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SPEC

Tutorial No. 6

# Fundamentals and Application-Oriented Evaluation of **Solid-State Transformer Concepts**

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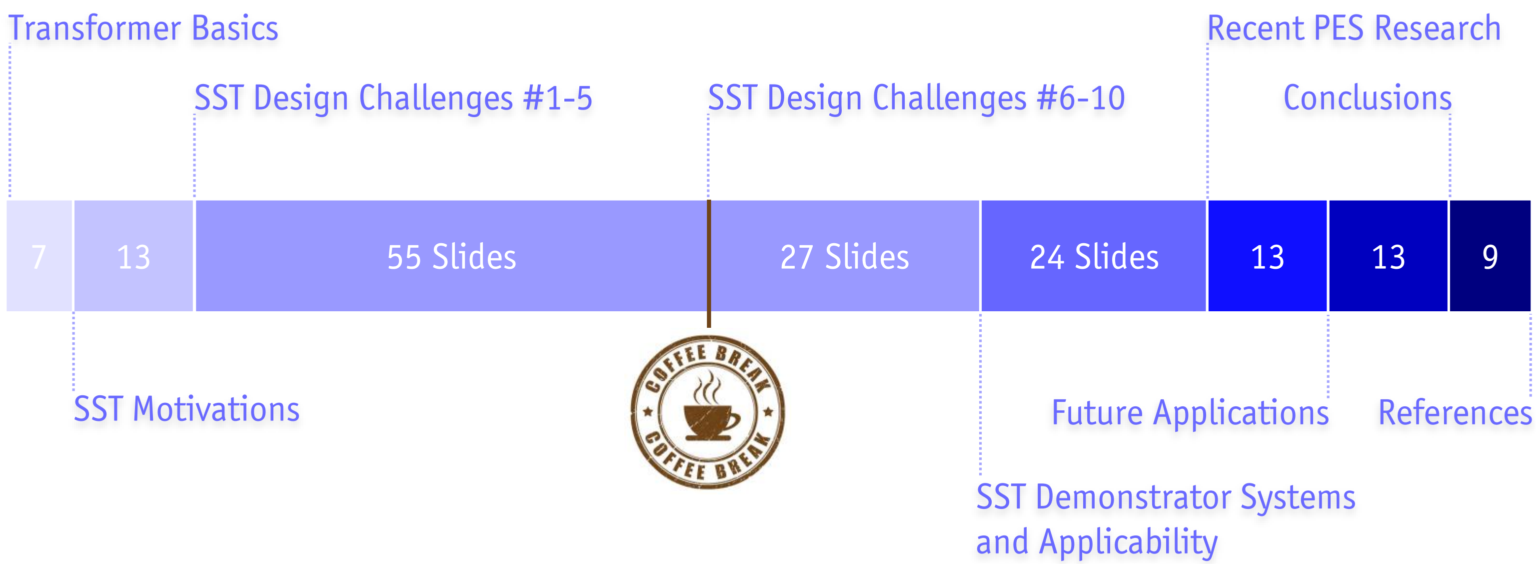
Power Electronic Systems Laboratory
ETH Zurich, Switzerland

# Agenda

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# Transformer Basics

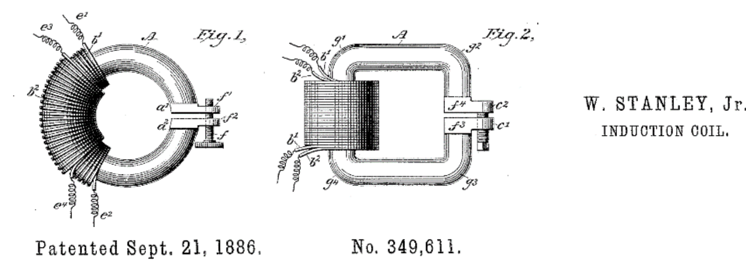
*History*
*Scaling Laws*
*Efficiency/Power Density Trade-Off*

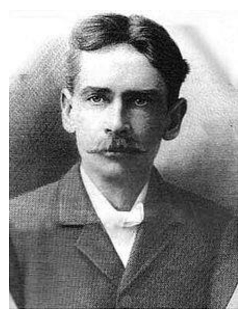
# ▶ Classical Transformer — History (1)

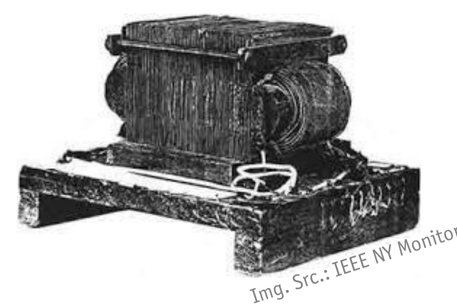
| | | |
|---|---|---|
| ■ 1830 | Henry / Faraday | → Property of Induction |
| ■ 1878 | Ganz Company (Hungary) | → Toroidal Transformer (AC Incandescent Syst.) |
| ■ 1880 | Ferranti | → Early Transformer |
| ■ 1882 | Gaulard & Gibs | → Linear Shape XFMR (1884, 2kV, 40km) |
| ■ 1884 | Blathy / Zipernowski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

Europe

USA






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

[Stanley1886]

# ▶ Classical Transformer — History (2)

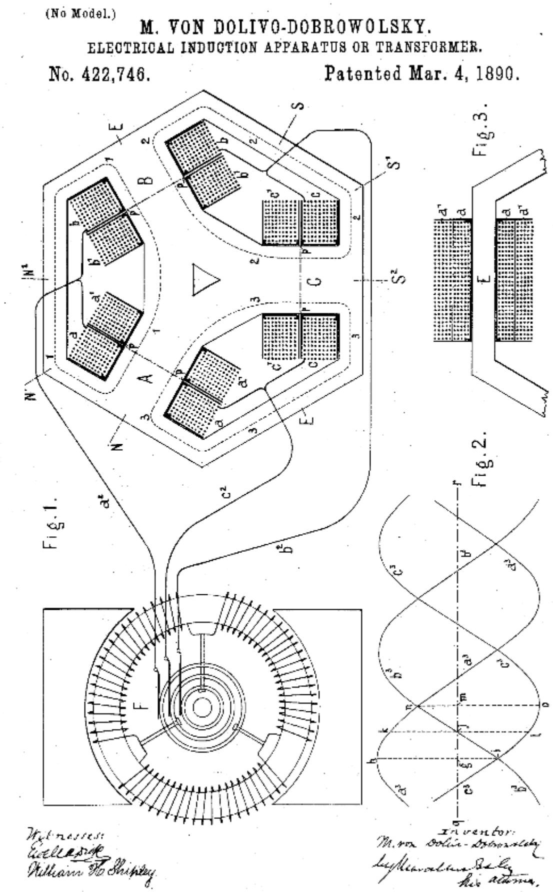
UNITED STATES PATENT OFFICE.

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)

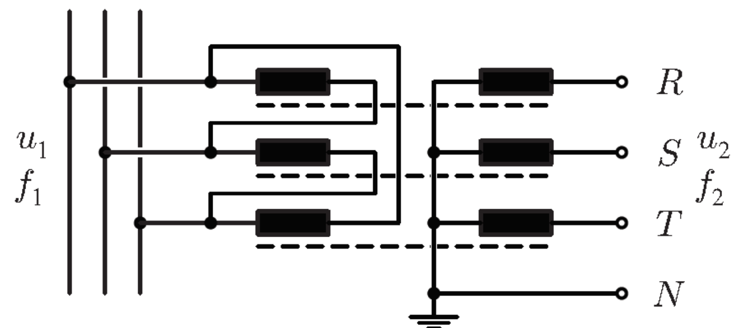
[Dobrovolski1890]

# ▶ Classical Transformer – Basics (1)

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

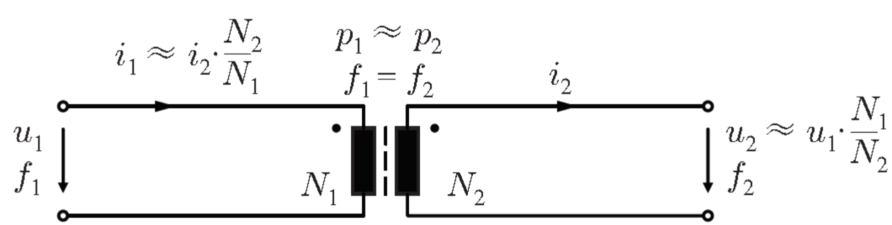
- **Operating Frequency** • 50/60Hz (El. Grid, Traction) or $16^2/_3$Hz (Traction)
- **Operating Voltage** • 10kV or 20kV (6...35kV) • 15kV or 25kV (Traction) • 400V

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

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



# ► Classical Transformer – Basics (2)

Source: www.faceofmalawi.com

## ■ Advantages

- Relatively Inexpensive
- **Highly Robust / Reliable**
- Highly Efficient
- Short Circuit Current Limitation

# ▶ Classical Transformer – Basics (3)

## ■ Advantages

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

## ■ Weaknesses

- Voltage Drop Under Load
- Losses at No Load
- Not Directly Controllable
- Dependency of Weight / Volume on Frequency
- Sensitivity to DC Offset Load Imbalances
- Sensitivity to Harmonics

## ■ Construction Volume

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

↑ ↑ ↑

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

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

**Vacuum Cast Coil Dry-Type Distribution Transformer**


**1 MVA – 12kV/400V @ 2600kg**
**0.2%/1% Losses @ No/Rated Load**

# ▶ Classical Transformer – Basics (4)

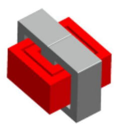
■ **Construction Volume**

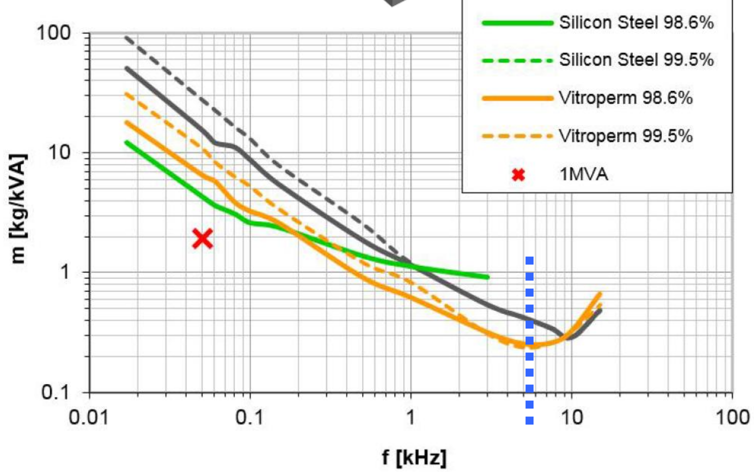
$$A_{\mathrm{Core}}A_{\mathrm{Wdg}} = \frac{\sqrt{2}}{\pi}\frac{P_{\mathrm{t}}}{k_{\mathrm{W}}J_{\mathrm{rms}}\hat{B}_{\max}f}$$

↑ ↑ ↑

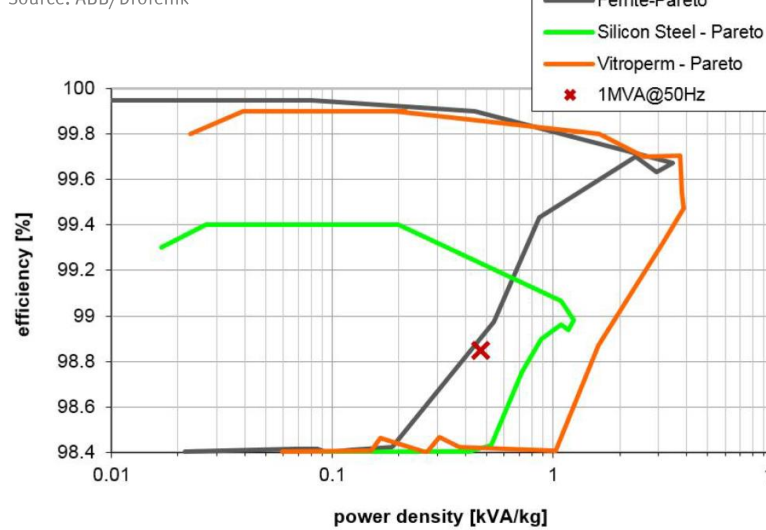
$P_{\mathrm{t}}$ .... Rated Power
$k_{\mathrm{W}}$ .... Window Utilization Factor
$B_{\max}$ ..Flux Density Amplitude
$J_{\mathrm{rms}}$... Winding Current Density
$f$ ..... Frequency

180kVA
Weight-Optimized
Air-Cooled / Insulation
Forced Convection
x ... 50Hz / Oil
...... Therm. Limit






Source: ABB/Drofenik




■ Higher Frequency → **Lower Weight/Volume**

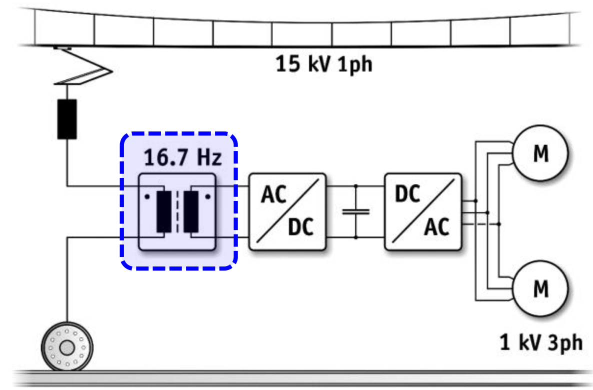
■ Higher Volume → **Higher Efficiency**

# SST Concept Motivations

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

# ▶ Classical Locomotives

- 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** $$A_{\mathrm{Core}} A_{\mathrm{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_{\mathrm{t}}}{k_{\mathrm{W}} \boldsymbol{J}_{\mathbf{rms}} \hat{\boldsymbol{B}}_{\mathbf{max}} f}$$

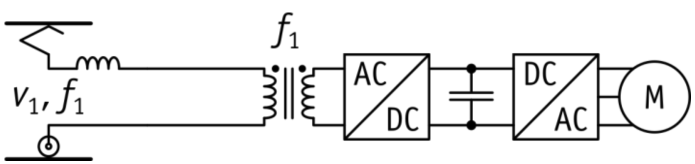
Img.: www.abb.com

**→ Volume/Weight Reduction By Increasing $J_{rms}$**

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

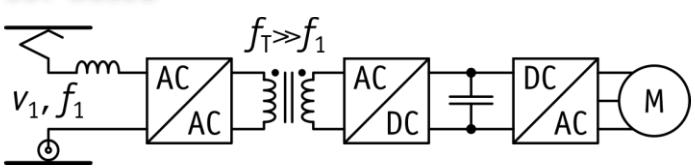
# ▶ Next Generation Locomotives (1)

- **Trends**
  - Distributed Propulsion → Volume Reduction (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.)



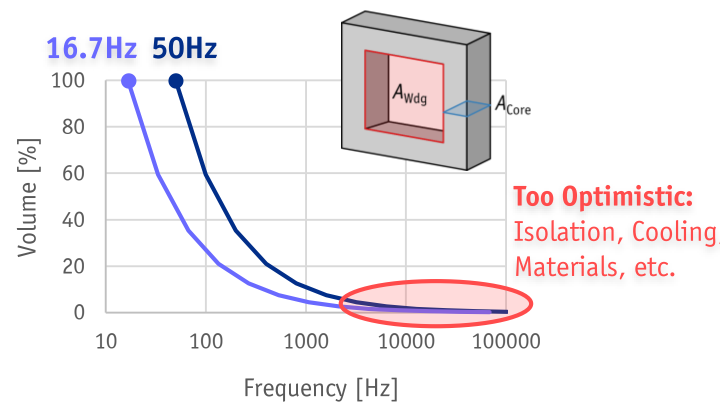

Conventional

SST-Based




- **Construction Volume of Transformer**

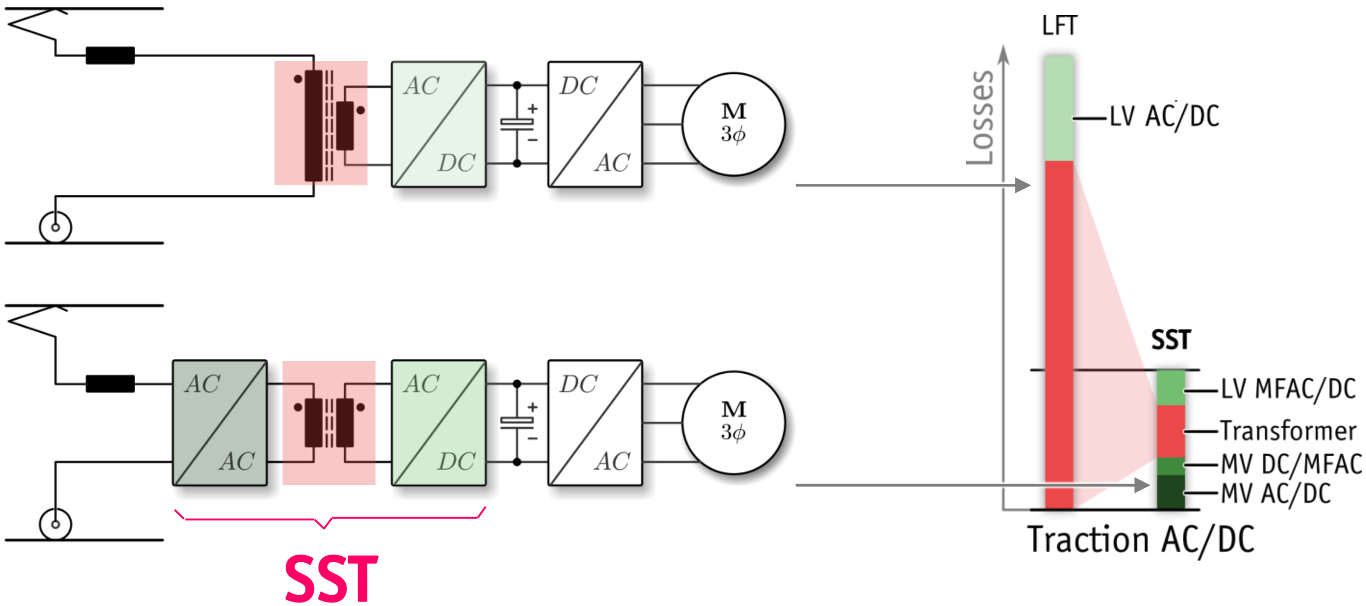
$$V \propto (A_{\mathrm{Core}} A_{\mathrm{Wdg}})^{\frac{3}{4}} \propto \frac{1}{f^{3/4}} \quad \text{(Same Power)}$$




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

# ▶ Next Generation Locomotives (2)

- Drivetrain Loss Distribution of Conventional Locomotives & Next Generation Locomotives




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

# SST Concept Motivations

Source: TU Munich

*Traction → Weight & Volume*

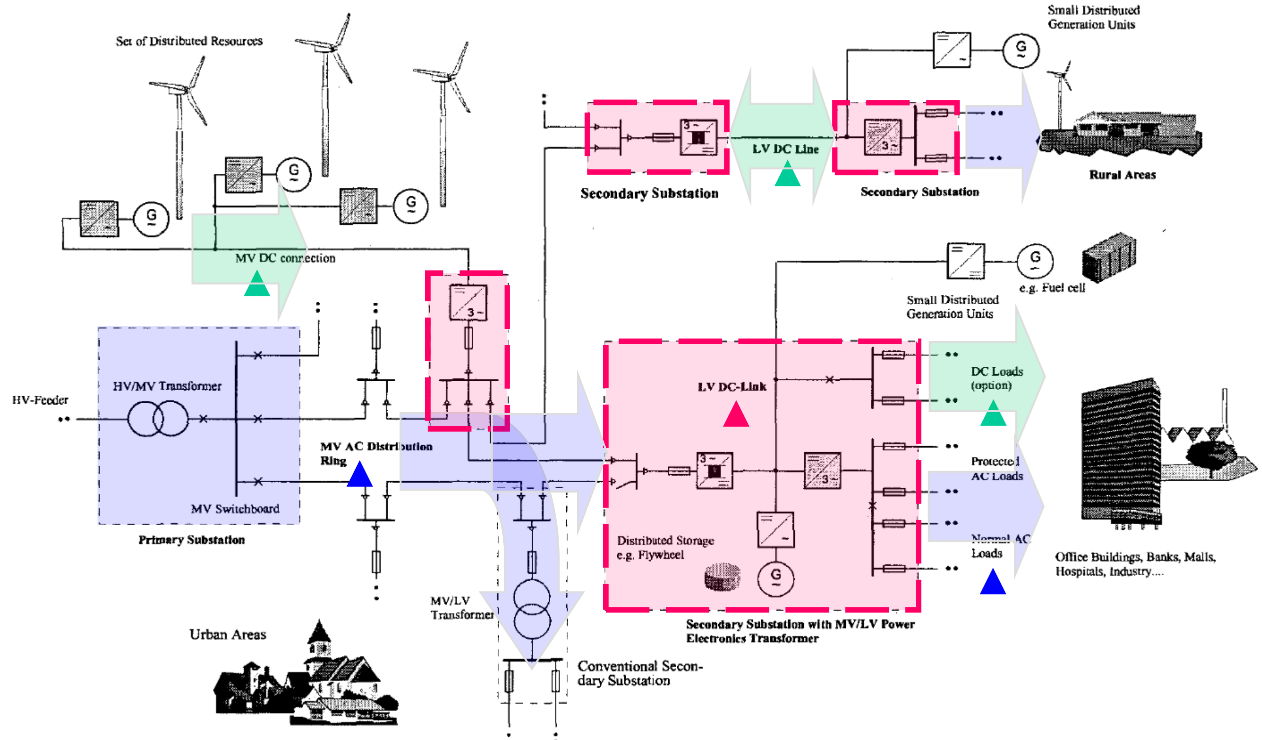
***Smart Grid → Controllability***

*DC-DC Conversion*

*Terminology*

# ▶ Advanced (High Power Quality) Grid Concept

- Heinemann / ABB **(2001)**




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

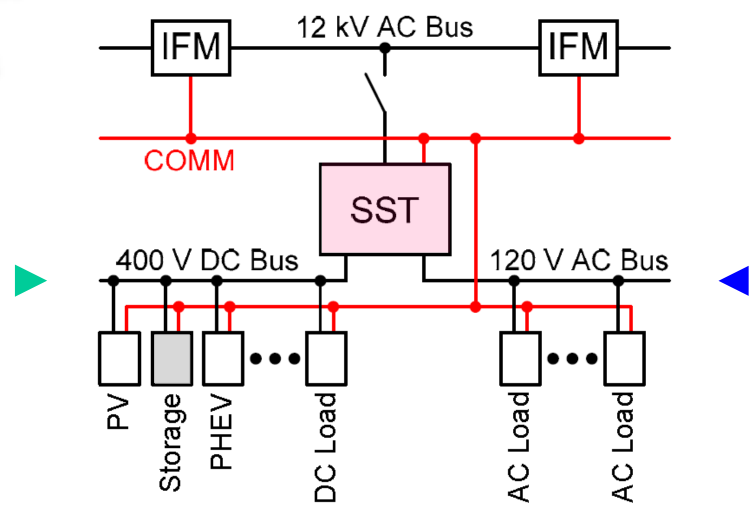
[Heinemann2001]

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

- Huang et al. (2008)

- **SST as Enabling Technology for the "Energy Internet"**
  - Full Control of the Power Flow
  - Integr. of DER (Distr. Energy Res.)
  - Integr. of DES (Distr. E-Storage) + Intellig. Loads
  - Protects Power System From Load Disturbances
  - Protects Loads from Power System Disturbances
  - Enables Distrib. Intellig. through COMM
  - Ensure Stability & Opt. Operation
  - etc.
  - etc.

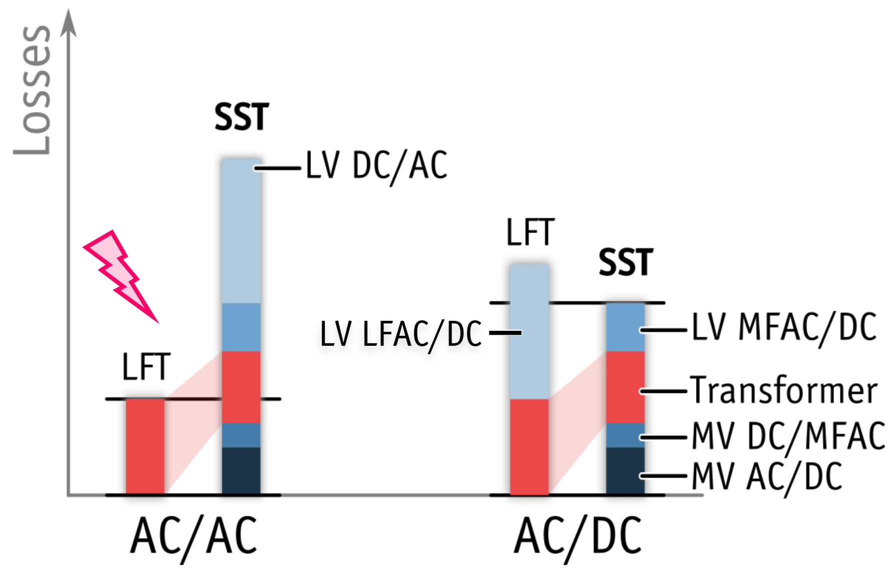
**IFM** = Intellig. Fault Management




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

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

# ▶ "Efficiency Challenge" (Qualitative)



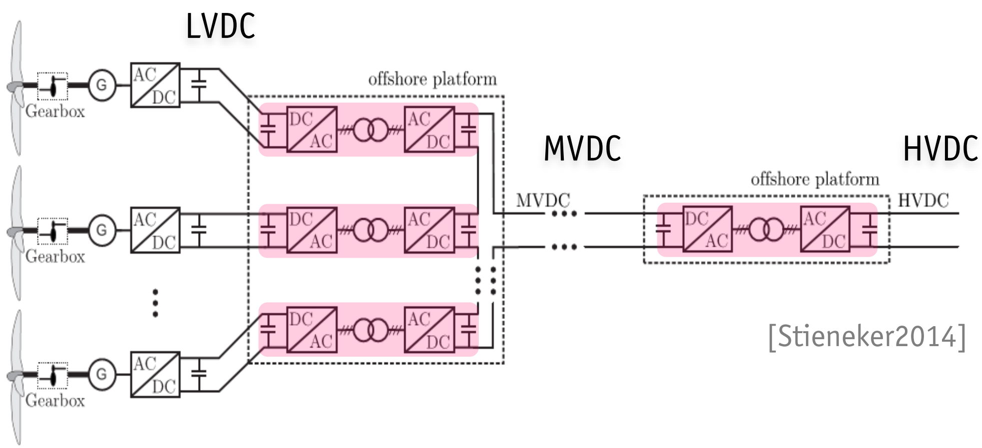

## ■ SSTs in Grid Applications – A Skeptic's View

- **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***
*Terminology*

# ▶ Isolated DC-DC Applications




■ **Examples**

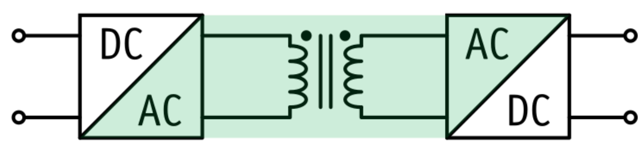
- In-Building DC Microgrids
- DC Collection Grids (Wind, PV)
- Future DC Grids in General

■ DC Systems With Requirements for
- Galvanic Separation
- High Voltage Transfer Ratios

→ **Isolated DC-DC Conversion = SST!**

■ Not Limited to MV Connection (Overlap With PSUs)

MVDC




LVDC

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

# SST Concept Motivations

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

# ▶ Terminology (1)

**United States Patent** [19]   [11] **4,347,474**

**Brooks et al.**   [45] **Aug. 31, 1982**

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

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

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

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

[22] Filed: **Sep. 18, 1980**

"… Solid State Regulated Power Transformer …"

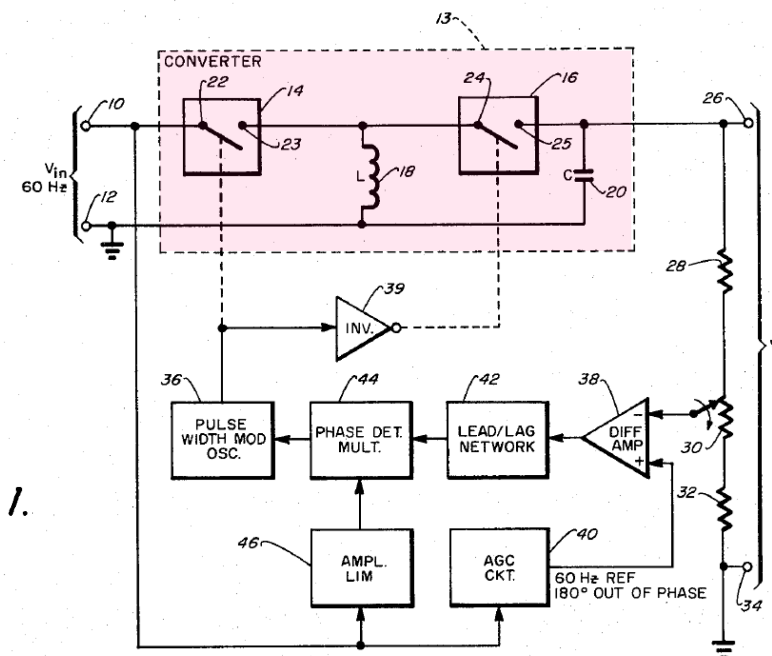
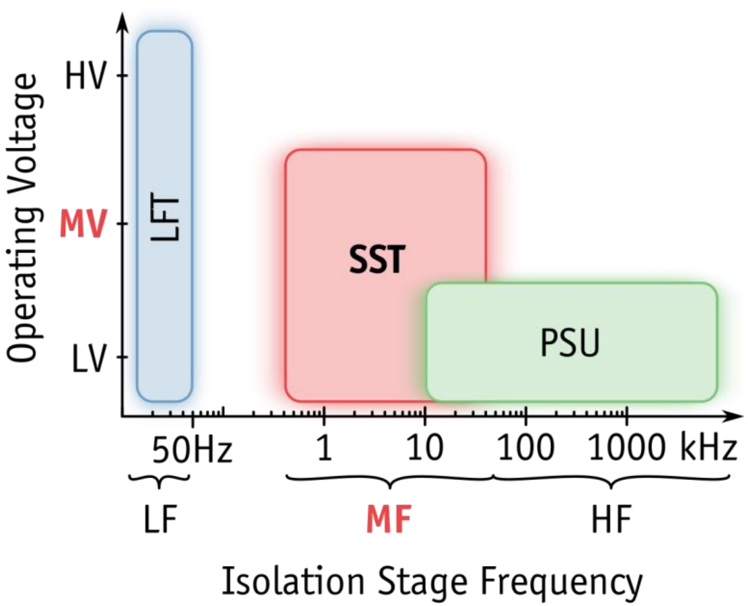


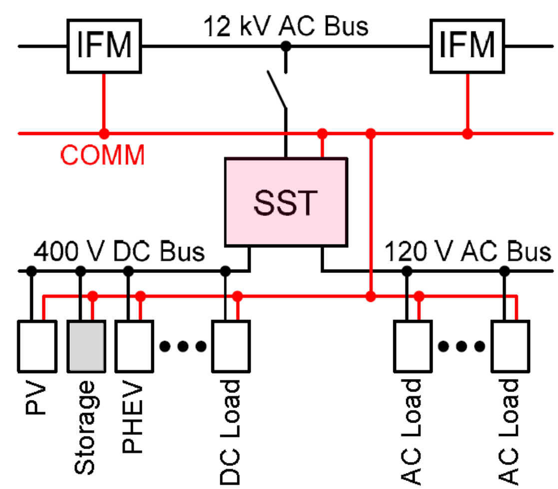

*Fig. 1.*

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

# ▶ Terminology (2)

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




[Brooks1980]

# 10 Key Challenges of SST Design

1. *Handling of Medium Voltage*
2. *5 Main SST Topologies*
3. *Reliability*
4. *MF Isolation*
5. *MF Transformer Design*
6. *Isolation Coordination*
7. *EMI*
8. *Protection*
9. *Control*
10. *Construction & Testing*

# Challenge #1/10

# Handling of Medium Voltage

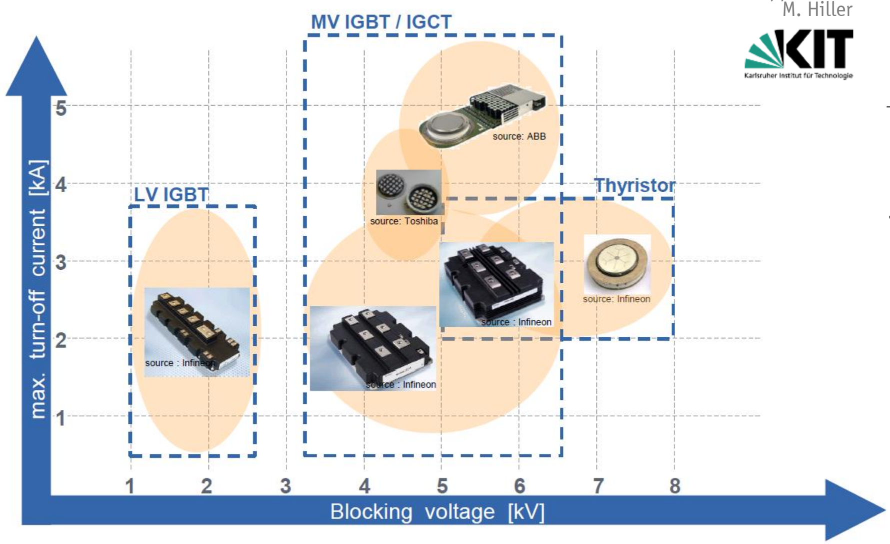
*Multi-Cell Approaches*
*Optimum Number of Cells*
*Single-Cell Approaches*
*Outlook*

# ▶ Available Si Power Semiconductors

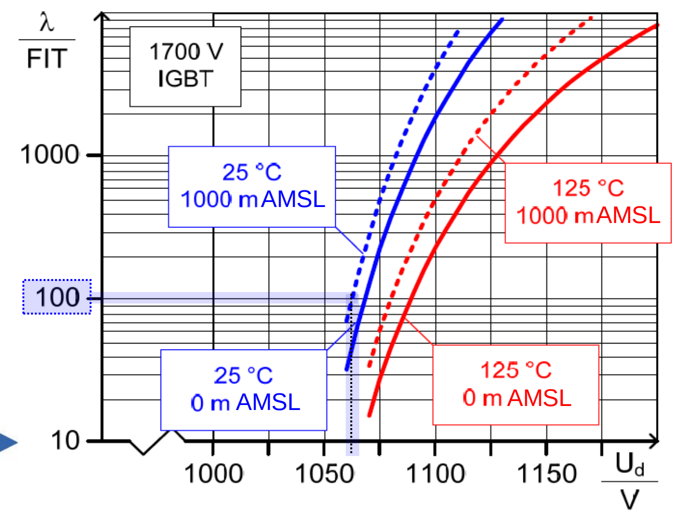
■ **1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications**

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

Source: M. Doppelbauer
M. Hiller



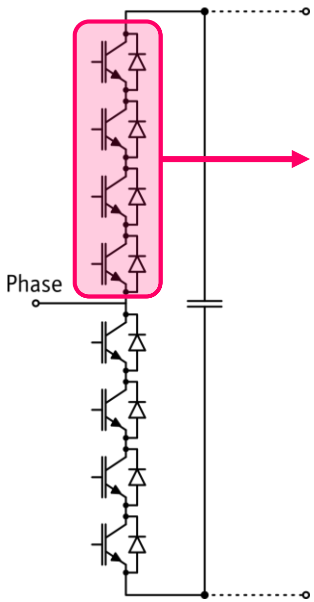

Source: H.-G. Eckel
Univ. Rostock



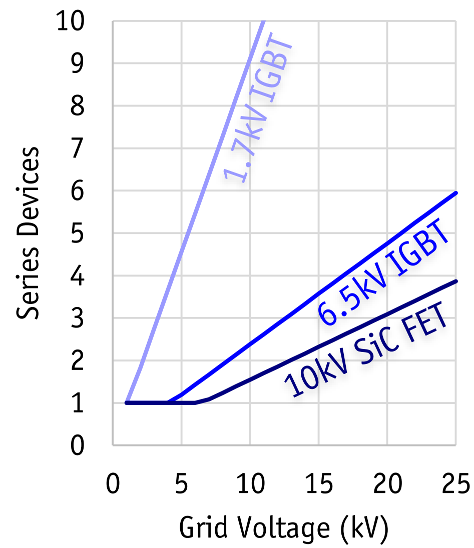

■ Interfacing to Medium Voltage → **Multi-Level Converter Topologies**

# ► Interfacing to Medium Voltage (1)

- 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)



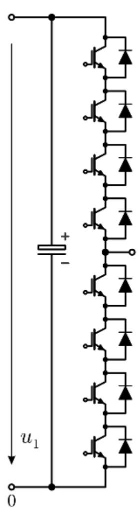

- **A Single Device Is Often Not Sufficient!**



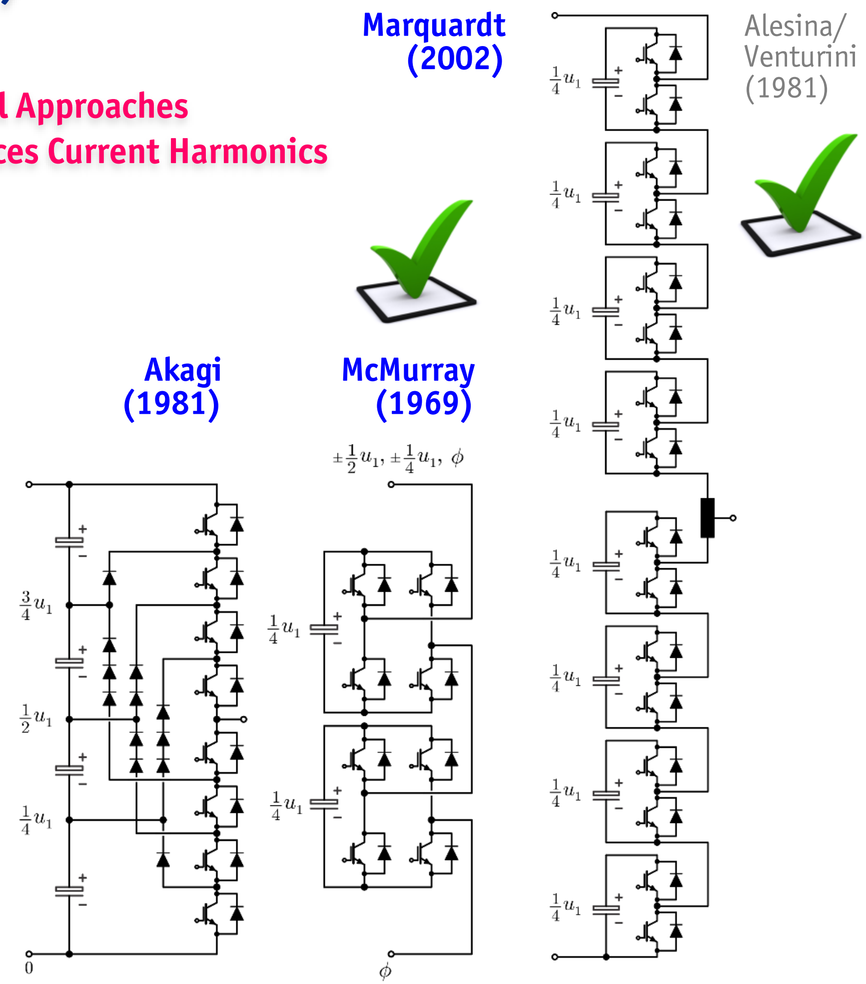

Mod. Index.: 0.8
Blocking Voltage Utilization: 0.66

# ▶ Interfacing to Medium Voltage (2)

- Partitioning of Blocking Voltage
- Series Connection or **Multi-Level and Multi-Cell Approaches**
- **High Number *N* of Cells → Quadratically Reduces Current Harmonics**




- Two-Level Topologies




- Multi-Level/Multi-Cell Topologies

# United States Patent

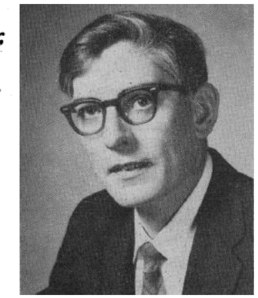
[11] **3,581,212**

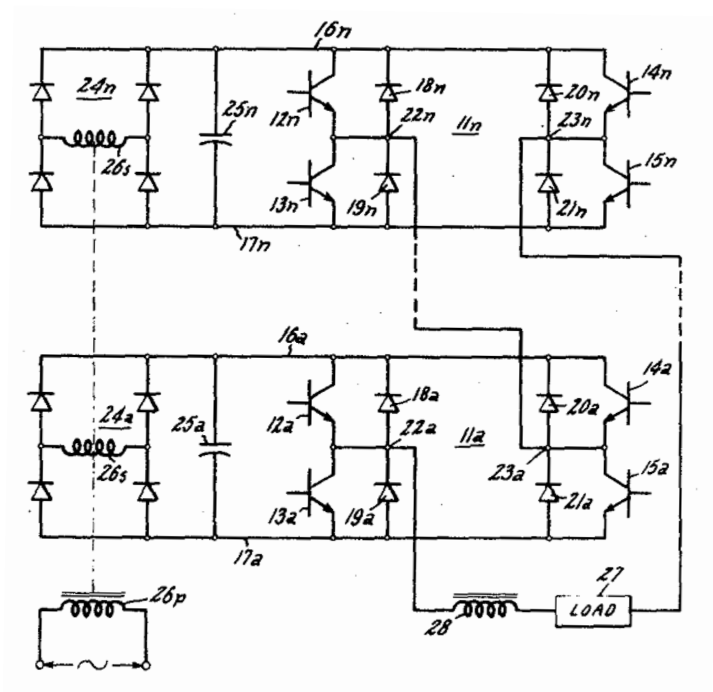
[54] **FAST RESPONSE STEPPED-WAVE SWITCHING POWER CONVERTER CIRCUIT**

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

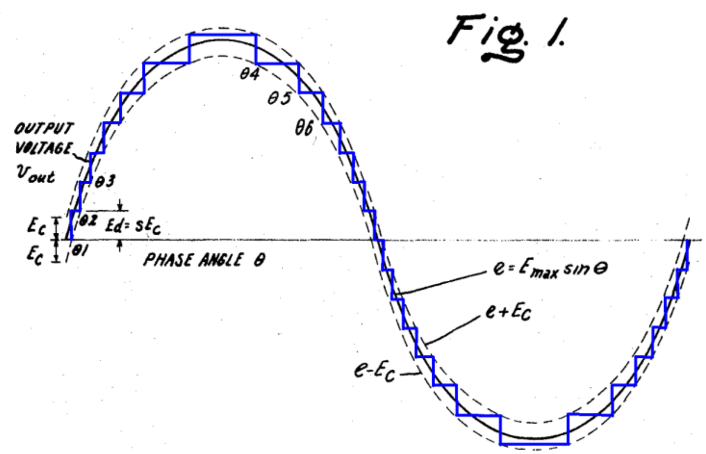
**1969 !**

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






- **Cascaded H-Bridge** Multi-Cell Converter
- Fully Modular System

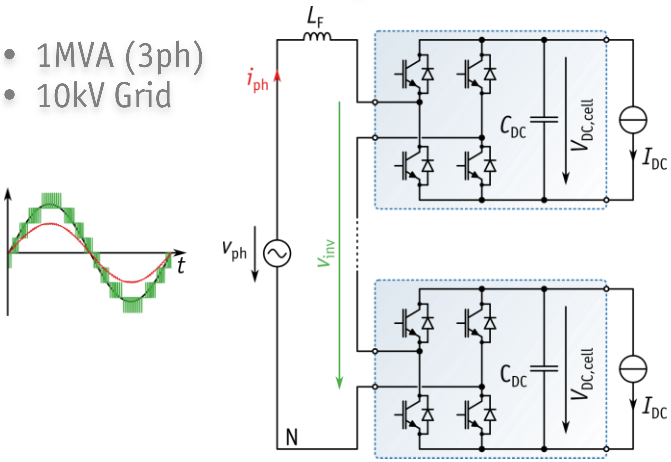



[McMurray1969]

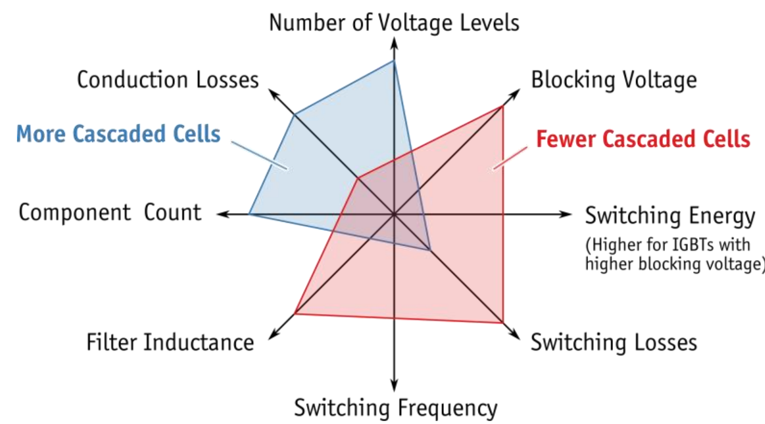
# ▶ Optimum Number of Cascaded Cells (1)

■ Generic Cascaded H-Bridges AC-DC Converter

- 1MVA (3ph)
- 10kV Grid



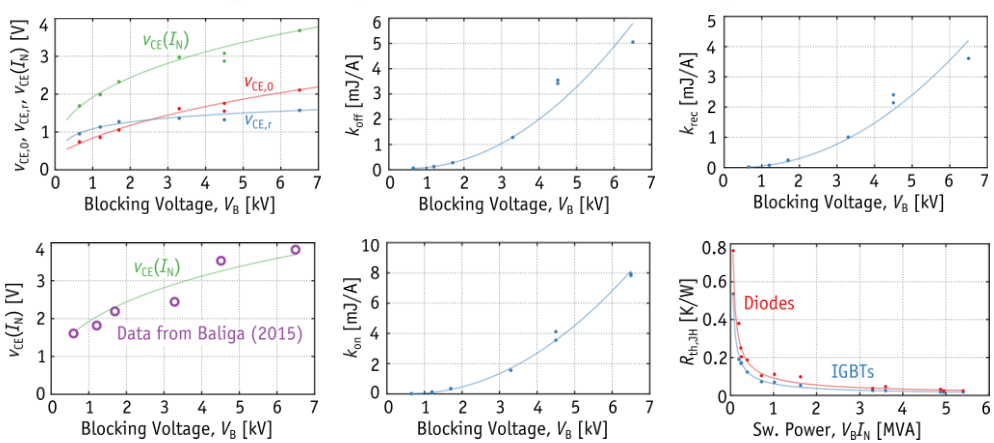

■ **Affected Trade-Offs (Qualitative)**




■ **Scaling of Silicon IGBT & Diode Parameters** → Physics-Inspired Models Fitted To Empirical Data

- Junction Voltage
- On-State Resistance
- Specific Switching Losses
- Thermal Resistances

*f*( **Blocking Voltage,** Current Rating )

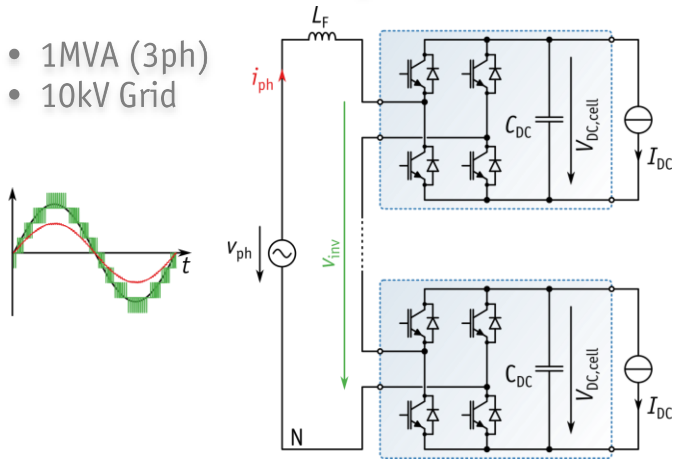



[Huber2016b]

# ▶ Optimum Number of Cascaded Cells (2)

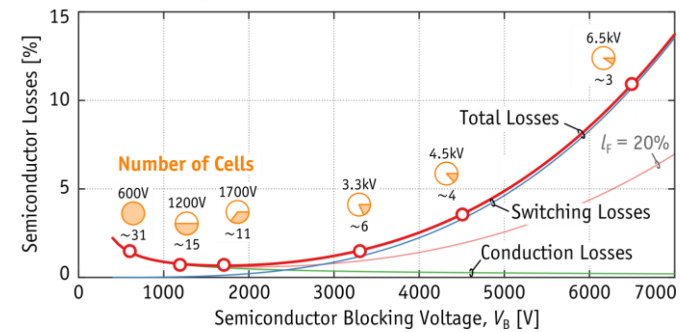
■ Generic Cascaded H-Bridges AC-DC Converter

- 1MVA (3ph)
- 10kV Grid




■ **Analytic 1D Optimization**

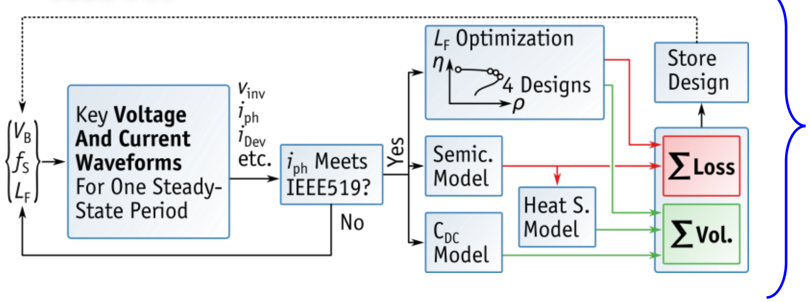
- Constant Total Chip Area
- Constant $L_F$ and Current Ripple

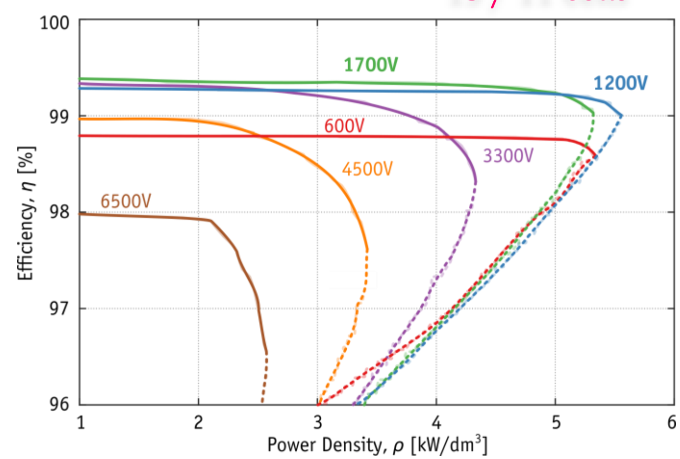



**10kV Grid** **Optimum: 1200V / 1700V**
15 / 11 Cells

■ **Full 2D $\eta\rho$-Pareto Optimization**

- Constant Total Chip Area
- IEEE 519

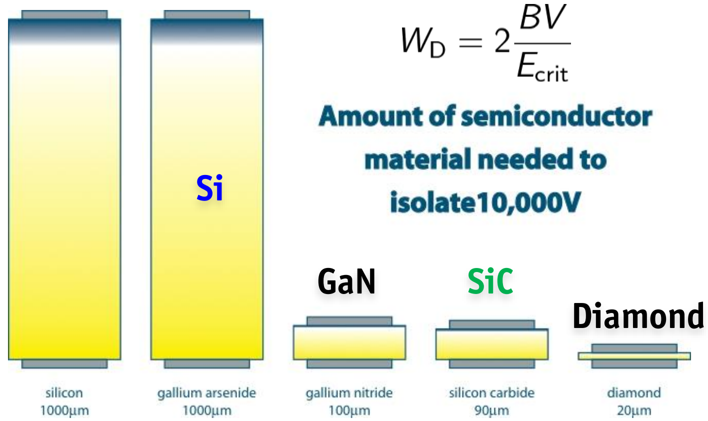



[Huber2016b]

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

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




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

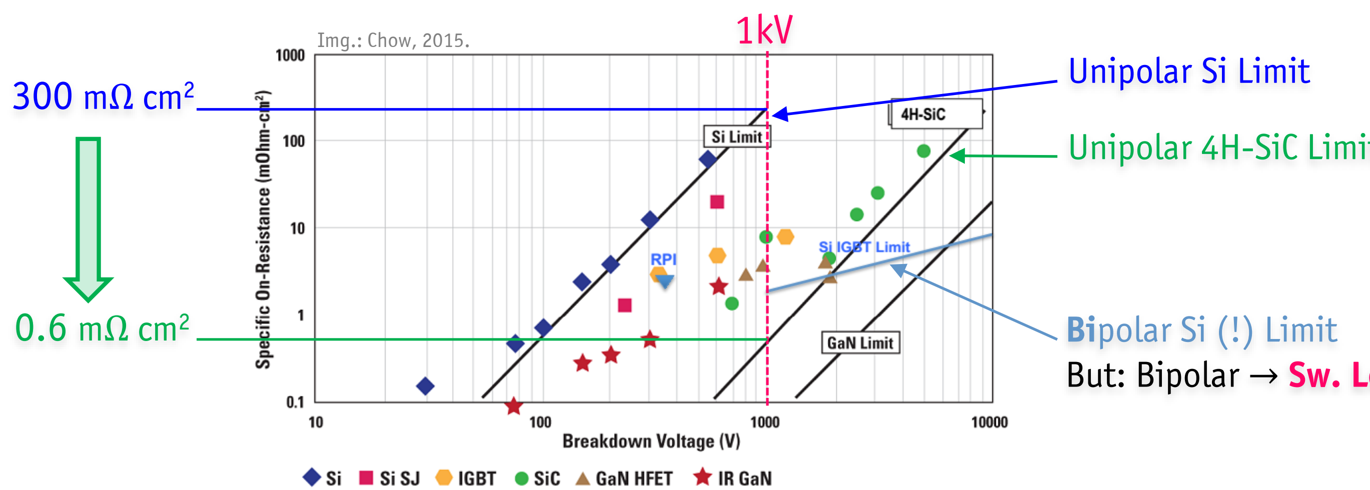
- Specific On-State Resistance

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

Blocking Voltage

Critical Electric Field

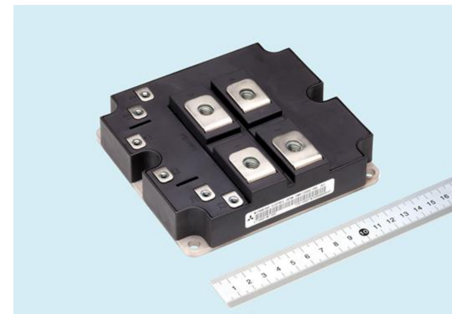
- $E_C$ in SiC ca. 9x Larger Than in Si
- **Lower $R_{on,sp}$ For Given Blocking Voltage**




But: Bipolar → **Sw. Losses!**

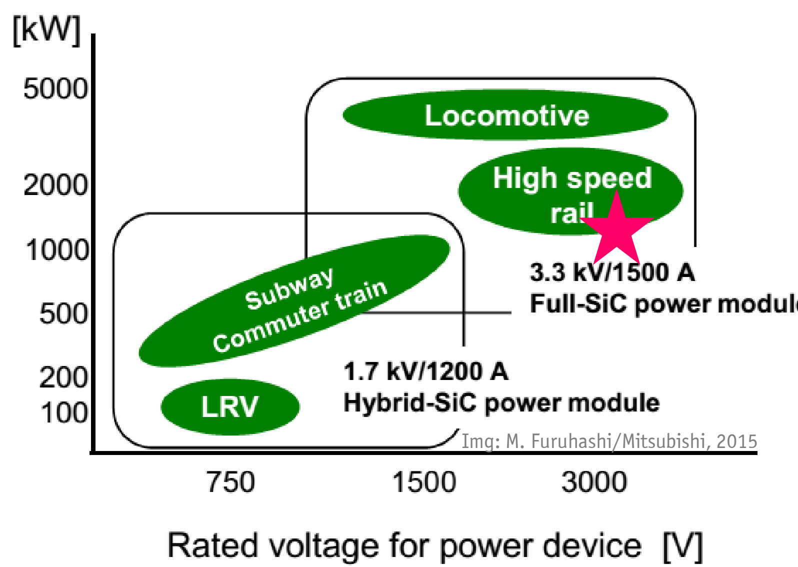
## ► Example: All-SiC Traction Inverter

- 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

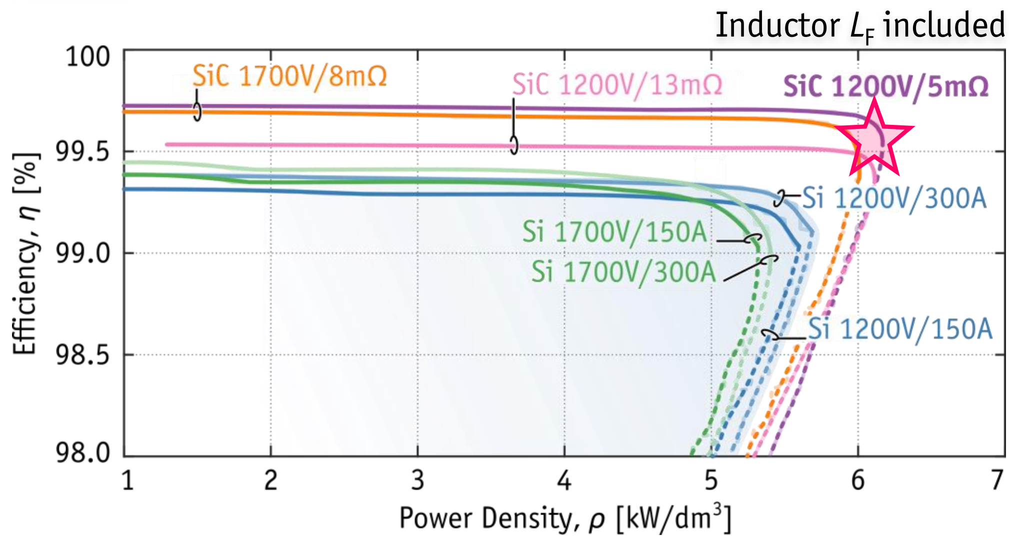



Img: M. Furuhashi/Mitsubishi, 2015

# ▶ Optimum Number of Cascaded Cells using LV SiC

- 1200V and 1700V SiC FET Power Modules
  - Commercially Available
  - "Drop-In" Replacement

Wolfspeed 1200V/5mΩ ▼



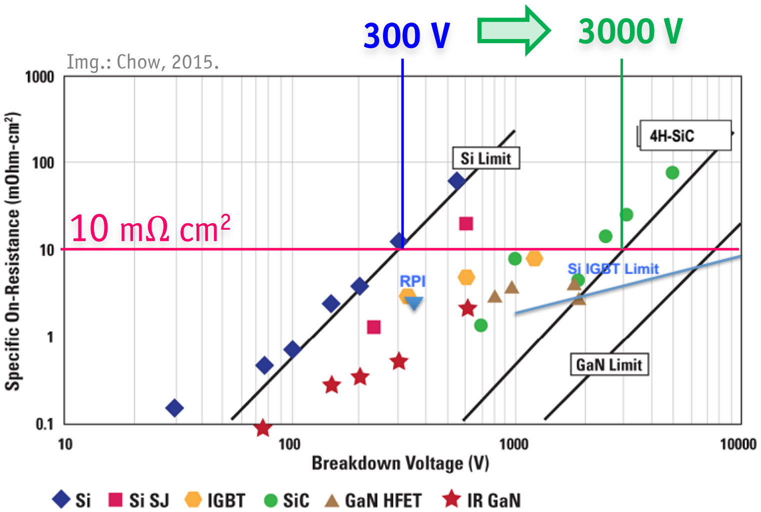

- **Caution:** Minimum Filter Inductance Might be Defined By Application-Dependent **Protection Considerations**
- **Si IGBT → SiC Transition Yields Significant Benefits!**

**Further Reading:** ETH / [Huber2016b]

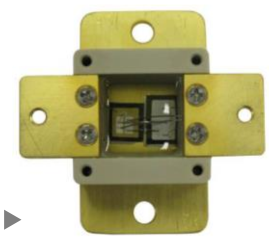
# ▶ Enter HV SiC Power Semiconductors

- $E_C$ 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

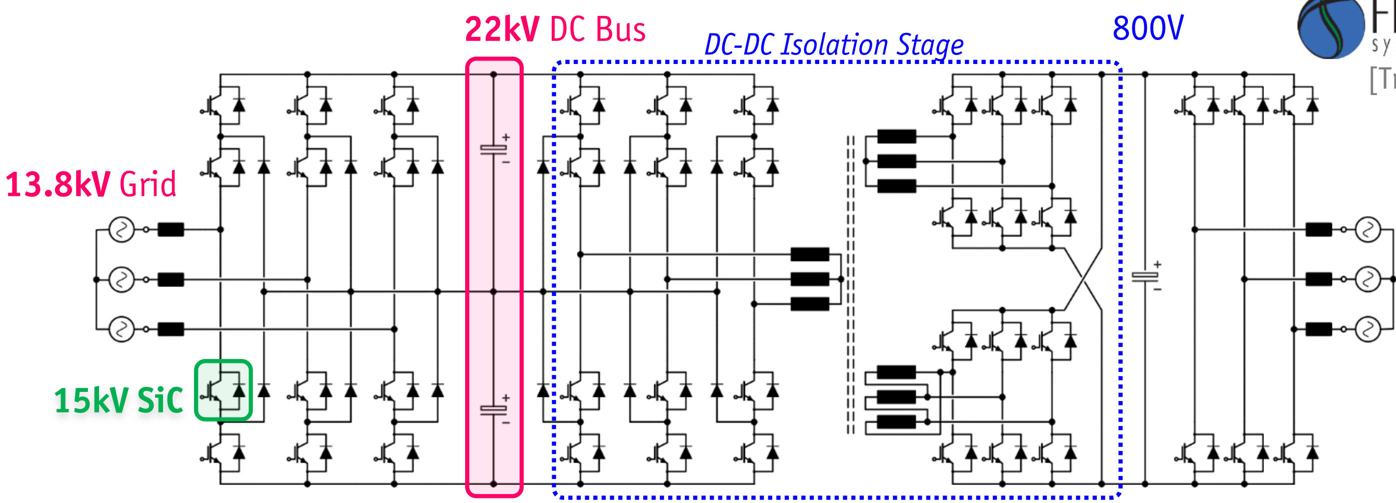


10kV SiC MOSFET ▶
(Wolfspeed)

- Challenging HV **Packaging**

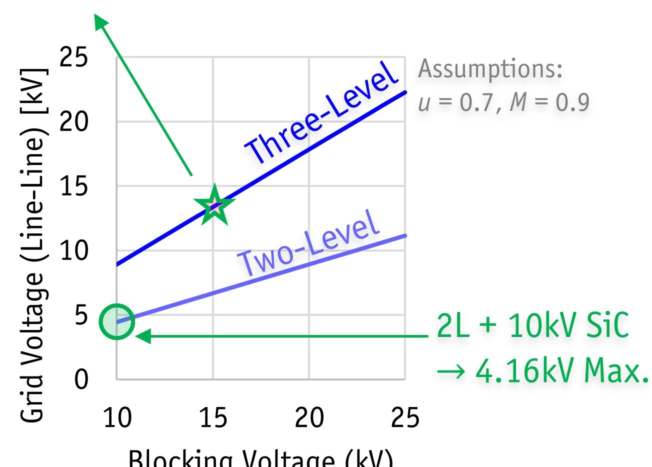

15kV/80A Package ▶
(Wolfspeed)

# ▶ Single-Cell Approach: Positive Aspects




FREEDM systems center
[Tripathi2012]

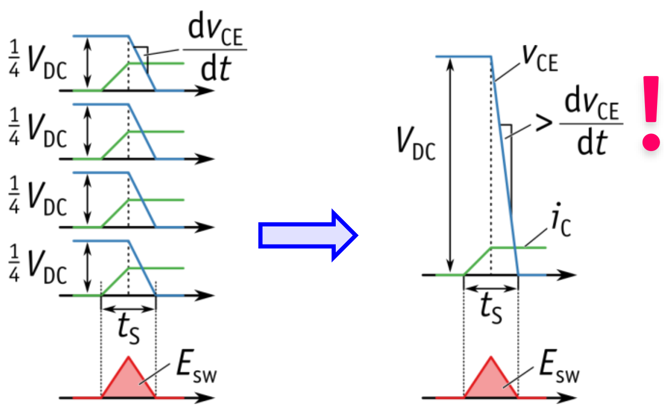
- Standard Inverter Topologies Can Be Employed (Two-Level, Three-Level)
- Comparably **Low System Complexity**
- **Three-Phase Inverter Stage** **→ Constant Power Flow In Isolation Stage (!)**
- Max. Feasible Grid Voltages Limited By Blocking Voltages

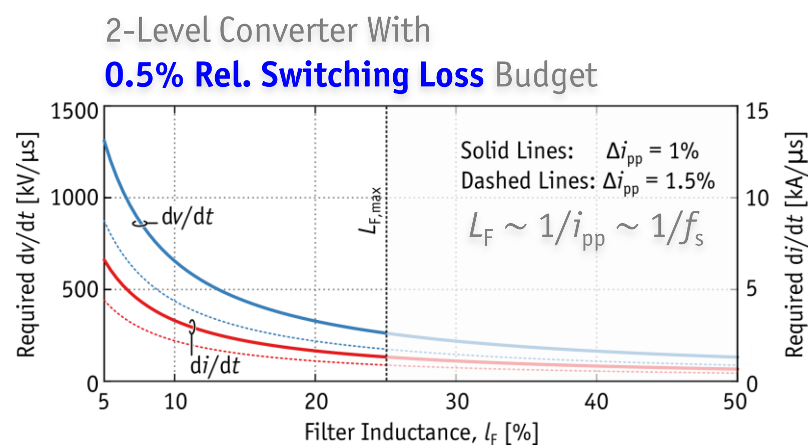


# ▶ Single-Cell Approach: Challenges

- Single Cell → Two-Level Output Voltage
- **High Switching Freq. and/or Large Filter Required**
  (Remember: $f_S \propto 1/n^2$)

- **High Switching Speeds to Limit Sw. Losses**




- Implementation of **Redundancy?**

- High $dv/dt$ → **CM Disturbances**
- High $di/dt$ → **Overvoltages**

Further Reading: ETH / [Huber2016b]

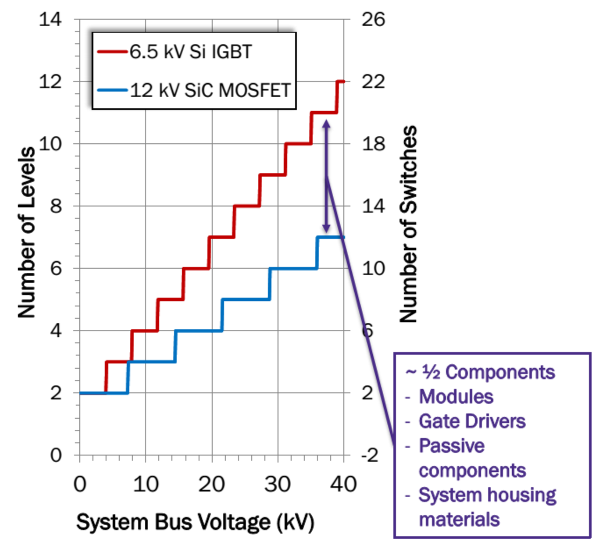
# ▶ Summary: Single-Cell vs. Multi-Cell

## ■ 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

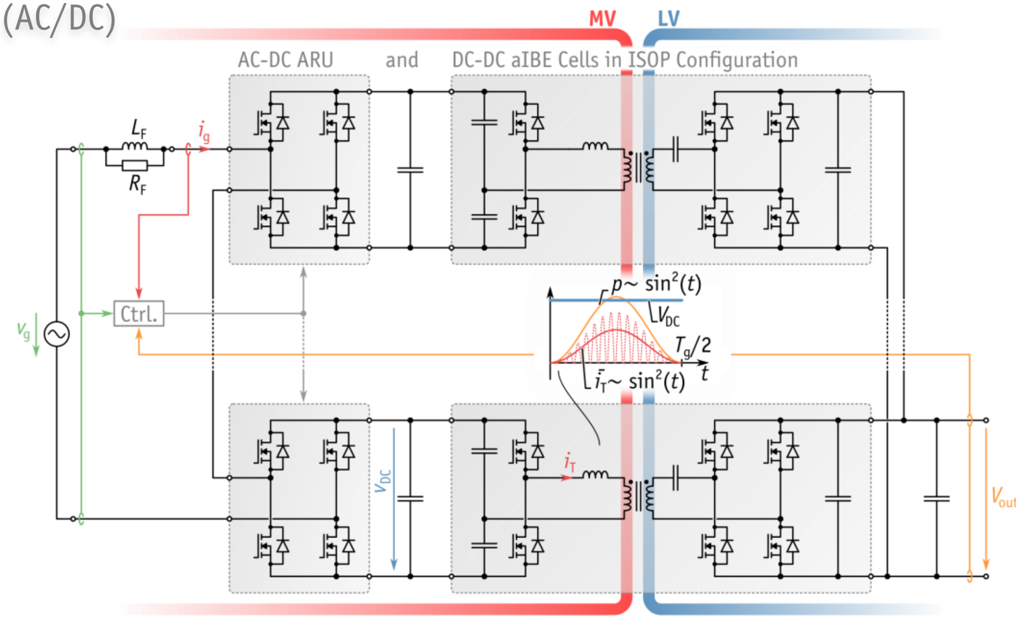
# Challenge #2/10

# 5 Main SST Topologies

*Isolated Back End (IBE)*
*Isolated Front End (IFE)*
*Matrix-Type*
*Modular Multilevel*
*Single-Cell*

# ▶ Main SST Topologies (1)

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




- **Main Characteristics**
  - Direct Grid Current Ctrl.
  - Most Frequently Used Top.

- 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]

# ▶ Partitioning of Single-Phase AC/DC PFC Functionality

## ■ Required Functionality

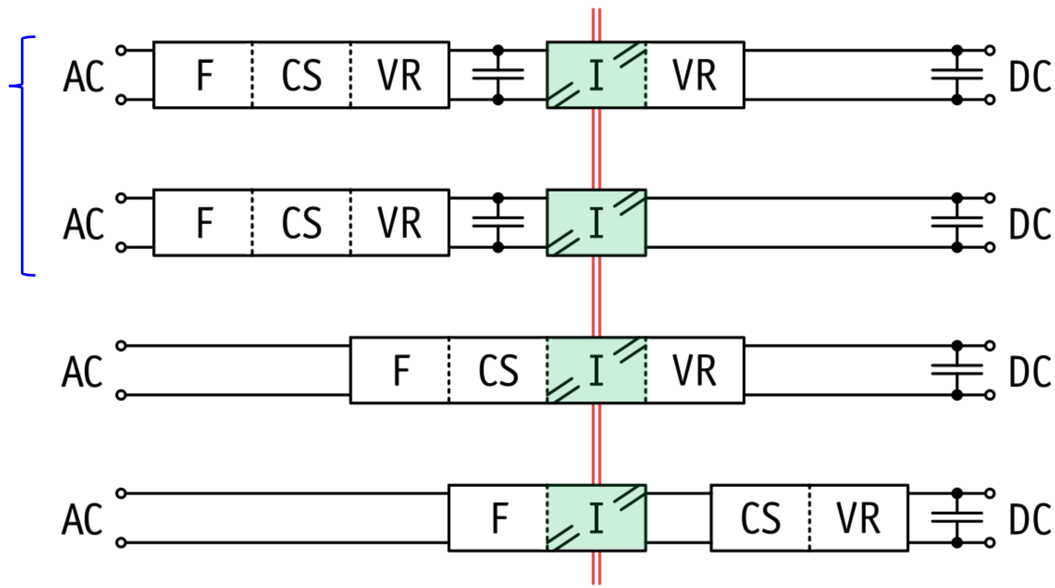
- **F**: Folding of the AC Voltage Into a |AC| Voltage
- **CS**: Input Current Shaping
- **I**: Galvanic Isolation & Voltage Scaling
- **VR**: Output Voltage Regulation

## ■ Isolated PFC Task Partitioning Variants

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

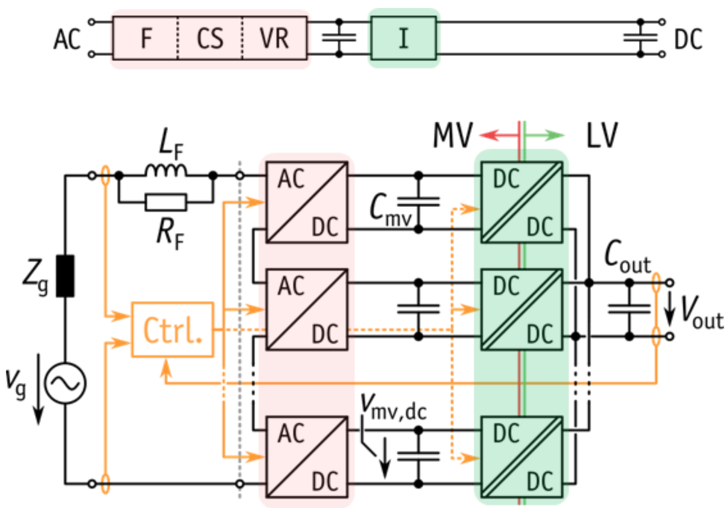
Fully Integrated ▶

**Isolated Front End (IFE)** ▶
→ Less Common Alternative

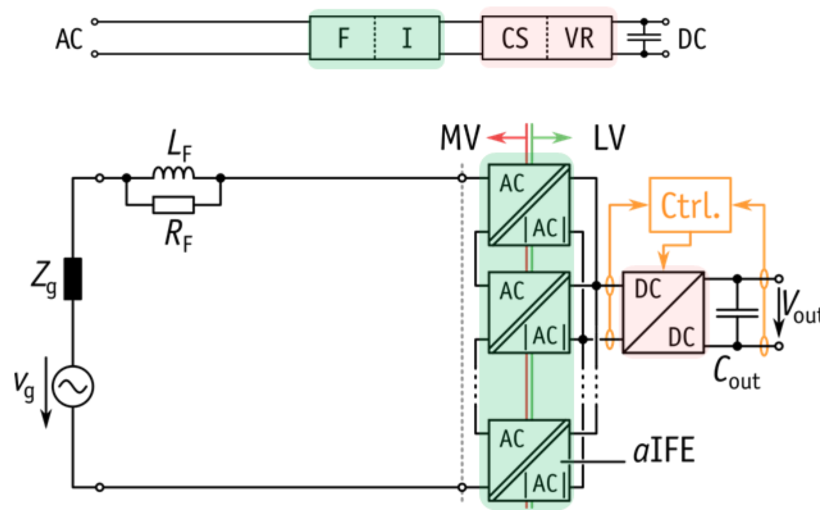


# ► Reversal of the Sequence of Current Shaping & Isolation

■ **Isolated DC-DC Back End**




■ **Isolated AC-|AC| Front End**




■ **Typical Multi-Cell SST Topology**

- Two-Stage Multi-Cell Concept
- Direct Input Current Control
- Indirect Output Voltage Control
- **High Complexity** on MV Side

■ **Swiss SST ($S^3T$)**

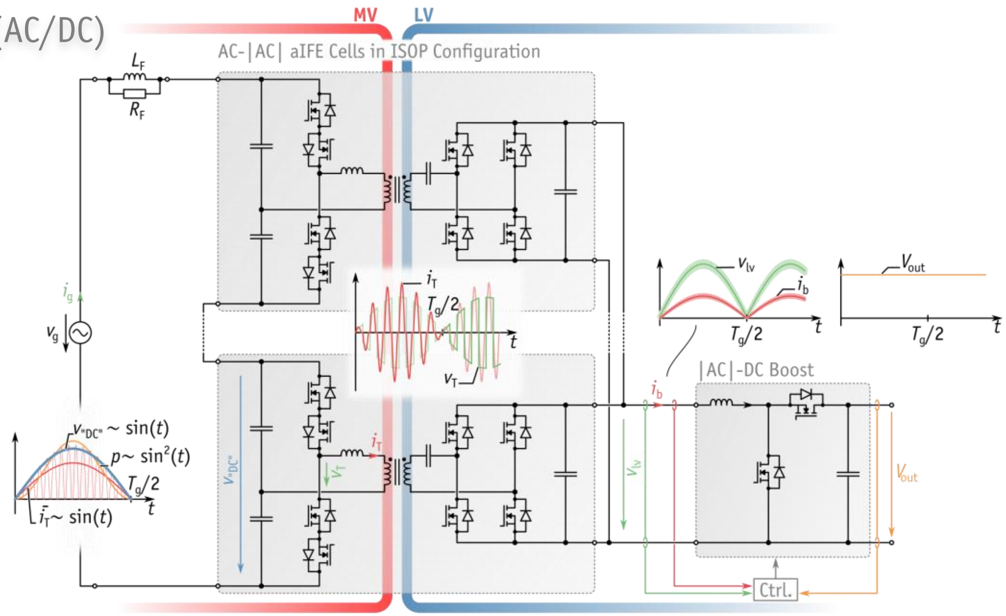
- Two-Stage Multi-Cell Concept
- Indirect Input Current Control
- Direct Output Voltage Control
- **Low Complexity** on MV Side

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
70 NRP Energy Turnaround
National Research Programme

# ▶ Main SST Topologies (2)

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

- Single-Cell Topologies



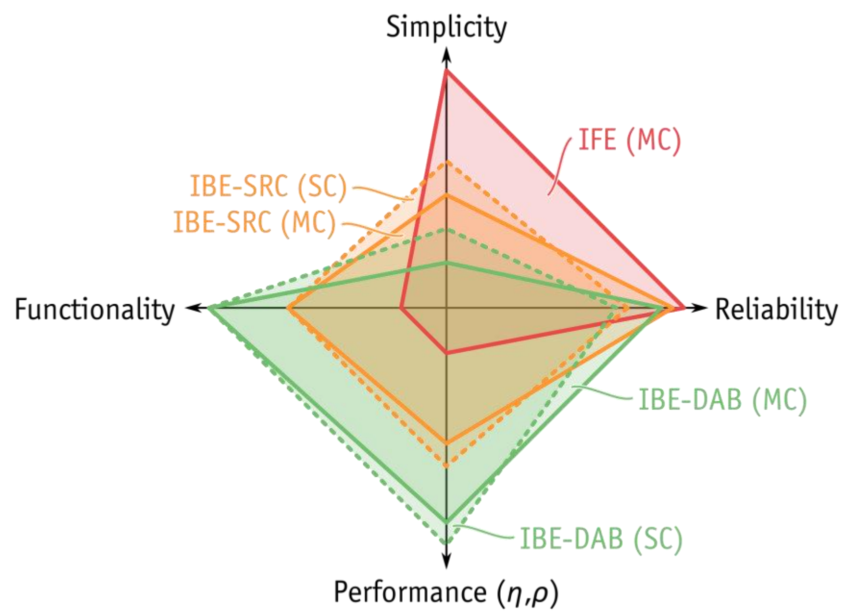

- **Main Characteristic**
  - Low MV-Side Complexity

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

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

# ▶ Comparison of IBE and IFE

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



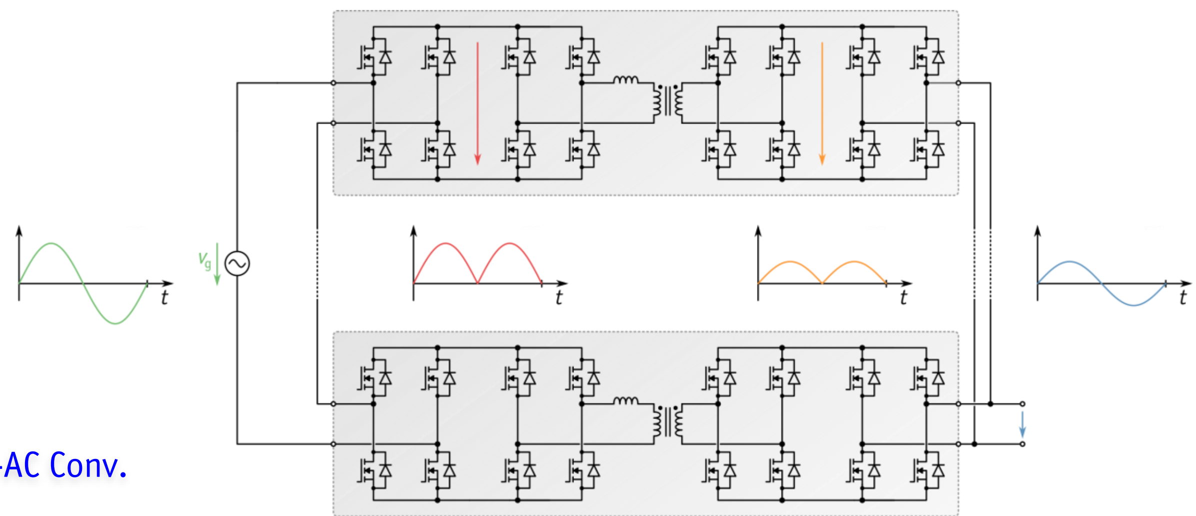

- **Trends And Outlook**
  - LV SiC Devices
  - **HV SiC Devices / Single-Stage SSTs**
  - Reliability Considerations Are Highly Important

**MC:** Multi-Cell
**SC:** Single-Cell
**DAB:** Dual Active Bridge DC/DC Converter
**SRC:** Series-Resonant Converter DC/DC Converter

# ▶ Main SST Topologies (3)

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

- Single-Cell Topologies



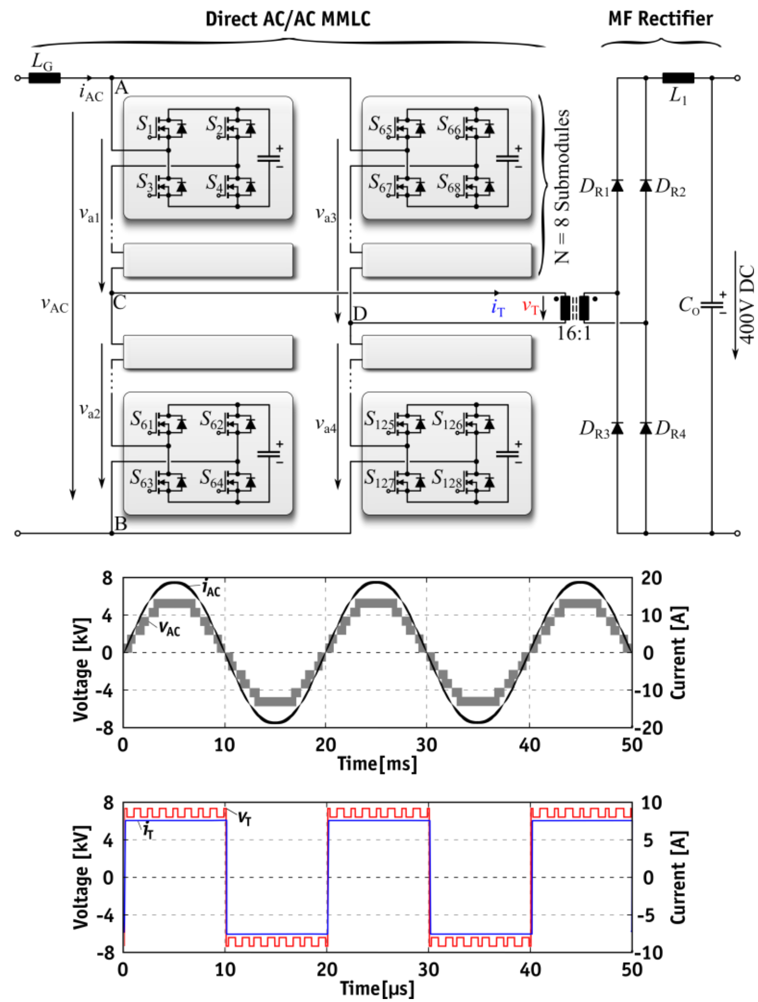

- **Main Characteristics**
  - Minimum Overhead for AC-AC Conv.
  - No DC Output

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




- **Main Characteristics**
  - Single Transformer
  - Modularity of Less Reliable Power Electron.
- Note: Specific Realizations May Vary (e.g., 3-Phase Configurations, AC/AC Conversion, Bidirectionality, etc.)

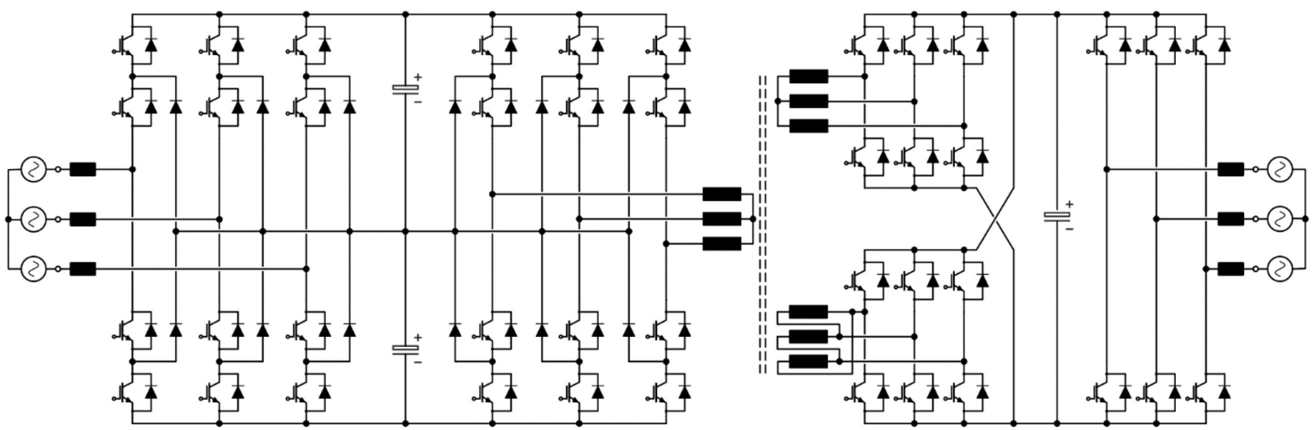
[Glinka2003], Img.: ETH / [Rothmund2014]

# ▶ Main SST Topologies (5)

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

- **Single-Cell Topologies**

- **Main Characteristics**
  - Low Complexity
  - Difficult Implementation of Reliability

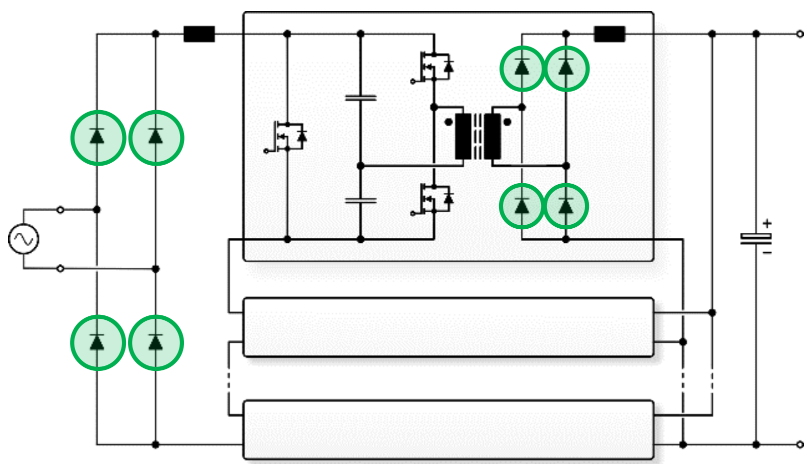


- Note: Specific Realizations May Vary
  (e.g., DC-DC Converter Type, Unidirectionality, etc.)

[Tripathi2012]

# ▶ 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

[VanDerMerwe2009a]
[VanDerMerwe2009b]
ETH / [Rothmund2014]

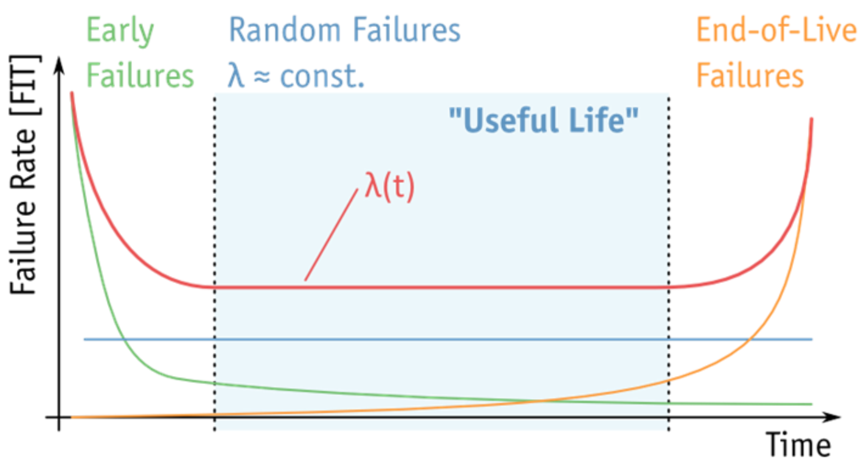
# Challenge #3/10

# Reliability

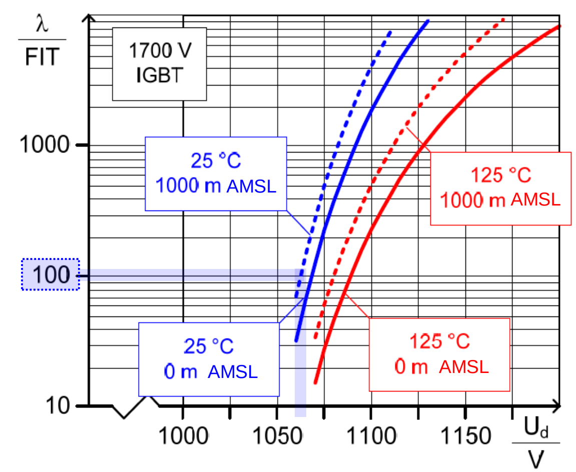
*Basics of Reliability Modeling*
*Cell-Level Redundancy*
*“Reliability Bottlenecks”*

# ▶ Reliability Modeling (1) – Failure Rate

- **Failure Rate $\lambda(t)$** is a Function of Time – "Bathtub Curve"
- Useful Life Dominated by Random Failures → **$\lambda(t)$ = const.**
- **[$\lambda$] = 1 FIT** (1 Failure in $10^9$ h)




Source: H.-G. Eckel
Univ. Rostock



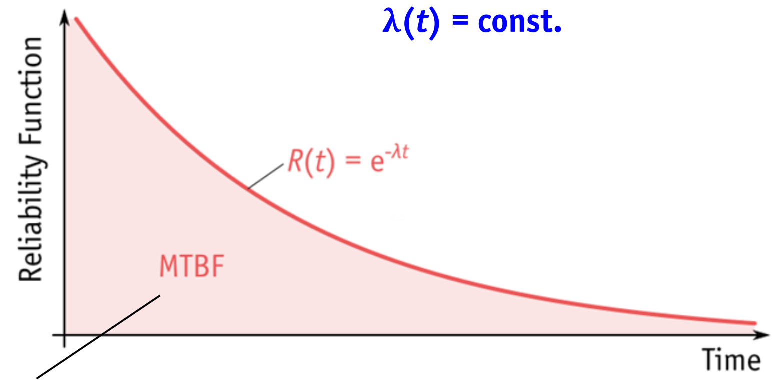

- Sources for Empirical Component Failure Rate Data: MIL-HDBK-217F, IEC Standard 62380, etc.

# ▶ Reliability Modeling (2) – Reliability Function

- **Reliability Function:** Probability of System being Operational after $t$:

$$R(t) = e^{-\int_0^t \lambda(x)dx} = e^{-\lambda t}$$

$\lambda(t)$ = const.

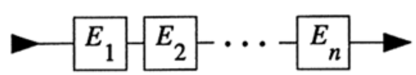



- **Mean Time Between Failures**

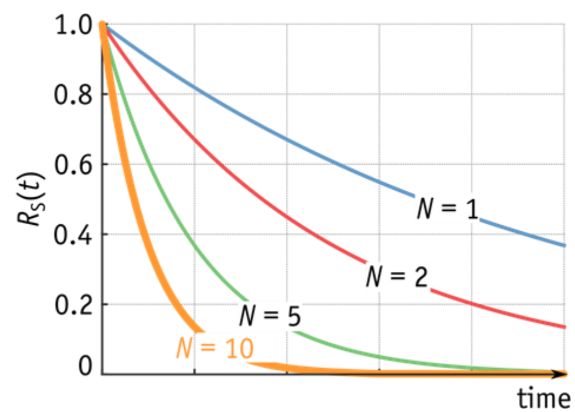
$$\text{MTBF} = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda}$$

- **Multiple Elements: Series Structure**

$$\lambda_S = \sum_{i=1}^{n} \lambda_i$$




Independent Cells
with Equal Failure Rate

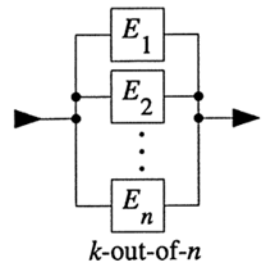


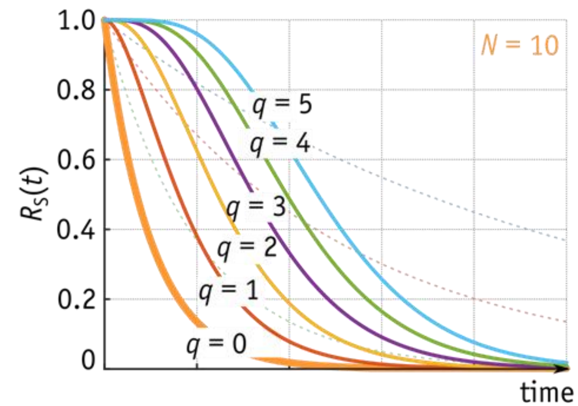

Textbook: [Birolini1997]

# ▶ Redundancy in Multi-Cell Converter Systems

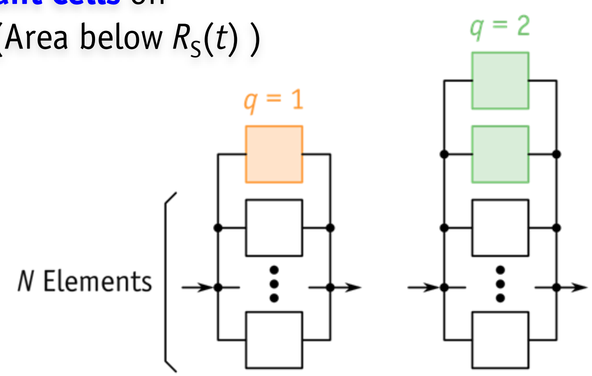
- ***k*-out-of-*n* Redundancy**
  Redundancy of Cells in Phase Stack

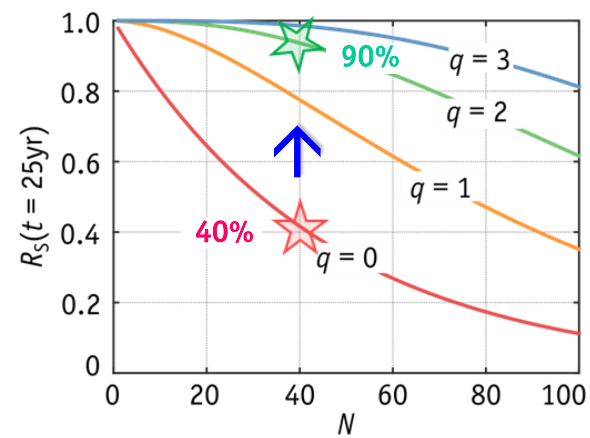
  *System is Operational as Long as at Least k-out-of-n Subsystems are Working*




- Effect of ***q* Redundant Cells** on $R_S(t)$ and/or MTBF (Area below $R_S(t)$ )



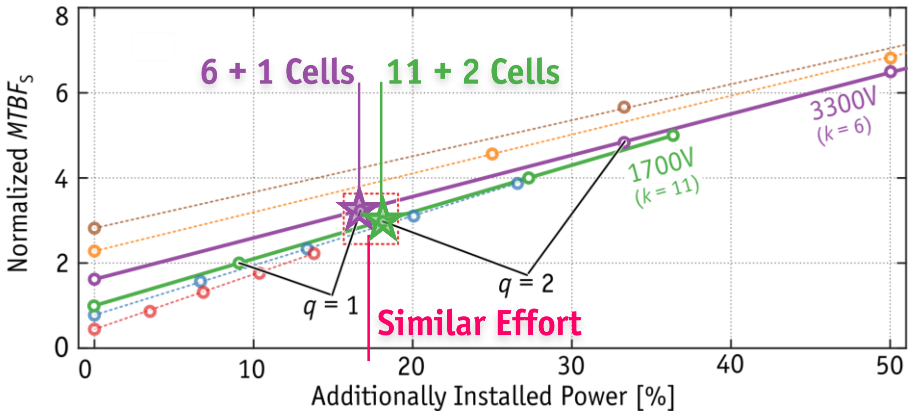




- **Redundancy Significantly Improves System Level Reliability (!)**

Textbook: [Birolini1997]

# ▶ Redundancy vs. Costs in Multi-Cell Converter Systems

- **Cost of Cell Redundancy**
  Redundant Cells = Additionally Installed Power Processing Capability

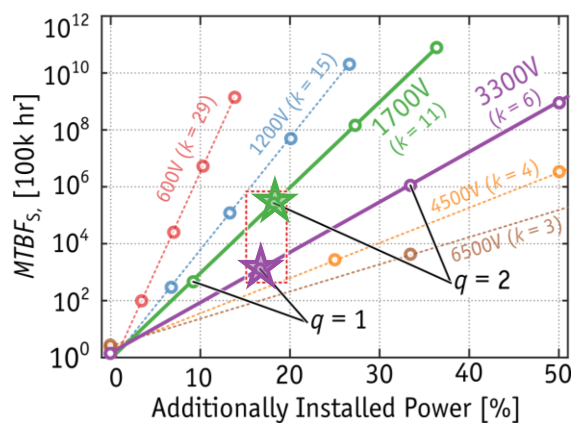



- Standby Redundancy

$$MTBF_S = \frac{n-k+1}{k\lambda_{Cell}(V_B)} \propto \frac{1}{\lambda_B}$$

- Figure Shows Normalized $MTBF_S$
  → **Independent** of Assumed $\lambda_B$

- **Repairable Systems**
  - 1 Week Mean Time To Repair (*MTTR*)

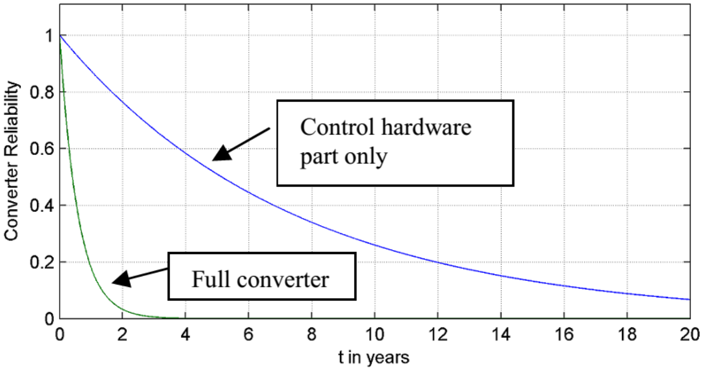



- **Cell Redundancy Boosts Multi-Cell System Redundancy**
- Caution: Reliability Bottlenecks (E.g., Control System)

# ▶ Reliability "Bottlenecks"

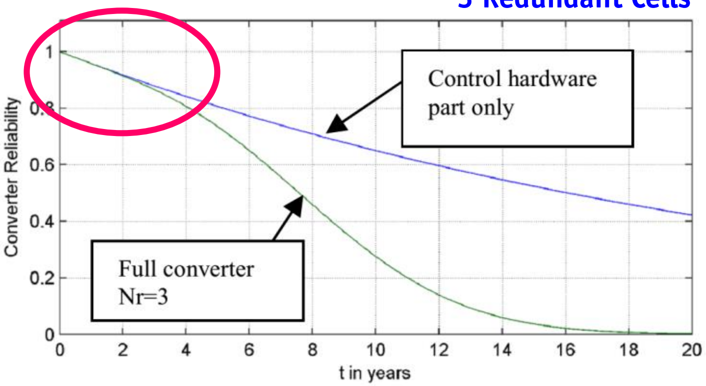
- Reliability Improvement by Means of **Cell-Level Redundancy** Is
  - Very **Effective**

No Redundancy




**Control Hardware Becomes Limiting Factor!**

**3 Redundant Cells**



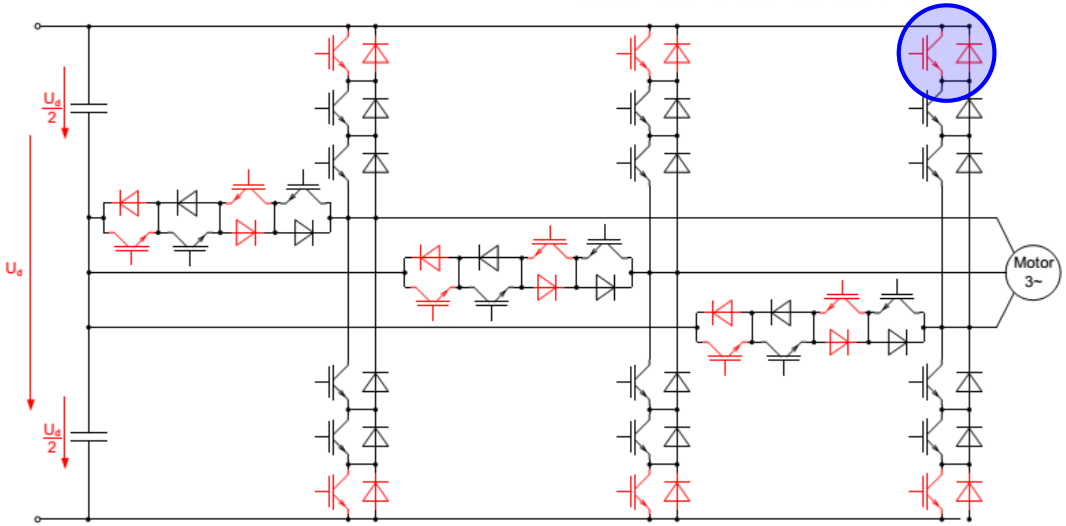

- **But Limited by Other Parts of the Converter System**
  - Control
  - Auxiliary Supplies
  - Communication
  - Bypass Devices
  - ...

[Grinberg2013]

# ▶ Redundancy In Single-Cell Systems

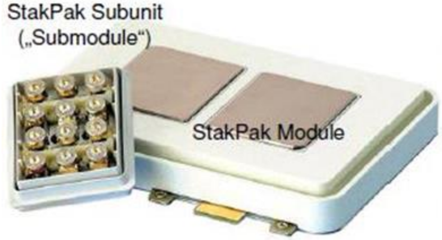
- Example: MV Motor Drive

**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 #4/10

## MF Isolation

*Dual Active Bridge*
*HC-DCM Series Resonant Converter*

# United States Patent Office

3,517,300
Patented June 23, 1970

1

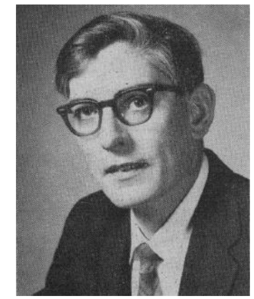
3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York
Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims


ABSTRACT OF THE DISCLOSURE

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

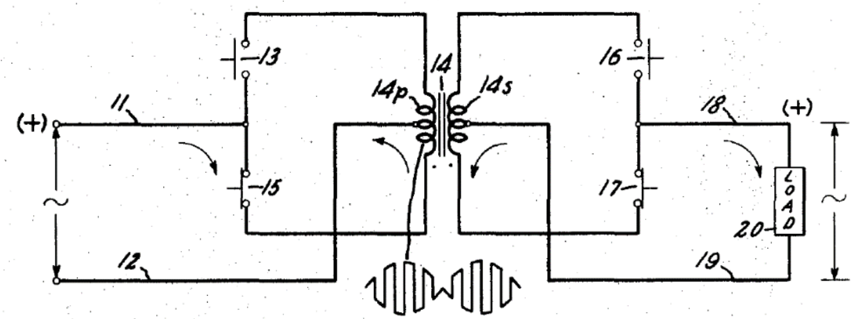

1968 !

Filed April 16, 1968



Inventor:
William McMurray
by Donald R. Campbell
His Attorney

Fig. 1a




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

[McMurray1968]

# ▶ Electronic Transformer

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

Fig. 3.

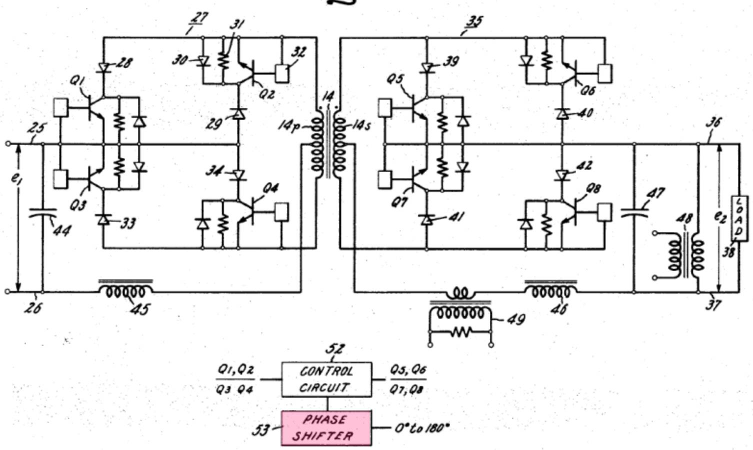
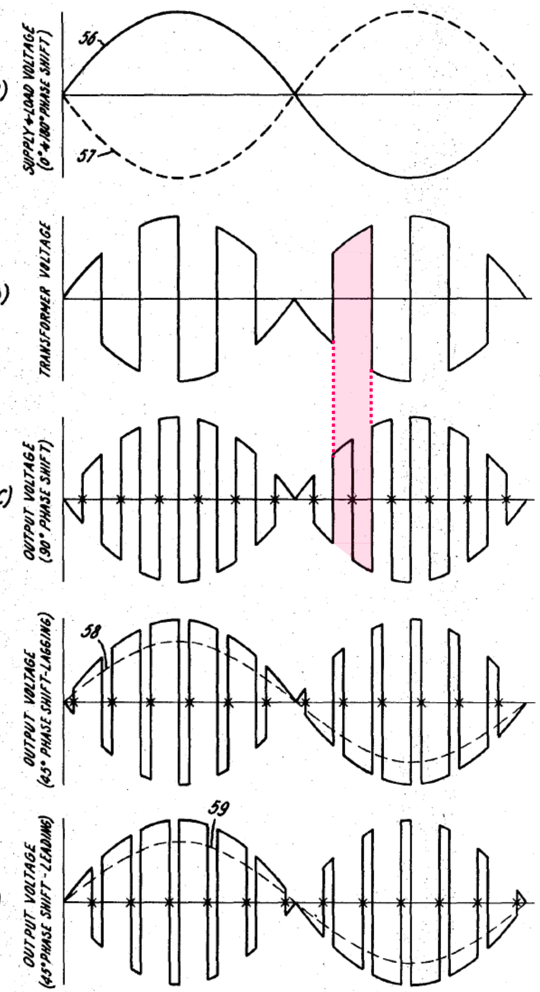



Fig. 4(a)
Fig. 4(b)
Fig. 4(c)
Fig. 4(d)
Fig. 4(e)




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

[McMurray1968]

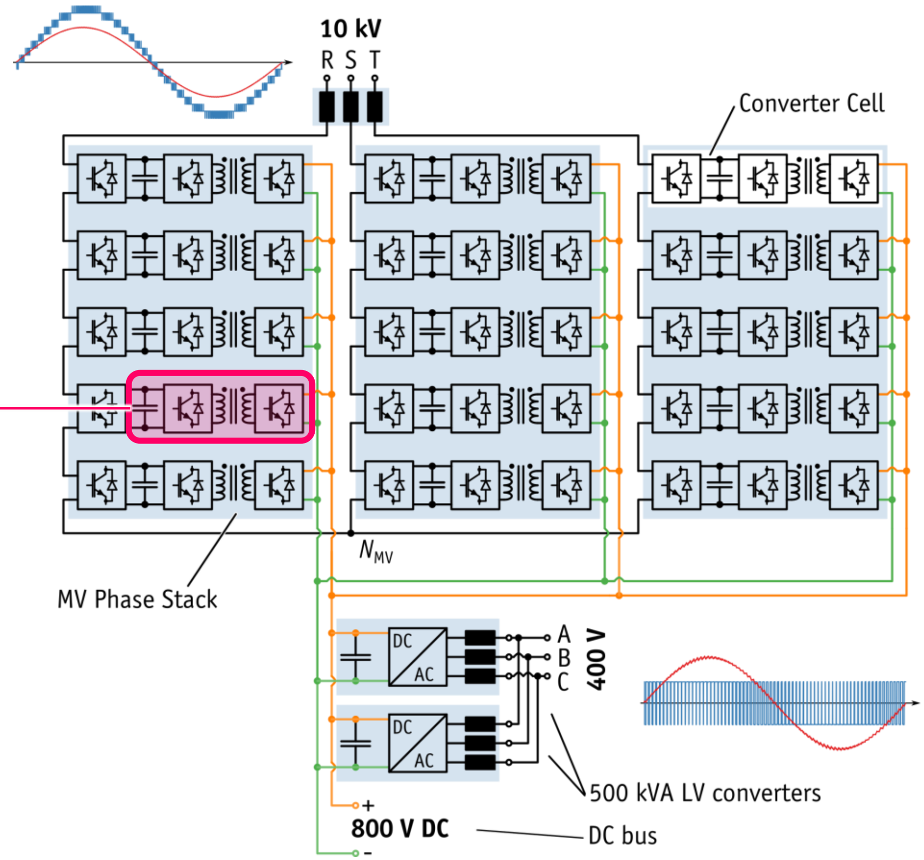
# ▶ Example SST System: ETH 1MVA *MEGAlink* SST Concept

**Specifications**

- MV: 10 kV AC
- LV: 800 V DC
  400 V AC (opt.)

- **ISOP** Multi-Cell Configuration
  → 1700V IGBTs
  → 4+1 NPC Converter Cells

- **DC-DC Converter Per Cell**
  - Isolation
  - Voltage Scaling



# Challenge #4/11

# MF Isolated Power Converters

***Dual Active Bridge***

*HC-DCM Series Resonant Converter*

**United States Patent** [19] — [11] **Patent Number:** 5,027,264

**DeDoncker et al.** — [45] **Date of Patent:** Jun. 25, 1991

1991

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

"… 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**

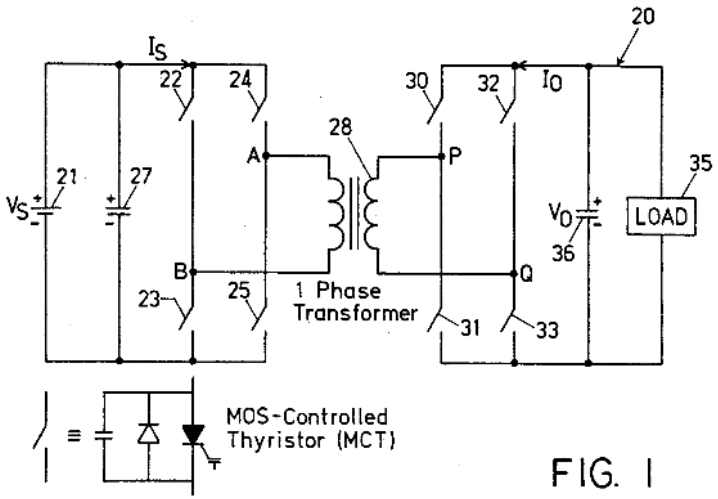



FIG. 1

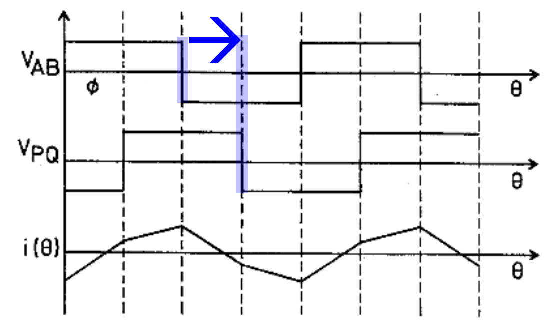


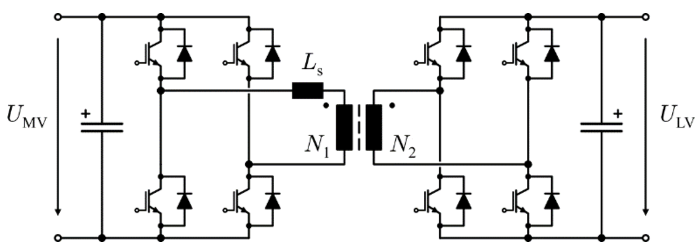

FIG. 2

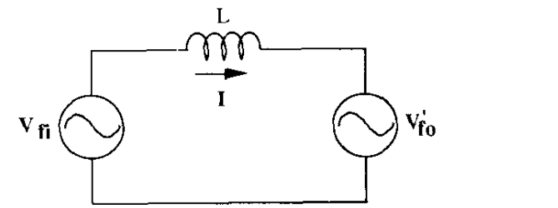
- Soft-Switching in a Certain Load Range
- **Power Flow Control by Phase Shift between Primary & Secondary Voltage**

[DeDoncker1989]

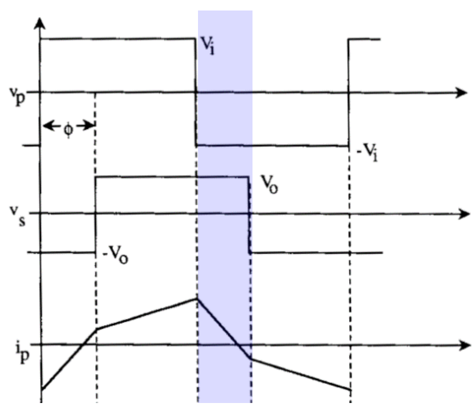
# ▶ Phase-Shift Modulation (1)

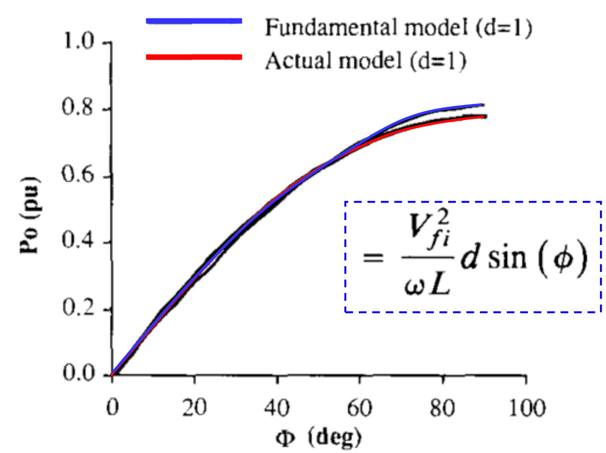
- **Power Transfer Controlled** Through Phase Shift Between MV and LV Bridges




Fundamental model of the dual bridge dc/dc converter.



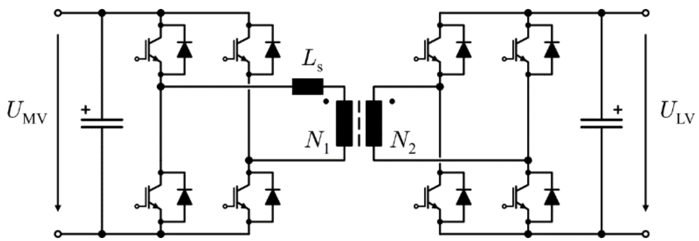



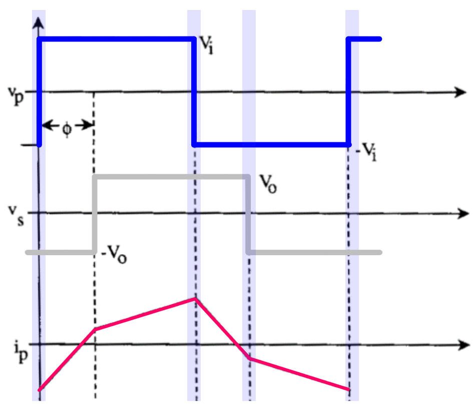

Comparison of the output power versus $\phi$, at $d = 1$, from the fundamental model and actual model.

[DeDoncker1989]

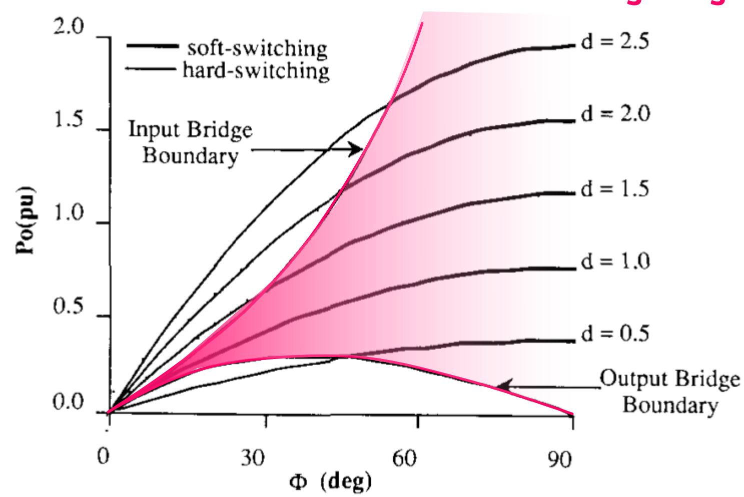
# ▶ Phase-Shift Modulation (2)

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



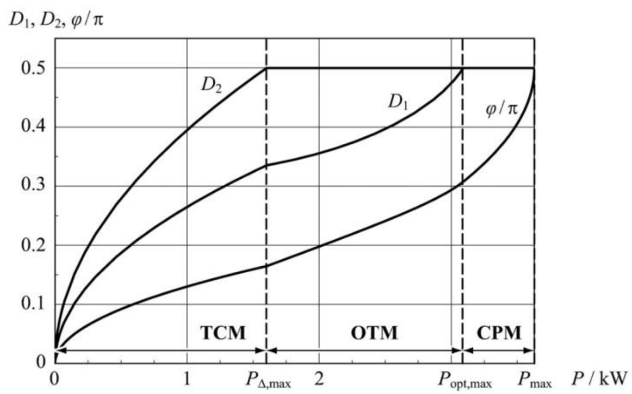



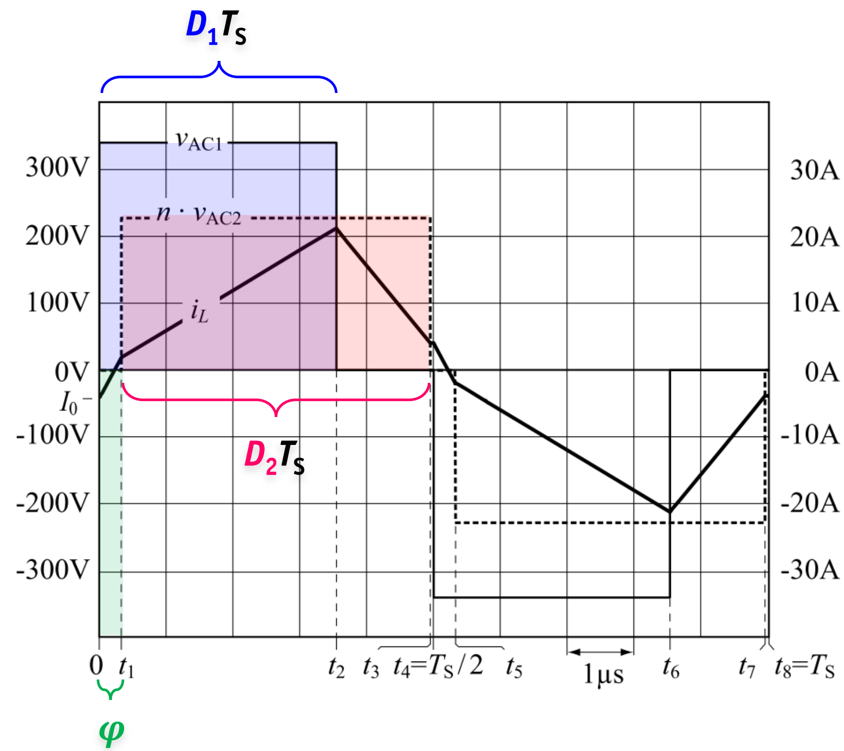

Soft Switching Range



# ▶ 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]

# Challenge #4/11

## MF Isolated Power Converters

*Dual Active Bridge*

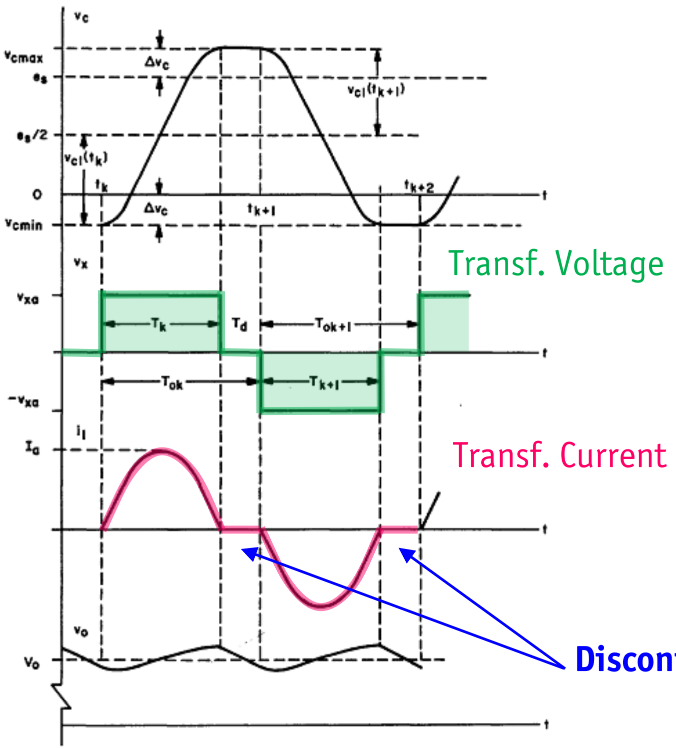
***HC-DCM Series Resonant Converter***

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




Discontinuous Conduction Mode (!)

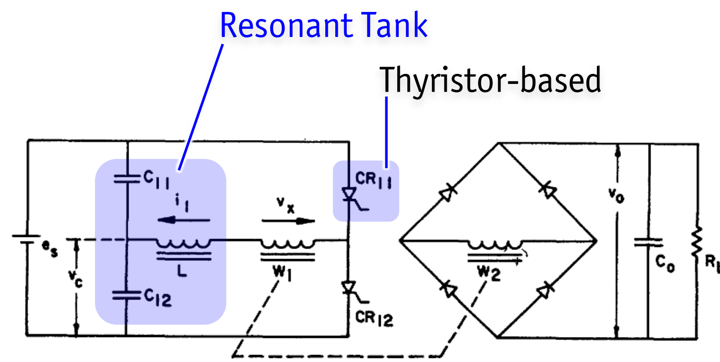
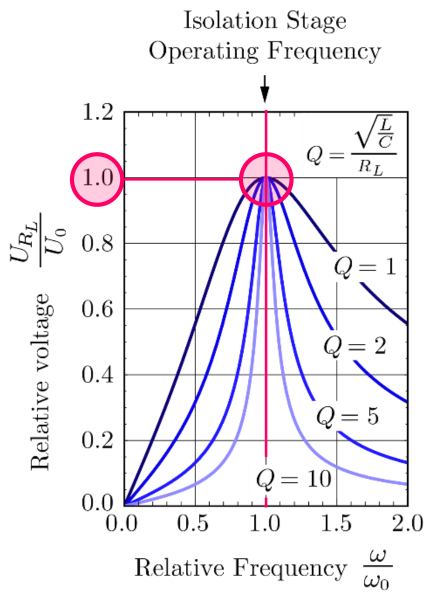


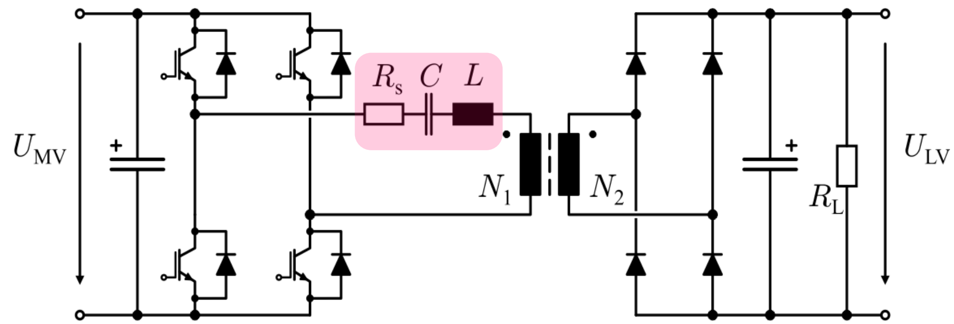

Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

[Schwarz1970]
(!) [McMurray1969b, McMurray1971]

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

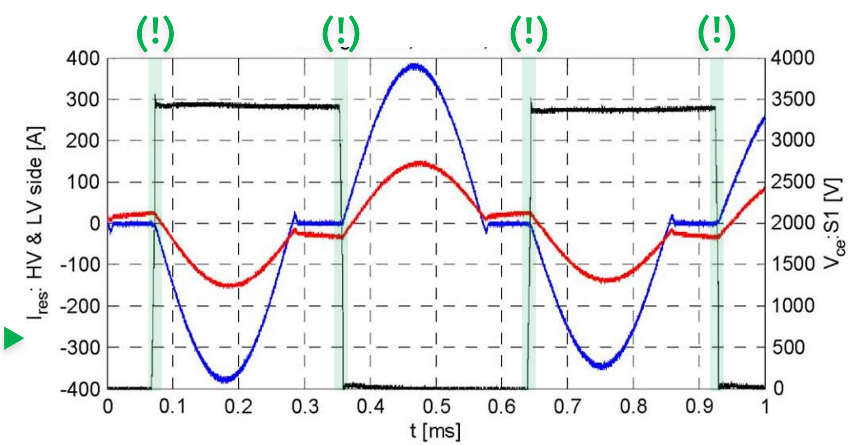
- Operating Principle: **Resonance Frequency ≈ Switching Frequency → Unity Gain**



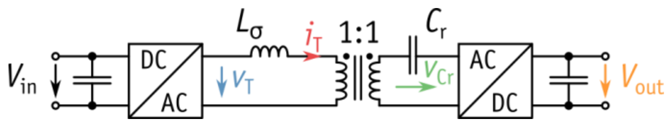

- The Input/Output Voltage Ratio is Close to Unity, Independent of Power Transfer

**ZCS of All Devices ►**
**Load-Independent ZVS Using Mag. Current**




Img.: [Zhao2014]

# ▶ 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

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

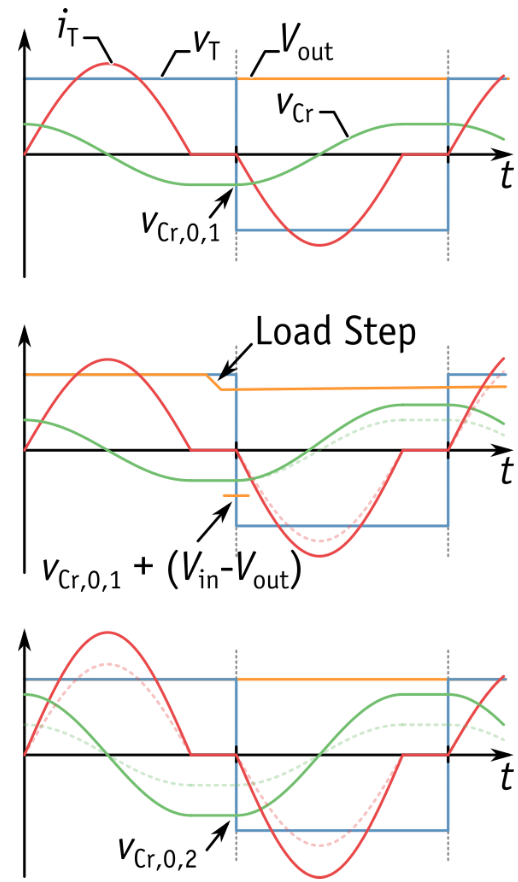
- **Disturbance**

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

**→ Add. Excit. Volt.**

- Steady State 2

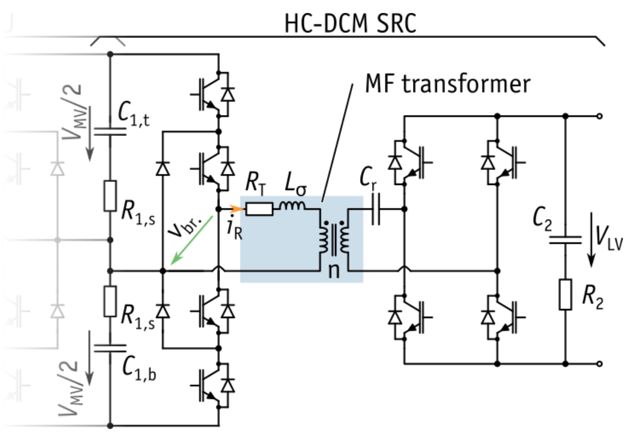
$$\hat{i}_{T,2} = \frac{\hat{v}_{Cr,0,2}}{Z_0}$$
$$V_{out} = V_{in}$$



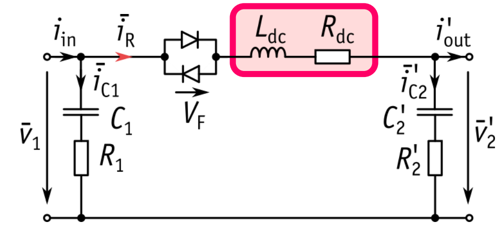

▶ **Acts as "DC Transformer" with Certain Dynamics!**

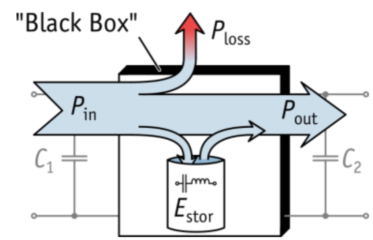
▶ **No Control Possible/Required!**

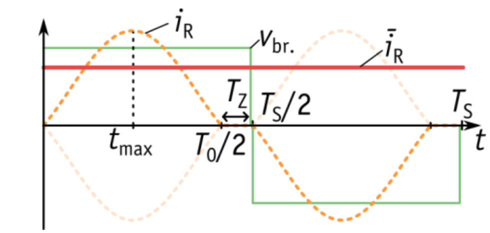
# ▶ Dynamic Modeling of HC-DCM SRC's Terminal Behavior




- **Dynamic Equivalent Circuit**
  → Based on Local Average Current




## ■ Generic Calculation of Eq. Circ. Element Values

- Equal RMS Losses → $\boldsymbol{R_{dc}}$

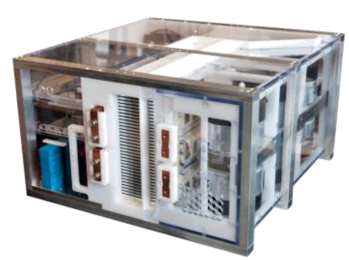
$$i^2_{\mathrm{R,avg}} = i^2_{\mathrm{R,rms}} R_{\mathrm{total}}$$

$$\Longrightarrow \boldsymbol{R_{dc}} = \frac{i^2_{\mathrm{R,rms}}}{i^2_{\mathrm{R,avg}}} R_{\mathrm{total}} = \beta^2 R_{\mathrm{total}}$$

- Equal Stored Energy → $\boldsymbol{L_{dc}}$

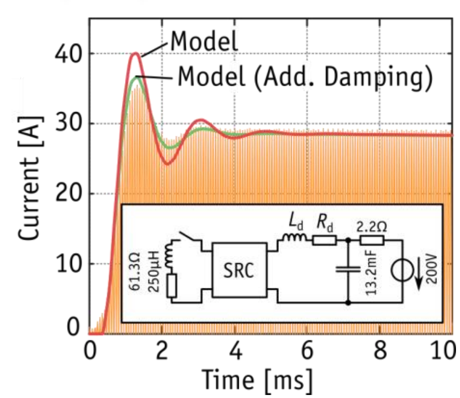
$$i^2_{\mathrm{R,avg}} L_{\mathrm{dc}} = i^2_{\mathrm{R,pk}} L_\sigma$$

$$\Longrightarrow \boldsymbol{L_{dc}} = \frac{i^2_{\mathrm{R,pk}}}{i^2_{\mathrm{R,avg}}} L_\sigma = \alpha^2 R_{\mathrm{total}}$$



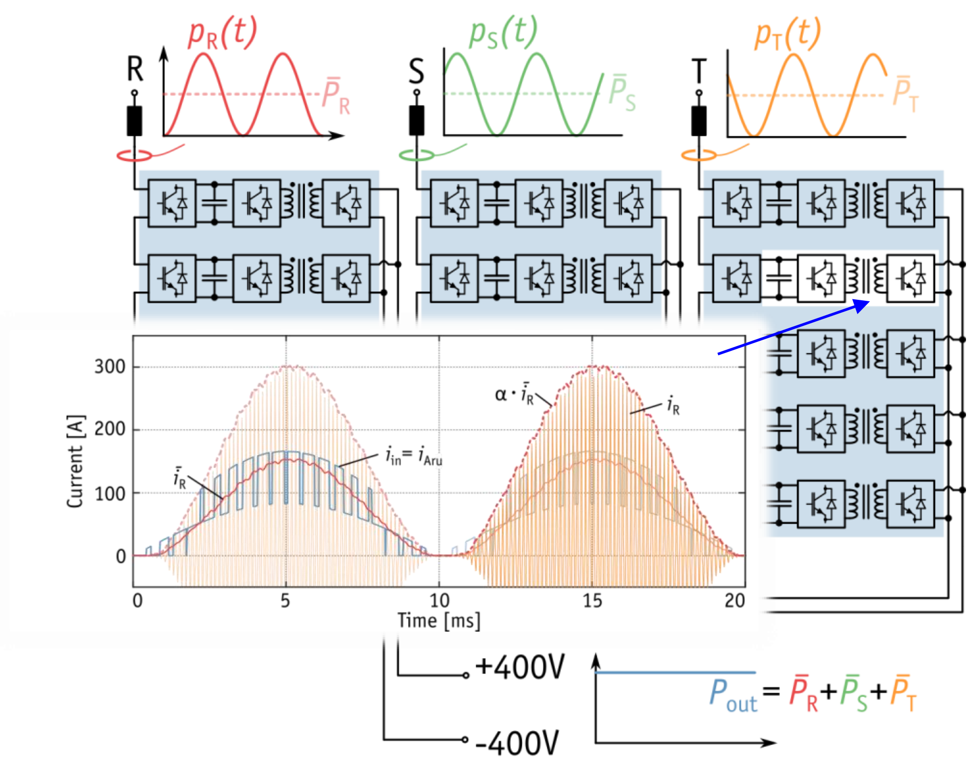
## ■ Experimental Verification

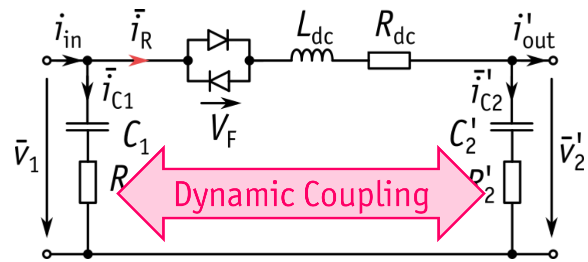
Step Response Model vs. Meas.



# ▶ 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

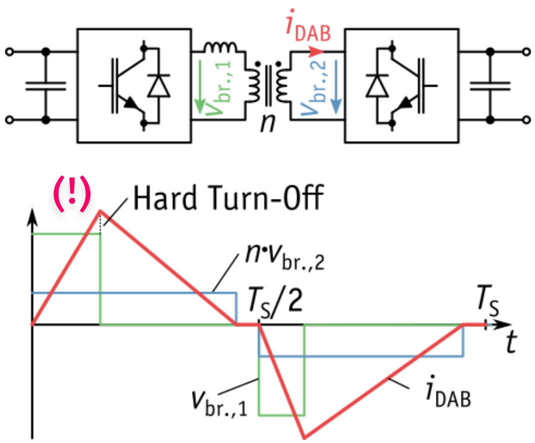
→ **Transmission of Full Single-Phase Power Fluctuation!**
  - Higher RMS Current (23%) in Transformer and DC-DC Switches
  - Appropriate Dimensioning

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

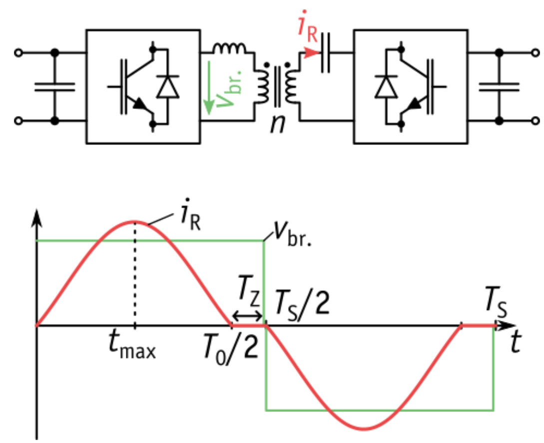
Further Reading: ETH / [Huber2015]

# ▶ Realization Options for DC-DC Converters in SST Cells

- **Dual Active Bridge (DAB – Triangular Cur. Mode)**




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




- **Can (Must!) Be Fully Controlled**
  - Fully Controllable Power Flows in Phase-Modular SSTs
  - 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 #5/10

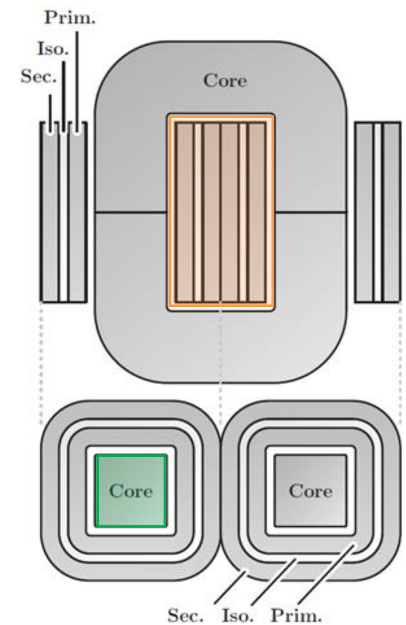
# MF Transformer Design

*Transformer Types*
*Litz Wire Issues*

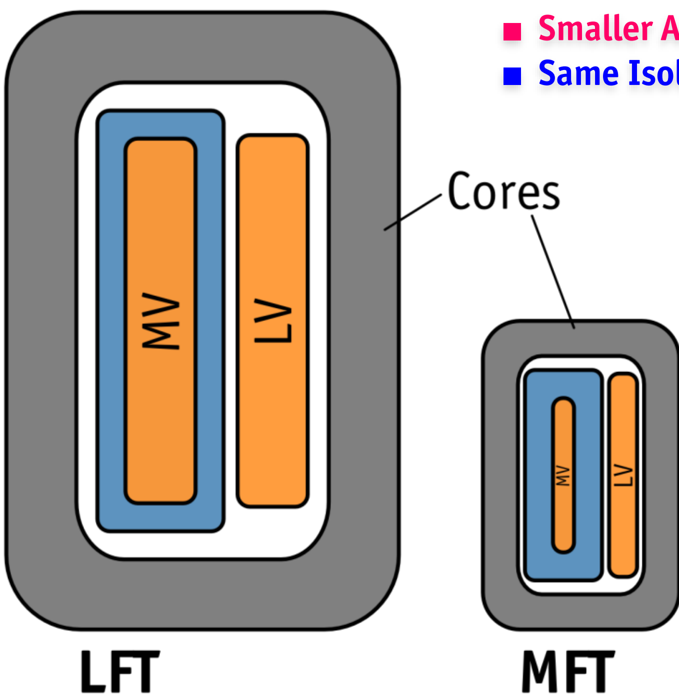
# ▶ General Challenge of MF Transformers

- Higher Operating Frequency
- Lower Unit Power Rating

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




- **Smaller Active Volume**
- **Same Isolation Voltage (!)**



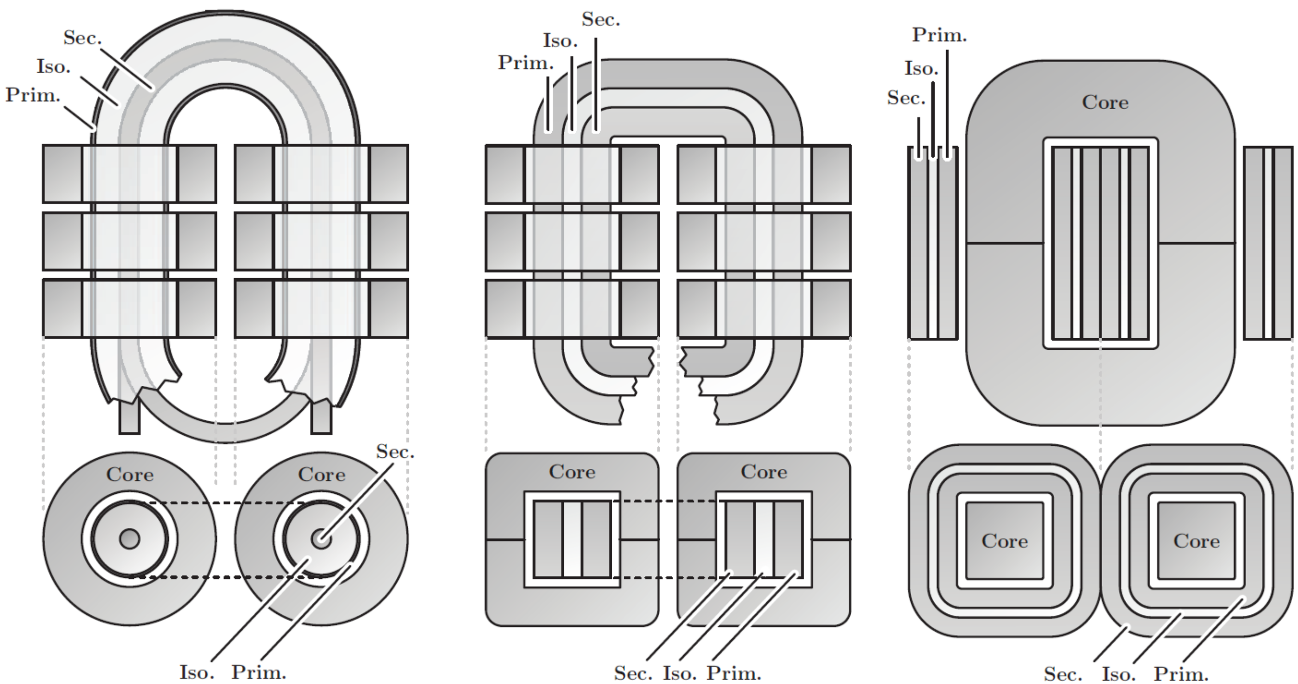

**MV Winding Cooling Through Isolators**

- 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



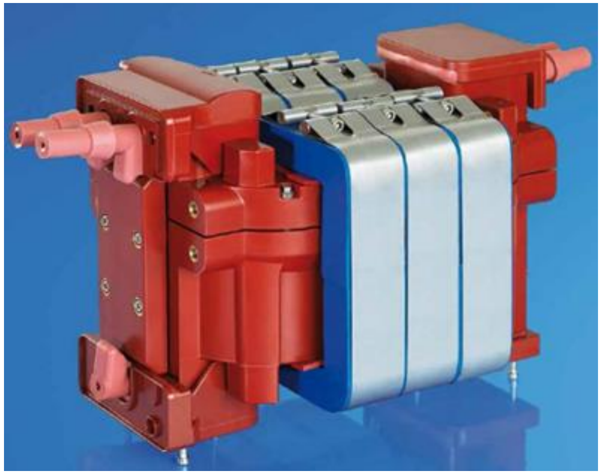

**Coaxial Cable** | **Shell-Type** | **Core-Type**

- 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 Realization Examples

- Coaxial Windings – Shell Type
- Tunable Leakage Inductance
- Simple Terminations

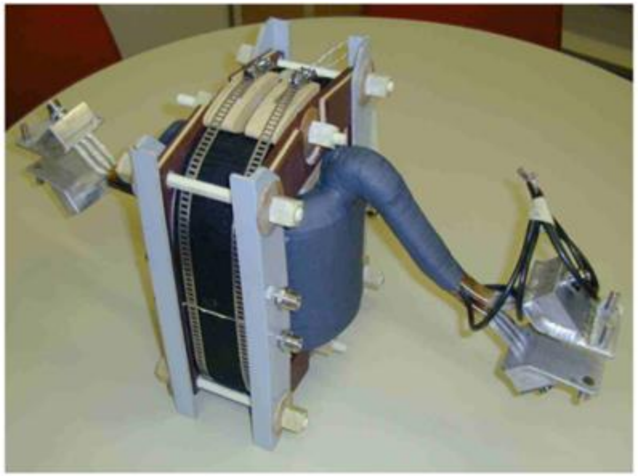
- 450kW @ 8 kHz / 50kg
- 99.7% Efficiency
- Dry Type / Liquid Isolation for 34.5kV



STS (2014)
www.sts-trafo.com

- 350kW @ 8 kHz
- Water Cooling / Hollow Conductors
- Isolation for 33kV

Steiner (2007)



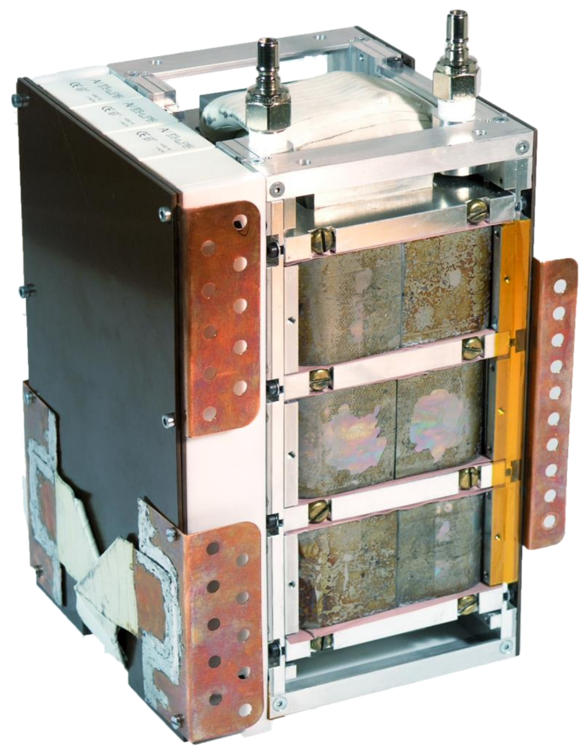
[Steiner2007]

# ► ETH Water-Cooled 20kHz Transformer (1)

- Power Rating 166 kW
- **Efficiency 99.5 %** (Meas.)
- **Power Density 32.7 kW/dm³**
- Nanocrystalline Core

- ETH / Ortiz, Leibl (2013)

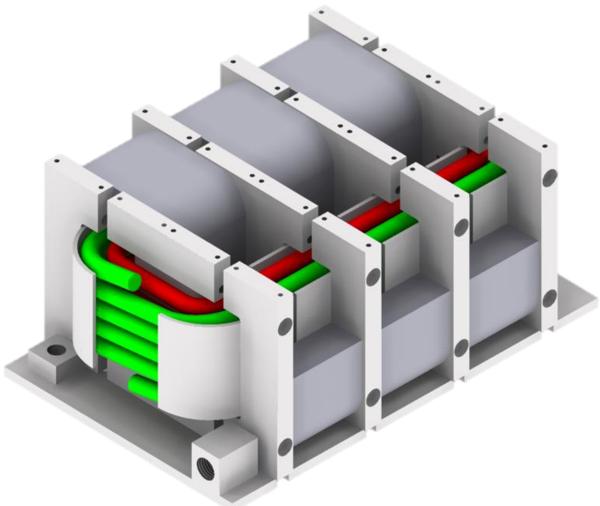
166kW / 20kHz Water-Cooled
Nanocrystalline Core Transformer ►

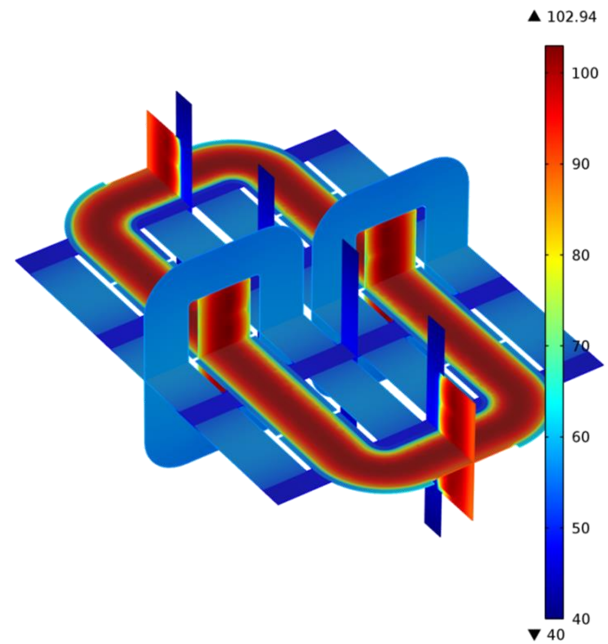


ETH / [Ortiz2013b]

# ► ETH Water-Cooled 20kHz Transformer (2)

- **Cold Plates / Water Cooling**






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

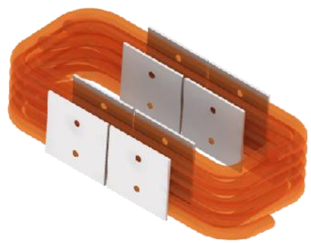
ETH / [Ortiz2013b]

# ▶ ETH Water-Cooled 20kHz Transformer (3)

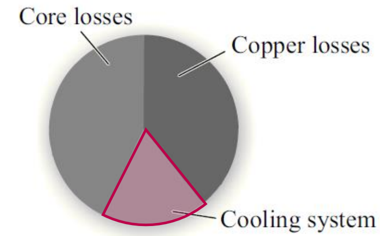
- **Cooling System Losses**

Windings
$\Delta P = 353$ W

Inner Cooling Plates
$\Delta P = 57$ W



Outer Cooling Plates
$\Delta P = 19$ W

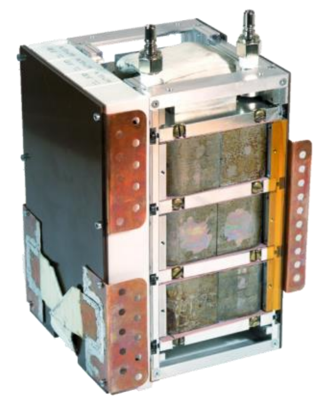



**20% (!)**

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

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

Heat Sinks
$\Delta P = 2.8$ W



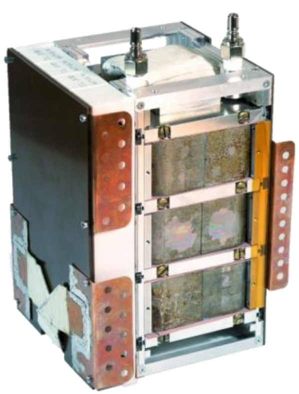
- Losses Generated in Internal Cooling System Amount to ca. **20% of Total Transformer Losses**

ETH / [Ortiz2013b]

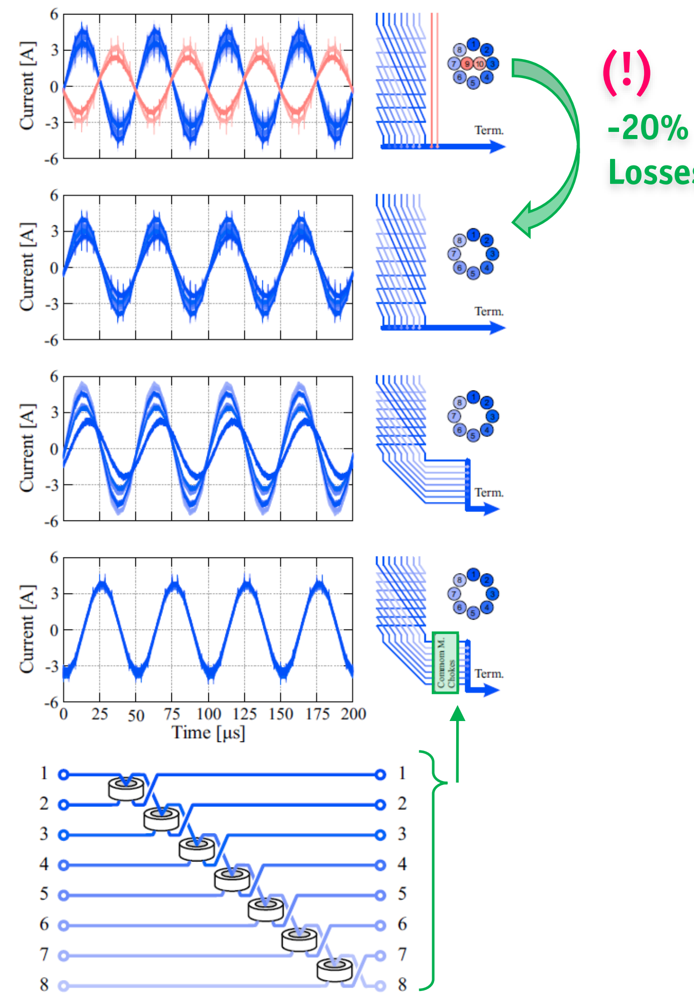
# ▶ Anecdote: Litz Wire Issues

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

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



- Common-Mode Chokes for Forcing Equal Current Sharing




ETH / [Ortiz2013b]

# Coffee
## *Break*

# Challenge #6/10
# Isolation Coordination

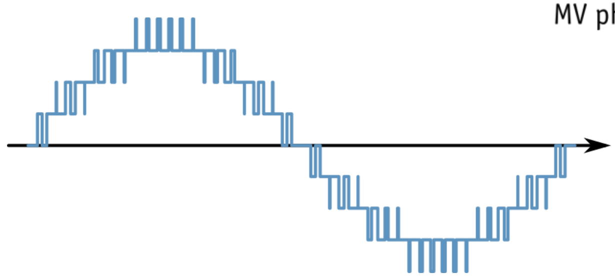
*Isolation Barrier Positioning*
*Mixed-Frequency Stress*

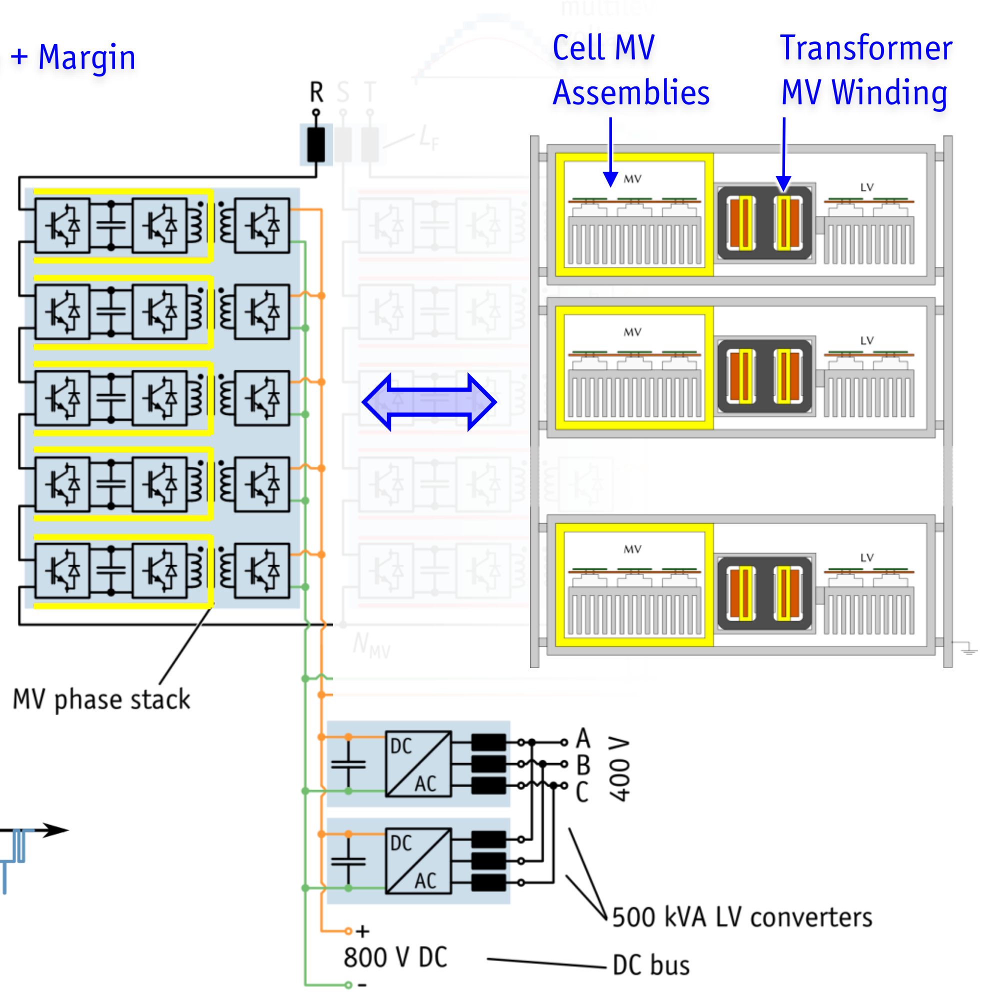
# ▶ Isolation Barriers In A Multi-Cell SST

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

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

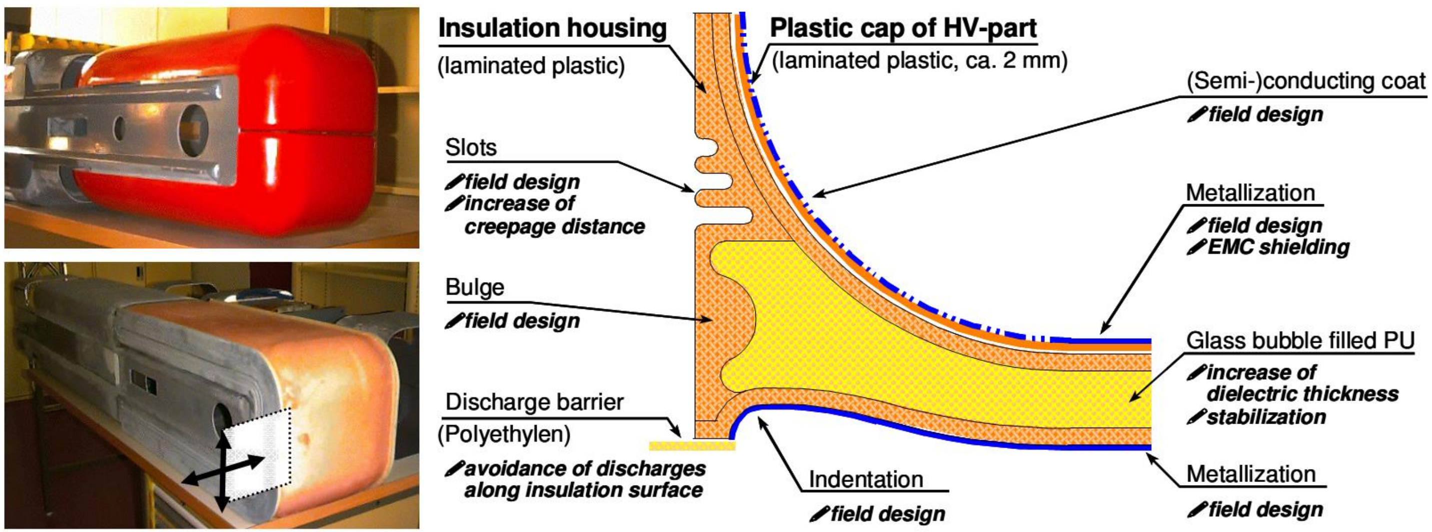
▼ Typical Isolation Voltage (Qualitative)





# ▶ Example: Isolation Coordination of Cascaded Cells' MV Part

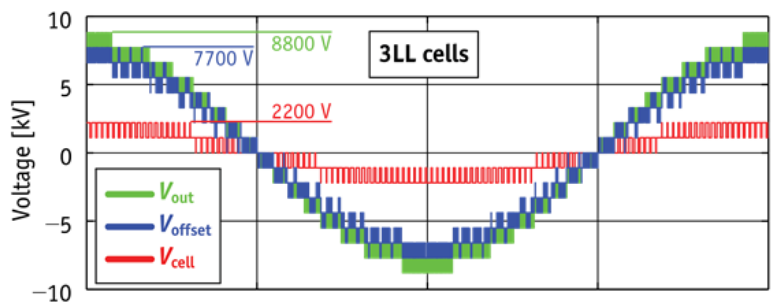
- Components on MV Potential (e.g., Heat Sink)
- Isolation Towards Cabinet Required
- **Field Grading to Avoid Partial Discharges**, etc.

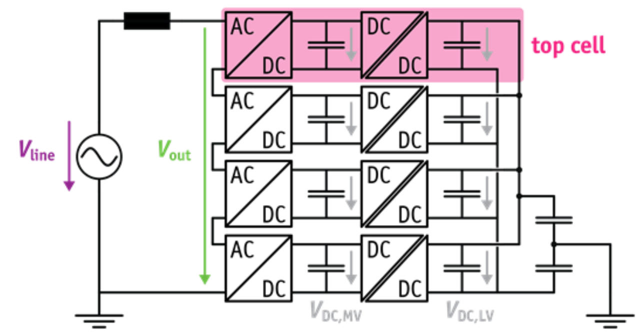



Bombardier / [Steiner2007]

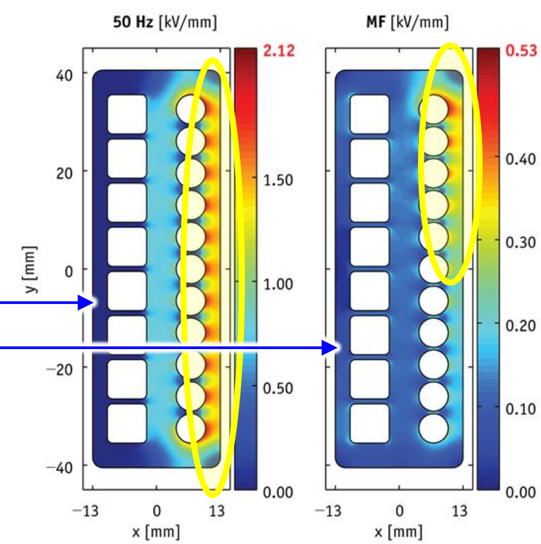
# ▶ Mixed-Frequency Electrical Field Stress

- **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**



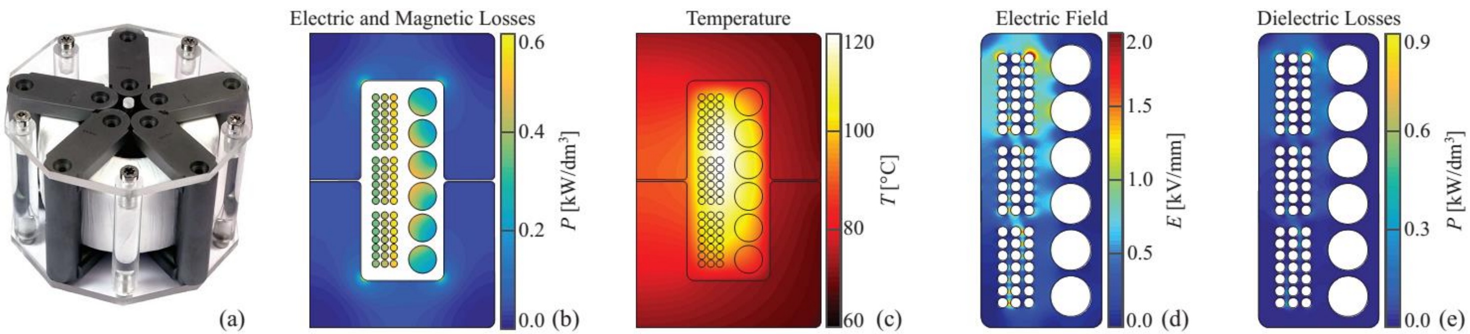

- 50Hz Stress    Common-Mode
- MF Stress    Differential-Mode (Mostly)

→ 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:** ETH/ [Guillod2016]

# Challenge #7/10

## EMI

*Common-Mode Ground Currents*
*EMI Limits*

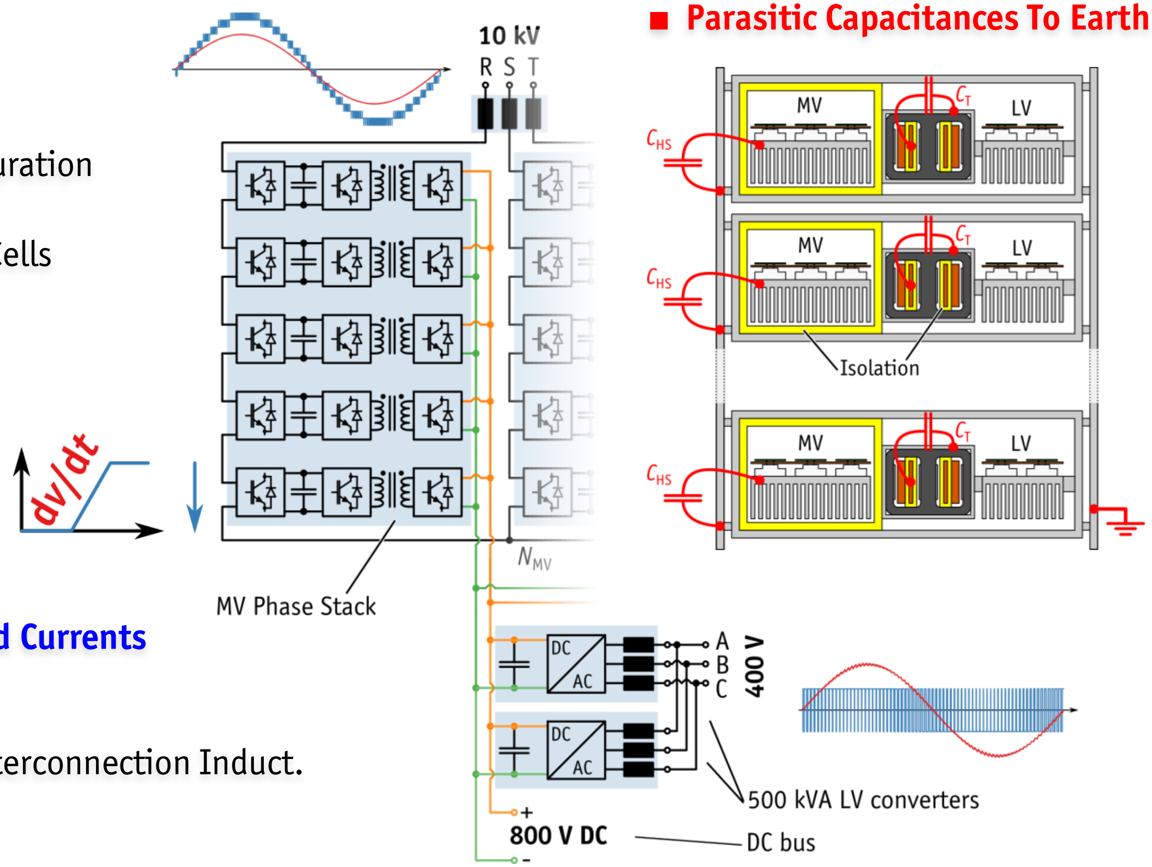
# ▶ Common-Mode Ground Currents in Multi-Cell SSTs (1)

## Specifications

- MV: 10 kV AC
- LV: 800 V DC
  400 V AC (opt.)

- **ISOP** Multi-Cell Configuration
  → 1700V IGBTs
  → 4+1 NPC Converter Cells

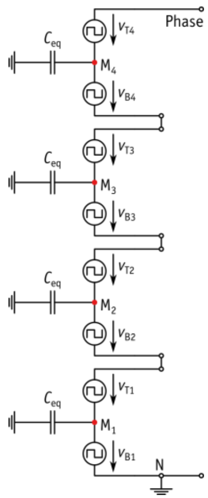
- Parasitic Capacitances To Earth




- **Common-Mode Ground Currents**

  → $i_{CM} = C_{Par}\, dv/dt$
  → Oscillations With Interconnection Induct.

# ▶ Common-Mode Ground Currents in Multi-Cell SSTs (2)



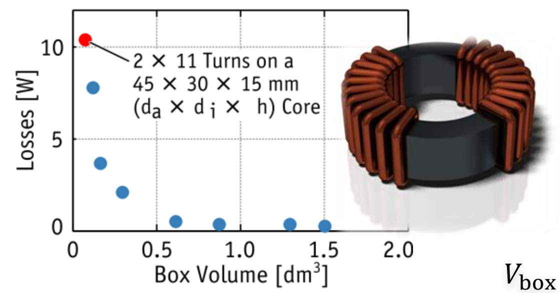

■ Analytic Modeling Based on CM Equivalent Circuits

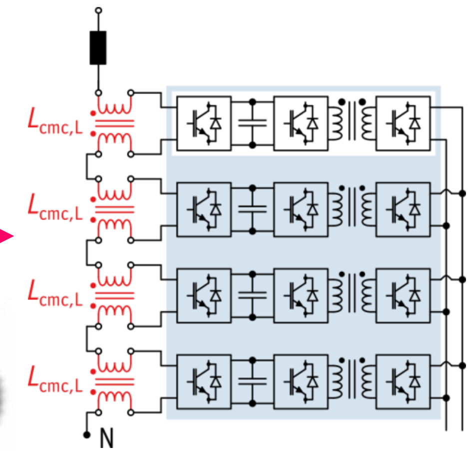
$$i_{\mathrm{CM,rms}} = \sqrt{f_{\mathrm{S}} V_{\mathrm{DC}} \frac{\mathrm{d}v}{\mathrm{d}t} \cdot \left(\frac{4}{3} N^3 + \frac{2}{3} N\right)} \quad \text{etc.}$$

■ **Common-Mode Chokes At Cells' AC Inputs**

→ Low Effort

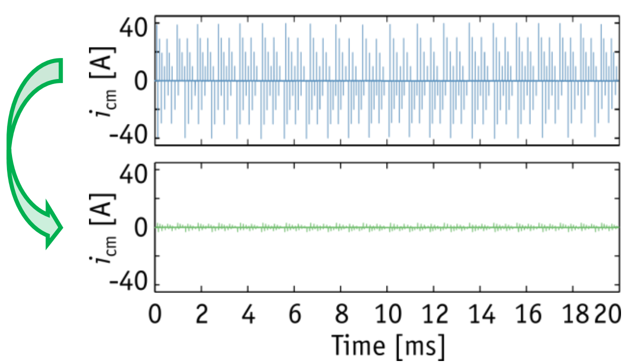
→ Low Volume

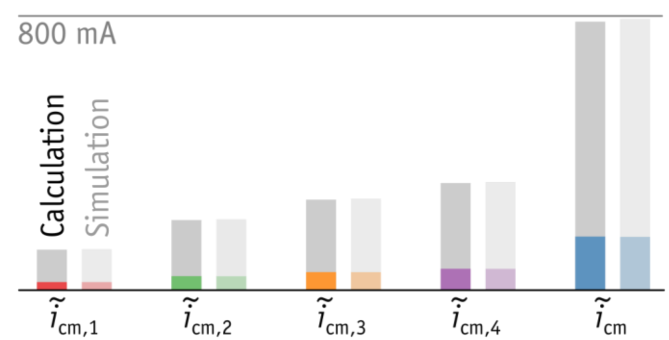



$$V_{\mathrm{box}} = 4 s_{\mathrm{h}} \cdot \left(\frac{2\sqrt{L_{\mathrm{cmc,L}} C_{\mathrm{eq}}} V_{\mathrm{DC}} \mathrm{e}^{-1} I_{\mathrm{rms}}}{\hat{B} k_{\mathrm{w}} J_{\mathrm{rms}} \pi s_{\mathrm{h}} s_{\mathrm{r}}^2 \cdot (1 - s_{\mathrm{r}})}\right)^{\frac{3}{4}}$$

■ **Verification:** Simulations With/Without CM Chokes



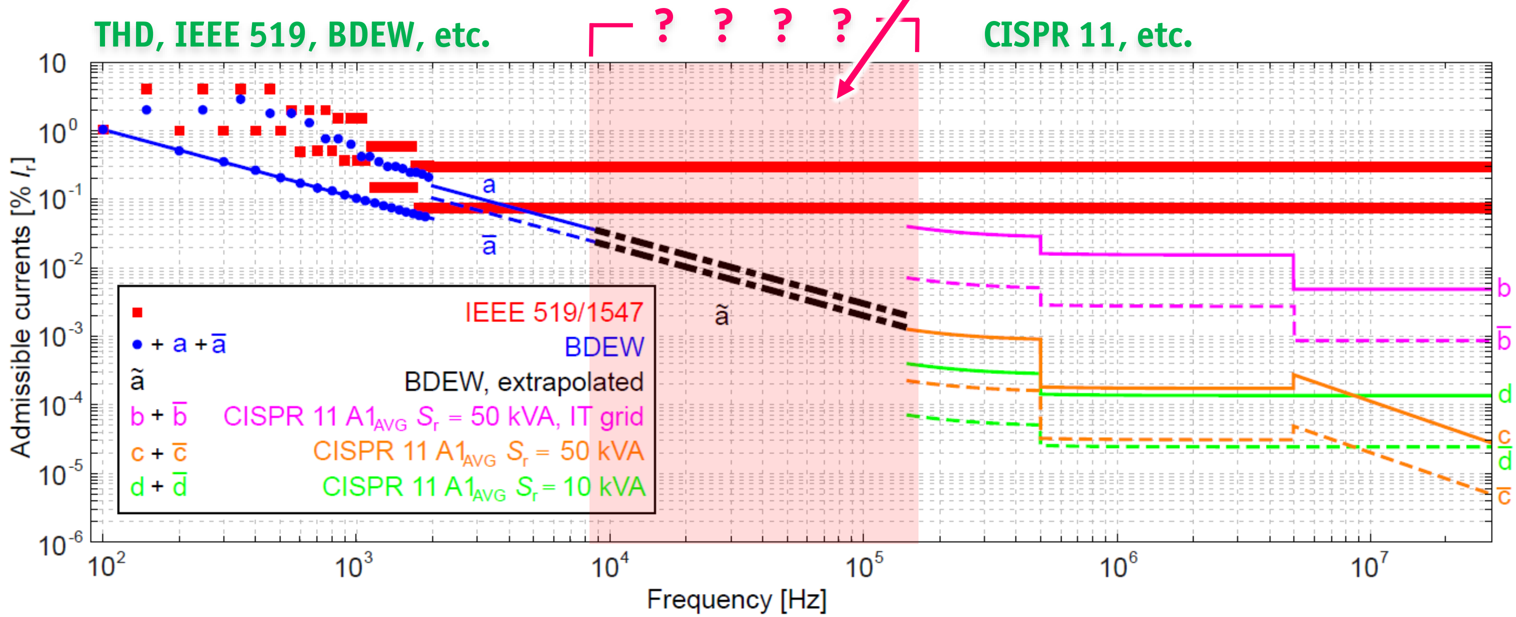
# ▶ Grid Harmonics and EMI Standards

- 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]

**BDEW:** "Bundesverband der Energie- und Wasserwirtschaft e.V." (Germany)

# Challenge #8/10

## Protection

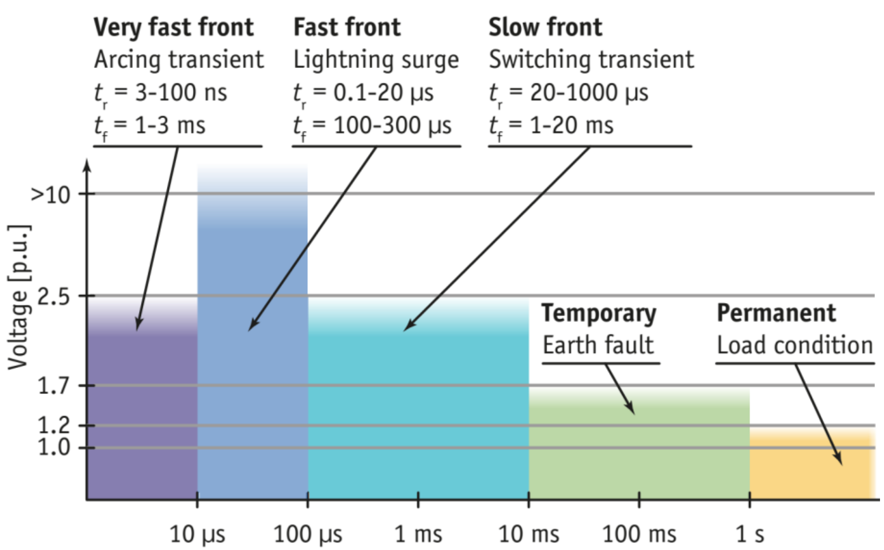
*Protection of the SST*

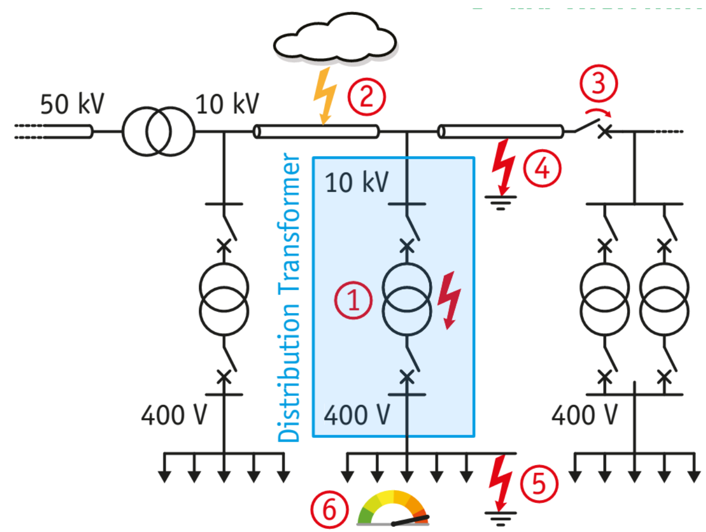
# ▶ Potential Fault Situations in MV and LV Grids

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

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

- Conv. MV Grid Time-Voltage Characteristic

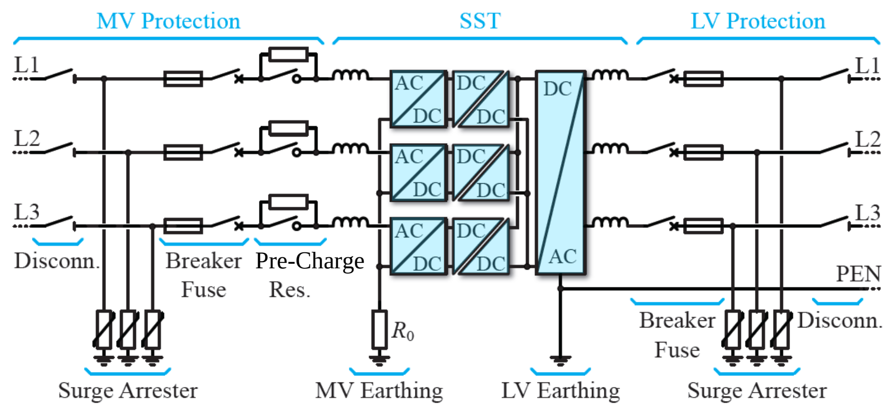


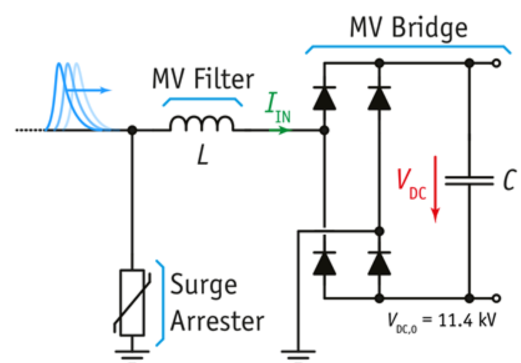

**Further Reading:** ETH / [Guillod2015]

# ▶ Protection of LF-XFRM vs. SST Protection

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




- Proposed SST Protection Scheme with Minimum # of Protection Devices




- **Overvoltage Protection** (Lightning Strike)
  - High Arrester Clamping Voltage
  - **Filter Inductor > 8% for Current Limiting**
  - **Min. DC Link Capacitance**
  - Sufficient Blocking Capability
  - Grounding – Lower Stress if Unearthed

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

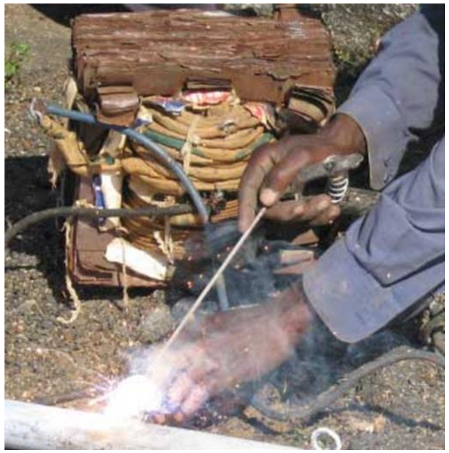
**Further Reading:** ETH / [Guillod2015]

# Challenge #9/10

## Control

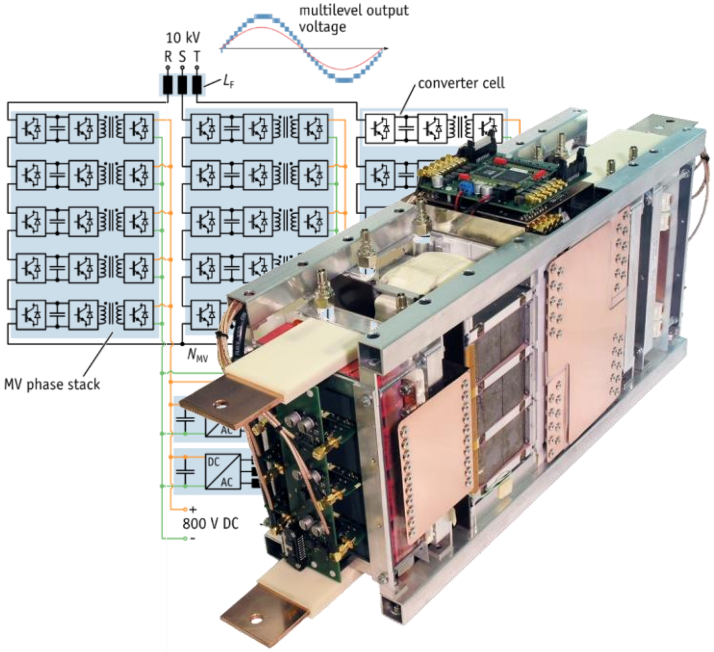
*It's Not Just Passives!*

# ▶ An SST is Not Just Passives!



Source: http://www.africancrisis.org

**vs.**




- **High Complexity of SST** due to Required 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, 400$V_{AC}$ ↔ 800$V_{DC}$ ↔ 400$V_{AC}$

# ▶ Example of SST Control System Partitioning

**MV** - Volt. - Cur.

**LV** - Volt. - Cur.

Battery Management

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

SCADA Interface

Smart Grid Integration

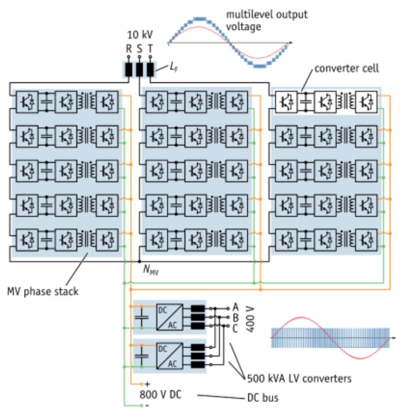
**Cascaded MV Inverter**
- Time Sync.
- Current Ctrl. & Ref. Gen.
- Redundancy Mgmt.

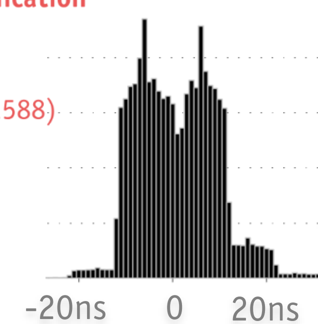
**LV Inverter** (FPGA)

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

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

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




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

# Challenge #10/10
# Construction & Testing

*Modular Approach*
*MV Test Facility*

# ▶ 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

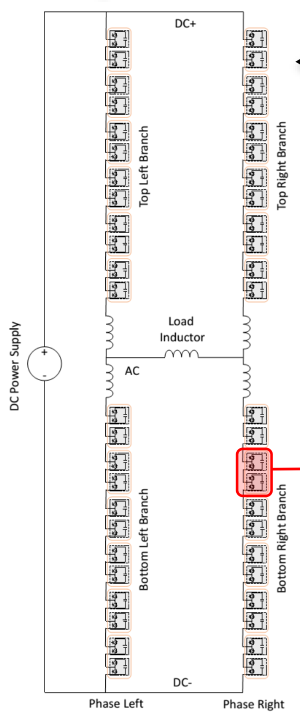
**Integration Technologies for a Fully Modular and Hot-Swappable MV Multi-Level Concept Converter**

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 (!)**

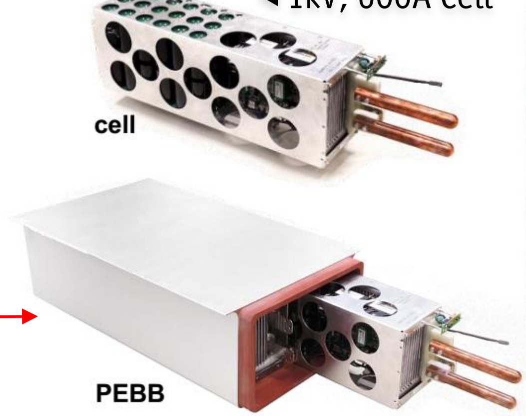
[Cottet2015a]
[Cottet2015b]

- **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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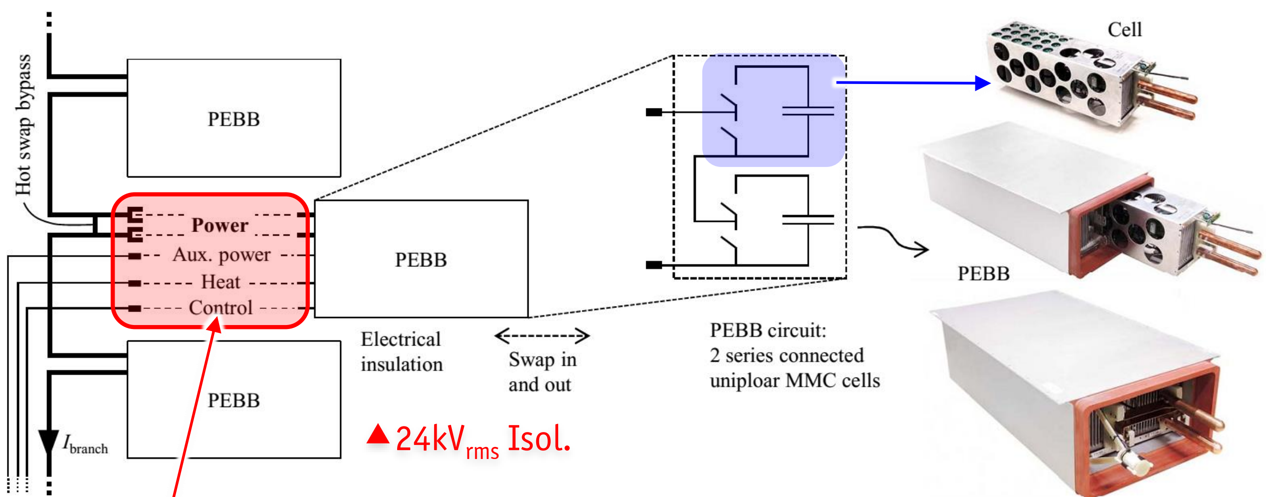
[Cottet2015a]
[Cottet2015b]

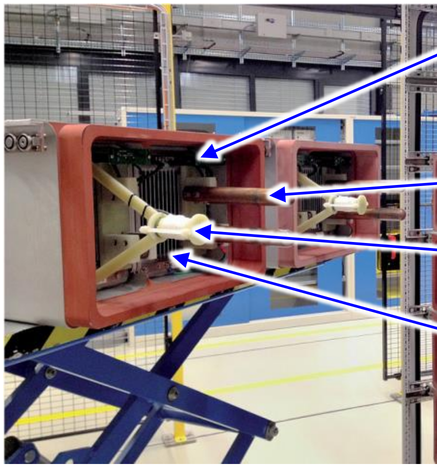



▲ $24kV_{rms}$ Isol.

**Complex Interface**

# ▶ From Conceptualization to Realization (3): Modularity

- All Interfaces Must Support Modularity – **Hot-Swapping Test @ 24kV (!)**



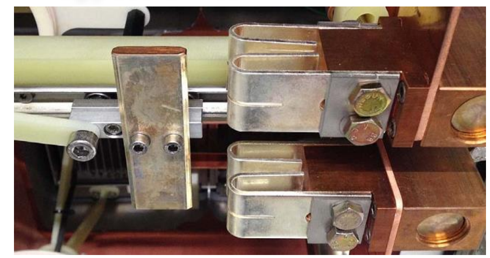
Communication (Wireless Optical)

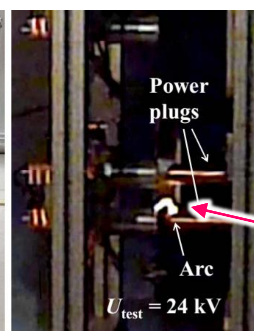
Power

Auxiliary (IPT)

Cooling (Air)

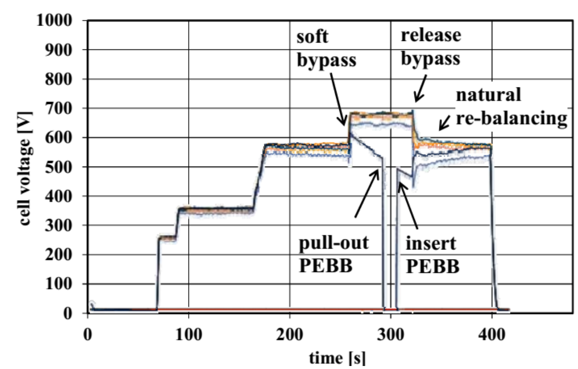
▼ Bypass Switch





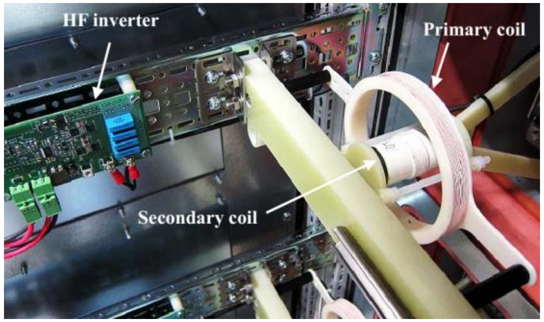

◀ Lab Test ▶

24kV Sw. Arc

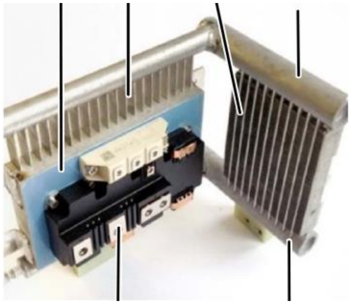


# ▶ From Conceptualization to Realization (3): Advanced Integr. Tech.

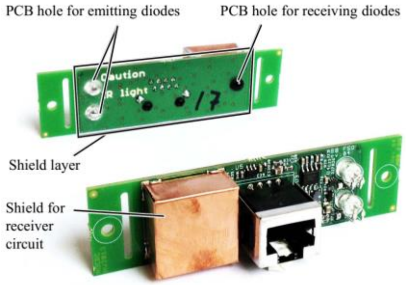
■ IPT for Auxiliary Power Supply



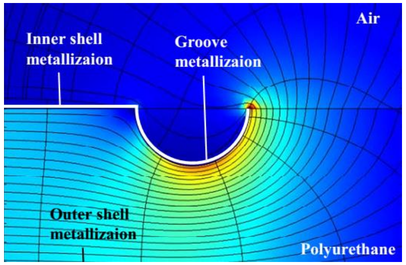

■ Two-Phase Cooling



■ Wireless Optical EtherCAT Comm.



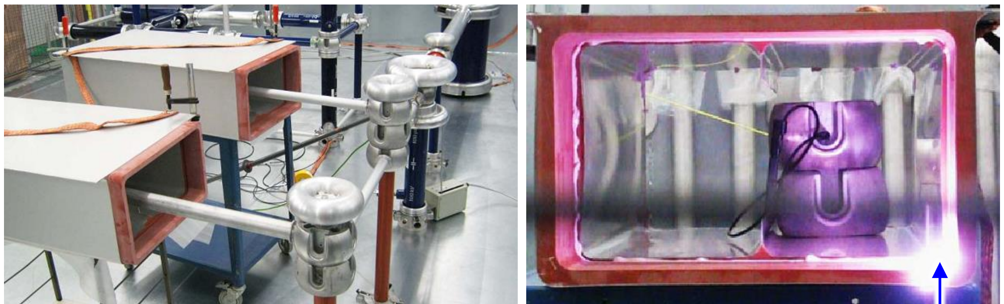

■ Solid Isolation of PEBBs




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

# ▶ Testing Infrastructure (1)

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



Imgs.: [Cottet2015b]

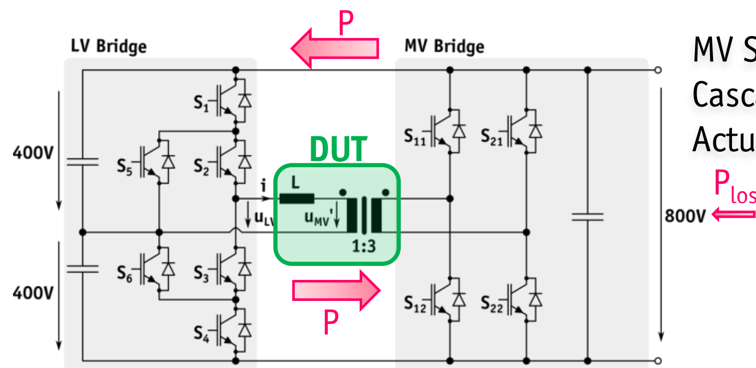
**60kV** Flashover

Img.: High Voltage Lab, ETH Zurich]

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

Img.: electrical-engineering-portal.com

- Or Back-To-Back Testing Concepts → **Complexity**

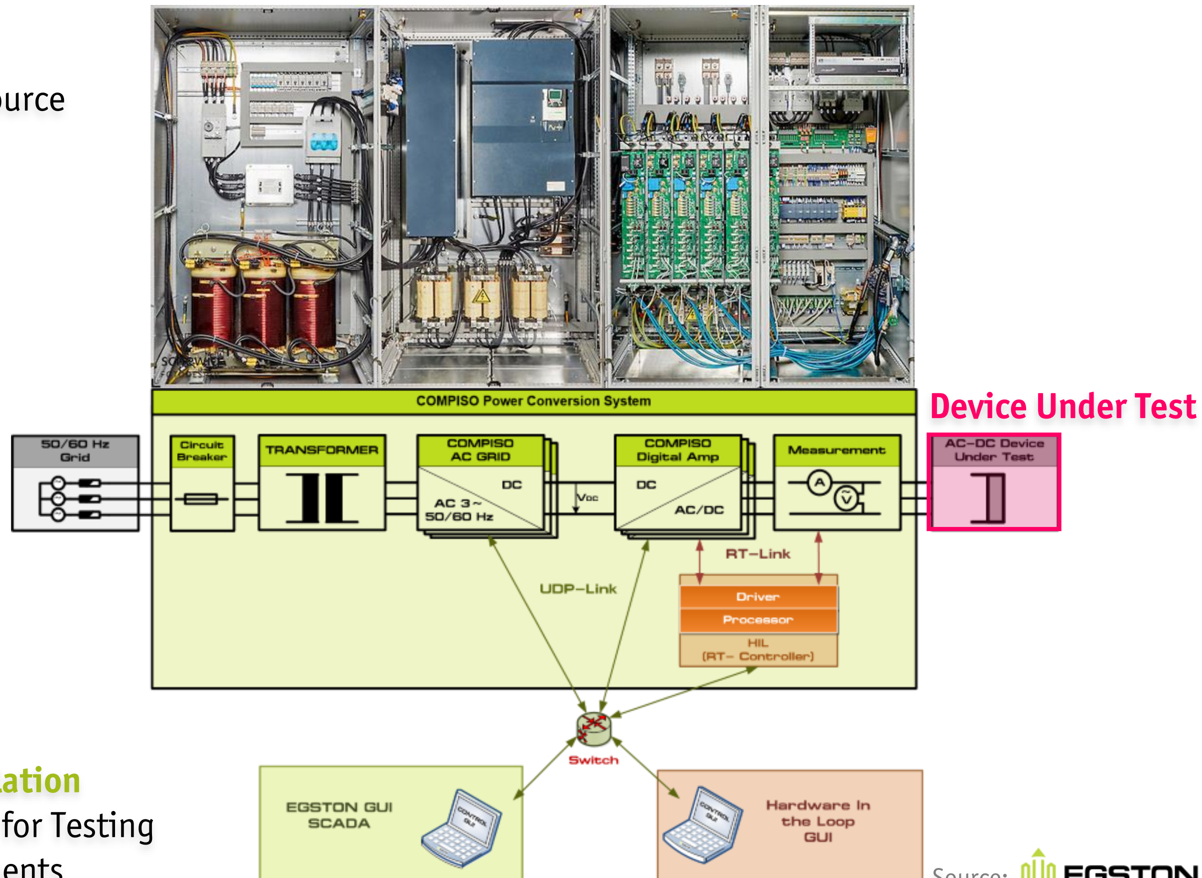



MV Side Cascaded in Actual Conv.

# ▶ Testing Infrastructure (2)

- **Power Hardware-in-the-Loop (P-HIL) Testing**

- Example:
  200kVA 4Q AC Test Source

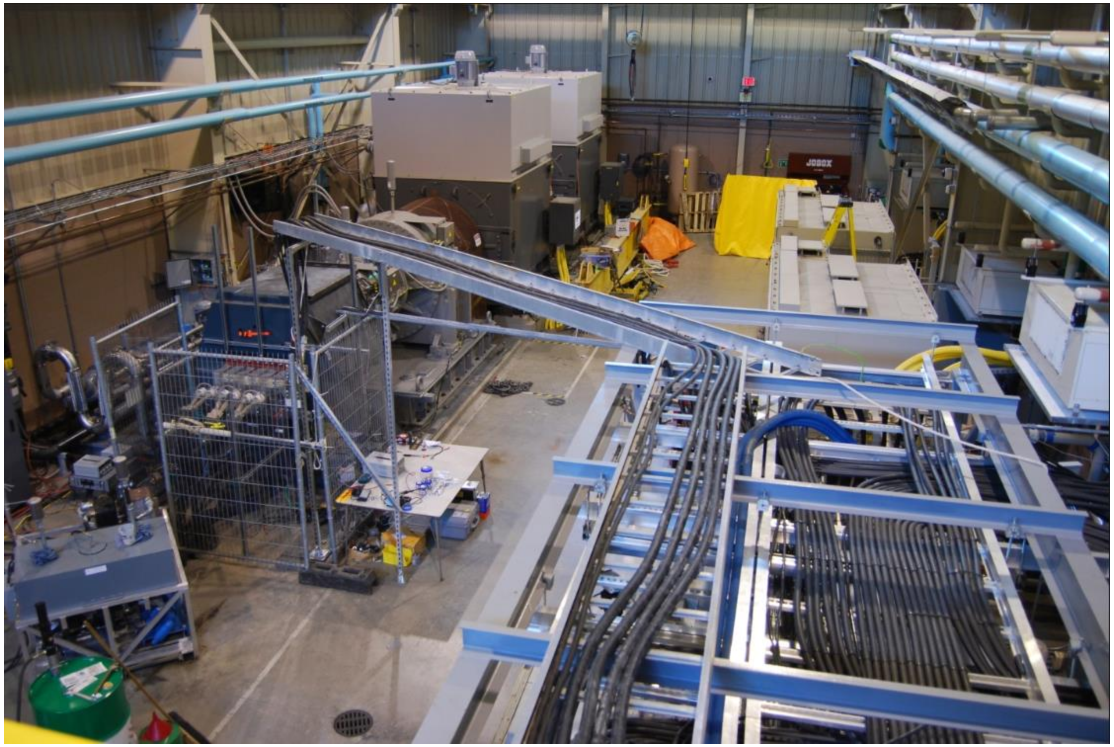



Source: EGSTON

- Complex **(Grid) Emulation Equipment** Required for Testing
- High Power Requirements

# ▶ Testing Infrastructure (3)

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

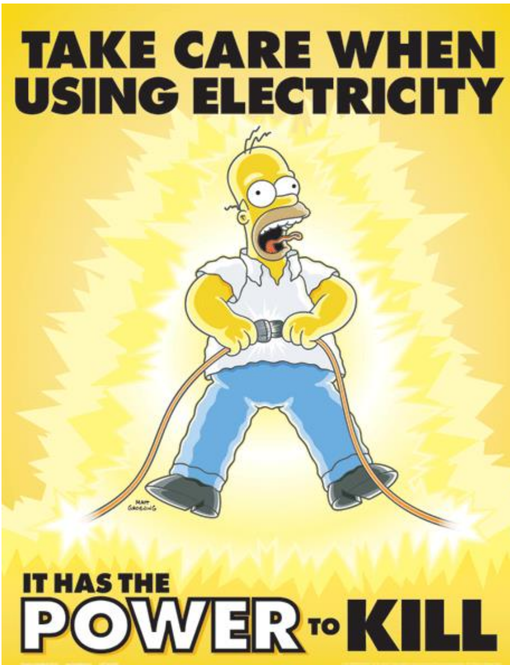



Img.:Center for Advanced Power Systems / Florida State University

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

# ► Education: MV Power Electronics – Safety Issues, etc.

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



Source: www.safetyposters.com

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

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

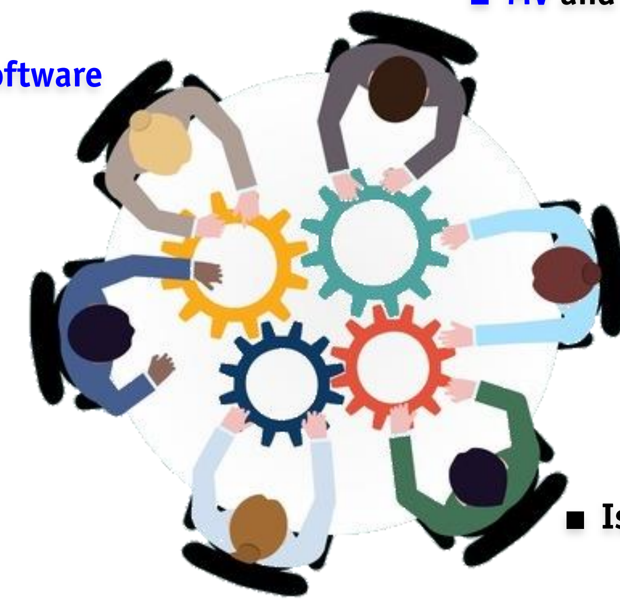
# Core Competencies of SST Design

1. *Handling of Medium Voltage*
2. *5 Main SST Topologies*
3. *Reliability*
4. *MF Isolation*
5. *MF Transformer Design*
6. *Isolation Coordination*
7. *EMI*
8. *Protection*
9. *Control*
10. *Construction & Testing*

# ▶ Core Competencies for SST Design

- The **10+ 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!**

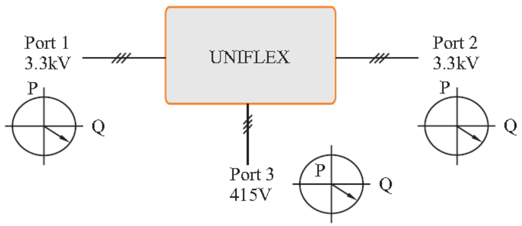
Img.: macrovector / 123RF Stock Photo

# SST Demonstrator
# Systems and Applicability

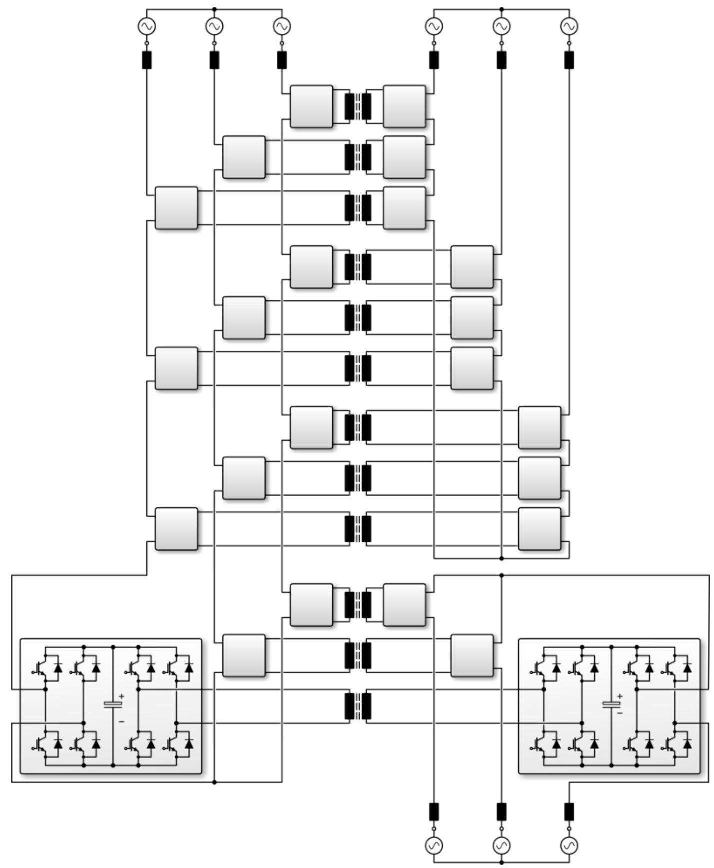
***Smart Grid***
*Traction*
*DC-DC*

# ▶ UNIFLEX Project

- EU Project (2009)




Demonstrator at Univ. of Notthingham



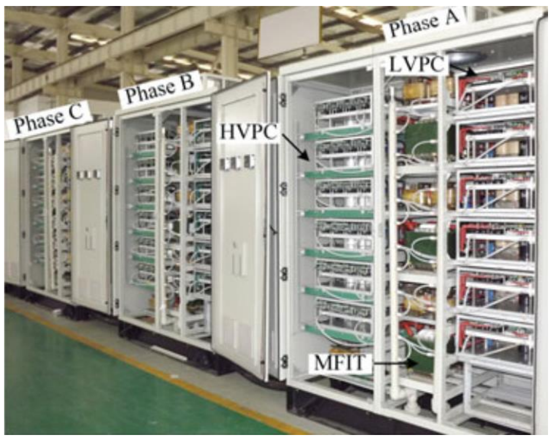
- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- **Cellular 300kVA Demonstrator of 3-Port Topology** for 3.3kV Distr. System & 415V LV Grid Connection

[Watson2009]

# ▶ 10kV/400V 500kVA/1kHz Electronic Power Transformer

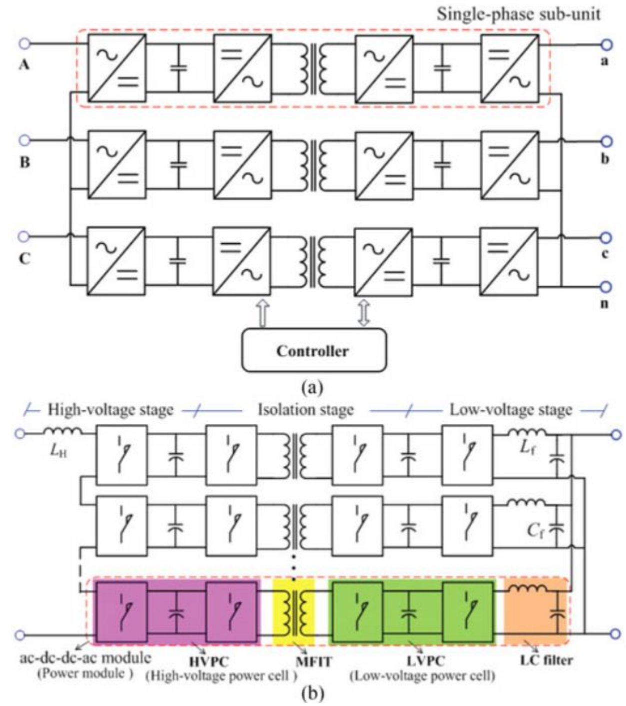
- Industry/Univ. Project, China 2016

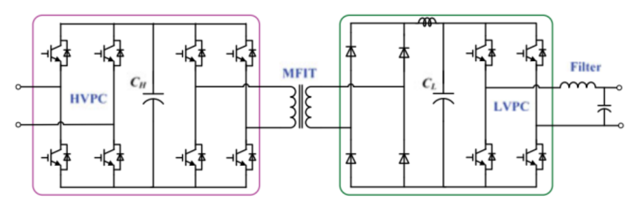
- Provide Const. Volt./Freq. for **Nonlinear Impact Loads**
- Protect Utility Grid from Load Harmonics




- Fully Phase-Modular Topology
- 3.3kV IGBT Technology, 6 Cascaded Cells

- **AC-AC Efficiency 93.7%** @ 300kW



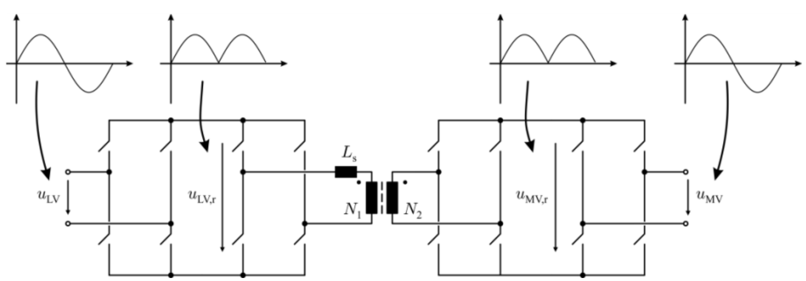



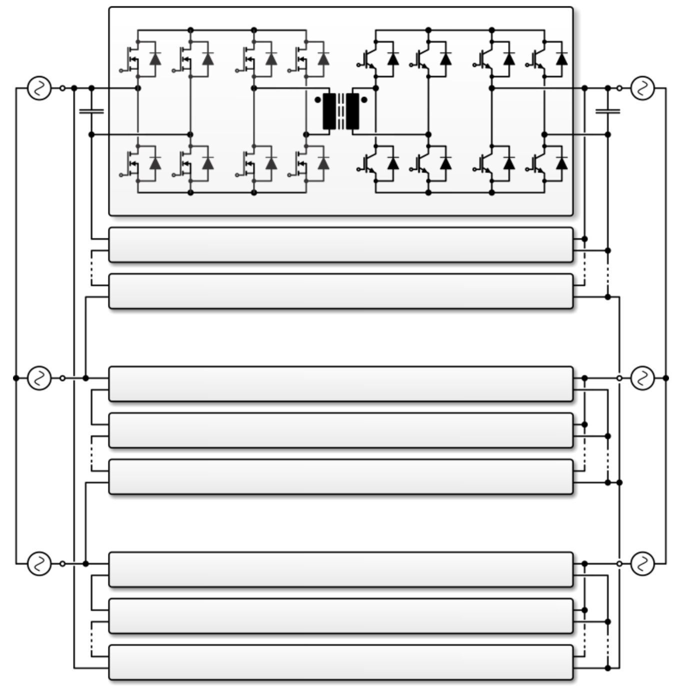

[Wang2016]

# ▶ 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 ($13.8\text{kV}_{\text{l-l}}$, 4 Modules in Series)
- LV Y-Connection ($465\text{V}/\sqrt{3}$, Modules in Parallel)



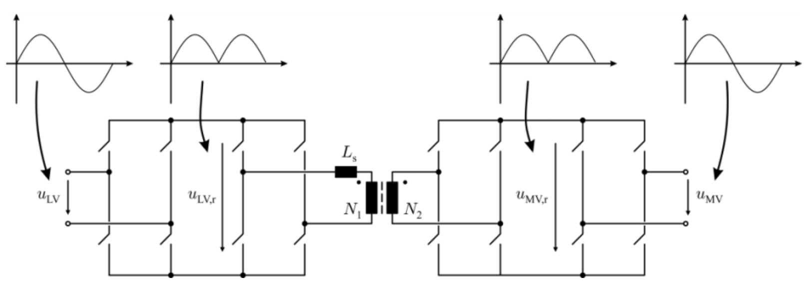
- **Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency**

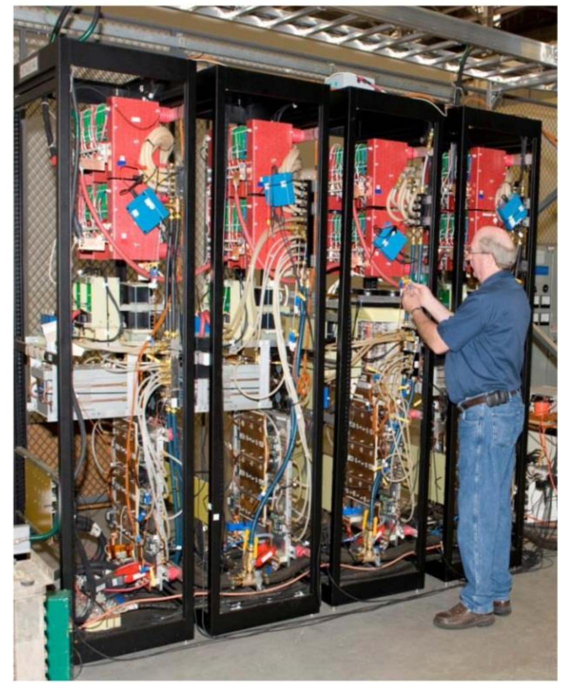
[Das2011]

# ▶ 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)

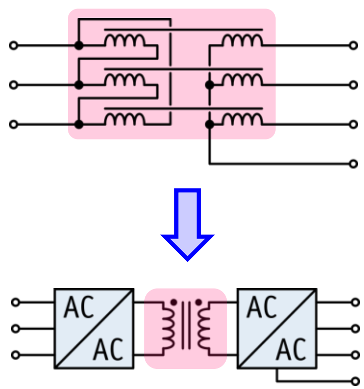


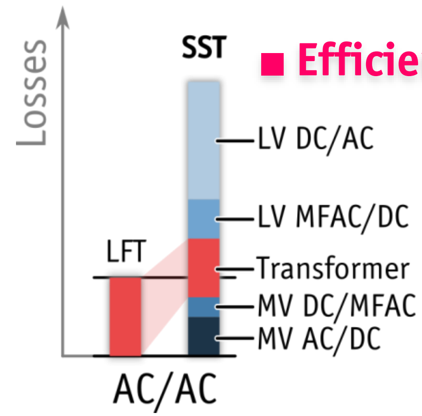



- **Comp. to 60Hz: 25% Weight / 50% Volume Reduction @ 97% Efficiency**

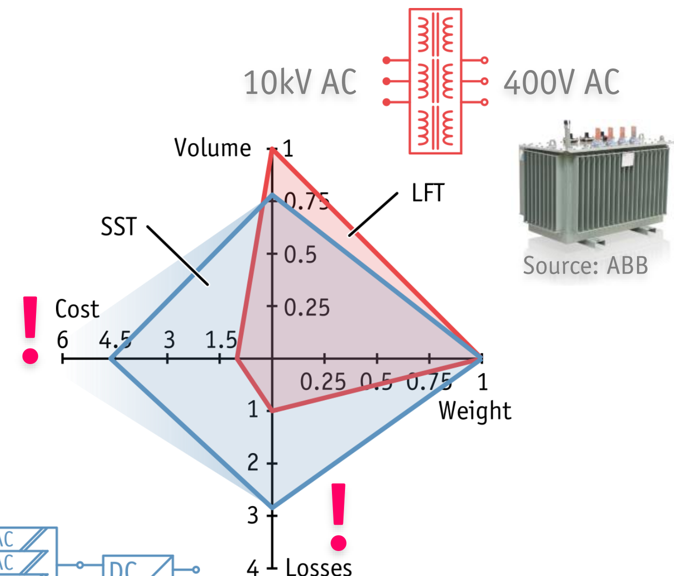
[Das2011]

# ► SSTs in Grid Applications: Isolation & Voltage Scaling



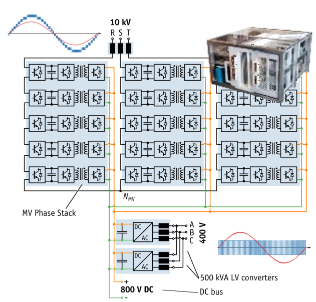



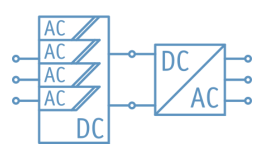

■ **Efficiency Challenge !**




■ **Efficiency Challenge Quantified**
**1MVA**, 10kV AC Input

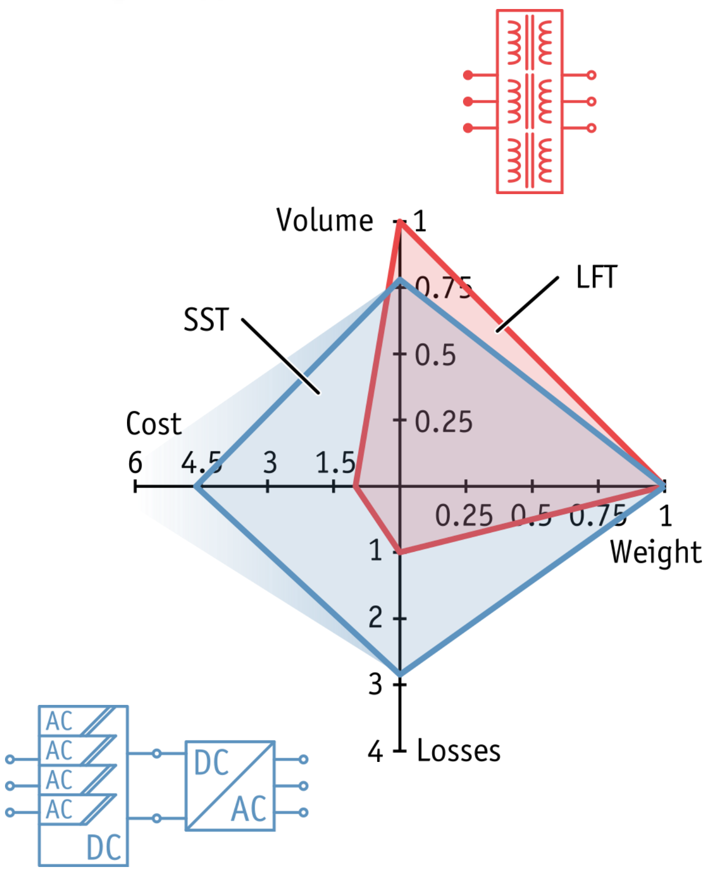
- LFT Data:
  Manufacturer Datasheets
- SST Data:
  Prototype Converter Cell
  & Theor. Models



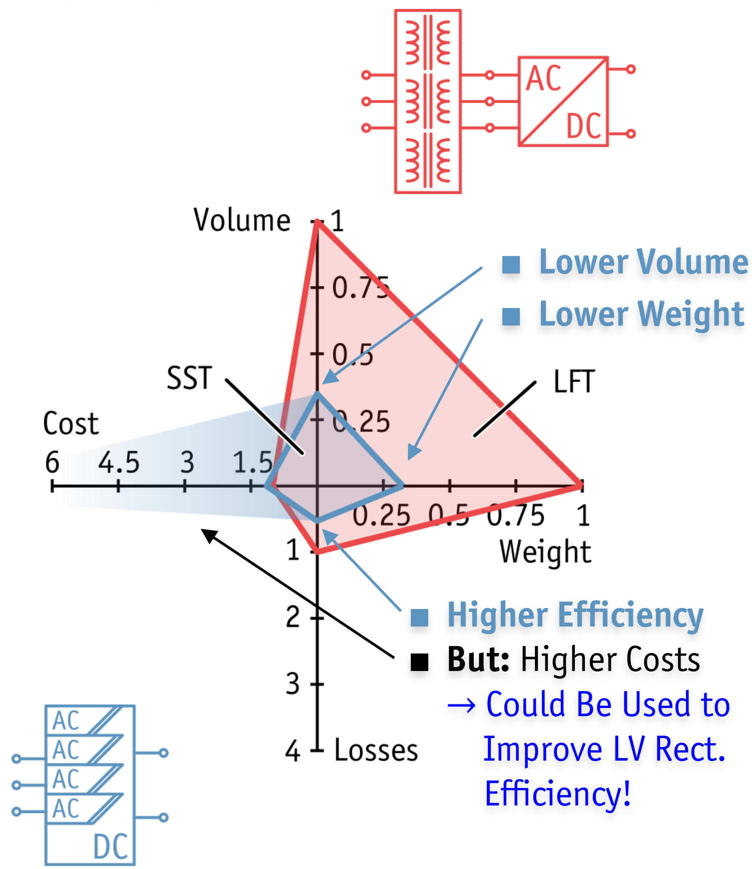



# ▶ SST vs. LFT Quantified – AC/AC and AC/DC Conversion

■ **AC/AC** Application




■ **AC/DC Application**

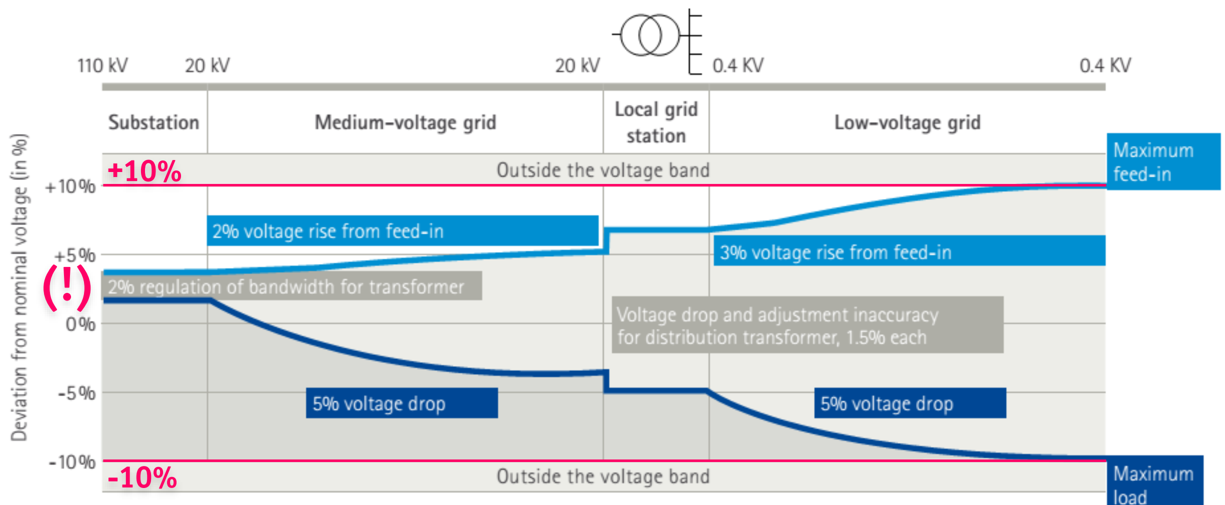



**Further Reading:** ETH / [Huber2014b]

# ▶ Controllability Requirements in Distribution Grids

- Example: Voltage Band Specified by EN 50160: **Nominal Volt. ± 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.

# ▶ SSTs in Grid Applications: Controllability

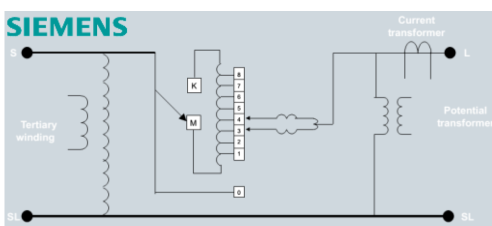
- ***Some*** Controllability Required
  - Voltage Regulation (Voltage Band vs. Renewables)
  - Power Quality (Sensitive Loads)
  - …

- Major Companies Offer A **Wide Portfolio of Solutions**

- **Solutions Without Power Electronics**
  - Regulation Distribution Transformer

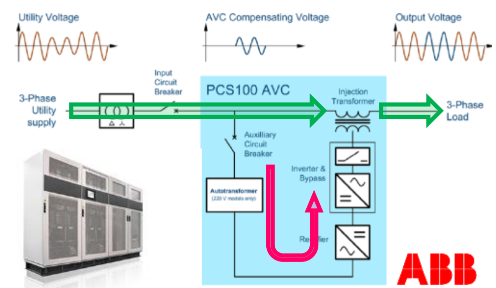

Img: Maschinenfabrik Rheinhausen

  - Distribution Voltage Regulators



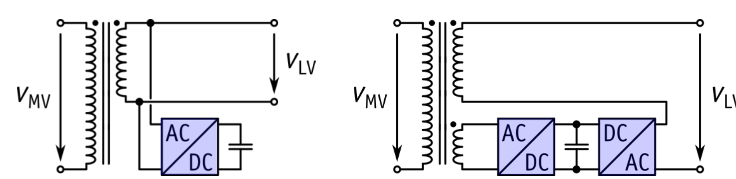

Source: SIEMENS Voltage-Regulator-Catalogue

- **Power Electronics Not Processing Full Power**
  - Active Series Voltage Regulators




Source: ABB PCS100 Brochure

  - **Hybrid SSTs**

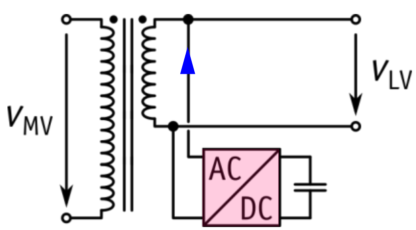



→ "The Best of Both Worlds"?
→ Still In **Research** State

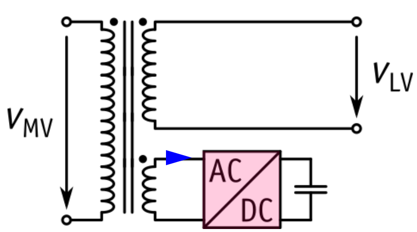
# ▶ Hybrid Transformers: Combinations of LFT and SST

## ■ Shunt

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

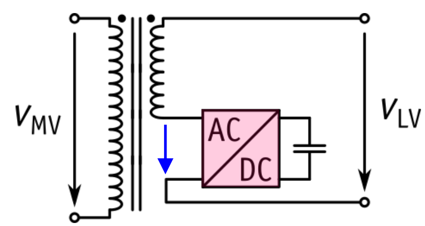



- Shunt Conv. Volt. Indep. of $V_{LV}$



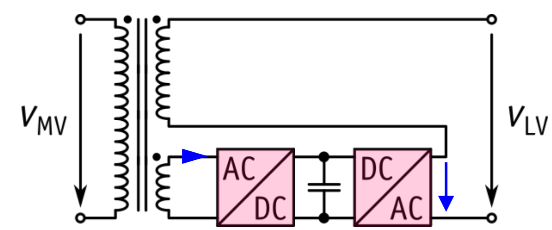

## ■ Series

Reactive Voltage Injection
- Phase Shifting
- Voltage injection




## ■ Combined

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



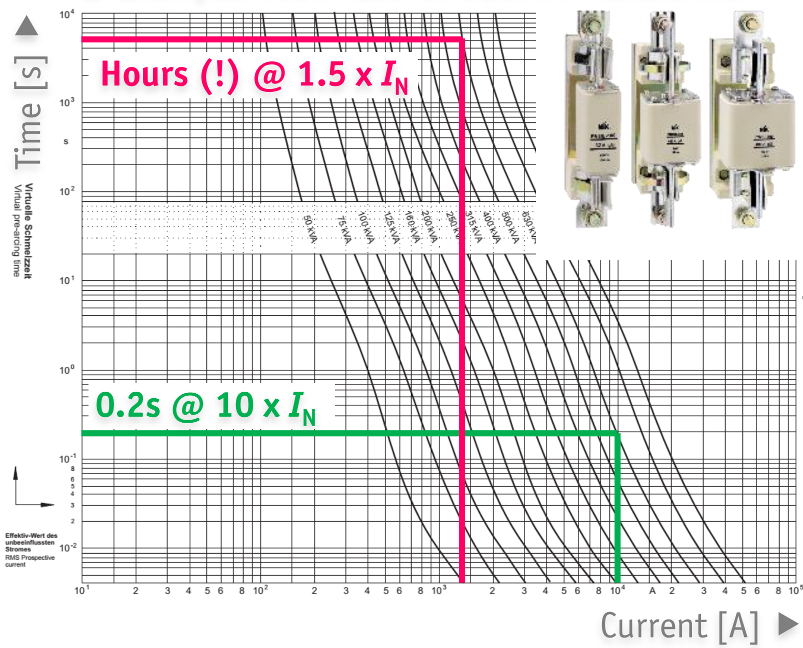

▶ **Fractional Power Processing**

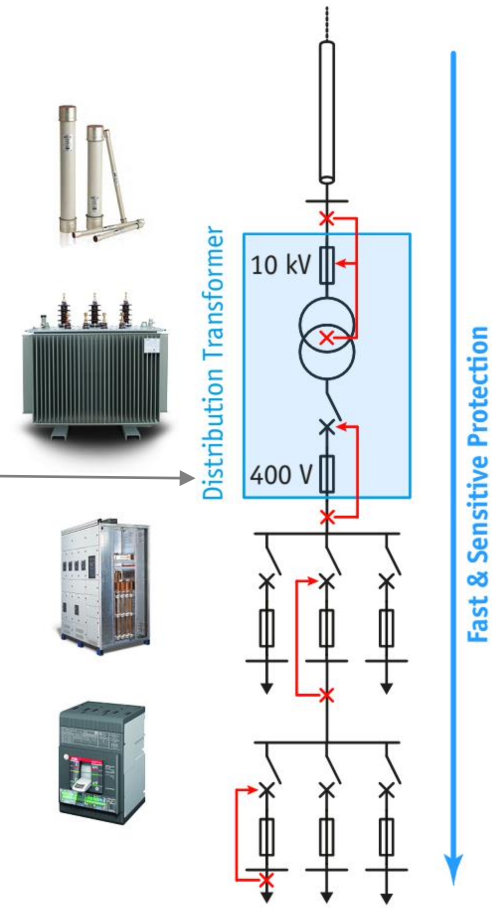
→ Power Electronics Processes Only A Fraction Of The Power and/or Voltage

[Bala2012], [Burkard2015]

# ▶ SSTs in Grid Applications: Compatibility (1)

- Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed / Safety / Reliability
  - **Selectivity:** Only Closest Upstream Breaker/Fuse Should Trip to Isolate Faults Quickly
    - Example: 400V Fuse for 630kVA Transformer



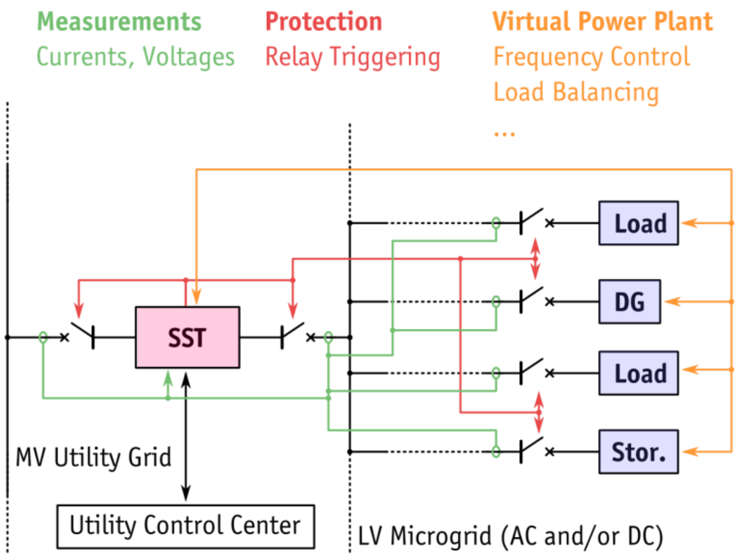

- **Very Large Short-Circuit Currents Required** to Trigger Fuses and/or Other Protection Relays

Imgs.: ETH / [Guillod2015]

# ▶ SSTs in Grid Applications: Compatibility (2)

## ■ SST Grid Integration Requires Adaptions of Existing Grid Infrastructure

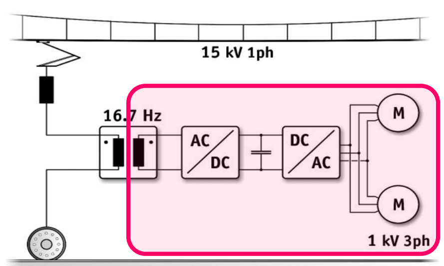
- SST Requires A **Controlled Environment** on its LV Side
- SST Is Thus **Not a Direct Replacement** for a Distribution LFT!




- **Novel Grid Protection Schemes** Based on Communication Facilities

- Micro Grid Can Act as a “Virtual Power Plant”
- DC Distribution
- Etc.

## ■ Comparison: **Traction Application**




→ Locomotive is a **User-Controlled, Self-Contained** Environment!

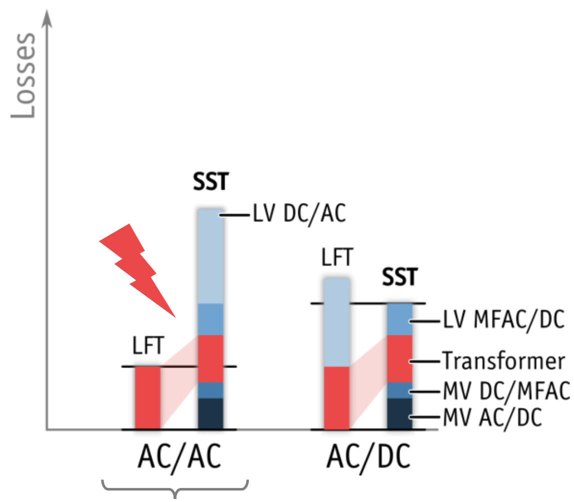
# SST Demonstrator Systems and Applicability

*Smart Grid*
***Traction***
*DC-DC*

Img.: www.futuretimeline.net

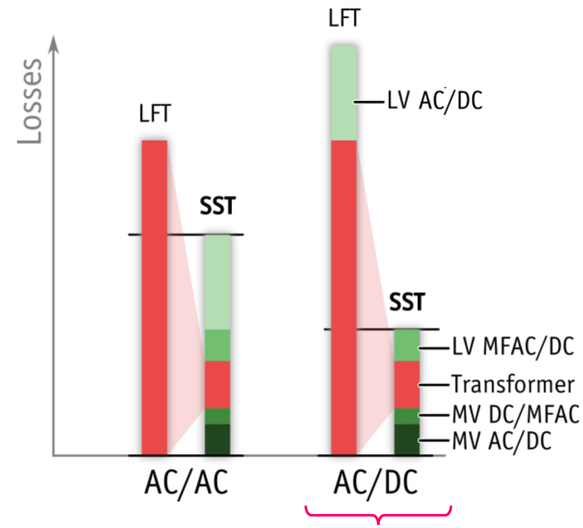
# ▶ Efficiency Challenge for Weight/Volume Constrained Appl.

■ **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!**

# ▶ 1ph. AC-DC Power Electronic (Traction) Transformer – PETT

**ABB** PETT

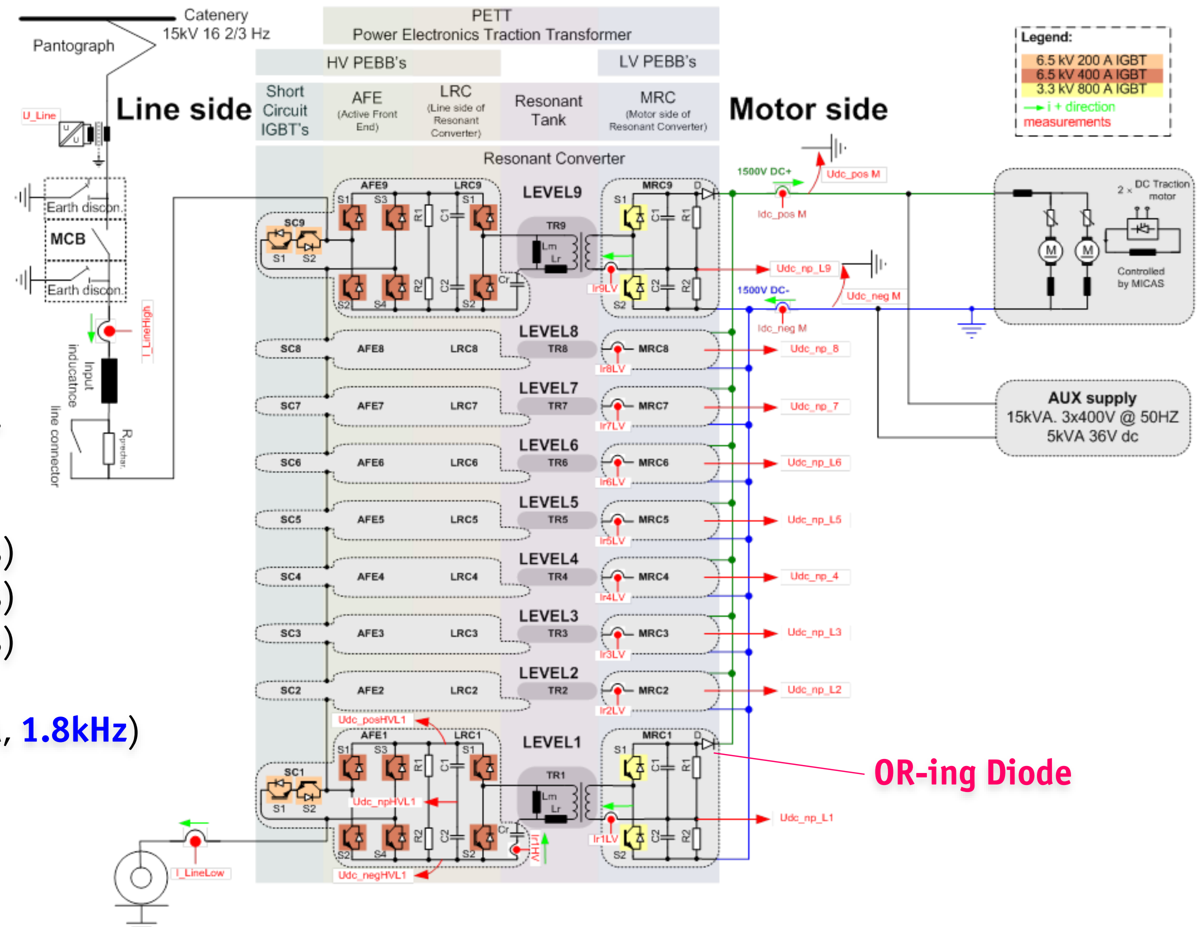
- Dujic et al. (2011)

- 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)

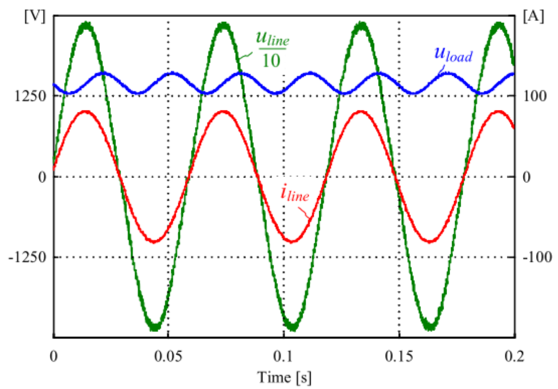
**9 x** MF Transf. (150kVA, **1.8kHz**)
1 x Input Choke

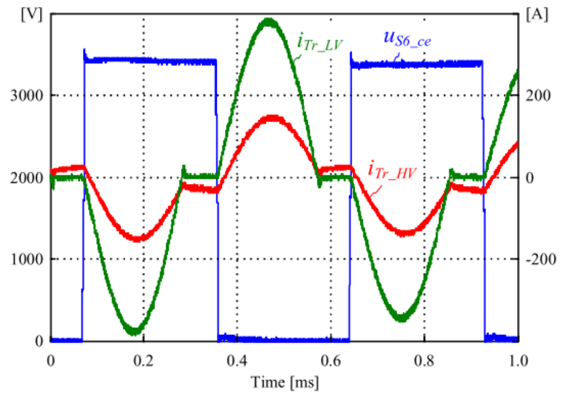



[Dujic2013] & [Zhao2014]

# ▶ 1.2 MVA 1ph. AC-DC Power Electronic (Traction) Transformer (1)

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

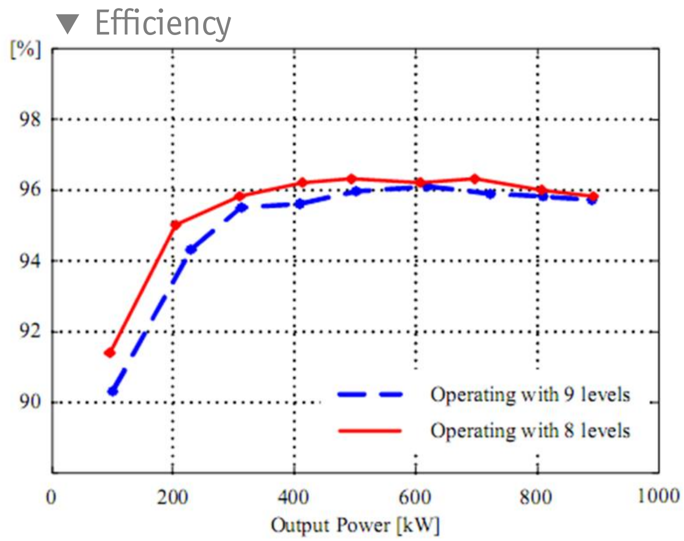



[Dujic2013] & [Zhao2014]

# ▶ 1.2 MVA 1ph. AC-DC Power Electronic (Traction) Transformer (2)

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

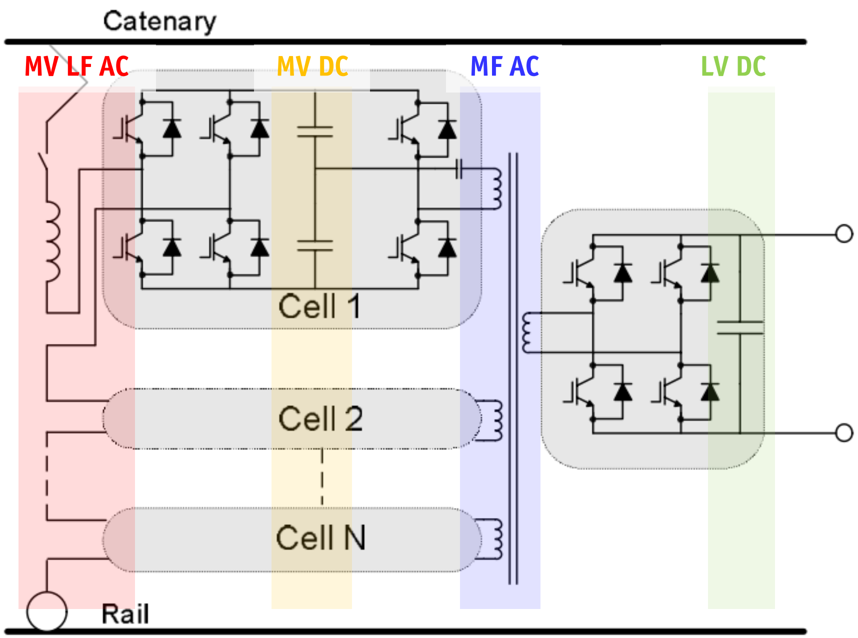




[Dujic2013] & [Zhao2014]

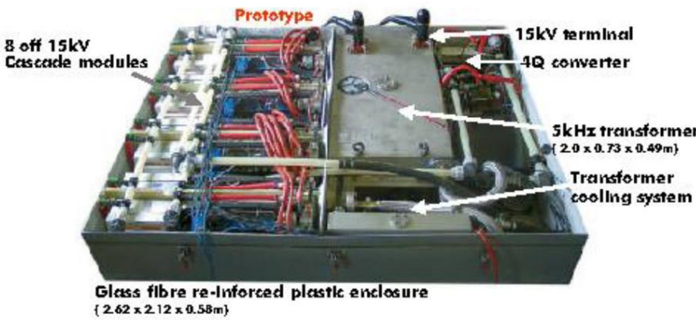
# ▶ Traction SST with Multi-Winding MF Transformer

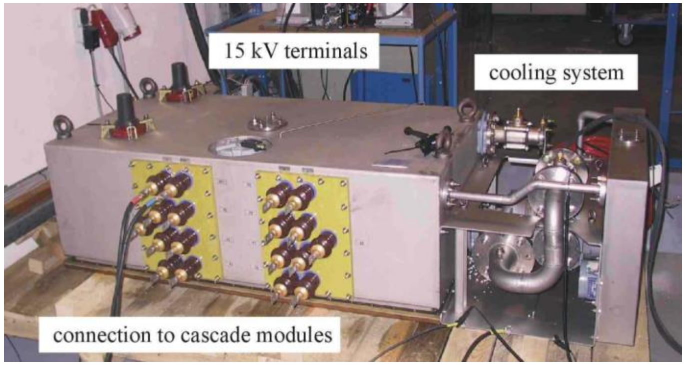
## ■ ALSTOM e-Transformer (Engel, 2003)

- Module Power 180 kW
- Frequency 5 kHz




Img.: [Dujic2011]



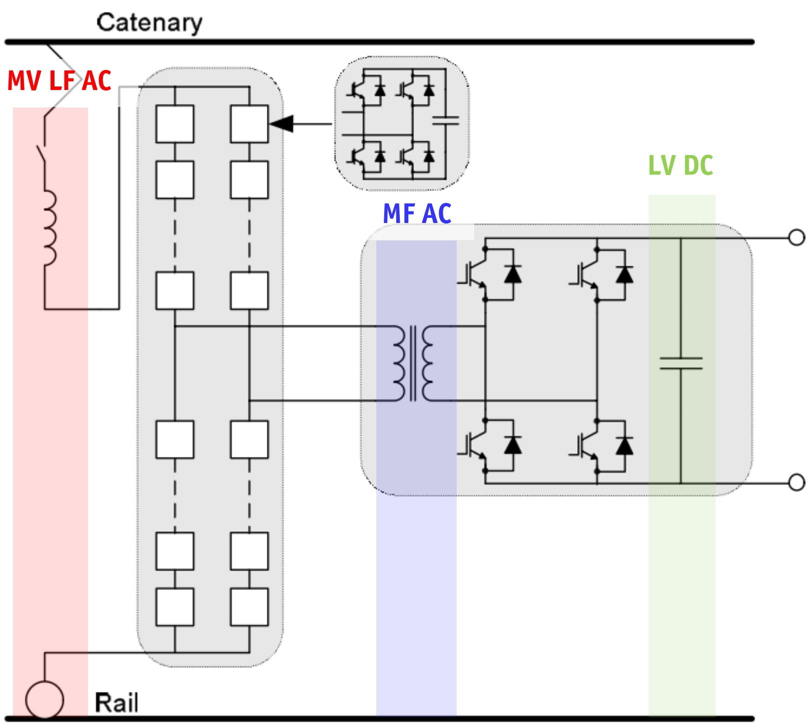




■ **Multi-Winding Transformer**

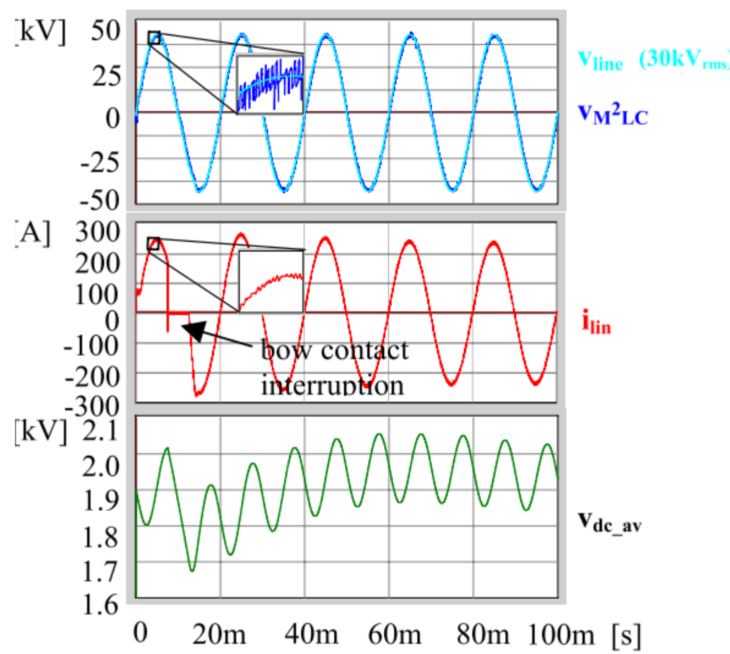
[Engel2003], [Taufiq2007]

# ▶ Traction SST with Modular Multilevel Converter (1)

- Marquardt/Glinka (SIEMENS, 2003)



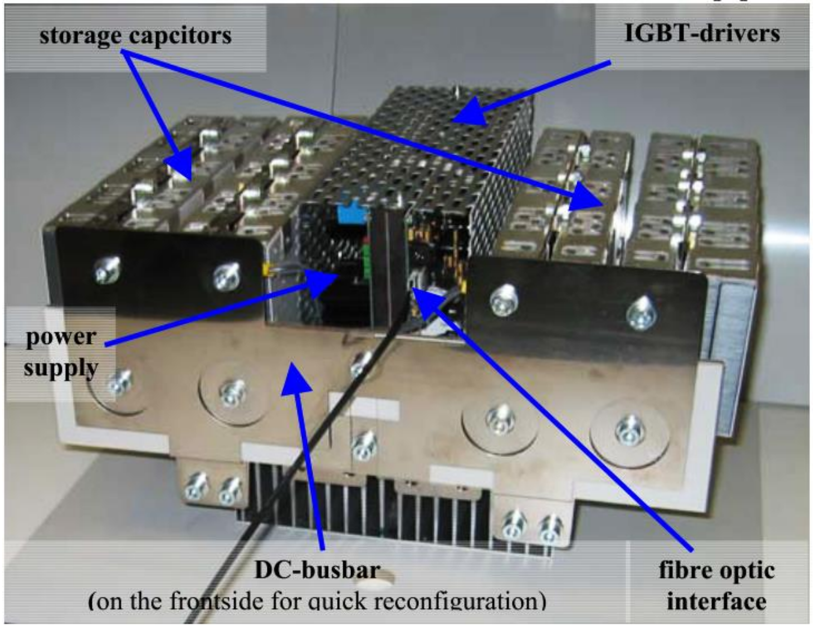

Img.: [Dujic2011]




[Glinka2003]

# ▶ Traction SST with Modular Multilevel Converter (2)

- **Marquardt/Glinka (SIEMENS, 2003)**
  - Module Power 270 kW
  - Frequency 350 Hz



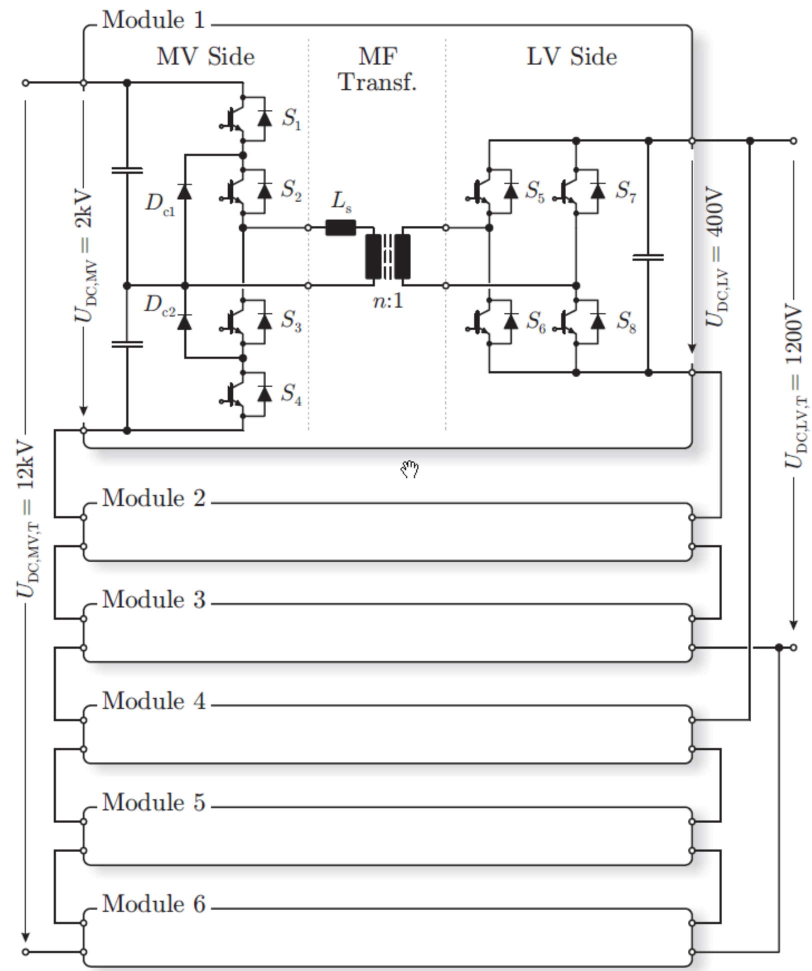

[Glinka2003]

# SST Demonstrator
# Systems and Applicability

*Smart Grid*
*Traction*
***DC-DC***

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

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

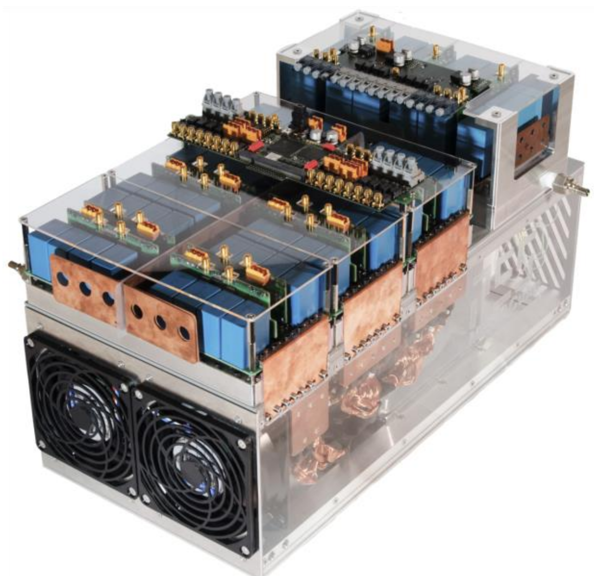



- MV Level 12.0 kV
- LV Level 1.2 kV

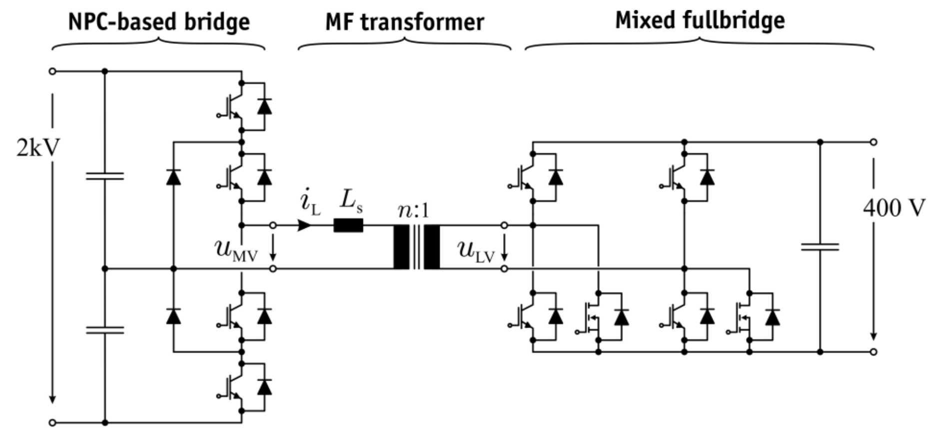
[Ortiz2010], [Ortiz2013c]

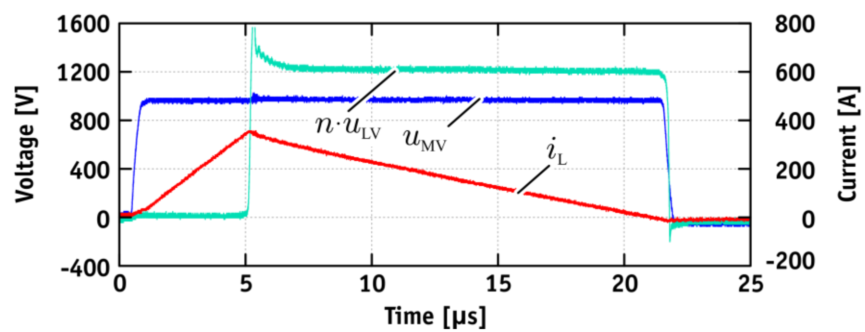
# ▶ Example: *MEGACube* @ ETH Zurich (2)

- **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)



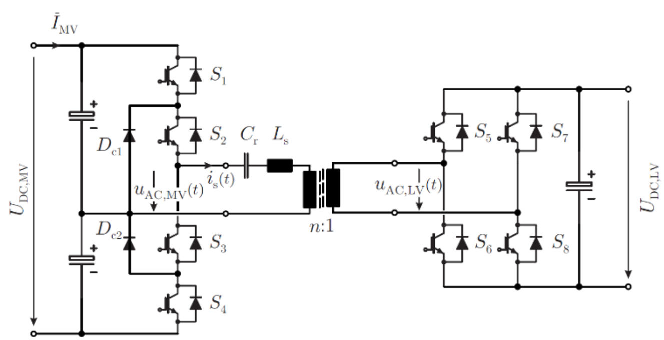




▲ Structure of the 166kW Module and MV Side Waveforms

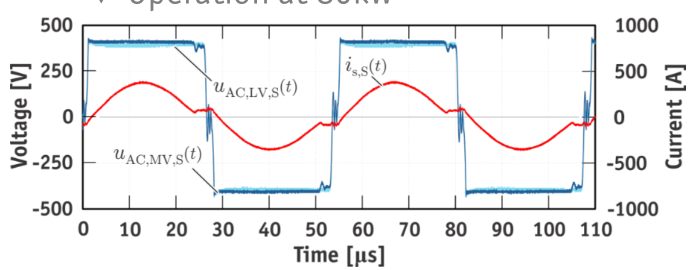
[Ortiz2013c]

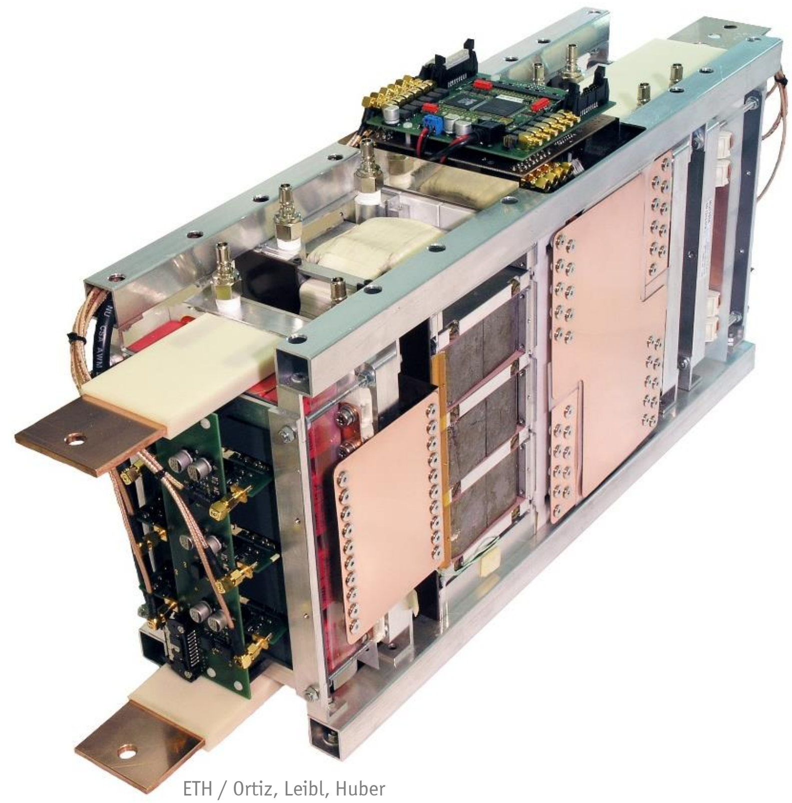
# ▶ Example: *MEGACube* @ ETH Zurich (3)

- **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

# Recent Research @

Power Electronic Systems Laboratory

*Swiss SST ($S^3T$) IFE-Based SST*
*10kV SiC for SSTs*

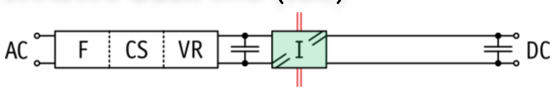
# ▶ Partitioning of Single-Phase Isolated AC-DC PFC Functionality

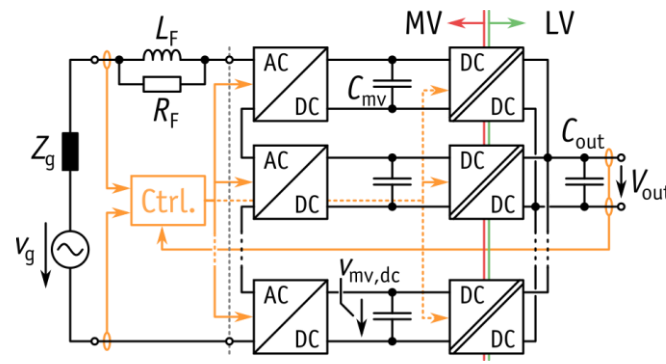
■ **Possible Applications For Isolated MVAC-LVDC Conversion**
- MV-Interface for High-Power Loads/Generators
- MV-Connected Auxiliary Supplies

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

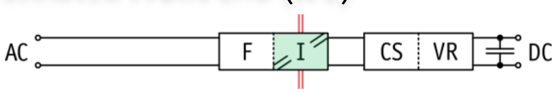
■ **Partitioning Variants**

Isolated **Back** End (IBE) →

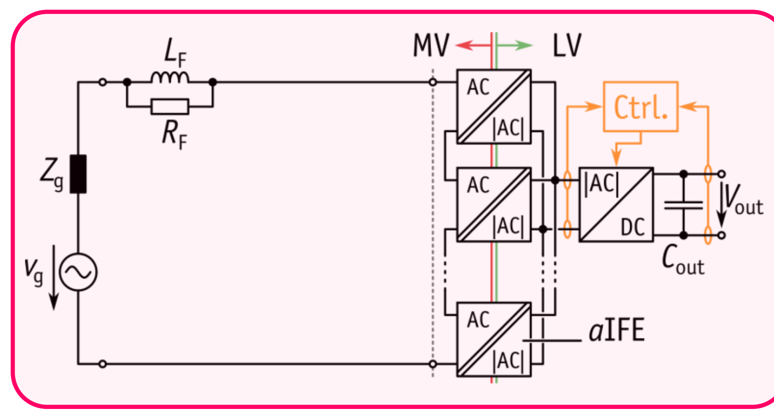



Isolated **Front** End (IFE) →

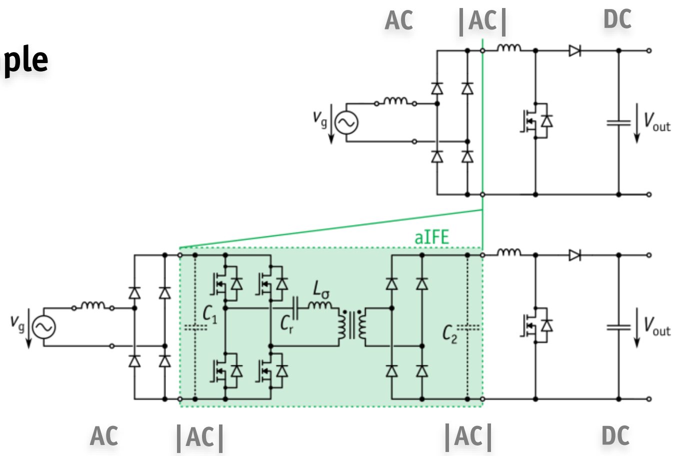



→ Less Common Alternative
→ Reduced MV-Side Size & Complexity

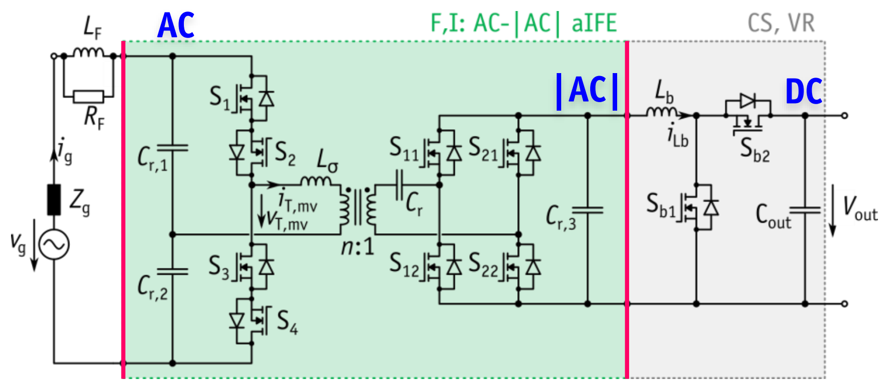


# ▶ IFE Topology Derivation

- **Single-Cell Example**




- Non-Isolated, Unidirectional Boost-Type PFC
- Extension By An Autonomous Isolation Front End (*a*IFE)
  → HC-DCM SRC Operating As An |AC|-|AC| Converter!



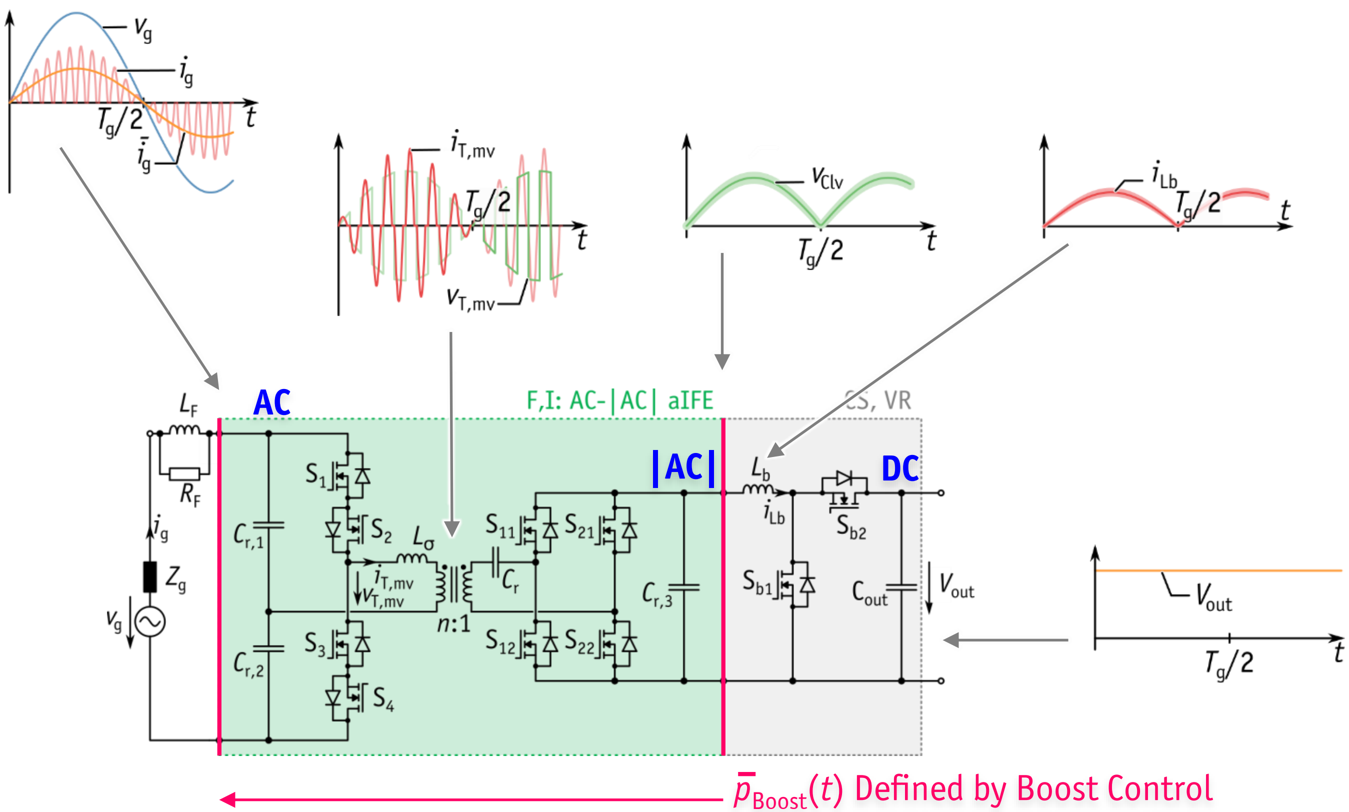

- **Bidirectional** Switches On Primary Side
  → SRC Switching And Folding of The Grid Voltage
- Note: $C_{r1}$, $C_{r2}$, and $C_{r3}$ are Resonant/Commutation Cap.!

$\bar{p}_{Boost}(t)$ Defined by Boost Control

- **No Energy Storage in *a*IFE**
  → Boost Stage Input Characteristics Are Translated to the Grid

[Huber2016a]

# ▶ IFE Key Waveforms (Single Cell)



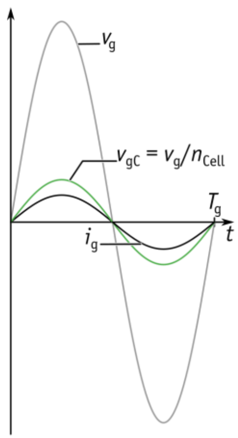

■ **No Energy Storage in *a*IFE**

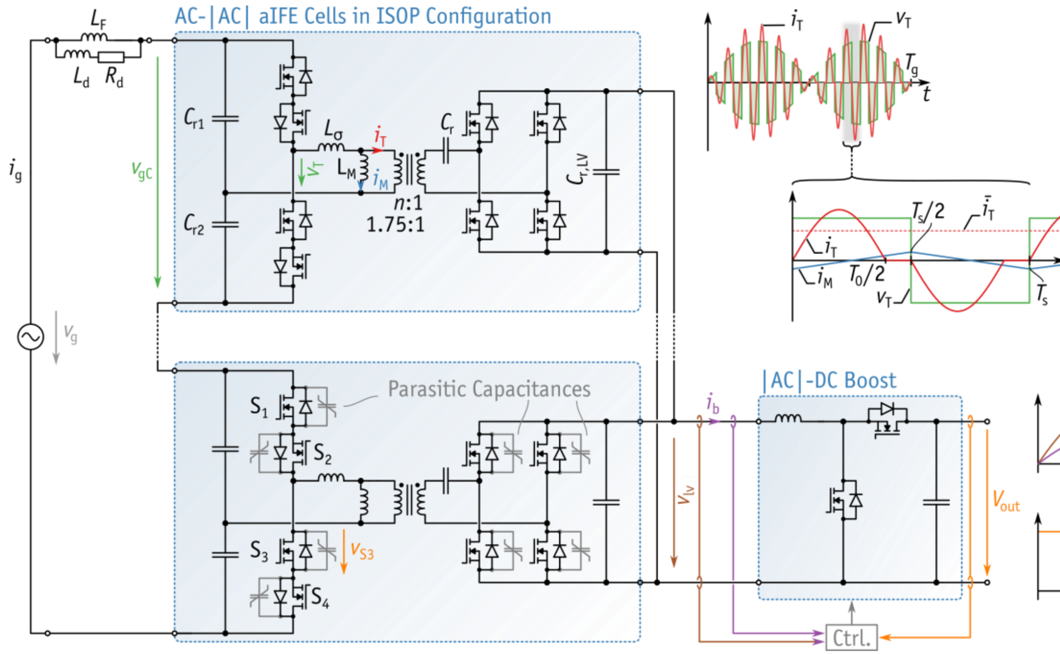
→ Boost Stage Input Characteristics Are Translated to the Grid

[Huber2016a]

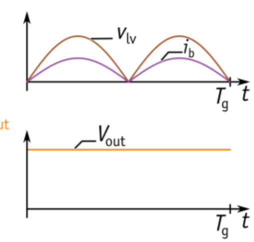
# ▶ Going MV: IFE-Based Multi-Cell AC-DC SST In ISOP Configuration

- **6.6kV Grid**

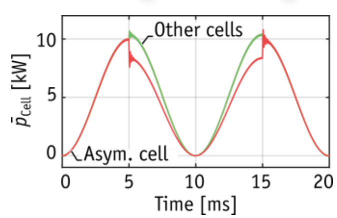


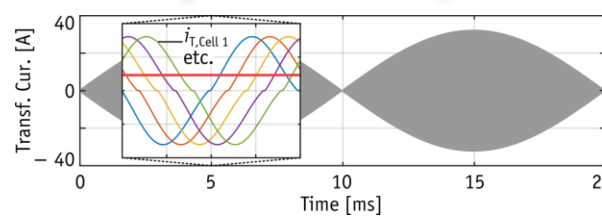

- **400V DC**
- **25kW**




- **MV Voltage Sharing**



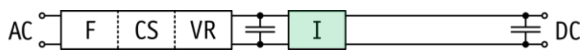

- **Interleaving** of *a*IFE Switching



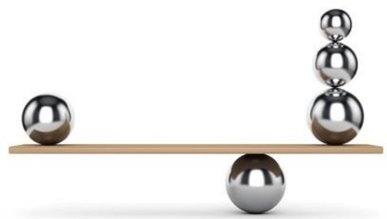

[Huber2016a]

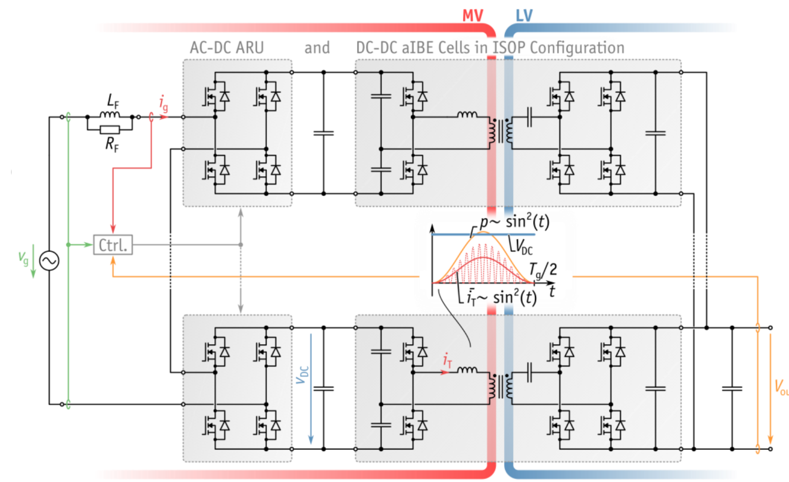
# ▶ IFE vs. IBE Comparative Evaluation (1): Overview

## ■ Isolated Back End (IBE)

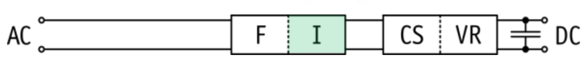



→ Approx. Constant MV DC Voltage
→ Lower Transformer RMS Currents
→ Flexibility (Reactive Power, etc.)

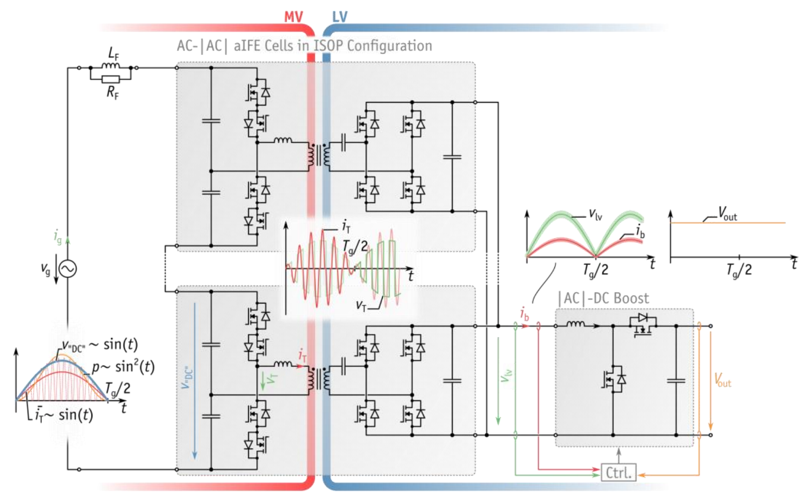





## ■ Isolated Front End (IFE)

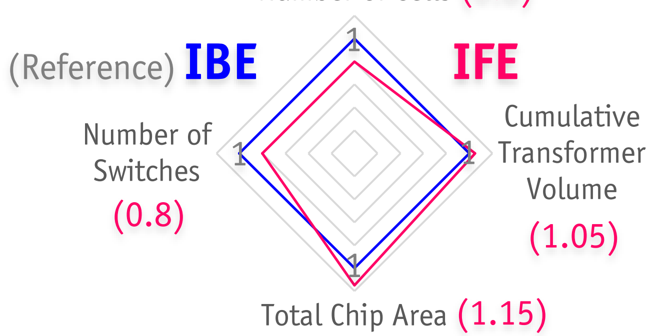



→ Low MV Side Complexity and Size
→ Lower Total MV Blocking Voltage
→ **Fewer Cascaded Cells**



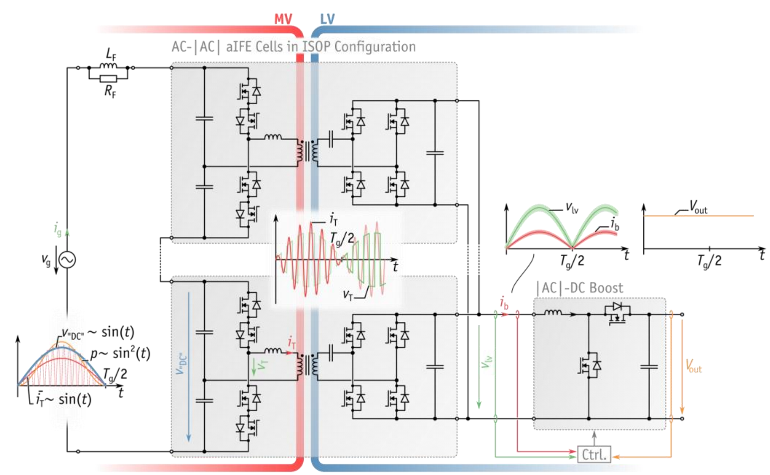
# ▶ IFE vs. IBE Comparative Evaluation (2): Generic Results

- **Analytical Derivation of Performance Indices**
  - Main Component Stresses
  - Transformer Volumes
  - Chip Area Requirements.
  - …




- **For the Same Specifications, IFE Requires …**
  - **Fewer** Cascaded Cells
  - **Fewer** Individual Switches / Gate Drives
  - Similar Total Transformer Volume
    (Higher Winding Losses, Lower Core Losses)
  - Larger Total Chip Area
    (But on the LV Side – Costs!)

- **Other Interesting IFE Features**
  - Only **Small** (Resonant) **Capacitors on MV Side**
    → Smaller Assembly on Float. Potential
    → Reduced Energy Stor. for 3ph Config.
  - Cells Change Potential Only With **Low *dv/dt***
    → Reduced Common-Mode Ground Currents
    → Reduced Isolation Stress

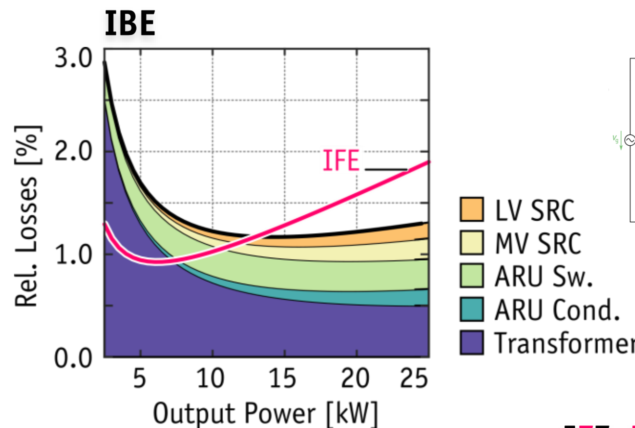


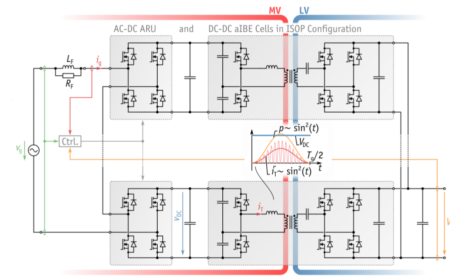

[Huber2016a]

# ▶ IFE vs. IBE Comp. Evaluation (3): "Swiss SST (S$^3$T)" Case Study

■ **Isolated Back End**

- 6 Cells, 6 Transformers
- 36 x 1700V/45mΩ
- 24 x 900V/11.5mΩ



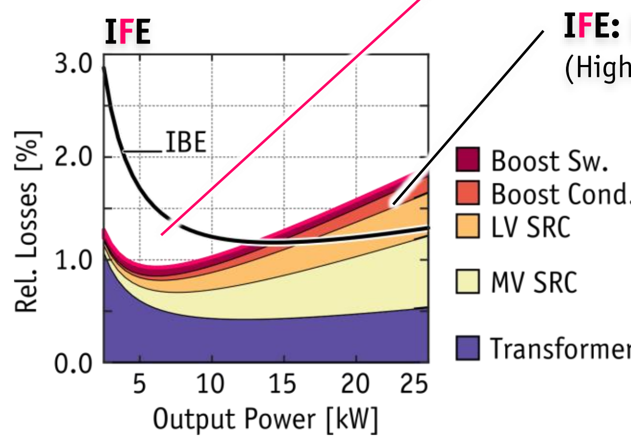



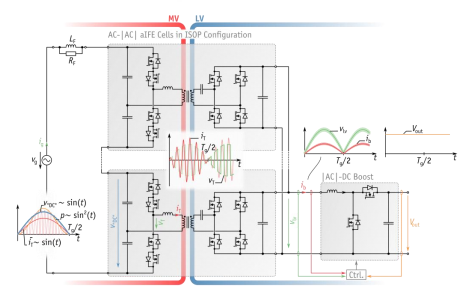

**S$^3$T Specs.**

- 25kW
- 6.6kV AC (line-line)
- 400V DC
- **All-SiC**

**IFE: Lower Losses at Part Load**
(Lower Core Losses, Lower Hard-Switching Losses on LV Side)

**IFE: Higher Losses at Full Load**
(Higher RMS Currents)



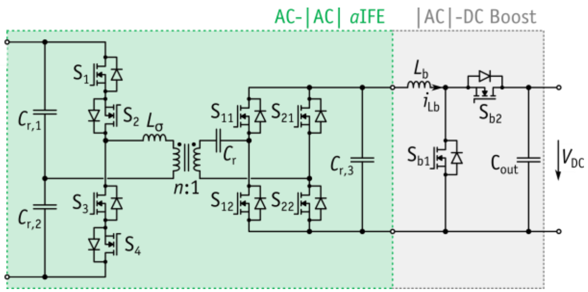




■ **Isolated Front End**

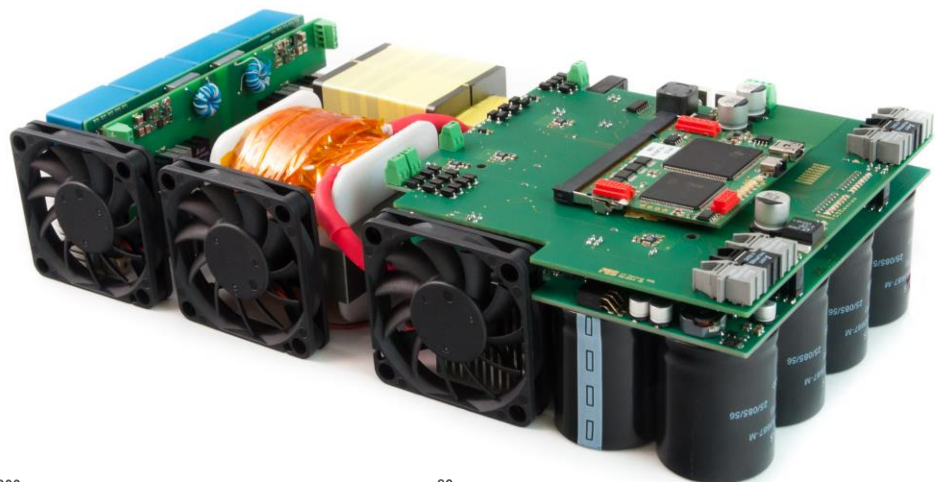
- **5** Cells, **5** Transformers
- **20** x 1700V/45mΩ
- **30** x 900V/11.5mΩ

→ **Lower Realiz. Effort!**

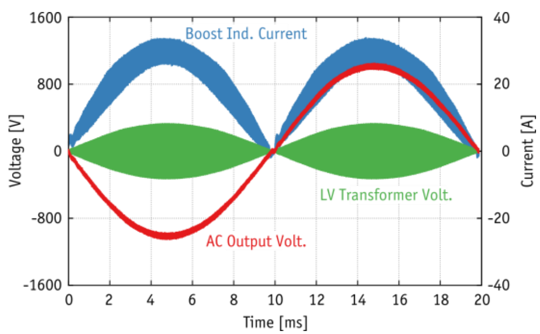
# ▶ $S^3T$ Cell Prototype

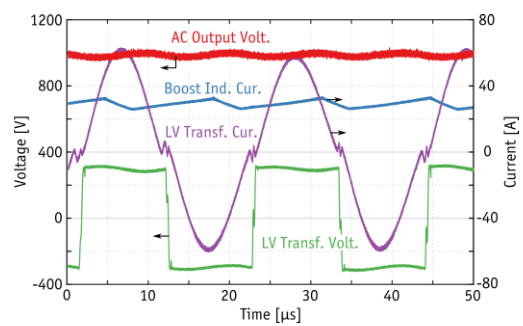



- 5kW, 1.1kV AC (peak) to 400V DC
- Full-Load LVDC → MVAC Operation



ETH / Böhler, Rothmund, Huber



# Recent Research @

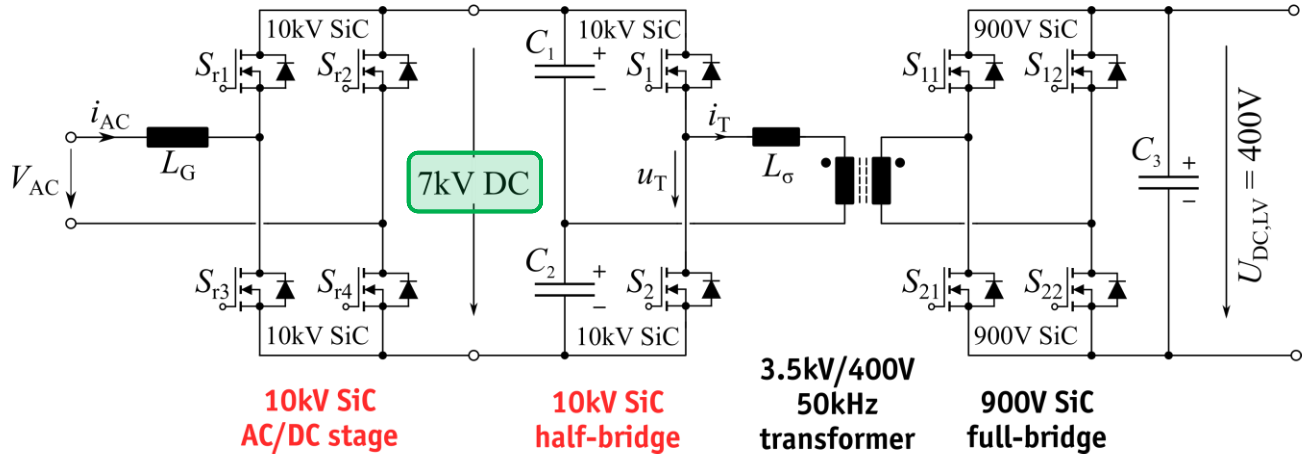
Power Electronic Systems Laboratory

Swiss SST ($S^3T$) IFE-Based SST

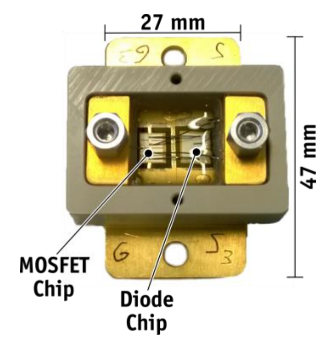
***10kV SiC for SSTs***

# ▶ Single-Cell Approach: 25kW, 6.6kV AC to 400V DC SST

■ Low Complexity Using Single-Cell Approach




■ **DAB DC-DC Converter Operating at 7kV and 50kHz**
- Soft-Switching (ZVS) Necessary
- Soft-Switching Losses of the 10kV SiC MOSFET Must be Measured



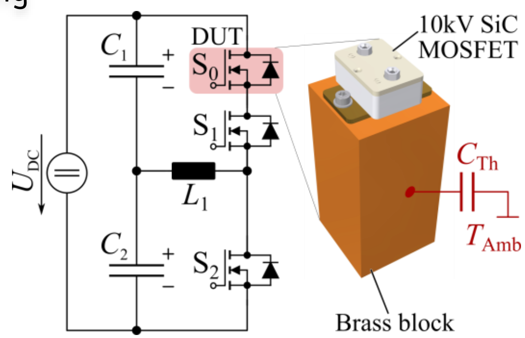

10kV, 30A SiC MOSFET ▶

ETH / [Rothmund2016]

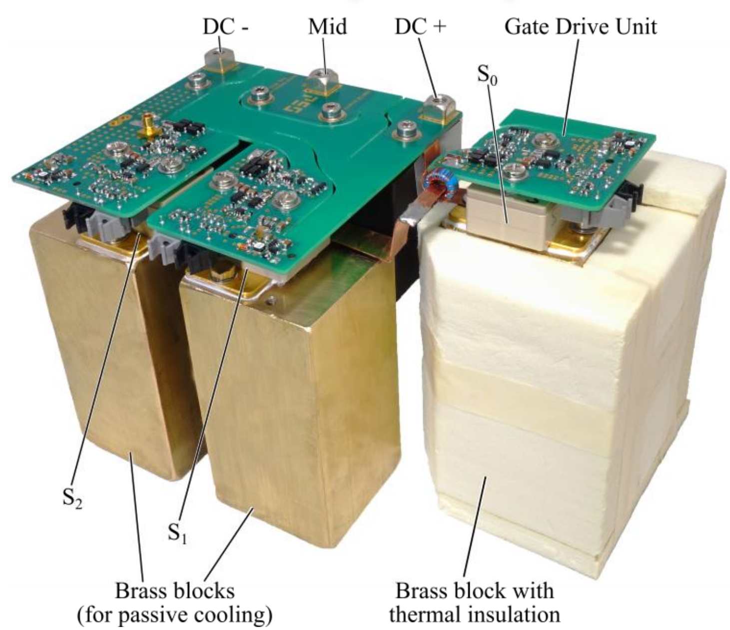
# ▶ Accurate Calorimetric Measurement of ZVS Losses (1)

- DUT on a Thermally Insulated Brass Block
- Continuous Operation, Different Modes:
  - DUT Conducting Only
  - DUT Switching

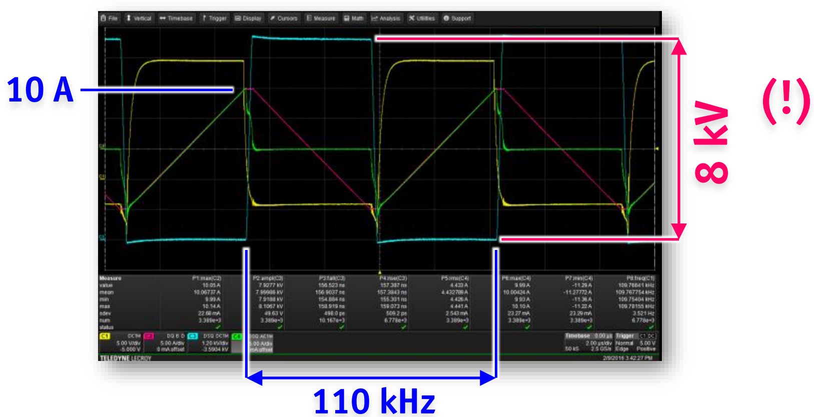
→ Directly Measure Losses via Temperature Increase and Thermal Capacitance
→ Separation of Cond. And Sw. Losses
→ No Issues With Skew, Probe Accuracy, etc.




- 10kV SiC Half-Bridge Assembly

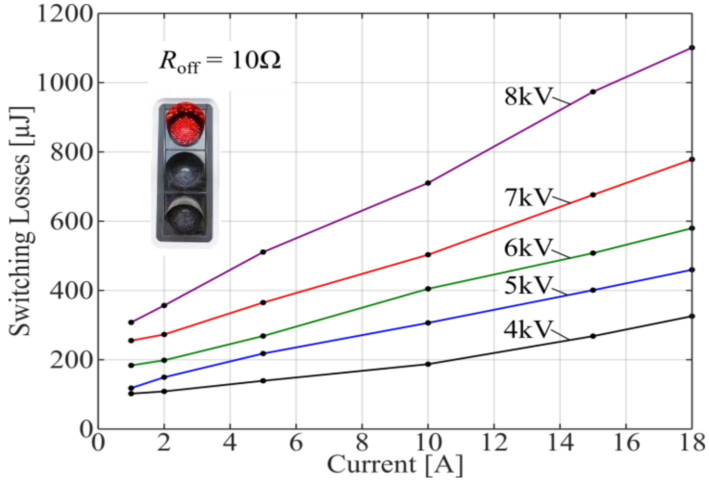



- Continuous Operation Waveforms

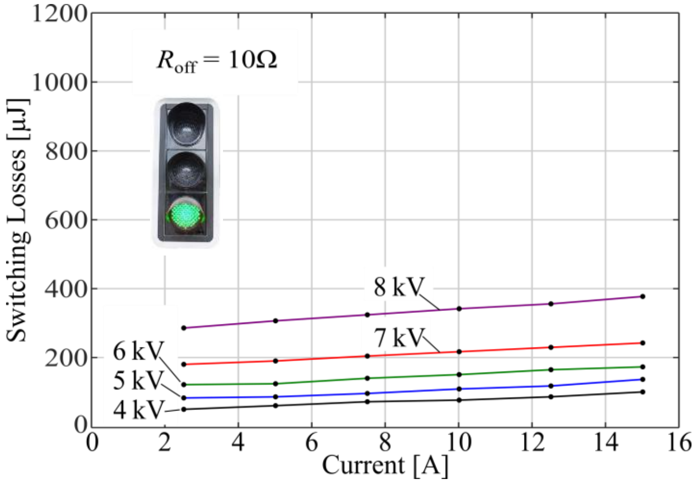


# ▶ Accurate Calorimetric Measurement of ZVS Losses (2)

■ Electrically Measured Soft-Switching Losses



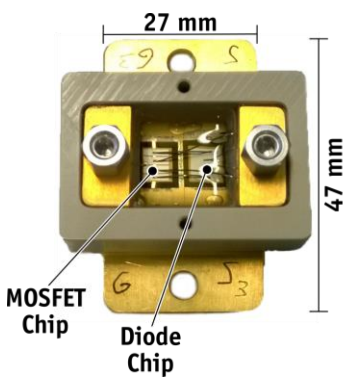

■ Calorimetrically Meas. Soft-Switching Losses




## Conclusions

- Calorimetric Measurements Are More Trustworthy
  → Much Higher Meas. Accuracy

- Soft-Switching Losses Factor 100 Smaller Than Hard-Switching Losses
- At 50kHz Still in the Range of Conduction Losses
  → Must Be Considered During Design!



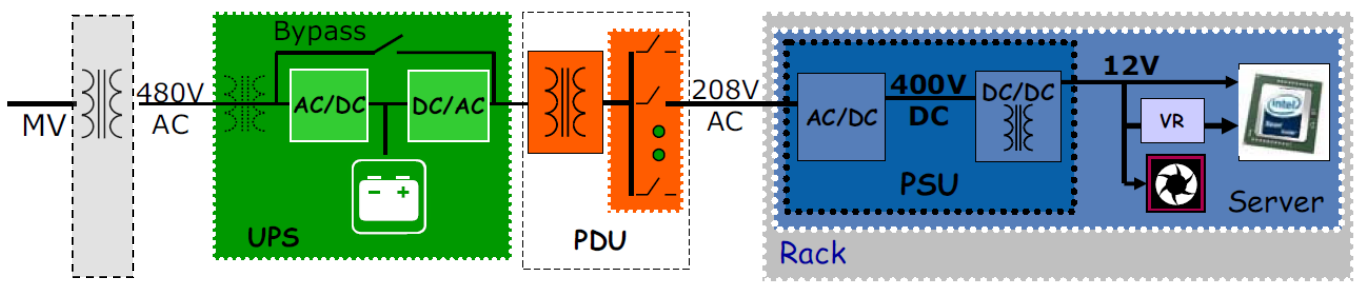
# Future
# SST Applications

# ▶ AC vs. Facility-Level DC Systems for Datacenters

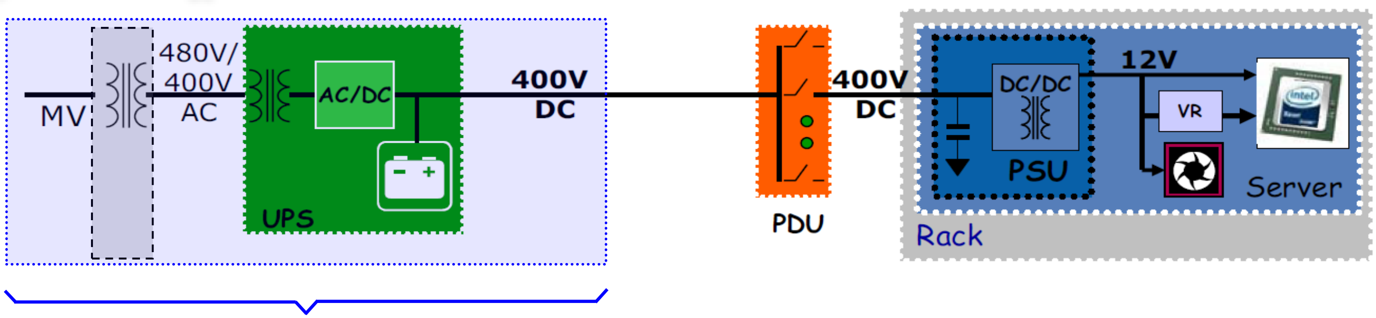
- **Reduces Losses & Footprint**
- Improves Reliability & Power Quality

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

Source: intel 2007



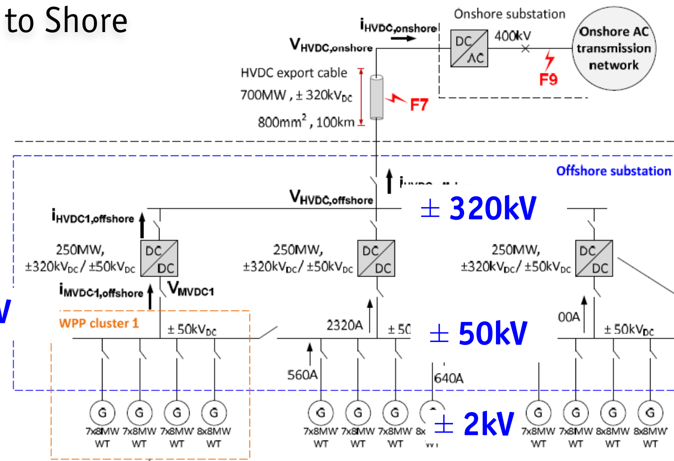

- **Facility-Level 400V$_{DC}$ Distribution**

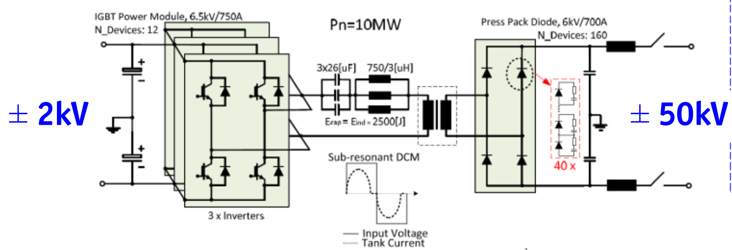



- **Future Concept:** Unidirectional SST / **Direct 6.6kV AC → 400V DC Conversion**

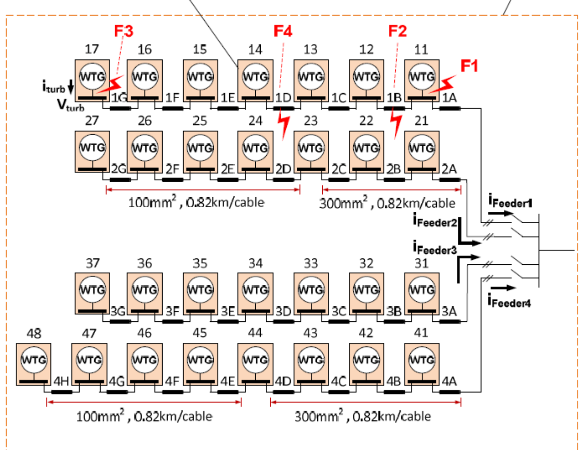
# ▶ DC Collecting Grids for Offshore Wind Parks

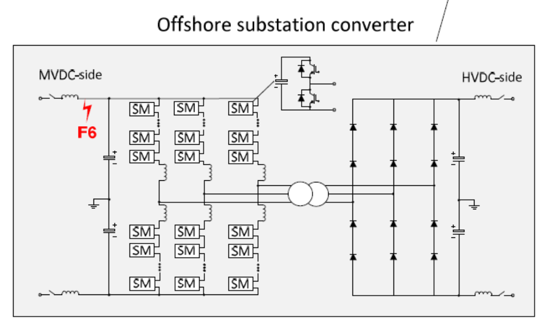
- $\pm 320kV_{DC}$ HVDC Transmission to Shore




- Unidirectional **Series Resonant MF DC→MVDC** Conversion in each Wind Turbine

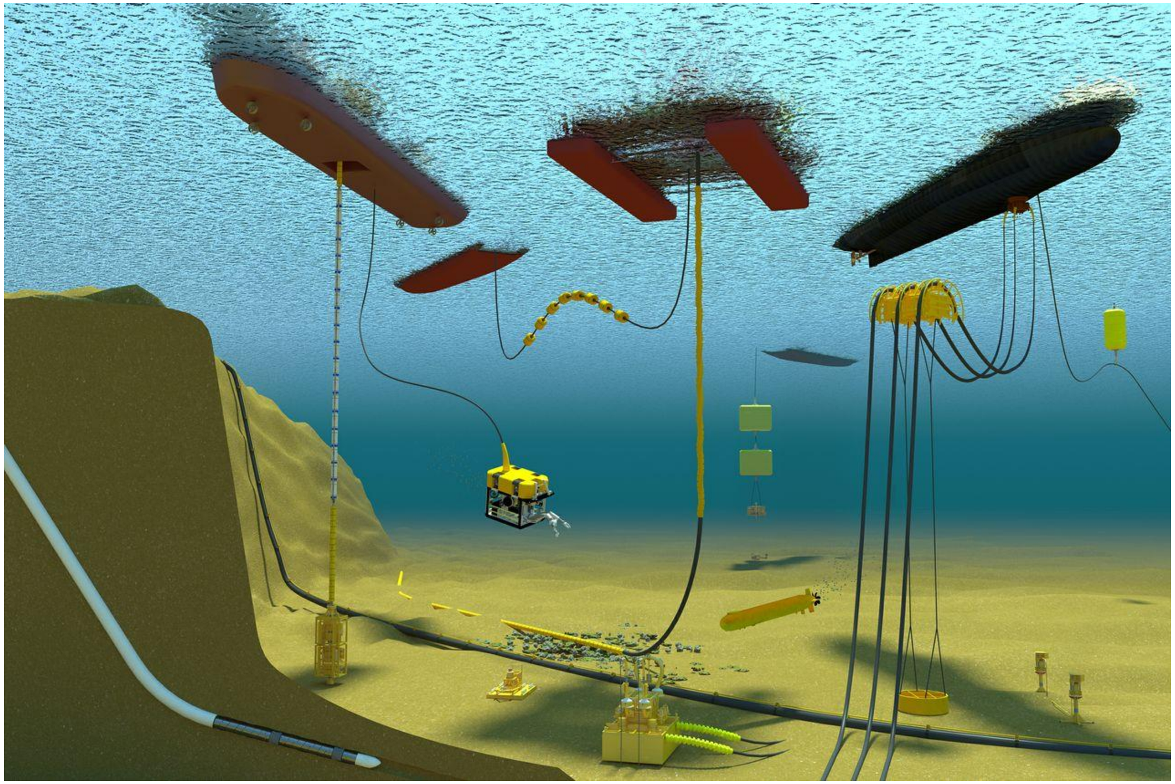



- ±50kV Offshore Collection Grid
- ±50kV / ±320kV Offshore Substation
- **MMLC-Based MF Isolation**

[Kjaer2016]

# ► Subsea Applications: Oil & Gas Processing



Img.: matrixengineered.com

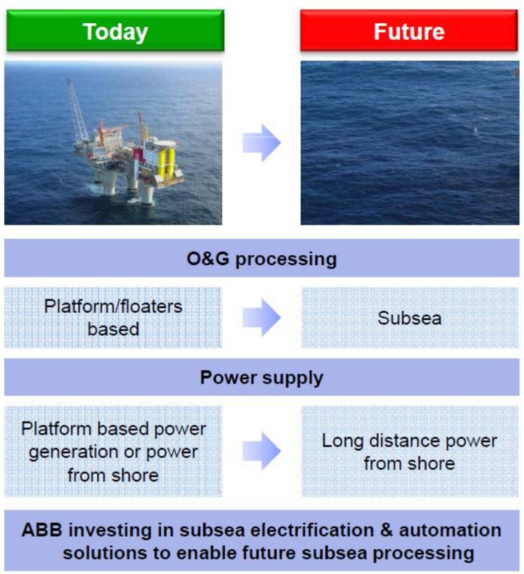
- ABB's Future **Subsea Power Grid** → **"Develop all Elements for a Subsea Factory"**

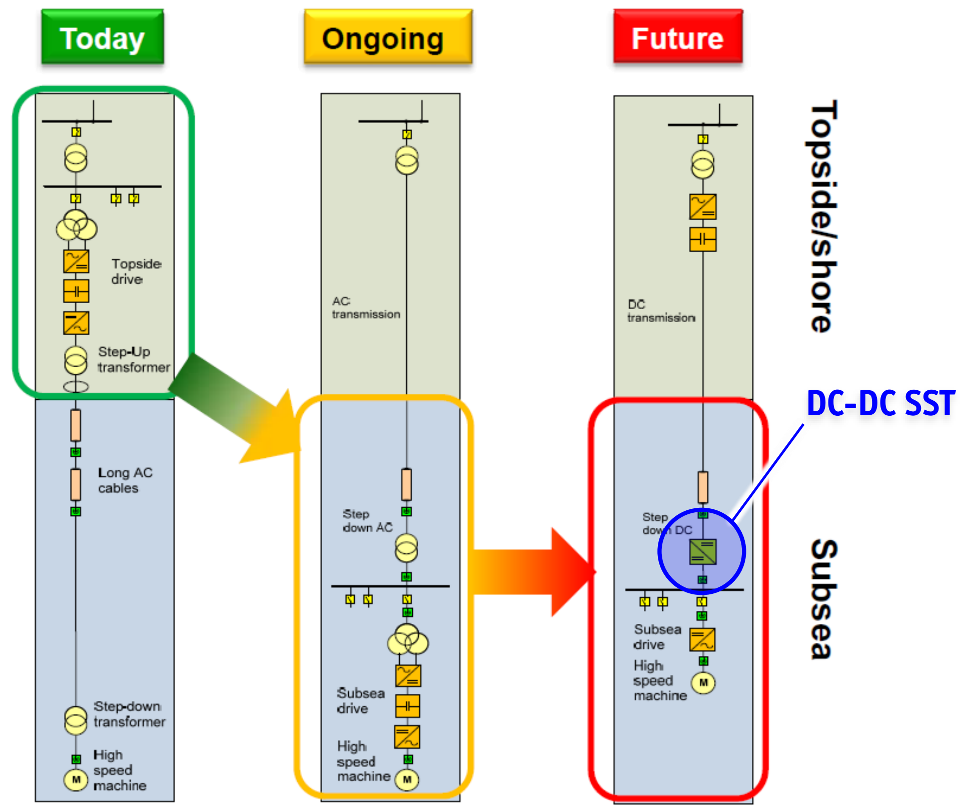
# ▶ Future Subsea Distribution Network

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

- **Weight Optimized Power Electronics**

Source: Devold (ABB 2012)

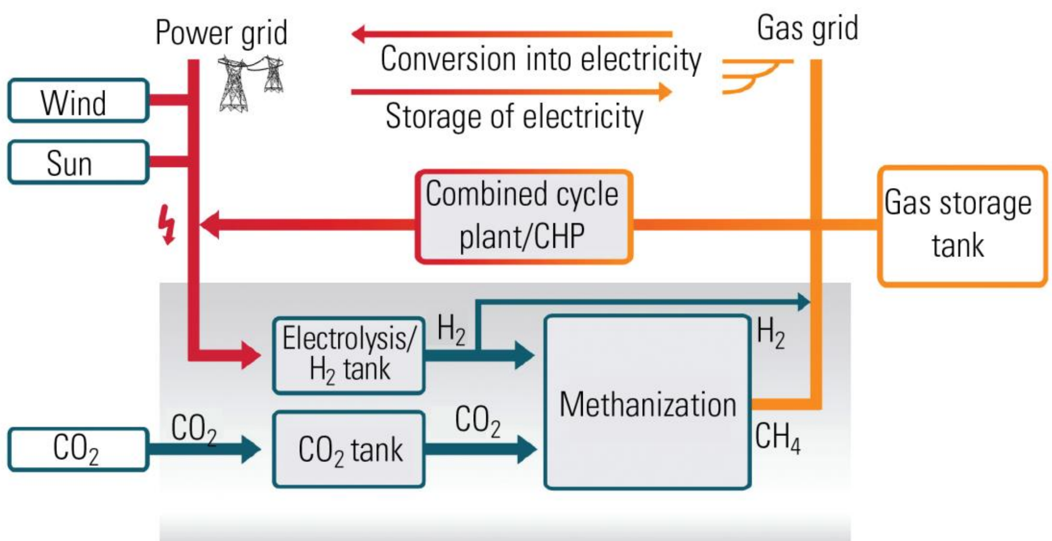


# ▶ Power-to-Gas

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

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

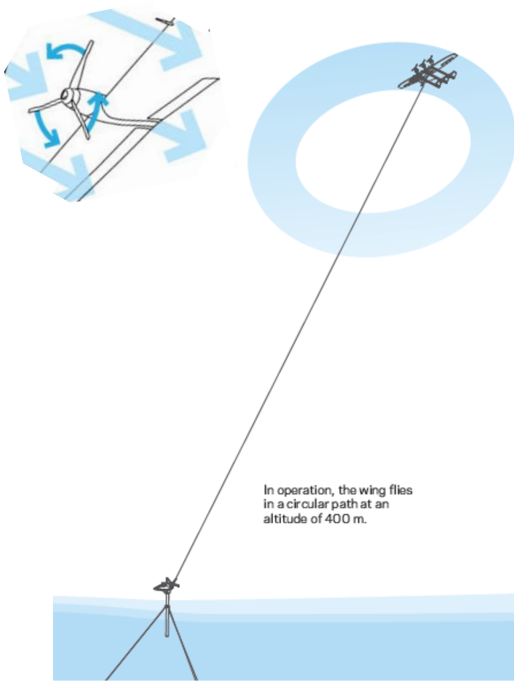




Source: www.r-e-a.net

- Hydrogenics 100kW H2-Generator (η=57%)

# ► Airborne Wind Turbines

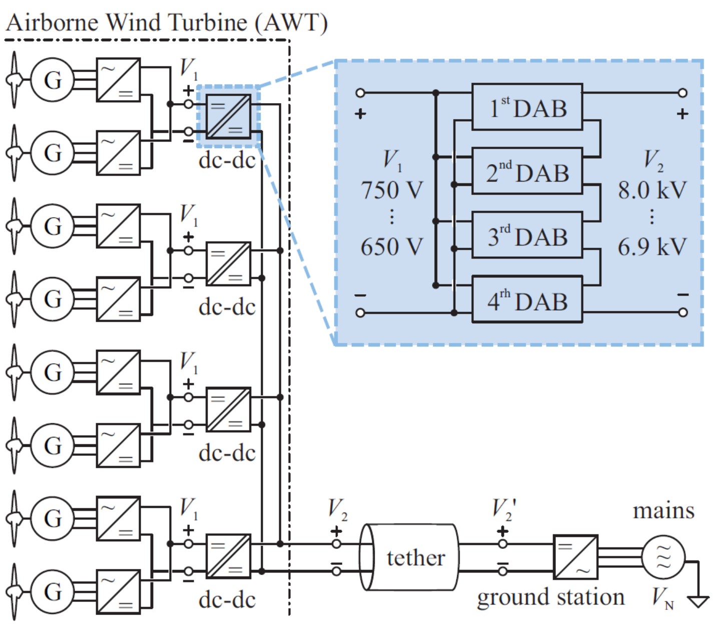
- Power Kite Equipped with Turbine / Generator / Power Electronics
- **Power Transmitted to Ground Electrically**
- Minimum of Mechanically Supporting Parts




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/dm³
  - Specific Weight 4.4 kW/kg

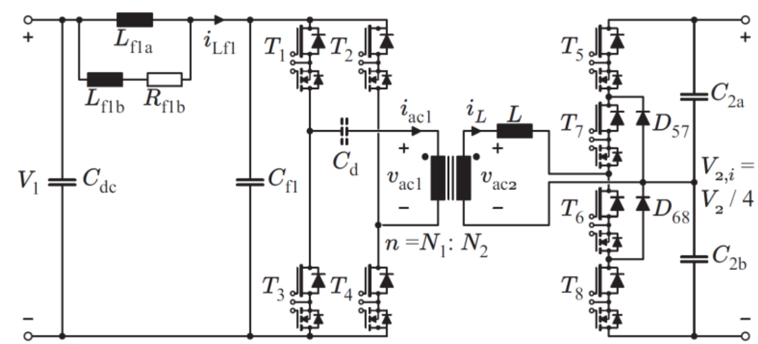


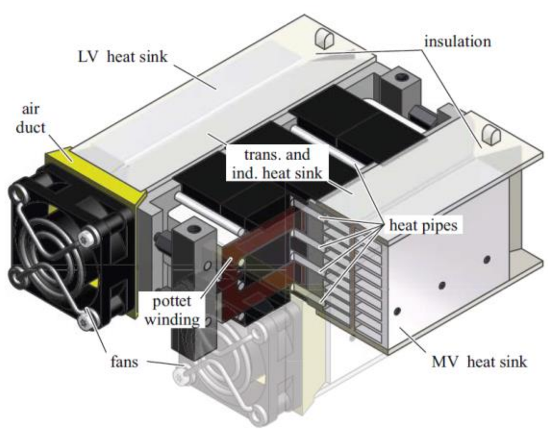

ETH / [Gammeter2015]

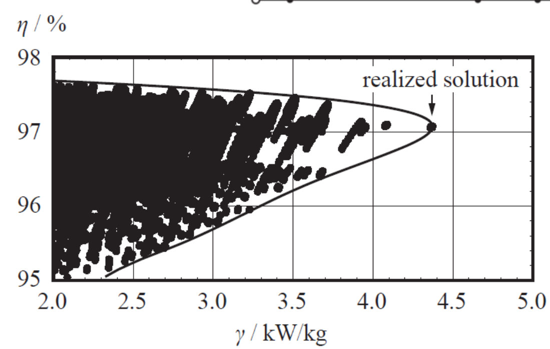
# ▶ 100kW Airborne Wind Turbine (2)

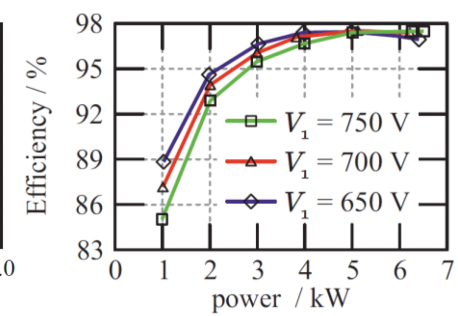
- Ultra-Light Weight Multi-Cell **All-SiC DC-DC Solid-State Transformer** – $8kV_{DC} \rightarrow 700V_{DC}$

  - 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]

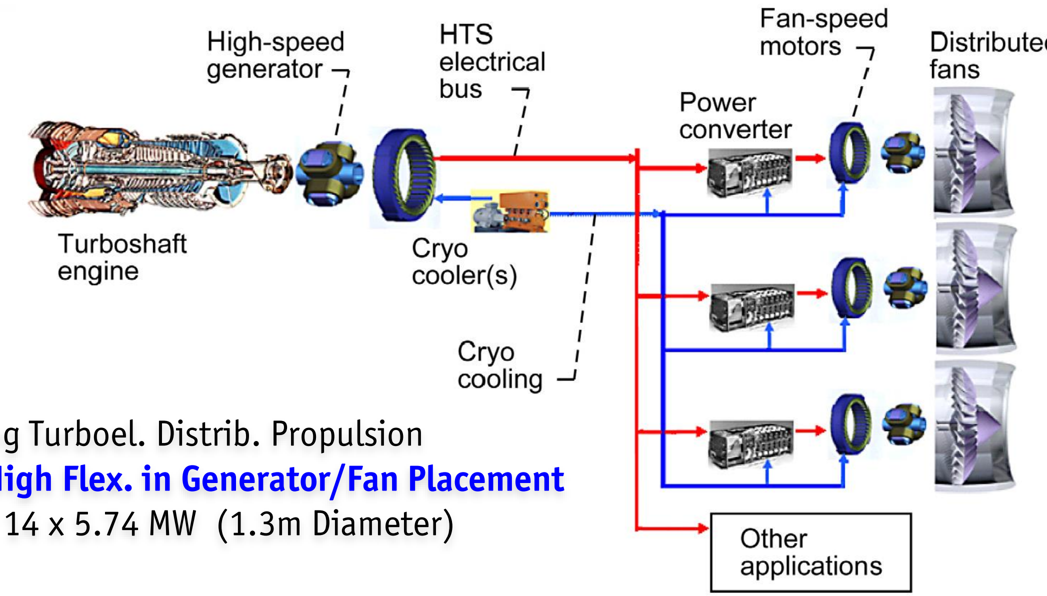
# ► Future Hybrid Distributed Propulsion Aircraft

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 $CO_2$ Emissions by 75%, $NO_x$ by 90%, Noise Level by 65%**

# ▶ Future Distributed Propulsion Aircraft

Source: NASA

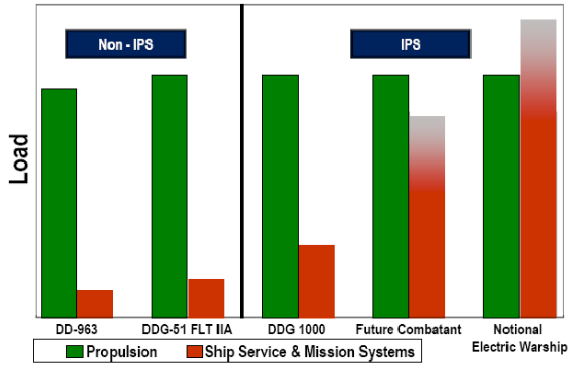




- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- **Electr. Power Transm. Allows High Flex. in Generator/Fan Placement**
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

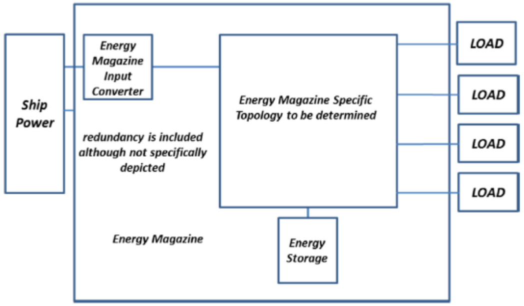
- **Potential SST Application: Supply of LV AC or DC Loads from MVDC Bus**

# ▶ Future Naval Applications (1)

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



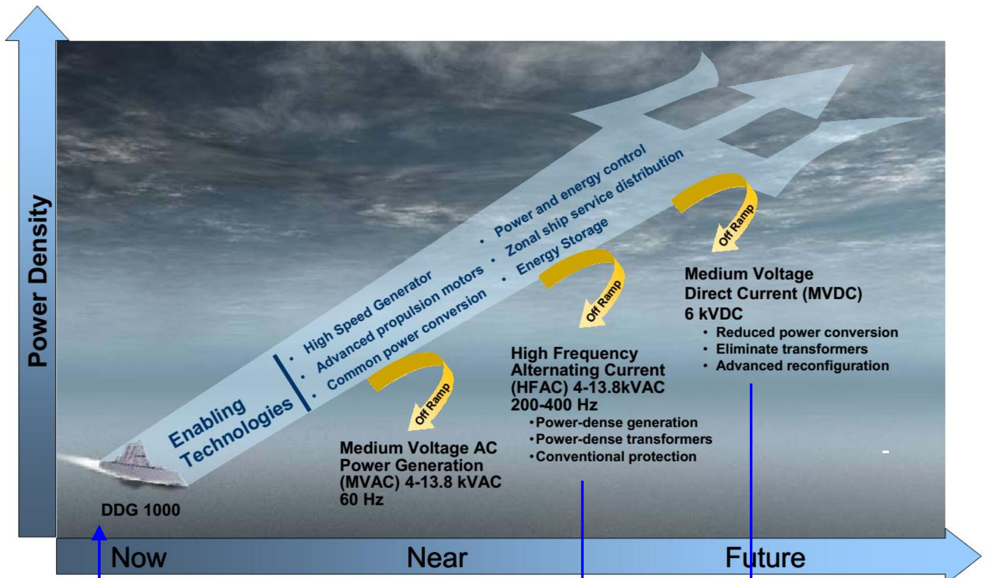

[Doerry2009]




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

# ▶ Future Naval Applications (2)




**MVDC**
**6kV DC/DC SST for Size/Weight Reduction**

**HFAC** (High-Frequency AC)
Reduce Size/Weight of Equipment

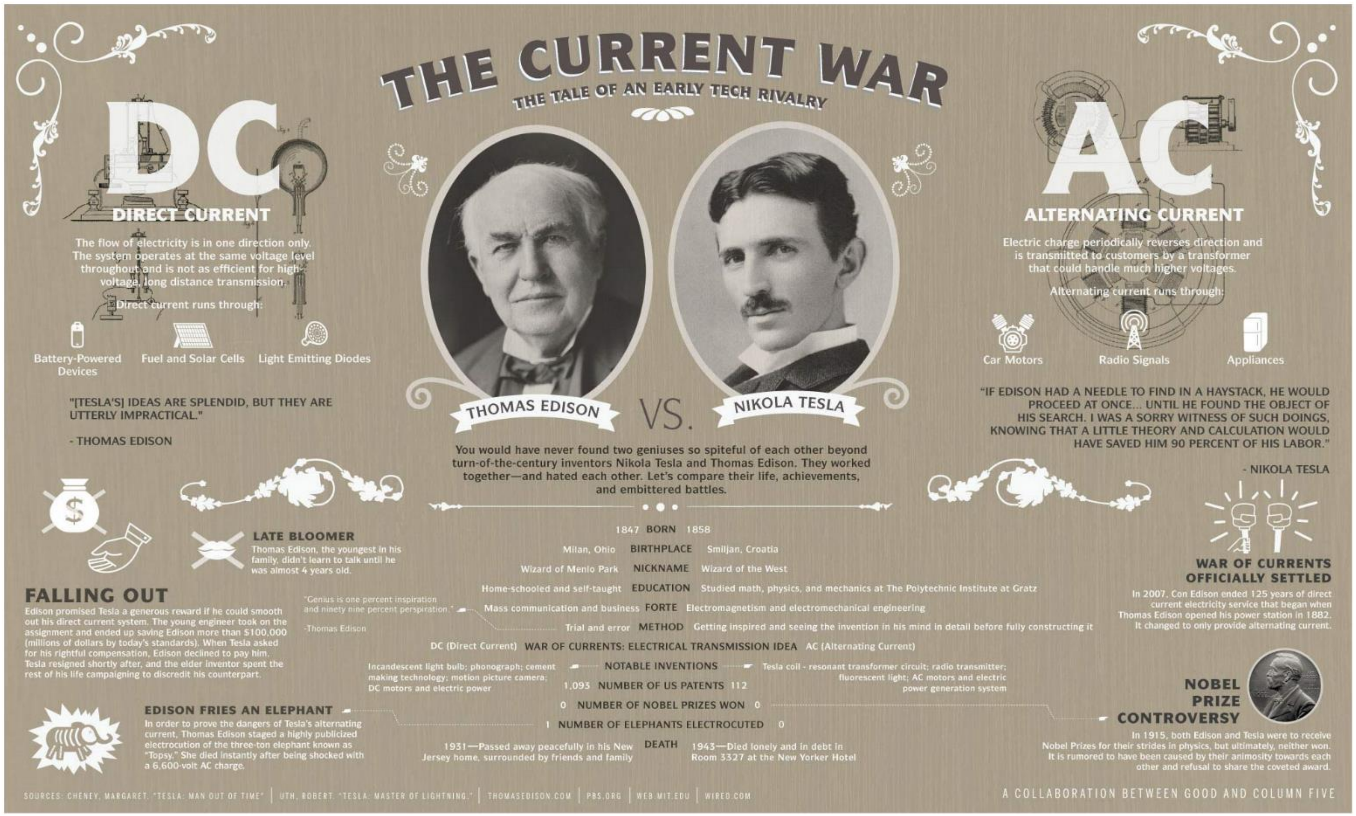
USS Zumwalt
Img.: US Navy, CC BY 2.0

[Doerry2009]

# 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!

# ▶ SST Applications – The Road Ahead

## NOT (!) Weight/Space Limited

■ Smart Grid, Stationary Applications

■ **AC/AC**
- **Efficiency Challenge**
- Controllability also by More Eff. Altern.
  - Tap Changers
  - Series Regulators (Partial Power Proc.)
- Not Compatible w. Exisiting Infrastr.
- **Cost / Robustness** / Reliability

■ **AC/DC**
- Efficiency Challenge more Balanced
- “Local” Applic. **(Datacenters, DC Distr.)**
- Cost / Robustness / Reliability

■ **DC/DC**
- **No Other Option (!)**
- MV DC Collecting Grids (Wind, PV)
- Sw. Freq. as DOF of Design

## Weight/Space Limited

■ Traction Appl., etc.

■ **DC/DC**

■ **AC/DC**

■ **AC/AC**
- Sw. Freq. as DOF of Design
- **Low Weight/Volume @ High Eff.**
- Local Appl. (Load/Source Integr.)

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*

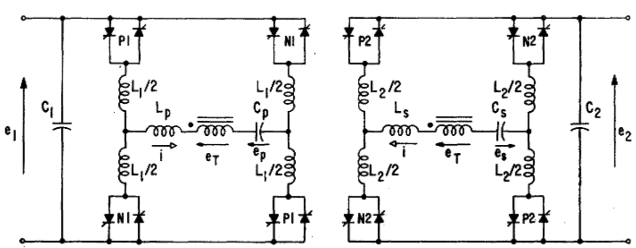
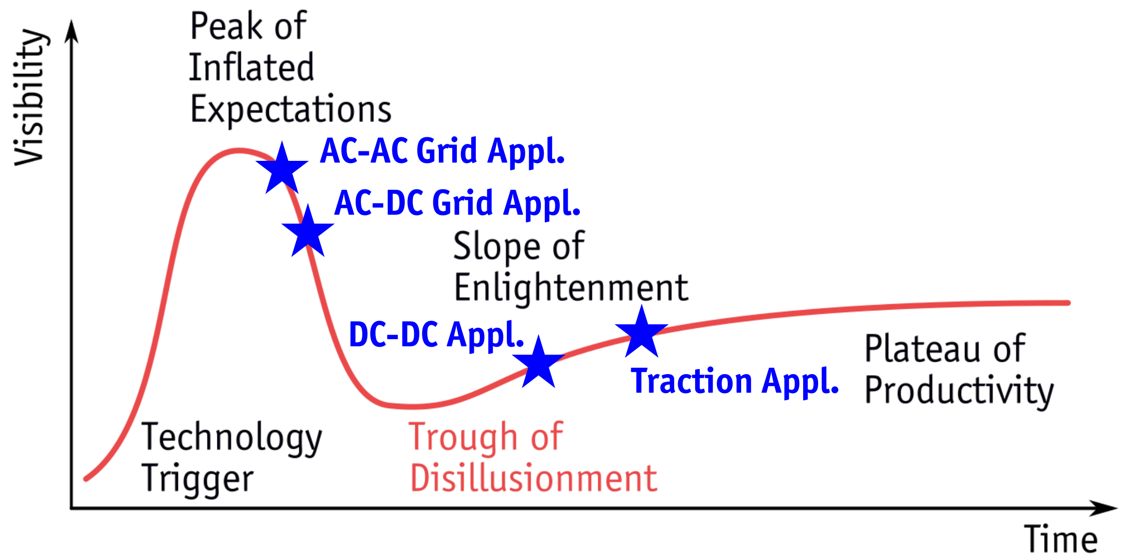



Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

### 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.

# ▶ SST Technology Hype Cycle

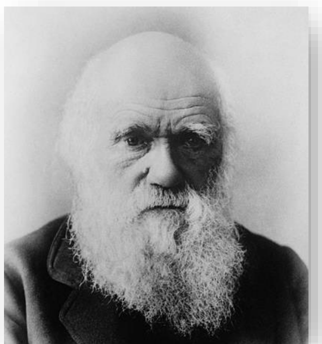



- Different State of Development of SSTs for → Traction Applications
  → Smart Grid Applications

# ▶ Single-Cell vs. Multi-Cell Topologies

## ▶ 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)

# ▶ Open SST Research Challenges

## ■ Main Research Challenges

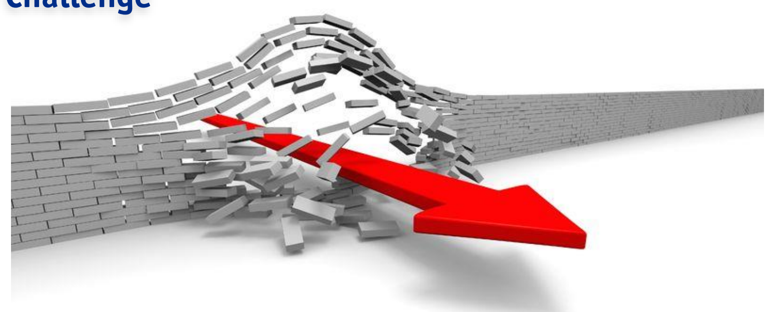
- **Multi-Level vs. Two-Level Topologies with HV SiC Switches**
- Low-Inductance MV Power Semiconductor Package
- **Mixed-Frequ./Voltage Stress on Insul. Materials**
- Low-Loss High-Current MF Interconnections / Terminals
- Thermal Management (Air and $H_2O$ Cooling, avoiding Oil)
- SST Protection
-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

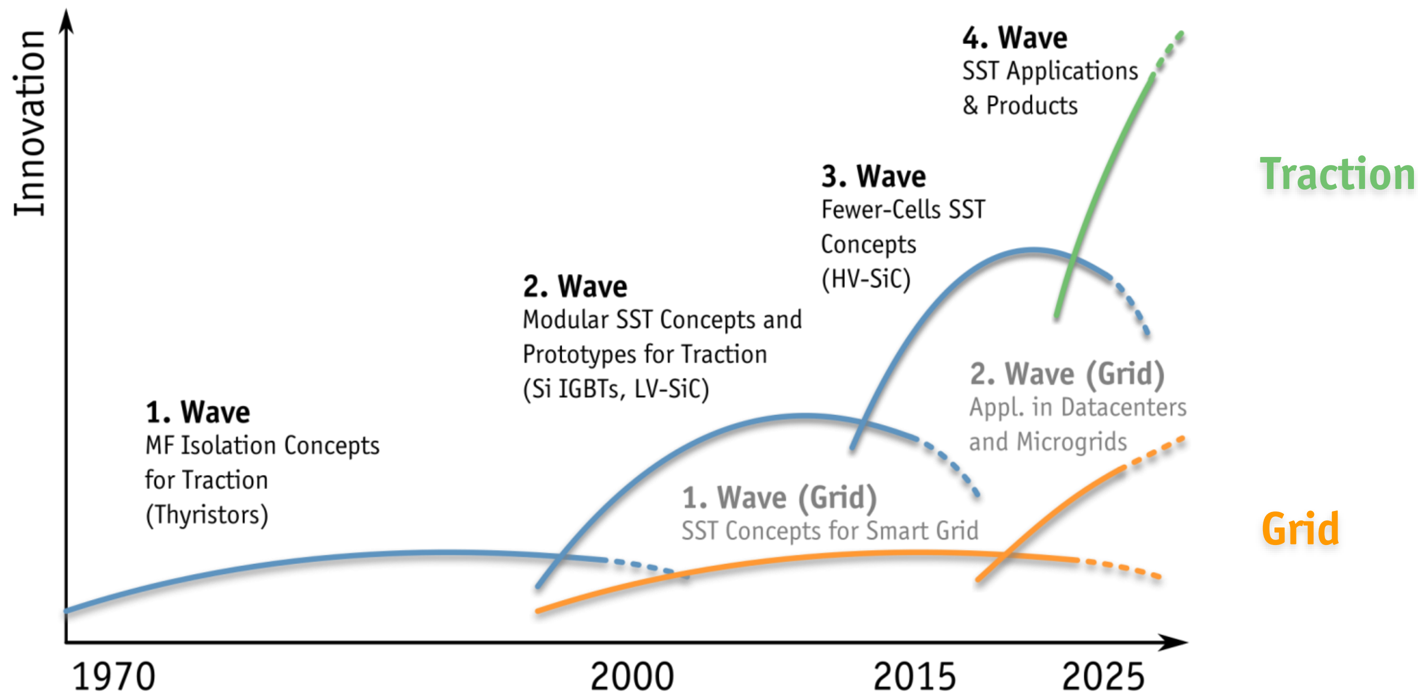
▶ **Required Competences**

- 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**

# ► SST Development Cycles – Outlook




- **Development Reaching Over Decades** – Matched to "Product" Life Cycle

# Thank You!

*Questions?*

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- ***Thomas Guillod***
- ***Daniel Rothmund***

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# ETH Zurich: Recent Key Publications (2)

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

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

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