ETH zürich

Solid-State Transformers in Future Traction and Smart Grids

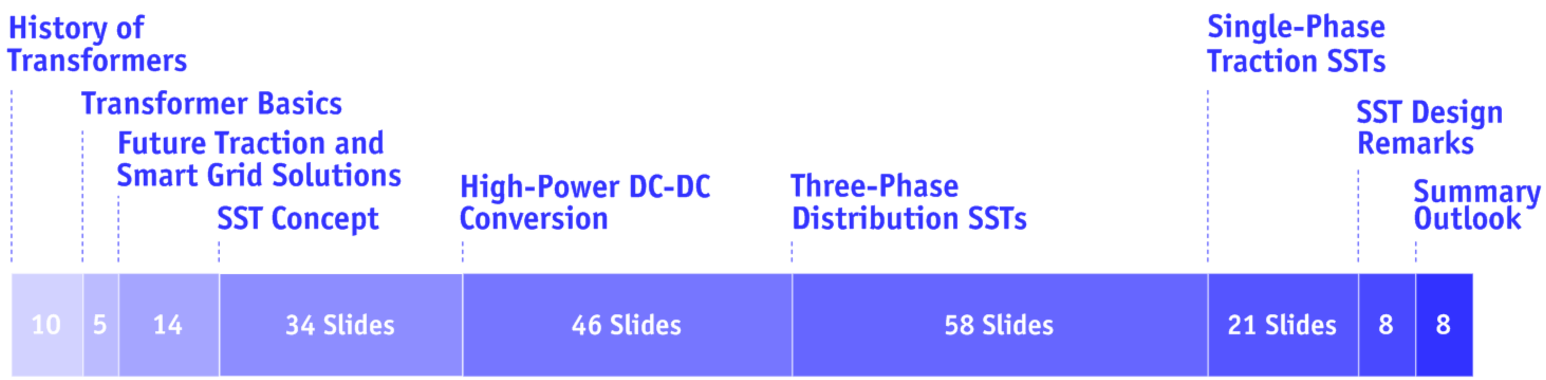
Johann W. Kolar, Gabriel Ortiz

Power Electronic Systems Laboratory
ETH Zurich, Switzerland

PCIM
SOUTH AMERICA

Seminar 3

Agenda


History of Transformers
Transformer Basics
Future Traction and Smart Grid Solutions
SST Concept
High-Power DC-DC Conversion
Three-Phase Distribution SSTs
Single-Phase Traction SSTs
SST Design Remarks
Summary Outlook
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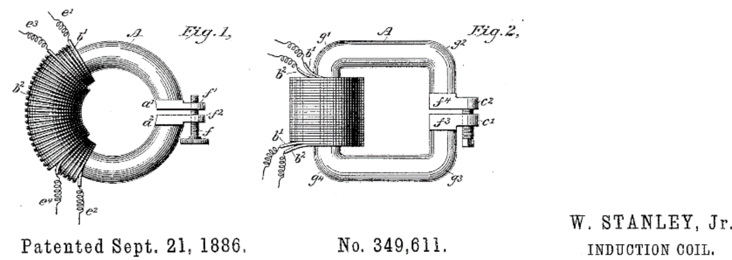
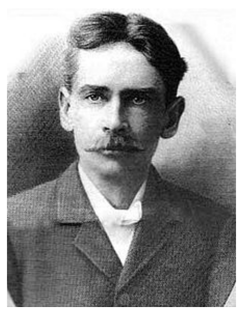
History of Transformers

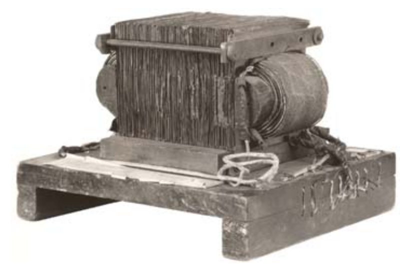
*Low Frequency and
Solid-State Transformers*

▶ Classical Transformer (XFMR) — History (1)

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







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

▶ Classical Transformer — History (2)

UNITED STATES PATENT OFFICE.

MICHAEL VON DOLIVO-DOBROWOLSKY, OF BERLIN, GERMANY, ASSIGNOR TO THE ALLGEMEINE ELEKTRICITÄTS-GESELLSCHAFT, OF SAME PLACE.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

SPECIFICATION forming part of Letters Patent No. 422,746, dated March 4, 1890.

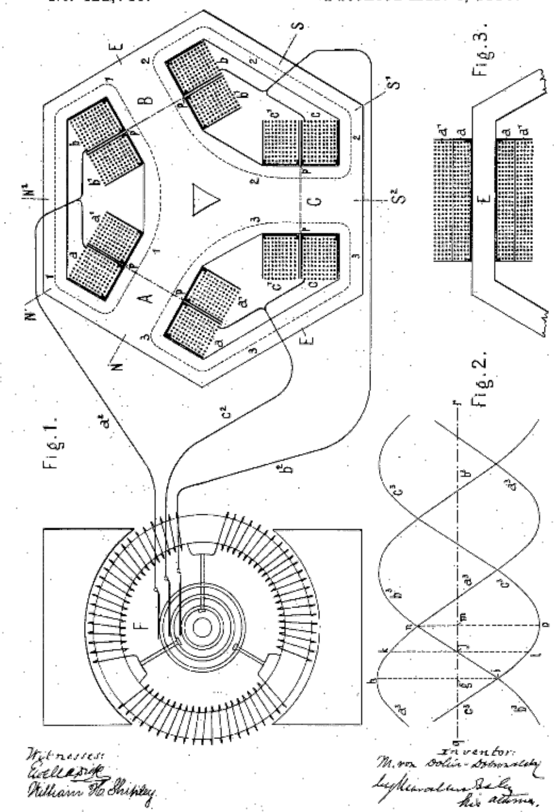
Application filed January 8, 1890. Serial No. 336,290. (No model.)

(No Model.)

M. VON DOLIVO-DOBROWOLSKY.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

No. 422,746. Patented Mar. 4, 1890.



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

► Valve-Controlled MF Transformer Link DC/AC Converter

- Isolated Medium Frequency Link DC/AC Converter

Patented Feb. 19, 1929. 1,702,402

UNITED STATES PATENT OFFICE.

LOUIS A. HAZELTINE, OF HOBOKEN, NEW JERSEY.

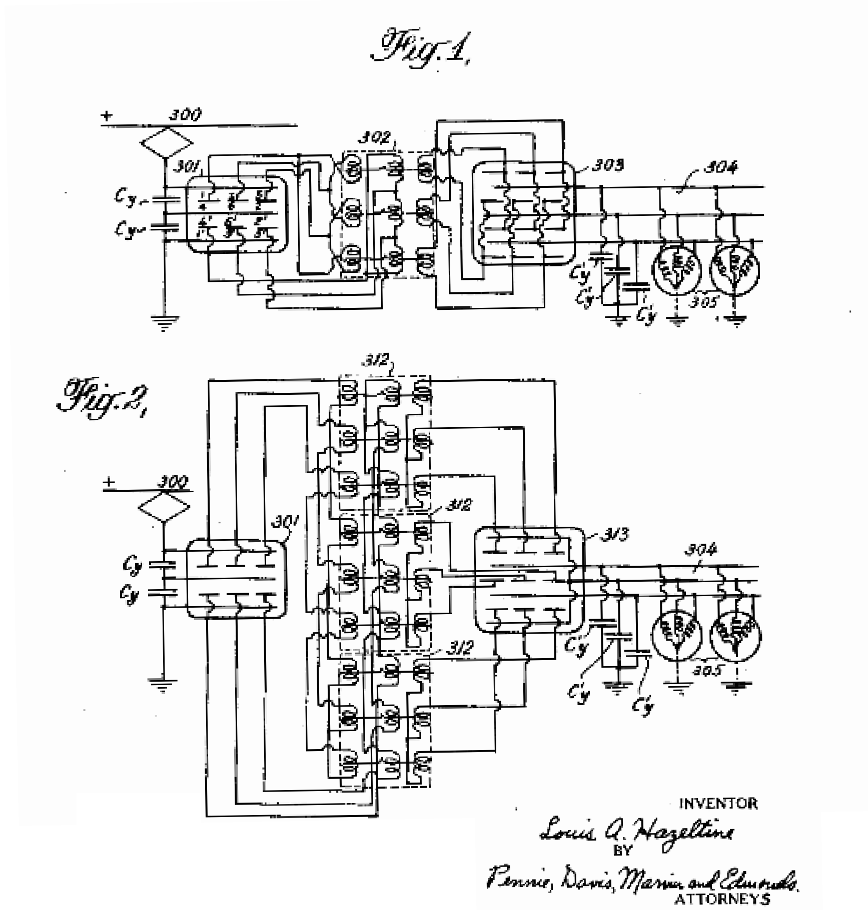
METHOD AND APPARATUS FOR CONVERTING ELECTRIC POWER.

Original application filed July 5, 1923, Serial No. 649,536, and in Great Britain July 4, 1924. Divided and this application filed January 20, 1927. Serial No. 162,237.

1923 !

I claim:

1. A system for operating an alternating-current motor from a source of direct-current power, which comprises a cascade electrostatically controlled valve converter which converts the direct-current power first into high-frequency power and then into low-frequency polyphase power for supply to the motor, two positively connected control commutators for said valve converter, a set of brushes for each of said commutators, and means for driving one set of brushes relatively to the other, the relative motion determining the frequency supplied to the motor.



United States Patent Office

3,517,300
Patented June 23, 1970

1

3,517,300

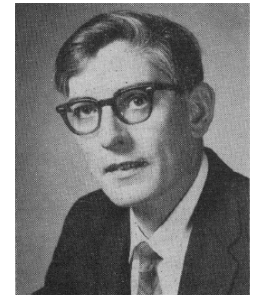
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK

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.

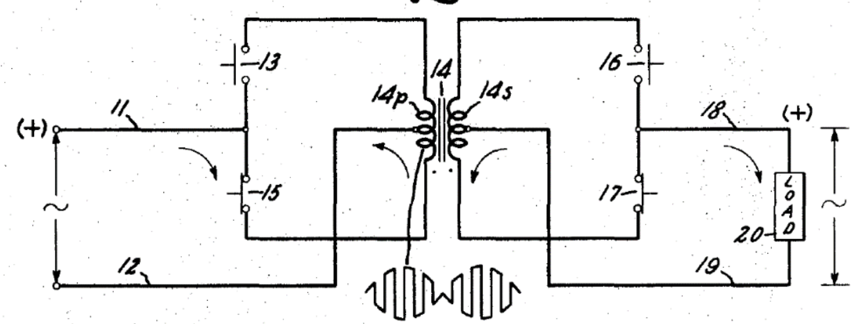


Inventor: William McMurray,
by Donald R. Campbell
His Attorney.

1968!

Filed April 16, 1968

Fig. 1a

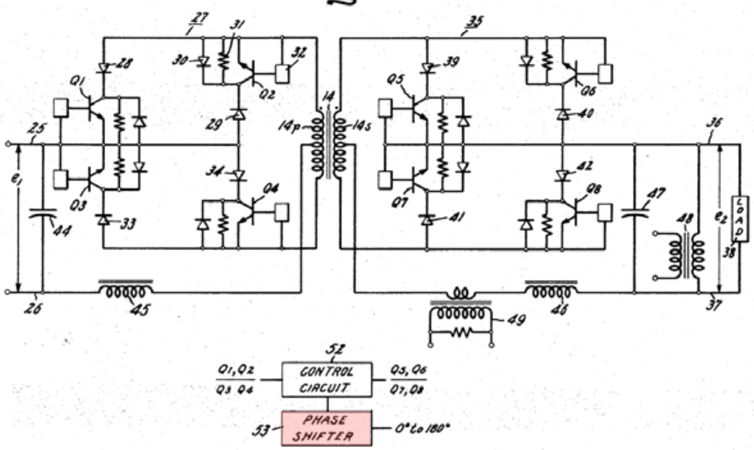


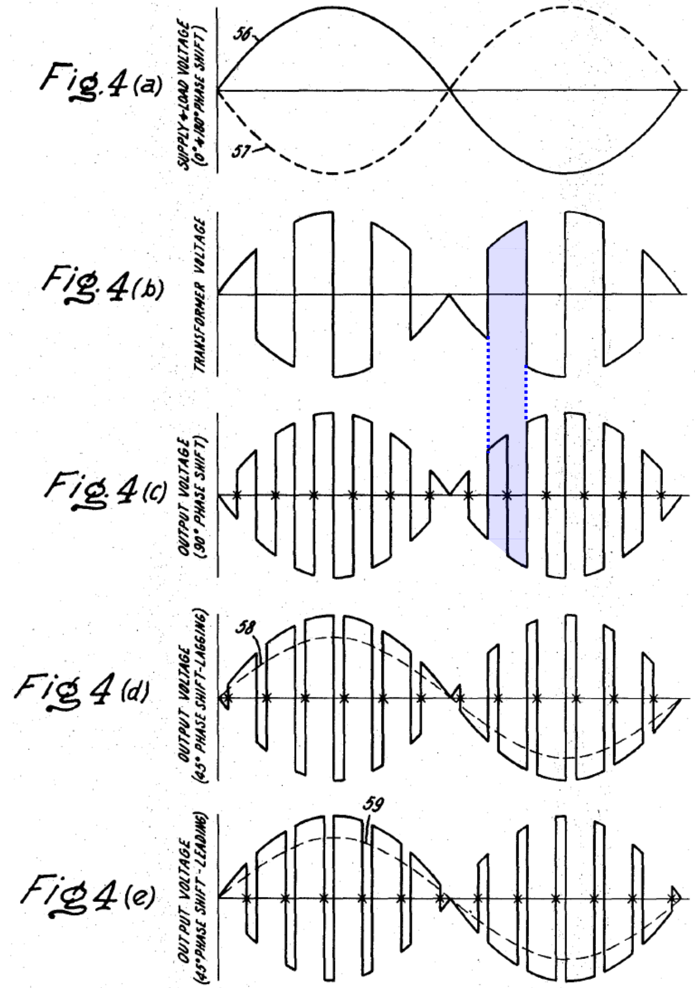
- **Electronic Transformer ($f_1 = f_2$)**
- AC or DC Voltage Regulation & Current Regulation / Limitation / Interruption

► Electronic Transformer

- 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

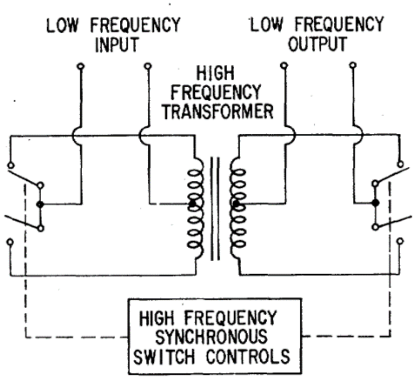


Fig. 1. Principle of electronic transformer.

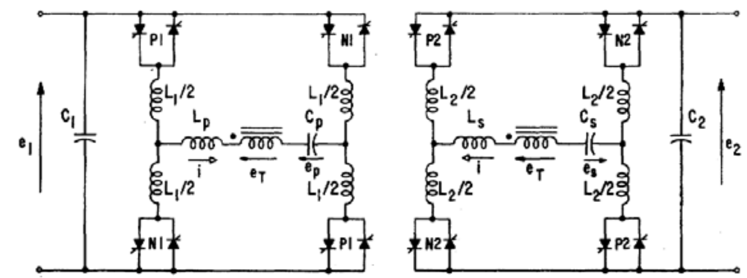


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

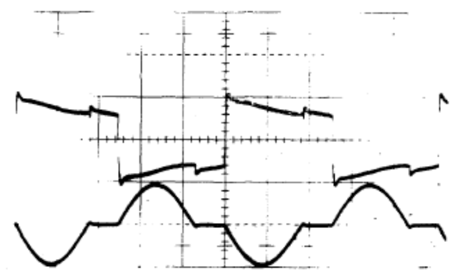


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 μs/div.

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

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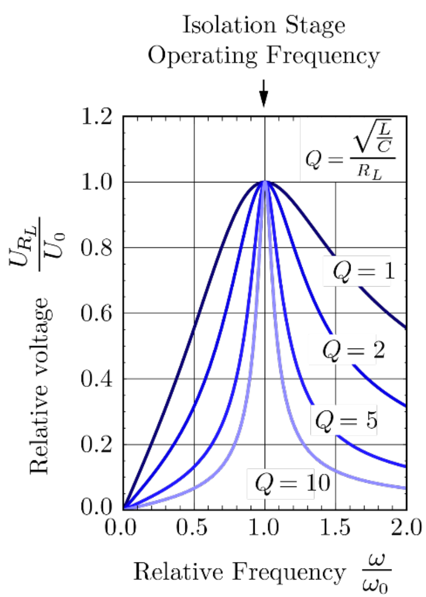

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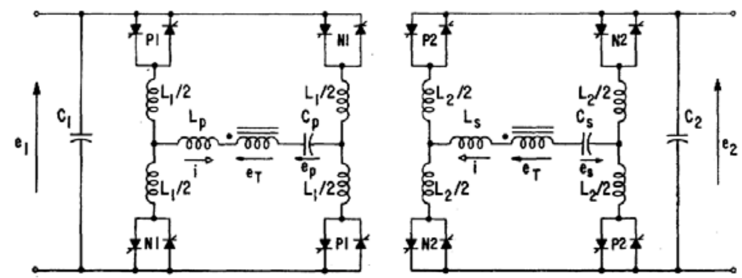

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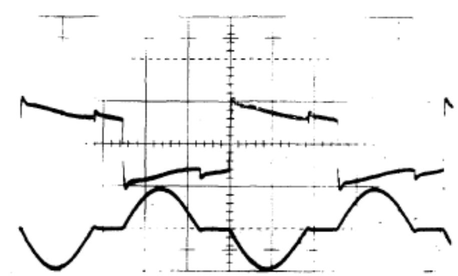


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 µs/div.

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** ← 1980 !

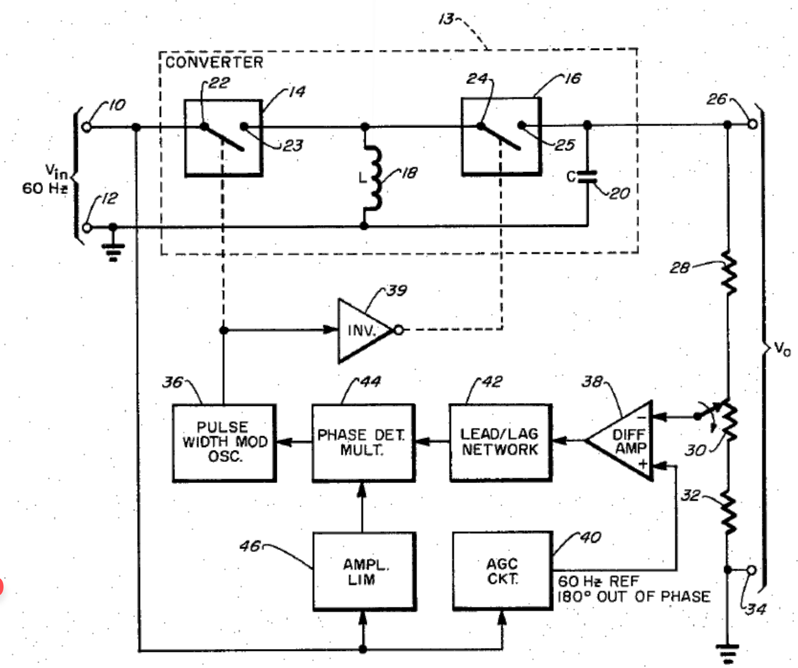


Fig. 1.

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

OTHER PUBLICATIONS

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

United States Patent [19] | [11] **Patent Number:** 5,027,264
DeDoncker et al. | [45] **Date of Patent:** Jun. 25, 1991

← 1991

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

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

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

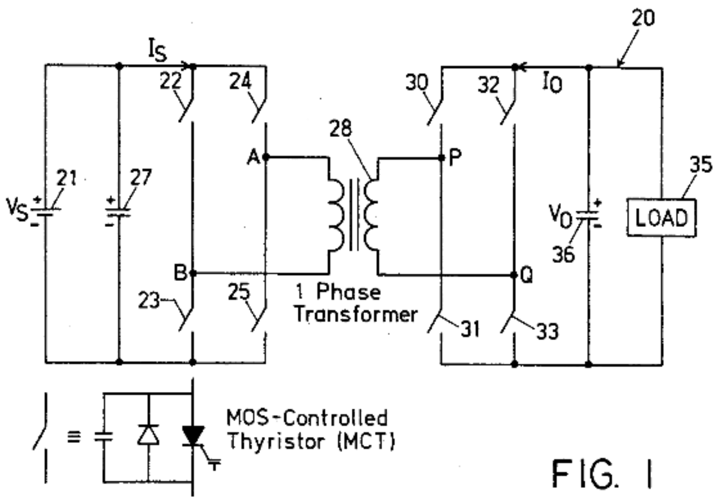


FIG. 1

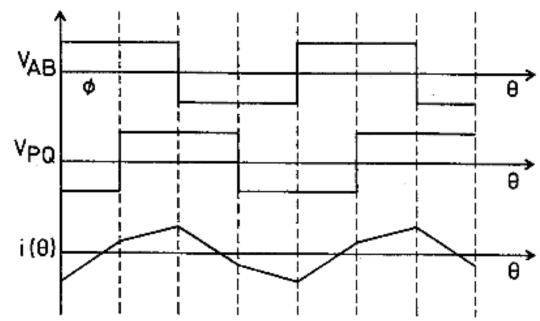


FIG. 2

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

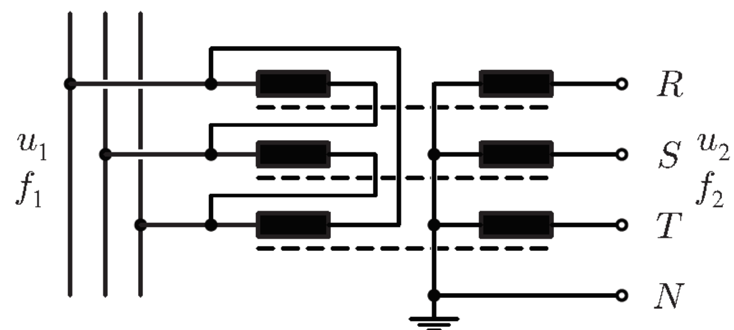
Transformer Basics

▶ Classical Transformer — Basics (1)

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

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

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

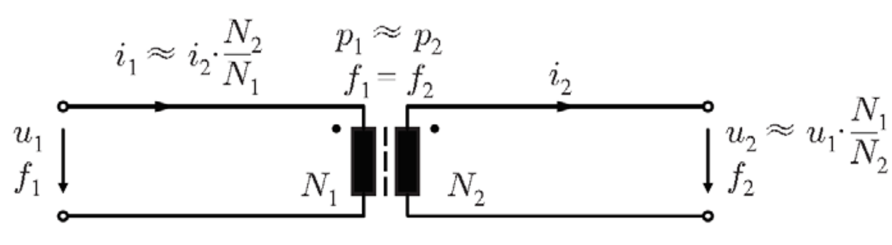


- **Magnetic Core Cross Section**

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

- **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

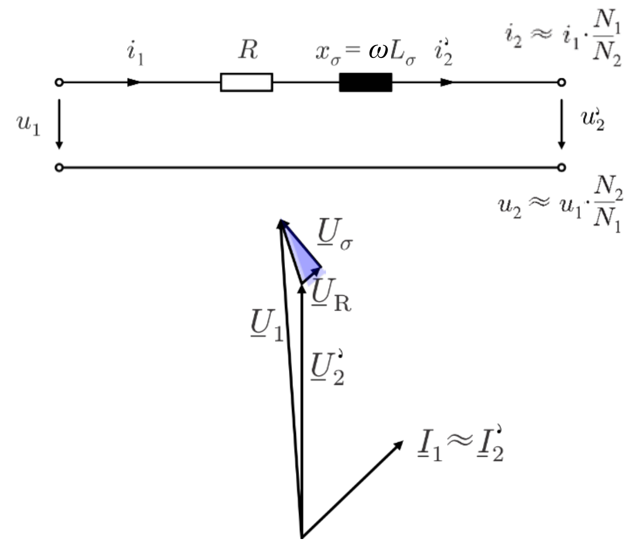
- Construction Volume

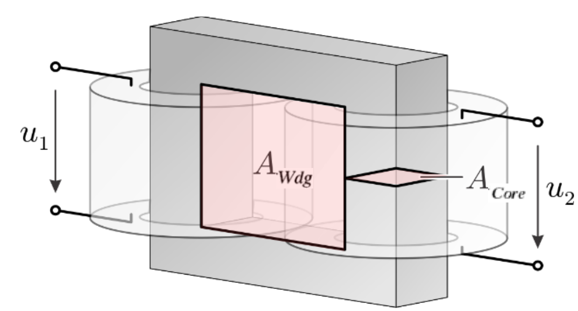
$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

↑ ↑ ↑

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)

- Scaling of Core Losses

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

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

- Scaling of Winding Losses

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

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

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

▶ Classical Transformer — Basics (2)

- Advantages

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

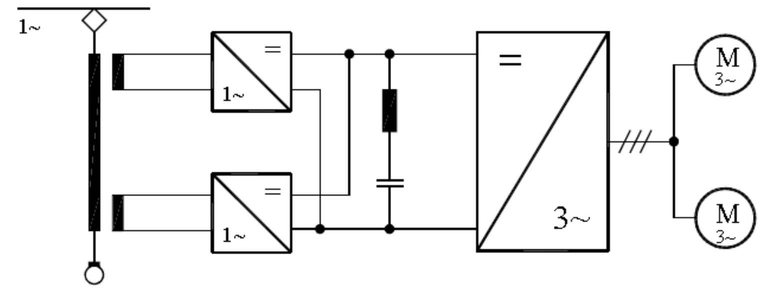
Welding Transformer (Zimbabwe) – Source: http://www.africancrisis.org

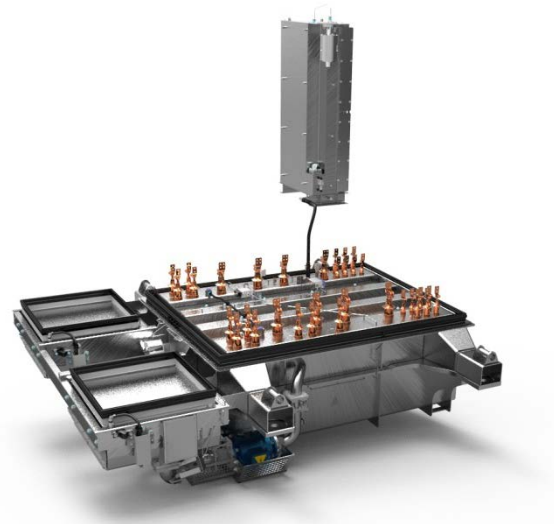
Solid-State Transformers

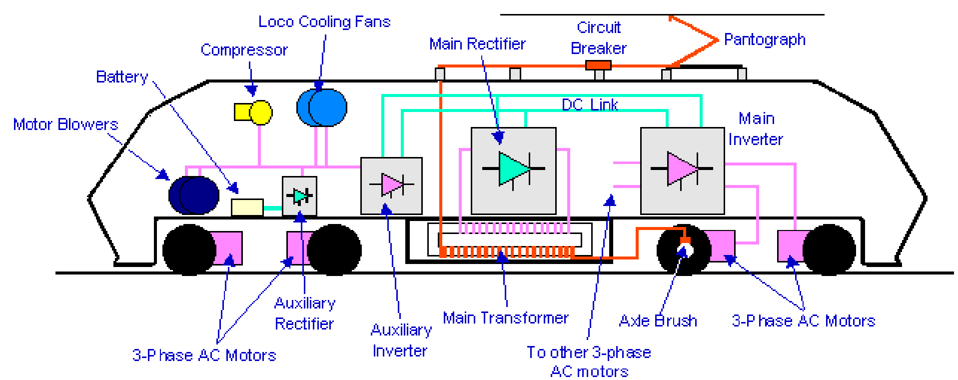
*For Future Traction Vehicles
and Smart Grid*

► Classical Locomotives

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



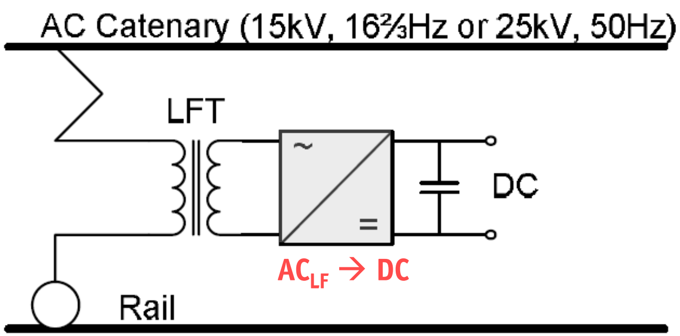




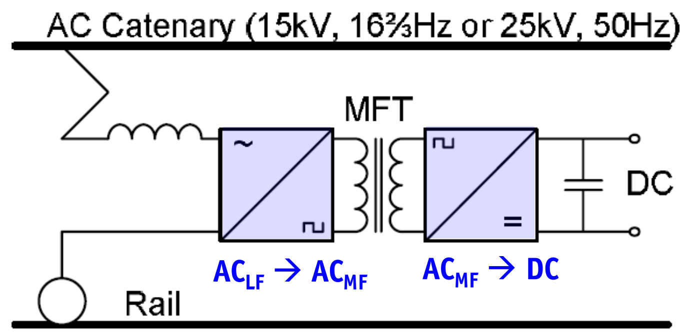
- Transformer	**Efficiency**	**90…95%** (due to Restr. Vol., 99% typ. for Distr. Transf.)
	Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
	Power Density	2…4 kg/kVA

▶ Next Generation Locomotives

- Trends
  * Distributed Propulsion System → **Weight Reduction** **(pot. Decreases Eff.)**
  * Energy Efficient Rail Vehicles → **Loss Reduction** **(would Req. Higher Vol.)**
  * Red. of Mech. Stress on Track → **Mass Reduction** **(pot. Decreases Eff.)**



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

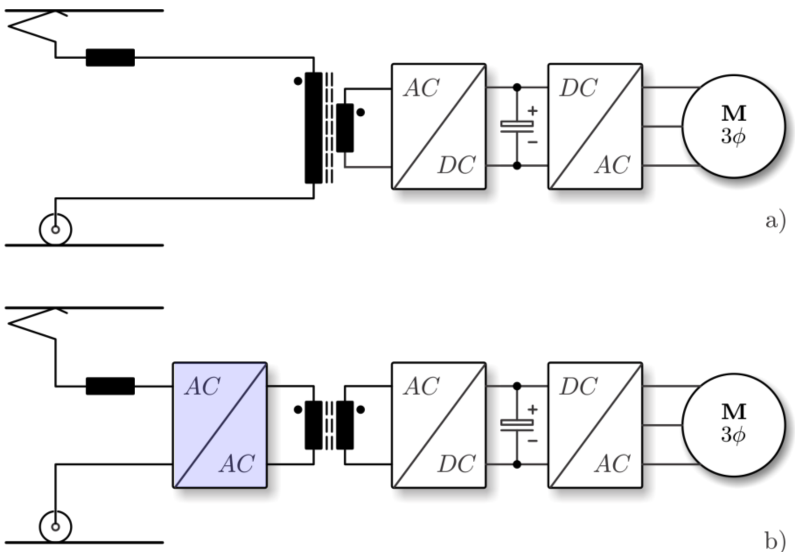


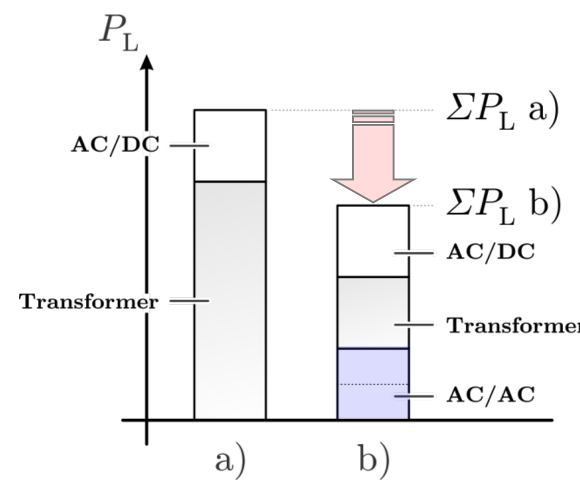
AC-DC conversion with medium frequency transformer (MFT).

- **Replace Low Frequency Transformer by Medium Freq. (MF) Power Electronics Transformer (PET)**
- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction AND Volume Reduction
- El. Syst. of Next Gen. Locom. (1ph. AC/3ph. AC) represents Part of a 3ph. AC/3ph. AC SST for Grid Appl.

▶ Next Generation Locomotives

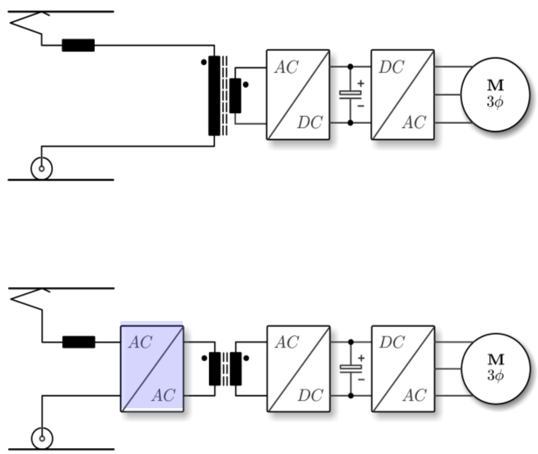
- Loss Distribution of Conventional & Next Generation Locomotives

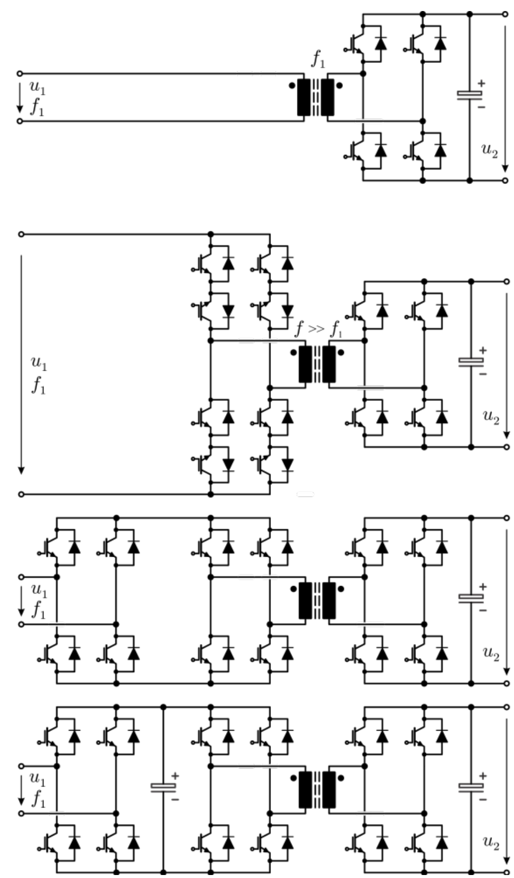




- Medium Freq. Provides Degree of Freedom → **Allows Loss Reduction AND Volume Reduction**

► Next Generation Locomotives





- Basic Front End Converter Topologies

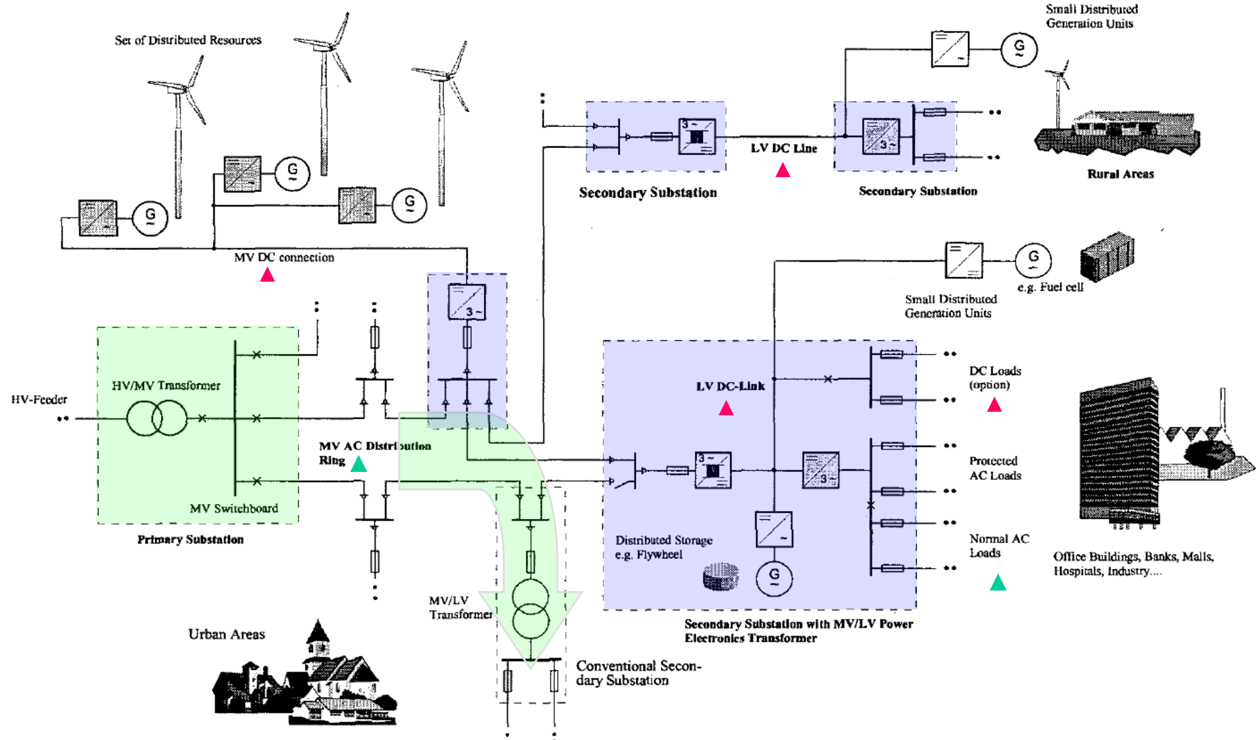
- Direct Matrix Converter
- Indirect Matrix Converter
- DC Link AC-DC-AC Converter

Solid-State Transformers

Traction Vehicles
Smart Grid

► Advanced (High Power Quality) Grid Concept

- Heinemann (2001)



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

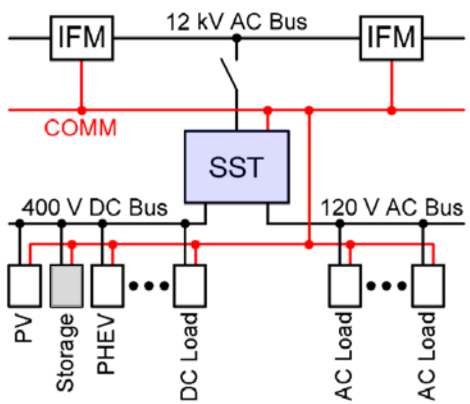
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

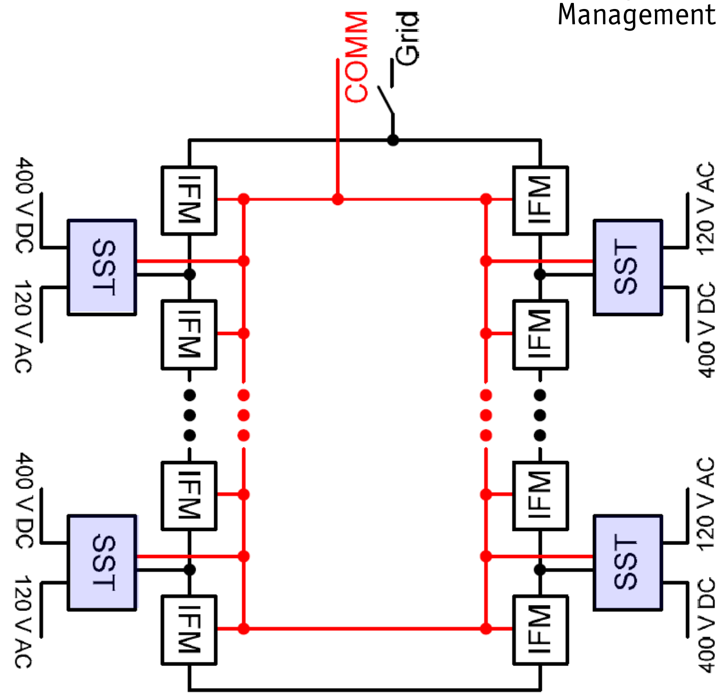
- Huang et al. (2008)

- **SST as Enabling Technology for the "Energy Internet"**

- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation

IFM = Intellig. Fault Management





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

▶ Smart Grid Concept

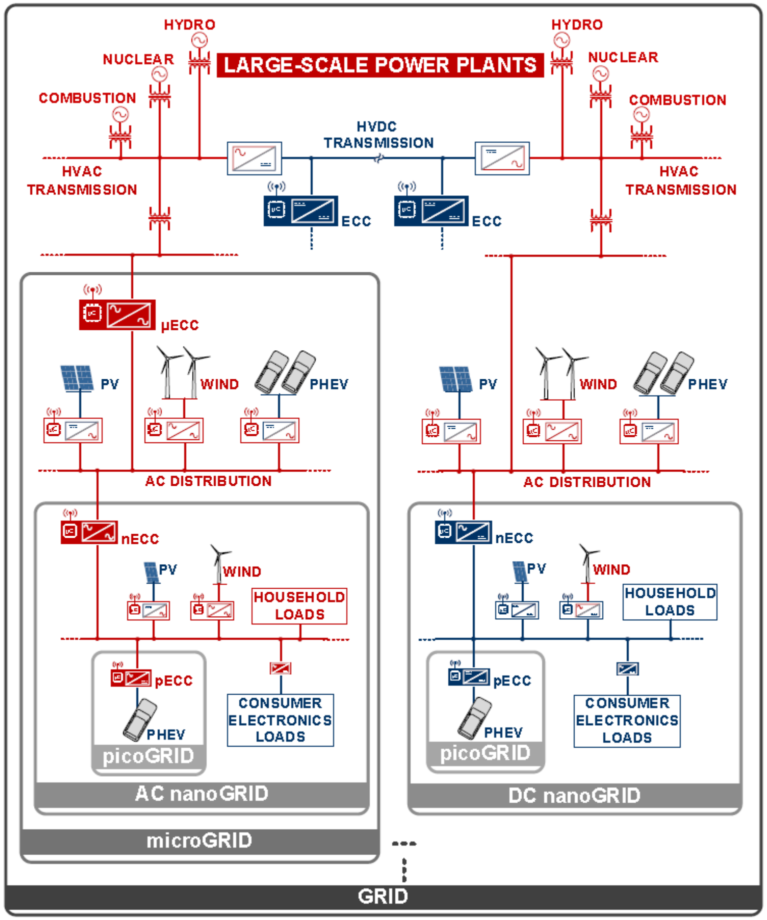
- Borojevic (2010)

• Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids

- Distr. Syst. of Contr. Conv. Interfaces
- Source / Load / Power Distrib. Conv.
- **Picogrid-Nanogid-Microgrid-Grid Structure**
- **Subgrid Seen as Single Electr. Load/Source**
- **ECCs provide Dyn. Decoupling**
- Subgrid Dispatchable by Grid Utility Operator
- Integr. of Ren. Energy Sources

• ECC = Energy Control Center

- Energy Routers
- Continuous Bidir. Power Flow Control
- Enable Hierarchical Distr. Grid Control
- Load / Source / Data Aggregation
- Up- and Downstream Communic.
- Intentional / Unintentional Islanding for Up- or Downstream Protection
- etc.



▶ SST Functionalities

- **Protects Load from Power System Disturbance**

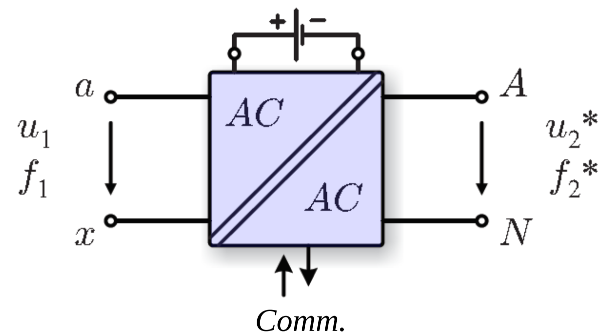
  - Voltage Harmonics / Sag Compensation
  - Outage Compensation
  - Load Voltage Regulation (Load Transients, Harmonics)

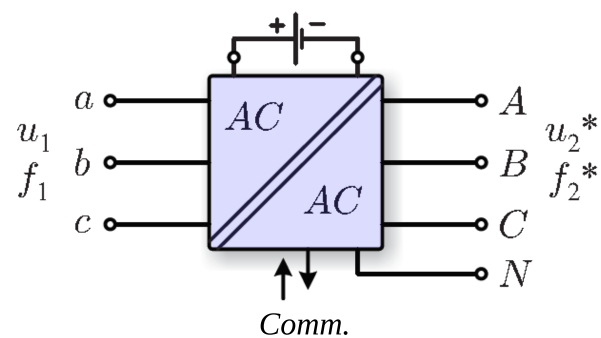
- **Protects Power System from Load Disturbance**

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

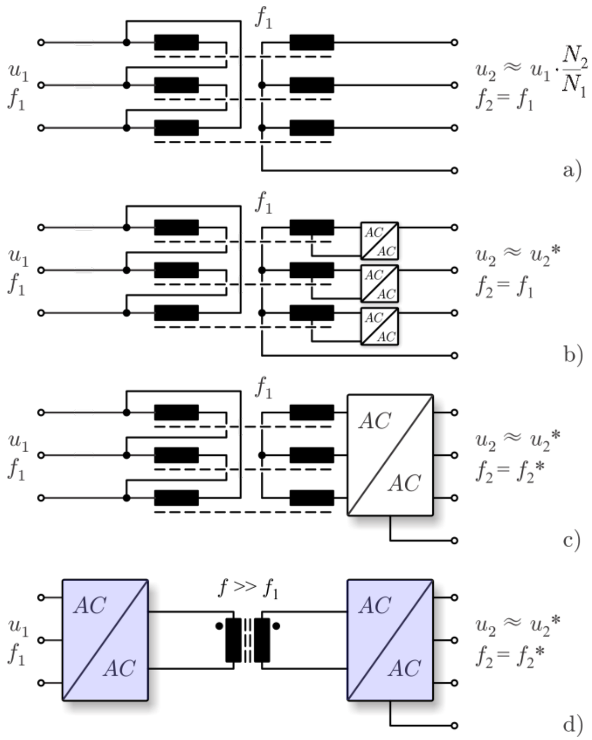
- **Further Characteristics**

  - Operates on Distribution Voltage Level (MV-LV)
  - Integrates Energy Storage (Energy Buffer)
  - DC Port for DER Connection
  - **Medium Frequency Isolation → Low Weight / Volume**
  - Definable Output Frequency
  - High Efficiency
  - No Fire Hazard / Contamination



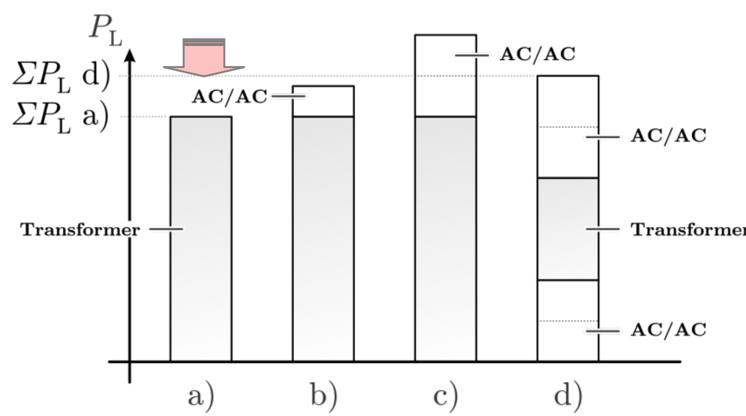


▶ SST Efficiency Challenge



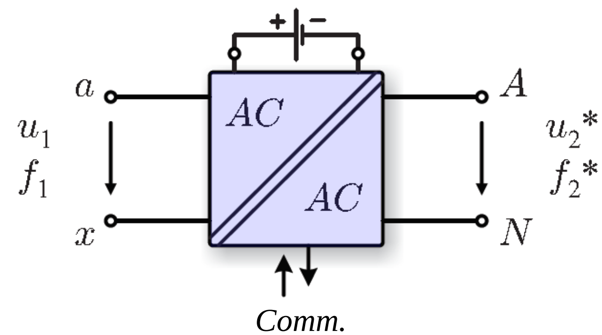
LF Isolation
Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

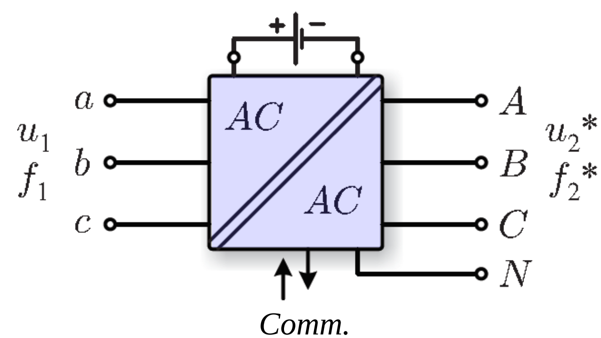
MF Isolation
Active Input & Output Stage (d)



- **Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses**

▶ Terminology





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

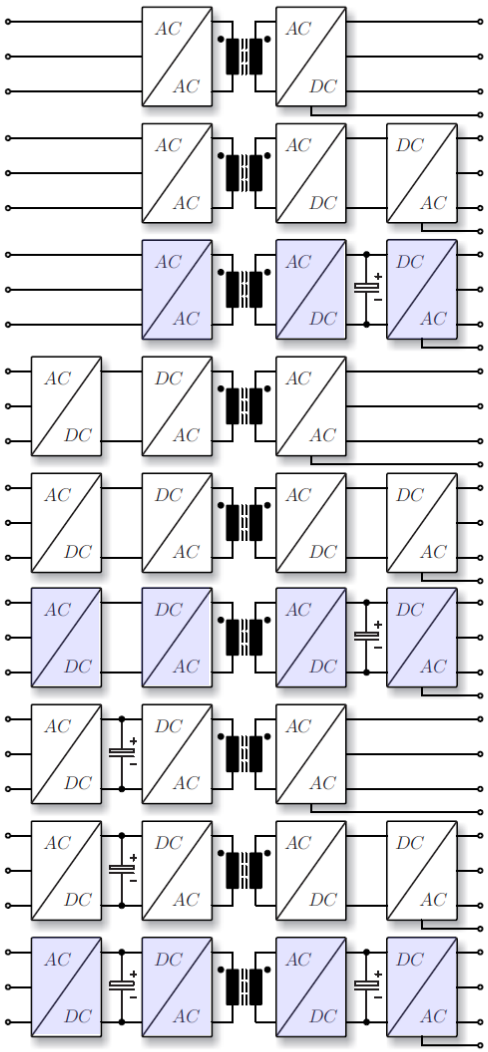
Classification of SST Topologies

Partitioning of AC/AC Power Conversion
Partial or Full Phase Modularity
Partitioning of Medium Voltage

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- 1st Degree of Freedom of Topology Selection:

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



▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

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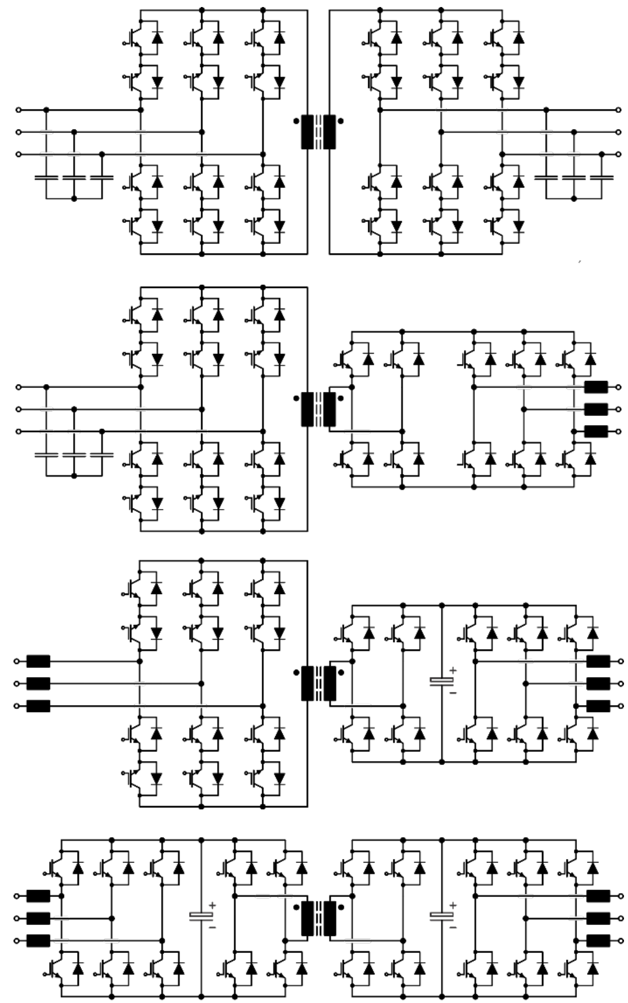
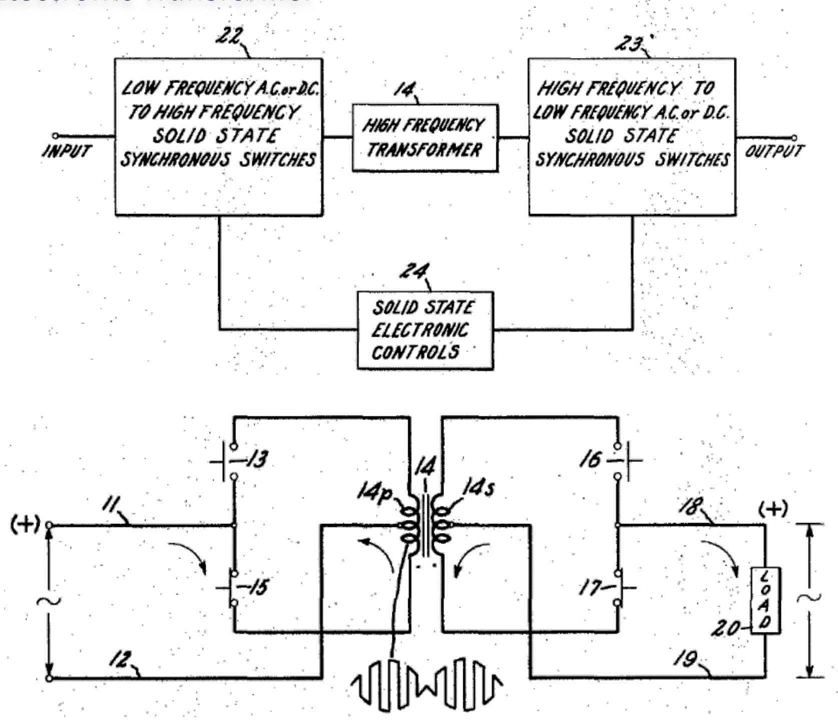
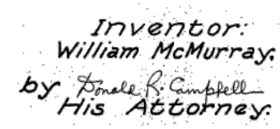


- 1-Stage Matrix-Type Topologies
- 2-Stage with MV DC Link (Connection to HVDC System)
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 3-Stage Power Conversion with MV and LV DC Link

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- 1-Stage Direct Matrix-Type
- McMurray (1968) — Electronic Transformer

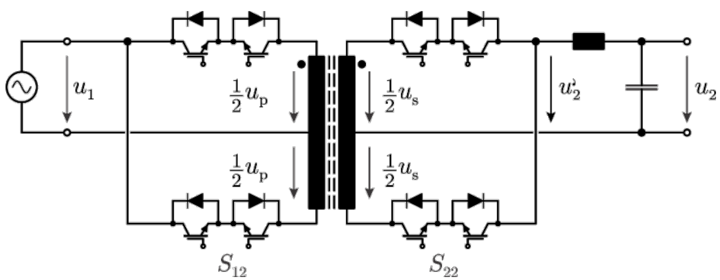


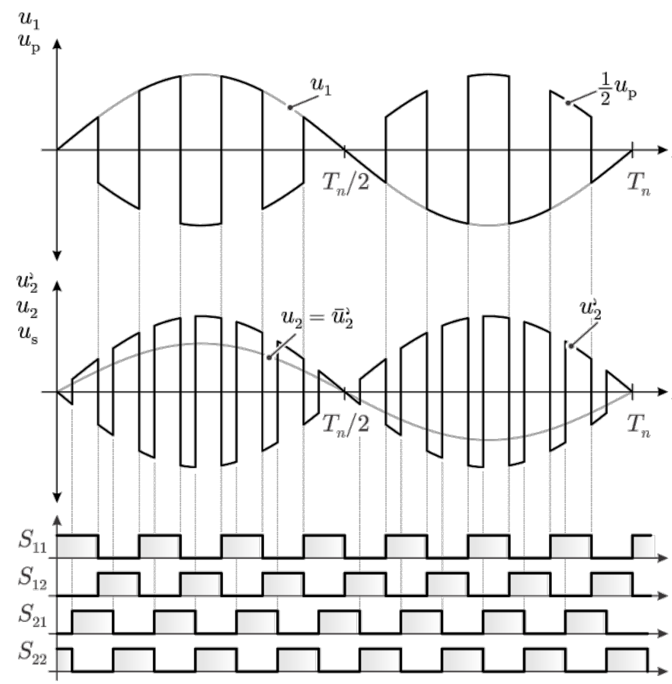


- Electronic Transformer = HF Transf. Link & Input and Output Solid-State Switching Circuits
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- 1-Stage Direct Matrix-Type
- McMurray (1968) — Electronic Transformer



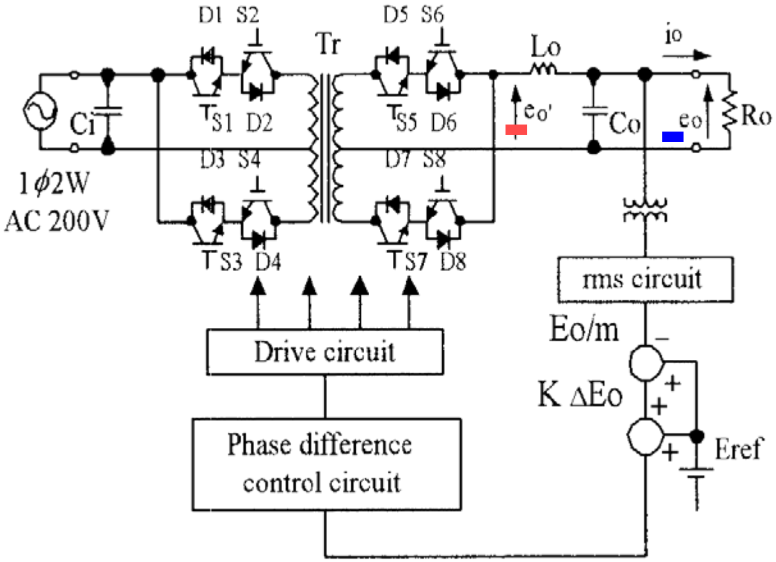


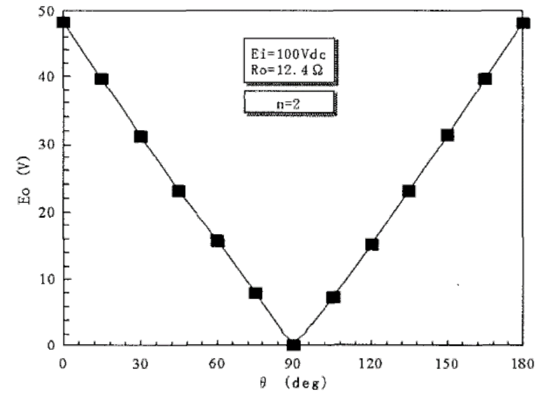
- **50% Duty Cycle Operation @ Primary and Secondary Sides**
- **Output Voltage Control via Phase Shift Angle**

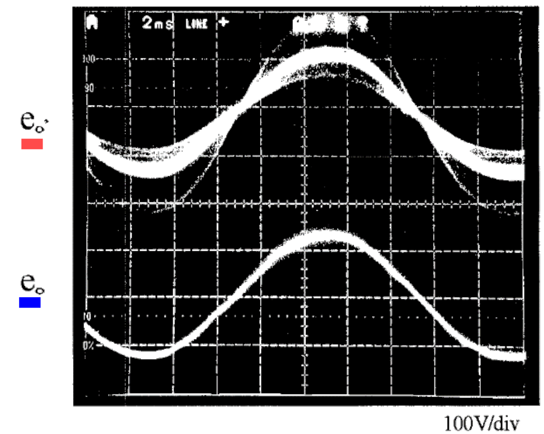
▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- 1-Stage Direct Matrix-Type
- Harada (1996) — Electronic Transformer
  (Based on Patent from McMurray)

- Experimental Verification (200V/3kVA) of Basic Operation and Control Characteristic

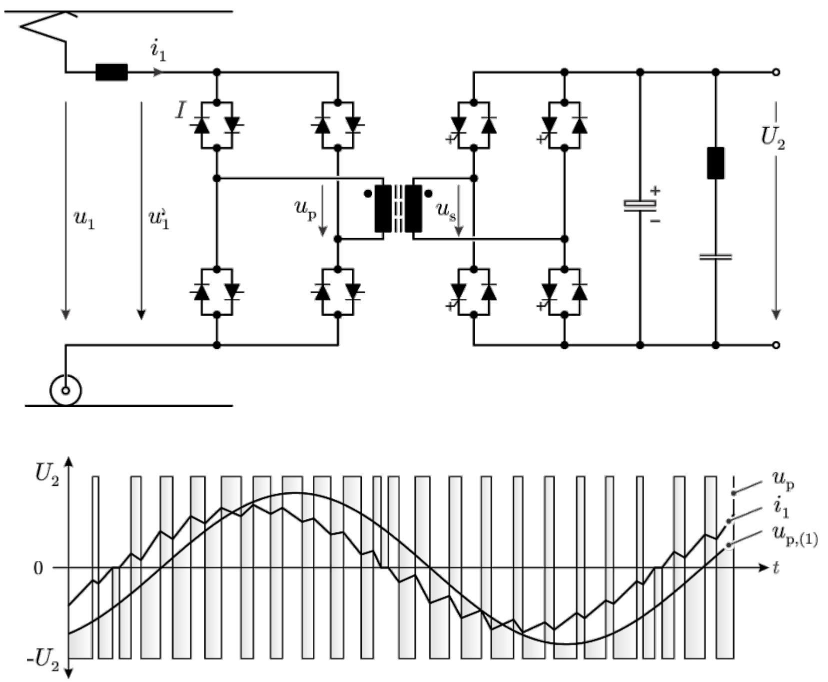






► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

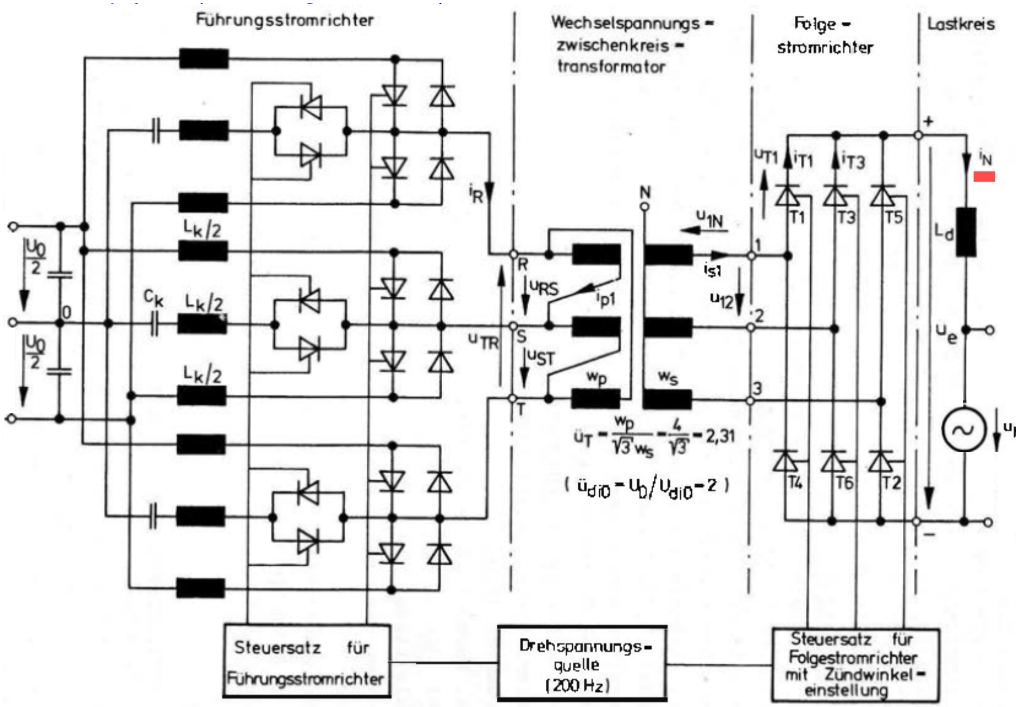
- Direct Matrix-Type 1ph. AC/DC Converter
- Mennicken (1978, *f* = 200Hz)

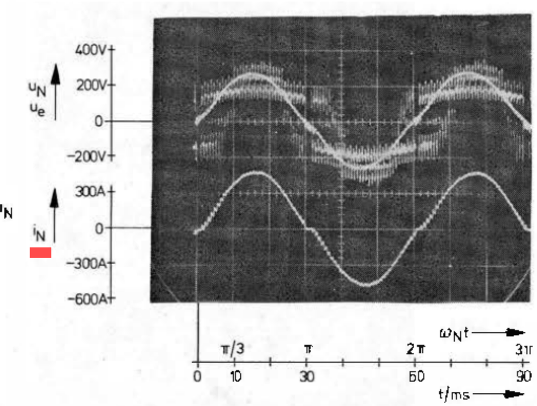


- Targeting Traction Application
- **Combination of Forced Commutated VSC & Thyristor Cycloconverter**
- **VSC Defines Transformer Voltage & Generates Thyristor Converter Commutation Voltage**
- Energy Flow Defined by Control Angle of Thyristor Converter !

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/DC Converter

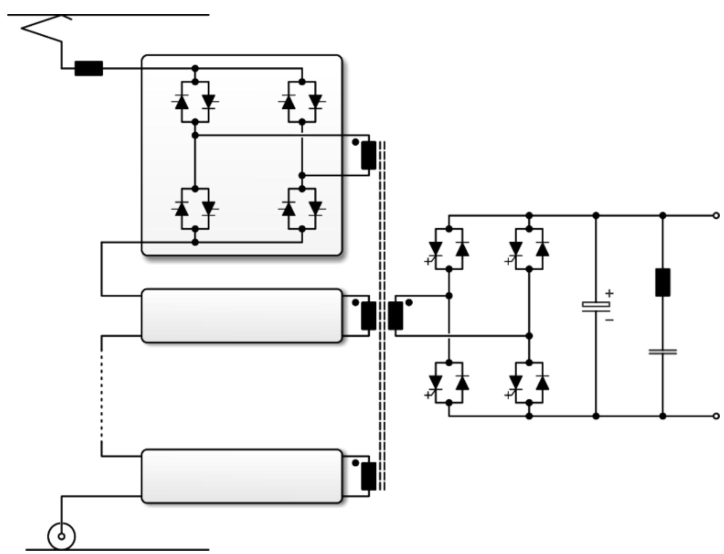


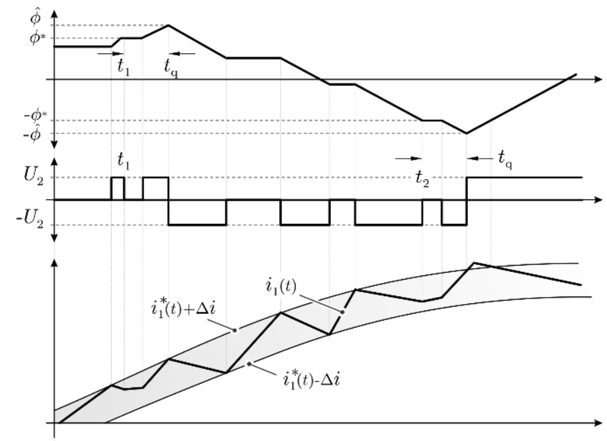


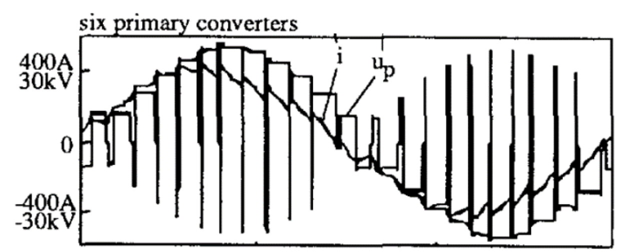
- Experimental Verification (Switching Frequency f =200Hz, f_N=16$^2/_3$ Hz)

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/DC Converter
- Östlund (1993)I-Input, V-Output (McMurray, Mennicken)





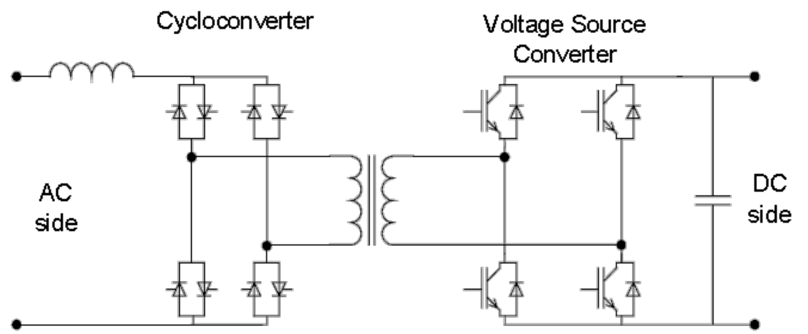


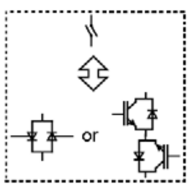
- Targeting Traction Applications
- Novel AC Current Control Concept for Mennicken Syst.
- Several Switchings of the VSC within Cycloconv. Cycle
- Lower Transformer Flux Level (Size) / Requires Transformer Flux Balancing Control

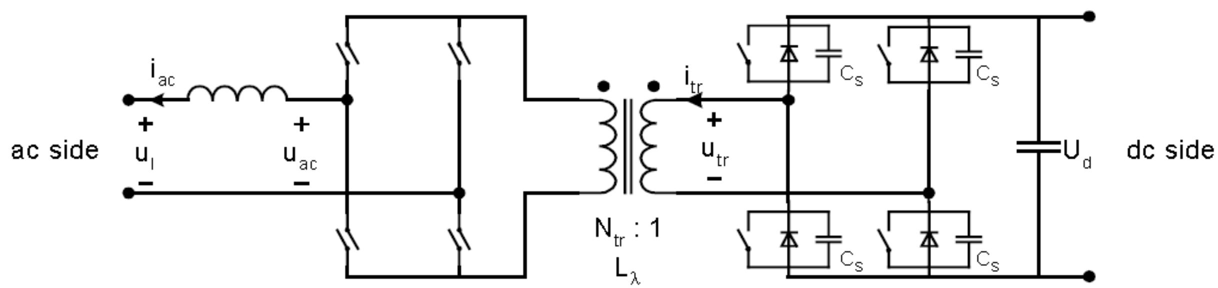
▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/DC Converter
- Mennicken

- Kjaer et al. (2001)
- Norrga (2002)



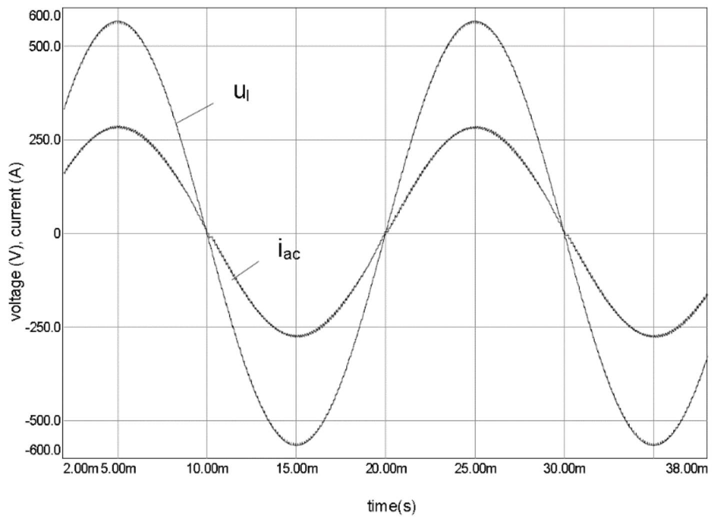


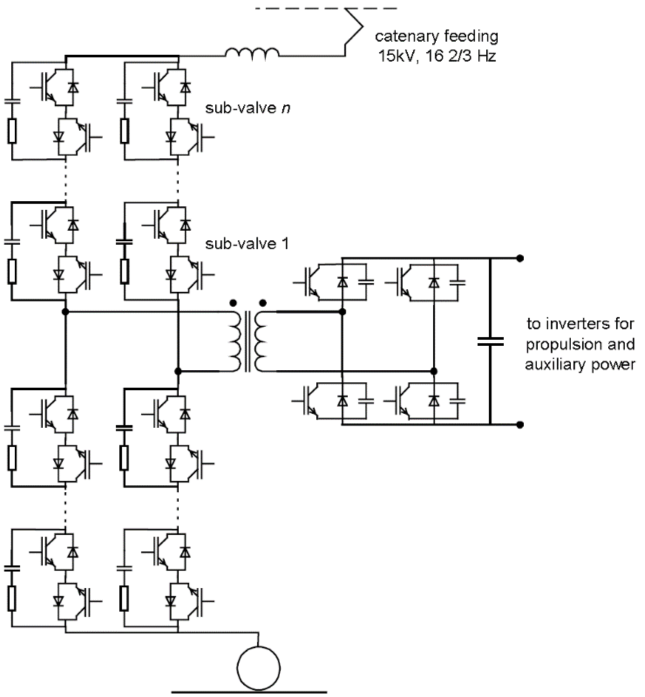


- Extension of the Topology of Mennicken - VSC Capacitive Snubbers & Turn-off Cycloconv. Switches
- New Control Scheme Ensuring ZVS for the VSC and ZCS for the Cycloconverter (Matrix Conv.)

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/DC Converter
- Norrga (2002)
  I-Input, V-Output (McMurray, Mennicken)

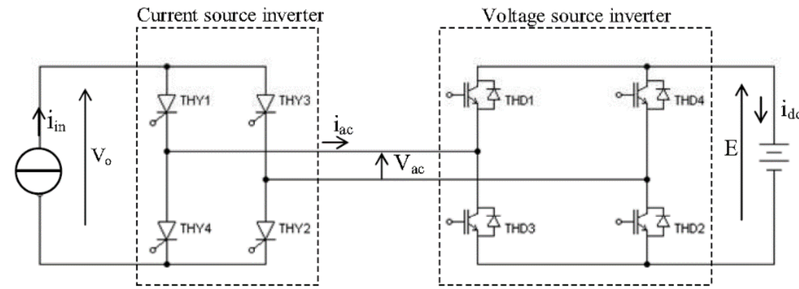


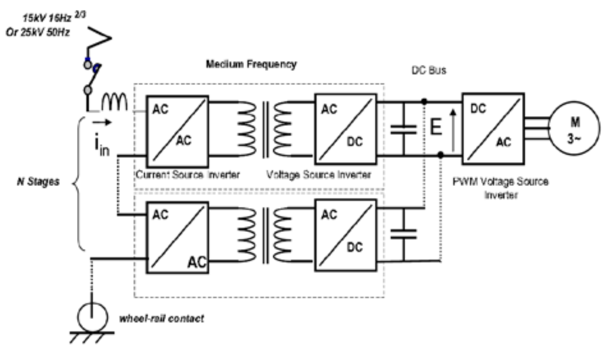


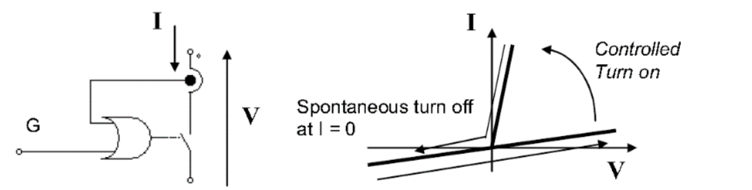
- Simulation Results and Extension to MV Input
- VSC Quasi-Resonant Commutation Ensuring ZVS for Low Load (Current Insufficient for ZVS)

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

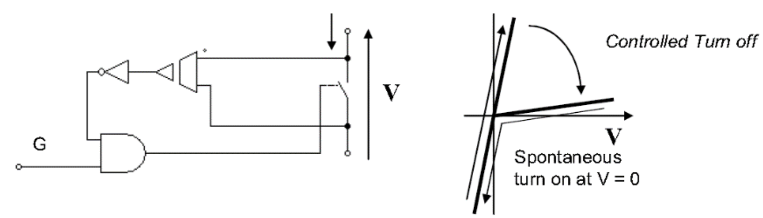
- Direct Matrix-Type 1ph. AC/DC Converter
- Ladoux (1998)
  I-Input, V-Output (McMurray, Mennicken)







Thyristor commutation mode.

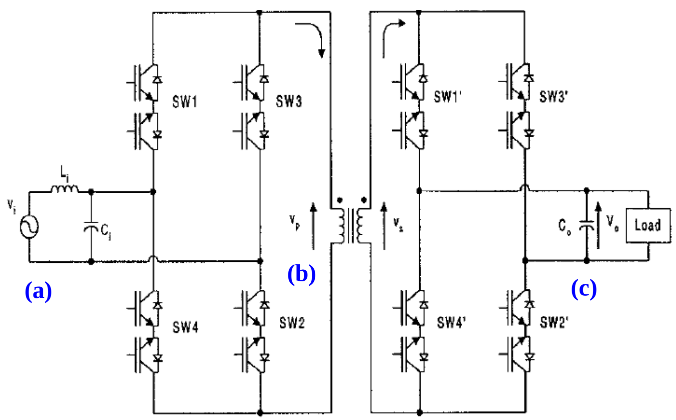


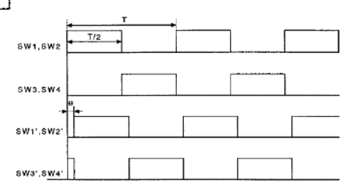
Dual Thyristor commutation mode.

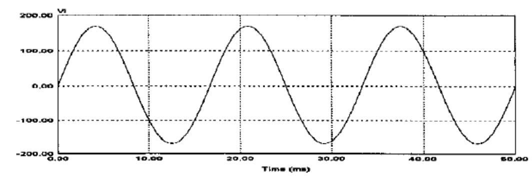
- Targeting Traction Applications
- Dual Structure Association (VSC & CSC) & Phase Control & Dual Thyristor Control (ZVS)
- Soft Commutation of All Switches

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

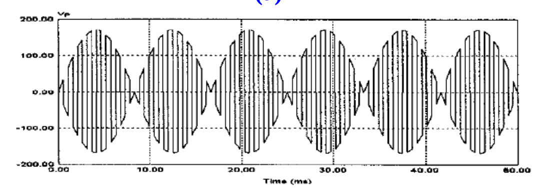
- Direct Matrix-Type 1ph. AC/AC Converter
- Enjeti (1997) V-Input, V-Output, $\theta = 0$
- Krishnaswami (2005) Liu (2006) V-Input, I-Output
- Kimball (2009) V-Input, V-Output



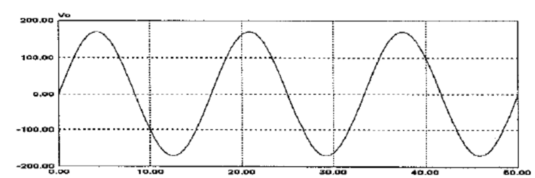




(a)



(b)

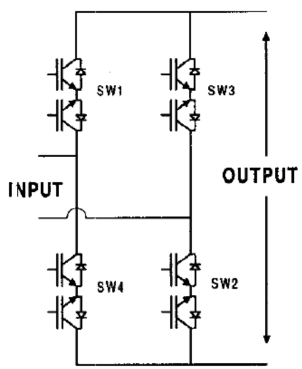


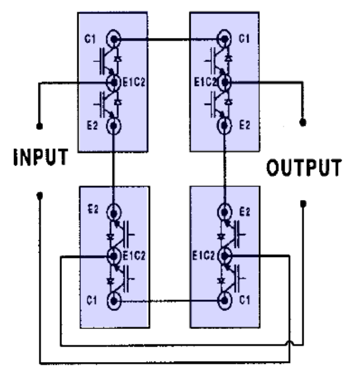
(c)

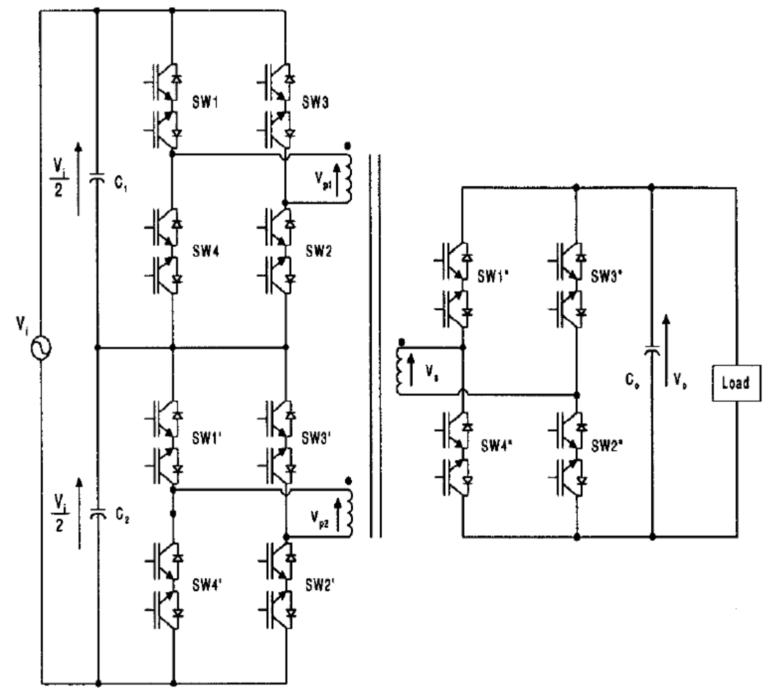
- $f_1 = f_2$,
- Input Power = Output Power (and No Reactive Power Control)
- Same Switching Frequency of Primary and Secondary Side Converter
- Power Transfer / Outp. Volt. Contr. by Phase Shift θ of Primary & Sec. Side Conv. (McMurray)
- **$\theta = 0$ (shown) Allows to Omit Output Filter Ind. (V-Output), But does Not Allow Output Control**

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/AC Converter
- Enjeti (1997) V-Input, V-Output, $\theta = 0$



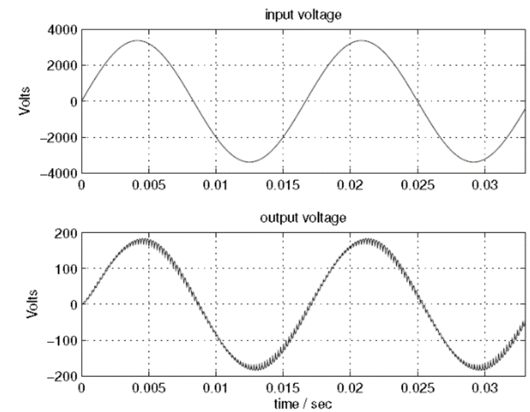


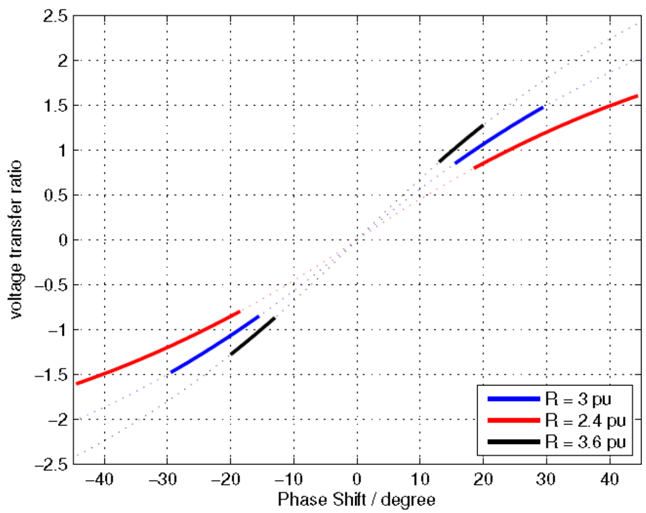


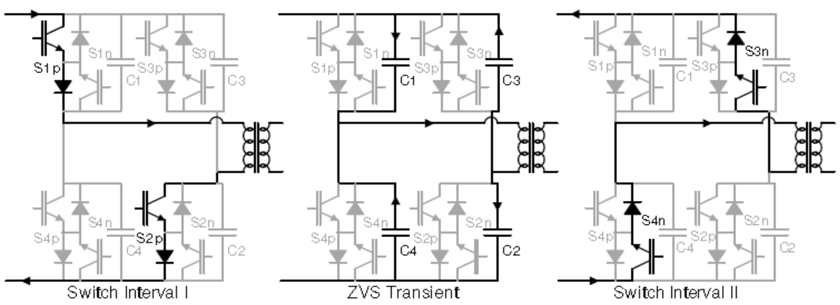
- Realization of Matrix Stages with Conventional IGBT Modules
- Cascaded Converter Input Stages for High Input Voltage Requirement
- Single Transformer / Split Winding Guarantees Equal Voltage Sharing

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/AC Converter
- Kimball (2009) V-Input, V-Output



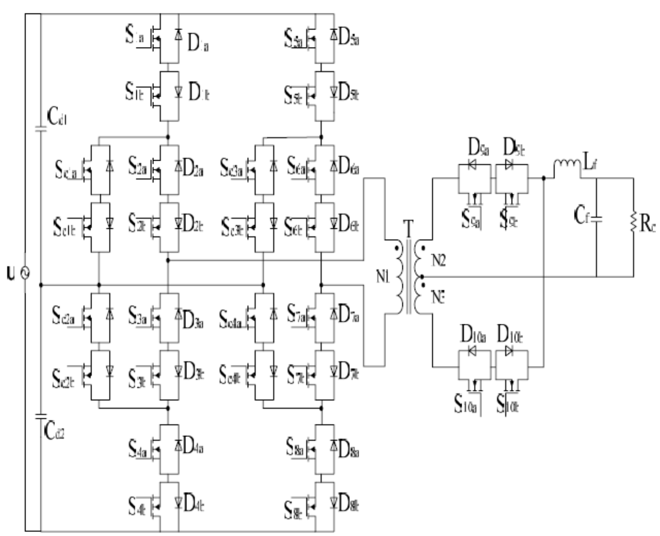


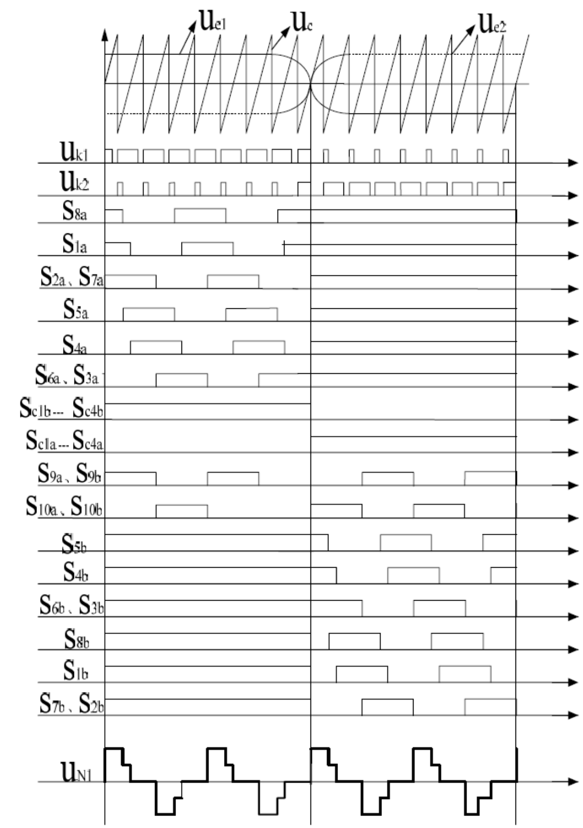


- ZVS Strategy
- ZVS Range Dependent on Load Condition & Voltage Transfer Ratio (Stray Ind. as Design Parameter)

► Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Direct Matrix-Type 1ph. AC/AC Converter
- Yang (2009)   V-Input, I-Output

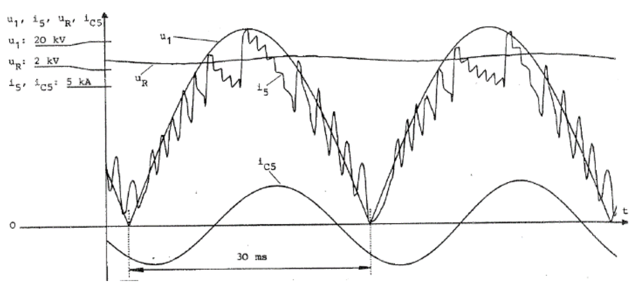


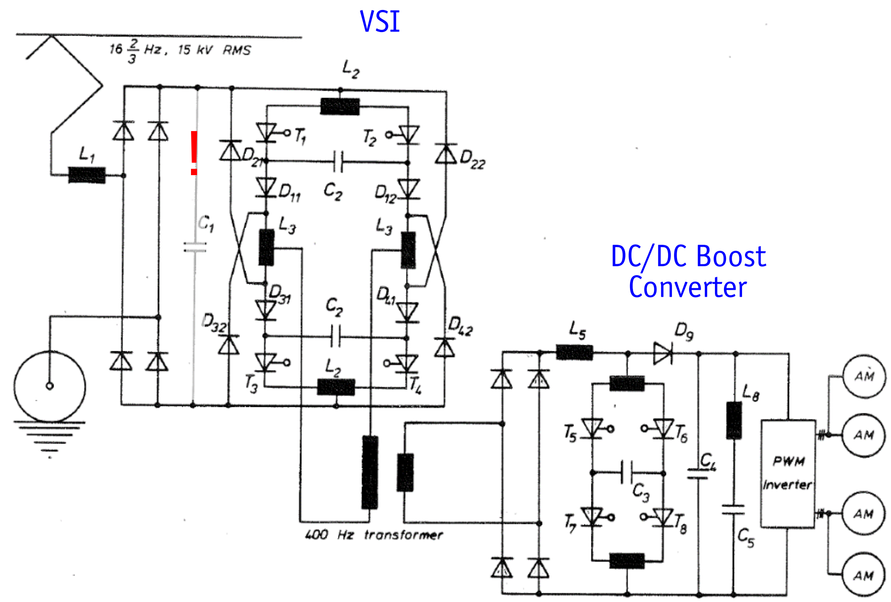


- Topological Variation of the Basic 1ph. AC/AC DAB Topology
- Three-Level Input Stage, Center-Tap Secondary Winding Rectifier Stage

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Indirect Matrix-Type 1ph. AC/DC Converter
- Weiss (1985)   I-Input, V-Output

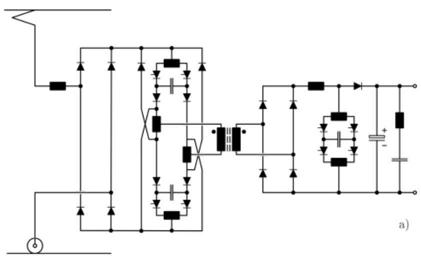


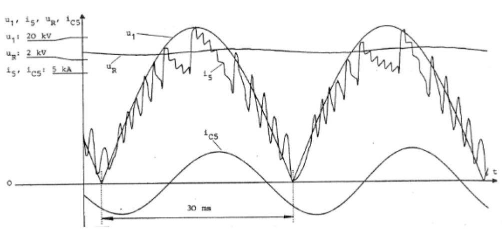


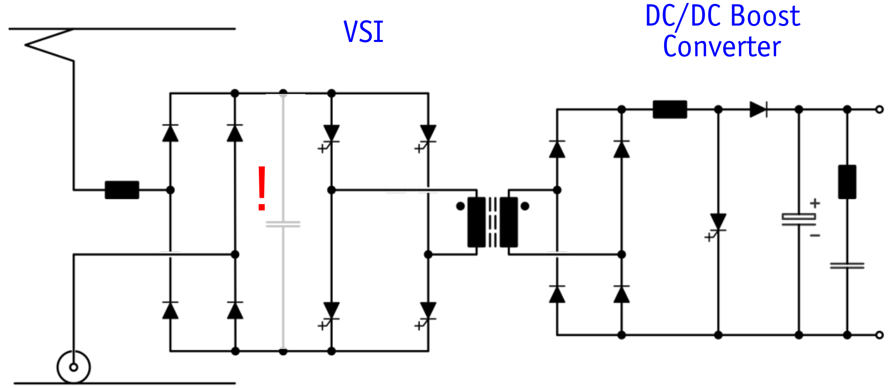
- AC/DC (Rectifier Bridge, No Output Capacitor) and Subsequent MF AC Voltage Generation
- **Secondary Side Rectifier and DC/DC Boost Converter for Sinusoidal Current Shaping**
- Switching Frequency f = 400Hz

▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Indirect Matrix-Type 1ph. AC/DC Converter
- Weiss (1985)   I-Input, V-Output







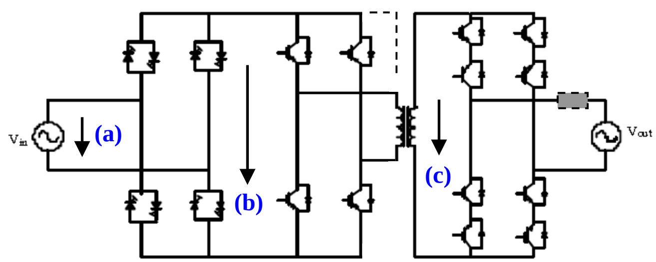
- AC/DC (Rectifier Bridge, No Output Capacitor) and Subsequent MF AC Voltage Generation
- **Secondary Side Rectifier and DC/DC Boost Converter for Sinusoidal Current Shaping**
- Switching Frequency f = 400Hz

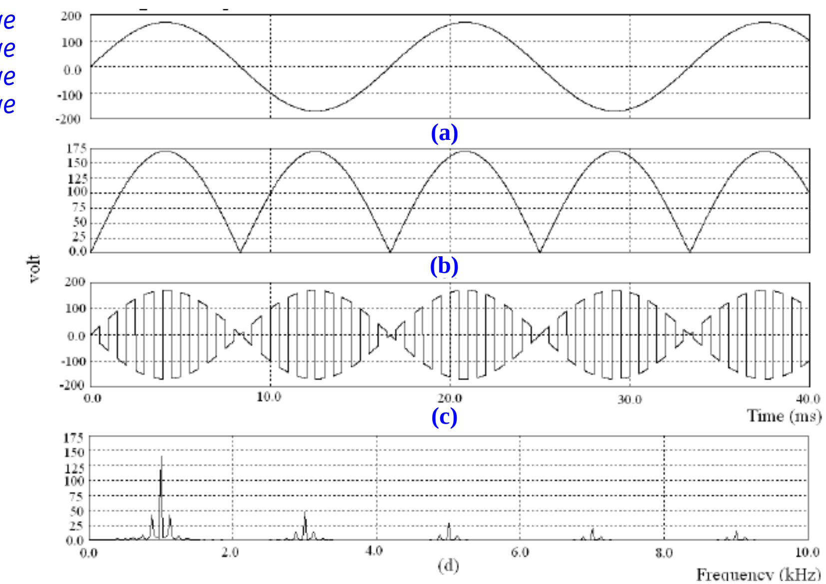
▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

- Indirect Matrix-Type 1ph. AC/AC Converter
- Lipo (2010) V-Input, I-Output

AC Input Voltage
Rectifier Output Voltage
Transformer Input Voltage
Spectrum of Transformer Voltage

!



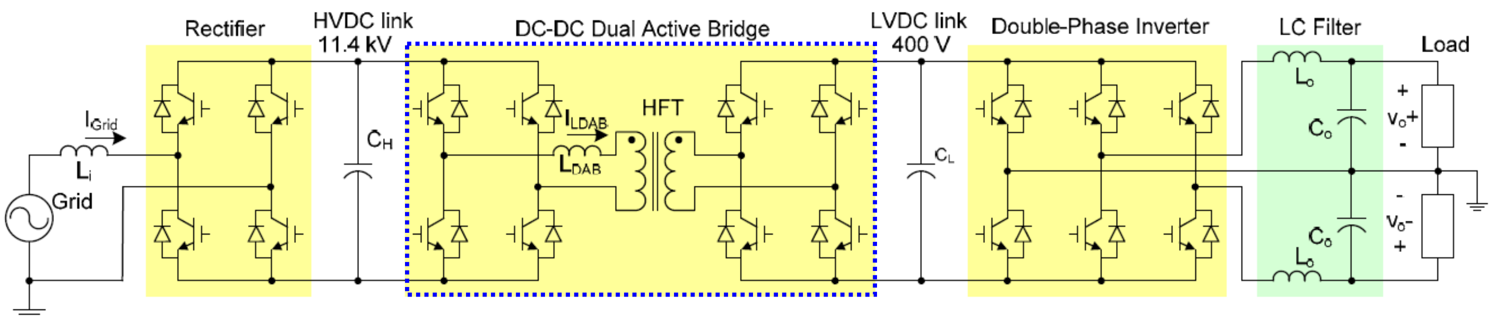


- AC/DC Input Stage (Bidir. Full-Wave Fundamental Frequ. GTO Rect. Bridge, No Output Capacitor)
- Subsequent DC/DC Conversion & DC/AC Conversion (Demodulation, $f_1 = f_2$)
- Output Voltage Control by Phase Shift of Primary and Secondary Side Switches (McMurray)
- Lower Number of HF HV Switches Comp.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

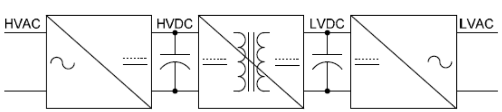
▶ Basic SST Structures (1): Partitioning of AC/AC Power Conversion

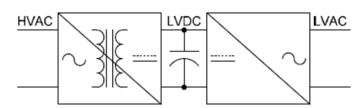
- DC-link-Type (Indirect) 1ph. AC/AC Converter

- AC/DC – DC//DC – DC/AC Topologies
- **Dual Act. Bridge-Based DC//DC Conv. (Phase Shift Contr. Relates Back to Thyr. Inv. / McMurray)**

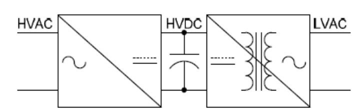


(Ayyanar, 2010)





- Alternatives: AC//DC — DC/AC Topologies
  AC/DC — DC//AC Topologies



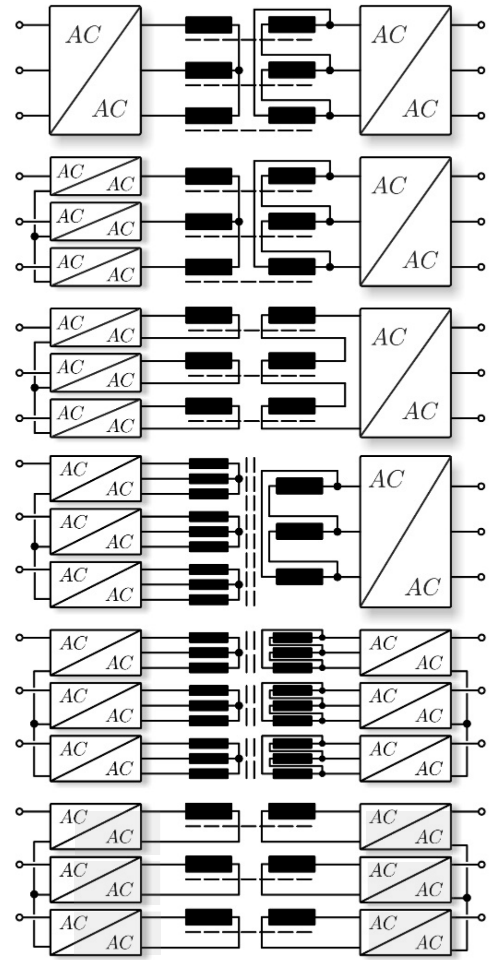
Classification of SST Topologies

Partitioning of AC/AC Power Conversion
Partial or Full Phase Modularity
Partitioning of Medium Voltage

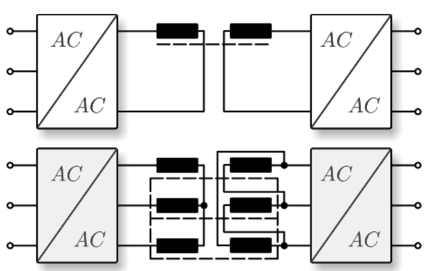
▶ Basic SST Structures (2): Partial or Full Phase Modularity

- 2nd Degree of Freedom of Topology Selection:

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

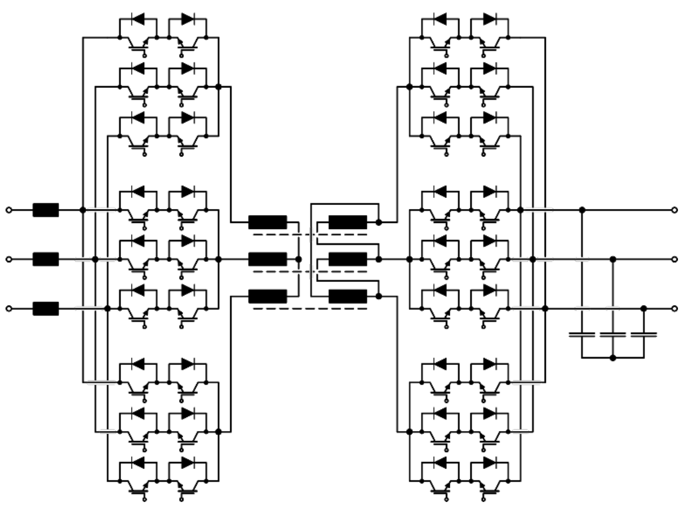


* Phase-Integrated SST



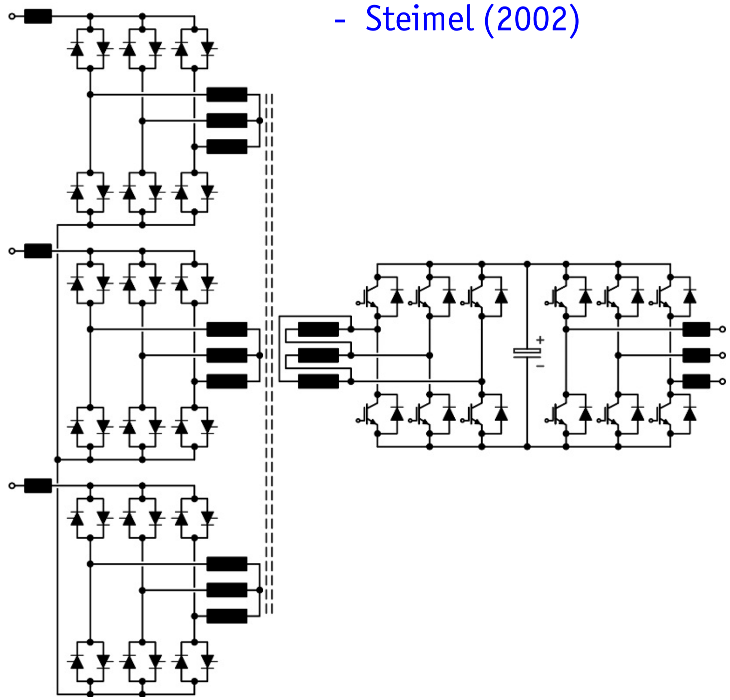
► Basic SST Structures (2): Partial or Full Phase Modularity

- Enjeti (1997)



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

- Steimel (2002)



- Example of Partly Phase-Modular SST

Classification of SST Topologies

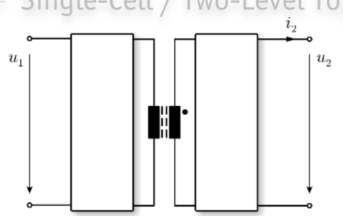
Partitioning of AC/AC Power Conversion
Partial or Full Phase Modularity
Partitioning of Medium Voltage

▶ Basic SST Structures (3): Partitioning of Medium Voltage

- **3rd Degree of Freedom of Topology Selection:**

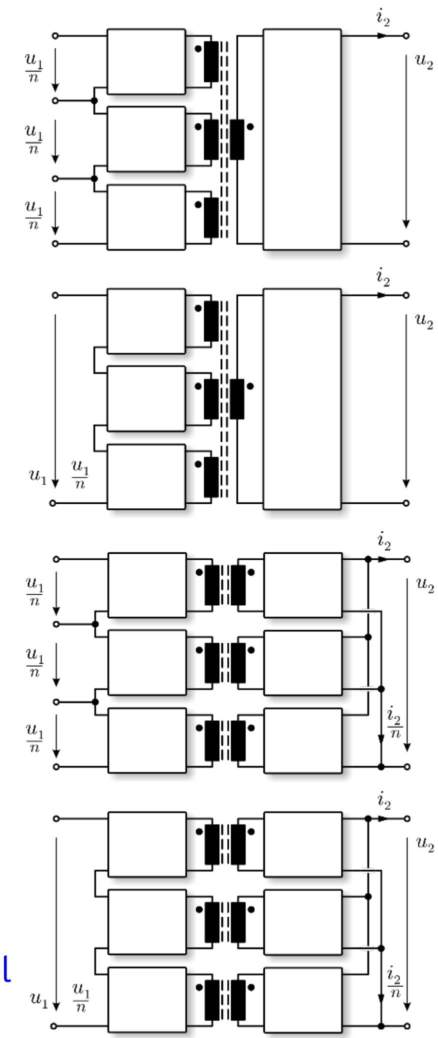
- **Multi-Cell and Multi-Level Approaches:**
  - Low Blocking Voltage Requirement
  - Low Input Voltage / Output Current Harmonics
  - Low Input/Output Filter Requirement

- Single-Cell / Two-Level Topology



a)

ISOP = Input Series / Output Parallel Topologies

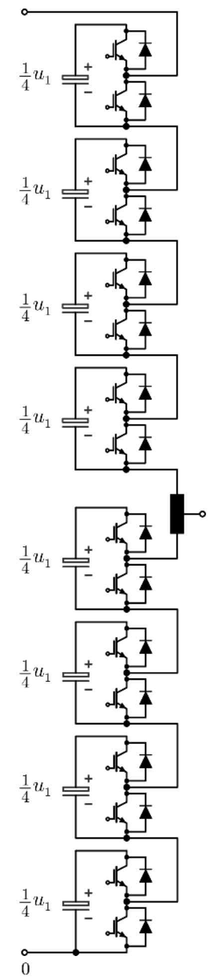


▶ Basic SST Structures (3): Partitioning of Medium Voltage

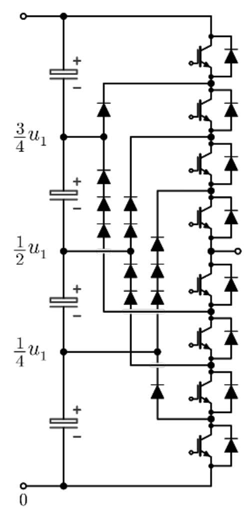
- 3rd Degree of Freedom of Topology Selection:
- Multi-Cell and Multi-Level Approaches:

Marquardt

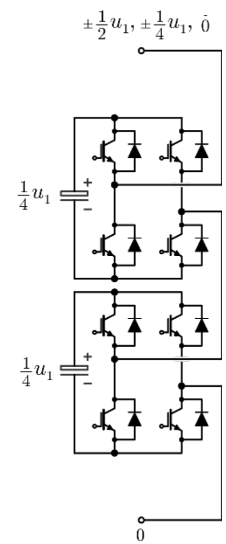
Alesina/
Venturini
(1981)

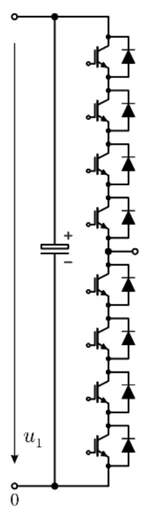


Akagi
(1981)



McMurray
(1969)



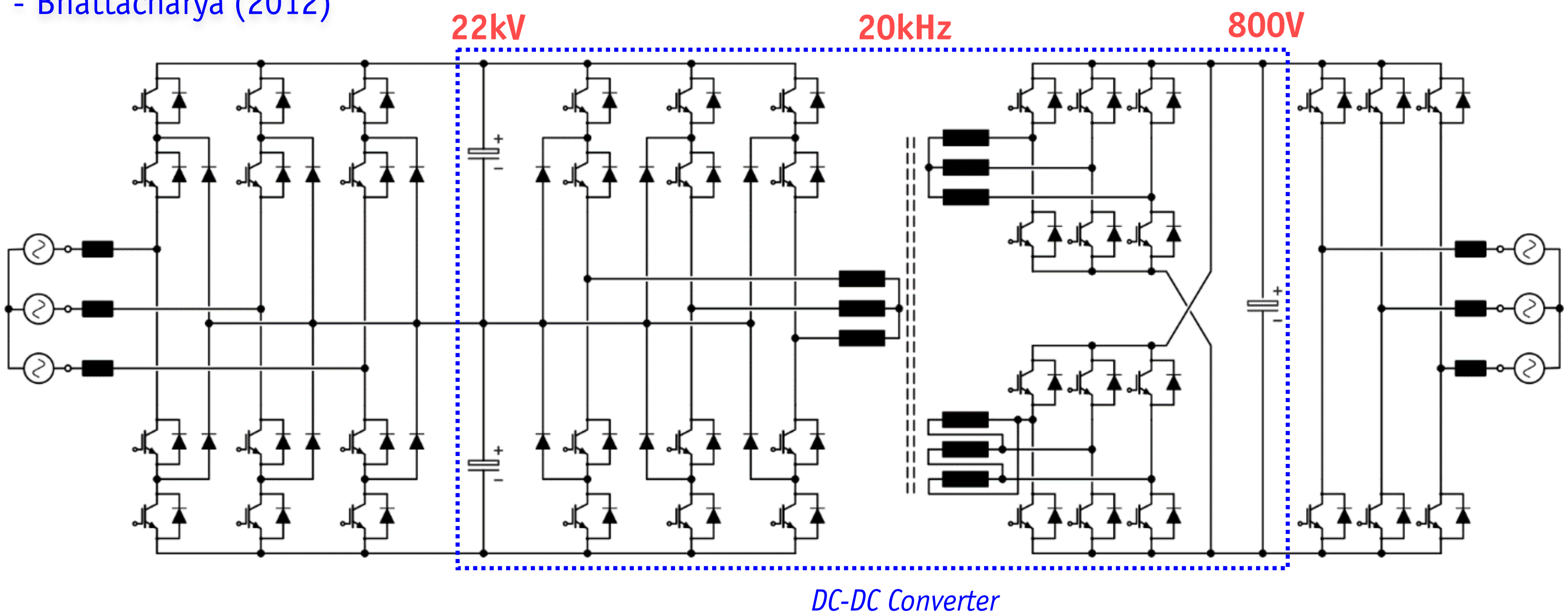


* Two-Level Topology

* Multi-Level/
Multi-Cell
Topologies

▶ Basic SST Structures (3): Partitioning of Medium Voltage

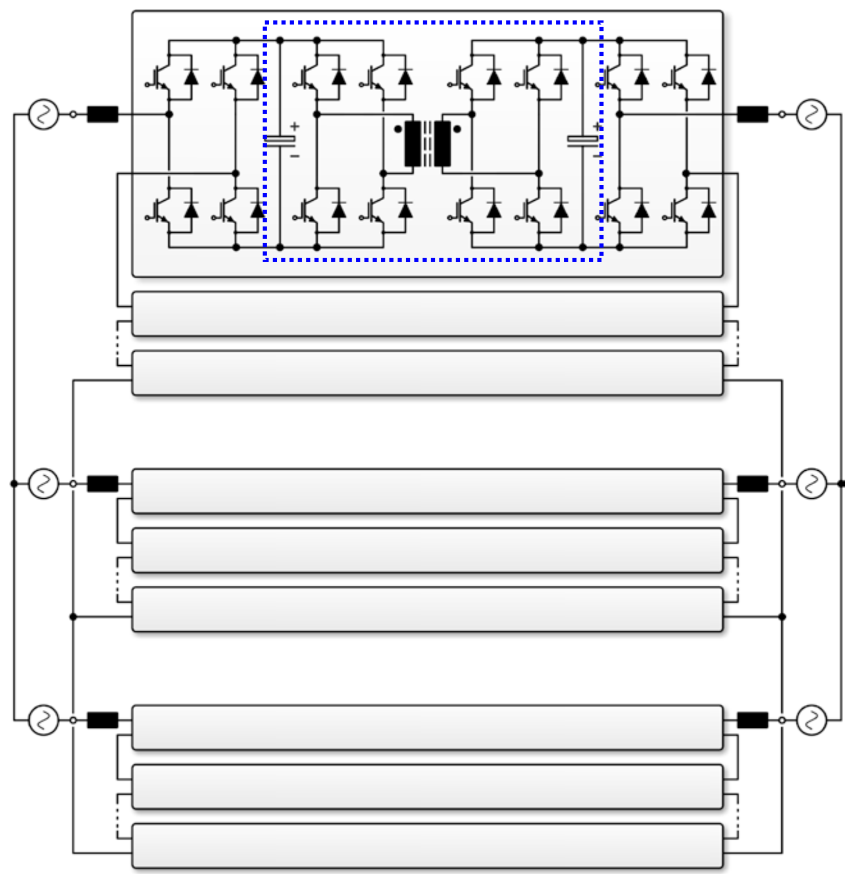
- Bhattacharya (2012)



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

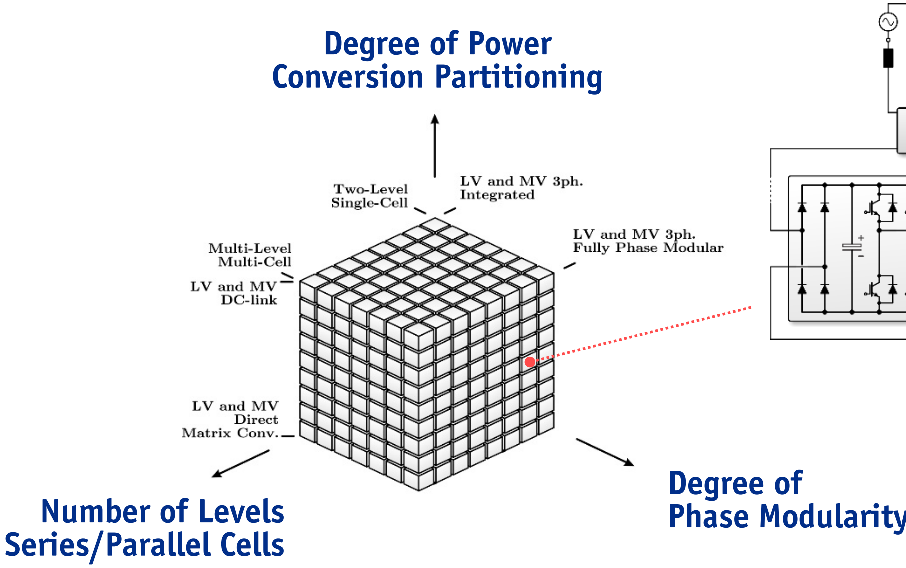
► Basic SST Structures (3): Partitioning of Medium Voltage

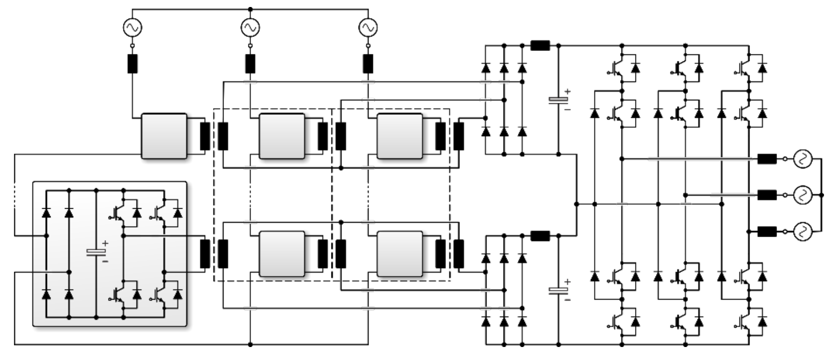
- Akagi (2005)



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

▶ Classification of SST Topologies





- 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

Coffee

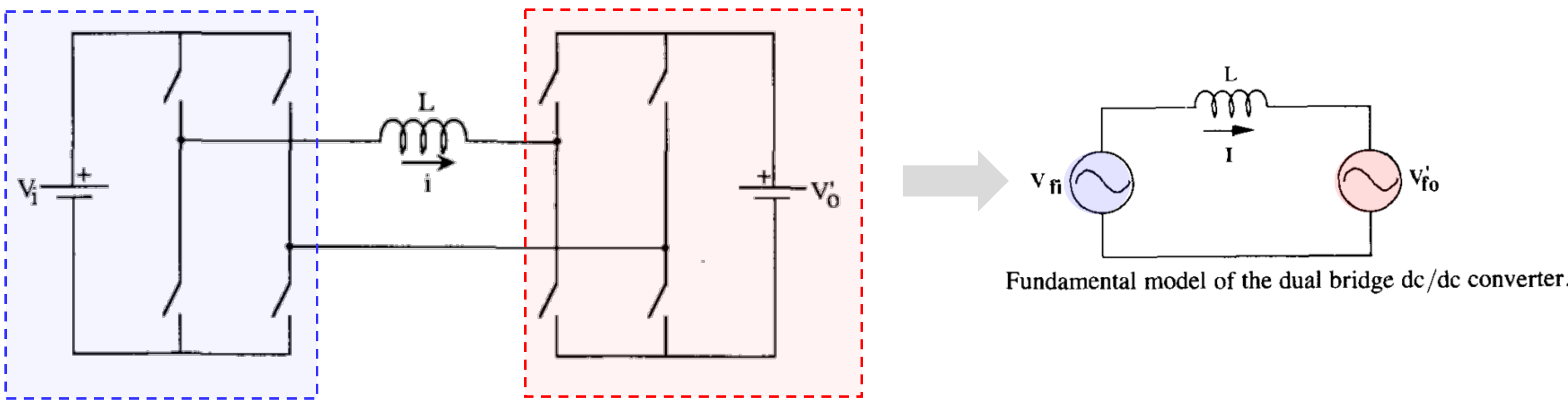
Break

High-Power DC-DC Conversion

DAB Converter
HC-DCM-SRC System
Stored Charge Dynamics
MF Transformer Design

▶ Dual Active Bridge

- DeDoncker (1991)

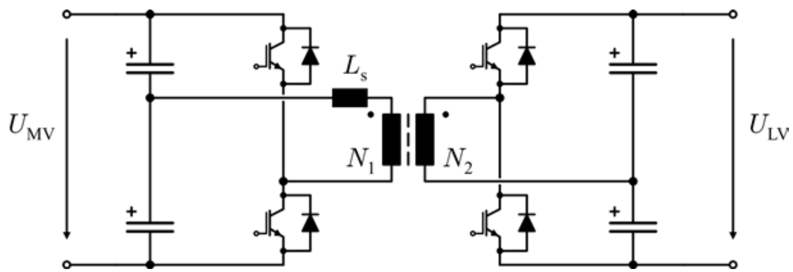


Fundamental model of the dual bridge dc/dc converter.

- Two Voltage Sources Linked by an Inductor
- Operated at Medium/High Frequencies

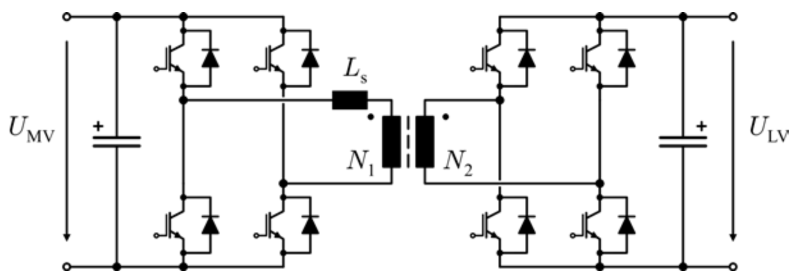
▶ DAB — Common Bridge Configurations

- Half-Bridge



- Two Voltage Levels from each Side

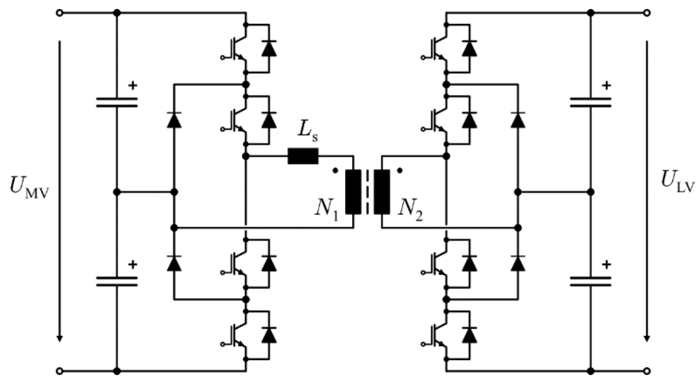
- Full-Bridge



- Three Voltage Levels from each Side
  Additional Freewheeling State

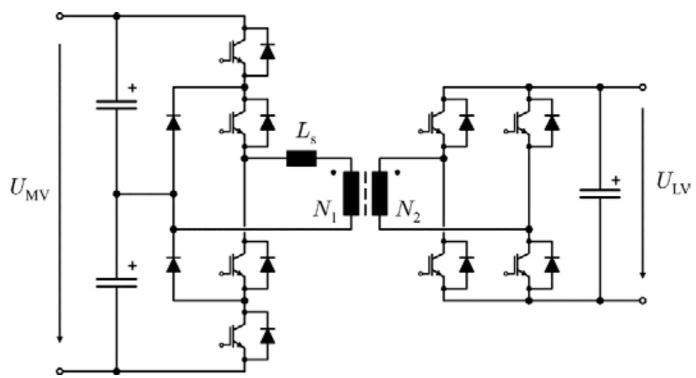
▶ DAB — Common Bridge Configurations

- Neutral Point Clamped (NPC, Multilevel)



- Three Voltage Levels from each Side
- Operation as Voltage Doubler

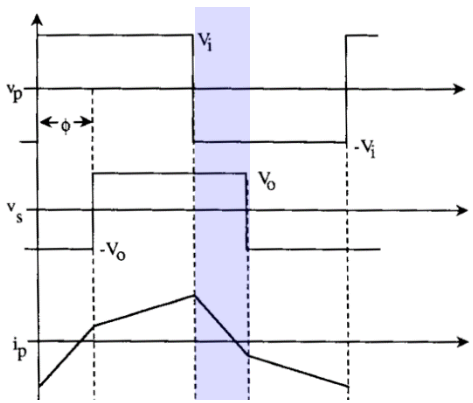
- NPC / Full-Bridge Configuration

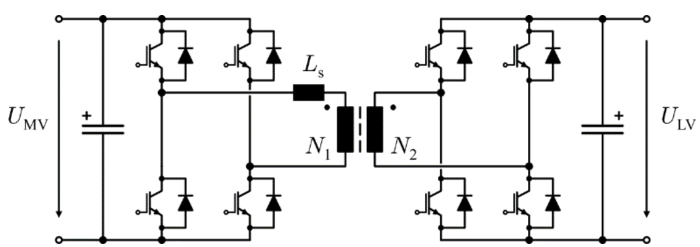


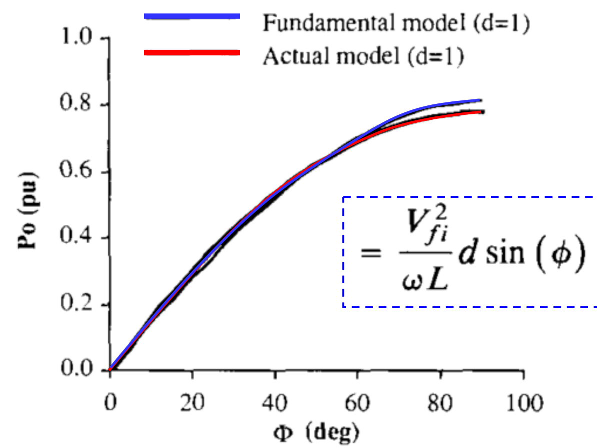
- Suitable for Higher MV/LV Ratios

▶ DAB — Phase-Shift Modulation

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





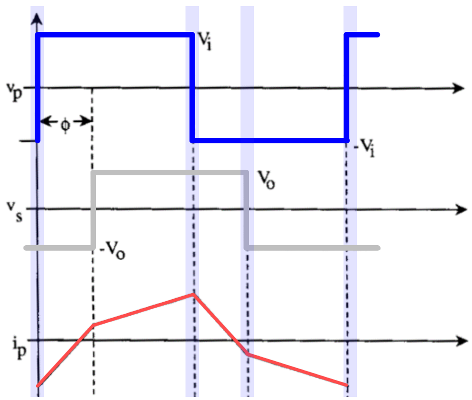


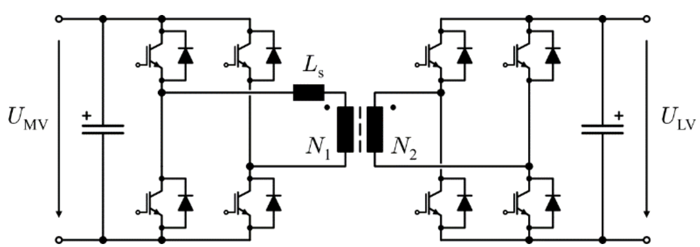
Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

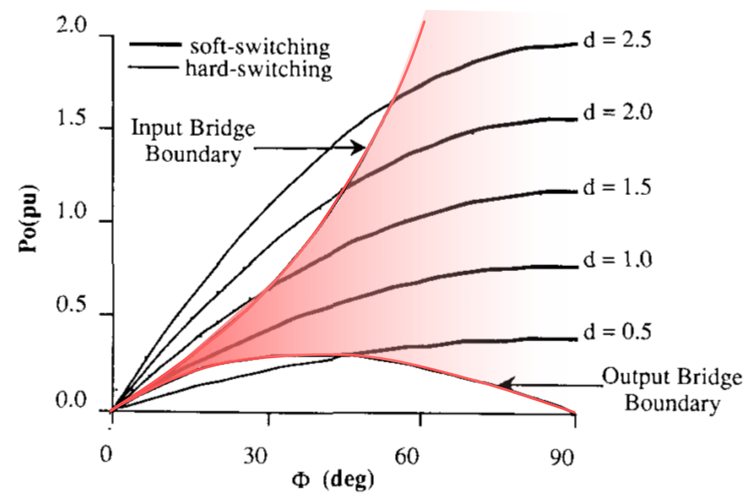
- Fundamental Model suitable for Calculation of Power Transfer

▶ DAB — Phase-Shift Modulation

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



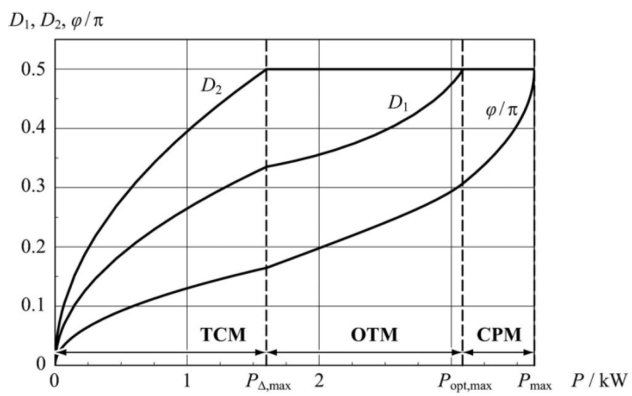


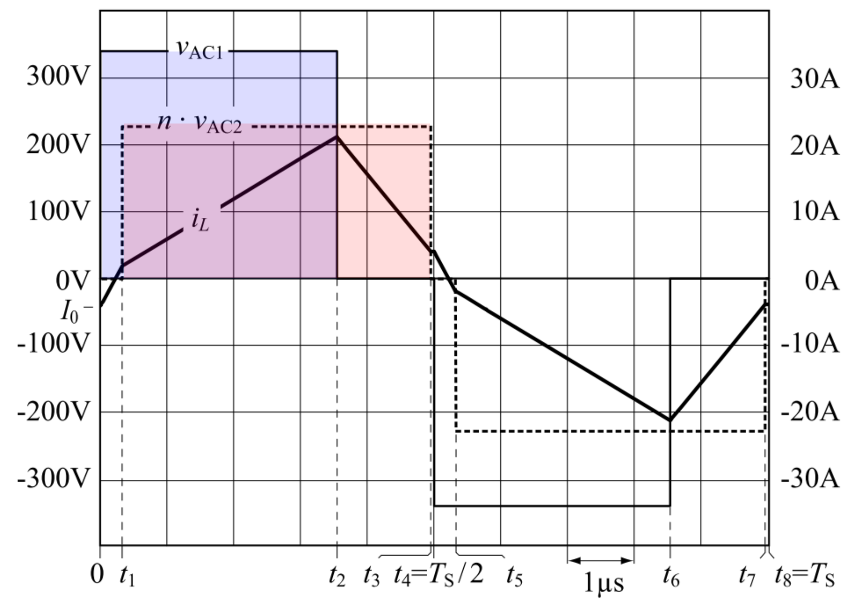


- Soft Switching Range

▶ DAB — Phase-Shift / Duty Cycle Modulation

- Additional Degrees of Freedom Can Be Utilized to Optimized Targeted Criteria
- For Example: Minimization of the RMS Currents through the Transformer (ETH, Krismer, 2012)

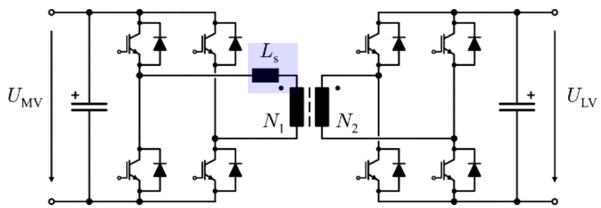


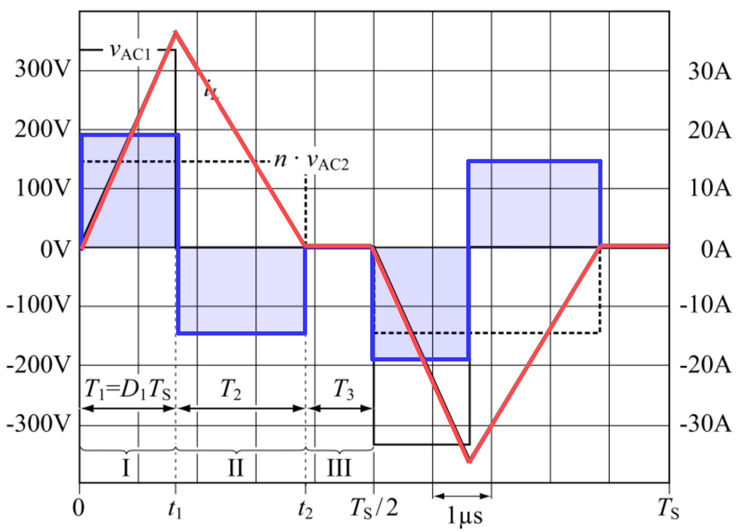


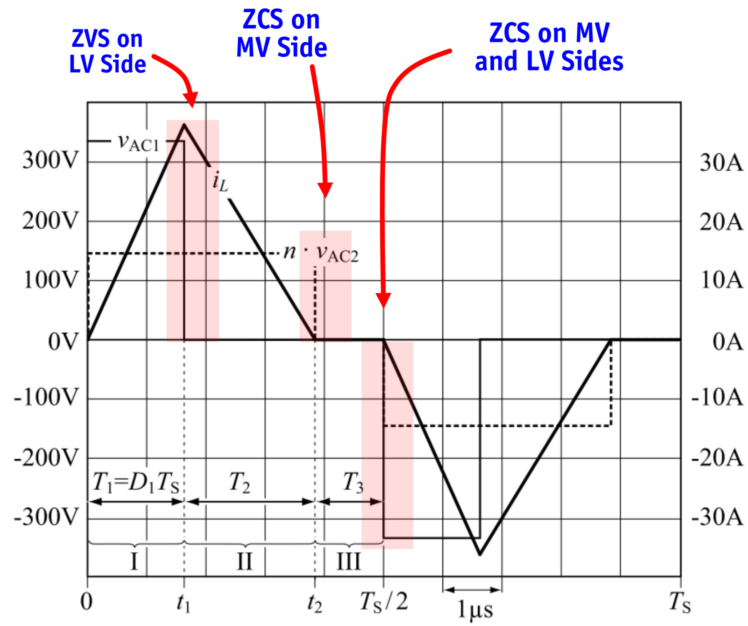
- Not Possible in Half-Bridge Configurations

▶ DAB — Triangular Current Mode

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



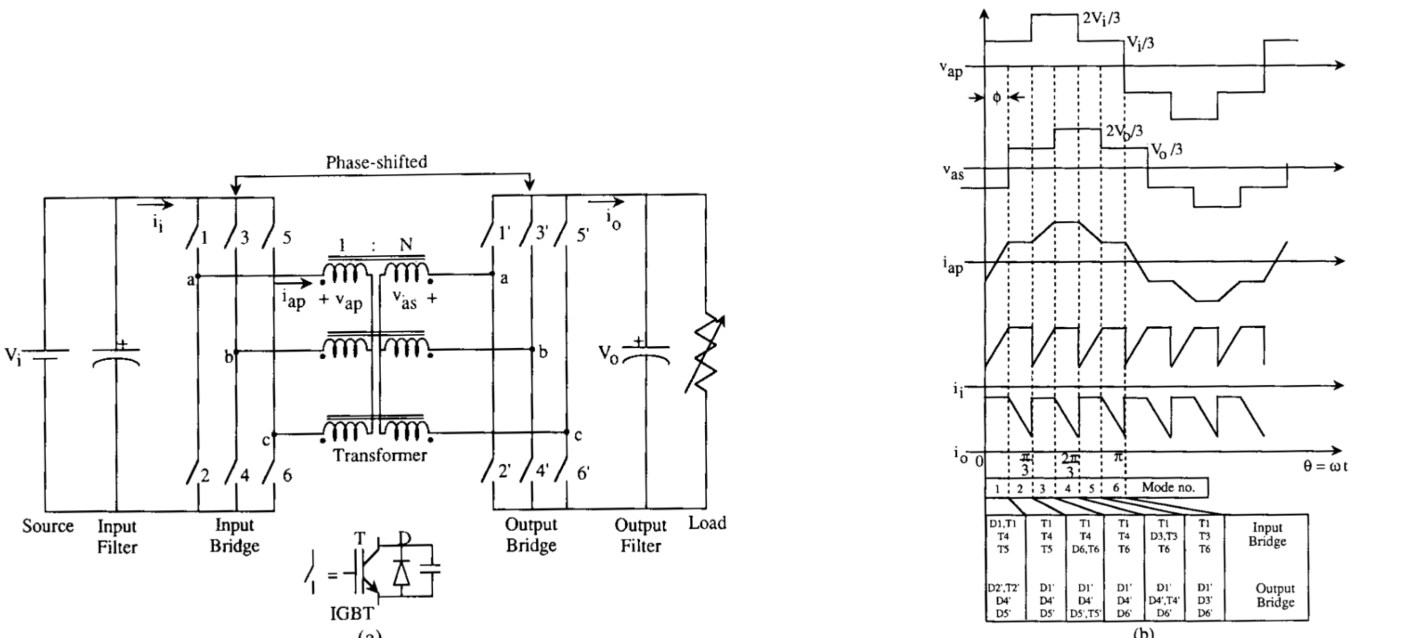




ZCS on MV Side

▶ Three-Phase Dual Active Bridge

- DeDoncker (1991)



(a) Three-phase dual active bridge dc/dc converter, Topology C; (b) idealized operating waveforms for topology C.

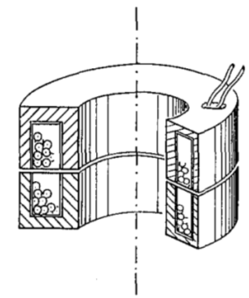
- ZVS of All Devices within Certain Power Range
- **ZCS Only Possible at One Operating Point**

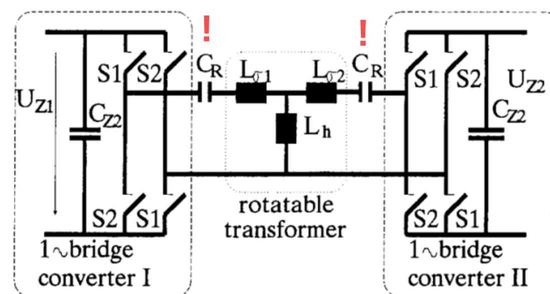
High-Power DC-DC Conversion

DAB Converter
HC-DCM-SRC System
Stored Charge Dynamics
MF Transformer Design

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

- Power Supplies for Robots — RWTH, Esser (1991)



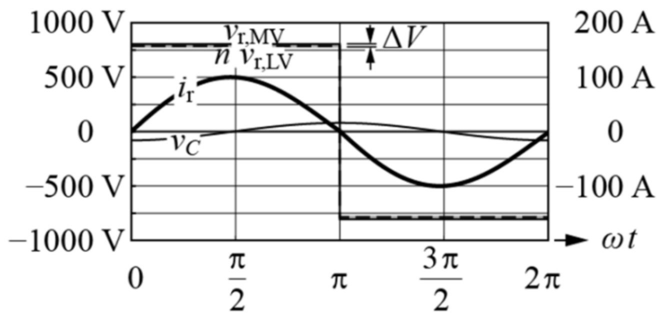


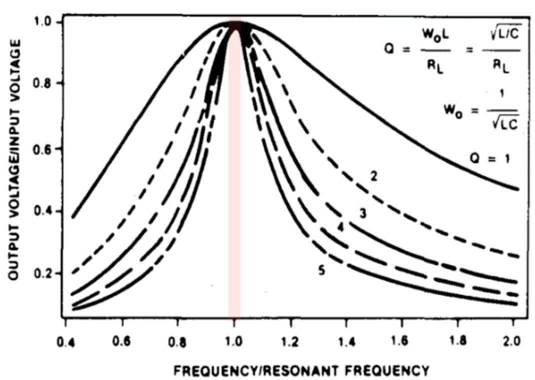
Equivalent circuit of the rotatable transformer and the 1-bridge converters

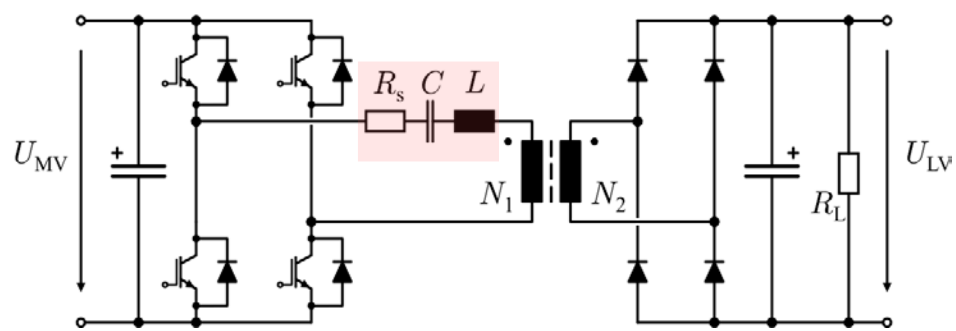
- Energy Transfer Through the Robot's Arm Joints

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

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



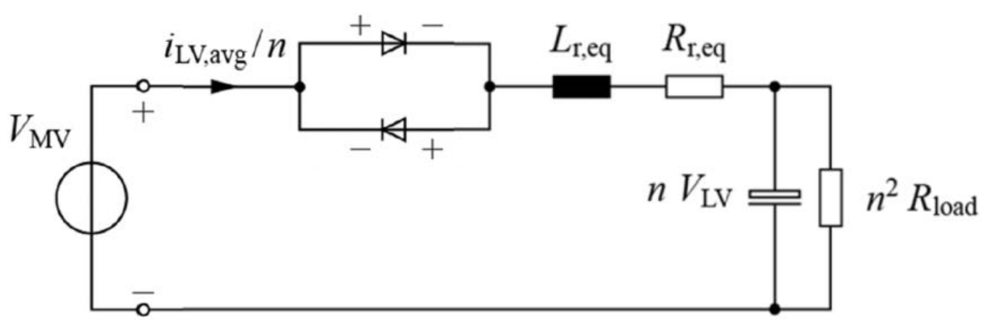




- The Input/Output Voltage Ratio is Close to Unity Independent on Power Transfer (Steigerwald, 1988)

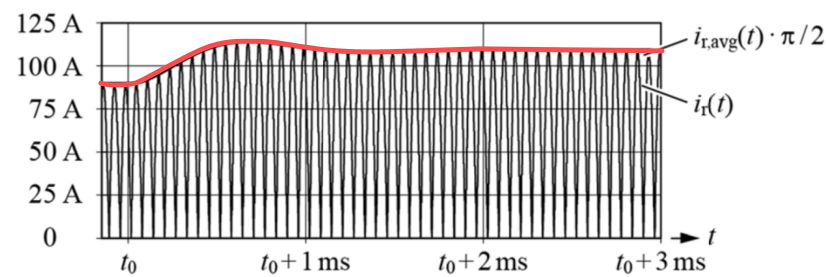
▶ Half-Cycle Discont.-Cond.-Mode Series-Res.-Conv. (HC-DCM-SRC)

- Equivalent Circuit for Transient Analysis — Esser (1991)



$$L_{r,eq} = \frac{\pi^2}{4} L$$

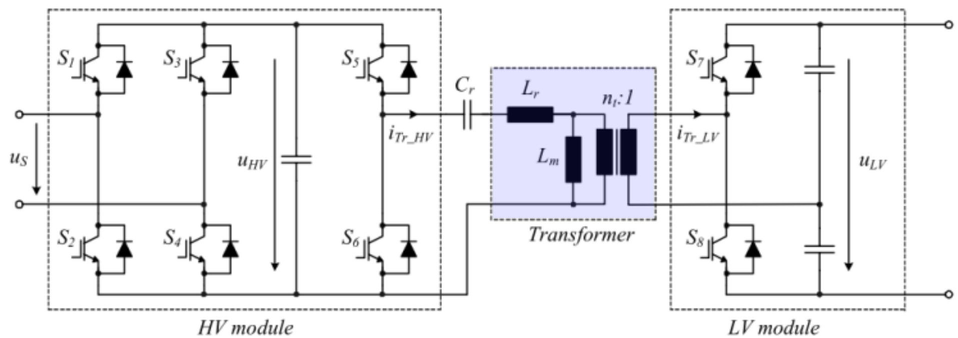
$$R_{r,eq} = \frac{\pi^2}{8} R$$

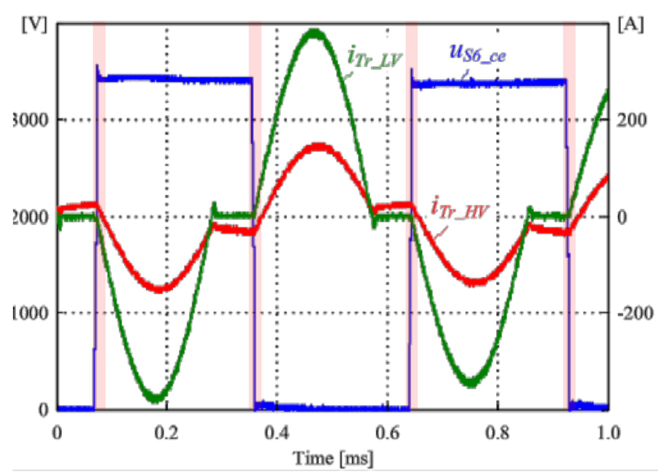


- **Output Voltage is $V_{LV} \approx V_{MV} \cdot n$ for Any Output Power**

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

- Dujic (2012)



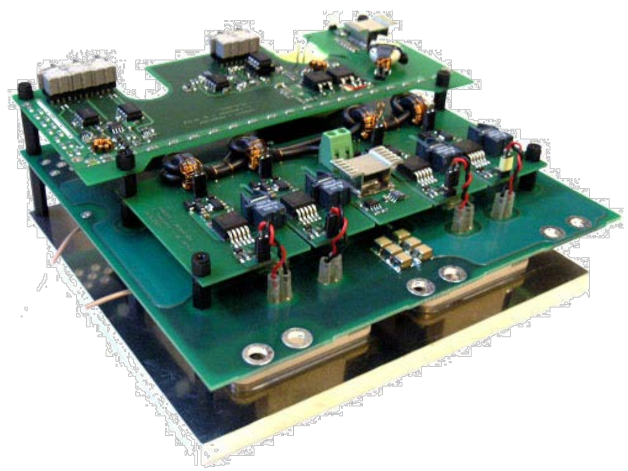


- LLC Structure to Reduce Switching Losses
- **Zero-Current-Switching of All Devices**

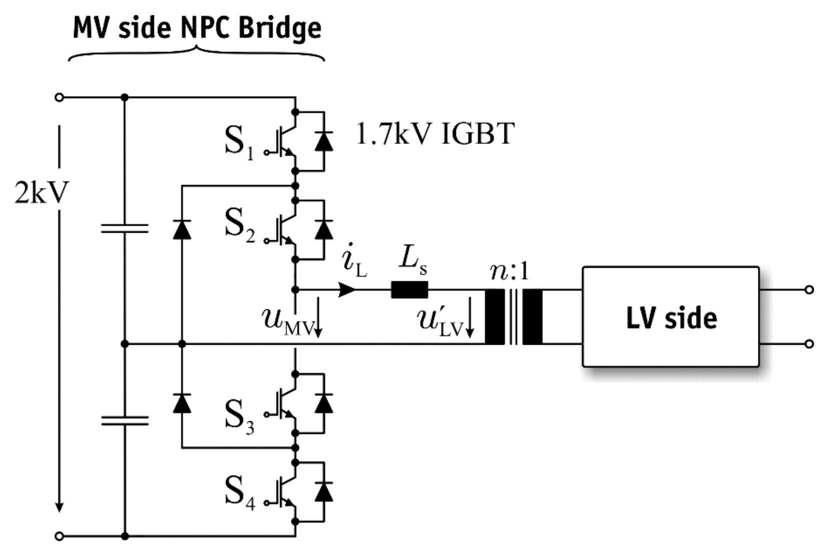
High-Power DC-DC Conversion

▶ ZCS and ZVS of IGBTs

- Analysis of IGBT Losses Under ZCS Conditions for the Triangular Current Mode DAB
- Tested on an NPC Half-Bridge Structure Based on 1.7kV IGBTs



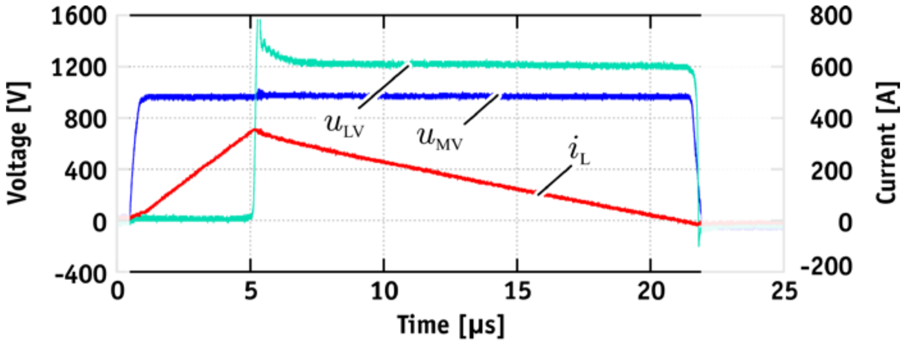
- 1.7kV Field-Stop IGBT-Based Testbench

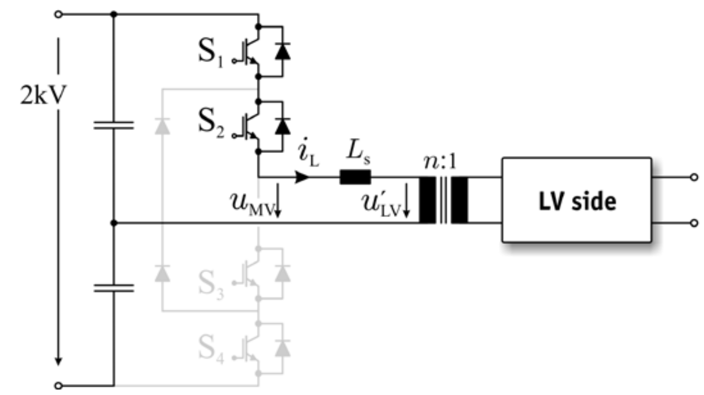


- NPC Half-Bridge Connected to MF Transformer and LV Side Full-Bridge

▶ Triangular Current Mode DAB Operation

1) NPC Half-Bridge Applies
2) The NPC Half-Bridge Commutates to Freewheeling, Achieving ZCS on S_1

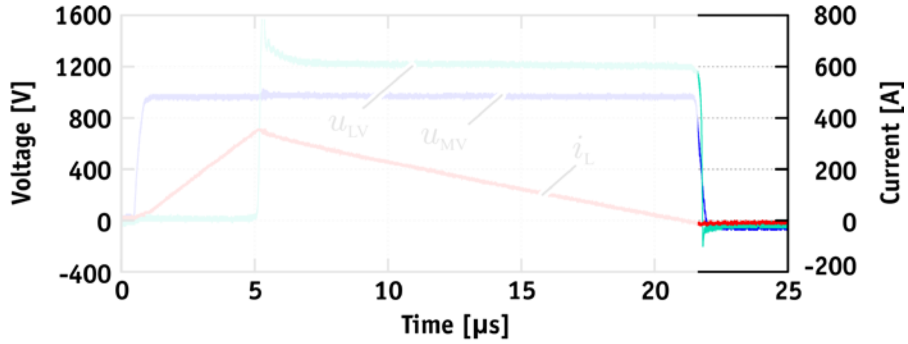


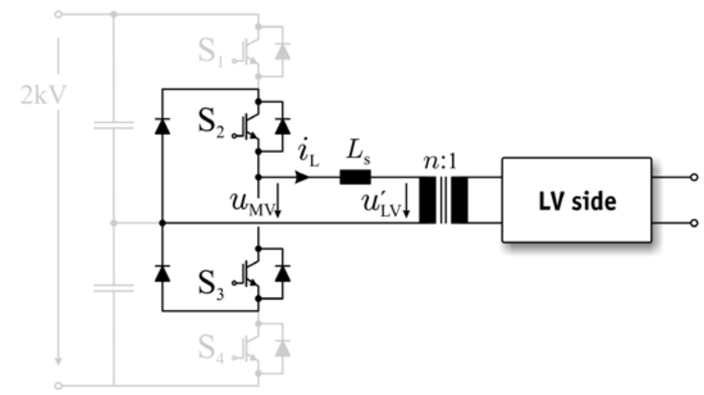


- NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV and LV

▶ Triangular Current Mode DAB Operation

1) NPC Half-Bridge Applies
2) The NPC Half-Bridge Commutates to Freewheeling, Achieving ZCS on S_1

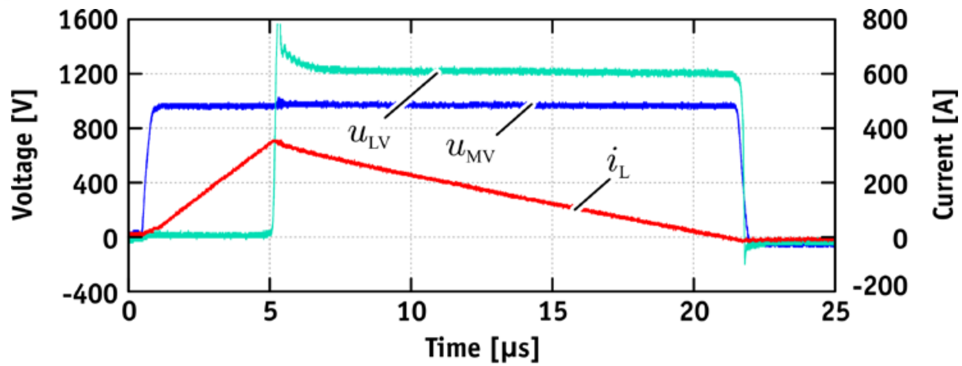


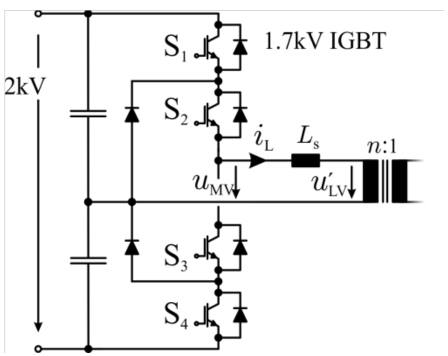


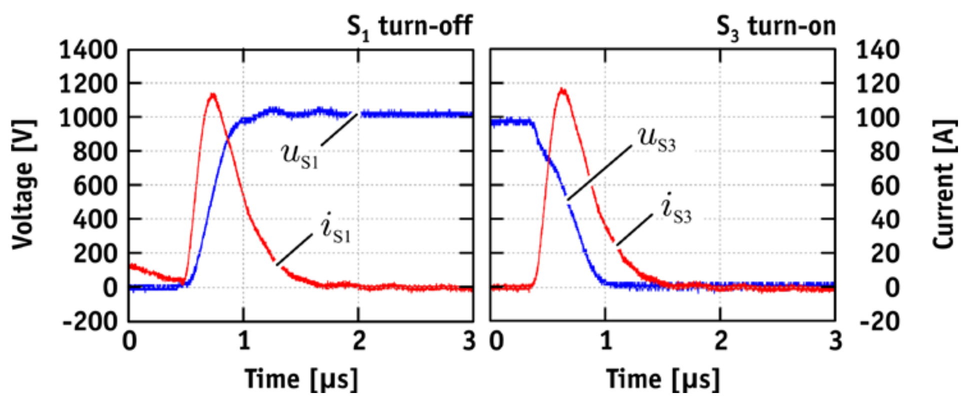
- NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV and LV

► Standard TCM-DAB ZCS Operation

- Large Current Spike in S_1 when Switching Zero Current
- **Large Turn-On Losses on S_3 (Even at ZCS)**





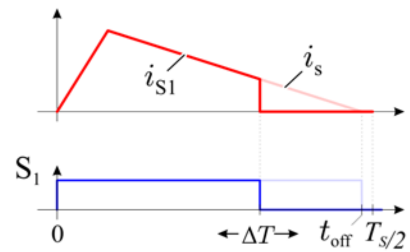


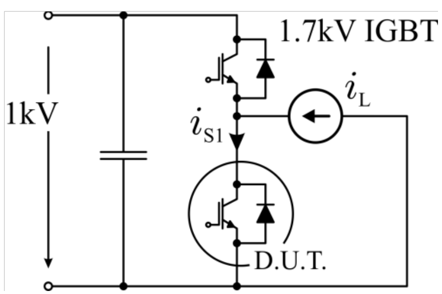
- 1.7kV IGBT NPC Half-Bridge

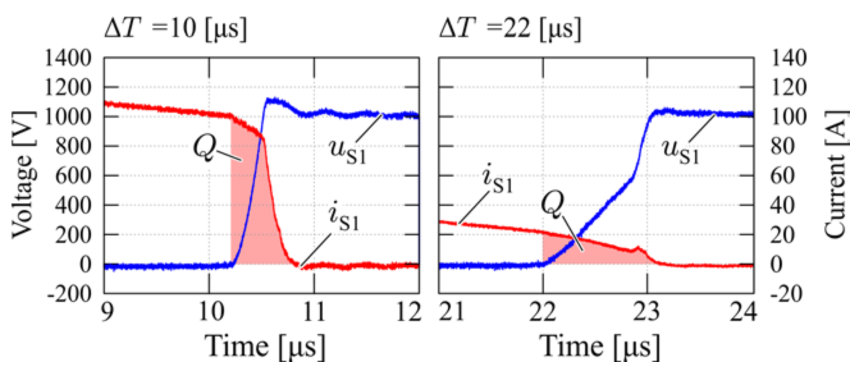
- NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV

▶ Measurement of IGBT Stored Charge Behavior

- Exp. Measurement of Internal Charge
- Dynamic Behavior of Charge Carriers





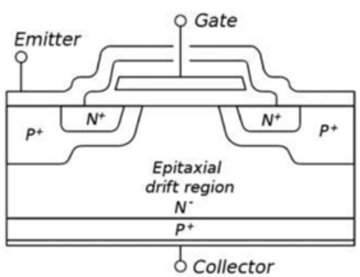


- 1.7kV IGBT Test Circuit for Charge Behavior Analysis

- Experiment used to Study Stored Charge Dynamics
Ortiz (ETH 2012)

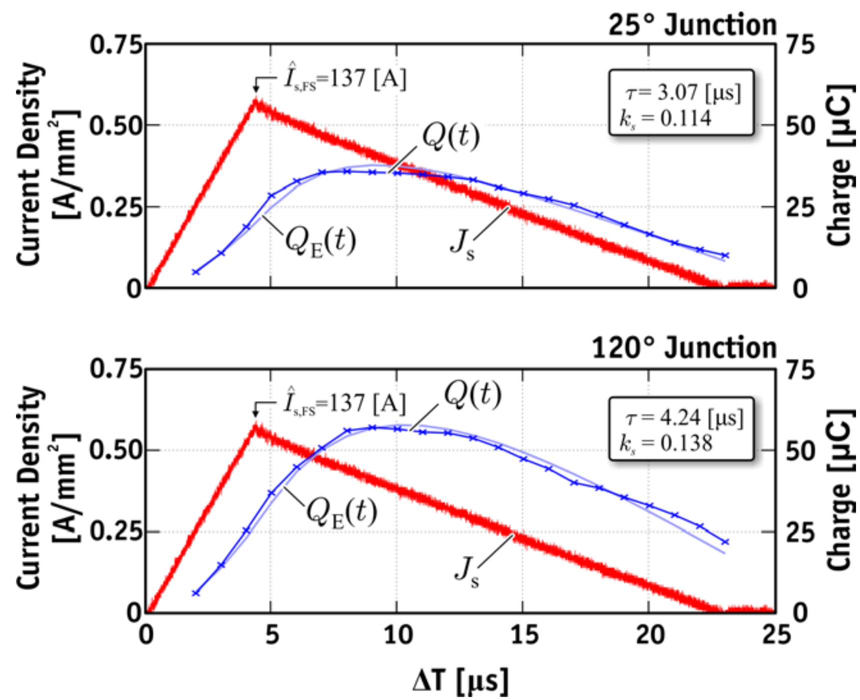
▶ Measurement of IGBT Stored Charge Behavior

- Field-Stop 1.7kV IGBT
- 62mm Package



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

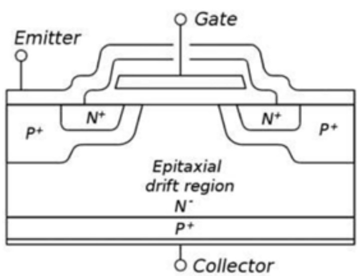
- IGBT Charge Control Equation



- Experimental stored charge dynamic behavior on 1.7kV field-stop IGBT

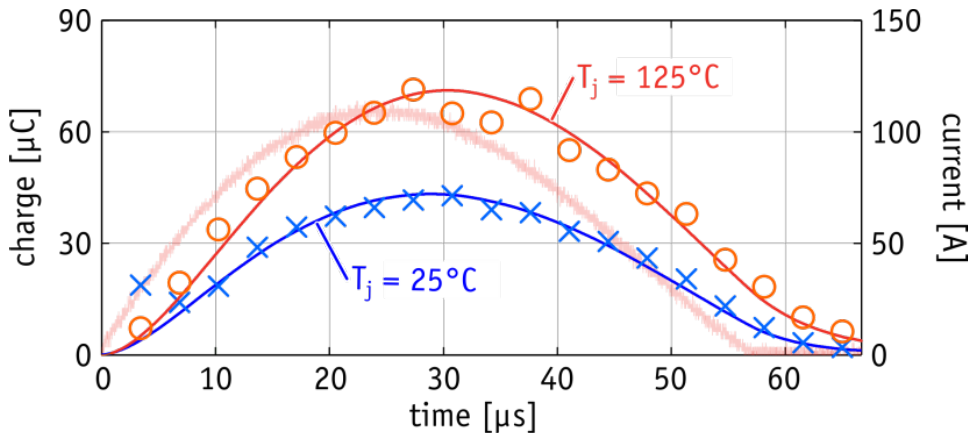
▶ Measurement of IGBT Stored Charge Behavior

- Field-Stop 1.7kV IGBT
- 62mm Package



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

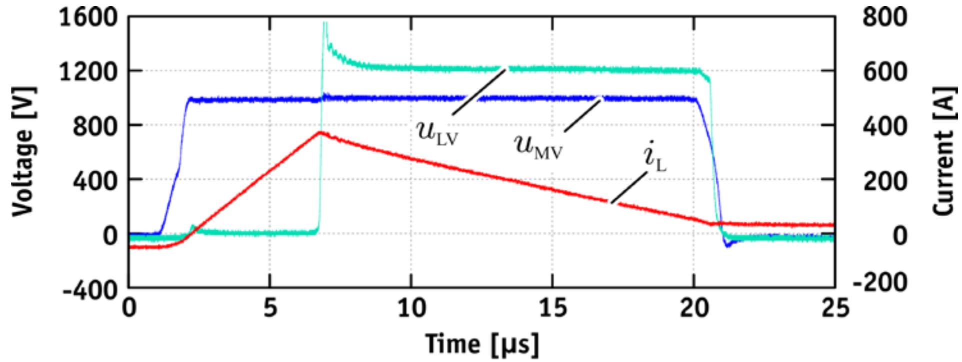
- IGBT Charge Control Equation

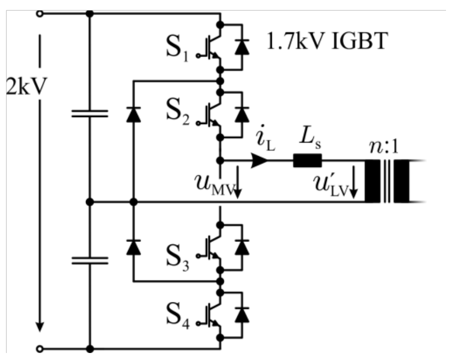


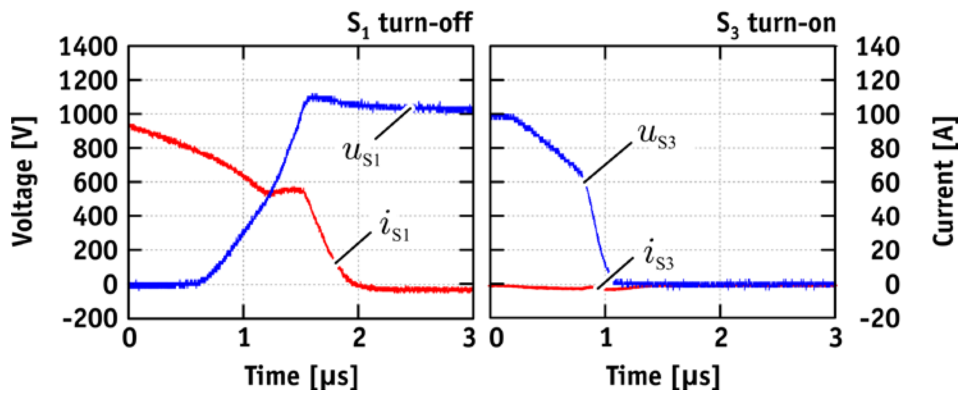
- Experimental stored charge dynamic behavior on 1.7kV field-stop IGBT and **Resonant Sine Pulse**

▶ Residual Current Switching — ZVS

- Low Turn-Off Losses due to Low Switched Current
- **Virtual Elimination of Turn-On Losses**







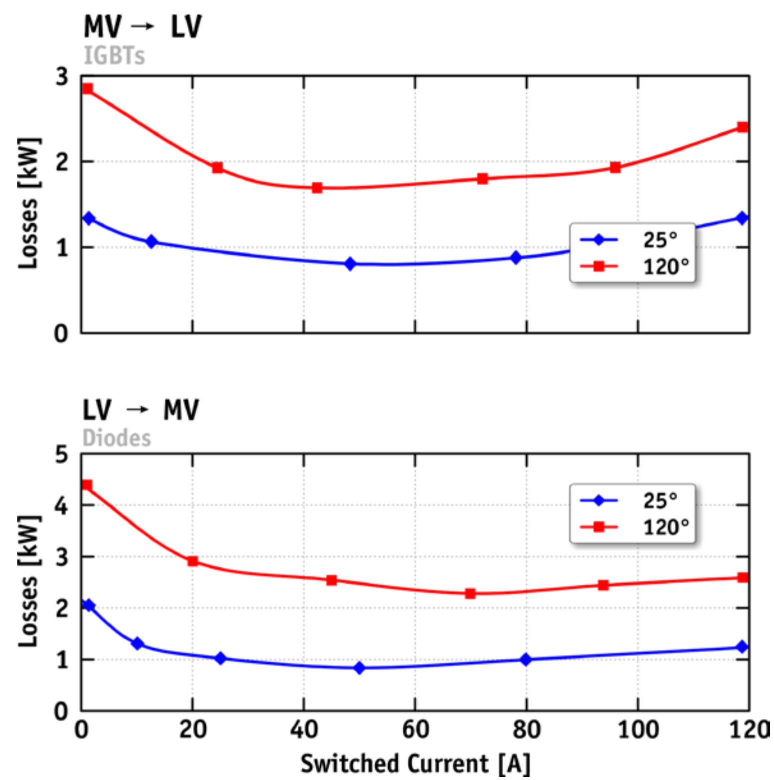
- 1.7kV IGBT NPC Half-Bridge

- NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV

▶ Residual Current Switching — ZVS

- Minimum Losses around 40A @120°C and MV → LV
- Minimum Losses around 70A @120°C and LV → MV

- **Total Reduction of ≈37%@120°C for MV → LV**
- **Total Reduction of ≈50%@120°C for LV → MV**



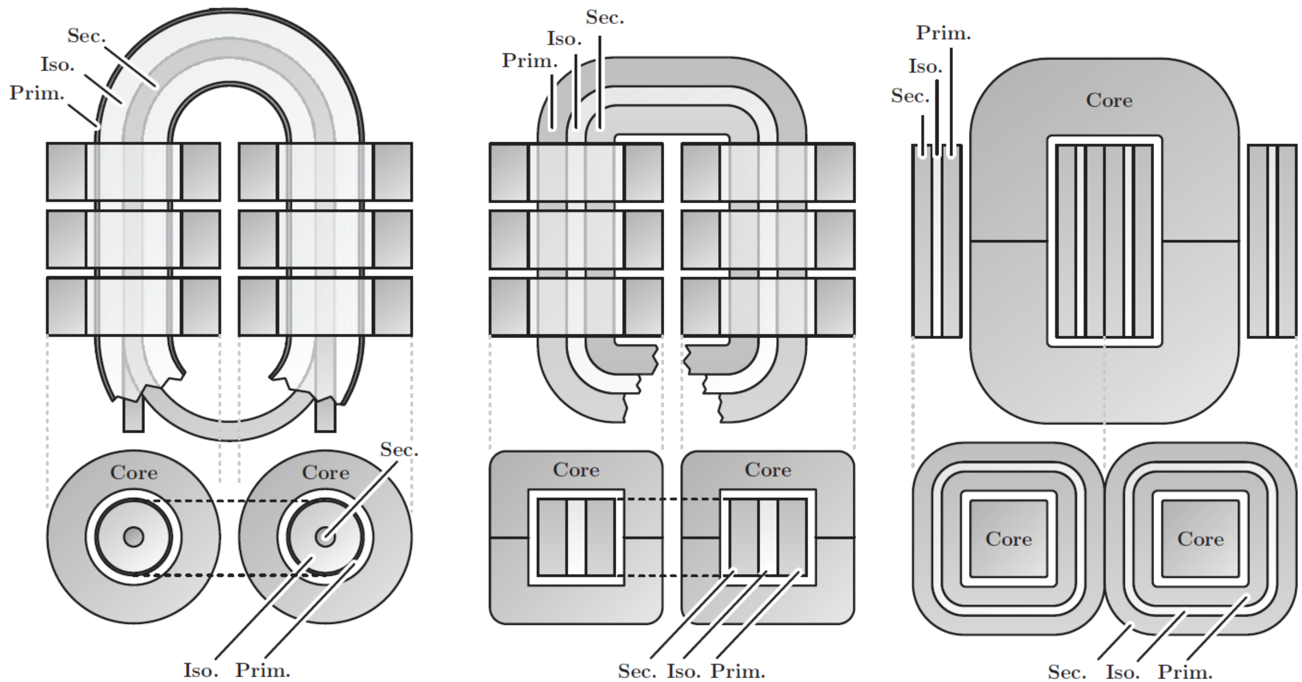
- ZCS Losses for Both Power Flow Directions and 25°C & 120°C for 166kW Transferred Power

High-Power DC-DC Conversion

DAB Converter
HC-DCM-SRC System
Stored Charge Dynamics
MF Transformer Design

▶ MF Transformer Design — Transformer Types

- Main Transformer Types as Found in Literature

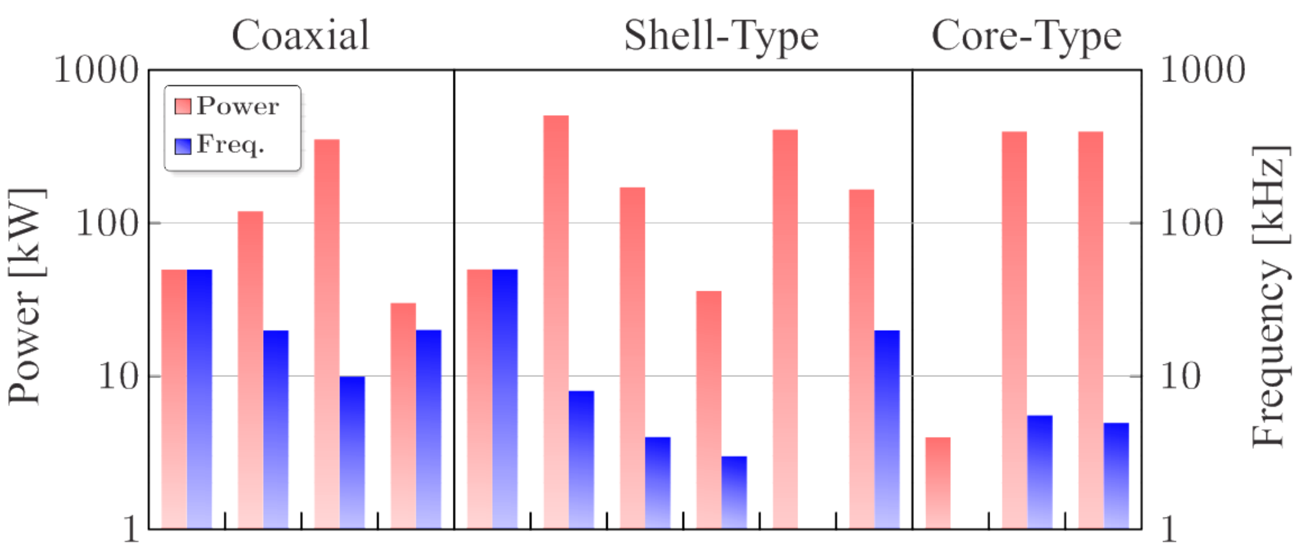


Coaxial Cable *Shell-Type* *Core-Type*

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

▶ MF Transformer Design — Transformer Types

- Main Transformer Types as Found in Literature



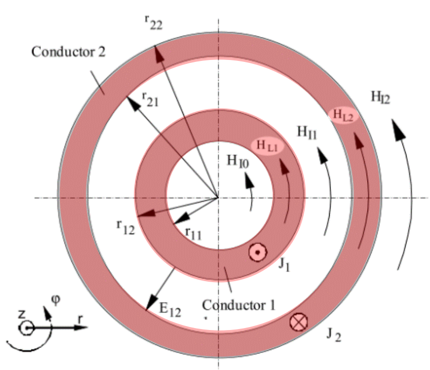
- Transformer Construction Types Very Limited by Available Core Shapes in this Dimension Range
- **Shell-Type has Been Favored Given Its Construction Flexibility and Reduced Parasitic Components**

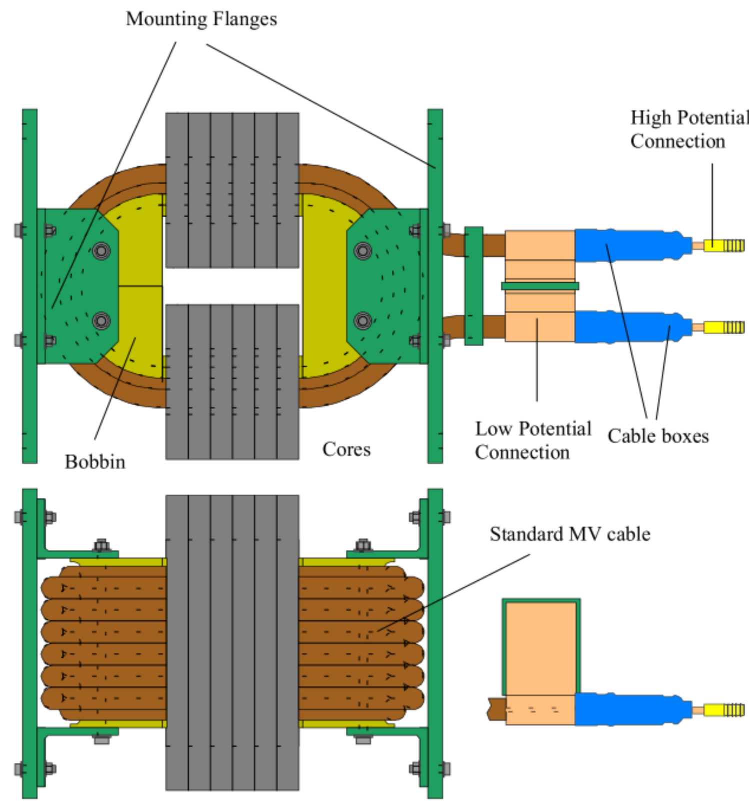
► MF Transformer Design — Winding Arrangements

- Coaxial Cable Winding

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

- Low Flexibility on Turns Ratio
- Complex Terminations



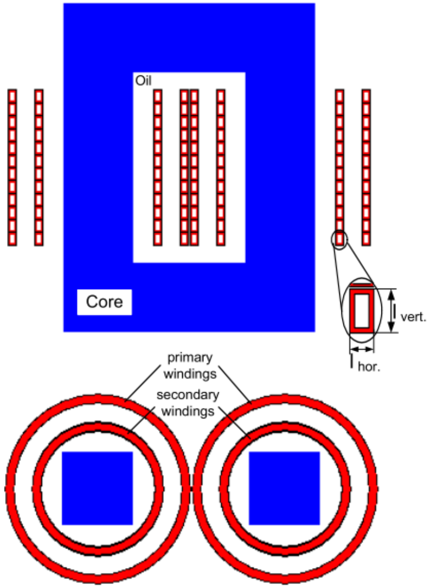


- Heinemann (2002)

► MF Transformer Design — Winding Arrangements

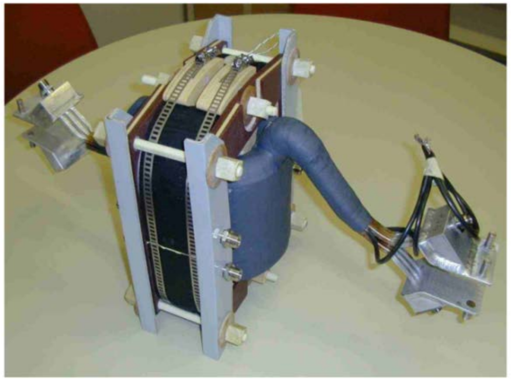
- Coaxial Windings

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



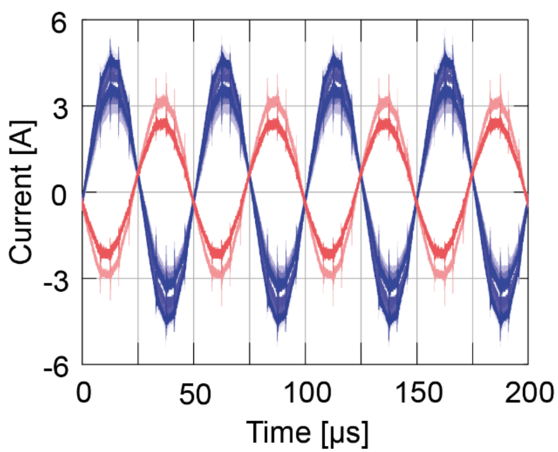
- Hoffmann (2011)

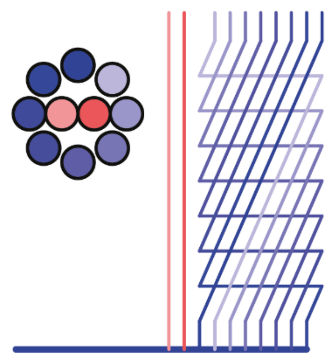
- Steiner (2007)



▶ MF Transformer Design — Litz Wire Bundles

- Case Study: Litz Wire (Tot. 9500 strands of 71μm Each) with 10 Sub-Bundles
- Current Distribution in Internal Litz Wire Bundles Depends Strongly on Interchanging Strategy





10 Bundles 950 with 71μm Strands Each

- Total Copper Losses for 10 Bundles: 438W

▶ MF Transformer Design — Litz Wire Bundles

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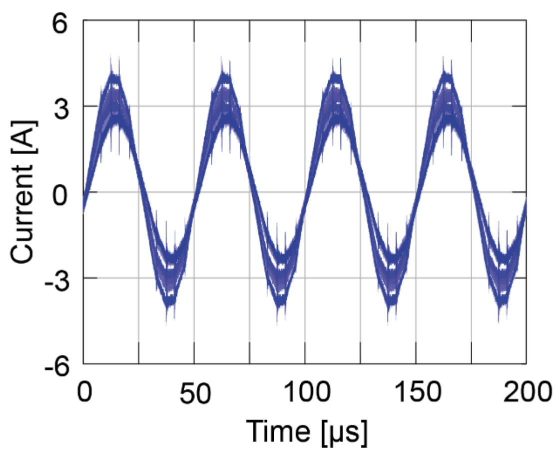
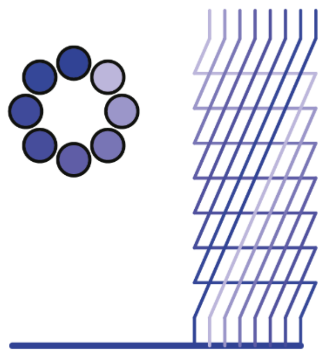


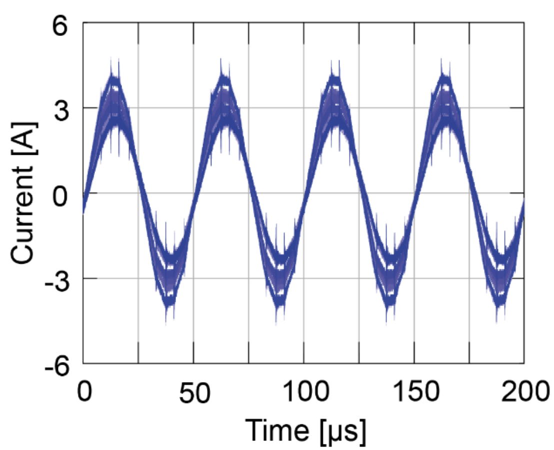


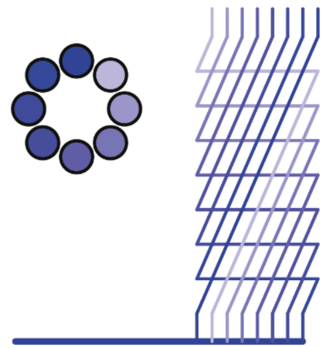
10 Bundles 950 with 71µm Strands Each

- Total Copper Losses for10 Bundles: 438W
- **Total Copper Losses for 8 Bundles: 353W**

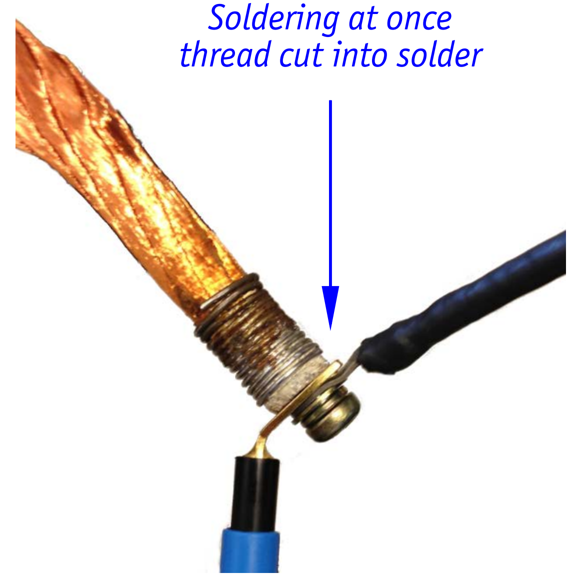
► MF Transformer Design — Litz Wire Bundles

- Effect of Termination Type on Bundle Current Distribution





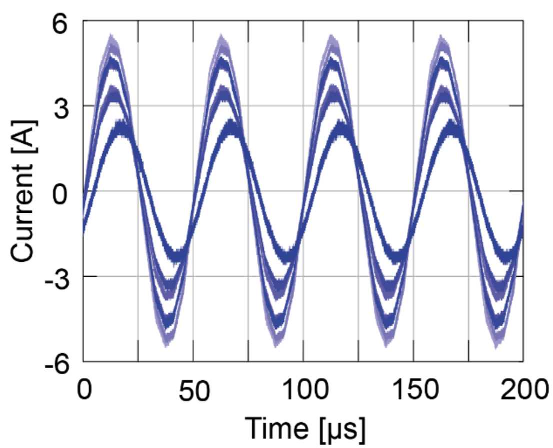
Soldering at once
thread cut into solder

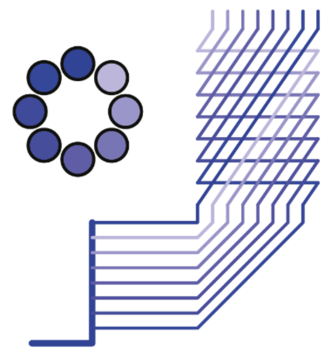


- All Bundles with Equal Lengths and Bulk Solder Connection
- Relatively Good Current Distribution if Center Bundles Are Disconnected
- High AC Resistance of Termination Is Expected due to High Frequency Effects

▶ MF Transformer Design — Litz Wire Bundles

- Effect of Termination Type on Bundle Current Distribution

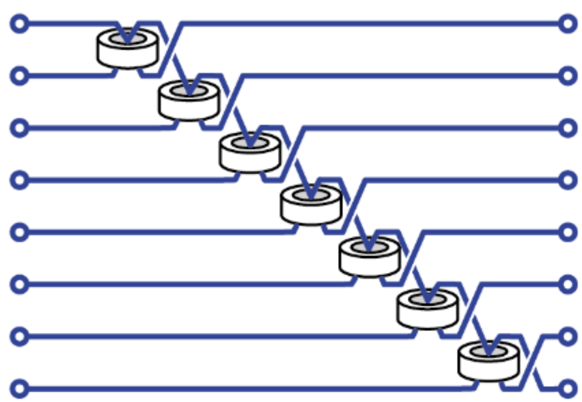




- Each Bundle Soldered Separately to Busbar
- Different Lengths and Induced voltages Cause Asymmetric Current Distribution
- **Total Copper Losses for 8 Bundles: 360W**

▶ MF Transformer Design — Litz Wire Bundles

- Effect of Termination Type on Bundle Current Distribution
- Utilization of Common Mode Chokes for Symmetrization of Litz Wire Currents



▶ MF Transformer Design — Litz Wire Bundles

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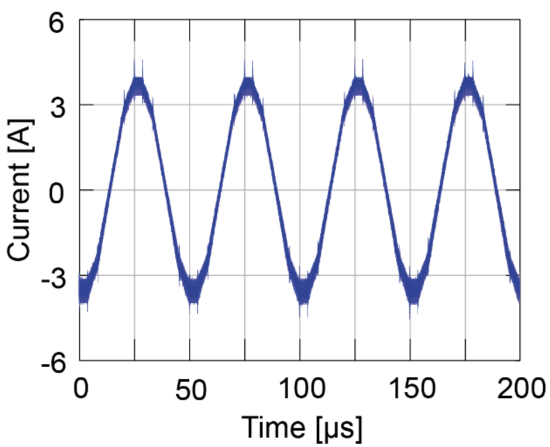
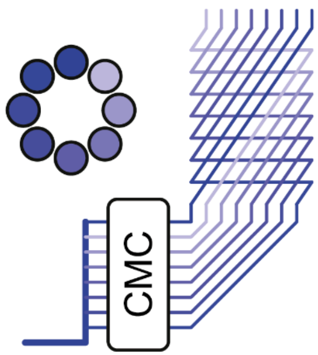
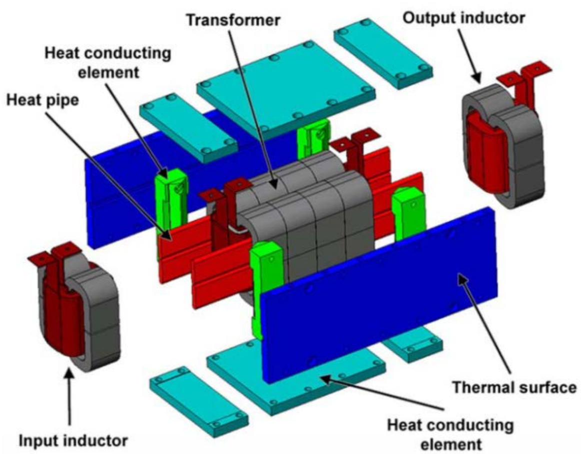


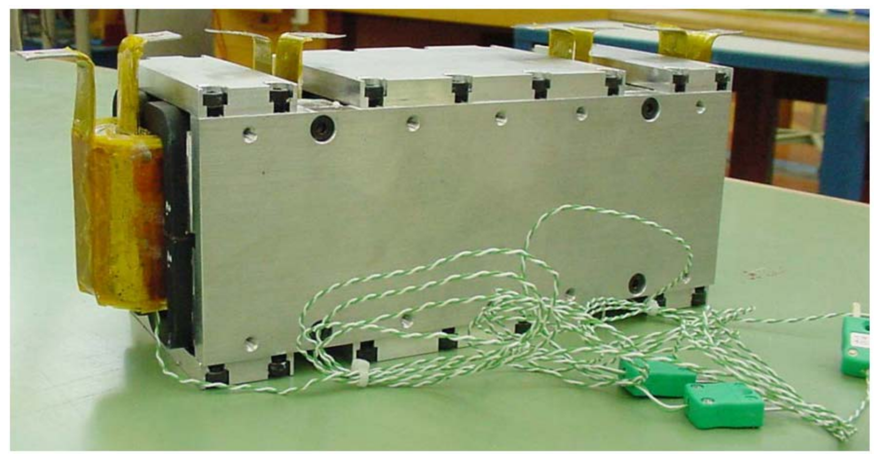


- **Losses decrease (Only) by 2% → Possible Uneven Distribution Within Litz Wire Bundle**

► MF Transformer Design — Cold Plates Cooling

- Heat Conducted from Inner Parts (Winding/Cores) to Outer Actively Cooled Cold Plates





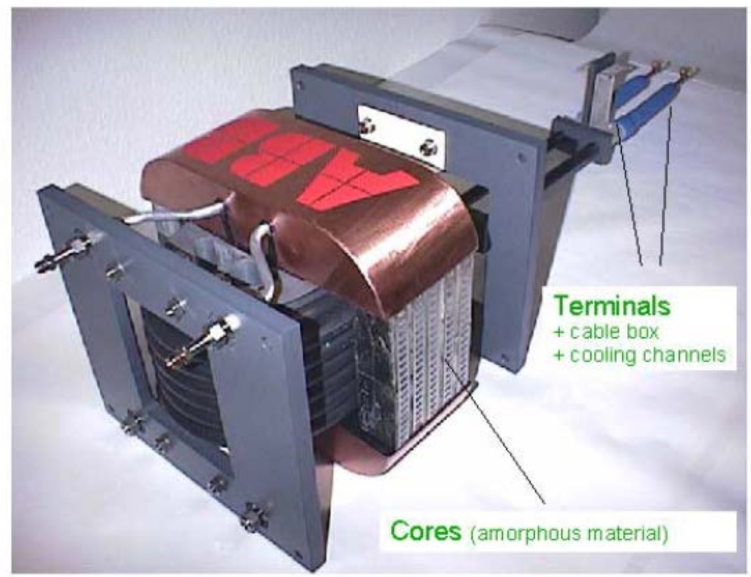
- Pavlovsky (2005)

▶ MF Transformer Design — Water Cooling

- Hollow Aluminum Conductor with Forced Water Cooling
- **Isolation: De-Ionized Water or MIDEL**

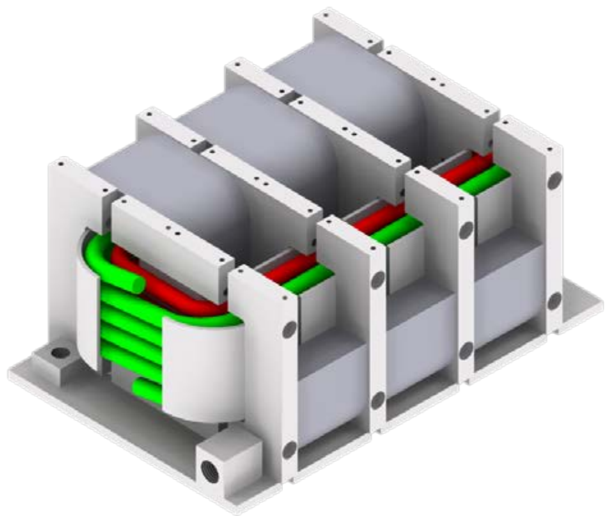
- Hoffmann (SIEMENS, 2011)

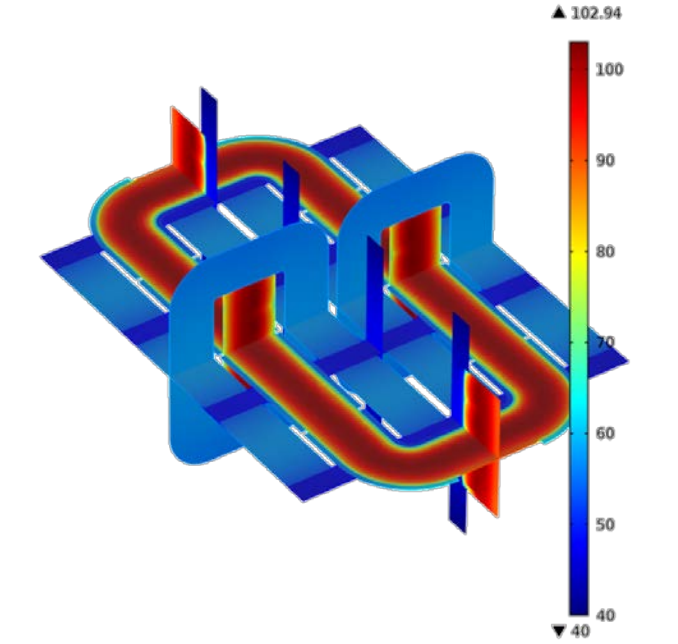
- Heinemann (ABB, 2002)



► MF Transformer Design — Cold Plates/Water Cooling

- Nanocrystalline 160kW/20kHz Transformer (ETH, Ortiz 2013)

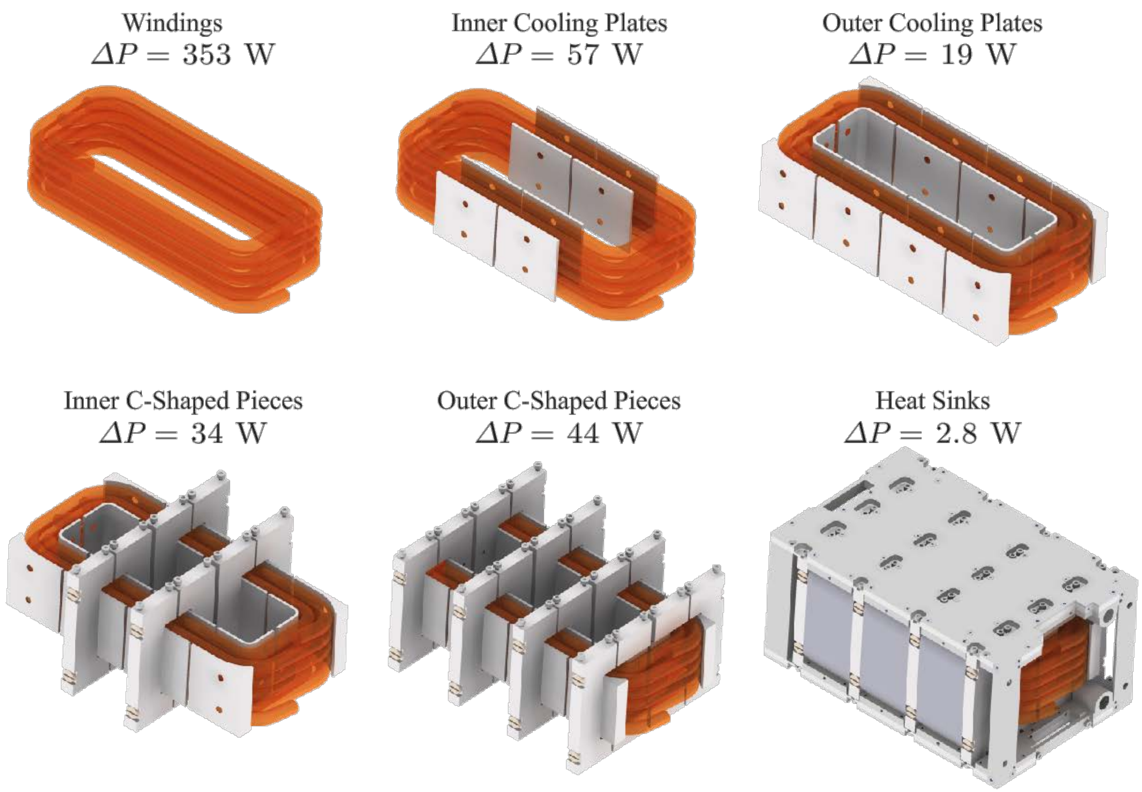




- Combination of **Heat Conducting Plates** and Top/Bottom **Water-Cooled Cold Plates**
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

▶ MF Transformer Design — Cold Plates/Water Cooling

- Nanocrystalline 160kW/20kHz Transformer (ETH, Ortiz 2013)

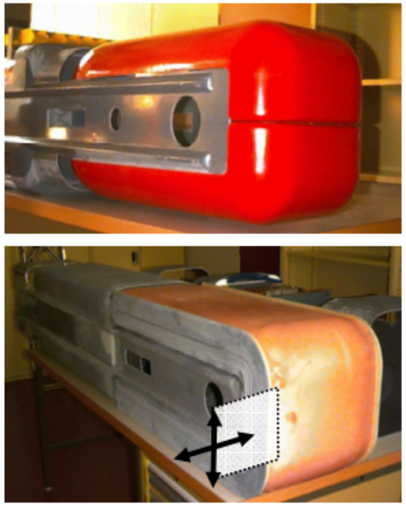


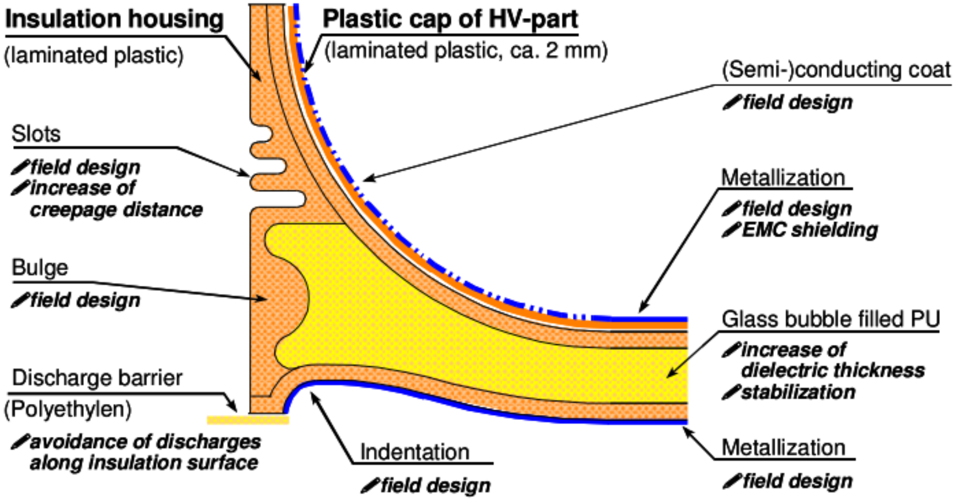
- Losses Generated in Internal Cooling System Amount to ca. 20% of Total Transformer Losses

▶ MF Transformer Design — Isolation

- Specially Designed Isolated Housing for High Isolation to Ground

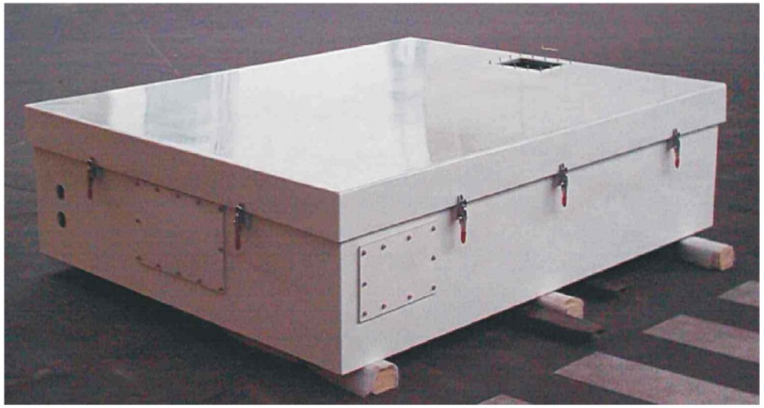
- Steiner (Bombardier, 2007)

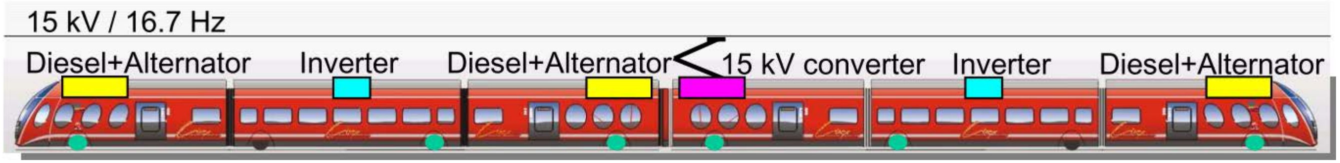




▶ MF Transformer Design — Isolation

- Glass-Fiber Container
  Engel (ALSTOM, 2003)

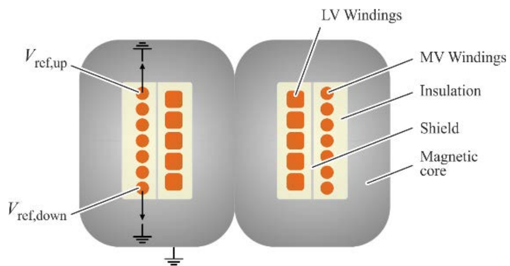


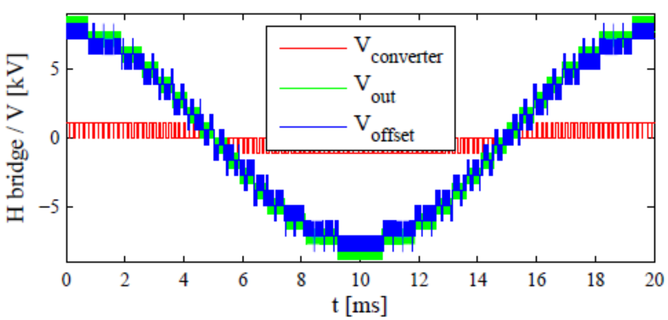


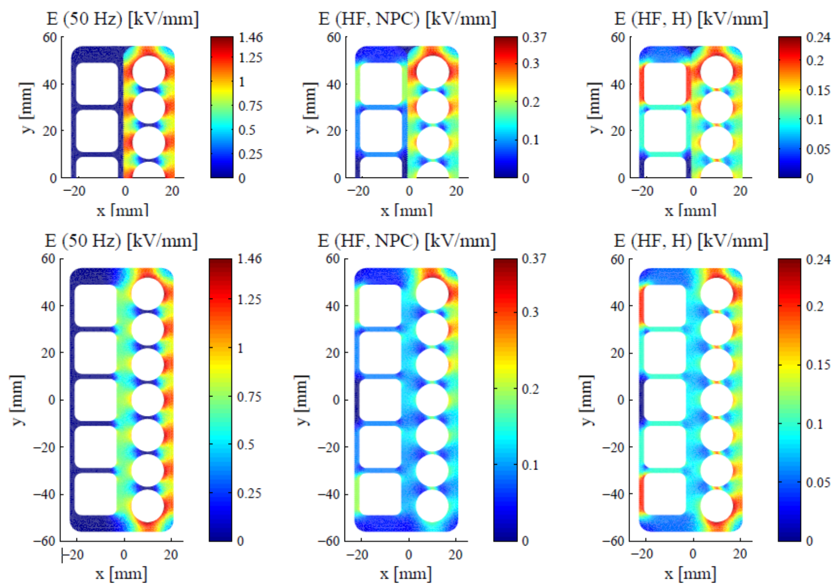
▶ MF Transformer Design — Isolation

- 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







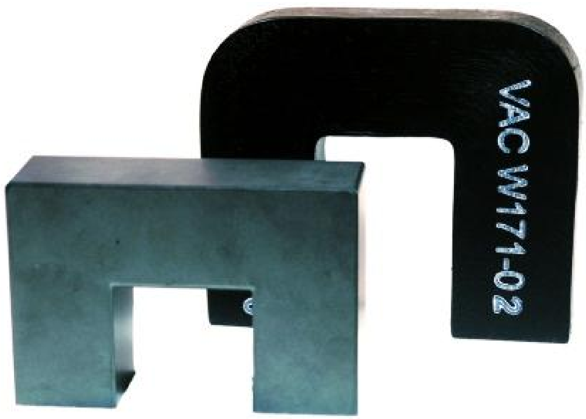
- Negligible Dielectric Losses
- Specific Test Setup Required for Insulation Material Testing

► MF Transformer Design — Acoustic Noise Emissions

- Magnetostriction of Core Materials (Zhao, 2011)

• Nanocrystalline ~ 0ppm
• Amorphous ~ 27ppm

- Other Influences from Production Processes, Shapes and Assembly Procedures Affect the Emitted Noise



- **Acoustic Noise Emitted at 2·f_s (!)**

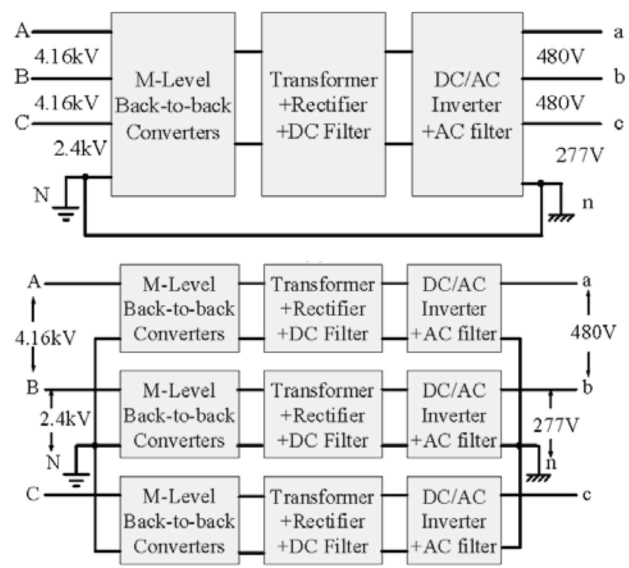
Three-Phase SST Distribution System Applications

Phase Modular / Direct 3ph. Concepts
Matrix / DC-Link Based Concepts
ISOP Converter Topologies
Example SST Projects
SST Concepts Employing LF Transformers

▶ 3ph. SST Concepts

- Phase-Modular (3ph. Comb. of 1ph. Units) or
- Direct 3ph. Topologies

- Direct or Indirect Matrix Type Topologies or
- DC-Link Based Topologies

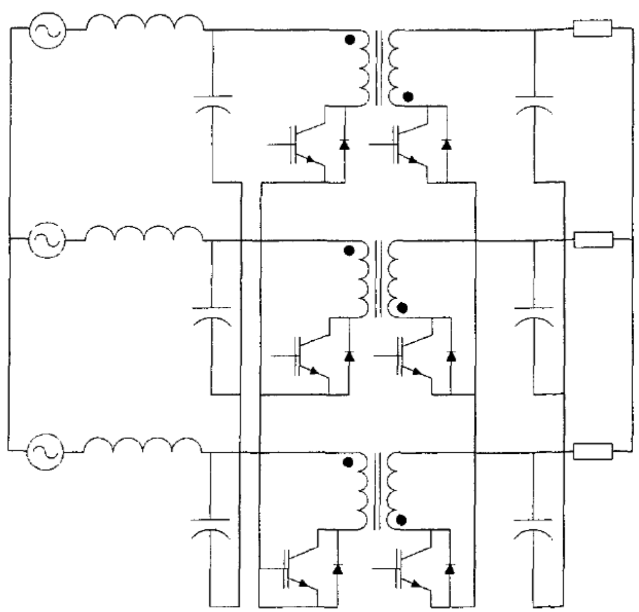


- Frequently 1ph. AC/3ph. AC Converter Topologies Analyzed Instead of Full 3ph. Systems
- Frequently Unidir. (MV□LV) Topologies Proposed/Analyzed Instead of Bidir. Systems

- **1ph. AC/3ph. AC Conv. Topologies are Directly Applicable for Traction Applications**

► Phase-Modular Direct Matrix-Type 3ph. SST Concepts

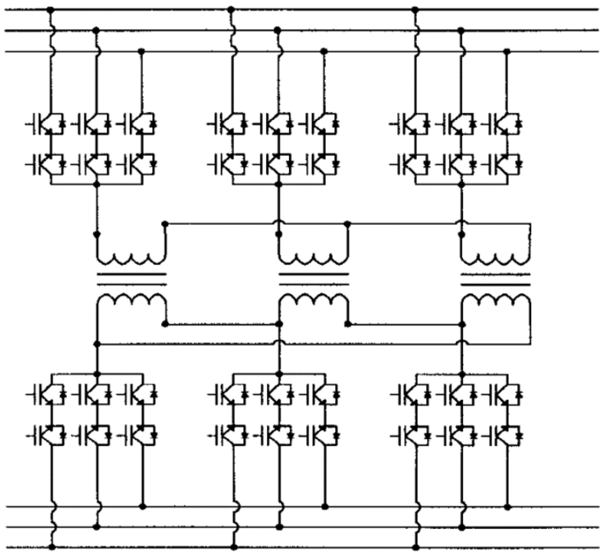
- Venkataramanan (2000)



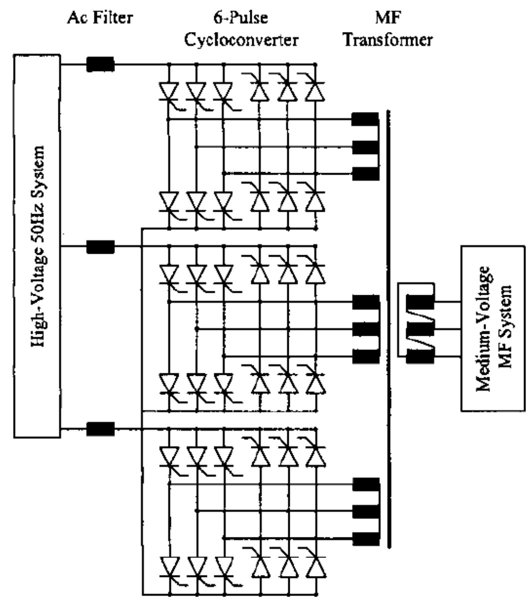
- Only Interesting for Low-Voltage / Low-Power Applications

► Partly Phase-Modular Direct Matrix-Type 3ph. SST Concepts

- Enjeti (1997)



- Steimel et al. (2002)

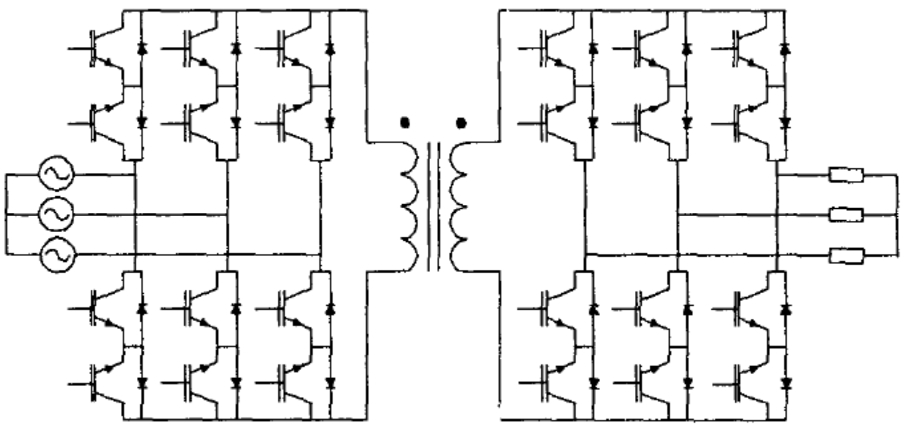


- **Steimel:** Thyristor Cycloconv. Commut. Voltage Impressed by MV VSI (Mennicken, 1978)
Thyristor Recovery Time Limits Switching Frequency to f_P≈200Hz (α=150°)
Reactive Power Demand of the Thyristor Cycloconverter
Implementation of Cycloconv. with (Turn-Off) RB IGCTs (6.5kV) allows f_P≈ 500Hz

- **Enjeti:** Three-Limb Core could be Employed for Realiz. of MF D-y-Transformer (Enjeti, 1997)

► Direct 3ph. Direct Matrix-Type 3ph. SST Concepts

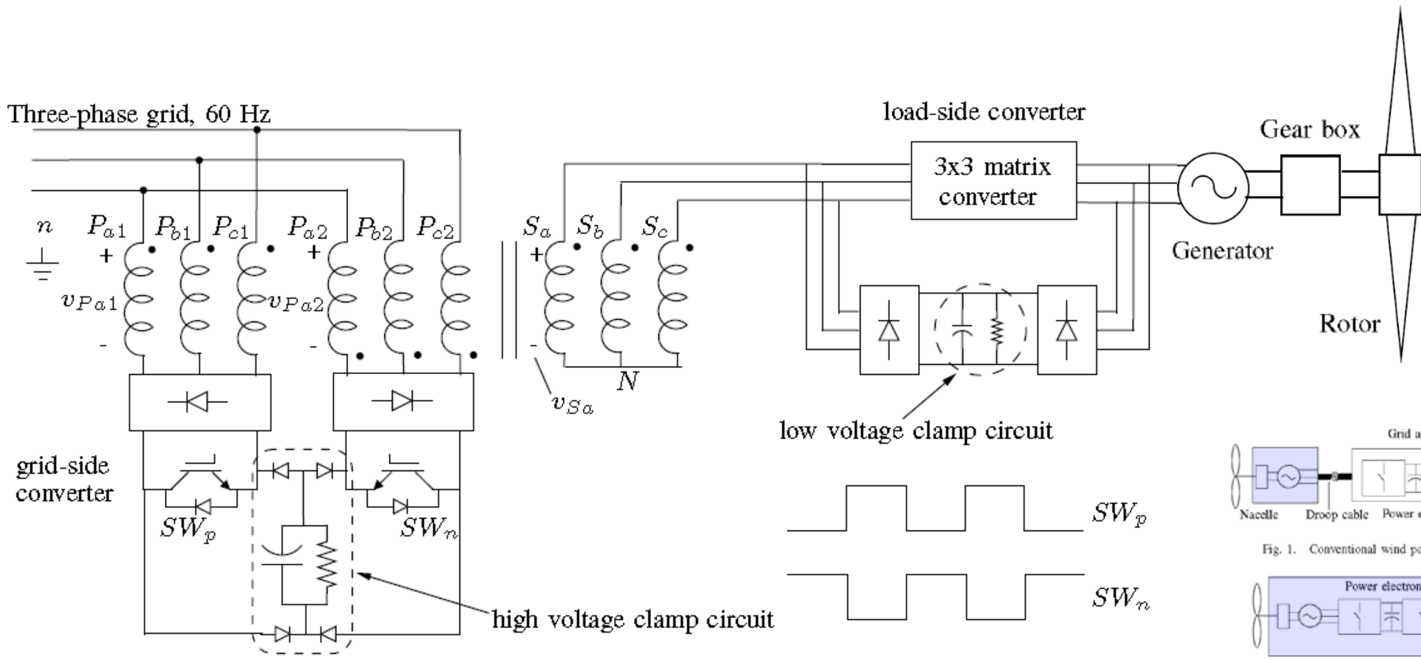
- Venkataramanan (2000)

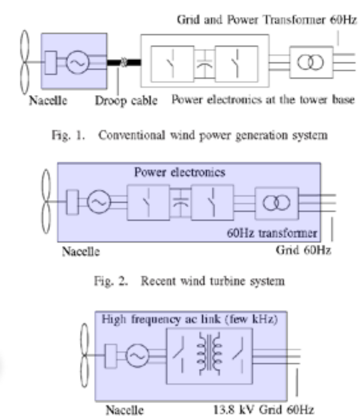


- **No Energy Storage / DC Port**
- Large Number of Power Semiconductors (24)
- Limited IGBT Blocking Capability does Not Allow MV Application of Basic Conv. Topology

▶ Direct 3ph. Direct Matrix-Type 3ph. SST Concepts

- Mohan (2009)

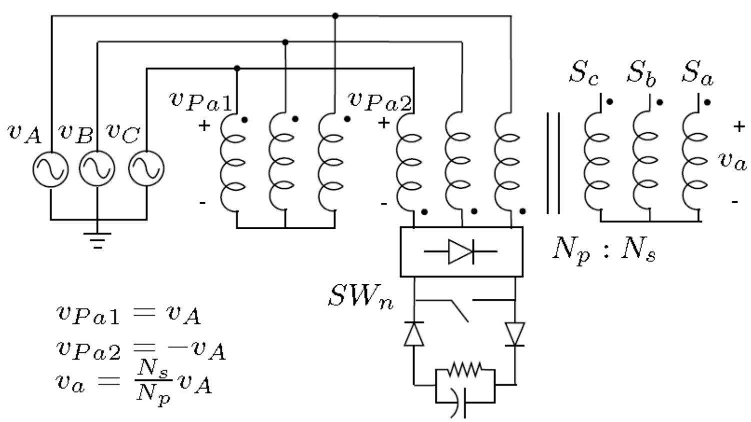


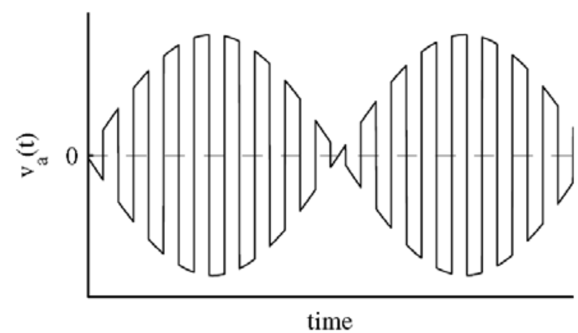


- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency
- Switching CM Voltage Eliminated at Generator Terminals by Proper MC Control

▶ Direct 3ph. Direct Matrix-Type 3ph. SST Concepts

- Mohan (2009)

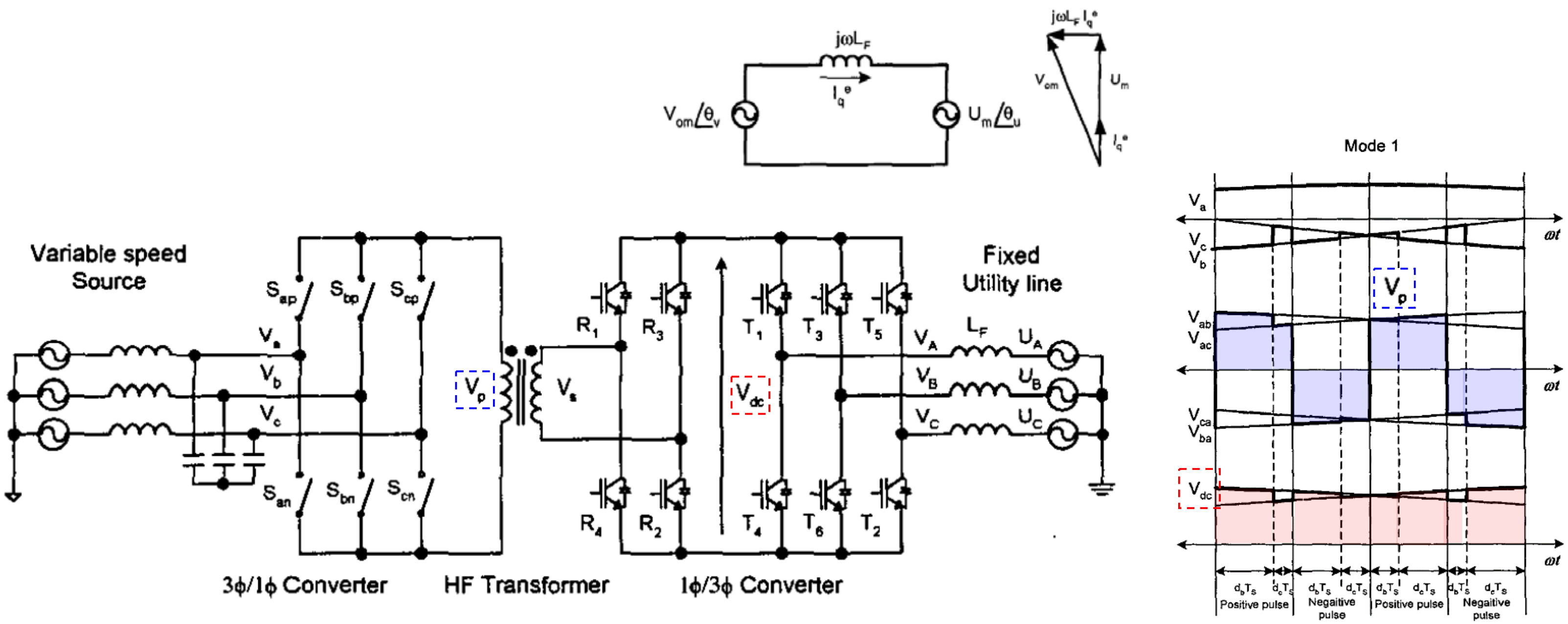




- Equivalent Circuit of the Transformer for SWp-on and SWn-off and Input Phase a Voltage of MC
- Clamp Circuit Sinks Energy Stored in the Leakage Inductance
- **Clamp Voltage = 2 x Grid Line-to-Line Voltage**

▶ Indirect Matrix-Type Direct 3ph. SST Concepts

- Enjeti (2003)

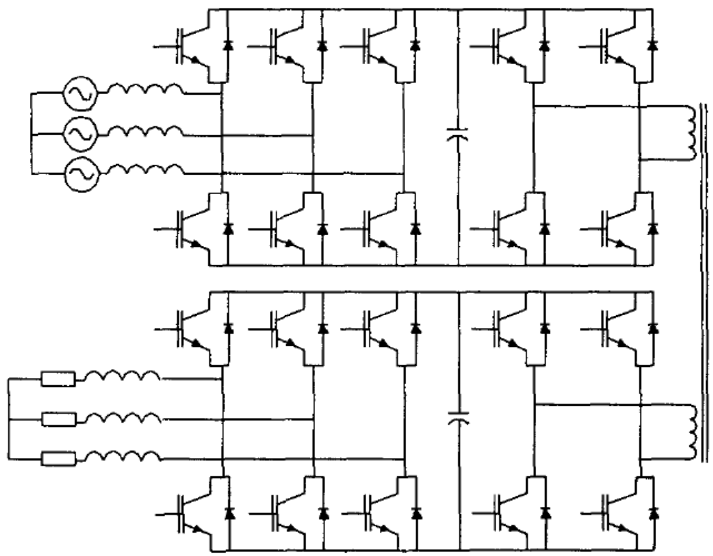


- Modification of Direct MC Topology Proposed by Venkataramanan (2000)

- Formation of Transf. Voltage Involving all Phases a,b,c and Ensuring Balanced Flux
- Transformer Sec. Voltage Rectified into Fluctuating DC Link Voltage V_{dc}
- **V_{dc} Converted into V_A, V_B, V_C by Space Vector PWM for Mains Current Control**

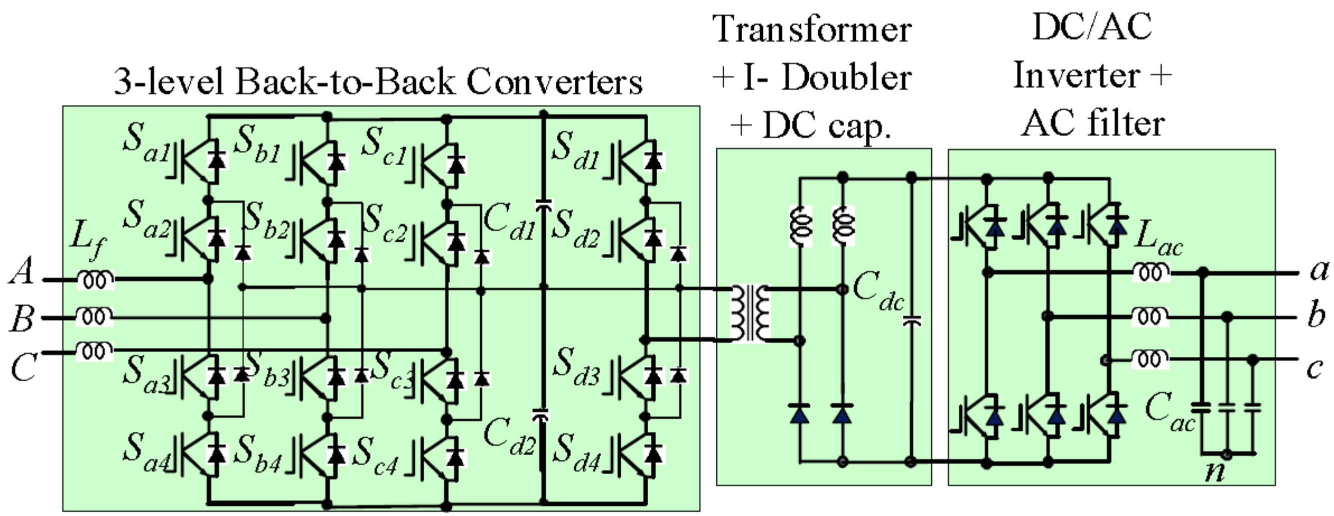
Three-Phase SST Distribution System Applications

► DC-Link Based Direct 3ph. SST Topologies



- Lower Number of Switches (20) Comp. to Matrix Approach (24)
- Three-Stage Power Conversion (3ph.AC/DC – DC//DC – DC/3ph.AC) → Eff. Red.
- Limited IGBT Blocking Capability does Not Allow MV Application of Basic Conv. Topology

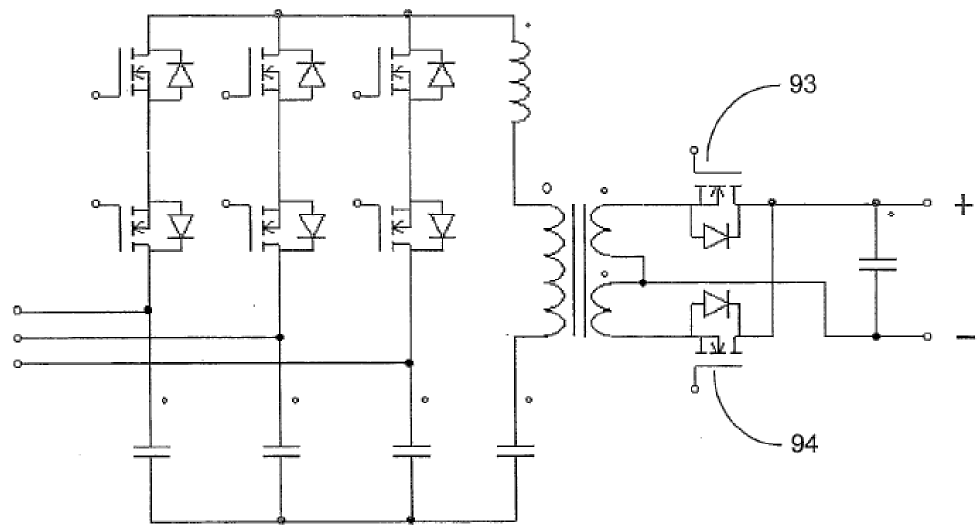
► DC-Link Based Direct 3ph. SST Topologies



- **M-Level Topology & HV IGBTs** for Incr. Input Voltage Capability (Front-End and DC/DC Conv.)
- **Current Doubler Rectifier** for Increasing Output Current Capability / Low Output Current Ripple
- Bidirectional Extension by Switches Antiparallel to Rectifier Diodes Possible (Snubber)

► DC-Link Based Direct 3ph. SST Topologies

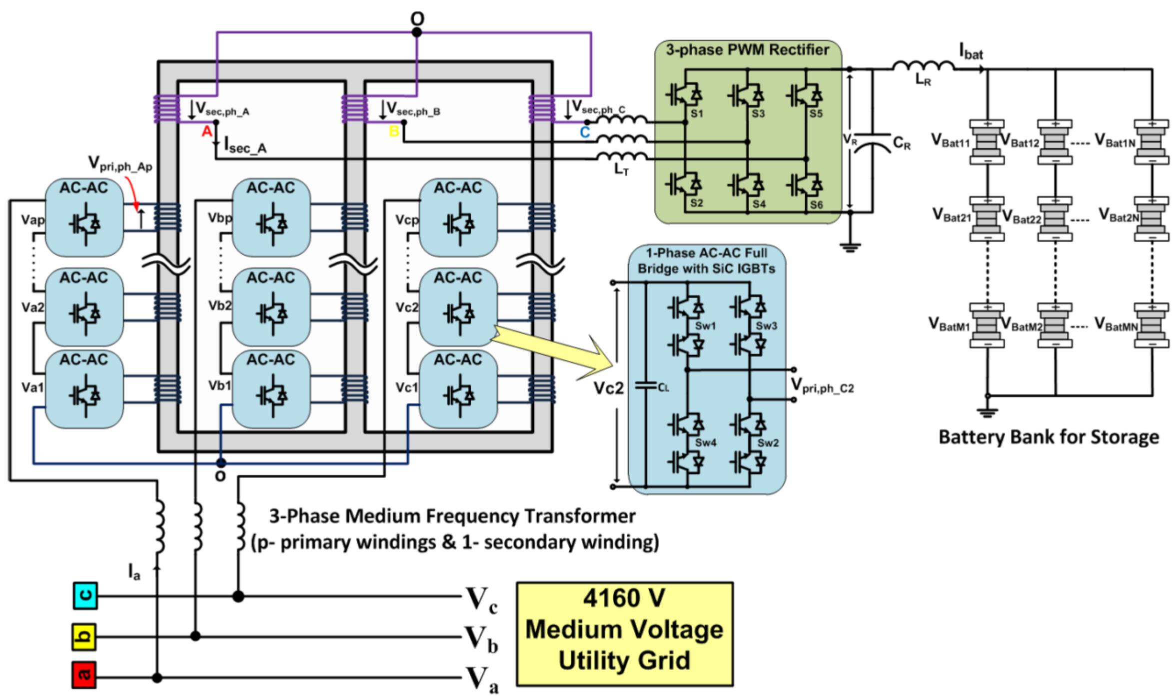
- EATON (Patent Appl. WO 2008/018802, Inv.: M.J. Harrison, 1997)



- Only Interesting for Low-Voltage / Low-Power Applications

► DC-Link Based Direct 3ph. SST Topologies

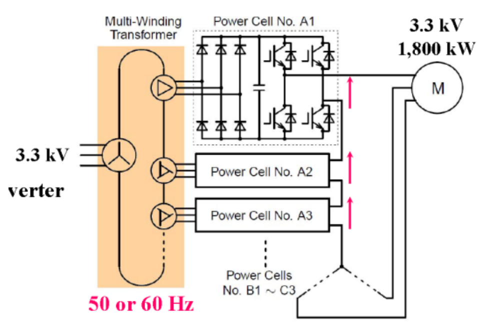
- Proposed for Energy Storage Systems (Enjeti, 2012)

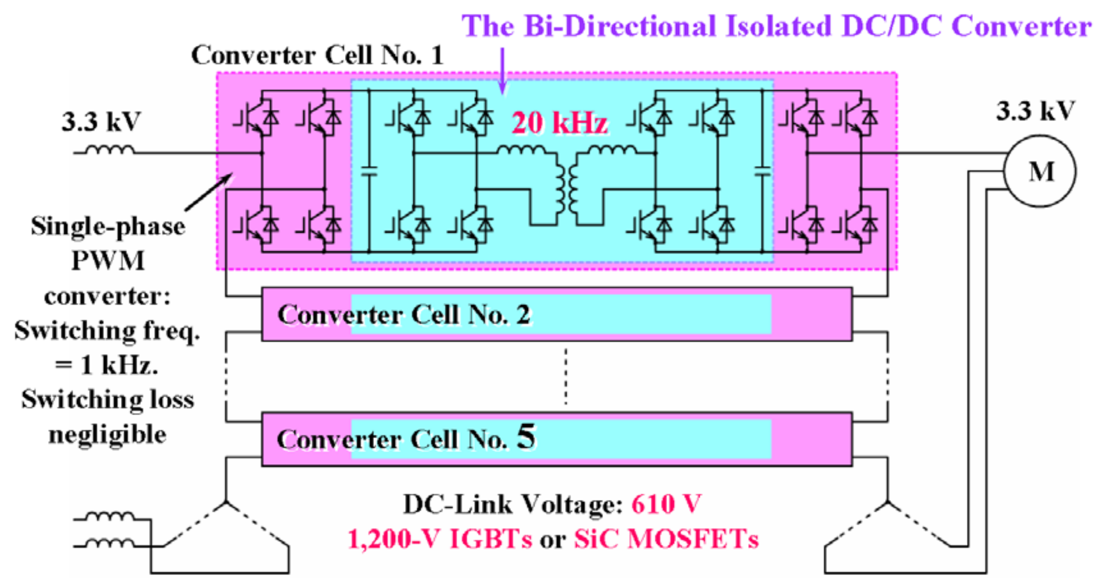


- MV Side Series Direct Matrix Structure with Single 3ph. MF Transformer Core
- Single LV Side 2-Level 3ph. Inverter

► DC-Link Based Fully Phase Modular SST Topologies

- Akagi (2005/2007)



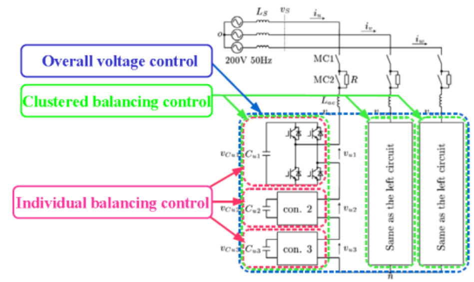


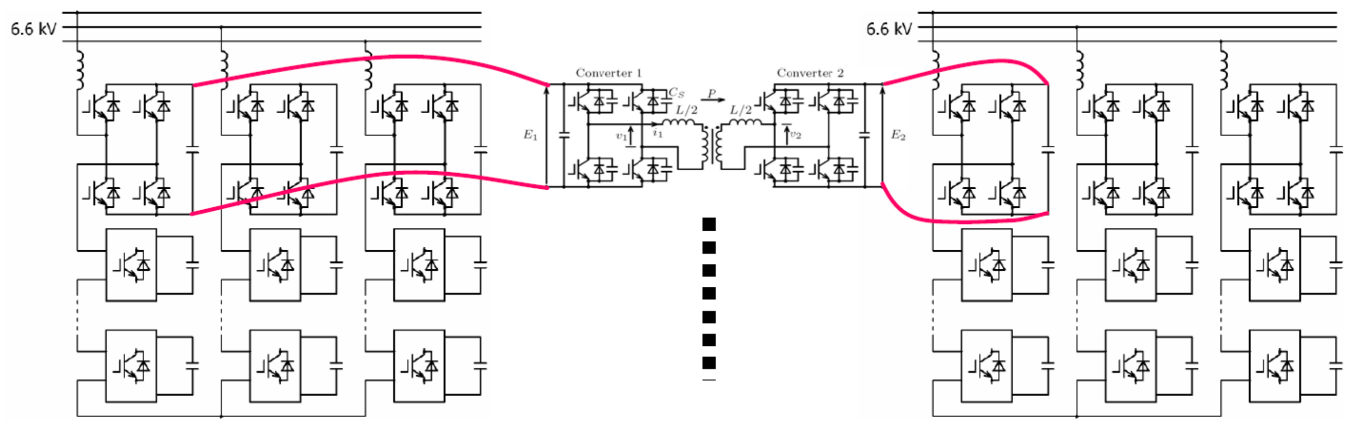
- Application for **MV Motor Drives** Replacing the 50/60 Hz Transformer

► DC-Link Based Fully Phase Modular SST Topologies

- Akagi (2005)

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





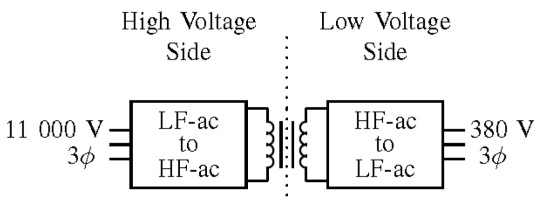
STATCOM

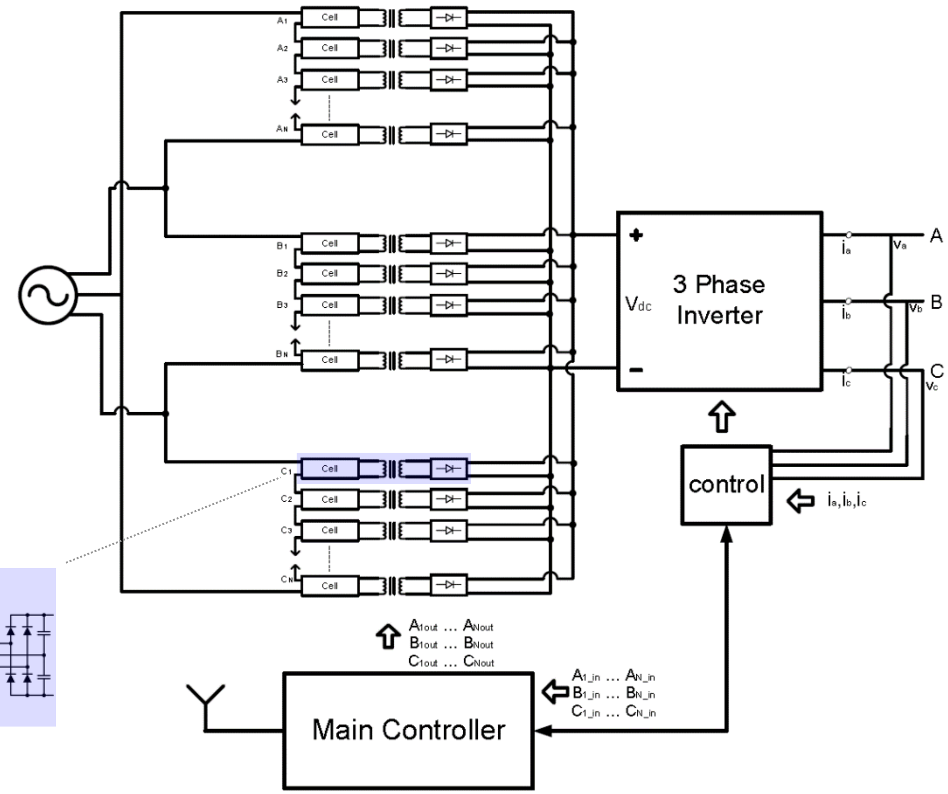
STATCOM

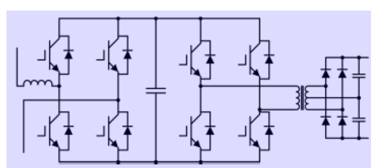
- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control

► DC-Link Based Partly Phase Modular SST Topologies

- van der Merwe (2009)



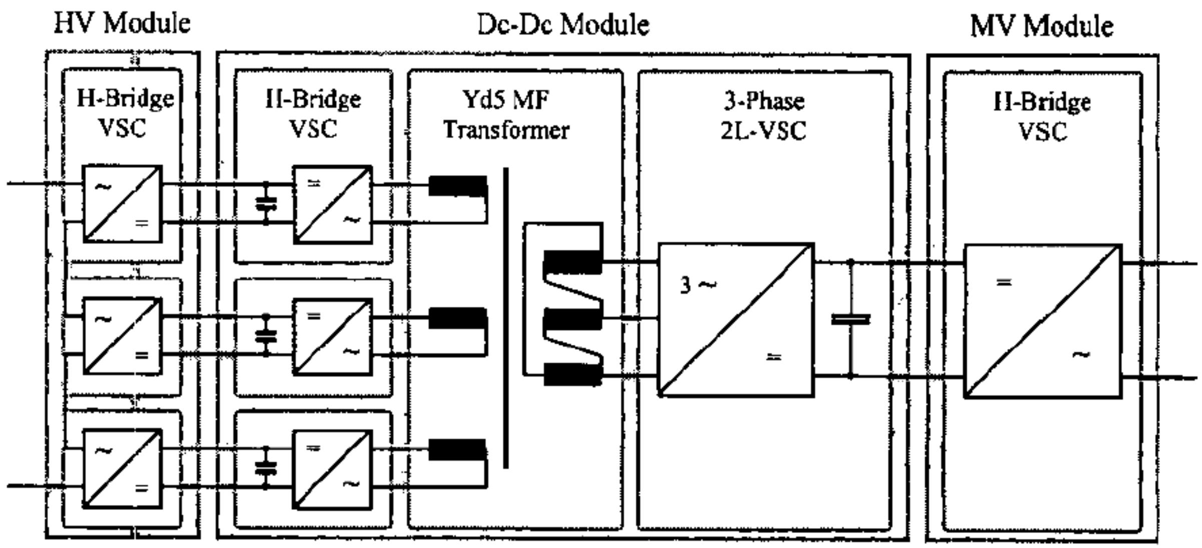




- SST Concept Without Accessible MV DC Bus
- Extension to Bidirectional Power Flow by Replacing the Passive Rectifiers with Active Systems

► DC-Link Based Partly Phase Modular SST Topologies

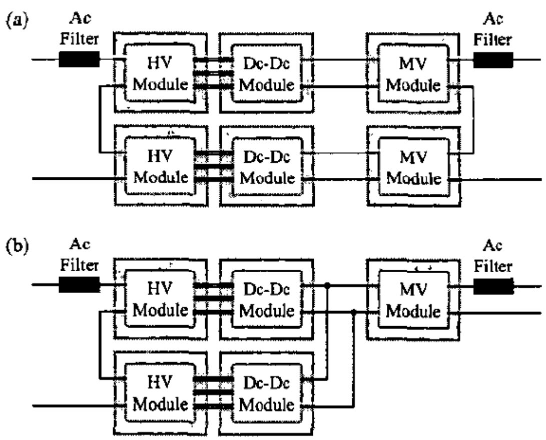
- Steimel et al. (2002)



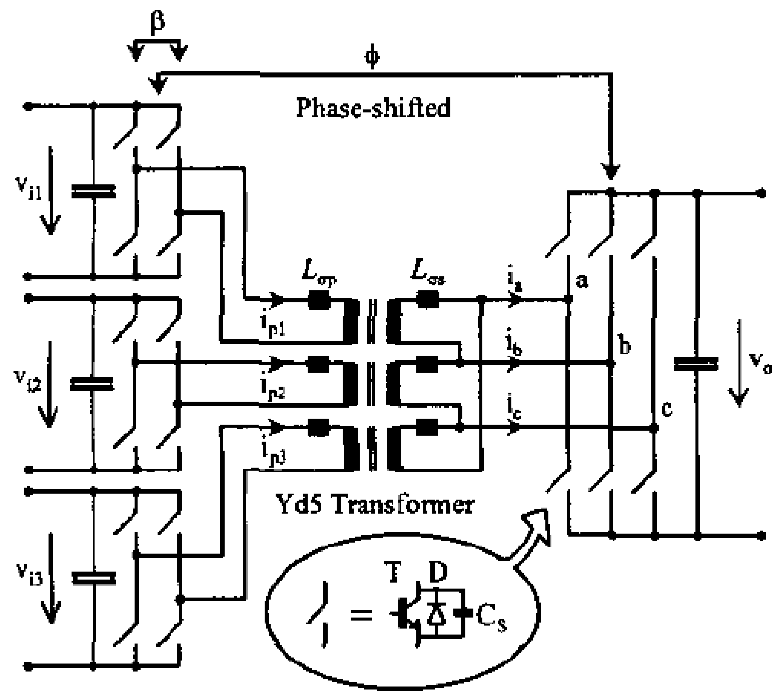
- Electronic Power Transformer for 110/20kV and 110/10kV Applications
- Truck Movable Temporary Replacement of Failed Conventional Transformer

► DC-Link Based Partly Phase Modular SST Topologies

- Steimel et al. (2002)



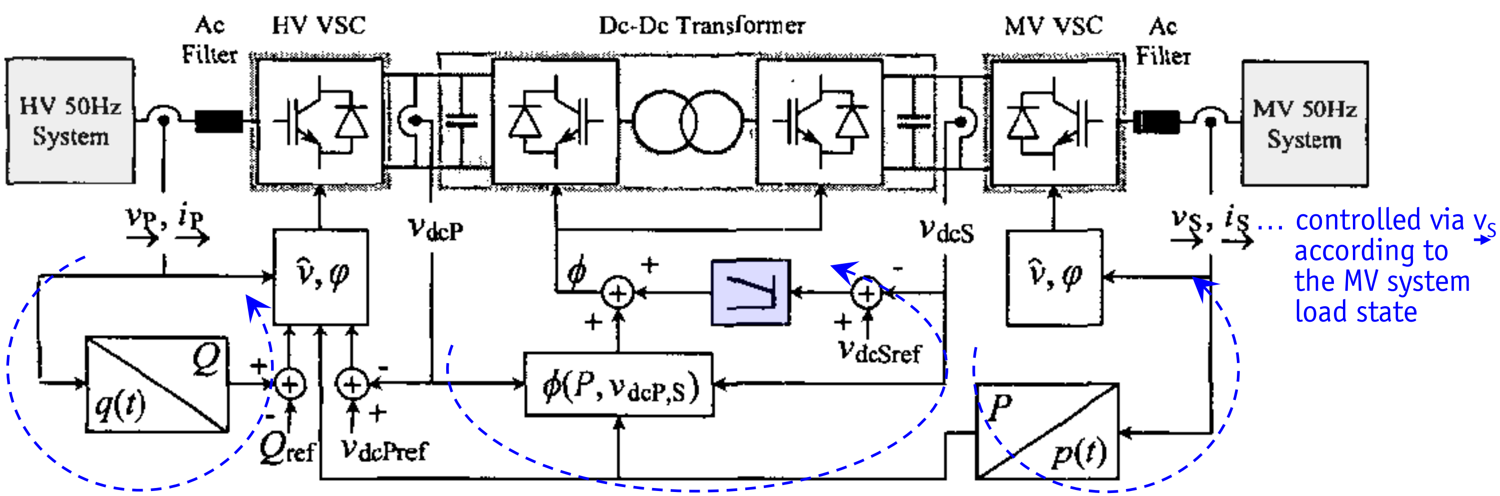
'ig.7. Single-Phase Design of an Electronic Power Transformer for (a) 110kV/20kV (b) 110kV/10kV Ac/Ac Conversion



- Configuration of Cells for 10kV and 20kV MV System
- Implementation of Soft-Switching DC/DC Module (Self Balancing of DC Link Voltages, Cable Transf.)

▶ DC-Link Based Partly Phase Modular SST Topologies

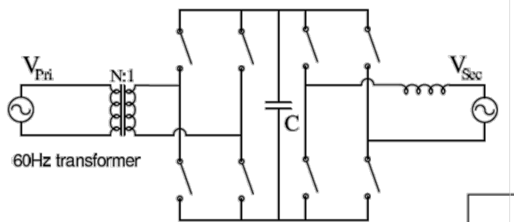
- Steimel et al. (2002)

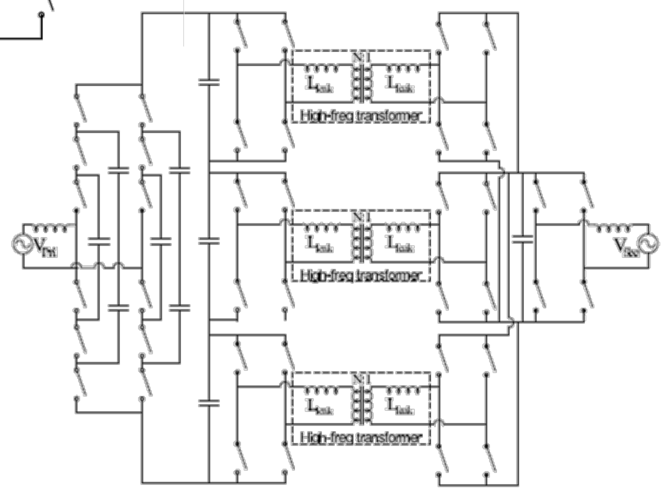


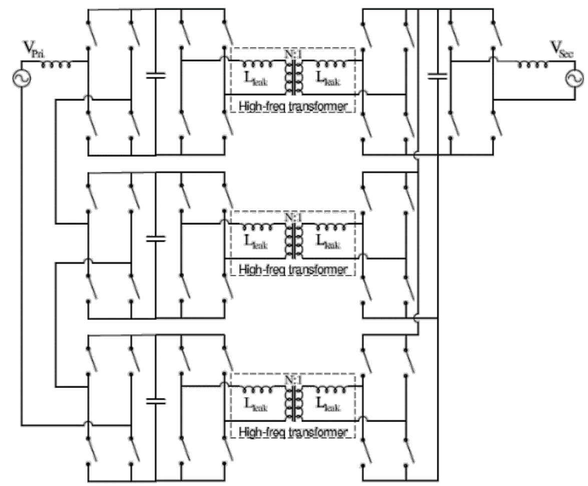
- Multi-Loop Control Structure of the Electronic Power Transformer

Three-Phase SST Distribution System Applications

► Multilevel & Input Series Output Parallel (ISOP) SST Topologies







- Multi-Level or Cascaded H-Bridge Interfaces for MV Connection
- Parallel Connection of Modules on the LV Side for Distribution of High Output Current
- Low Total Input Voltage / Output Current Harmonics (Low Ind. Volume / Low Cap. Curr. Stress)
- Cascaded H-Bridges Preferable due to Voltage Balancing Problem and Scaling of ML Converters

► Classification System for Multi-Level & Multi-Cell Power Converters

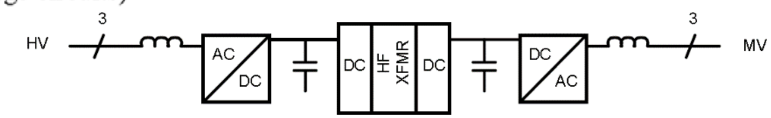
- Clare/Wheeler et al. (2001)

- Classification of Structures with HV (Side A) and MV (Side B) DC Link
- Nomenclature for Topological Arrangement

Side A Side B

$$X\,{}^{M}L^{N}\,Y$$

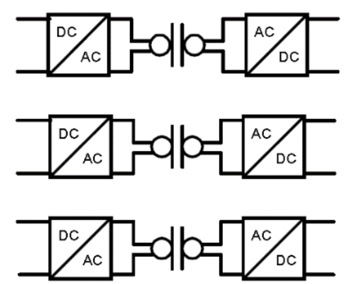
X, number of DC links on Side A (equal to number of Side A AC/DC bridge circuits)
Y, number of DC links on Side B (equal to number of Side B AC/DC bridge circuits)
L, number of HF transformers
M, windings per HF transformer (Side A)
N, windings per HF transformer (Side B)



- Structure of HF Transformer Defined by L,M,N

$${}^{M}L^{N} = {}^{1}1^{1}$$

$${}^{M}L^{N} = {}^{1}3^{1}$$

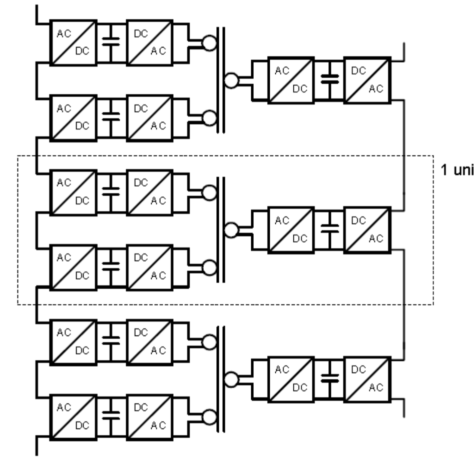


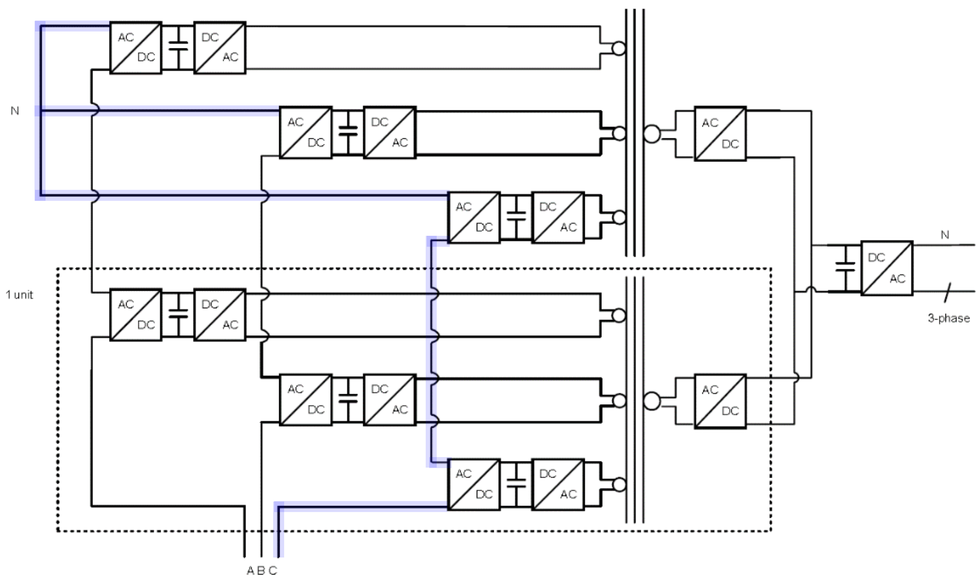
- Transformer Classification Independent of Number of DC Links

► Classification System for Multi-Level & Multi-Cell Power Converters

- Complete Converter Structures

$$X\ ^{M}L^{N}\ Y = 6\ ^{2}3^{1}\ 2$$



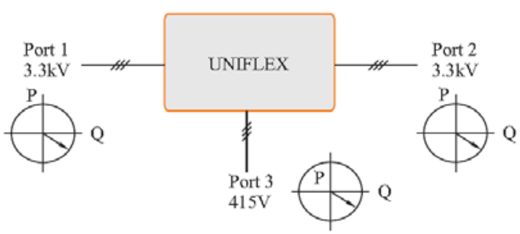


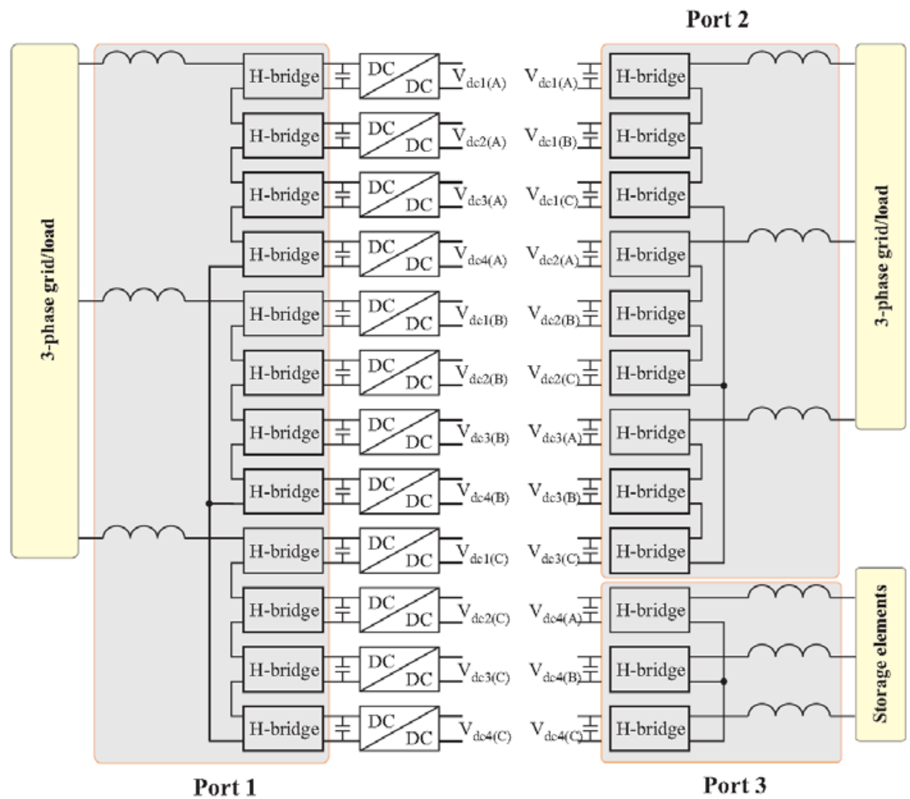
$$X\ ^{M}L^{N}\ Y = 6\ ^{3}2^{1}\ 1$$

Three-Phase SST Distribution System Applications

▶ UNIFLEX Project

- EU Project (2009)

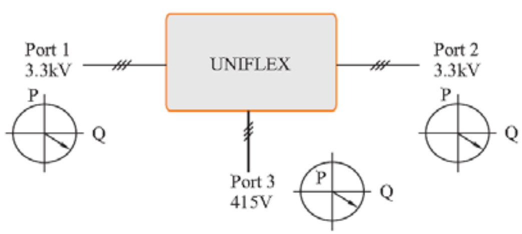


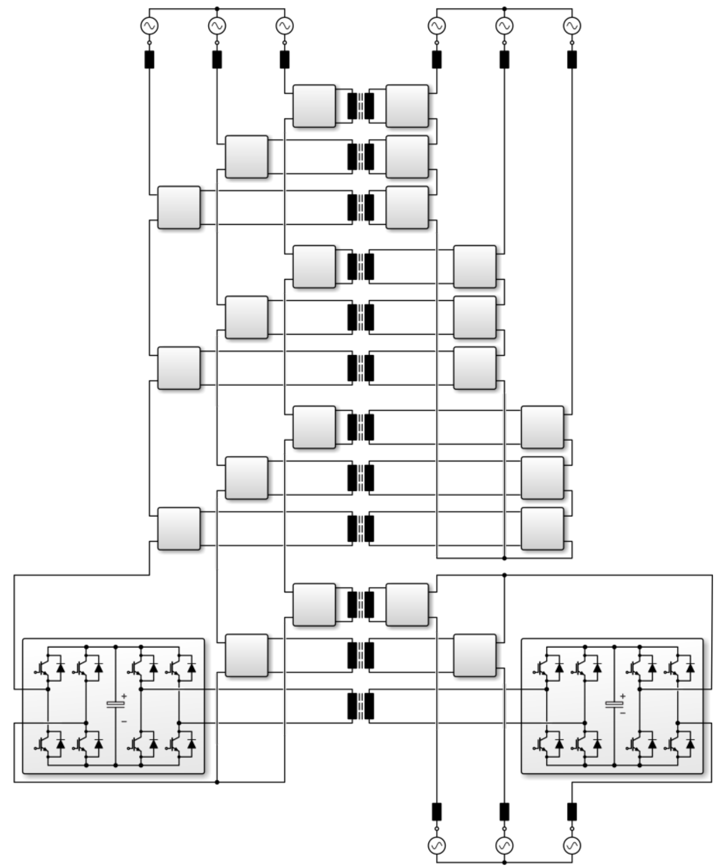


- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- **Cellular 300kVA Demonstrator of 3-Port Topology** for 3.3kV Distr. System & 415V LV Grid Connection

▶ UNIFLEX Project

- EU Project (2009)





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

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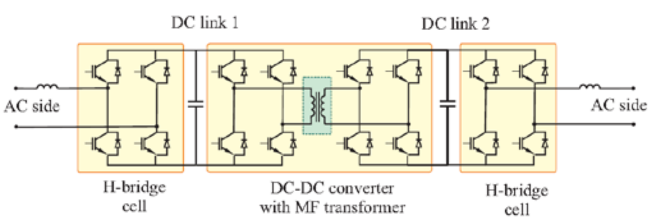
- EU Project (2009)

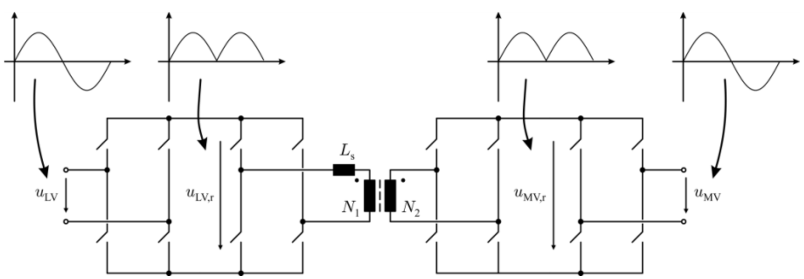


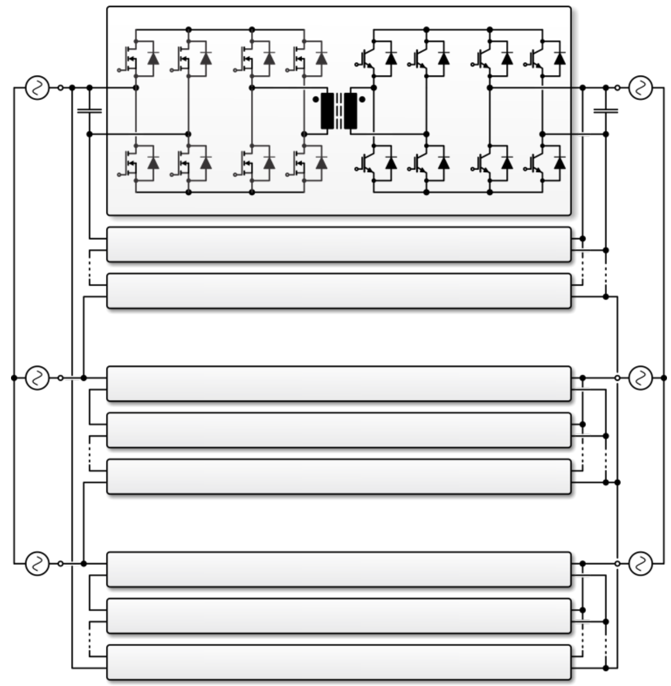
- AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham

► 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)

► SiC-Enabled Solid State Power Substation

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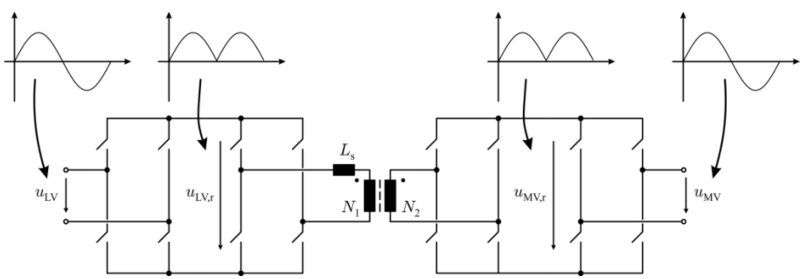
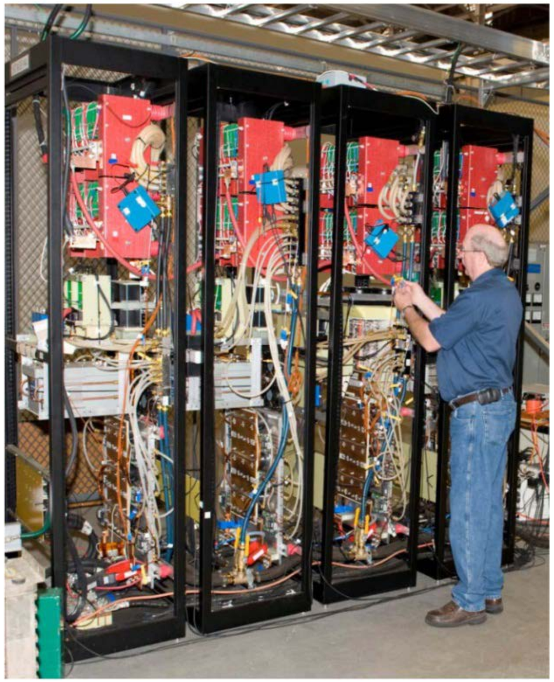
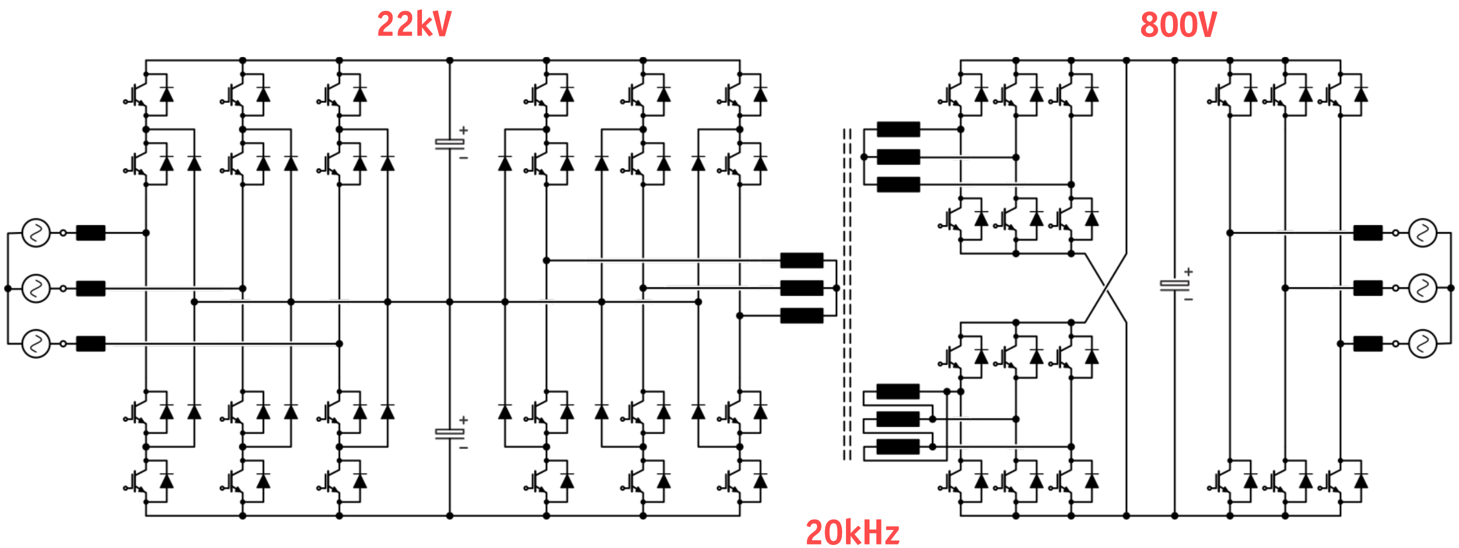




- **SiC-Enabled 20kHz/1MVA "Solid State Power Substation"**
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

► Transformerless Intelligent Power Substation (TIPS)

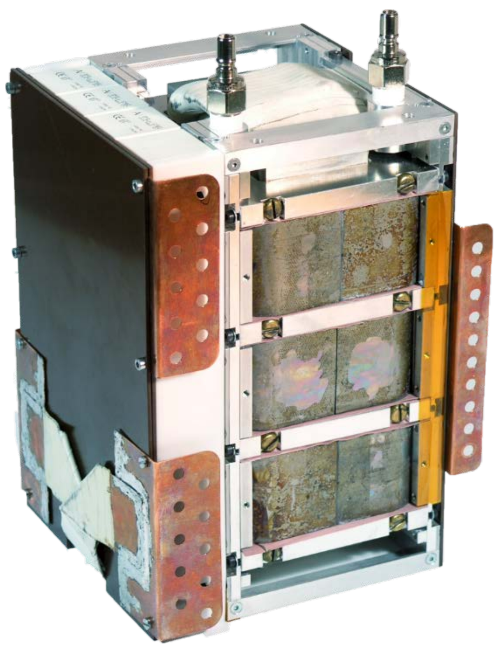
- Bhattacharya / FREEDM Center (2012)

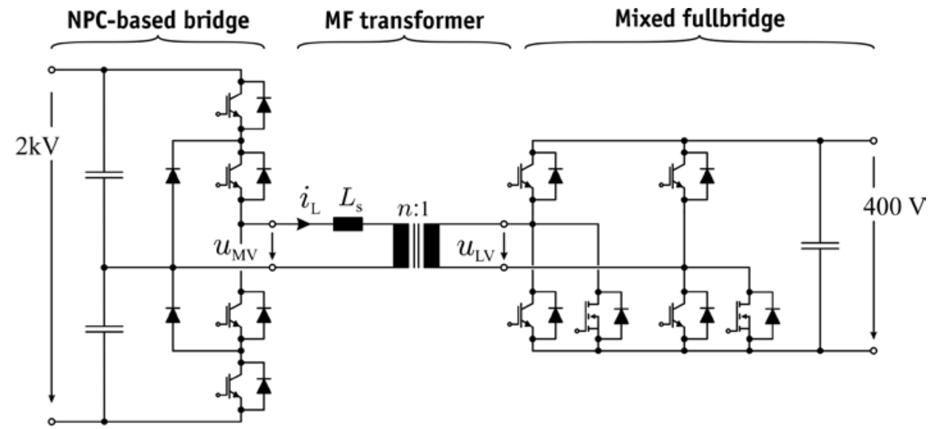


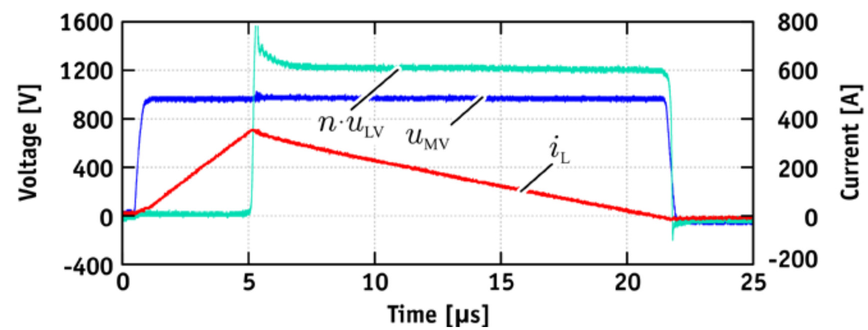
- 13.8kV → 480V
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype

▶ The MEGACube @ ETH Zürich

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



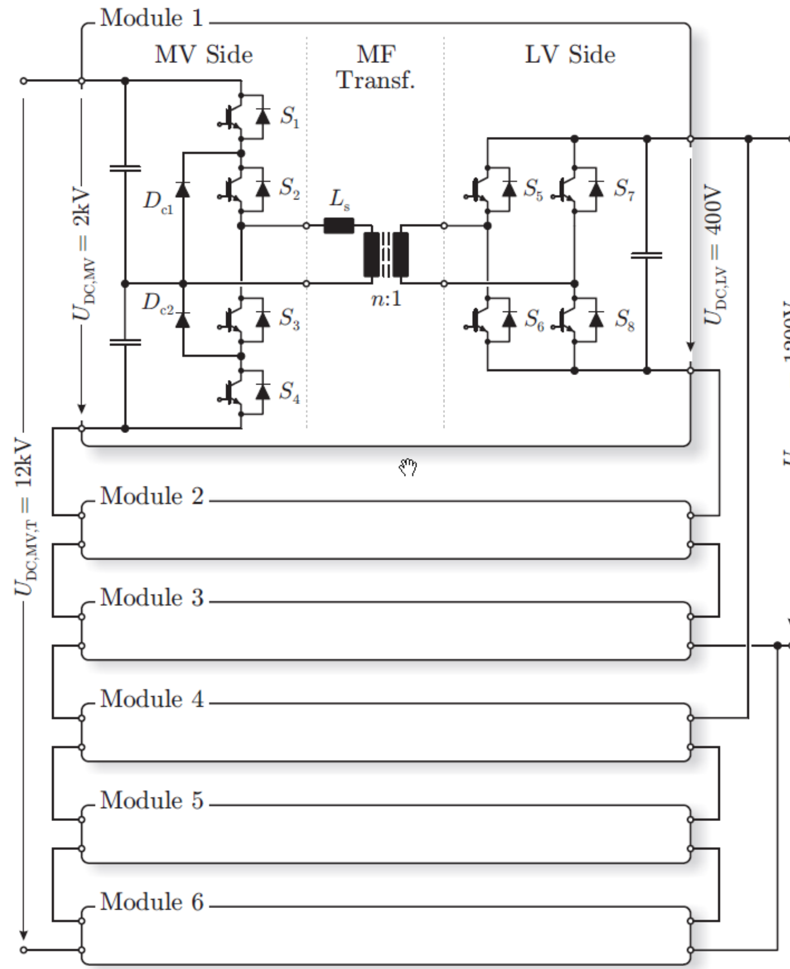




- Structure of the 166kW Module and MV Side Waveforms

▶ The MEGACube @ ETH Zürich

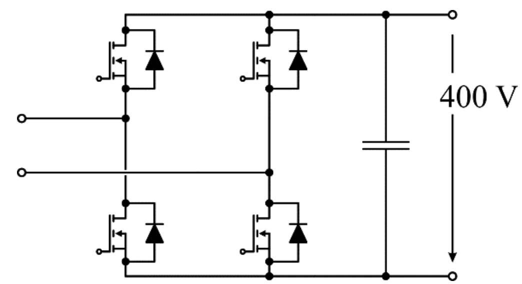
- Total Power 1MW
- Frequency 20kHz
- Efficiency Goal 97%

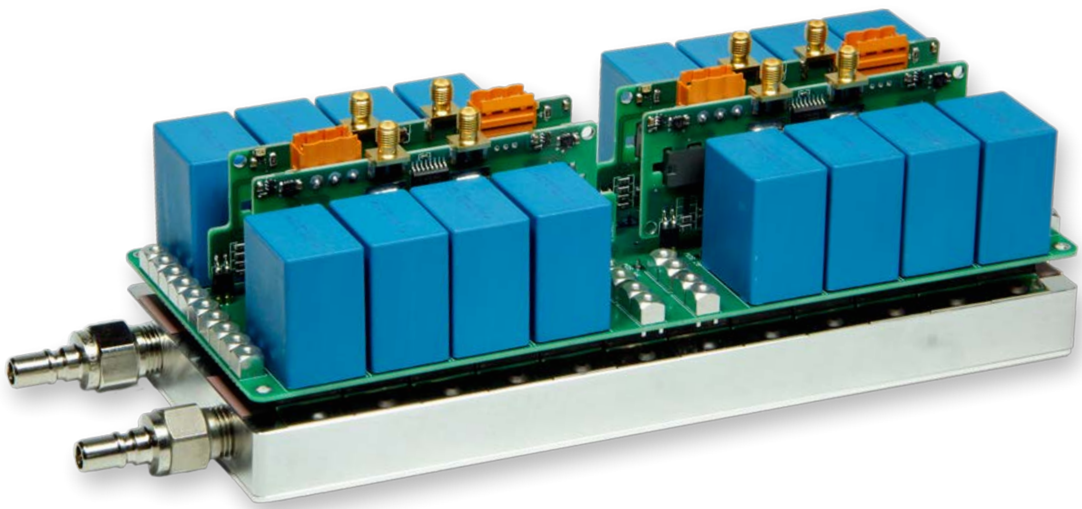


- MV Level 12kV
- LV Level 1.2kV

► The MEGACube — MOSFET-based LV Full-Bridge

- Power Rating 55kW
- Losses 0.31kW
- Based on Single TO-247 Devices
- Water-Cooled

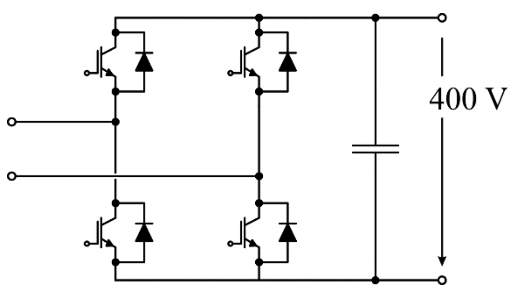




- 55kW Water-Cooled LV Full-Bridge

► The MEGACube — IGBT-Based LV Full-Bridge

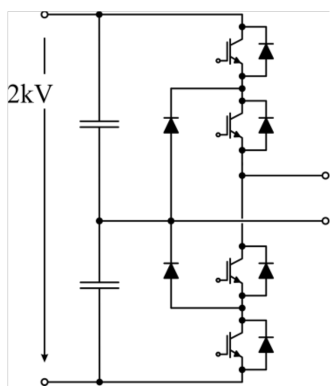
- Power Rating 83kW
- Losses 0.9kW
- Based on ECONOdual IGBT Module
- Water-Cooled



- 83 kW Water-Cooled LV Full-Bridge

▶ The MEGACube — MV NPC Module

- Power Rating 166kW
- Losses 3.1kW
- Based on ECONOdual IGBT Module
- Water-Cooled



- 166 kW Water-Cooled MV NPC Module

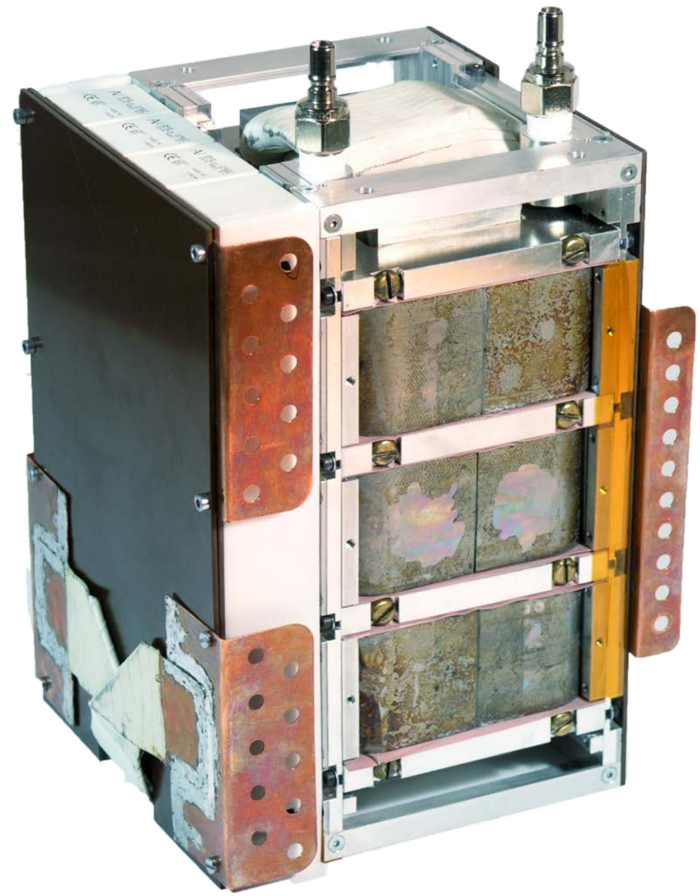
▶ The MEGACube — Air-Cooled Ferrite Core Transformer

- Power Rating	166kW
- Losses (incl. Fan Power)	0.59kW
- Forced-Air-Cooled	

- 166 kW Air-Cooled Ferrite Core Transformer

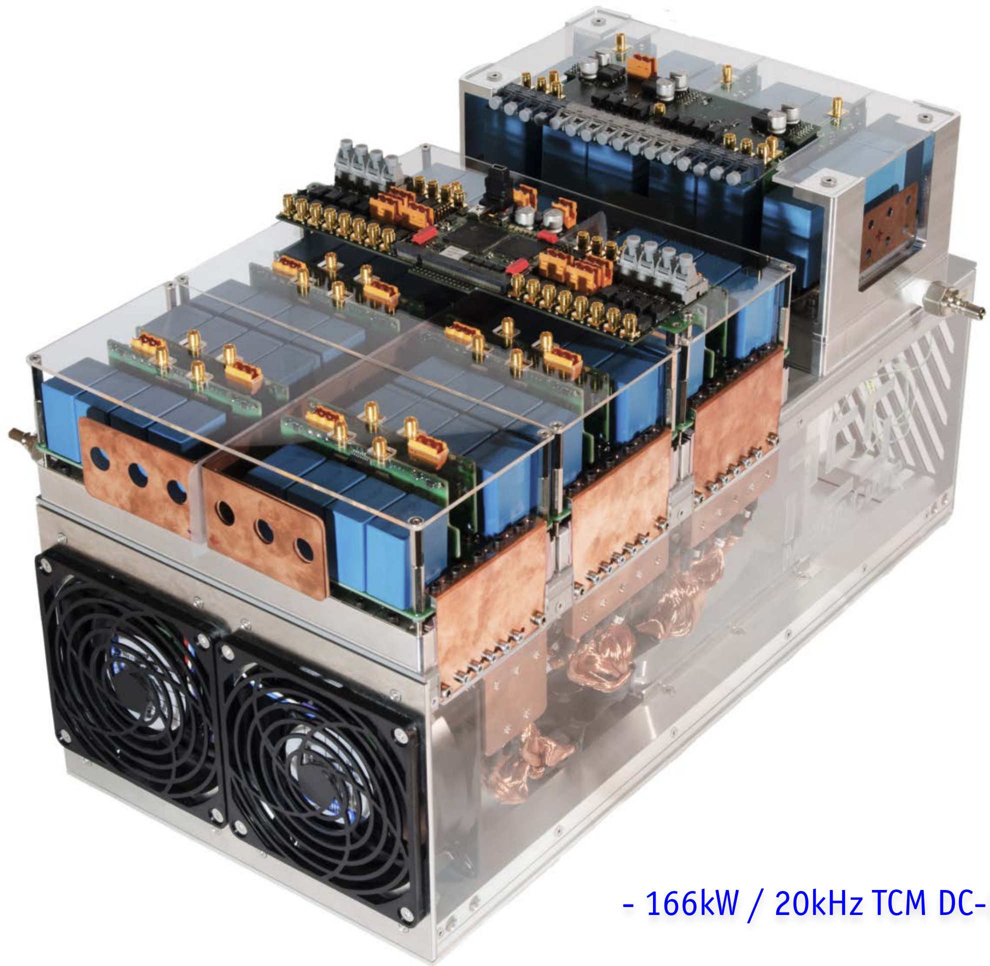
► The MEGACube — Water-Cooled Nanocrystalline Transformer

- Power Rating 166kW
- Losses 0.34kW
- **Power Density 45kW/dm3**



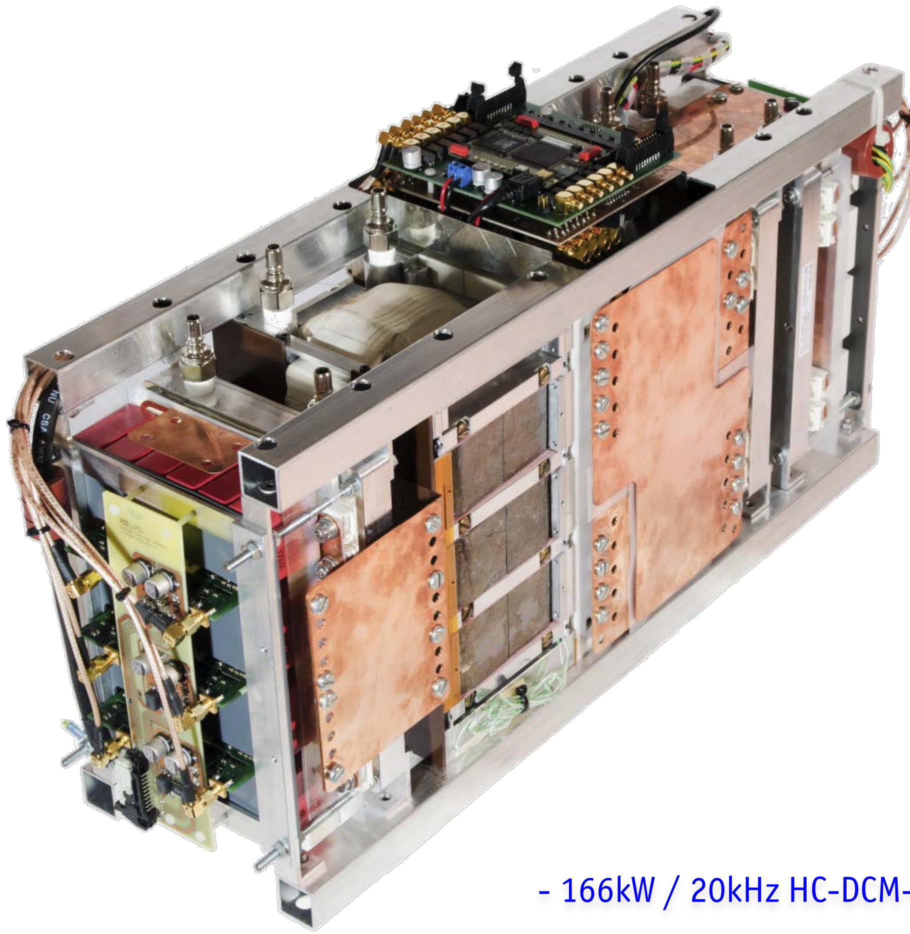
- 166 kW Water-Cooled Nanocrystalline Core Transformer

► The MEGACube — TCM 166kW/20kHz Converter Module



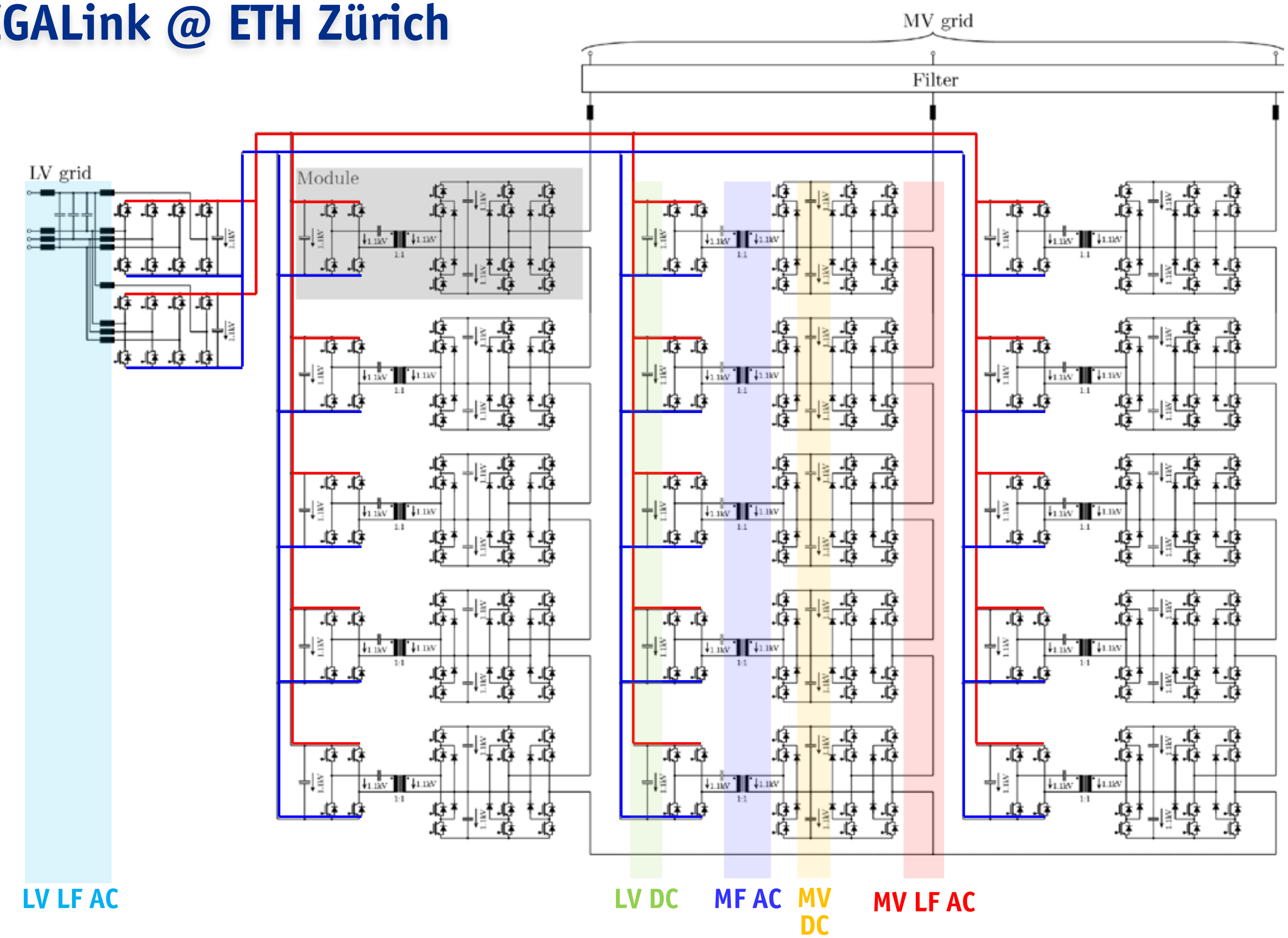
- 166kW / 20kHz TCM DC-DC Converter

► The MEGACube — Resonant 166kW / 20kHz Converter Module



- 166kW / 20kHz HC-DCM-SRC DC-DC System

▶ The MEGALink @ ETH Zürich



- 2-Level VSI on LV Side / HC-DCM-SRC DC-DC Conversion / Multilevel MV Structure

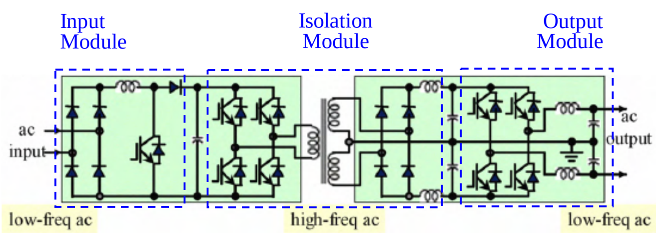
Three-Phase SST Distribution System Applications

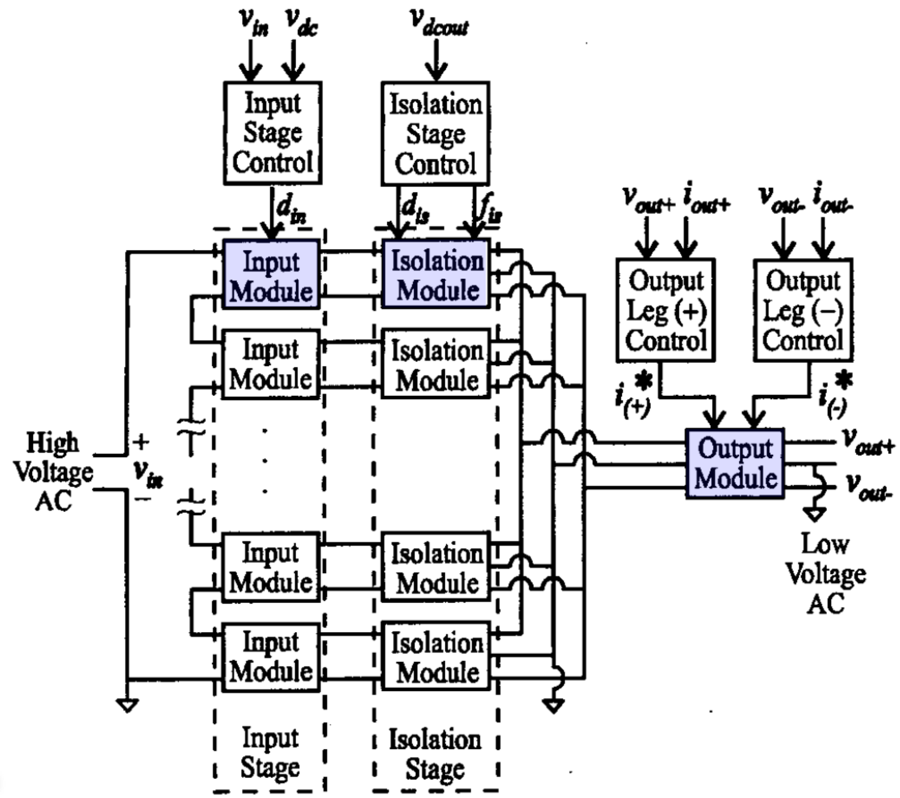
Phase Modular / Direct 3ph. Concepts
Matrix / DC-Link Based Concepts
ISOP Converter Topologies
Example SST Projects
Unidirectional SST Concepts
SST Concepts Employing LF Transformers

► Unidirectional DC-Link Based SST Structures

- Ronan et al. (2000)

- **AC Input** **7.2kV**
- **DC/DC** **1000V/±275V**
- **AC Output** **120V/240V**



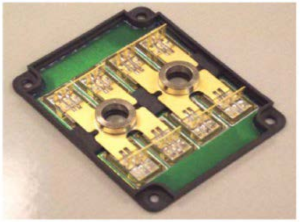


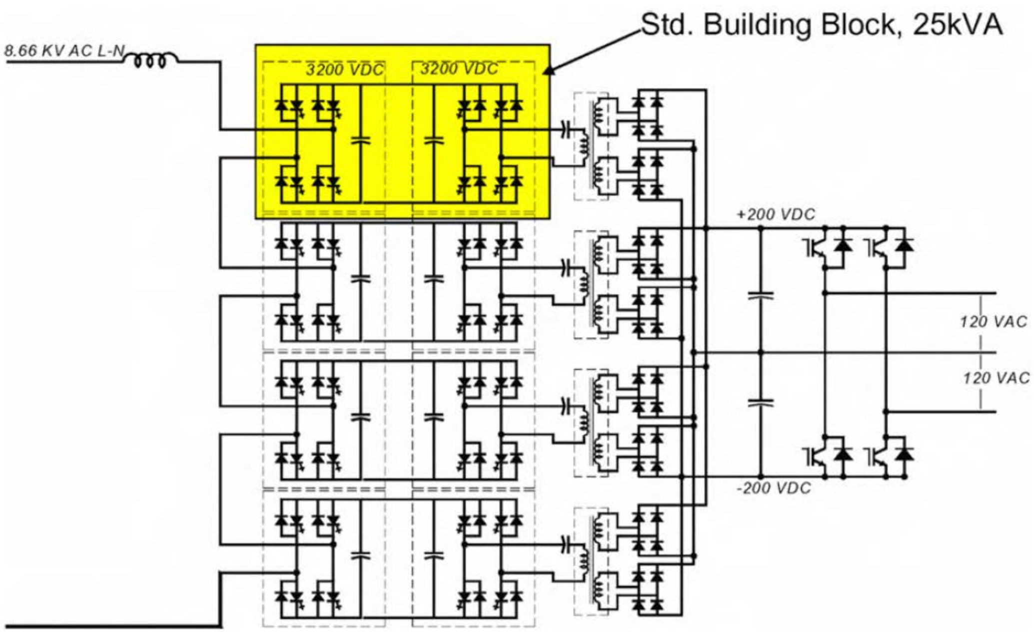
- **ISOP Modular Topology**
- Three-Stage (AC/DC-DC/DC-DC/AC) Approach

► Unidirectional DC-Link Based SST Structures

- EPRI (2009)

- AC Input 8.6kV (15kVl-l)
- DC/DC 3.5kV/400V
- AC Output 120V/240V

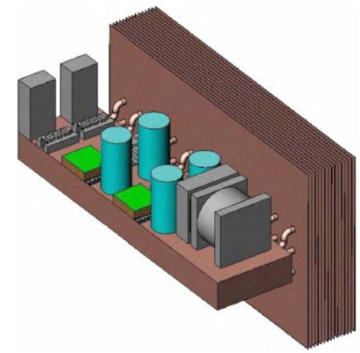


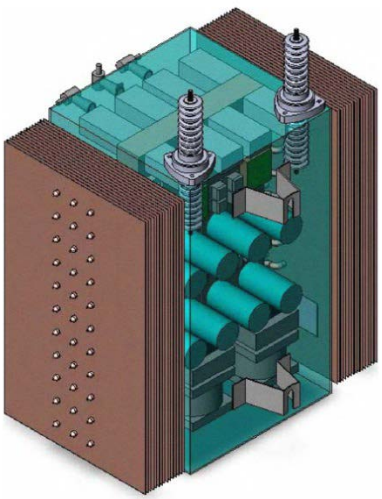


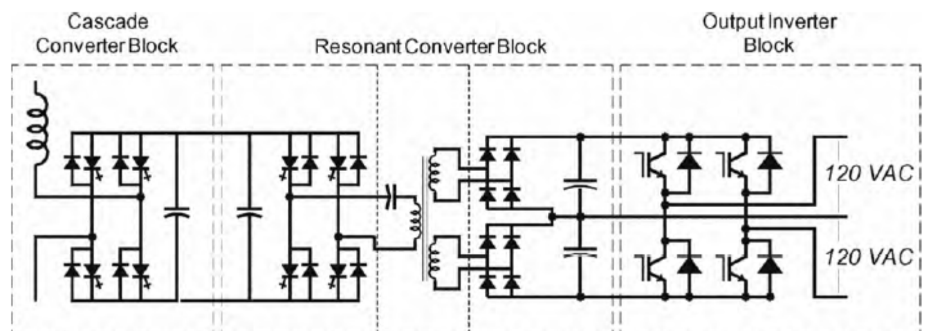
- 100kVA 15kV Class Intelligent Universal Transformer (IUTTM)
- Development of HV Super GTO (S-GTO) as MV Switching Device / SiC Secondary Diodes
- 20kHz Series Resonant DC/DC Converter Utilizing Transformer Stray Inductance

► Unidirectional DC-Link Based SST Structures

- EPRI (2009)



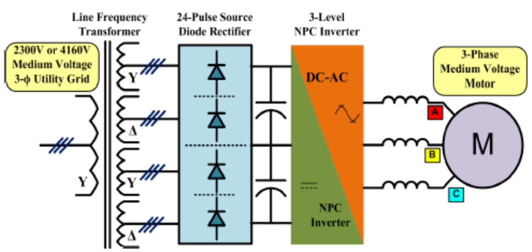


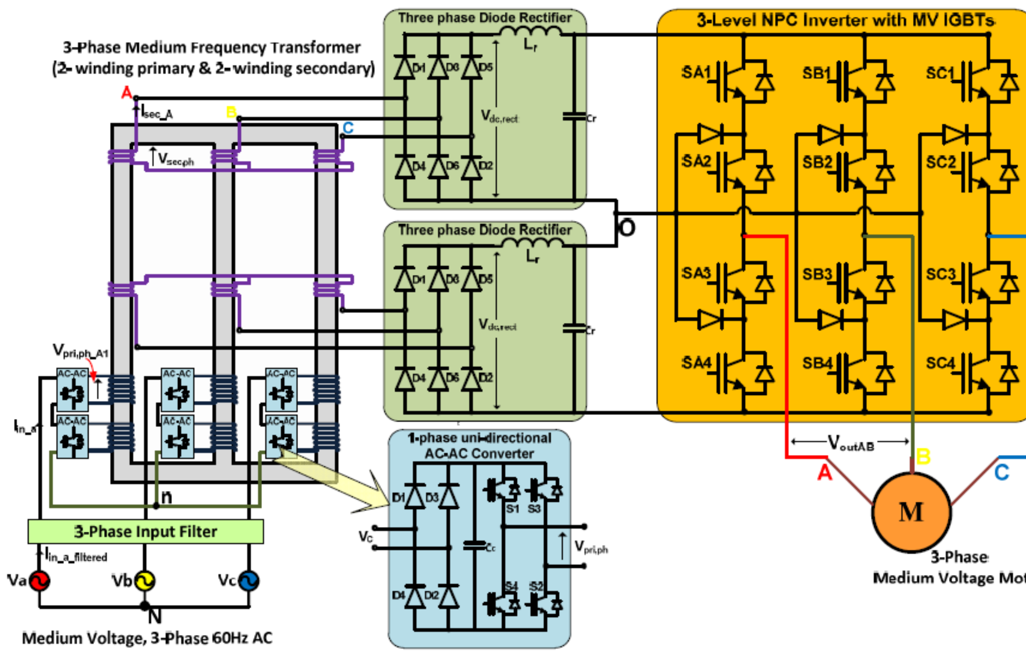


- **Outline of 100kVA (4x25kVA) IUT** (Pole Mount Layout, 35"H 35"W 20"D, 1050 lbs)
- Natural Air Cooling / S-GTO Module (No Wire Bonds, 50kHz Switching Frequency Target)

► Unidirectional DC-Link Based SST Structures

- Enjeti (2012)

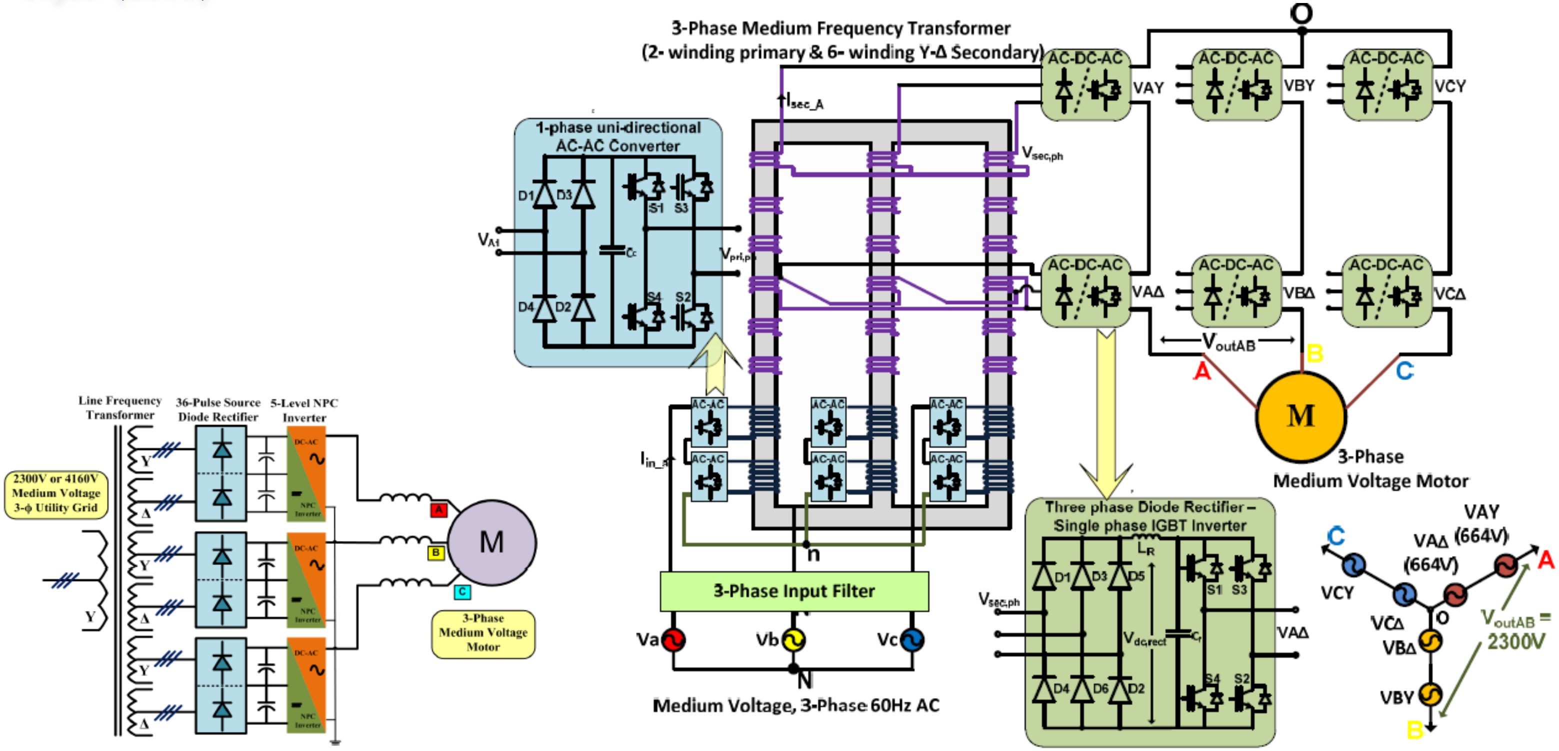




- SST Application for MV Adjustable Speed Drive (Unidirectional AC/AC Front End / 3L NPC Inverter)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

► Unidirectional DC-Link Based SST Structures

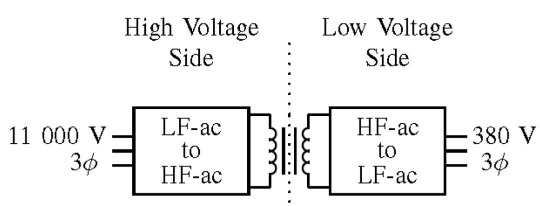
- Enjeti (2012)

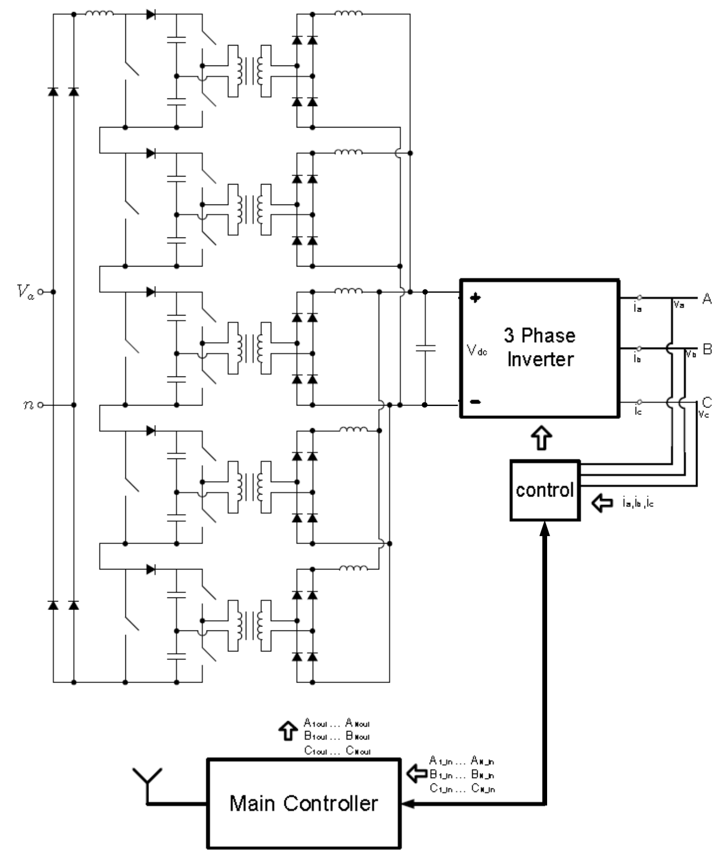


- SST Appl. for MV Adjustable Speed Drive (Unidir. AC/AC Front End / Cascaded 2L 1ph.-Inverters)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

► Unidirectional DC-Link Based SST Structures

- van der Merwe (2009)



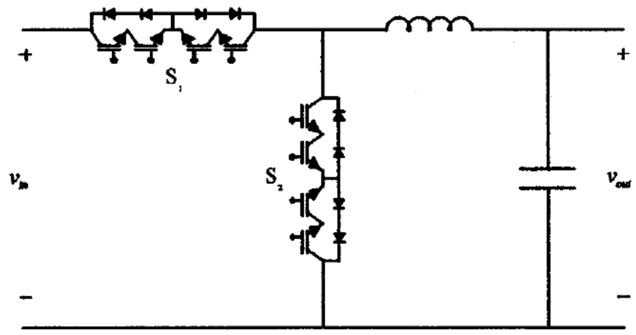


- 5-Level Series Stacked Unidir. Boost Input Stage

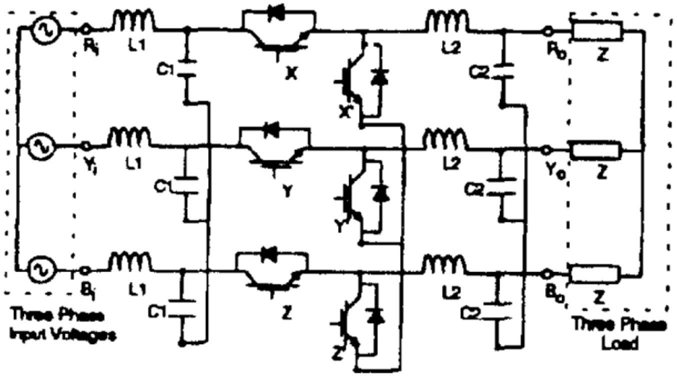
Three-Phase SST Distribution System Applications

Phase Modular / Direct 3ph. Concepts
Matrix / DC-Link Based Concepts
ISOP Converter Topologies
Example SST Projects
Unidirectional SST Concepts
SST Concepts Employing LF Transformers

▶ Full Power SST Employing LF Transformers



- Basic 1ph AC chopper - J.L. Brooks (1980) "Solid State Transformer Concept Development"
- Provides AC Voltage Regulation and Low Sensitivity to Harmonics
- **Isolation Provided with LF Transformer (Not Shown)**



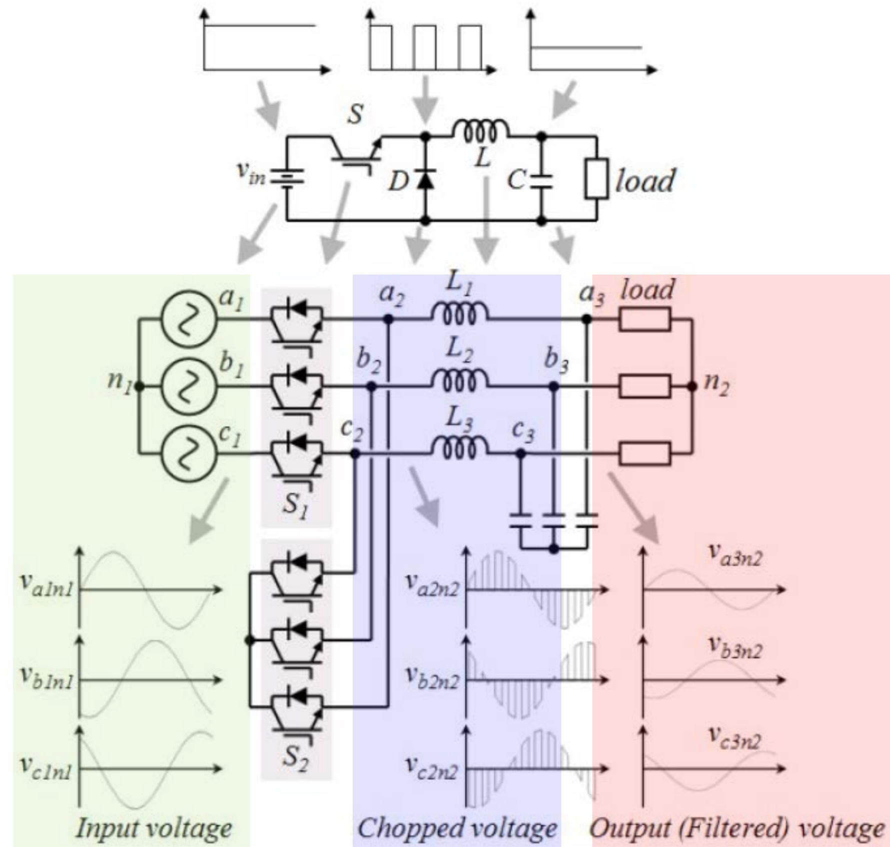
Three Phase Buck Converter with input filters

- 3ph AC Version – G. Venkataramanan (1995)
- No 4-Quadrant Switches Required
- **Isolation with LF Transformer (Not Shown)**

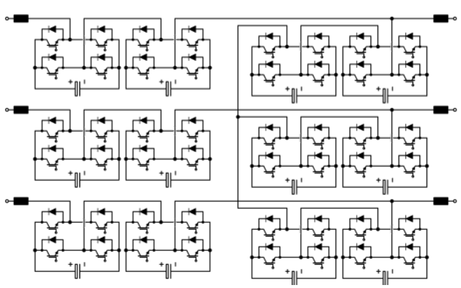
▶ Full Power SST Employing LF Transformers

- Derived from DC Buck Converter

- J. C. Rosas-Caro (2010)



* Modular Multi-Cell 3ph. AC Chopper (Patent SIEMENS)

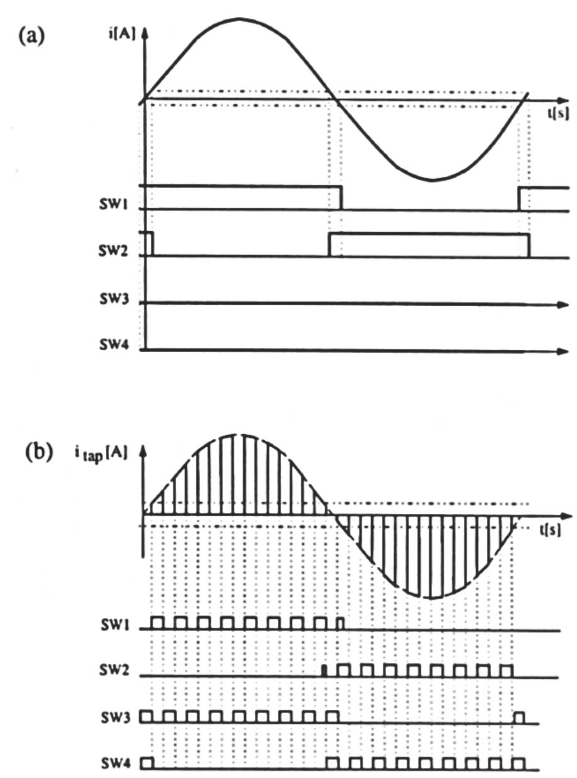


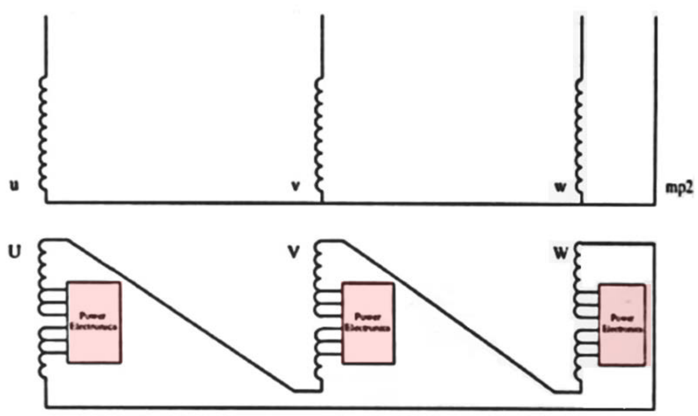
c)

► Partial Power SST Employing LF Transformers

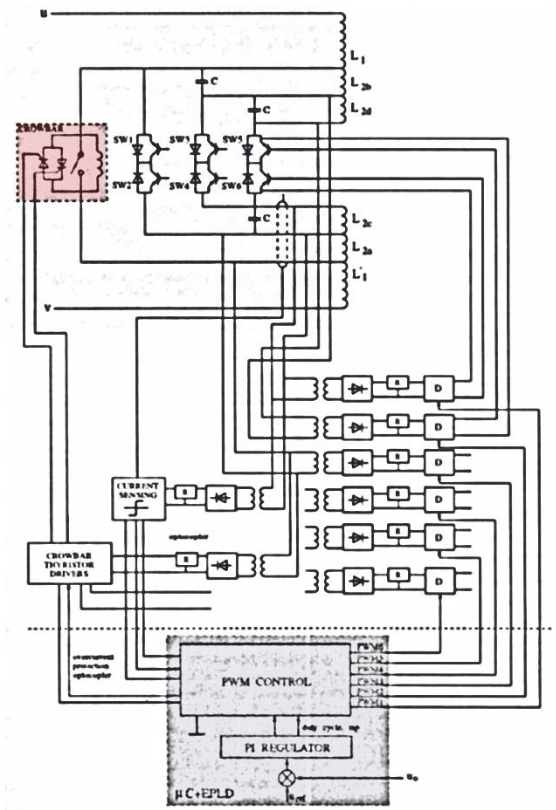
- P. Bauer (1997)

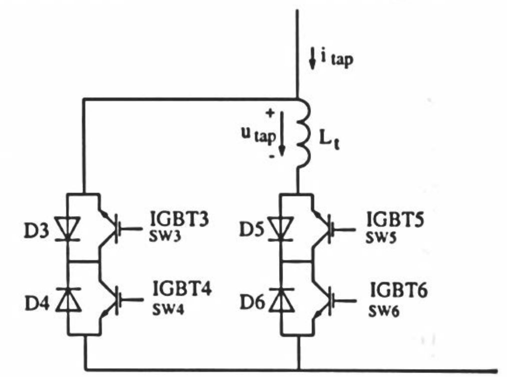
- Electronic Tap Changer of LF Transformer
- MV Winding with Power Electronic Switched Tap.
- Two Modes of Operation:
  - Single Tap Position (a)
  - PWM Modulated Tap (b)



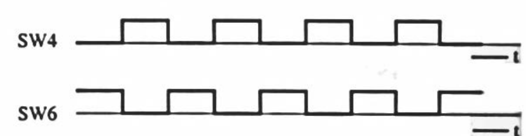


► Partial Power SST Employing LF Transformers





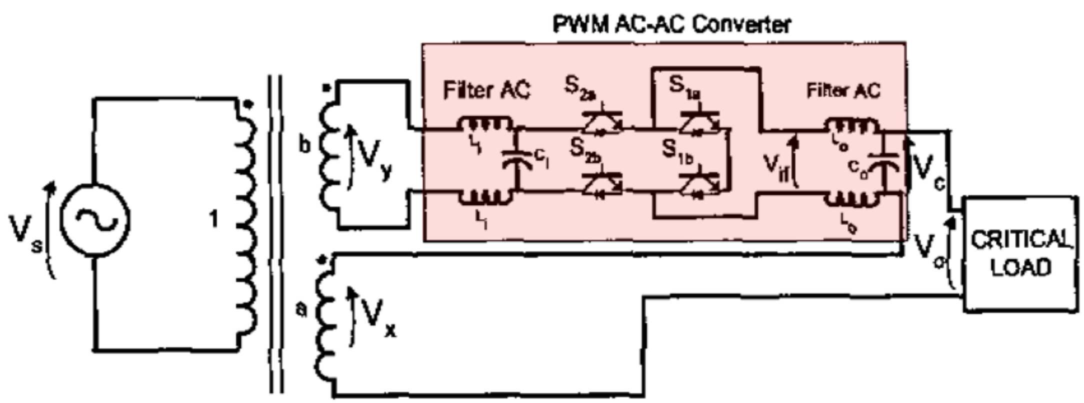
Switching cell of the tap switching.



- Electronic Tap Changer — Complex Control Circuit
- Crowbar for Emergency Ride-Through
- Commutation Sequence of the 4-Quadrant Switches

▶ Partial Power SST Employing LF Transformers

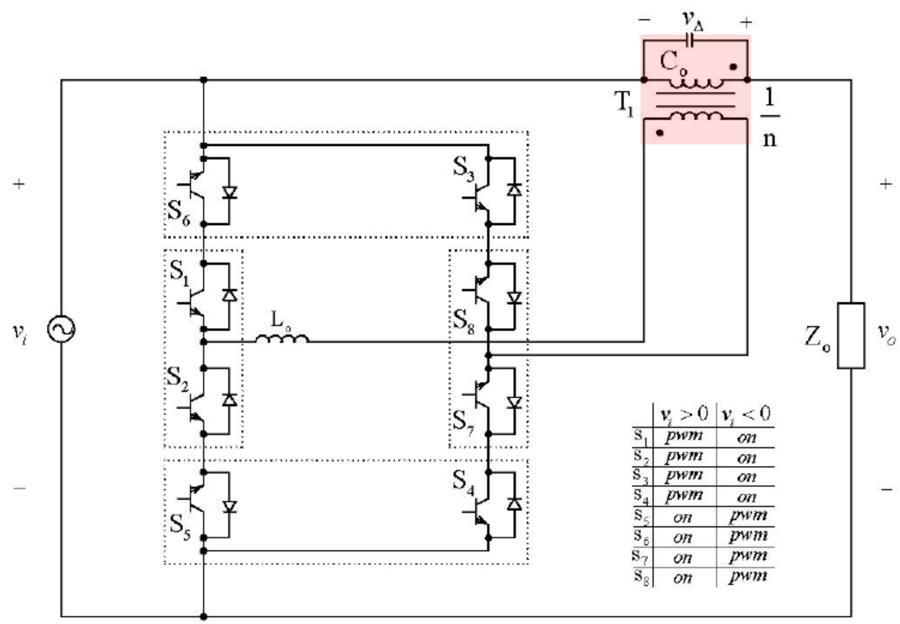
- Enjeti (2003)



- Controlled Output Voltage: Vo= Vx + Vc
- **LF Isolation Transformer**

► Partial Power SST Employing LF Transformers

- Barbi (2006)



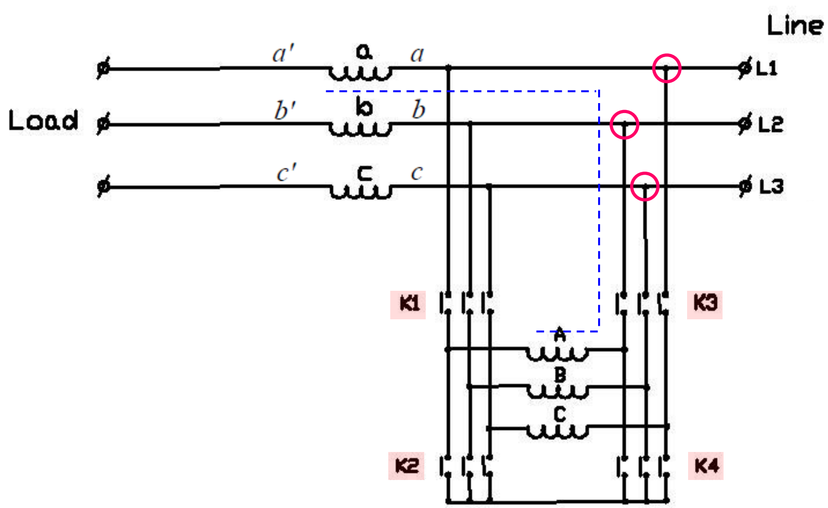
	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*pwm*	*on*
S_4	*pwm*	*on*
S_5	*on*	*pwm*
S_6	*on*	*pwm*
S_7	*on*	*pwm*
S_8	*on*	*pwm*

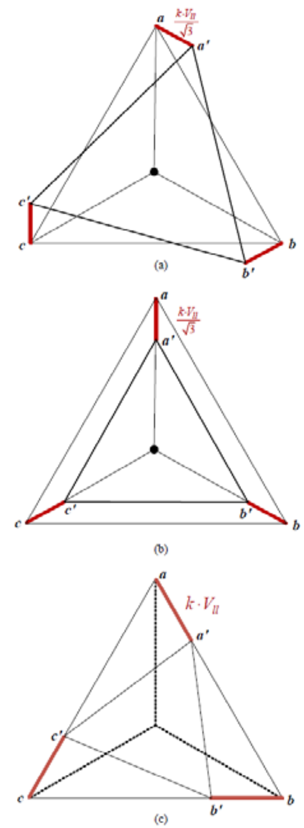
$$\left.\frac{V_o}{V_i} = 1 + \frac{2D-1}{n}\right|_{\text{2 levels}} \qquad \left.\frac{V_o}{V_i} = 1 + \frac{D}{n}\right|_{\text{3 levels}}$$

- Controlled Output Voltage: vo= vi + Δv
- **Isolation Provided with LF Transformer (Not Shown)**

▶ Partial Power SST Employing LF Transformers

- Shmilovitz (2011)





- K2 and K3 = ON

$$V_{ll-motor} = \sqrt{1-k+k^2} \cdot V_{line}$$

- K1 and K4 = ON

$$V_{ll-motor} = (1-k) \cdot V_{line}$$

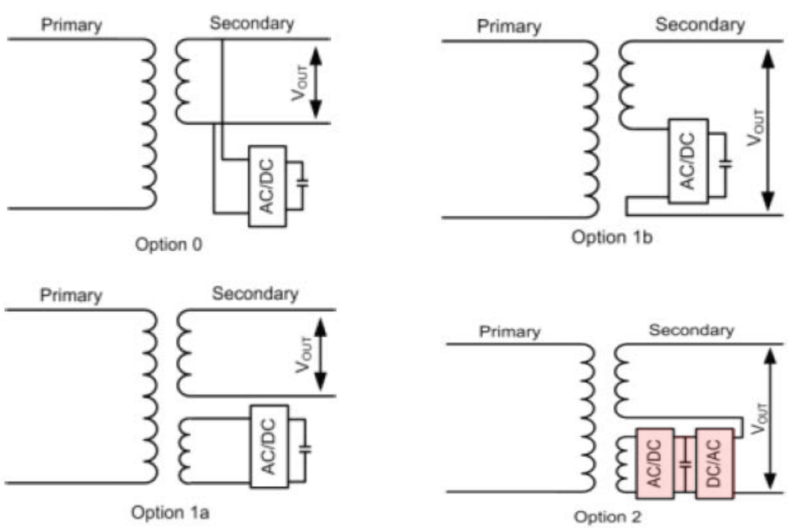
- K1 and K3 = ON

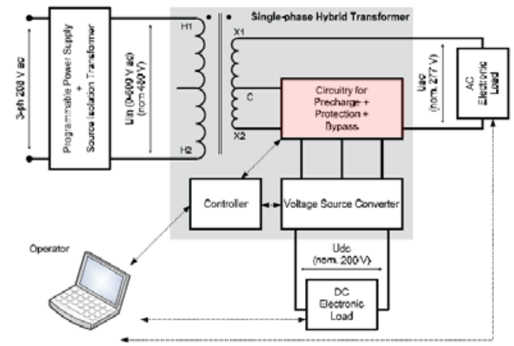
$$V_{ll-motor} = \sqrt{1-3k+3k^2} \cdot V_{line}$$

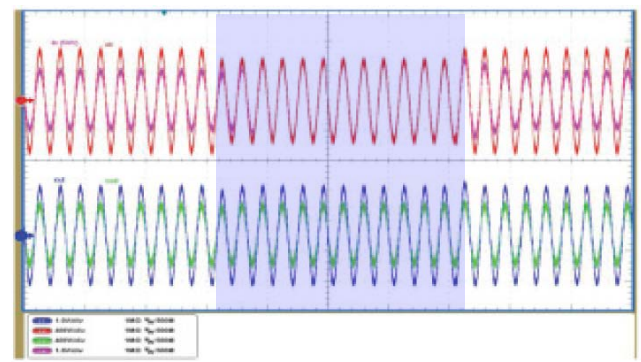
- Reconfigurable Auto-Transformer
- Switches K1, K2, K3 and K4 Used to Modify Output Voltage

▶ Partial Power SST Employing LF Transformers

- Bala (ABB 2012)



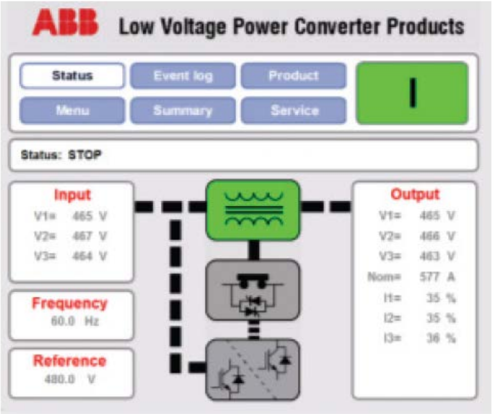


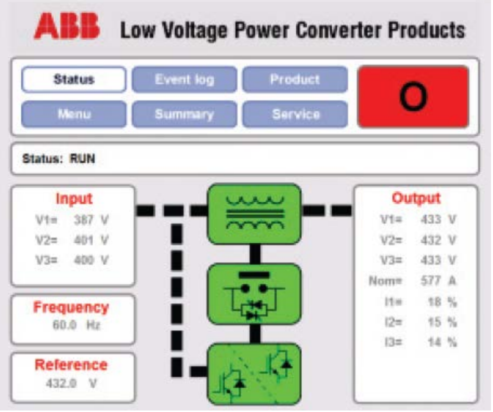


- Reactive Power Compensation (PFC, Active Filter, Flicker Control)
- Available DC Port (Isolated in Option 1a)
- **Option 2: Controlled Output Voltage**

▶ Partial Power SST Employing LF Transformers

- Bala (ABB, 2012)





- Commercial Product (ABB)
- Direct Connection of Input to Output (Bypass) or
- **Compensation of Inp. Voltage Sag (Contr. Output Voltage)**

SST Concepts for Traction Applications

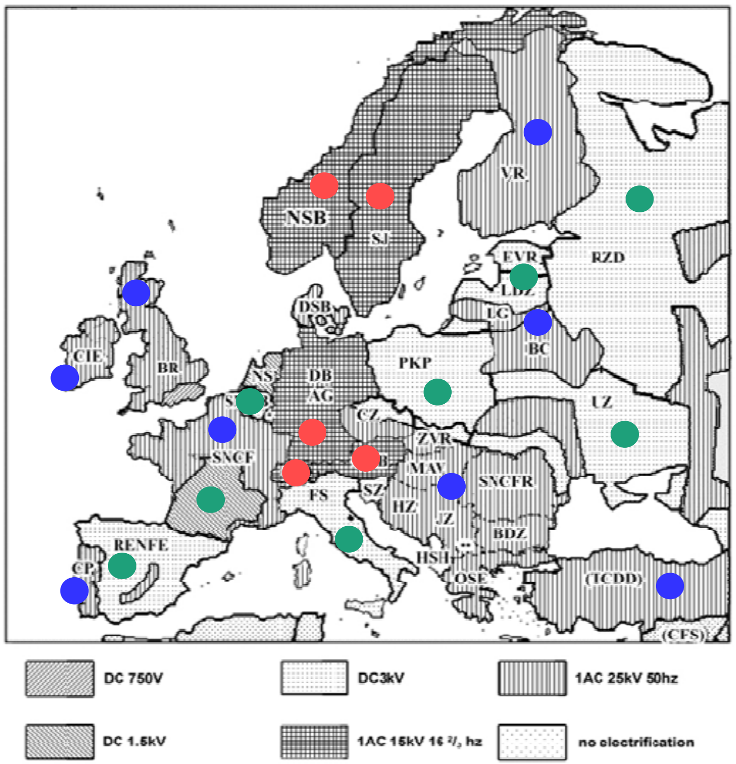
Railway Systems Voltage/Freq.
Modern Railway Systems' Requirements
SST Concepts for Traction

► Electric Railway Systems – A Little History

- Siemens Electric Railway – Werner von Siemens (1879)
- Speed: 7km/h — Power: 2.2 kW — Length: 300m

▶ Electric Railway Systems – A Little History

- Electrification of European Railways – Steimel (2012)



Railway main-line power-supply systems in Europe

- 16 2/3 Hz / 15kV AC - (1912)
- 3kV DC and 1.5kV DC - (1920)
- 50Hz / 25kV AC - (1936)

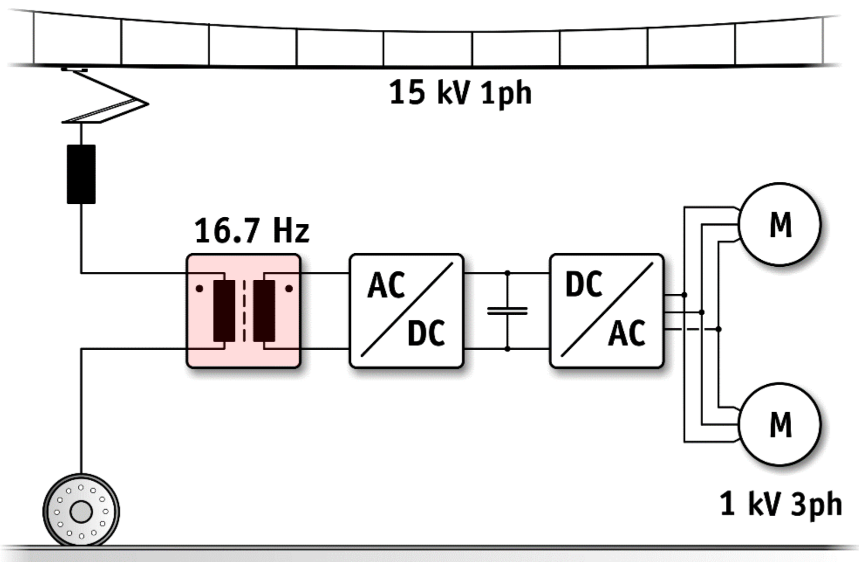
Network line lengths and proportion of electrical railway systems (2003)

DC 1500 V	15,320 km	6.5 %
DC 3000 V	72,105 km	30.3 %
AC 15 kV/16²/₃ Hz	32,390 km	13.6 %
AC 25kV/50 (and 60) Hz	106,437 km	44.8 %
Others	11,350 km	4.8 %
Total	237,600 km	100.0 %

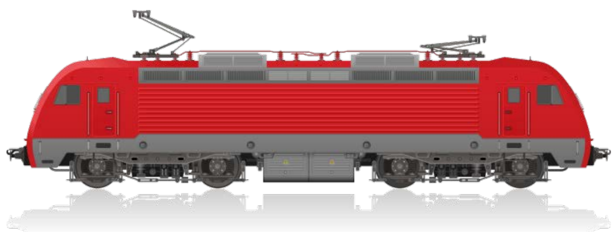
≈ 6 Turns Around the Earth

► Electric Railway Systems – Today's Drive Scheme

- 16.7Hz 1ph.-Transformer Required to Step-Down the Catenary Voltage to the Drive's Operating Voltage



- Low Frequency Transformer
  - 15% Weight of Locomotive
  - e.g. for **2MW ca. 3000kg**
  - **90-92% Efficiency**

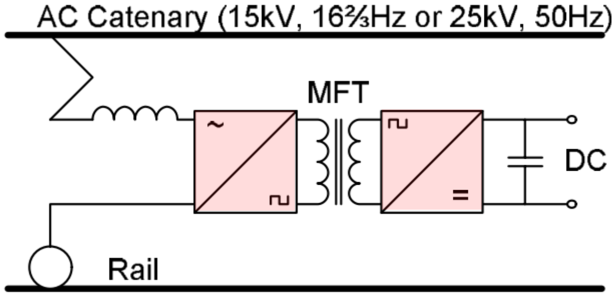


SST Concepts for Traction Applications

▶ Trends in Modern Railway Systems

- Electric Multiple Units (EMUs)
  e.g. Under-Floor Mounted

- Weight Reduction
- Energy Efficient Railways



AC-DC conversion with medium frequency transformer (MFT)

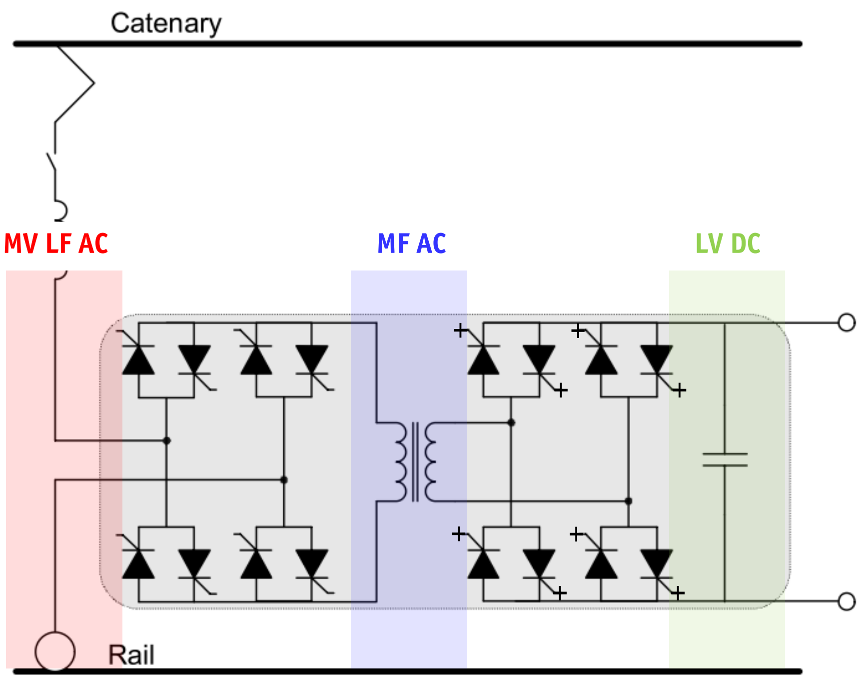
- **All Goals Lead to a Medium-Frequency Isolation / Conversion Syst. (Dujic 2011)**

SST Concepts for Traction Applications

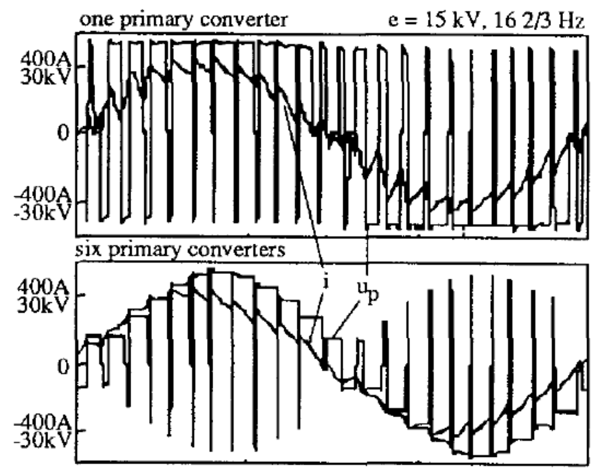
Railway Systems Voltage/Freq.
Modern Railway Systems' Requirements
SST Concepts for Traction

► VSI Commutated Primary Converter

- Menniken (1978)
- Östlund (1992)

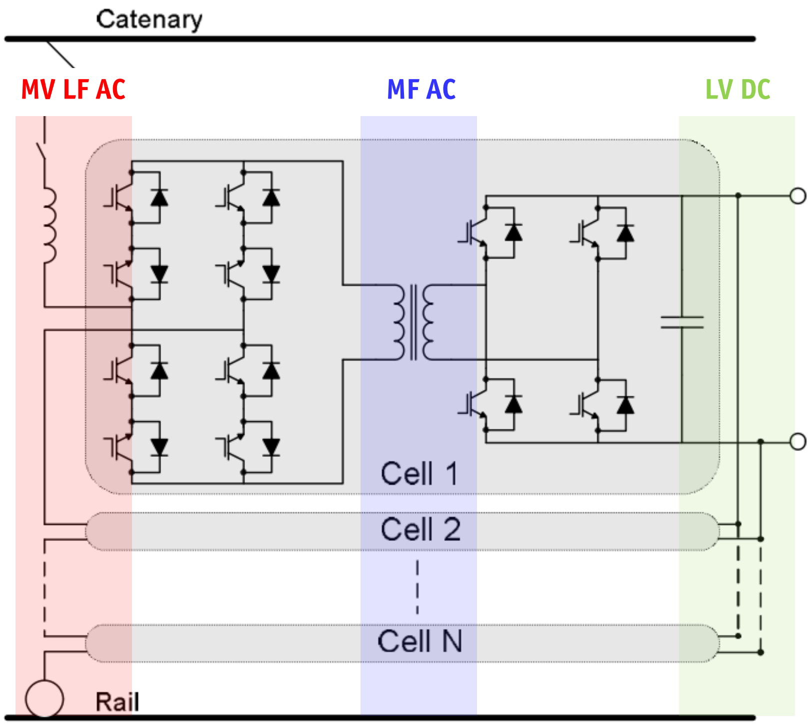


PET topology with source commutated primary converter

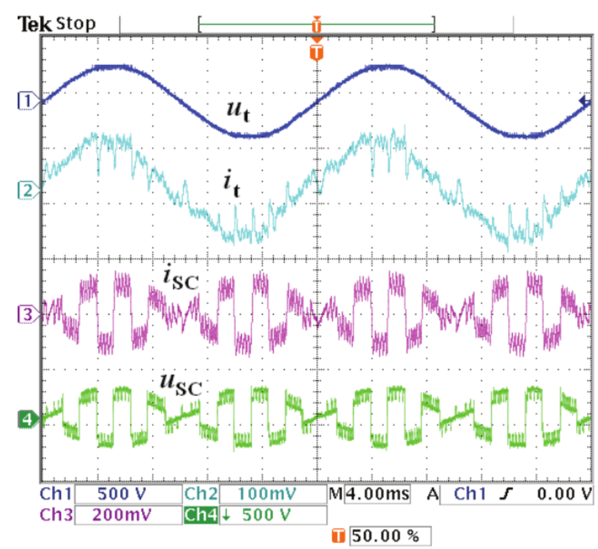


► Cascaded VSI Commutated Primary Converter

- Hugo (ABB, 2006)
- Pittermann (2008)

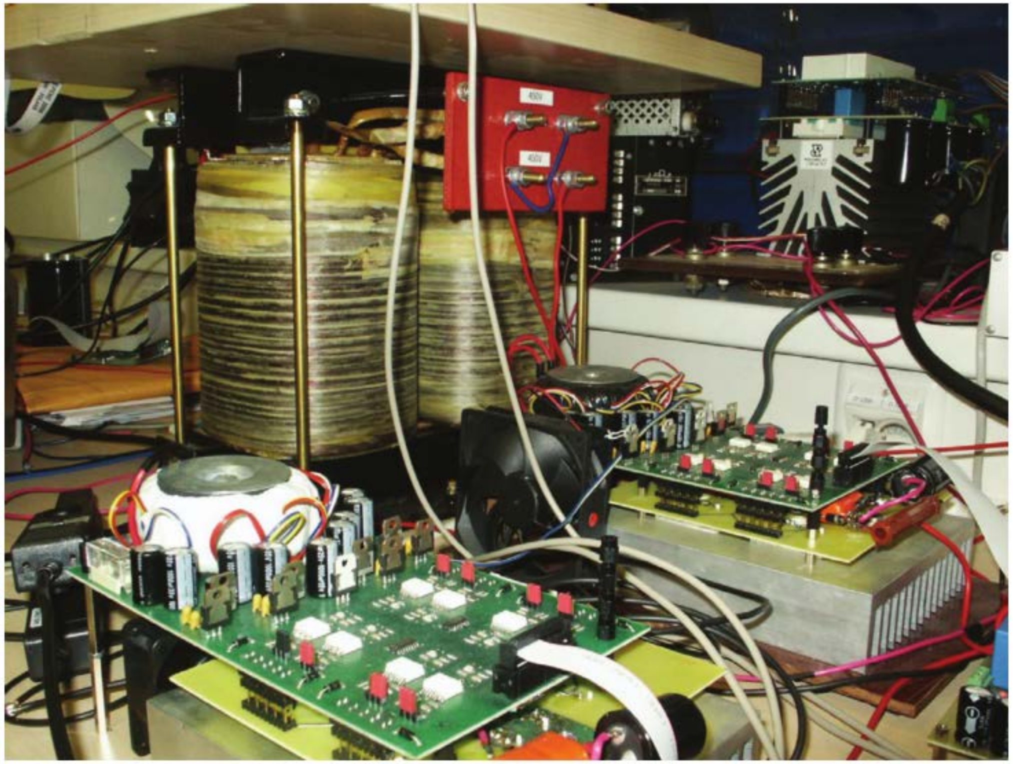


PET topology with cascaded source commutated primary converters



Experiment: steady-state; rectifier mode; load 2 kW;
Ch1-u_t, Ch2-i_t: 10A/100mV, Ch3-i_{SC} : 10A/100mV, Ch4- u_{SC}

► Cascaded Source Commutated Primary Converter



- Pittermann (2008)

- Module Power 2kW (downscaled)
- Frequency 800Hz

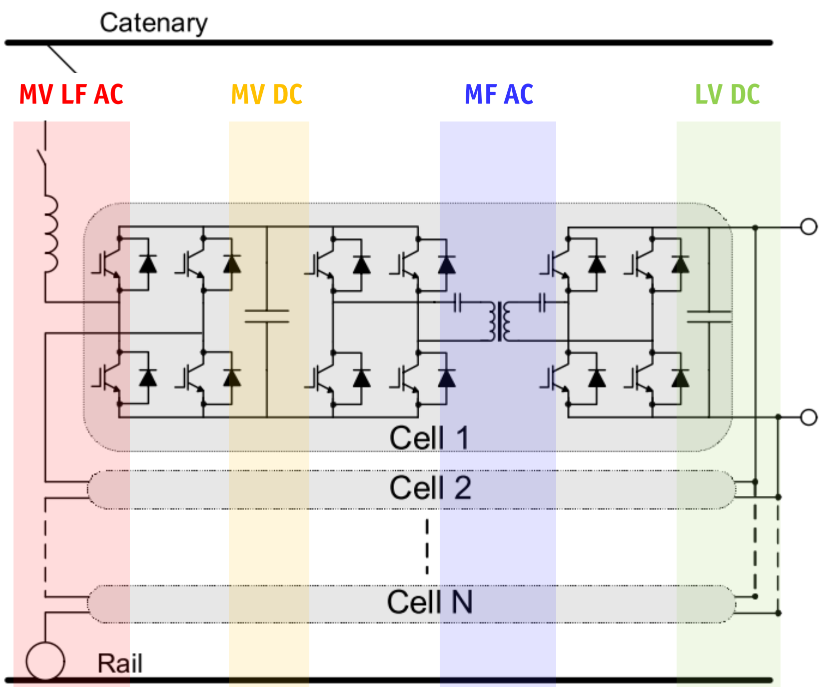
► Cascaded Source Commutated Primary Converter

- Hugo (ABB, 2006)

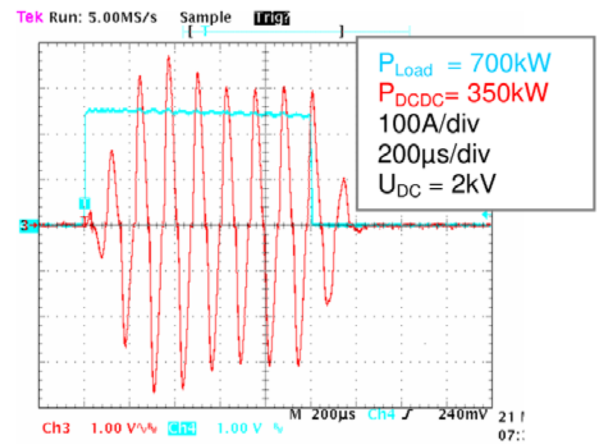
- Total Power 1.2MVA/15kV
- Module Power 75kW
- Frequency 400Hz

▶ Cascaded H-Bridges with Resonant/Non-Resonant DC-DC Stages

- Steiner (Bombardier, 2007)
- Weigel (SIEMENS, 2009)



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

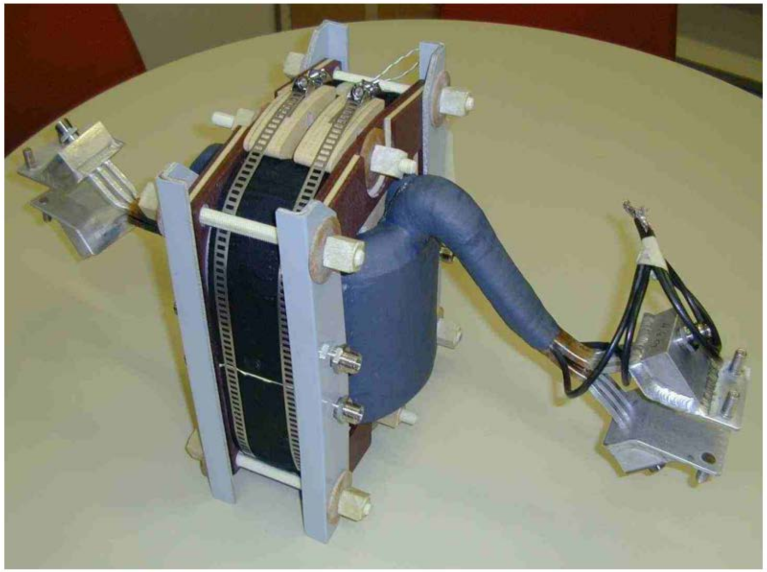


Dynamic behavior of DC-DC converter

► Cascaded H-Bridges with Resonant/Non-Resonant DC-DC Stages

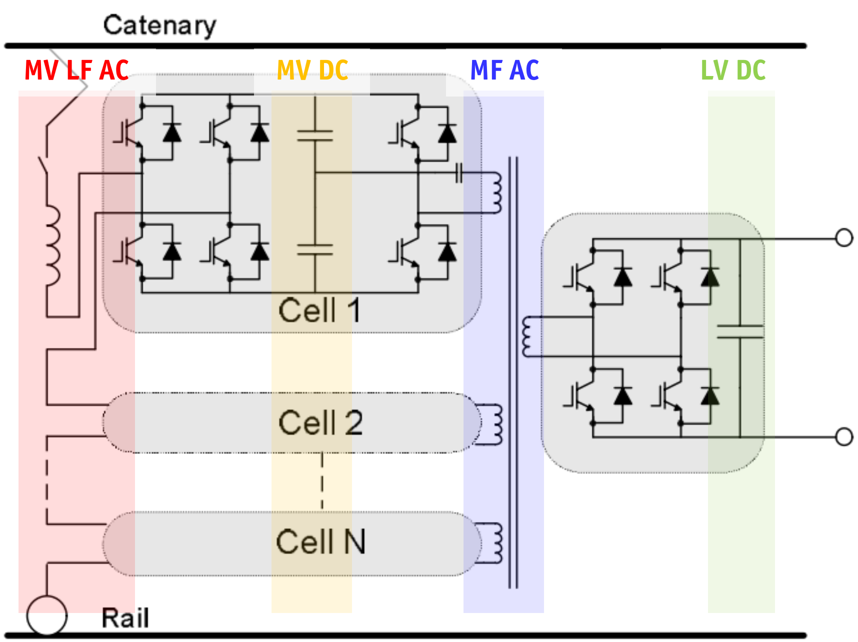
- Weigel (SIEMENS, 2009)
  - Module Power 450kW
  - Frequency 5.6kHz

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

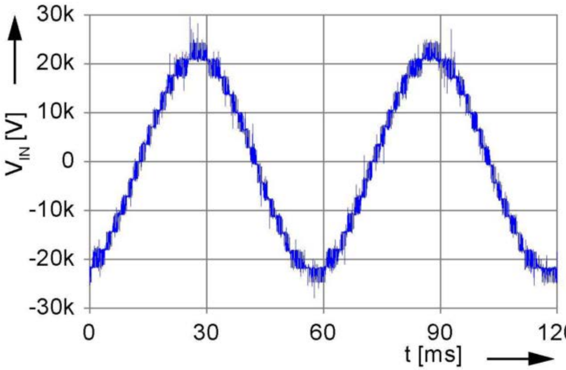


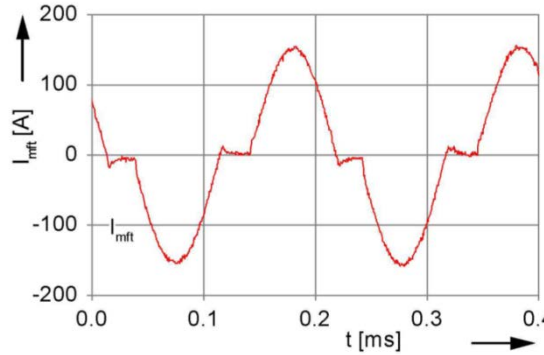
► Cascaded H-Bridges with Multi-Winding MF Transformer

- Engel (ALSTOM, 2003)

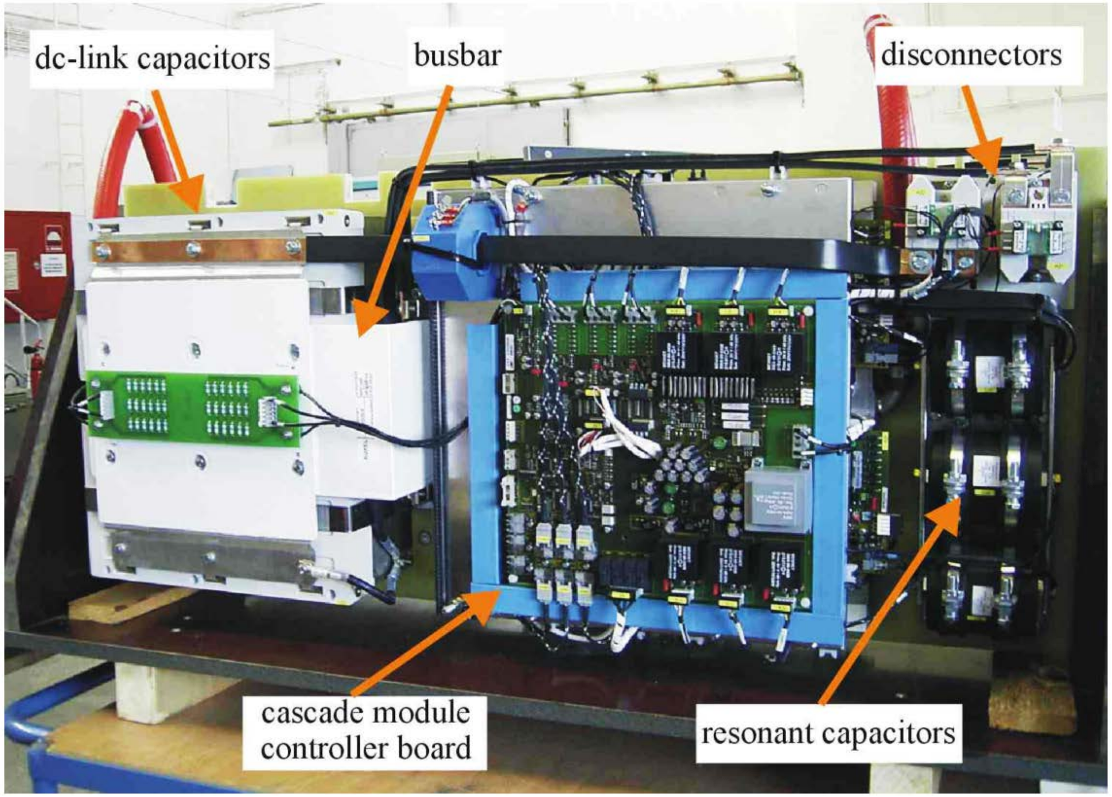


PET topology with cascaded H-bridges and multi-winding MFT





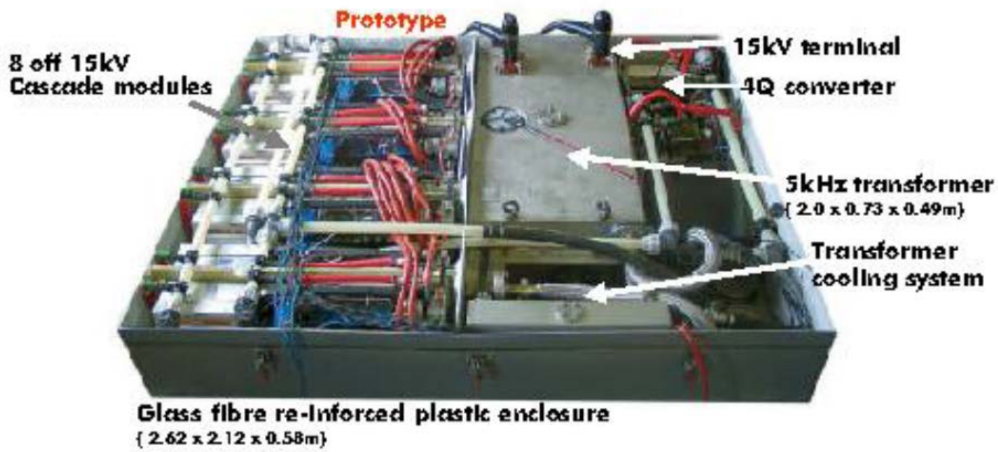
► Cascaded H-Bridges with Multi-Winding MF Transformer



- Engel (ALSTOM, 2003)

- Module Power 180kW
- Frequency 5kHz

► Cascaded H-Bridges with Multi-Winding MF Transformer

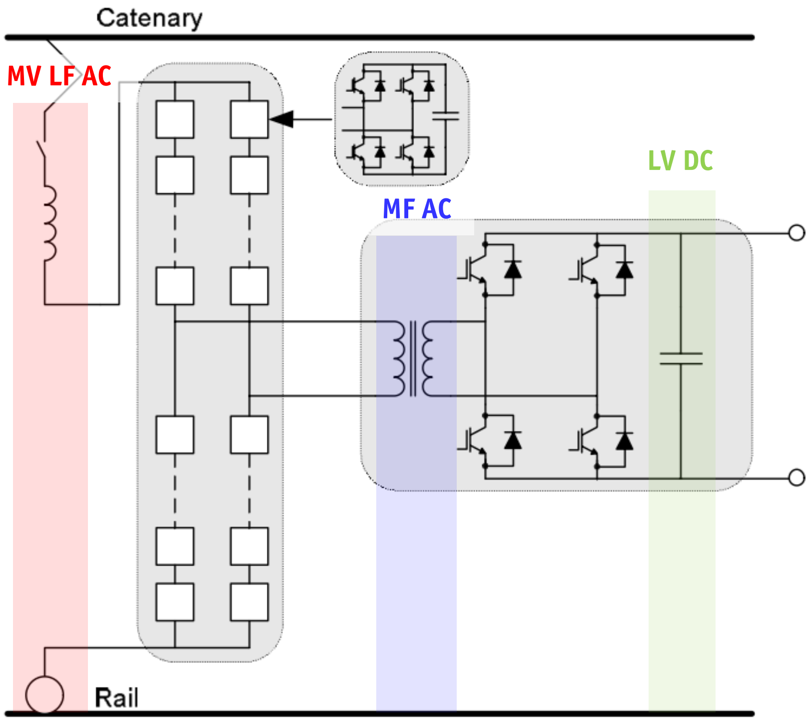


- Taufiq (ALSTOM, 2007)

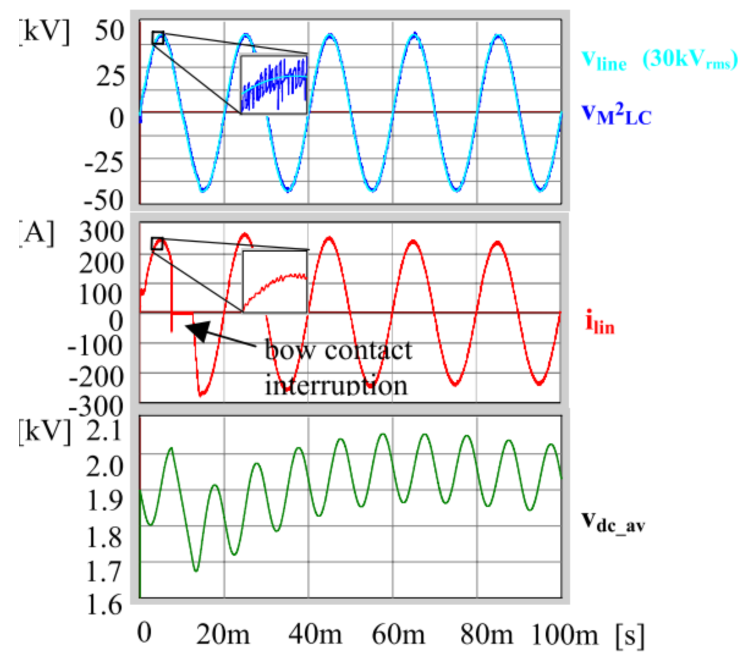
- Module Power 180kW
- Frequency 5kHz

▶ Modular Multilevel Converter

- Marquardt/Glinka (SIEMENS, 2003)



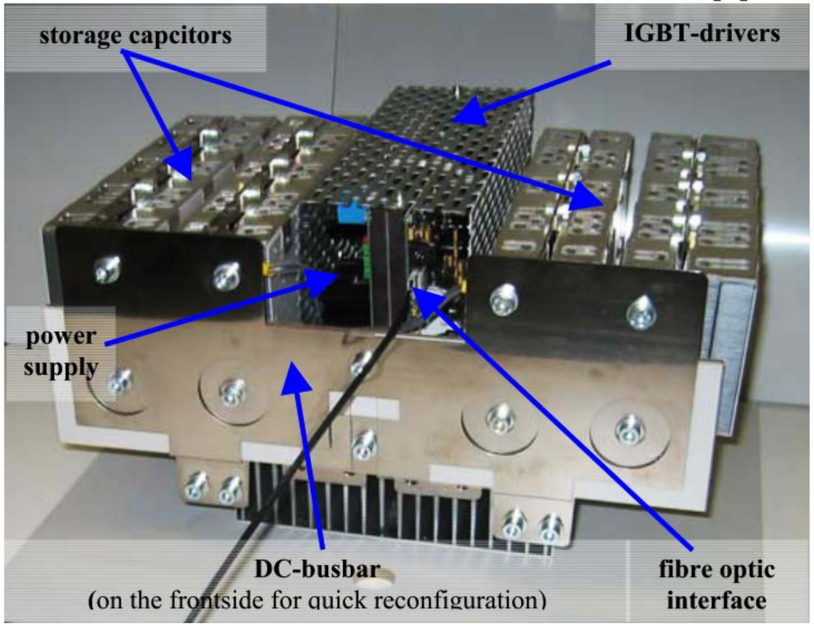
PET topology using M2LC converter



▶ Modular Multilevel Converter

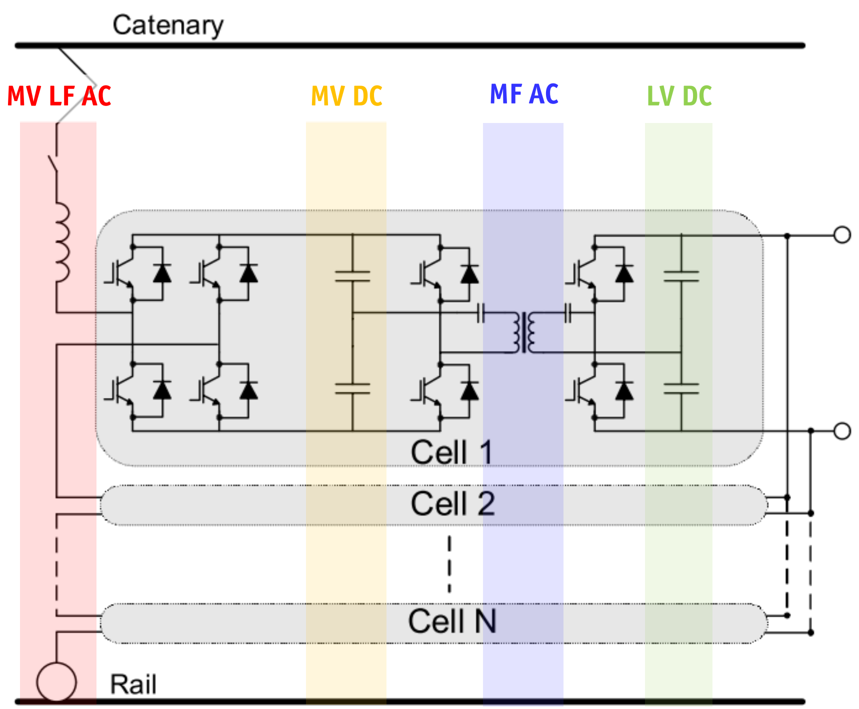
- Marquardt/Glinka (SIEMENS, 2003)

- Module Power 270kW
- Module Frequency 350Hz

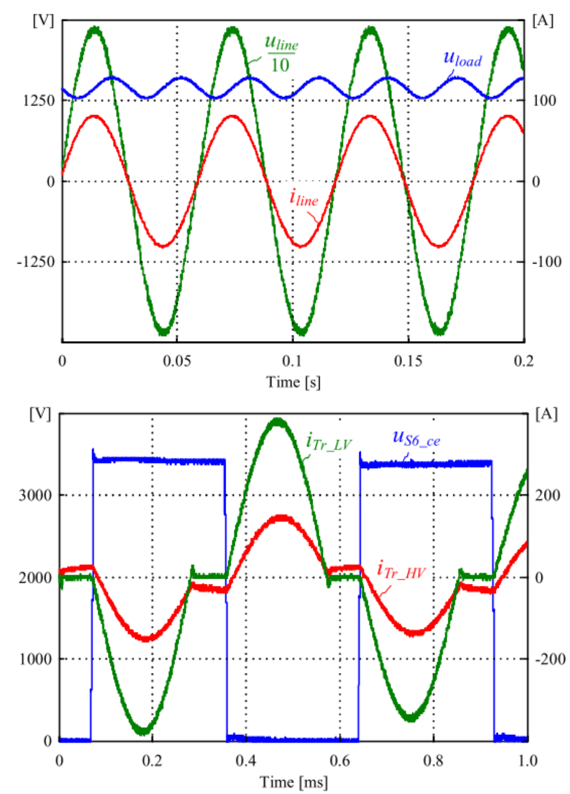


▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages

- Zhao et al. (ABB, 2011)



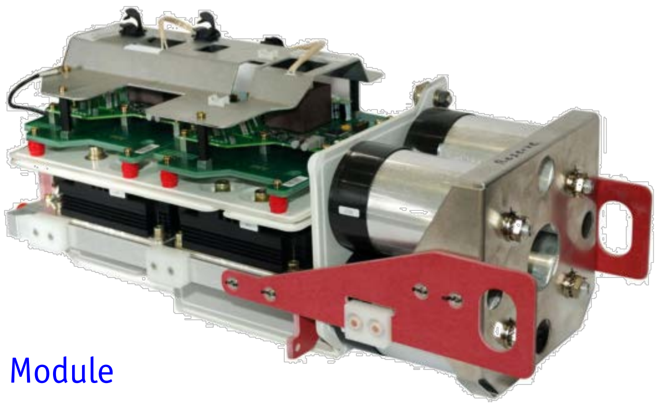
PET topology with cascaded H-bridges and resonant (LLC)DC-DC stages



► Cascaded H-Bridges and Resonant LLC DC-DC Stages

- Zhao et al. (ABB, 2011)

MV Module



LV Module

Assembled Converter

- Module Power 170 kW
- Frequency 2kHz

SST Design Remark

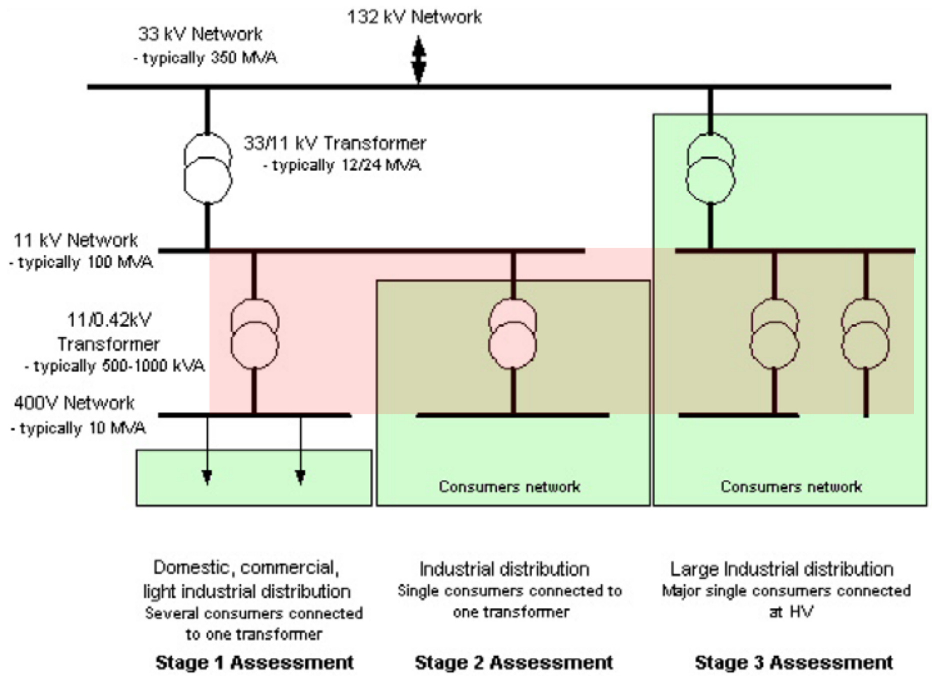
Current Ratings
Cooling Considerations
MF Transformer Design
Flux Balancing

► Current Ratings – Overcurrent Requirements

- MV Transformers must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)

- Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)

- Power Electronics: Very Short Time Constants!

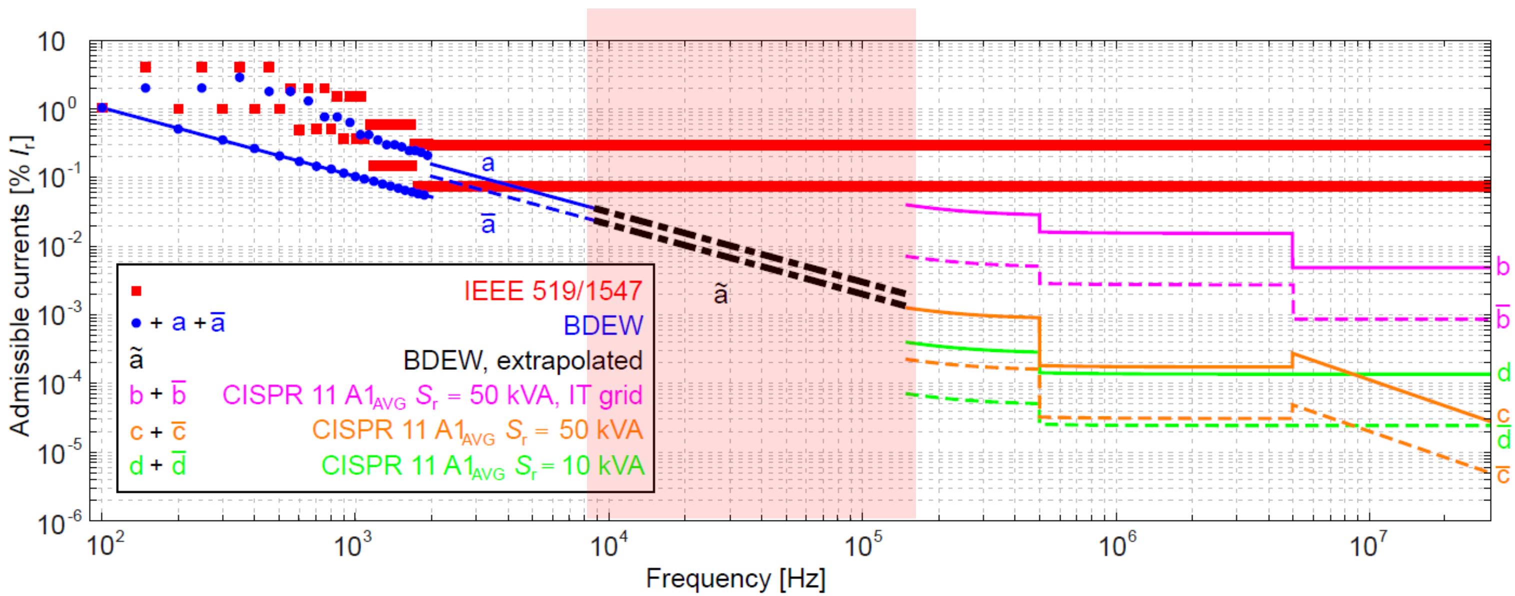


▶ Grid Harmonics and EMI Standards

- Medium Voltage Grid Considered Standards (Burkart, 2012)

- IEEE 519/1547
- BDEW
- CISPR

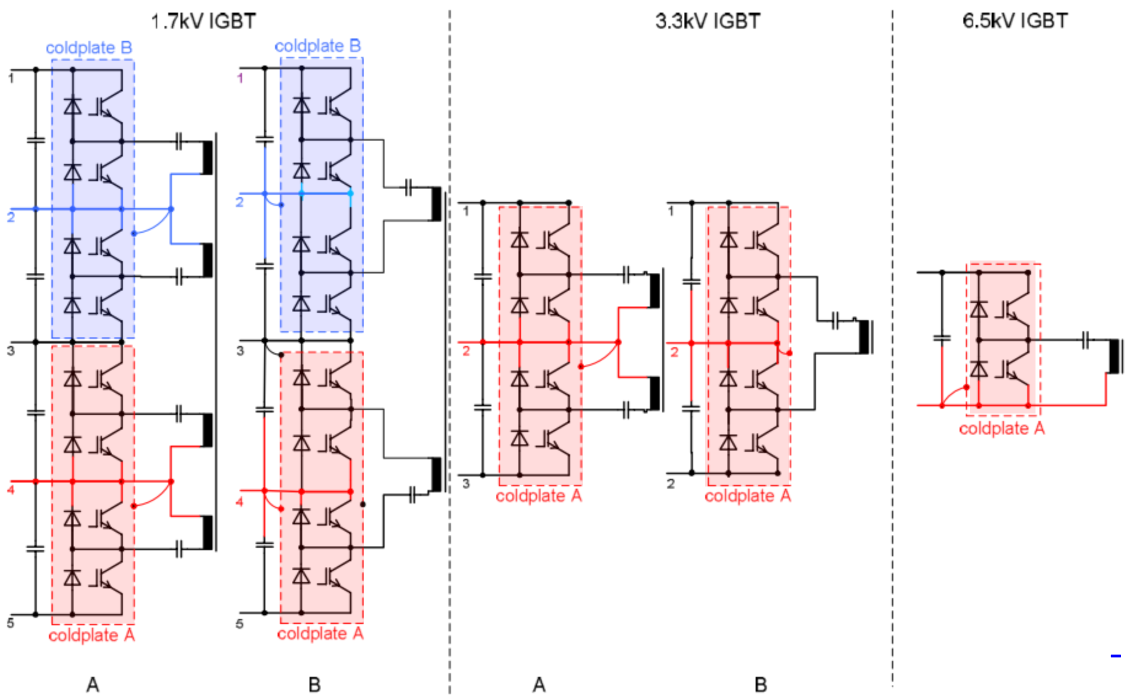
- Requirements on Switching Frequency and EMI Filtering



▶ Semiconductor Cooling and Isolation

- 1.7kV IGBTs → Semiconductor Modules on Cold Plates/Heat Sinks Connected to Different Potentials (CM Voltage Problems)

- 3.3kV or 6.5kV IGBTs → Isolation Provided by the Modules' Substrate, No Splitting of the Cooling System Necessary.



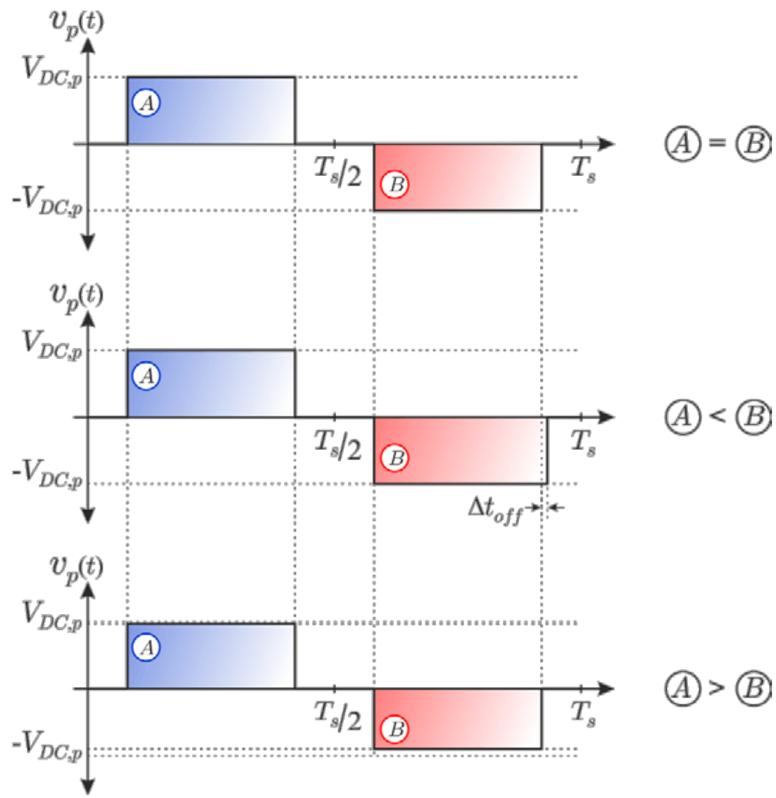
- Hoffmann (2009)

▶ Flux Balancing - DC Magnetization

- Higher Losses
- Over-currents
- Audible Noise

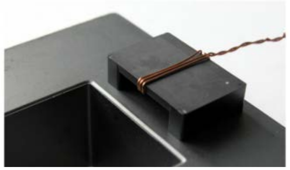
- Diff. Turn-on/Turn-off Times

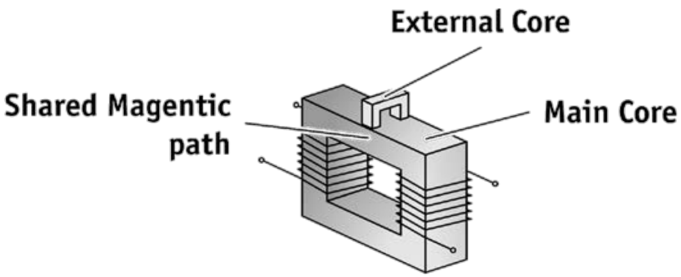
- Diff. Switch On-Characteristics

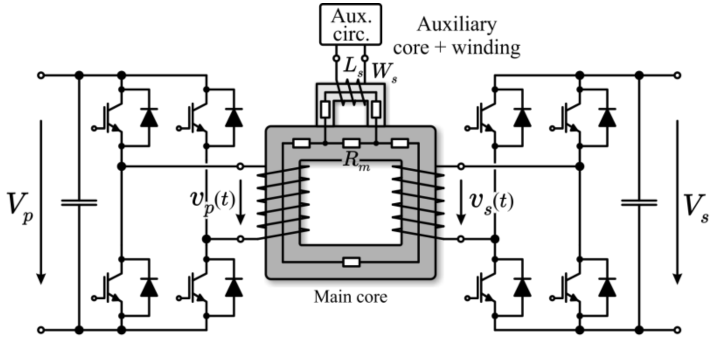


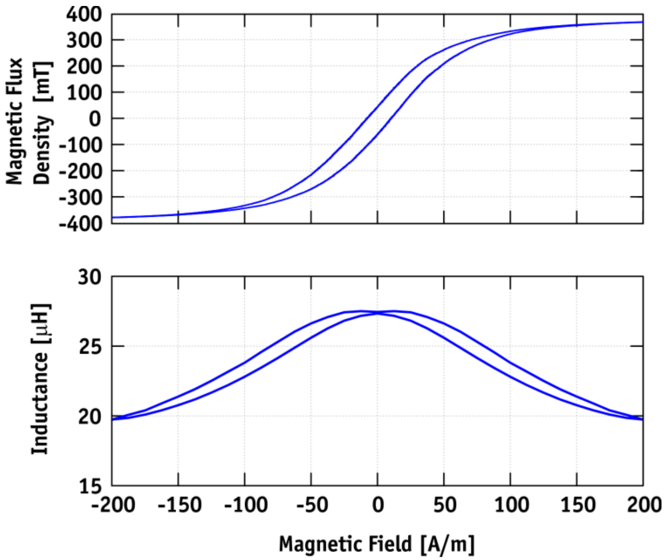
► Flux Density Transducer – The Magnetic Ear

- Shared Magnetic Path between Main and Auxiliary Core
- Change in Inductance on the Auxiliary Core is Related to the Magnetization State



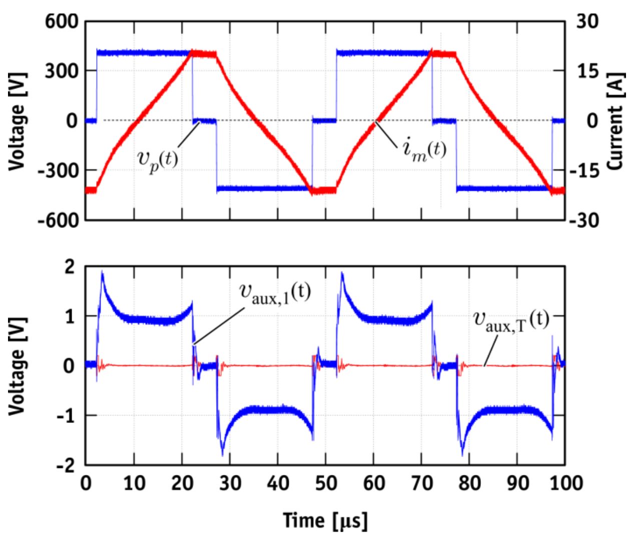


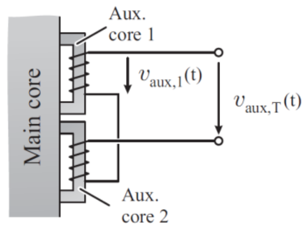


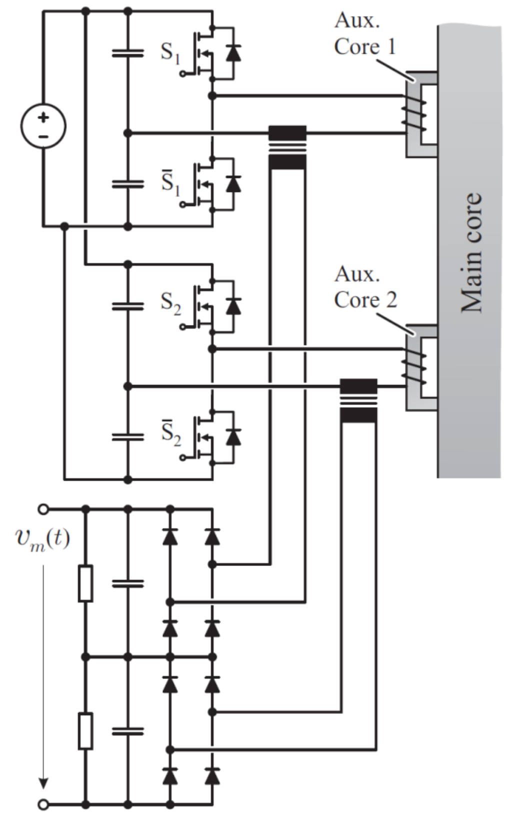


▶ Flux Density Transducer – The Magnetic Ear

- Compensation Network to Decouple Main and Auxiliary Flux



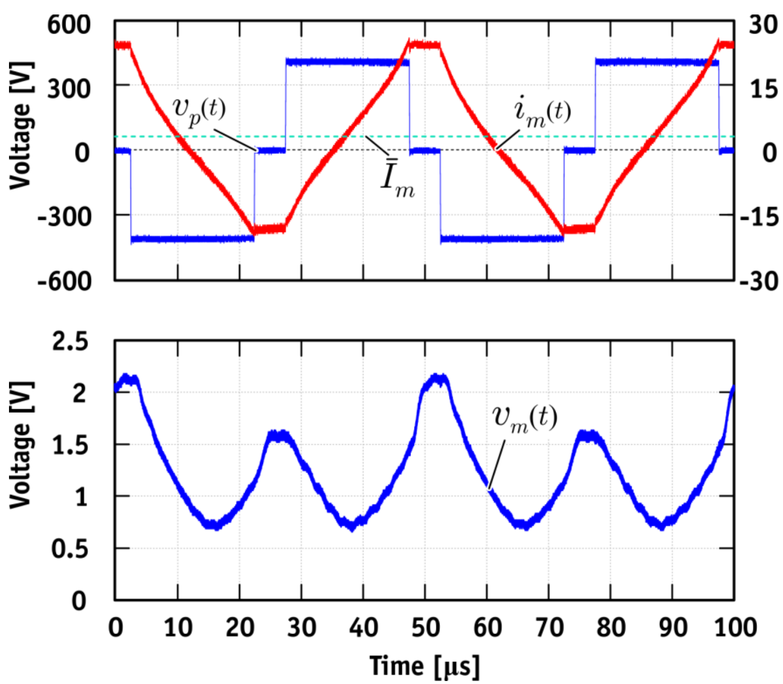




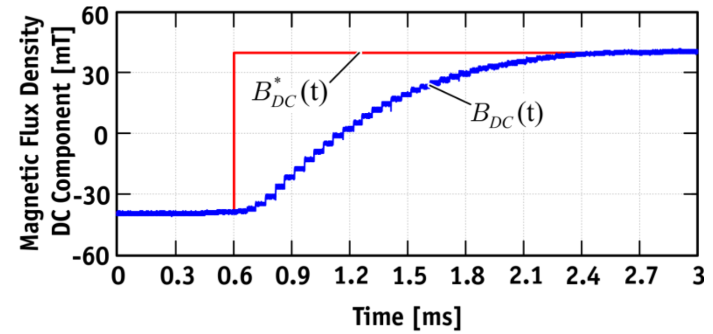
- Interleaved Operation for Maximum Bandwidth (ETH/Ortiz, 2013)

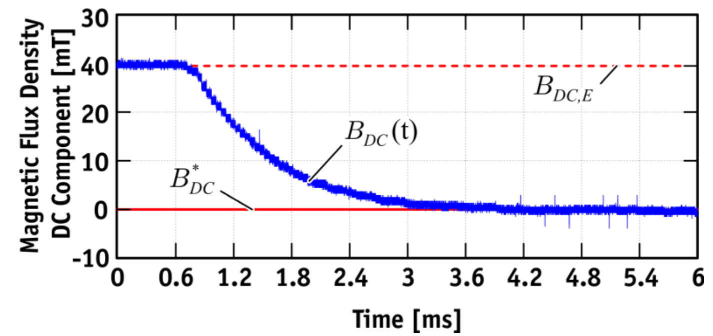
► Flux Density Transducer – The Magnetic Ear

- Transducer Output for Biased Magnetic Operation



- Closed Loop Response
  - Reference Step
  - Disturbance Rejection

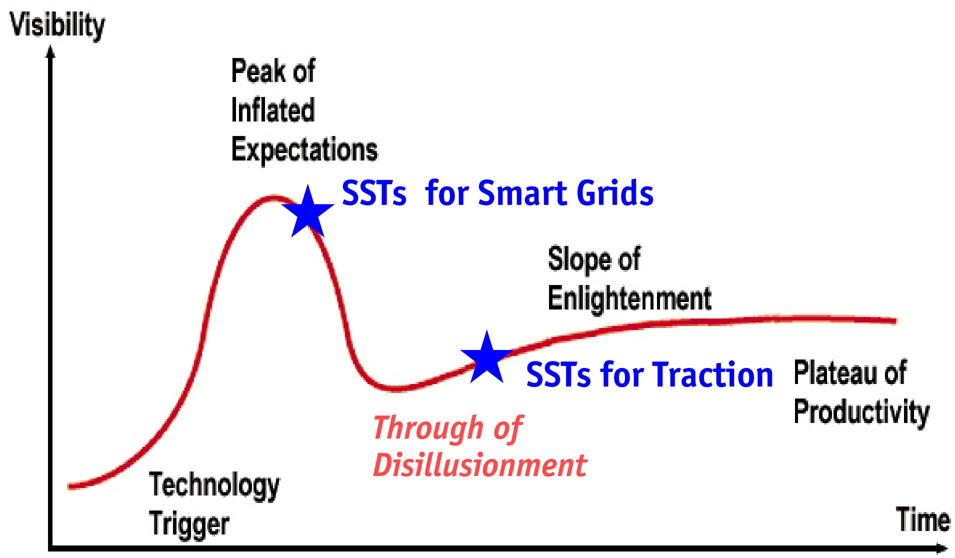




Summary / Outlook

▶ Technology Hype Cycle

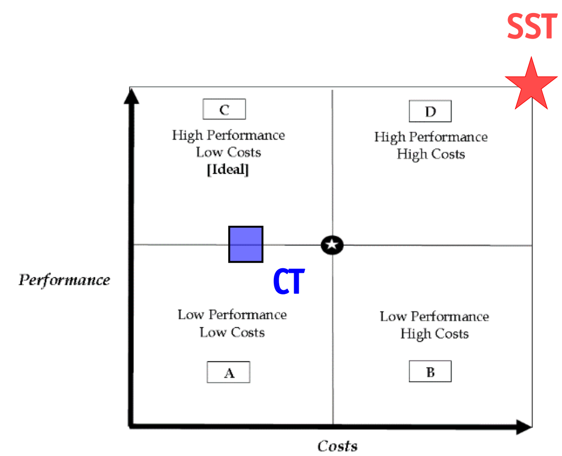
- Different State of Development of SSTs for Smart Grid and Traction Applications



► SST Limitations – Application Areas

- SST Limitations

- Efficiency (Rel. High Losses 3-6%)
- High Costs (Cost-Performance Ratio still to be Clarified)
- Limited Volume Reduction vs. Conv. Transf. (Factor 2-3)
- Limited Overload Capability
- (Reliability)

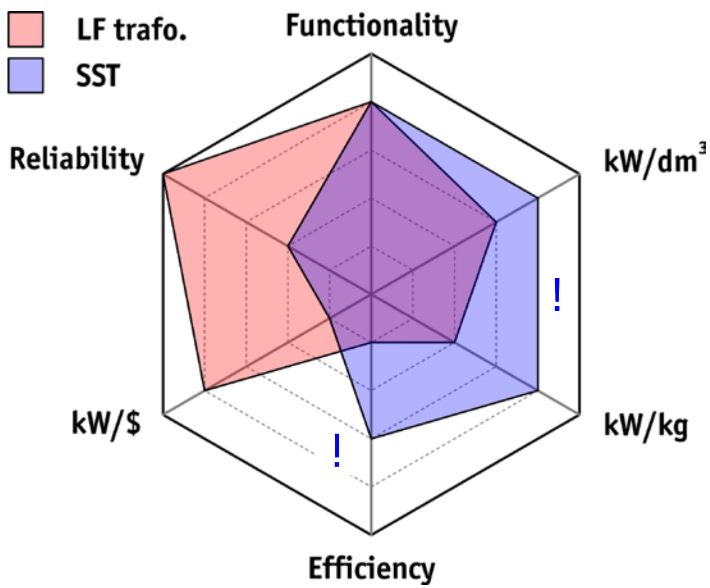


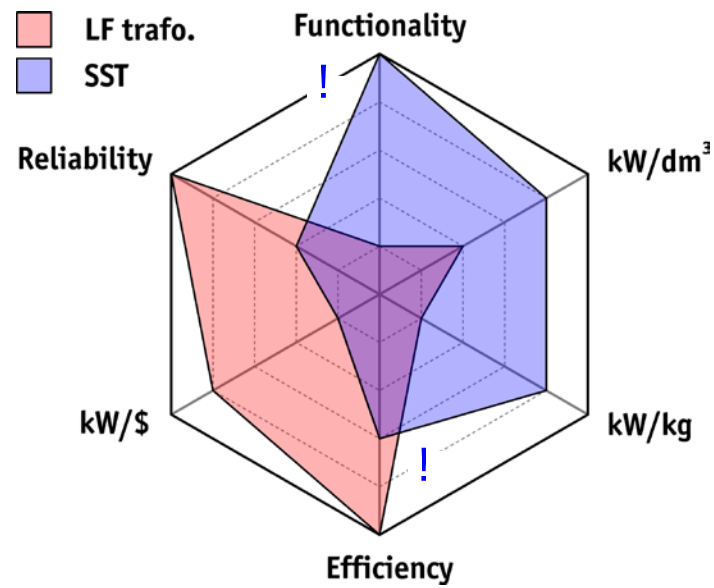
- Potential Application Areas

► Applications for Volume/Weight Limited Systems where 3-4 % of Losses Could be Accepted

- Traction Vehicles
- UPS Functionality with MV Connection
- Temporary Replacement of Conv. Distribution Transformer
- Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
- Military Applications

► Application Areas → SST Advantages/Weaknesses





- Traction - LF Transf. vs. SST

- Distribution - LF Transf. vs. SST

► Main SST Optimization Potential

- Cost & Complexity Reduction by Functionality Limitation (e.g. Unidirectional Power Flow)

► Future Research Topics

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- **MF Transformer Construction featuring High Insulation Voltage**
- **Thermal Management (Air and H2O Cooling, avoiding Oil)**
- "Low" Voltage SiC Devices for Efficiency Improvement

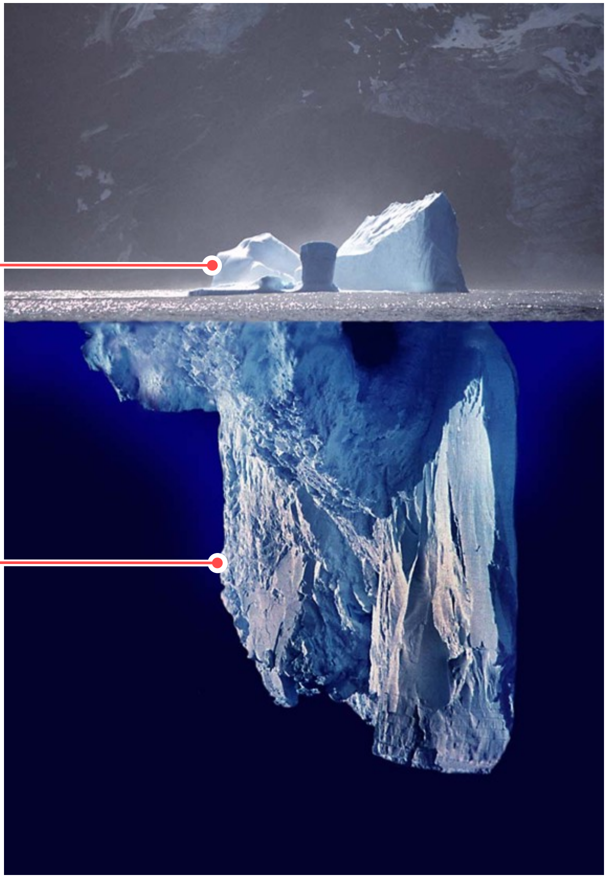
- **Multi-Level vs. Two-Level Topologies with SiC Switches → "Optimum" Number of Levels**
- Multi-Objective Cost / Volume /Efficiency Optimization (Pareto Surface)
- SST Protection (e.g. Overvoltage)
- SST Reliability

- **Hybrid (LF // SST) Solutions**
- SST vs. FACTS (Integration vs. Combination of Transformer and Power Electronics)
- System-Oriented Analysis → Clarify Benefits on System Level (Balancing the Low Eff. Drawback)

▶ Future Research Topics

Done !

To be Done...



► 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)
- 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

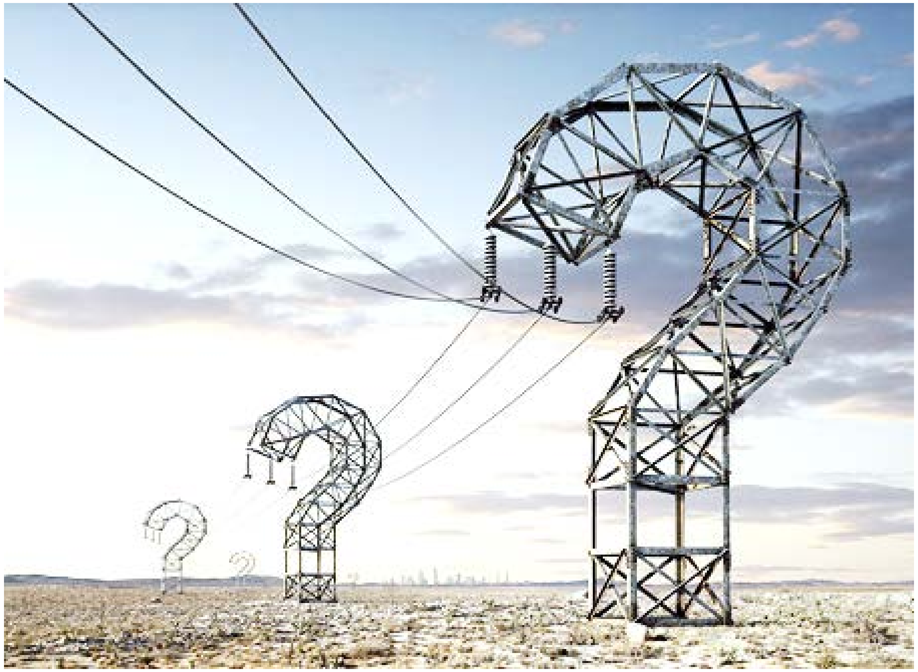
@ Generation End (e.g. Nacelle of Windmills)
@ Load End - Micro- or Nanogrids (incl. Locomotives, Ships etc.)

→ Environments with Pervasive Power Electronics for Energy Flow Control (No Protection Relays etc.)
→ Environments which Could be Designed for SST Application

- SST is NOT AT ALL Reflecting the Actual Functionality → EEnergy Router (?)

Thank You!

Questions?



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Authors

Johann W. Kolar (F´10) received his M.Sc. and Ph.D. degree (summa cum laude / promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria. Since 1982 he has been working as an independent international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drives. He has proposed numerous novel converter topologies and modulation/control concepts, e.g., the VIENNA Rectifier, the SWISS Rectifier, and the three-phase AC-AC Sparse Matrix Converter. Dr. Kolar has published over 400 scientific papers at main international conferences, over 150 papers in international journals, and 2 book chapters. Furthermore, he has filed more than 110 patents. He was appointed Assoc. Professor and Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich on Feb. 1, 2001, and was promoted to the rank of Full Prof. in 2004. Since 2001 he has supervised over 60 Ph.D. students and PostDocs.

The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, e.g. for data centers, More-Electric-Aircraft and distributed renewable energy systems, and on Solid-State Transformers for Smart Microgrid Systems. Further main research areas are the realization of ultra-compact and ultra-efficient converter modules employing latest power semiconductor technology (SiC and GaN), micro power electronics and/or Power Supplies on Chip, multi-domain/scale modeling/simulation and multi-objective optimization, physical model-based lifetime prediction, pulsed power, and ultra-high speed and bearingless motors. He has been appointed an IEEE Distinguished Lecturer by the IEEE Power Electronics Society in 2011.

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

He initiated and/or is the founder/co-founder of 4 spin-off companies targeting ultra-high speed drives, multi-domain/level simulation, ultra-compact/efficient converter systems and pulsed power/electronic energy processing. In 2006, the European Power Supplies Manufacturers Association (EPSMA) awarded the Power Electronics Systems Laboratory of ETH Zurich as the leading academic research institution in Power Electronics in Europe.

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

Authors

Gabriel Ortiz (M´10) studied Electronics Engineering at Universidad Técnica Federico Santa María, Valparaíso, Chile, joining the power electronics group early on 2007. During his Master Thesis he worked with reconfiguration of regenerative and non-regenerative cascaded multilevel converters under fault condition, obtaining maximum qualification on his Thesis Examination. He received his M.Sc. degree in December 2008, and he has been a Ph.D. student at the Power Electronic Systems Laboratory, ETH Zürich, since February 2009.

The focus of his research is in solid state transformers for future smart grid implementations and traction solutions. Specifically, his PhD. research deals with the modeling, optimization and design of high-power DC-DC converters operated in the medium frequency range with focus on modeling of soft-switching processes in IGBTs and medium frequency transformer design, among others.