ETH zürich

Solid-State Transformers

Key Components for Future Transportation and Smart Grid Applications

J.W. Kolar and G. Ortiz

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Outline

- ▶ Transformer (XFMR) History
- ▶ Solid-State Transformer (SST) Concept

- ▶ Classification of Topologies
- ▶ Demonstrator Systems
- ▶ Research Topics @ ETH Zurich

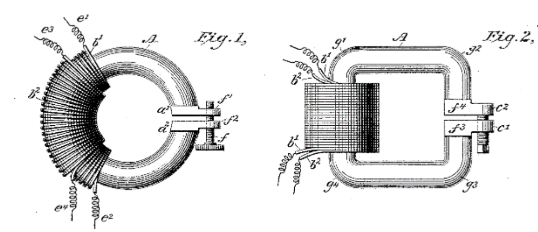
- ▶ Evaluation / Challenges
- ▶ Conclusions

History

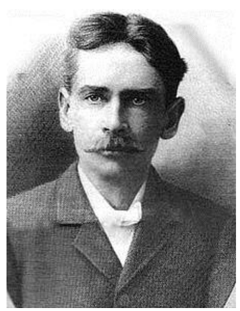
Transformer
"Electronic" Transformer

▶ Classical Transformer (XFMR) – History (1)

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



Patented Sept. 21, 1886. No. 349,611. W. STANLEY, Jr. INDUCTION COIL.



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

United States Patent Office

3,517,300
Patented June 23, 1970

1

3,517,300

POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK

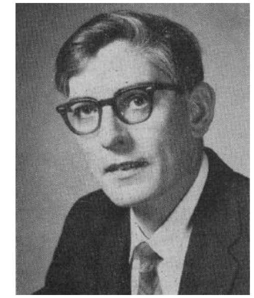
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York

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

1968 !

ABSTRACT OF THE DISCLOSURE

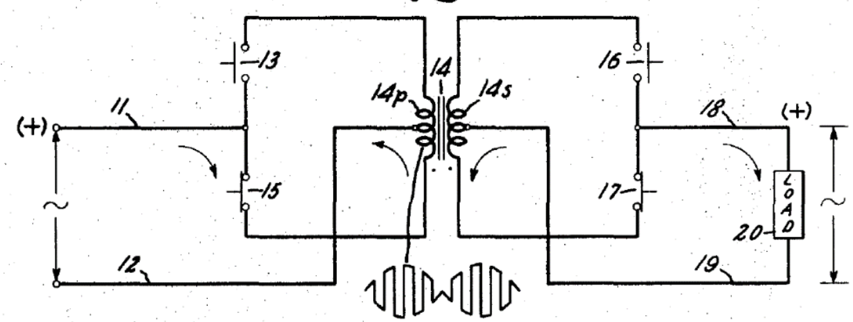
Several single phase solid state power converter circuits have a high frequency transformer link whose windings are connected respectively to the load and to a D-C or low frequency A-C source through inverter configuration switching circuits employing inverse-parallel pairs of controlled turn-off switches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



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

Filed April 16, 1968

Fig. 1a

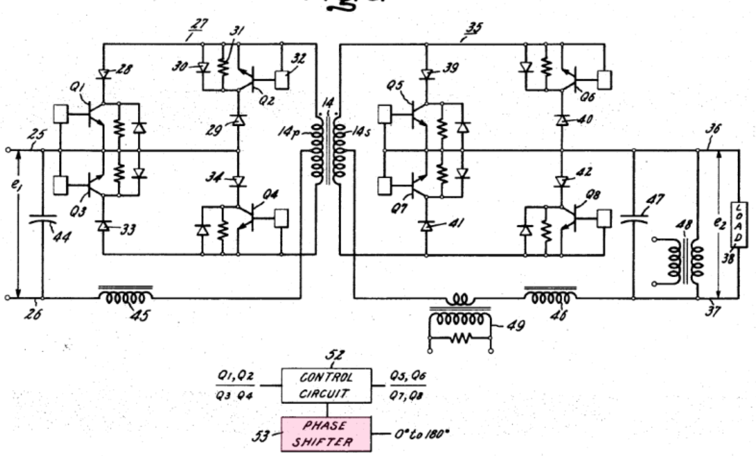


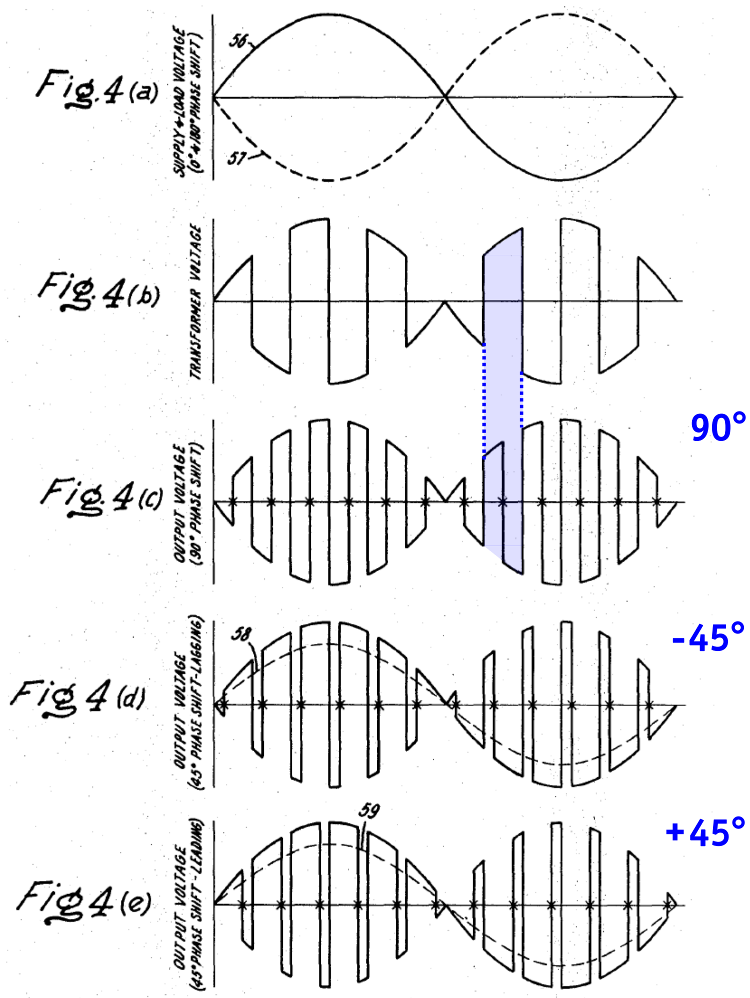
- HF Transformer Link AC/AC Power Converter ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption

▶ HF Transformer Link Converter

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

Fig. 3.





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

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

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

WILLIAM McMURRAY, SENIOR MEMBER, IEEE

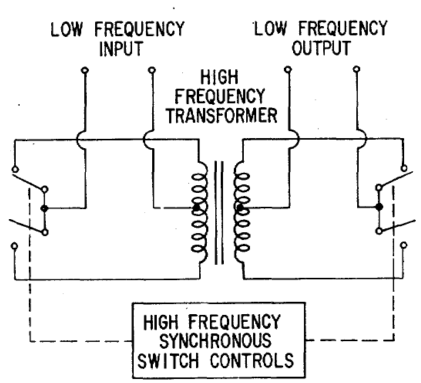


Fig. 1. Principle of electronic transformer.

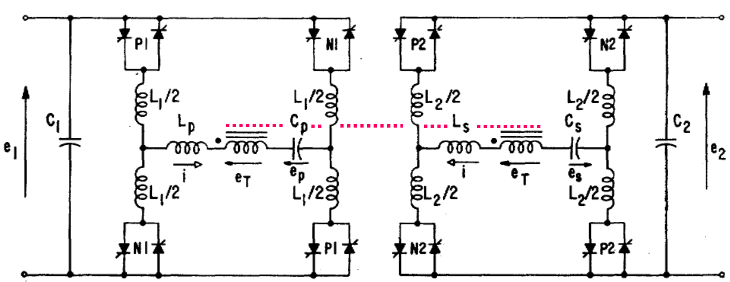


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

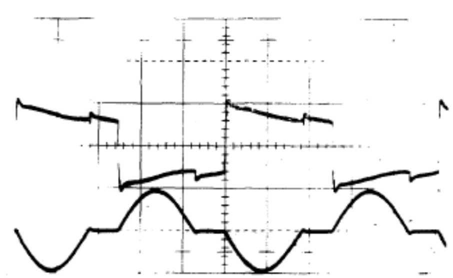


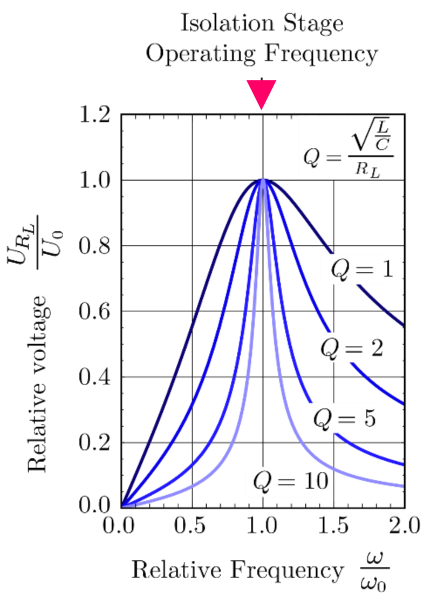
Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

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

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

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

WILLIAM McMURRAY, SENIOR MEMBER, IEEE



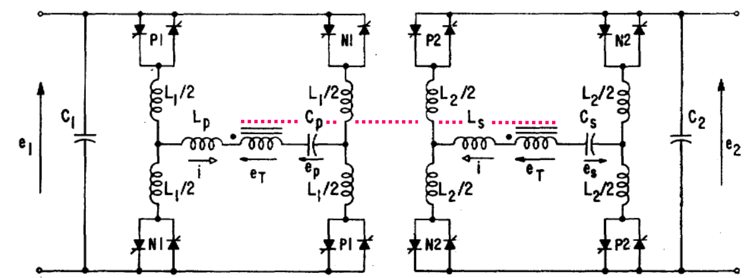


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

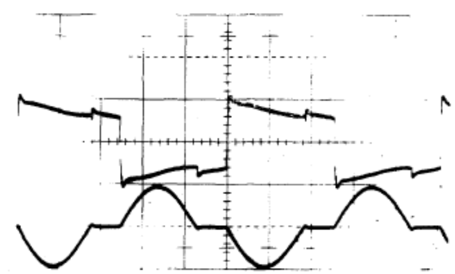


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

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

► "Solid-State" Transformer

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

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

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

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

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

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

[22] Filed: **Sep. 18 1980** ← **1980 !**

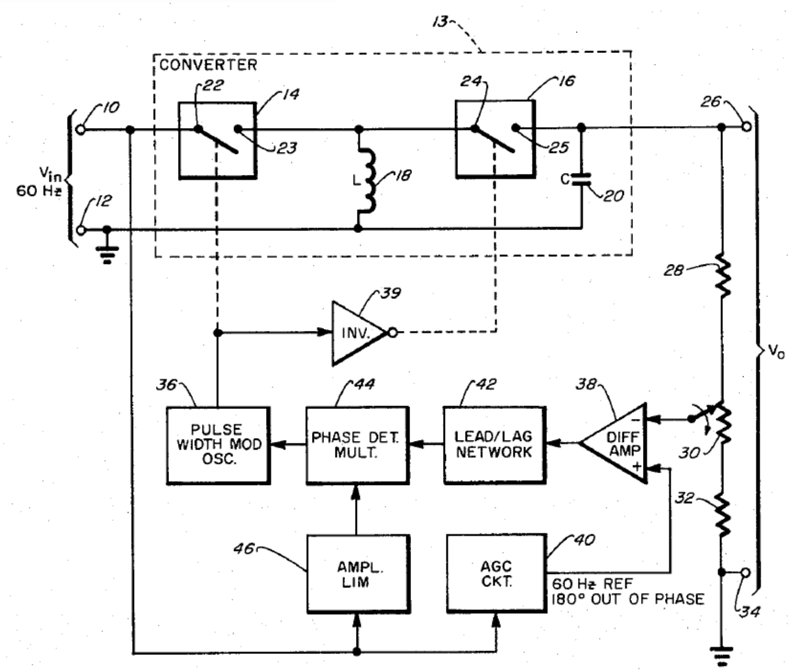


Fig. 1.

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

OTHER PUBLICATIONS

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

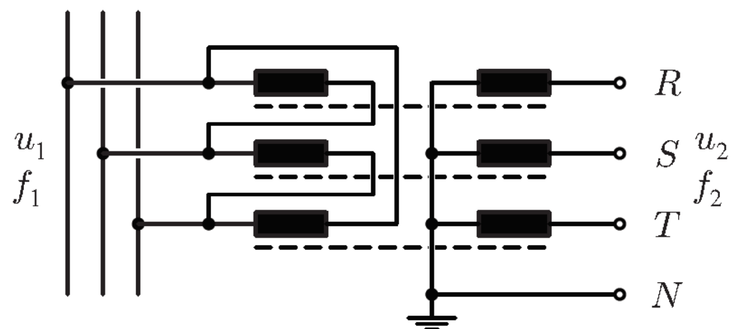
"Solid-State" Transformer (SST)

XFMR Scaling Laws
SST Application Areas / Concept

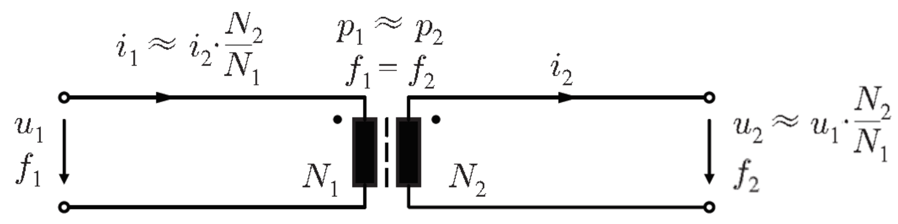
▶ Classical Transformer – Basics (1)

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

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



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

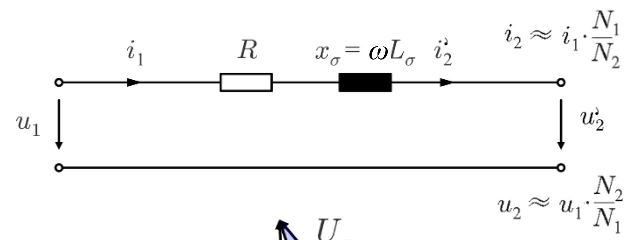


- Magnetic Core Cross Section $$A_{Core} = \frac{1}{\sqrt{2}\pi} \frac{U_1}{\hat{B}_{max} f} \frac{1}{N_1}$$
- Winding Window $$A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$$

▶ Classical Transformer – Basics (2)

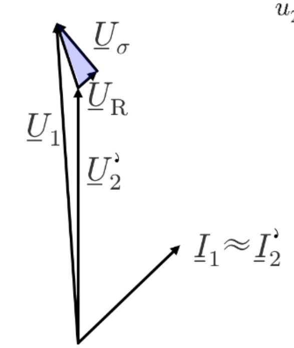
- Advantages

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



- Weaknesses

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

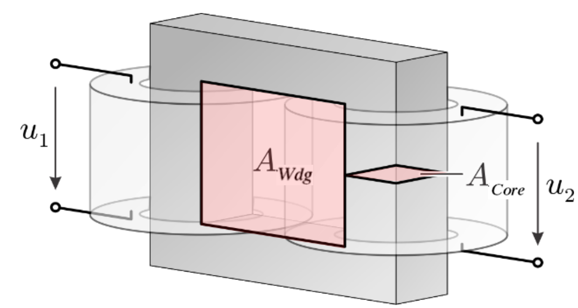


- Construction Volume

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

↑ ↑ ↑

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



- Low Frequency → Large Weight / Volume

▶ Classical Transformer – Basics (2)

- Advantages

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

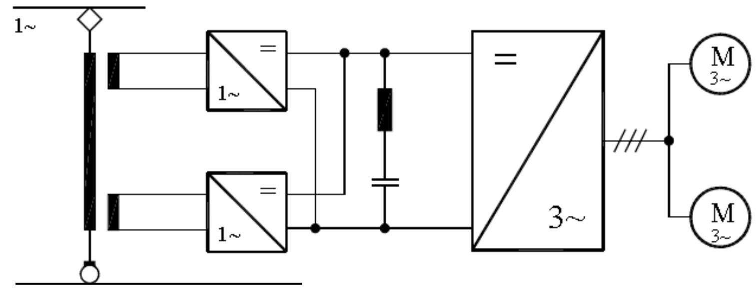
Welding Transformer (Zimbabwe) – Source: http://www.africancrisis.org

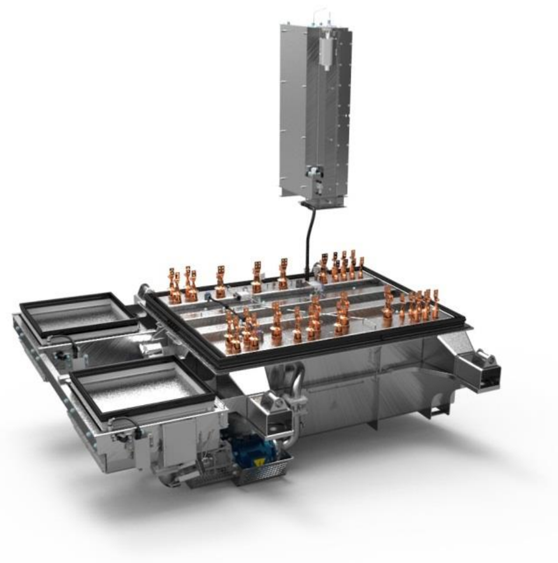
SST Applications

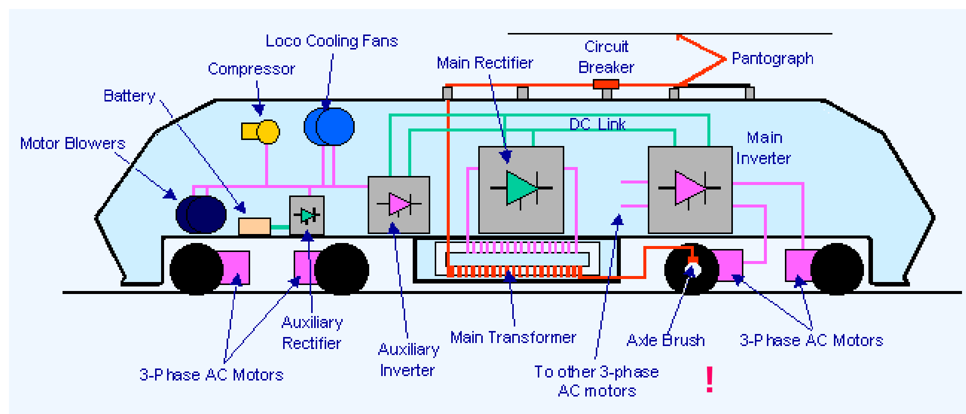
Traction (Locomotives)

▶ Classical Locomotives

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







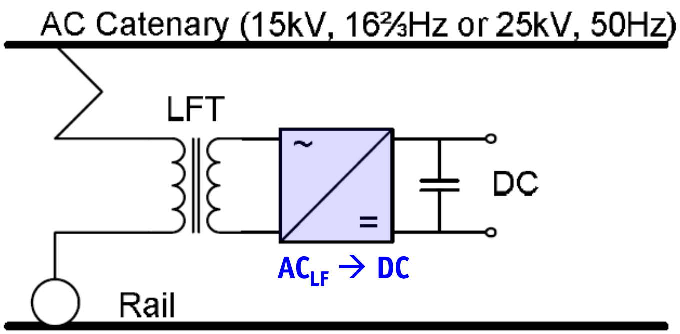
- Transformer:

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

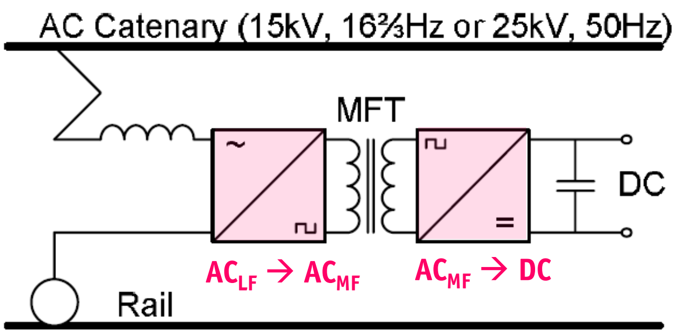
▶ Next Generation Locomotives

- Trends
  * Distributed Propulsion System → Volume Reduction (Decreases Efficiency)
  * Energy Efficient Rail Vehicles → Loss Reduction (Requires Higher Volume)
  * Red. of Mech. Stress on Track → Mass Reduction

Source: ABB



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

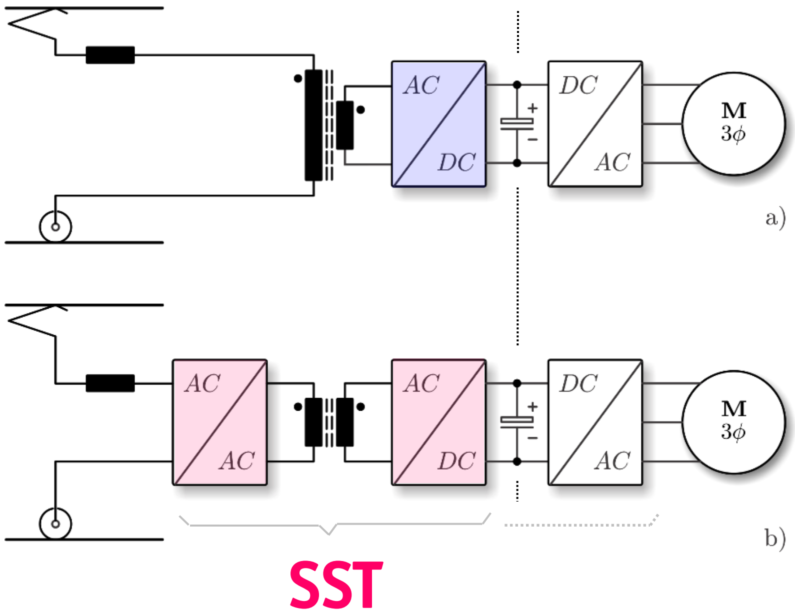


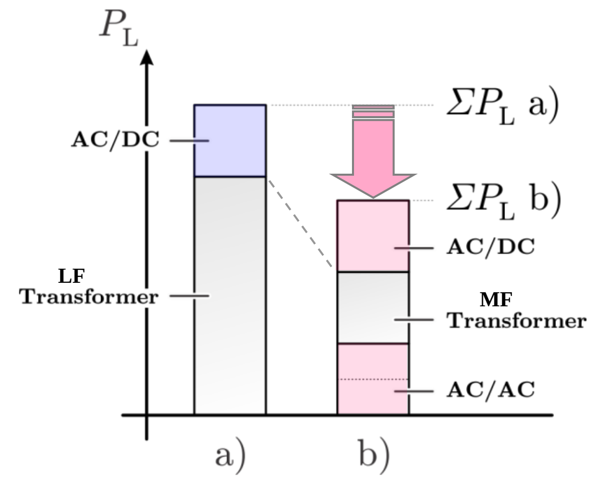
AC-DC conversion with medium frequency transformer (MFT).

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

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives





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

Future Smart EE Distribution

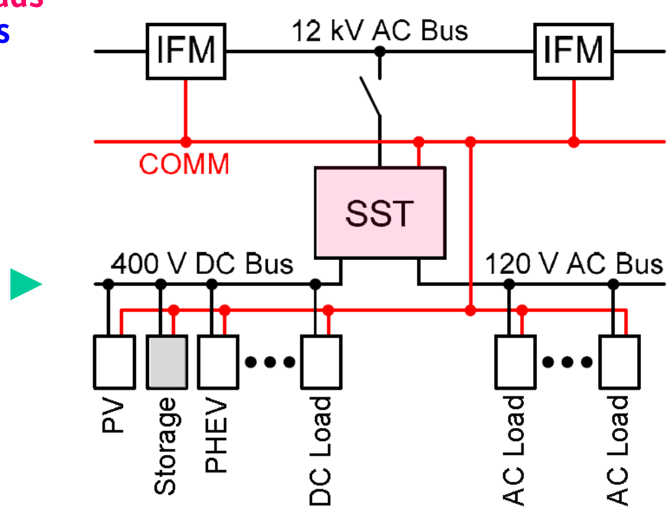
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- 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 Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.
- etc.

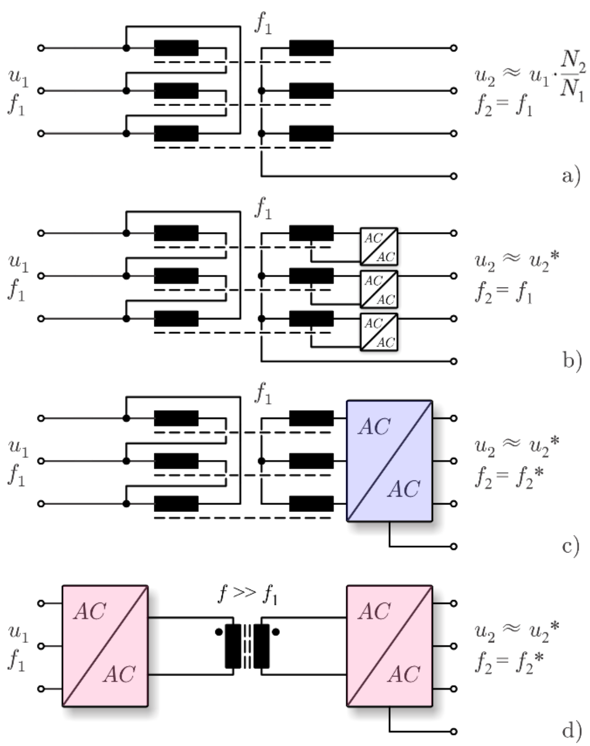
IFM = Intellig. Fault Management



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

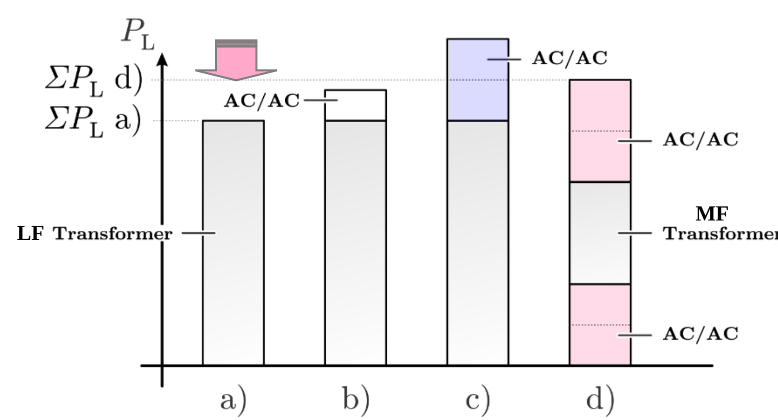
▶ Passive Transformer → SST

- Efficiency Challenge



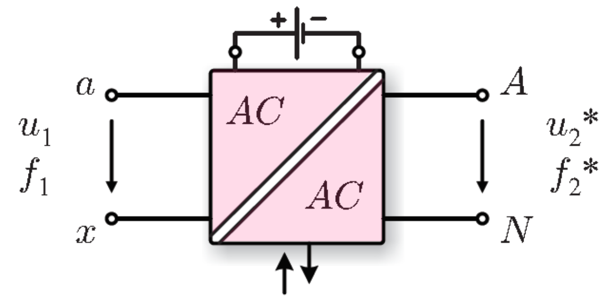
LF Isolation
Purely Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

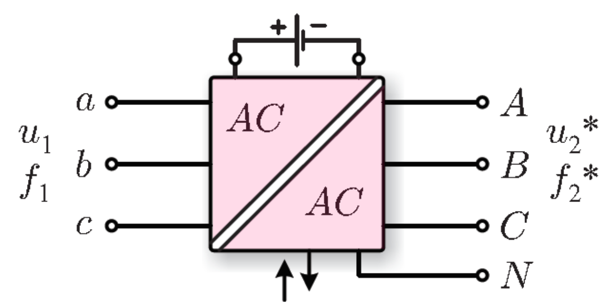
MF Isolation
Active Input & Output Stage (d)



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

Terminology





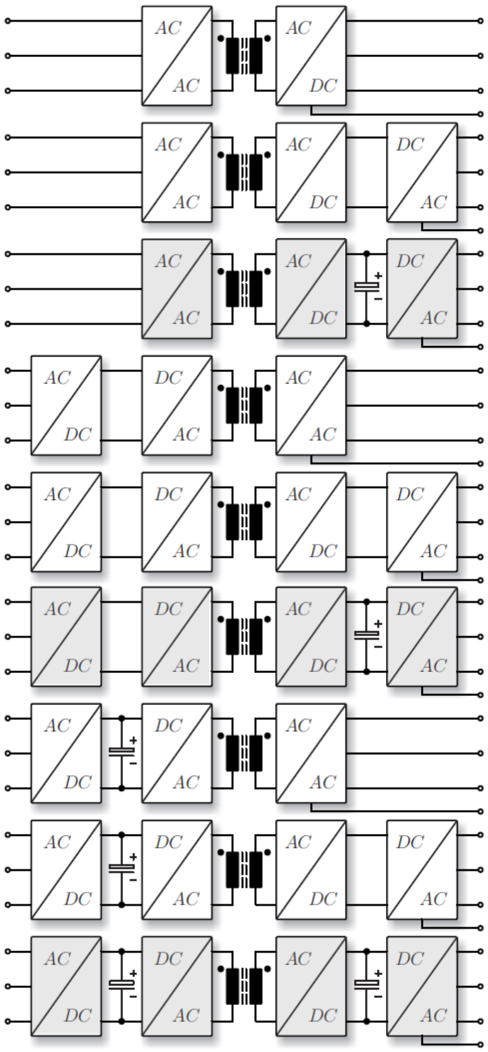
McMurray	Electronic Transformer (1968)
Brooks	Solid-State Transformer (SST, 1980)
EPRI	Intelligent Universal Transformer (IUT™)
ABB	Power Electronics Transformer (PET)
Borojevic	Energy Control Center (ECC)
Wang	Energy Router
etc.	

Classification of SST Topologies

▶ Basic SST Structures (1)

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

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

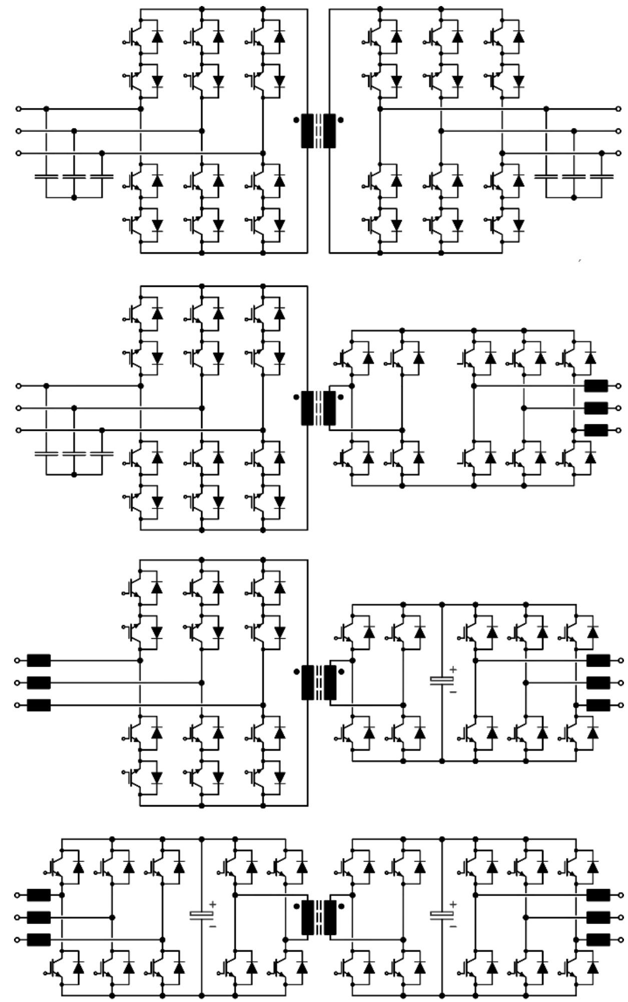


- 1-Stage Matrix-Type Topologies
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 2-Stage with MV DC Link (Connection to HVDC System)
- 3-Stage Power Conversion with MV and LV DC Link

▶ Basic SST Structures (1)

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

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

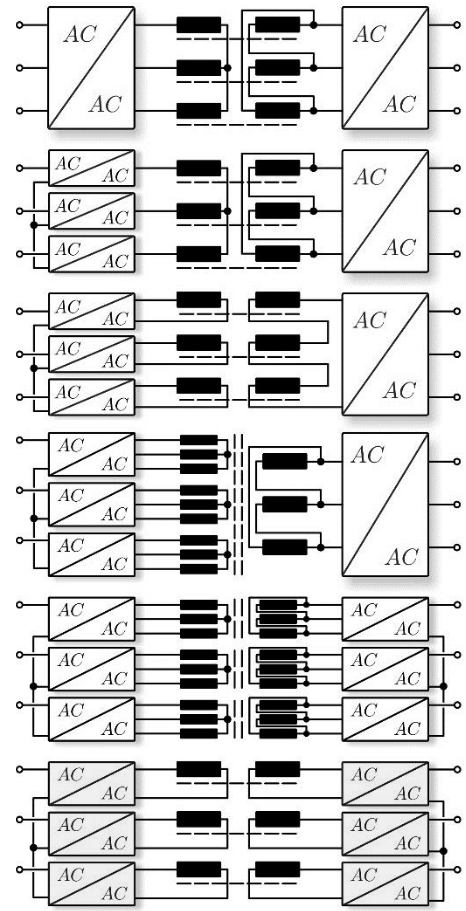


- 1-Stage Matrix-Type Topologies
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 3-Stage Power Conversion with MV and LV DC Link

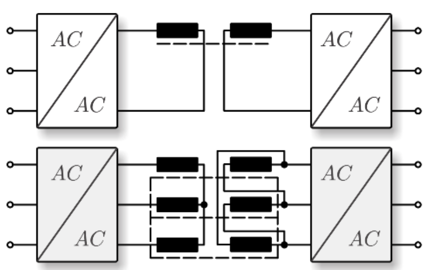
▶ Basic SST Structures (2)

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

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



* Phase-Integrated SST

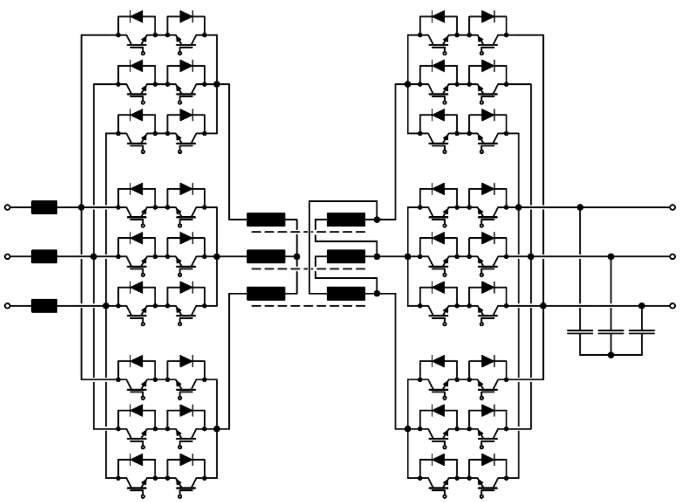


* Possibility of Cross-Coupling of Input and Output Phases (UNIFLEX)

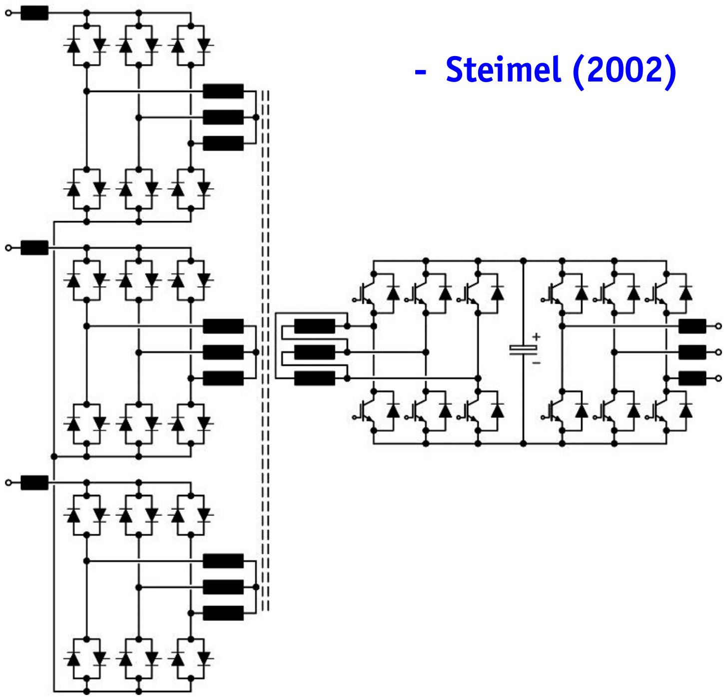
▶ Basic SST Structures (2)

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

- Enjeti (1997)



- Steimel (2002)

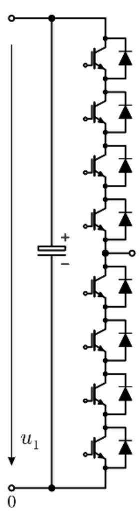


- Example of Three-Phase Integrated (Matrix) Converter & Magn. Phase-Modular Transf.
- Example of Partly Phase-Modular SST

▶ Basic SST Structures (3)

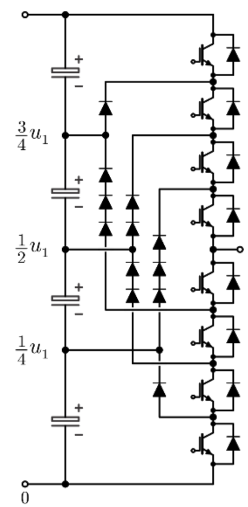
- 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

- Multi-Cell and Multi-Level Approaches

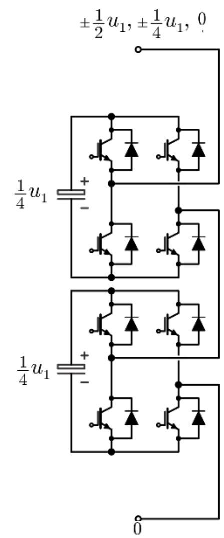


* Two-Level Topology

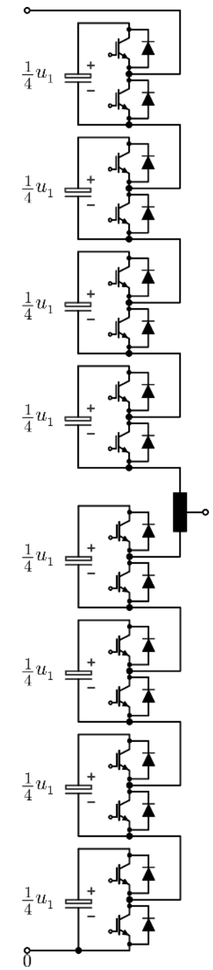
Akagi (1981)



McMurray (1969)



Marquardt



Alesina/ Venturini (1981)

* Multi-Level/ Multi-Cell Topologies

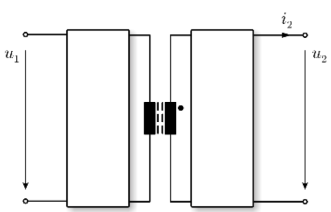
▶ Basic SST Structures (3)

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

- Multi-Cell and Multi-Level Approaches

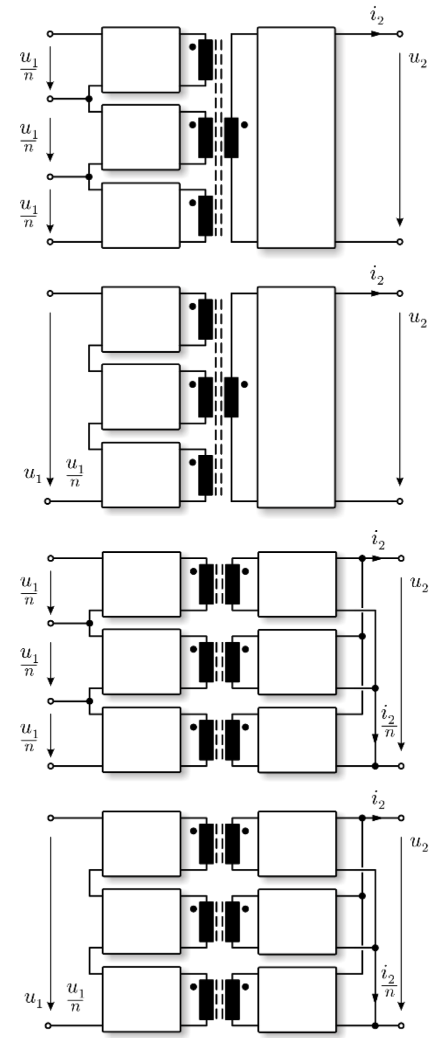
- Low Blocking Voltage Requirement
- Low Input Voltage / Output Current Harmonics
- Low Input/Output Filter Requirement

* Single-Cell / Two-Level Topology



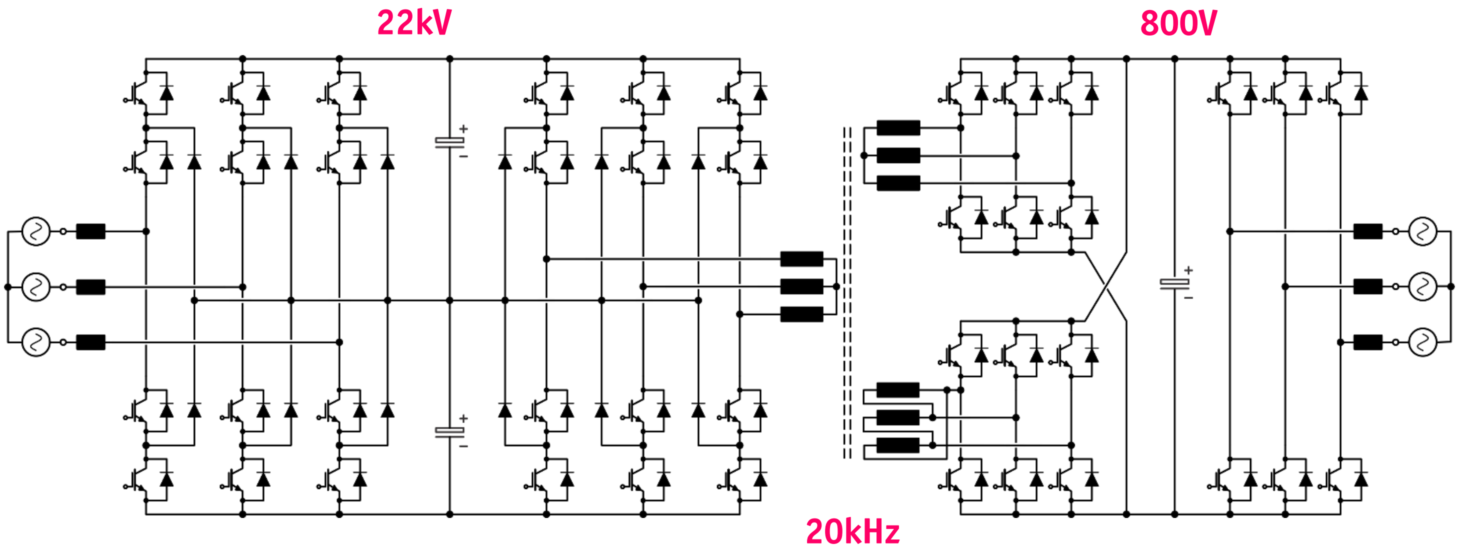
a)

ISOP = Input Series / Output Parallel Topologies



▶ Basic SST Structures (3)

- Bhattacharya (2012)

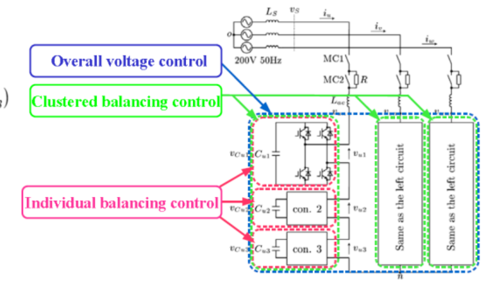


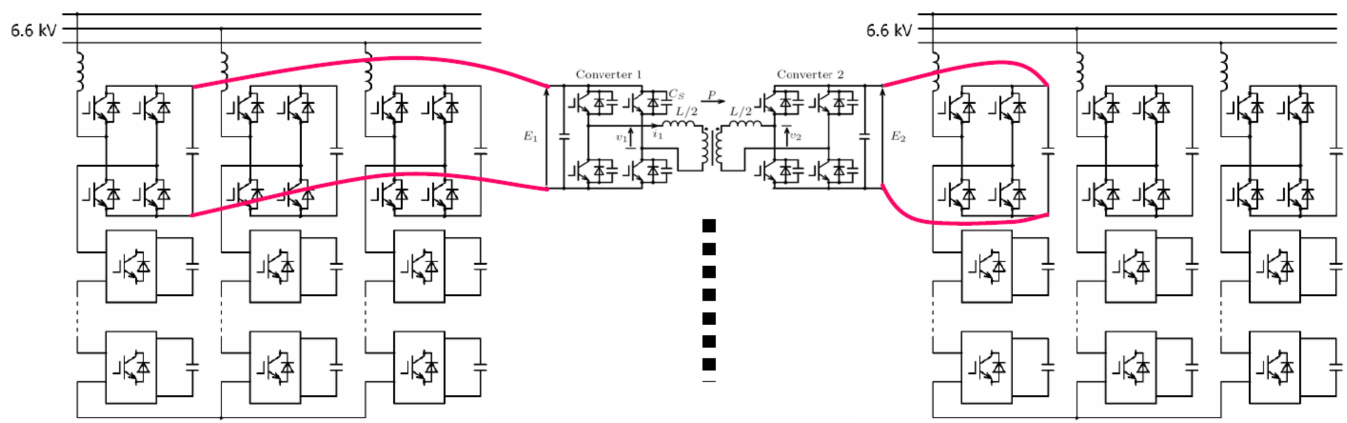
- 13.8kV → 480V
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype

▶ Basic SST Structures (3)

- Akagi (2005)

$$\bar{v}_{Cu}=\frac{1}{3}(\bar{v}_{Cu1}+\bar{v}_{Cu2}+\bar{v}_{Cu3})$$

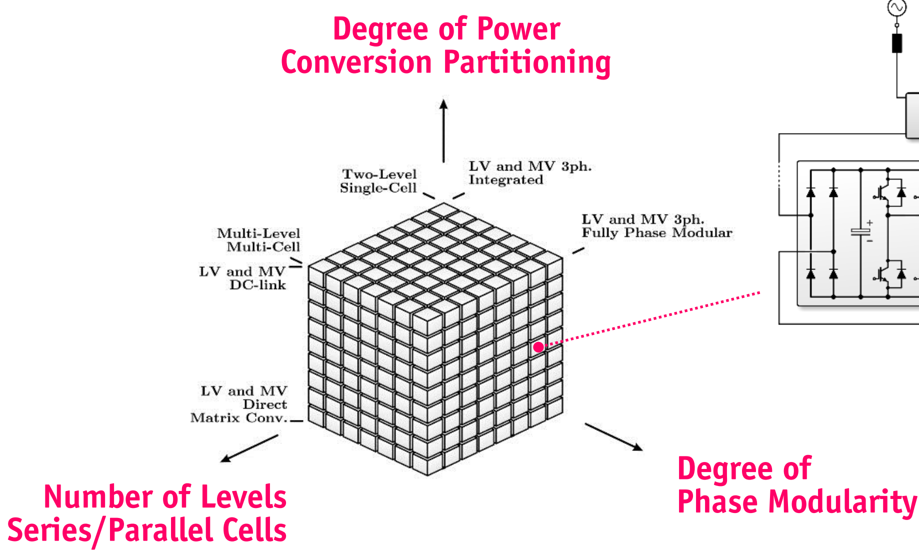


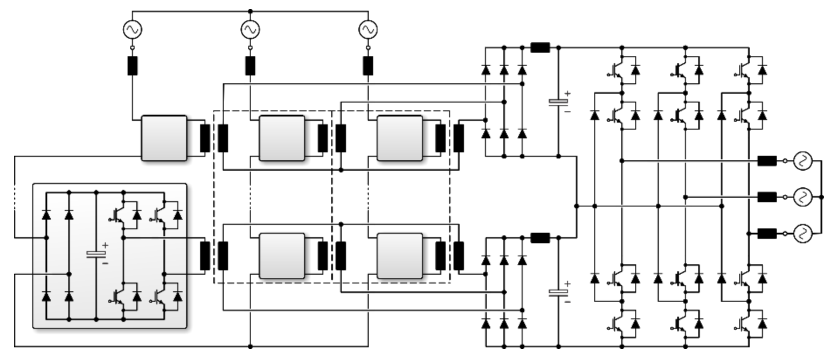


STATCOM STATCOM

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

► Classification of SST Topologies Summary





- Enjeti (2012)

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

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

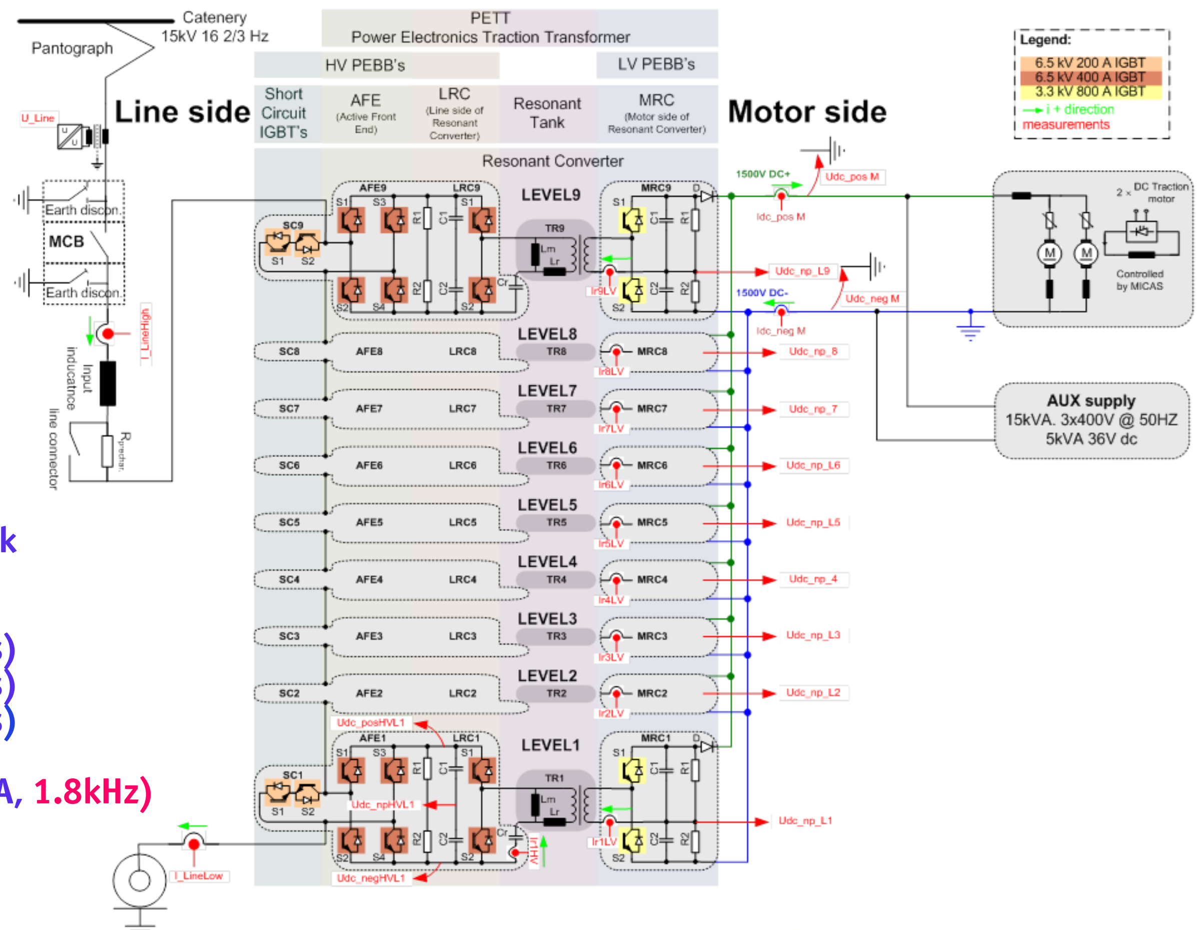
Industry Demonstrator System

- *Future Locomotives*
- *Future Smart Grid Applications* →

▶ 1ph. AC/DC Power Electronic Transformer - PET

- Dujic et al. (2011)

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



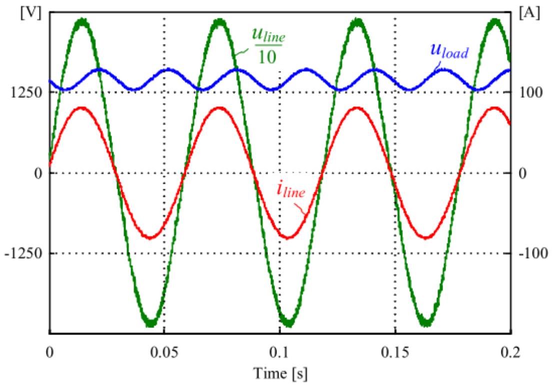
P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

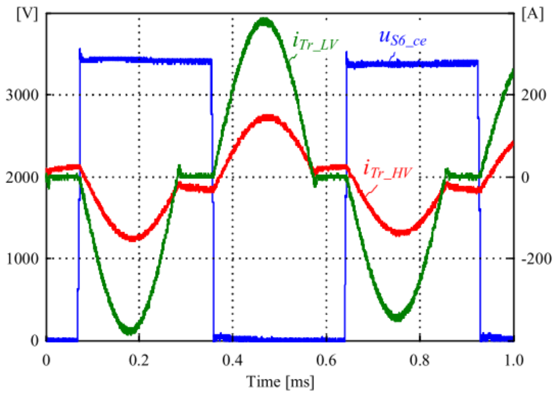
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

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

▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

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

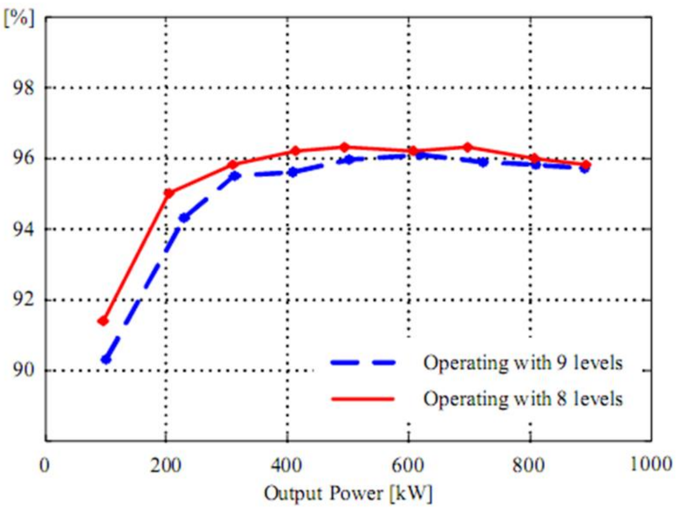




▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

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

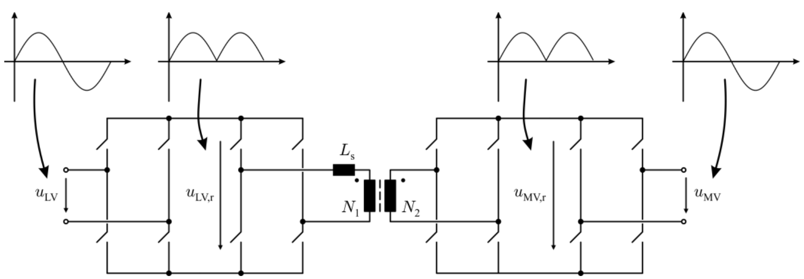
Efficiency

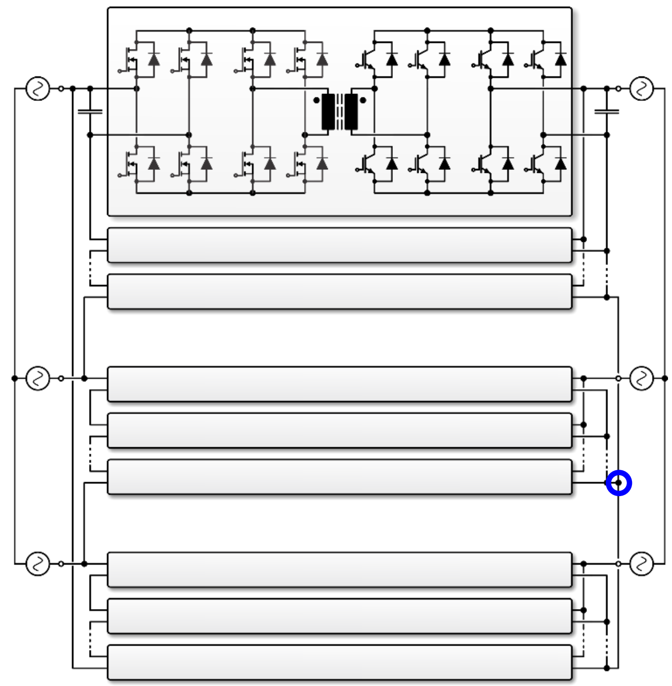


▶ SiC-Enabled Solid-State Power Substation

- Das et al. (2011)
- Lipo (2010)
- Weiss (1985 for Traction Appl.)

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



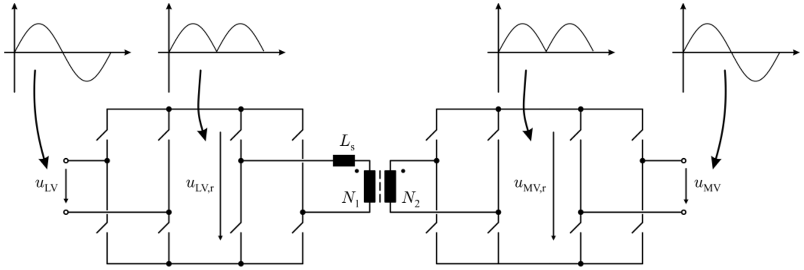


- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

▶ SiC-Enabled Solid-State Power Substation

- Das (2011)

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



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

SST Research @ ETH Zurich

MEGA Link

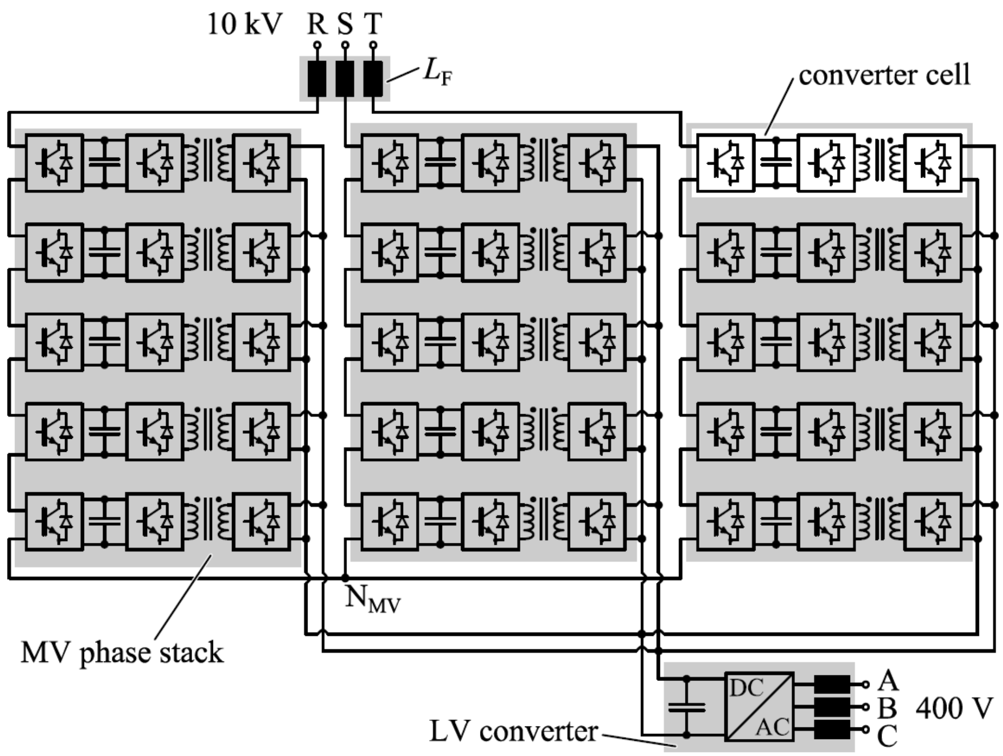
MEGA Cube
Unidirectional SSTs

Ch. Gammeter
Th. Guillod
J. Huber
M. Leibl
D. Rothmund

G. Ortiz

▶ MEGALink @ ETH Zürich

S_N = 630kVA
U_{LV} = 400 V
U_{MV} = 10kV

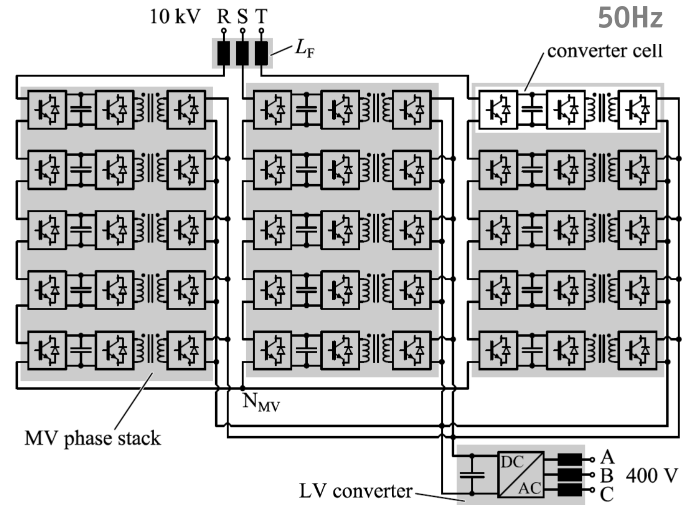


- 2-Level Inverter on LV Side / HC-DCM-SRC DC-DC Conversion / Cascaded H-Bridge MV Structure

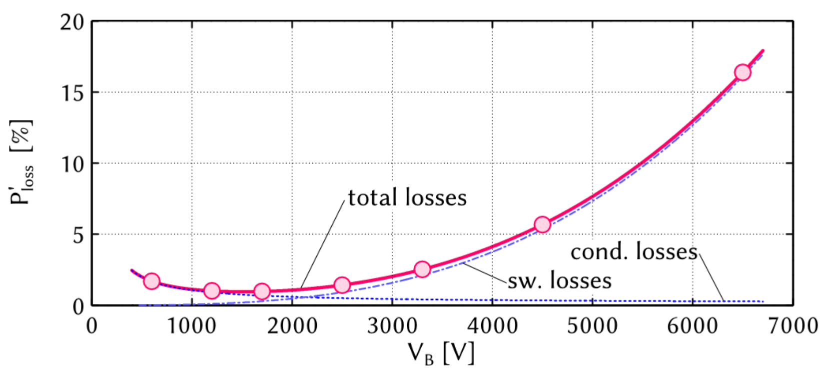
▶ Optimum Number of Converter Cells

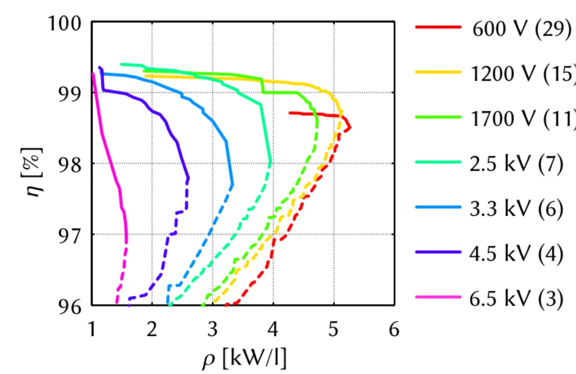
1 MVA
10kV → 400V
50Hz

- **Trade-Off** High Number of Levels → High Conduction Losses/ Low Cell Switchng Frequ./Losses (also because of Device Char.)



- Opt. Device Voltage Rating for Given MV Level
- ηρ-Pareto Opt. (Compliance to IEEE 519)





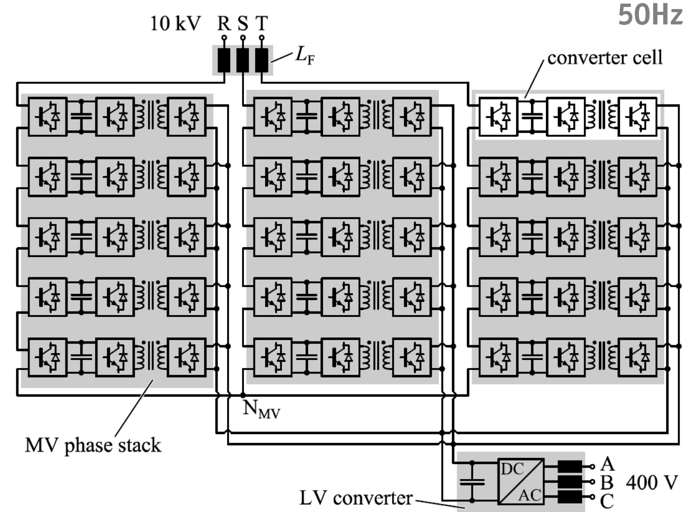
- **1200V ... 1700V Power Semiconductors best suited for 10kV Mains → No Advantage of SiC (!)**

▶ Optimum Number of Converter Cells

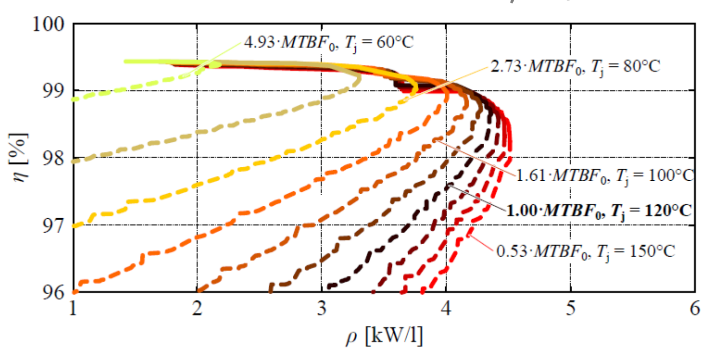
- Trade-Off → Mean-Time-to-Failure vs. Efficiency / Power Density

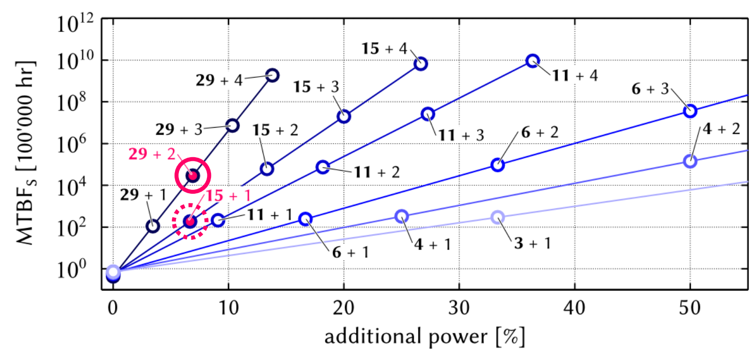
- Influence of
  * FIT Rate (Voltage Utilization)
  * Junction Temperature
  * Number of Redundant Cells

1 MVA
10kV → 400V
50Hz



No Redundancy
1700V IGBTs, 60% Utilized



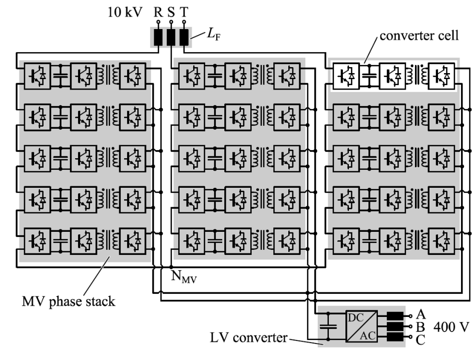


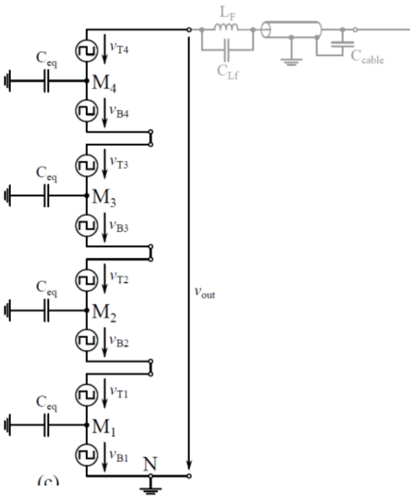
- High MTBF also for Large Number of Cells (Repairable) / Lower Total Spare Cell Power Rating

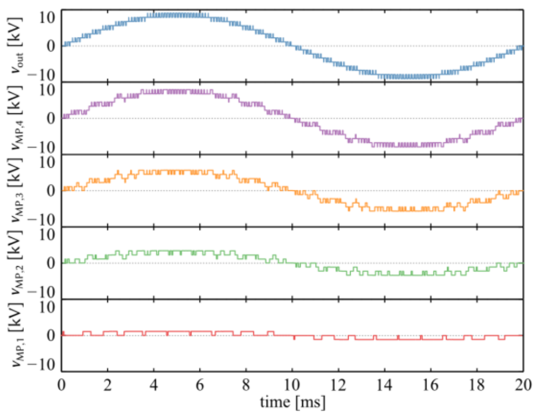
▶ Common-Mode Currents of Cascaded H-Bridge SSTs

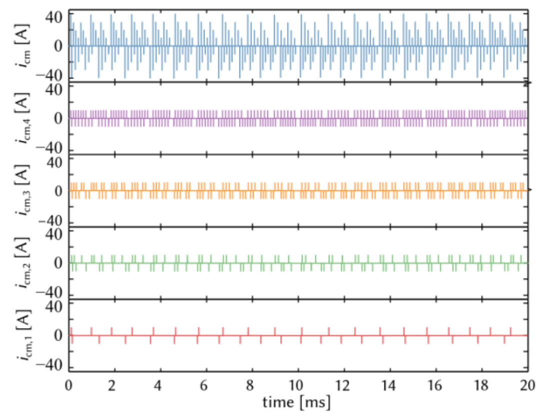
- Switching Actions of a Cell *i* Changes the Ground Potential of Cells *i*, *i*+1,... *N*
- CM Currents through Ground Capacitances

- Example 1MVA
  10kV Input
  400V Output
  1kHz/Cell
  $C_{eq} \approx 650\text{pF}$









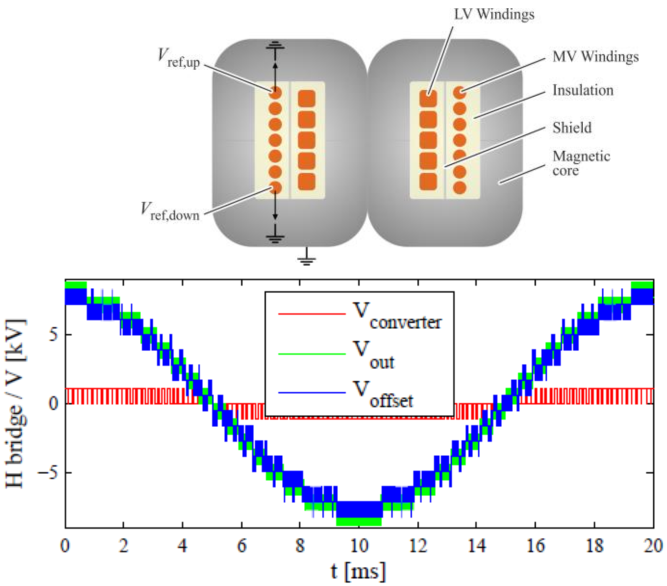
- 6.2mH  at the Input of Each Cell for Limiting i_{CM}

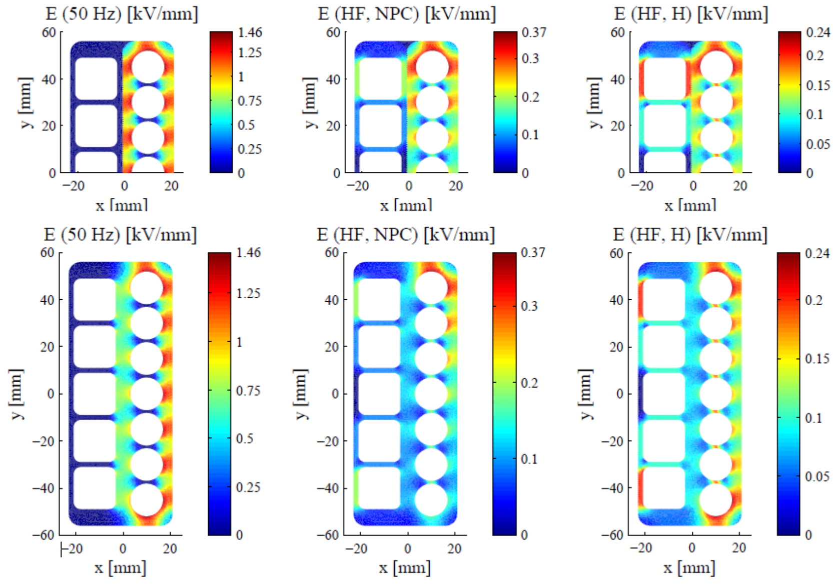
dv/dt=15kV/μs

▶ Voltage and E-Field Stresses in SSTs

- Mixed-Frequency (LF + Switching Frequency) Voltage Stress on Isolation
- Unequal Dynamic Voltage Distribution
- Potentially Accelerated Aging (!)

RMS Electric Field
LF, NPC-Cells, H-Cells
Bottom: w/o Shield
Top: With Shield



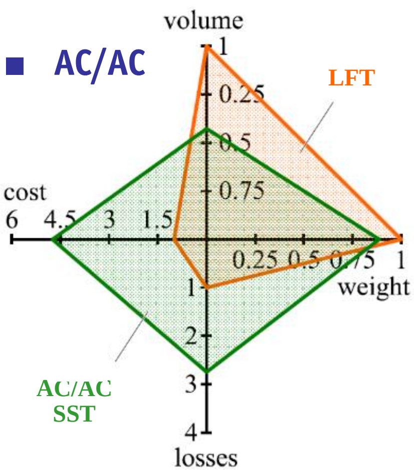


- Neglectable Dielectric Losses
- Specific Test Setup Required for Insulation Material Testing

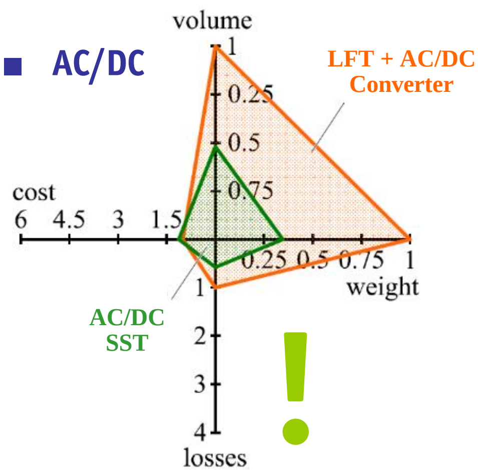
▶ SST vs. LF Transformer + AC/DC Converter

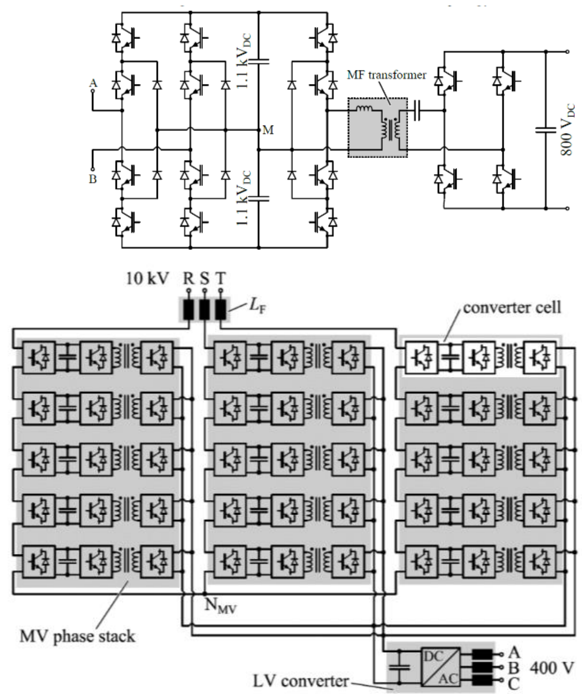
- **Specifications**: 1MVA, 10kV Input, 400V Output, 1700V IGBTs (1kHz/8kHz/4kHz)
- **LF Transformer**: 98.7 %, 16.2 kUSD, 2600kg (5700lb)

■ AC/AC



■ AC/DC



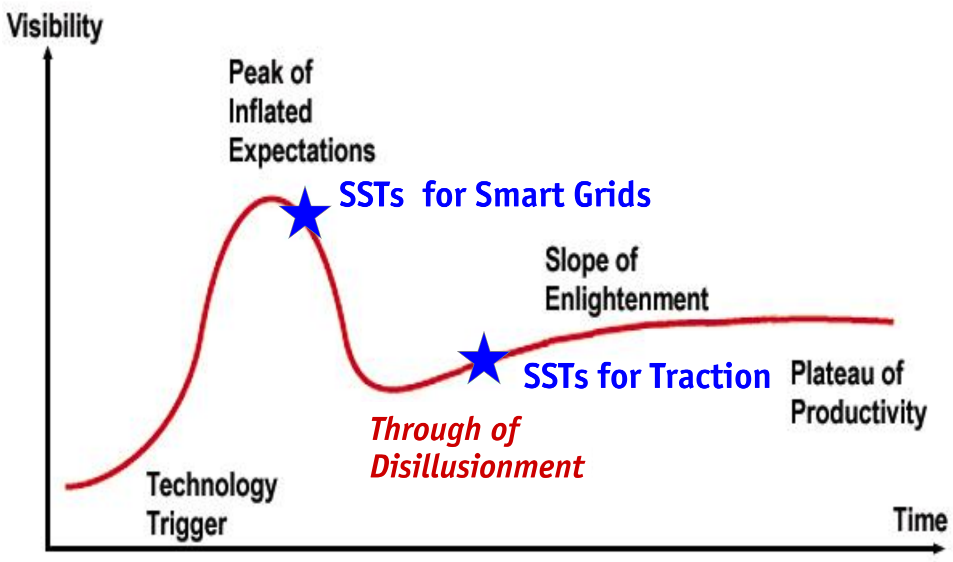


■ Clear Efficiency/Volume/Weight Advantage of SST for DC Output (98.2%)
■ Weakness of AC/AC SST vs. Simple LF Transformer (98.7%) - 5 x Costs, 2.5 x Losses

Conclusions

SST Evaluation / Application Areas
Future Research Areas

▶ Technology Hype Cycle



- **Different States of Development of SSTs for Smart Grid & Traction Applications**

▶ Overall Summary

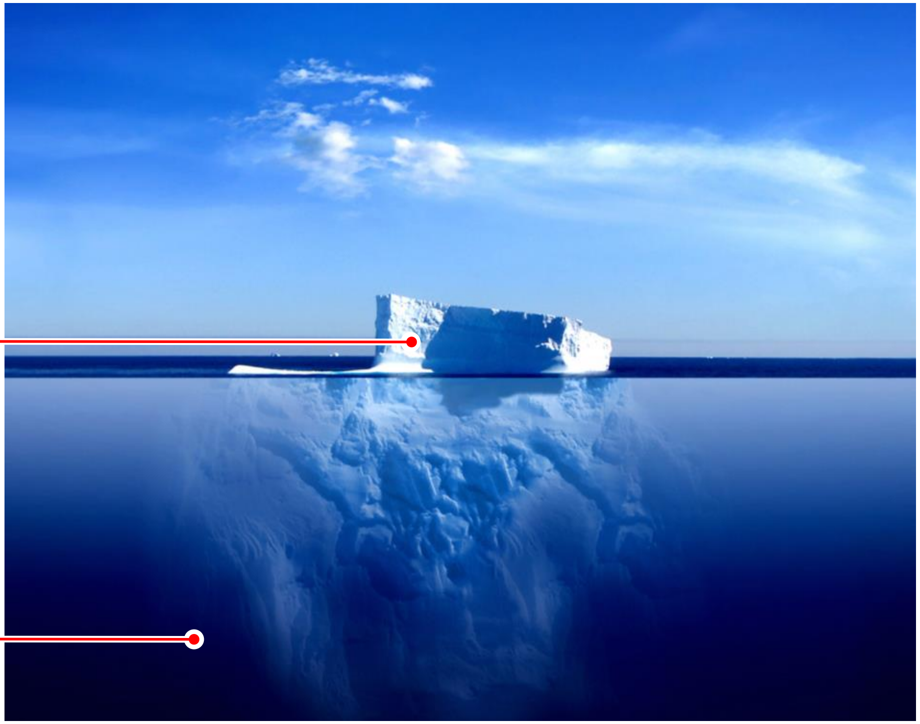
- SST is NOT a 1:1 Replacement for Conv. Distribution Transformers
- SST will NOT Replace All Conv. Distribution Transformers (even in Mid Term Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations

→ SST Requires a Certain Application Environment (until Smart Grid is Fully Realized)
→ SST Preferably Used in LOCAL Fully SMART EEnergy Systems

@ Generation End (e.g. Nacelle of Windmills)
@ Load End - Micro- or Nanogrids (incl. Locomotives, Ships etc.)

- Environments with Pervasive Power Electronics for Energy Flow Control (No Protection Relays etc.) →
- Environments which Could be Designed for SST Application
- (Unidirectional) Medium Voltage Coupling of DC Distribution Systems

▶ Future SST Research Topics



- Huge *Multi-Disciplinary* Challenges / Opportunities (!) are Still Ahead

Thank You!

Questions ?