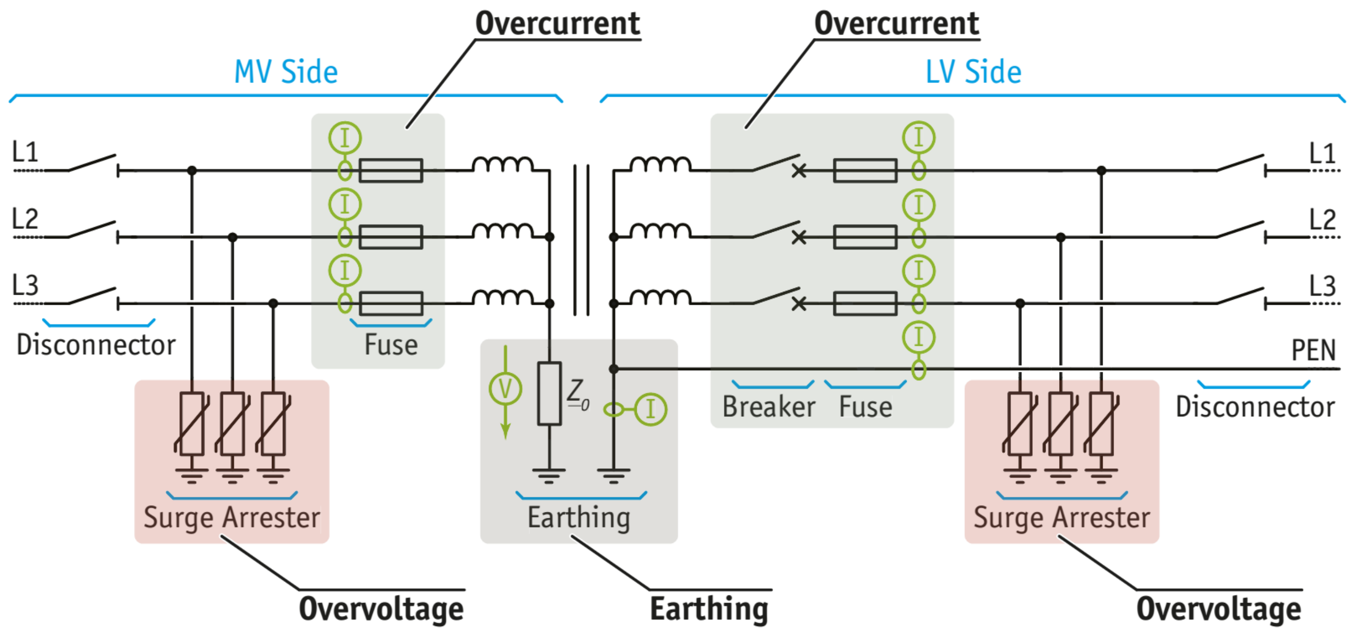
▶ Possible Fault Situations

- Transformer / SST May Be Exposed To
  - Overvoltages
  - Overcurrents



ETH / [Guillod2015]

▶ Typical LFT Protection Scheme



▶ Trade-Off Betw. Over-voltages and Overcurrents

Img.: ABB

◀ Surge Arresters

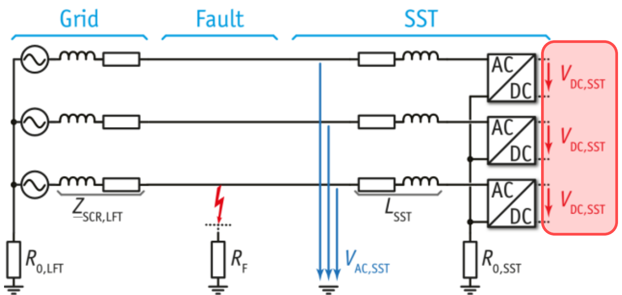
LV and MV Fuses ▶

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

ETH / [Guillod2015]

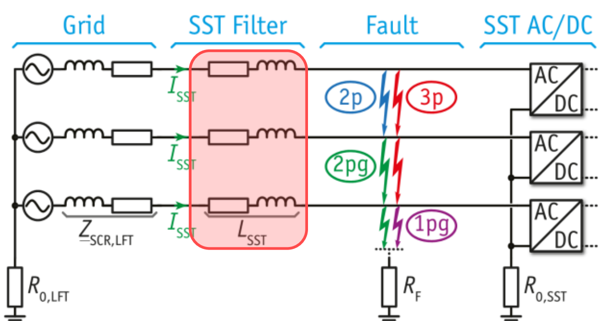
▶ MV Side SST Protection (1)

■ Grid Short Circuit



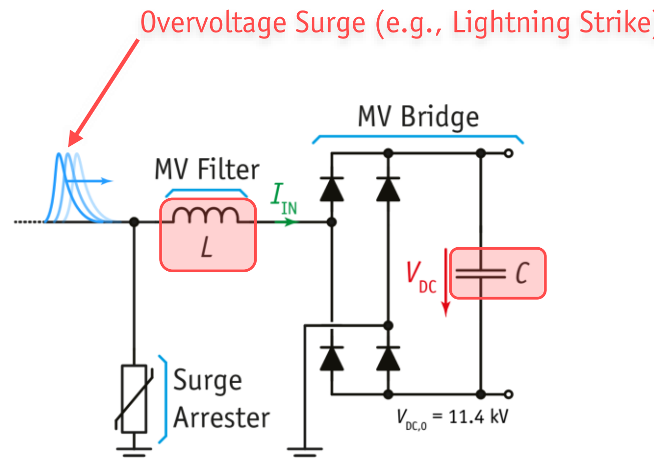
- Phase-To-Phase Voltage (!) Must Be Blocked → DC Capacitor Volt. Ratings!

■ SST Short circuit



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

■ Overvoltage Protection



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

- Current Limiting → Filter Inductor > 8%
- Energy Absorption in DC Link Capacitors
  → DC Capacitance Requirement

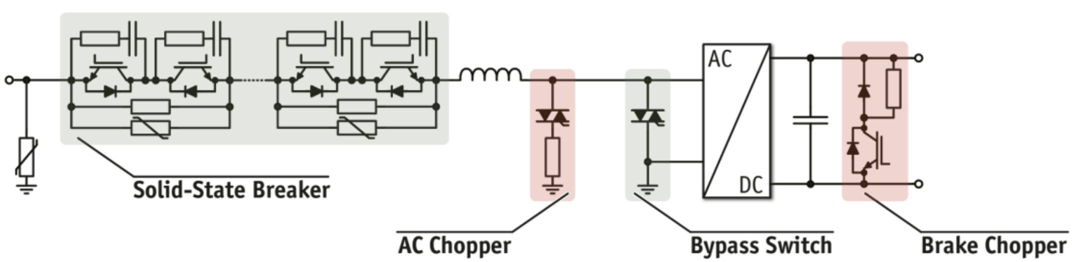
Further Reading: ETH / [Guillod2015]

▶ MV Side SST Protection (2)

- **Protection Considerations Affect SST Design & Limit Performance**

- Example: **Boost/Filter Inductor** → Low Frequency Magnetic Component (!)
  - **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"**
  - Limits Control Bandwidth (e.g., Act. Filtering, etc.)
  - Volume Reductions Due to Higher Switching Frequencies Might be Limited By Protection Considerations

- **Outlook: Advanced Protection Concepts**
  - E. g., Solid-State Protection



- Reliability?
- Cost?
- Losses?

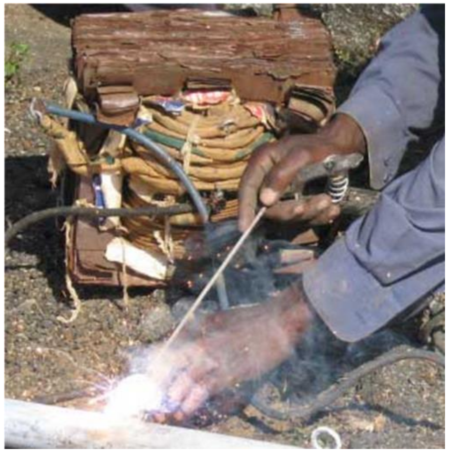
Further Reading: ETH / [Guillod2015]

Challenge #9/11

Control

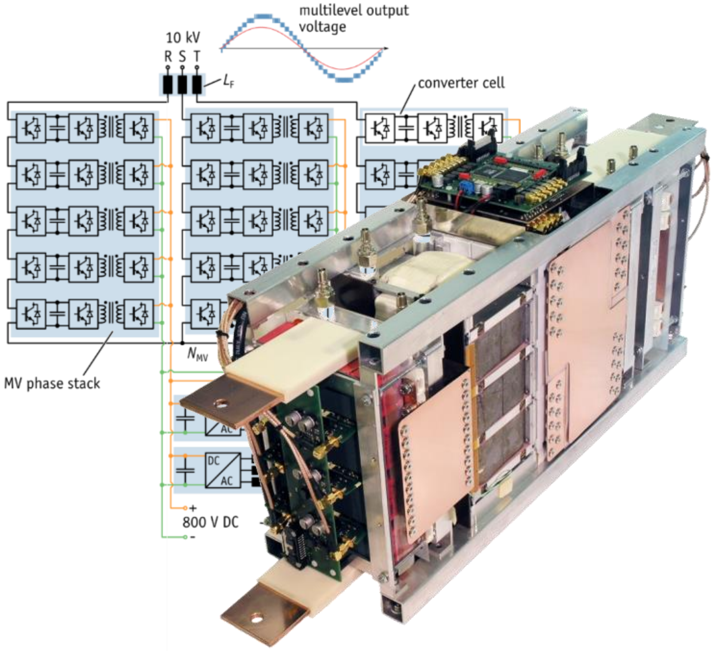
It's Not Just Passives!

▶ A SST is Not Just Passives!



Source: http://www.africancrisis.org

VS.



■ **High Complexity** of SST Control System Compared to Passive Low Frequency Transformers

▶ SST Control System Partitioning

- Very Different Timing Requirements
  - IGBT Protection: us
  - Grid Transients: ms to s
- Feasible Approach: Several Hierarchical Layers
- **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, $400V_{AC} \leftrightarrow 800V_{DC} \leftrightarrow 400V_{AC}$

▶ Example of SST Control System Partitioning

MV - Volt. - Cur.

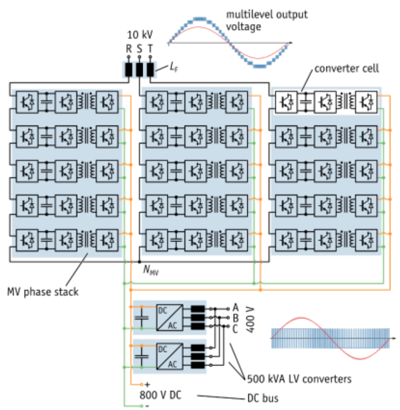
- Volt. - Cur. LV

Battery Management

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

SCADA Interface

Smart Grid Integration



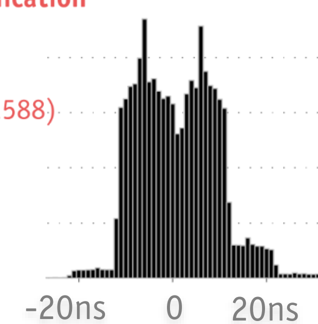
Cascaded MV Inverter
- Time Sync.
- Current Ctrl. & Ref. Gen.
- Redundancy Mgmt.

LV Inverter (FPGA)

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

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

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



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

Challenge #10/11

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

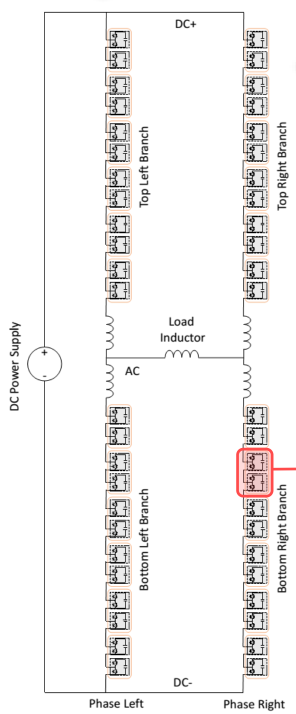
Integration Technologies for a Fully Modular and Hot-Swappable MV Multi-Level Concept Converter

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.

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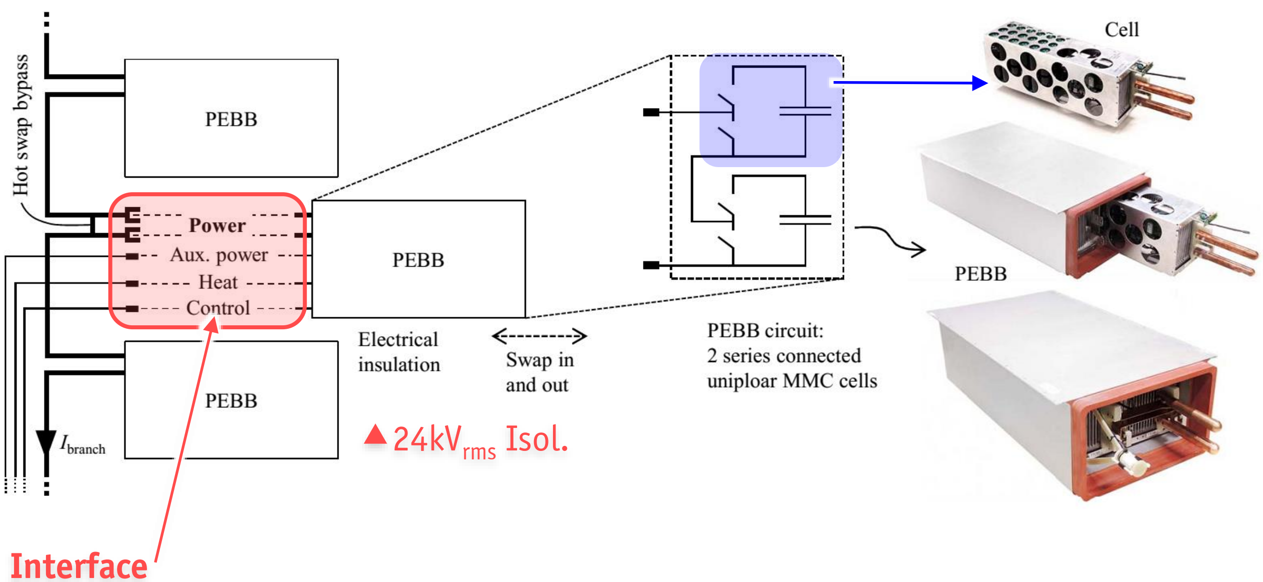
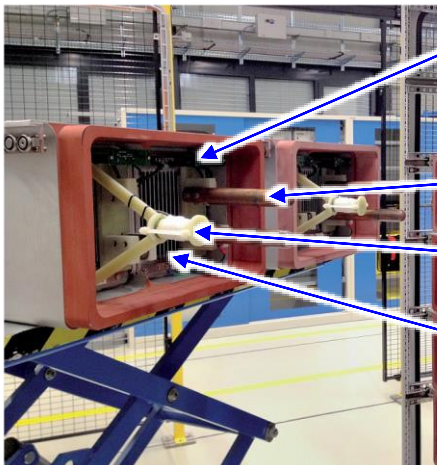
[Cottet2015a]
[Cottet2015b]



▶ Modularity: Hot-Swapping at 24kV

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

- All Interfaces Must Support Modularity



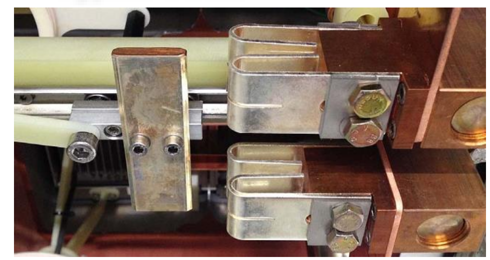
Communication (Wireless Optical)

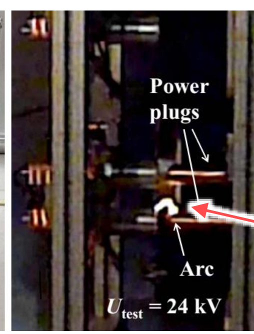
Power

Auxiliary (IPT)

Cooling (Air)

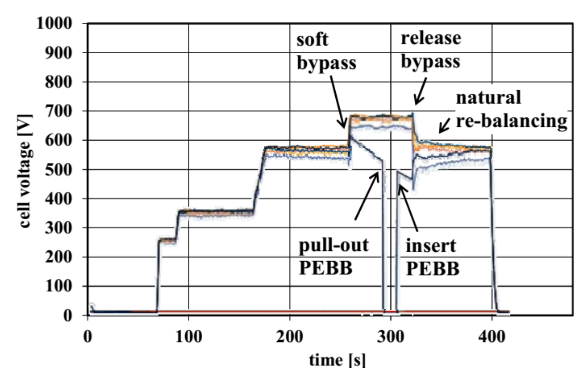
▼ Bypass Switch





24kV Sw. Arc

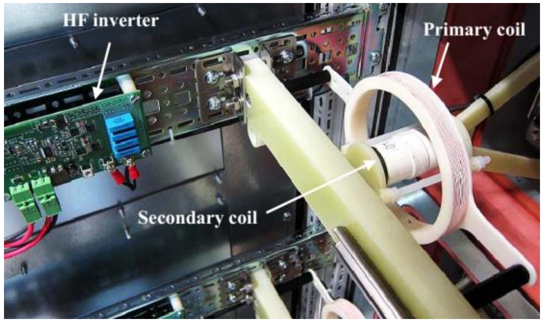
◀ Lab Test ▶



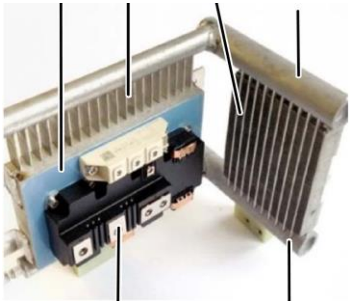
▶ Advanced Integration Technologies

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

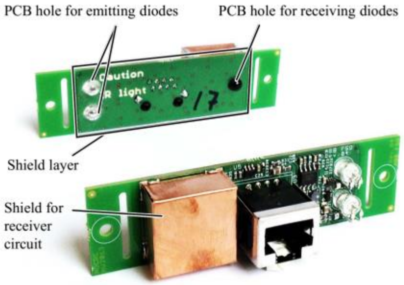
■ IPT for Auxiliary Power Supply



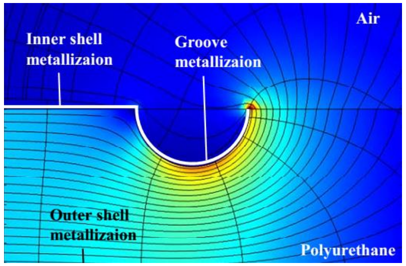
■ Two-Phase Cooling



■ Wireless Optical EtherCAT Comm.



■ Solid Isolation of PEBBs



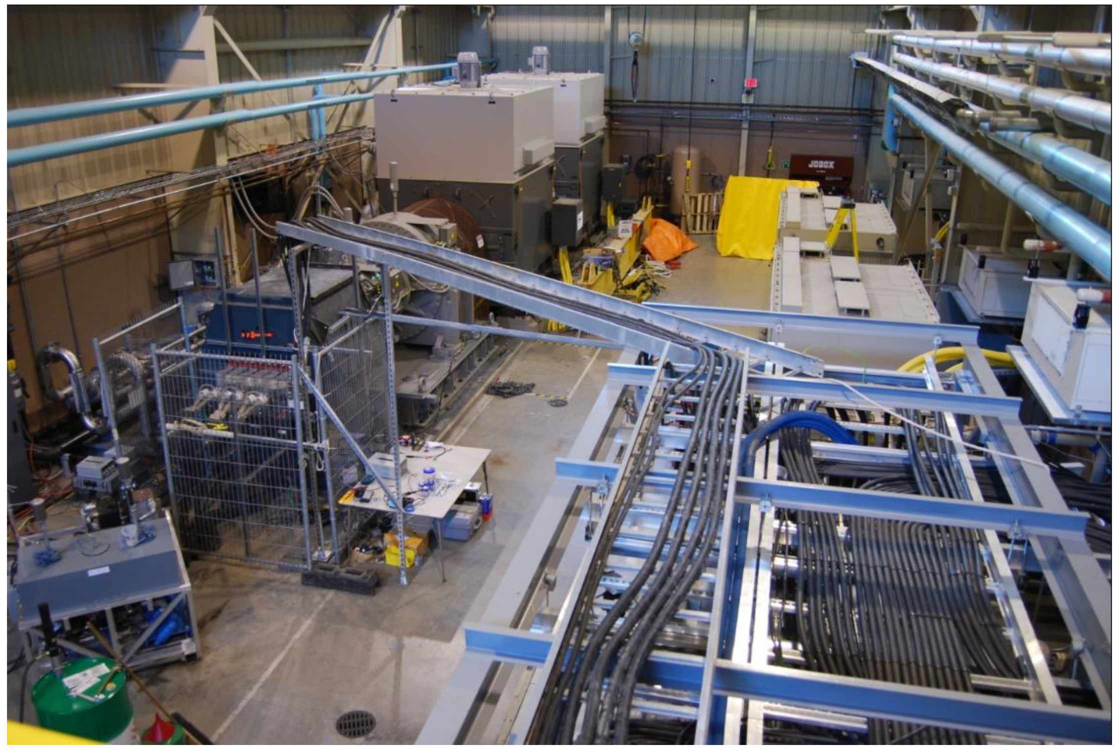
→ Actually Building an SST is a Multi-Disciplinary, Highly Complex Task!

Challenge #11/11

Testing of MV Converters

▶ Infrastructure

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

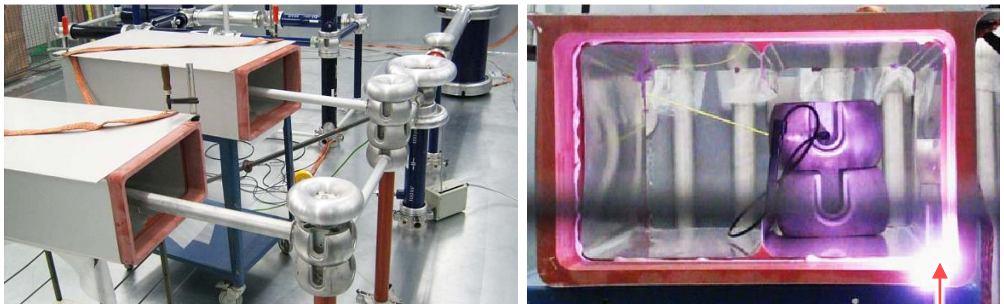


Img.:Center for Advanced Power Systems / Florida State University

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

▶ Infrastructure Examples

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



Imgs.: [Cottet2015b]

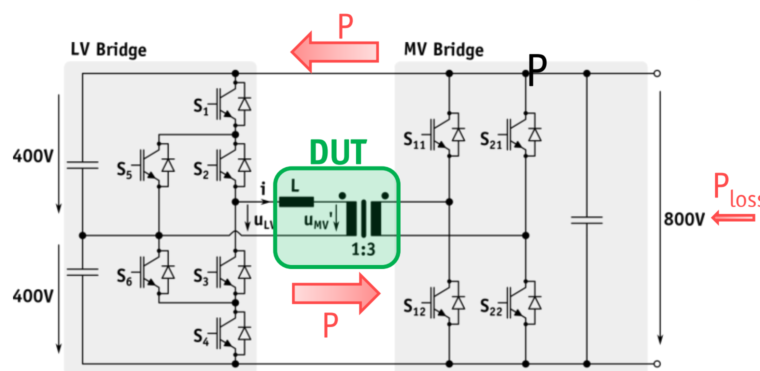
60kV Flashover

Img.: High Voltage Lab, ETH Zurich]

- Source/Sink for **100s of kW**

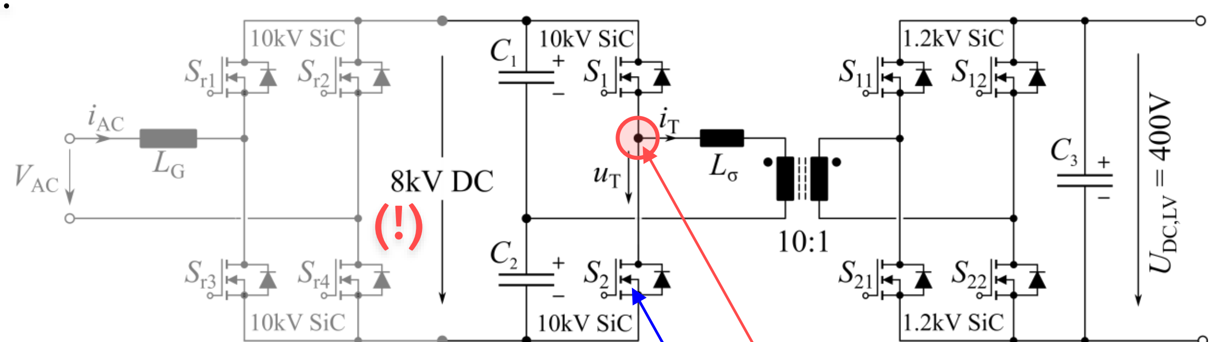
Img.: electrical-engineering-portal.com

- 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
  - ...

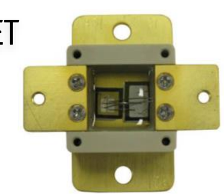


Switch Node: 8kV at 50kHz (!)

- Special High-Voltage Measurement Eq.

Img.: www.Tektronix.com

10kV SiC FET



Img.: Cree Inc.

Circuit: ETH / [Rothmund2015]

11 Key Challenges

Core Competencies

1. *Handling of Medium Voltage*
2. *Topology Selection*
3. *Reliability*
4. *MF Isolated Power Converters*
5. *MF Transformer Design*
6. *Isolation Coordination*
7. *EMI*
8. *Protection*
9. *Control*
10. *Construction of Modular Conv.*
11. *Testing of MV Converters*

► Core Competencies for SST Design

- The 11+ 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, Complex Task!

Img.: macrovector / 123RF Stock Photo

SST Applicability In Grid Applications

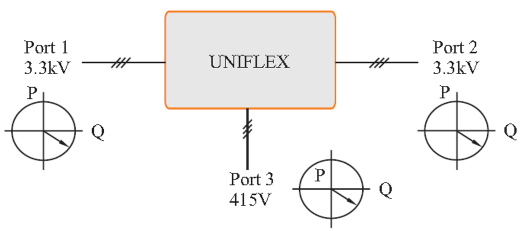
Grid SST Examples

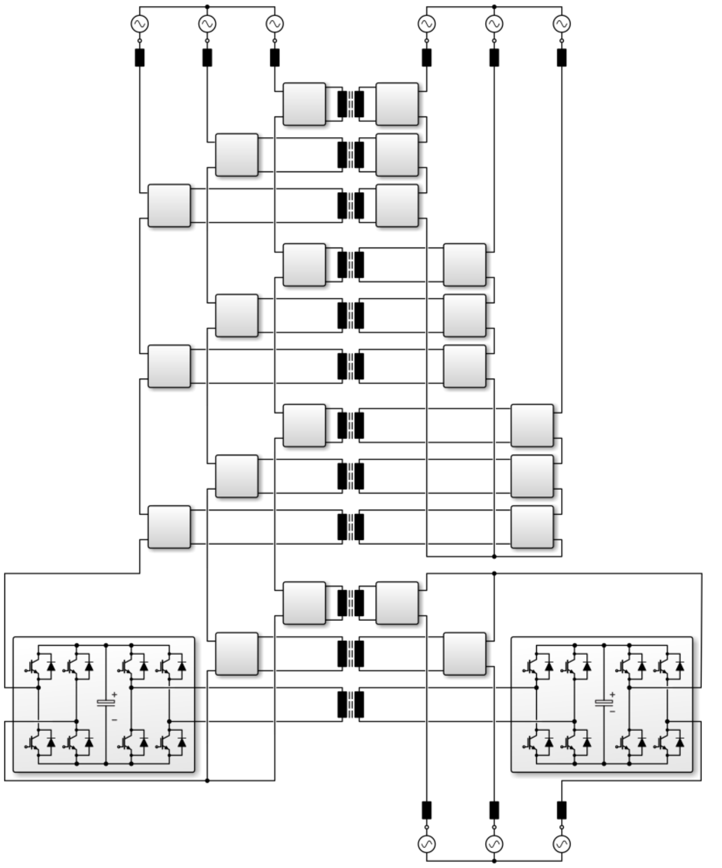
Competing Approaches

Compatibility w. Existing Infra-structure

▶ UNIFLEX Project (1)

- EU Project (2009)



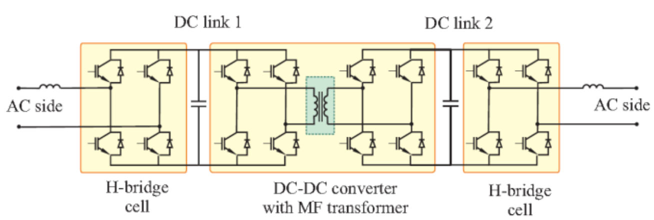


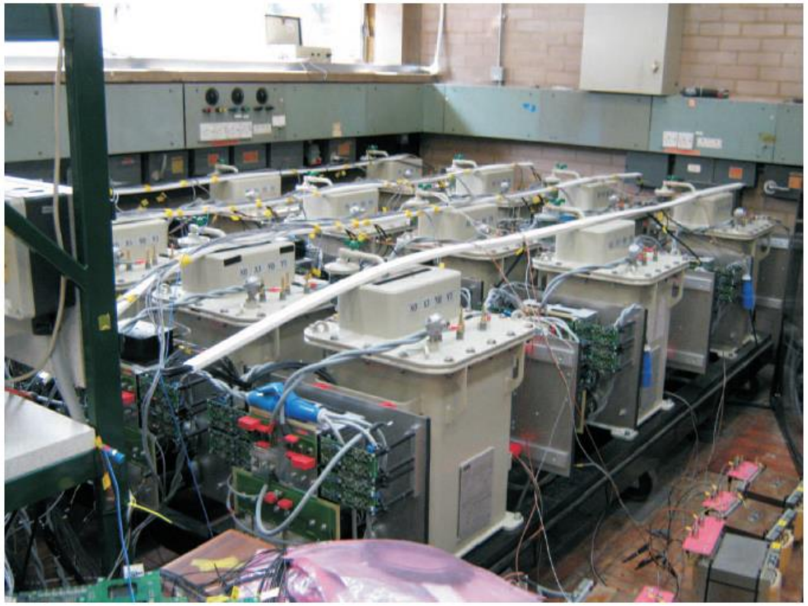
- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- **Cellular 300kVA Demonstrator of 3-Port Topology** for 3.3kV Distr. System & 415V LV Grid Connection

[Watson2009]

▶ UNIFLEX Project (2)

- EU Project (2009)





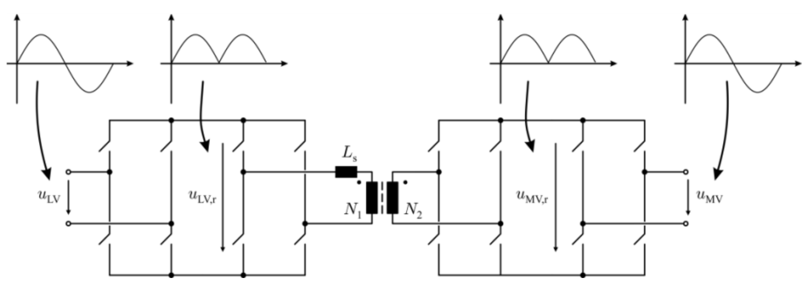
- AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham

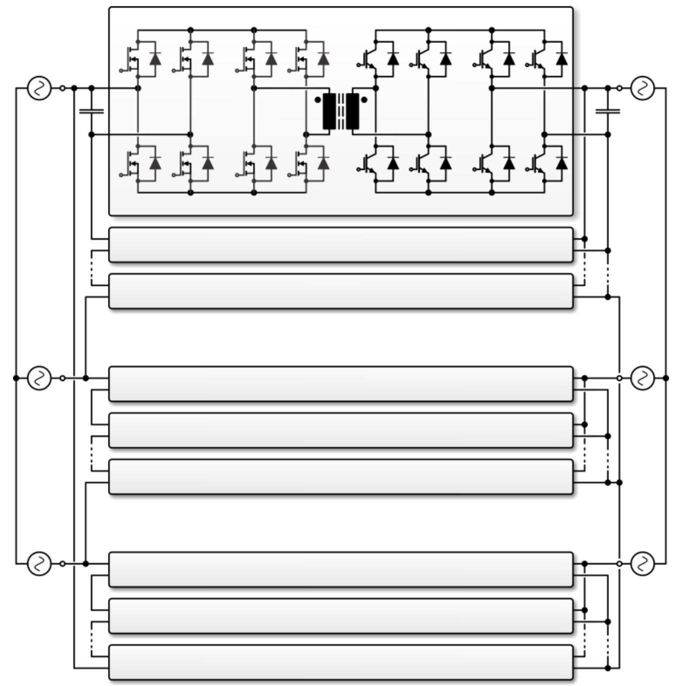
[Watson2009]

▶ SiC-Enabled 1MVA/20kHz 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/√3, Modules in Parallel)





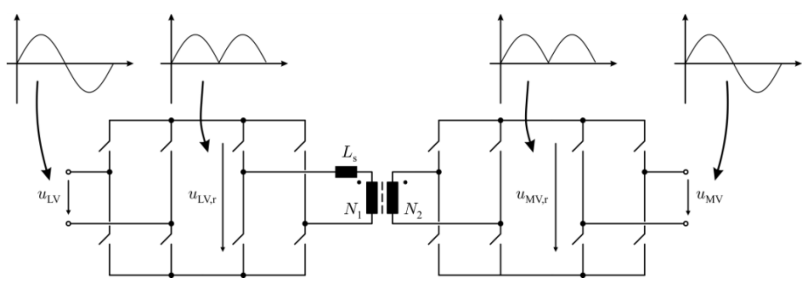
- **Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency**

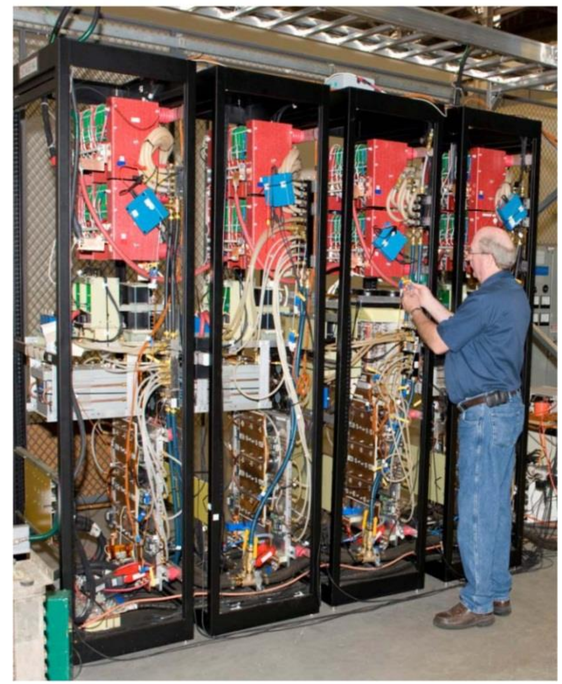
[Das2011]

▶ SiC-Enabled 1MVA/20kHz Solid State Power Substation (2)

- 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)





- **Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency**

[Das2011]

Applicability
Grid Applications

Grid SST Examples

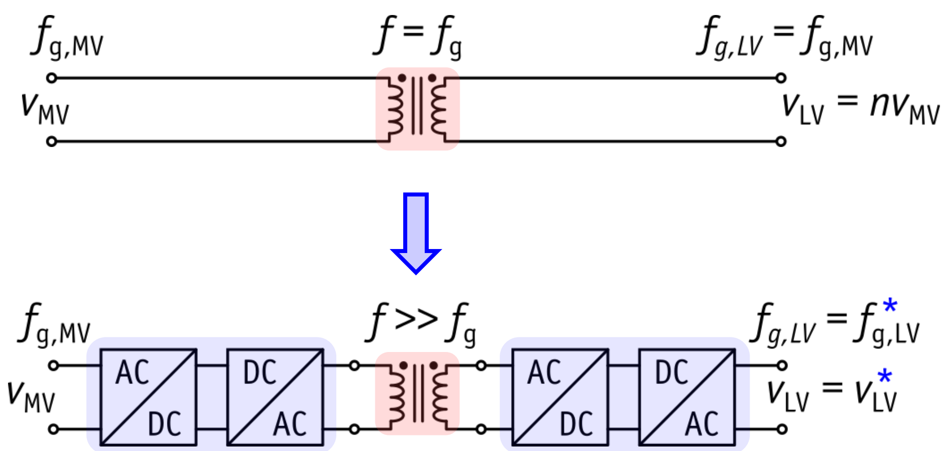
Competing Approaches: Isolation

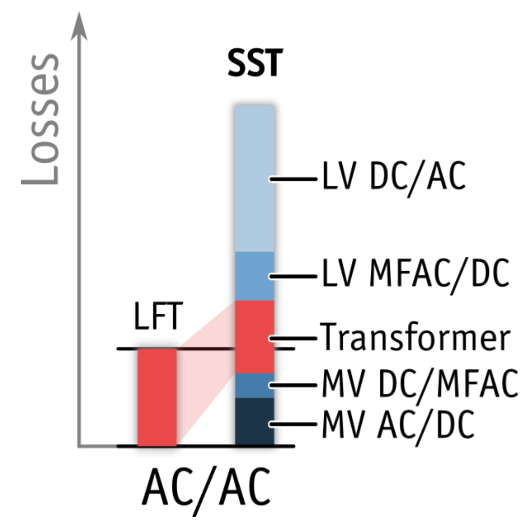
Compatibility w. Existing Infra-
structure

► Grid Application Task No. 1: Isolation & Voltage Scaling

- Typical Grid Application: MV**AC** // LV**AC**

- **Low Frequency Transformer → SST**
  - No Significant Efficiency Gain of Magnetic Transformer
  - Additional Conversion Stages Generate Additional Losses

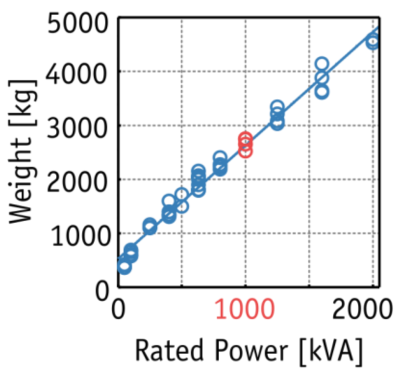


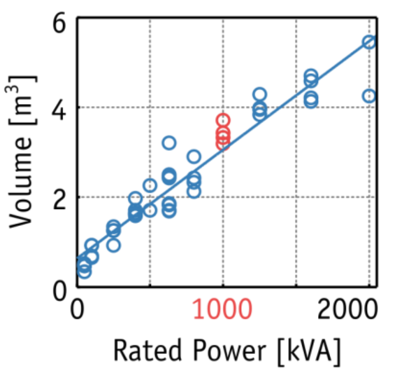


→ Remember **"Efficiency Challenge"**

▶ Task: Isolation & Voltage Scaling

- The Competitor: **1000kVA LF Distribution Transformer**
  - Standard Off-the-Shelve Products
  - Typically Liquid Filled (Oil): Isolation, Cooling

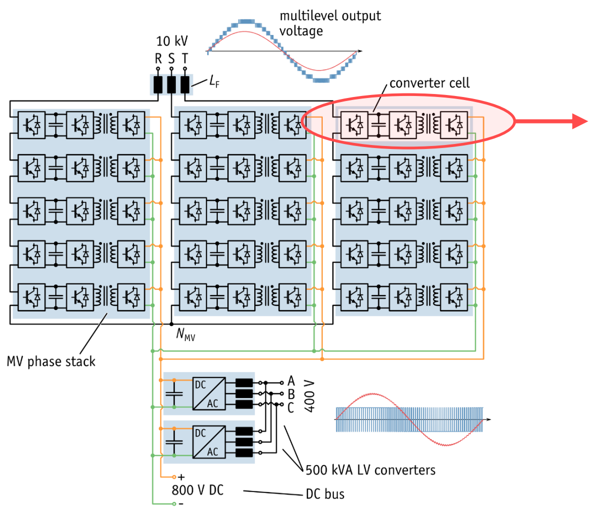




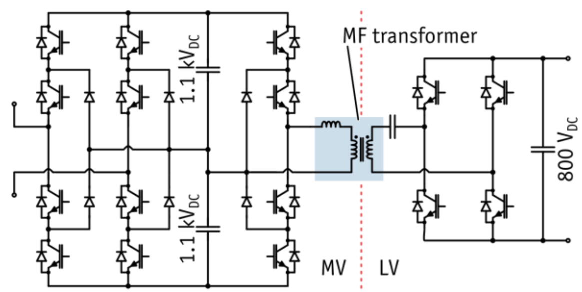
- **Averaged Data from Different Manufacturers**

	LFT	
Efficiency	98.7	%
Volume	3.43	m^3
Weight	2590	kg
Material Cost	11.3	kUSD

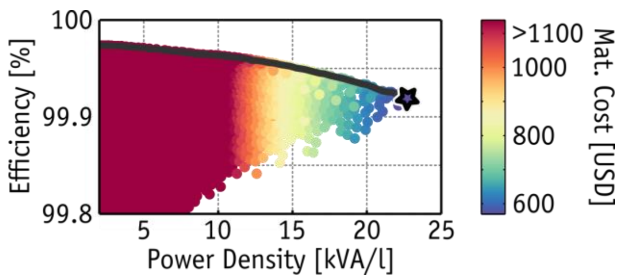
▶ SST vs. LFT Quantified – MV Side Modeling



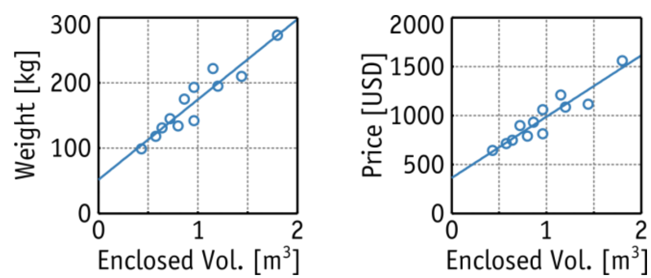
■ Fully Rated 80kW Converter Cell Prototype



■ Filter Inductor Pareto Optimization



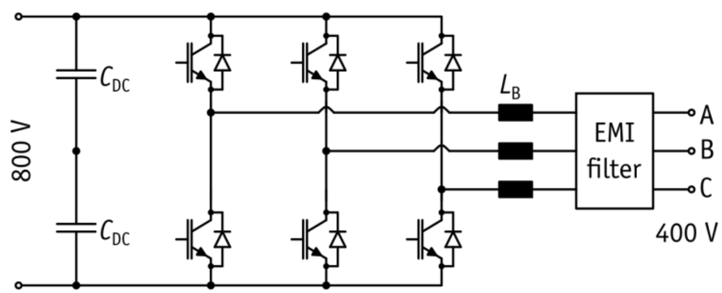
■ Cabinet Modeling Based on Empirical Data

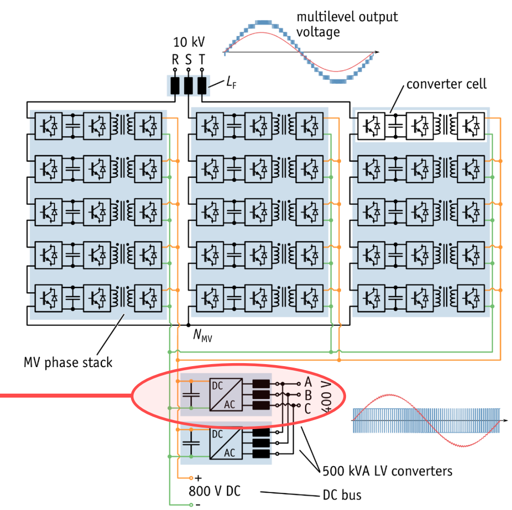


■ Material Costs: High-Volume Component Cost Models [Burkart2012]

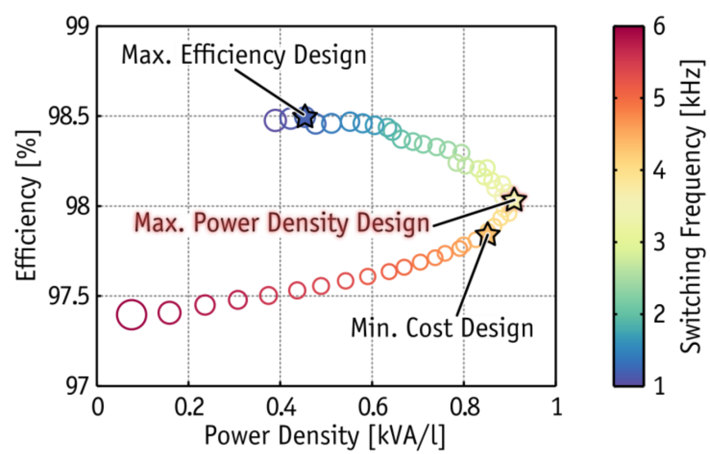
▶ SST vs. LFT Quantified – LV Side Modeling

■ Pareto Optimization of Standard 500kVA Inverter/Rectifier





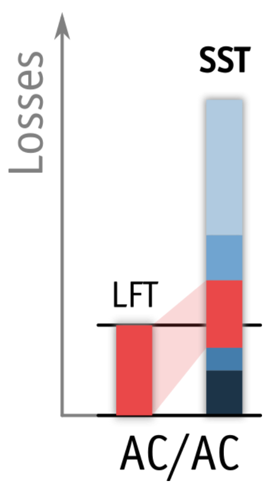
- Calculated Results (Losses, Volumes)
- Good Agreement with Specs of Commercially Available Active Frontend Converter



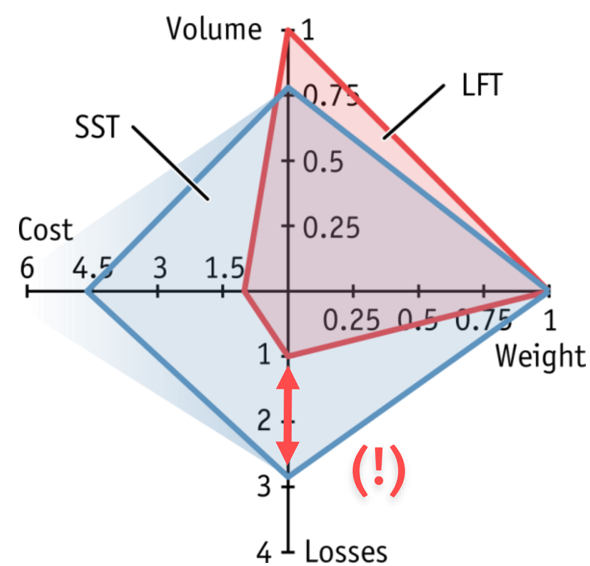
▶ SST vs. LFT Quantified – AC/AC Conversion

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

	LFT	AC/AC SST	
Efficiency	**98.7**	**96.3**	%
Volume	**3.4**	**2.6**	m^3
Weight	**2590**	**2600**	kg
Material Cost	**11.3**	**> 52.7**	kUSD

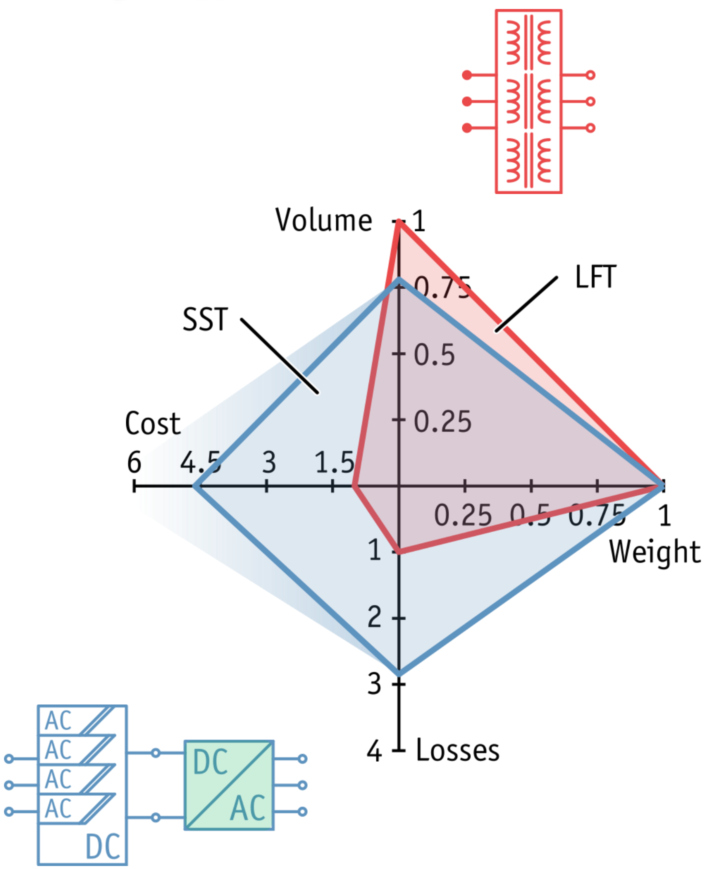


Efficiency Challenge Confirmed by Quantitative Analysis

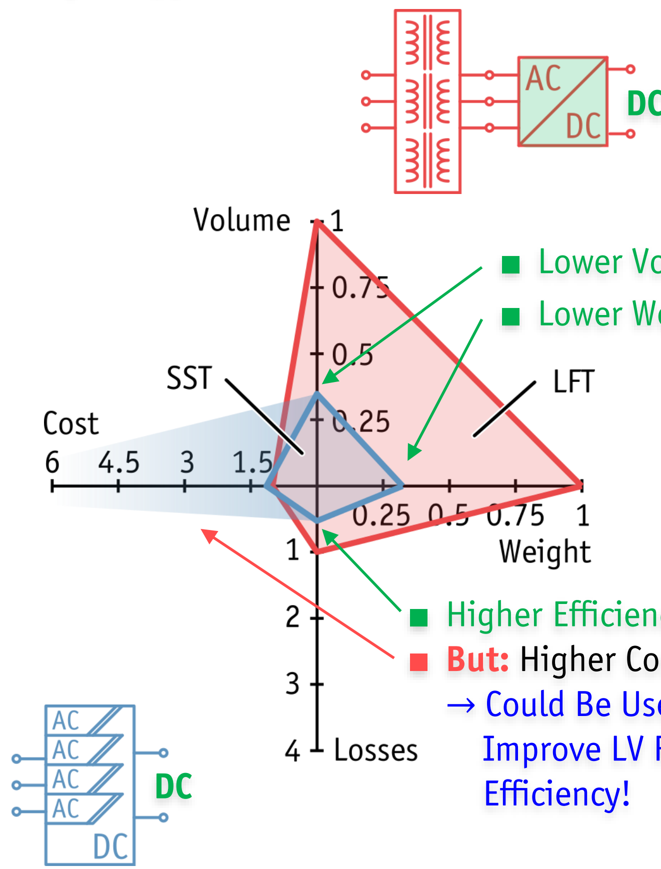


▶ SST vs. LFT Quantified – AC/AC and AC/DC Conversion

■ **AC/AC** Application



■ **AC/DC Application**



- Lower Volume
- Lower Weight
- Higher Efficiency
- **But:** Higher Costs

→ Could Be Used to Improve LV Rect. Efficiency!

Further Reading: ETH / [Huber2014b]

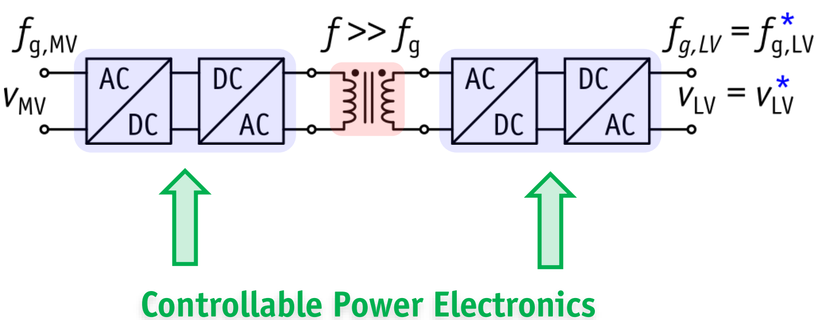
Applicability
Grid Applications

Grid SST Examples
Competing Approaches: Control
Compatibility w. Existing Infra-structure

▶ Controllability As Unique SST Selling Point?

- SST Is Not Competitive If Only Isolation & Voltage Scaling Are Required!

- **Added Value: Commonly Envisioned SST Features**



- Reactive Power Compensation
- **Voltage Regulation**
- Active Filtering
- Power Flow Control
- Fault Current Limiting
- DC Interface (e.g., Energy Storage)
- …

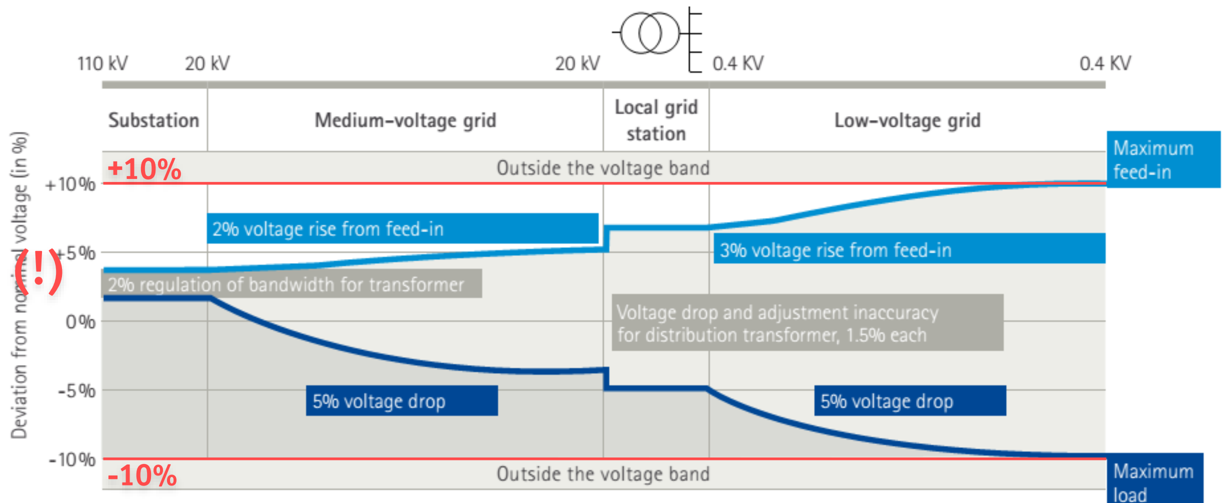
- Alternative Approaches To Provide These Features? → Several Examples In The Following!

- **Is It Necessary To Process The *Full* Power Flow With The Controllable (Less Efficient) Stage?**

▶ 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

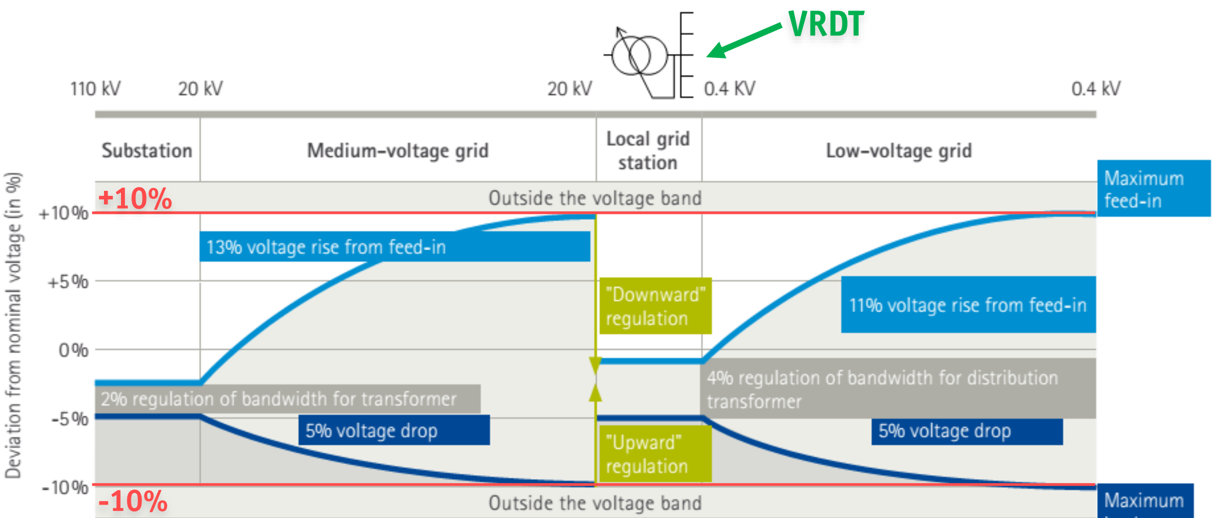
- **Grid Expansion Becomes Necessary Even Though Equipment Capacities Are Not Exhausted**
- SST Can Control Voltages – But So Can Voltage Regulation Distribution Transformer (VRDT), etc.

▶ 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
  - LFT Efficiency & Robustness!

Img: Maschinenfabrik Rheinhausen

Img: ABB



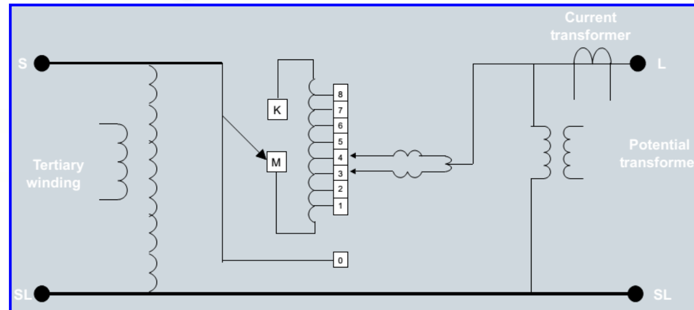
Source: Maschinenfabrik Rheinhausen GRIDCON Brochure

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

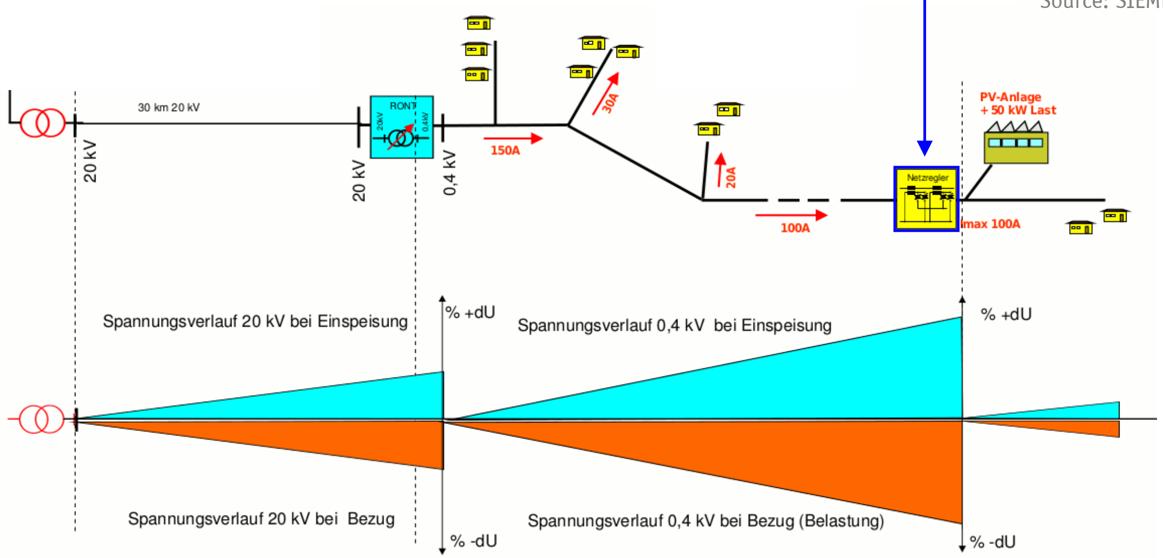
▶ Distribution Voltage Regulators

- Available for MV or LV Systems
- Easy **Retrofit** (No Modification of Existing LFT)
- Typ. Regulation ±10% in 32 Steps of 0.625%
- Comparably Slow (Several Seconds)
- Voltage Symmetrization (Three 1ph-Units)

- Mechanical Solution: Auto-Transformer With Tap Changer



Source: SIEMENS Voltage-Regulator-Catalogue



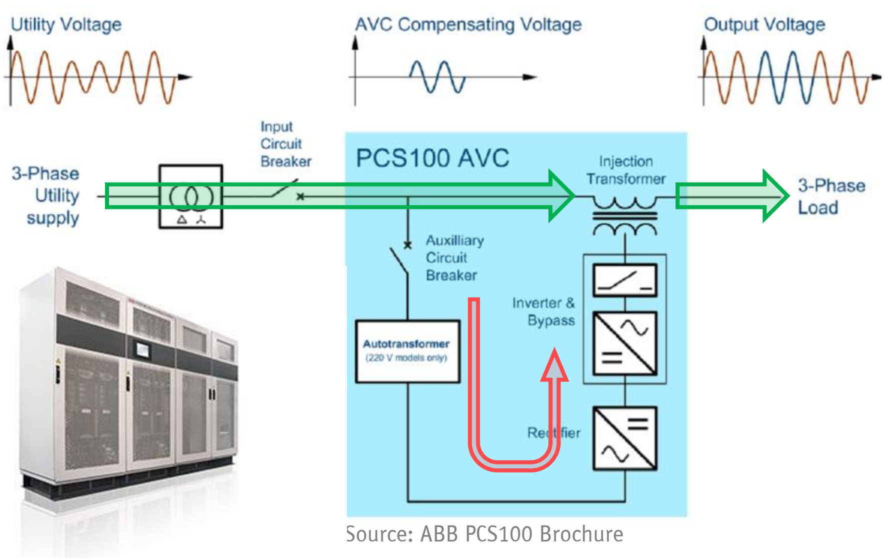
Source: www.walcher.com

▶ Active Series Voltage Regulators

- Protection of Sensitive Industrial and Commercial Loads from Voltage Disturbances
- Power Electronic Solution: Converter With Injection Transformer

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

- Typical Features Envisioned For SSTs (!)
- But: **Power Electronics Do Not Process The Full Power Flow**

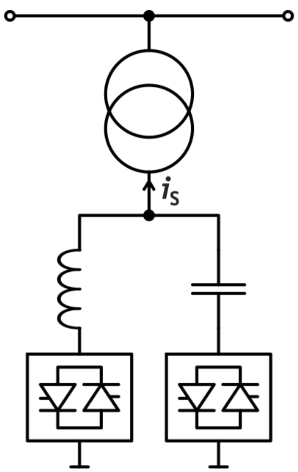


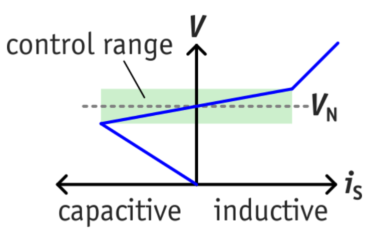
Source: ABB PCS100 Brochure

▶ Reactive Power Compensation

■ Static VAr Compensation

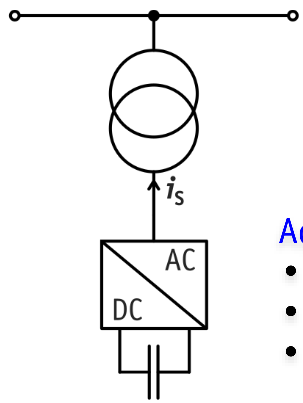
Switched Capacitor or Reactor Banks





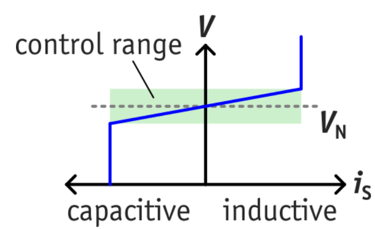
■ STATCOM

Power Electronic Converter



Additional Features

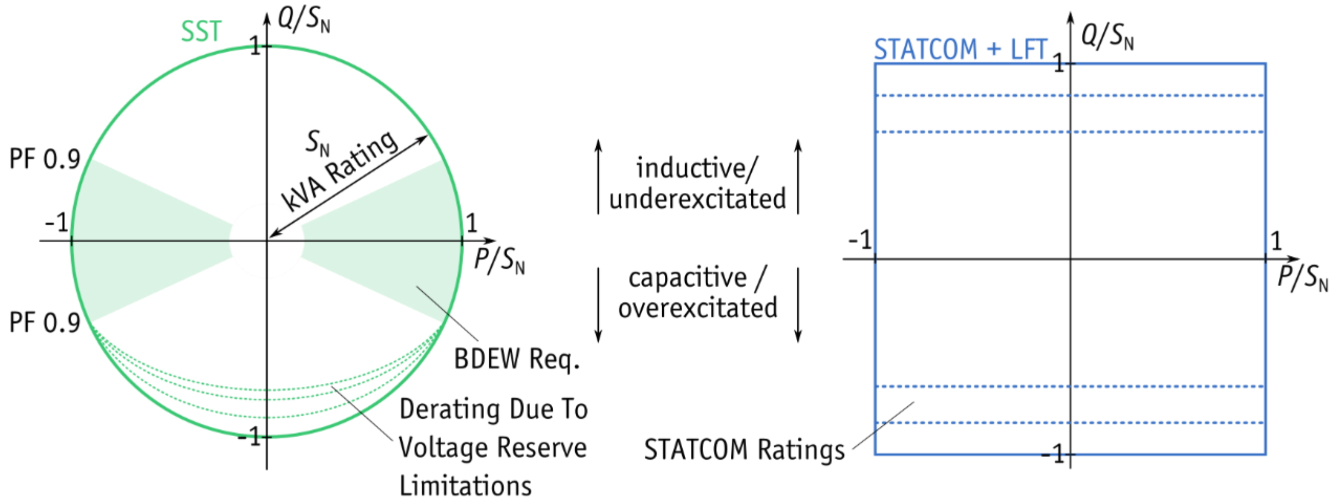
- Improved Power/Voltage Quality
- Voltage Regulation
- Compensation of Harmonics, Flicker, etc.



► SST vs. LFT + STATCOM

- **SST's VAr Capability Depends on Active Power Flow!**

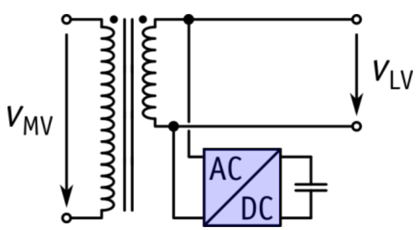
- Or: SST Max. Reactive Power Capability Is **Limited** By Active Power Demand



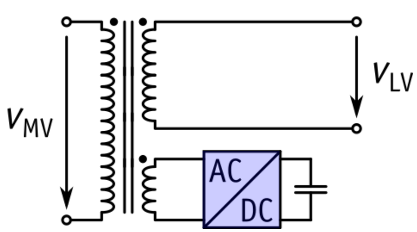
- SST Provides Complete **Decoupling of Reactive Power Flow** of MV and LV Grid
  - No Propagation of Disturbances
  - Different STATCOM OPs in MV and LV Grid

▶ Hybrid Transformers: Combinations of LFT and SST

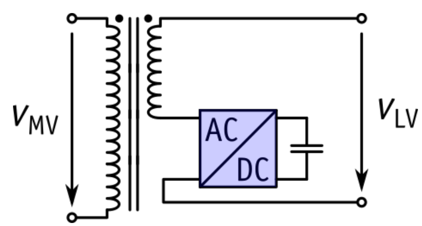
■ Shunt
Reactive Current Injection
- Power Factor Correction
- Harmonic Filtering
- Flicker Control



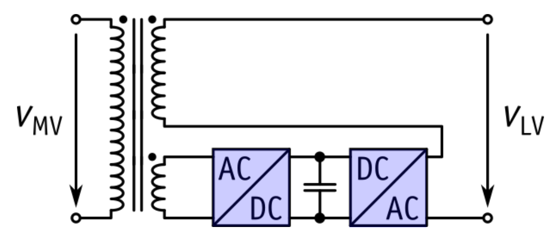
- Isolated DC Port



■ Series
Reactive Voltage Injection
- Phase Shifting
- Voltage injection



■ Combined
- Power Factor Correction
- Harmonic Filtering
- Flicker Control
- AC Regulation
- Phase Shifting



▶ **Fractional Power Processing**
→ Power Electronics Processes Only A Fraction Of The Power And/Or Voltage

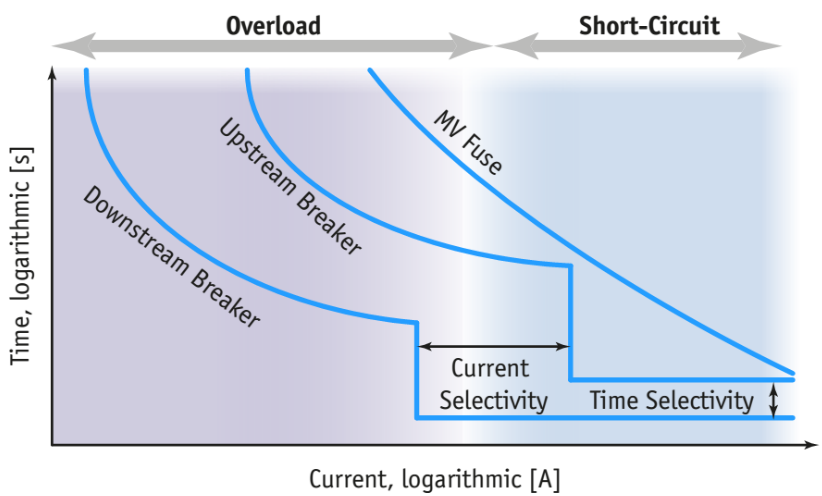
[Bala2012], [Burkard2015]

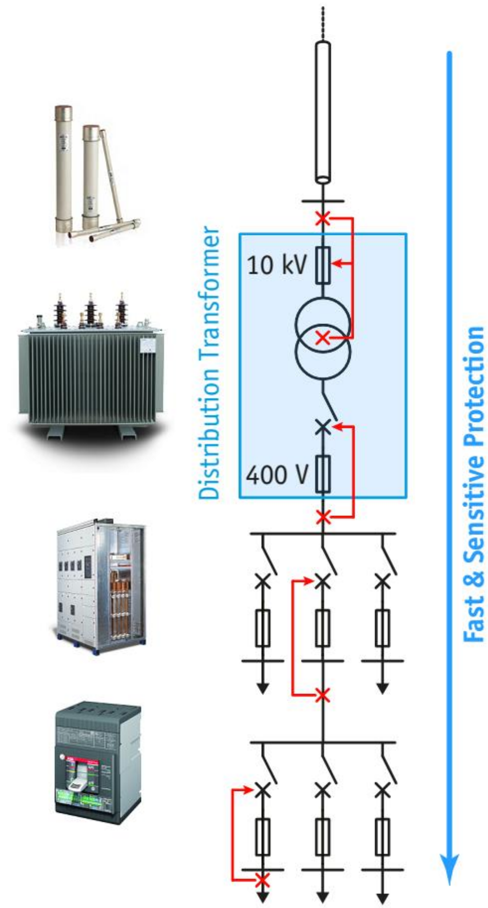
Applicability
Grid Applications

Grid SST Examples
Competing Approaches
Compatibility w. Existing Infra-structure

▶ 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



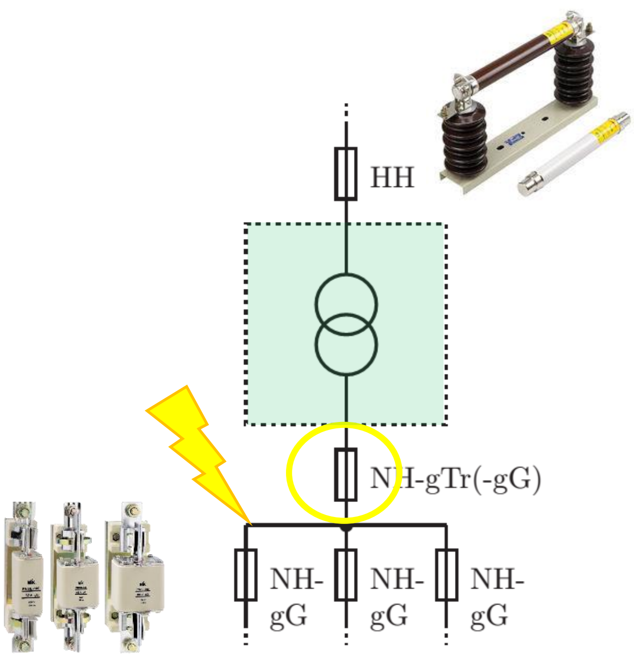


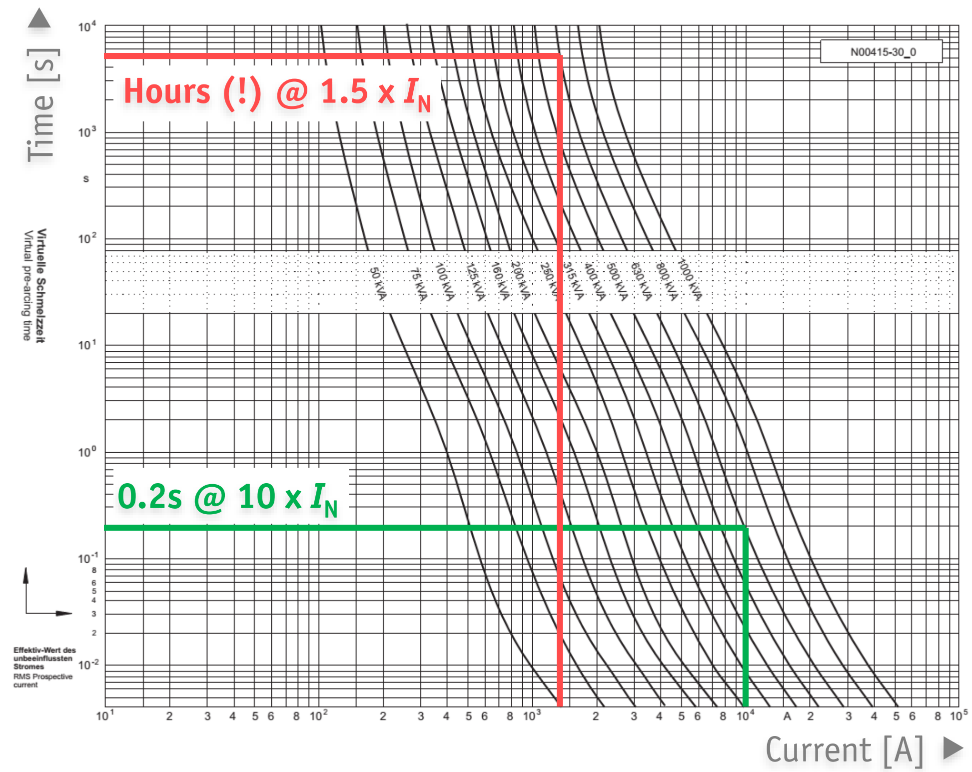
- **Certain Overcurrents Required To Trip Fuses And/Or Breakers**

Imgs.: ETH / [Guillod2015]

▶ Tripping of LV Side Fuses

- Example: 400V Fuse for 630kVA Transformer

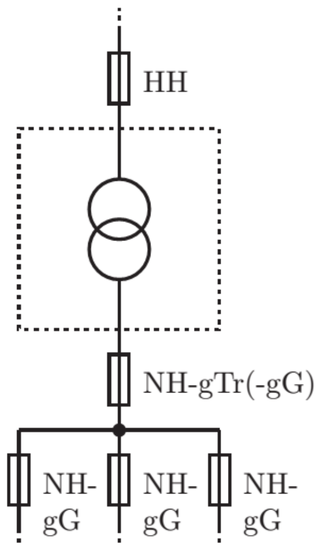


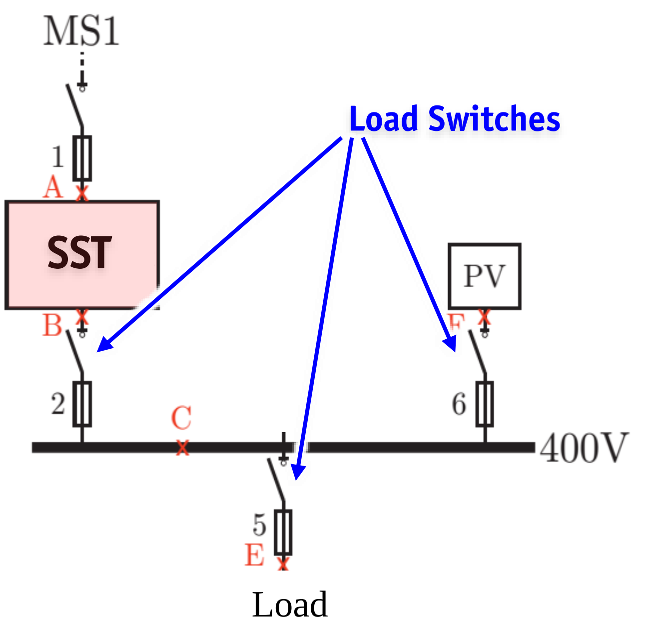


- Very High Short-Circuit Currents Required To Trip Fuses → No Problem for LFT!
- **But Not Possible With Power Electronic Converter (Semiconductors!)**

▶ Alternative Protection Schemes

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



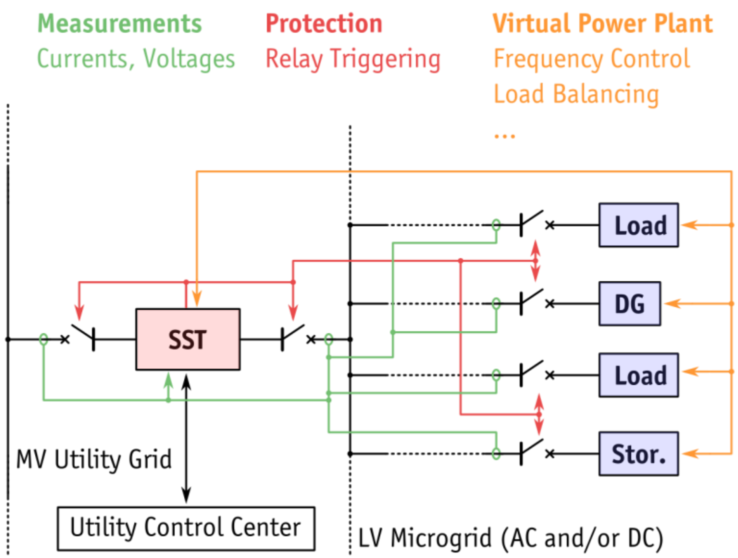


- Integration of SST in Existing LV Distribution System Remains Challenging
- **Communication** Between (Protection) Devices Becomes Essential

- **SST Requires a “Smart Grid”** → Coordination of Protection Relays

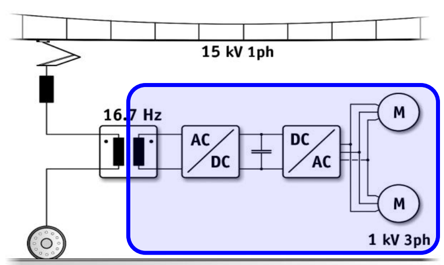
▶ SST Grid Integration

- SST Requires A **Controlled Environment** On Its LV Side
- SST Is Thus **Not a Direct Replacement** For A Distribution LFT!



- Novel Protection Schemes
- Micro Grid Can Act as a "Virtual Power Plant"
- DC Distribution
- Etc.

- Comparison: **Traction Application**

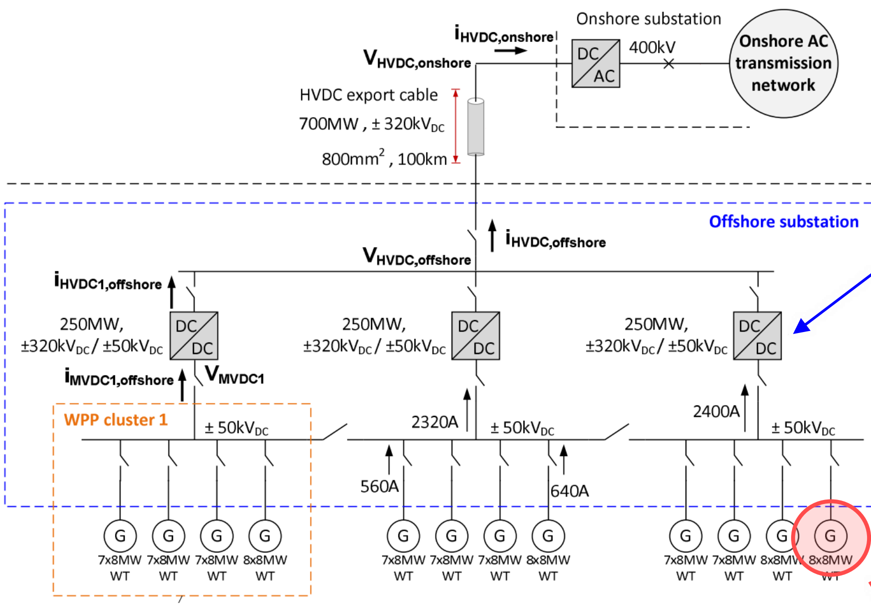


→ Locomotive Is A **User-Controlled, Self-Contained** Environment!

Applicability
DC-DC Applications

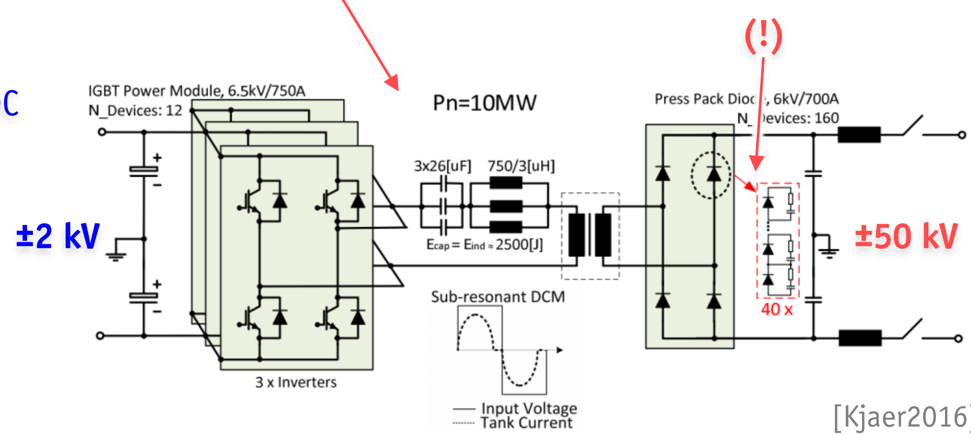
No Alternatives!

► Example: DC Collection Grids for Offshore Wind Parks



- ±320kV$_{DC}$ HVDC Transmission to Shore
- ±50kV$_{DC}$ / ±320kV$_{DC}$ Offshore Substations with M2LC-Based MF Isolation and Step-Up Stage
- **50kV$_{DC}$ Offshore Collection Grid**

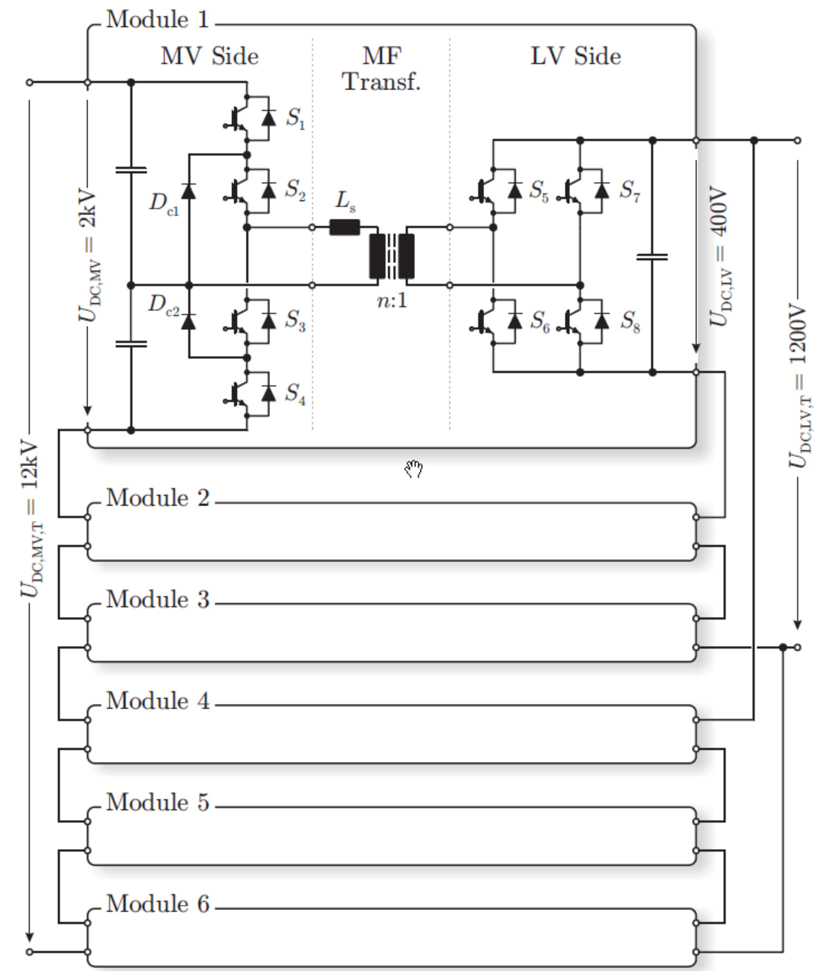
- Series Resonant Unidir. DC → MVDC Conversion in the Individual Wind Turbines
- **Transformer Frequency Can Be Freely Chose**



[Kjaer2016]

▶ Example: *MEGACube* @ ETH Zurich (1)

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

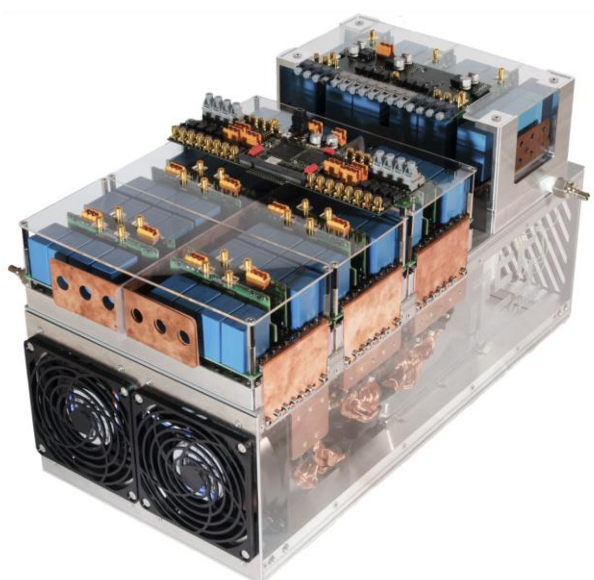


- MV Level 12.0 kV
- LV Level 1.2 kV

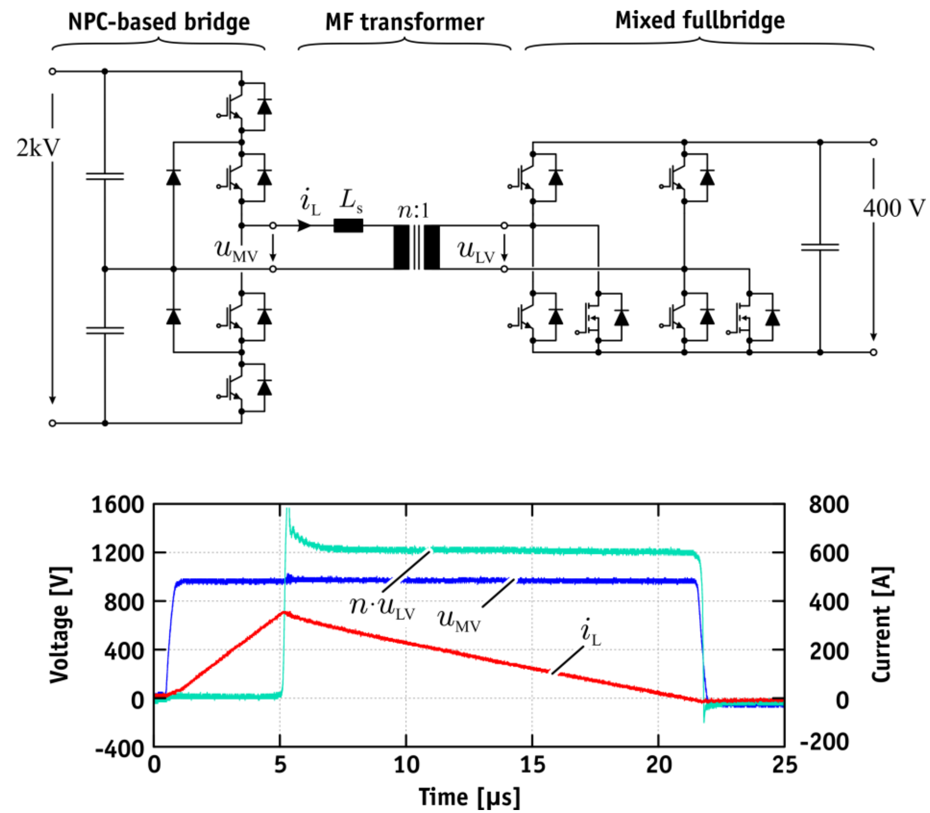
[Ortiz2010], [Ortiz2013c]

▶ Example: *MEGACube* @ ETH Zurich (2)

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



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

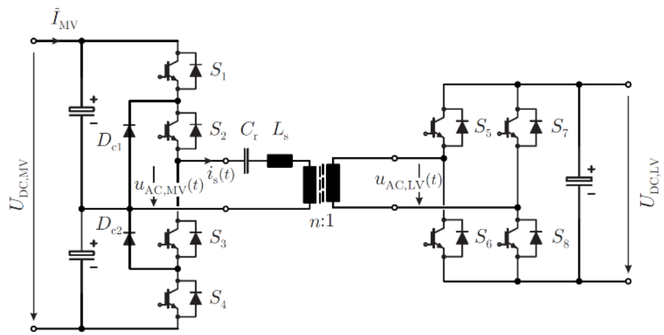


▲ Structure of the 166kW Module and MV Side Waveforms

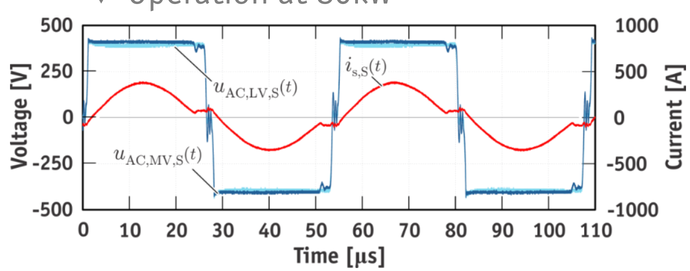
[Ortiz2013c]

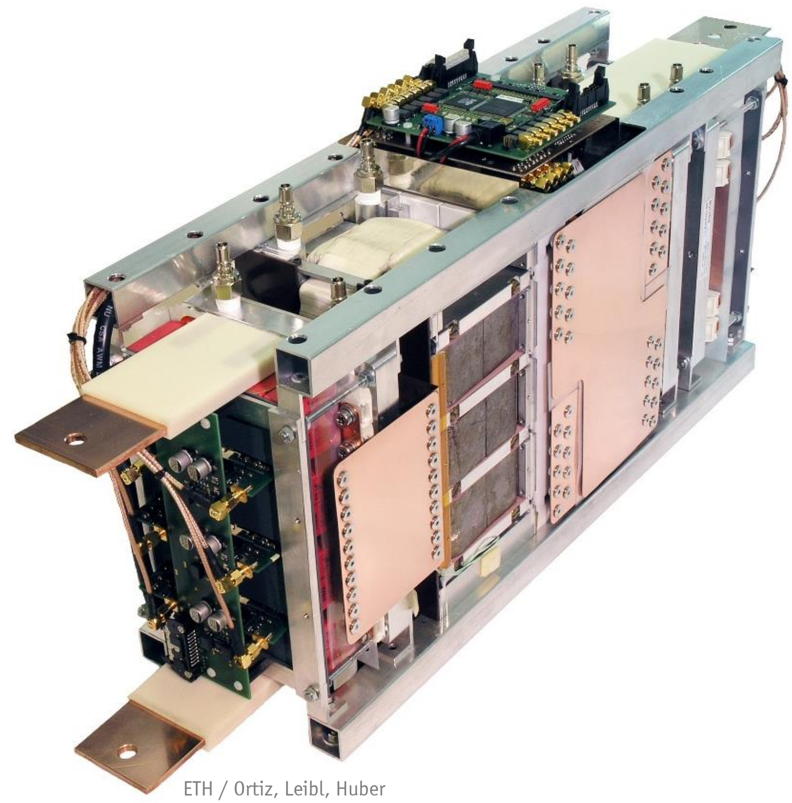
▶ Example: *MEGACube* @ ETH Zurich (3)

- **HC-DCM SRC** DC-DC Converter Stage
- Module Power 166 kW
- Frequency 20 kHz
- Medium Voltage Side 2 kV
- Low Voltage Side 400 V



▼ Operation at 80kW





ETH / Ortiz, Leibl, Huber

SST Applicability In Traction Applications

Traction SST Example

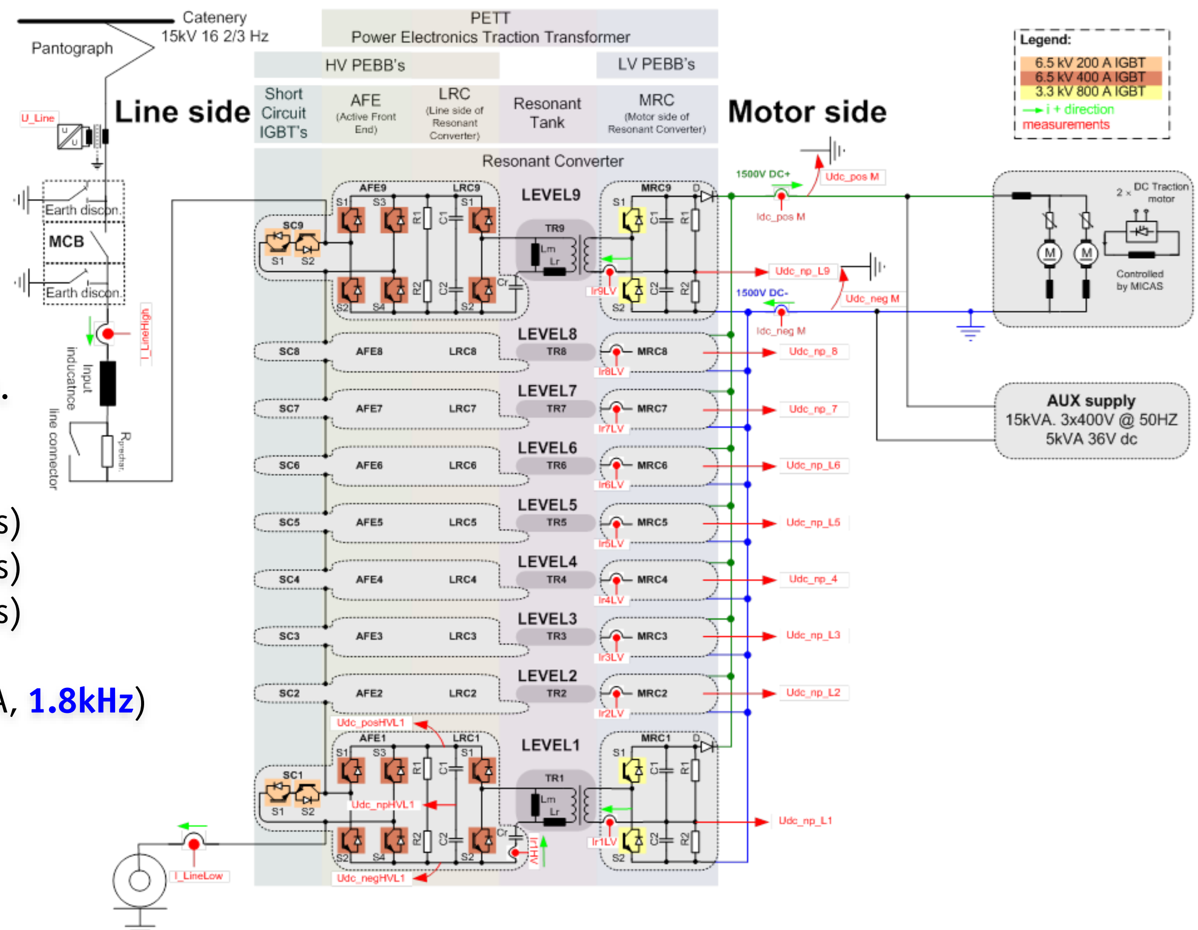
Img.: www.futuretimeline.net

▶ 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)

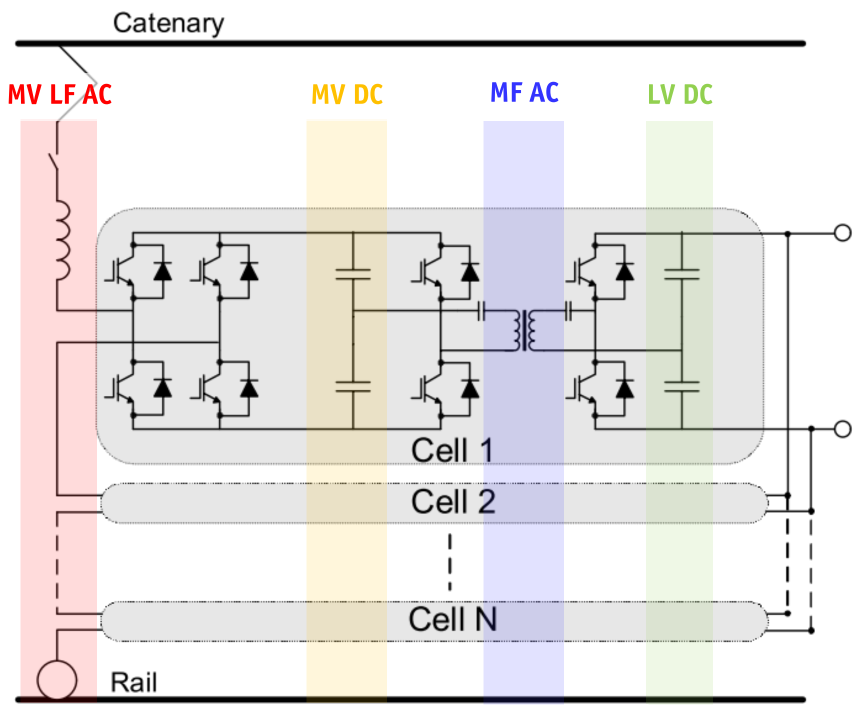
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

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

[Dujic2013] & [Zhao2014]

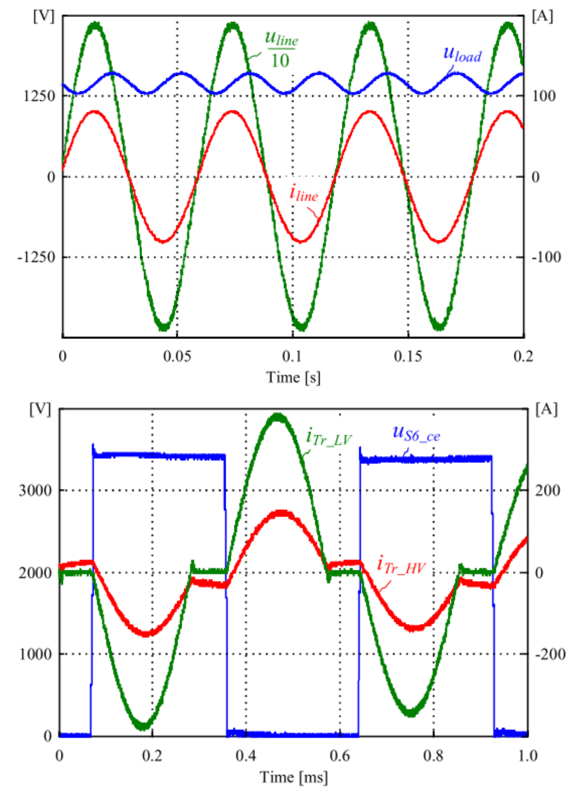
▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages (2)

- 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.

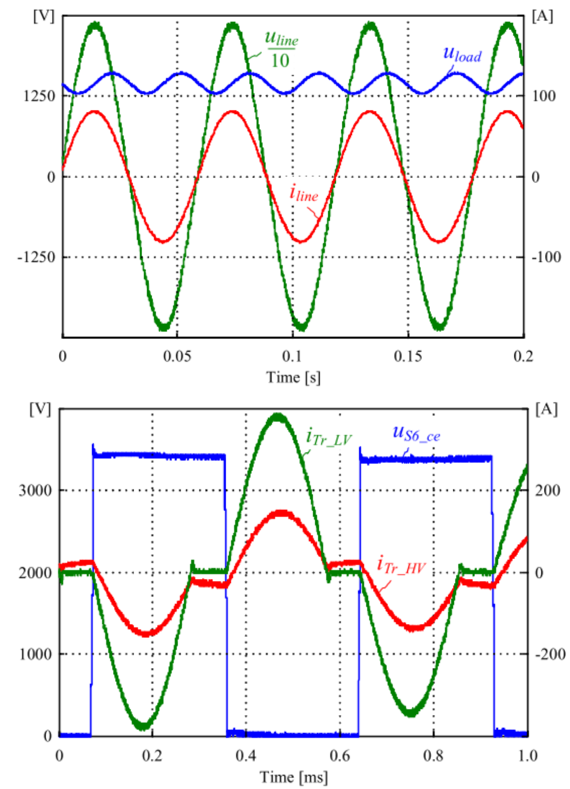
Img.: [Dujic2011]



[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

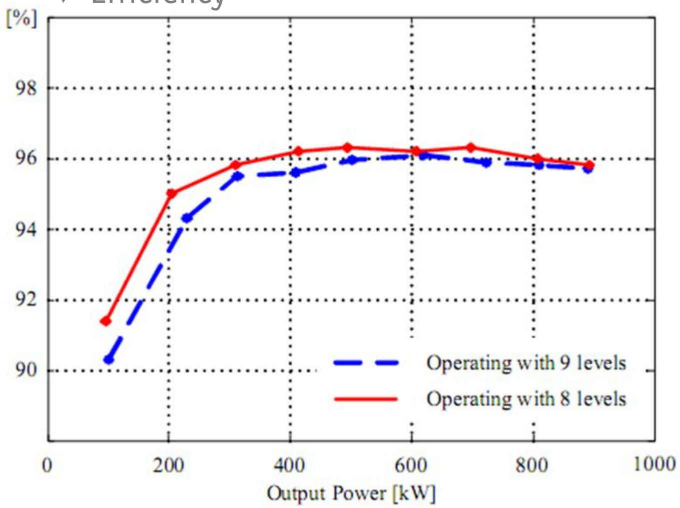


[Dujic2013] & [Zhao2014]

► 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

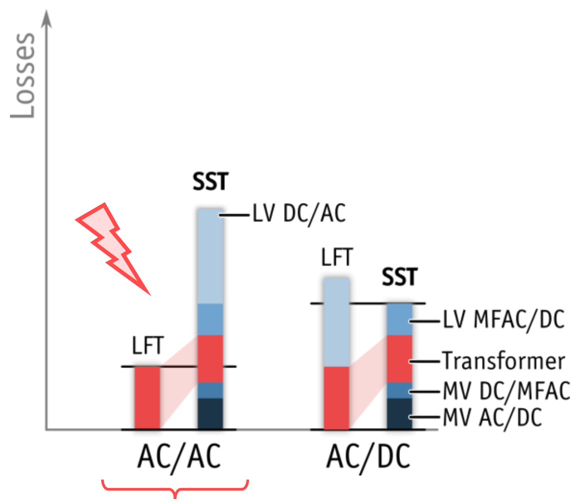


[Dujic2013] & [Zhao2014]

SST Applicability
Summary

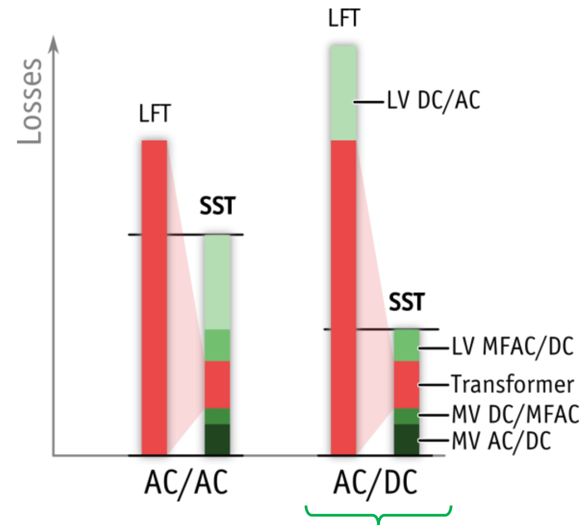
► "Efficiency Challenge" (Qualitative)

■ No Weight/Volume Constraints



Typical **Grid** Application

■ Weight/Volume Constraints



Typical **Traction** Application

■ SSTs in Grid Applications – A Skeptic's View

- **Efficiency** of LFT for AC/AC Very Hard To Attain
- Weight/Volume Typically Not an Issue In Stationary Grid Applications
- Robustness, Reliability?
- Cost?

■ SSTs in Traction Applications

- SST Shows Efficiency Benefits for Applications with **Volume/Weight Constraints!**

▶ SST Applicability: The Road Ahead

Grid AC-AC

- Efficiency Challenge
- Controllability Can Be Provided By Alternative Approaches
  - More Efficient (e.g., Tap Changers)
  - Partial Power Processing
- Compatibility Issues With Existing Infrastructure (e.g., Protection)
- Cost, Robustness, Reliability Issues

DC-DC Applications

- Isolation Stage Frequency Is A Free Parameter
- Future Applications, e.g. MV DC Collection Grids for Wind/PV

Grid AC-DC

- Efficiency Challenge More Balanced
- Self-Contained Applications (e.g., Datacenter DC Distr.)
- Cost, Robustness, Reliability

Weight/Space Limited Appl.

- Medium Frequency Systems Offer
  - Weight/Volume Reduction

    AND
  - Efficiency Improvement
- Typically Self-Contained Environ-ments On One Side Of The SST
- Several Industrial Prototypes, But So Far No Products

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

"Initial Use May be Found in Special **Applications where Cost and Efficiency are Secondary to Size and Weight**."

W. McMurray, 1971

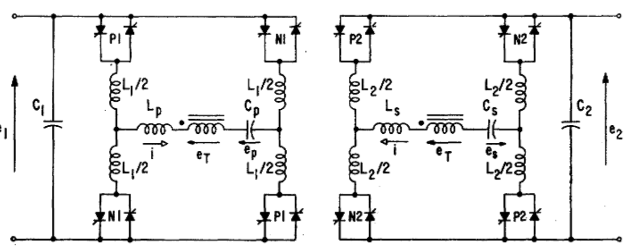


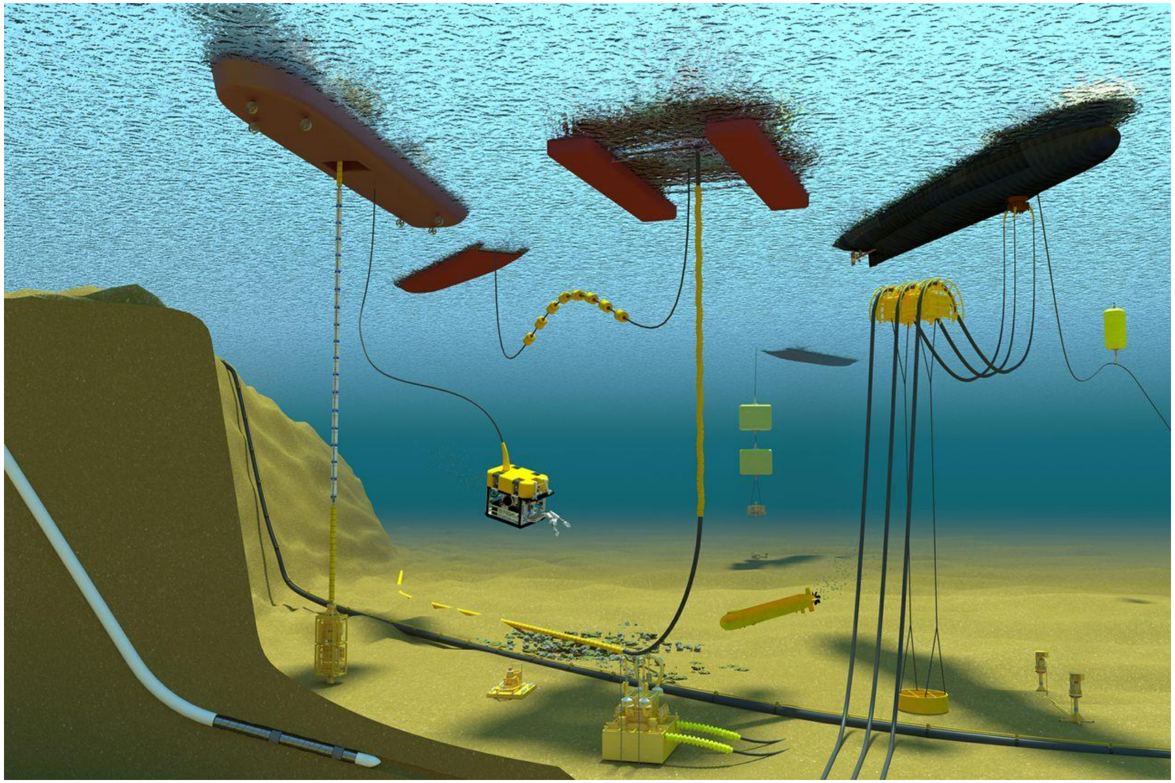
Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

CONCLUSIONS

thyristors. Thus practical application of the electronic transformer is dependent upon further circuit development and component improvements. Initial use may be found in special applications where cost and efficiency are secondary to size and weight.

Future
SST Applications

► Subsea Applications: Oil & Gas Processing (1)

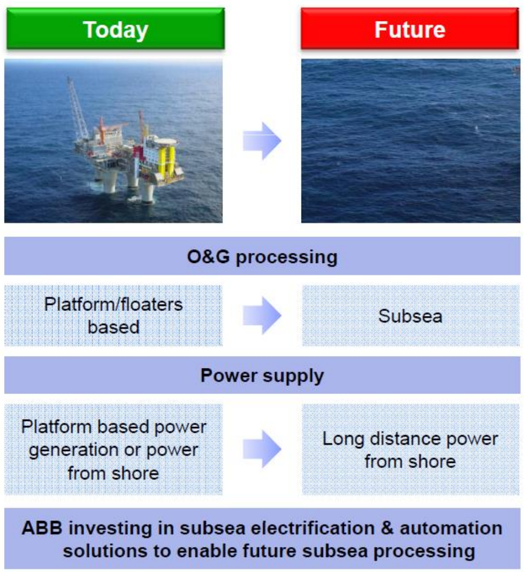


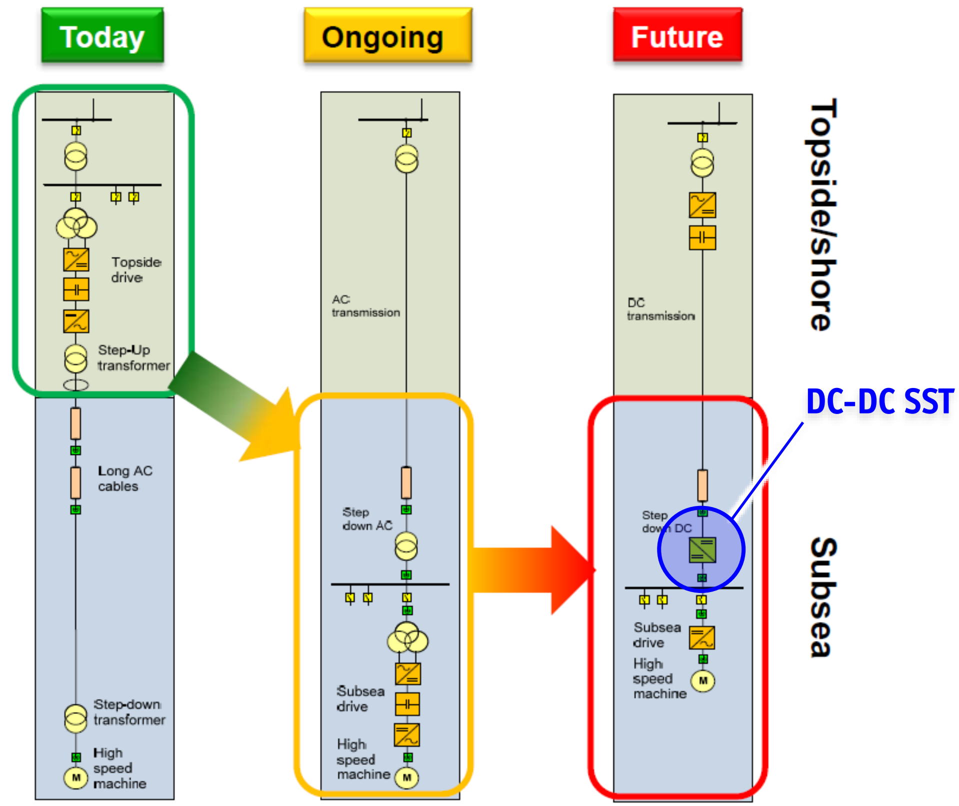
Img.: matrixengineered.com

- ABB's Future Subsea Power Grid → **"Develop all Elements for a Subsea Factory"**

▶ Subsea Applications: Oil & Gas Processing (2)

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



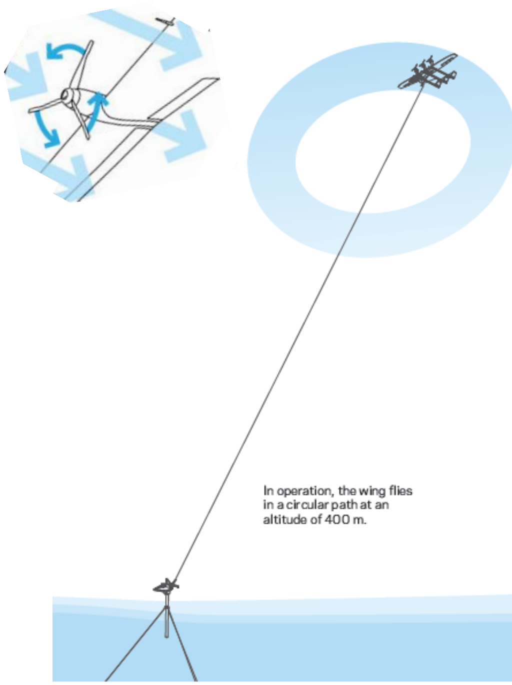


- Transmission Over **DC**, No Platforms/Floaters
- Longer Distances Possible
- Subsea O&G Processing

■ **Weight Optimized Power Electronics**

▶ Airborne Wind Turbines

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



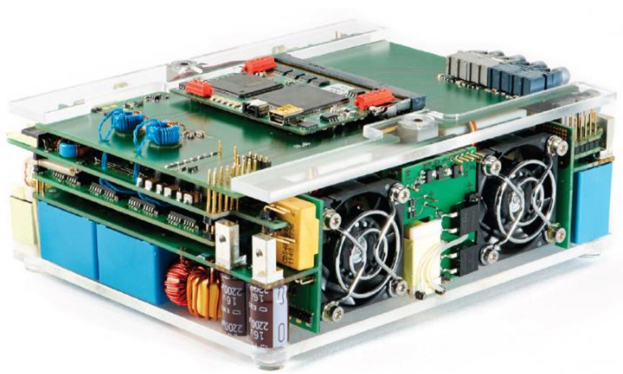
MAKANI POWER

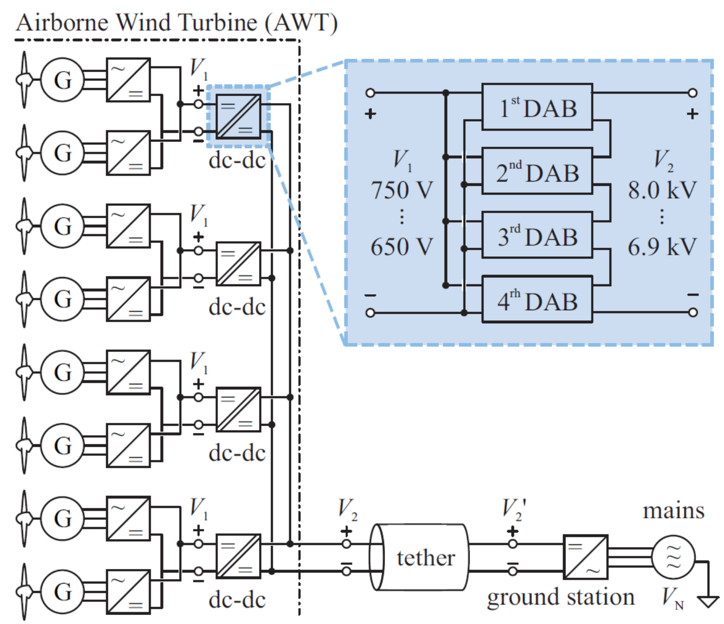
Google X

▶ 100kW Airborne Wind Turbine (1)

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

- 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

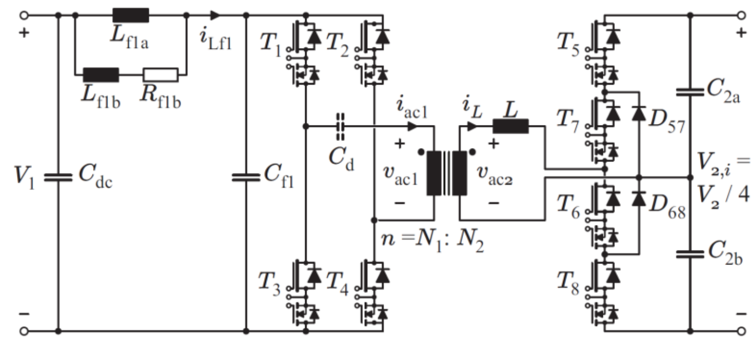


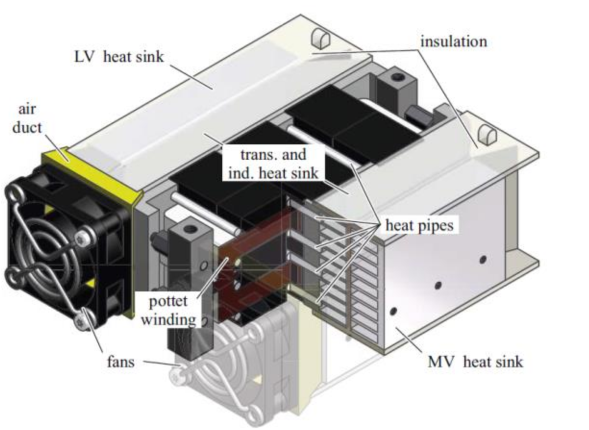


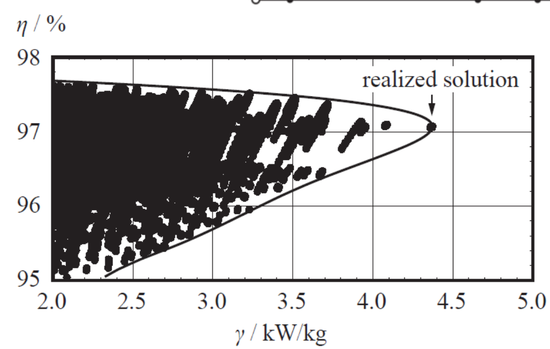
ETH / [Gammeter2015]

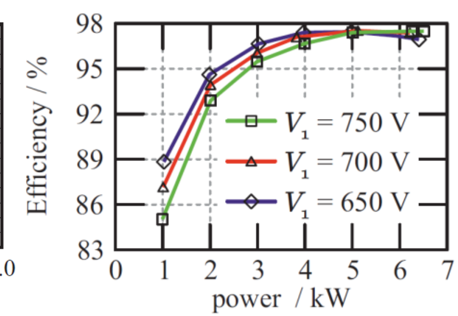
▶ 100kW Airborne Wind Turbine (2)

- Ultra-Light Weight Multi-Cell **All-SiC Solid-State Transformer** – 8kV$_{DC}$ → 700V$_{DC}$
  - Medium Voltage Port 1750 ... 2000 VDC
  - Switching Frequency 100 kHz
  - 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 / [Gammeter2015]

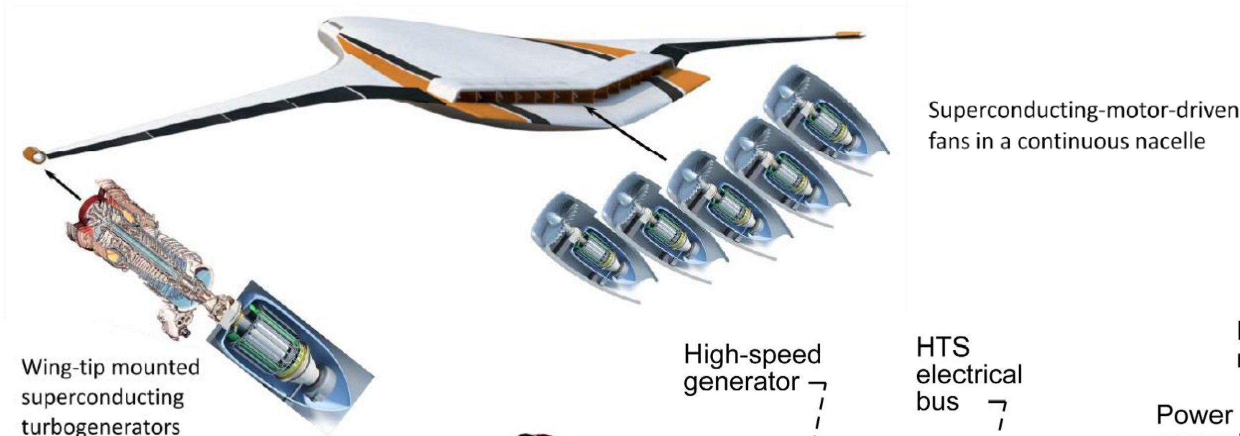
► Future Hybrid or All-Electric Aircraft

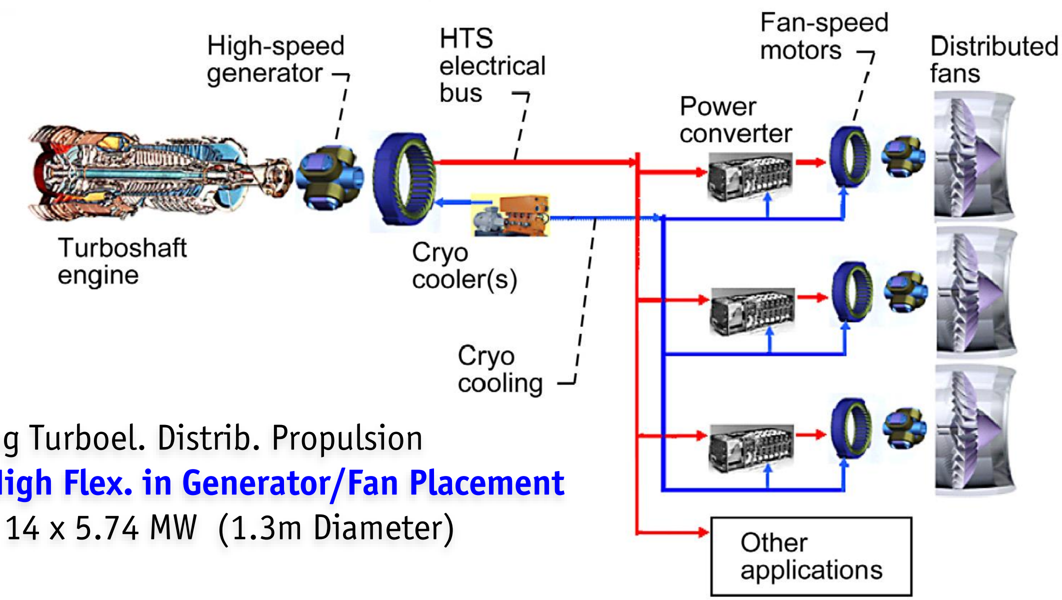
Source: EADS

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- **Until 2050: Cut CO2 Emissions by 75%, NO_x by 90%, Noise Level by 65%**

▶ Future Hybrid Aircraft

Source: NASA

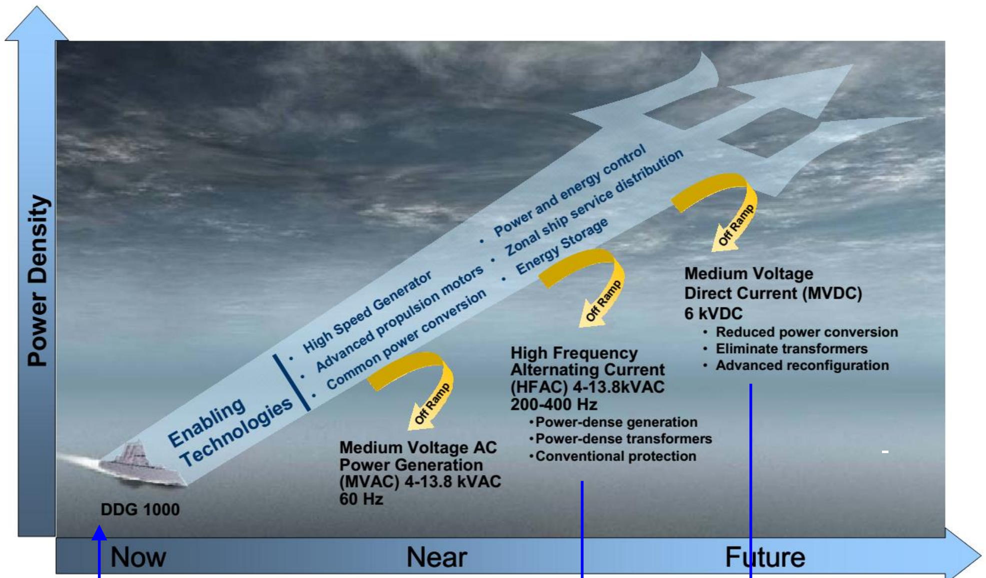




- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- **Electr. Power Transm. Allows High Flex. in Generator/Fan Placement**
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

- **Potential SST Application: Supply of LV AC or DC Loads From MVDC Bus**

▶ Future Naval Applications (1)



MVDC

- Further Size/Weight Reduction
- **DC-DC SSTs**

HFAC
(High-Frequency AC)

- Reduce Size/Weight of Equipment

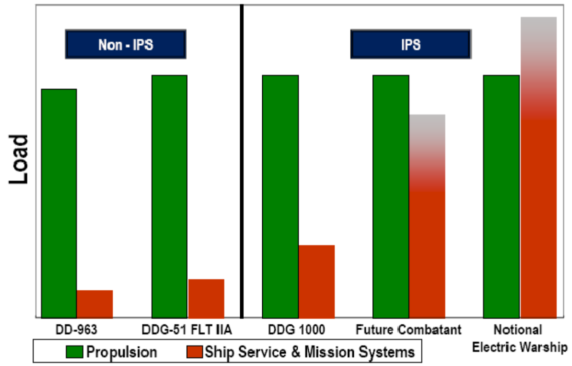
USS Zumwalt
Img.: US Navy, CC BY 2.0

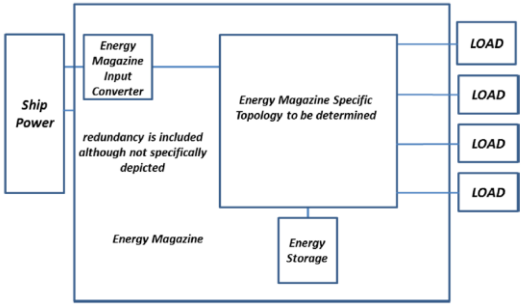
[Doerry2009]

▶ Future Naval Applications (2)

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

[Doerry2009]





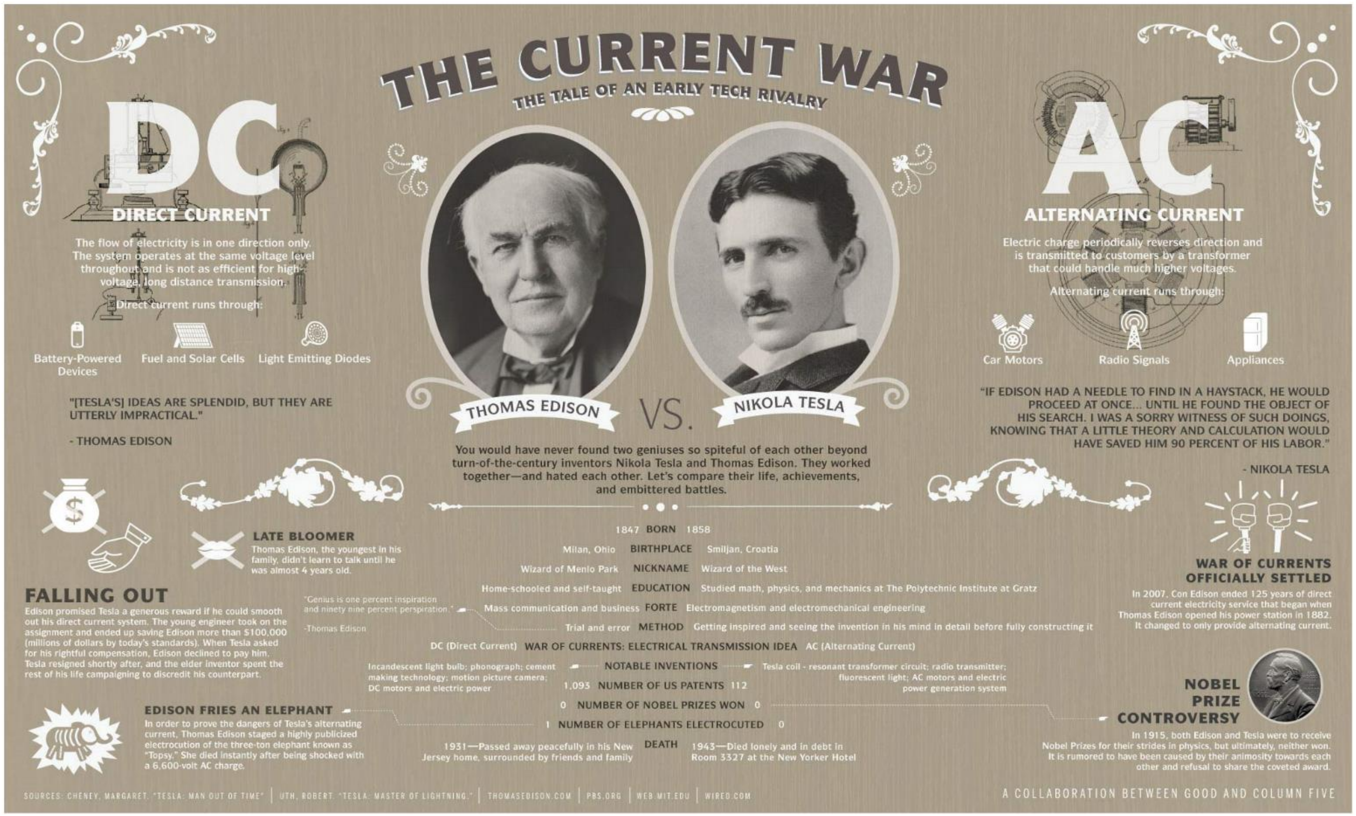
Source:
General Dynamics

- **"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

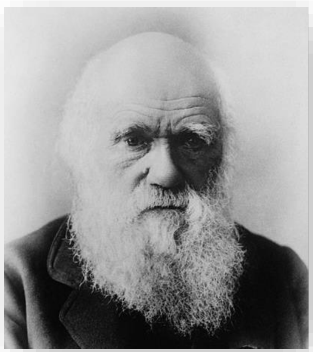
Img.: Marina Gallud / 123RF Stock Photo

▶ 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

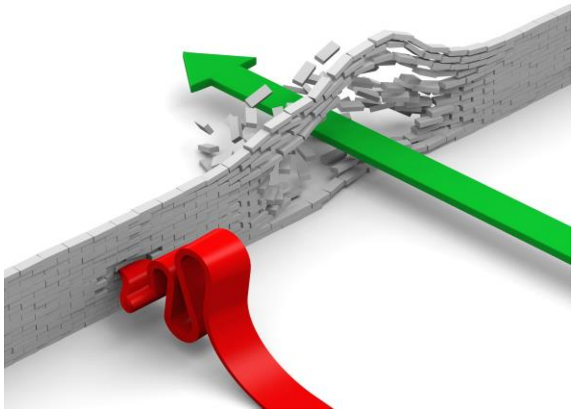
- **Multi-Level vs. Two-Level Topologies with HV SiC Switches**
- Low-Inductance MV Power Semiconductor Package
- **Mixed-Frequ./Voltage Stress on Insul. Materials**
- Low-Loss High-Current MF Interconnections / Terminals
- Thermal Management (Air and H_2O Cooling, avoiding Oil)
- SST Protection
- SST 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**

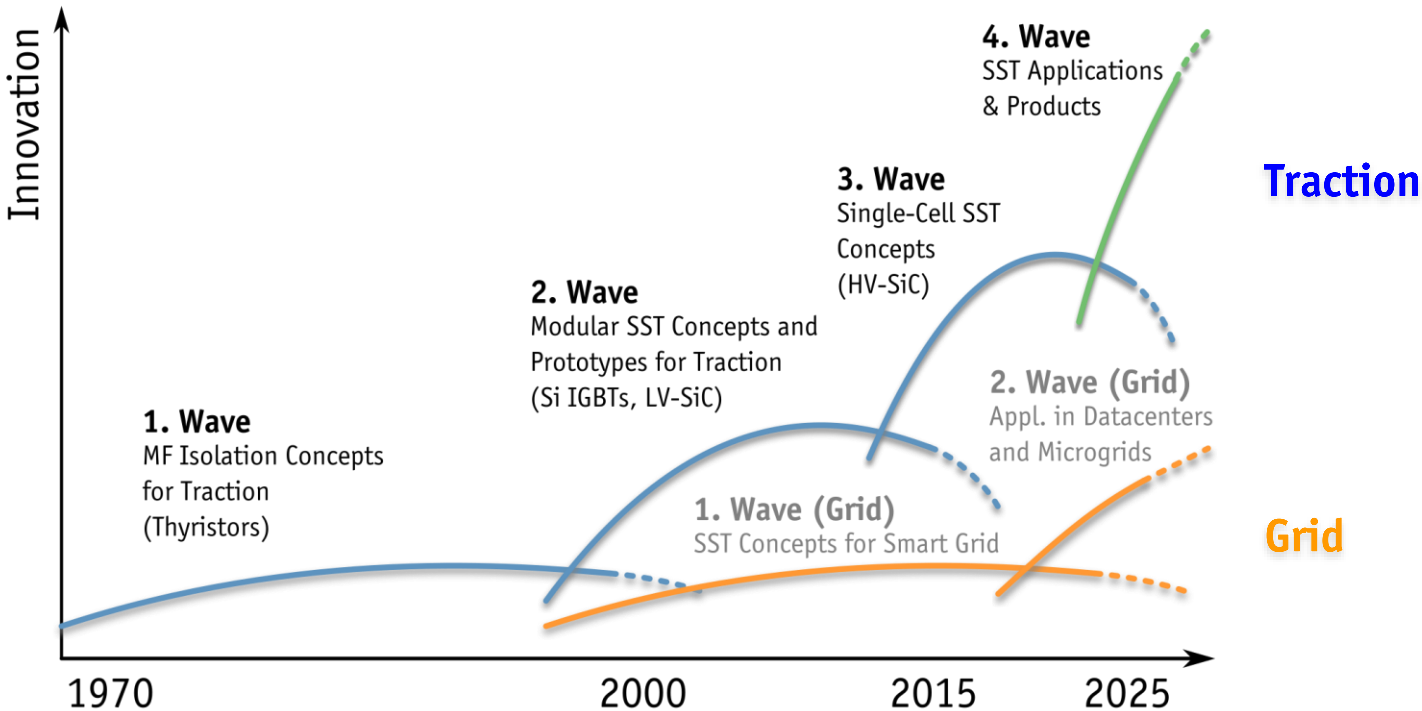
- MV (High) Power Electronics incl. Testing
- Digital Signal Processing (DSP & FPGA)
- MF High Power Magnetics
- Isolation Coordination / Materials
- Power Systems
- etc.

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

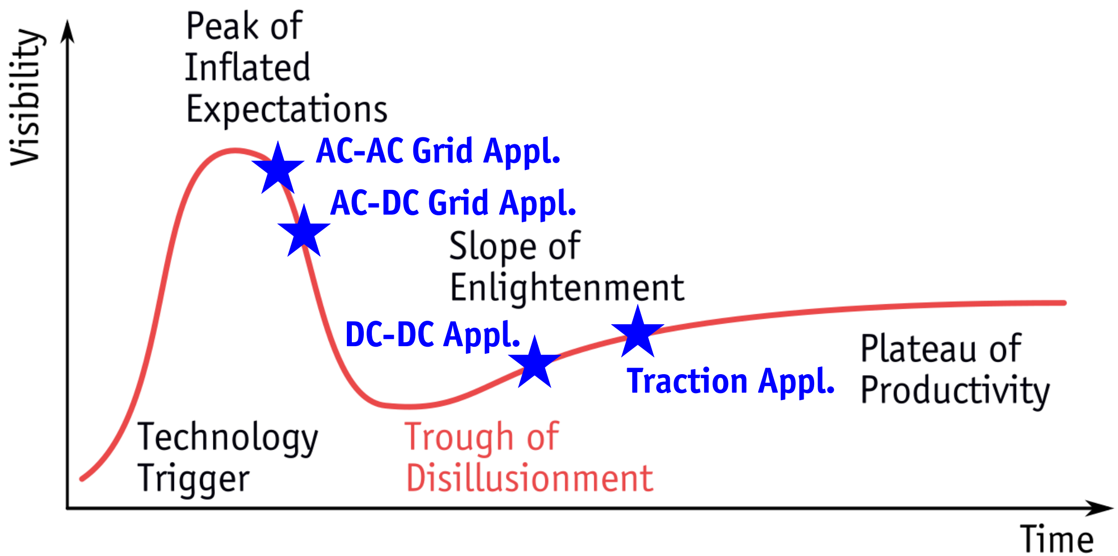


Tomas Griger / 123RF Stock Photo

► Waves of SST Innovations



▶ SST Technology Hype Cycle



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

► SST for Future Grid Applications

SST Research Status

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

Required for Successful Application

- Huge Multi-Disciplinary Challenges / Opportunities (!)

Thank You!

Questions?

Source: Saddington Baynes / tmar.com

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- *Thomas Guillod*
- *Daniel Rothmund*

for their contributions.

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