Power Electronic Systems Laboratory

ETH zürich

The Essence of Solid-State Transformers

Fundamentals, Design Challenges, R&D Overview, Comparative Evaluation, Outlook

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Agenda

1. Introduction & SST Origins
2. SST Concepts & Key Design Aspects

30min

3. Selected Results of Recent University / Industry SST R&D Activities
4. Comparative Evaluation of SSTs for Datacenters and EV Charging
5. Summary & Research Vectors

Acknowledgment
Dr. T. Guillod
Dr. P. Czyz
Dr. D. Rothmund
Dr. G. Ortiz

Full Version

https://u.ethz.ch/bWWoV

Part I

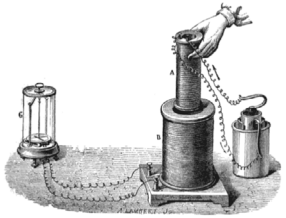
Introduction & SST Origins

- Transformer Basics and Key SST Motivations
- Terminology

Transformer History

1800
1810
1820
1830
1840
1850
1860
1870
1880
1890
1900

1830 Henry / Faraday
Property of Induction

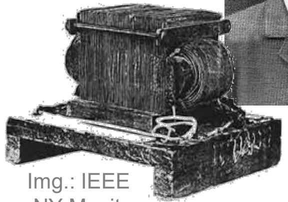


1880 Ferranti
Early Transformer

1882 Gaulard & Gibbs
Linear-Shape Xfmr (1994, 2 kV, 40 km)

1884 Bláthy / Zipernowksi / Déri
Toroidal Core Xfmr

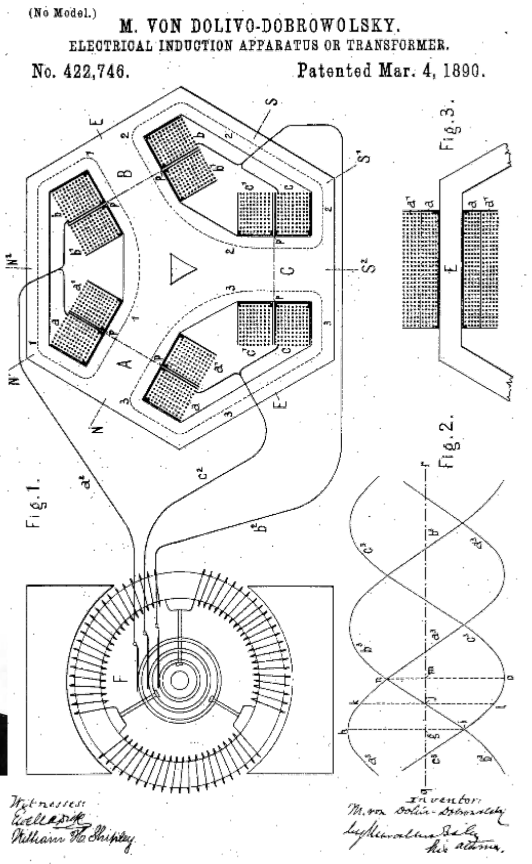
1885 Stanley (& Westinghouse)
Easily Manufact. Xfmr
(1st Full AC Distr. System)



Img.: IEEE
NY Monitor

1889 Dolivo-Dobrowolsky
→ Three-Phase Transformer

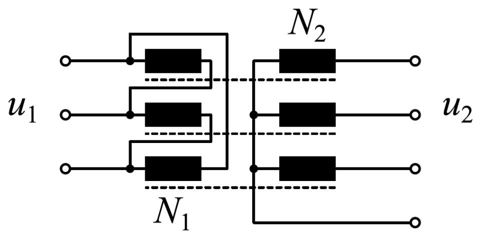
1891 1st Complete AC System
(Gen. + Xfmr + Transm. + El. Motor+ Lamps, 40 Hz, 25 kV, 175 km)



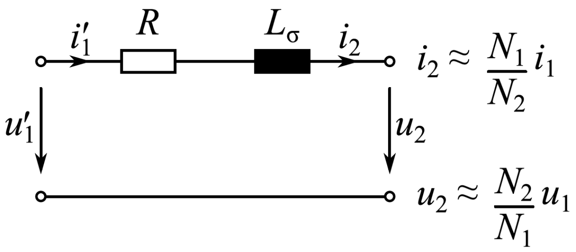
[Stanley1886, Dobrowolski1890]

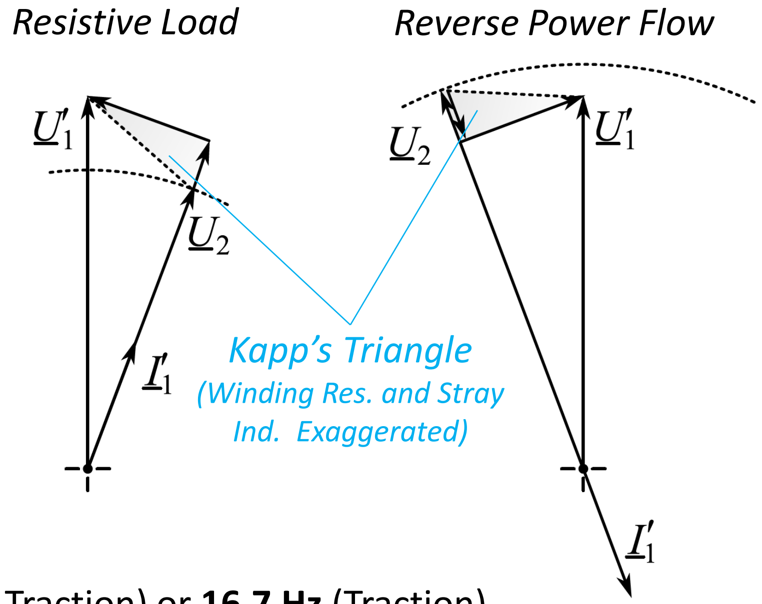
Transformer Basics (1)

■ 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 ($f_1 = f_2$)



$$u_1' = u_1 \cdot \frac{N_2}{N_1}$$





■ Typ. Operating Frequency	**50/60 Hz** (Power Grid, Traction) or **16.7 Hz** (Traction)
■ Typ. Operating Voltages	**6…35 kV** (Power Grid)
	400 V (Power Grid)
	15 kV or **25 kV** (Traction)

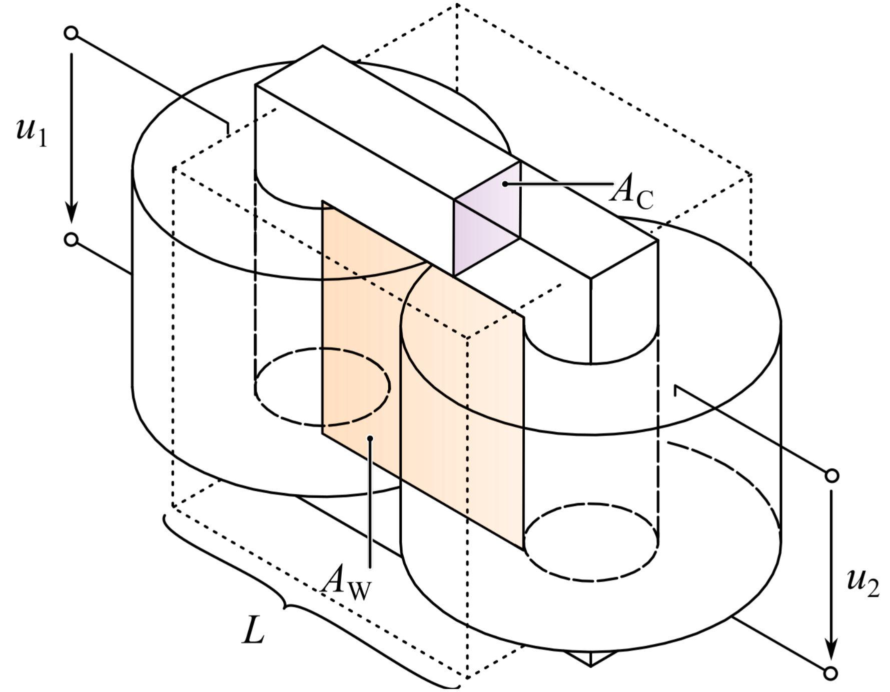
Transformer Basics (2)

Construction Equations

- Core Area $$A_C = \frac{U_1}{\sqrt{2}\pi B_{max} f N_1}$$
- Window Area $$A_W = \frac{2I_1}{k_W J_{rms}} N_1$$

Area Product $$A_C A_W \propto \frac{S}{k_W J_{rms} B_{max} f}$$

S	Rated Power ($S = U_1 I_1$)
k_W	Window Utilization Factor
B_{max}	Flux Density Amplitude
J_{rms}	Winding Current Density
f	Frequency



Construction Volume $$A_C A_W \propto L^4 \propto \frac{S}{f} \rightarrow V \propto L^3 \propto \frac{S^{3/4}}{f^{3/4}}$$

for given B_{max}, J_{rms}, k_W

Transformer Basics (3)

Advantages

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

Weaknesses

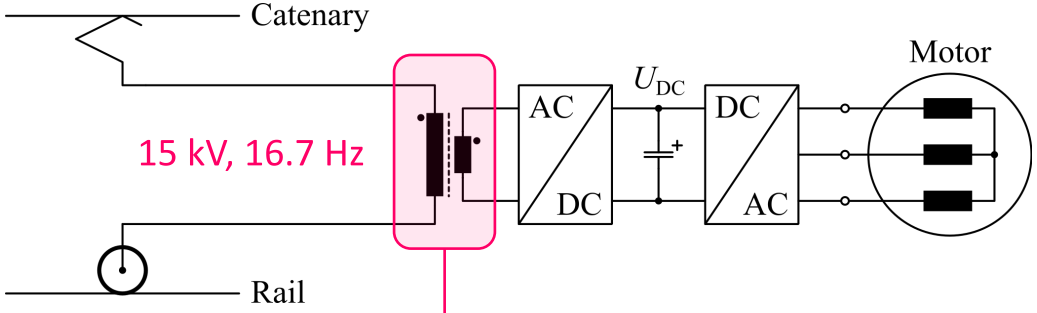
- Voltage Drop Under Load
- Losses at No Load
- Not Directly Controllable
- Sensitivity to DC Offset & Load Imbalances
- Sensitivity to Harmonics

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

Vacuum Cast Coil Dry-Type Distribution Transformer

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

Classical Traction Vehicles



■ **Isolated AC-DC Conversion**

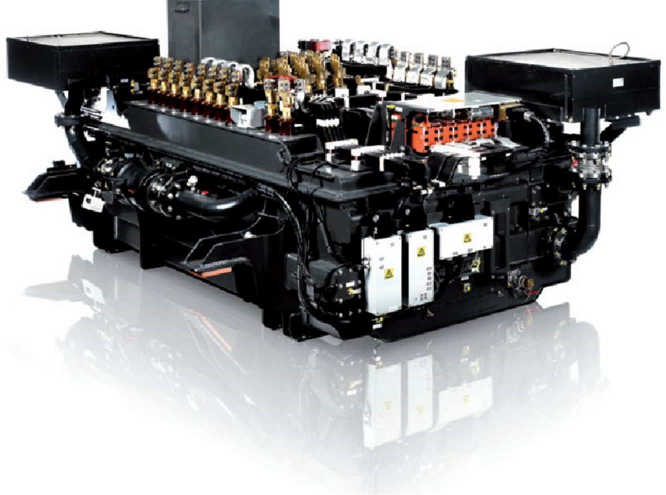
● Catenary AC Voltage	15 kV or 25 kV
● Frequency	16.7 Hz or 50 Hz
● Power Level	1…10 MW typ.

■ **Volume & Weight Constraints**

$$A_C A_W \propto \frac{S}{k_W J_{rms} B_{max} f}$$

k_W	< 1
J_{rms}	"Soft" Limit: Losses / Cooling
B_{max}	Hard Limit: Saturation
f	Fixed

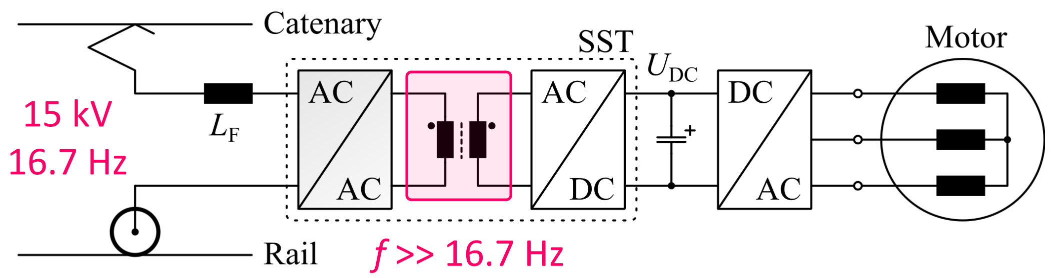
➔ **Volume & Weight Reduction by Increasing J_{rms} (the Only DoF!)**


Img.: www.abb.com

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

Next-Generation Traction Vehicles (1)

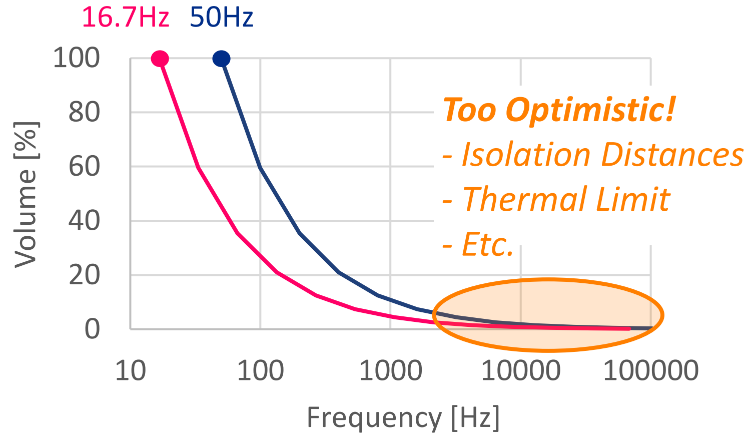
- **Isolated AC-DC Conversion**
  - Catenary AC Voltage 15 kV or 25 kV
  - Frequency 16.7 Hz or 50 Hz
  - Power Level 1…10 MW typ.



- **Power Electronic Converter Stages Unlock *f* as DoF**
  - LF Transformer ➔ Medium-Frequency Transformer (MFT)

$$A_C A_W \propto \frac{S}{k_W J_{rms} B_{max} f}$$

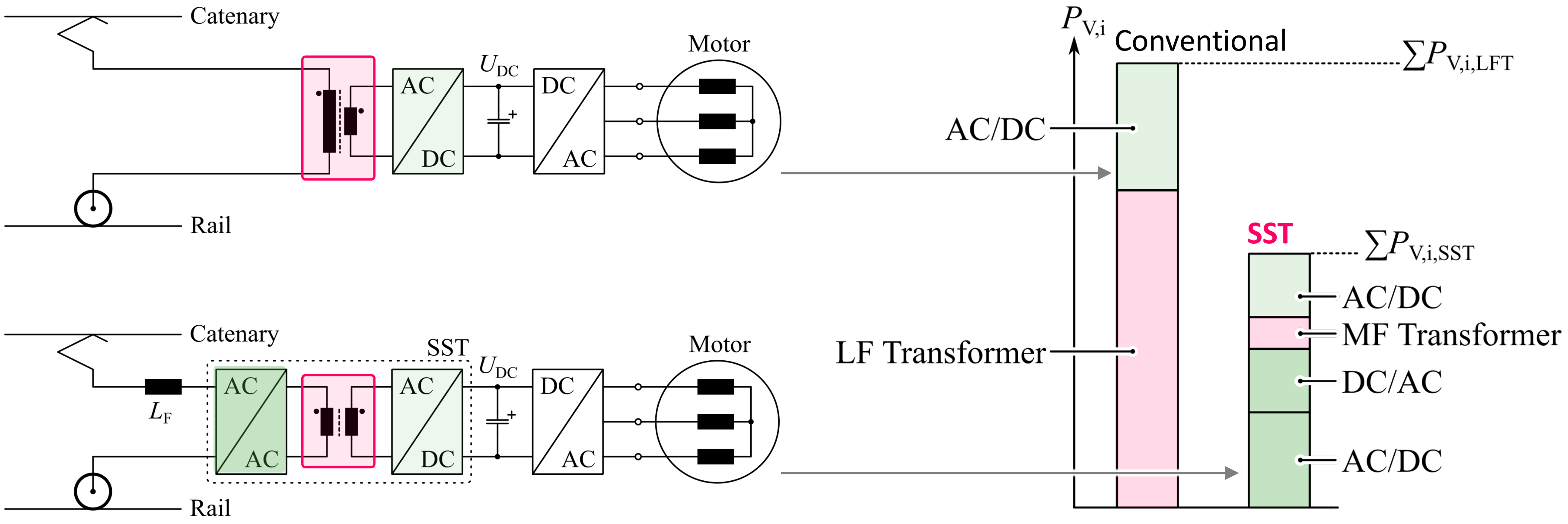
➔ **Volume & Weight Reduction by Increasing *f***



- **AC-DC SST with MFT and AC-AC and AC-DC Conversion Stages**
  - Volume/Weight Contribution?
  - Overall MVAC-LVDC Efficiency?

Next-Generation Traction Vehicles (2)

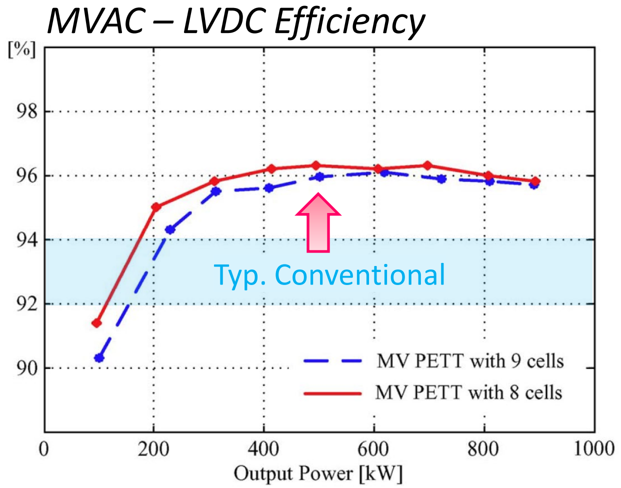
■ **Drivetrain Loss Distribution of Conventional & Next-Generation Traction Vehicles**



■ **Key Motivation for SSTs: Space/Weight-Limited Applications**
● Medium Frequency Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction

Example: 1.2 MVA AC-DC Power Electron. Traction Transf.

- 15 kV, 16.7 Hz AC Input to 1.5 kV DC Output / Silicon IGBT Technology / Modular Topology
- Significant Efficiency Improvement (+2…4 %)
- Significant Weight Reduction (0.5…0.75 kVA/kg vs. 0.2…0.35 kVA/kg for Conventional Traction AC-DC Conv.)

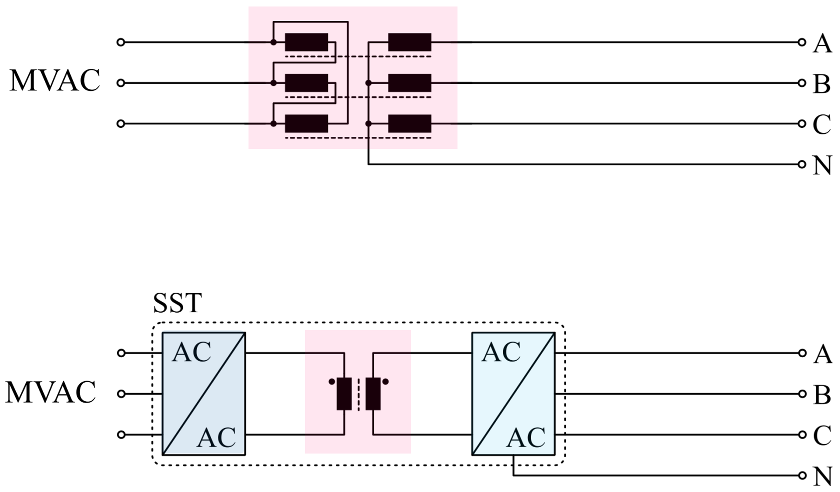


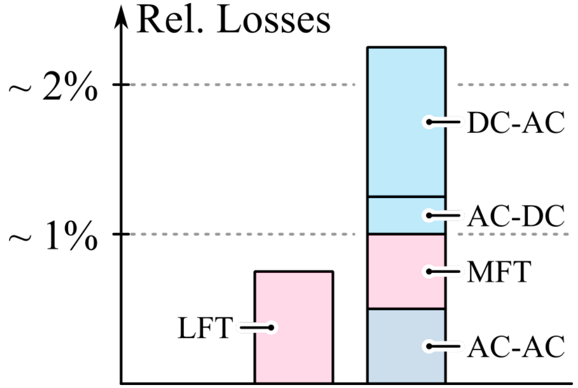
- World's First Locomotive with an SST (2012) / Field Test on Swiss Railway System > 13'000 km

[Zhao2014]

Traditional AC-AC Grid Applications

- Power Transformers Typ. w/o Volume/Weight Constraint → High Efficiency of 99+ %

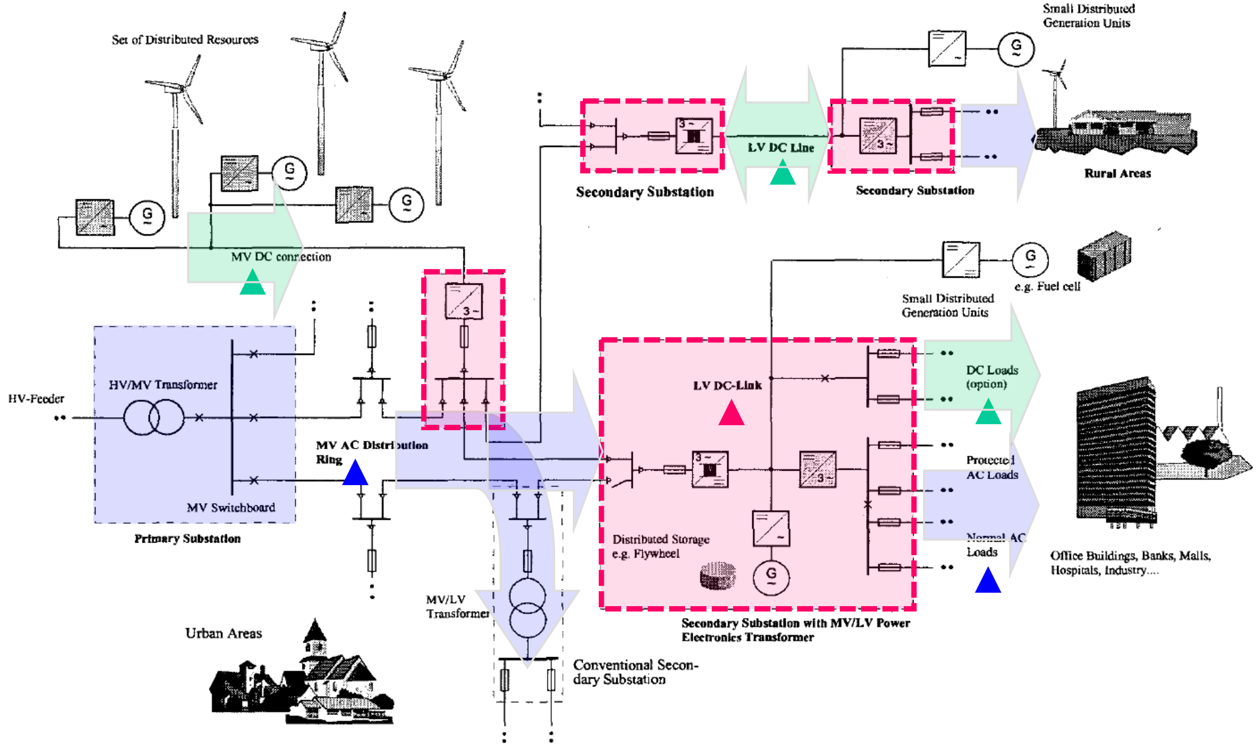




- SST Efficiency Significantly Worse (Two Power Electronic Conversion Stages!)
- SST Functionality Significantly Higher → Not a 1:1 Replacement!

Advanced (High Power Quality) Grid Concept

- **Heinemann / ABB (2001)**



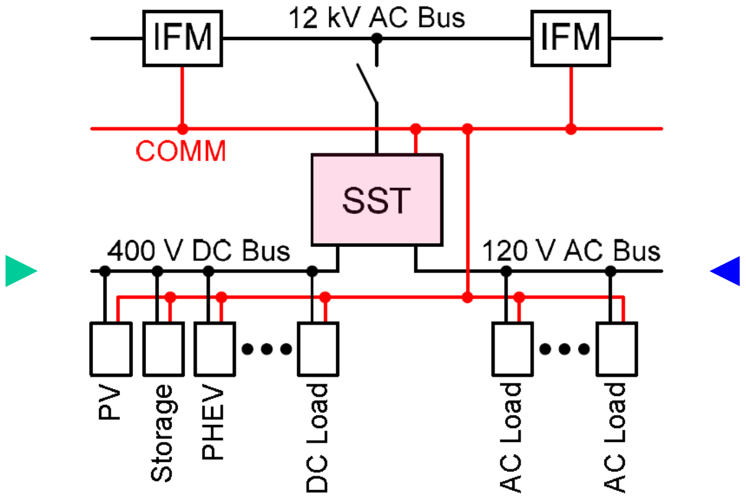
- MV AC Distribution with DC Subsystems (LV and MV) and Large Number of Distributed Resources
- MF AC-AC Conv. with DC-Link Coupled to Energy Storage provide High Power Qual. for Spec. Customers

FREEDM System

- **Future Ren. Electric Energy Delivery & Management 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.

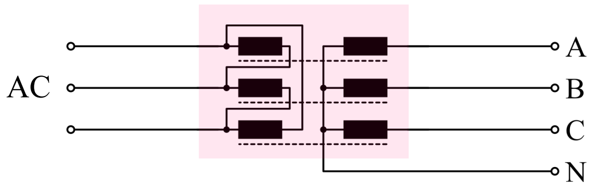
IFM = Intellig. Fault Management

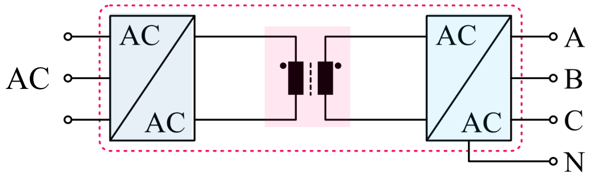


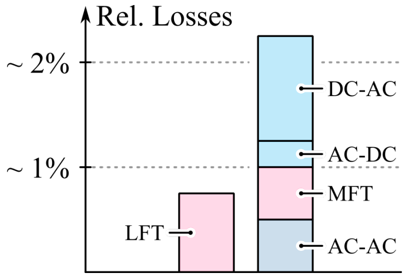
- **Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonom. Ctrl.**

Functionality for Future Grids

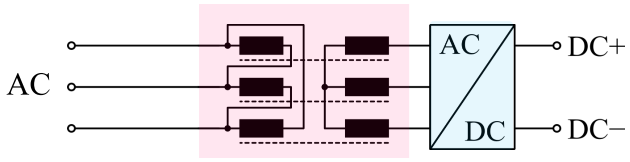
- MVAC-LVAC | Note SST with Add. Functionality!

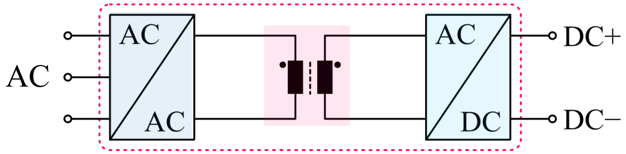




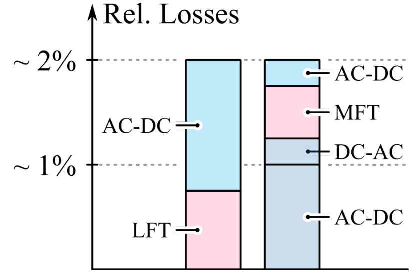


- MVAC-LVDC (Energy Storage, LVDC Grids)



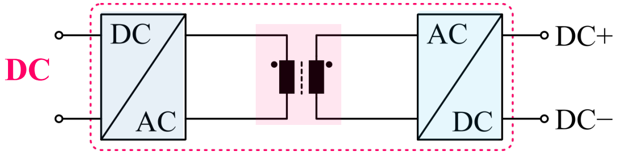


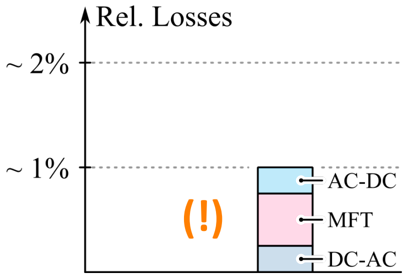
Note: SST with MV-Side PFC Stage



- MVDC-LVDC for Future MVDC Grids

LFT-Based: n/a (!)

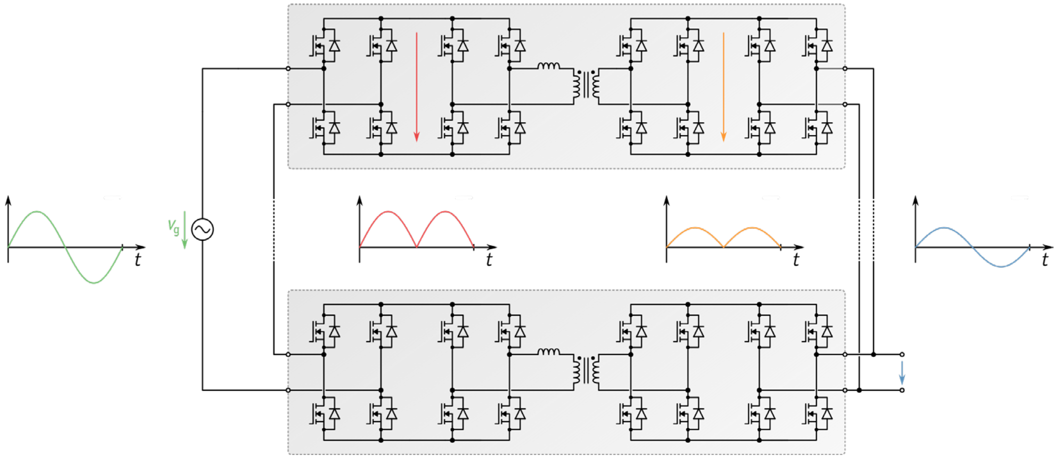




- **Key Motivation for SSTs: Functionality & Enabler for DC Grids**

Example: 1 MVA, 20 kHz Solid-State Power Substation

- 1 MVA, 13.8 kV to 270 V Single-Phase Demonstrator / One Phase-Module of a Three-Phase System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
- DCX Isolation Stages w. ZVS → 20 kHz Transformers
- 4 Modules w. 10 kV SiC MOSFETS / Input Series & Output Parallel



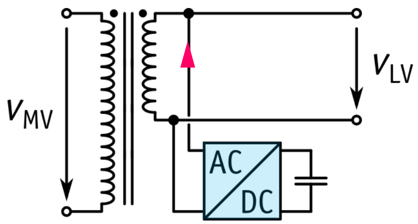
- **97% Efficiency** at 855 kVA / 3 x Losses of LFT w. 99+% Efficiency
- –70% Weight & –50% Volume Compared to LFT / Limited Gain Despite 400 x Higher Transformer Freq.

[Das2011, Beermann2012, Raju2014]

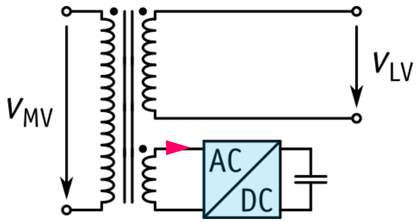
Remark: Hybrid Transformers

- **Shunt**

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

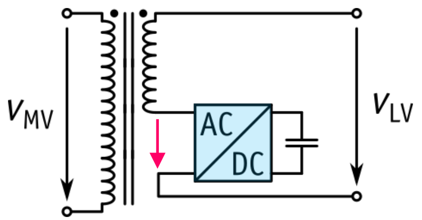


  - Shunt Conv. Volt. Indep. of V_{LV}

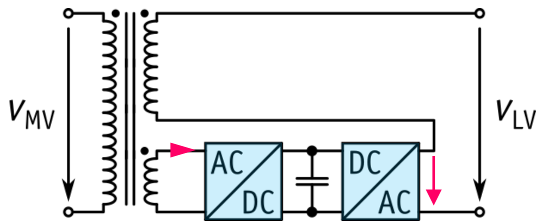


- **Series**

  Reactive Voltage Injection
  - Phase Shifting
  - Voltage injection



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



- **Fractional Power Processing → Power Electronic Stage Processes Only a Fraction of the Power/Voltage**

[Bala2012, Burkard2015]

Part I

Introduction & SST Origins

– Transformer Basics and Key SST Motivations
– **Terminology**

Terminology (1): Origin of "SST"

United States Patent [19]
Brooks et al.

[11] 4,347,474
[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 ..."

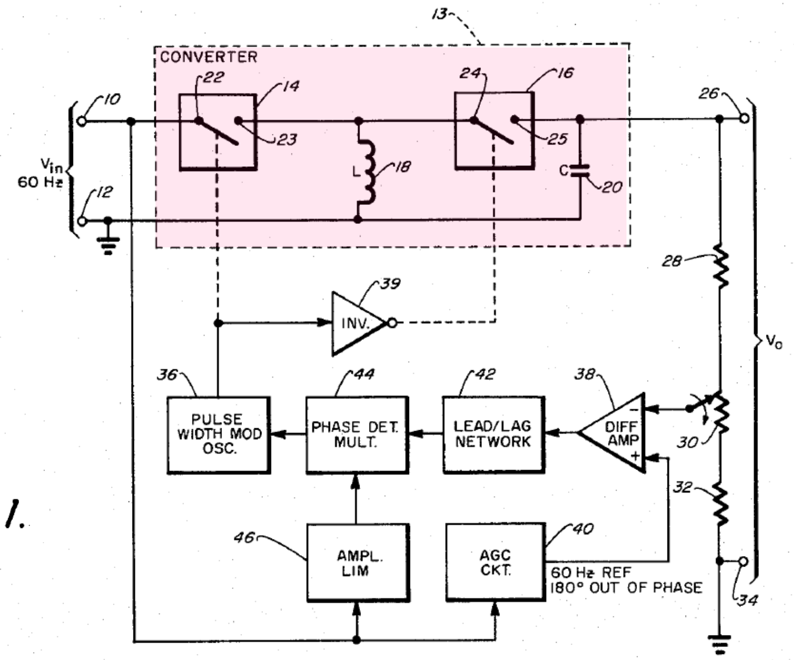
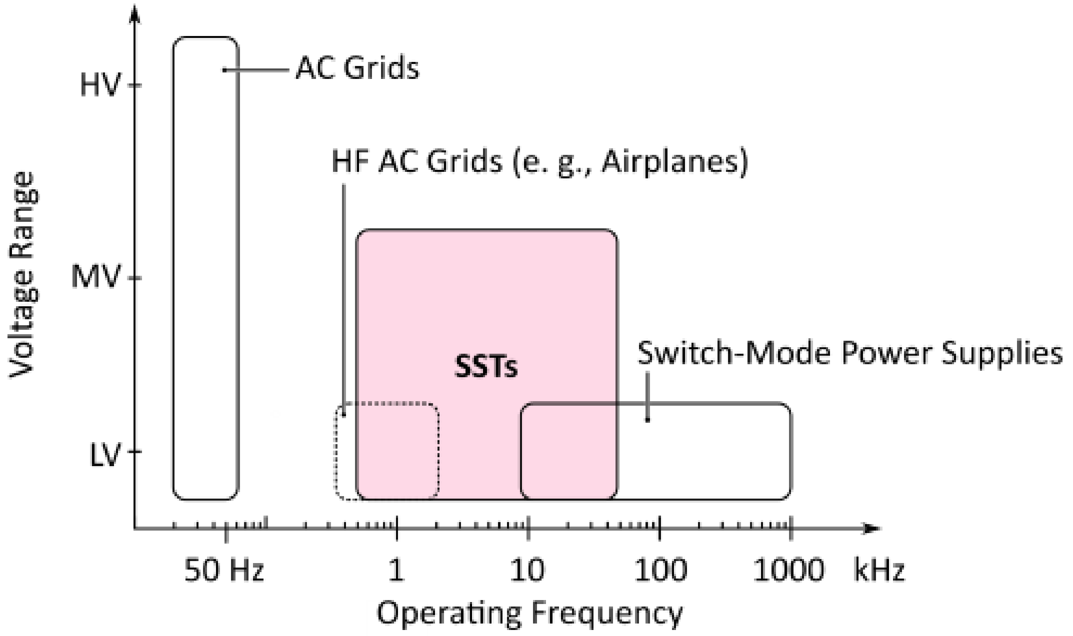


Fig. 1.

- 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**
- …



- **Defining Properties**
  - Interface to Medium-Voltage
  - Medium-Frequency Isolation
  - AC or DC Input and/or Output

Part II

SST Concepts & Key Design Aspects

– Medium-Frequency Power Conversion
– Power Semiconductors
– Key SST Topologies
– Medium-Frequency Transformers
– Isolation Coordination
– Protection
– Construction

Part II

SST Concepts & Key Design Aspects

- **Medium-Frequency Power Conversion**
- Power Semiconductors
- Key SST Topologies
- Medium-Frequency Transformers
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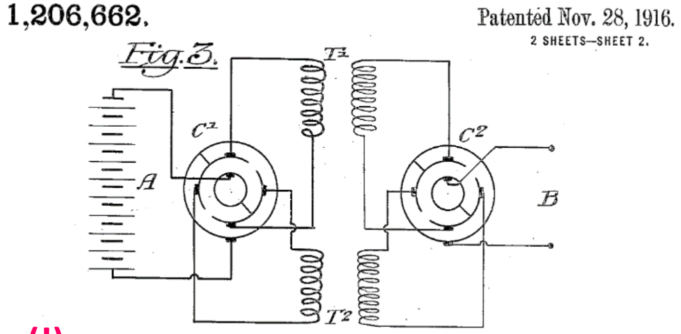
- Protection
- Construction

A Brief History of MF Power Conversion

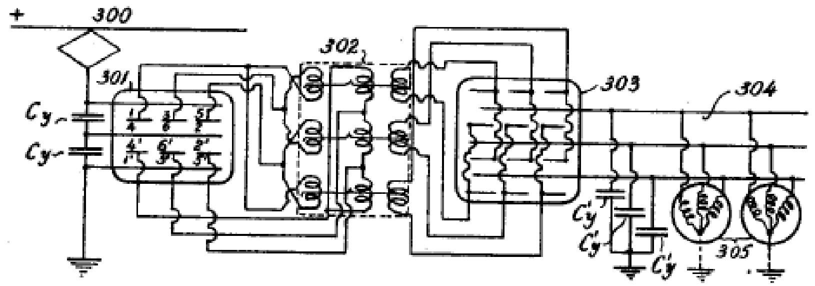
■ **Bouchérot (1914)**

● DC-DC, Mechanical Switches



■ **Hazeltine (1923)**

● DC-AC, Mercury-Arc Valves



(!)

■ **D. C. Prince (1928)**

● "Direct-Current Transformer Circuit"

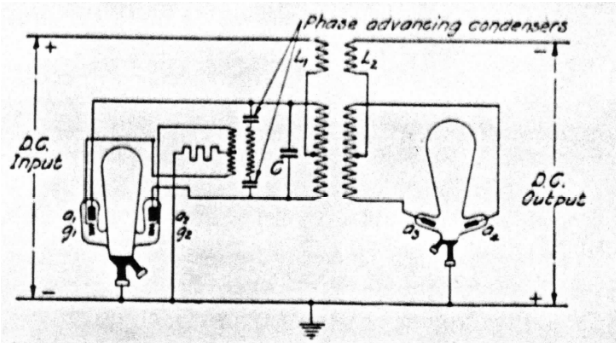
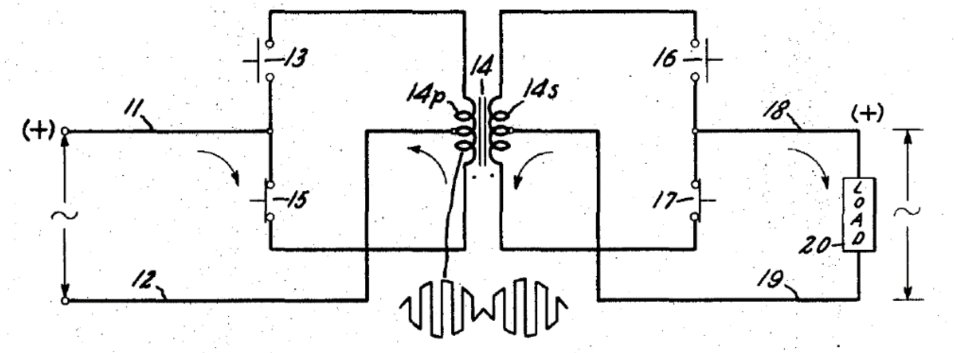


Fig. 7. Direct-current Transformer Circuit, Showing the Combination of Rectifier Circuit (Fig. 5, on right) and Inverter Circuit (Fig. 3, on left)

■ **McMurray (1968)**

● Electronic Transformer with Solid-State Switches



Electronic Transformer (1)

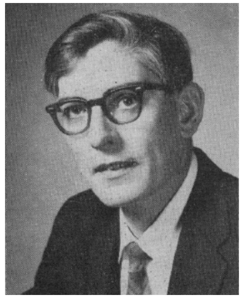
United States Patent Office — 3,517,300 — Patented June 23, 1970

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.

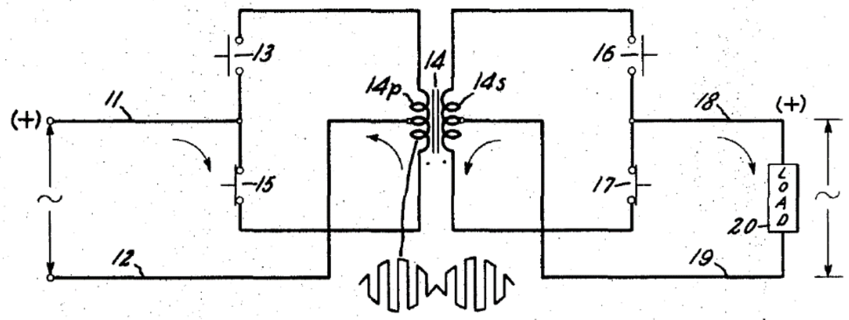


Inventor: William McMurray,
by Donald R. Campbell
His Attorney.

1968

Filed April 16, $\boxed{1968}$

Fig. 1a

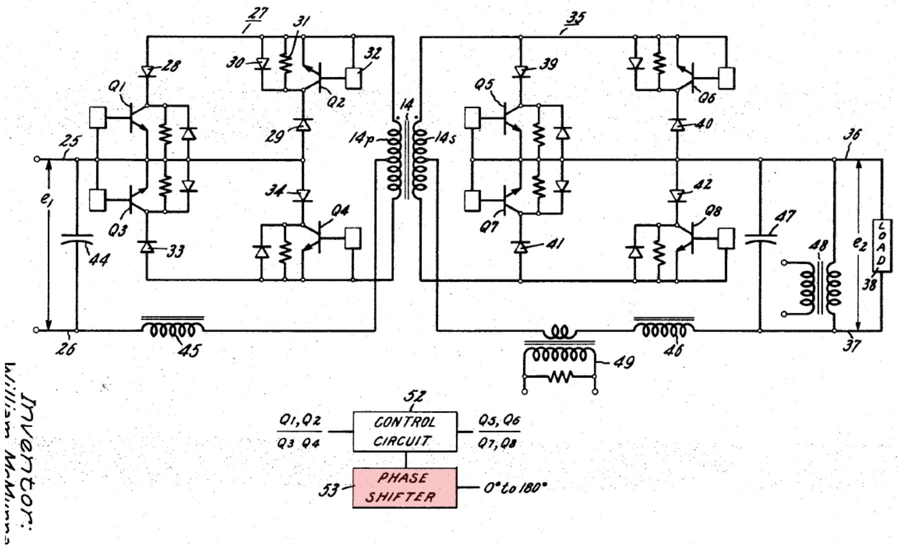


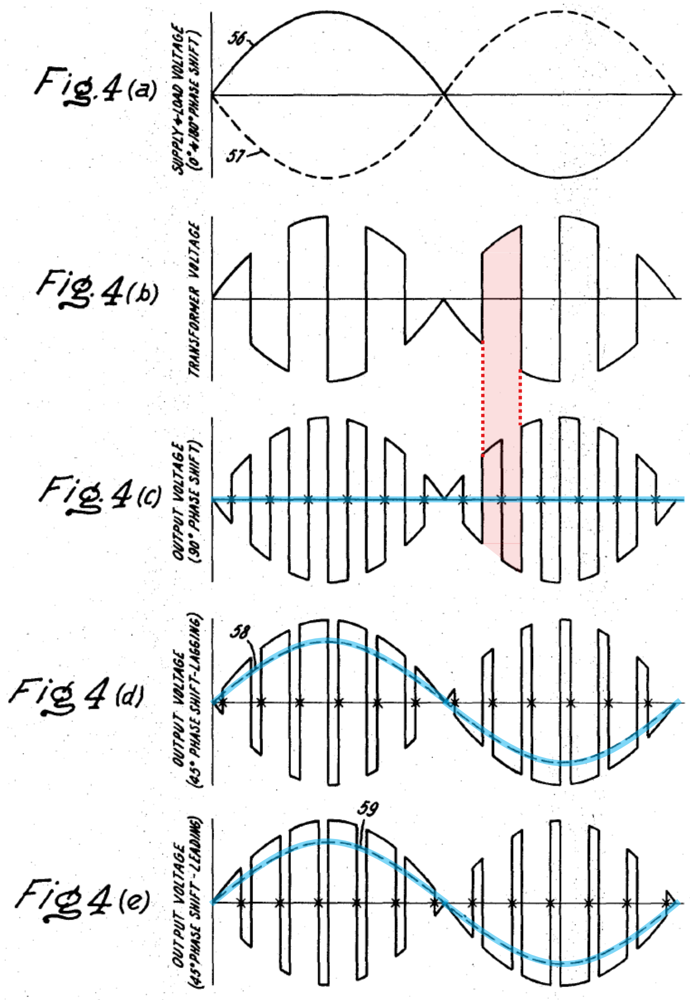
- Electronic Transformer ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption

Electronic Transformer (2)

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

Fig. 3.





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

[McMurray1968]

Dual Active Bridge (DAB)

Dual Active Bridge

United States Patent [19] | [11] **Patent Number:** 5,027,264
DeDoncker et al. | [45] **Date of Patent:** Jun. 25, 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** 1989

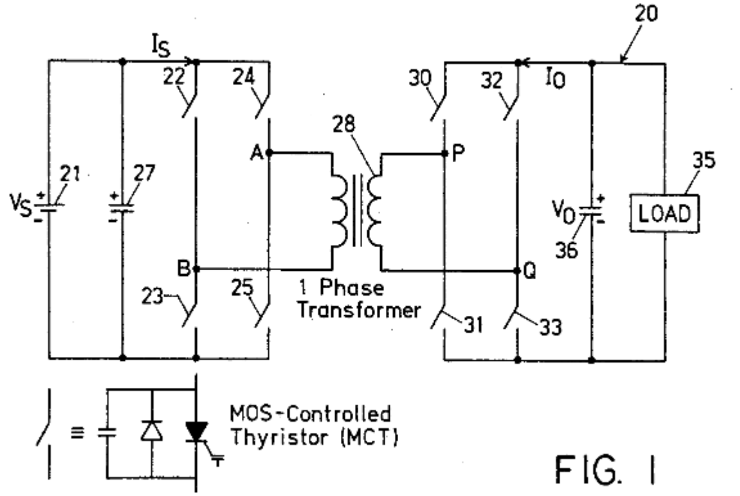


FIG. 1

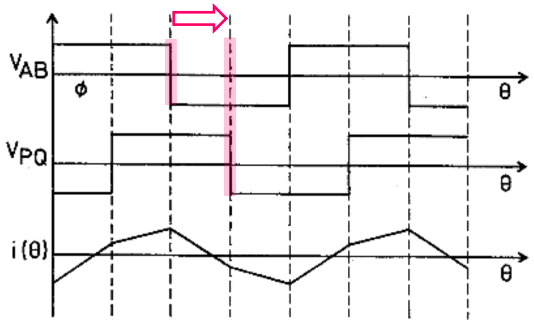
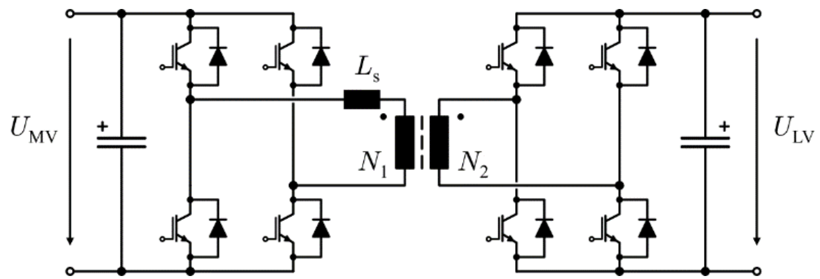


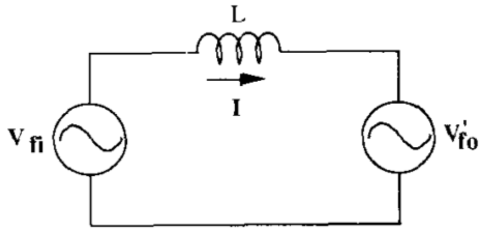
FIG. 2

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

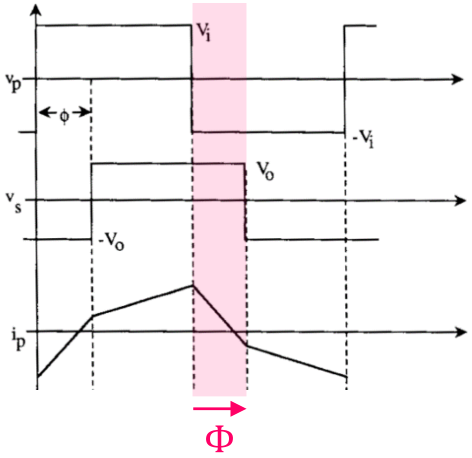
Phase-Shift Modulation (1)

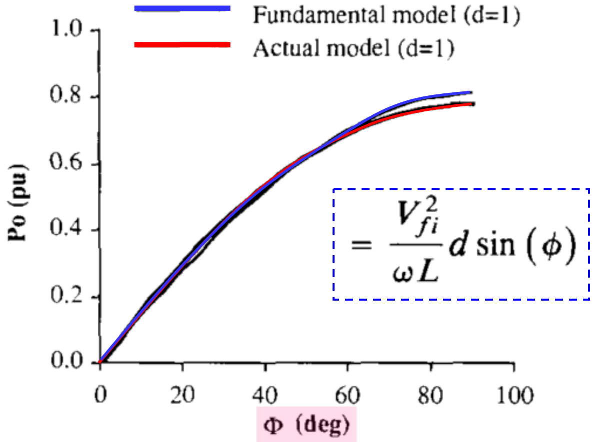
- **Power Transfer Controlled** Through Phase Shift Between MV and LV Bridges





Fundamental model of the dual bridge dc/dc converter.



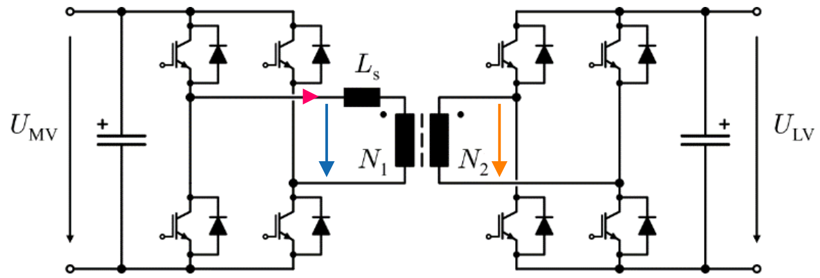


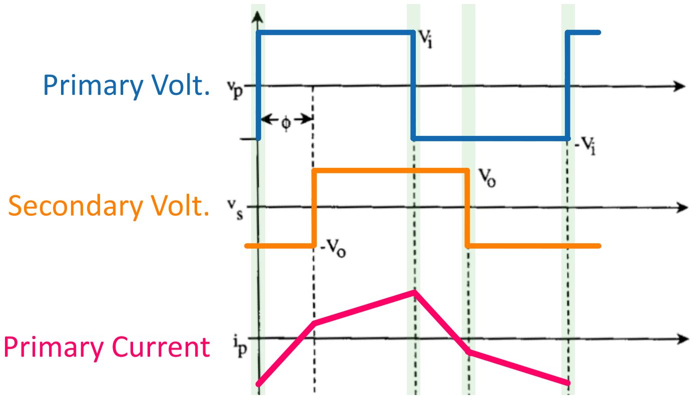
Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

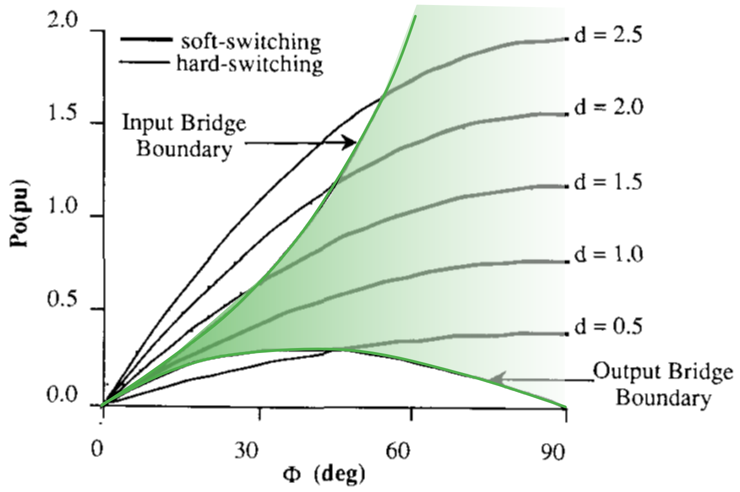
[DeDoncker1989]

Phase-Shift Modulation (2)

- **Zero-Voltage Switching (ZVS) for All Transitions (in a Certain Operating Range)**





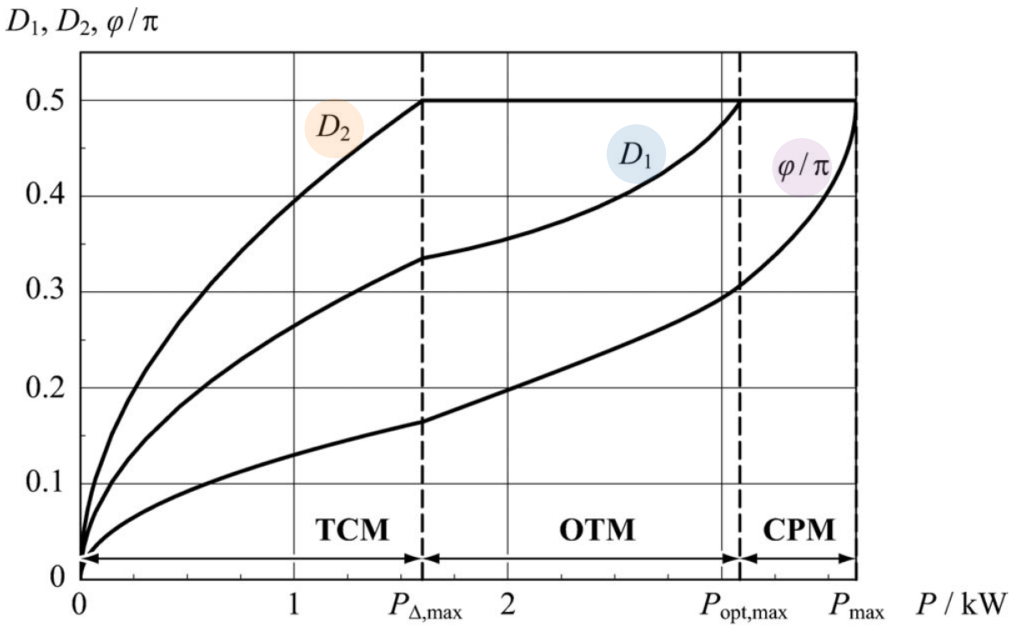


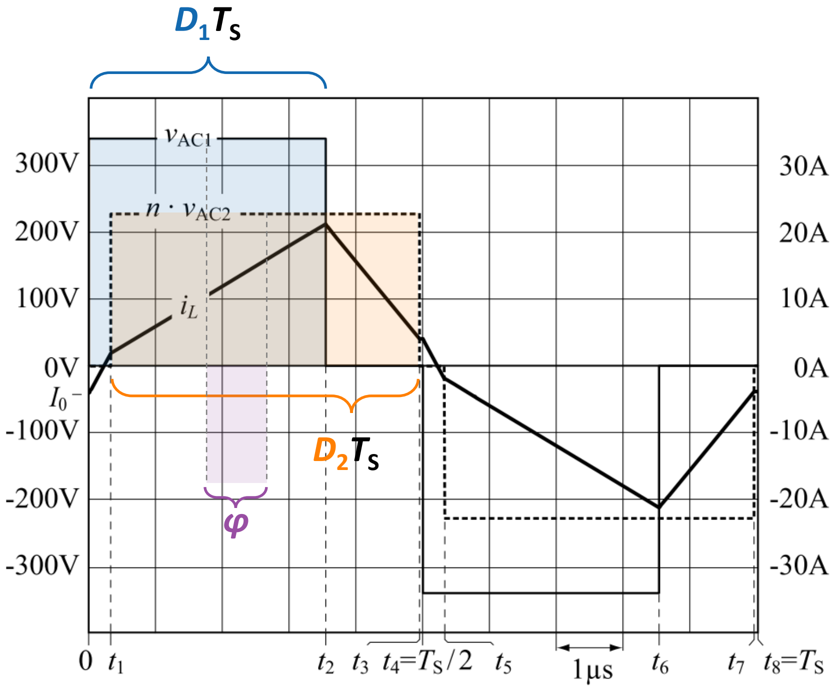
- MV or LV Bridge Loose ZVS Outside of Soft-Switching Range

[DeDoncker1989]

Phase-Shift / Duty Cycle Modulation

- Additional Degrees of Freedom Can Be Utilized for Current Shaping → Optimization!
- For Example: Minimization of the RMS Currents through the Transformer





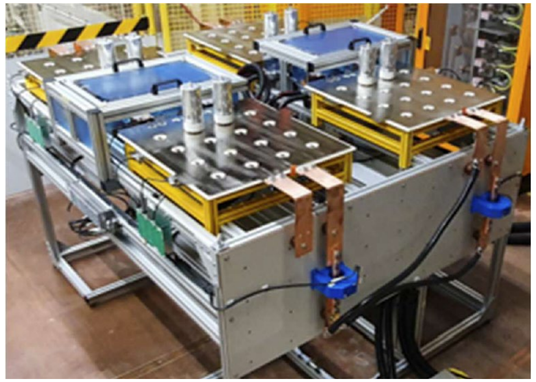
- Note: Not Possible in Half-Bridge Configurations (No Zero Voltage Intervals)

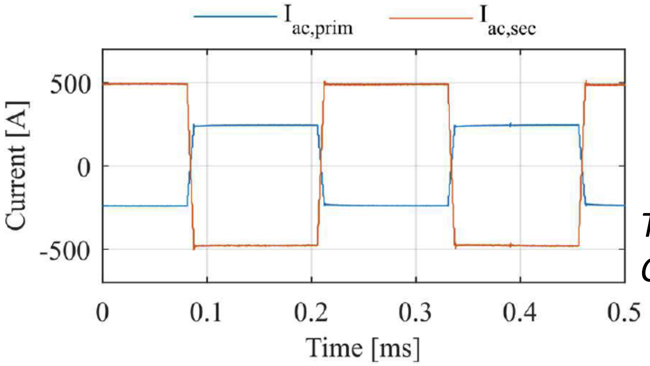
[Krismer2012]

Example: 0.5 MW, 2.5 kV / 1.2 kV DAB

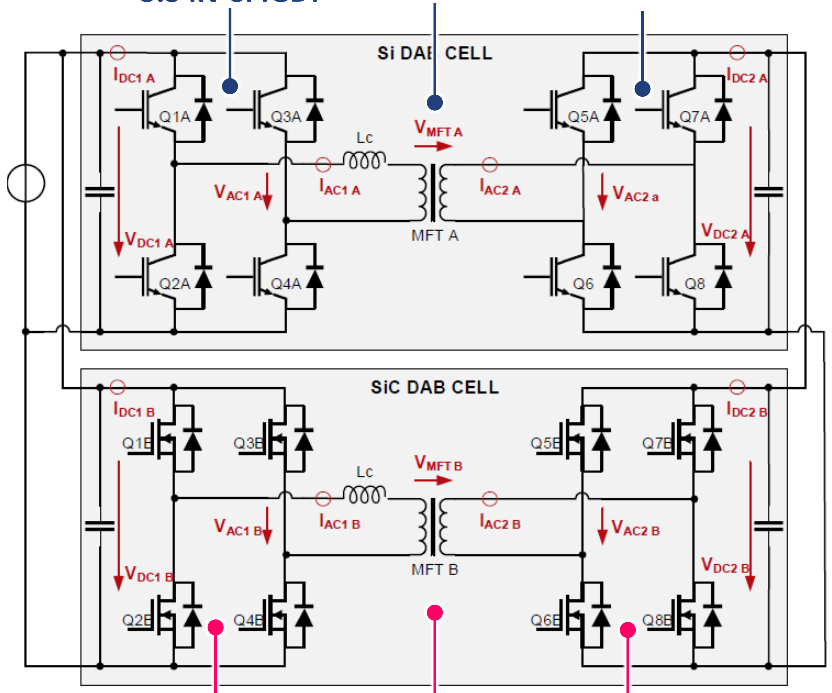
- Back-to-Back Testing of Si-Based and SiC-Based DAB Modules

Hitachi Energy





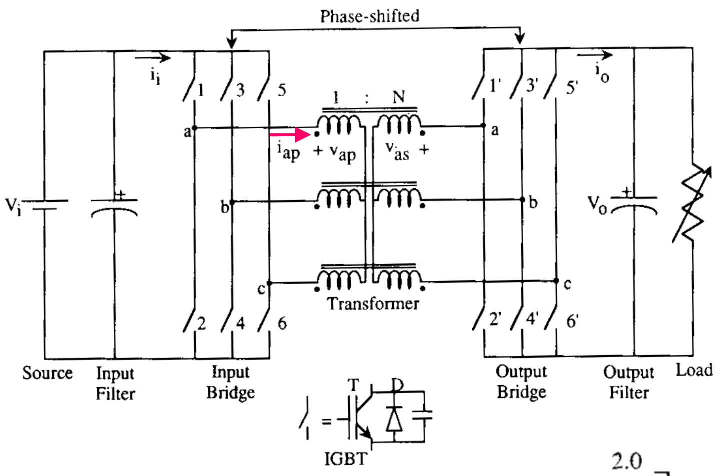
Transformer Currents (SiC-DAB)

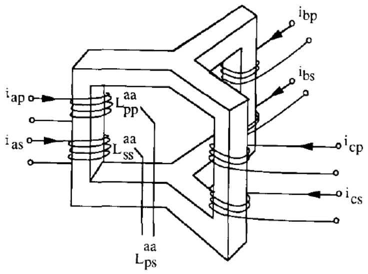


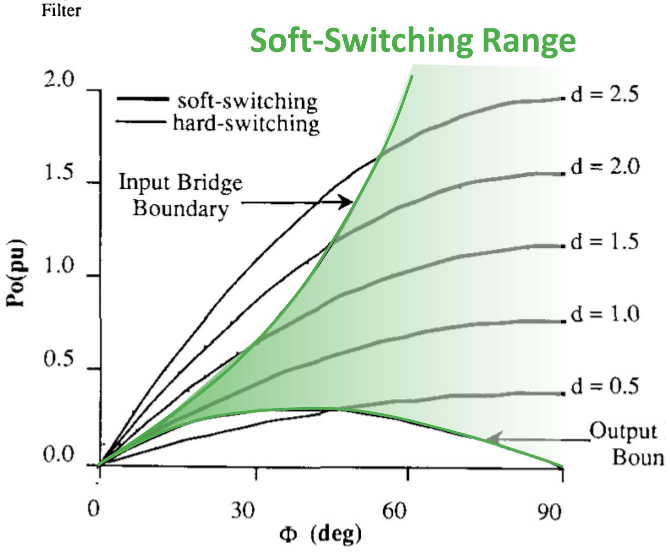
- Si IGBTs: 98.4% Efficiency @ 360 kW and 2.5 kHz (Calorimetric Measurement)
- SiC MOSFETs: 99.2% Efficiency @ 360 kW and 4.0 kHz (Calorimetric Measurement)

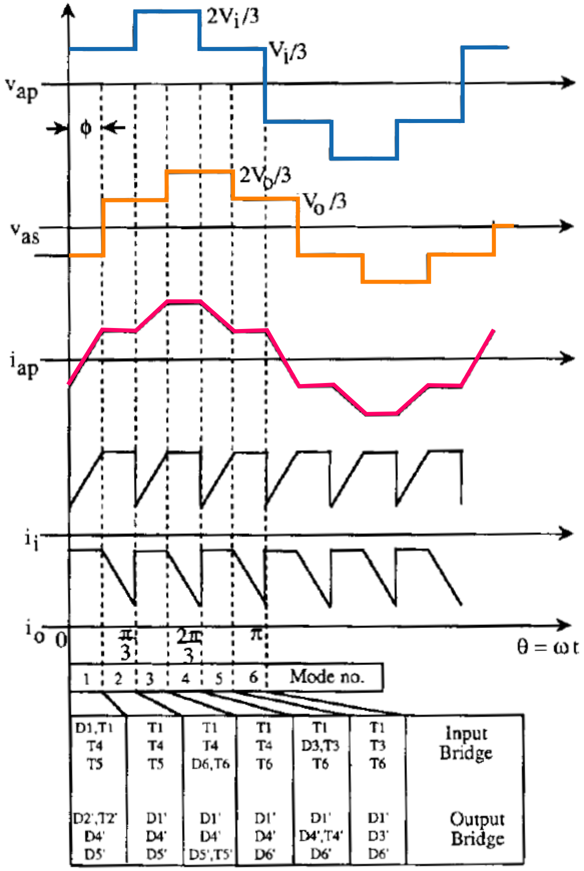
Three-Phase DAB

- Power Flow Control by Phase Shift between Primary & Secondary Voltage
- Zero-Voltage Switching (ZVS) for All Transitions (in a Certain Operating Range)







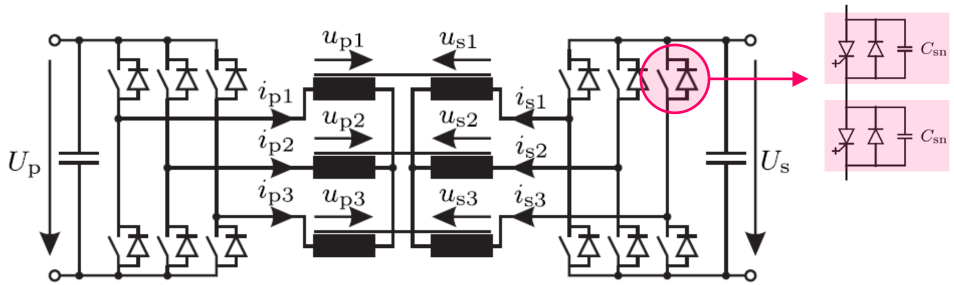


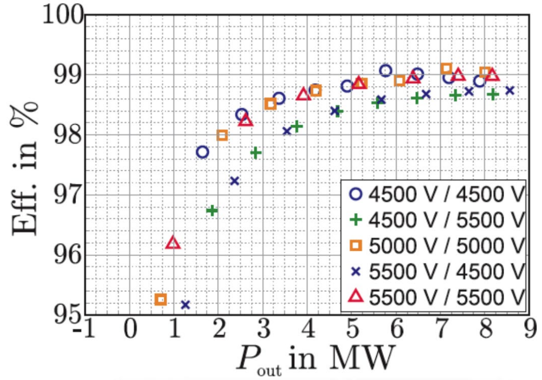
- Full-Range ZVS for $d = 1$ ($V_{in} = V_{out} N_{in}/N_{out}$), i.e., similar input/output voltages

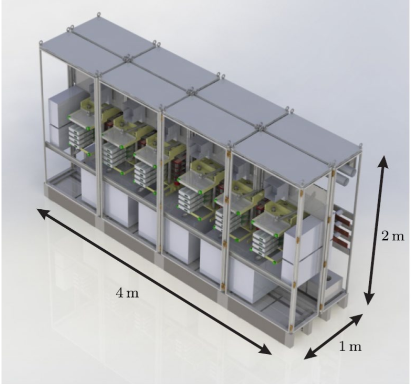
[DeDoncker1991]

Example: 7 MW / 5 kV Three-Phase DAB

- 7 MW Power Transfer, 5 kV ± 10% Input & Output Voltages, 99.2 % Pk. Efficiency
- Series-Connection of 2 x 4.5 kV IGCTs / Three MFTs Operating at 1 kHz







- Power Density 0.9 kW/dm^3 (14.3 W/in^3) with Optimized Arrangement

[Soltau2014, DeDoncker2018]

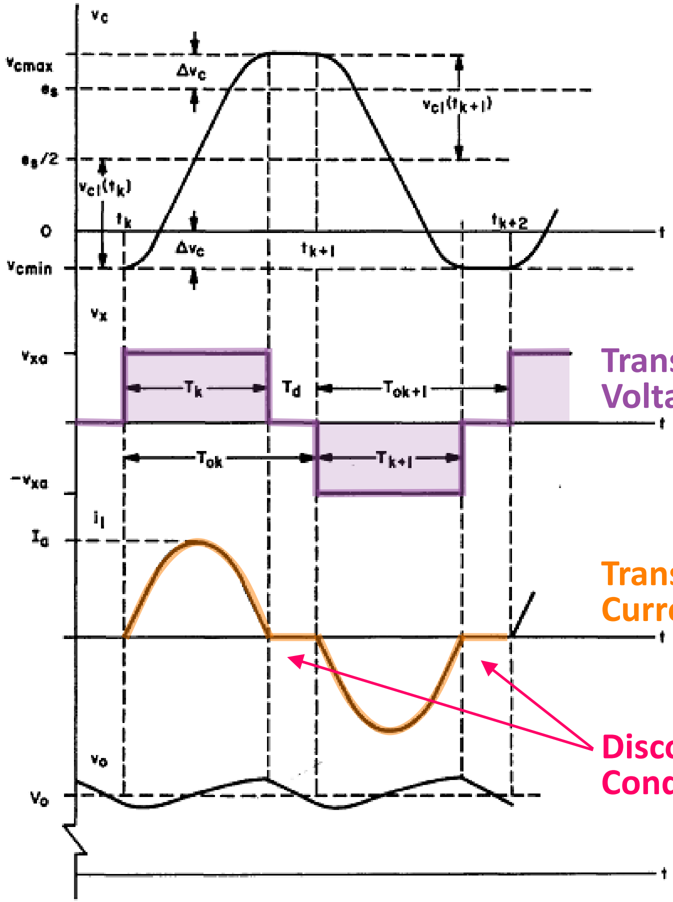
DC Transformer (DCX)

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

FRANCISC C. SCHWARZ, SENIOR MEMBER, IEEE

Img.: ewh.ieee.org



Resonant Tank

Thyristors

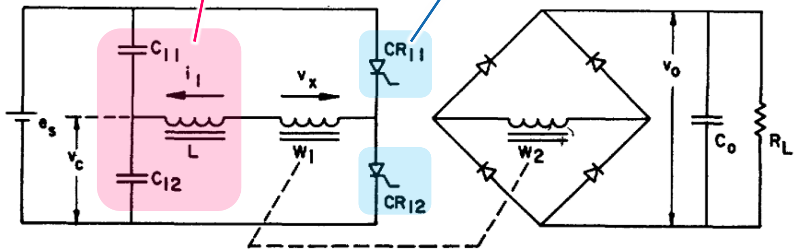


Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

"... load-insensitive series capacitor dc converter ..."

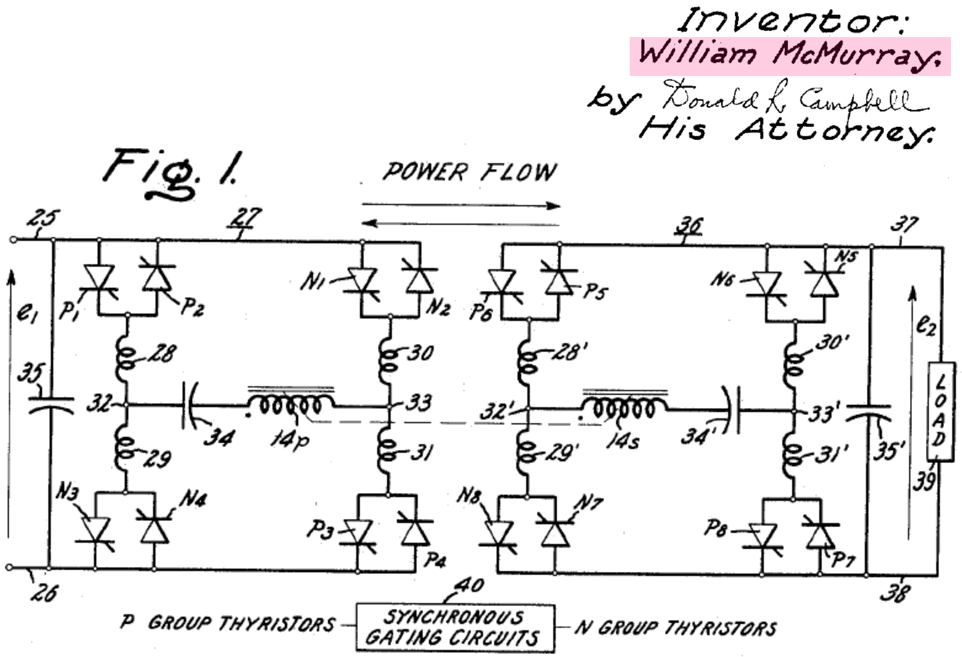
(!) [McMurray1969, Schwarz1970, McMurray1971]

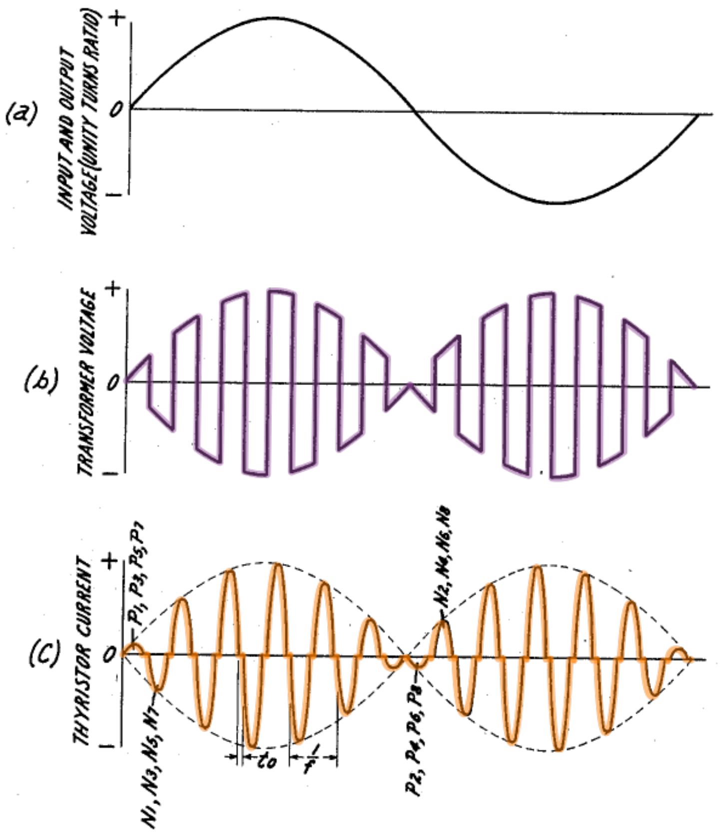
Remark: "Electronic Transformer"

United States Patent Office 3,487,289
Patented Dec. 30, 1969

1969

- **AC-AC Electronic Transformer**
- Resonant Tank with Series Capacitor
- Current Zero Crossing Facilitates Thyristor Turn-Off





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

– W. McMurray, 1971

"Electronic DC Transformer"

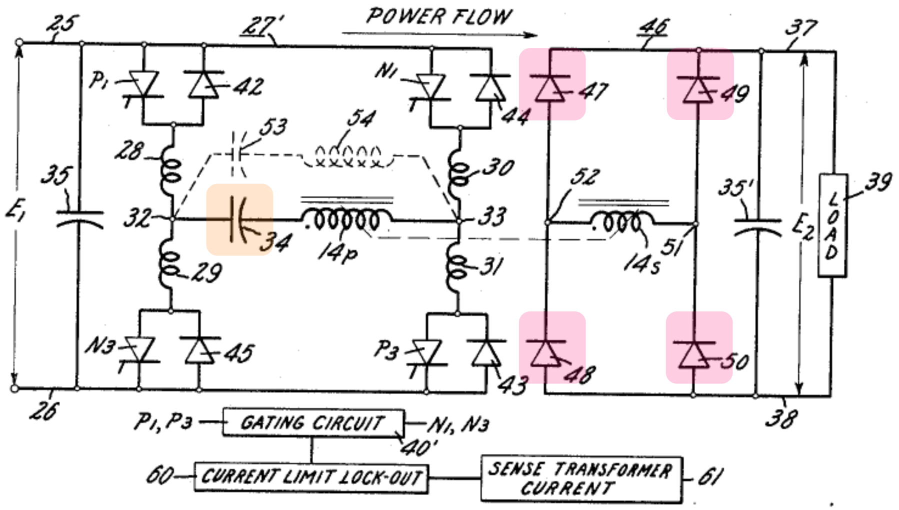
- **DC-DC Electronic Transformer**
  - Resonant Tank with Series Capacitor
  - Current Zero Crossing Facilitates Thyristor Turn-Off

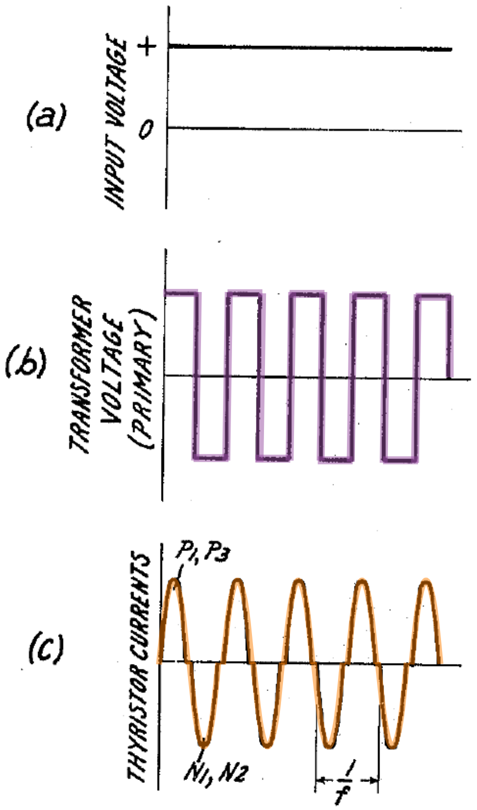
United States Patent Office 3,487,289
Patented Dec. 30 1969

1969

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

Fig. 5.

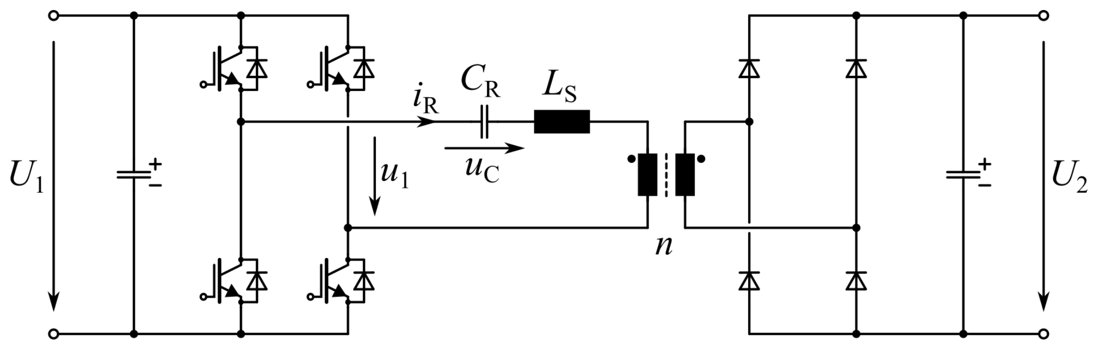




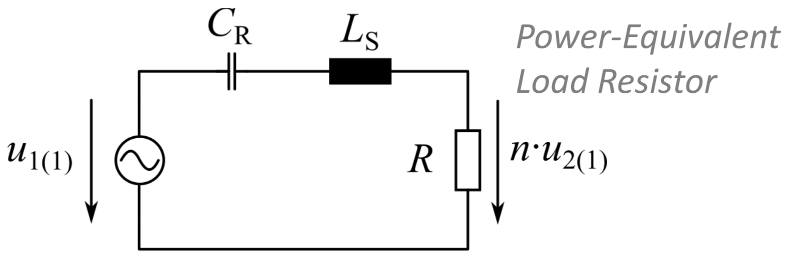
[McMurray1969, McMurray1971]

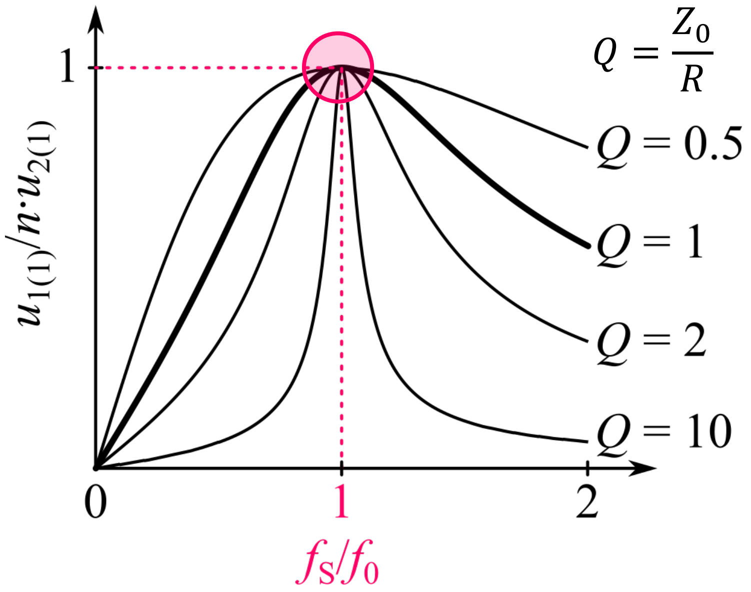
DCX Operating Principle

- **Resonance Frequency ≈ Switching Frequency → Unity Gain**



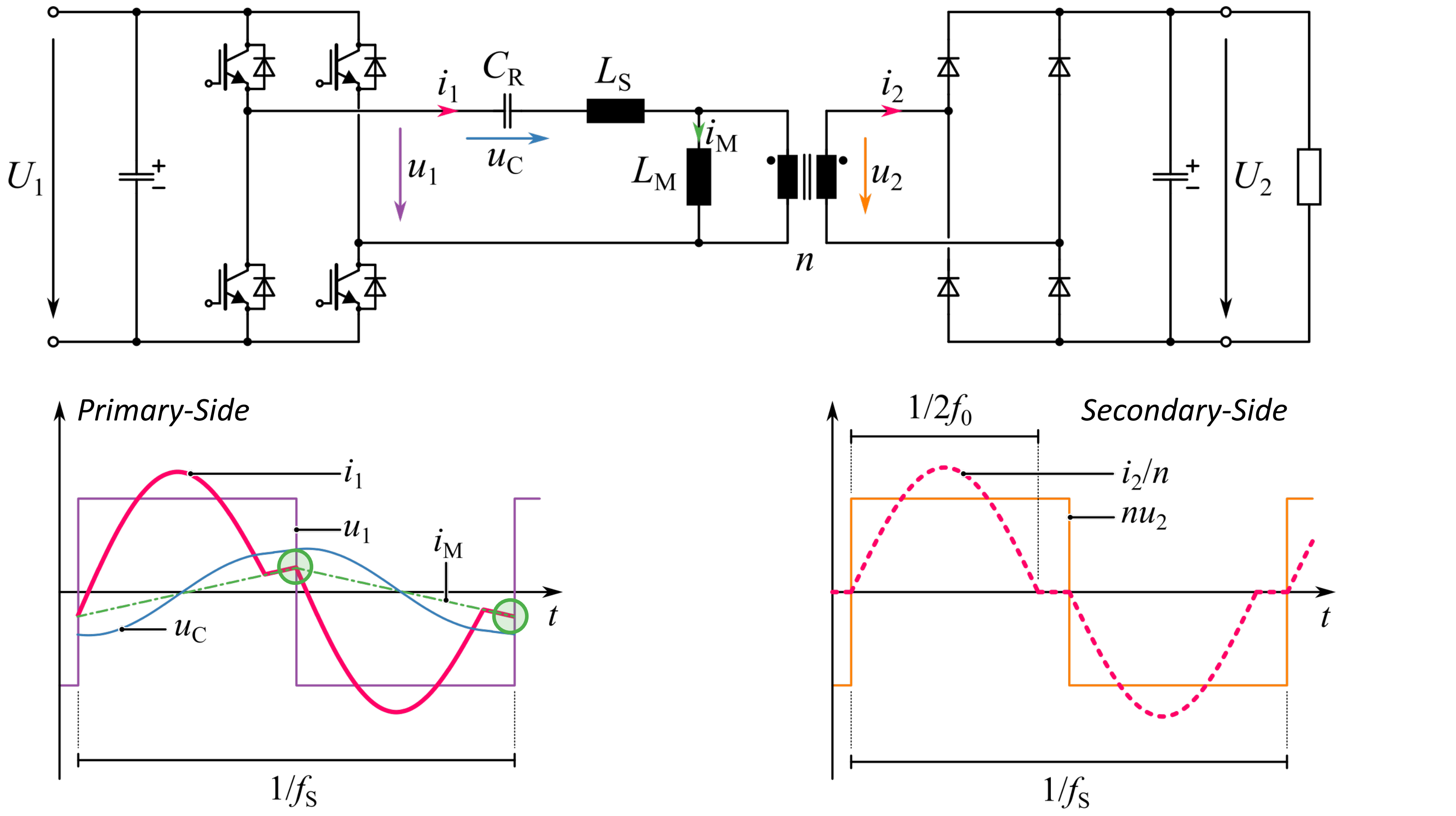
First-Harmonic Equivalent Circuit





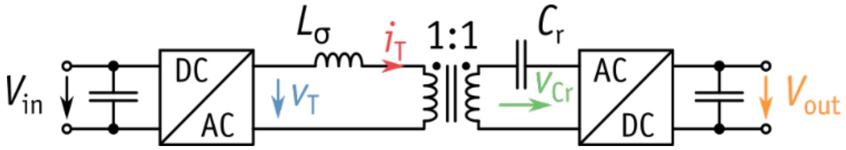
- **Fixed Voltage Transfer Ratio / Independent of Transferred Power (!)**

DCX Key Waveforms



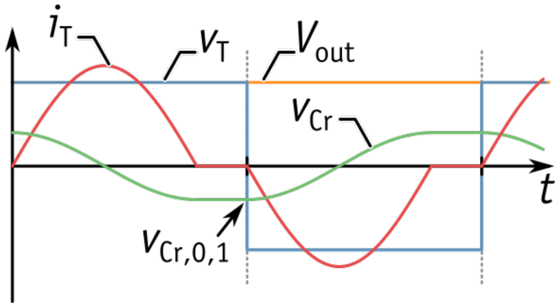
■ Magnetizing Current Enables Load-Independent Zero-Voltage Switching / DoF for Optimization (see Later)

DCX "DC Transformer Behavior" Explained



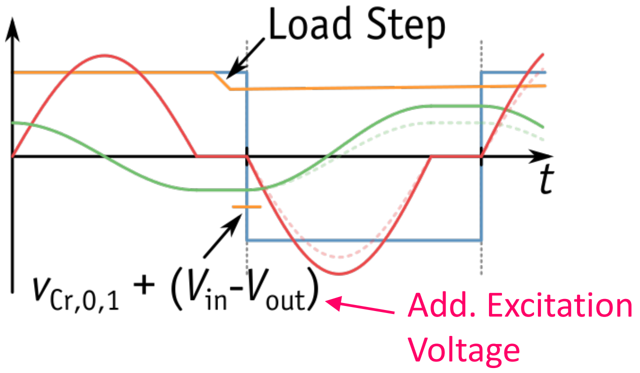
Source Bridge → Actively Switched
Sink Bridge → Diodes

Steady State 1 ($P = P_0$)



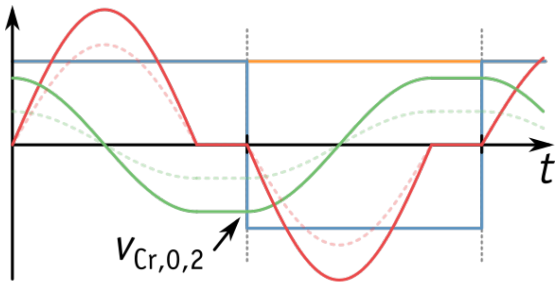
$\hat{\imath}_{T,1} = \frac{\hat{v}_{Cr,0,1}}{Z_0}$ $V_{out} = V_{in}$

Disturbance



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

Steady State 2 ($P > P_0$)



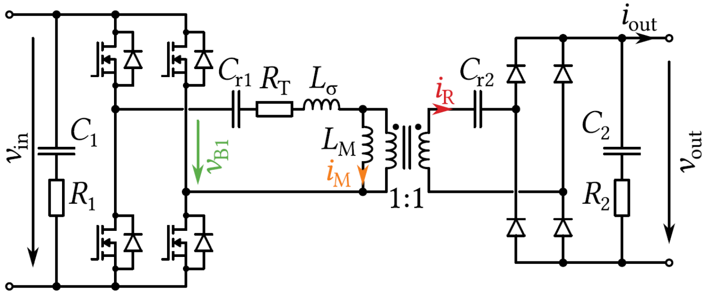
$\hat{\imath}_{T,2} = \frac{\hat{v}_{Cr,0,2}}{Z_0}$ $V_{out} = V_{in}$

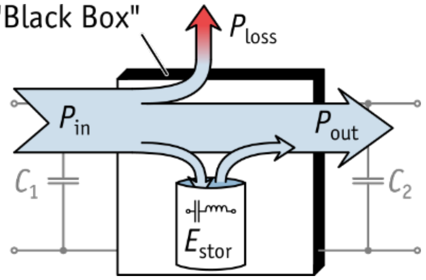
- **Tight Coupling of DC Input and Output Voltages**
  - Ideal: $V_{out} = V_{in}$ (Lossless Components)
  - Real: $V_{out} \approx V_{in}$ (Voltage Drop Due to Losses)

- **No Control Possible/Required – Acts as "DC Transformer" (DCX) with Certain Dynamics!**

[Huber2018]

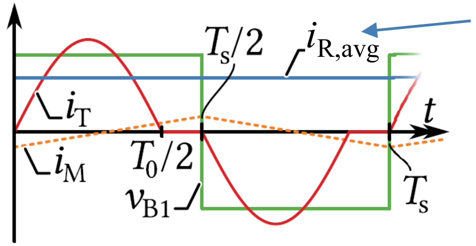
Dynamic Modeling of Terminal Behavior (1)



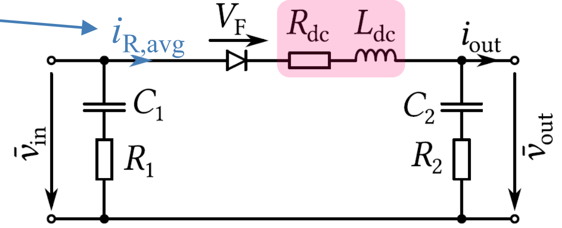


- **Capture Load-Dependency of**
  - Losses
  - Stored Energy

- **Dynamic Equivalent Circuit with Identical Terminal Behavior**



Local Average Current



- **Generic Calculation of Equivalent Circuit Element Values (R_{dc}, L_{dc})**

Equal RMS Losses:

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

Equal Stored Energy:

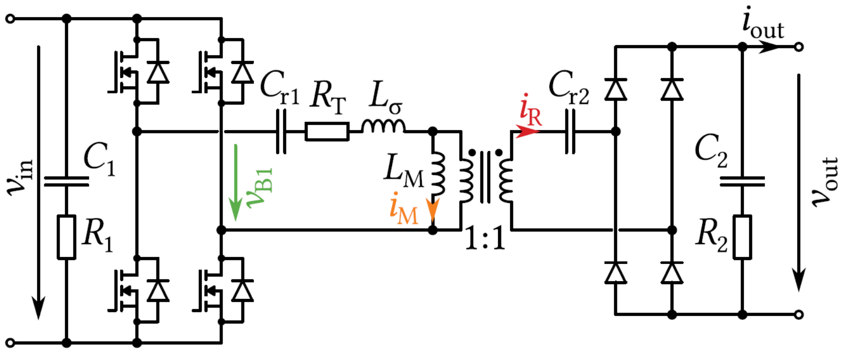
$$i^2_{R,avg} L_{dc} = i^2_{R,pk} L_\sigma \qquad \boldsymbol{L_{dc}} = \frac{i^2_{R,pk}}{i^2_{R,avg}} L_\sigma = \alpha^2 L_\sigma$$

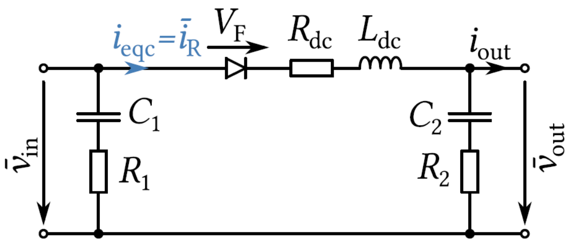
- Parametrization from Actual Waveforms (Calc., Sim., Meas.) – Not Exactly Sinusoidal (!)

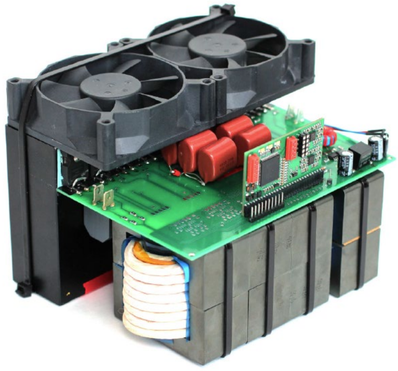
[Huber2018]

Dynamic Modeling of Terminal Behavior (2)

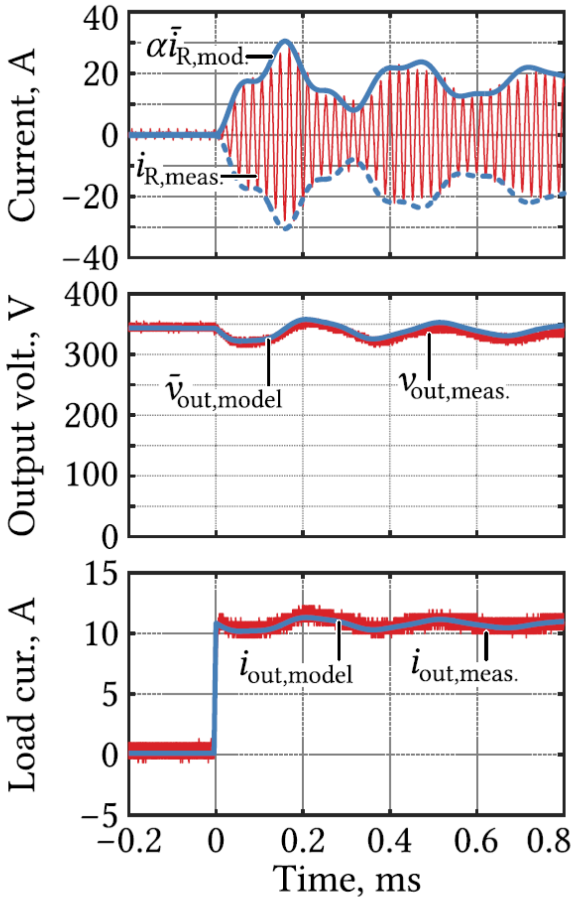
- **Experimental Verification** w. Parametrization from Measured Steady-State Waveforms







10 kW
350 V (in/out)
50 kHz



[Huber2018]

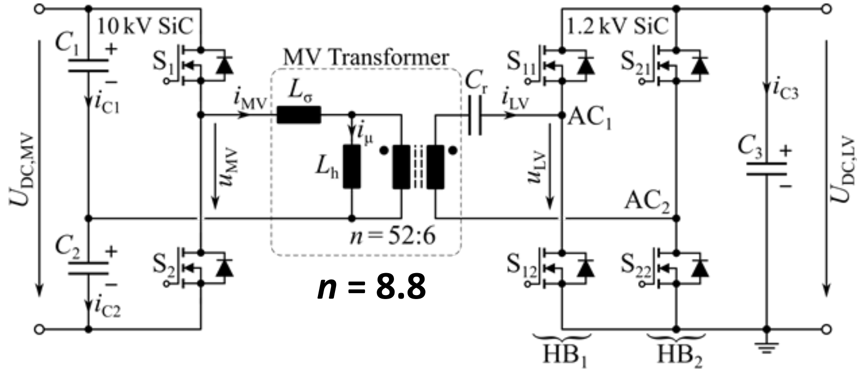
Active Magnetizing Current Splitting (1)

- **Ensure ZVS for Primary and Secondary Bridge (Synchronous Rectification)**
- Critical for Very Asymmetric Semiconductor Output Capacitances (Referred to Same Side of Transf.)

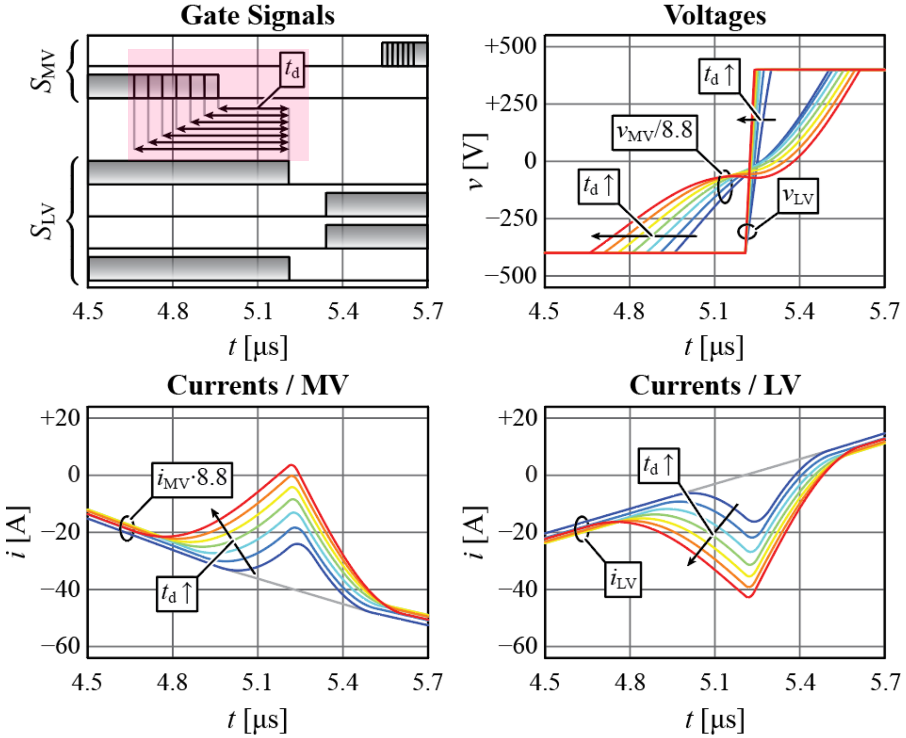
- **New Method: Both Bridges are Actively Operated**
- Very Small Phase Shift Between the Bridges
- Circulating Current Shifts the Magnetization Current

MV / 10 kV SiC
C_{oss} = 150 pF

LV / 1200 V SiC
C_{oss} = 1700 pF



***n* = 8.8**

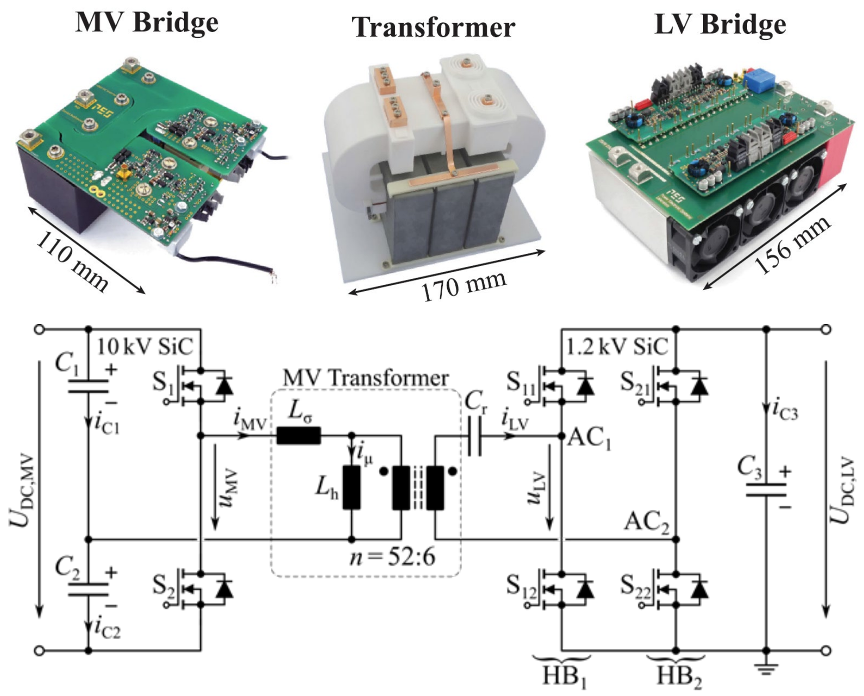


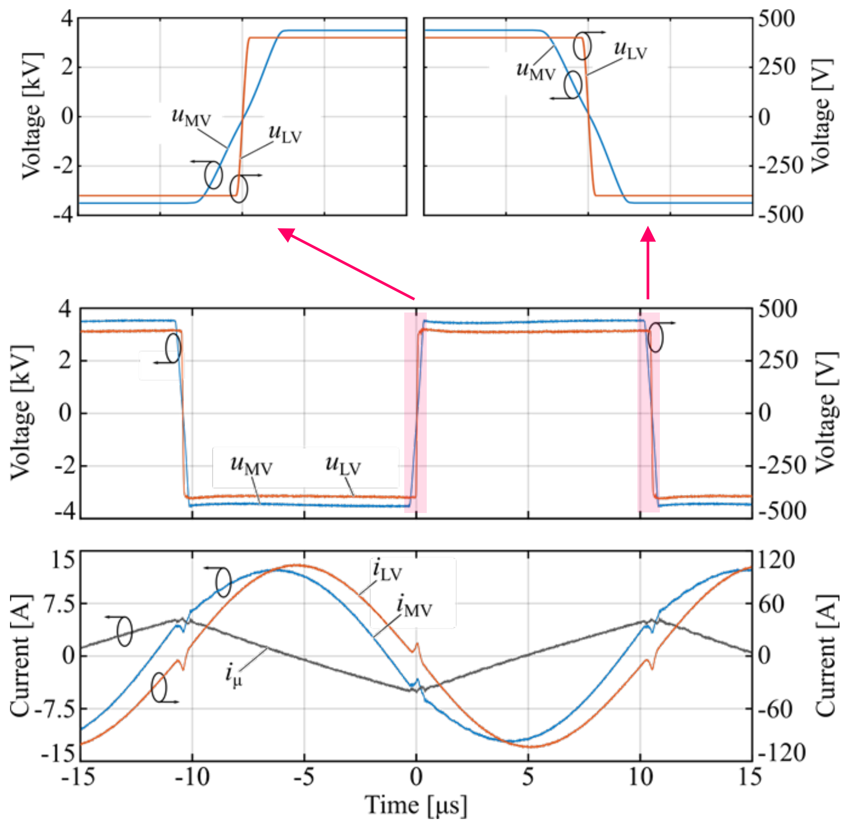
- **Control of the Switching Speed / No Closed-Loop Control Required / Extremely Robust**

[Guillod2020]

Active Magnetizing Current Splitting (2)

- **Experimental Results**
- 400 V → 7 kV Operation @ 25 kW / 48 kHz



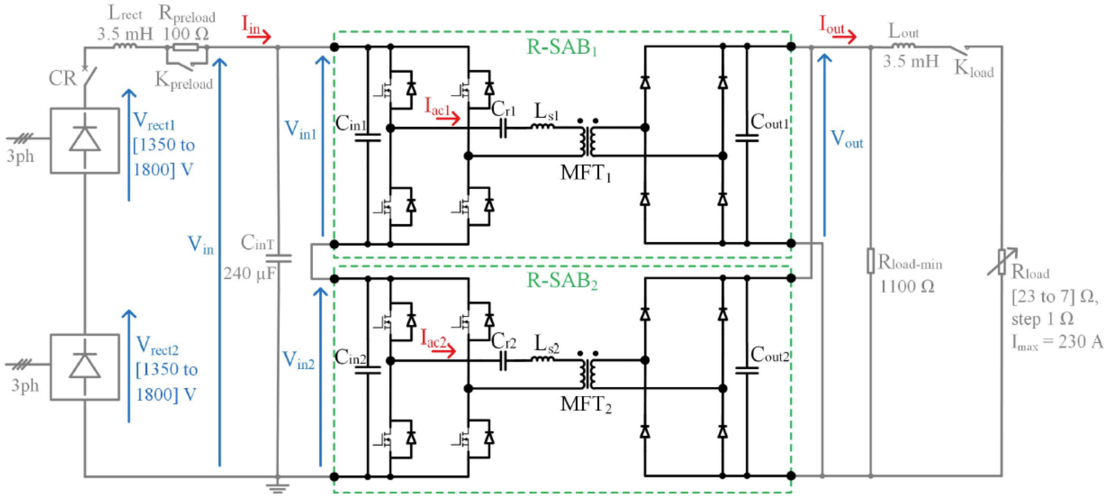


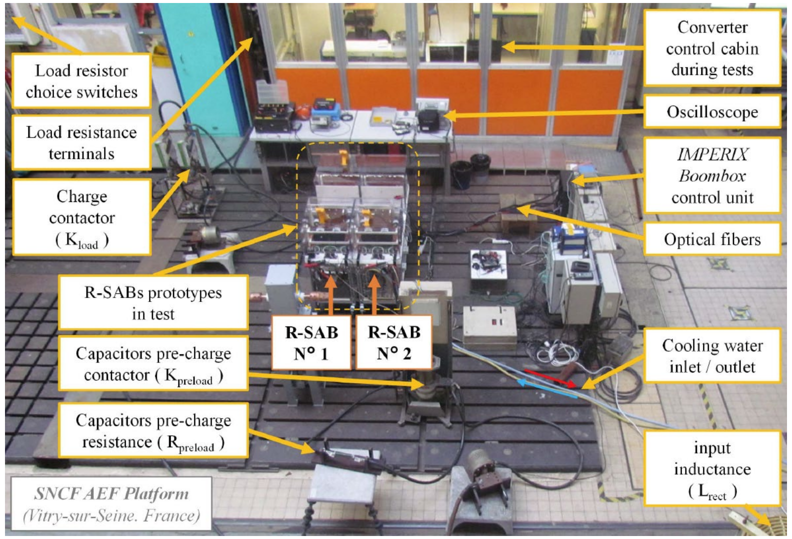
- **ZVS of All MOSFETs Independent of Load**
- **Load-Independent Voltage Transfer Ratio (< 0.8% Deviation) / 99% DC-DC Efficiency**

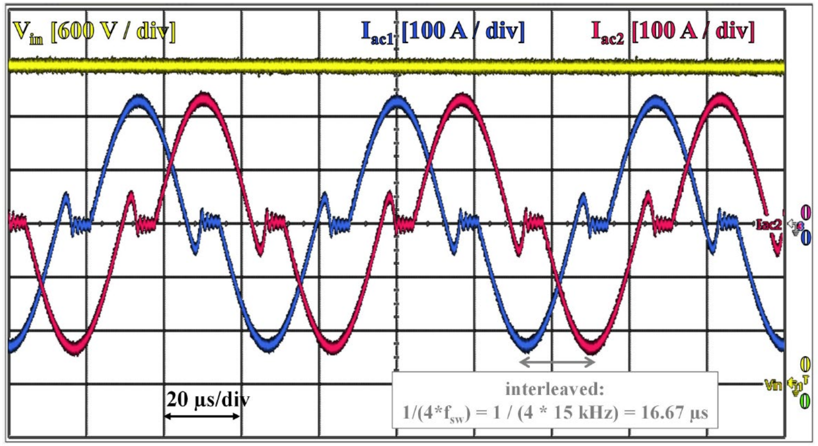
Example: DC Traction DCX System (1)

- 300 kW DCX Modules / 1.8 kV to 1.8 kV
- 3.3 kV SiC / 15 kHz MFT / 99% Peak Efficiency

- Input-Series Output-Parallel Arrangement of Two DCXs
- Two-Cell ISOP: 3 kV to 1.5 kV DC @ 600 kW
- Natural Input Volt. Balancing & Output Cur. Sharing
- Interleaving Reduced Output Voltage Ripple







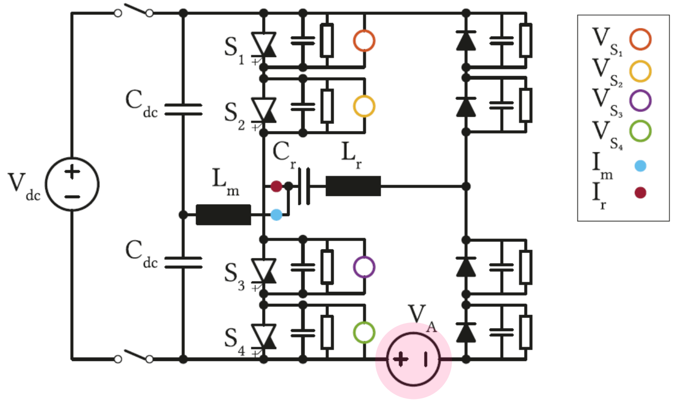
[Fabre2021]

Example: IGCT-Based DCX System (2)

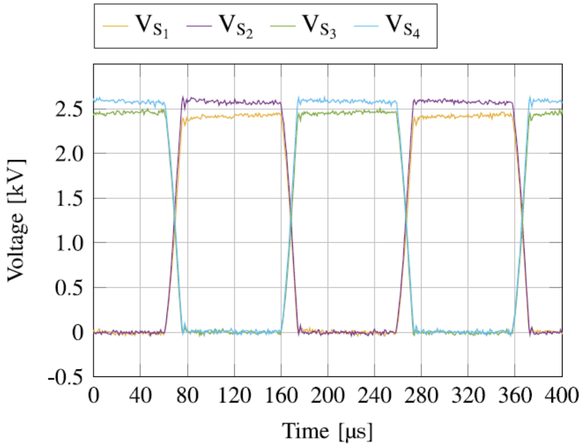
- Series-Connected 4.5 kV, 68 mm RC-IGCTs (Reverse-Conducting IGCTs)
- Custom Gate Unit Optimized for ZVS Operation
- Back-to-Back Test @ 5 kV DC and 500 kW

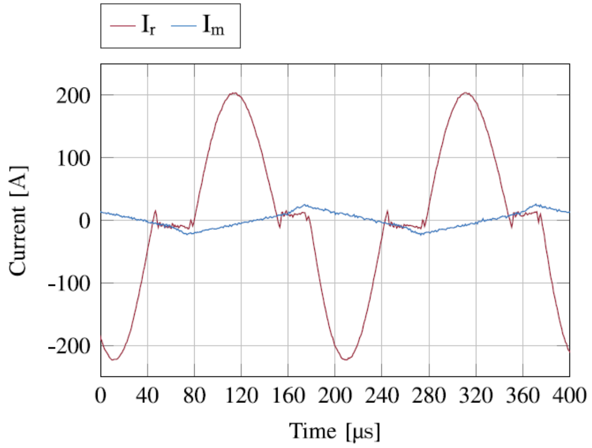
EPFL pel

SRC Test Bench



Series Voltage to Adjust Power Flow



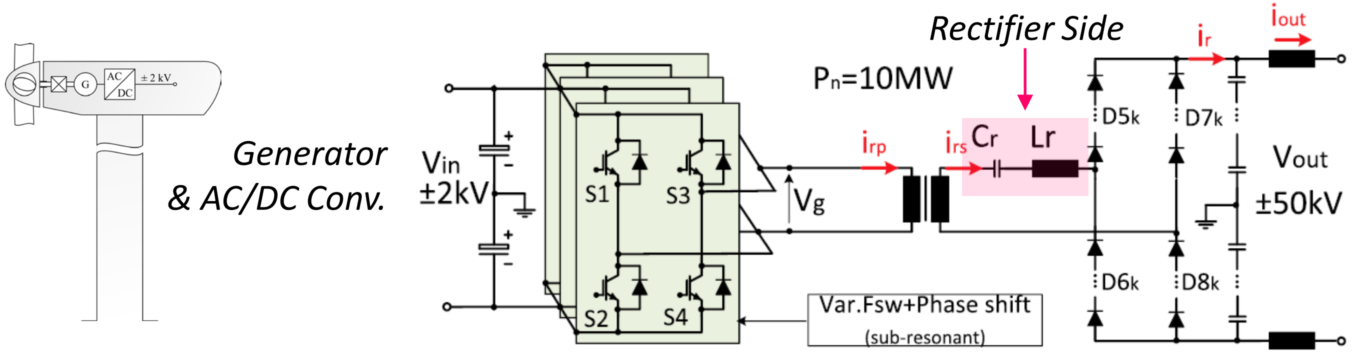


- f_s = 5 kHz, f_{res} = 7.4 kHz → 20 µs Dead Time to Ensure IGCT ZVS

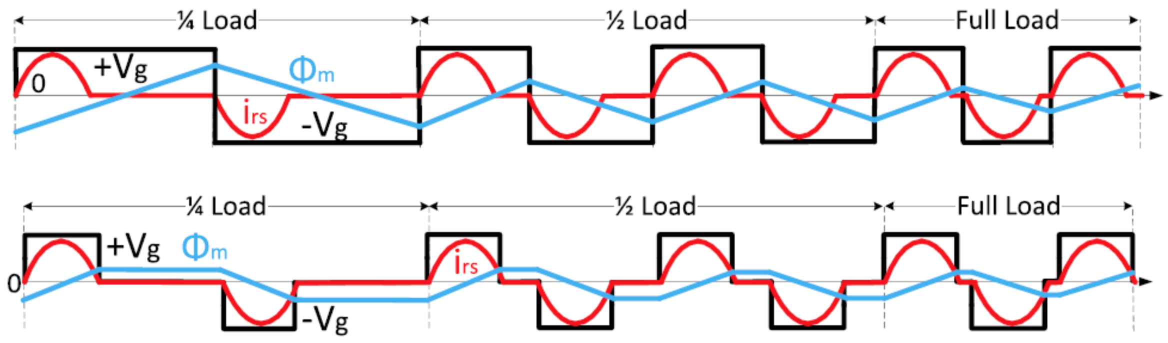
Remark: DCX Power Flow Control

- Step-Up for MVDC Wind Park Collector Grid

Vestas



- Power Flow Control via Pulse Removal Technique



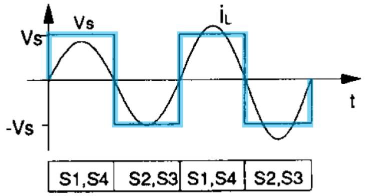
Frequency Variation Only
Peak Core flux Defined by Lowest Frequency

Frequency & Duty-Cycle
Peak Core Flux Defined by Nominal Frequency

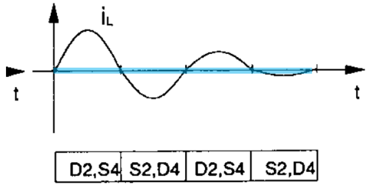
- High Efficiency for $V_{in} \approx nV_{out}$ (Otherwise: High Peak/RMS Currents w.r.t. Average Current/Power)

Remark: DCX Quantum Operation

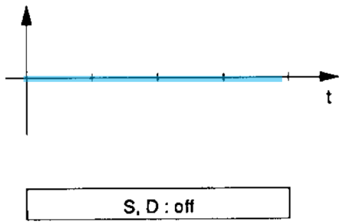
- Output Voltage Control by Combining Different Operating Modes
- Mode Transition Only at Current Zero Crossing → ZCS/ZVS and Constant Operating Frequency



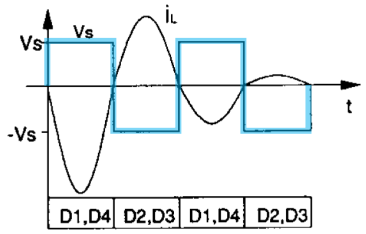
Powering Mode



Free Resonant Mode

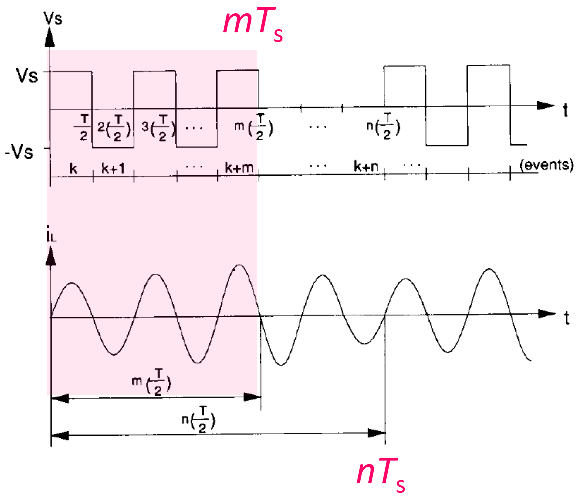


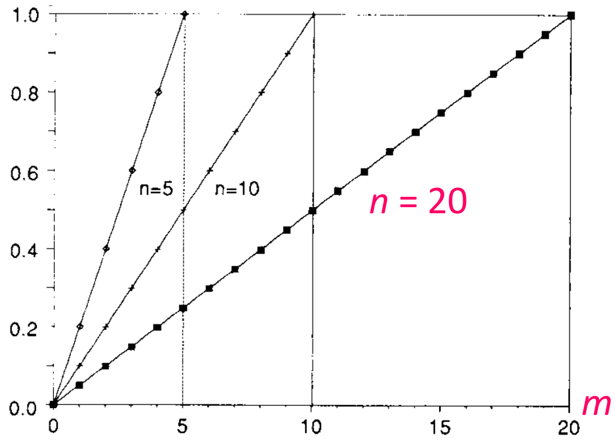
Discontinuous Mode
(Occurs Naturally)



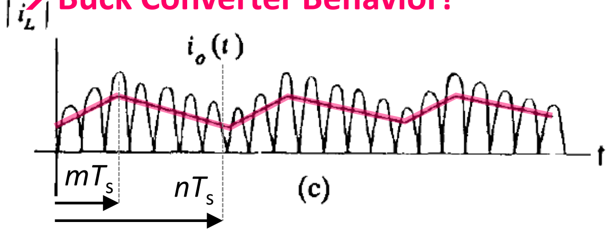
Regeneration Mode
(Low Inp. Power Fact.)

- Powering Mode for *m* out of *n* Cycles → Discrete DC Voltage Transfer Ratios





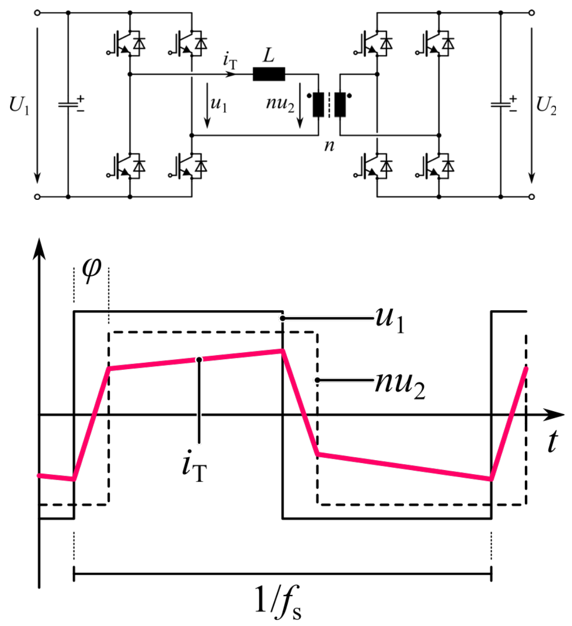
Rectified Current
→ **Buck Converter Behavior!**



[Joung1988, Joung1989]

Summary: MF Power Conversion for SSTs

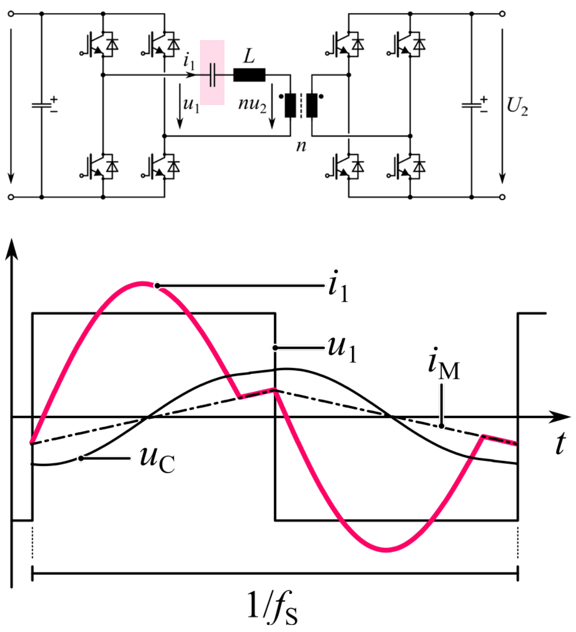
Dual Active Bridge



■ **Can (Must!) Be Fully Controlled**

- Fully Controllable Power Flows
- Lower RMS Currents for $U_1 \approx nU_2$

DC Transformer ("DCX")



■ **Control Not Needed (Not Directly Possible!)**

- Reduces Complexity in Multi-Cell Syst. (e.g., Natural MV-Side Volt. Balancing)
- Predominant Solution in Multi-Cell SSTs

Part II

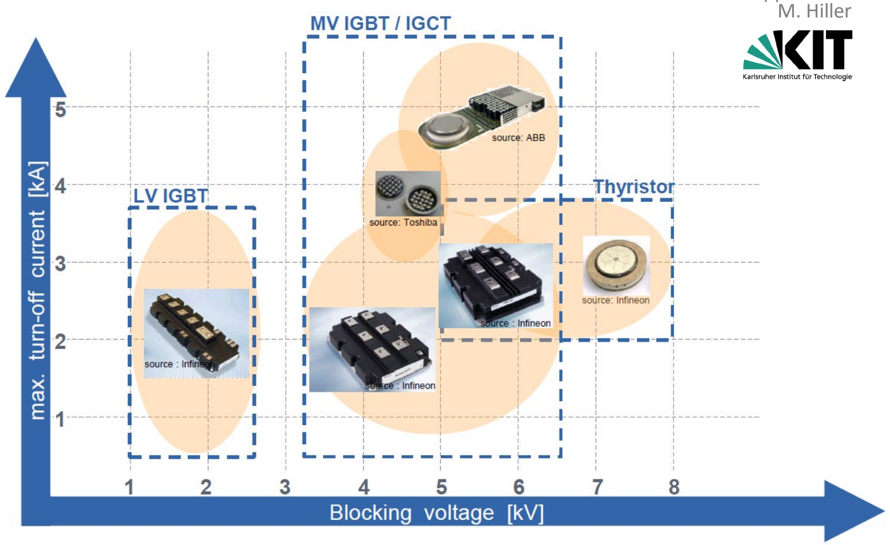
SST Concepts & Key Design Aspects

- Medium-Frequency Power Conversion
- **Power Semiconductors**
- Key SST Topologies
- Medium-Frequency Transformers
- Isolation Coordination
- Protection
- Construction

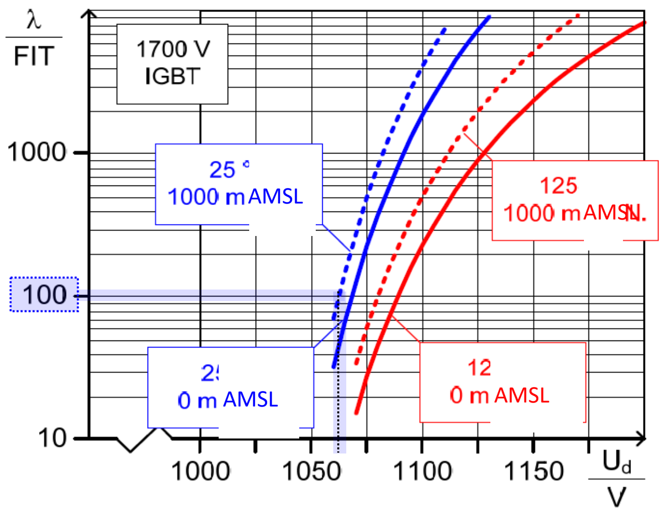
Available Si Power Semiconductors

- 1200 V & 1700 V Si IGBTs Most Frequently Used in Industry Applications / Max. 6.5 kV Available
- Derating Requirement due to Cosmic Radiation: 1700 V Si IGBTs → ca. 1000 V max. DC Voltage

Source: M. Doppelbauer
M. Hiller

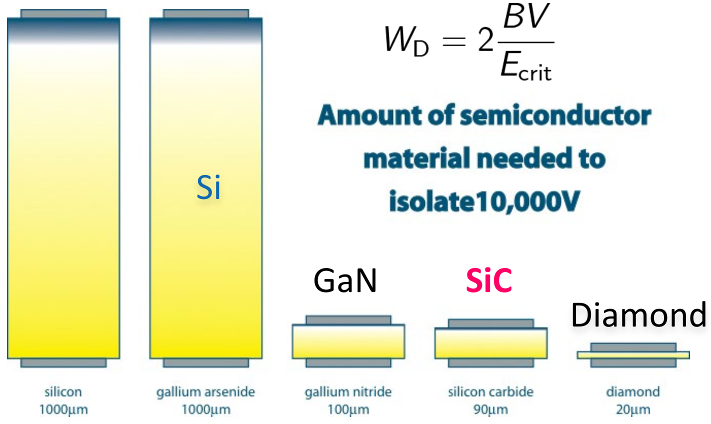


Source: H.-G. Eckel
Univ. Rostock



- Interfacing to Medium Voltage → Series Connections or Multi-Level Converter Topologies

Si vs. SiC Power Semiconductors (1)



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

Amount of semiconductor material needed to isolate10,000V

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. 9 x Larger Than in Si

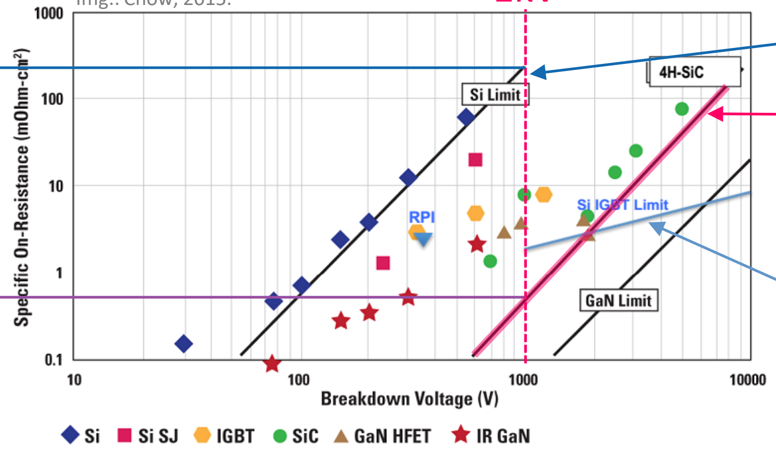
■ Lower $R_{on,sp}$ for Given Blocking Voltage

300 mΩ cm^2

0.6 mΩ cm^2

1kV

Img.: Chow, 2015.



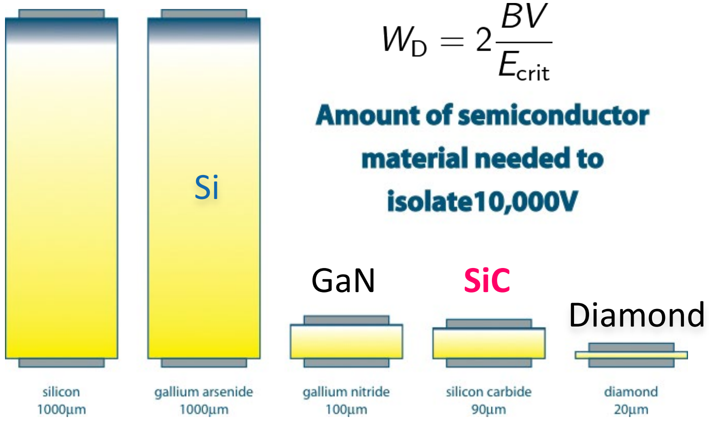
Unipolar Si Limit

Unipolar 4H-SiC Limit

Bipolar Si (!) Limit

But: Bipolar → Sw. Losses!

Si vs. SiC Power Semiconductors (2)



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

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

- Specific On-State Resistance

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

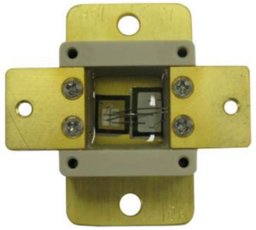
Blocking Voltage

Critical Electric Field

- E_C in SiC ca. 9 x Larger Than in Si

Higher Blocking Voltage for Given $R_{on,sp}$

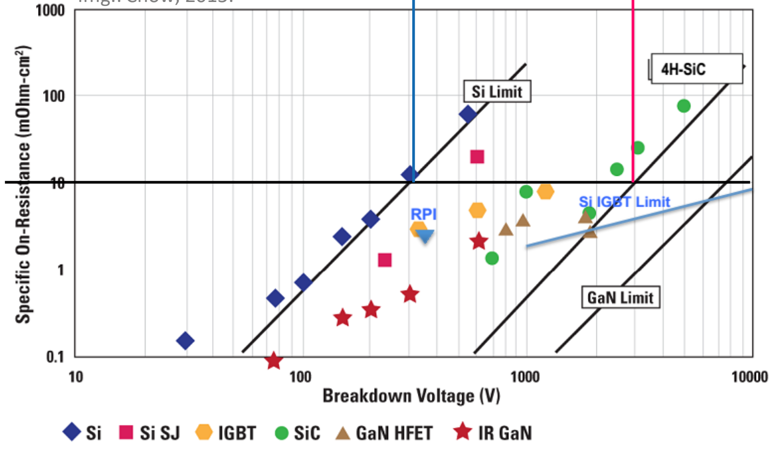
10 kV SiC MOSFET (Wolfspeed)



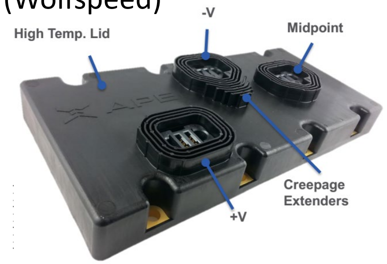
10 mΩ cm²

300 V ⇨ 3000 V

Img.: Chow, 2015.



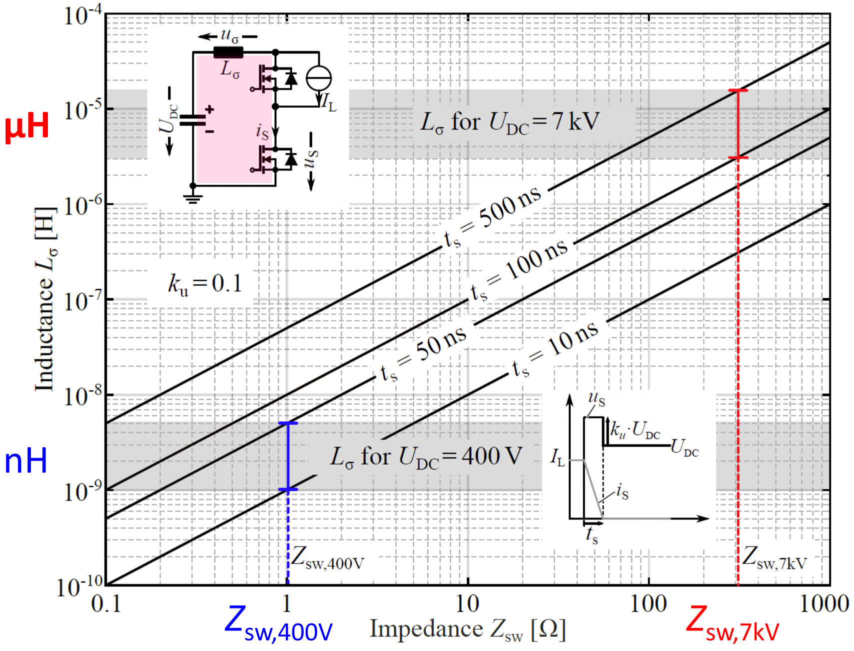
15 kV, 80 A Package (Wolfspeed)



Remark: HV SiC Parasitics

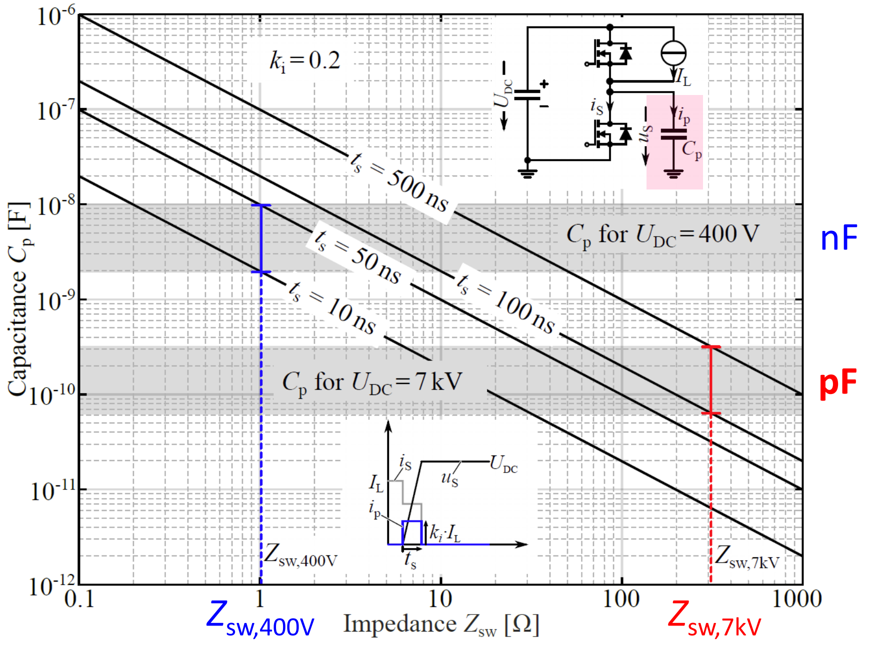
- High di/dt + Stray Inductance → Overvoltages
- High dv/dt + Parasitic Capacitance → Ground Currents
- Exemplary Analysis for a 25 kW, 7 kV to 400 V System

Stray Inductance vs. Z_{sw} for 10% Overshoot



$$Z_{sw} = U_{DC}/I_L$$

Stray Capacitance vs. Z_{sw} for 20% Ground Current



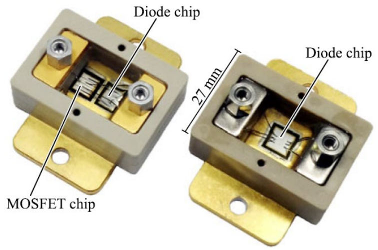
$$Z_{sw} = U_{DC}/I_L$$

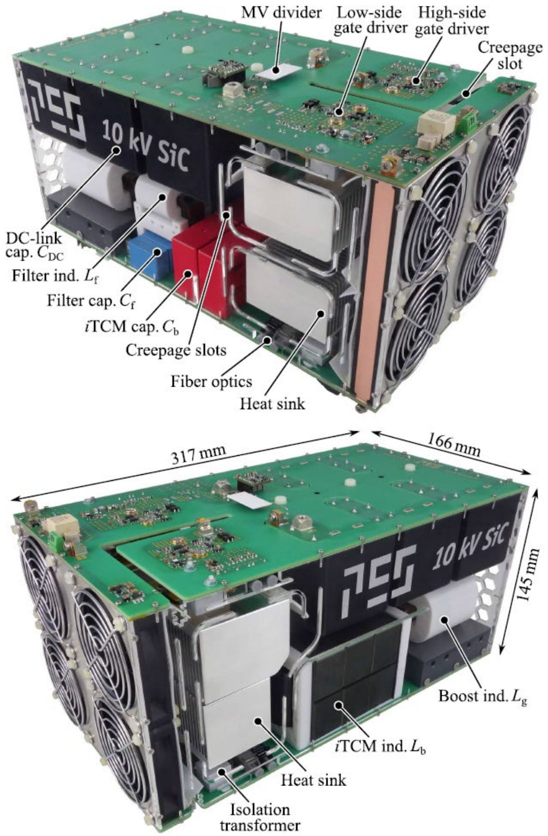
- LV Devices: Minimize Stray Inductance
- HV Devices: Minimize Stray Capacitance

[Rothmund2018]

Example: 10 kV SiC AC-DC Converter

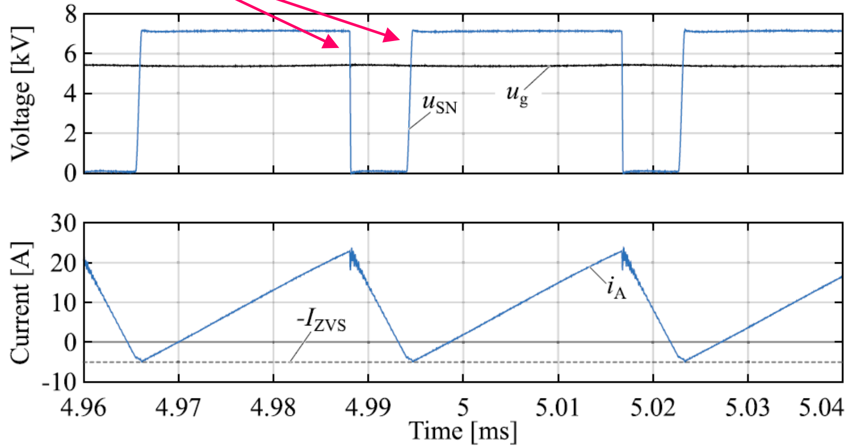
- 25 kW / 7 kV DC / iTCM Soft-Switching AC-DC Topology
- 99.1% Efficiency at Rated Load / 3.3 kW/dm³ (54 W/in³) Power Density





Clean 7 kV Switching Waveforms

f_s = 35 kHz

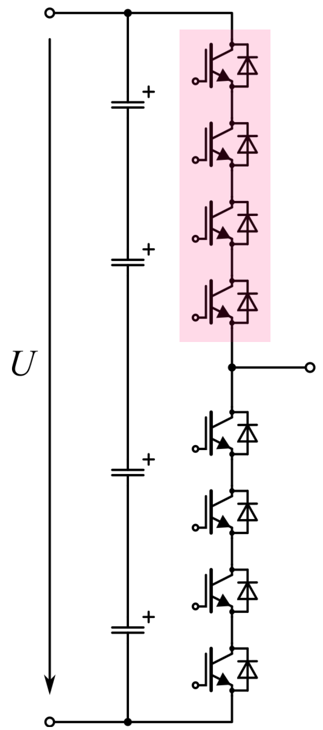


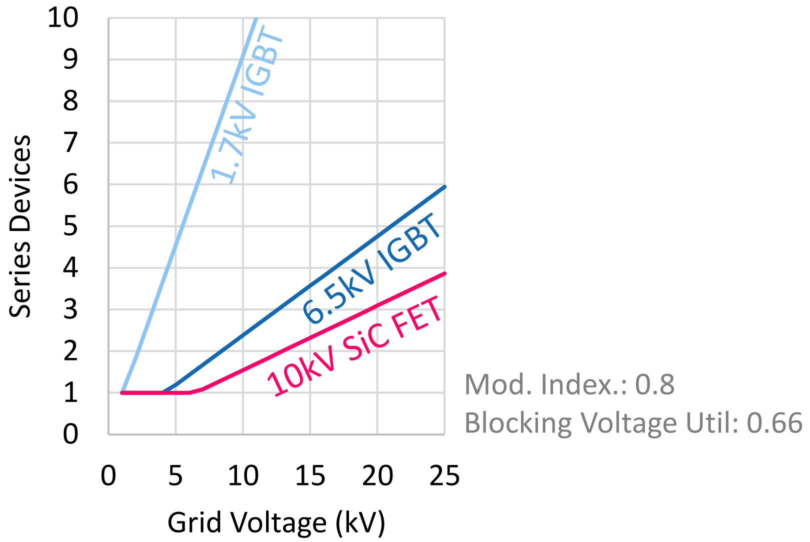
- Converter Systems with 10 kV SiC MOSFETs Can Be Realized (See Also Further Examples Later)

[Rothmund2019a]

Interfacing to Medium Voltage (1): Direct Series Connection

- **Limited Blocking Voltages of Available Semiconductors & Max. Utilization Only ca. 50…70%**
  - 6.5 kV for Si IGBTs
  - 10…15 kV for SiC FETs (Prototype Devices Only)

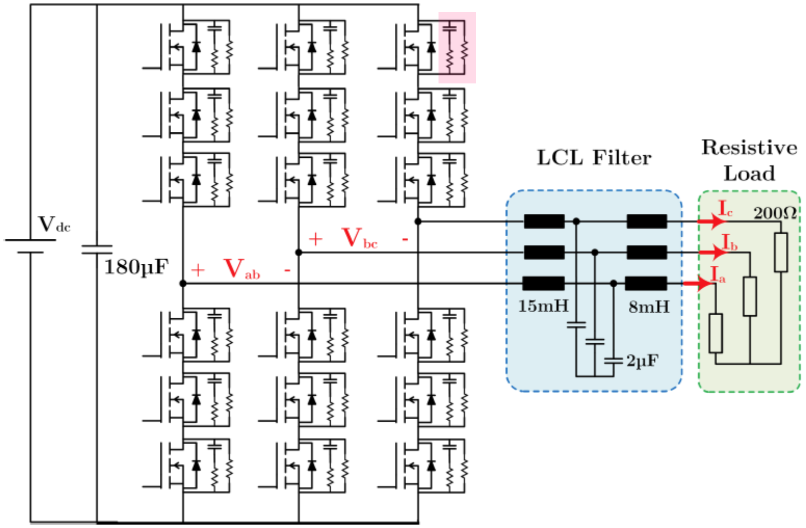


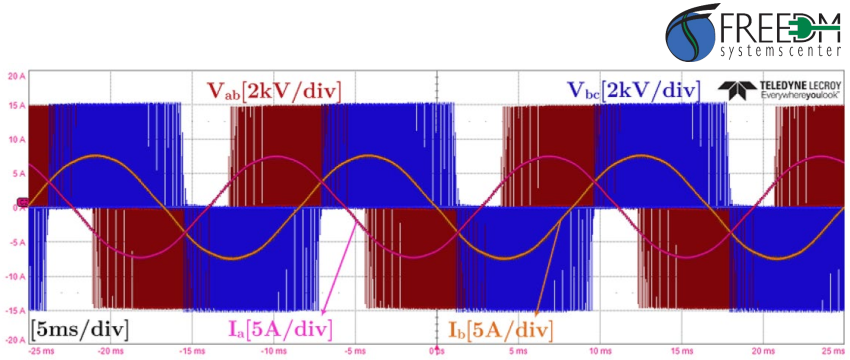


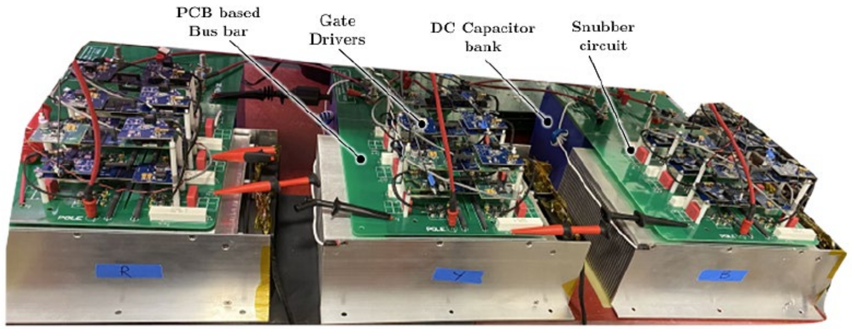
- **Key Challenge: Static & Dynamic (!) Voltage Sharing**

Direct Series Connection: Example

- 100 kW, 7.2 kV DC Three-Phase Inverter
- Direct Series Connection of 3 x 3.3 kV SiC MOSFETs





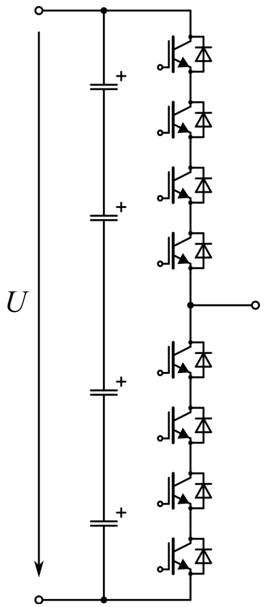


- Steady-State Balancing with Parallel Resistors
- Dynamic balancing with RC Snubber

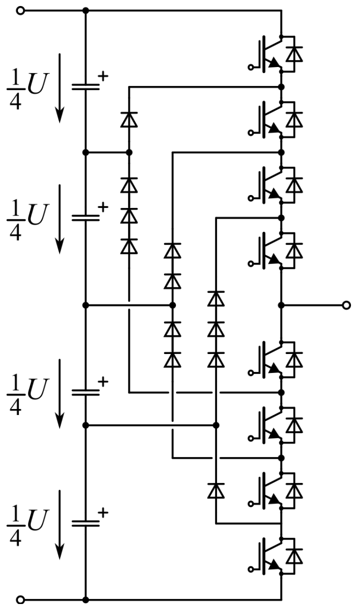
- Advanced Balancing Approaches (e.g., Active Gate Signal Delay Control, …)

[Lin2022]

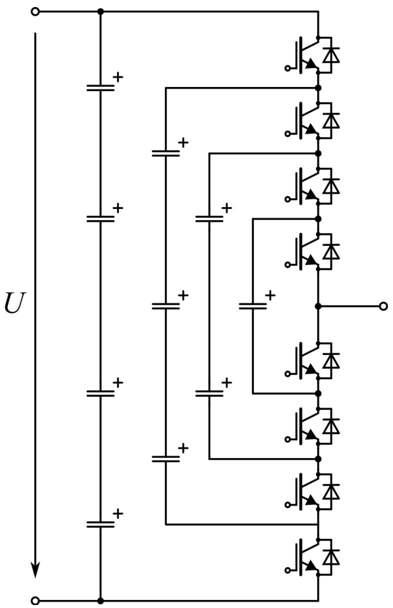
Interfacing to MV (2): Multilevel & Multicell Topologies



Neutral Point Clamped (NPC)
Baker (1979, Pat. Filed)
Nabae et al. (1981)

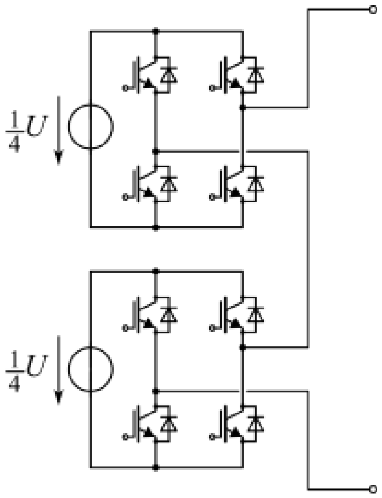


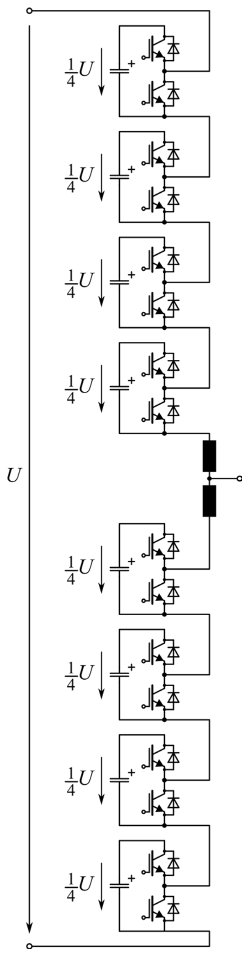
Flying-Capacitor Converter (FCC)
Meynard et al. (1992)



MMC →
Marquardt et al. (2002)
See also Baker et al. (1974)

Cascaded H-Bridge
McMurray (1969)





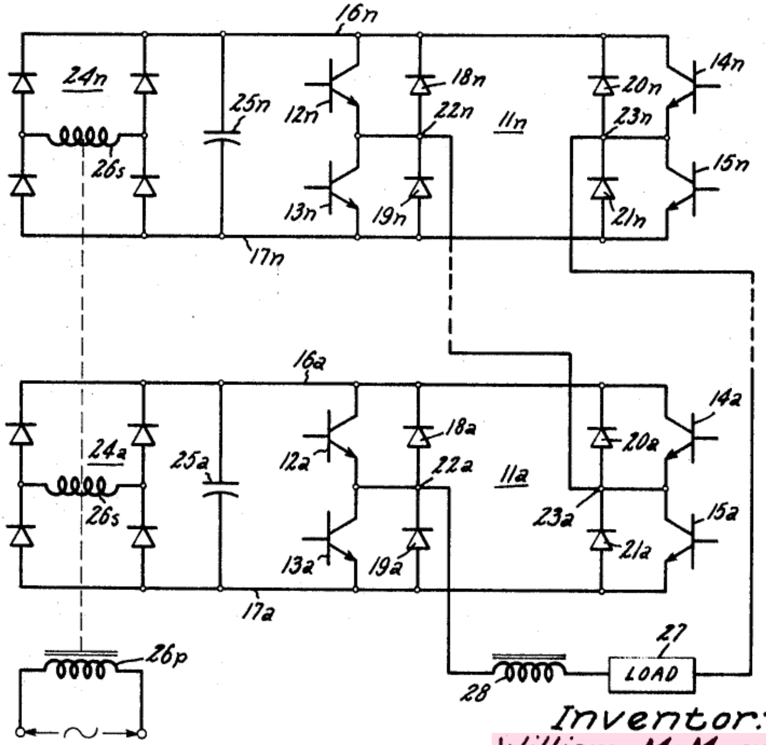
Non-Modular | ***Modular***

- Defined Partitioning of Blocking Voltage & Improved Device FoMs for Lower Voltages
- Modular: High Number *N* of Cells → Quadratically Reduces Current Harmonics

[Baker1974, Baker1979, Nabae1981; Meynard1992; McMurray1971a; Marquadt2002, Lesnicar2003]

United States Patent [11] **3,581,212**

Fig. 2.

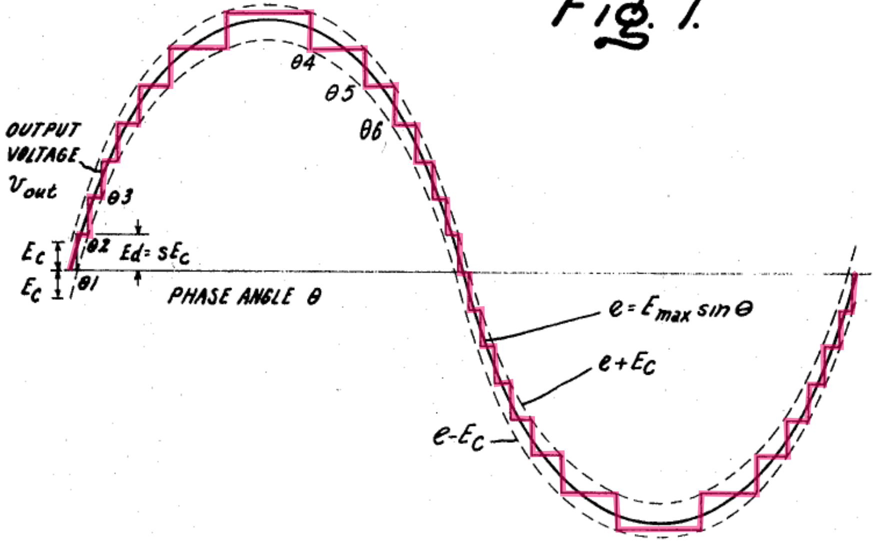


Inventor:
William McMurray
by Donald R. Campbell
His Attorney.

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

1969

Fig. 1.

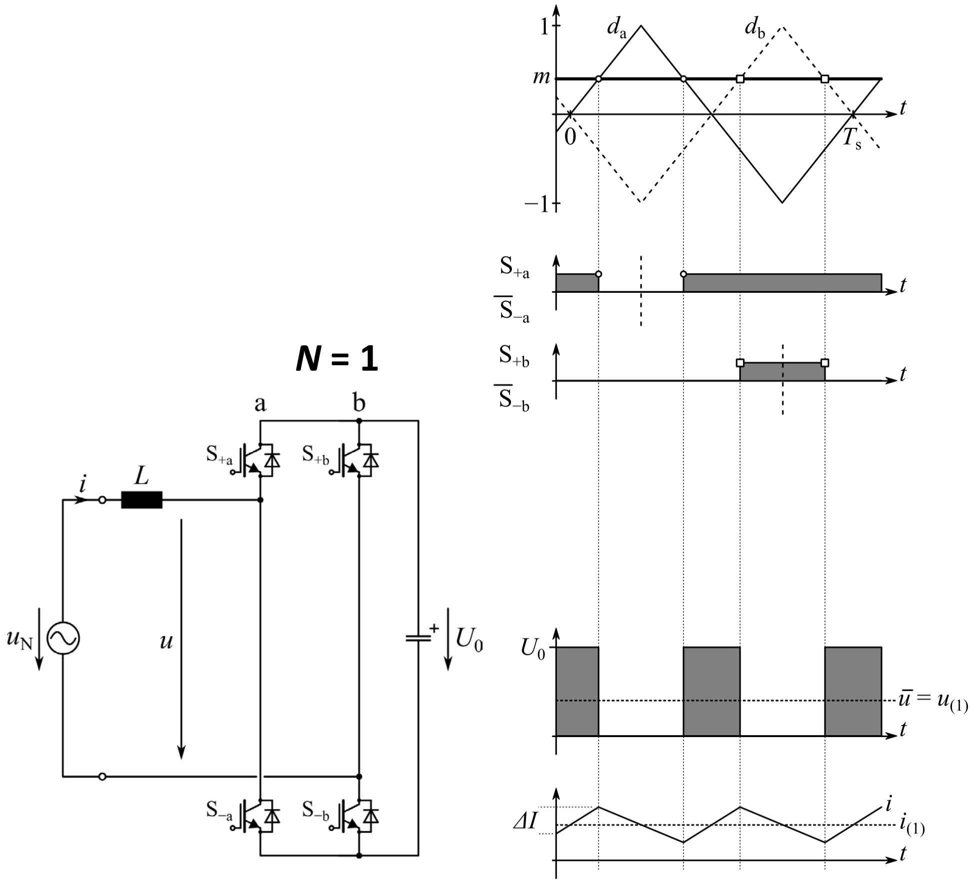


■ “Fast Response Stepped-Wave Switching Power Converter Circuit”

Multi-Cell Concept: Interleaving (1)

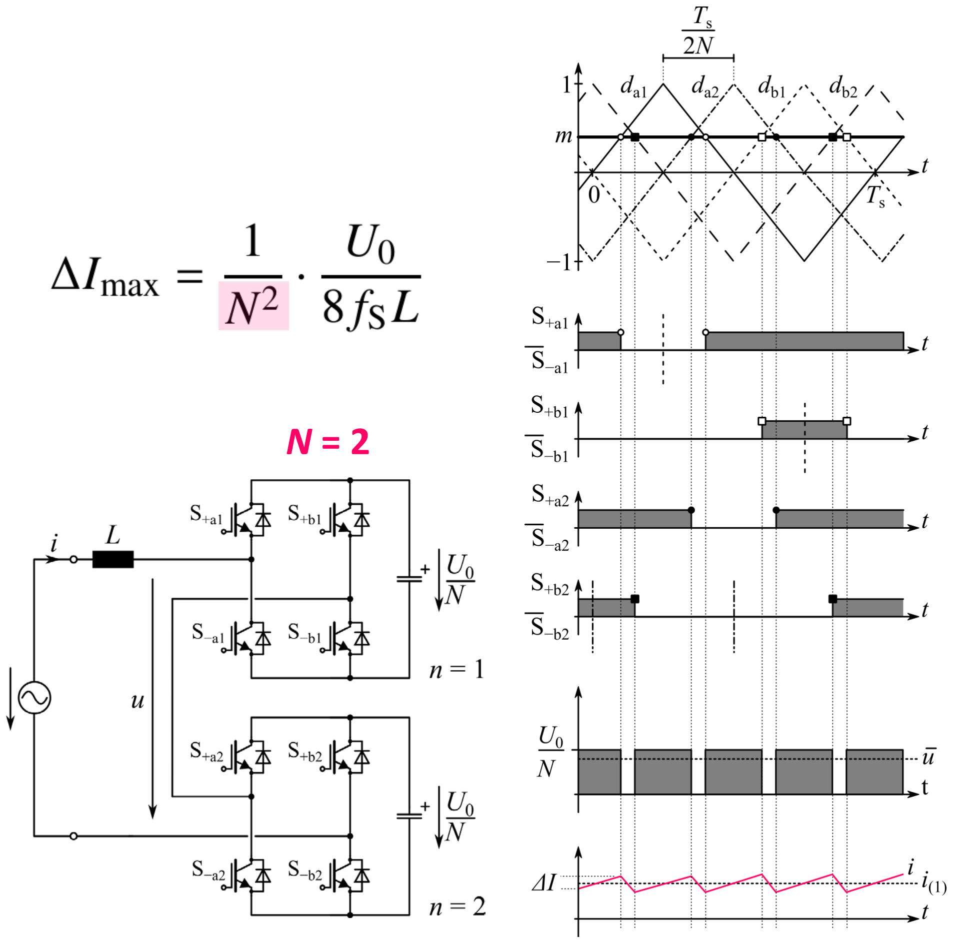
- Example N = 1 → N = 2: Effective Sw. Frequency x 2 and Voltage Step x 0.5 → 0.25 x ΔI
- Or f_s/N^2 for Same Current Ripple!

N = 1



$$\Delta I_{max} = \frac{1}{N^2} \cdot \frac{U_0}{8 f_S L}$$

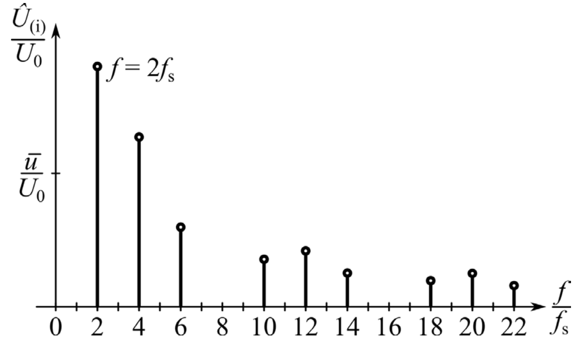
N = 2

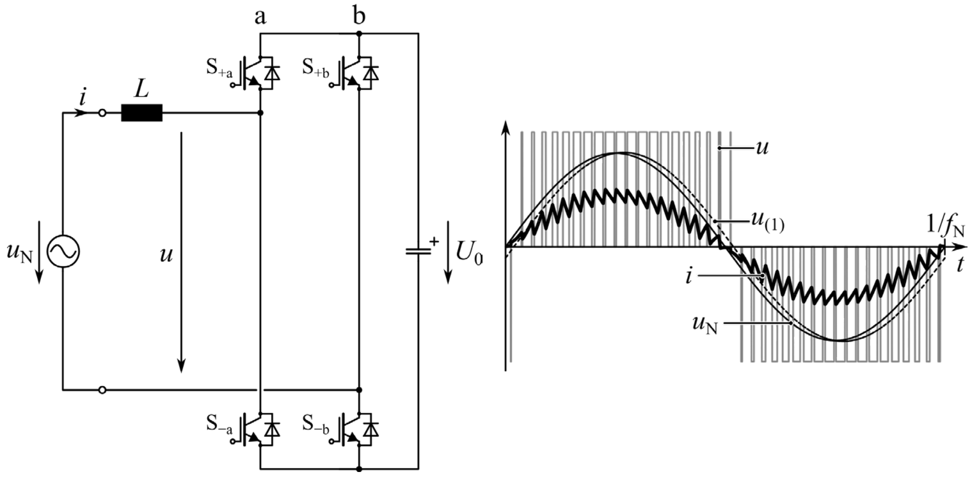


Multi-Cell Concept: Interleaving (2)

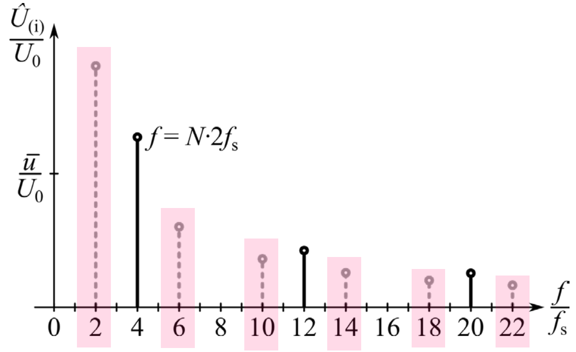
- Example $N = 1 \rightarrow N = 2$: Cancelling of Harmonics at $2 \cdot kf_s$ (k = 1, 3, 5, 7, …)

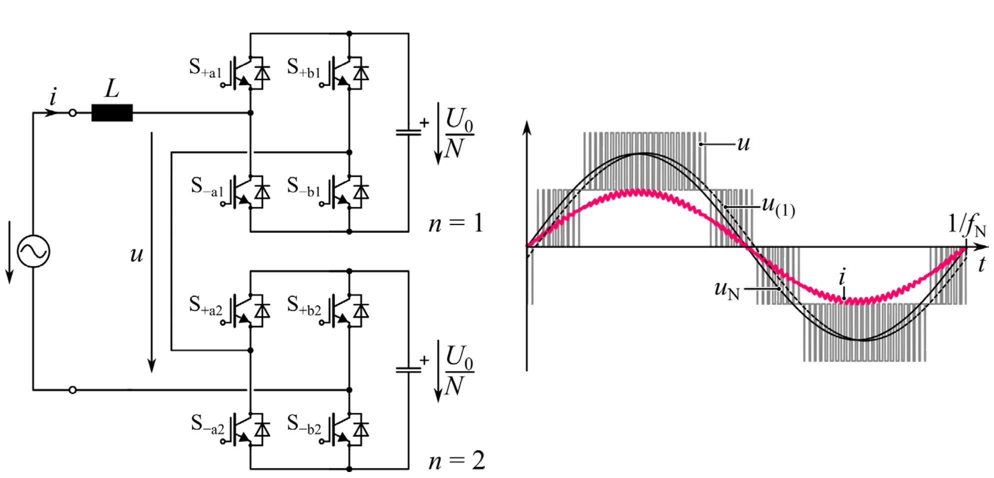
N = 1





N = 2





Multi-Cell Concept: Switching Losses

- **Scaling of Switching Losses for Same Ripple Ampl. *ΔI***
- Same *dv/dt* and Same *di/dt* for All Devices (Conservative Assumption!)

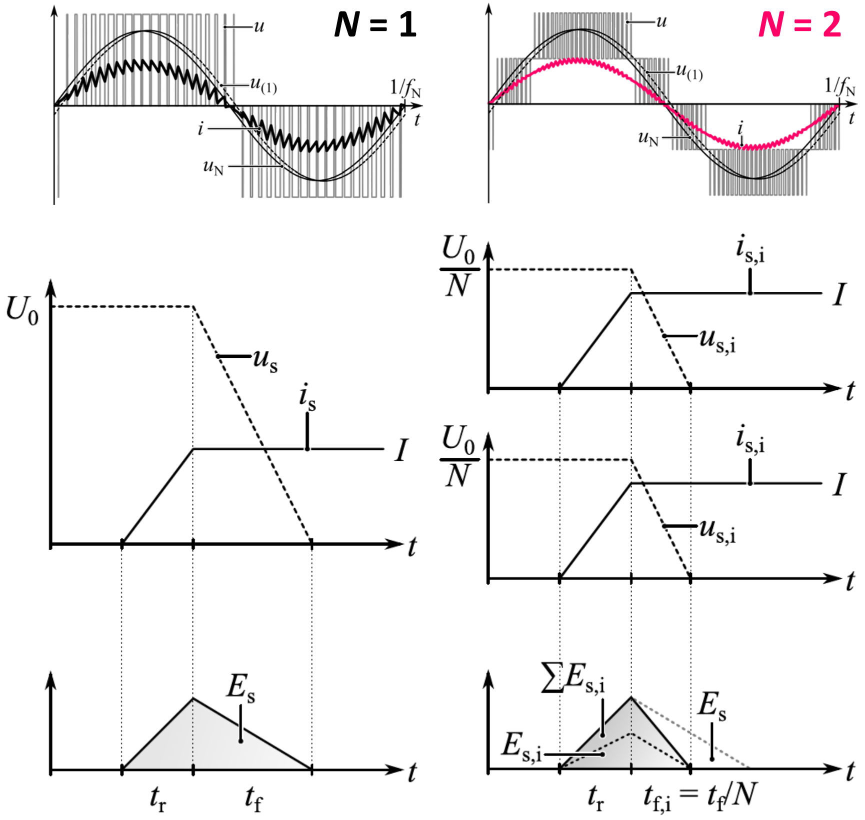
N = 1:

$$P_{\mathrm{sw},N=1} = 2\mathrm{E}_{\mathrm{sw},N=1} f_\mathrm{s} = 2 \cdot \frac{1}{2} \cdot (t_\mathrm{r} + t_\mathrm{f}) \cdot U_0 I \cdot f_\mathrm{s}$$

N > 1: *Same ΔI*

$$P_{\mathrm{sw},N} = N \cdot 2 \cdot \frac{1}{2} \cdot \left(t_\mathrm{r} + \frac{t_\mathrm{f}}{N}\right) \cdot \frac{U_0}{N} \cdot I \cdot \frac{f_\mathrm{s}}{N^2} = \frac{1}{N^2} \cdot \left(t_\mathrm{r} + \frac{t_\mathrm{f}}{N}\right) \cdot U_0 I \cdot f_\mathrm{s}$$

$$P_{\mathrm{sw},N} \approx \frac{P_{\mathrm{sw},N=1}}{N^2} \ldots \frac{P_{\mathrm{sw},N=1}}{N^3}$$



- **Series Interleaving Dramatically Reduces Switching Losses (or Harmonics)**
- Converter Cells Can Operate at <u>Very</u> Low Switching Frequency
- Minimization of Passives (Filter Components)

Multi-Cell Concept: Conduction Losses

- **On-State Resistance of MOSFETs Roughly Scales with $BV^{2.5}$ (e.g., Silicon Limit)**

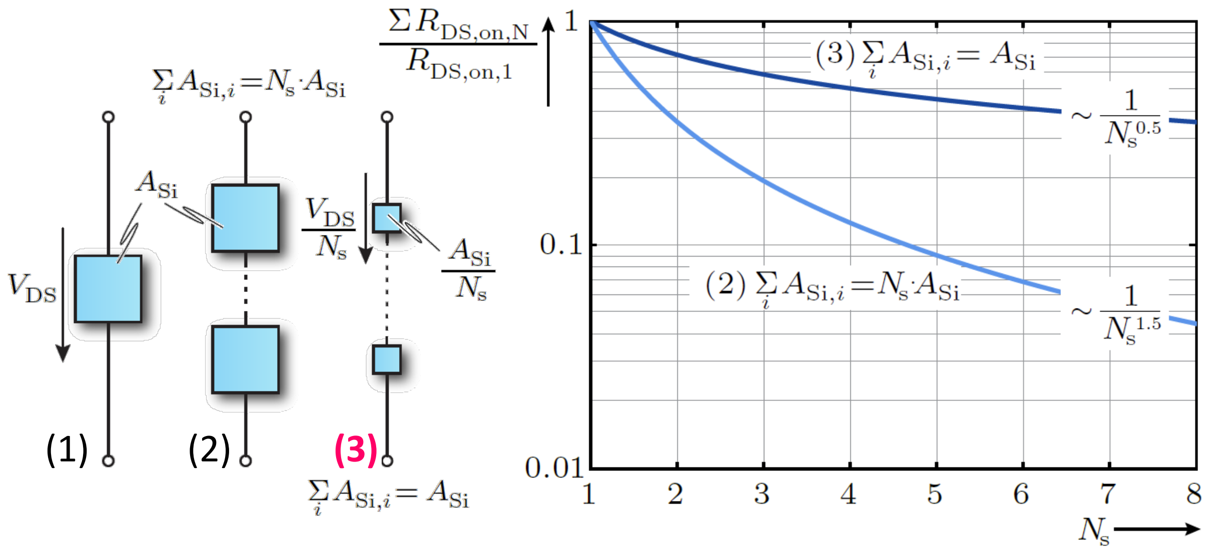
(1) $R_{\mathrm{DS,on},N=1} \propto \frac{1}{A_{\mathrm{Si}}}(V_{\mathrm{DS}})^{2.5}$

(2) $R_{\mathrm{DS,on},N} \propto N \frac{1}{A_{\mathrm{Si}}}\left(\frac{V_{\mathrm{DS}}}{N}\right)^{2.5}$

$\Rightarrow R_{\mathrm{DS,on},N} = \frac{R_{\mathrm{DS,on},N=1}}{N^{1.5}}$

(3) $R_{\mathrm{DS,on},N} \propto N \frac{N}{A_{\mathrm{Si}}}\left(\frac{V_{\mathrm{DS}}}{N}\right)^{2.5}$

$\Rightarrow R_{\mathrm{DS,on},N} = \frac{R_{\mathrm{DS,on},N=1}}{N^{0.5}}$



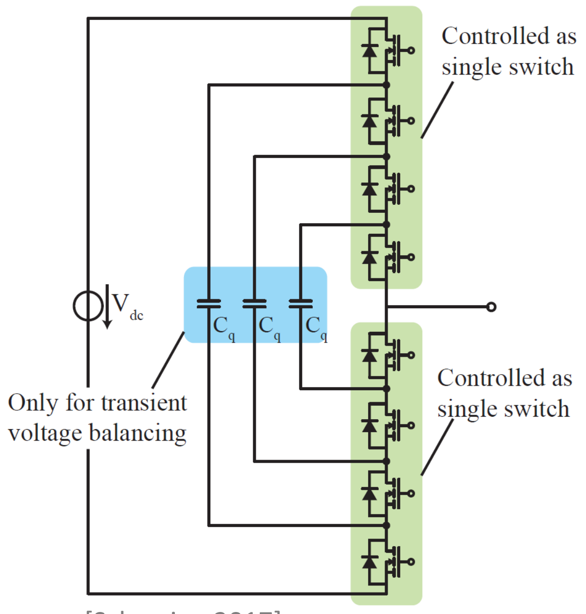
- **Even With Constant Total Chip Area, Conduction Losses Decrease with Increasing *N***
  - Beware: Does Not Hold for IGBTs / Bipolar Devices with Approx. Constant Forward Voltage Drop

[Kasper2016]

Remark: Quasi-2-Level Operation

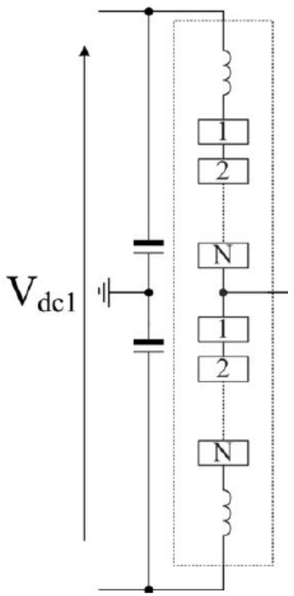
- Operation of *N*-Level Topology in 2-Level Mode
- Intermediate Voltage Levels Only Used During Switching Transients

Flying-Capacitor Bridge-Leg

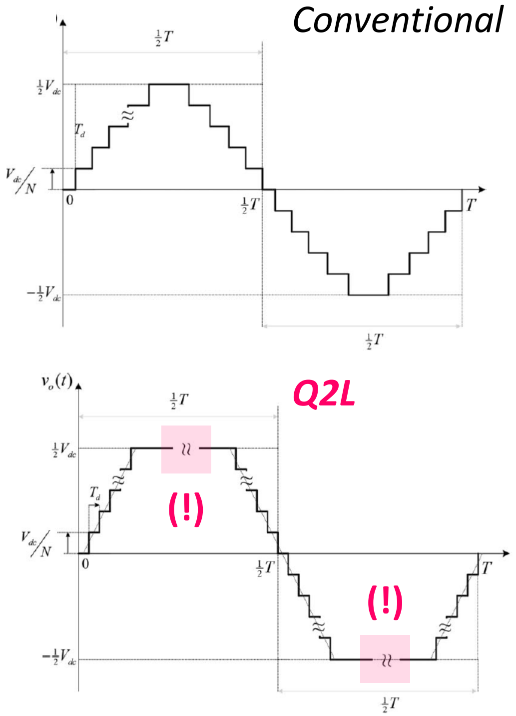


[Schweizer2017]

MMC Bridge-Leg



[Gowaid2015]



- Defined Partitioning of Blocking Voltages & Small Flying / Cell Capacitors
- Benefit from Cond. & Sw. Loss Scaling But Higher Harmonic Content (No Interleaving)

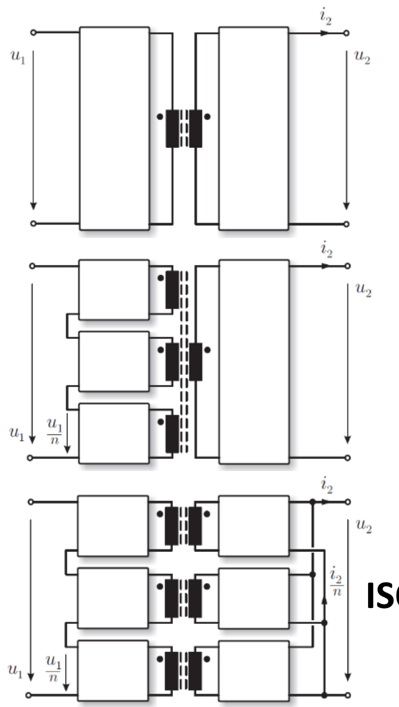
Part II

SST Concepts & Key Design Aspects

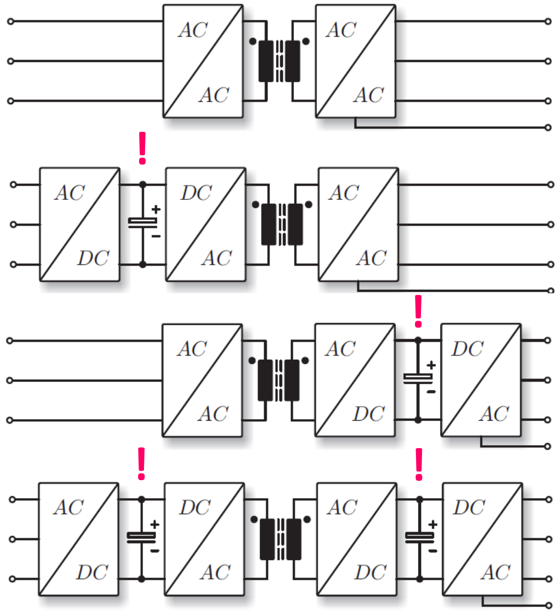
– Medium-Frequency Power Conversion
– Power Semiconductors
– **Key SST Topologies**
– Medium-Frequency Transformers
– Isolation Coordination
– Protection
– Construction

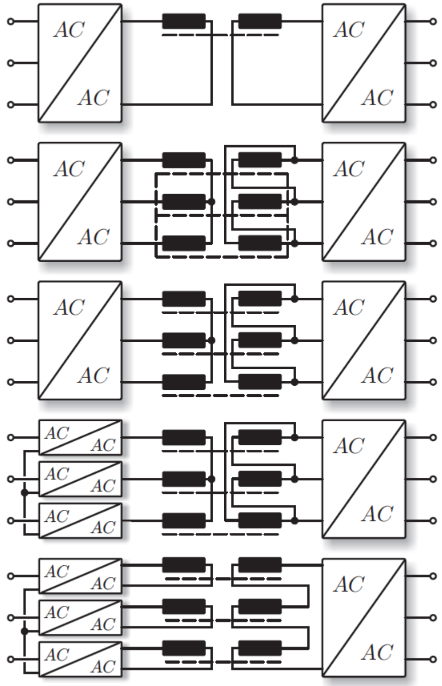
Classification of SST Topologies (1)

- **Number of Levels Series/Parallel Cells**
- **Degree of Power Conversion Partitioning**
- **Degree of Phase Modularity**



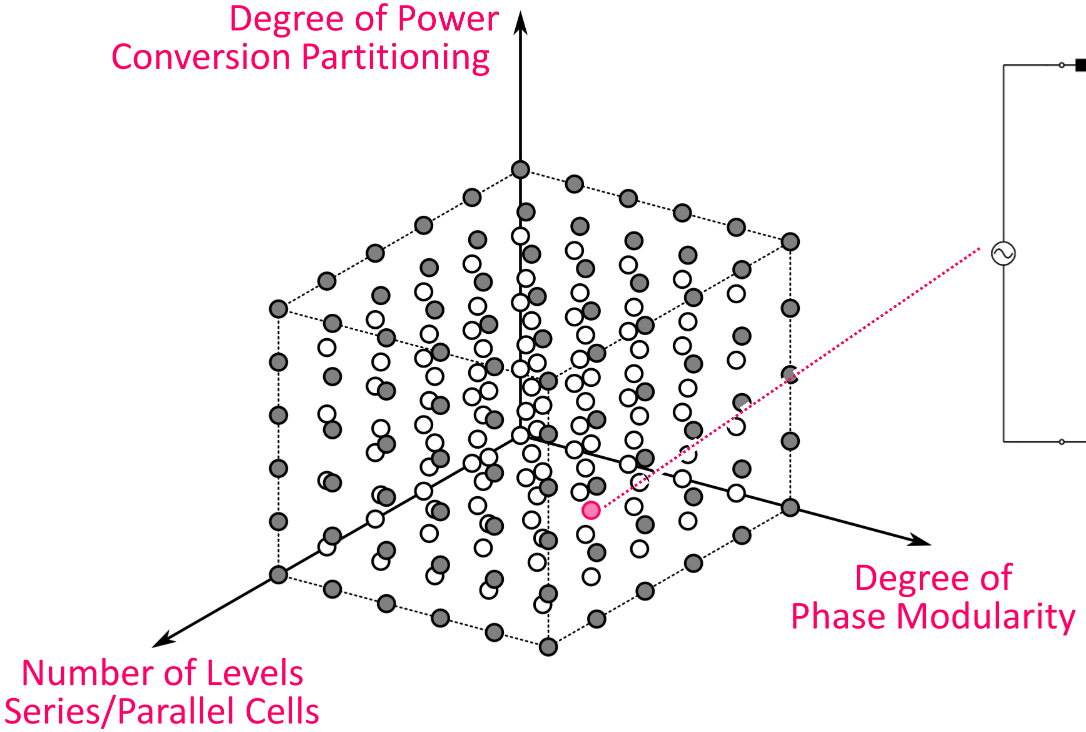
ISOP (!)

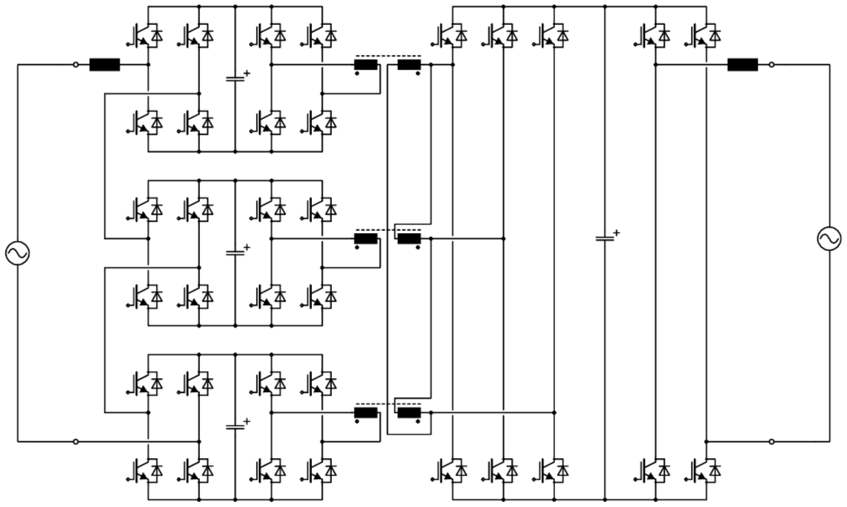




- **Three-Dimensional Topology Selection Space!**

Classification of SST Topologies (2)





Example: [Wrede2003]

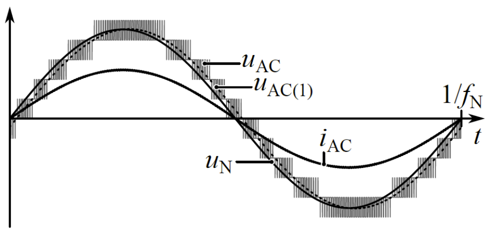
■ **Very (!) Large Number of Possible Topologies**

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

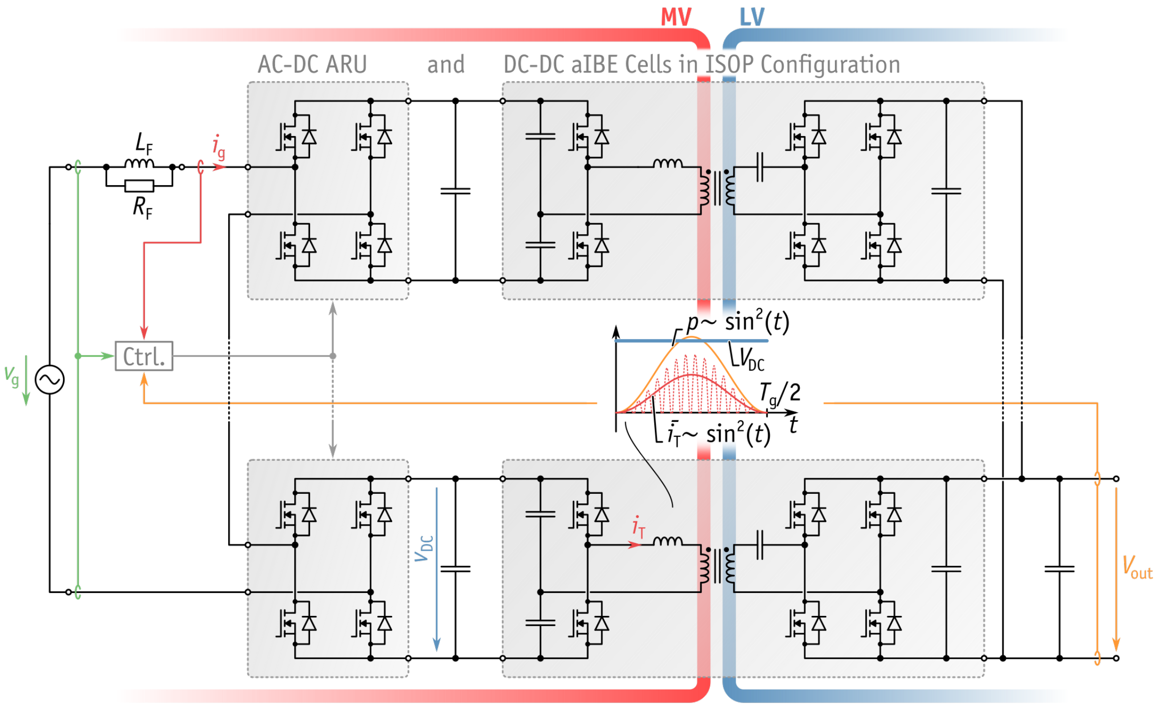
Modular Topologies

Isolated Back-End (IBE) AC-DC Conversion

- Input-Series Output-Parallel (ISOP) Configuration of AC-DC + DC-DC Converter Cells



Note: Single-Phase Power Fluctuation Could be (Partly) Buffered on the MV Side with Larger DC Capacitors

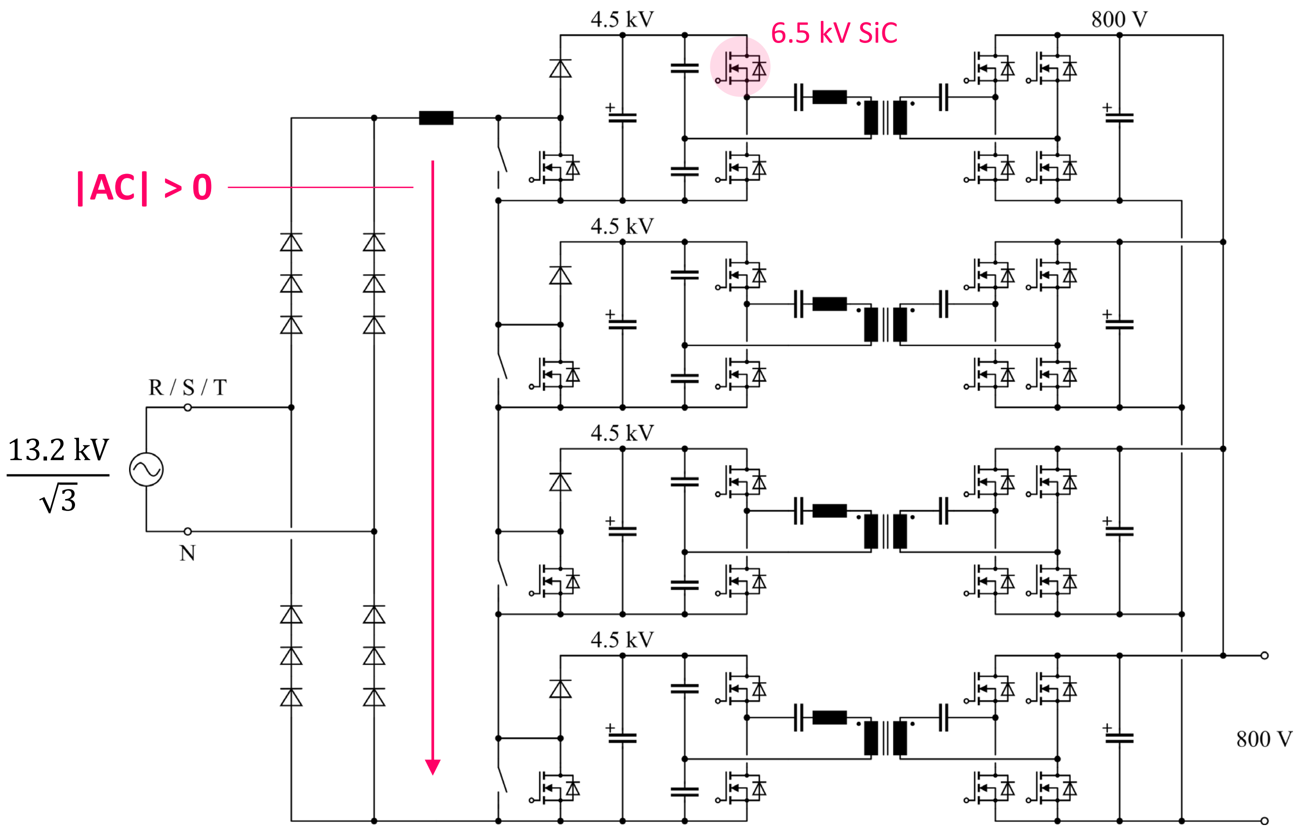


- Direct Mains Current Control with Cascaded AC-DC Front End
- Most Frequently Used Topology Typ. with DCX Isolation Stages
- (Specific Realizations May Vary, e.g., 3-Phase Configurations, Cell Topology, DC-DC Converter Type, etc.)

[Steiner1996, Steiner1998]

Remark: Unidirectional Topologies

- Opportunity for Complexity Reduction (# MOSFETs, Gate Drives, …)



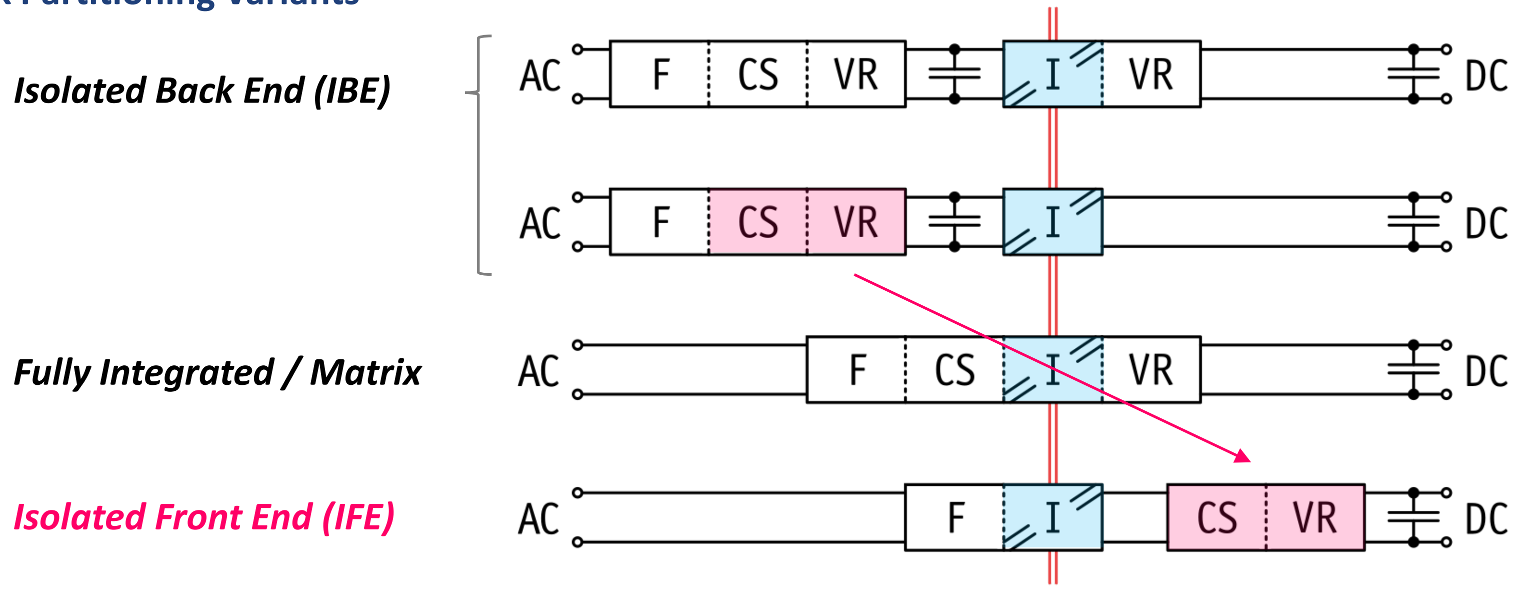
- Example: Multi-Cell Boost ISOP Topology with DCX Isolation Stages

[vanderMerwe2009]

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 (No Regulation Capability)
  - **VR** Output Voltage Regulation

- **Isolated PFC Task Partitioning Variants**

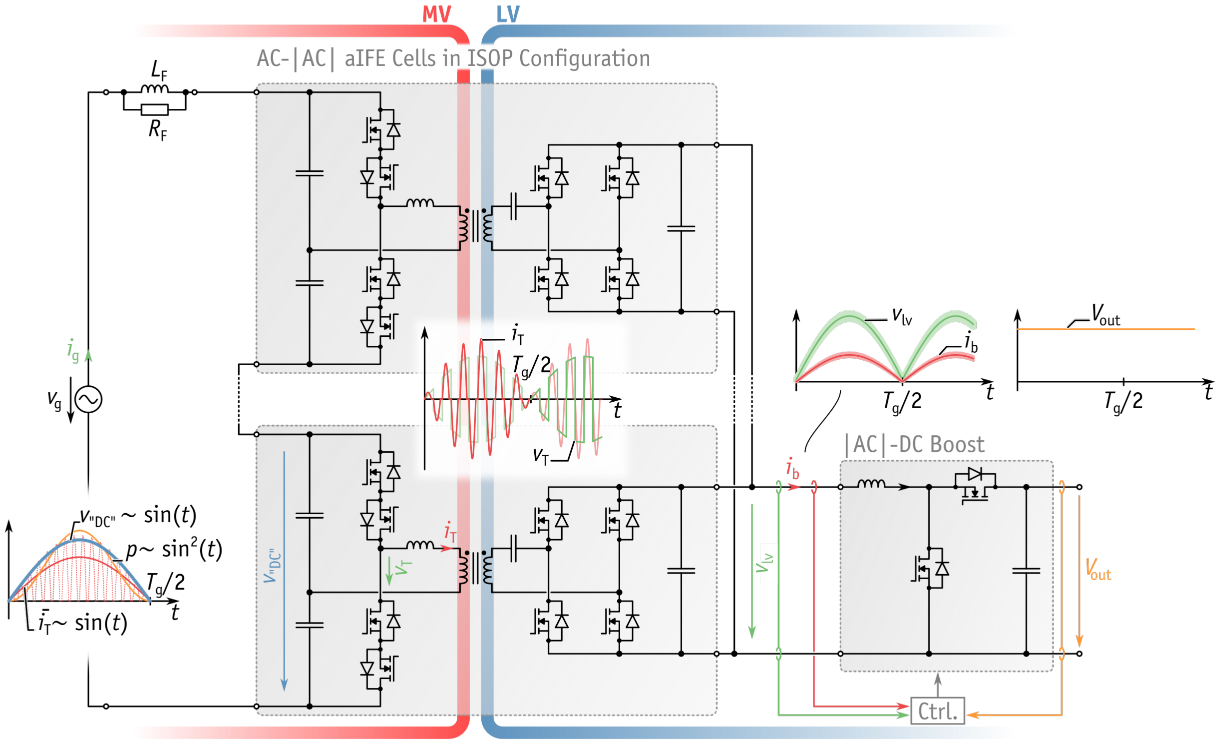


- **IFE Shifts Input (!) Current Shaping and Output Voltage Regulation to the LV Side**

[Huber2016]

Isolated Front-End (IFE) AC-DC Conversion

- **Input-Series Output-Parallel (ISOP) Configuration of Isolated AC-|AC| Stages with LV-Side |AC|-DC Stage**
- **Minimum MV-Side Complexity with Unregulated AC-|AC| "DCX" Stages**



- LV-Side |AC|-DC Operates as in 1-Ph. PFC Rect. | Input Cur. Shaping through Transparent AC-|AC| "DCX"
- Variants: Indirect AC-|AC| Matrix Stages, Parallel-Interleaved |AC|-DC Boost Stages, …

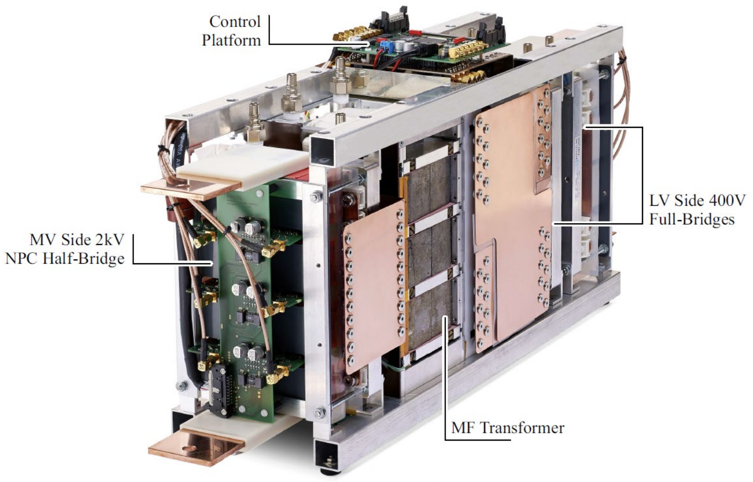
(!)

[Weiss1985, Han2014, Huber2016]

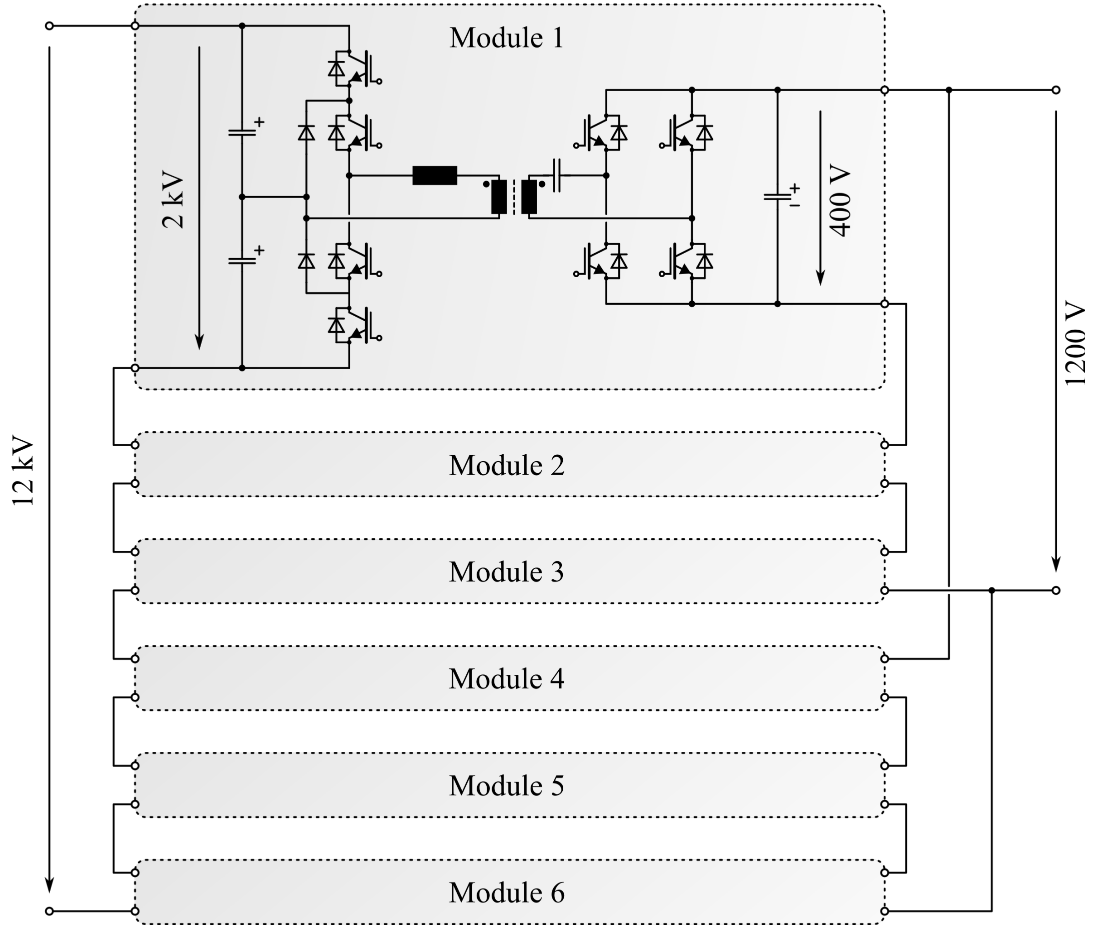
Remark: DC-DC Topologies

- Fully Modular Approach

- MEGA-Cube @ ETH Zurich
  - 1 MW, 2 kV → 1200 V DC-Transformer
  - 2 x 3 Connection on LV Side



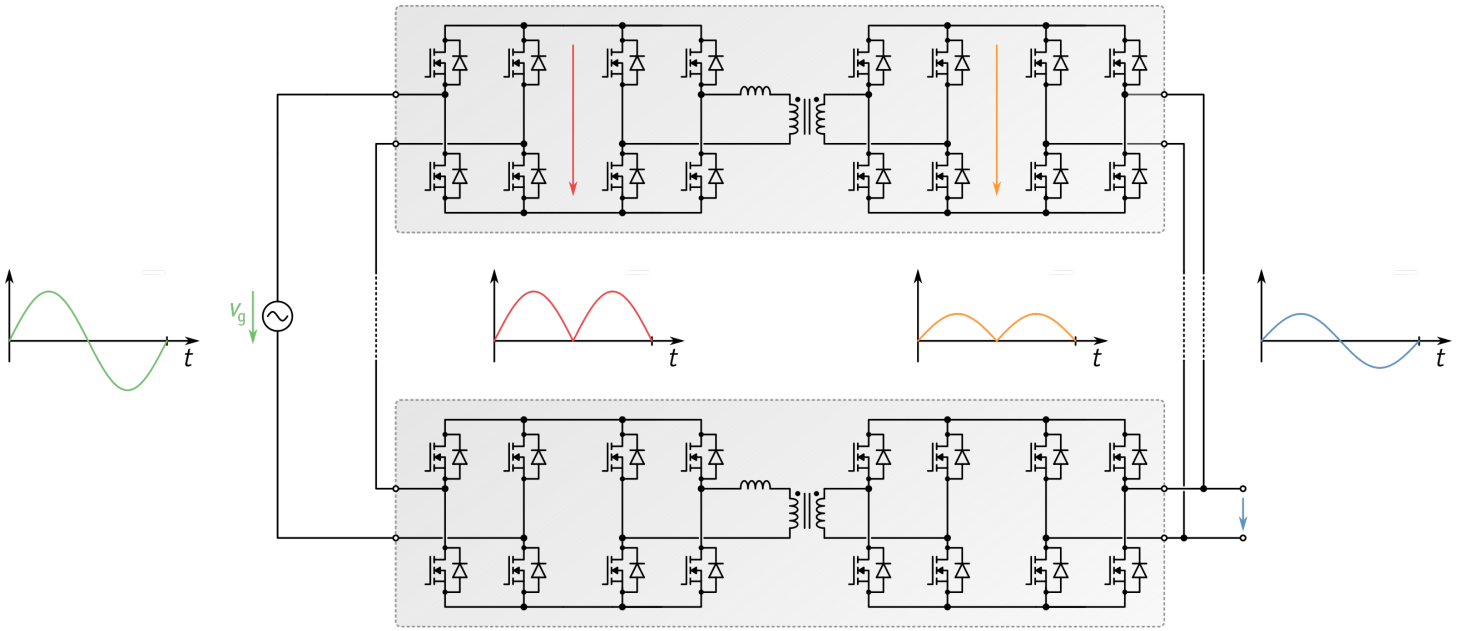
  - 166 kW / 20 kHz Si-IGBT DC-DC Converter Module



[Ortiz2017]

Remark: AC-AC Topologies

■ **Fully Modular AC-AC Topology w. Indirect Matrix Converter Modules → $f_1 = f_2$**



● Specific Realizations May Vary (3-Phase Configurations, Non-Resonant DC-DC Stage, …)

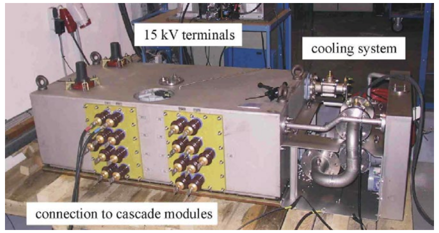
Partly Modular Topologies

IBE AC-DC with Multi-Winding Transformer

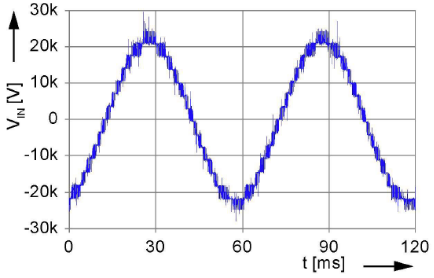
- **Single Transformer w. Full Isolation Voltage Rating / Modular Power Electronics (Redundancy)**
- **Coupling Between Primary Windings → Undesired Current Flows & Oscillations**

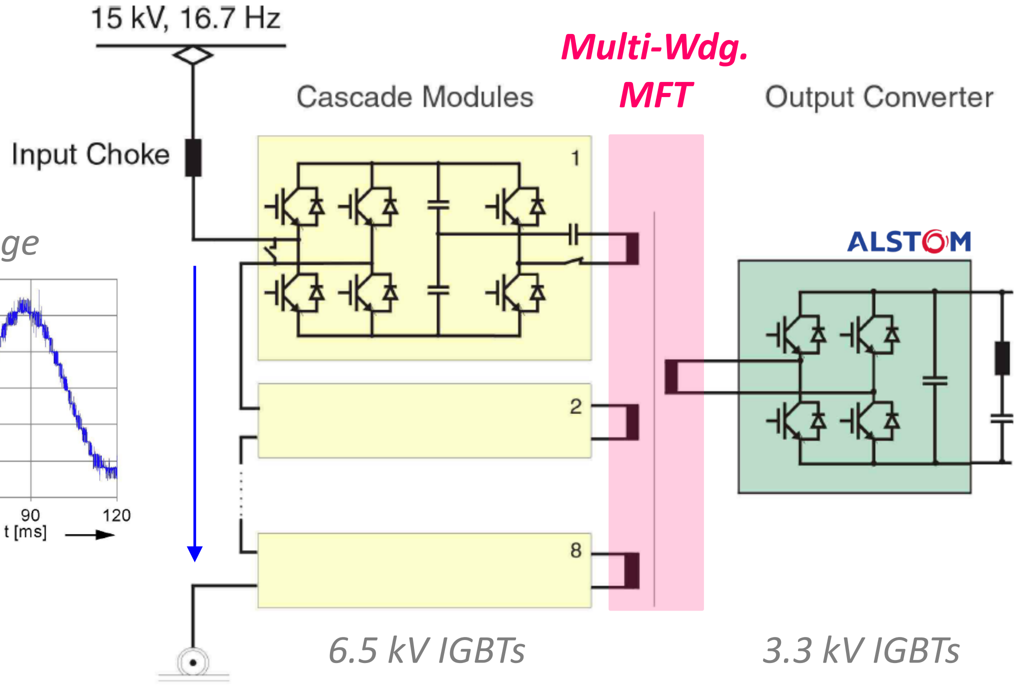
- **ALSTOM (2003) Traction Prototype**

1.5 MW / 5 kHz
Multi-Winding MFT



Switched AC Voltage





- 15 kV / 16.7 Hz Input, 8 Cascaded Modules (7-out-of-8 Redundancy), 1.5 MW (2.25 MW for 30 s)
- Si-IGBT Technology / 5 kHz MFT / 94 % Efficiency & 0.47 kW/dm^3 Power Density

[Engel2003]

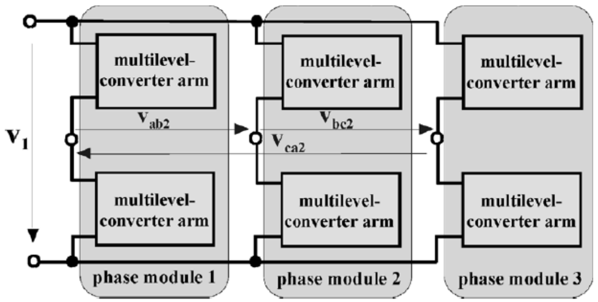
Modular Multilevel Converter (MMC)

- **Single Transformer w. Full Isolation Voltage Rating**
- **Modular Power Electronics (Redundancy)**

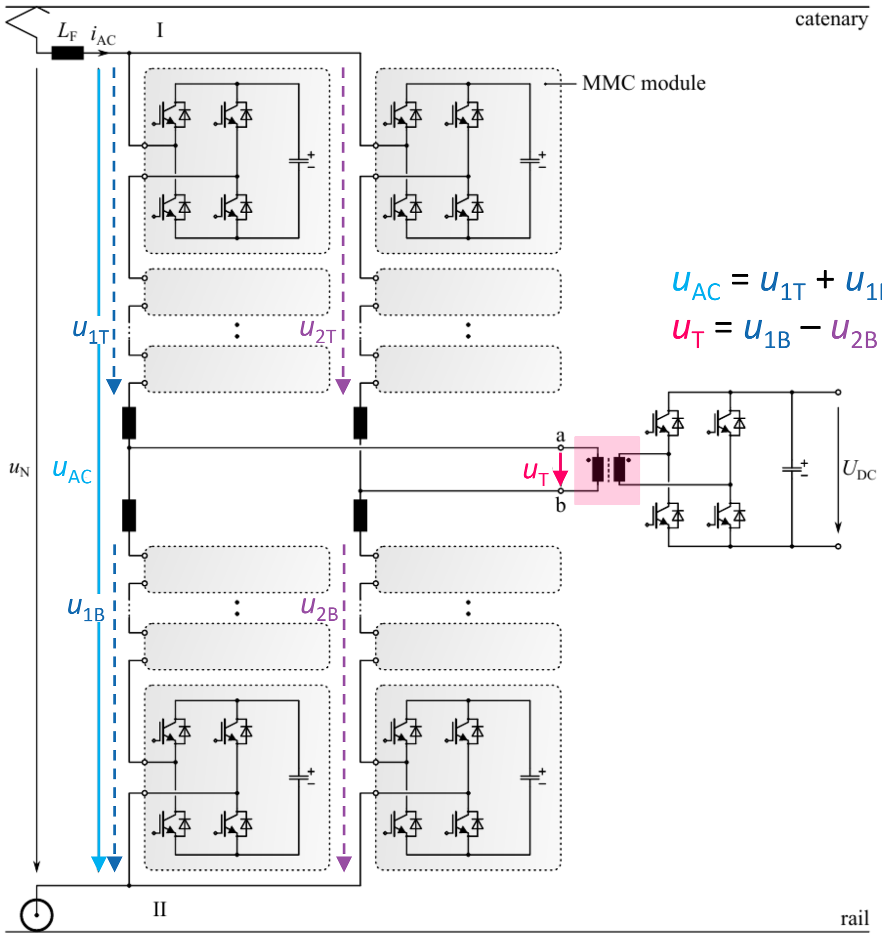
- AC-AC Matrix Converter with Fully Independent Generation of u_{AC} and u_T

- High Semicond. Effort (Each Arm Provides Total DC Volt.)
- Active Balancing of Module Cap. Volt. Necessary (Sensing / Control)

- **Variants:**
- 3-Phase AC → 1-Phase HF AC, DC-DC



Universität der Bundeswehr München

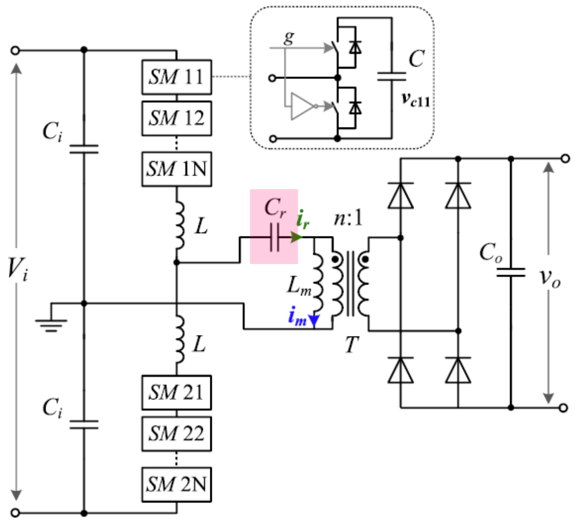


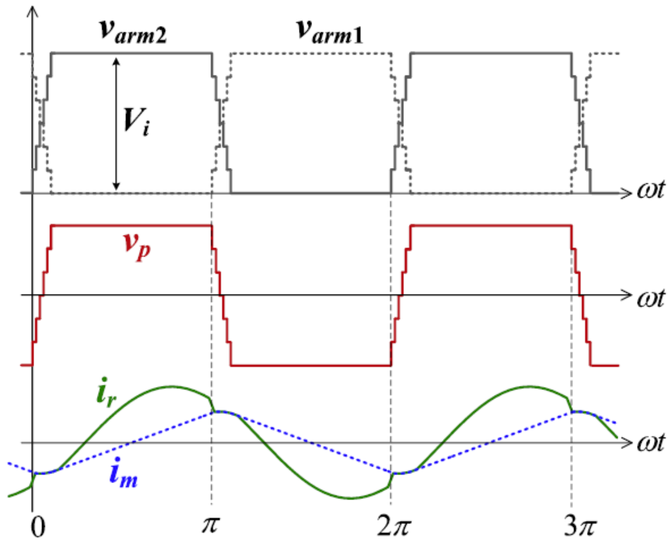
$$u_{AC} = u_{1T} + u_{1B} = u_{2T} + u_{2B}$$
$$u_T = u_{1B} - u_{2B} = u_{2T} - u_{1T}$$

[Glinka2005]

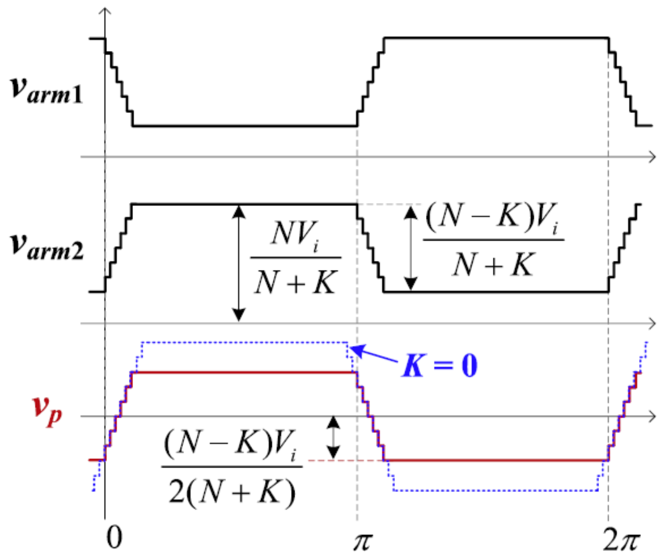
Remark: DC-DC MMC w. Resonant Operation

- **DCX with MMC in Q2L Operation**
- **Output Voltage Regulation: MMC Primary Voltage Amplitude Adaption (Coarse) + Var. Freq. (Fine)**





Typ. Operating Waveforms



Primary Volt. Ampl. Adaption

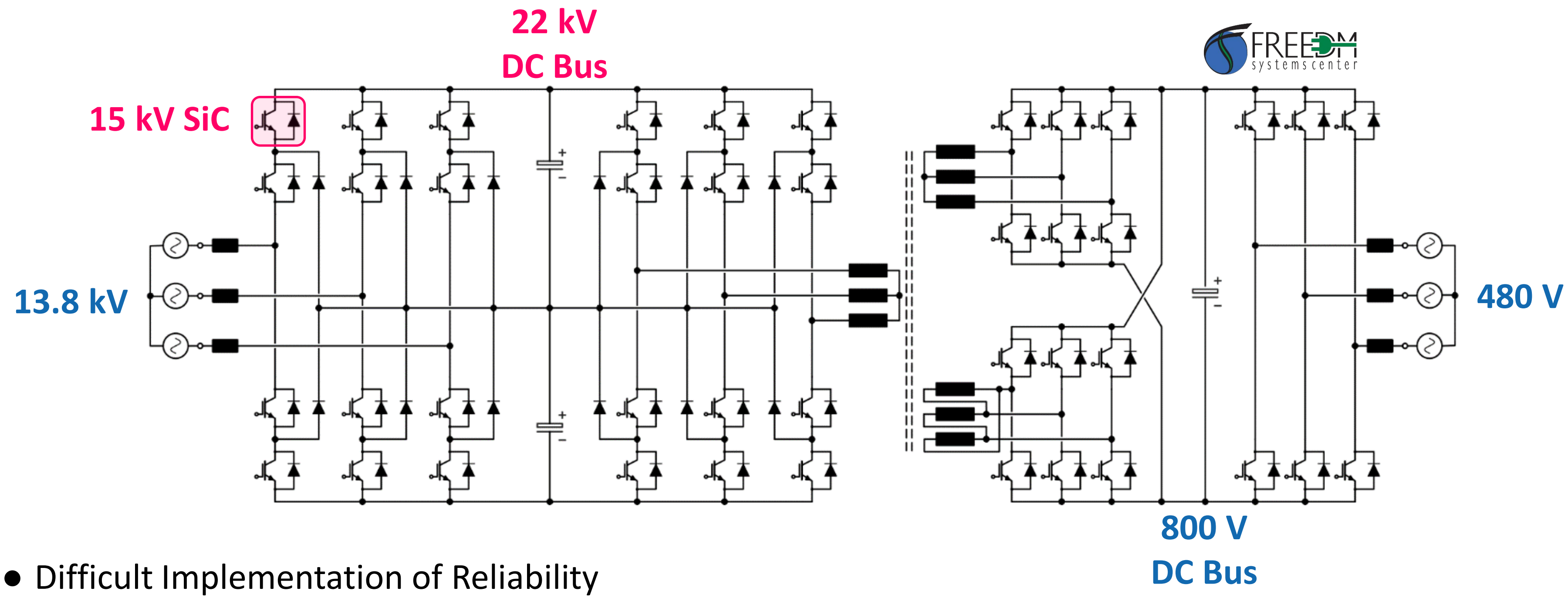
- Module Capacitor Voltage Balancing w. Sorting Algorithm
- Not All Devices Achieve ZVS because of DC Circulating Current

[Shao2020]

Non-Modular / Single-Cell Topologies

Single-Cell Topologies Enabled by HV SiC

- Low Complexity / Standard Converter Topologies w. Relatively Few Switches / Single MFT
- HV SiC Devices Needed (10+ kV) / Scarce Availability Outside of R&D

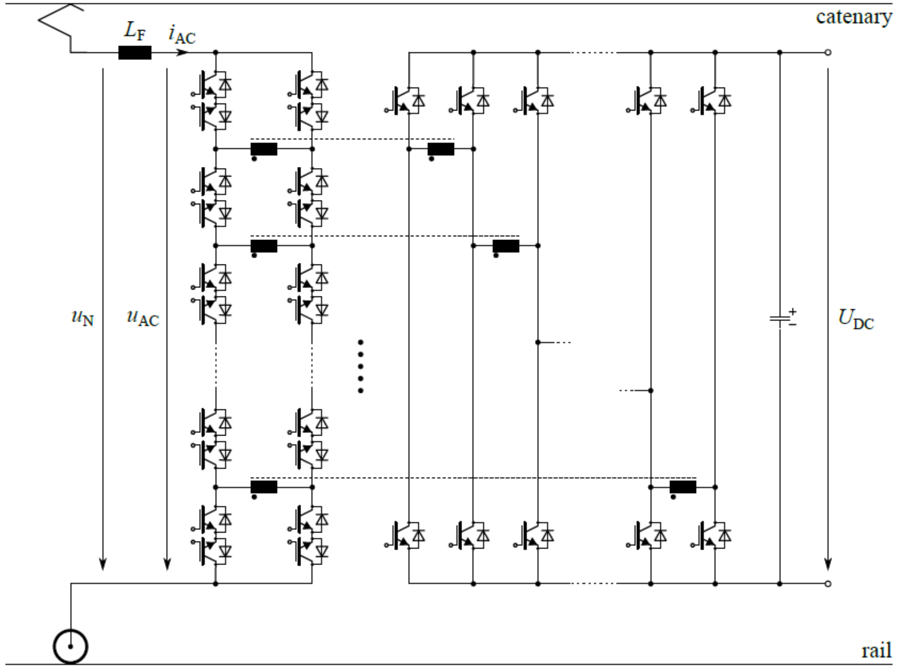


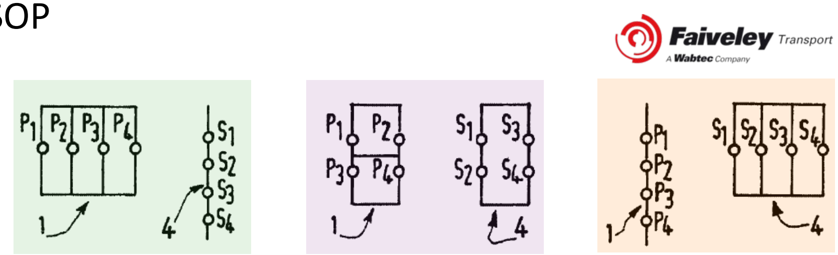
- Difficult Implementation of Reliability
- Not Scalable to Higher Voltages

[Mainali2015]

SPARC Converter

■ **Serial and Parallel Auto Regulated Configuration (SPARC) Converter**
- Series/Parallel Connections of Primary/Secondary Transformer Windings
- Input Voltage Distribution & Output Current Sharing as in ISOP





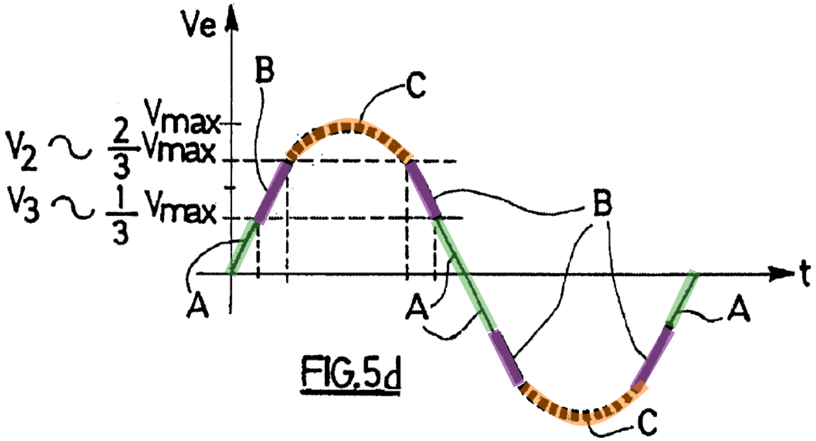
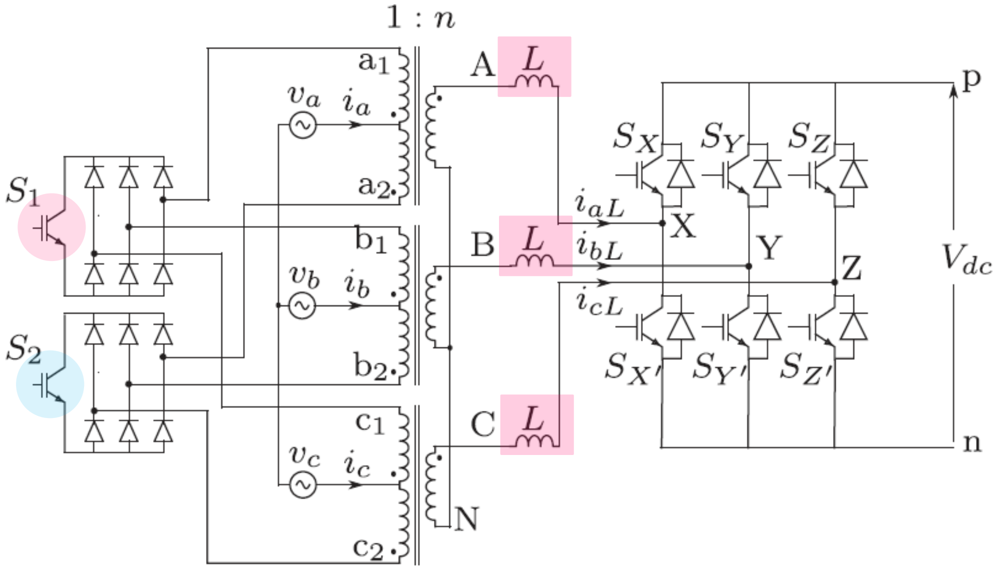


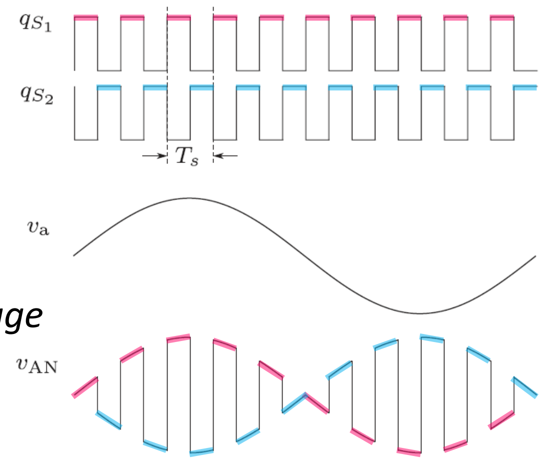
FIG.5d

- Input AC Voltage Synthesis from Available Converter Sw. States / # of States Increases with # of Transformers
- Soft-Switching Modulation Possible (Primary CSI with ZCS, VSI with ZVS)

Single-Stage 3-Phase AC-DC Conversion (1)

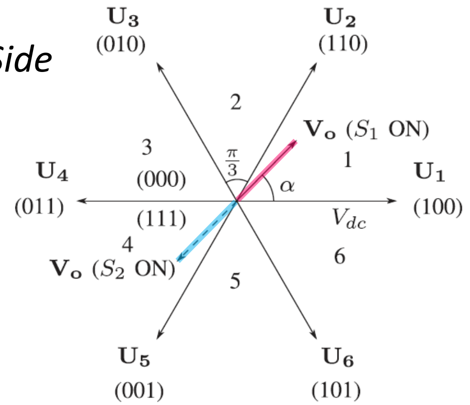
- **Single-Stage Power Conversion with Minimum Complexity on the MV Side**
- **S_1 & S_2 Sync. Switching w. 50% Duty → Amplitude-Modulated HF Transf. Volt.**





Transf. Voltage (Phase a)

Secondary-Side SV Diagram



- **Three-Phase Voltage-Source Inverter Output Stage**
  - DAB-Like Operating Mode / Inductor Current Shaping Using Space-Vector PWM
  - Integrated IFE Approach: LV-Side Stage Shapes the Grid Currents

  - AC-AC Version with 3x3 Direct Matrix Converter Output Stage

University of Minnesota

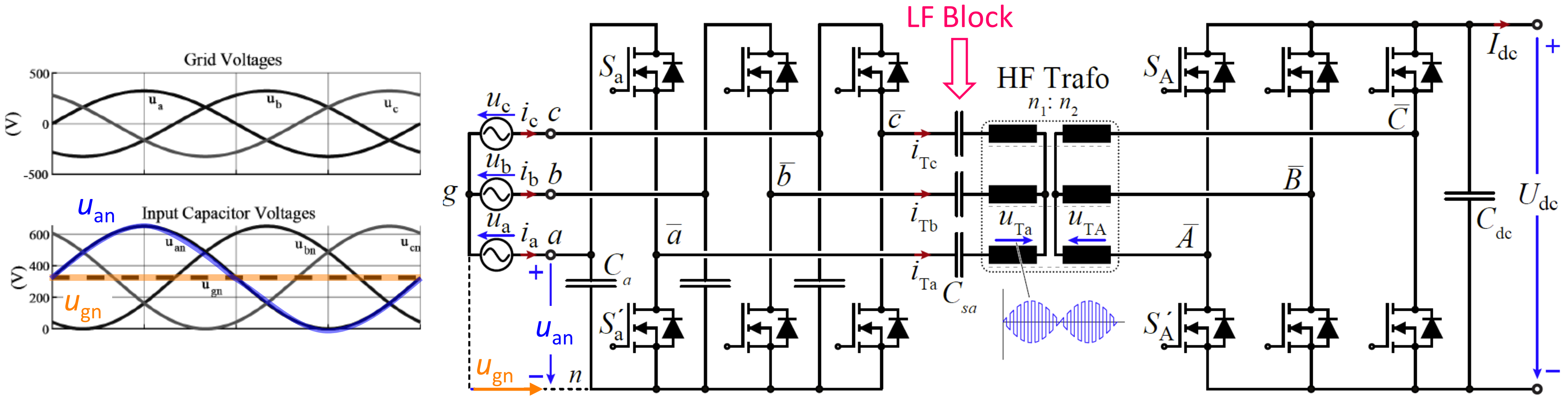
[Gupta2009, Gupta2010, Baranwal2018]

Single-Stage 3-Phase AC-DC Conversion (2)

Paper T39.3
Thu, 2:25 PM
NEW ARRIVAL

- **Y-Rectifier with Standard Half-Bridge Modules**
  - Common-Mode Offset Voltage u_{gn} for Strictly Positive Input Capacitor Voltages
  - Sync. Switching with 50% Duty ([000] ⇔ [111]) / Low-Frequency-Blocking Series Capacitors

→ **Amplitude-Modulated Three-Phase HF Transformer Voltages**



- **Three-Phase Voltage-Source Inverter Output Stage Operated as on Previous Slide (!)**
  - DAB-Like Operating Mode / Inductor Current Shaping Using Space-Vector PWM
  - Integrated IFE Approach: LV-Side Stage Shapes the Grid Currents

- **Extension to Higher Input Voltages w. Multilevel Bridge-Legs or MMC / AC-AC Versions Possible**

[ETH Pat. Pending: Menzi2022]

Part II

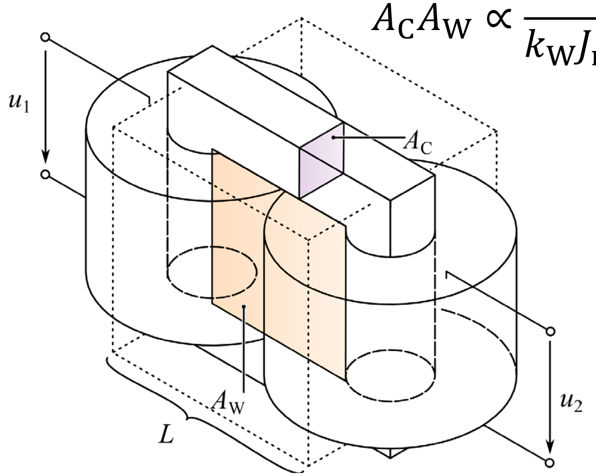
SST Concepts & Key Design Aspects

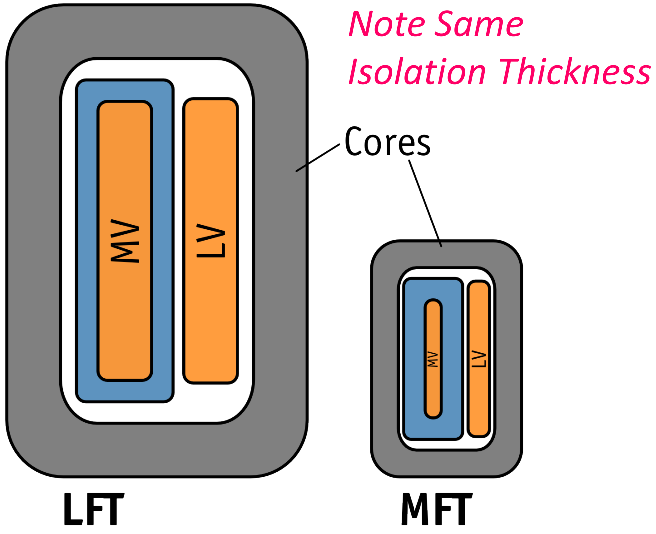
- Medium-Frequency Power Conversion
- Power Semiconductors
- Key SST Topologies
- **Medium-Frequency Transformers**
- Isolation Coordination
- Protection
- Construction

General Challenge of MF Transformers

- **Higher Operating Frequency / Lower Unit Power Rating → Smaller Active Volume**
- **Isolation Requirements/Distances Don't Scale**

$$A_C A_W \propto \frac{S}{k_W J_{rms} B_{max} f}$$

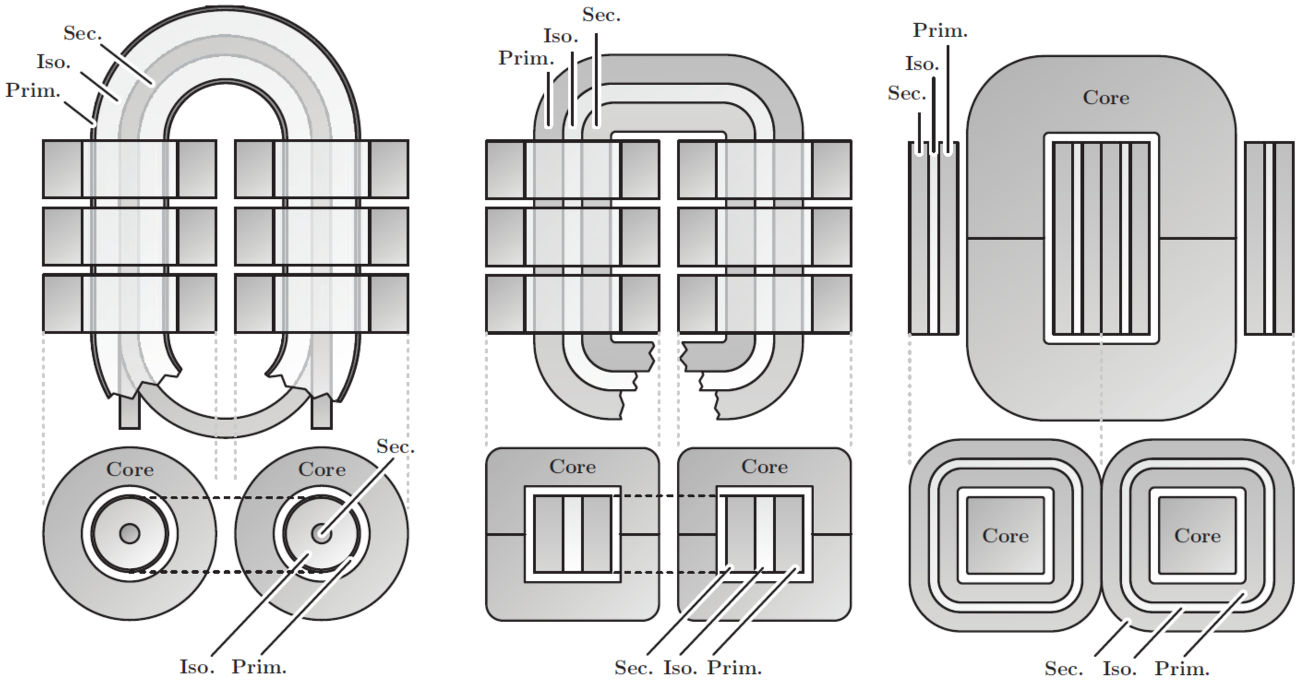




- **MV Winding Cooling Through Isolation → Isolation vs. Cooling Trade-Off**

- Solid Isolators → Bad Thermal Conductors
- Oil → Coolant And Isolator (!)

MF Transformer Design – Transformer Types

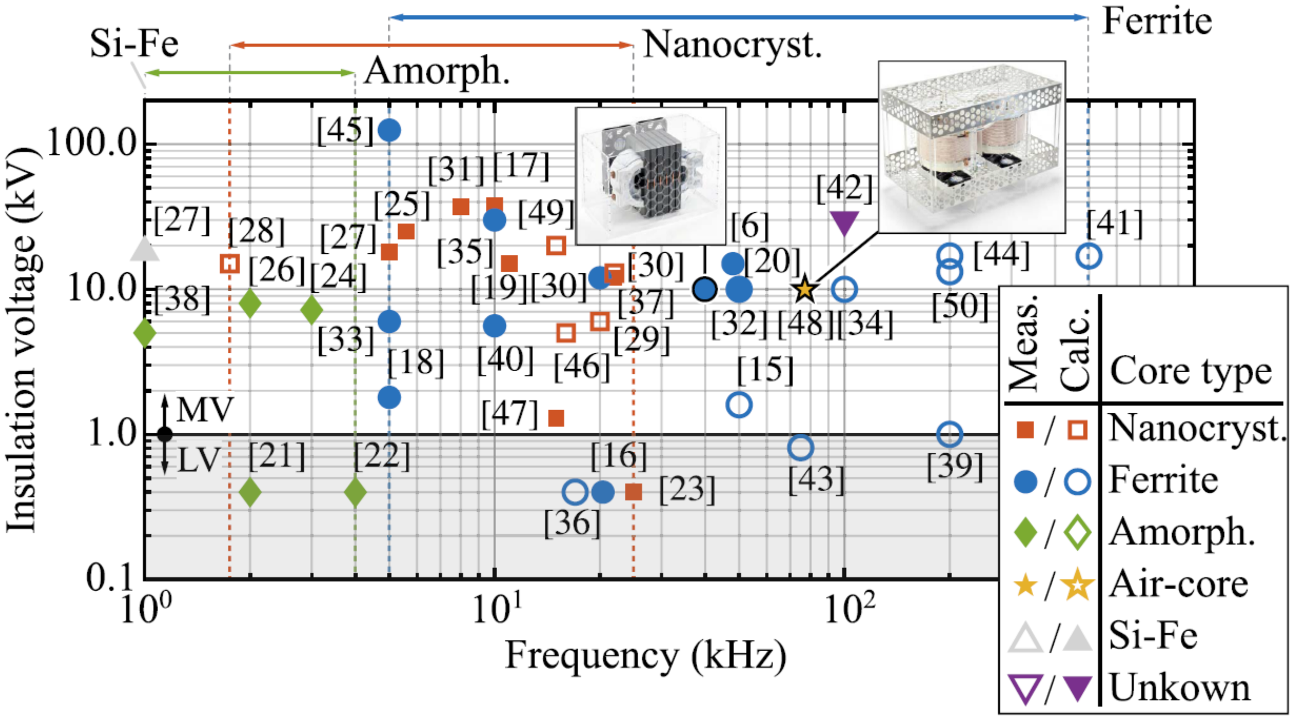


Coaxial-Cable Winding | *Shell-Type ("E"-Core)* | *Core-Type ("U"-Core)*

- 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

MFT Core Materials

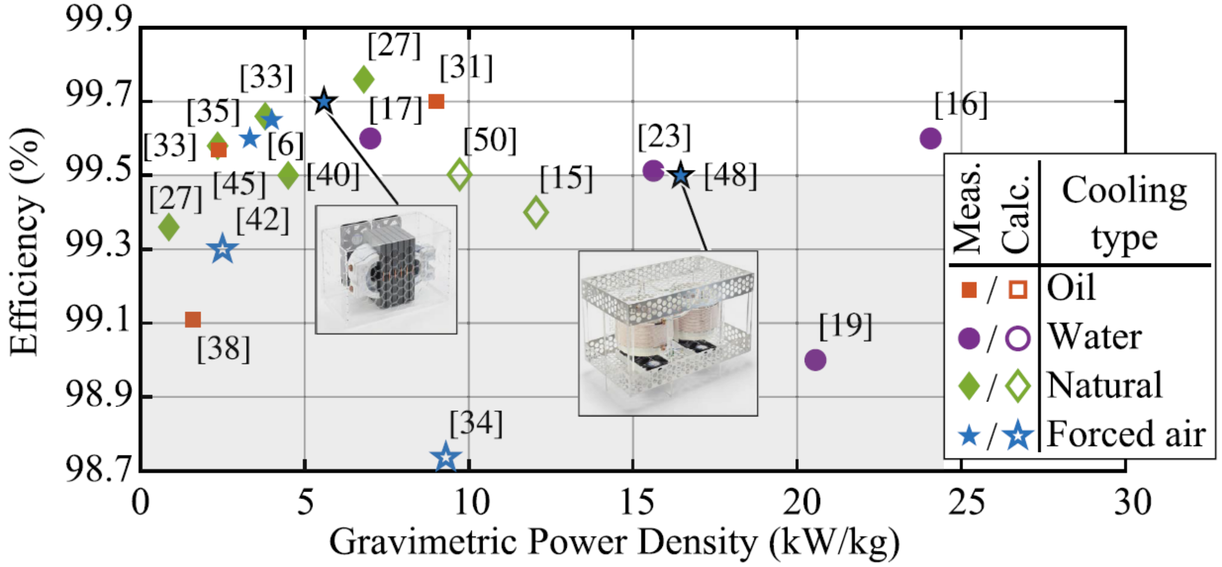
- Silicon Steel / Amorphous Iron / Nanocrystalline / Ferrite / Air (!)



- Frequency-Dependent Choice of Core Materials

MFT Cooling Methods

- Natural Convection / Forced Air / Water / Oil

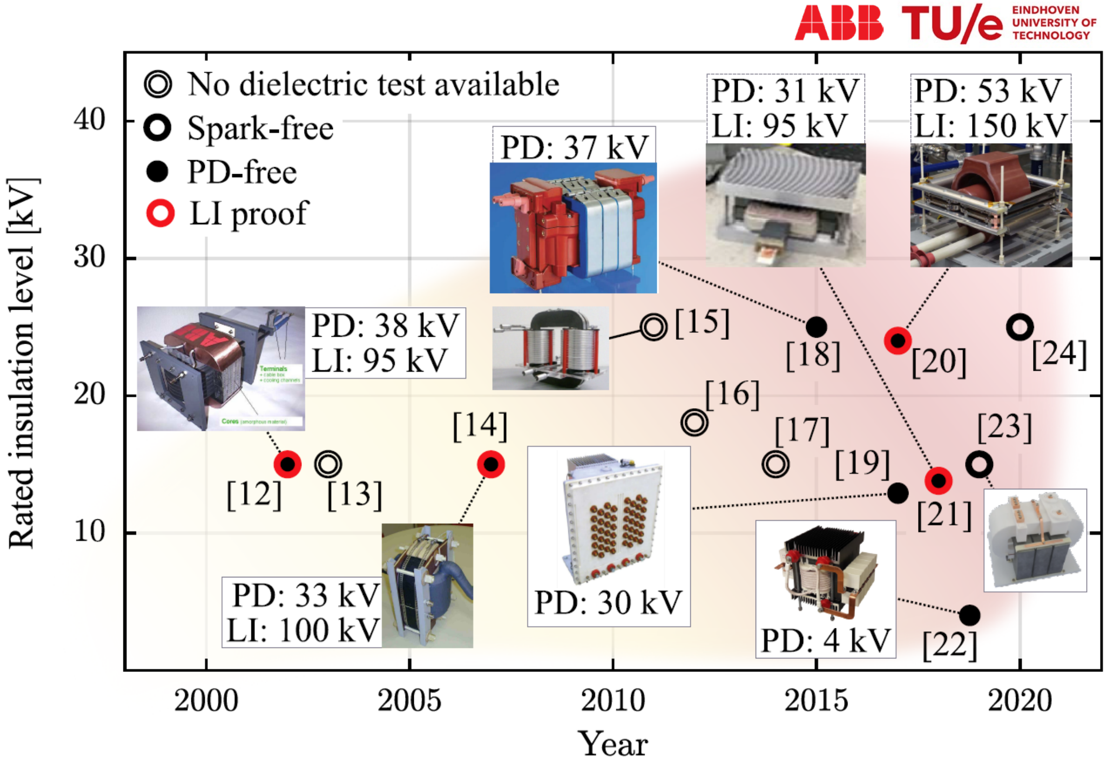


- High Efficiency Facilitates Air Cooling
- Liquid Cooling Facilitates Maximum (Gravimetric) Power Density / Needs External Heat Exchanger

[Czyz2022]

MFT Isolation Systems

- **Solids / Air / Oil**
- **Extreme Lightning-Impulse (LI) Test Voltage Requirements > 100 kV**



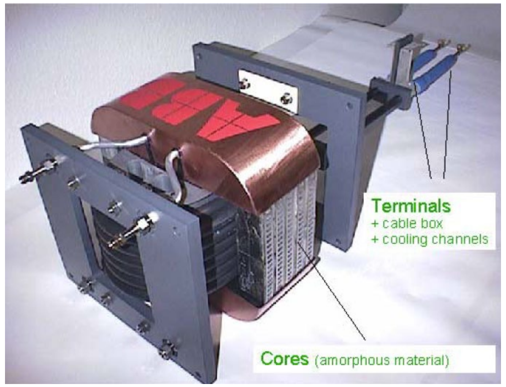
- Wide Variety of Published Designs / Many not Tested at Required LI Levels

[Cremasco2022]

MFT Example #1: Early Traction MFT Prototypes

■ **Coaxial Cable Winding**

[Heinemann2002]



- **350 kVA / 10 kHz / < 50 kg**
- Nanocrystalline Core
- 38 kV PD / 95 kV LI Surge
- Water Cooling w. Hollow Inner Conductor of Coax. Cable
- Unity Turns Ratio (!)

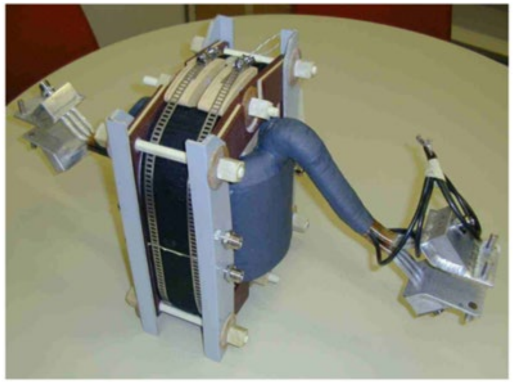
■ **Core-Type**

[Hoffmann2011]

- **450 kW / 5.6 kHz**
- Nanocrystalline Core
- Oil Isolation / Core Cooling
- Hollow Conductor Water Cooling

■ **Shell-Type**

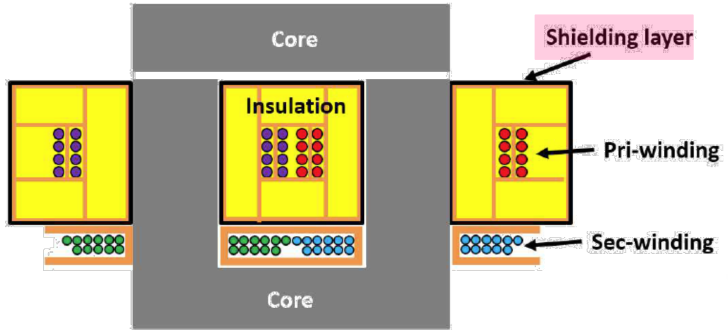
[Steiner2007]

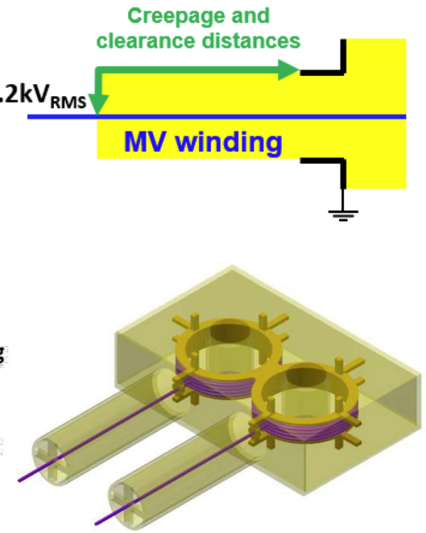


- **500 kW / 8 kHz / 18 kg**
- Nanocrystalline Core
- 33 kV PD / 100 kV LI Surge
- Water Cooling w. Hollow Conductors

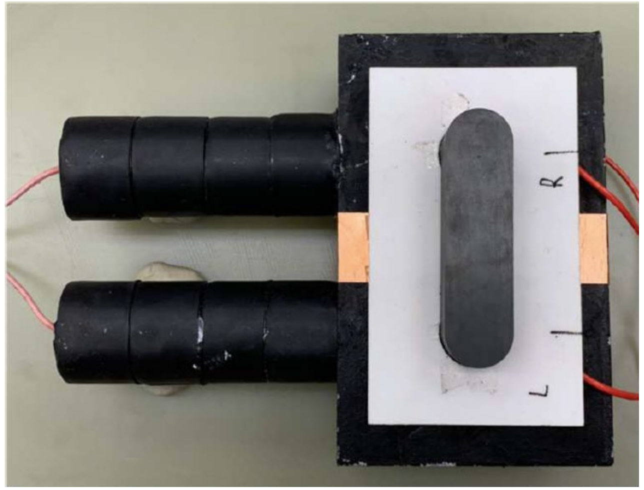
MFT Example #2: 15 kW / 200 kHz

- Multi-Cell SST Connecting to 13.2 kV MV Grid / CLLC DC-DC Isolation Stages
- 15 kW / 200 kHz / > 99.4% Efficiency / PD Test @ 17.2 kV, HiPot Test 60 s @ 34 kV RMS
- Vacuum-Pressure Impregnation (VPI) with Silicone Gel Material





Ca. 180 mm x 140 mm

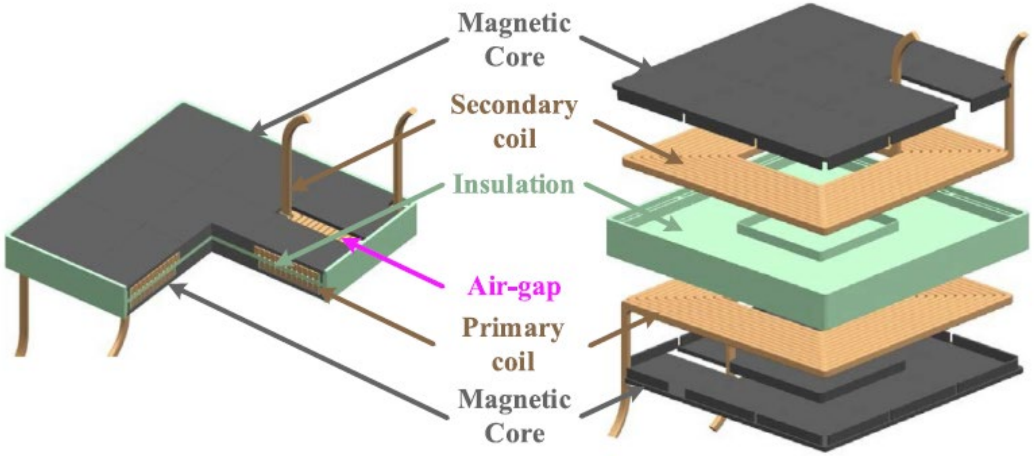


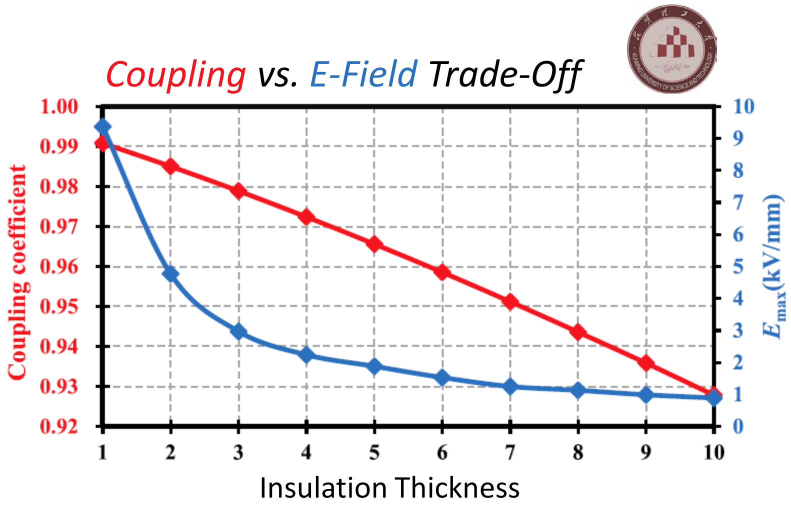
- Isolation System w. Semi-Conductive Shielding & E-Field Stress Grading on Bushings
- Bushing Overhead: > 50% of Total Volume (!)

[Li2021]

MFT Example #3: 80 kW / 43 kHz

- Planar Transformer w. Low-Cost Ferrite Core
- Epoxy FR4 Isolation for 10 kV Distribution Grid / Tested at 42 kV RMS for 72 s





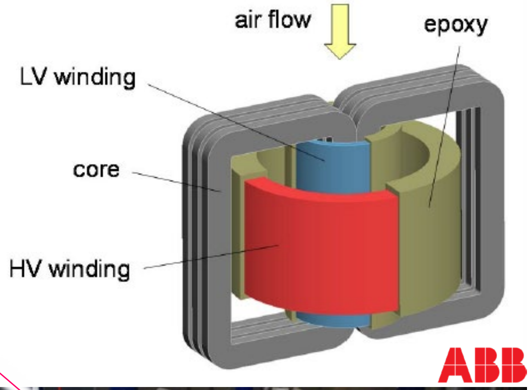
- Compact Design (21.1 kW/dm^3, 308 mm x 308 mm x 40 mm) w. Large Cooling Surfaces
- Full-Load Efficiency of 99.25% (Calc.) → 850 V DC SiC CLLC DC-DC w. 99.3% @ 24 kW and 98.7% @ 80 kW (Meas.)

[Lu2022]

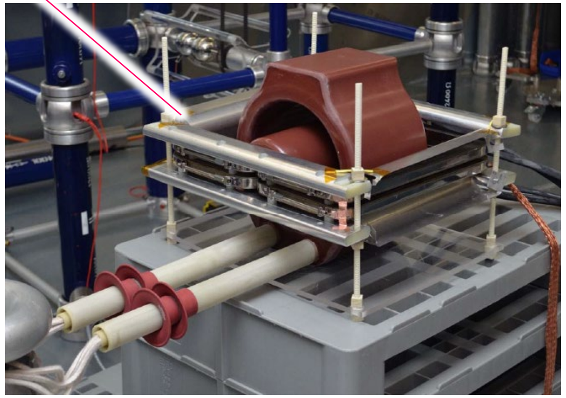
MFT Example #4: 240 kW / 10 kHz

- Hybrid Solid/Air Isolation System Design for 50 kV DC System Voltage
- Air Gap Wide Enough to Avoid PD / Discharges in Air Allowed During LI Tests (Solid Insulation Takes Over)
- Low El. Field in Solid Insulation During Normal Operation & High Surface Area for Cooling

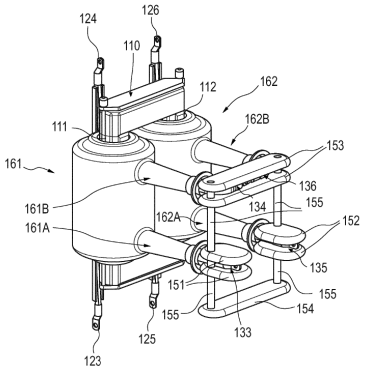
- Full Dielectric Testing of Prototype
  - 70 kV rms / 1 min
  - 150 kV LI (10 Pos., 10 Neg. Pulses)
  - PD Inception at 35 kV rms (Target: 53 kV rms)
    → Improved Field Grading Necessary



Field Grading Around Core

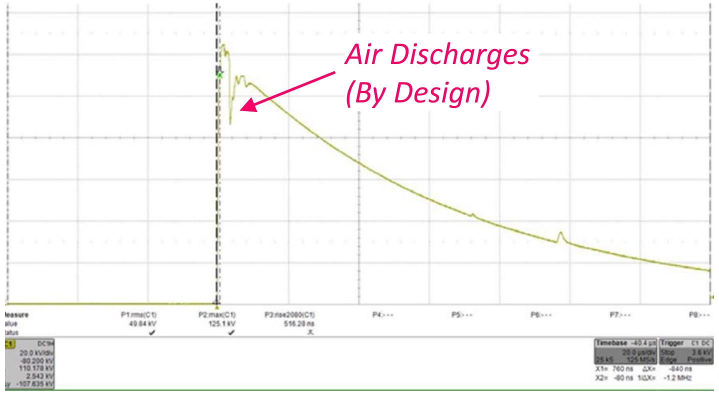


(Bushings Longer than Necessary)



- Alt./Opt. Bushing Arrangement

150 kV LI Test

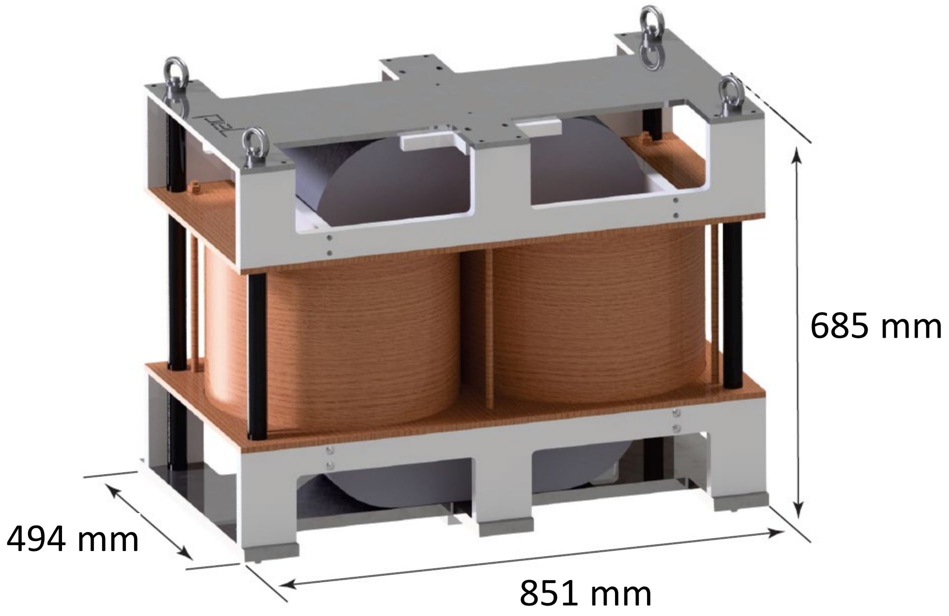


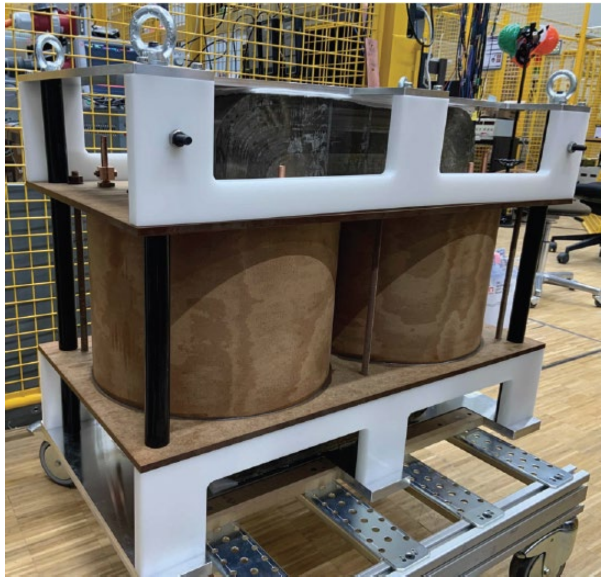
[gradingerNovelInsulationConcept2017, Gradinger2018a]

MFT Example #5: 1 MW / 5 kHz

- **Two-Vessel Concept w. 2 x 2 Identical Oil-Immersed Windings (Biodegradable Synthetic Ester Midel 7131)**
- **Hollow Cooper Conductors (Deionized Water Cooling) & Air-Cooled Nanocrystalline Core (400 kg)**
- **2:1 Turns Ratio (Primary: 2 Wdg. in Series, Secondary: 2 Wdg. in Parallel)**

EPFL pel



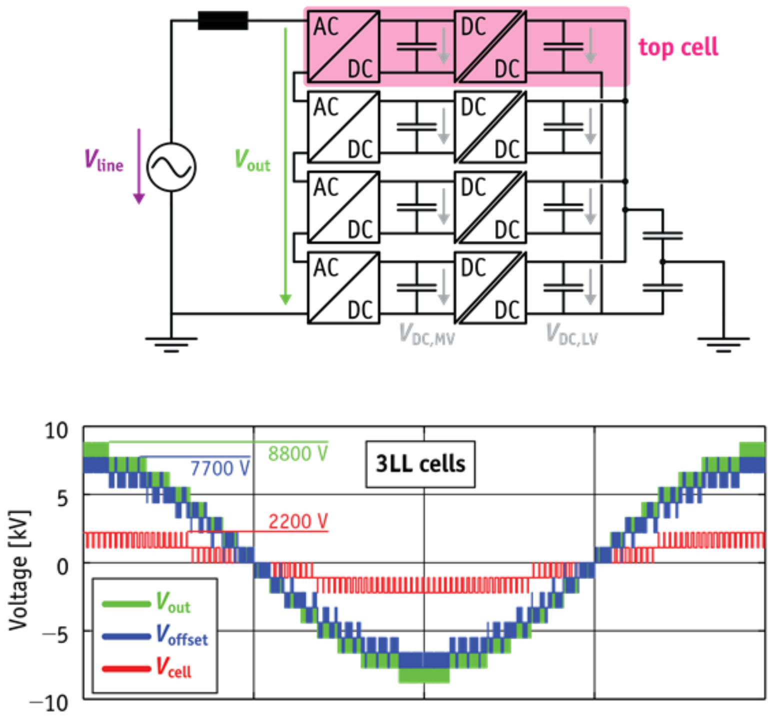


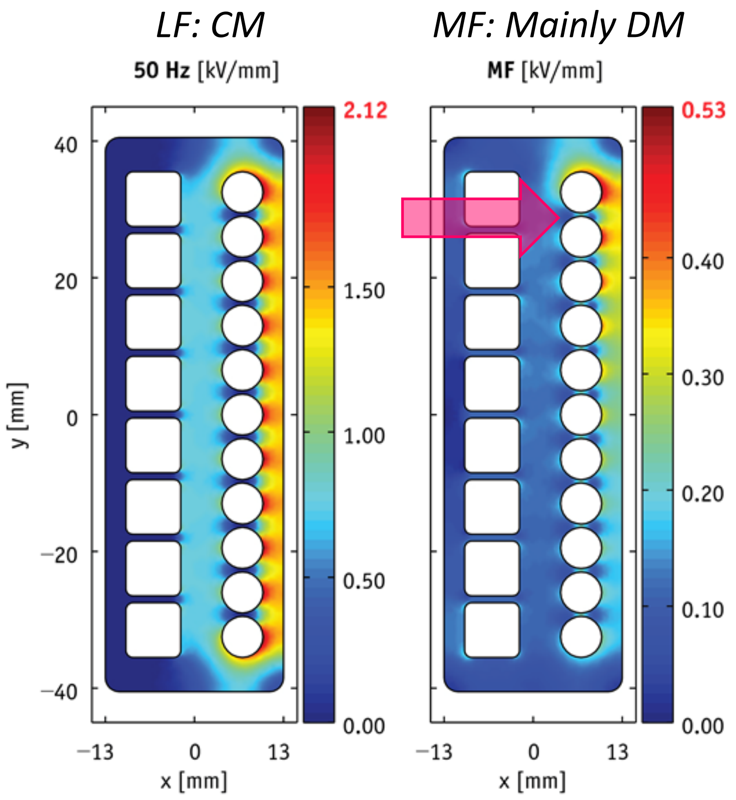
- Calculated MFT Performances: 99.18 % Efficiency, 3.47 kW/dm^3 and 2.36 kW/kg Power Density
- Target Application: IGCT-based 1 MW 10 kV to 5 kV DC Transformer

[Djekanovic2022]

Remark: Mixed-Frequency Electric Field Stress

- Combined Electrical Field Stress: Large DC or Low-Frequency Comp. + Smaller Medium-Frequency Comp.
- Common-Mode LF Stress + (Mainly) Differential-Mode DM Stress → DoF for Insulation Syst. Optimization





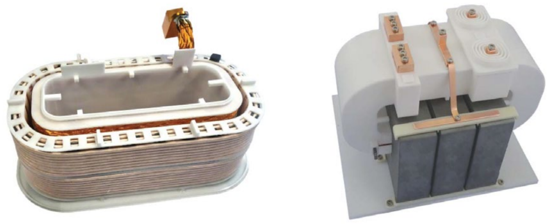
- Known From Electric Machine Insul. Systems / Physical Breakdown & Ageing Mechanisms To Be Clarified

[Guillod2014]

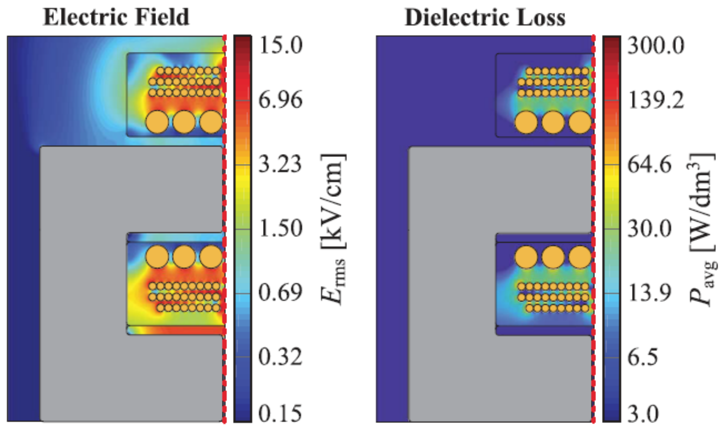
Remark: Dielectric Losses

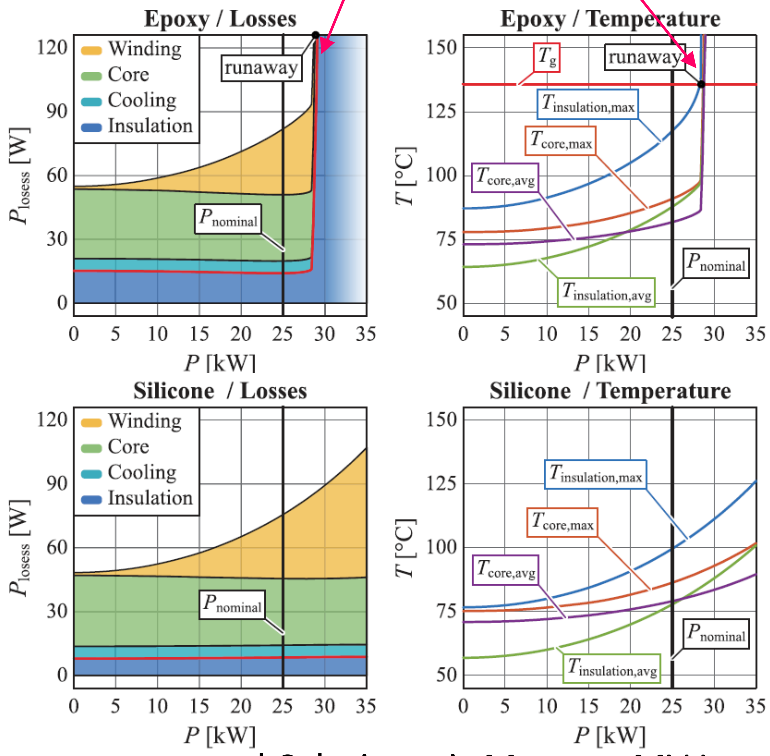
- Frequency-Dependent Dielectric Losses / Full Description w. Freq.-Dep. & Temp.-Dep. Complex Permittivity
- Case Study w. 25 kW / 48 kHz MFT for 7 kV DC to 400 V DC DCX

Runaway @ Glass Transition Temp.



$$P_{\text{diel}} \propto f \cdot E_{\text{rms}}^2$$





Epoxy Resin
27% @ 0 kW
17% @ 25 kW

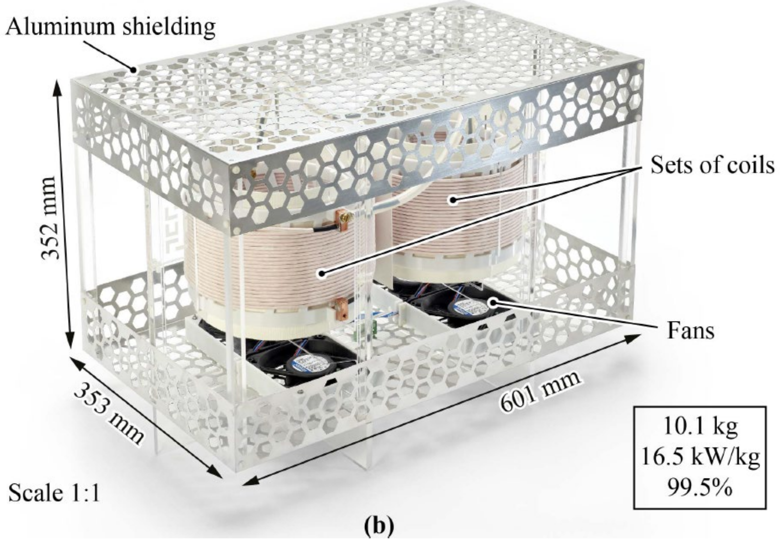
Silicone Elastomer
16% @ 0 kW
11% @ 25 kW
No Runaway

- Experimental Verification w. Small-Signal Diel. Spectroscopy and Calorimetric Meas. at MV Levels
- Careful Choice of Insulation Material is Essential (Field Strength/Thermal Cond./Dielectric Losses)

MFT Example #6: 166 kW / 77 kHz Air-Core Transformer

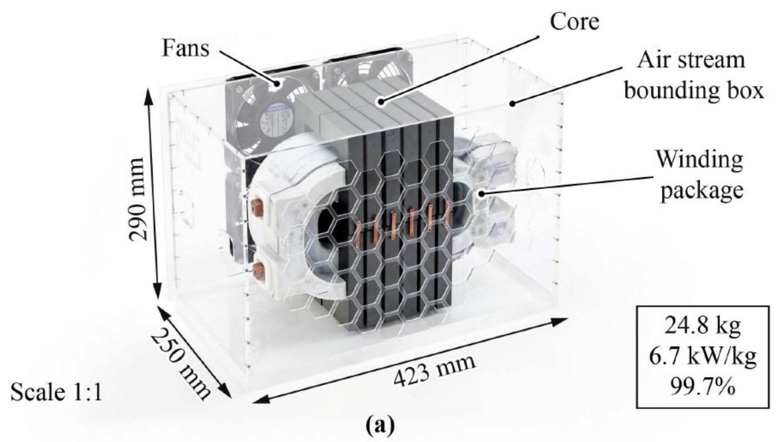
- **MFT for 166 kW DCX (7 kV DC Input/Output) / Clarification of Efficiency vs. Weight Trade-Off**
- **Full Pareto Optimization / Design Selection $\eta_{DC\text{-}DC} \geq 99\%$ & Transf. w. Highest Gravimetric Power Density**

Air-Core Transformer (ACT) @ 77 kHz



m_{ACT} = 10.1 kg η_{ACT} = 99.5%
$m_{DC\text{-}DC}$ = 17.2 kg $\eta_{DC\text{-}DC}$ = 99.0%

Magnetic-Core Transf. (MCT) @ 40 kHz



m_{MCT} = 24.8 kg η_{MCT} = 99.7%
$m_{DC\text{-}DC}$ = 29.7 kg $\eta_{DC\text{-}DC}$ = 99.2%

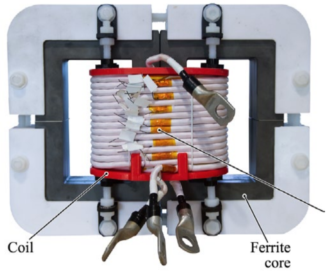
- ACT with Aluminum Shielding → Meets ICNIRP 2010 Guidelines for Exposure to Magn. Fields @ 20 cm
- ACT: A-Posteriori Creepage/Clearance Tuning by Barrier Elements / Isol. Test. ±9.6 kV DC, 6.4 kV AC (1 min)

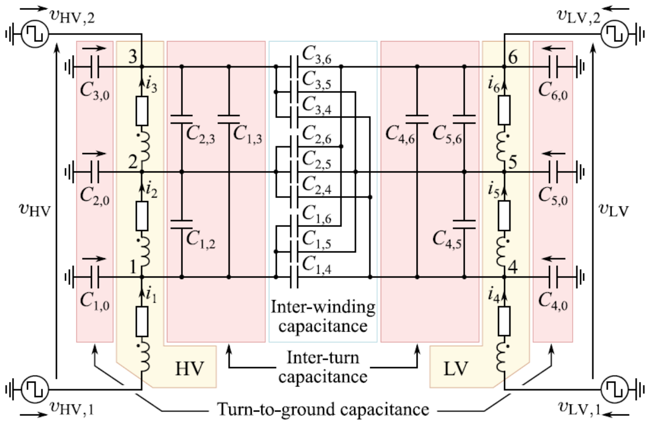
[Czyz2022]

Remark: Parasitic Effects in MFTs

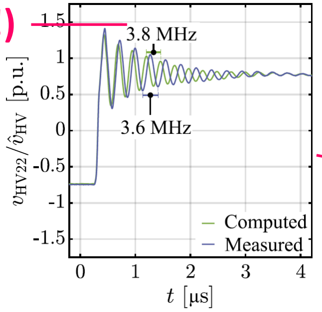
- PWM Excitation with Short Rise Times Non-Uniform Volt. Distr. in Windings (Prop. Delays, Resonances)
- Similar Phenomena Known from PWM Motor Drives

HF Model of a 3:3 MFT

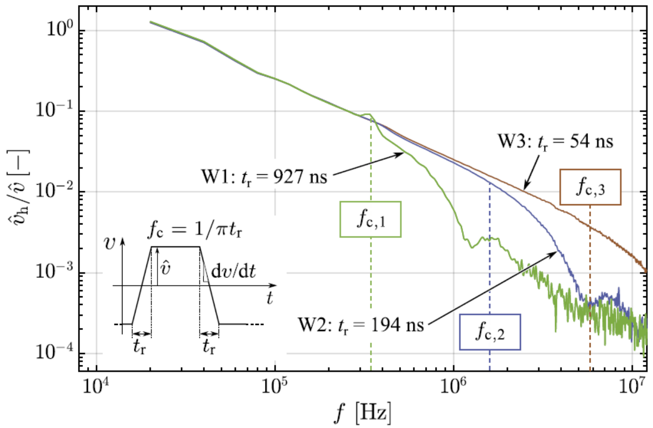




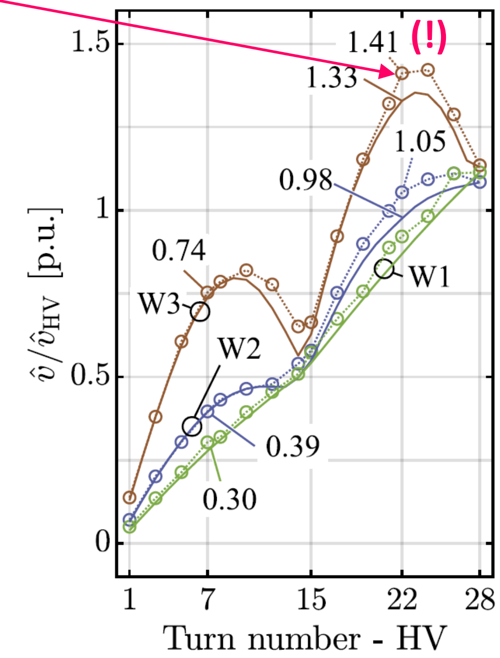
(!)



PWM Spectra (Diff. Rise Times)



Meas. Turn-by-Turn Peak Voltages



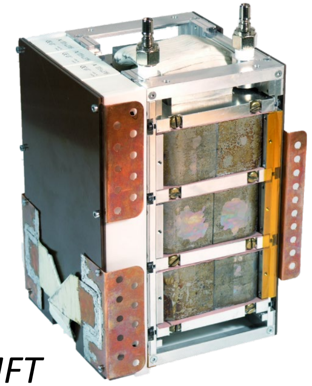
- Mitigation: Spectrum Corner Frequency < Transformer Series Resonant Frequency
- dv/dt Limitation (cf. Motor Drives!) or Minimizing Transformer Stray Capacitance

ABB TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

[Cremasco2022]

Anecdote: Litz Wire Issues

- Unequal Current Sharing in Imperfectly Twisted Litz Wires



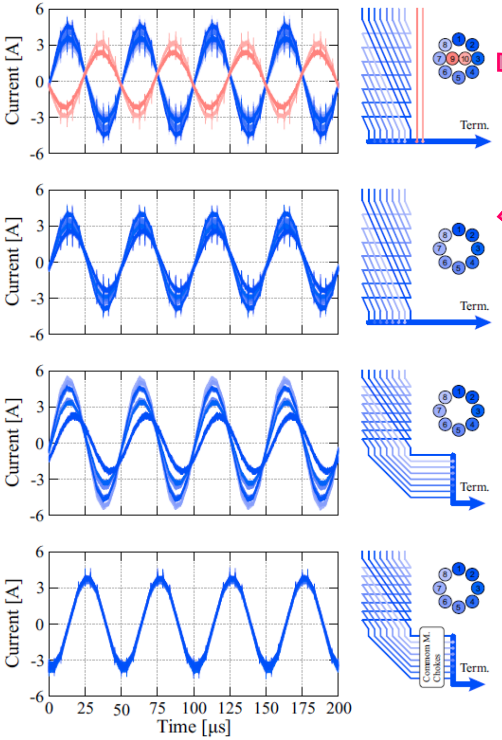
Example: 20 kHz MFT
Litz w. 10 Sub-Bundles and 9500 x 71µm

Incorrect Twisting

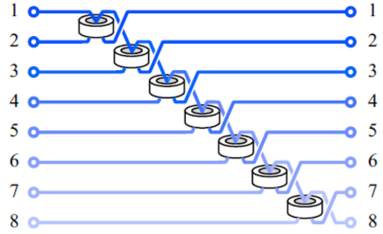
Center Bundles Removed

Impact of Terminations

Common-Mode Chokes



– 20% Losses (!)



- Common-Mode Chokes Force Equal Current Sharing

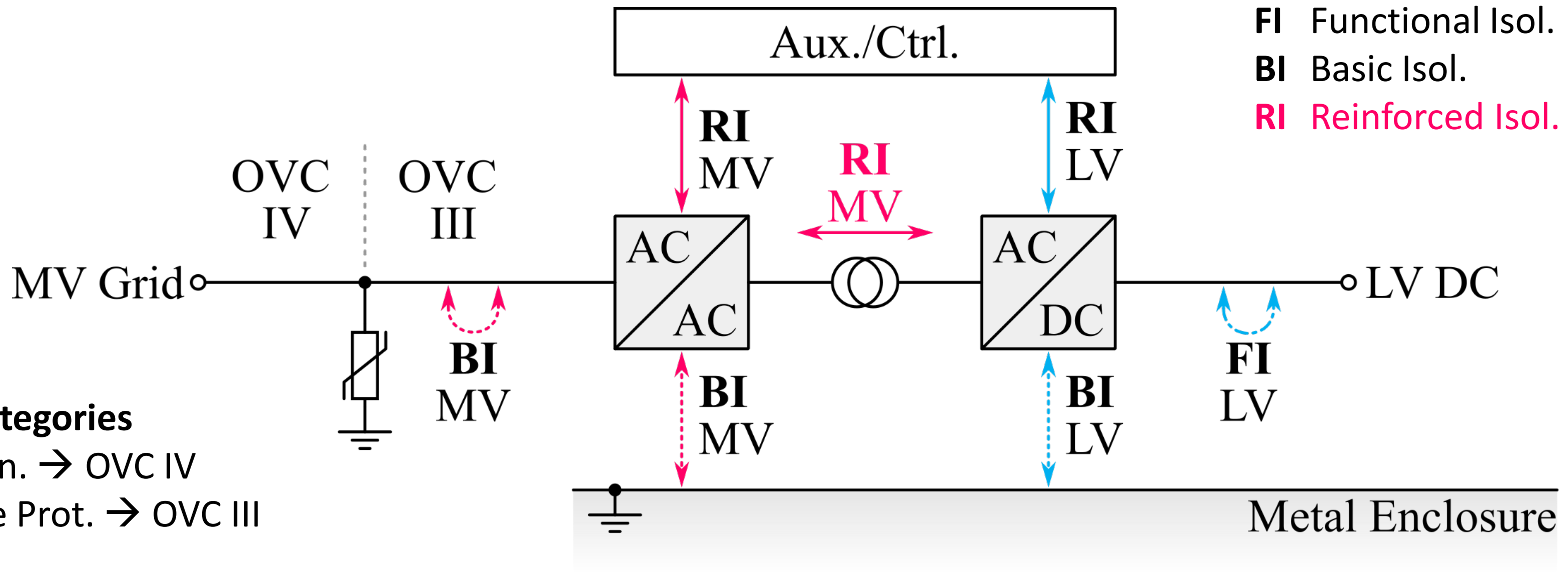
Part II

SST Concepts & Key Design Aspects

- Medium-Frequency Power Conversion
- Power Semiconductors
- Key SST Topologies
- Medium-Frequency Transformers
- **Isolation Coordination**
- Protection
- Construction

Isolation Coordination

- **Decisive Voltage Class (DVC) of MV Side Circuitry: DVC-D (> 1 kV AC or > 1.5 kV DC)**
  - "Safe Isolation" Towards Circuits with Other DVC / Direct Contact → **RI** Required
  - **BI** Towards Touchable Grounded Parts Sufficient / **BI** or **FI** Between Circuits with same DVC



FI Functional Isol.
BI Basic Isol.
RI Reinforced Isol.

Overvoltage Categories
Direct Grid Conn. → OVC IV
OVC IV → Surge Prot. → OVC III

- Simplified Example Only
  Always Consider Applicable Standards in Full Detail!

Schweizer Norm
Norme Suisse
Norma Svizzera

EN IEC 62477-2
Safety requirements for power electronic converter systems and equipment - Part 2:
Power electronic converters from 1 000 V AC or 1 500 V DC up to 36 kV AC or 54 kV DC

Clearance

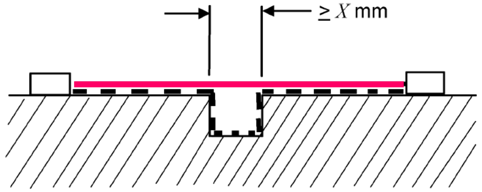
■ Example: 13.2 kV MV Grid / Based on IEC 62477-2 (Simplified)

- **Step 1:** System Voltage 13.2 kV (Phase-to-Phase RMS)
- **Step 2:** Overvoltage Category OVC-III

x 1.6 for RI!

- **Step 3:** Basic Impulse Level (BIL) / Lightning Imp. (LI): 63.3 kV (BI) 101.2 kV (RI) Tab. 101 (Linear Interp.)
  Temporary Overvoltage (peak): 42.7 kV (BI) 68.3 kV (RI) Tab. 101 (Linear Interp.)
- **Step 4:** Basic Isolation (BI) BIL 63.3 kV 120 mm Tab. 102 (Grid-Connected Circuit / No Interp.)
  TO 42.7 kV 106 mm Tab. 102 (Linear Interp.)

  Reinforced Isol. (RI) BIL 101.2 kV **220 mm** Tab. 102 (Grid-Connected Circuit / No Interp.)
  TO 68.3 kV 183 mm Tab. 102 (Linear Interp.)



- Special Considerations Apply for f > 30 kHz (Appendix F) and for Altitudes > 2000 m
- Simplified Example Only – Always Consider Applicable Standards in Full Detail!

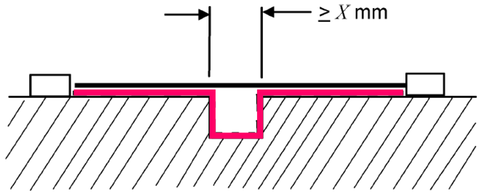
Creepage

- **Example: 13.2 kV MV Grid / Based on IEC 62477-2 (Simplified)**

● **Step 1:**	Working Voltage	13.2 kV	(Exemplary; Depends on Specific Volt. Waveforms, etc.)
● **Step 2:**	Pollution Degree	PD-2	Typically Only Non-Conductive Pollution
● **Step 3:**	Isol. Material Group	Group I	CTI ≥ 600 (CTI: Comparative Tracking Index)
● **Step 4:**	Basic Isolation (BI)	66.4 mm	Tab. 103 (Linear Interp..)
	Reinforced Isol. (RI)	**132.8 mm**	2 x BI

- **But: Creepage Requirement Cannot Be Smaller Than Clearance!**

Basic Isolation (BI)	120 mm
Reinforced Isol. (RI)	**220 mm**



- Special Considerations Apply for for $f > 30$ kHz (Appendix F)
- Simplified Example Only – Always Consider Applicable Standards in Full Detail!

Testing Requirements

- **Basic Isolation** — **BIL Test + AC or DC Test**
- **Reinforced Isolation** — **BIL Test + AC or DC Test + PD Test (for Solid Insulation)**

BIL Test

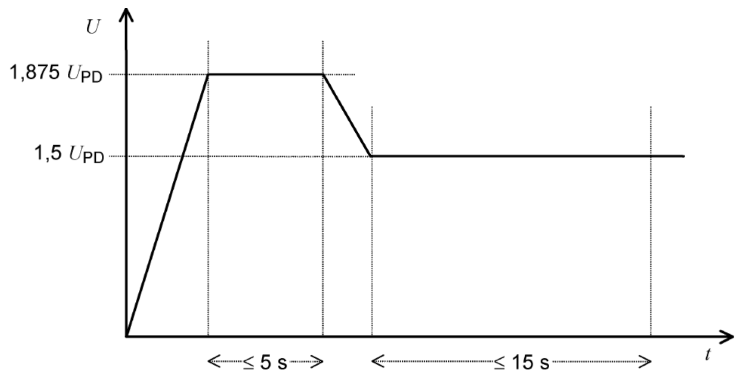
- 1.2/50 µs Surges: 3 x Positive + 3 x Negative Polarity w. Pauses > 1 s
- Alternative: AC Test w. Peak Voltage = BIL, min. 3 Periods
- Type Test & Random Tests

AC or DC Test

- BI: Temporary Overvoltage
- RI: 1.6 x Temporary Overvoltage (Type Test Only)
- Type Test > 60 s / Routine Test > 1 s

PD (Partial Discharge) Test

- Test Voltage U_{PD} = Sum of All Repetitive Peak Volt. Sep. by Isol.
- Specific Voltage Profile / PD Discharges < 10 pC During Test
- Type Test & Random Tests

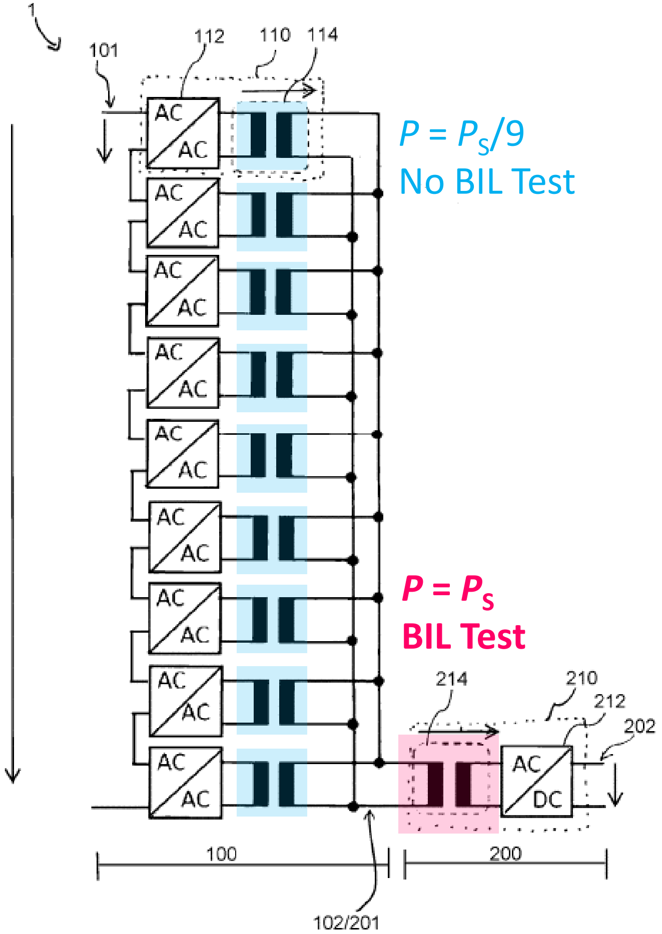


- Simplified Example Only – Always Consider Applicable Standards in Full Detail!

Remark: System-Level Perspective

- **Two-Stage Transformer Approach**
  First-Stage: Isolation for Nominal Voltage (PD Tests)
  Second Stage: Isolation for BIL

- **More Compact Real. of 1st Stage MFTs, e.g., w/o Bushings**



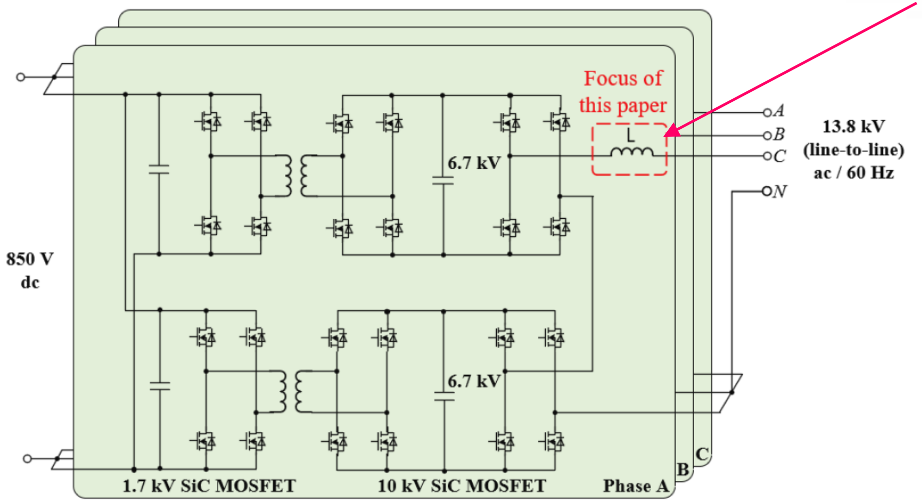
- Design DoF / Separate Optimization
- Especially Interesting for Lower Voltage & Power Ratings (Construction Overhead)

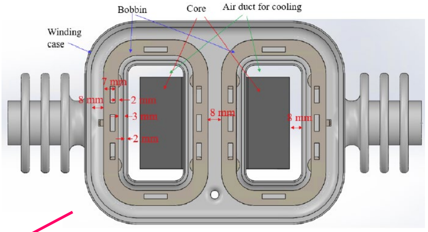
[Drofenik2020]

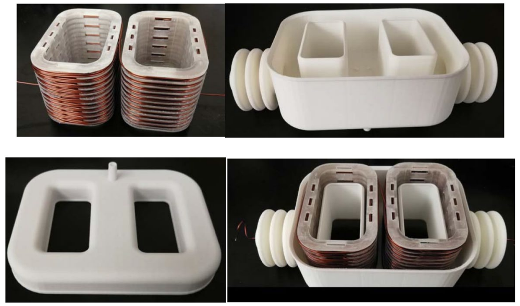
Isolation Design Example: MV Inductor

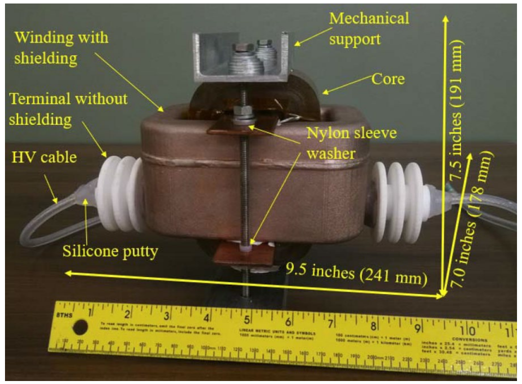
■ **13.8 kV Grid Filter Inductor for 100 kW, 10-kV-SiC-Based Converter**

- Specs.: 44 mH / 4.2 A RMS / 23 A Inrush / 40 kHz Eff. Sw. Freq. / PDIV > 10 kV RMS / BIL 95 kV









THE UNIVERSITY OF TENNESSEE KNOXVILLE

- Compartmentalized Winding to Reduce Max. Layer-Layer Stress
- Silicone Elastomer Insulation / Field Grading w. Shielding Layer on Winding Package Surface
- DC HiPot Test Pass @ 46 kV for 1 min / PD Test Pass @ 12.1 kV RMS

[Li2022]

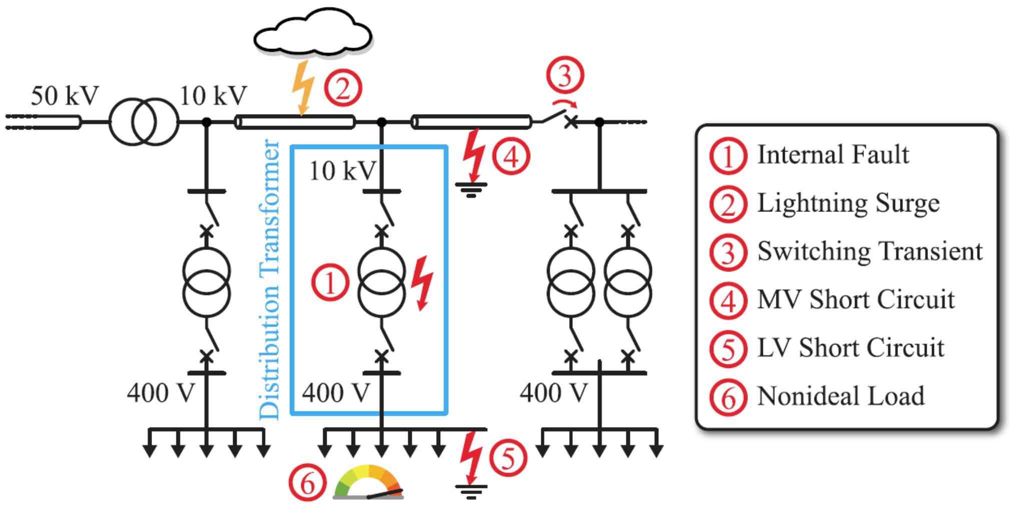
Part II

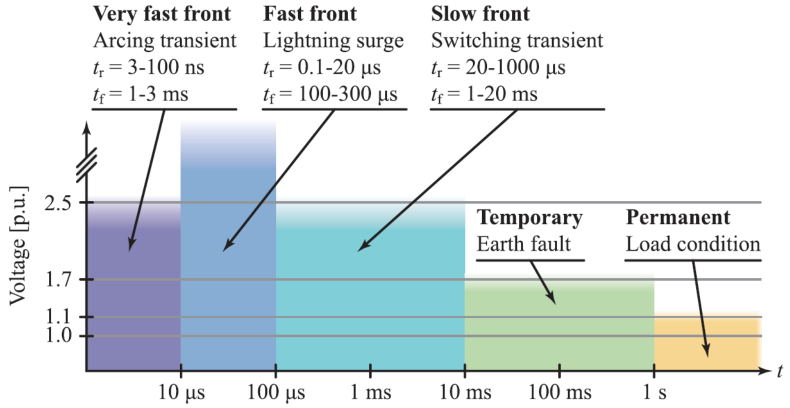
SST Concepts & Key Design Aspects

- Medium-Frequency Power Conversion
- Power Semiconductors
- Key SST Topologies
- Medium-Frequency Transformers
- Isolation Coordination
- **Protection**
- Construction

Potential Fault Situations in MV and LV Grids

■ **Extreme Overvoltage Stresses** on the MV Side for Conv. Distr. Grids

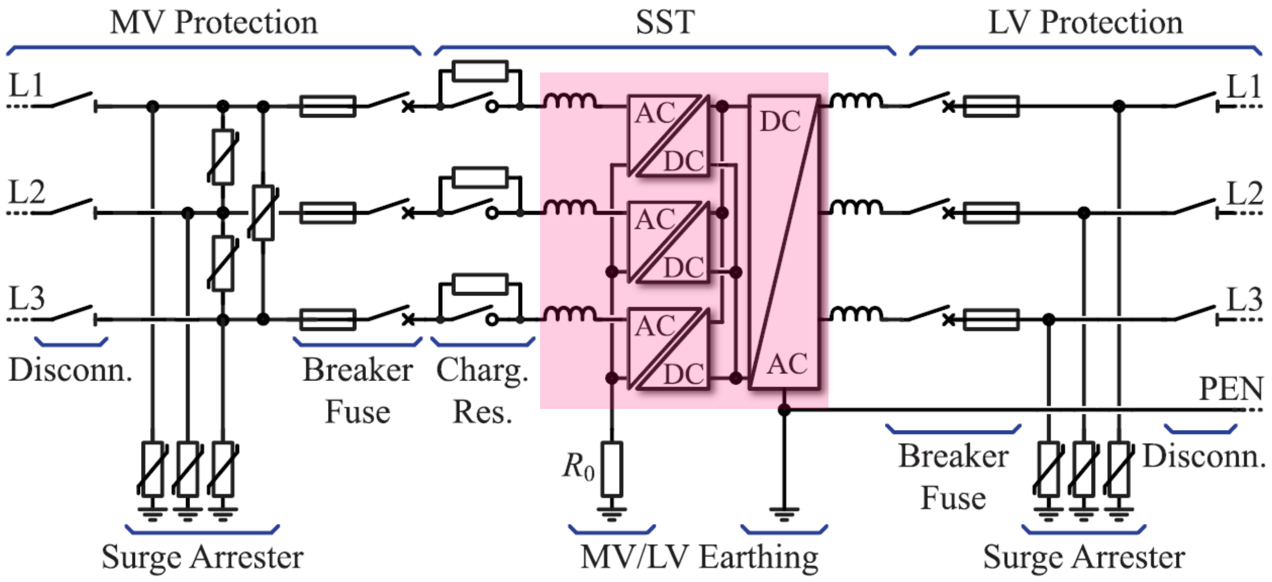




■ **Short-Circuit Events** on MV and LV Side
- Protection Scheme Needs to Consider Selectivity / Sensitivity / Speed / Safety / Reliability

Possible SST Protection Concept

■ **Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids**

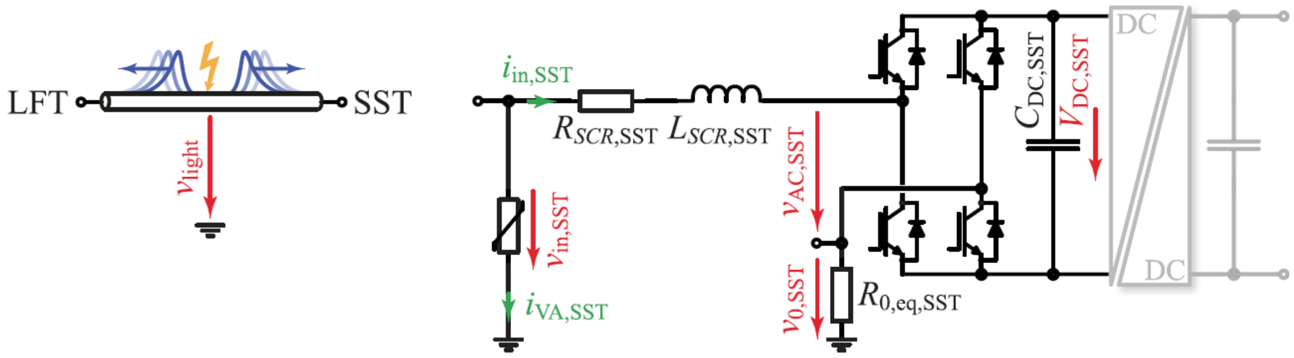


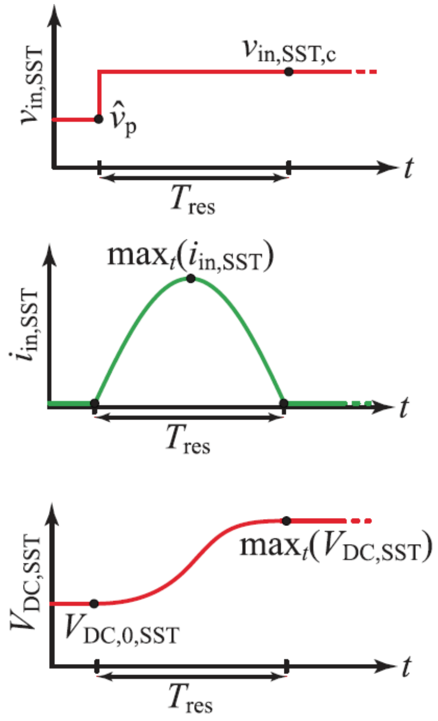
■ **Short-Circuit Events on MV and LV Side**

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

Example: Surge Protection

- Lightning Impulse Defines Dielectric Strength Requirements (Isol. Coord.)
- But Consider Also Surge Energy Propagation Inside of the SST



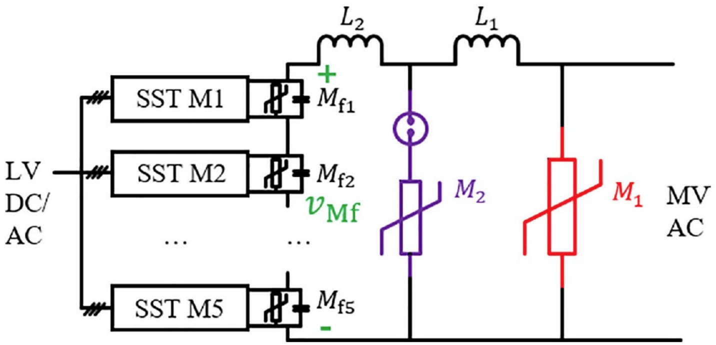


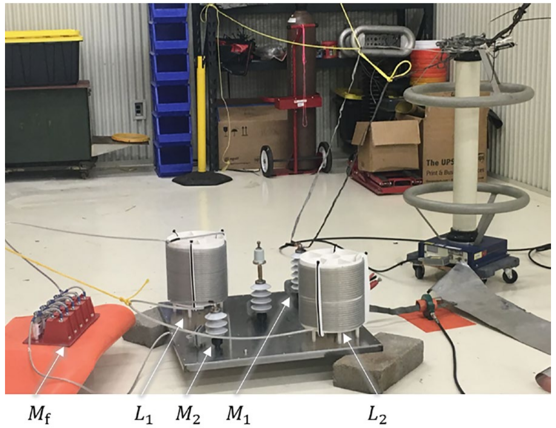
- Depends on Operating State of SST (Active/Passive) & Grounding Scheme
- Defines Minimum Values for Input Ind., DC-Link Cap., Blocking Capability, … → **Strongly Affects SST Design!**

Example: Lightning Protection Scheme

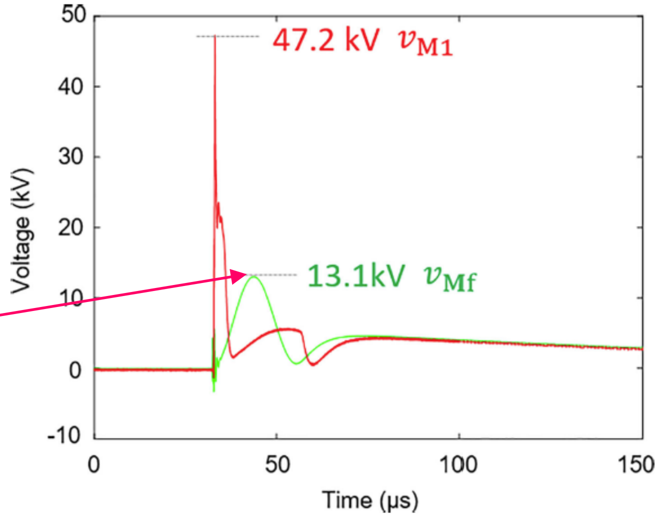
- Two-Stage Lightning Protection Scheme for 7.2 kV / 50 kVA Current-Source SST
- Five Stacked Cells w. 3.3 kV SiC → Max. Total Blocking Volt. 16.5 kV

Georgia Tech





M1:	15 kV Gapped MOV
M2:	3 kV Gapped MOV
	(Eff. Sparkover @ 12 kV > Peak Grid Volt.)
L1, L2:	150 µH Air-Core Inductors

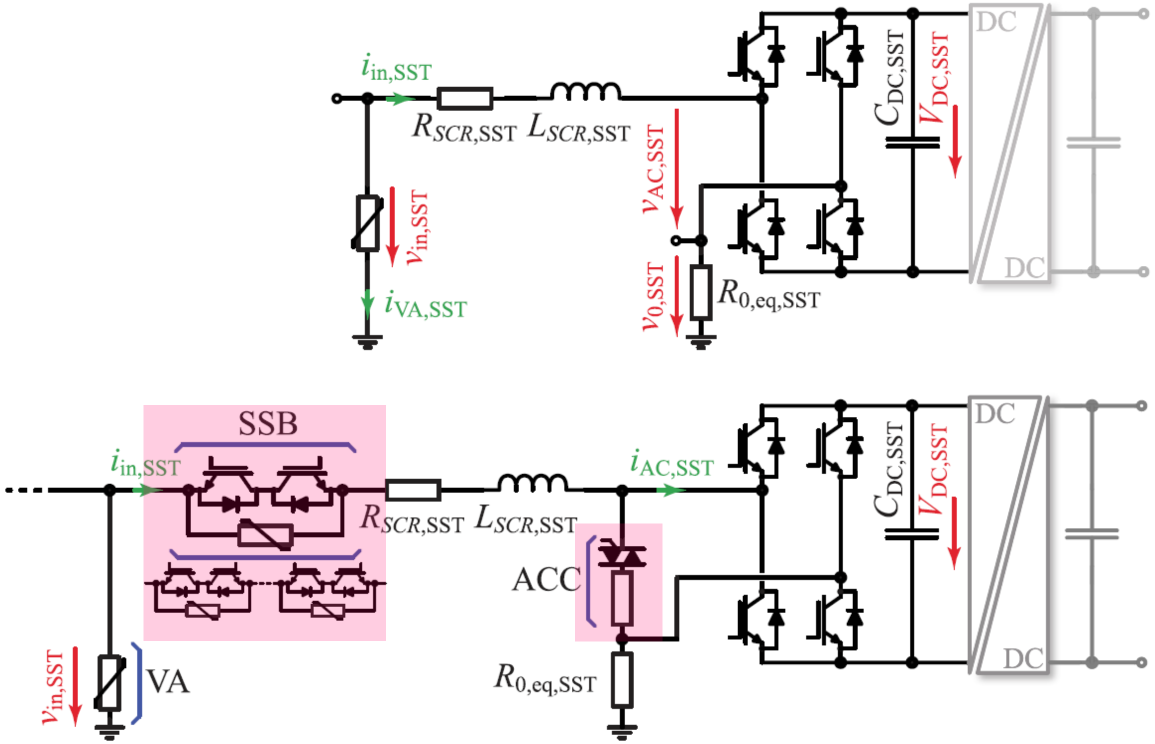


- 90 kV LI Test → Stack Input Voltage < 13.1 kV

[Zheng2022]

Outlook: Advanced Protection Schemes

■ **Mitigation of High Impact on SST Design: Solid-State Breakers / AC Crowbar / …**



● Applications in Industrial Grids / Microgrid w. Central OV Prot. & Coord. SC Protection / Fault Cur. Limit.

Part II

SST Concepts & Key Design Aspects

- Medium-Frequency Power Conversion
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From Conceptualization to Realization

- **Actual Realization of a Modular MV Converter Systems → Complex / Interdisciplinary Task**
  - Isolation Coordination / Cooling / Control & Communication / Hot-Swapping / Auxiliary Supply / Mechanical Assembly / …

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

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

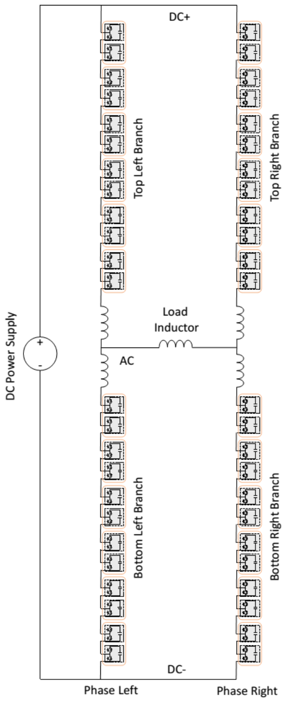
Didier Cottet, Wim van der Merwe, Francesco Agostini, Gernot Riedel, Nikolaos Oikonomou, Andrea Rüetschi, Tobias Geyer, Thomas Gradinger, Rudi Velthuis, Bernhard Wunsch, David Baumann, Willi Gerig, Franz Wildner, Vinoth Sundaramoorthy, Enea Bianda, Franz Zurfluh, Richard Bloch, Daniele Angelosante, Dacfey 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

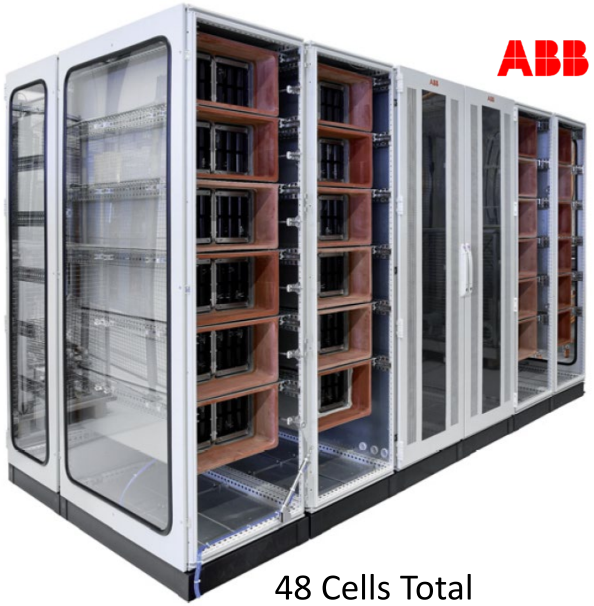
Jonathan Bradshaw, DPS Ltd., Auckland 1010, New Zealand

Contact: didier.cottet@ch.abb.com

> 25 Authors (!)



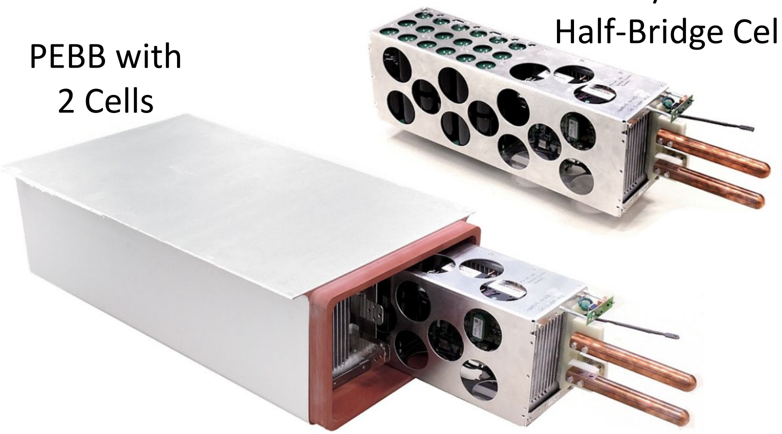
Img.: W. van der Merwe



48 Cells Total

PEBB with 2 Cells

1 kV / 600 A Half-Bridge Cell

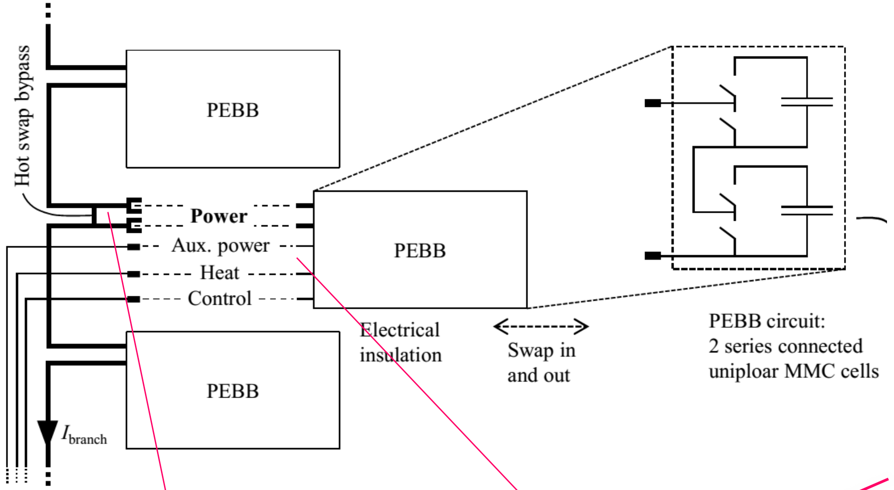


- **2 x 1ph MMC in Back-To-Back Conf. | 12 Cells/Arm | 11 kV DC max. | Isol. for 4 kV rms Syst. Volt. / 70 kV BIL**

[Cottet2015, Cottet2015a]

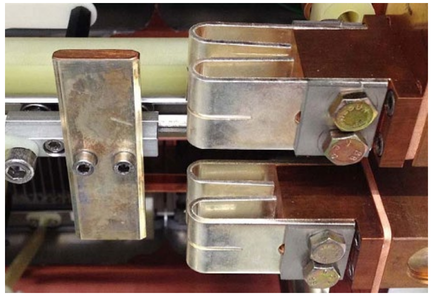
Interfaces & Hot-Swapping

- All Interfaces Support **Hot-Swapping @ 24 kV rms**

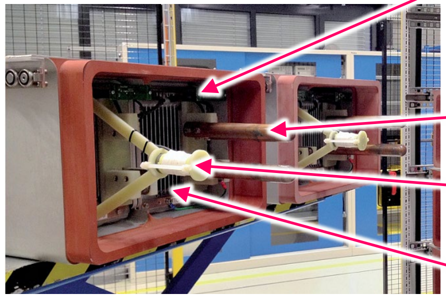


Hot-Swapping Test Setup

24 kV
Sw. Arc



Bypass Switch



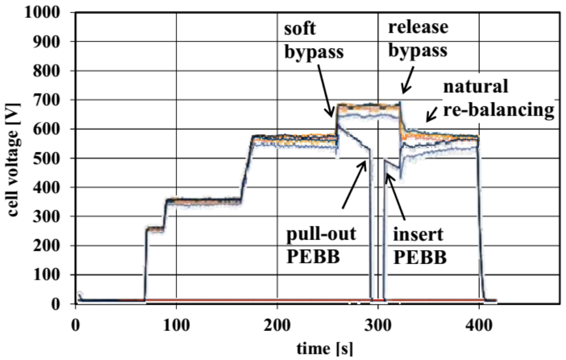
Cell Interface

Communication (Wireless Optical)

Power

Auxiliary (IPT)

Cooling (Air)

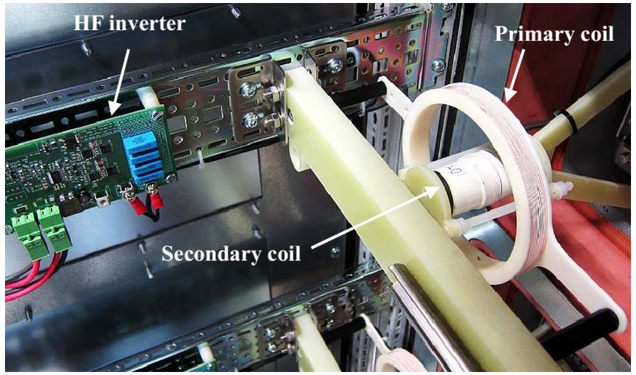


[Cottet2015, Cottet2015a]

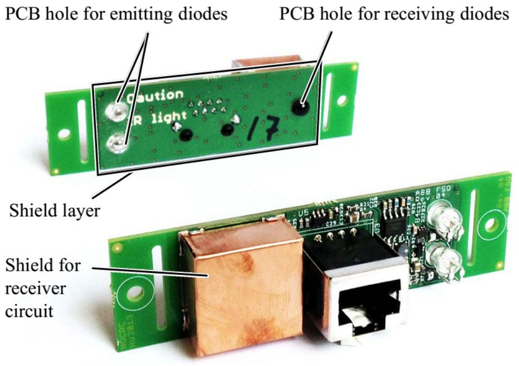
Advanced Integration Technologies

- **Building a High-Power/Voltage Demonstrator is a Multi-Disciplinary, Highly Complex Task!**

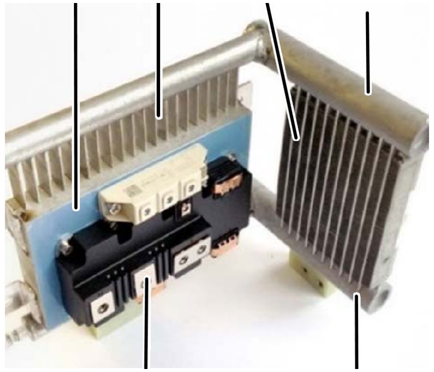
Wireless/Contactless Aux. Power Supply



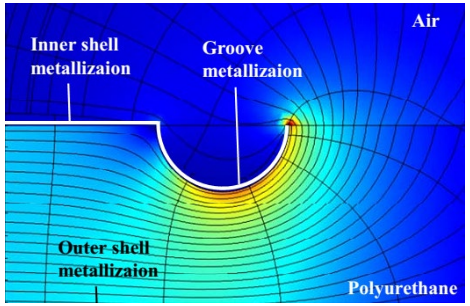
Wireless Optical EtherCAT Comm.

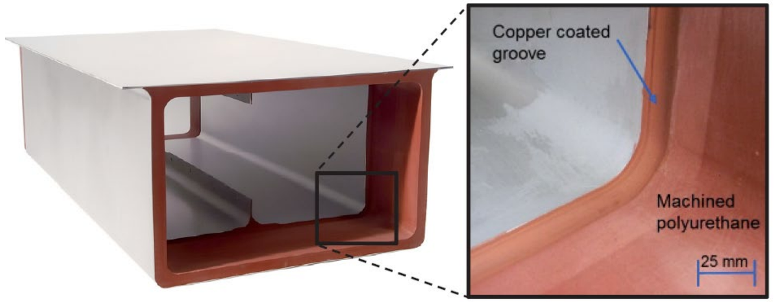


Two-Phase Cooling



Solid Isolation of PEBBs w. Field Grading





[Cottet2015, Cottet2015a]

Coffee Break

Part III

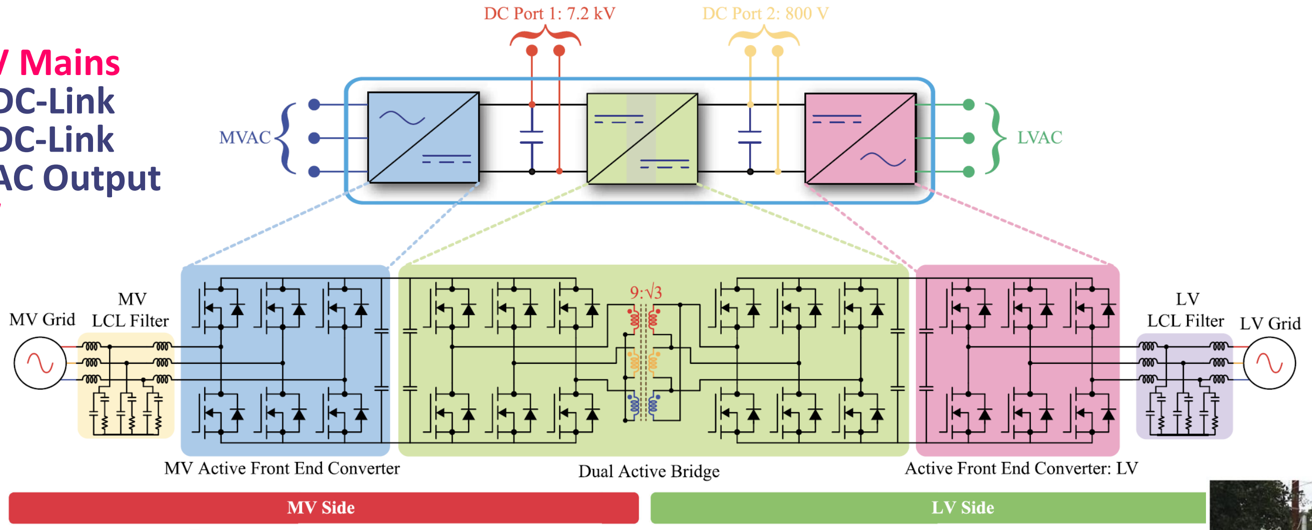
Selected Results of Recent University / Industry SST R&D Activities

NC STATE UNIVERSITY

3-Φ 2-Level AC/DC—DC/DC—DC/AC SST (1)

- AC/AC SST for MV Mobile Utility Support Equipment (MUSE-SST) Placed in Mobile Container
- MV and LV DC-Links Facilitate Integration of Renewables / Energy Storage

4.16 kV Mains
7.2kV DC-Link
800V DC-Link
480V AC Output
100kW



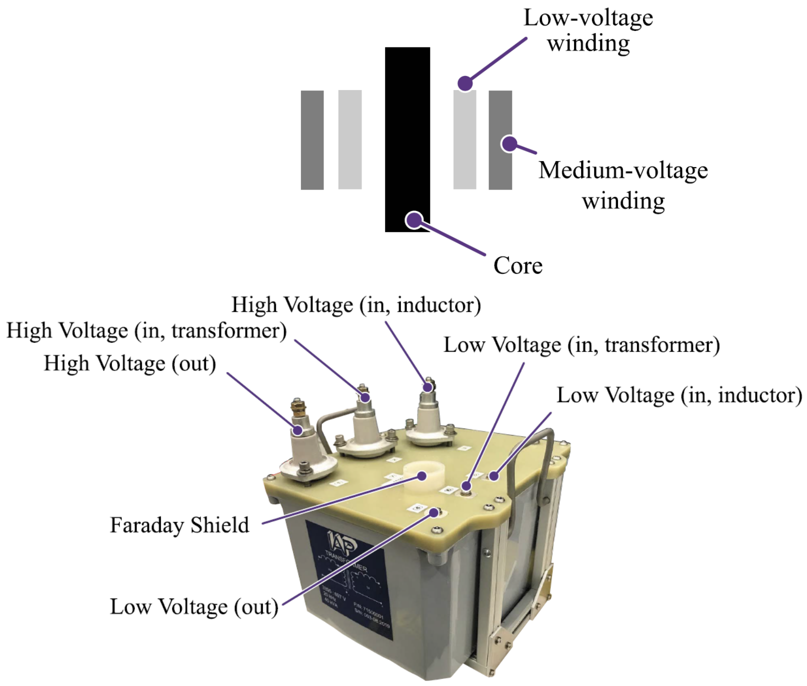
Device used:
10 kV SiC MOSFET module
XHV-6/XHV-9 modules

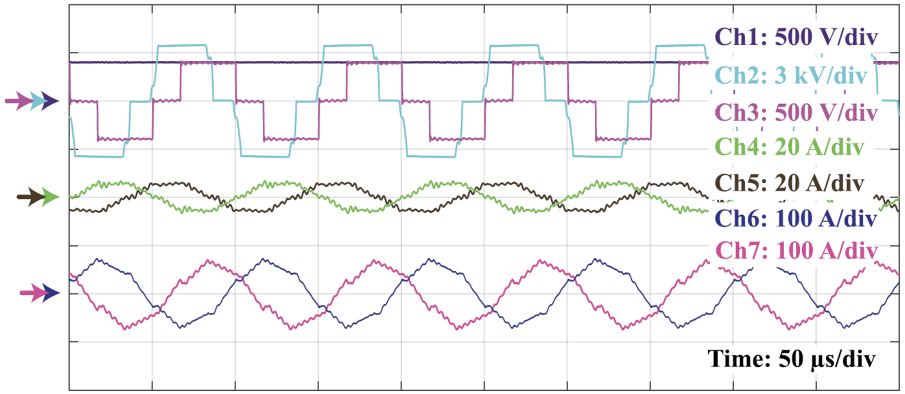
Device used:
1200 V - 325 A SiC MOSFET
CAS325M12HM2

- 10kV Gen 3 SiC MOSFETs in Extra High Voltage (XHV) Half-Bridge Module | 50A @ 150°C | 6 Dies / Switch
- Thermosyphon Air Cooling | Series-Parallel Film Capacitors | Sandwiched Busbar

3-Φ 2-Level AC/DC—DC/DC—DC/AC SST (2)

- 3x 1-Φ Xfrm — Lower Basic Isolation Level (BIL) Voltage Comp. to a 3-Φ Xfrm – 26.7kV vs. 40kV
- Oil-Filled Plastic Container | 20kV Bushings | MV-Side Faradey Shield | Nanocryst. C-Cores | Ext. MV & LV Inductors



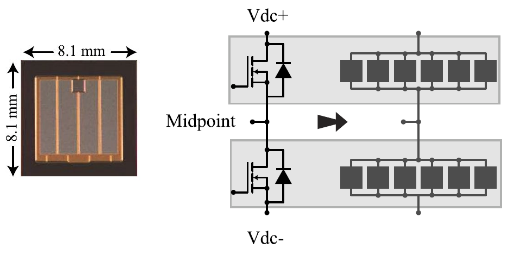


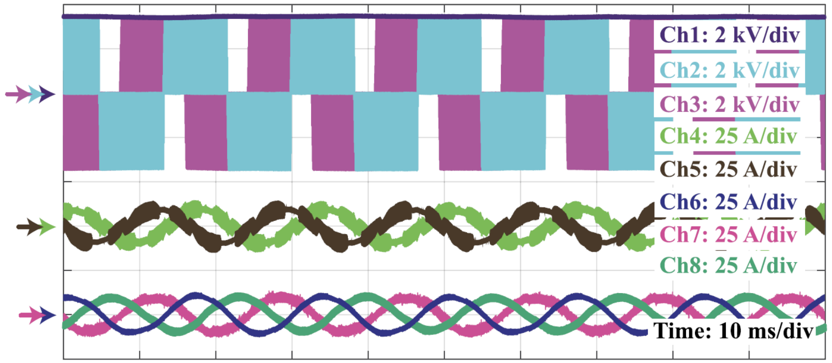
- Experimental Analysis @ 30kW | 3.5kV$_{DC}$ | f_{sw} = 10kHz — Xfrm Primary & Sec. Side Voltages / Currents

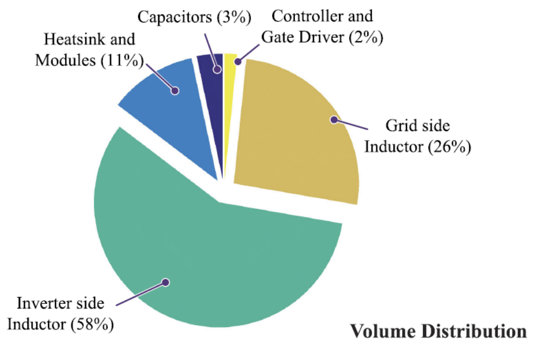
[Anurag2022, Anurag2022a]

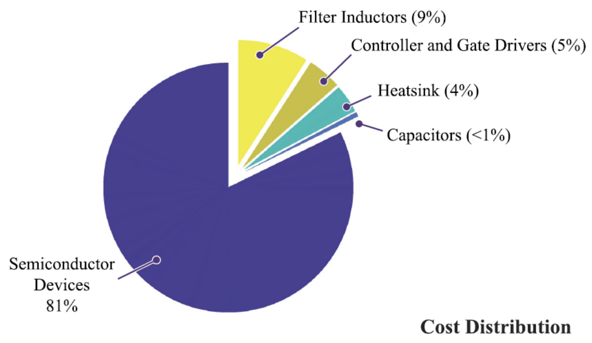
3-Φ 2-Level AC/DC—DC/DC—DC/AC SST (3)

- Experimental Analysis of MV Active Front-End Converter
- 30kW | 3.5kV$_{DC}$ | f_{sw} = 10kHz







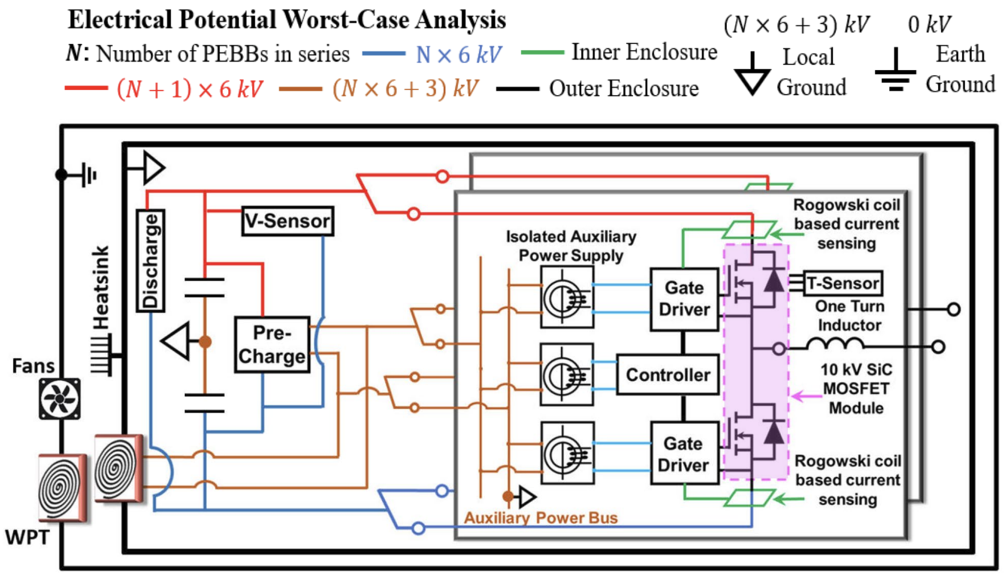


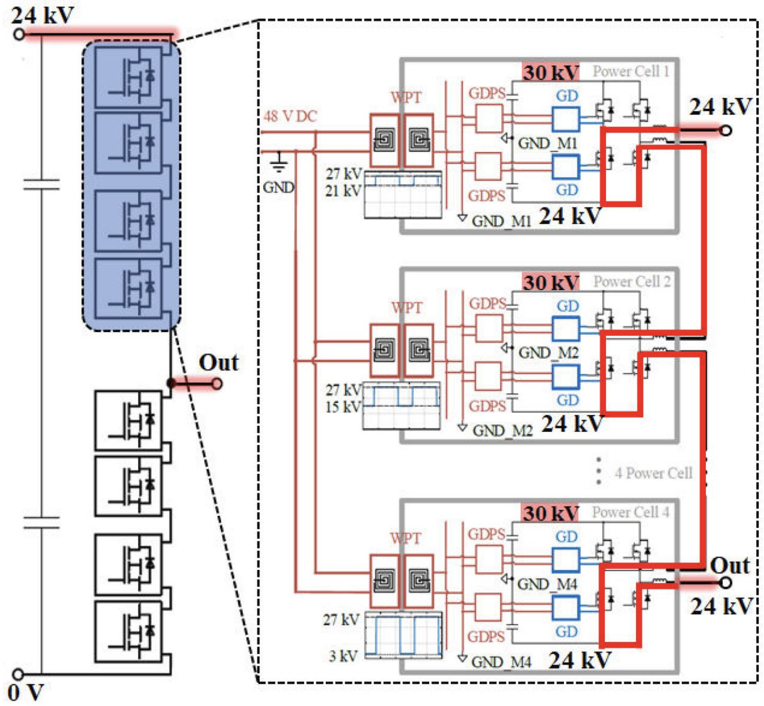
- Line-line Sw. Stage Voltages | Boost Ind. Currents | Mains Phase Currents — $\eta \approx 95.5\%$ @ 35kW
- Volume | Cost Distribution of MV Power Block | 0.2kW/dm³ | 550$ / kW | 0.6kW/kg

Center for Power Electronics Systems

10kV SiC Ultra-Compact High-Power PEBB

- 1MW Full-Bridge Power Electronics Building Block (PEBB)
- 10kV/240A XHV-6 Half-Bridge SiC MOSFET Modules | 6kV DC-Link
- $\rho \approx 15\ \mathrm{kW/dm^3}$





- Multi-Layer PCB MV Power Bus w/ Integr. Aux Power Distribution
- Voltage-Dependent Comp. Grouping / Isol. Coordination for 30kV CM Voltage w.r.t.e. | 25mm Heatsink Clearance
- Wireless or DC-Bus-Derived Aux. Supply / Curr. Loop Gate Drive Supply / Sw. Curr. Sensing / Temp. Sensing etc.

[Burgos2020, Dong2020, Mocevic2021, Mocevic2021a, Xu2022, Stewart2022, Lin2022, Fan2022]

10kV SiC Ultra-Compact High-Power PEBB

- 1MW Full-Bridge Power Electronics Building Block (PEBB)
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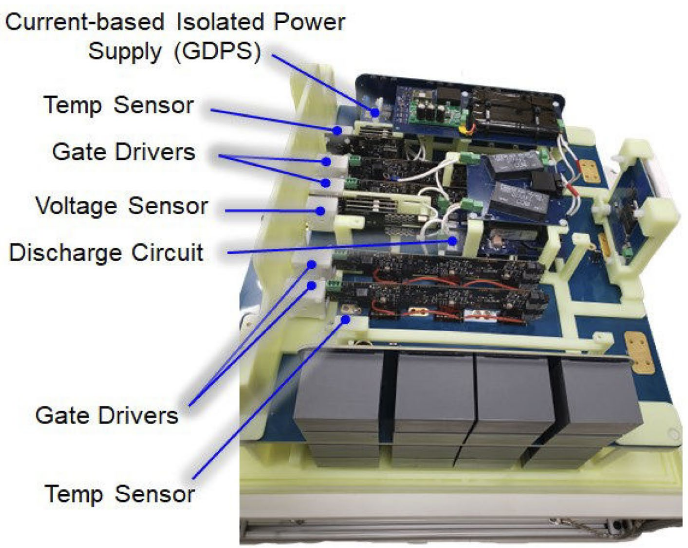

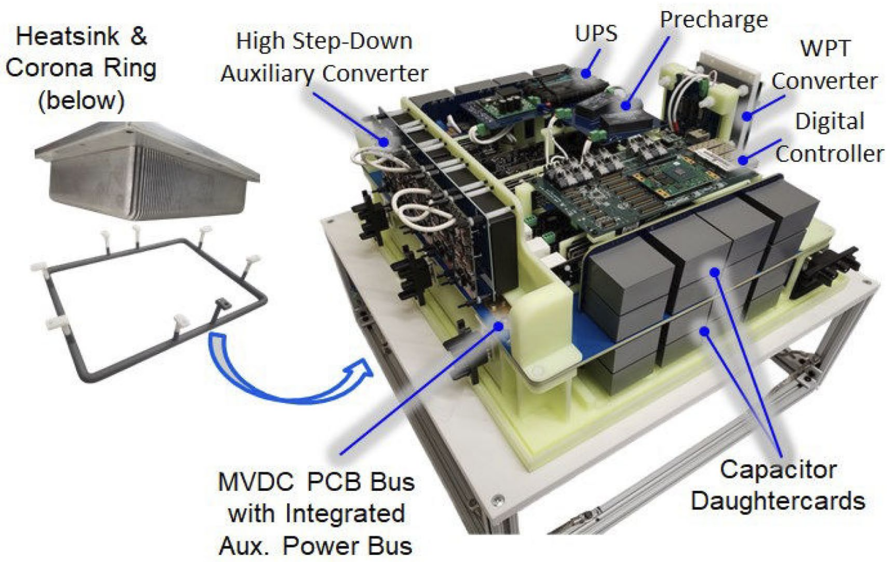

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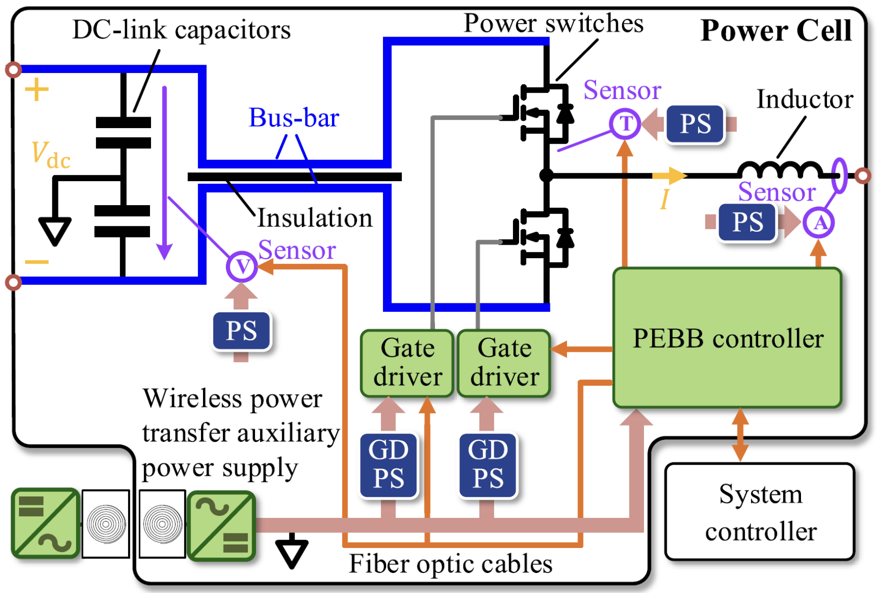
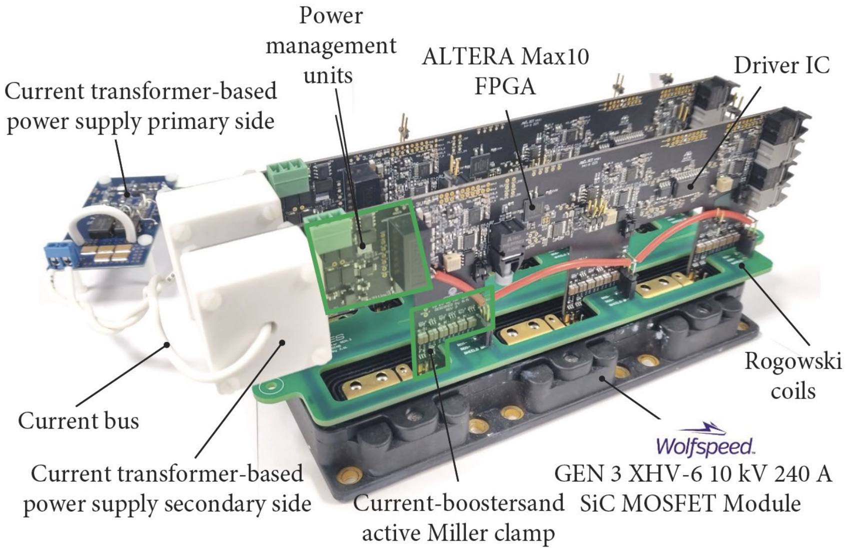
[Burgos2020, Dong2020, Mocevic2021, Mocevic2021a, Xu2022, Stewart2022, Lin2022, Fan2022]

10kV SiC Power-Cell w/ Integrated Output Inductor (1)

- 250kW Half-Bridge Power-Cell (HB-PEEB)
- 10kV/240A XHV-6 Half-Bridge SiC MOSFET Modules (4200kW/dm³) | 6kV DC-Link
- $\eta \approx 99.6\%$ @ f_{sw}= 5kHz | 99.3% @ 10kHz for D=0.5 Power Circulation
- $\rho \approx 12$ kW/dm³



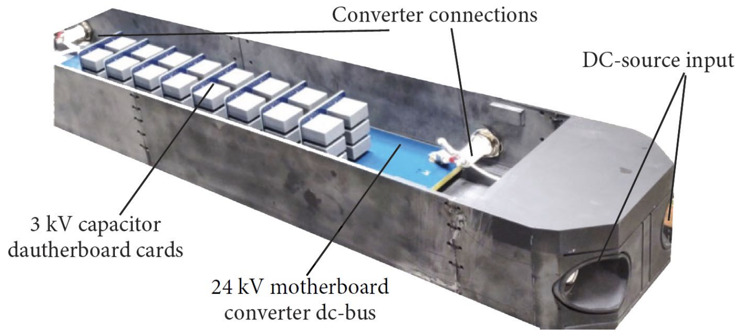


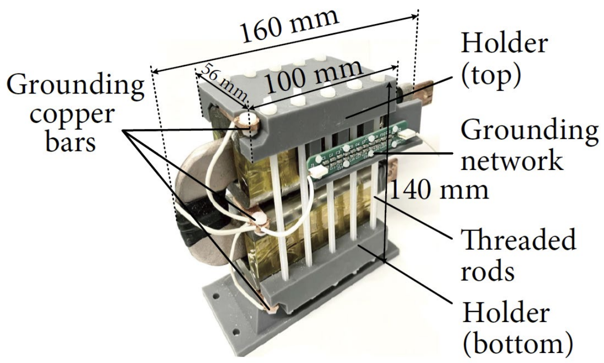
- Multi-Layer PCB DC-Bus | Gate Driver for 100V/ns Sw. Speed | PCB Rogowski Coil Sw. Curr. Sensing / Protection
- Local Controller & Voltage/Current Sensors | Wireless Aux. Supply | Curr. Loop GD supply | Temp. Sensing etc.

[Burgos2020, Dong2020, Mocevic2021, Mocevic2021a, Xu2022, Stewart2022, Lin2022, Fan2022]

10kV SiC Power-Cell w/ Integrated Output Inductor (2)

- 250kW Half-Bridge Power-Cell (HB-PEEB)
- 10kV/240A XHV-6 Half-Bridge SiC MOSFET Modules (4200 kW/dm³) | 6kV DC-Link
- $\eta \approx 99.6\%$ @ f_{sw} = 5kHz | 99.3% @ 10kHz for D=0.5 Power Circulation
- $\rho \approx 12$ kW/dm³



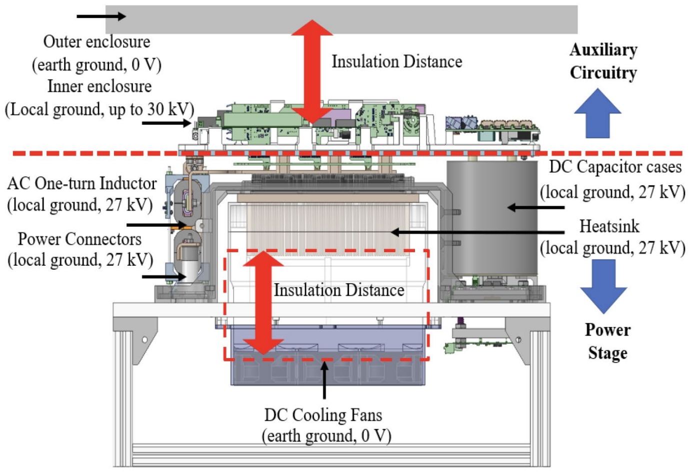


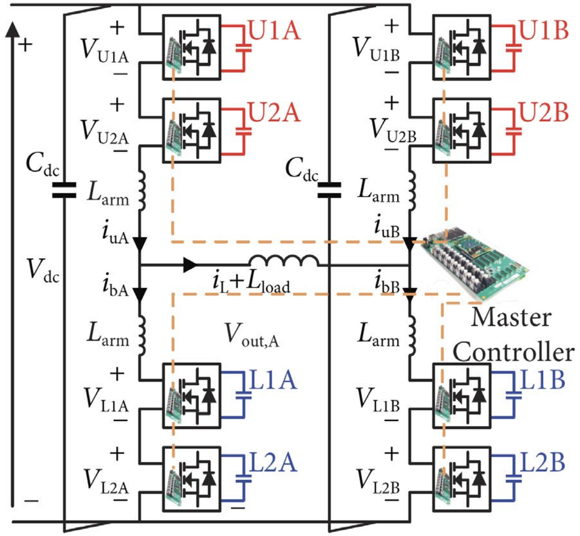
— Locally grounded wdg. outer shielding layer
— RC damping network btw shield & DC midpoint
— Double layer dielectric shield termination

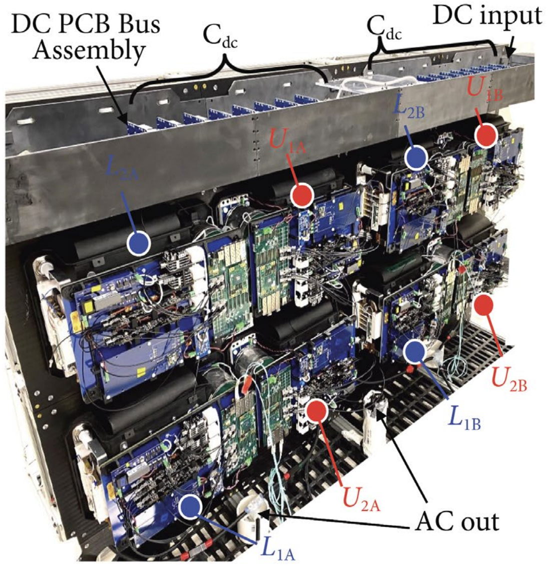
- Converter-Level PCB-Based DC-Bus Assembly | Power-Cell Integrated Output Inductor

10kV SiC Power-Cell w/ Integrated Output Inductor (3)

- Experimental Analysis in 2-Cell/Arm Converter | 12kV DC-Link
- $\eta \approx 99.2\%$ @ f_{sw}= 10kHz @ D=0.5 Power Circulation





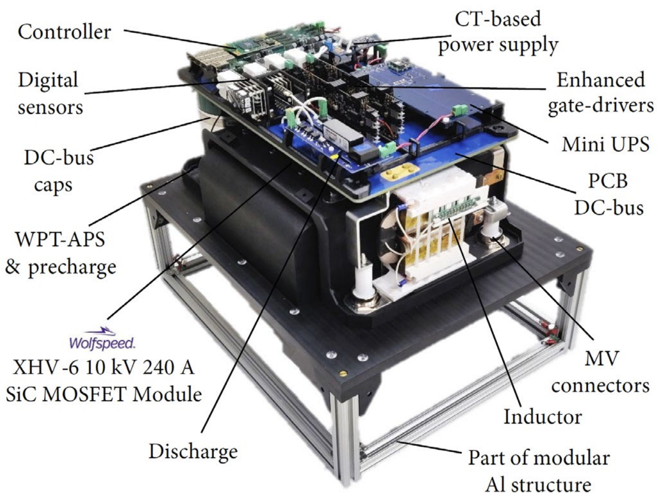


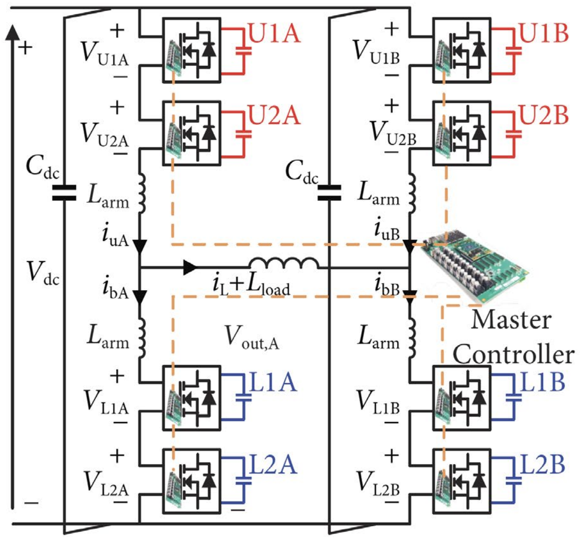
- 10kV SiC MOSFET-Based Power-Cell | 2-Cell/Arm MMC Bridge-Legs / Q2L-Modulation / Power Circulation

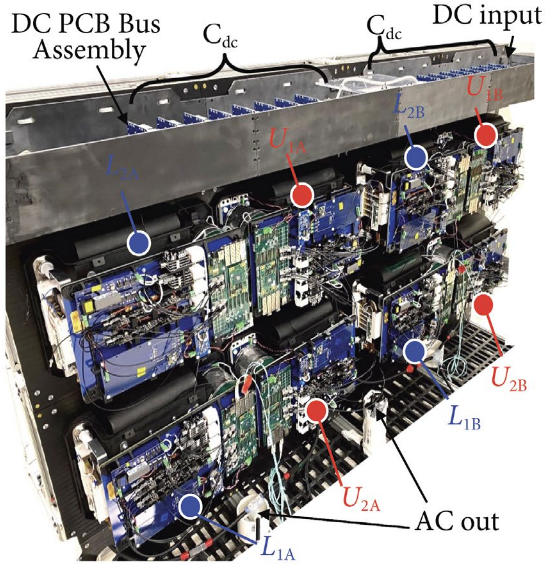
[Burgos2020, Dong2020, Mocevic2021, Mocevic2021a, Xu2022, Stewart2022, Lin2022, Fan2022]

10kV SiC Power-Cell w/ Integrated Output Inductor (4)

- **Experimental Analysis in 2-Cell/Arm Converter | 12kV DC-Link**
- **$\eta \approx$ 99.2% @ f_{sw}= 10kHz @ D=0.5 Power Circulation**



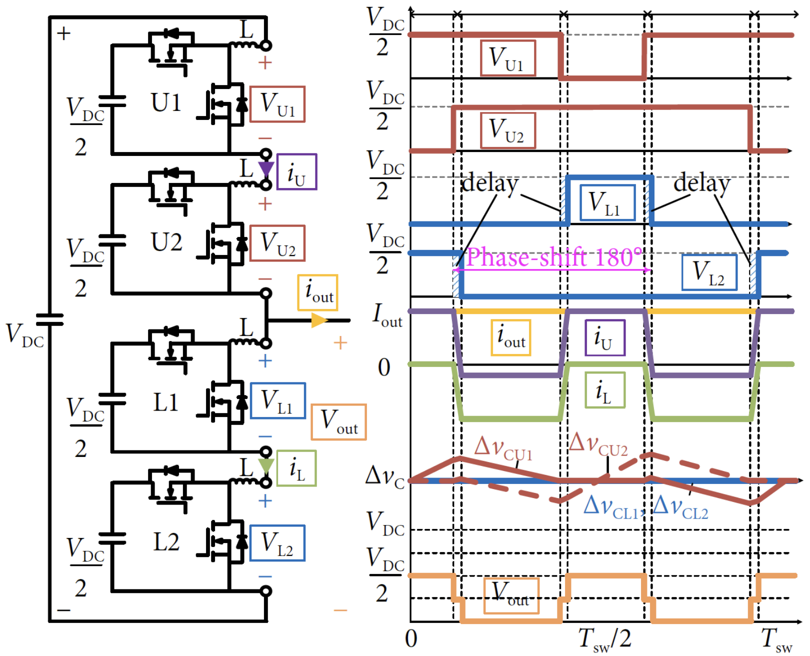


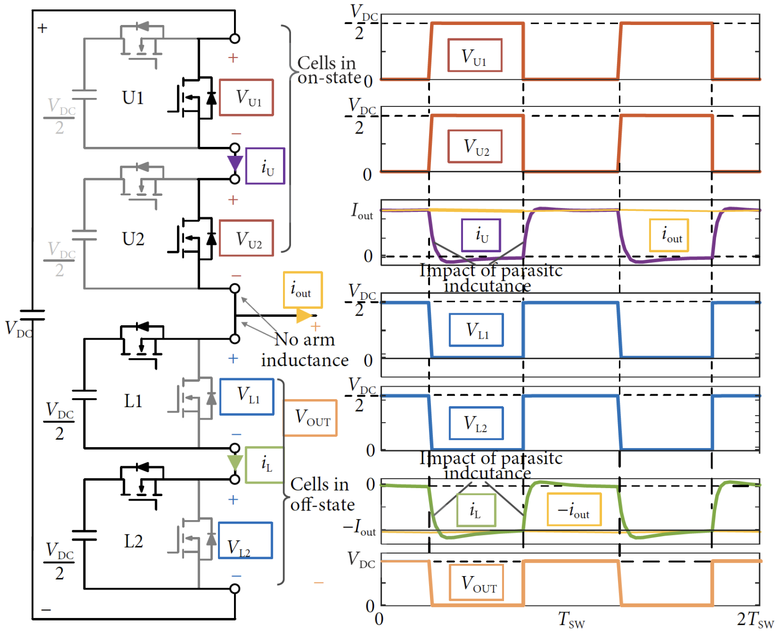


- **10kV SiC MOSFET-Based Power-Cell | 2-Cell/Arm MMC Bridge-Legs / Q2L-Modulation / Power Circulation**

Remark Advanced MMC Modulation Schemes

- Minimization of the Cell Capacitance & Arm Inductance
- Voltage Balancing of Cell Capacitors over Each Switching Cycle (SCC) — Enables DC/DC Operation (!)
- Quasi-2-Level (Q2L) Output Voltage Generation w/o Arm Inductor





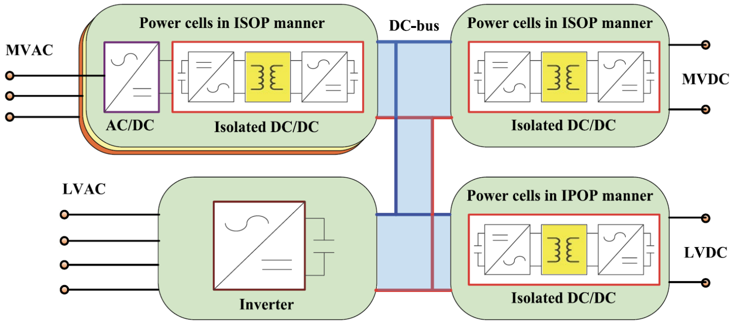
- SCC Cell Volt. Balancing & Shaping of Arm Currents | Q2L — Integr. Cap. Blocked Transistor (ICBT) Concept

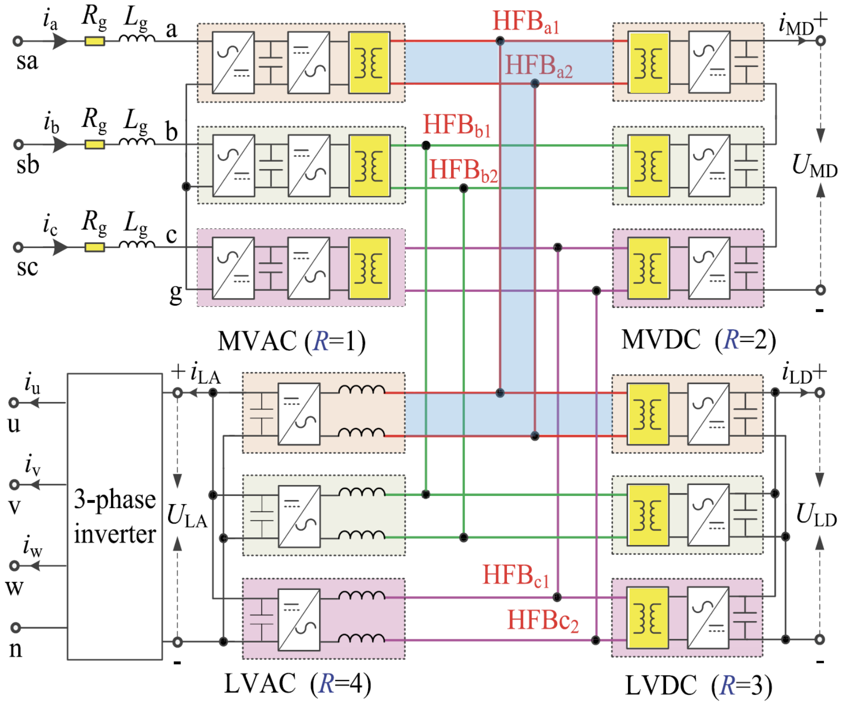
[Burgos2020, Dong2020, Mocevic2021, Mocevic2021a, Xu2022, Stewart2022, Lin2022, Fan2022]

清華大學
Tsinghua University

Medium-Frequency AC-Bus Multi-Port SST (1)

- Highly Modular / Scalable Modular Multi-Active Bridge (MMAB) Topology as Core Element
- MF Isolation / Synchronism of all Ports — Analogy to the 50/60Hz Grid



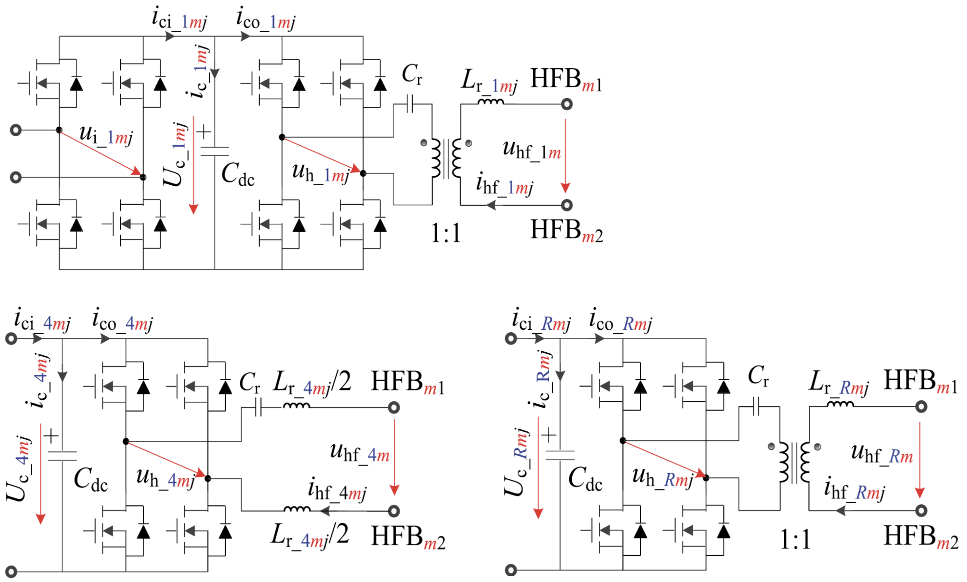


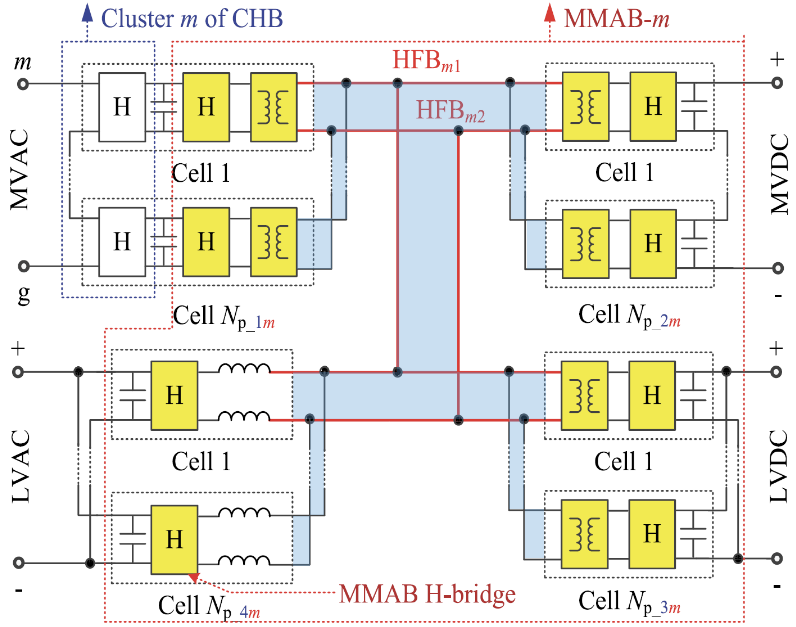
- MF AC-Bus Instead of DC-Bus Coupling of Converter Modules — Lower # of Converter Stages
- Direct Power Cross Coupling of all DC-Ports due to Missing Intermediate Energy Buffer Caps (!)

[Wen2021; see also Zumel2014]

Medium-Frequency AC-Bus Multi-Port SST (2)

- Individual Xfrms Instead of Single-Core Multi-Wgd Xfrm | Low Complexity Basic Converter Cells
- Large Number of Functional Combinations — ISOP / IPOP etc.



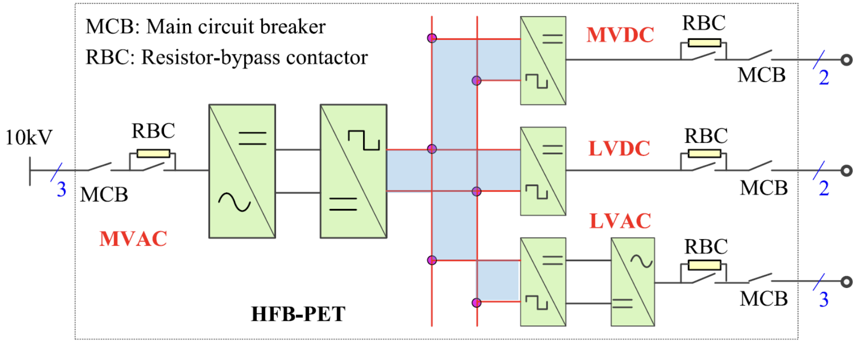


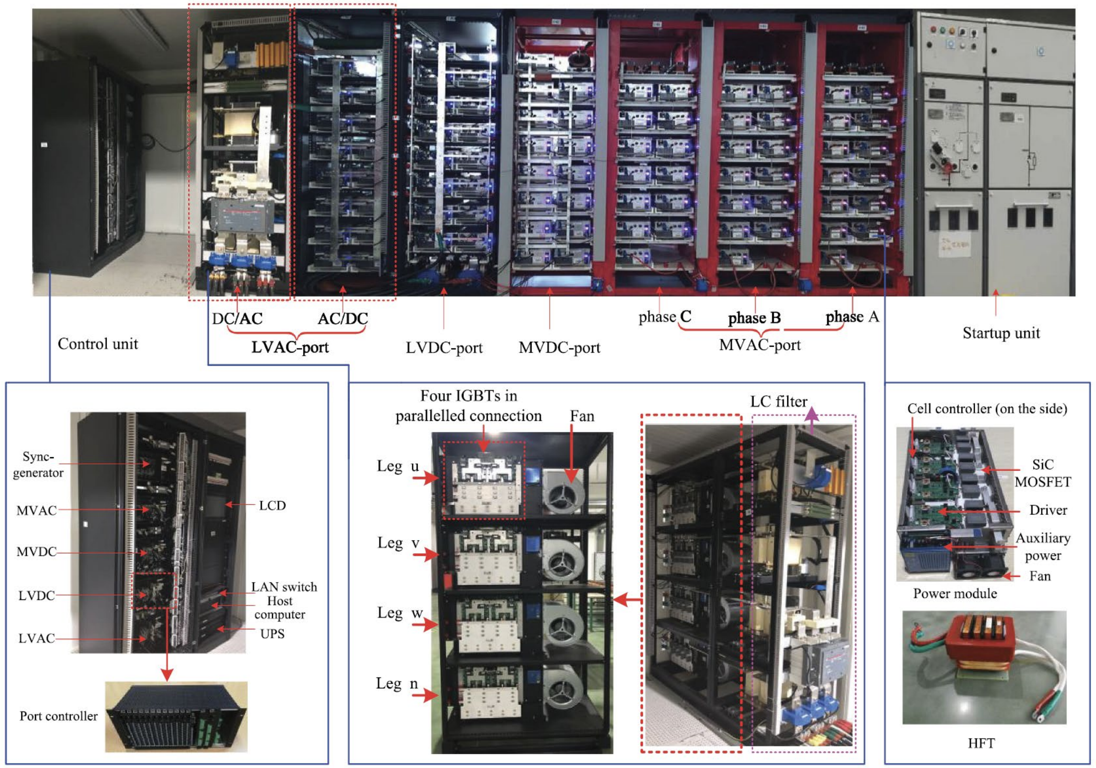
- 4-Port 1-Φ MVAC / MVDC / 1-Φ LVAC / LVDC SST Example
- Rectangular MF Voltages | DAB-Type Phase-Shift-Based Power Flow Control | Cross-Coupling Challenge (!)

Medium-Frequency AC-Bus Multi-Port SST (3)

- 2MVA 4-Port 3-Φ MVAC / MVDC / 3-Φ LVAC / LVDC Industrial Prototype
- 3 MMAB Units Corresponding to Phases of the 3-Φ AC-Ports / 2 MF AC-Buses per MMAB

10kV MVAC-Port
10kV MVDC-Port
750V LVDC-Port
380V LVAC-Port



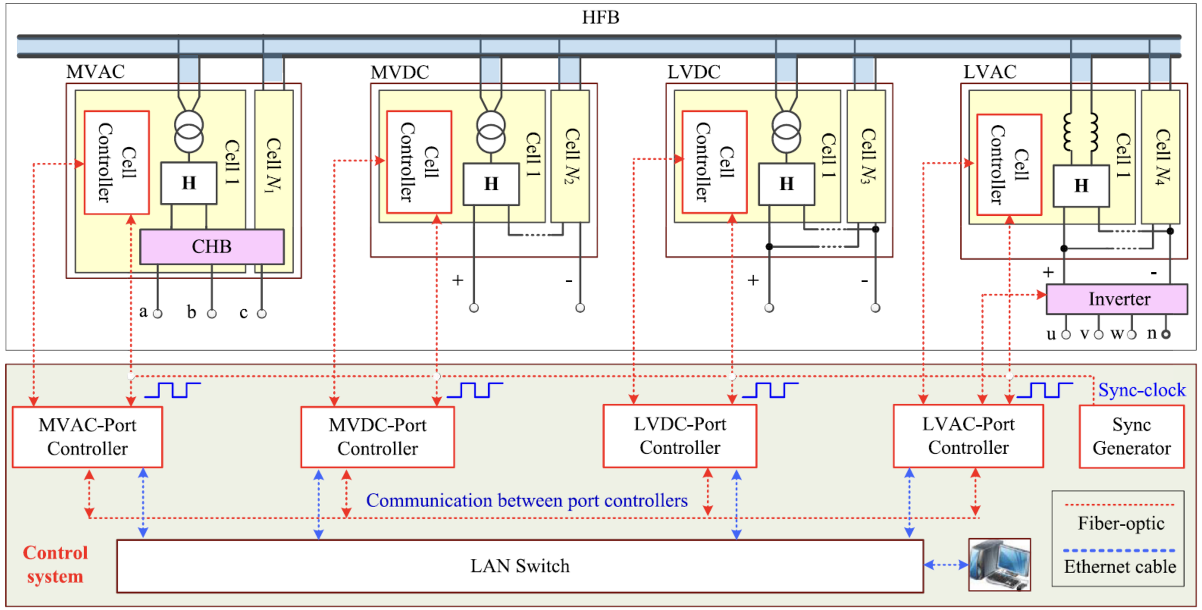


- 1200V/120A SiC MOSFETs | f_{sw}= 20kHz | 1:1 Xfrms / Ferrite UF130 | 850V_{DC} Cell DC-Link / Output Voltage

[Wen2021]

Medium-Frequency AC-Bus Multi-Port SST (4)

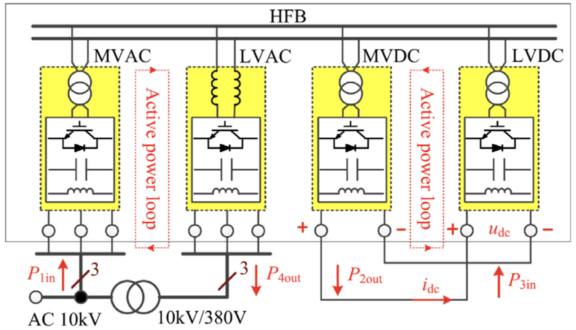
- 2MVA 4-Port 3-Φ MVAC / MVDC / 3-Φ LVAC / LVDC Industrial Prototype
- Hierarchical — Cell/Port/System — Control Framework with Global Synchronous Clock

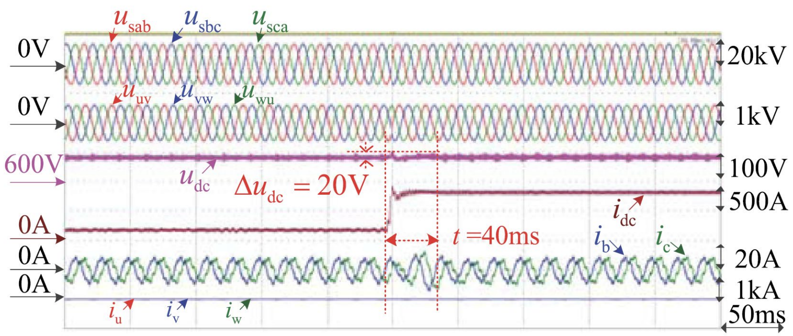


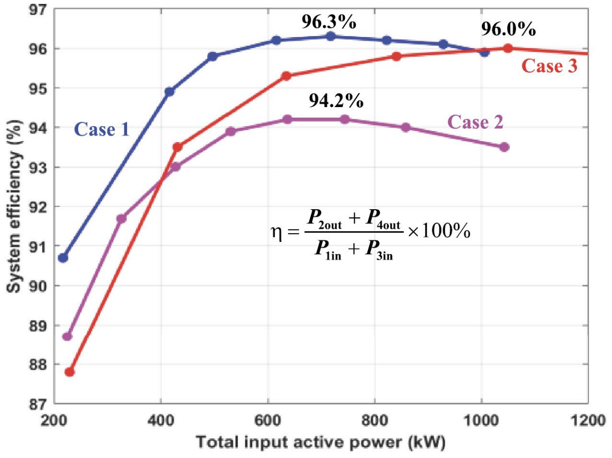
- Power Cross Coupling Suppression of MMAB Ports by Feedforward Control
- Power Decoupling Control of MVAC CHB Converter Enables Unbalanced Grid Operation
- Cell-Power Balance Control of the MVDC CHB Cells Ensures Equal DC-Link Voltages

Medium-Frequency AC-Bus Multi-Port SST (5)

- **Experimental Analysis** of 10kV / 2MVA 4-Port MVAC / MVDC / LVAC / LVDC Industrial Prototype
- Power Circulation Back-to-Back Connection of the Converter Modules







Case 1: $P_{4out} = 0$. Case 2: P_{2out} is about 90~100 kW.

Case 3: P_{2out} and P_{4out} increase from ~100kW to ~600kW in steps of 100kW.

- Series-to-Parallel Rearrangement of MVDC-Port Cells & Parallel Connection to LVDC-Port
- **Dynamic Behavior for Load Step of DC-Loop Power Circulation | Power Conversion Efficiency**

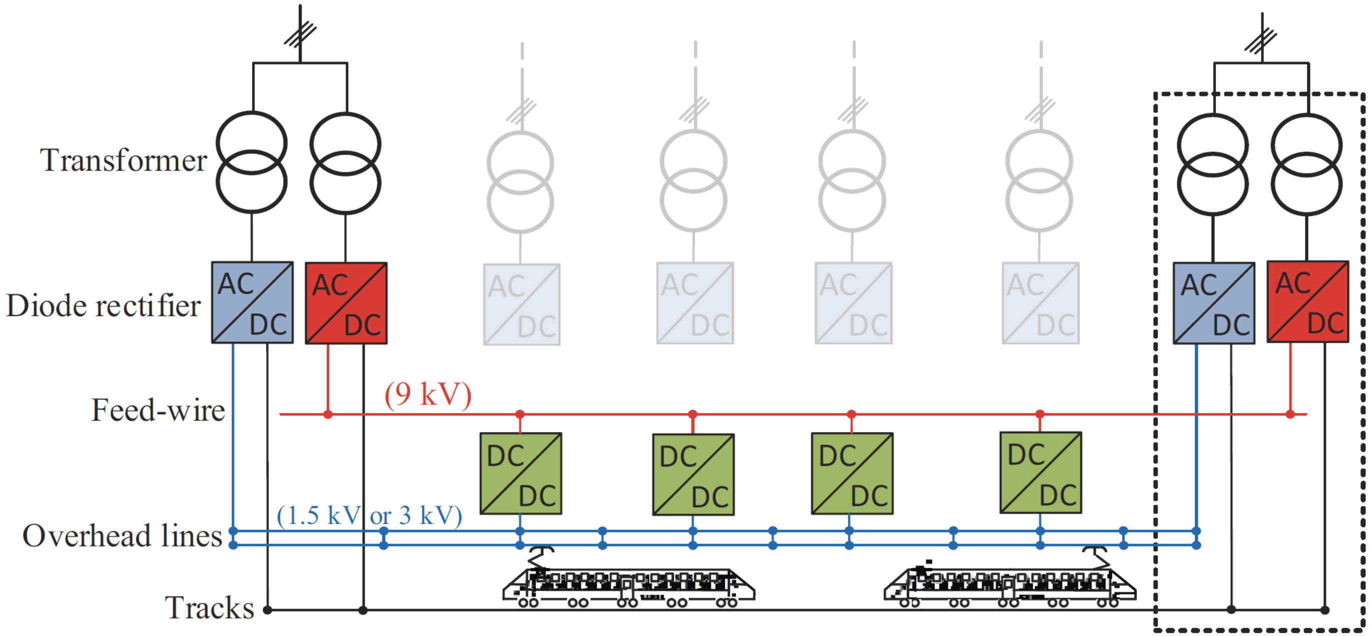
[Wen2021]

TOULOUSE INP

Institut National Polytechnique
de Toulouse

DC/DC SST for Future MVDC Railway Electrification (1)

- Increase in Regional & Freight Traffic Results in Higher Traction Power Demands
- Extension of Current 1.5kV | 3kV SNCF DC System (1000mm^2) with Parallel 9kV DC-Bus

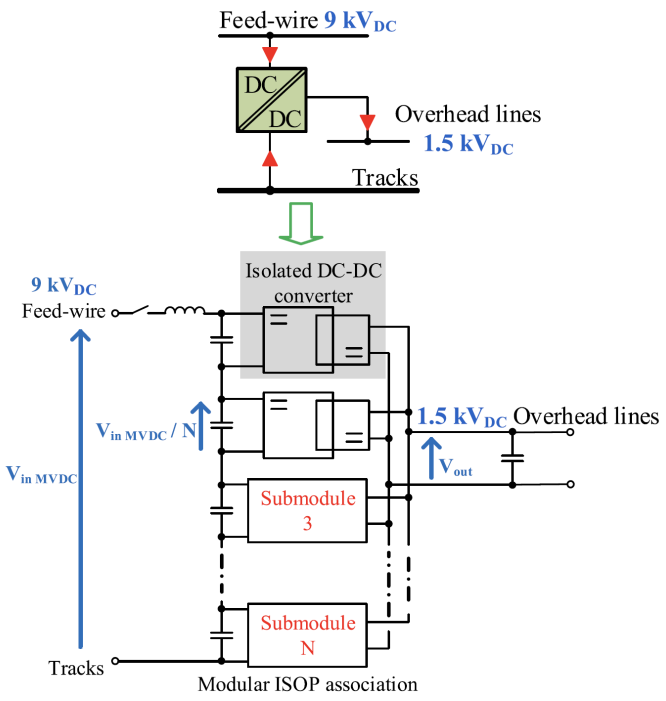


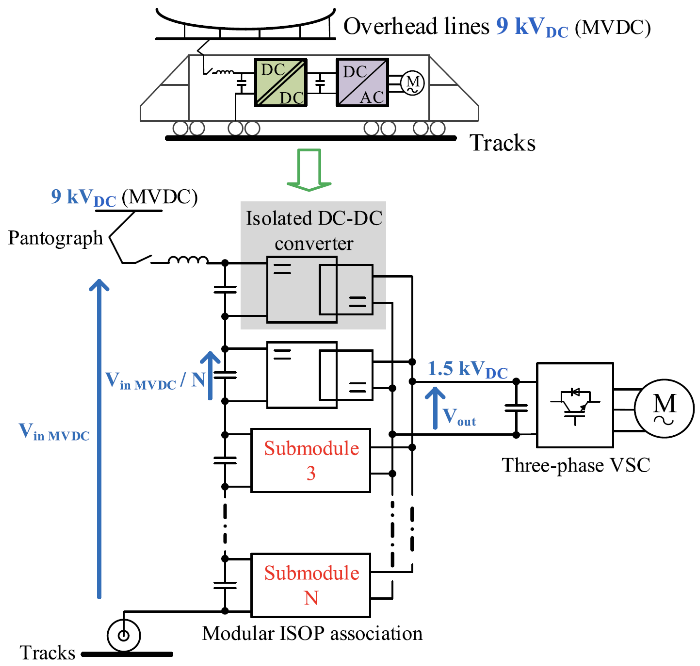
- DC/DC SSTs Instead of New AC/DC Substations — Lower Realization Effort | Higher Eff.
- Potential 9kV DC-Interface to Renewable Energy / Energy Storage / HVDC Lines etc.

[Fabre2019, Fabre2021, Fortes2021, Stackler2021]

DC/DC SST for Future MVDC Railway Electrification (2)

- **Increase in Regional & Freight Traffic Results in Higher Traction Power Demands**
- **Extension of Current 1.5kV | 3kV SNCF DC System ($1000mm^2$) with Parallel 9kV DC-Bus**



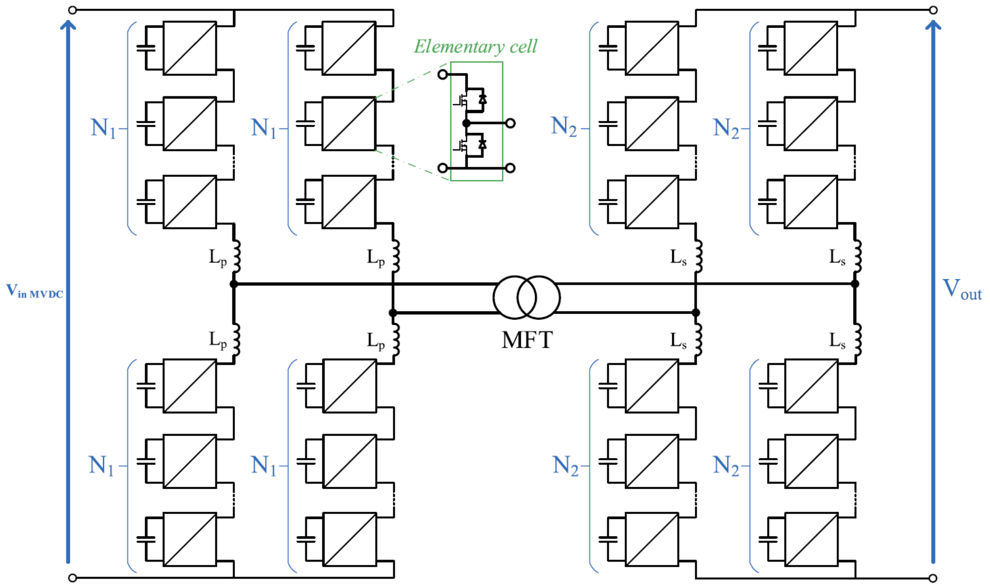


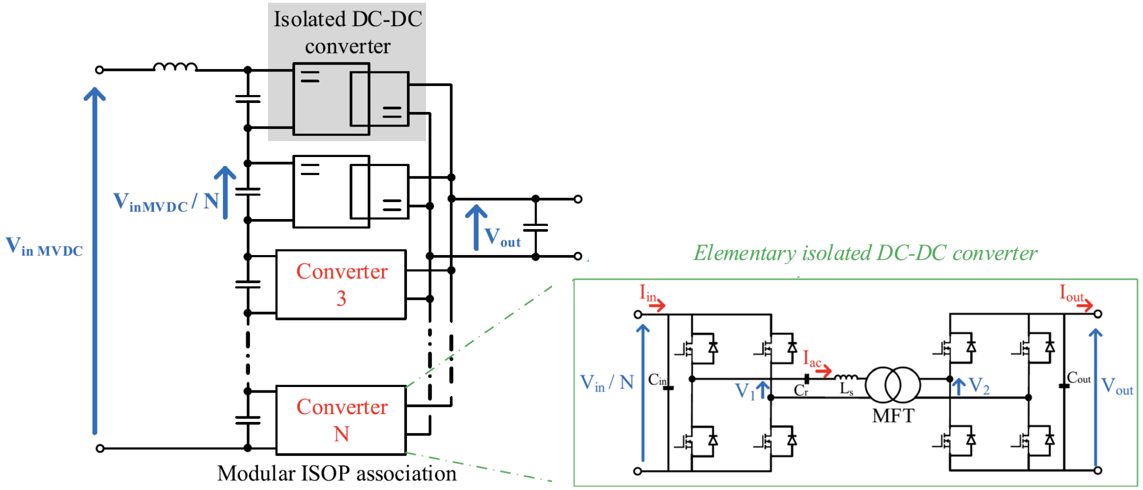
- **Future Elimination of 1.5kV Overhead Lines — Onboard 9kV/1.5kV DC/DC Conversion**

[Fabre2019, Fabre2021, Fortes2021, Stackler2021]

DC/DC SST for Future MVDC Railway Electrification (3)

- **CHB Arrangement vs. MMLC — Lower Stored Energy / Lower Losses / Lower Control Complexity**
- **Required 20kV Isolation Level can be Accommodated in Rel. Low Volume CHB Xfrms**



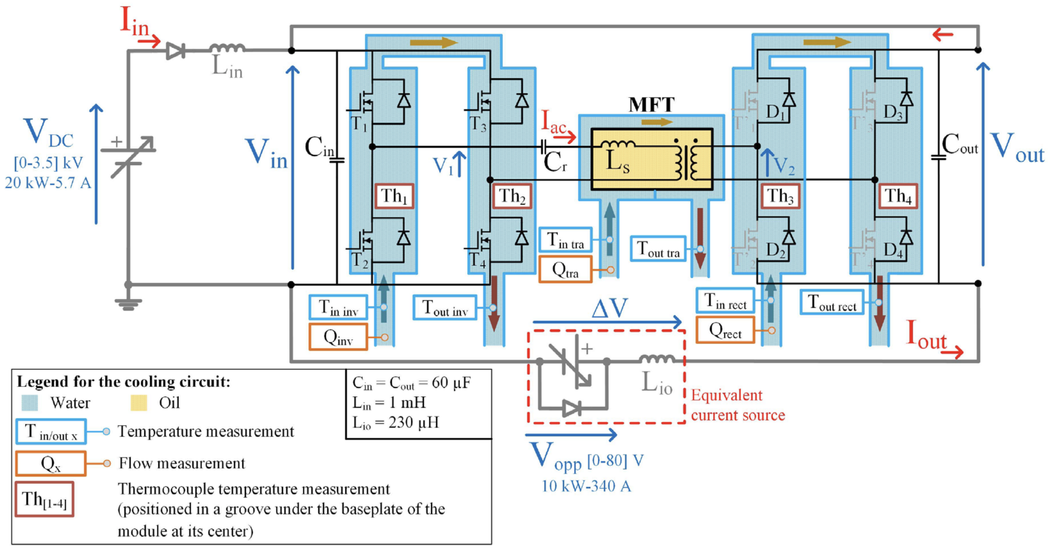


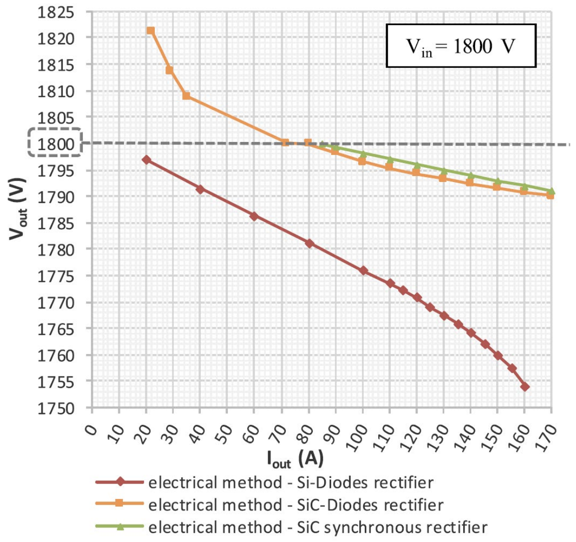
- **Series Res. Soft-Switching DCX-type CHB Conv. Stages | Lower React. Power Compared to DAB Operation**

[Fabre2019, Fabre2021, Fortes2021, Stackler2021]

DC/DC SST for Future MVDC Railway Electrification (4)

- Demonstrator System — 300kW | f_{sw}= 15kHz | 1.5kV/1.5kV DC/DC Conversion
- 3.3kV / 750A SiC MOSFETs | 400kVA 1:1 Water-Cooled Nanocryst. Core Oil-Tank MFT



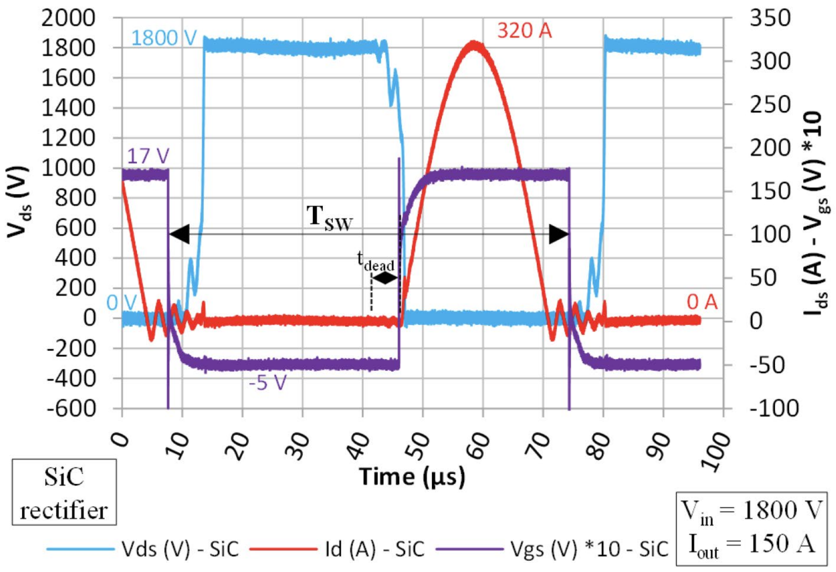


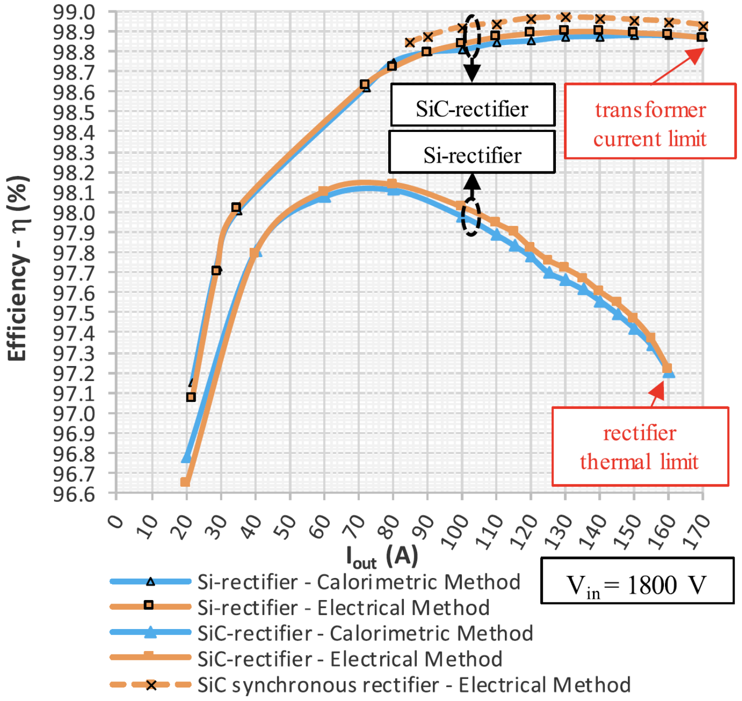
- Direct Connection of Converter Input and Output / Load Power Circulation
- Load Dependence of DCX V_{out} for Synchr. Rect. / SiC Diodes (750A) / Si Diodes (500A) – Paras. Cap. V_{out} Increase

[Fabre2019, Fabre2021, Fortes2021, Stackler2021]

DC/DC SST for Future MVDC Railway Electrification (5)

- Demonstrator System — 300kW | f_{sw}= 15kHz | 1.5kV/1.5kV DC/DC Conversion
- 3.3kV / 750A SiC MOSFETs | 400kVA 1:1 Water-Cooled Nanocryst. Core Oil-Tank MFT



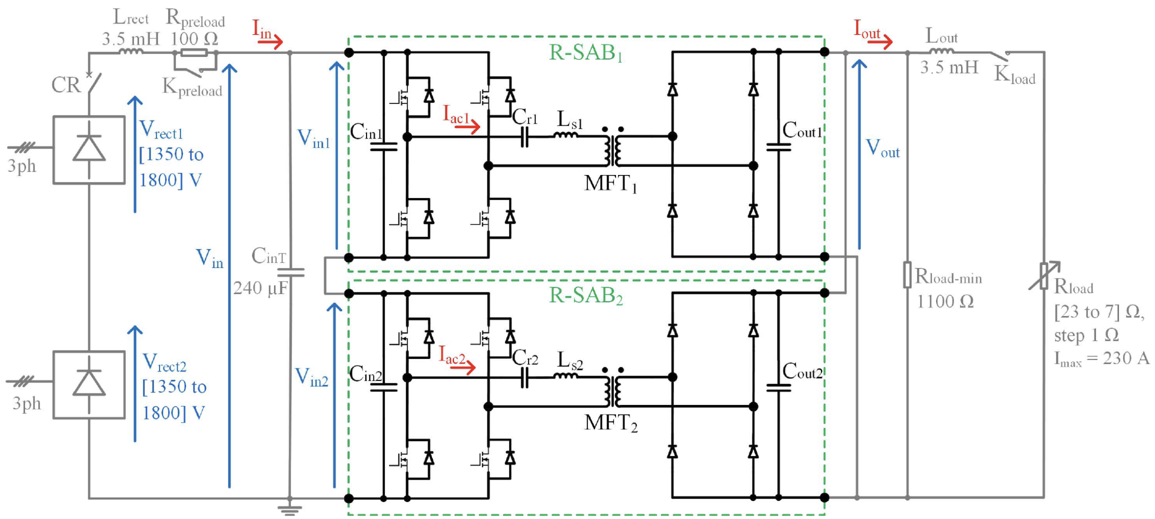


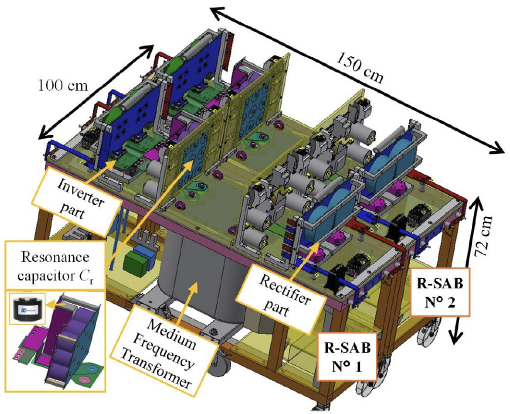
- Characteristic Waveforms for SiC Rect. Diodes
- Load Dependency of Converter Efficiency

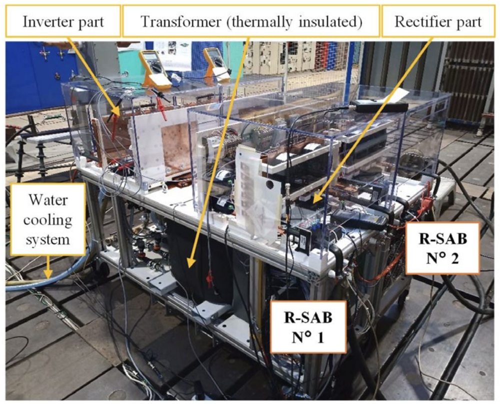
[Fabre2019, Fabre2021, Fortes2021, Stackler2021]

DC/DC SST for Future MVDC Railway Electrification (6)

- 2-Stage ISOP Demonstrator System — 600kW | 3.6kV/1.8kV DC/DC Conversion | $\rho \approx 0.6$ kW/dm³





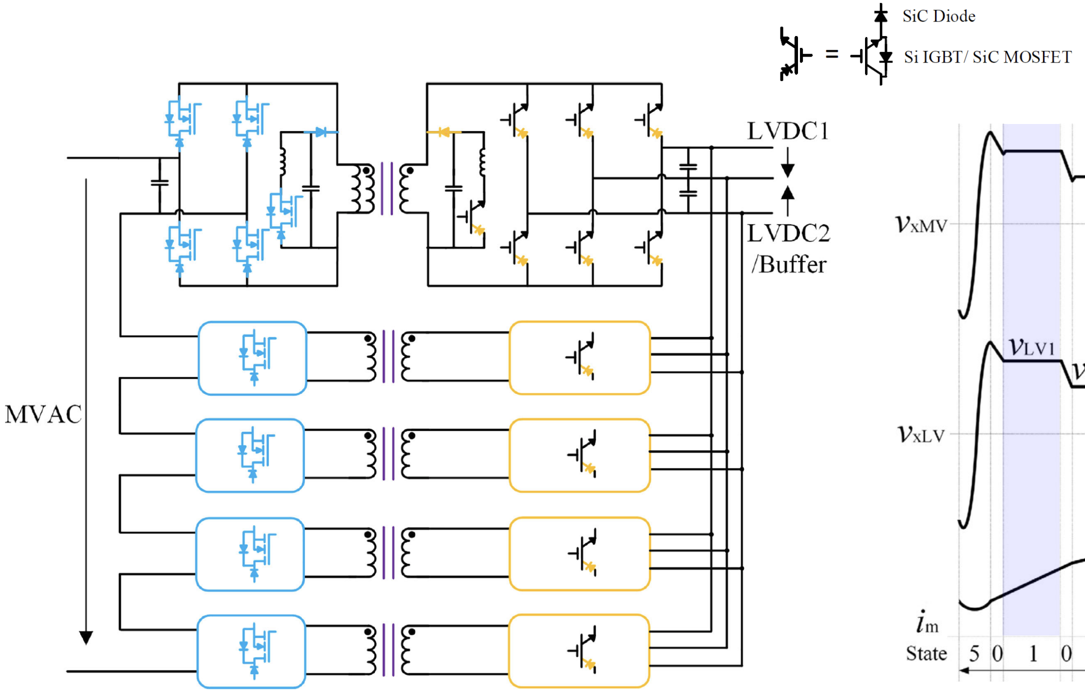


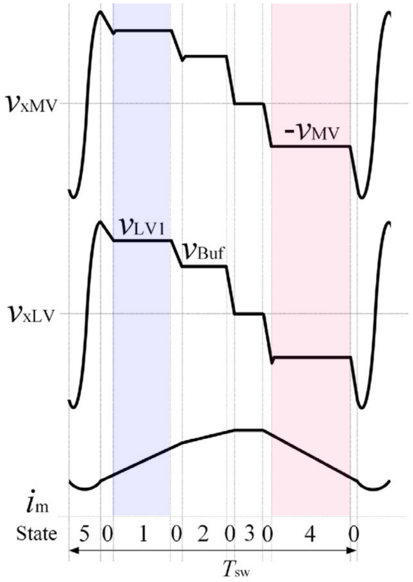
- Natural Voltage and Current Sharing Exp. Confirmed
- Interleaving of 2 Converter Stages Results in 4x 15kHz = 60kHz Output Voltage Ripple

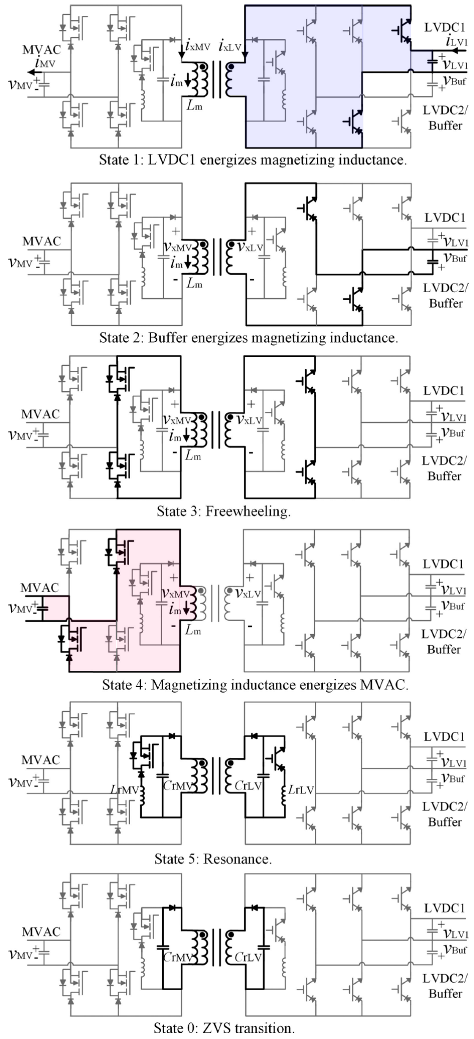
Georgia Tech

S4T – Soft-Switching Multi-Port SST (1)

- Modular Single-Stage Isol. Current Source Topology — M-S4T
- Cycle-by-Cycle Flyback-Type Power Transfer
- Full-Range ZVS Aux. Commutation Circuit





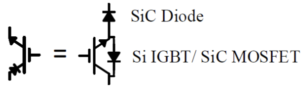


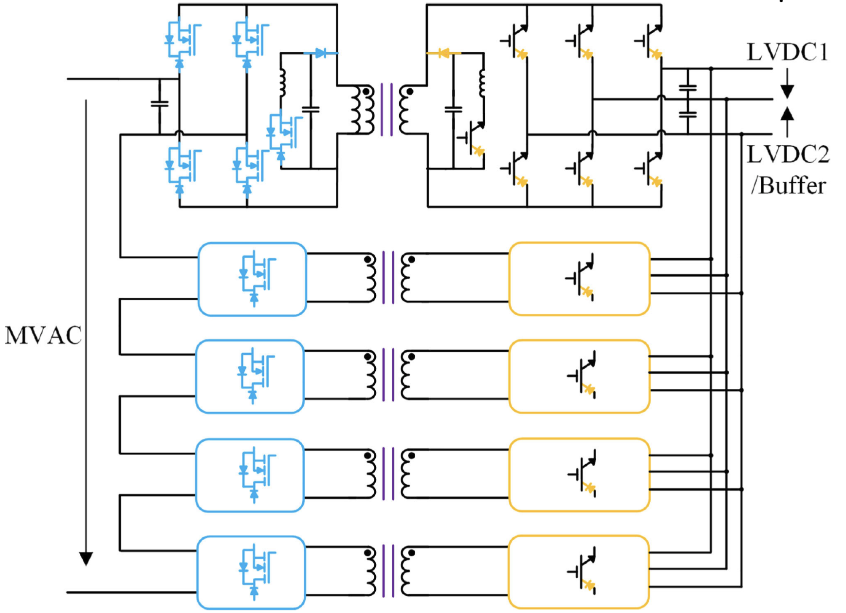
- DC/1-Φ AC System/Integr. Power Pulsation Buffer 3-Port System
- Sw. Cycle Waveforms & Operating States for LV/MV Power Transfer

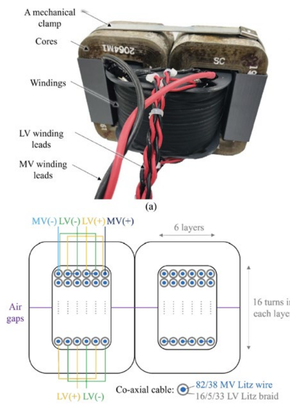
[Chen2018, Mauger2020ff., Zheng2020ff.]

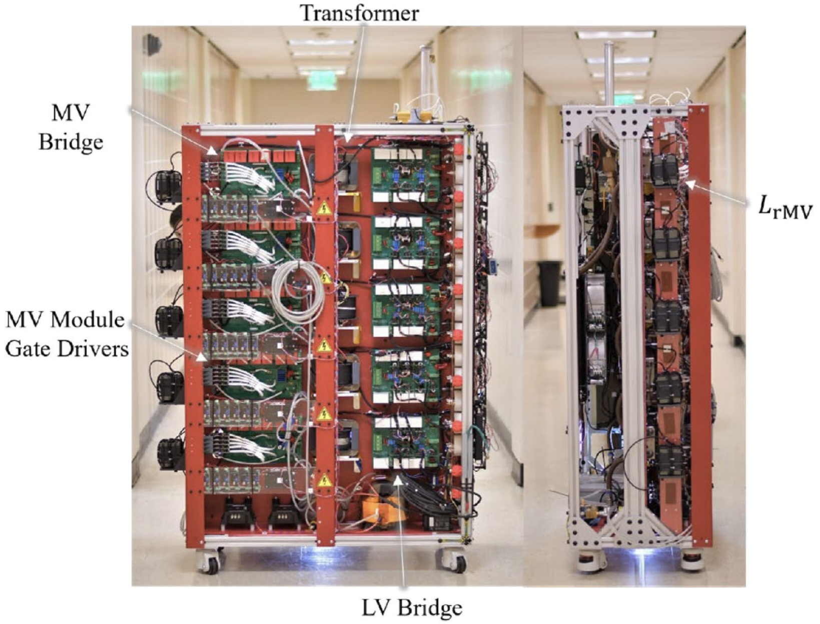
S4T – Soft-Switching Multi-Port SST (2)

- Modular Single-Stage Isol. Current Source Topology — M-S4T
- Cycle-by-Cycle Flyback-Type Power Transfer
- Full-Range ZVS Aux. Commutation Circuit







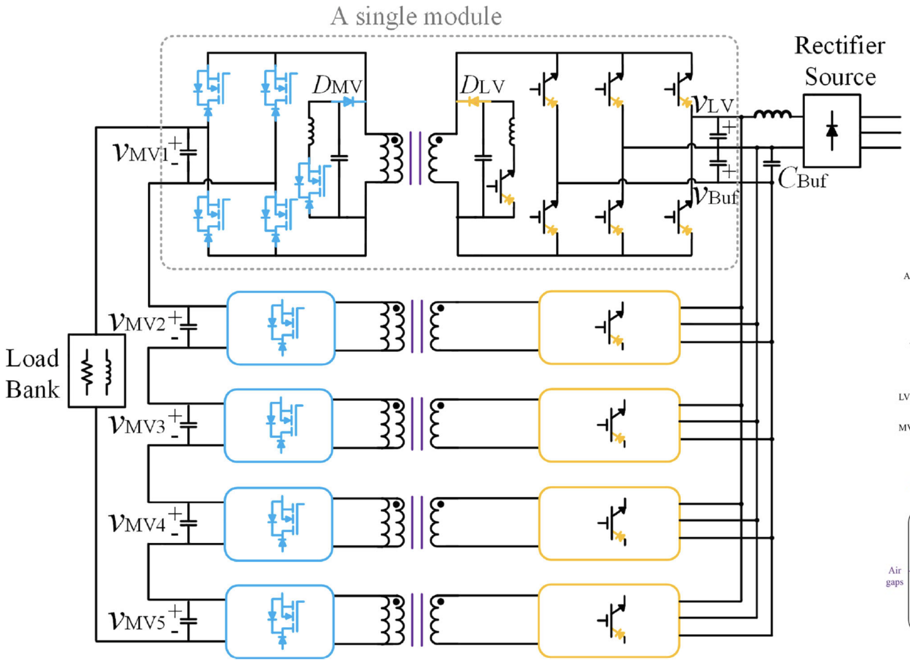


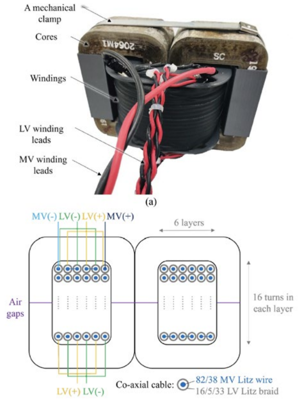
- 1-Φ 7.2kV 50 kVA 5-Module ISOP Demonstrator | 90kV BIL | DC/AC Operation | U_{in}= 350V_{DC}
- 3.3kV SiC MOSFET Module & Series SiC Diode | 650V Si IGBT & Series SiC Diode | f_{sw}= 16kHz
- Low Leakage Inductance 6:1 Xfrm Tested to 55kV Basic Insul. Level (BIL) | Nanocryst. Core w/ Airgap

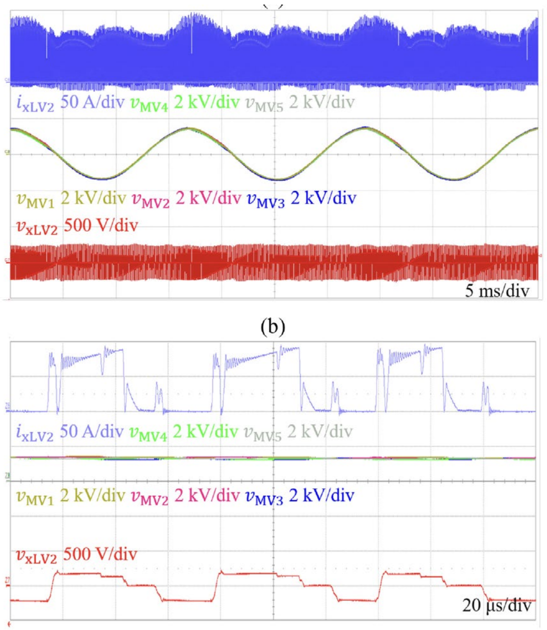
[Chen2018, Mauger2020ff., Zheng2020ff.]

S4T – Soft-Switching Multi-Port SST (3)

- Modular Single-Stage Isol. Current Source Topology — M-S4T
- Cycle-by-Cycle Flyback-Type Power Transfer
- Full-Range ZVS Aux. Commutation Circuit



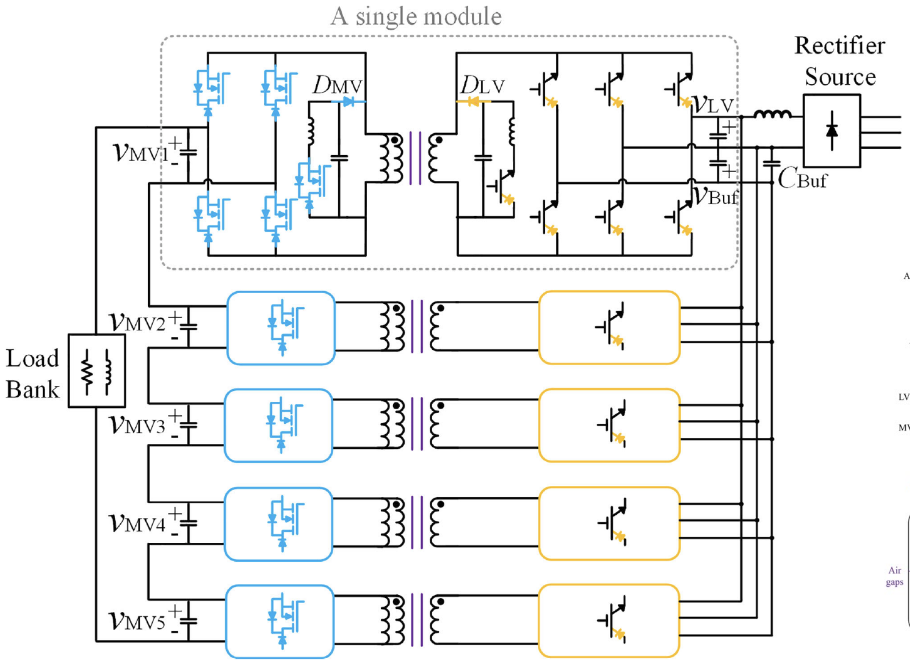


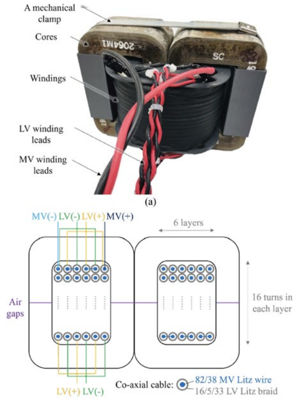


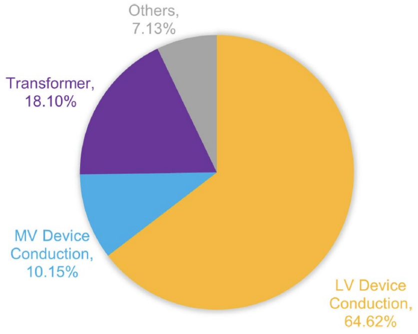
- Exp. Waveforms for 5-Module System | 20kVA @ 7.5kV$_{pk}$ | Line Cycle & Sw. Cycles | Low *dv/dt* of v_{xLV}

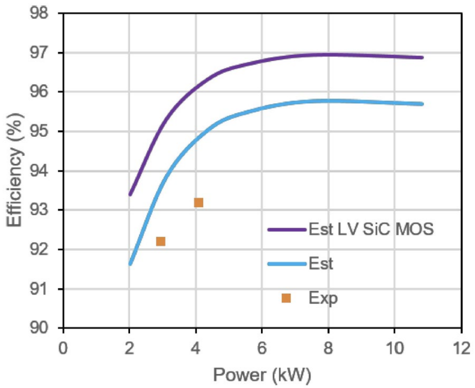
S4T – Soft-Switching Multi-Port SST (4)

- Modular Single-Stage Isol. Current Source Topology — M-S4T
- Cycle-by-Cycle Flyback-Type Power Transfer
- Full-Range ZVS Aux. Commutation Circuit









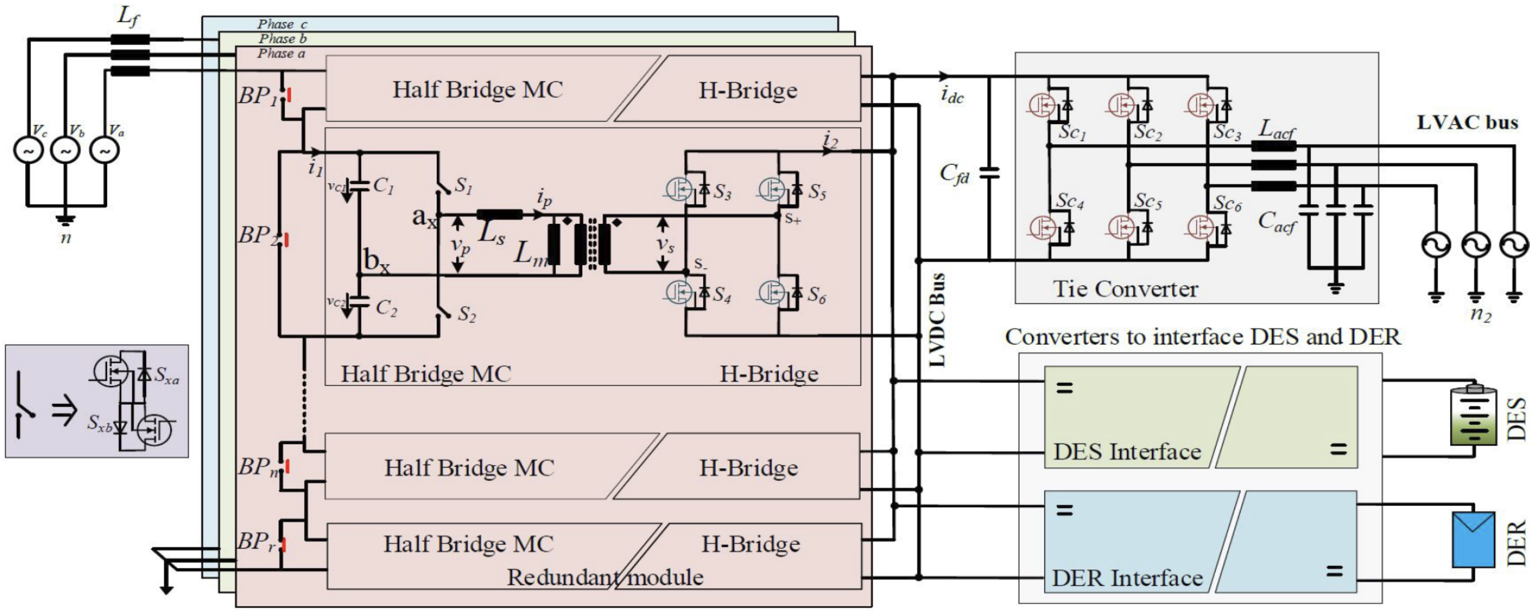
- Efficiency of a 10kVA 1.4kV/350V SST Module | Estimated Loss Breakdown

[Chen2018, Mauger2020ff., Zheng2020ff.]

NUS
National University of Singapore

3-Φ Phase-Modular IFE-Type ISOP SST Topology (1)

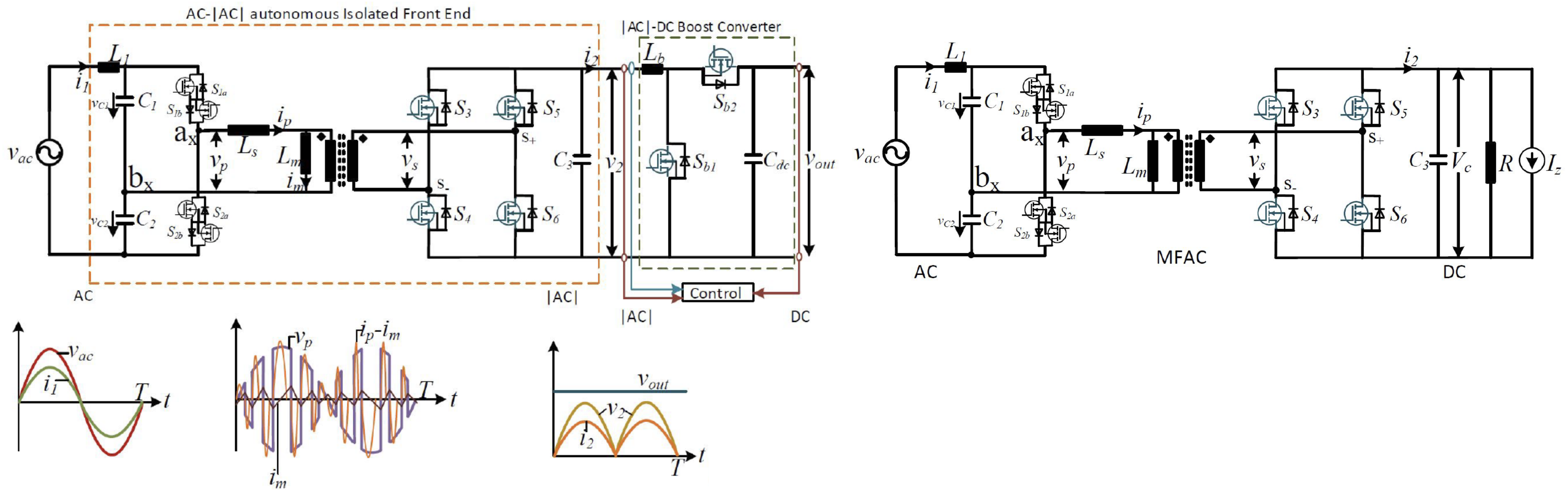
- Cascaded Single-Stage Dual-Active-Bridge-(DAB)-Based AC/DC Converter Sub-Modules
- Half-Bridge Primary Minimizes Number of MV-Side Power Semiconductors
- Application as Bidirectional 3-Φ Mains Interface of LV DC Nanogrids



- DAB AC/DC Operation → Single-Stage Power Conversion / High Component Current Stresses

3-Φ Phase-Modular IFE-Type ISOP SST Topology (2)

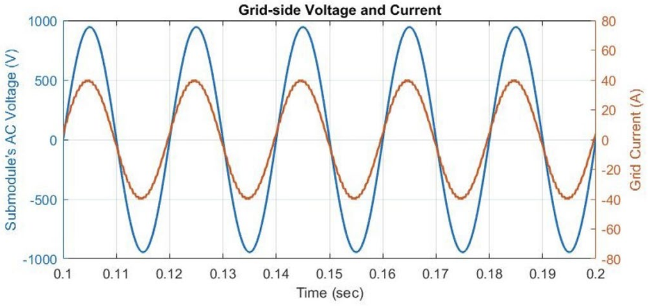
- Comparison of Two-Stage – Swiss SST – and Single-Stage DAB-Based AC/DC Power Conversion
- Funct. Separation OR Integration of MF AC Generation | Volt. Scaling | Rectification | Sin. Current Shaping

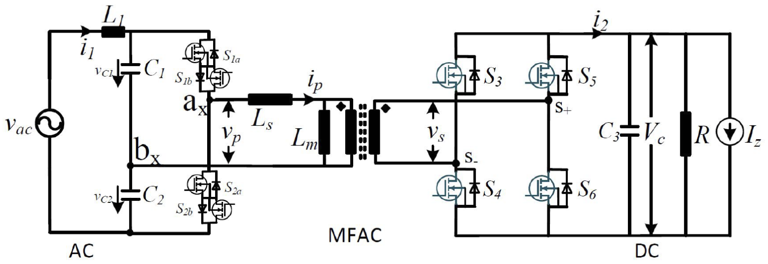


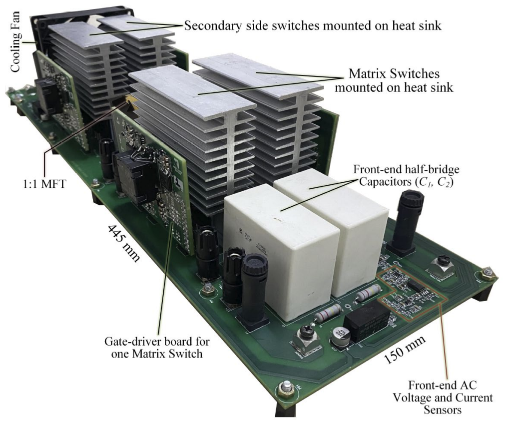
- Swiss SST Input Stage — Autonomous DCX-Type |AC| Voltage / Current Conversion @ Const. Duty Cycle
- Trade-Off Concerning Power Circuit & Control Complexity | Component Stresses

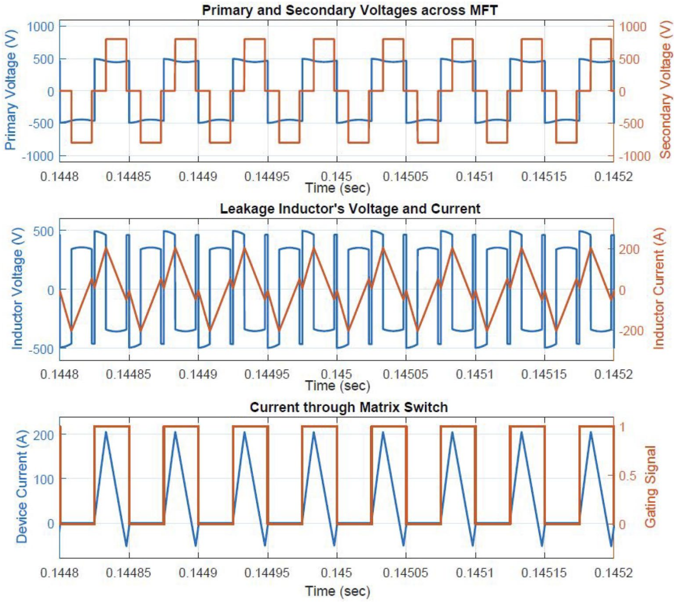
3-Φ Phase-Modular IFE-Type ISOP SST Topology (3)

- **Simulation of Sub-Module Operation — V_{ac} = 545V_{rms}, V_c = 800V_{DC}, P = 17.6kW, f_{sw} = 20kHz**
- **Modulation Ensuring Unity Power Factor Operation & ZCS**









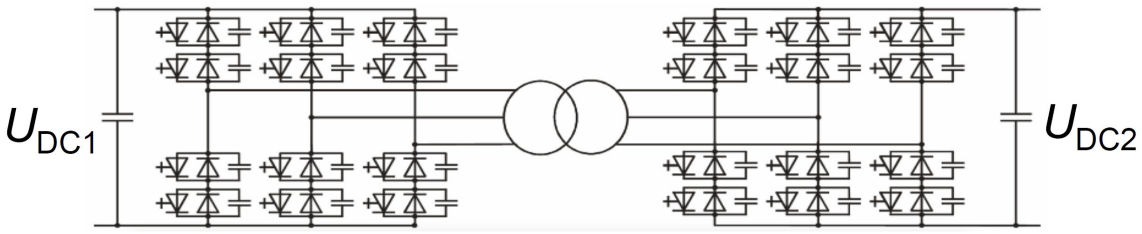
- **Mains Frequency Envelope of Square Wave Transformer Primary Voltage**
- **3-cell 15kVA 1.5kV_{rms} / 450V_{DC} Hardware Demonstrator | η ≈ 96% | ρ ≈ 3kW/dm³**

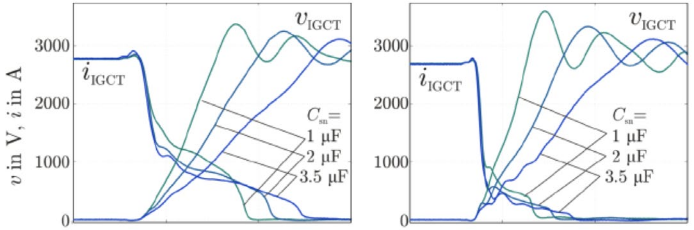
[Saha2018ff.]

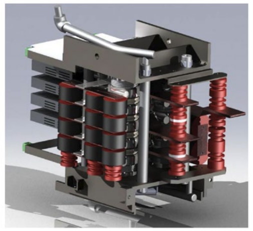
RWTH AACHEN UNIVERSITY

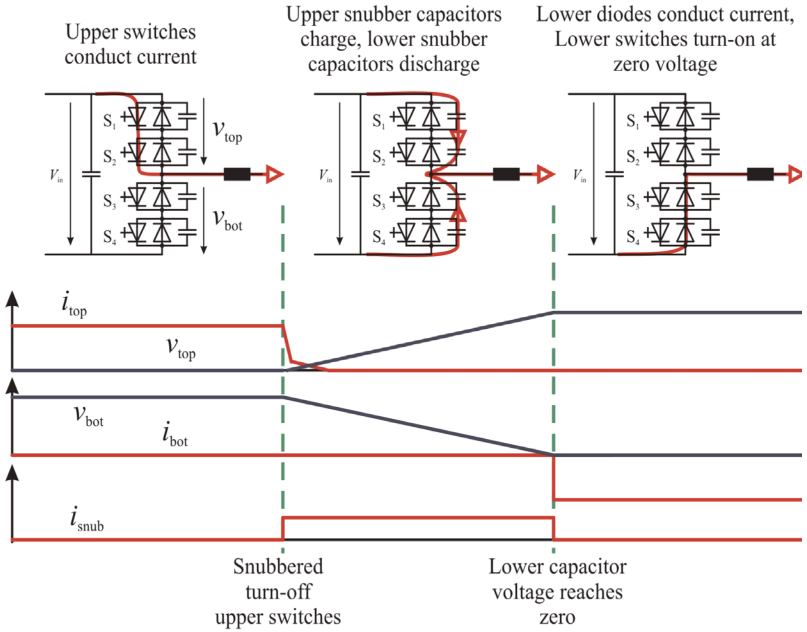
5kV DC/DC Dual-Active-Bridge-Based SST (1)

- 3x 1-Φ MFT-Based & 3-Φ MFT-Based Realization
- Series Connection of 2x 4.5kV IGCTs / Switch | ZVS Snubber Capacitors
- P = 7MW @ f_{sw} = 1kHz







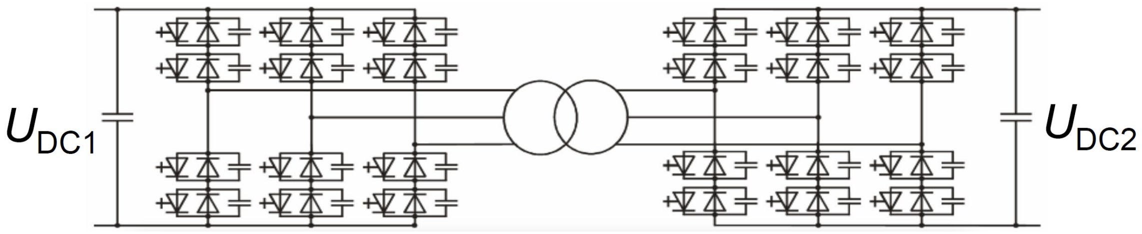


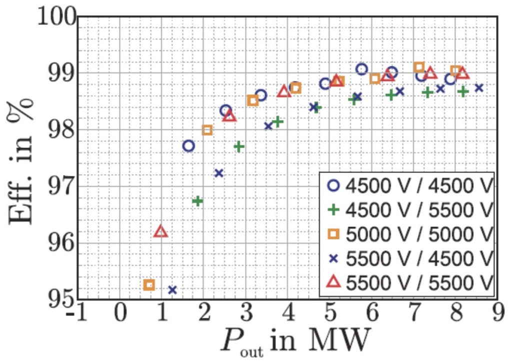
- C-Snubber — Significant Reduction of Sw. Losses | Lower dv/dt Insul. Stress | Voltage Balancing
- Evaluation of Fast-Sw. IGCTs vs. Low Saturation — Up to 80% Red. Sw. Losses @ 1kHz / Highest Overall Eff.

[DeDoncker2012ff., Soltau2014f.]

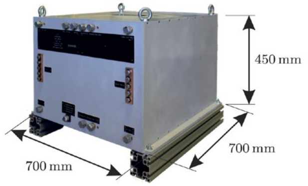
5kV DC/DC Dual-Active-Bridge-Based SST (2)

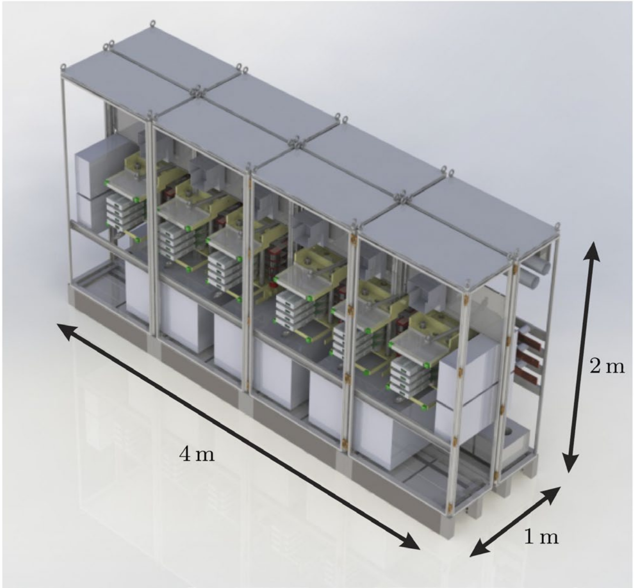
- 3x 1-Φ MFT-Based & 3-Φ MFT-Based Realization
- Series Connection of 2x 4.5kV IGCTs / Switch | ZVS Snubber Capacitors
- P = 7MW @ f_{sw} = 1kHz





3.6 kW/kg, 10 kW/dm³

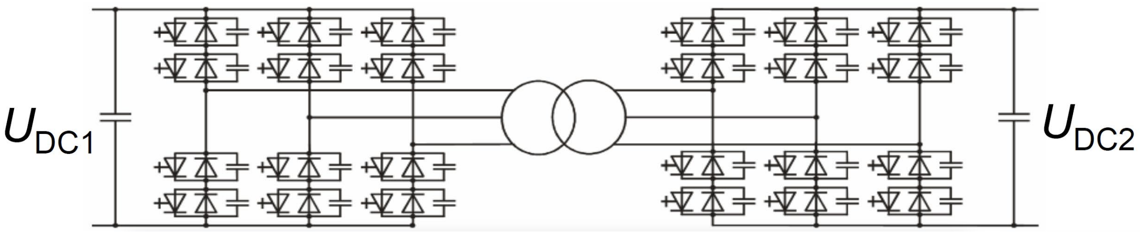


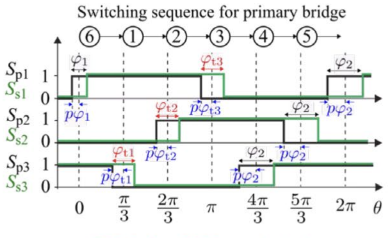


- 1-Φ 2.2MVA / 1kHz Xfrm | Silicon Steel Magnetic Core
- Efficiency up to 99.2% — Calcul. Based on Measured Semicond. Losses & Xfrm. Losses

5kV DC/DC Dual-Active-Bridge-Based SST (3)

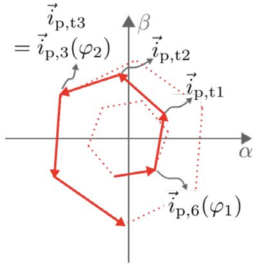
- 3x 1-Φ MFT-Based & 3-Φ MFT-Based Realization
- Series Connection of 2x 4.5kV IGCTs / Switch | ZVS Snubber Capacitors
- P = 7MW @ f_{sw} = 1kHz



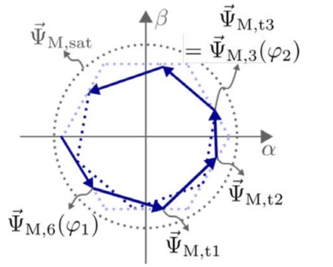


IFCC for SPS modulation

Winding current trajectory



Magnetizing flux-linkage trajectory



5 MVA, 7.4 kW/kg

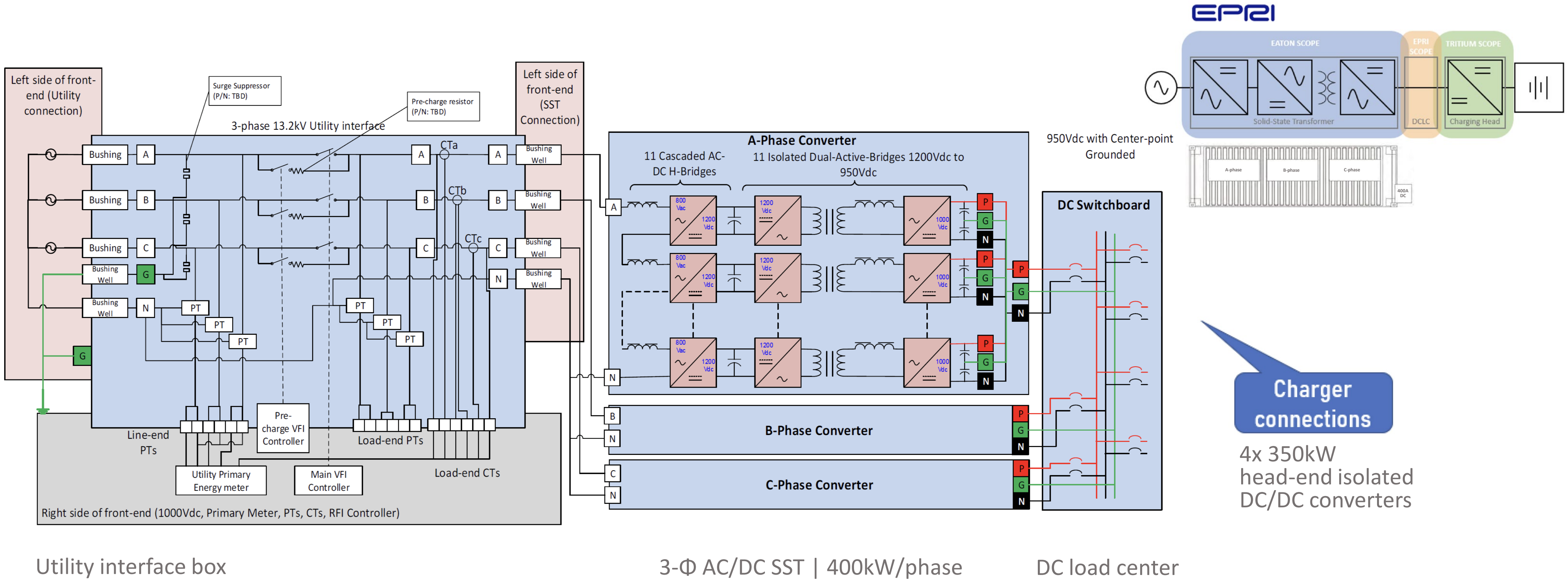
- 3-Φ 5.0 MVA / 1kHz Xfrm — 675kg (0.14kg/kVA) | 3-Φ 4.6 MVA / 50Hz Xfrm — 11.500kg (2.5kg/kVA)
- Low Hyst. Loss High $ Amorphous Iron vs. 0.18mm High Sat. Flux Si Steel — Similar Rated Load Efficiencies
- Instantaneous Flux and Current Control (IFCC) During Transients – Fast Dynamics / No Overshoot

[DeDoncker2012ff., Soltau2014f.]

Selected High-Power EV Charging Research Projects / Industry Demonstrators

1+ MW Multi-Port Charging of Heavy-Duty EVs (1)

- 3.75MW — 3000A @ 1250V — MW Charging System (MCS) / Charging Interface Initiative (CharIN)
- Aiming for Charging Times of 15…20min for 200…600kWh Battery Packs of Trucks

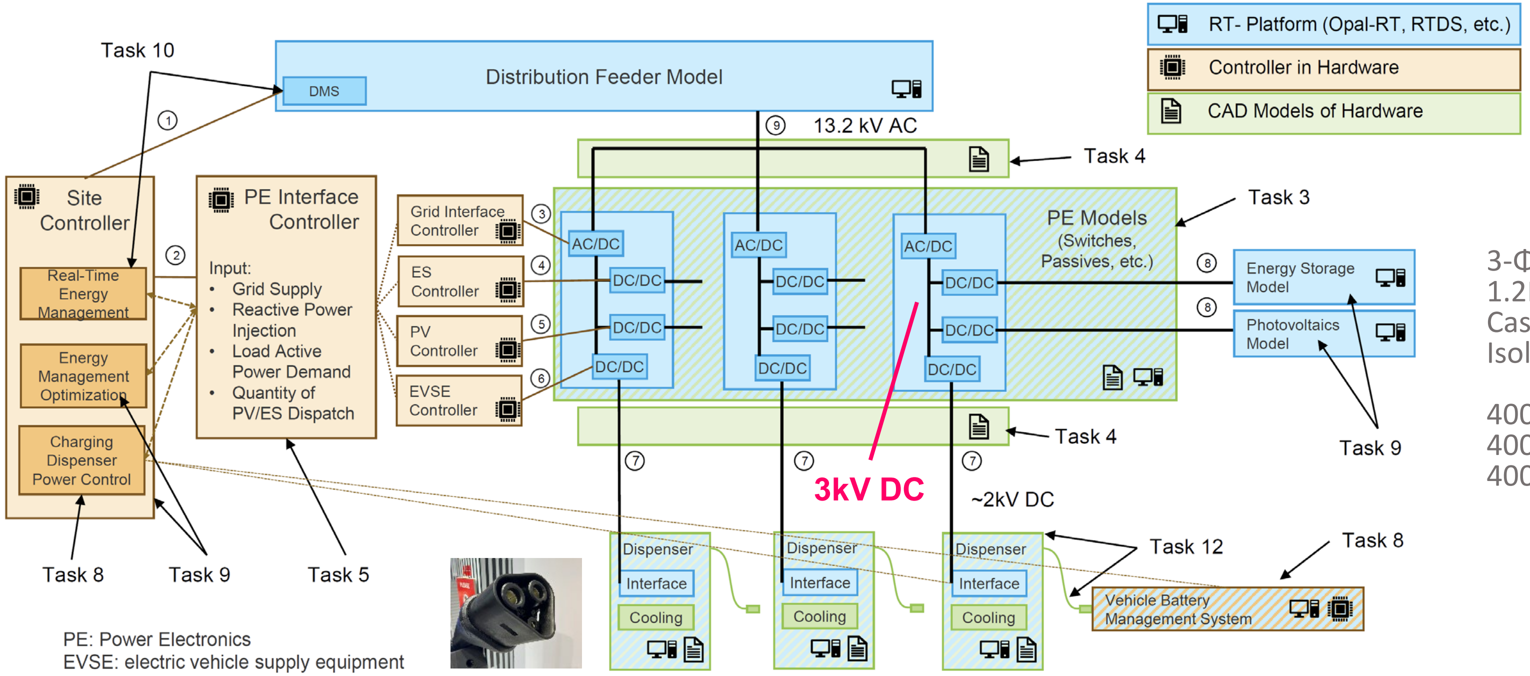


- EPRI Multi-Partner Project "DC as a Service" (DCaaS) for High-Power EV Charging
- 13.2kVAC MV Supply | 7.6kVAC / 1.2V DC-Link / 950VDC (±475VDC) Output | 3x 11-Cell SiC-Based SST @ 10kHz
- Potential Extension to DC Microgrid | Integration of (On-Site) PV | Peak Shaving Battery Storage

[Collins2020]

1+ MW Multi-Port Charging of Heavy-Duty EVs (2)

- 3.75MW — 3000A @ 1250V — MW Charging System (MCS) / Charging Interface Initiative (CharIN)
- Aiming for Charging Times of 15…20min for 200…600kWh Battery Packs of Trucks



3-Φ AC/DC SST
1.2MW/phase
Cascaded AC/DC HBs
Isol. DAB DC/DC converters

400kW…1.2MW DC isol. charging ports
400kW isol. PV interface
400kW isol. battery interface

PE: Power Electronics
EVSE: electric vehicle supply equipment
ES: energy storage
PV: photovoltaics
CAD: Computer aided design

OAK RIDGE National Laboratory | NREL | Argonne National Laboratory

- Multi-Partner Project on Key Components of a Multi-Port 1+ MW MV-Connected EV Charging System
- 13.2kVAC MV Supply | 7.6kVAC / 3kV DC-Link / 2kVDC Output | 3x 4-Cell SiC-Based SST @ 10kHz

Remark 480VAC Supplied TESLA Multi-Port Charging Site

- 350kW max. per Port | 6x 350kW = 2.1MW
- Local Battery Storage Coupled @ 480VAC Panel for Peak Shaving / Demand Management

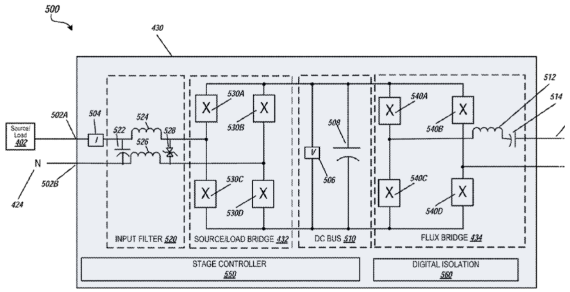
Single & dual output dispensers | 480VAC/DC conv. cabinets | 480VAC switchgear & 4 battery Powerpacks

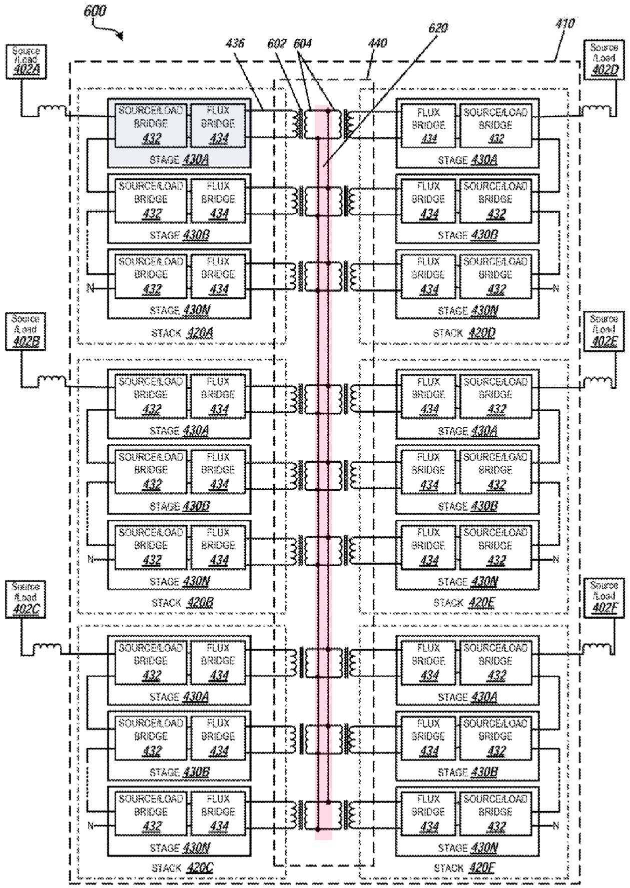
- Somedays All This will Charge 1 Truck (!) (T. Bohn, ANL)

3-Φ 15kV / 3.2MVA SST-Based EV Charger (1)

- **"Synchronous Common Coupling" of Converter Cells via MF AC-Bus**
- **Full Modularity / Low Converter Cell Complexity / 25% Redundancy**
- **High Scalability / Flexibility — AC or DC Output**
- **1.5m x 1.6m x 2.4m Outer Dimensions → 0.5kW/dm^3**
- **Efficiency Not Specified**

RESILIENT POWER



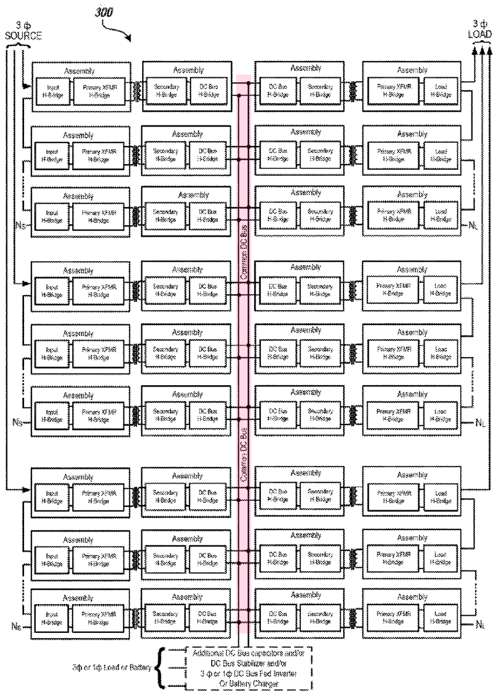


- **Insulation Type Not Specified (in Case of Oil → Maintenance / Pot. Environmental Issues & Fire Hazard)**

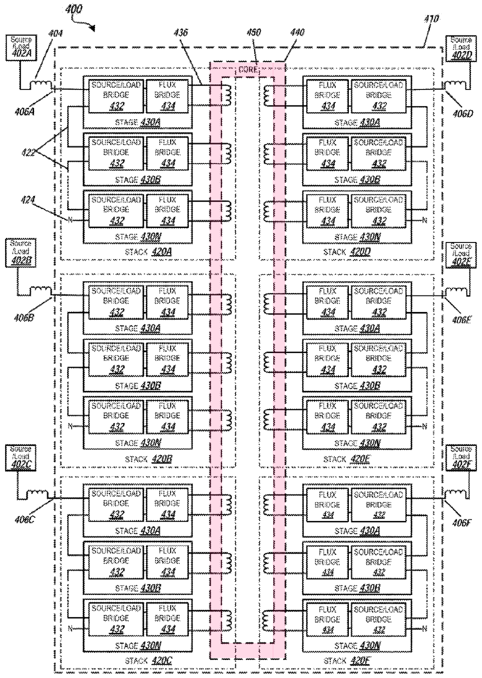
[Keister2018ff.]

Remark: Alternative Multi-Port Coupling Schemes

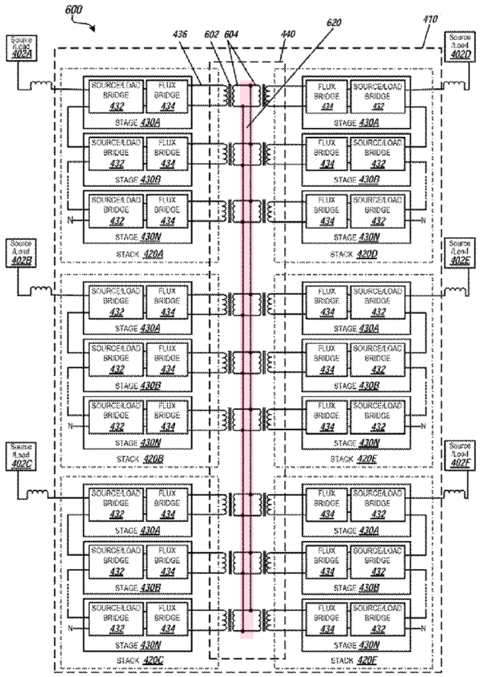
- DC-bus OR AC-bus (Magnetic/Electric) Coupling of Cascaded Cells
- Example of 3-Φ MF Isolated AC/AC Conversion



— DC-Bus Coupling



— Common Magn. Core AC-Coupl.



— AC-Bus Coupl. of Indiv. Xfrms

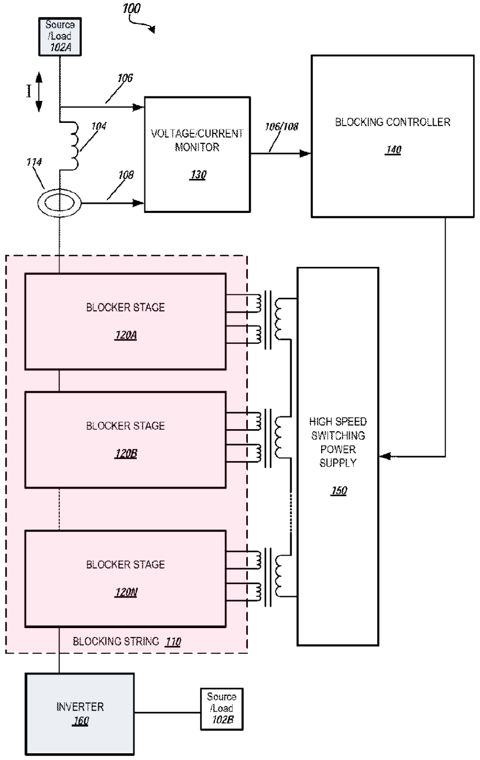
- AC-Bus Coupling Adopt „Synchronous Common Coupling" of the 50/60Hz Grid
- Low Complexity Converter Cells | Challenge of Power Flow Control / Stability

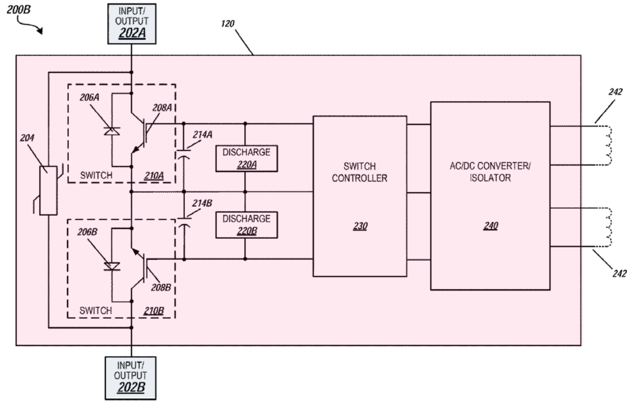
[Keister2018]

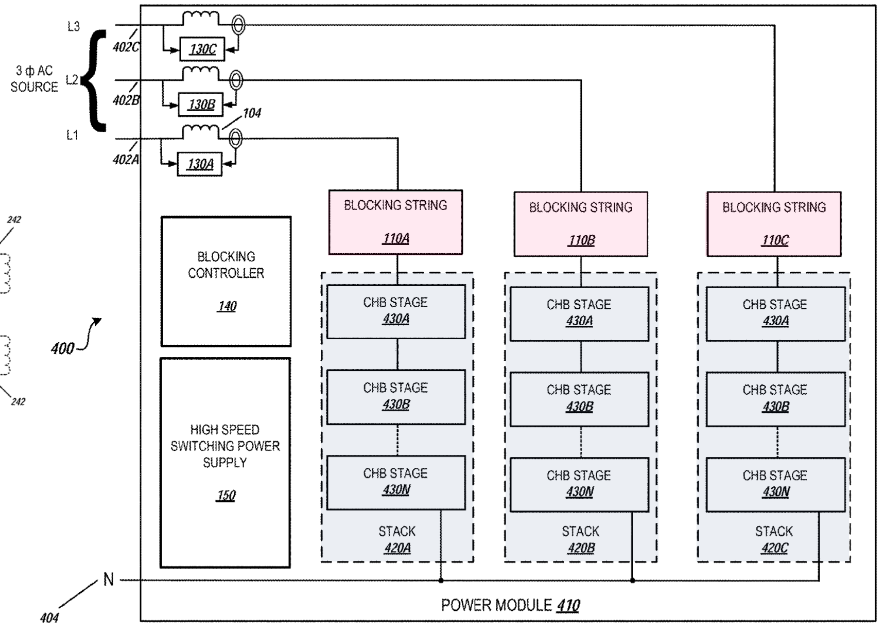
3-Φ 15kV / 3.2MVA SST-Based EV Charger (2)

- Zero Inrush Current
- Simple Fuse & Disconn. Switch as MV-Grid Interface
- 125 kV Impulse Basic Insulation Level w/o Arresters

RESILIENT POWER



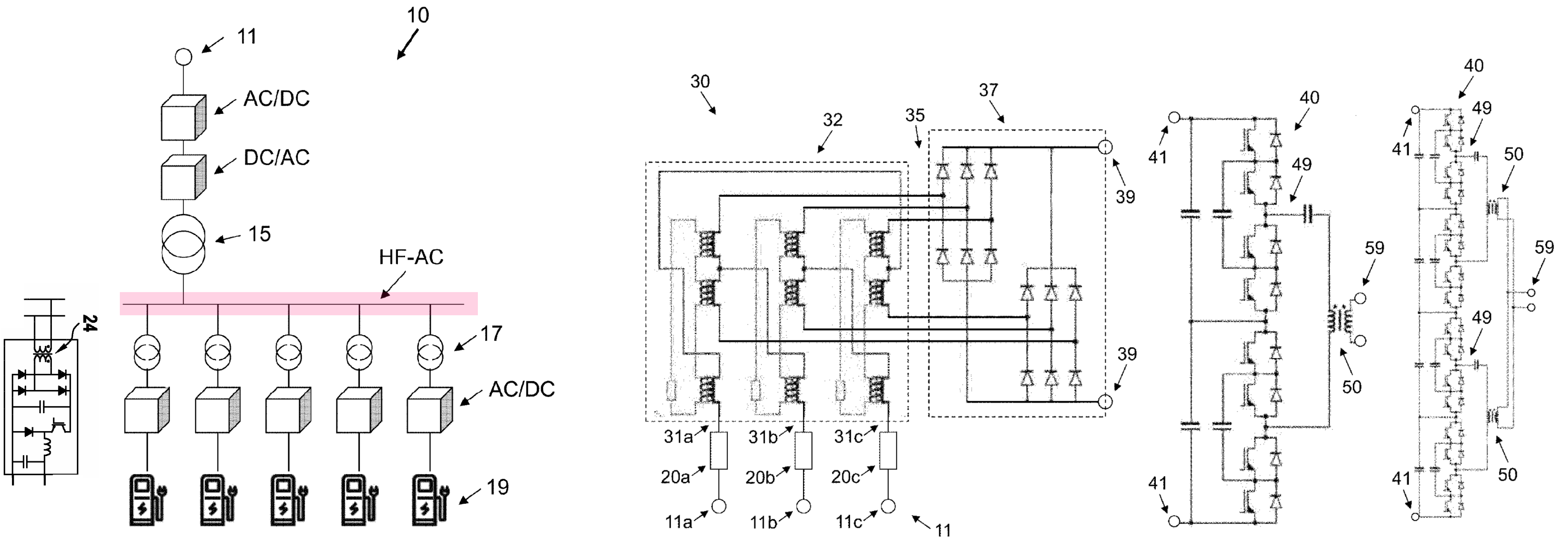




- Insulation Type Not Specified | In Case of Oil → Maintenance / Pot. Environmental Issues & Fire Hazard

Medium-Frequency AC Power Distribution

- 400 Hz / 360 … 800Hz Aviation Systems — Low Vol. of Xfrms & Filter Circuits Comp. to 50/60Hz
- MV-AC/DC Conv. Utilizing PWM OR Multi-Pulse Line-Interphase-Xfrm-Based PFC Rectifiers
- DC/MF-AC Conv. Integrating a MV/LV MF-Xfrm



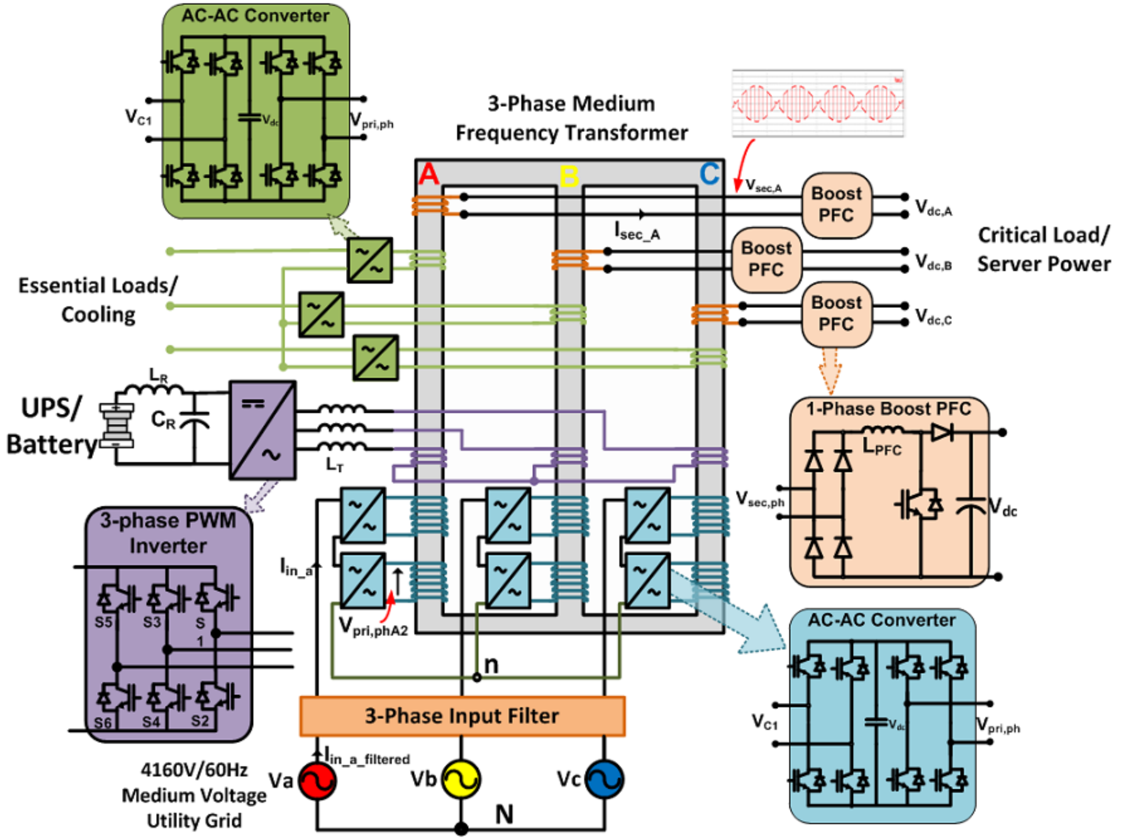
- LV/LV MF-Xfrms for Galv. Separation of the Charging Ports | Diode or PFC Rectifiers & Non-Isol. DC/DC Converters

Matrix-Type 3-Φ MFT-Link Multi-Port SST Topology

- **Bidirectional LF-AC/|AC|/MF-AC Grid Interfaces**
- Input Stage Operates as AC/|AC| Unfolder
- H-Bridge Generates MF-AC Rect. Prim. Voltage
- 50/60Hz Mains Def. MF-AC-Voltage Envelope

- **Multi-Wdg Arrangement per Xfrm Leg**
- Common Magn. Flux Interconnects All Wdgs
- Prim./Sec. Turns-Ratio Voltage Scaling

- **Sec.-Side 3x 1-Φ or 3-Φ Power Conversion**
- MF-AC Voltage Folding & LF-|AC|/DC Conv.
- 3-Φ MF-AC/DC PFC Rectifier Systems
- 3x 1-Φ (Star/Delta) MF-AC/DC/AC Conv.



- Proposed as MV Interface of Future Datacenters

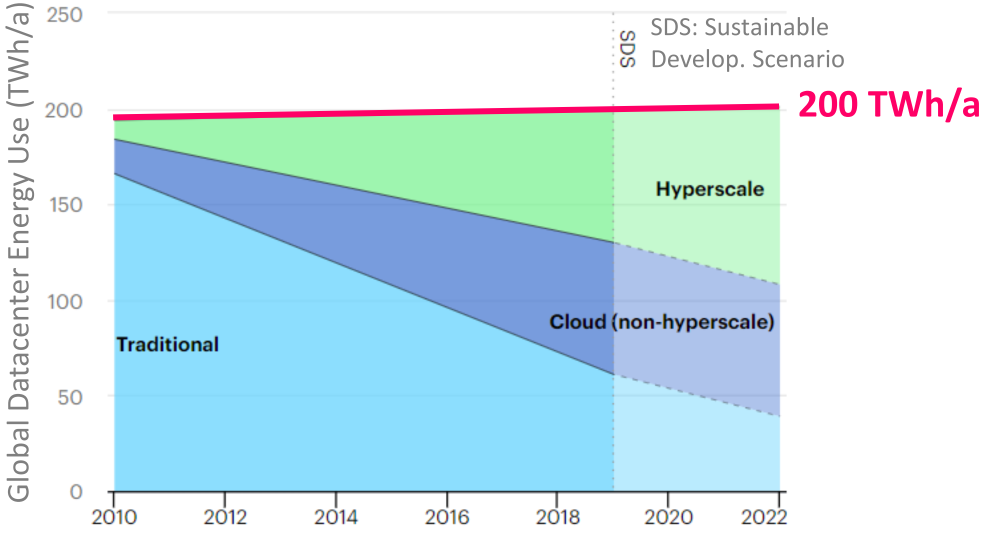
[Hafez2014]

Part IV

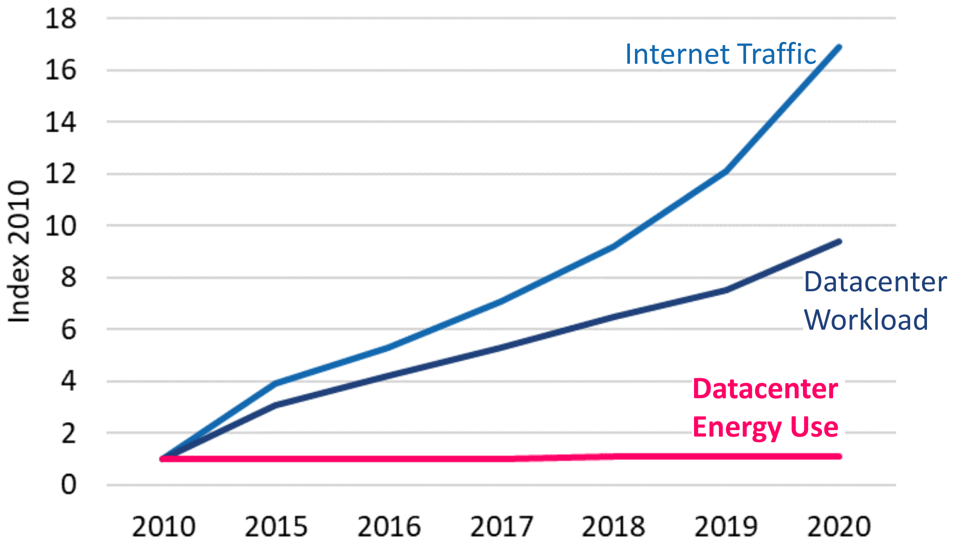
Comparative Evaluation of SSTs for Datacenters and EV Charging

Global Datacenter Electricity Demand

- Datacenters Consume > 200 TWh/a | About 1 % of Global Electricity Demand
- Energy Costs Dominate Overall Life-Cycle Costs

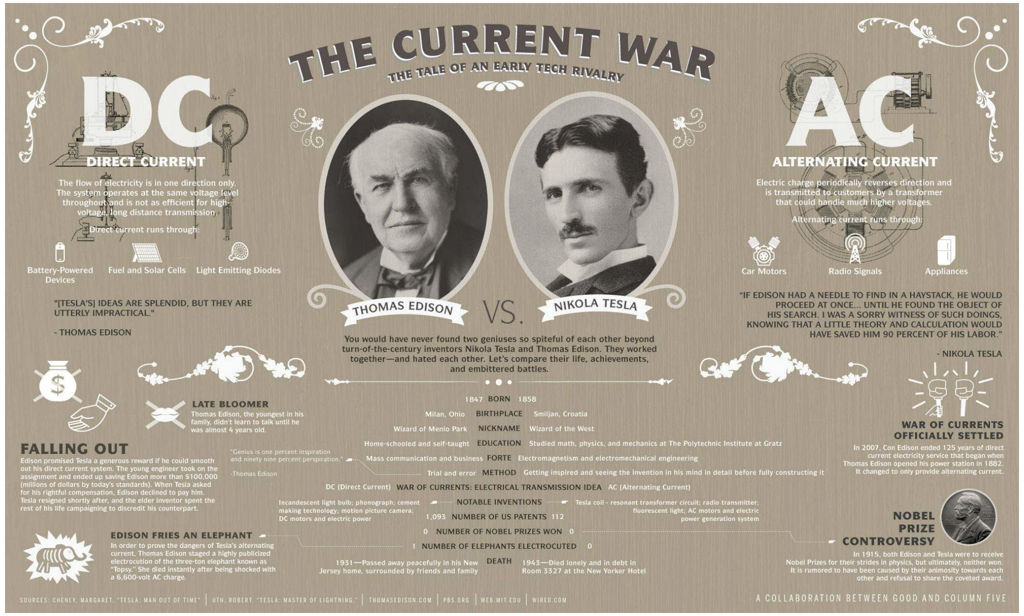


Source (Img., Data): https://www.iea.org/



- Decoupling of Computing Workload from Energy Use
- Efficiency Improvement on All Levels: Computing Equipment | HVAC | … | Power Supply System!

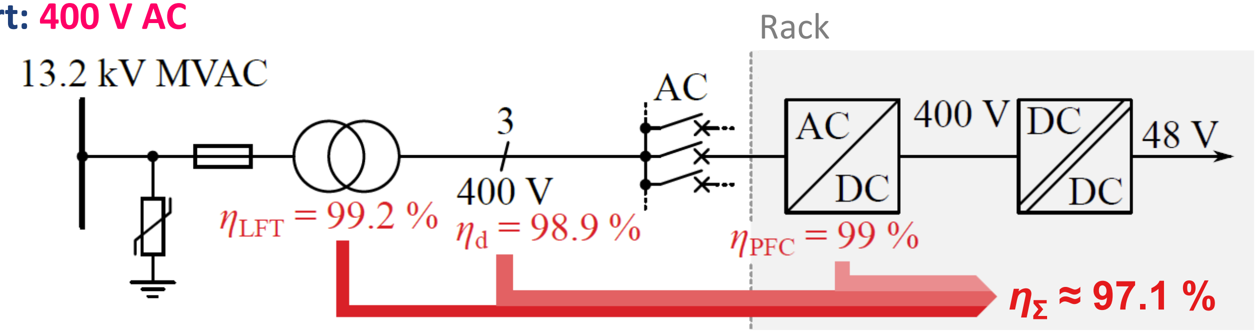
AC vs. DC Distribution



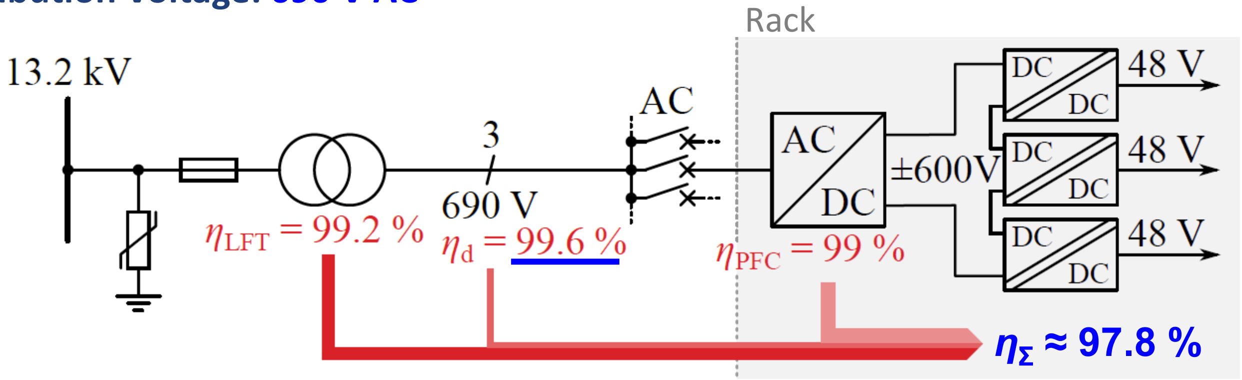
Source: GOOD/Column Five Media (https://good.is)

AC Power Distribution

- **State of the Art: 400 V AC**



- **Increased Distribution Voltage: 690 V AC**

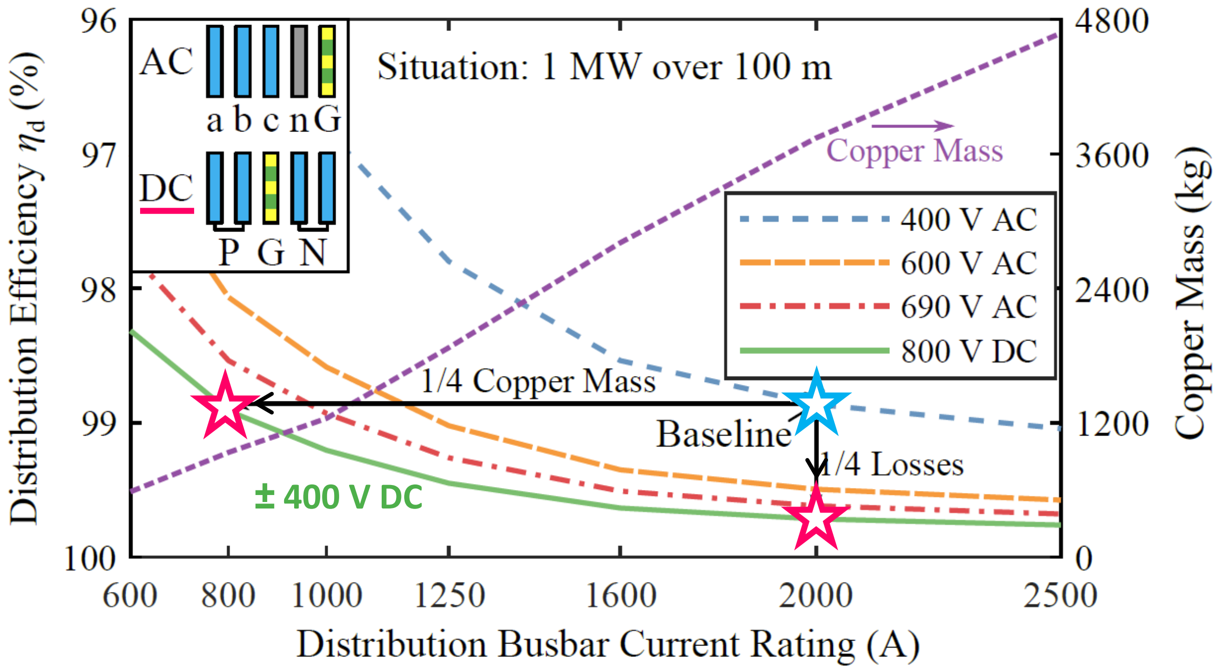


(w. 99% 3L PFC Rec.)

- **η_Σ: Efficiency from MVAC to Input of Rack-Level 400 V / 48 V DC-DC Conversion**
- η_d: Distribution Efficiency for 1 MW Over 100 m with Delta EcoTech BL 2000 A Busbar
- η_{LFT}: Requirement by, e.g., EU Ecodesign Directive 2009/125/EC

Distribution Losses

- **400 V AC → 690 V AC: Significant Loss Reduction <u>or</u> Lower Copper Usage**



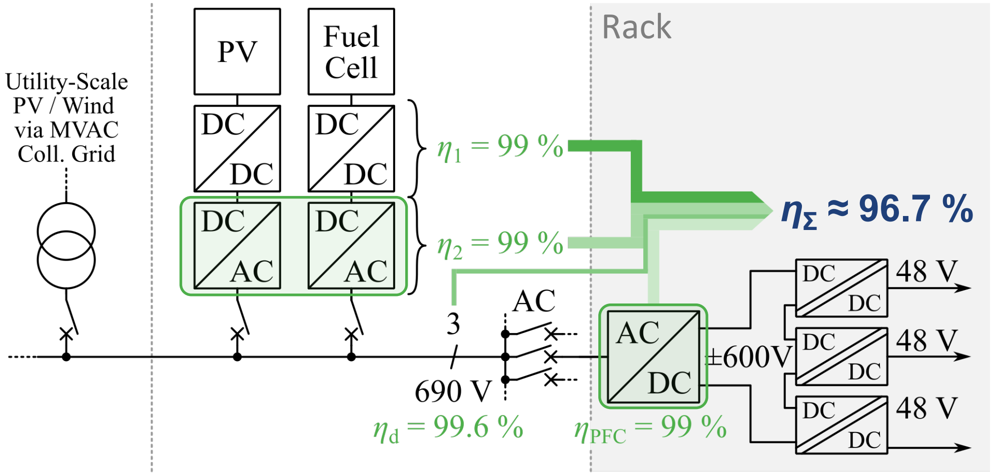
(Delta EcoTech BL Busbars @ 60 °C)

- **Same Busbar in AC or DC Configuration: 400 V AC → 800 V DC (± 400 V DC)**
- –75% Distribution Losses (<u>or</u> –75% Copper Mass)
- DC Distribution Challenges: Protection, DC Breakers, DC PSUs, …

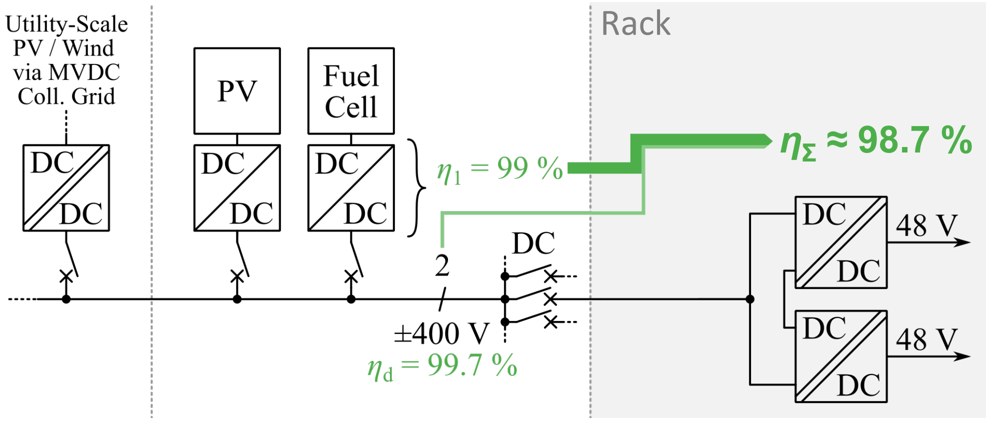
DC Power Distribution (1) – DC Sources

- **690 V AC**

Additional DC-AC Conversion Stage



- **±400 V DC**

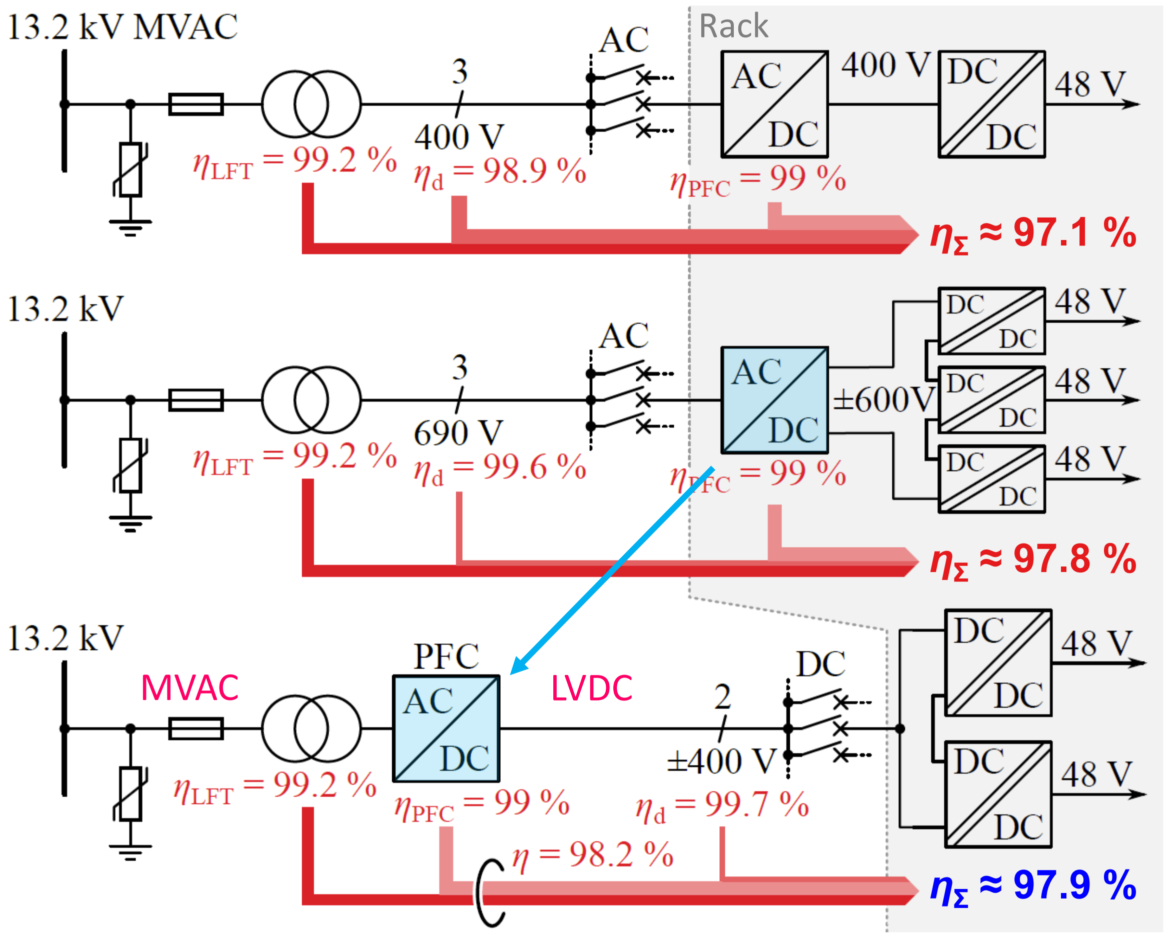


!

- **DC Distribution Leverages DC Output of Fuel Cells / Batteries / PV**
  - Note: Utility-Scale Renewable Energy System Requires Higher-Voltage DC Collector Grid

DC Power Distribution (2) – Grid Supply

- 400 V AC
- 690 V AC
- ±400 V DC



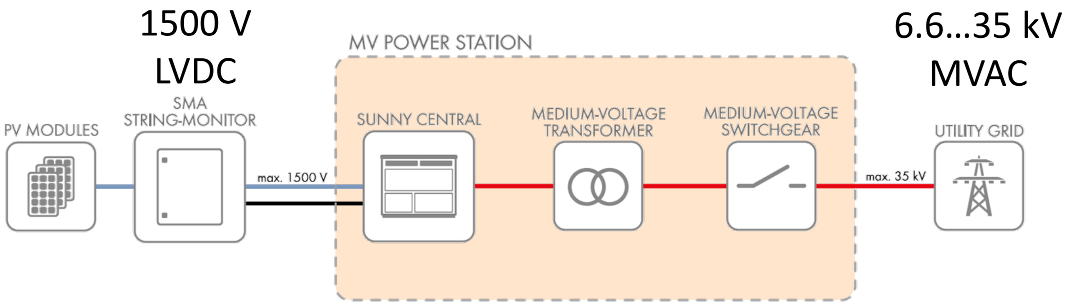
- Similar η_Σ as For 690 V AC Distr.

- Simply Centralizing the PFC Rectifier Functionality → Only Minor Efficiency Gain!

Medium-Voltage AC-DC Interfaces

MV Power Station for Photovoltaics

- State-of-the-Art 3 MVA Turnkey Solution
- 20 ft Container: PV Inverter, LFT, MV Switchgear, etc.
- 3 MVA | 6.1 m x 2.6 m x 2.4 m | ≈ 0.08 kW/dm³



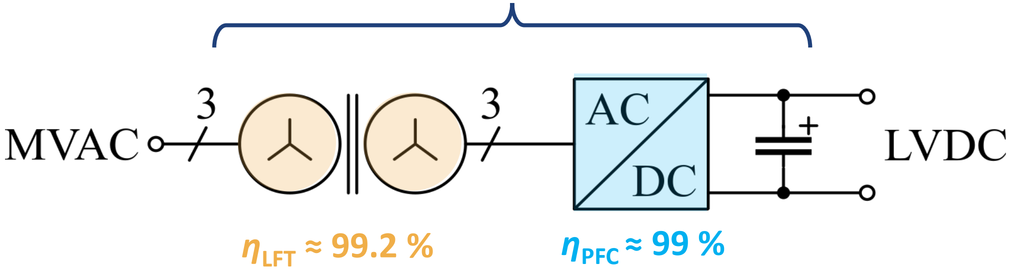
1200 V Si IGBT Technology | Oil-Filled LFT

- Inverter Efficiency: 98.5 % CEC
- Transformer Efficiency: 99 % (EcoDesign, oil-filled)
- Overall Efficiency ≈ 97.5 % → Improvements Expected for SiC and Dry-Type LFT → 98+ %

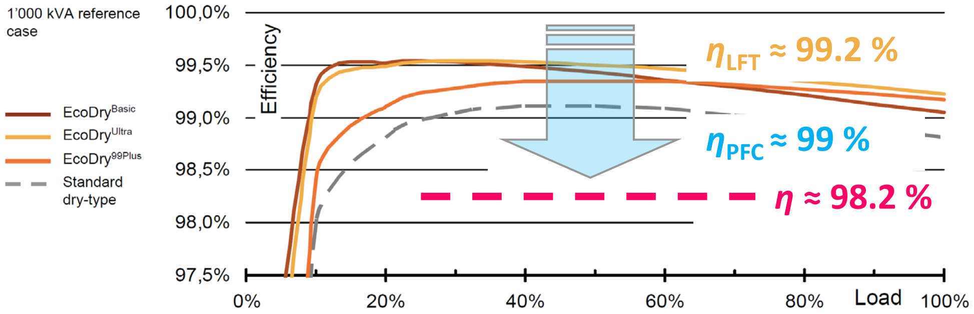
MVAC-LVDC with LFT and Central SiC PFC Rectifier

■ Centralized PFC Rectifier with 1200 V SiC Technology & High-Efficiency Dry-Type/Ecodesign LFT

MVAC-LVDC: $\eta \approx 98.2\ \%$, $\rho \approx 0.25\ \mathrm{kW/dm^3}$



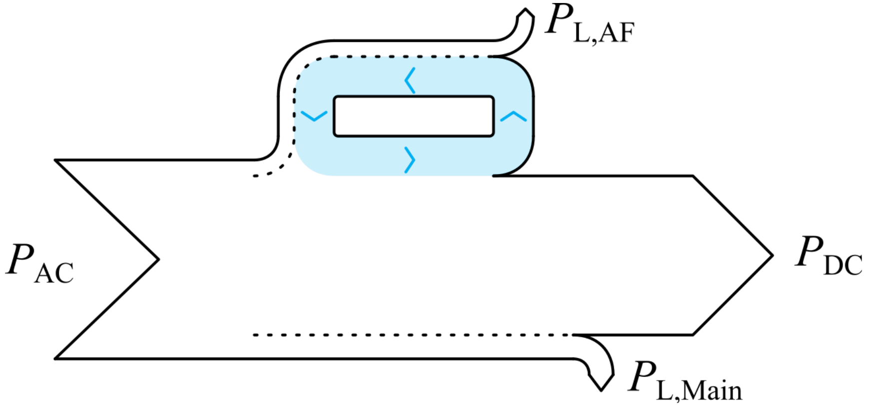
Example: ABB EcoDry™ High-Efficiency Transformers
(ABB, 2011 – Today, 99.2% Required by, e.g., EU EcoDesign Directive)



400 kVA

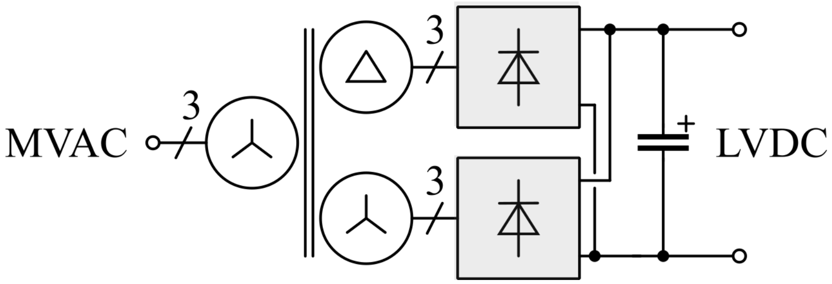
- Full Functionality (Reactive Power, Bidir. Power Flow, …)
- High Robustness & Low Complexity
- Scalability to Higher MVAC Levels
- Proven LV Converter Design Paradigms | Parallel-Interleaving (Modularization, Redundancy)
- Compatible with Existing MV-side Infrastructure
- No DC fault Current Limiting

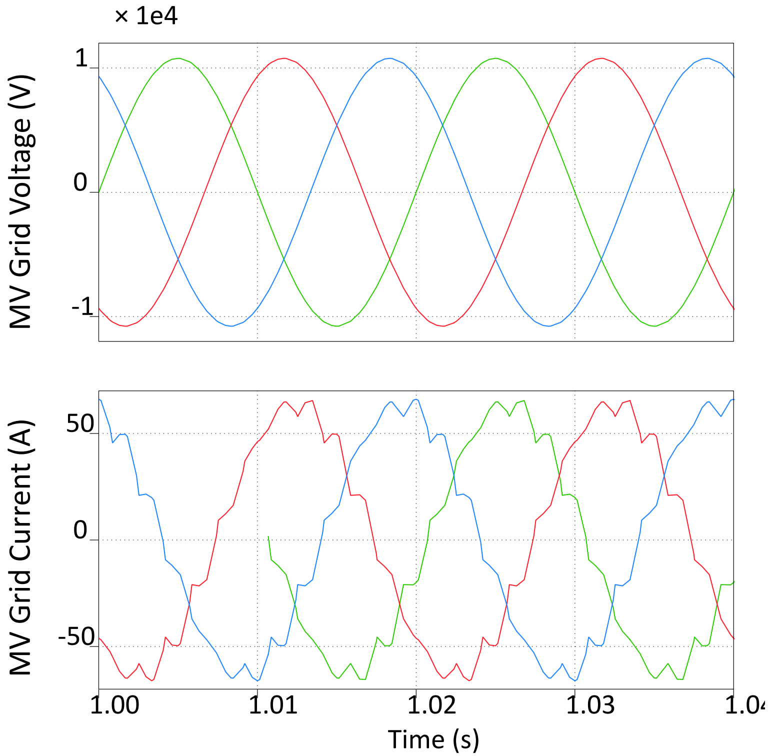
MVAC-LVDC Hybrid Transformers



12-Pulse / Multi-Pulse Rectifiers

- No Explicit PFC Stage (!) → Passive Realization of PFC Functionality with Phase-Shifting Transformer
- High Robustness
- Low Complexity
- High Efficiency (≈ 0.25% Diode Losses)
- No DC-Side Inductors Required (!)
- 18-Pulse or 24-Pulse for Higher Power Levels



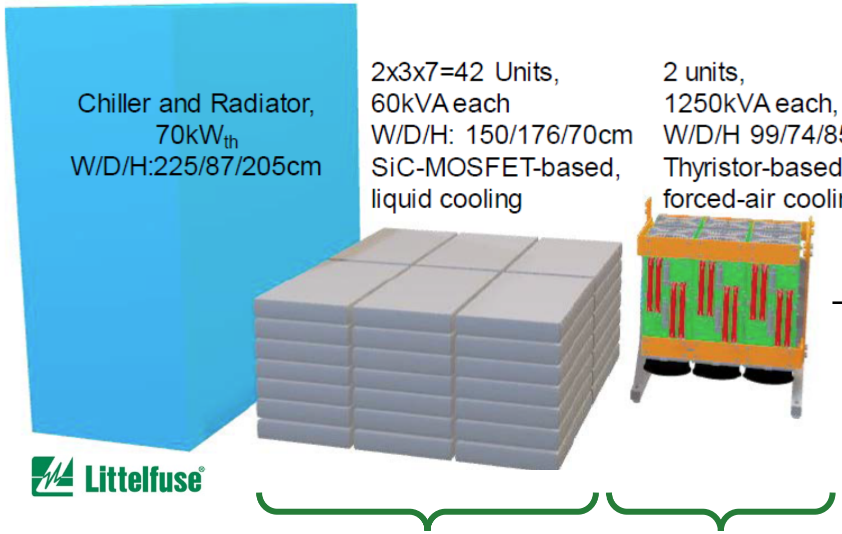


- Unidirectional
- No Active Output Voltage Control (Tap Changer: Wear & Tear, Limited Dynamics / Thyristors: High VAr Consumption)
- Remaining Current Distortions / Reactive Power Consumption

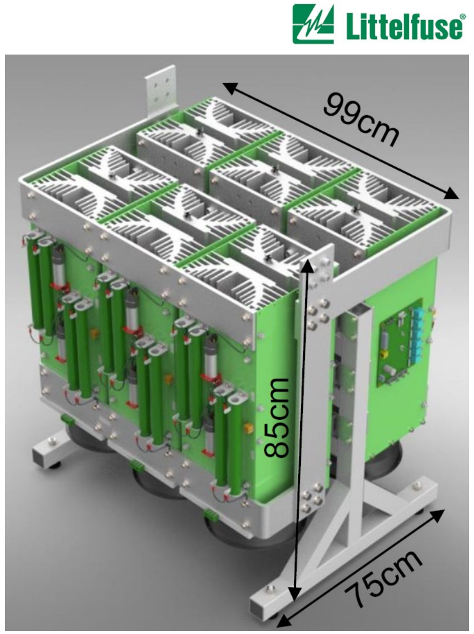
Example: MW-Level Charging of Commercial Vehicles

- Future Charging Power Up to 2.5 MW / Supply from MV → LFT for Galvanic Separation
- Modular: 2.5 MW = 42 x 60 kW PSU Mod. Parallel (AC-DC + DC-DC Non-Isol.) / 97% Effi. / Liquid Cooling
- Monolithic: 2.5 MW 12-Pulse Thyristor Rectifier / 2 x 1250 kW / 99.7% Efficiency / Air Cooling

Both Options with MV/LV LFT (Not Shown)



ρ_{PE} = 1.6 kW/dm³ ρ_{PE} = 4.0 kW/dm³



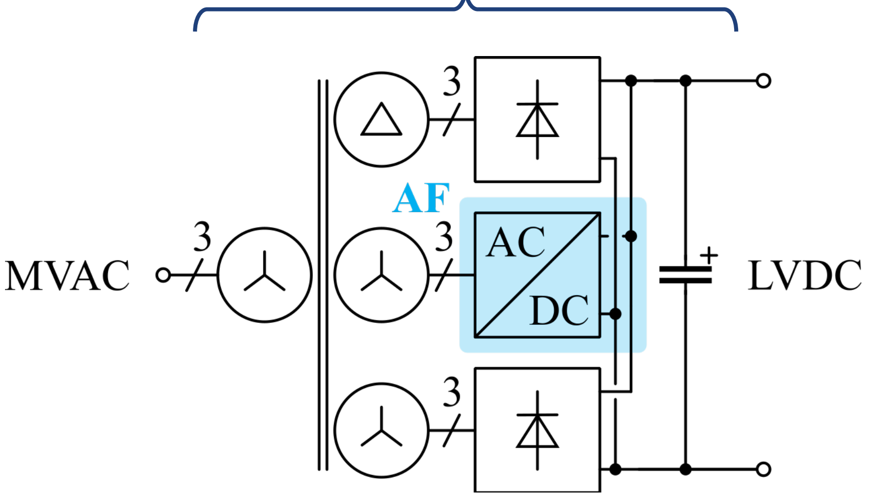
- Longevity of Disk-Type Thyristors / Decades in the Field → Electrolyzers w. Similar DC Volt./Cur. Control Req.

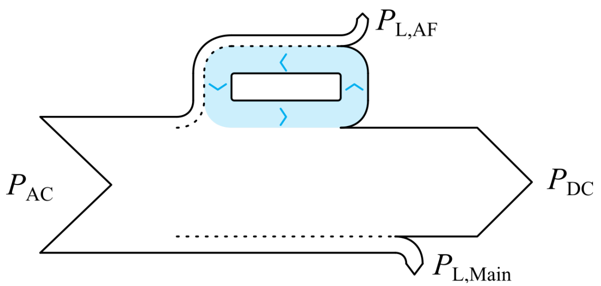
[Schulz2022]

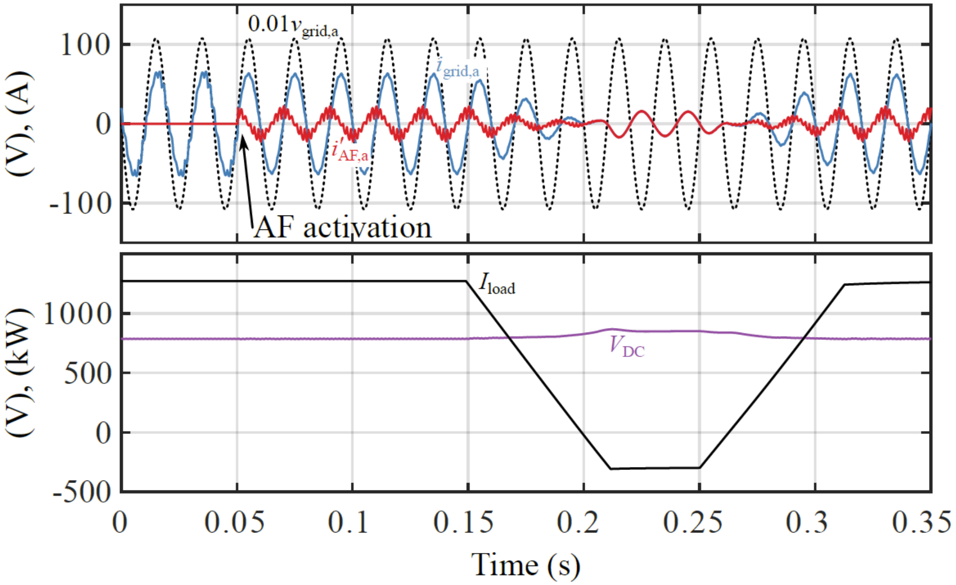
MVAC-LVDC Hybrid Transformer

- **Hybridization: Partial Switch-Mode Power Processing**
- **Active Filter (AF) Modules with ≈ 25 % Power Rating**
  → Sinusoidal Grid Currents & Reactive Power Compensation

MVAC-LVDC: $\eta \approx 98.5$ %, $\rho \approx 0.2$ kW/dm³







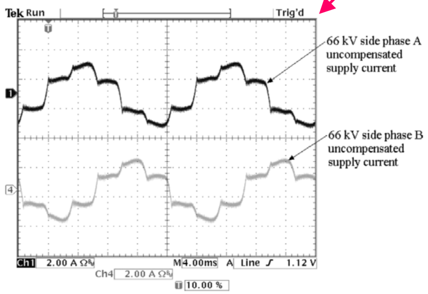
- Remaining 12-Pulse Operation in Case of AF Failure | Central, Shared FACTs as Complement/Alternative
- Connection of AF to Output DC Bus → Reverse Power Flow Capability
- No Active Output Voltage Control (Tap Changer: Wear & Tear, Limited Dynamics / Thyristors: High VAr Consumption)

Example: 3 kV DC Traction Substation

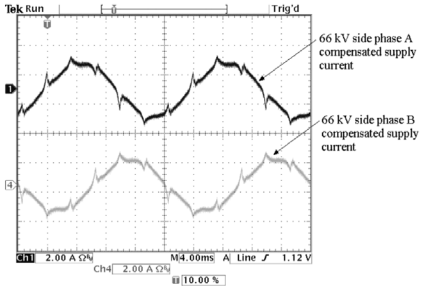
- Substation 66 kV AC → 3 kV DC Traction Grid w. Diode Rect. 5+ MW
- 1.5 MW Series-Stacked Converter Enables
  Active Power Filtering & Regeneration Capability

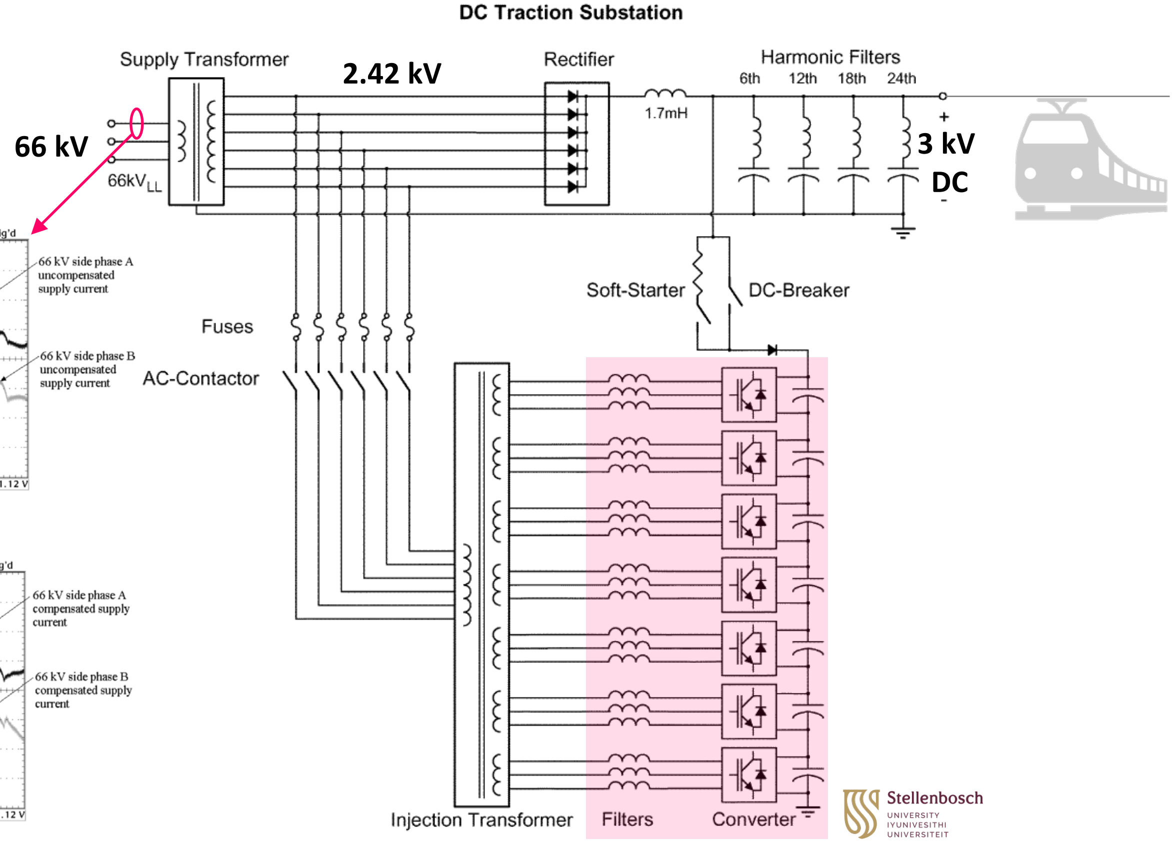
1.5 MW / 7 Stacked 3-Ph. Inv.
5.4 kV DC (7 x 800 V DC)
35 kHz Eff. Sw. Freq. (7 x 5 kHz)

W/o Act. Filt.



With Act. Filt.



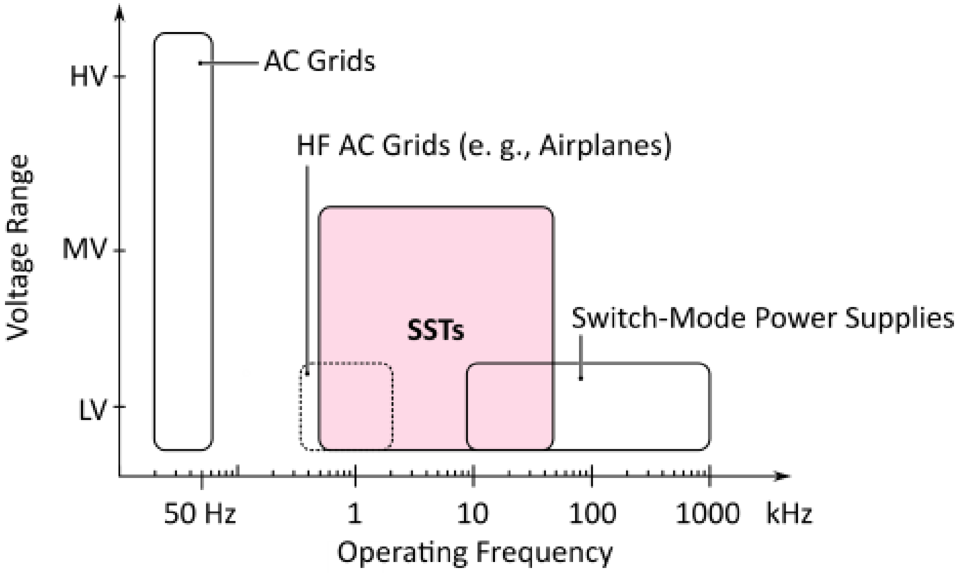


- Full-Scale Tests w. 5 MW Load (Accelerating Trains) and 1.5 MW Regeneration (Braking Trains)

Stellenbosch University

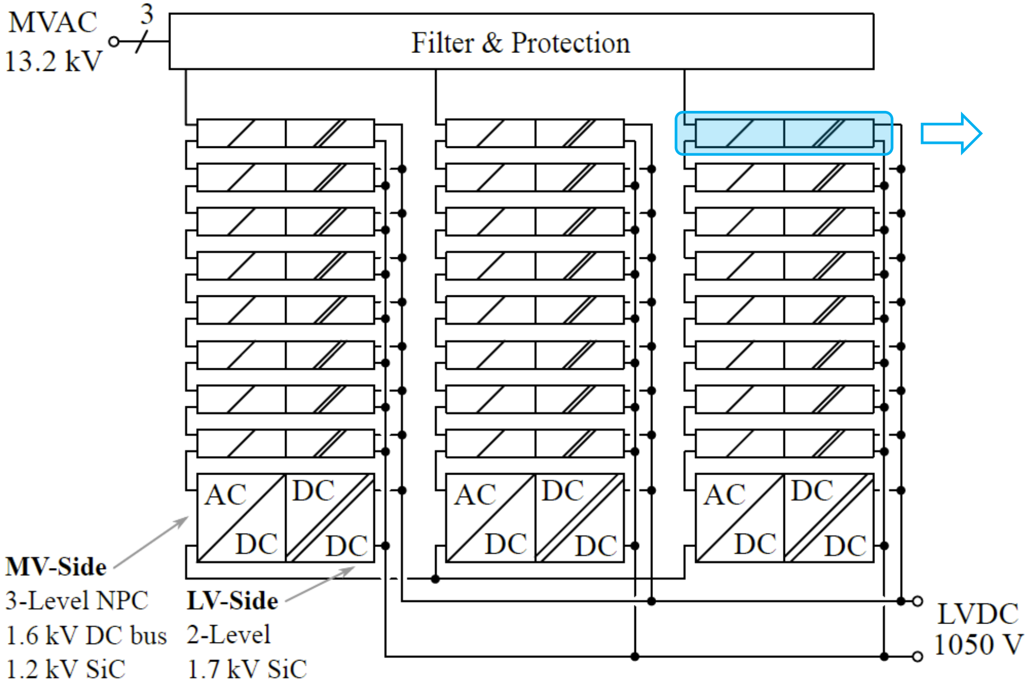
[Henning2008]

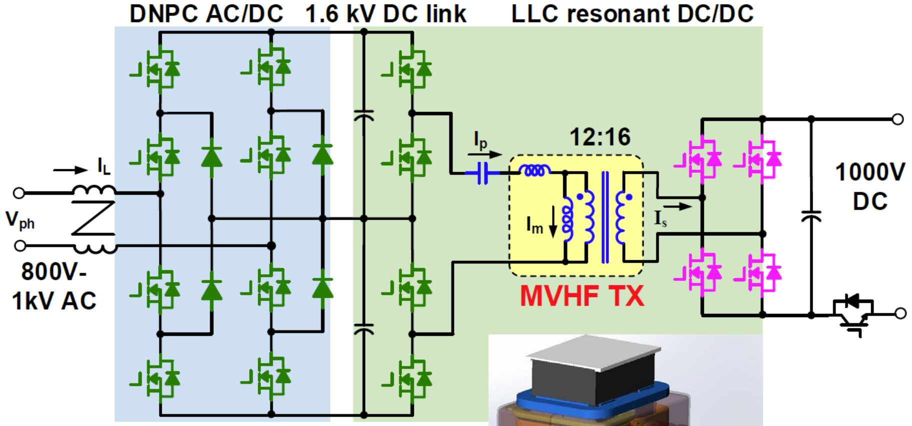
MVAC-LVDC Solid-State Transformers

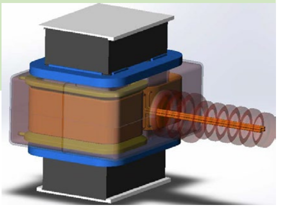


13.2 kV / 400 kW SST-Based EV Charger (1)

- **Fully Modular Input-Series-Output-Parallel (ISOP) Topology**
- 3 x 9 = 27 AC-DC/DC-DC Cells | **438 Switches**
- 15 kW per Cell | All-SiC Realization | Forced-Air Cooling



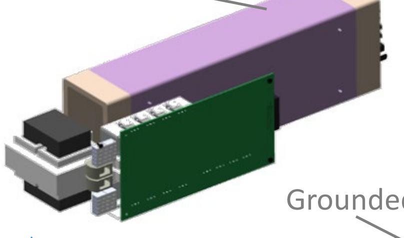




100+ kHz MFT

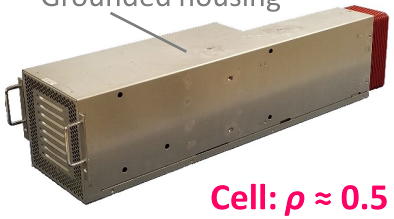
MFT: $\rho \approx 8.4$ kW/dm³
(w/o 30 kV Bushing!)

Isolation case



DELTA

Grounded housing



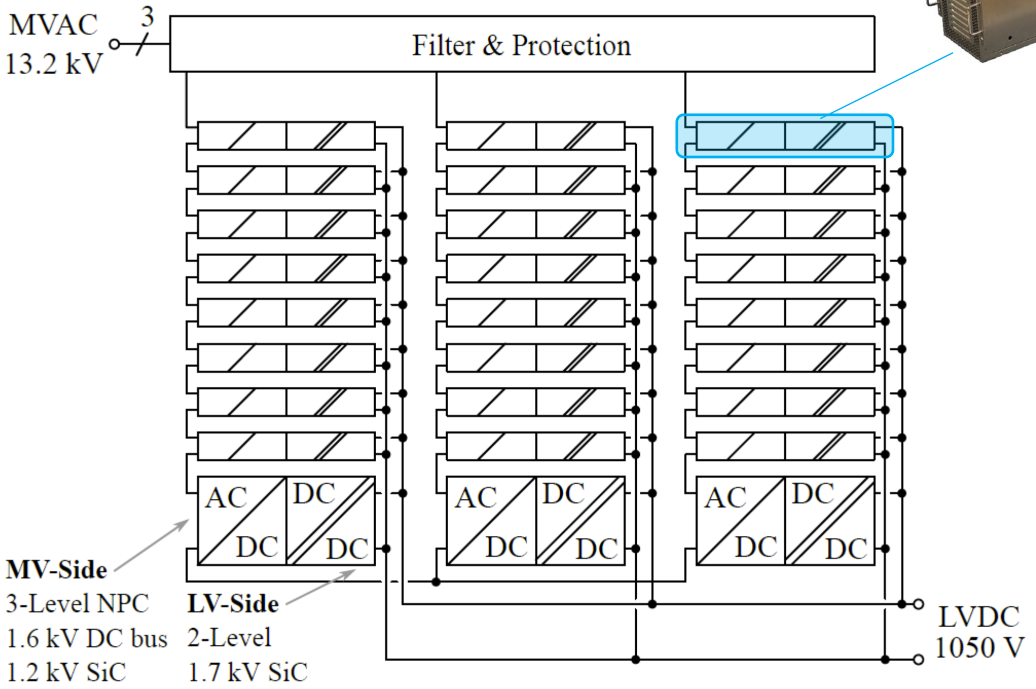
Cell: $\rho \approx 0.5$ kW/dm³

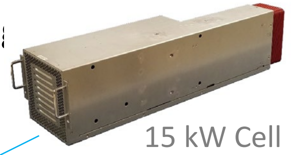
[Zhu2018ff.]

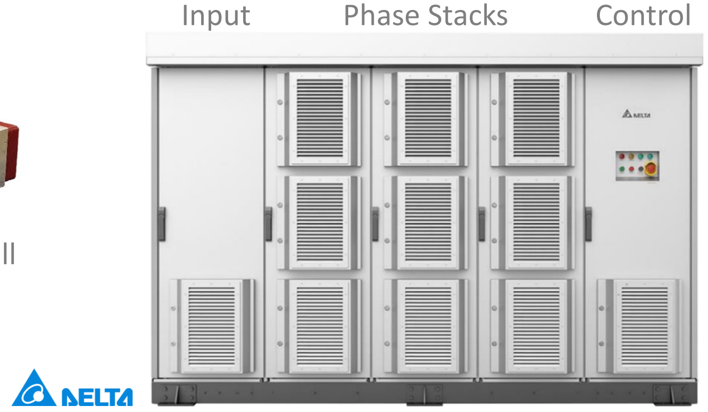
13.2 kV / 400 kW SST-Based EV Charger (2)

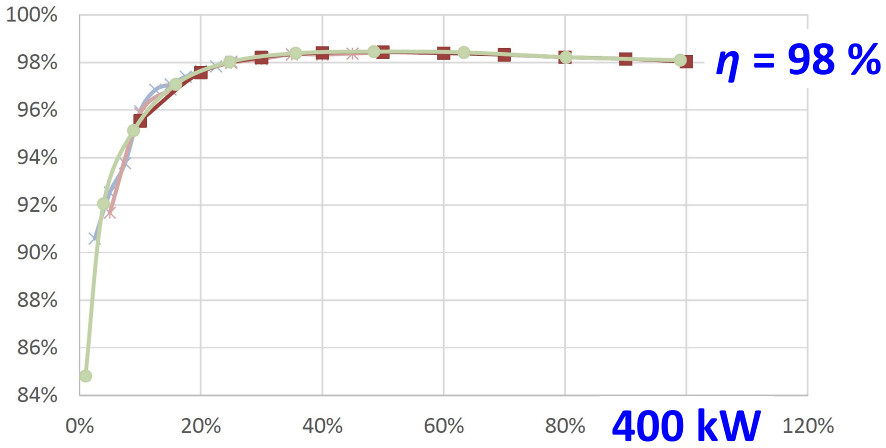
■ **One of the Most Advanced Industrial MVAC-LVDC SST Prototype**

- 3 x 9 = 27 AC-DC/DC-DC Cells | **438 Switches**
- 15 kW per Cell | All-SiC Realization | Forced-Air Cooling









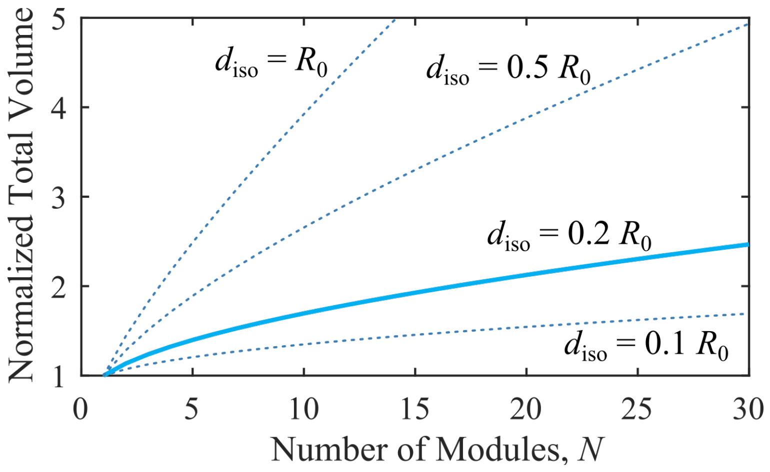
- 3000 kg Weight | 3.1 m x 1.3 m x 2.1 m Outer Dimensions
- **Power Density:** $\rho \approx 0.05$ kW/dm^3 | **0.5 kW/dm^3 (Cells) | 8.4 kW/dm^3 (MFT)**

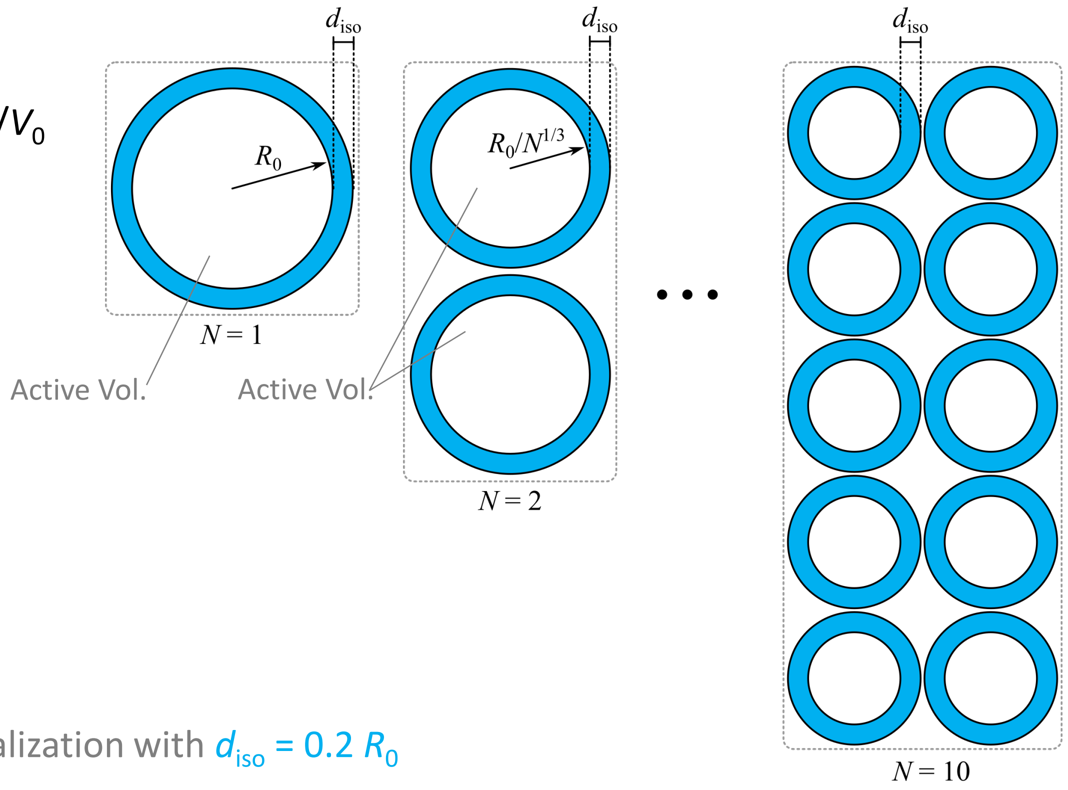
[Zhu2018ff.]

Intuition: Modularization Penalty

- ***Highly (!)* Simplified Consideration**
- Power P Processed in Sphere with Radius R_0
- Modularizing Assuming Constant Power Density P/V_0
- Const. Isolation / Overhead Distance d_{iso}

$$V(N) = \frac{4}{3}\pi\left(\frac{R_0}{N^{1/3}} + d_{\mathrm{iso}}\right)^3 \cdot N$$



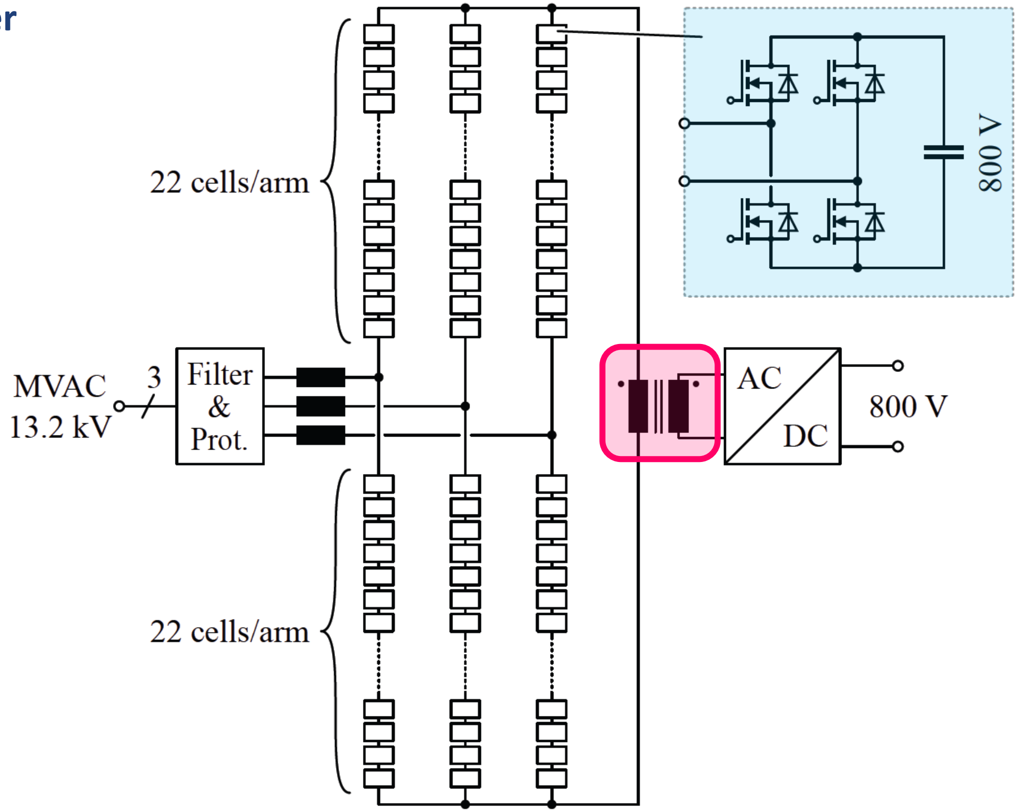


2D Visualization with $d_{iso} = 0.2\ R_0$

- **High Module Count → Massive Reduction of Overall Power Density Expected**
- **Additional Overhead: Input & Output Filters | Protection Equipment | Mech. Assembly | Cabinets etc.**

MMC-Based SST Concepts

- **Limit Modularity to PE | Single MF Transformer**
- Example for 13.2 kV Grid
- 22 Full-Bridge Cells per MMC Arm | 6 Arms
- 528 Switches (1200 V, MV-Side Only)



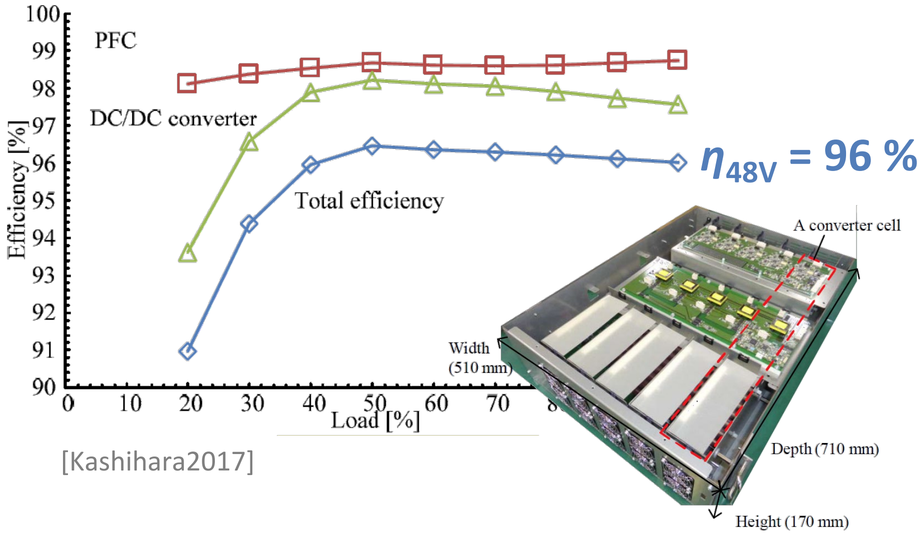
- **Benefits of Modularity → Redundancy | Availability | Economies of Scale | Transportability**

[Glinka2005]

Remark: Datacenter Rack-Level MVAC-LVDC SSTs

- **MVAC Distribution to the Rack & Small Rack-Level SSTs**

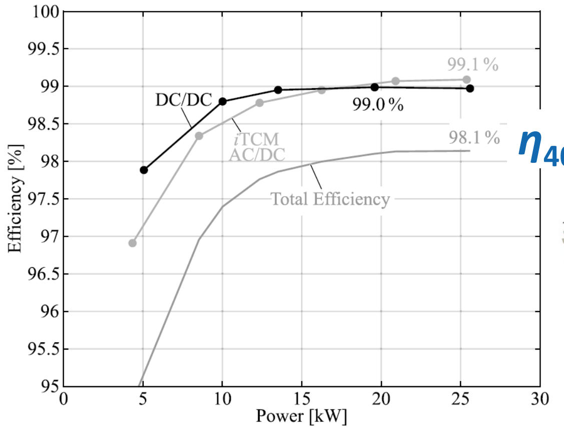
- **Fuji Electric, 2017**
  - 2.4 kV rms (l-n) | 25 kW | **48 V DC**
  - LV Si Multicell ISOP | 0.4 kW/dm^3



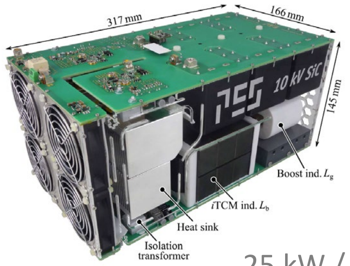
η_{48V} = 96 %

[Kashihara2017]

- **ETH Zürich, 2019**
  - 3.8 kV (l-n) | 25 kW | **400 V DC**
  - 10 kV SiC Single Cell | 3.5 kW/dm^3



η_{400V} = 98.1 %



25 kW / 7 kV PFC stage

[Rothmund2019]

- **Large Overhead!**
  - MV Protection Equipment & MV Switchgear (Disconnectors, Grounding Switches, …)
  - Central LFT Needed Unless Incoming MV Level is Distributed (Typ. >> 2.4 kV)

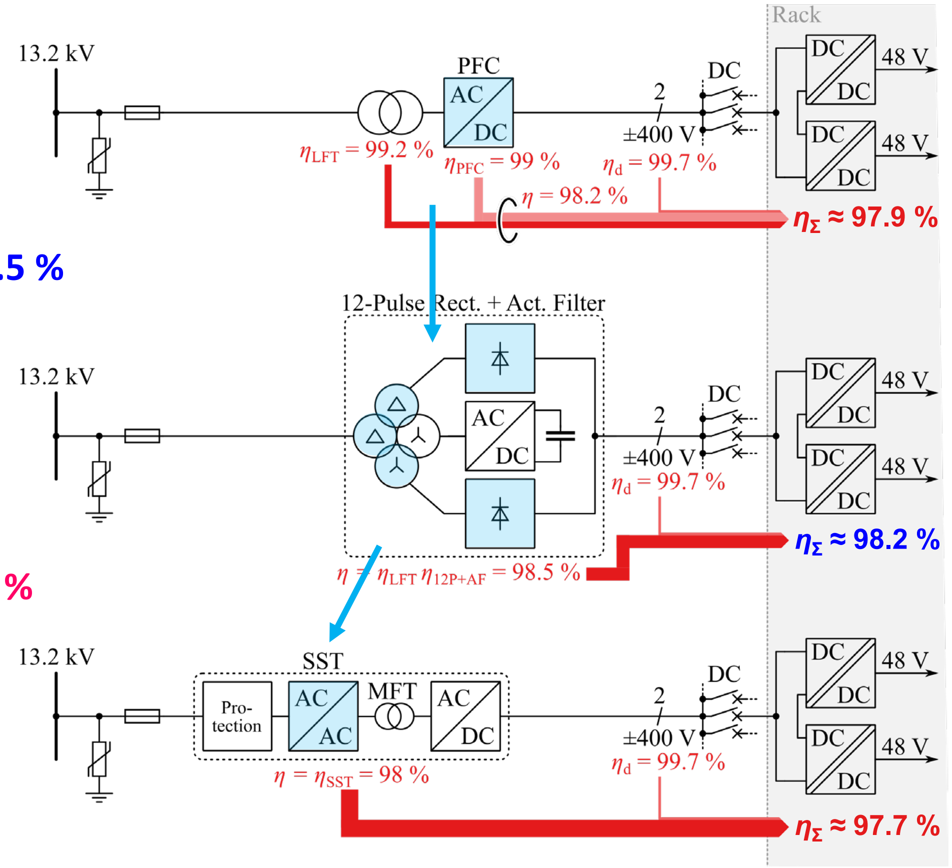
Comparative Evaluation of MVAC-LVDC Interfaces

Efficiency

■ **LFT + SiC PFC: $\eta \approx$ 98.2 %**

■ **12-Pulse + AF: $\eta \approx$ 98.5 %**

■ **Industrial SST: $\eta \approx$ 98 %**

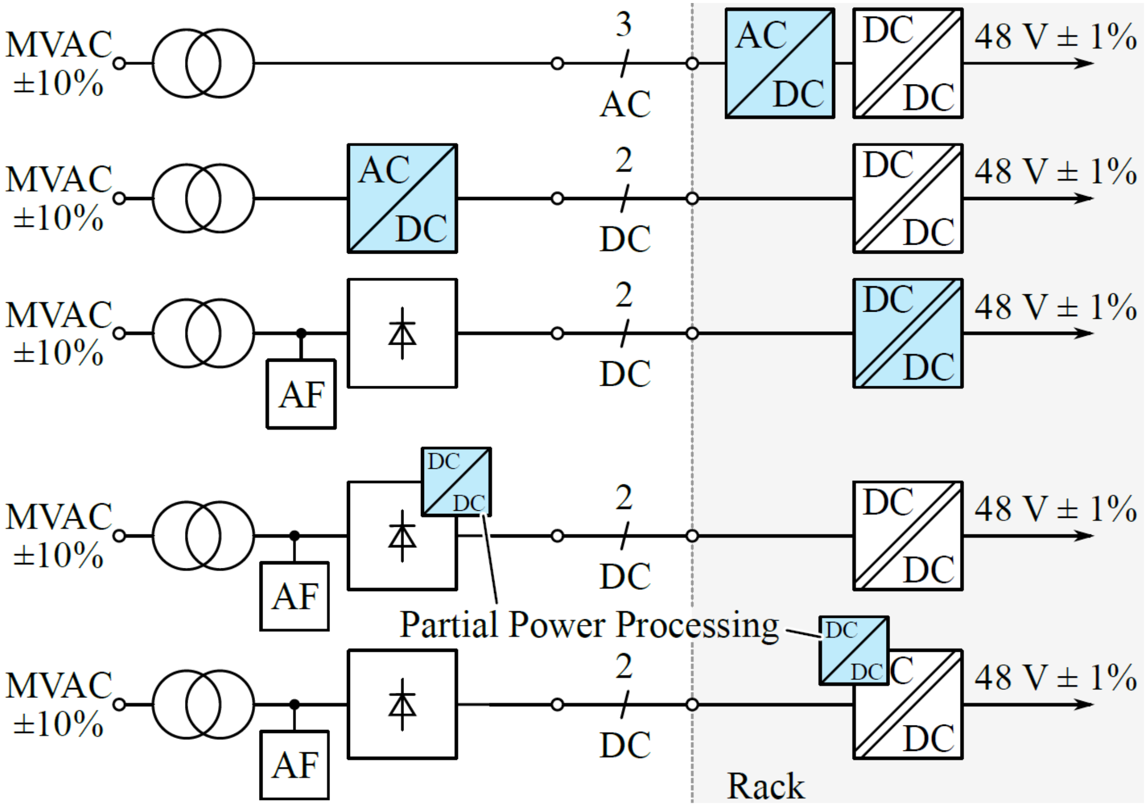


- Central PFC on LV-side
- No Switch-Mode PFC
- Active Filter / Partial-Power Proc.
- Central PFC on MV-side

■ **12-Pulse + AF → Highest Efficiency & Robustness vs. Reduced Functionality**

Remark: DC Voltage Control

- Grid Voltage Varies ±10% (EN 50160) | Stable 48 V DC for IT Equipment Needed

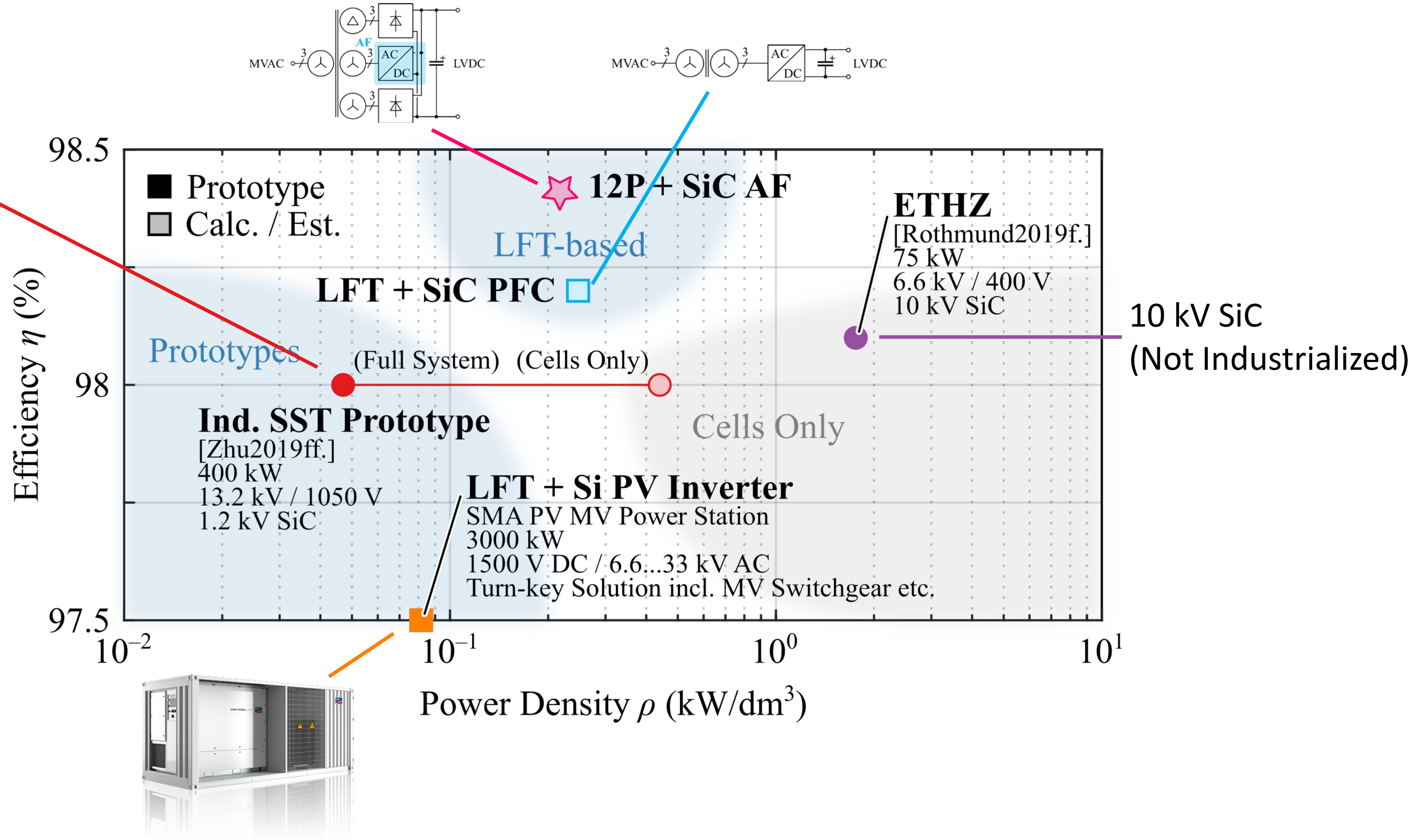


- One Converter Stage Must Provide Regulation Capability!

Efficiency & Power Density

- Industrial MVAC-LVDC SSTs → No Volume / Efficiency / Functionality Advantage Over LFT + LV SiC PFC
- LFT-Based Solutions → Robustness & Scalability
- 12-Pulse Rectifier + Act. Filter → Low Complexity | Reduced Functionality

400 kVA LFT
Shown for Comparison



Case Study Summary

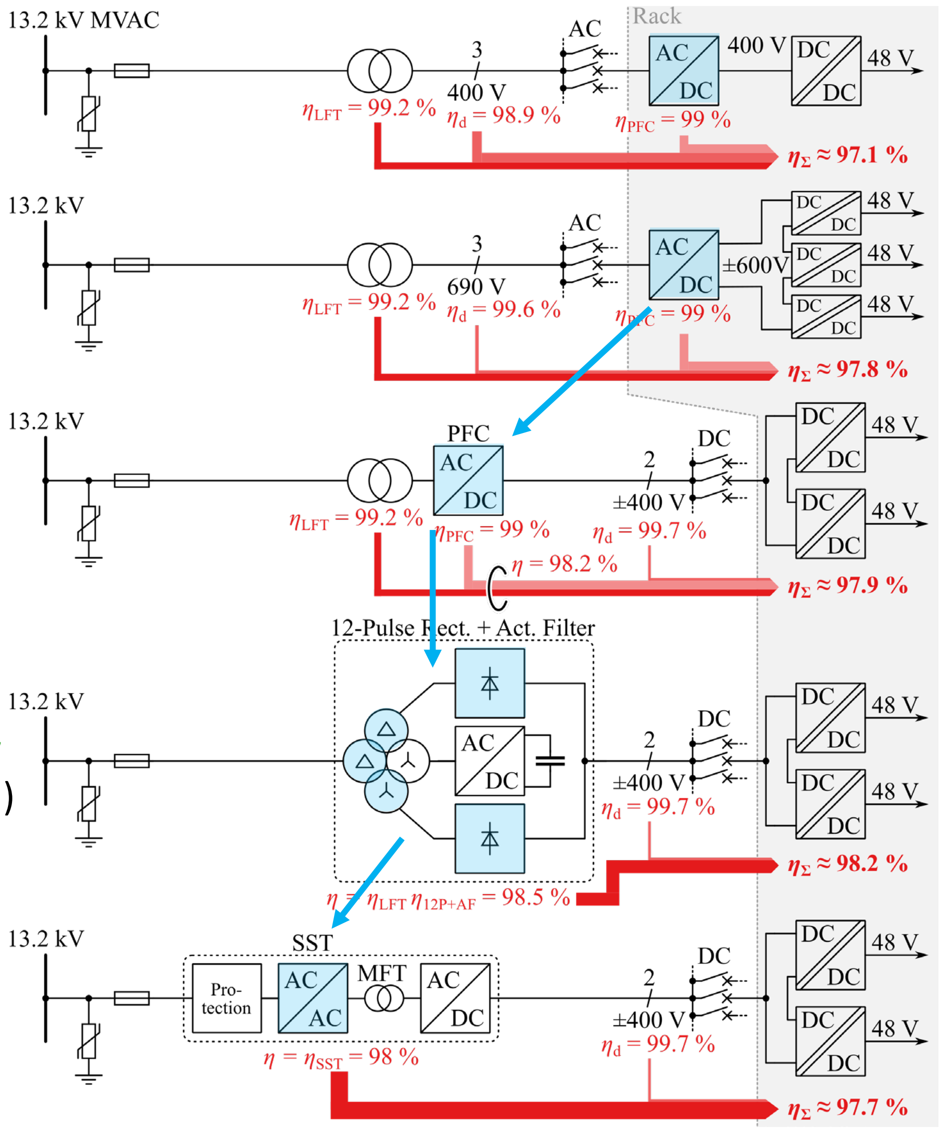
■ 690 V AC Competitive with ±400 V DC
- Add. Considerations on Integration of Renewables, Fuel-Cell Backup Power, Grid Services, etc.

■ LFT + LV SiC PFC
- Full Functionality, Scalability, High Robustness

■ 12-Pulse Rectifier & Act. Filter
- Low Complexity, High Efficiency, Scalability
- High Robustness, Long Lifetime, Good Recyclability
- Reduced Functionality (Unidir., No Act. DC Volt. Ctrl.)

■ Existing SST w/o Clear Advantages
- High Complexity Even for MMC-Based Designs
- Modularity / Economies of Scale / Protection / …

→ Need for Future Research!



400 V AC
$\eta_\Sigma \approx$ 97.1 %

690 V AC
$\eta_\Sigma \approx$ 97.8 %

±400 V DC
$\eta_\Sigma \approx$ 97.9 %

±400 V DC
$\eta_\Sigma \approx$ 98.2 %

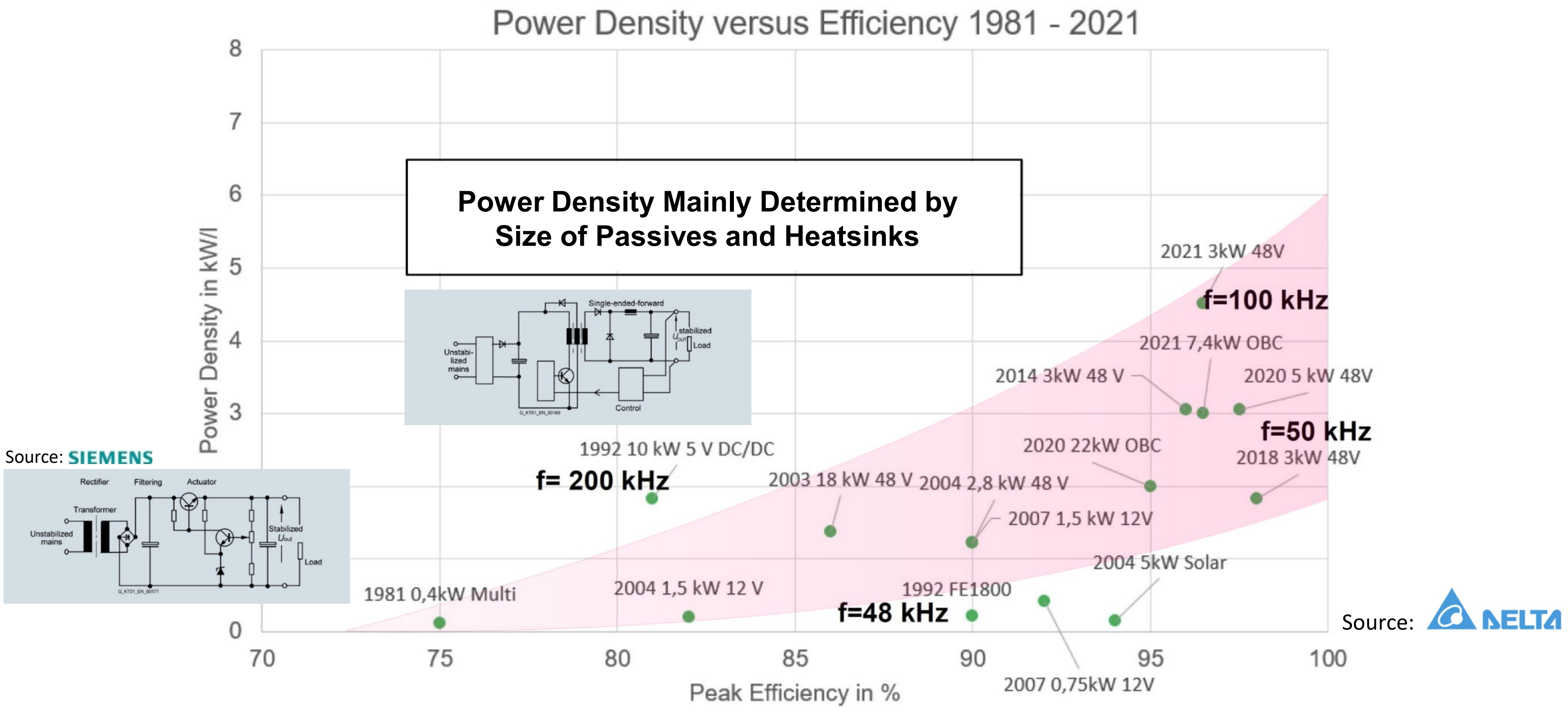
±400 V DC
$\eta_\Sigma \approx$ 97.7 %

Further Reading: [Huber2022]

Part V
Summary & Research Vectors

LV Low-Power SMPS Efficiency / Power Density 1981 – 2021

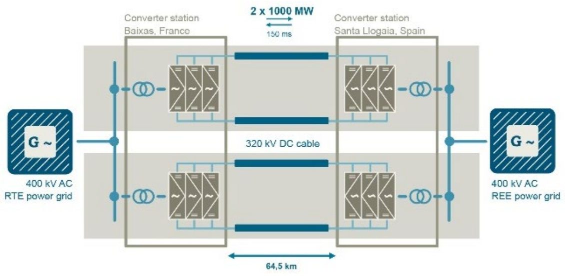
- 1981 — Large Volume Line-Frequ. Isolation/Voltage Step-Down | Diode Rectifier | Low Eff. Linear Stabilization
- 2021 — PFC Rectifier Front-End | High-Frequency Isol. DC/DC Converter



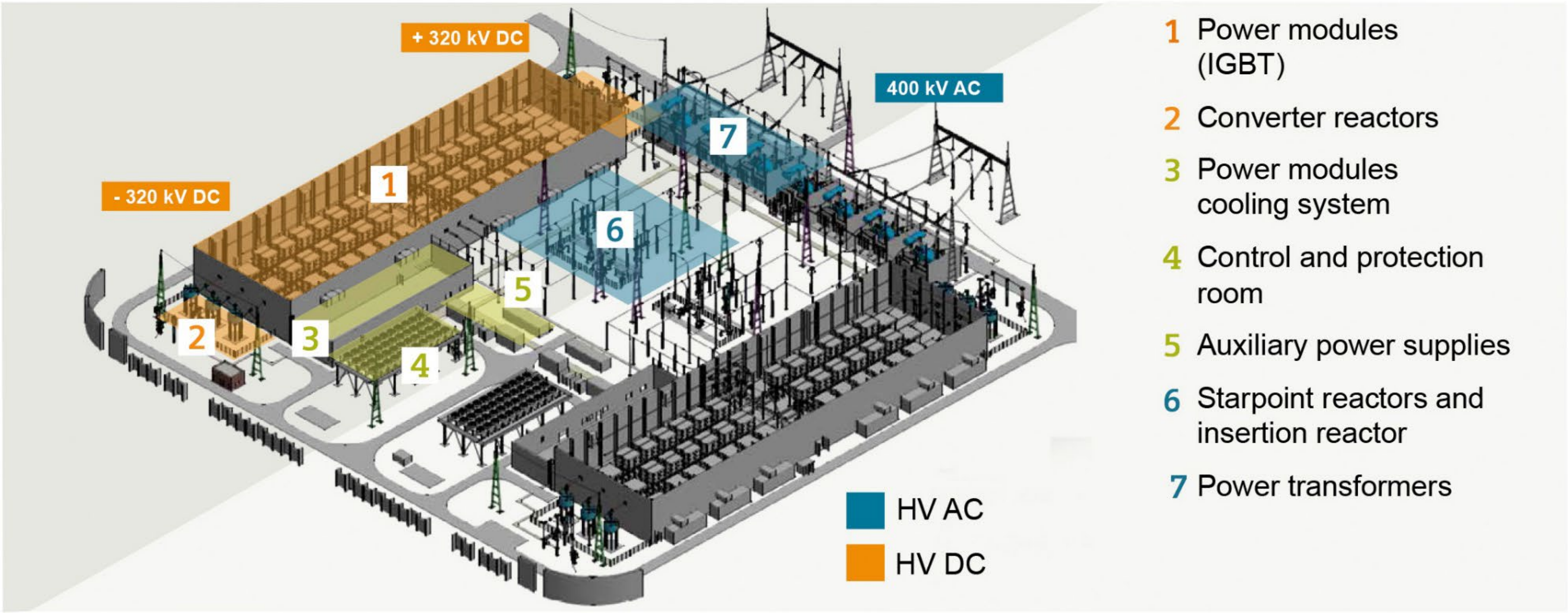
- Power Density AND Eff. Improvement | Line-Frequ. → High-Frequ. Conv. & Linear → Sw.-Mode Regulation

Remark HVDC Converter Station (1)

- 2 x 1 GW / ± 320 kV HVDC Transmission Link btw. France & Spain



Source: SIEMENS



- Isolation Clearances (!) Largely Determine Space Requirement | Low LFT Volume Contribution (!)

Remark HVDC Converter Station (2)

- 2 x 1 GW / ± 320 kV HVDC Transmission Link btw. France & Spain

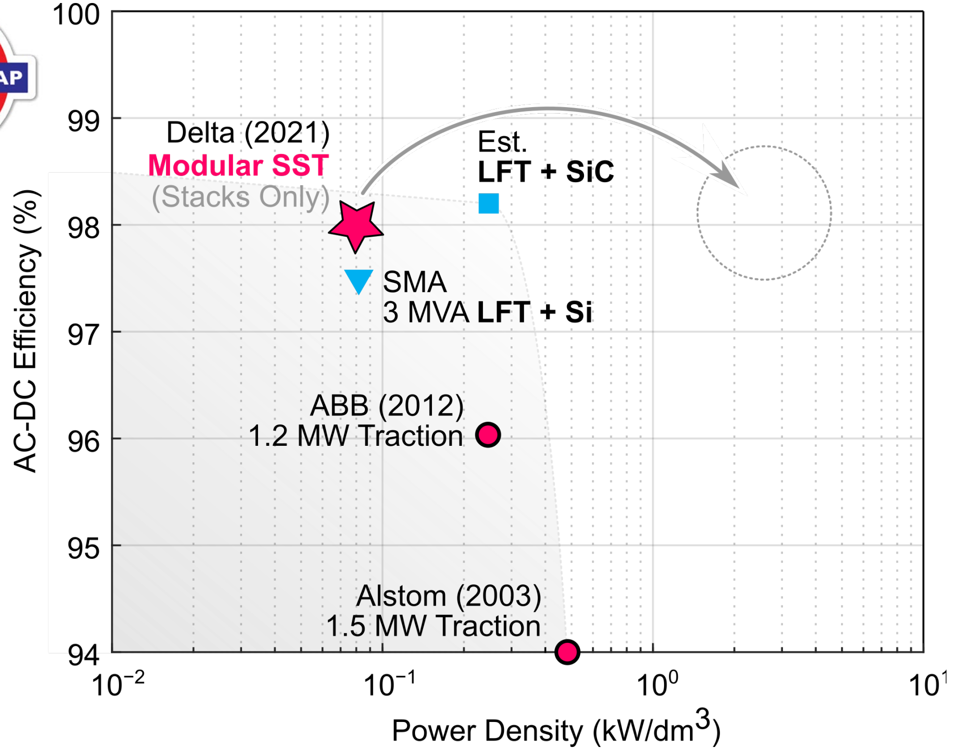
Source: SIEMENS

- Isolation Clearances (!) Largely Determine Space Requirement | Low LFT Volume Contribution (!)

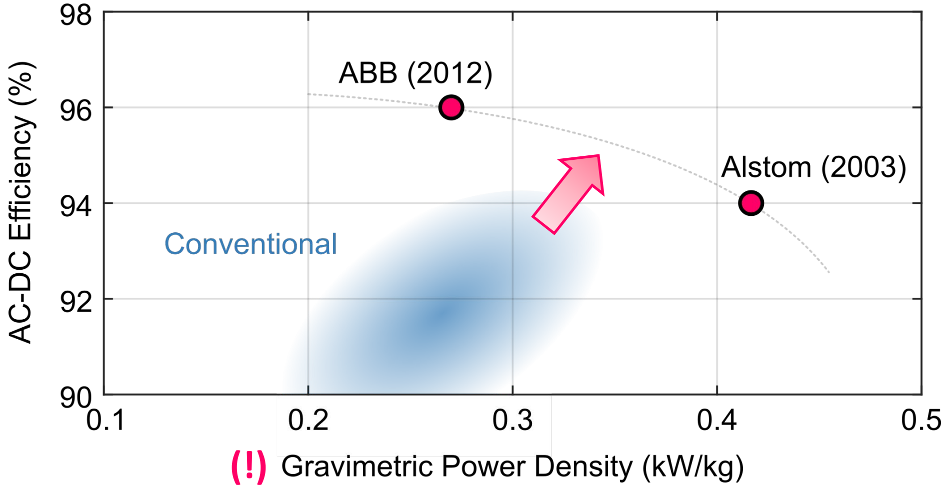
Status Quo: Traction & Grid AC-DC SSTs

- **Traction:** Clear Improvements in Efficiency / Power Density > 10 Years Ago
- **Grid:** Recently 1st Full Industrial Demonstrator w/o Performance Advantage

3-Phase Grid AC-DC SSTs



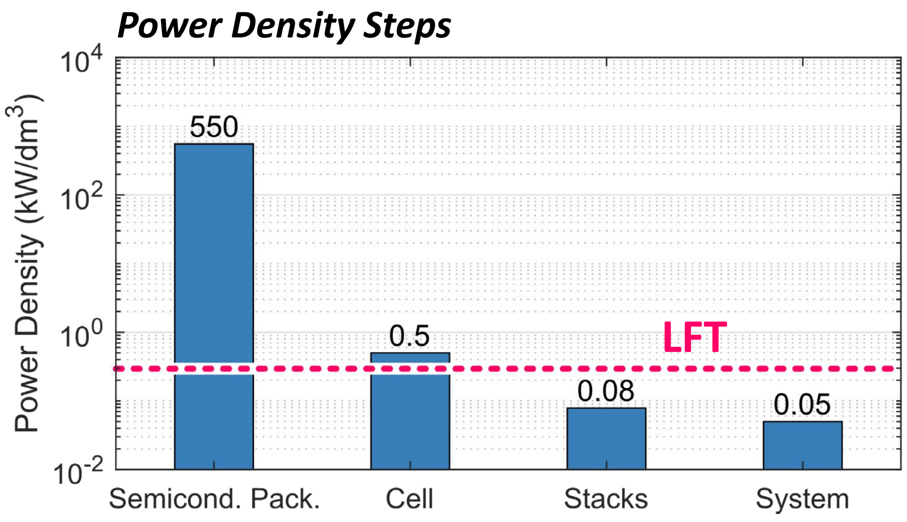
Traction AC-DC SSTs

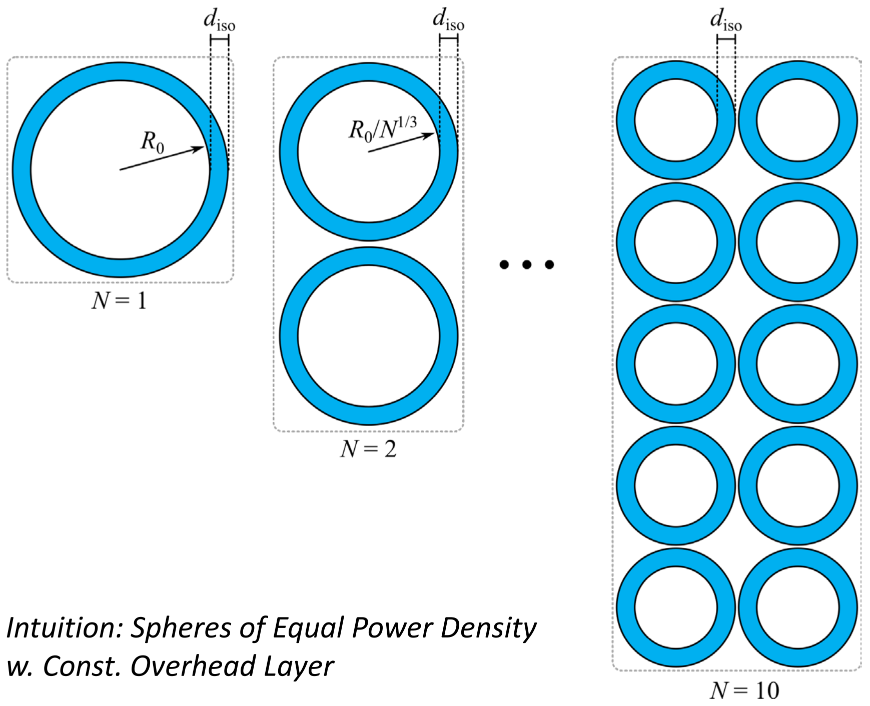


- **Full-Scale Demonstrators** Engineered to Standards Needed for Realistic Assessment!

Grid AC-DC SSTs: Challenges (1)

- Massive Reduction of Power Density from Cell to Full System → Modularity Penalty



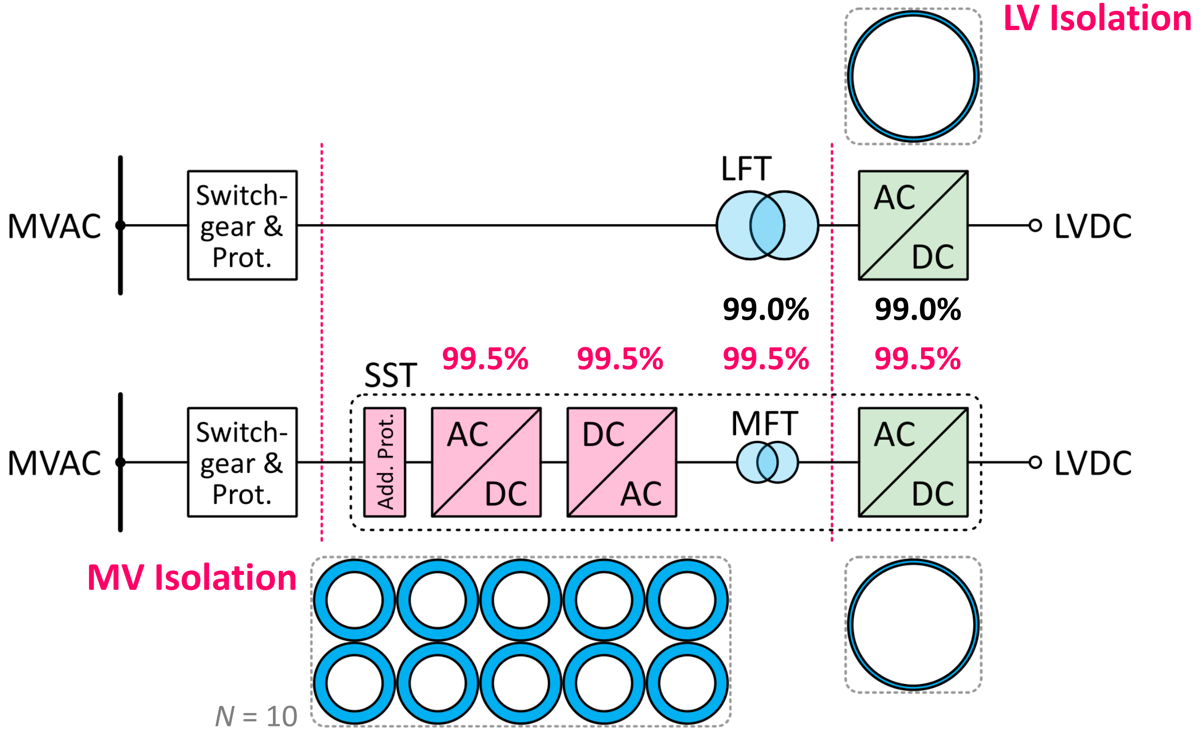


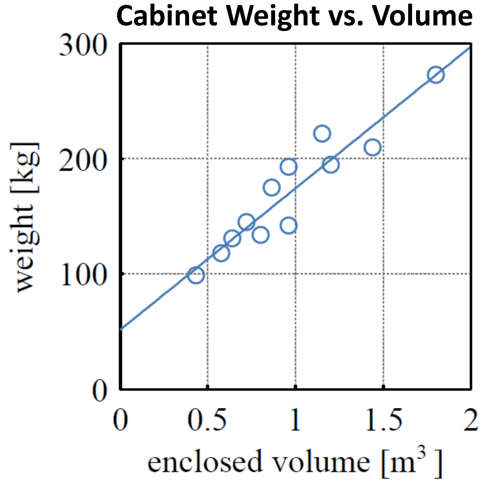
Intuition: Spheres of Equal Power Density w. Const. Overhead Layer

- Future High-Voltage SiC Devices (10+ kV) → Fewer Cells for Given System Voltage

Grid AC-DC SSTs: Challenges (2)

- PFC Functionality on MV Side → Modularity Penalty + Overhead
- Target Efficiency of 98% → 2% Loss Budget for 4 Conversion Stages vs. 2 Conversion Stages

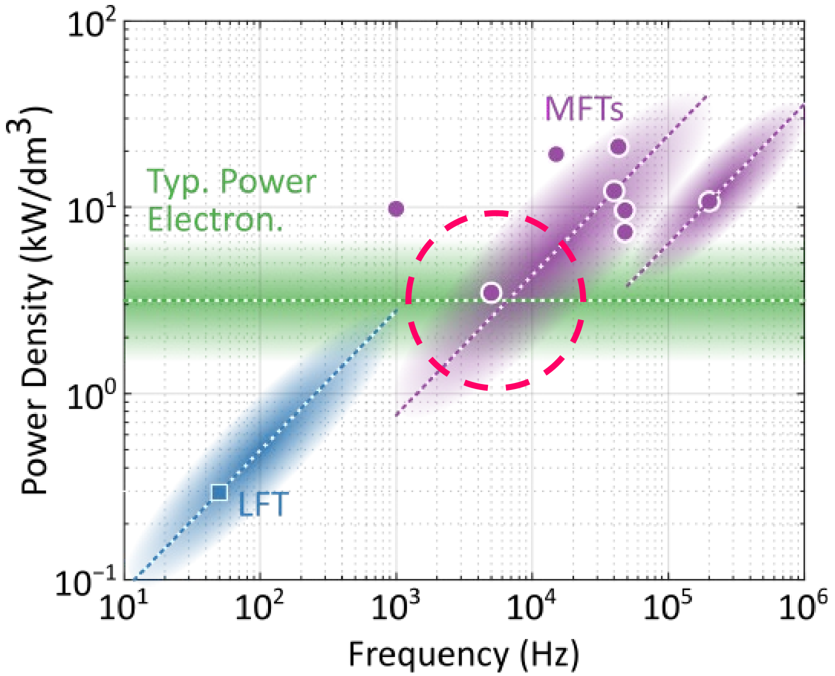




- MV PE Overhead: Protection, Connectors, Access for Maintenance, …
- Volume (Modularity Penalty + MV PE Overhead) → Larger Cabinets / Heavier Weight

Next-Gen. SSTs: Selection of MFT Operating Frequency

- 5…50 kHz Operating Frequency Sweet Spot ($\rho_{MFT} \approx \rho_{PE}$)

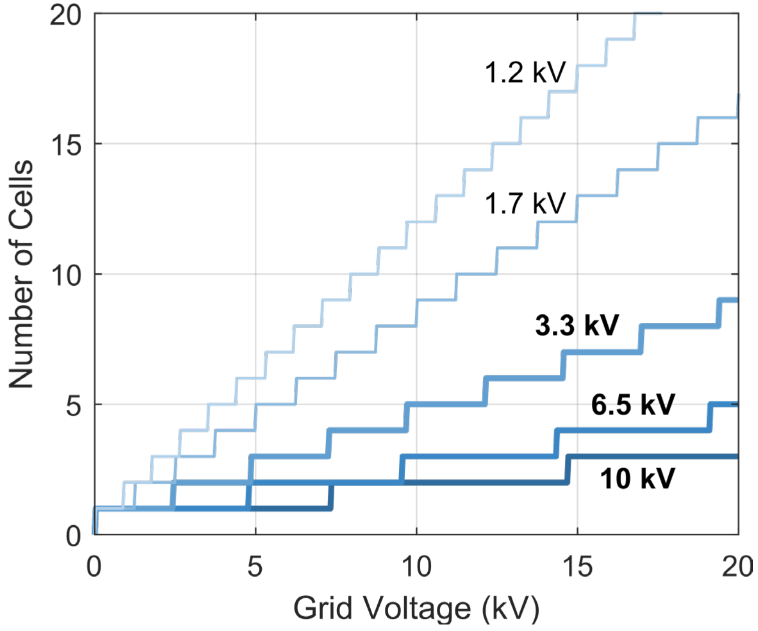


- Isolation Requirements (Clearance & Creepage Distances) Limit Power Density Gain from Higher Frequency

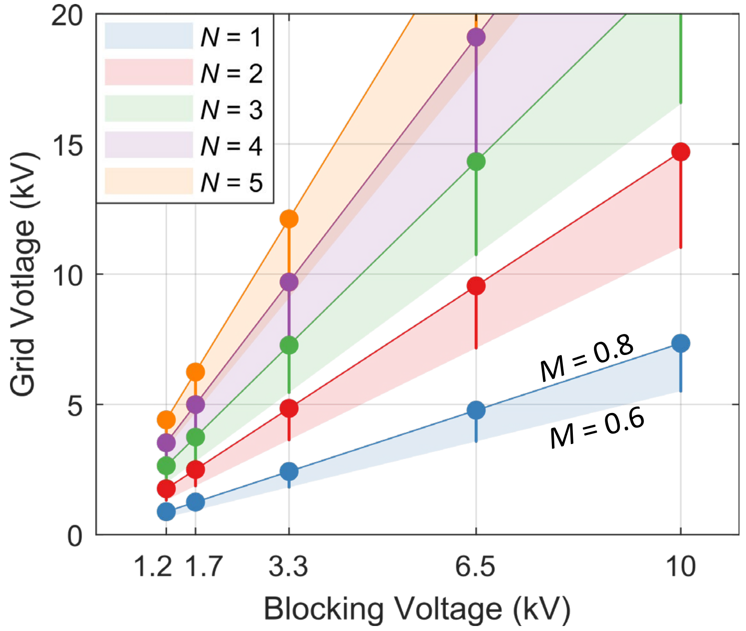
Next-Gen. SSTs: Selection of Number of Cascaded Cells

- Recent 6.5 kV and 10 kV SiC Devices → 13.8 kV Grid Reachable with < 4 Cells
- Today's Available Power Modules → Sensible Cell Power Ratings 250…500 kW w/o Paralleling

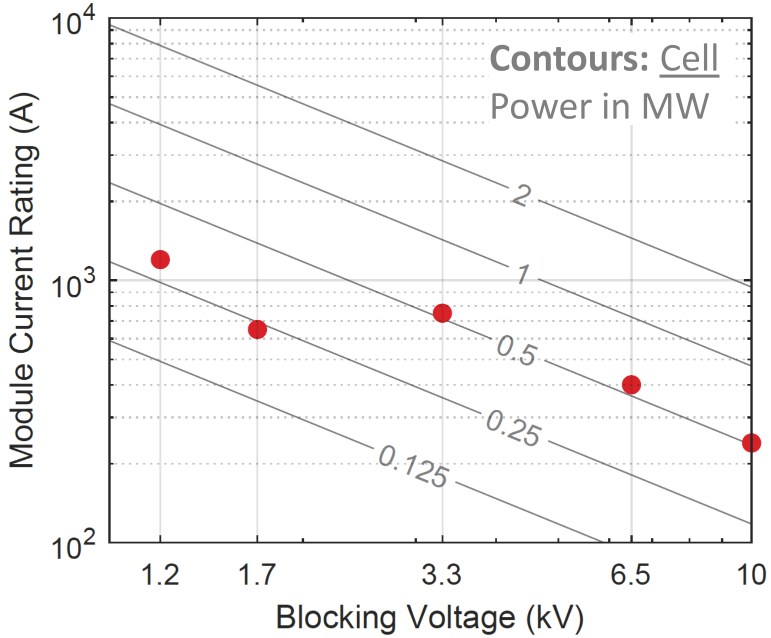
Number *N* of CHB Cells



Selection of Blocking Voltage & *N*



SiC Power Modules & Cell Power

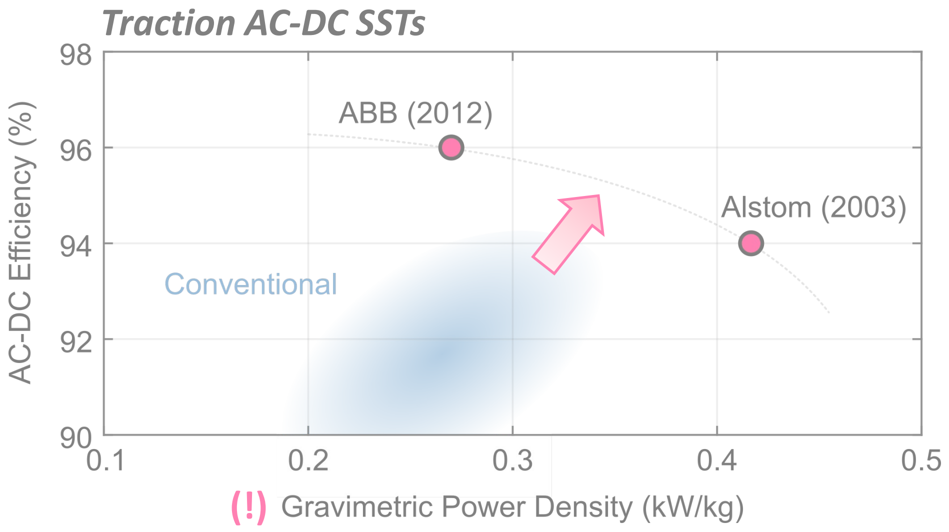


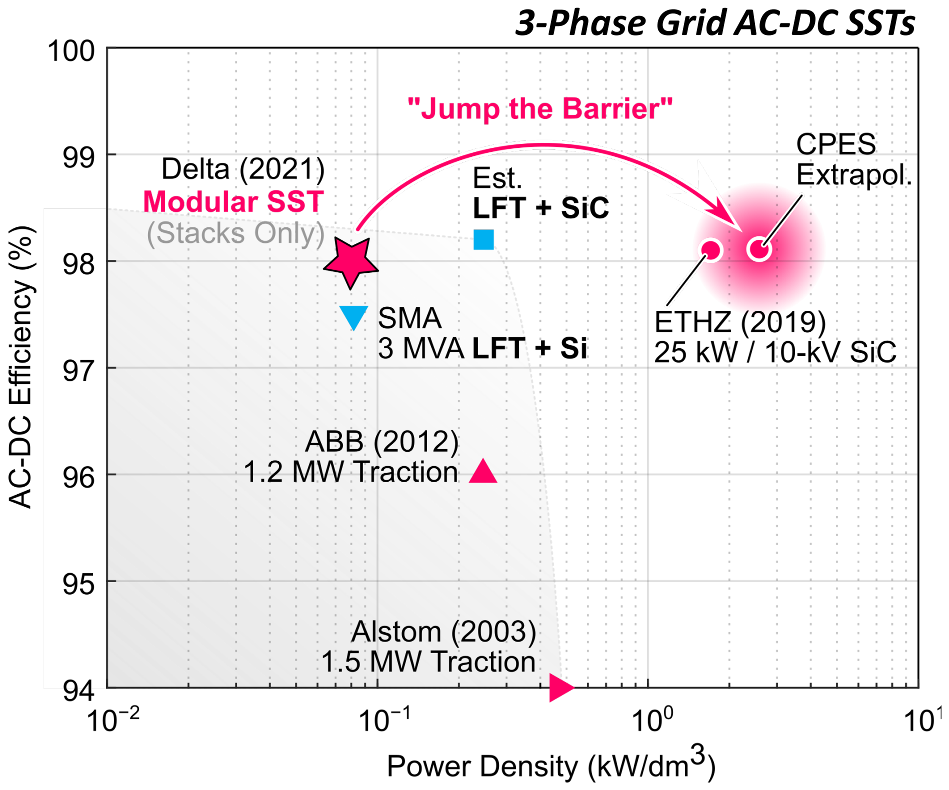
- CHB Topology w. 75% Semicond. Blocking Voltage Utilization and M = 0.8 (M < 0.6 → Uneconomic Utilization)

Next-Gen. SSTs: Improvement Potential

- 10 kV SiC and/or MMC Topology Might Facilitate the Jump Over the Power Density Barrier
- AC-DC Efficiencies >> 98% Remain Difficult to Attain

- Other Dimensions with Clear Improvement Potential Over the State of the Art Unclear

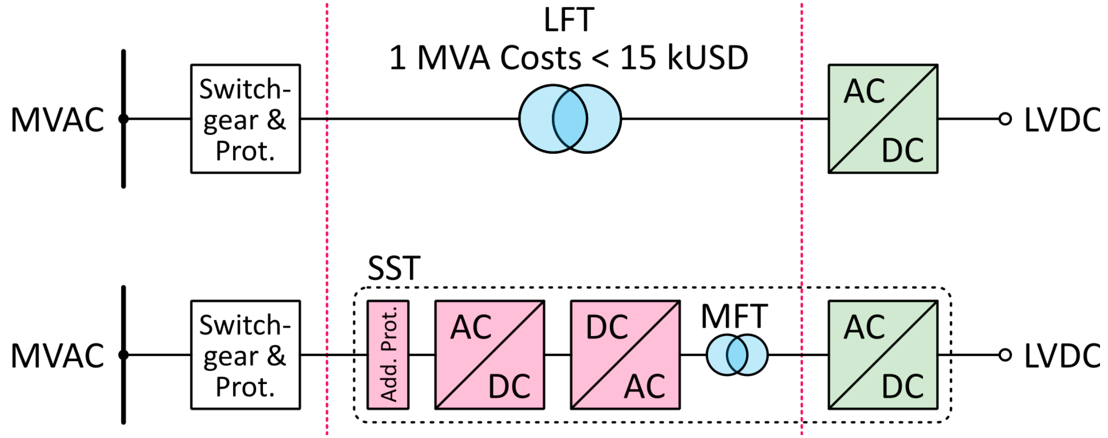




- Full-Scale Demonstrators Engineered to Standards Needed for Realistic Assessment!

SST Realization Costs (CAPEX)

- **High-Efficiency (Ecodesign) LFTs Cost < 15 kUSD/MVA**
  - MMC-Based SST: Similar LV-Side Power Electronics → Similar Cost
  - MFT Smaller But Likely Higher Specific Cost (e.g., Litz Wire vs. Solid Copper, etc.)



- **Budget for SST's MV-Side PE Incl. Additional Protection < 15 kUSD/MVA**

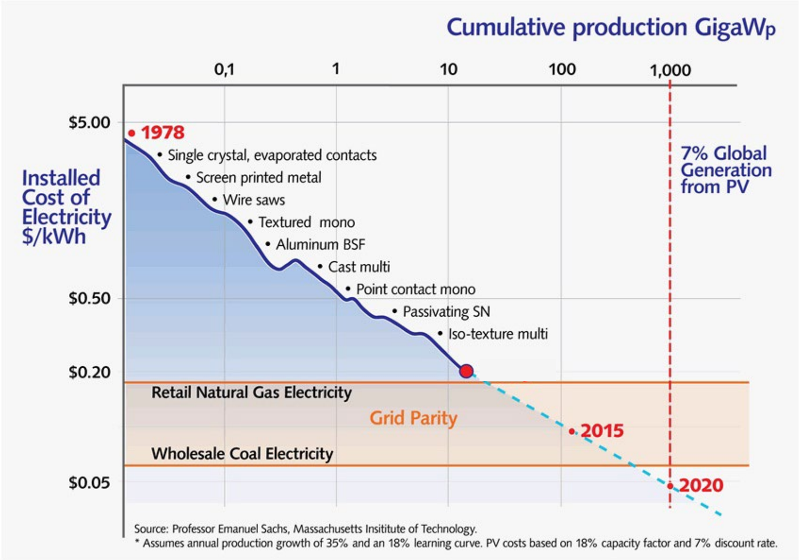
  - State of the Art
    - Automotive LV DC-AC Inv.: 3 USD/kW (U.S. Drive Roadmap R&D Target 2025; Only Transistors, GDs, Sensors)
    - Grid-Connected PV DC-AC Inv.: 30…55 USD/kW (Fraunhofer, 2022; Incl. Sw. Stage, Inductors, EMI Filter)

- **SST Cost Drivers: MFT, MV-Level Isolation Coordination, Assembly, Communication Systems, …**

Outlook: Experience Curve of Technologies

- Analysis of the Performance Improvement as Function of Accumulated Experience
- Learning Rate → Improvement / Cost Reduction for Each Doubling of Cumulative Installed Capacity

Experience Curve of PV Electricity Generation



Experience Curve of SST / SST Module Production?

- *Can SSTs Ever Become Cheaper than LFT-Based Solutions?*
- *How Would That Change the Picture?*
- *Procurement vs. Life-Cycle Cost (Energy Losses)?*

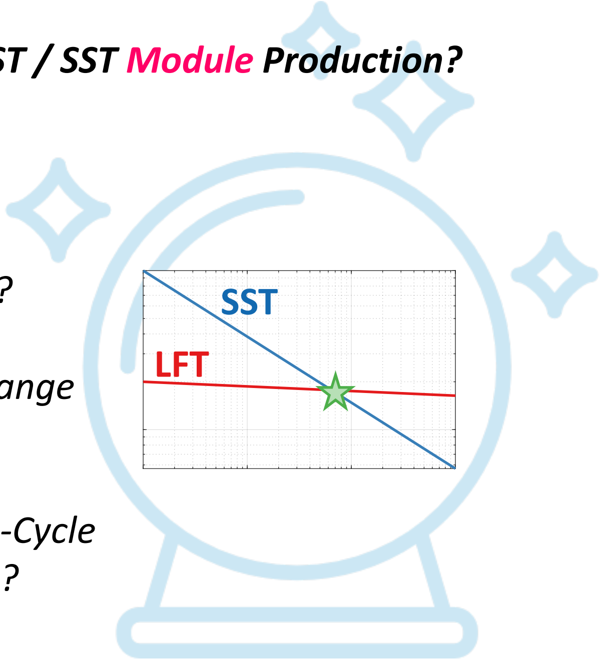
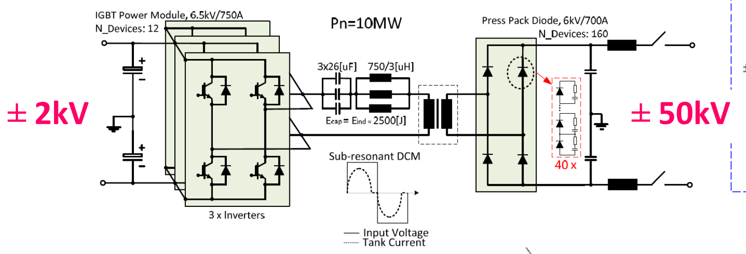


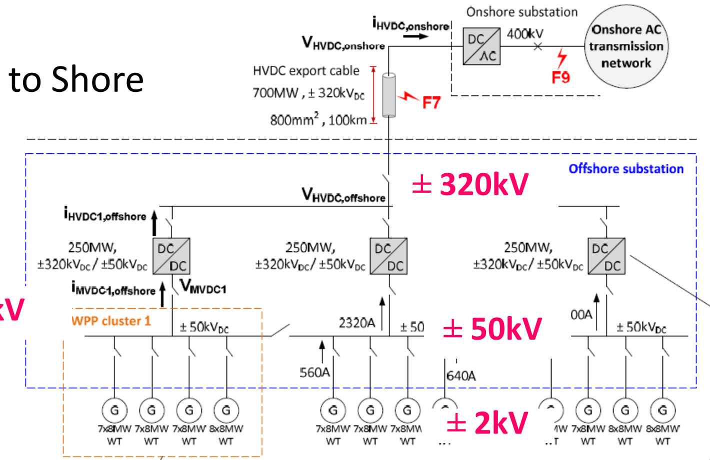
Image: Flaticon.com

- Typ. Empirical Learning Rates of 15…25 % → Dramatic Cost Reduction Over Longer Timespan
- Used for Prediction of Future Costs of a Technology (e.g., PV “Grid Parity”) → Long-Term Strategies

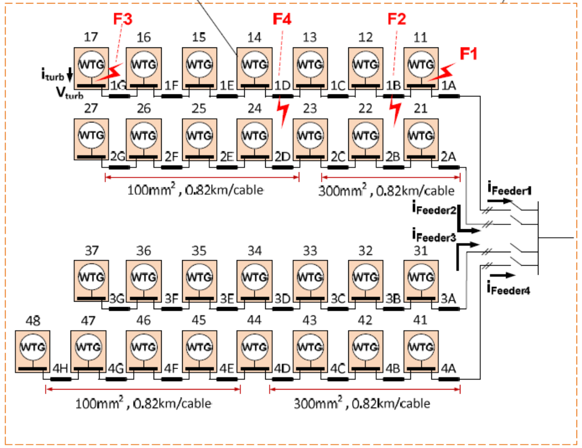
Outlook: DC Grids / MVDC-LVDC Conversion

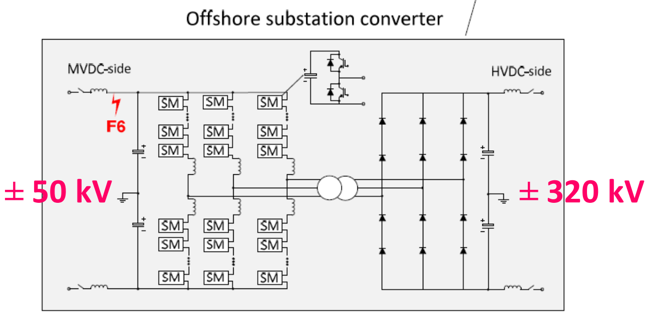
- **Example: Future Offshore Wind Park Collector Grids**
  - ±50 kV Offshore Collector Grid / ±320 kV HVDC Transmission to Shore
  - ±50 kV / ±320 kV Offshore Substation





- Unidirectional DCX MF LVDC→MVDC Conv. in Each Wind Turbine





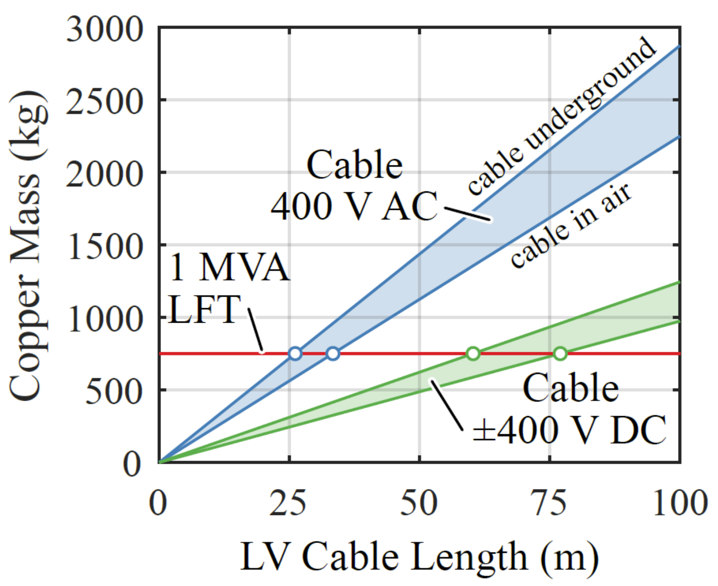
- MMLC-Based MF Isolation

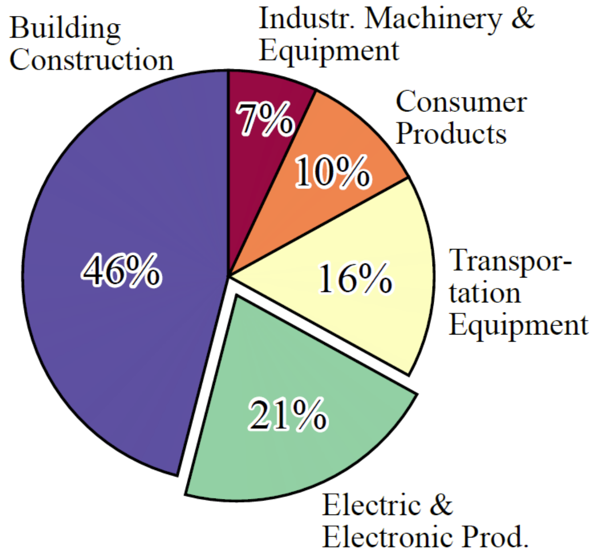
- **DC Grids Require "AC-Transformer"-Like Functionality → DC-DC SSTs w/o Alternative!**

[Kjaer2016]

Ecological Aspects / Resource Usage

- LV Distribution Busbars / Cables Dominate the Installed Copper Mass
- 40+ vs. 10 Years Typ. Lifetime of LFTs vs. Power Electronics/SSTs
- Recyclability Advantage of LFTs & High-Power Single Units (Such as Diode/Thyristor Rectifiers)





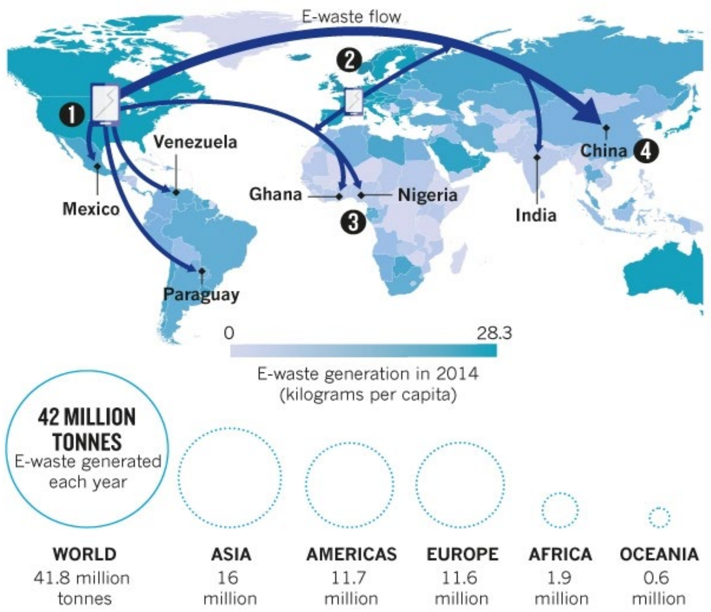
Copper Usage by Sector in the U.S. (2021)
U.S. Geological Survey

- Global Copper Usage Dominated by Other Sectors
- Life-Cycle Assessments—Cradle-to-Grave / Cradle-to-Cradle—Still Missing!

Remark Increasing E-Waste Problem

- 53´000´000 Tons of Electronic Waste Produced Worldwide in 2019 → 74´000´000 Tons in 2030
- Large Proportion Ends Up in Africa & China → Melting of PCBs & Cables etc. / Hazardous Substances
- Increasingly Complex Constructions → No Repair or Recycling

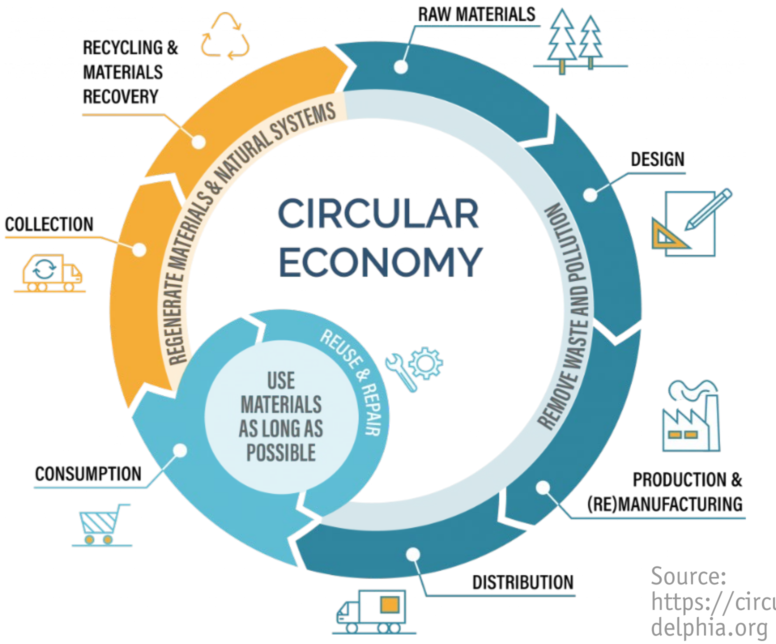
Source: Green IT Solution



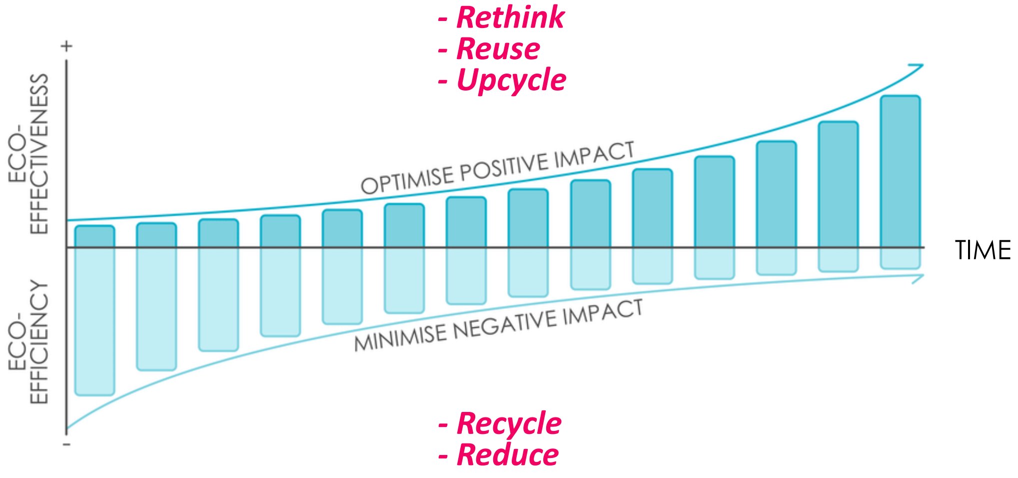
- Growing Global E-Waste Streams → Increasing Attention of the Public / Upcoming Regulations

Remark Cradle-to-Cradle (C2C) Design Concept

- "Linear" Economy / Take–Make–Dispose → "Circular" Economy / Perpetual Flow & Maintained Value of Resources
- Resources Returned Into the Product Cycle at the End of Use / Generation of Waste Minimized
- Maximized Use of Pure and Non-Toxic Reusable Materials



Source: https://circularphiladelphia.org



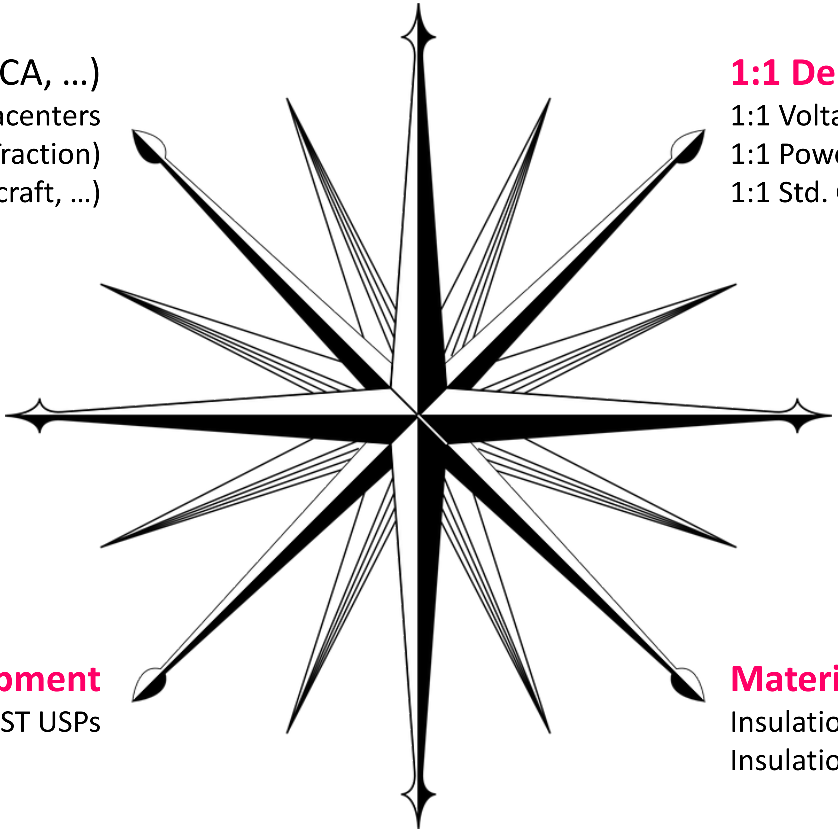
- Decoupling of Economic Growth & Use of Resources
- Measures Covering the Entire Lifecycle → Design | Manufacturing | Consumption | Repair | Reuse | Recycling

Research Vectors

"Jump the Gap"
More Compact Realizations

System Studies (TCO, LCA, …)
High-Power EV Charging & Datacenters
MVDC Grids (Collector Grids, Traction)
Special Applications (Naval, Subsea, Aircraft, …)

1:1 Demonstrators for Full Assessment
1:1 Voltage – 10+ kV
1:1 Power – 1+ MW
1:1 Std. Compl. (BIL, Prot.) – 50+ kV



Alternative Concepts
Local MFAC Distribution
Fully Opt. LFT-Based Solutions /
Multi-Pulse Rect.

Protection & Robustness
MV Solid-State AC & DC Prot. Sw. / Breakers
Design for 20+ Years Lifetime

Business Model Development
Demonstration of SST USPs

Materials
Insulation Material / Mixed-Frequency
Insulation Stress

Circular Economy & Sustainability
New/Future KPIs: **Longevity** / **Repair** / **Re-Use** / Recycle

Thank You!

Full Version

https://u.ethz.ch/bWWoV

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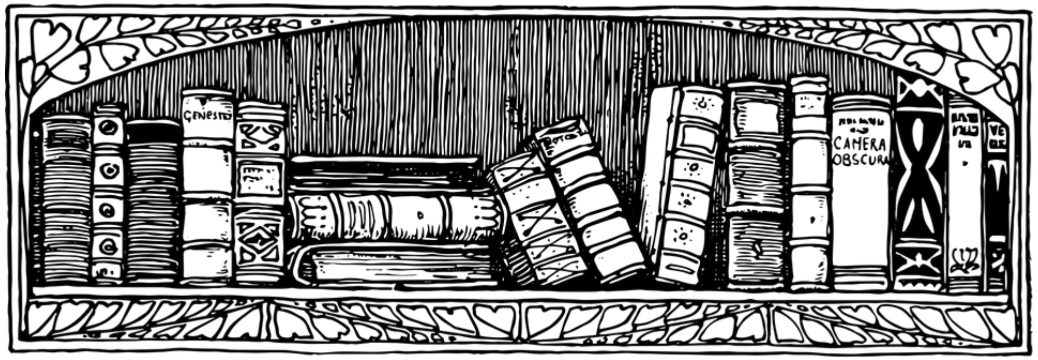

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