ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PEDG 2013

Solid State Transformer Concepts in Traction and Smart Grid Applications

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Schedule / Outline

- ► Introduction
- ► Basic SST Concepts
- ► DAB and ZVS/ZCS of IGBTs

- ► 3ph. AC/AC SST Concepts for Distribution Applications
- ► 1ph. AC/DC SST Traction Applications
- ► SST Design Remarks
- ► Conclusions / Questions / Discussion

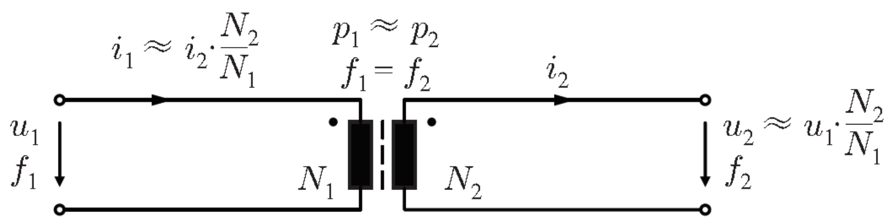
Introduction

Transformer Basics
Future Traction Vehicles
Future Smart Grid
SST Concept

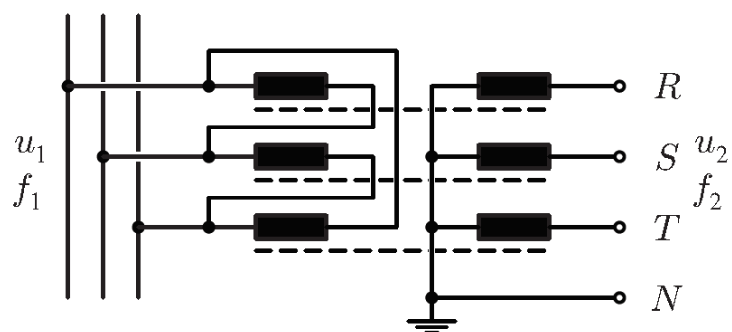
▶ Classical Transformer - Basics

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

- Operating Frequency * 50/60Hz (El. Grid, Traction) or $16^2/_3$ Hz (Traction)
- Operating Voltage * 10kV or 20 kV (6...35kV) - Distribution Grid MV Level (u_{SC} = 4...6% typ.)
  * 15kV or 25kV - Traction (1ph., u_{SC} = 20...25% typ.)
  * 400V - Public LV Grid



- Voltage Transf. Ratio * Fixed
- Current Transf. Ratio * Fixed
- Active Power Transf. * Fixed (P_1=P_2)
- React. Power Transf. * Fixed (Q_1=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

- Advantages

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

- 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

- No Controllability
- Low Mains Frequency Results in Large Weight / Volume

► Classical Transformer - Basics

- 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

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

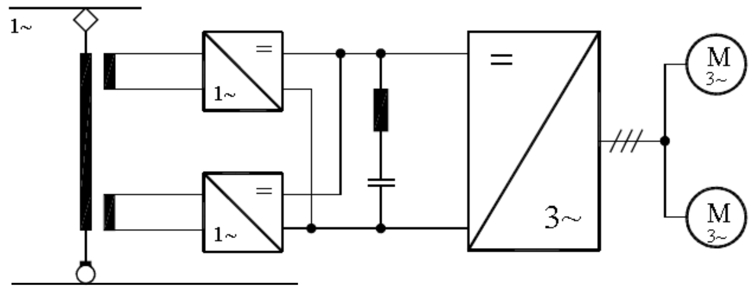
$$P_{Wdg} \propto \frac{1}{l}$$

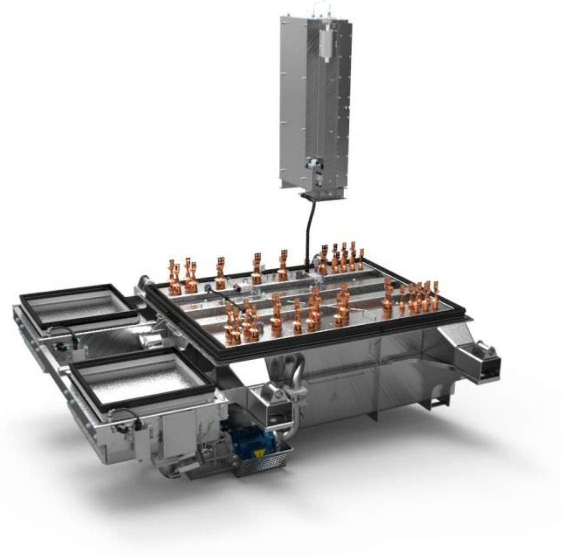
- Higher Relative Volumes (Lower kVA/m^3) Allow to Achieve Higher Efficiencies

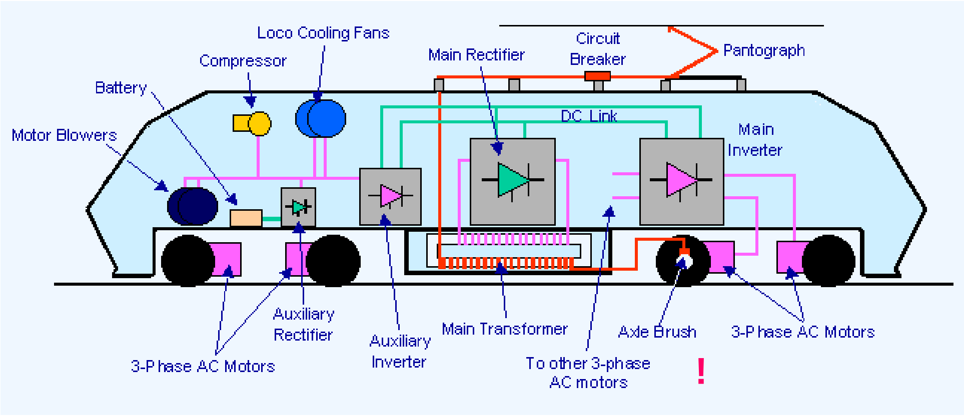
Classical / Next Generation Locomotives

▶ Classical Locomotives

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





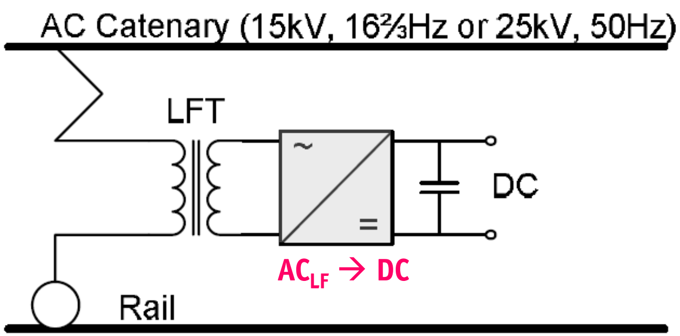


- Transformer:

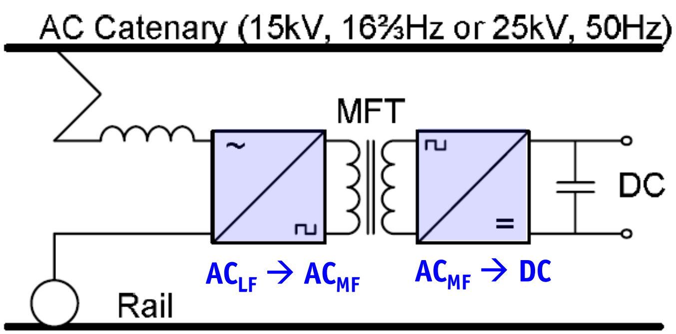
Transformer:	Efficiency	90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
	Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
	Power Density	2...4 kg/kVA

▶ 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).



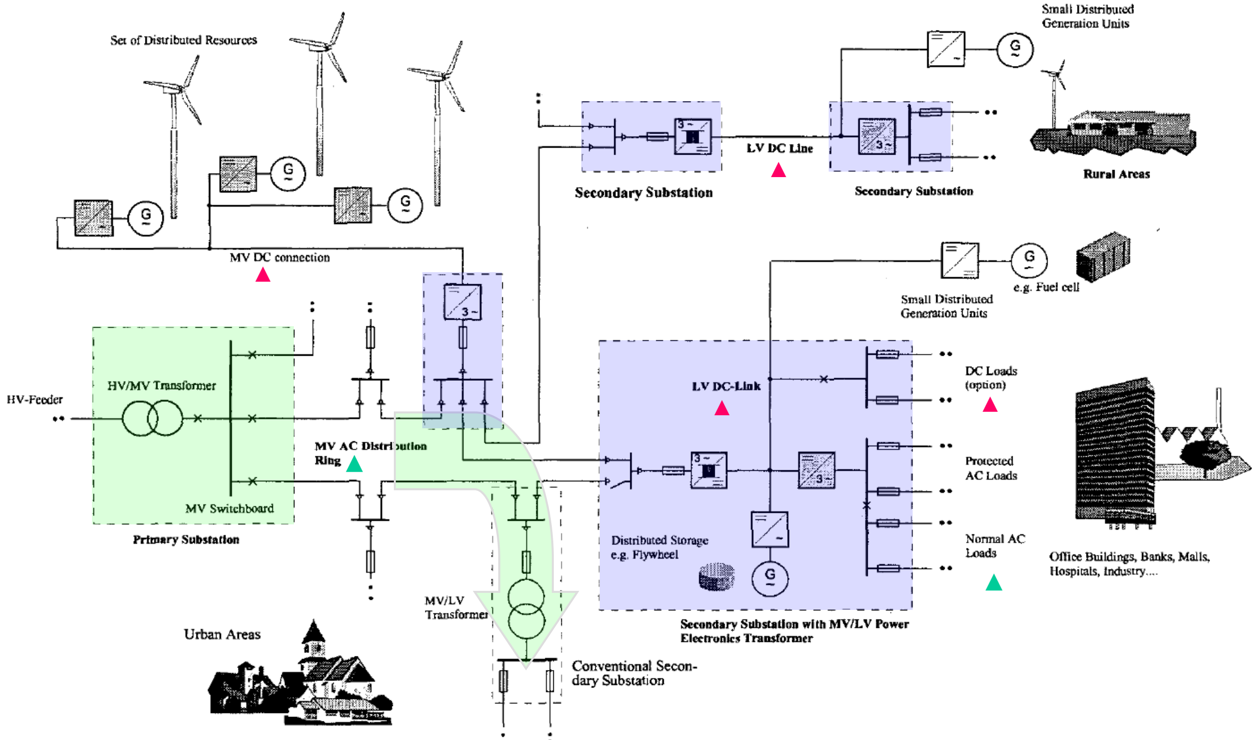
AC-DC conversion with medium frequency transformer (MFT).

- Replace Low Frequency Transformer by *Medium Frequ.* (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.

Future Smart EE Distribution

▶ 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

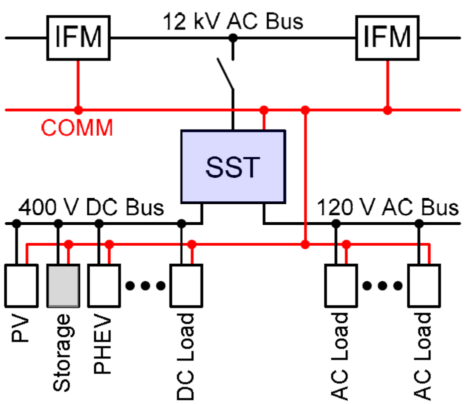
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

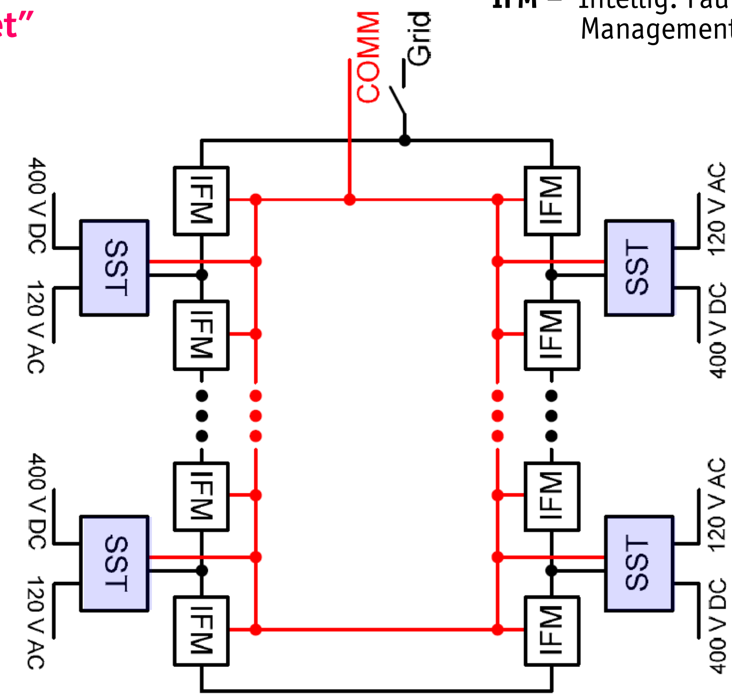
- Huang et al. (2008)

- 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





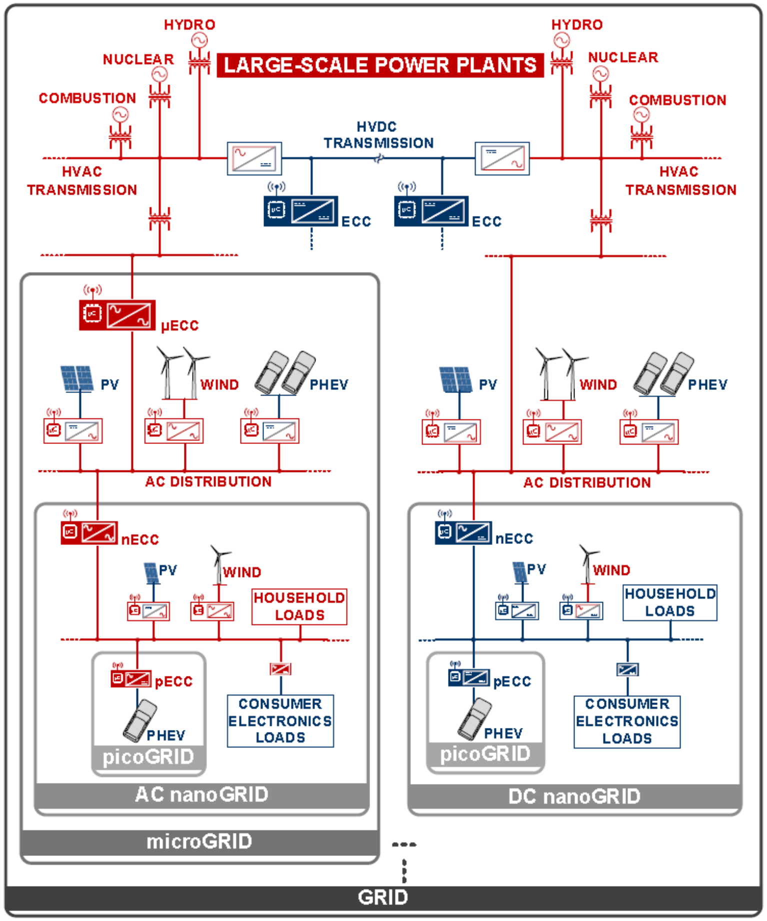
- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl

▶ Smart Grid Concept

- Borojevic (2010)

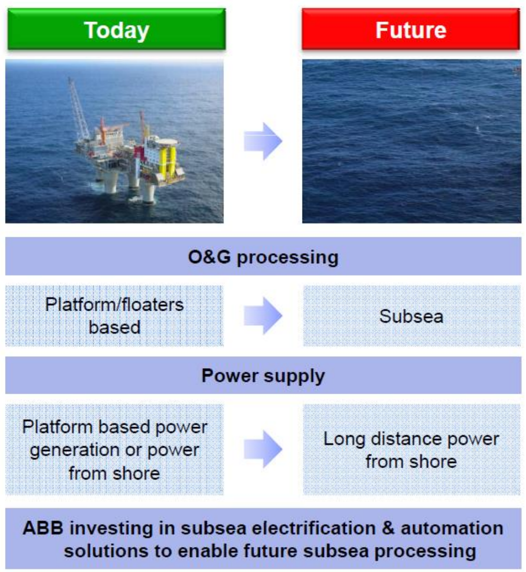
- Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids
  - Distr. Syst. of Contr. Conv. Interfaces
  - Source / Load / Power Distrib. Conv.
  - Picogrid-Nanogrid-Microgrid-Grid Structure
  - Subgrid Seen as Single Electr. Load/Source
  - ECCs provide Dyn. Decoupling
  - Subgrid Dispatchable by Grid Utility Operator
  - Integr. of Ren. Energy Sources

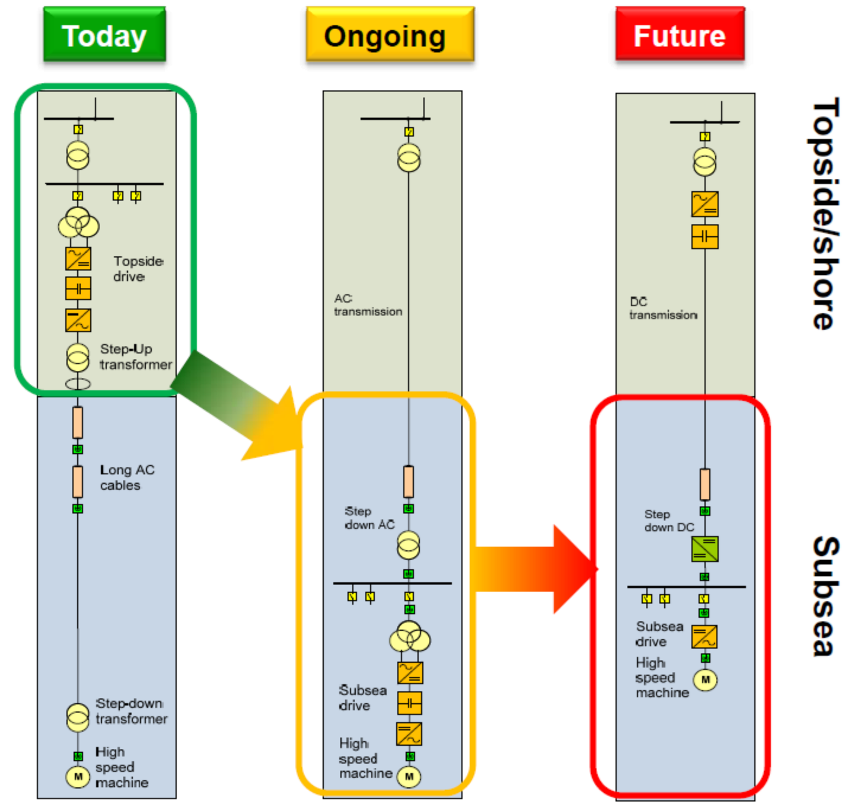
- ECC = Energy Control Center
  - Energy Routers
  - Continuous Bidir. Power Flow Control
  - Enable Hierarchical Distr. Grid Control
  - Load / Source / Data Aggregation
  - Up- and Downstream Communic.
  - Intentional / Unintentional Islanding for Up- or Downstream Protection
  - etc.



▶ Future Subsea Distribution Network – O&G Processing

- Devold (ABB 2012)



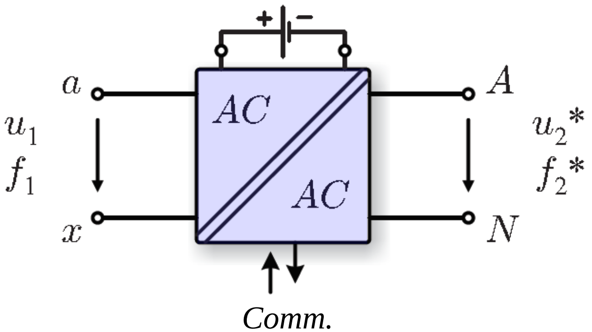


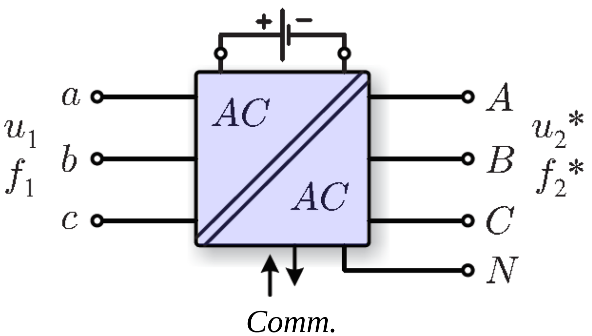
- Transmission Over DC, No Platforms/Floaters
- Longer Distances Possible
- Subsea O&G Processing

- Weight Optimized Power Electronics

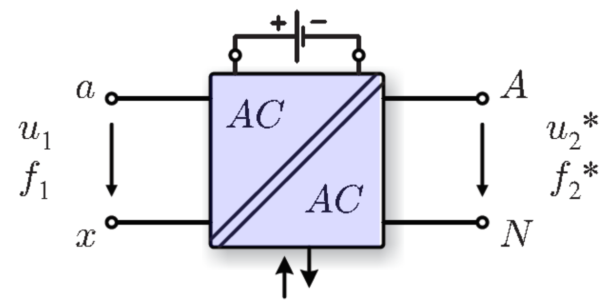
▶ SST Functionalities

- 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

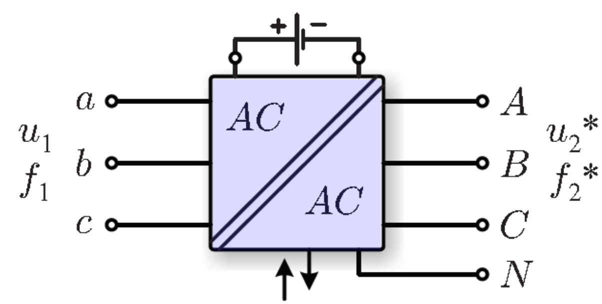




▶ Terminology



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



Basic SST Structures

- Power Conversion

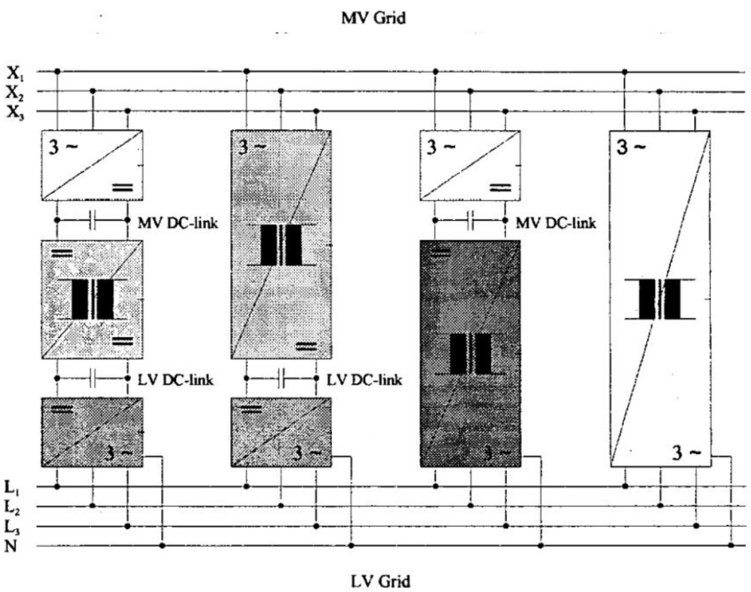
- Three-Stage Power Conversion with MV and LV DC Link
- Two-Stage Concept with LV DC Link (Connection of Energy Storage)
- Two-Stage Concept with MV DC Link (Connection to HVDC System)
- Direct or Indirect Matrix-Type Topologies (No Energy Storage)

- Realization of 3ph. Conversion

- Direct 3ph. Converter Systems
- Three-Phase Conn. of 1ph. Systems
- Hybrid Combinations

- Handling of Voltage & Power Levels

- Multi-Level Converters / Single Transf.
- Cascading / Parallel Connection of Modules
- Series / Parallel Connection of Semicond.
- Hybrid Combinations

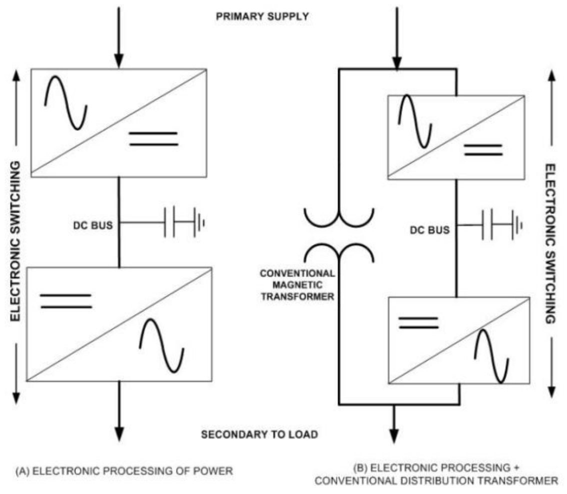


- Medium Freq. Required for Achieving Low Weight (Low Realiz. Effort) *AND* High Control Dynamics

► Challenges of Semiconductor Control of Distribution-Class Devices

- Heydt (2010)

- Losses / Efficiency
- Reliability
- Insulation Coordination
- Cost



Phenomenon	*Basic problem*	*Mitigation possibilities*
Basic impulse level – insulation coordination	Voltage breakdown of typical semiconductor components may be problematic (below distribution class voltages)	• Use of voltage limiting devices • Use lower distribution voltages • Development of more suitable semiconductor materials
Switching losses	High power loss, proportional to switching frequency	Low loss switching strategies (e.g., zero voltage or zero current switching)
Bulk resistive losses in semiconductors	I^2R loss in semiconductors	• Development of more suitable semiconductor materials • Use of low current configurations
Cost of components	High cost of high power switches	• Mass production • Development of better manufacturing techniques
Cooling semiconductor components	Losses in semiconductor switches	• Oil and air cooled technologies • Reduce losses in semiconductor switches
Isolation and safety	No ohmic isolation afforded by semiconductor switches	• Principle of 'insulation by isolation' • Judicious use of circuit breakers to isolate circuits • Use a magnetic transformer for isolation
Component lifetime	Loss of life due to heat	• Better cooling • Reduce losses

- Hybrid Approach of SST+Magnetic Transf. as Alternative to Pure SST Energy Flow Contr.

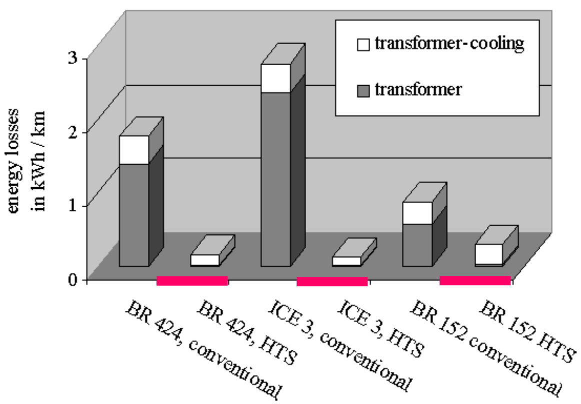
Remark

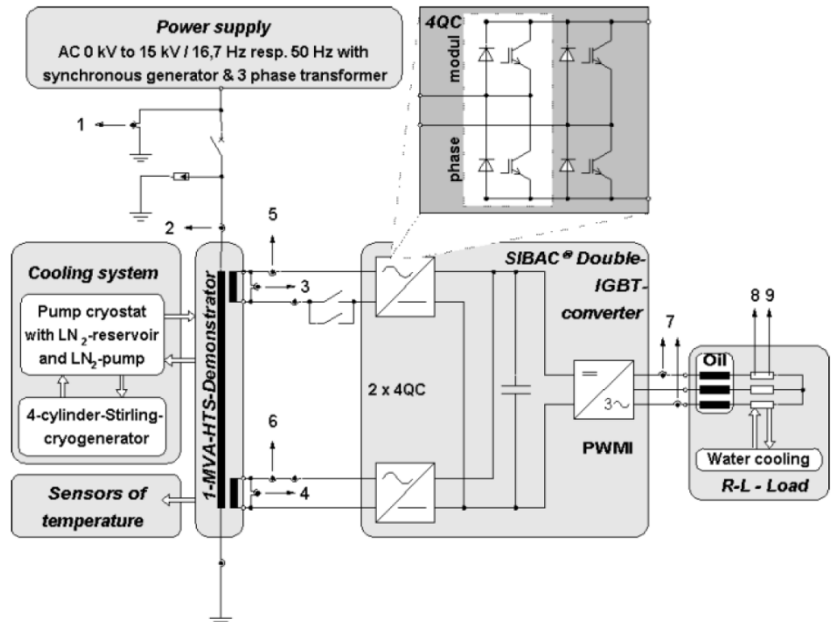
Volume / Weight Reduction & Efficiency Increase by Application of HT Superconductors

▶ High Temp. Superconducting (HTS) LF Transformer for Rail Vehicles

- Specifications 1MVA, 25kV/ 2x1389V, 50Hz, u_{SC}=25%
- Current Density 21A/mm²
- Cooling 66K (Liquid Nitrogen)

- SIEMENS / TU Darmstadt (2001)





- Power Flow of Conv. Locomotives is Fully Controlled by 4QC → No SST Required for Control
- 99% Efficiency (Significant Loss Red. vs. Conv. Transf.) → Substantial Energy Saving
- 50% Smaller than Conv. Transformer
- No Fire Hazard / Contamination and Thermal Aging

▶ High Temp. Superconducting (HTS) LF Transformer for Grid Applications

- Oak Ridge Nat. Lab. (ORNL) & Waukesha Electr. Systems & SuperPower (Manufacturer)
- Target 28MVA, 69kV/12.47kV-Class

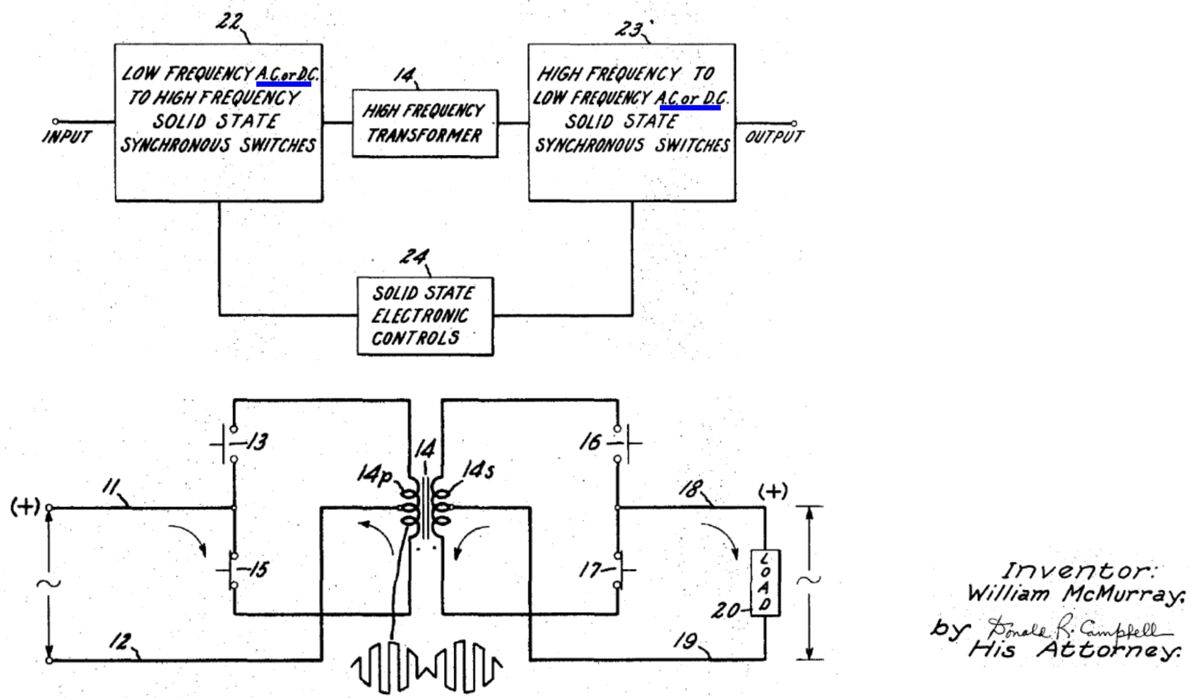
- Low Losses
- Self Fault Current Limitation (SFCL) Function (No Active Control)
- To be Installed in South. Calif. Edison Utility Substation 2013

Basic SST Concepts

Matrix-Type AC/AC Converters
Indirect Converter Topologies

▶ Electronic Transformer - McMurray 1968

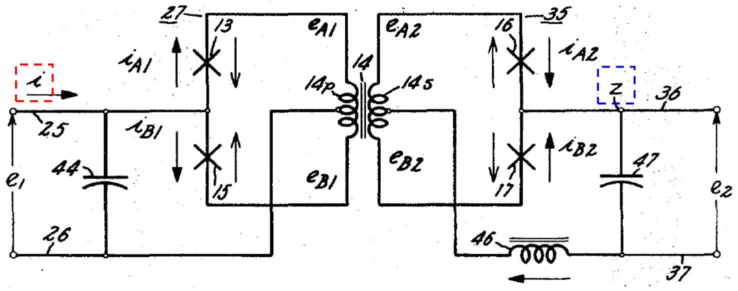
■ Matrix-Type f_1=f_2

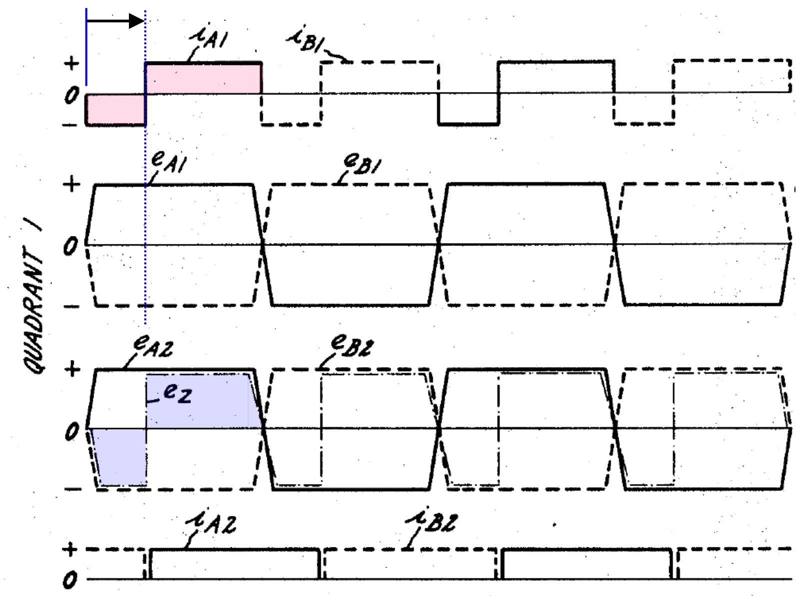


- Electronic Transformer = HF Transf. Link & Input and Output Sold State Switching Circuits
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption

▶ Electronic Transformer - McMurray 1968

■ Matrix-Type f_1=f_2

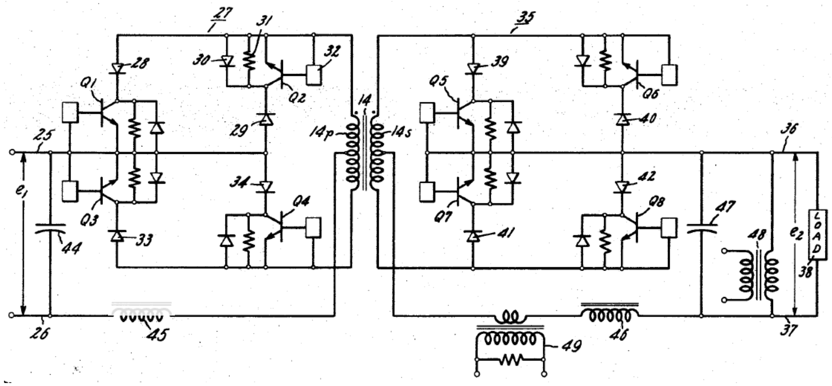


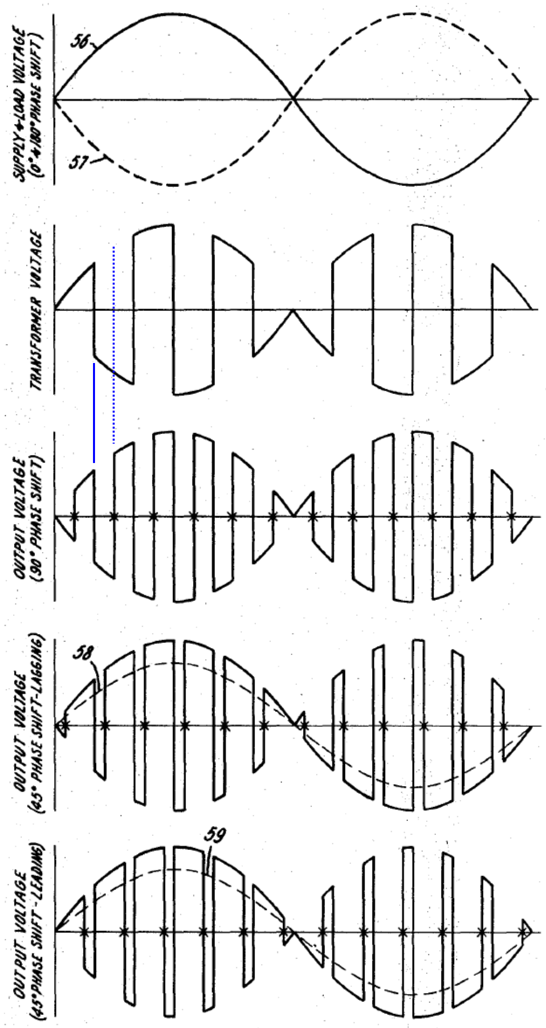


- 50% Duty Cycle Operation @ Primary and Secondary
- Output Voltage Control via Phase Shift Angle

▶ Electronic Transformer

■ **Matrix-Type f_1=f_2**

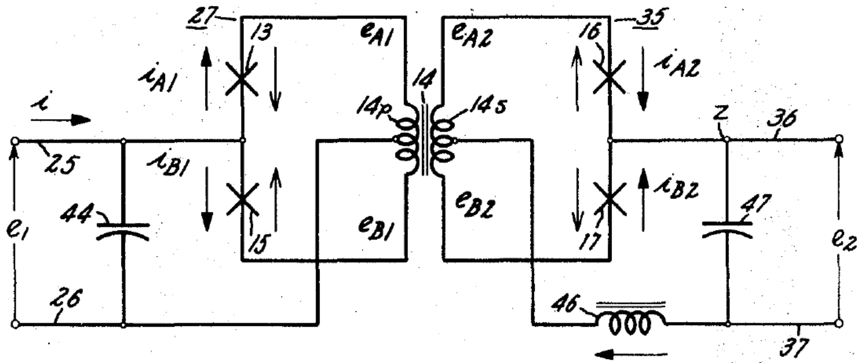


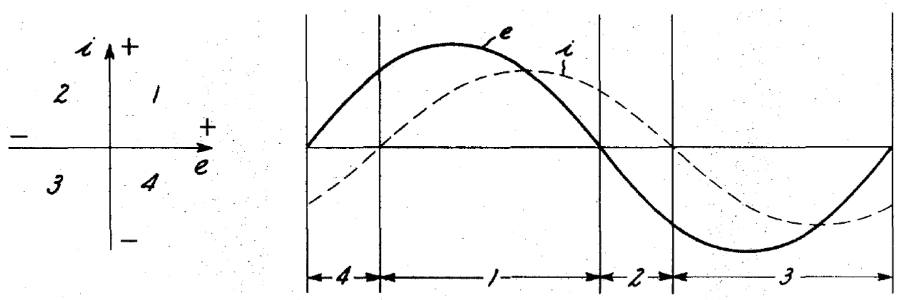


- **Inverse-Paralleled Pairs of Turn-off Switches**

▶ Electronic Transformer

■ Matrix-Type f_1=f_2

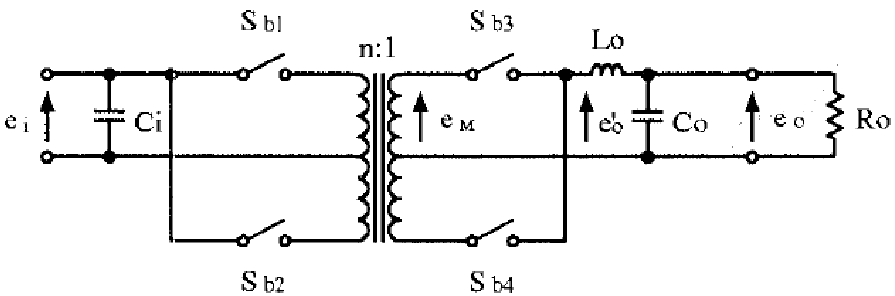


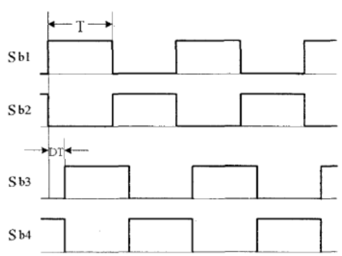


- Fully Bidirectional / 4Q-Operation
- Direct and Seamless Transition between the Quadrants

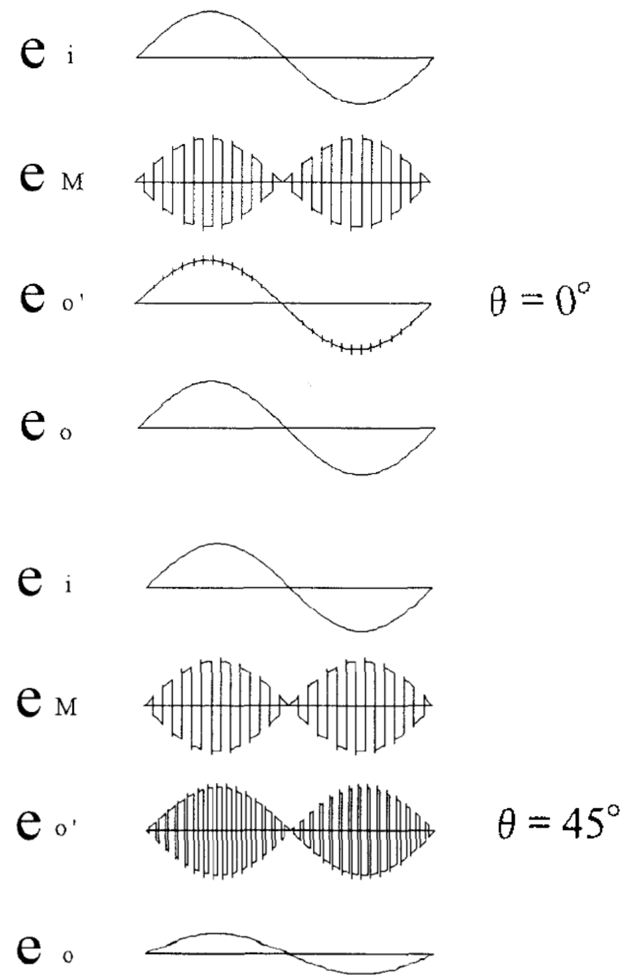
▶ Electronic Transformer

■ Matrix-Type $f_1=f_2$





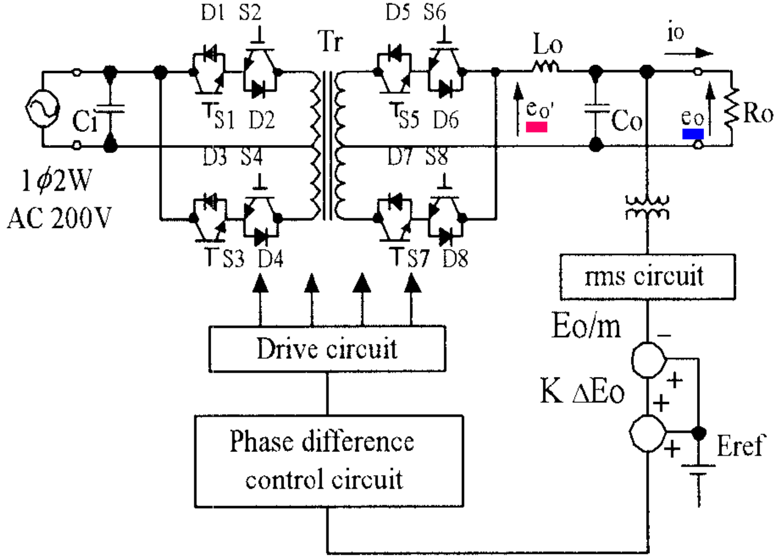
$$DT = \theta \cdot T/180$$

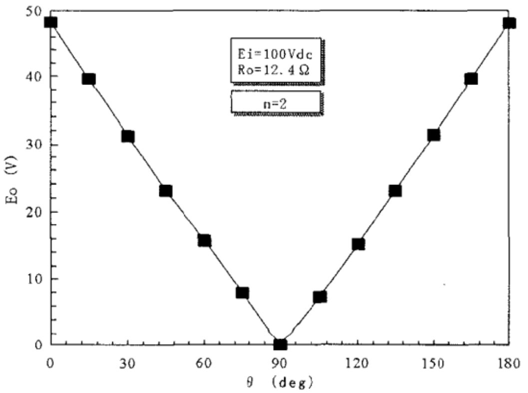


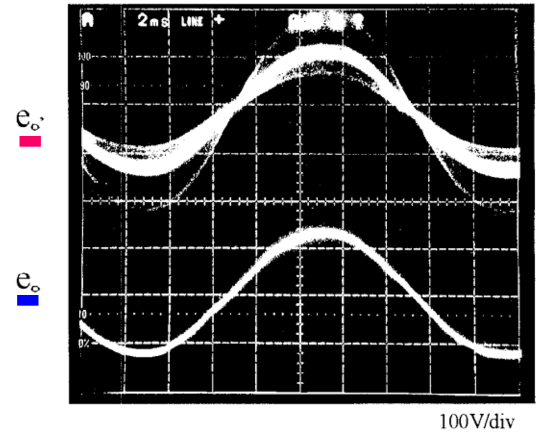
- Harada (1996) Based on McMurray Patent

▶ Electronic Transformer

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

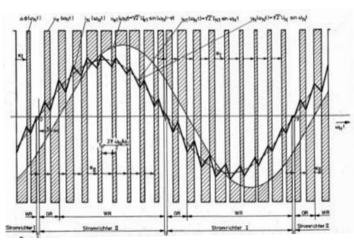


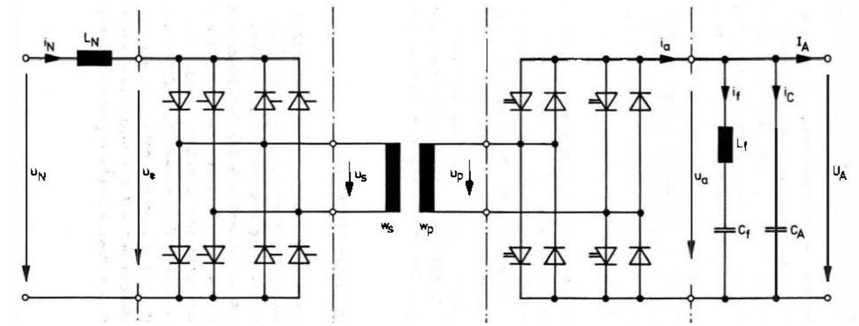


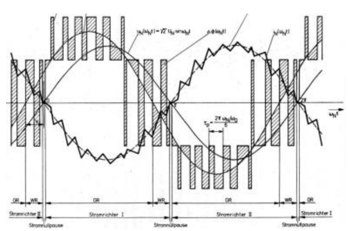


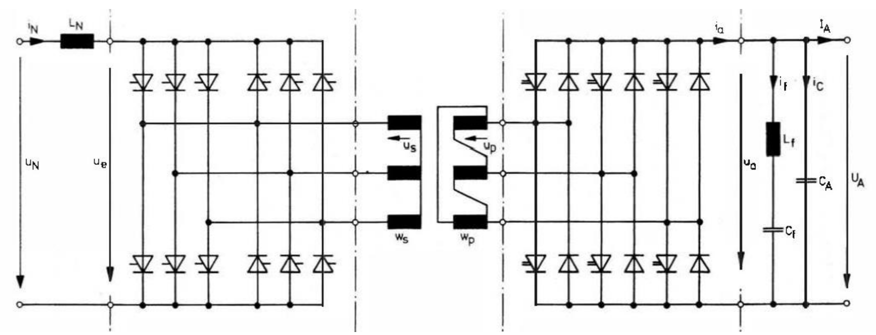
▶ Direct Matrix-Type 1ph. AC/DC Converter

- Mennicken (1978, f = 200Hz)
  I-Input, V-Output (McMurray)





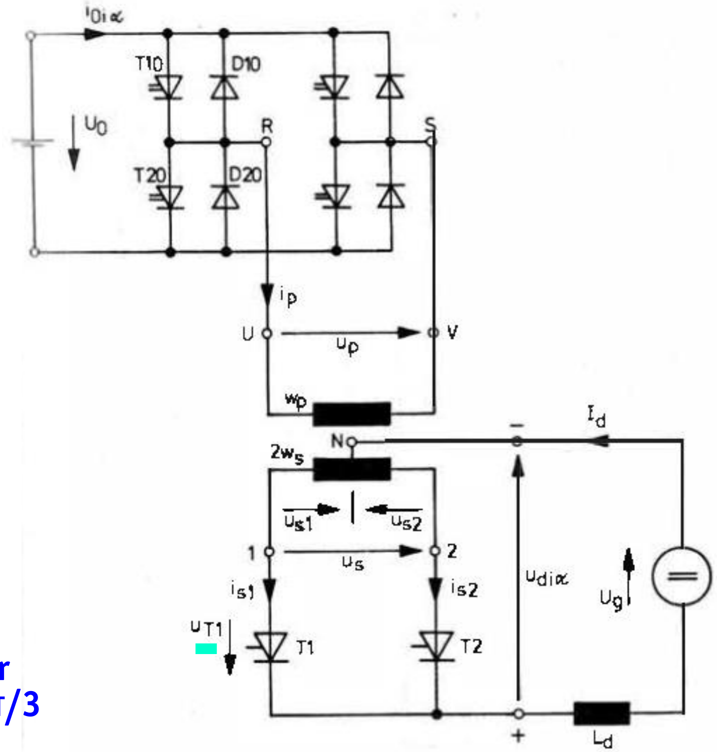


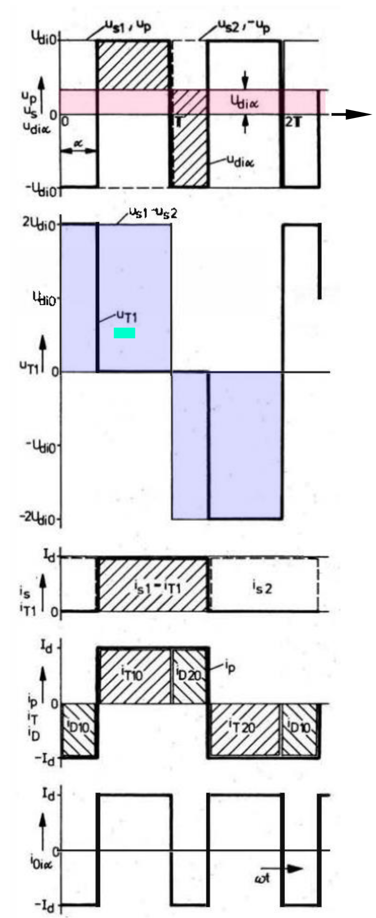


- Targeting Traction Application
- Combination of Forced Commutated VSC & Thyristor Cycloconverter
- VSC Defines Transformer Voltage & Generates Thyristor Converter Commutation Voltage
- Energy Flow Defined by Control Angle of Thyristor Converter !

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

- Mennicken (1978, f = 200Hz)
  I-Input, V-Output (McMurray)

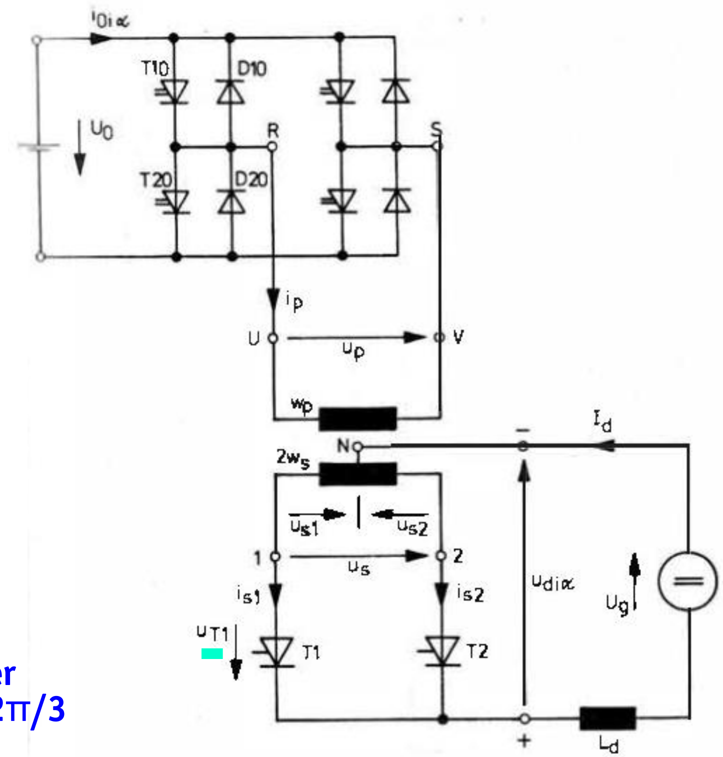


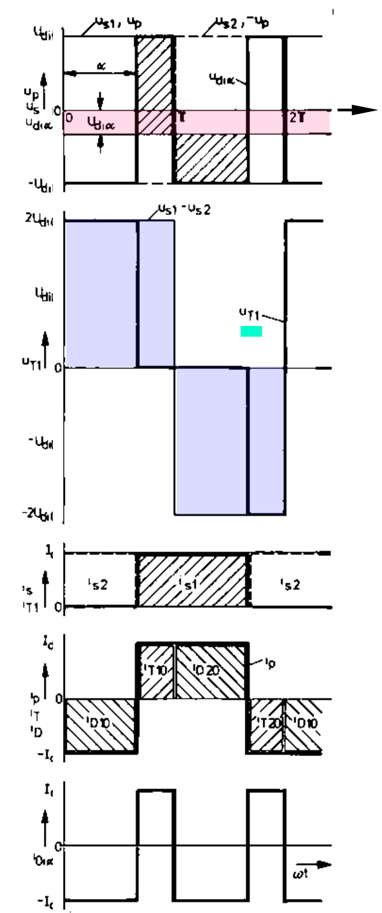


- **Thyristor Converter**
  Control Angle α= π/3

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

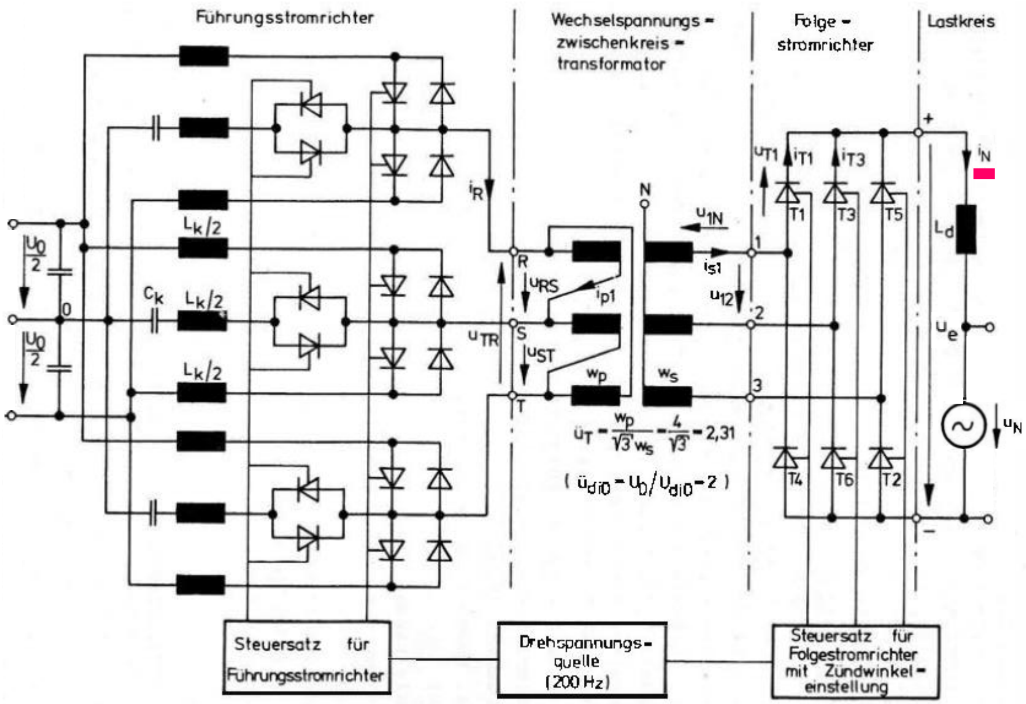
- Mennicken (1978, f = 200Hz)
  I-Input, V-Output (McMurray)

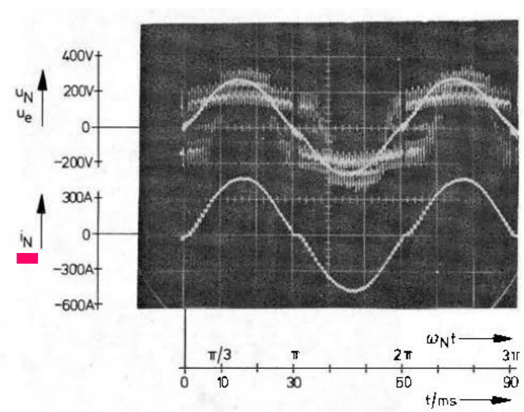




- Thyristor Converter
  Control Angle α= 2π/3

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

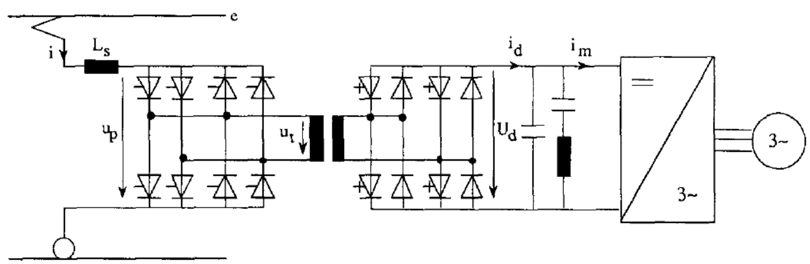


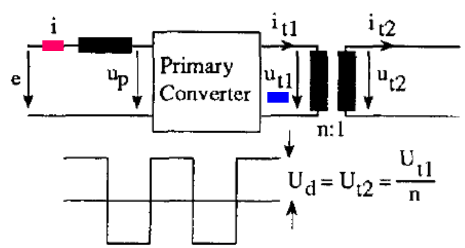


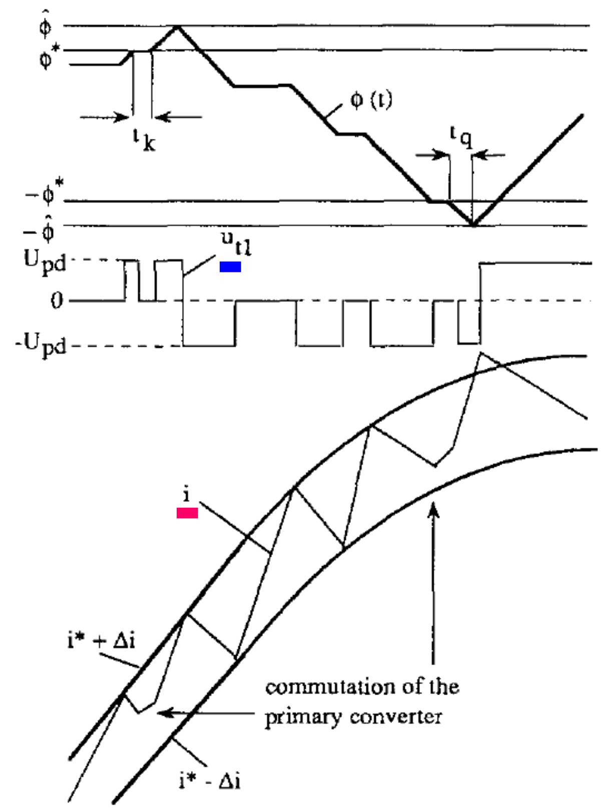
- **Experimental Verification (Switching Frequency f =200Hz, f_N=16$^2/_3$ Hz)**

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

- Östlund (1993)
  I-Input, V-Output (McMurray, Mennicken)



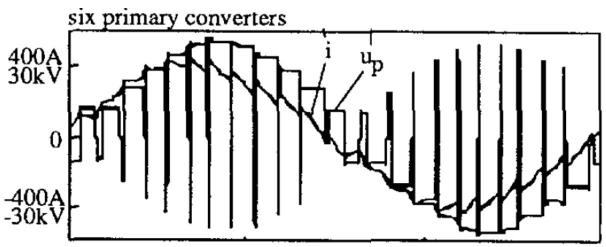


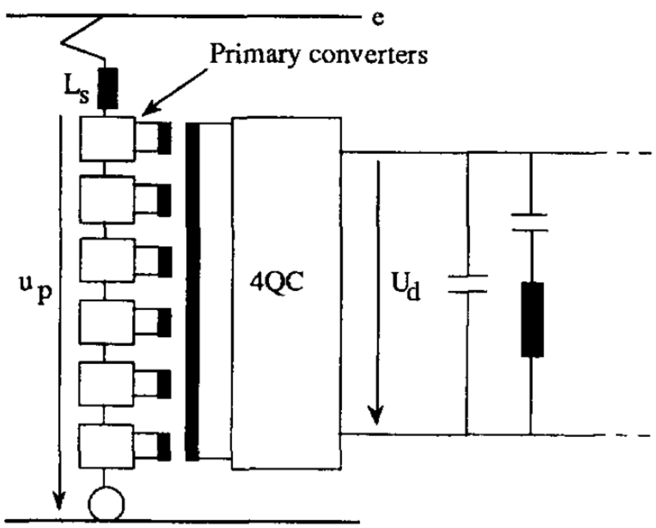


- Targeting Traction Applications
- Novel AC Current Control Concept for Mennicken Syst.
- Several Switchings of the VSC within Cycloconv. Cycle
- Lower Transformer Flux Level (Size) / Requires Transformer Flux Balancing Control

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

- Östlund (1993)
  I-Input, V-Output (McMurray, Mennicken)

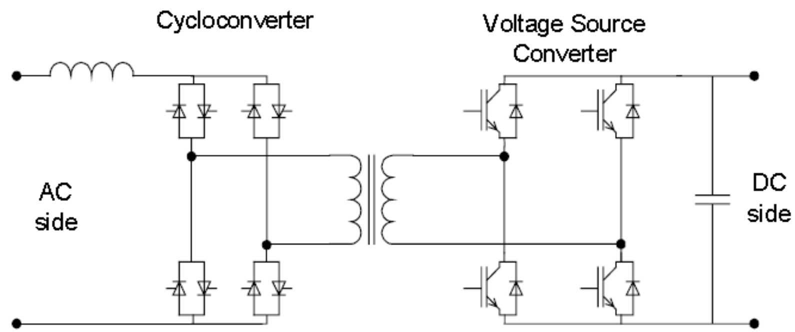




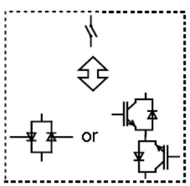
- Cascading of Primary Converters
- Reduction of Thyristor Blocking Voltage Stress
- Primary Winding Division for Sinusoidally Varying Staircase Voltage

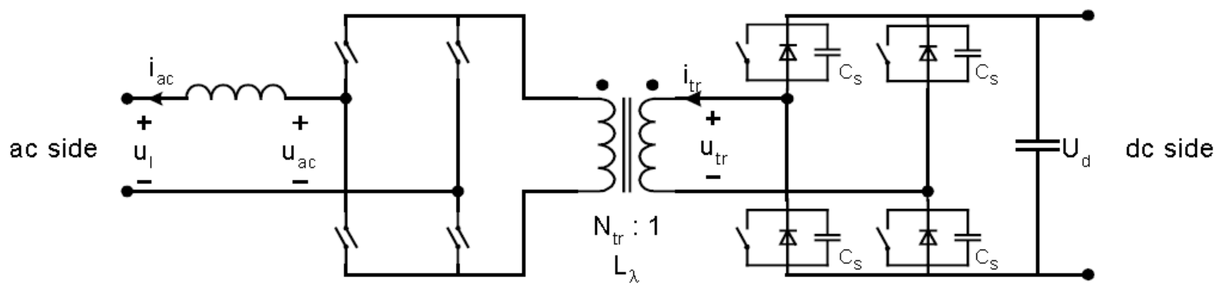
▶ Direct Matrix-Type 1ph. AC/DC Converter

- Mennicken



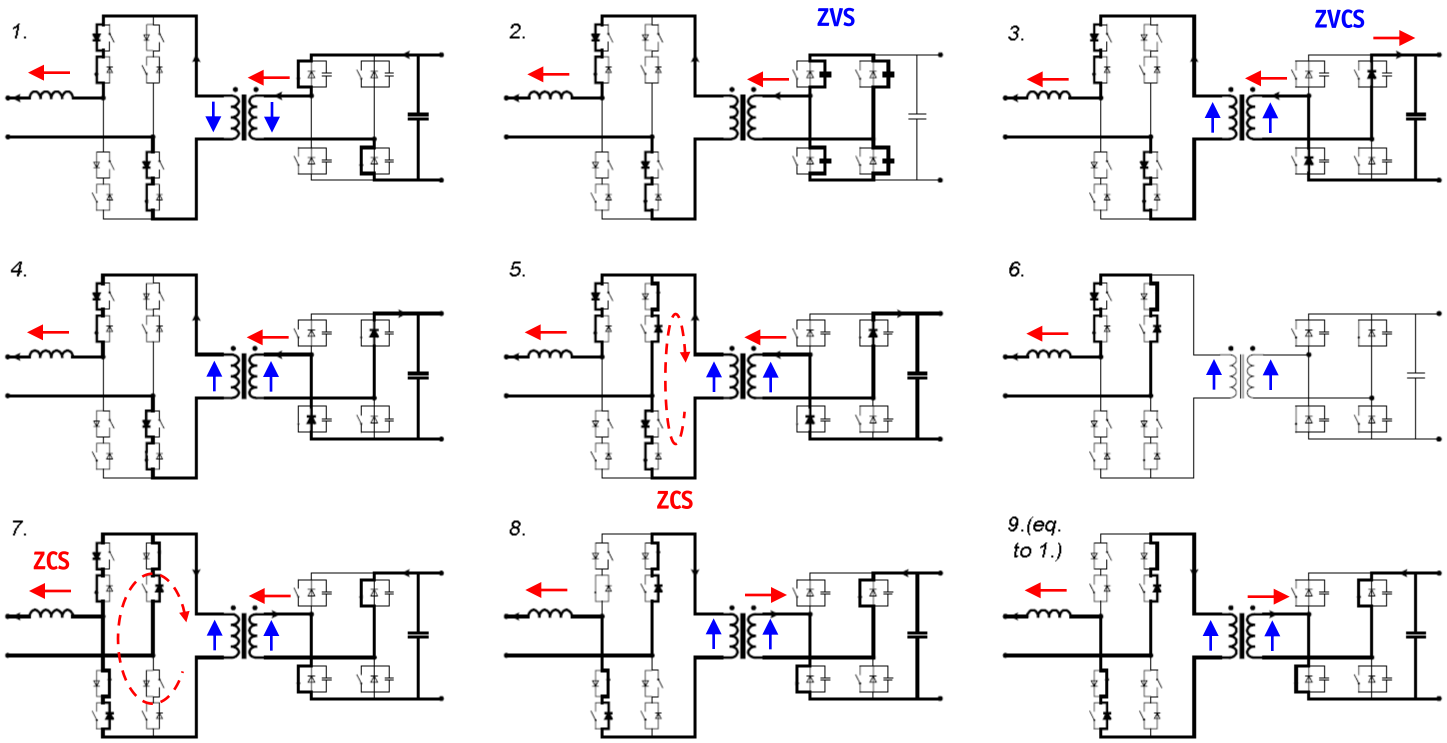
- Kjaer et al. (2001)
- Norrga (2002)





- 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.)

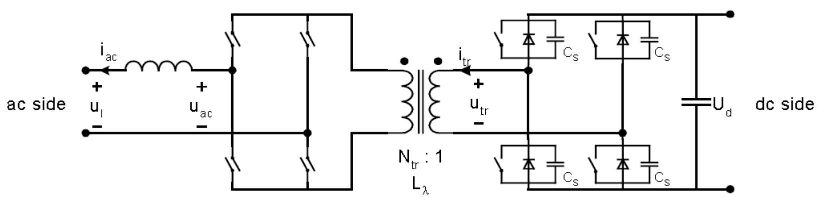
▶ Direct Matrix-Type 1ph. AC/DC Converter



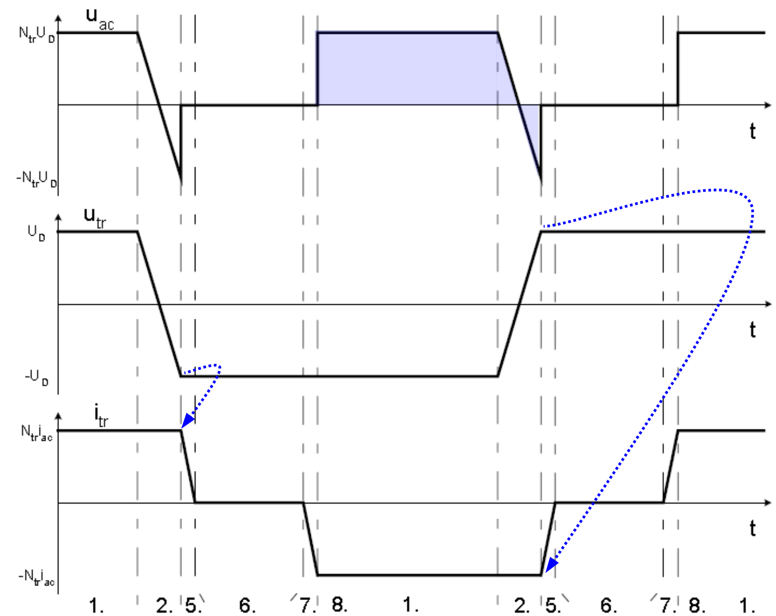
- Commutation Cycle of the ZVS/ZCS Control Scheme Proposed by Norrga
- Alternate Commutation of VSC and CSC

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

- Norrga (2002)
  I-Input, V-Output (McMurray, Mennicken)



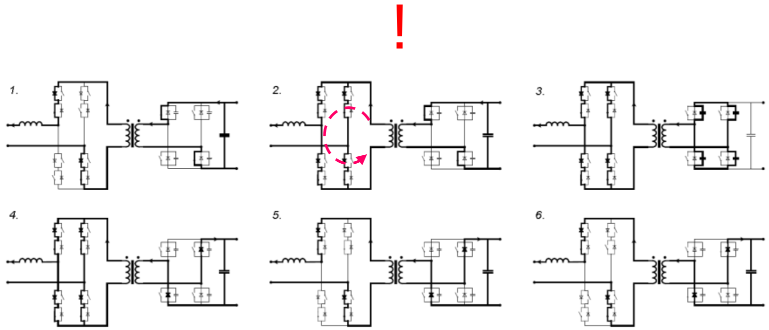
Power flow from dc side to ac side ($u_{ac}i_{ac}$ > 0)

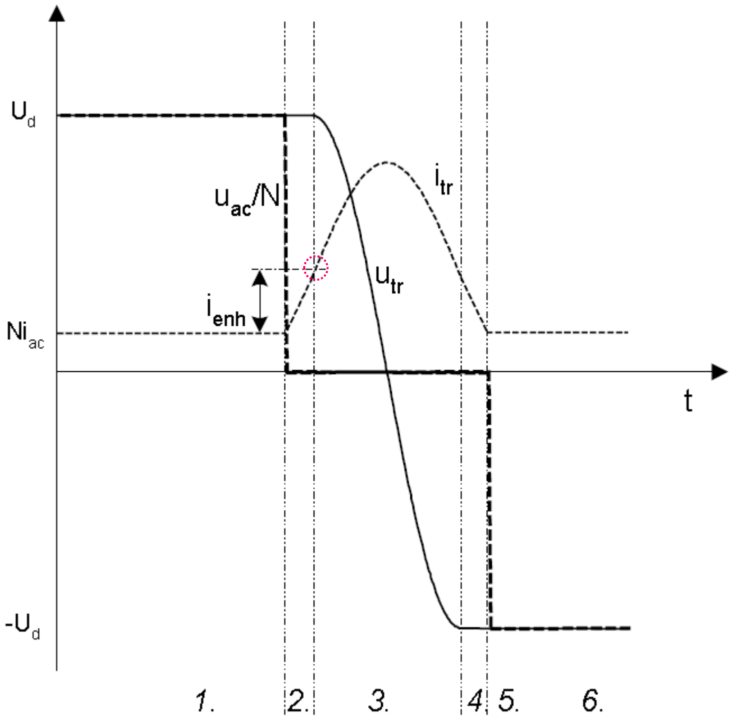


- Voltage and Current Waveforms for iac>0
- Commutation of Cycloconverter Immediately after VSC Commutation
- Three-Level AC Output Voltage & Very Limited Power Flow Reversal

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

- Norrga (2002)
  I-Input, V-Output

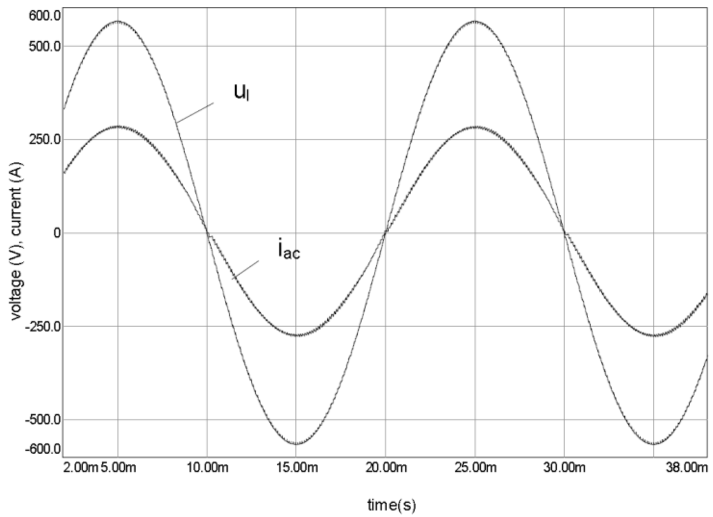


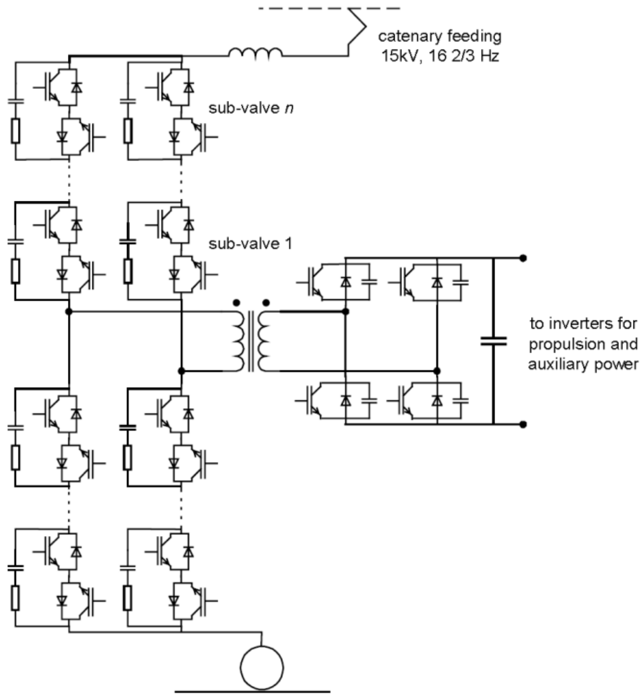


- VSC Quasi-Resonant Commutation Ensuring ZVS for Low Load (Current Insufficient for ZVS)
- Transformer Primary Winding Short Circuits by Cycloconverter During VSC Commutation

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

- Norrga (2002)
  I-Input, V-Output

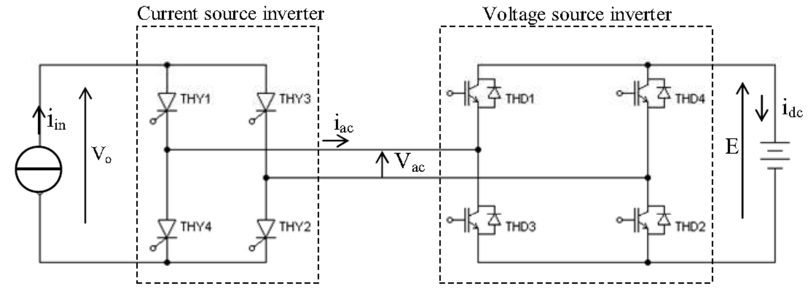


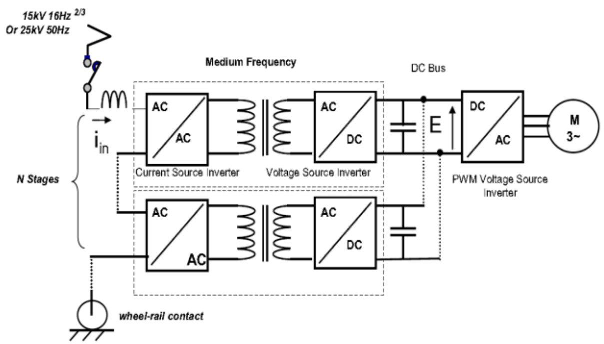


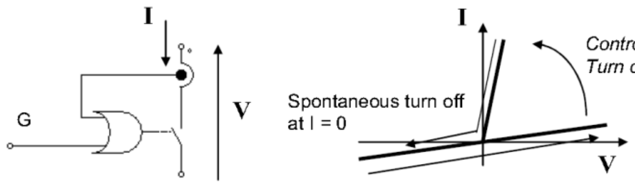
- Simulation Results and Extension to MV Input (Norrga, 2002)

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

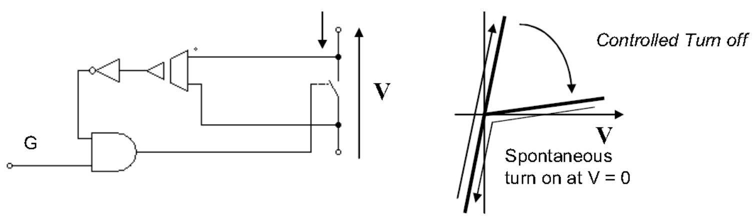
- **Ladoux (1998)**
  I-Input, V-Output (McMurray, Mennicken)







Thyristor commutation mode.

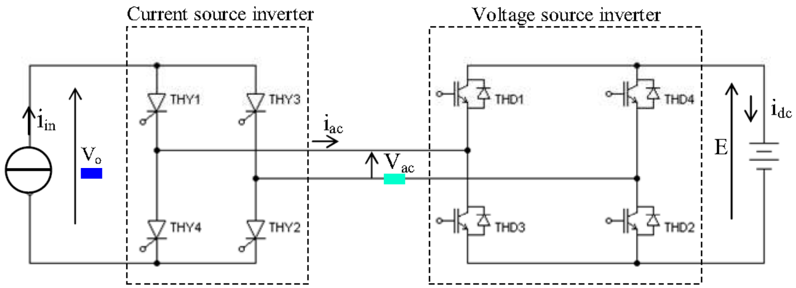


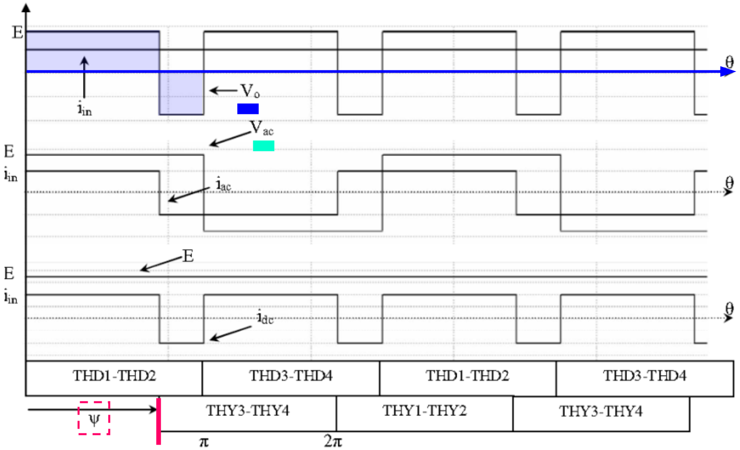
Dual Thyristor commutation mode.

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

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

- **Ladoux (1998)**
  I-Input, V-Output (McMurray, Mennicken)

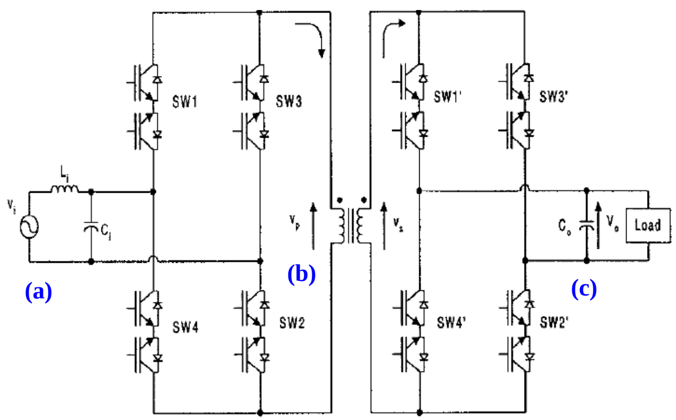


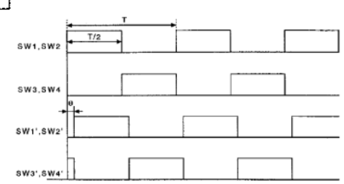


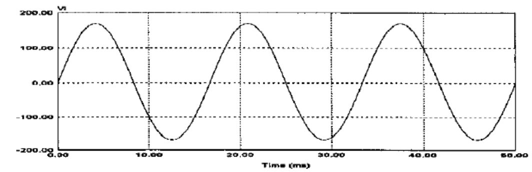
- Alternate Commutation of VSC and CSC → Natural Switching of CSI Dual Thyristors / Soft-Commut.
- Transformer Magnetizing Current for Supporting ZVS at Light Load or
- Quasi-Resonant Commutation (Short Circuit of CSI during VSC Commutation)
- Simplified Control Scheme – Two Level Voltage V_0 vs. Three-Level Contr. (Norrga)

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

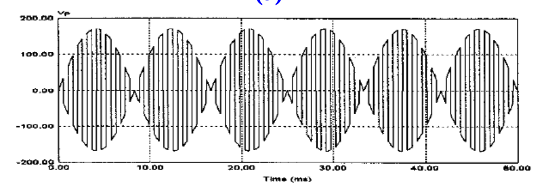
- Enjeti (V-Input, V-Output, θ = 0, 1997)
- Krishnaswami / 2005, Liu / 2006 (V-Input, I-Output)
- Kimball (V-Input, V-Output, 2009)



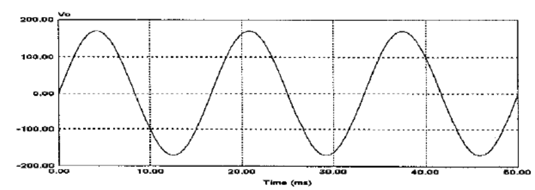




(a)



(b)

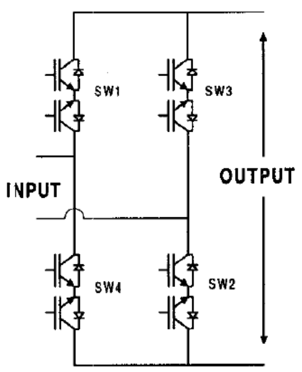


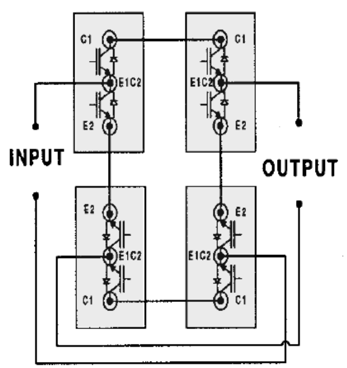
(c)

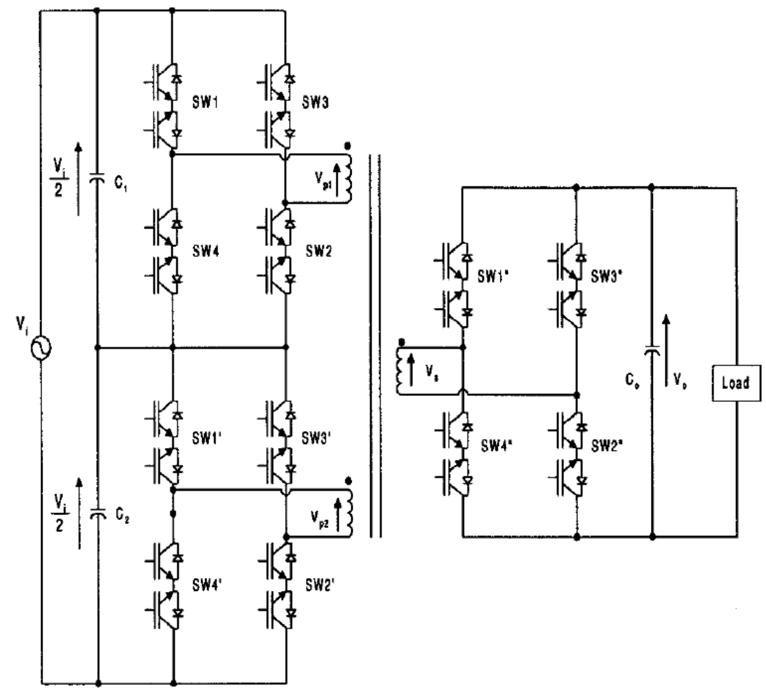
- $f_1 = f_2$
- Input Power = Output Power (and No Reactive Power Control)
- Same Switching Frequency of Primary and Secondary Side Converter
- Power Transfer / Outp. Volt. Contr. by Phase Shift θ of Primary & Sec. Side Conv. (McMurray)
- θ=0 (shown) Allows to Omit Output Filter Ind. (V-Output), But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

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

- Enjeti (V-Input, V-Output, θ = 0, 1997)



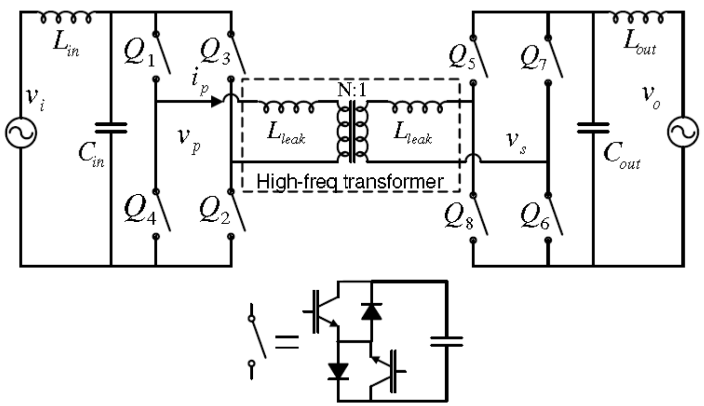


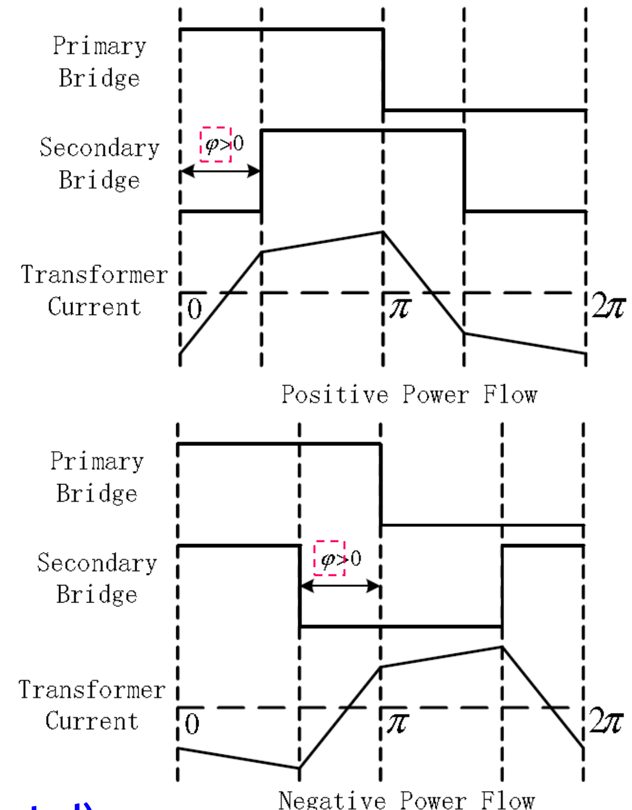


- Realization of Matrix Stages with Conventional IGBT Modules
- Cascaded Converter Input Stages for High Input Voltage Requirement
- Single Transformer / Split Winding Guarantees Equal Voltage Sharing

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

- Kimball (V-Input, V-Output, 2009)

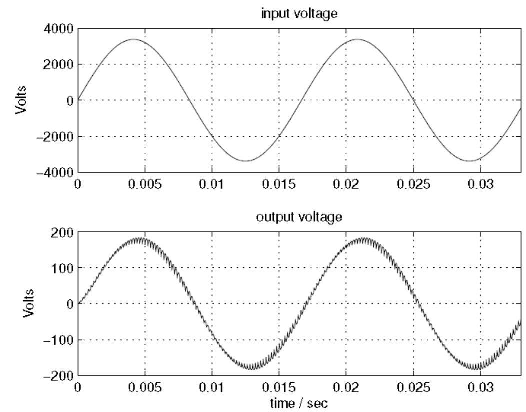


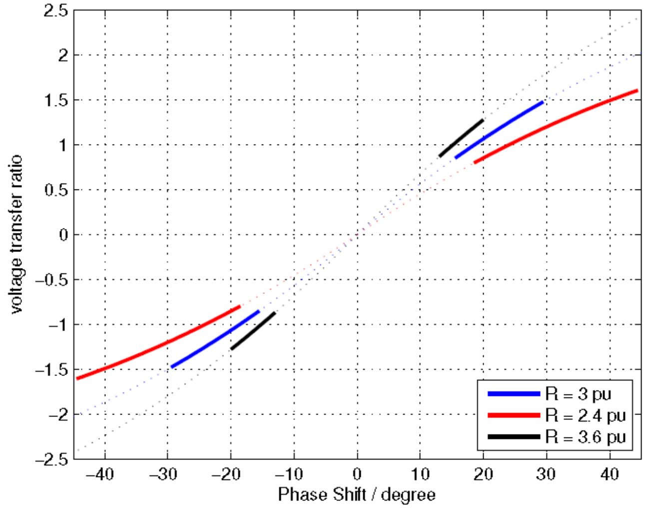


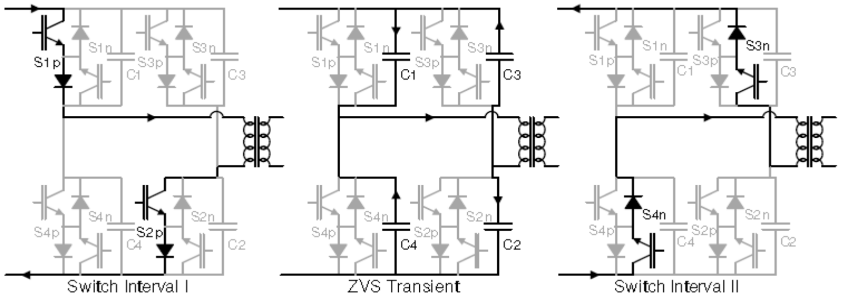
- $f_1 = f_2$
- Input Power = Output Power (and No Reactive Power Control)
- 1ph. AC/AC ZVS Dual Active Bridge (DAB) Converter (Voltage Impressed @ Inp. & Output)
- Power Transfer / Output Voltage Contr. by Phase Shift φ of Primary & Sec. Bridge Operation

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

- Kimball (V-Input, V-Output, 2009)



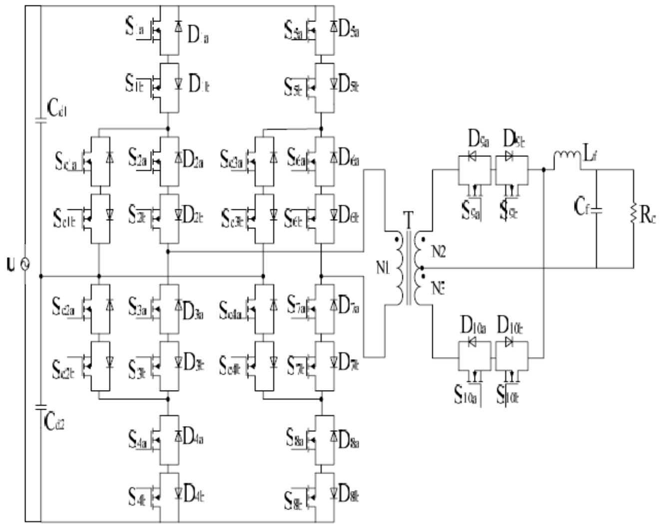


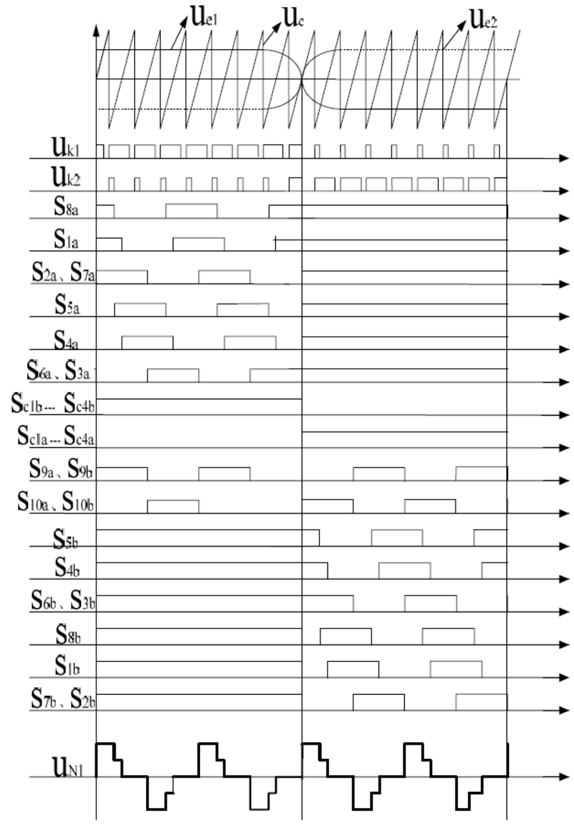


- ZVS Strategy
- ZVS Range Dependent on Load Condition & Voltage Transfer Ratio (Stray Ind. as Design Parameter)

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

- Yang (V-Input, I-Output, 2009)

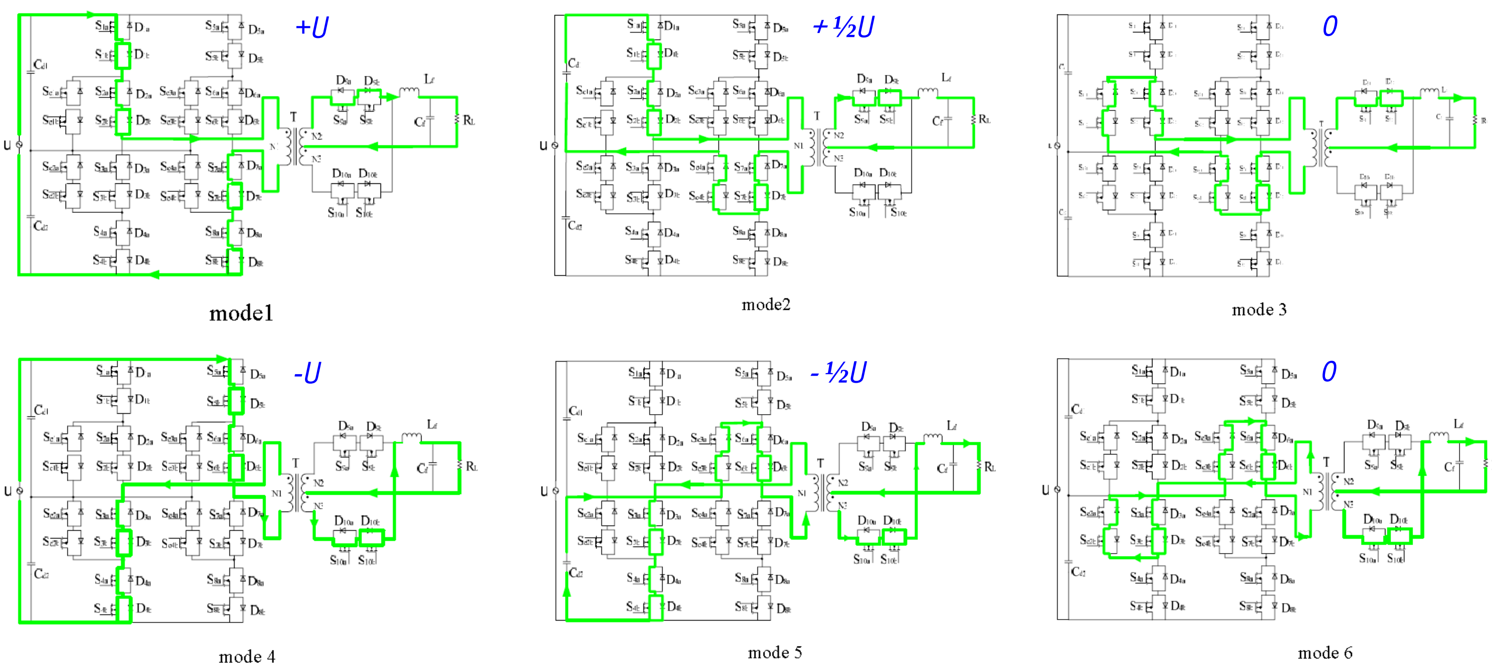




- Topological Variation of the Basic 1ph. AC/AC DAB Topology
- Three-Level Input Stage, Center-Tap Secondary Winding Rectifier Stage

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

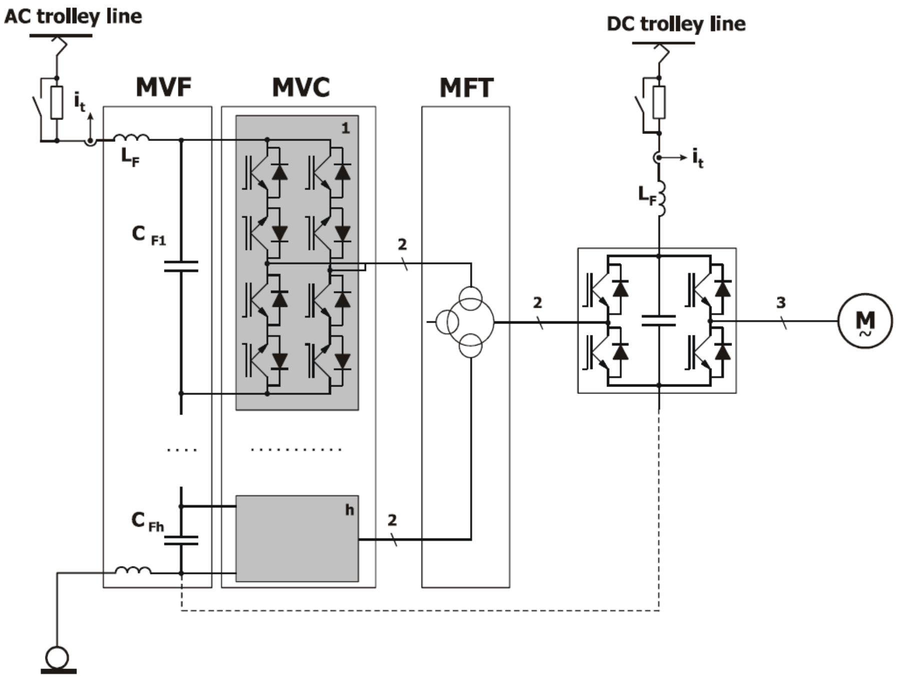
- Yang (V-Input, I-Output, 2009)



- **Six Conduction States within a Pulse Period**

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

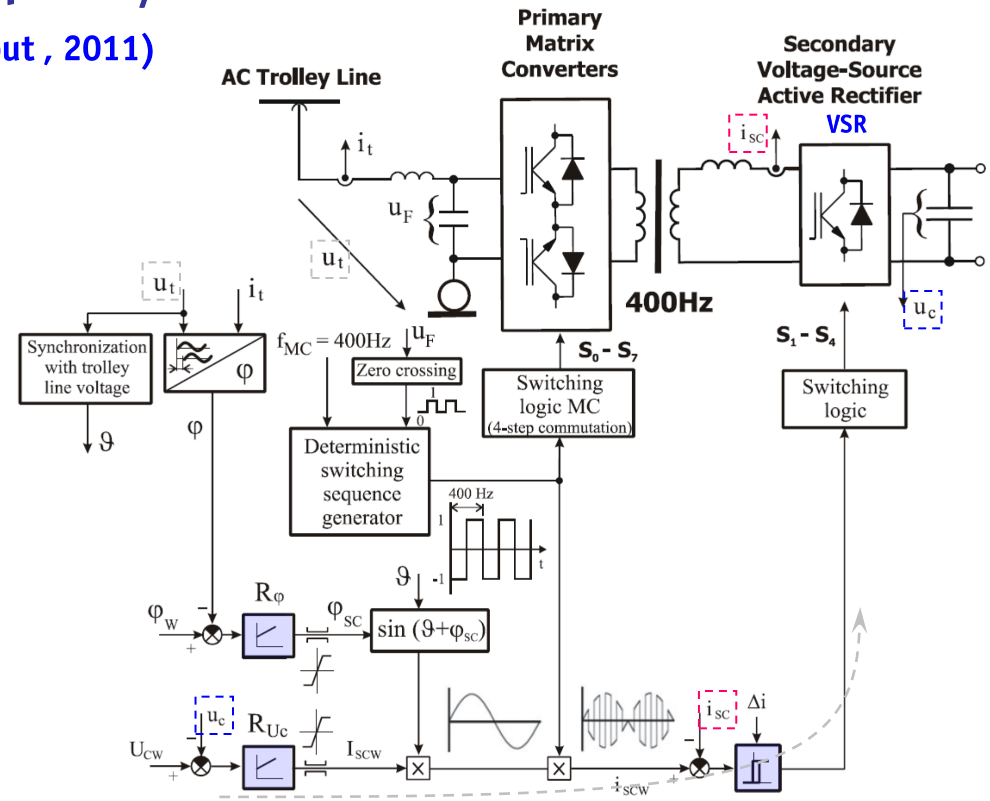
- Drabek et al. (2011)
  V-Input, V-Output



- Traction Application
- MF Transformer with Splitted/Cascaded Primary Windings & Single Secondary Winding
- DAB Topology but Higher Secondary Side Switching Frequency for Current Control
- Natural Balancing of the Input Filter Capacitor Voltages
- 400Hz Multi-Step Commutation of Primary Side Matrix Conv.
- Conceptual Relation of Control Concept to Östlund (Prim.: 400Hz, Sek.: 2.5kHz)

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

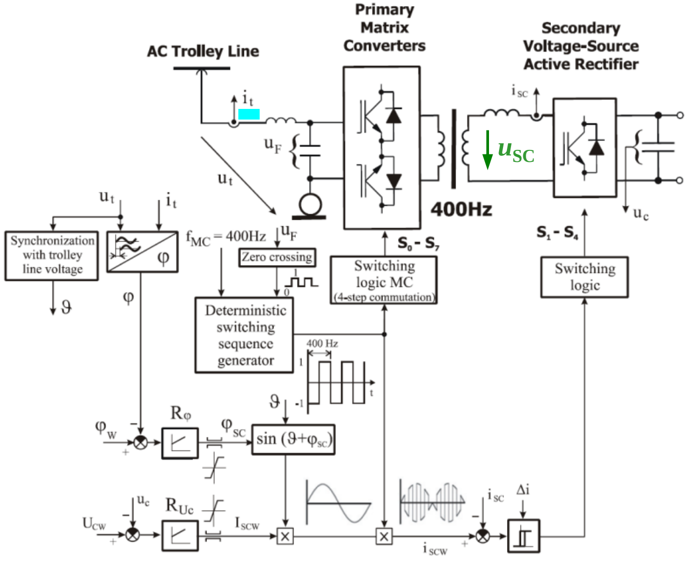
- Drabek et al. (V-Input, V-Output , 2011)

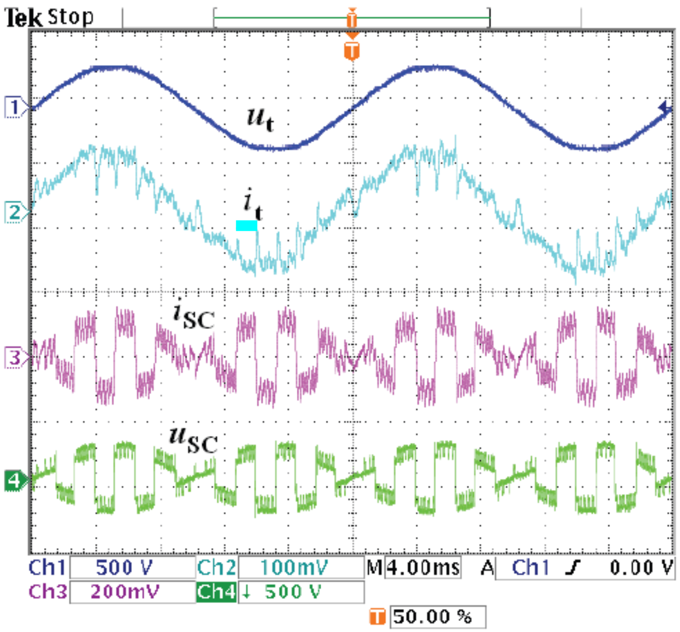


- Output Voltage Control via Current Amplitude / Phase Shift Controller Def. Inp. Current Phase Angle
- Hysteresis Contr. of VSR impresses 400Hz Ampl. Mod. Square Wave Current (def. Ampl. & Phase)
- Synchr. Switching (400Hz) Primary Matrix Stage Demodulates Transf. Current into Cont. Sinewave

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

- Drabek et al. (V-Input, V-Output , 2011)

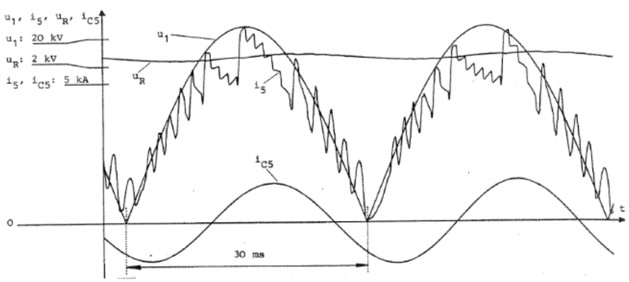


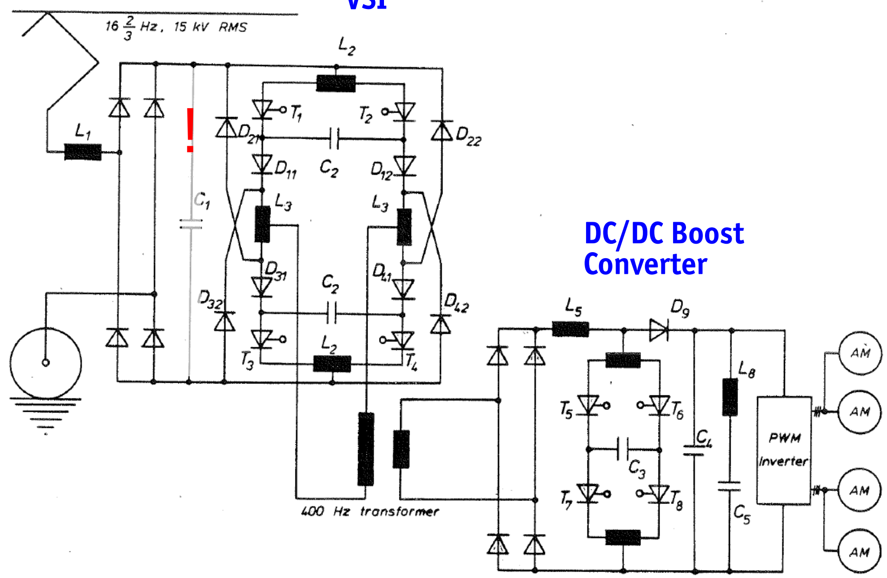


- **Experimental Analysis**

► Indirect Matrix-Type 1ph. AC/DC Converter

- Weiss (I-Input, V-Output, 1985)





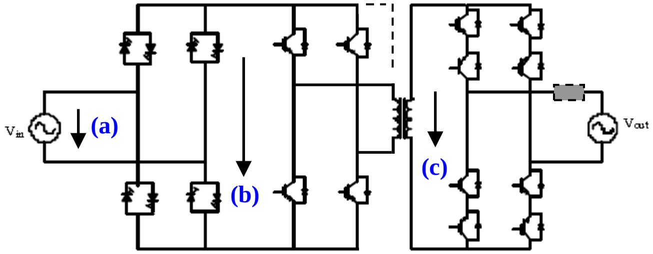
- AC/DC (Rectifier Bridge, No Output Capacitor) and Subsequent MF AC Voltage Generation
- Secondary Side Rectifier and DC/DC Boost Converter for Sinusoidal Current Shaping
- Switching Frequency f = 400Hz

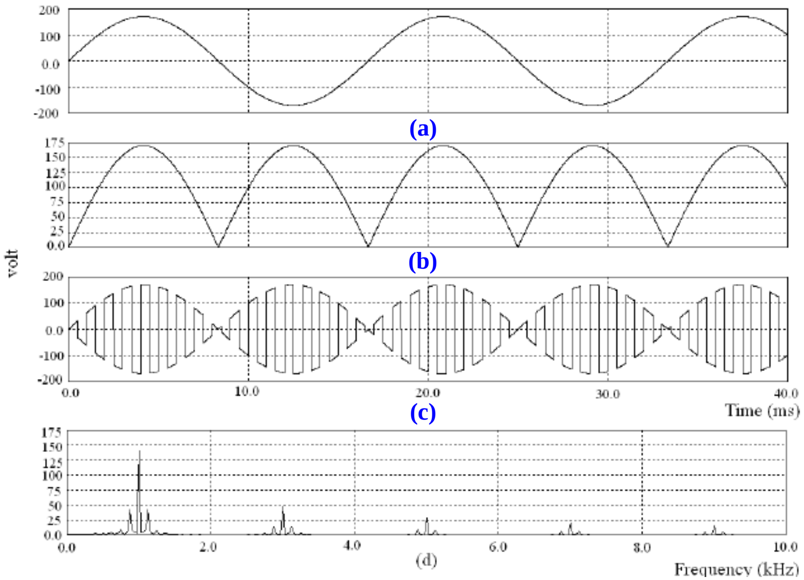
▶ Indirect Matrix-Type 1ph. AC/AC Converter

- Lipo (V-Input, I-Output, 2010)

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

!

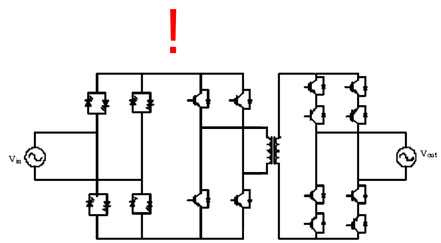


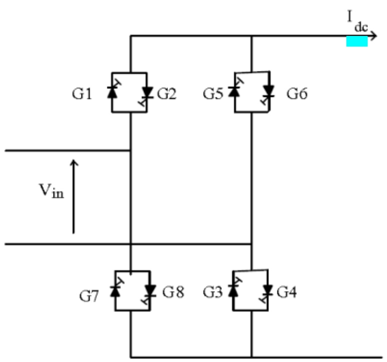


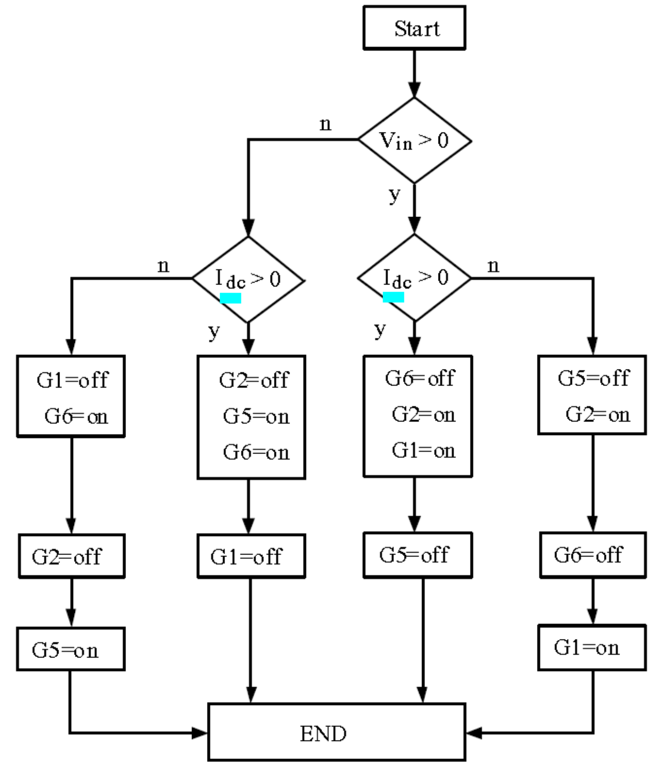
- AC/DC Input Stage (Bidir. Full-Wave Fundamental Frequ. GTO Rect. Bridge, No Output Capacitor)
- Subsequent DC/DC Conversion & DC/AC Conversion (Demodulation, $f_1 = f_2$)
- Output Voltage Control by Phase Shift of Primary and Secondary Side Switches (McMurray)
- Lower Number of HF HV Switches Comp.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

▶ Indirect Matrix-Type 1ph. AC/AC Converter

- Lipo (V-Input, I-Output, 2010)



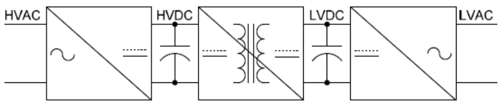


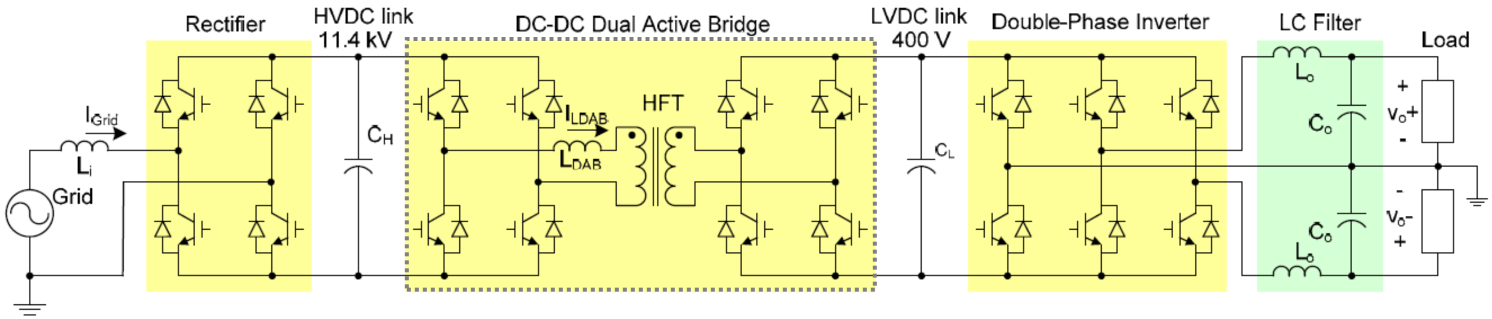


- Multi-Step Commutation of GTO Input Stage (at Mains Voltage Zero Crossings)
- Commutation Considers DC Link Current Direction and Input Voltage Polarity
- Same Gate Signals for Diagonal Thyristors (G_1,G_3), (G_2,G_4), (G_5,G_7), (G_6,G_8)

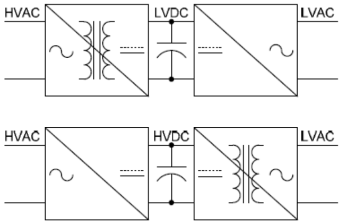
▶ DC-Link Type (Indirect) 1ph. AC/AC Converter

- 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)

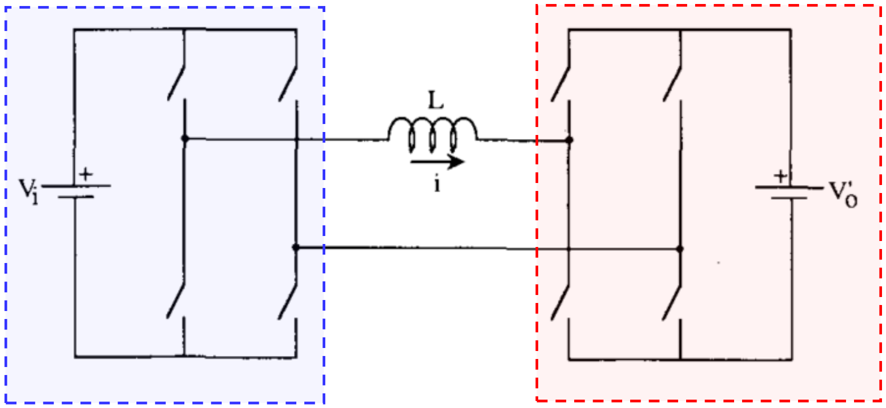


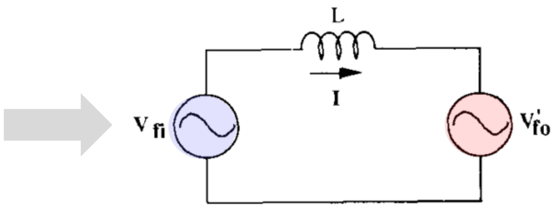
- Alternatives: AC//DC – DC/AC Topologies
  AC/DC – DC//AC Topologies

High-Power DC-DC Conversion

▶ Dual-Active-Bridge (DAB)

- De Doncker (1991)



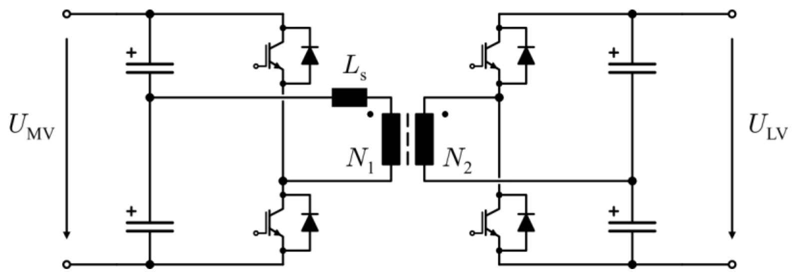


Fundamental model of the dual bridge dc/dc converter.

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

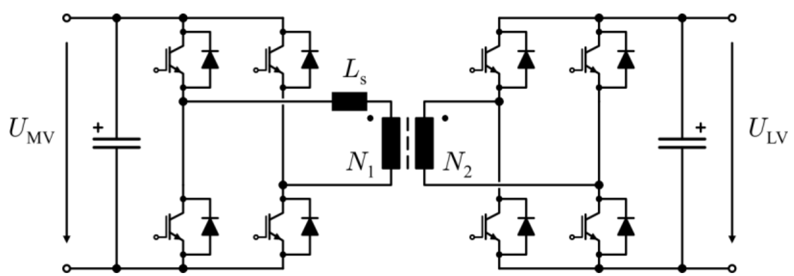
DAB – Common Bridge Configurations

Half-Bridge Configuration



- Two Voltage Levels from Each Side

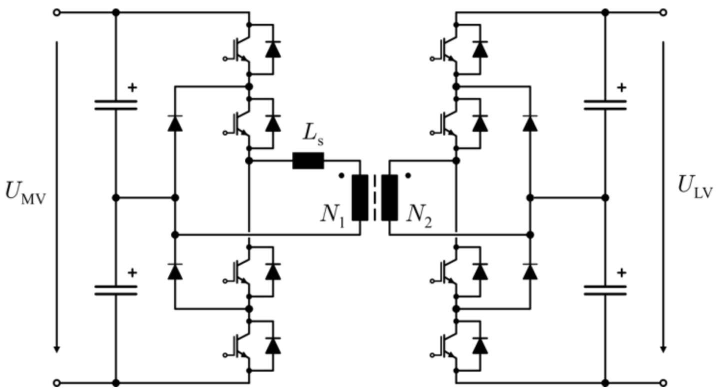
Full-Bridge Configuration



- Three Voltage Levels from Each Side (Additional Freewheeling State)

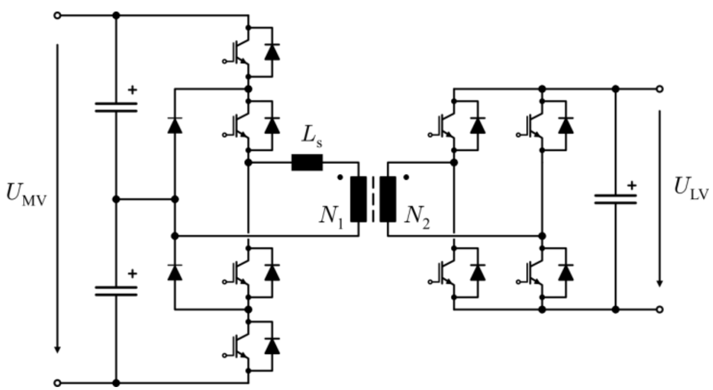
DAB – Common Bridge Configurations

Neutral-Point-Clamped (NPC) Configuration



- Three-Voltage Levels from Each Side
- Voltage-Doubler Behavior

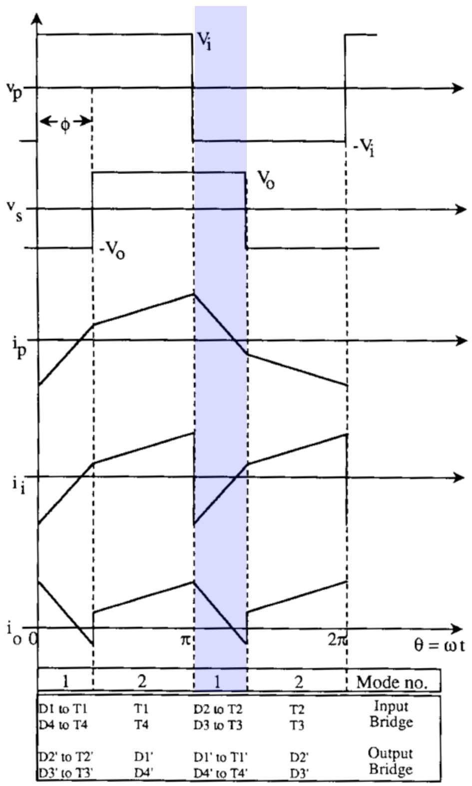
NPC / Full-Bridge Configuration

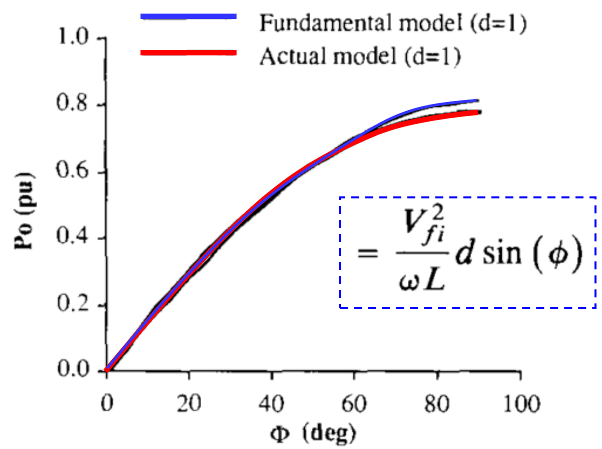


- Suitable for Higher MV/LV Ratios

▶ DAB – Phase-Shift Modulation

■ Power Transfer Controlled through Phase-Shift between Bridges



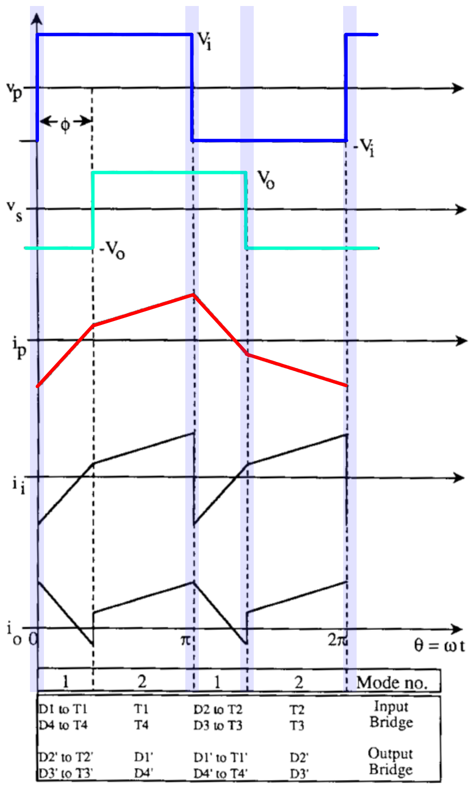


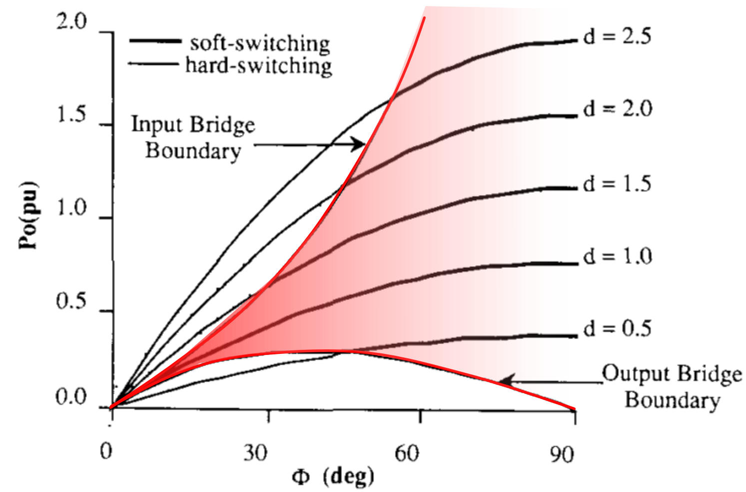
Comparison of the output power versus ϕ, at $d = 1$, from the fundamental model and actual model.

- **Fundamental Model suitable for Calculation of Power Transfer**

▶ DAB – Phase-Shift Modulation

■ In a Certain Range, All Switching Transitions done in ZVS Conditions



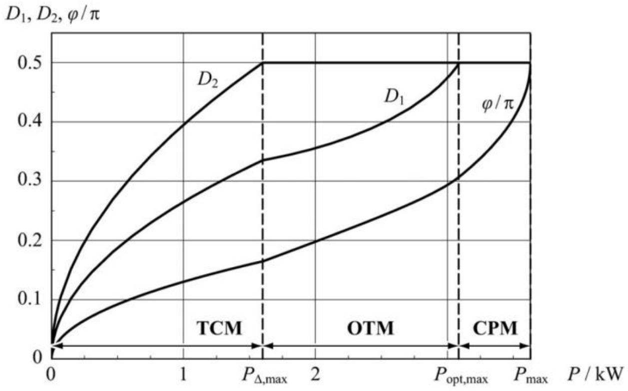


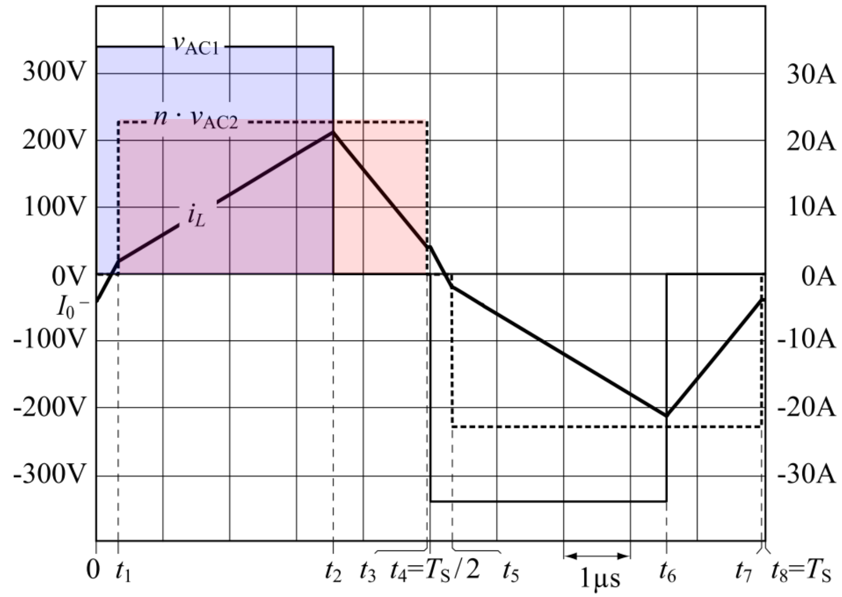
- Soft Switching Range

▶ DAB – Phase-Shift / Duty-Cycle Modulation

■ **Additional Degrees of Freedom can be Utilized to Optimize Targeted Criteria**

- **E.g. Minimize RMS Currents for Minimum Conduction Losses (ETH, Krismer, 2012)**

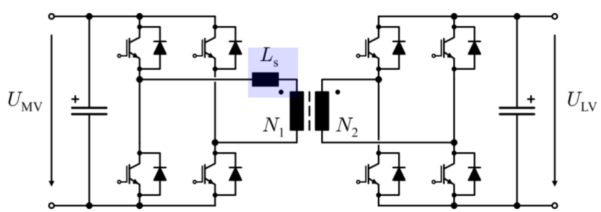


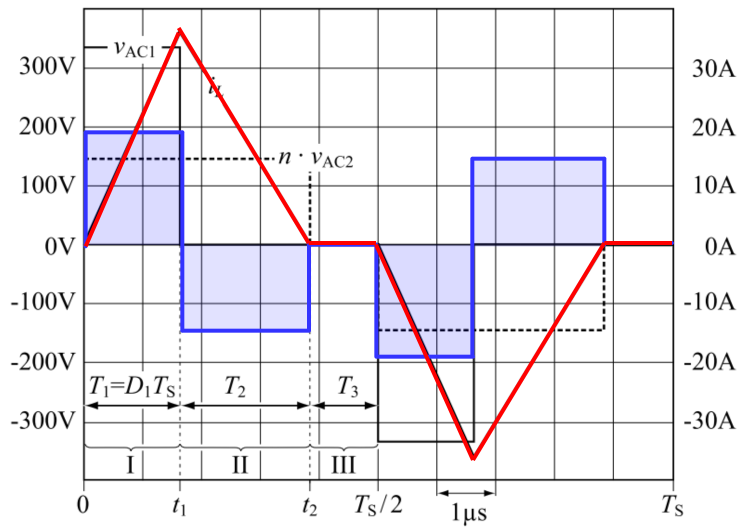


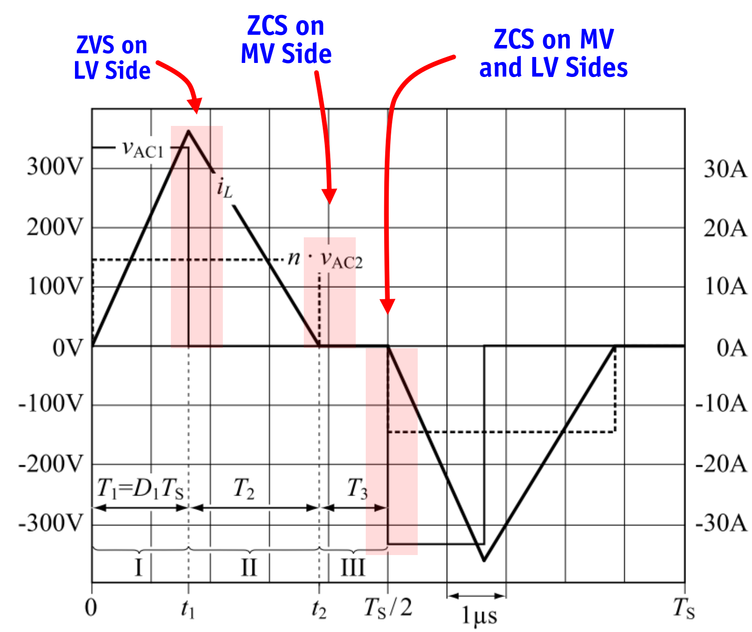
- **Not Possible in Half-Bridge Configuration**

▶ DAB – Triangular-Current Mode

■ Duty-Cycles and Phase-Shift Utilized to perform ZCS Switching





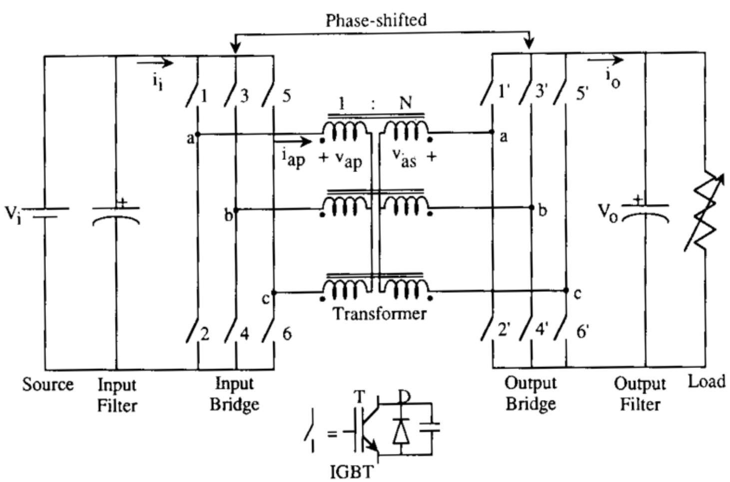


- **Inductor Voltage**

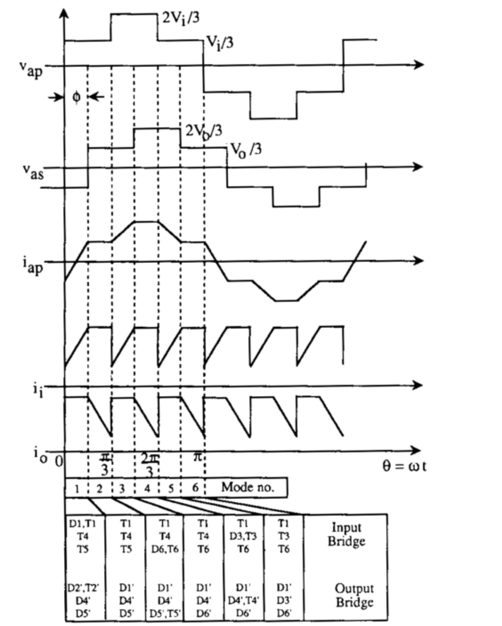
ZCS on MV Side

▶ Three-Phase DAB

- De Doncker (1991)



(a)



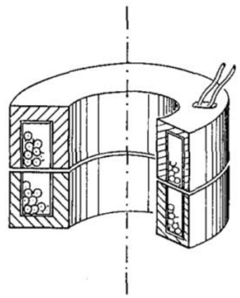
(b)

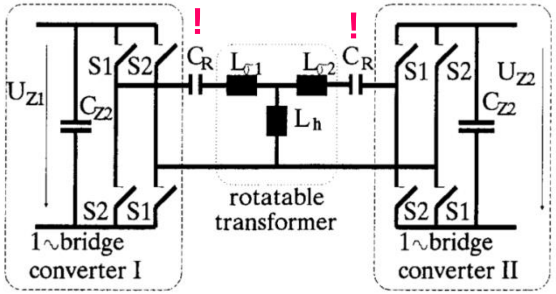
(a) Three-phase dual active bridge dc/dc converter, Topology C; (b) idealized operating waveforms for topology C.

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

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

■ Power Supplies for Robots – RWTH (Esser, 1991)



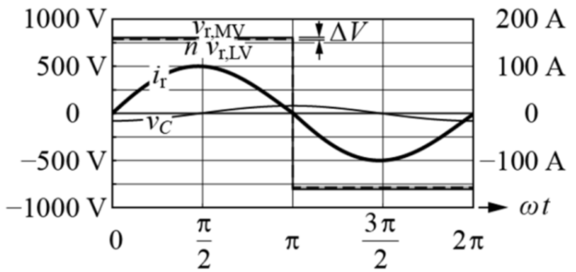


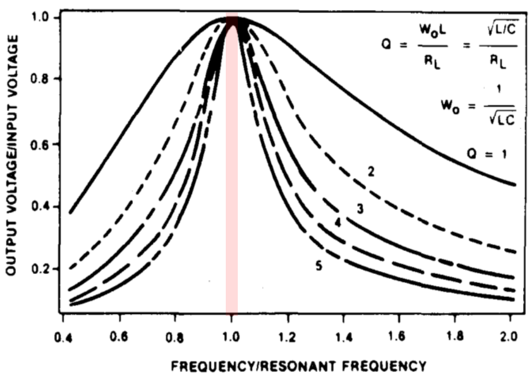
Equivalent circuit of the rotatable transformer and the 1-bridge converters

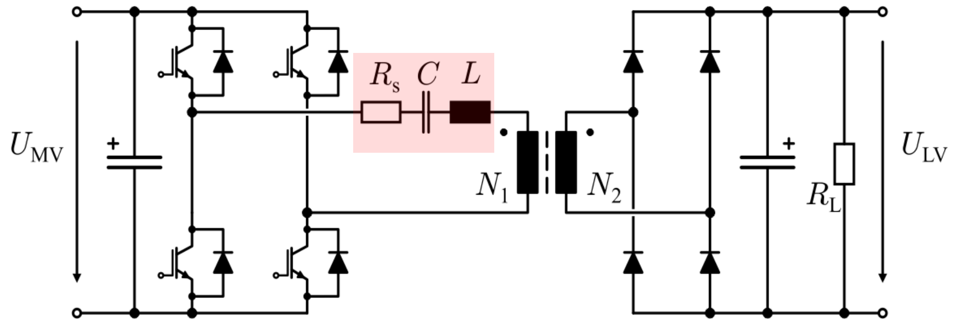
- Energy Transfer Through the Robot's Arm Joints

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

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



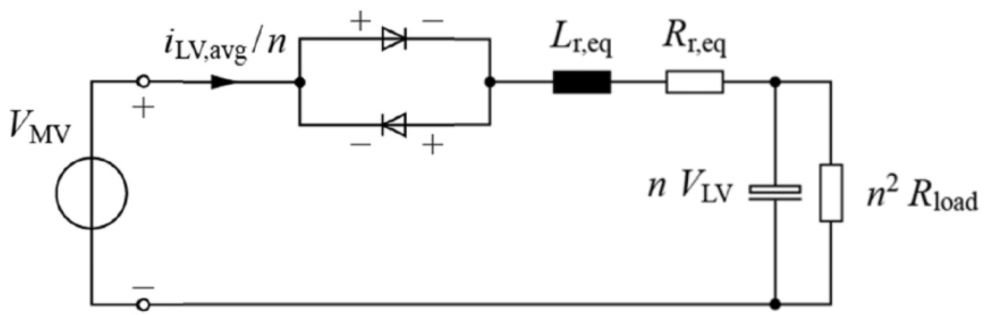




- **At Resonant Frequency, the Input/Output Voltage Ratio is Unity (Steigerwald, 1988)**

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

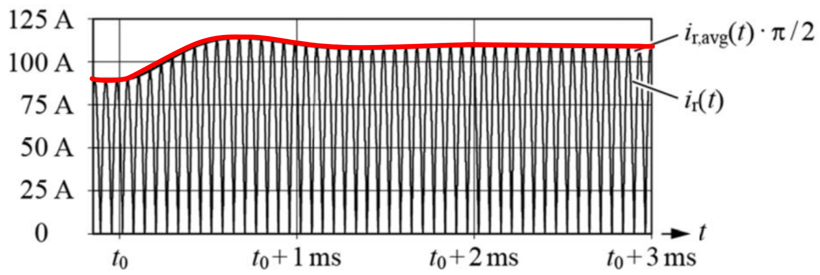
■ Equivalent Circuit for Transient Analysis (Esser, 1991)



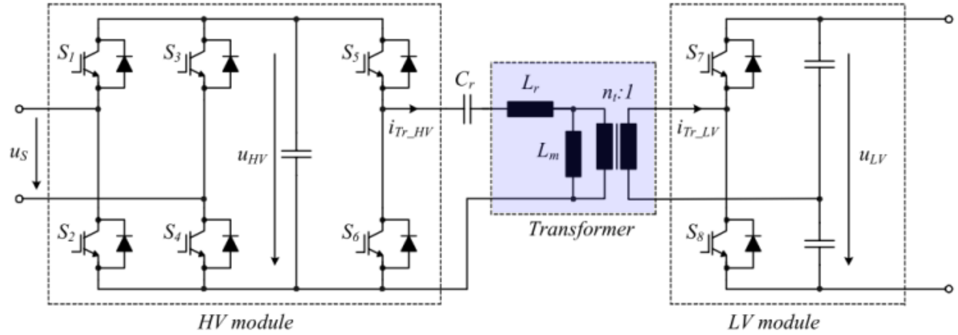
$$L_{r,eq} = \frac{\pi^2}{4} L$$

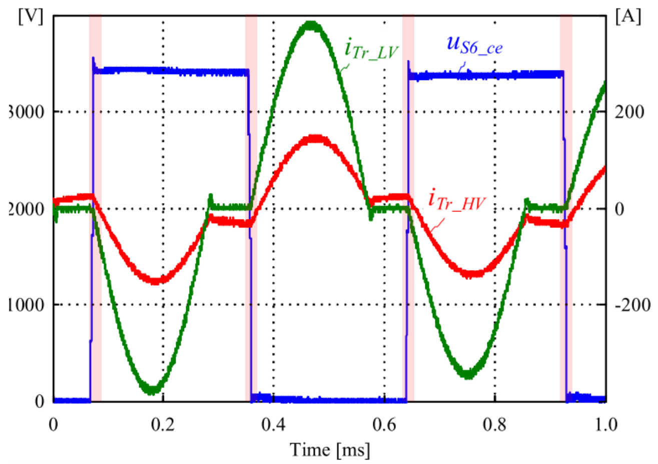
$$R_{r,eq} = \frac{\pi^2}{8} R$$

- 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)



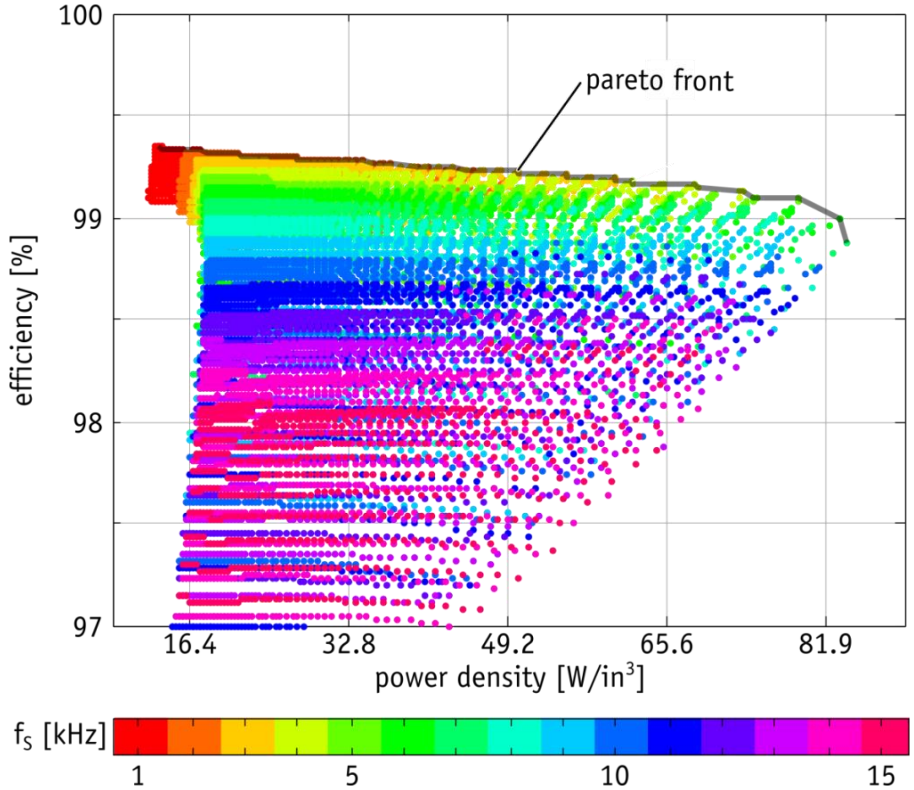


- LLC Structure to Reduce Switching Losses
- Zero-Current-Switching of All Devices

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

- ETH (Huber, 2013)

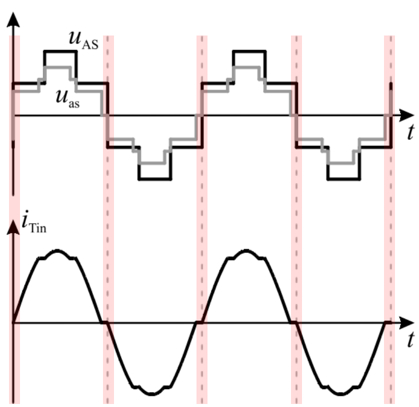
- Efficiency / Power-Density Optimization → Pareto Front
- Operating Frequency Used as Free Parameter

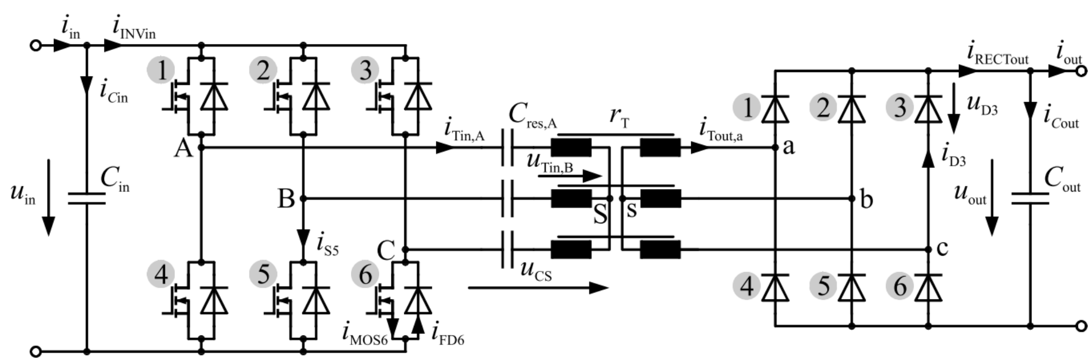


- HC-DCM-SRC is Suitable for Reaching High Efficiency
- Optimum f_S for 99% Efficiency is 6…8 kHz

▶ Three-Phase HC-DCM-SRC

- RWTH (Jacobs, 2005)

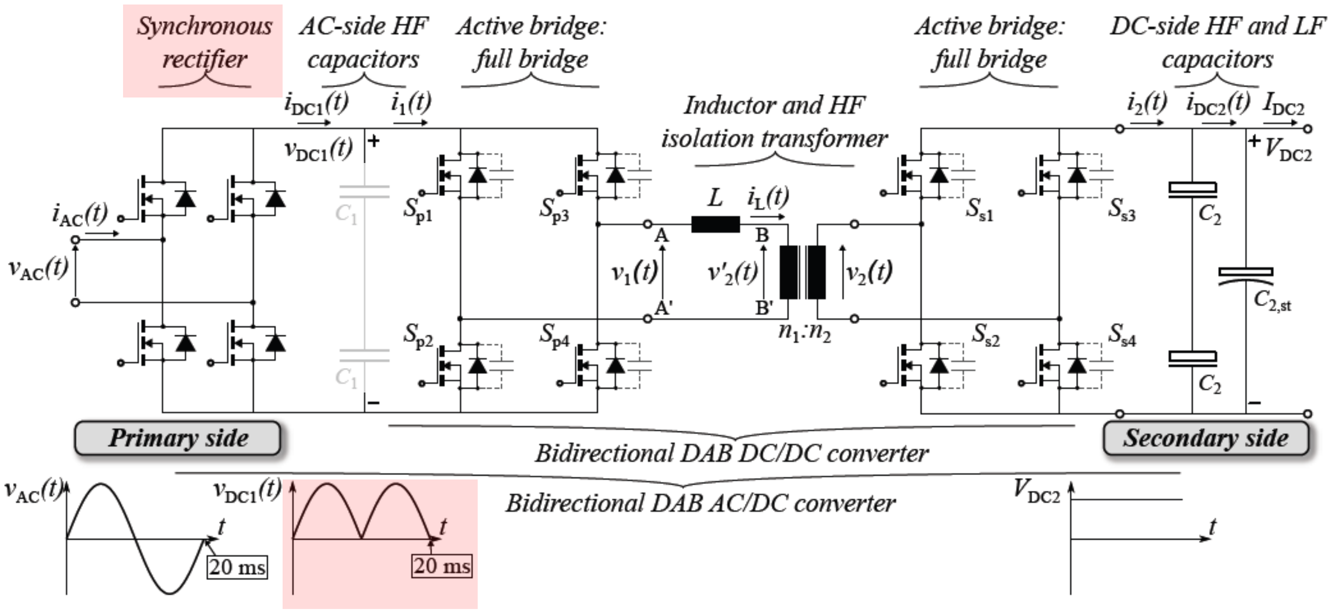




- Possible Power Density/Efficiency Improvement + Red. DC Filtering

▶ AC/DC Converter with DAB

- KU-Leuven (Everts, 2012, presented for LV Applications)

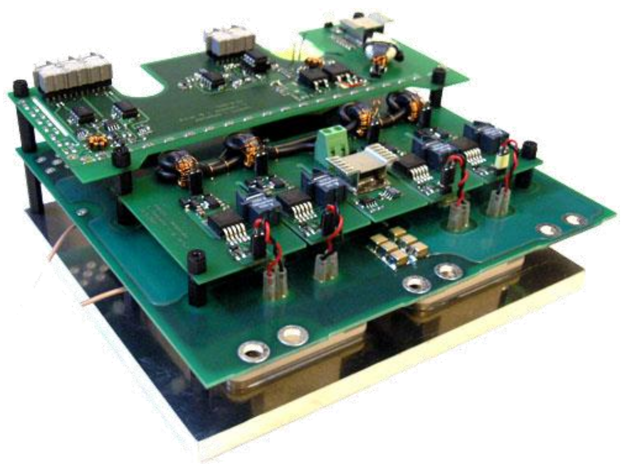


- **Direct MV-AC to LV-DC Conversion (No Constant Voltage MV-DC Link)**

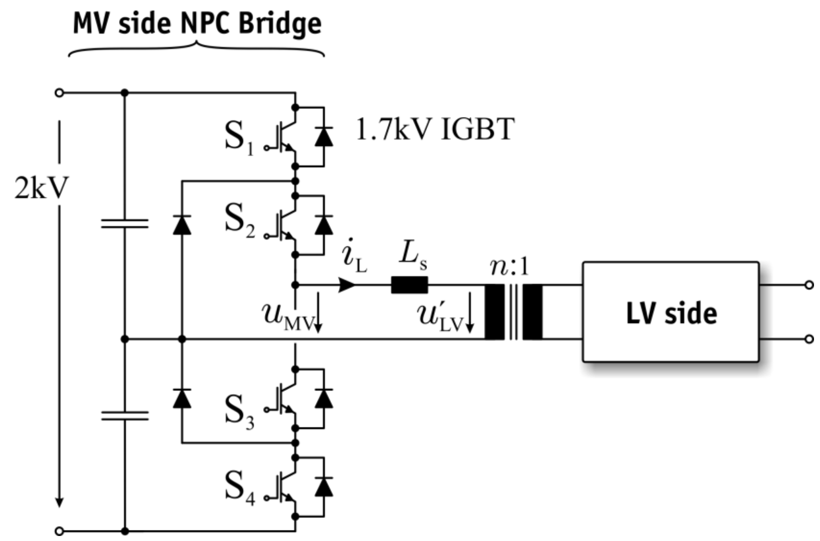
ZCS/ZVS of IGBTs

▶ ZCS and ZVS of IGBTs

- Analysis of IGBT Losses under ZCS Conditions for the TCM-DAB
- Tested on a NPC-3-Level Structure Based on 1.7kV IGBTs



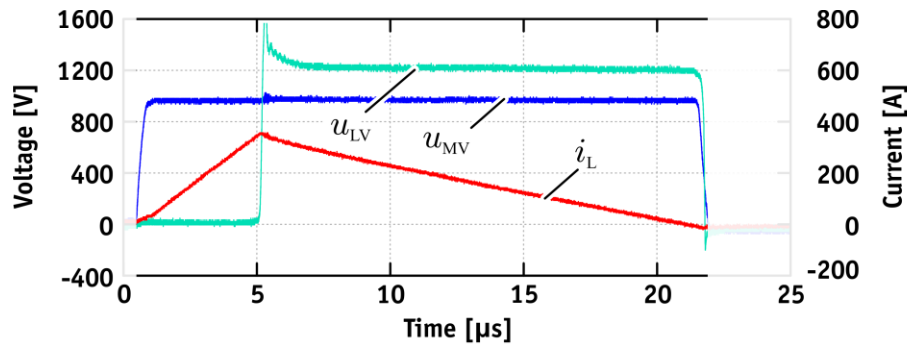
▲ 1.7kV PT IGBT Module-Based Testbench

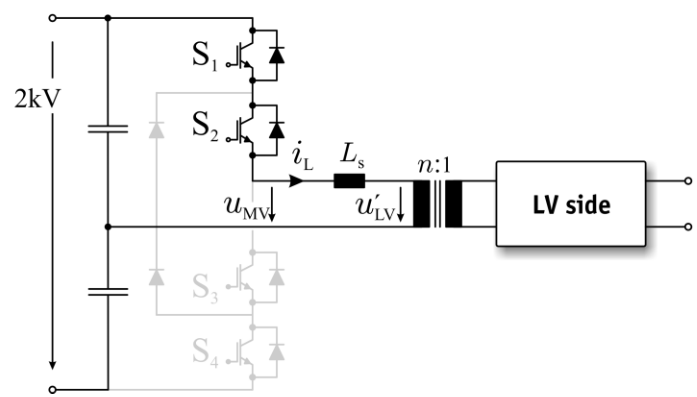


▲ NPC Bridge Leg Based on 1.7kV PT IGBTs Conn. to MF Transf. and LV Side Bridge

▶ Operation

- ▶ **NPC Bridge Applies Full Positive Voltage**
- ▶ As soon as the Current Reaches Zero, the NPC Bridge is Turned to Freewheeling, achieving ZCS on S_1



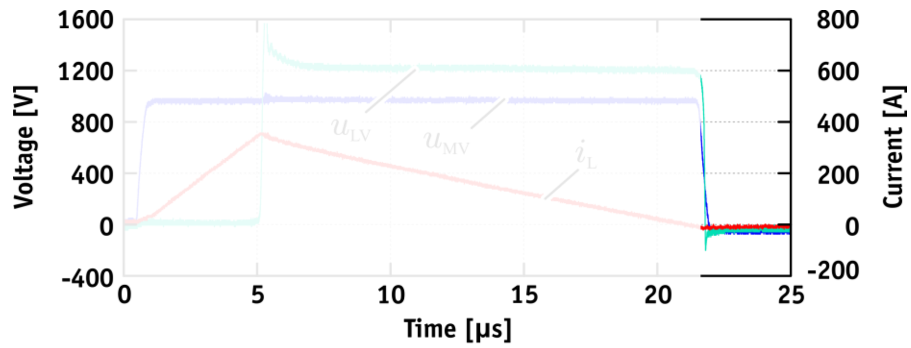


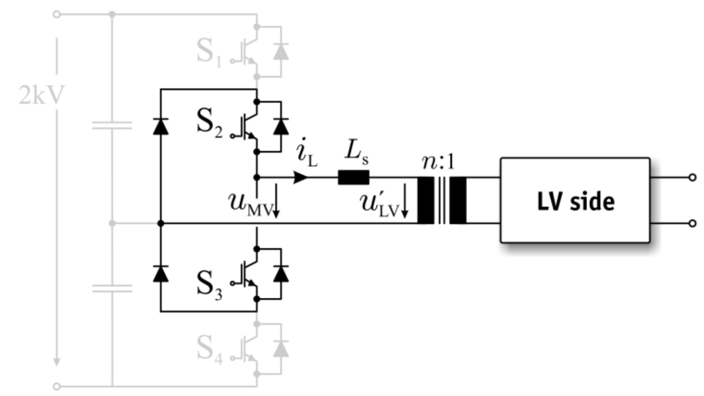
▲ NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV

▶ Operation

▶ NPC Bridge Applies Full Positive Voltage

▶ As soon as the Current Reaches Zero, the NPC Bridge is Turned to Freewheeling, achieving ZCS on S_1

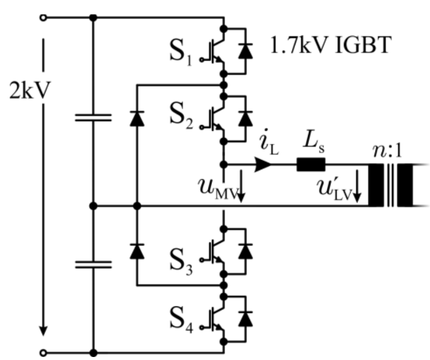




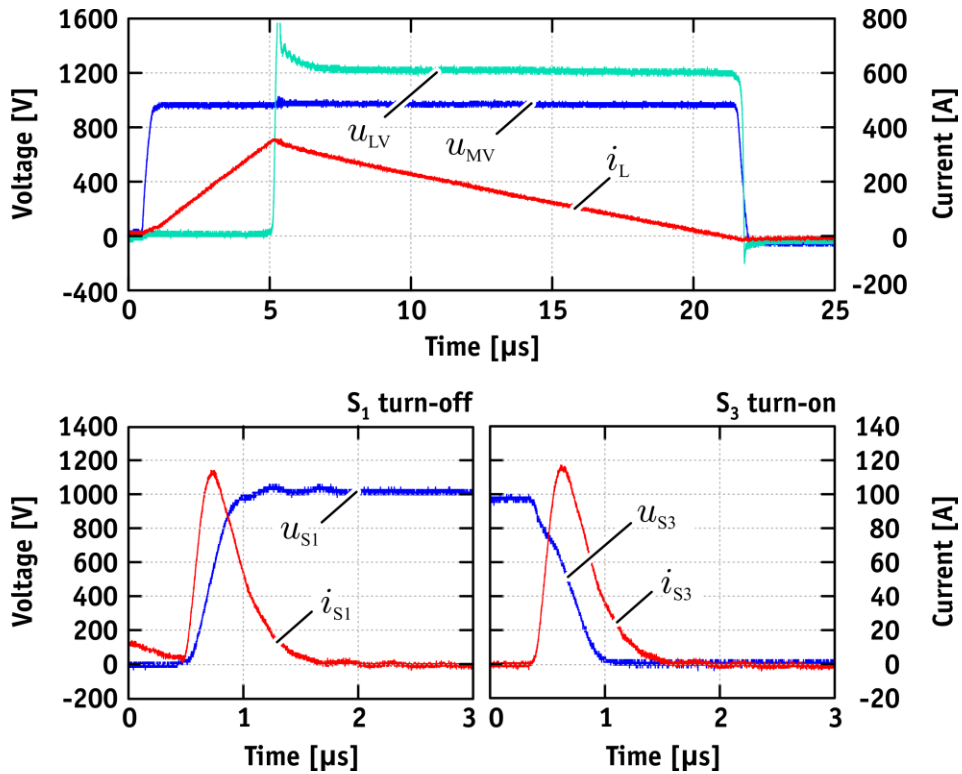
▲ NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV

▶ Standard ZCS: MV→LV

- ▶ Large Current Spike Even at Zero Current
- ▶ Large Turn-on Losses on Turning-on Device



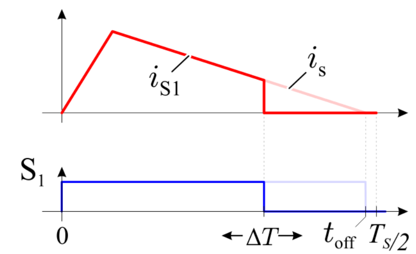
▲ 1.7kV IGBT NPC bridge

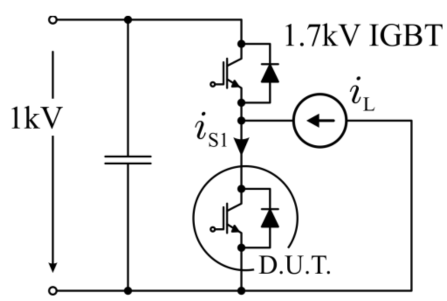


▲ NPC Bridge Structure and Experimental Waveforms for 166kW / 20kHz and Power from MV to LV

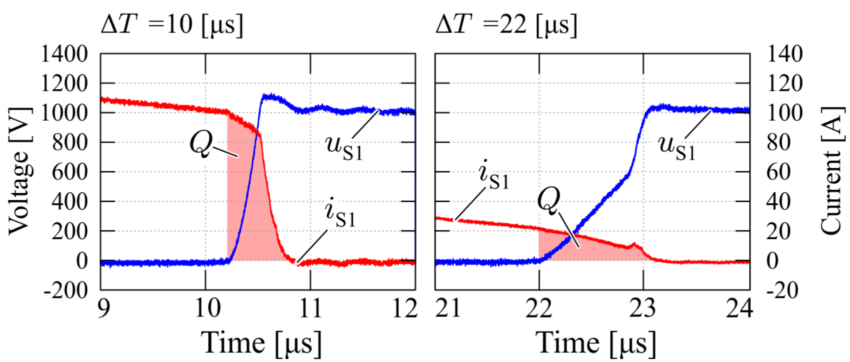
▶ Measurement of IGBT Stored Charge Behavior

▶ Exp. Measurement of Internal Charge
▶ Dynamic Behavior of Stored Charge





▲ 1.7kV IGBT Test Circuit for Charge Behavior Analysis



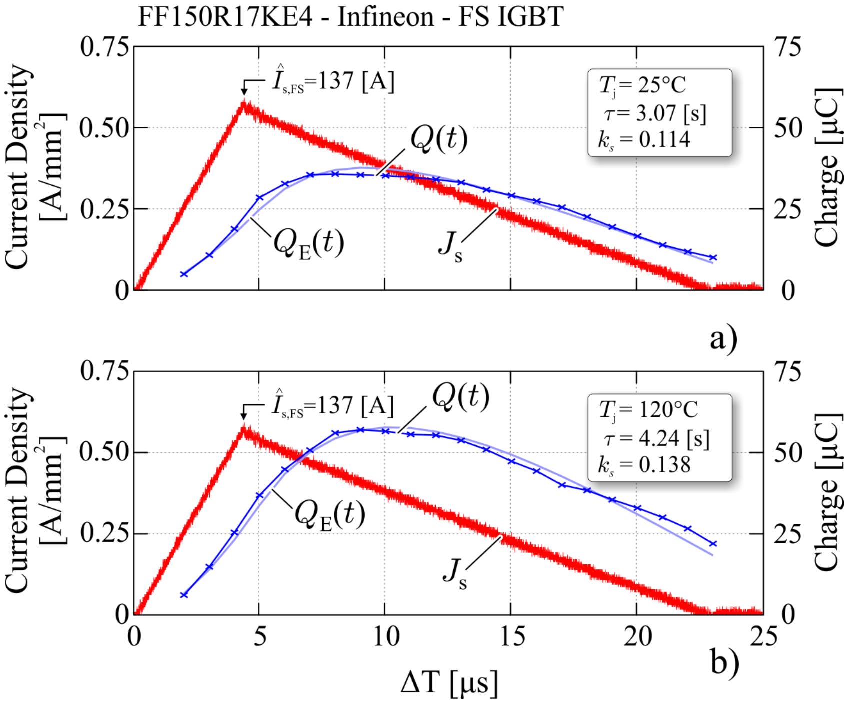
▲ Experiment used to Study Stored Charge Dynamics (Ortiz, 2012)

Measurement of IGBT Stored Charge Behavior

- Field-Stop 1.7kV IGBT
- 62mm Package

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

▲ Charge Control Equation to Estimate Charge Behavior



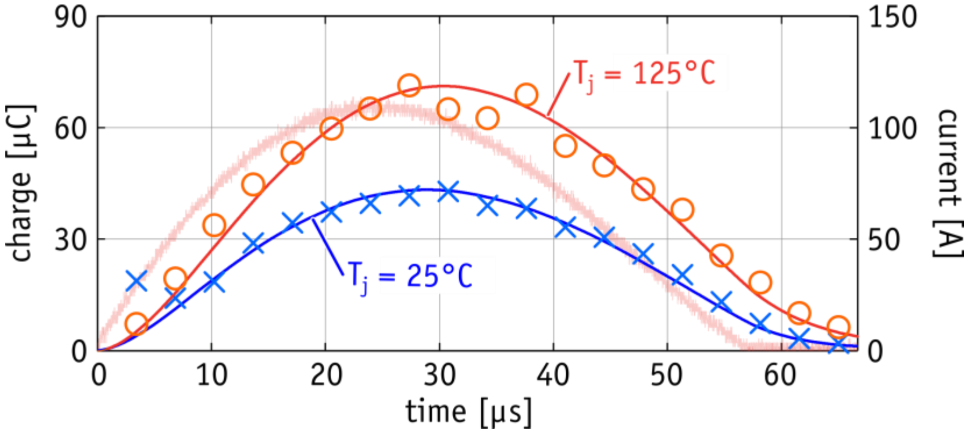
▲ Experimental Stored Charge Dynamic Analysis on 1.7kV FS IGBT

▶ Measurement of IGBT Stored Charge Behavior

▶ **Field-Stop 1.7kV IGBT**
▶ **62mm Package**

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

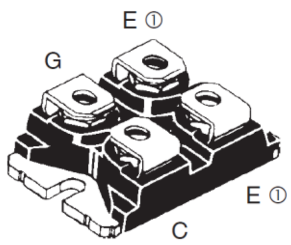
▲ **Charge Control Equation to Estimate Charge Behavior**



▲ **Experimental Stored Charge Dynamic Analysis on 1.7kV FS IGBT and Resonant Sine Pulse**

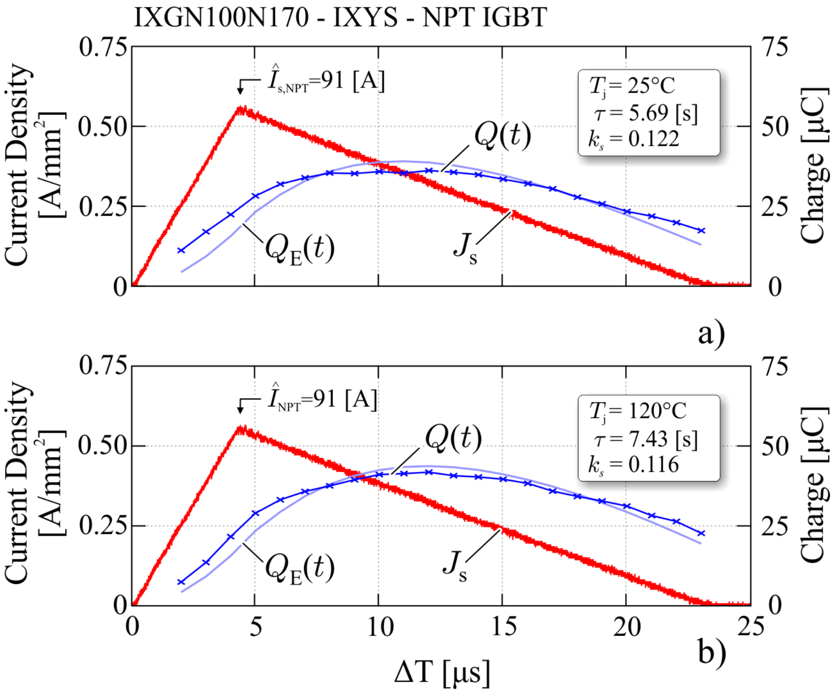
▶ Measurement of IGBT Stored Charge Behavior

- ▶ **Non-Punch-Through 1.7kV IGBT**
- ▶ **SOT-227B Package**



Switch	Temperature T_j	τ	k_s
FS	25 °C	3.07 µs	0.114
FS	120 °C	4.24 µs	0.138
NPT	25 °C	5.96 µs	0.122
NPT	120 °C	7.43 µs	0.116

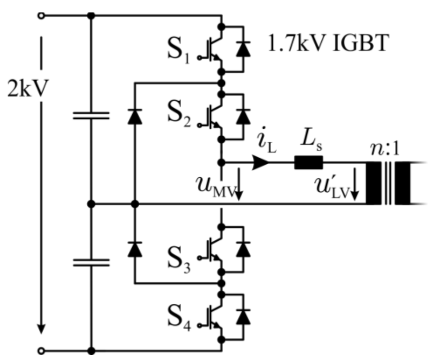
▲ **Summary of IGBTs' Parameters**



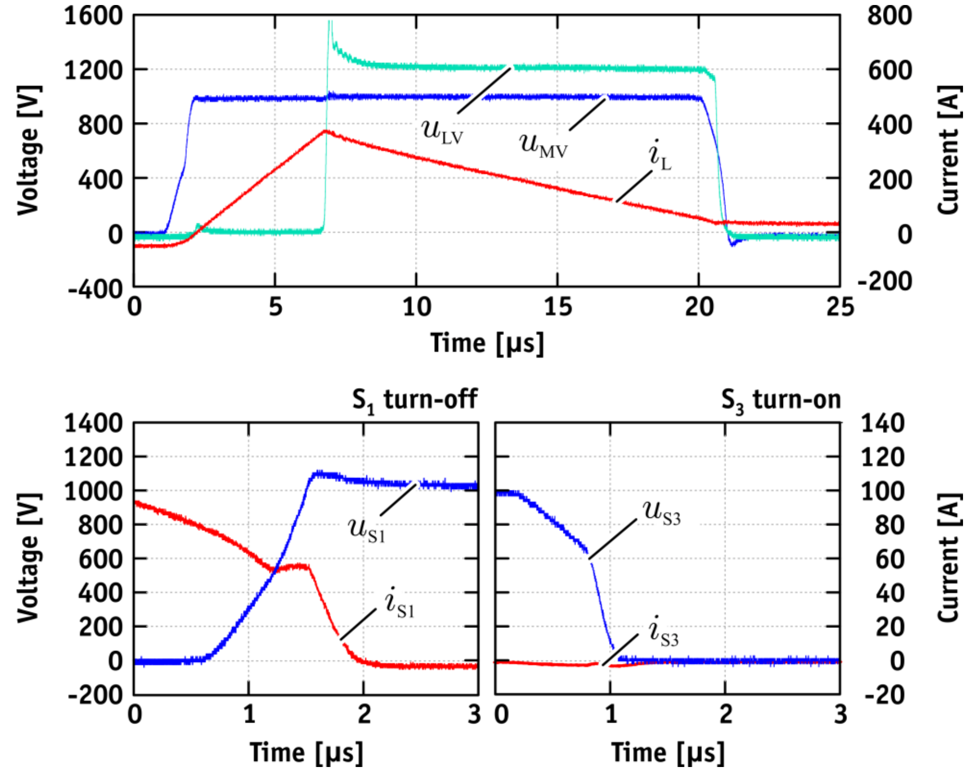
▲ **Experimental Stored Charge Dynamic Analysis on 1.7kV NPT IGBT**

Quasi ZCS and ZVS: MV → LV

- Low Turn-on Losses due to Low Switched Current
- Virtual Elimination of Turn-on Losses



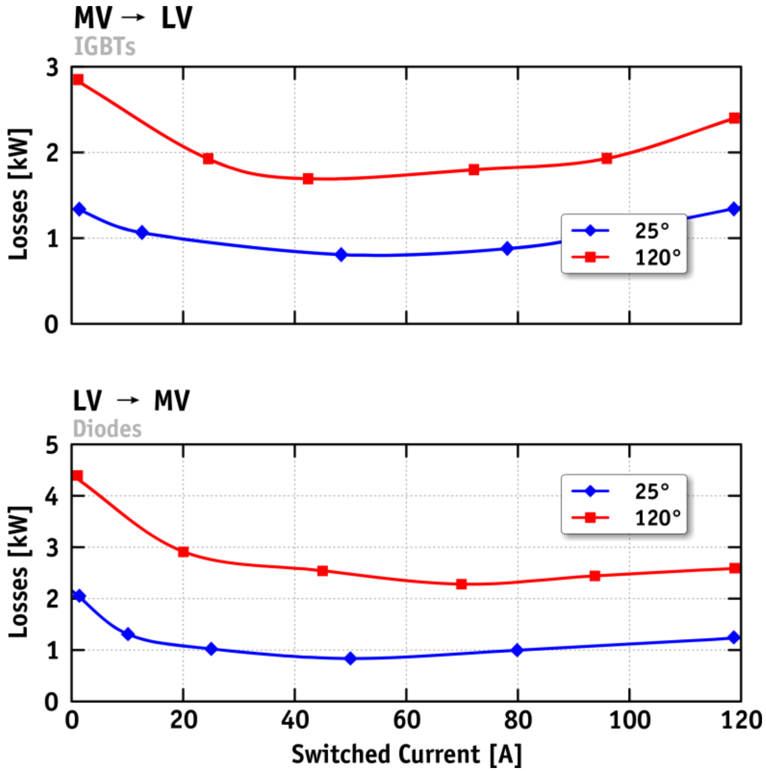
▲ 1.7kV IGBT NPC Bridge



▲ NPC Bridge Exp. Waveforms for QZCS/ZVS @ 166kW / 20kHz / 120°C and Power from MV to LV Side

▶ Quasi ZCS and ZVS: Switched Current Sweep

- ▶ 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



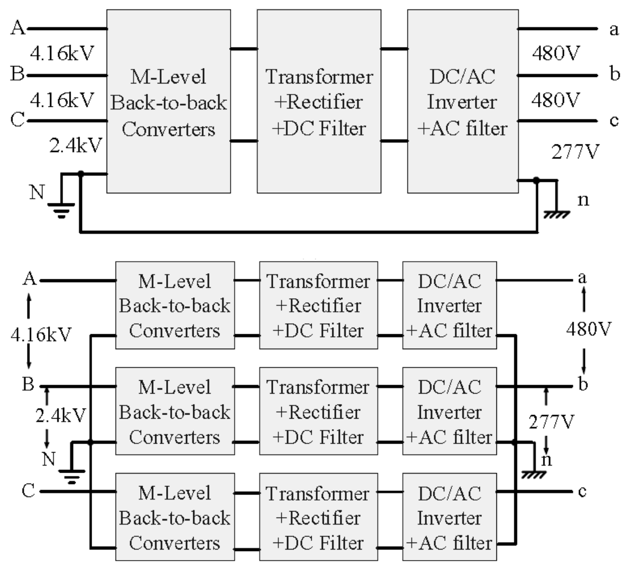
▲ ZCS Losses for Both Power Flow Directions and 25°C & 120°C @ 166kW Transferred Power

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**

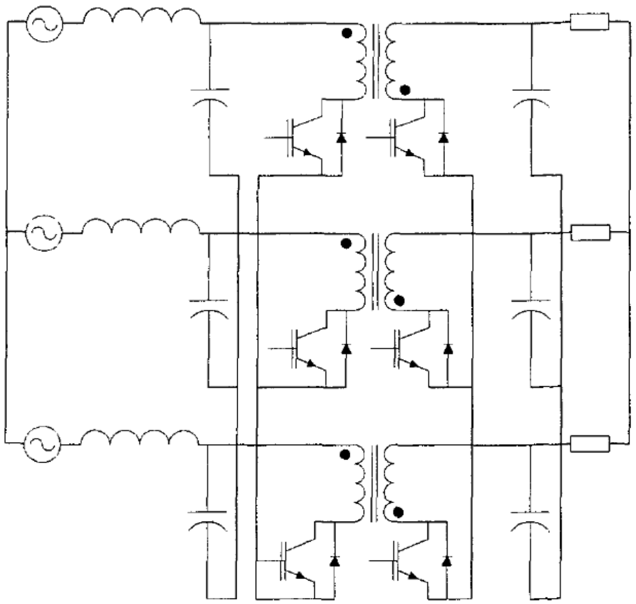


- **Frequently 1ph. AC/3ph. AC Converter Topologies Analyzed Instead of Full 3ph. Systems**
- **Frequently Unidir. (MV→LV) Topologies Proposed/Analyzed Instead of Bidir. Systems**

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

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

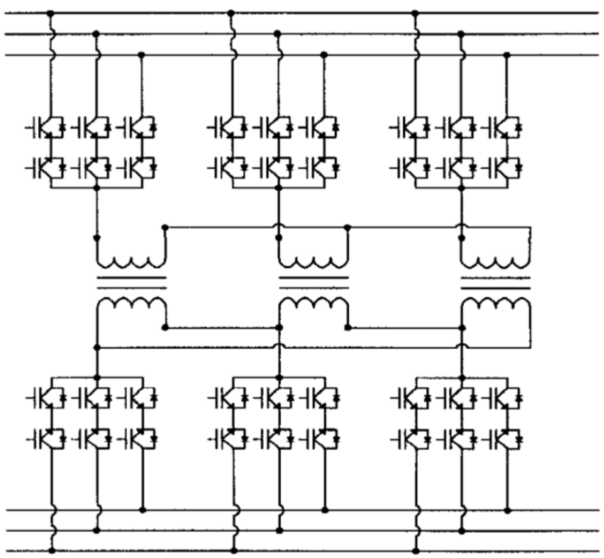
- Venkataramanan (2000)



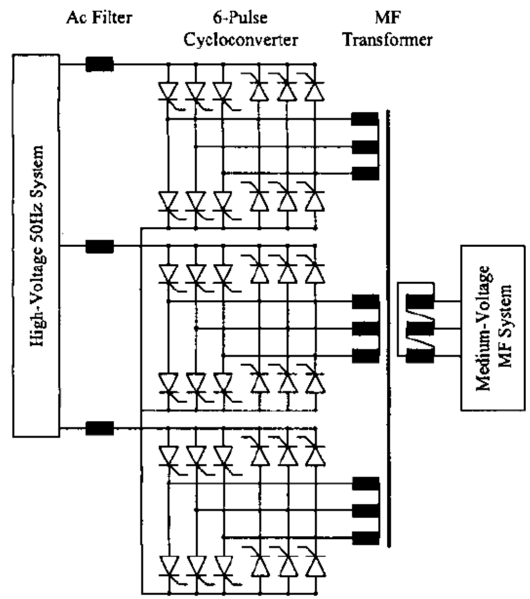
- Only Interesting for Low-Voltage / Low-Power Applications

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

- Enjeti (1997)



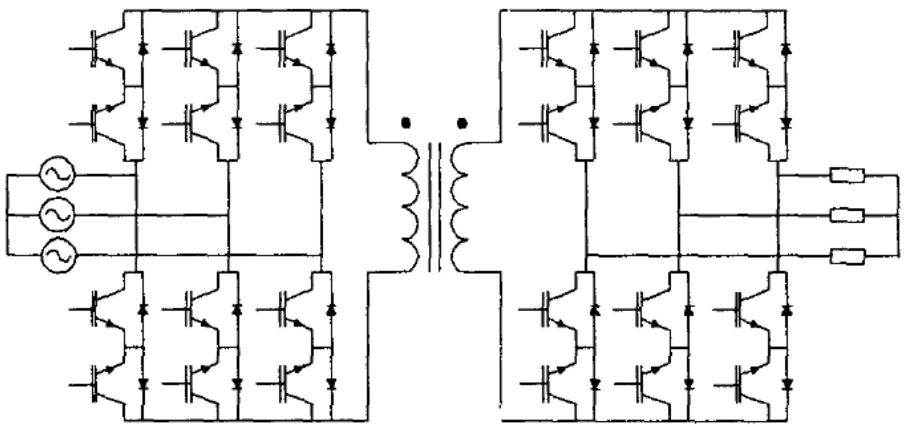
- Steimel et al. (2002)



- 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

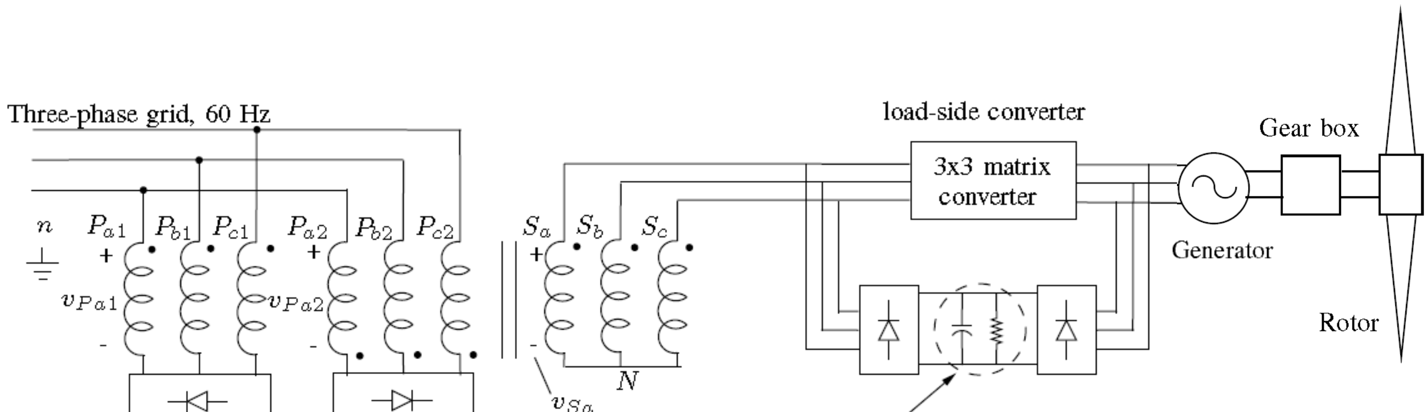
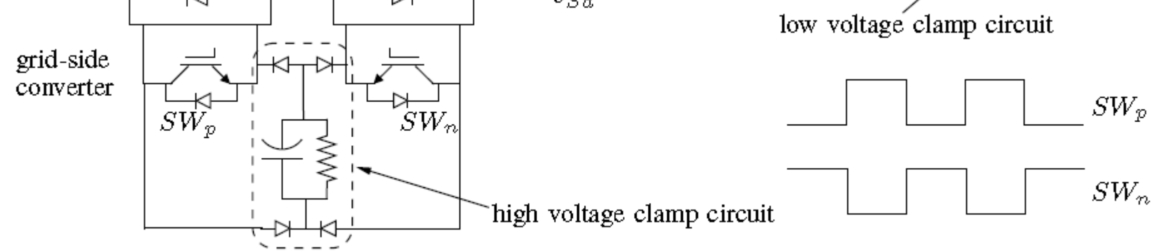
- Venkataramanan (2000)



- 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)

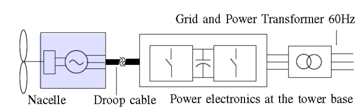


Fig. 1. Conventional wind power generation system

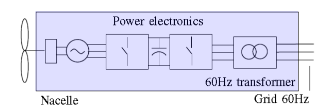
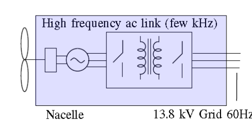


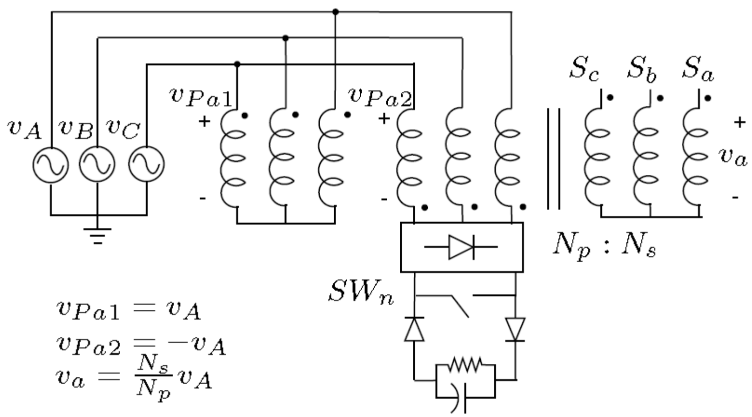
Fig. 2. Recent wind turbine system

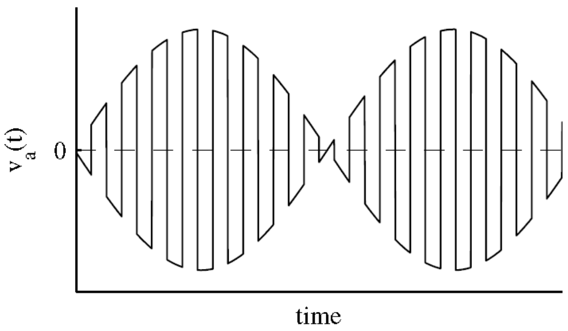


- Reduced HV Switch Count (Only 2 HV Switches @ 50% Duty Cycle / No PWM)
- LV Matrix Converter Demodulates MF Voltage to Desired Ampl. / Frequency
- Switching CM Voltage Eliminated at Generator Terminals by Proper MC Control

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

- Mohan (2009)

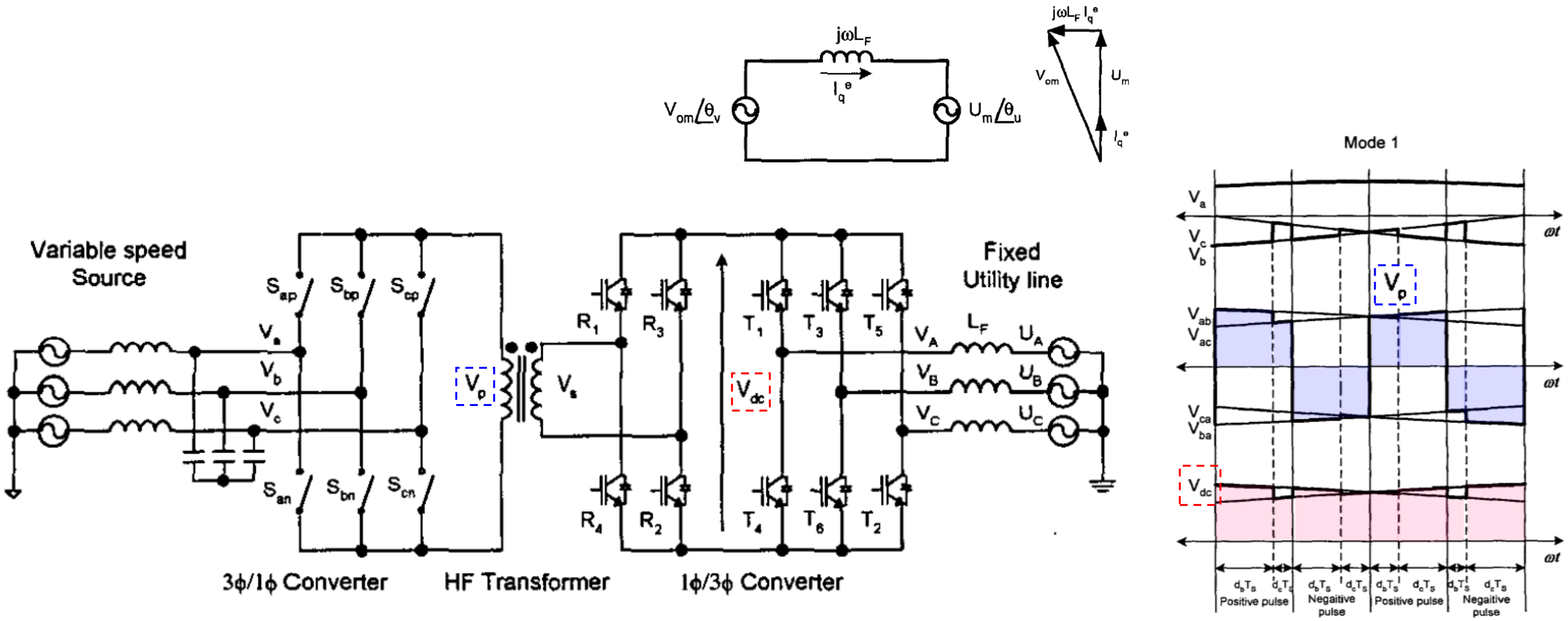




- Equivalent Circuit of the Transformer for SW_p-on and SW_n-off and Input Phase *a* Voltage of MC
- Clamp Circuit Sinks Energy Stored in the Leakage Inductance
- Clamp Voltage = 2 x Grid Line-to-Line Voltage

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

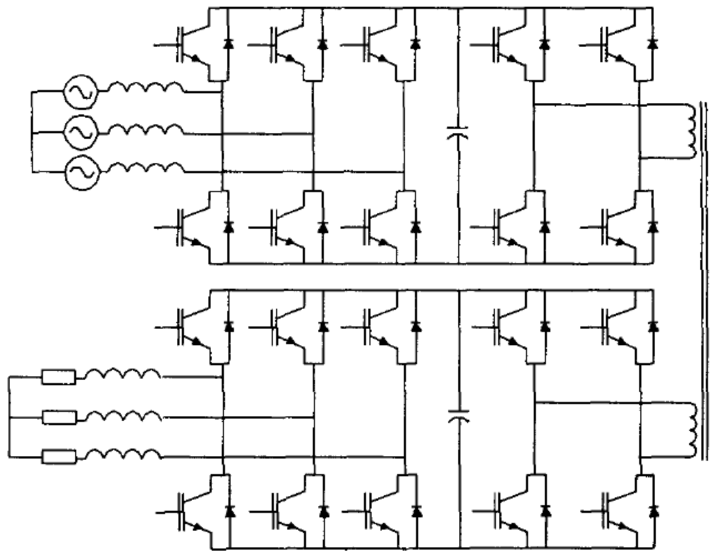
- Enjeti (2003)



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

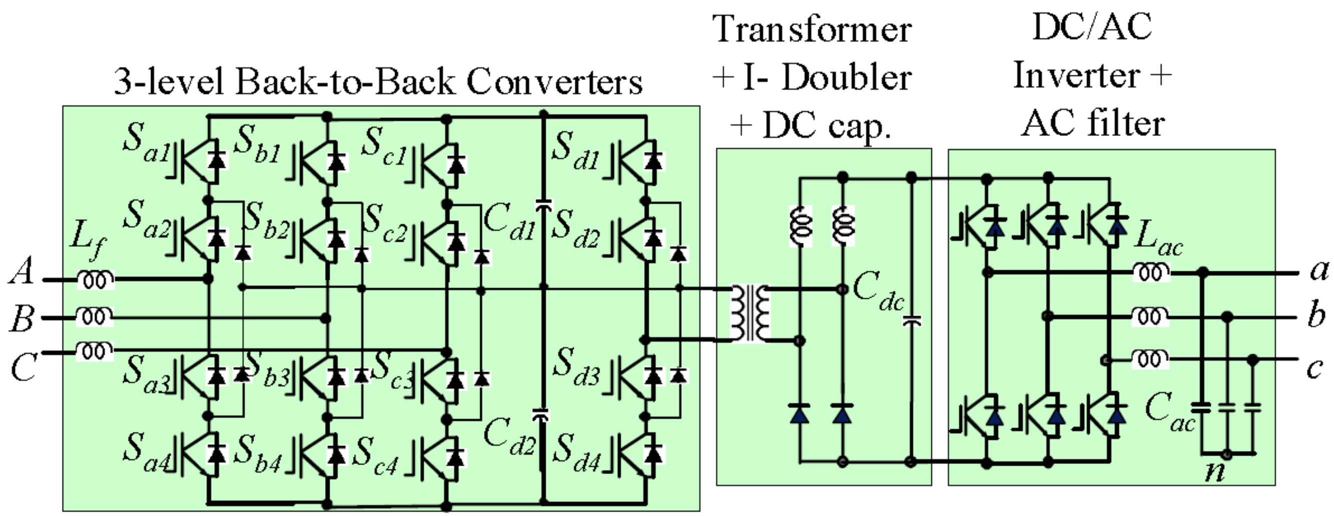
- Formation of Transf. Voltage Involving all Phases *a*,*b*,*c* and Ensuring Balanced Flux
- Transformer Sec. Voltage Rectified into Fluctuating DC Link Voltage V_{dc}
- V_{dc} Converted into V_A, V_B, V_C by Space Vector PWM for Mains Current Control

► 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

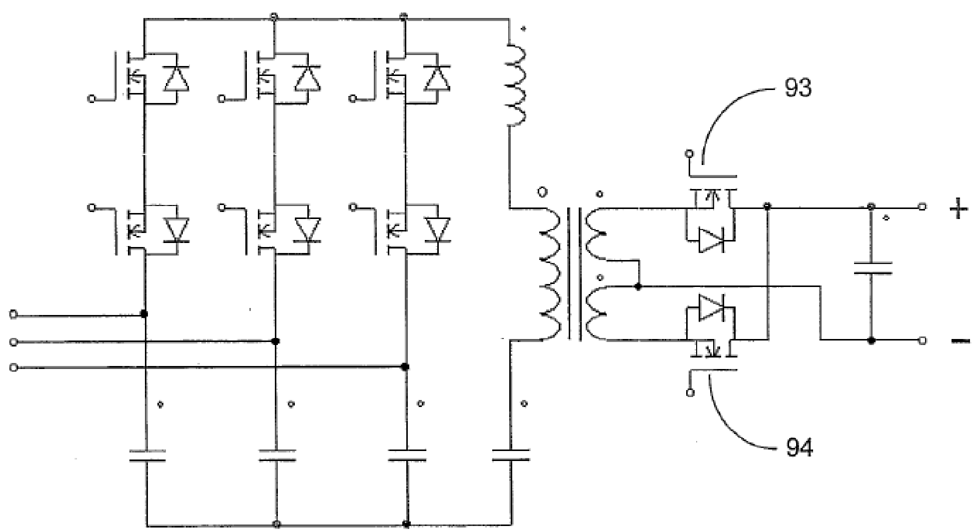
► DC-Link Based Direct 3ph. SST Topologies



- 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

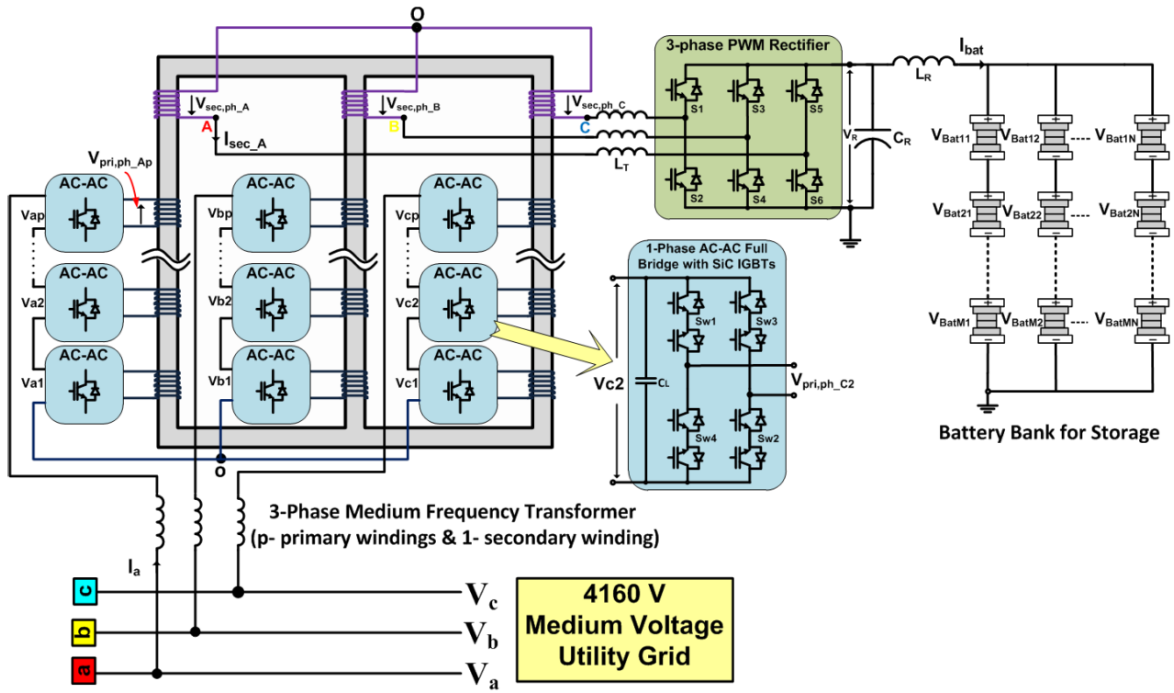
- EATON (Patent Appl. WO 2008/018802, Inv.: M.J. Harrison, 1997)



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

▶ DC-Link Based Direct 3ph. SST Topologies

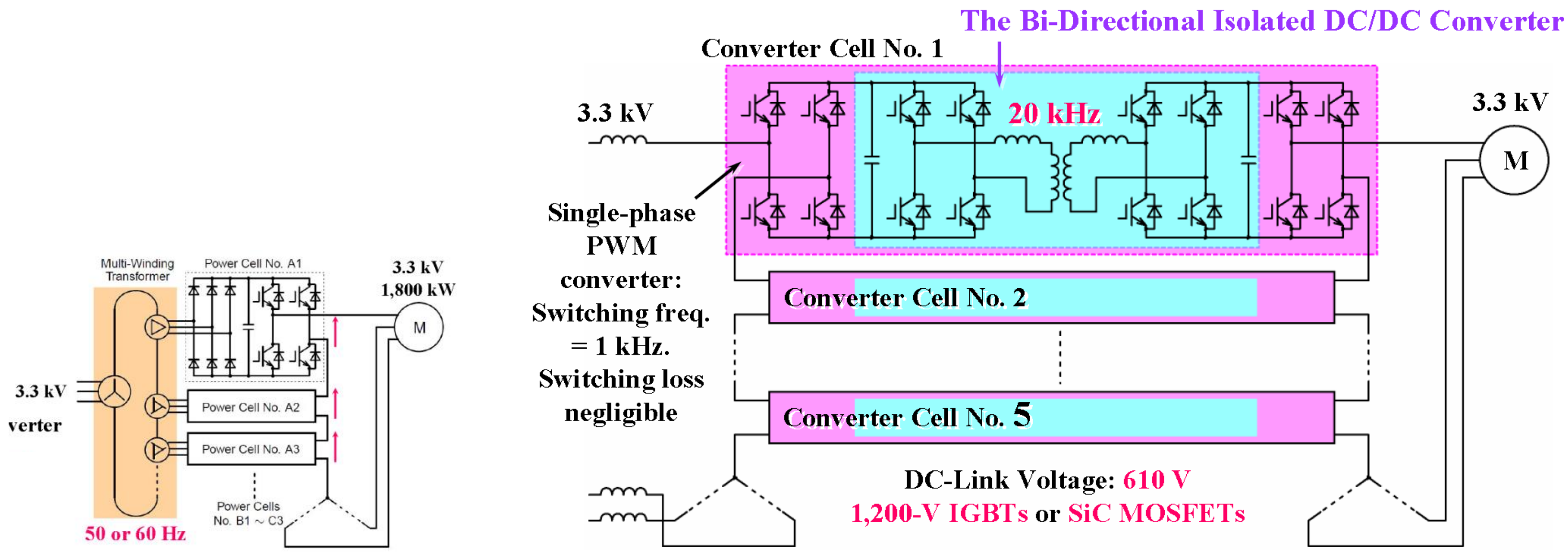
- Proposed for Energy Storage Systems (Enjeti, 2012)



- **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)

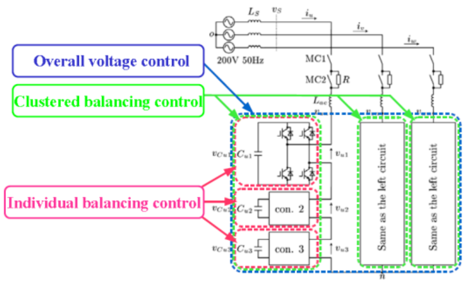


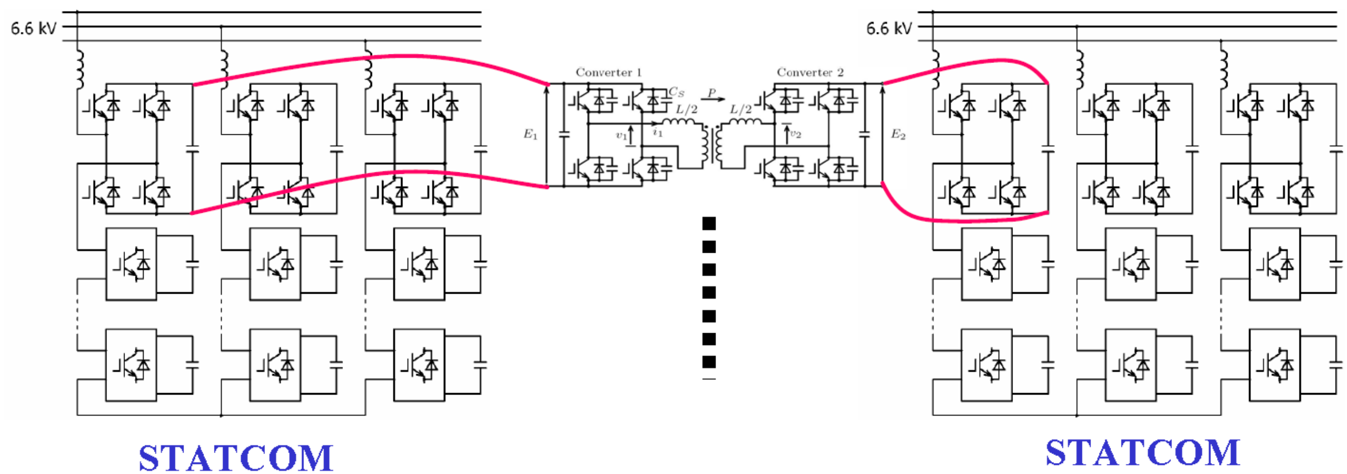
- Application for MV Motor Drives Replacing the 50/60 Hz Transformer

▶ DC-Link Based *Fully Phase Modular* SST Topologies

- Akagi (2005)

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

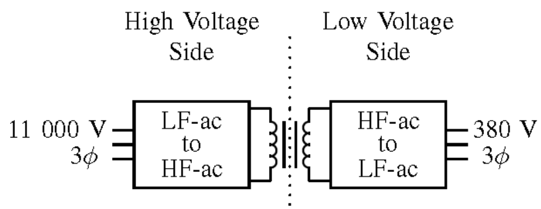


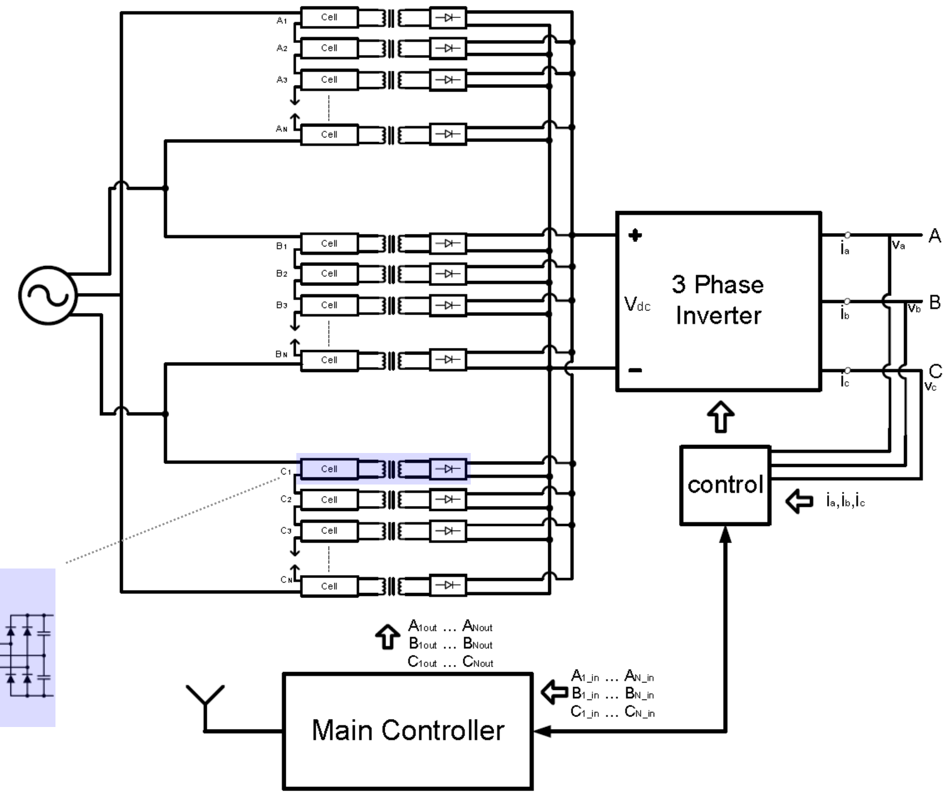


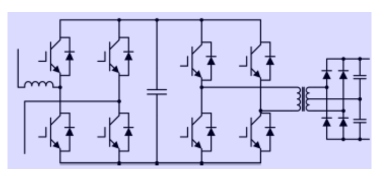
- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control

▶ DC-Link Based *Partly Phase Modular* SST Topologies

- van der Merwe (2009)



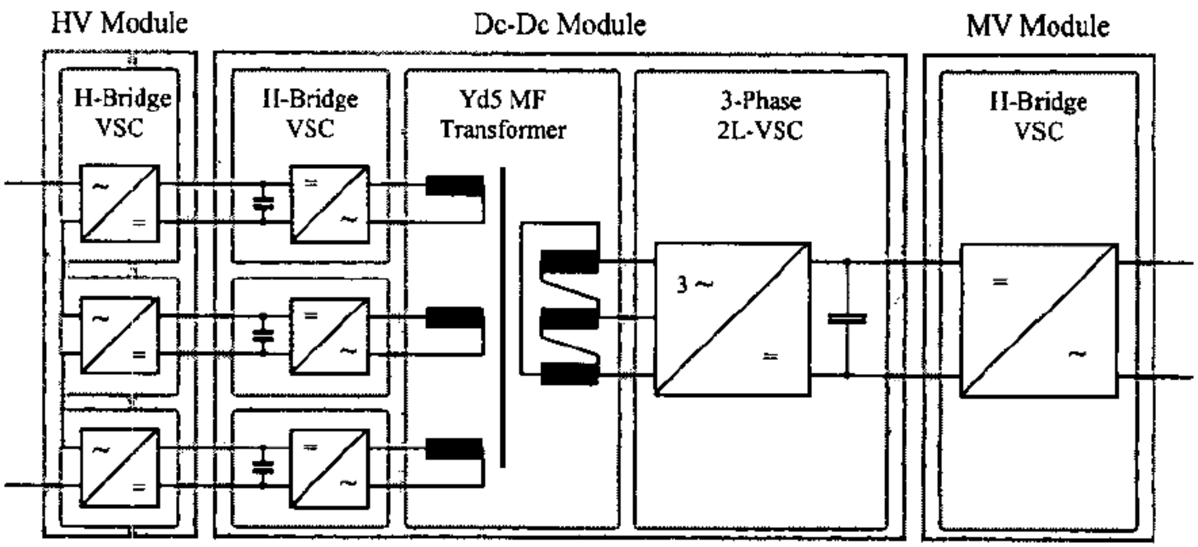




- **SST Concept Without Accessible MV DC Bus**
- **Extension to Bidirectional Power Flow by Replacing the Passive Rectifiers with Active Systems**

▶ DC-Link Based *Partly Phase Modular* SST Topologies

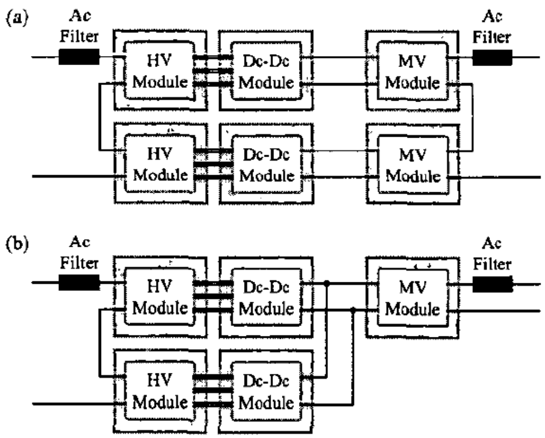
- Steimel et al. (2002)



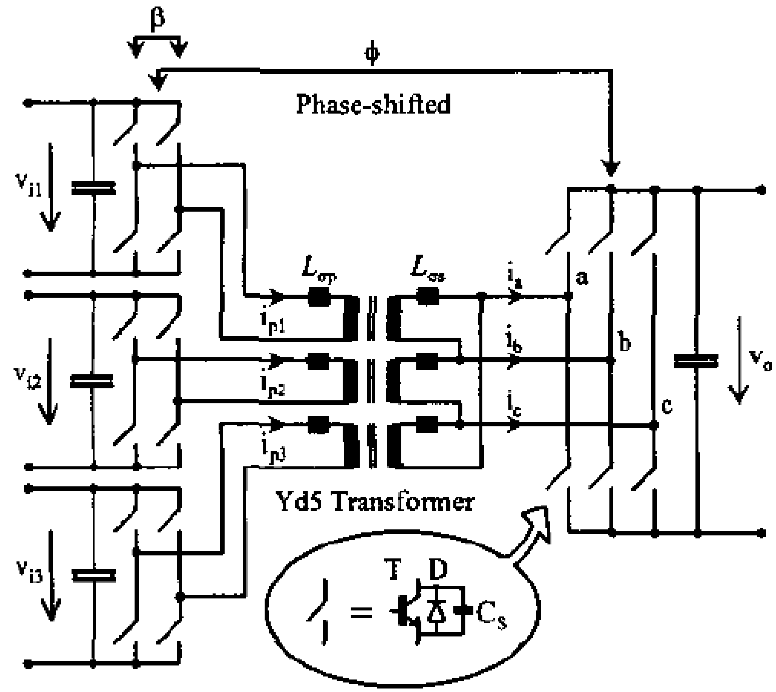
- Electronic Power Transformer for 110/20kV and 110/10kV Applications
- Truck Movable Temporary Replacement of Failed Conventional Transformer

▶ DC-Link Based *Partly Phase Modular* SST Topologies

- Steimel et al. (2002)



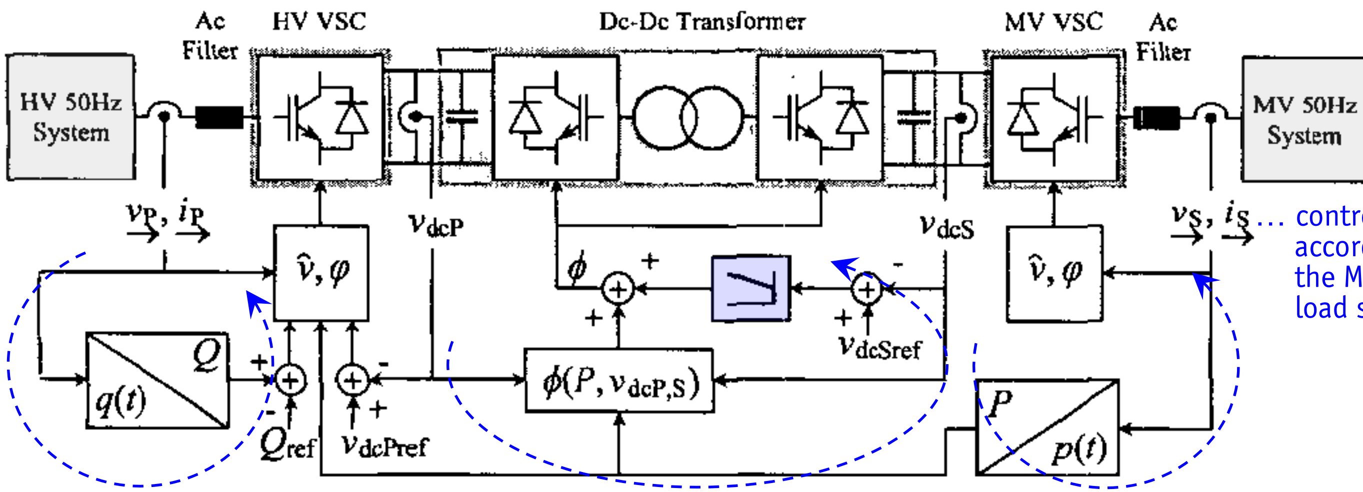
Single-Phase Design of an Electronic Power Transformer for
(a) 110kV/20kV (b) 110kV/10kV Ac/Ac Conversion



- 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

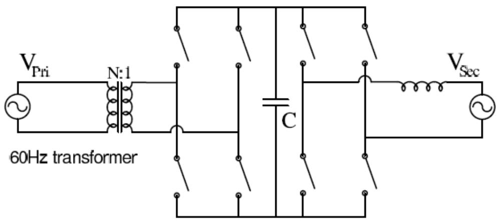
- Steimel et al. (2002)

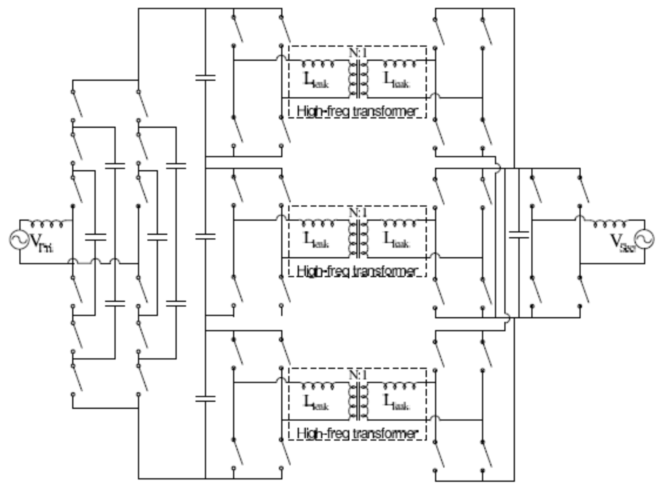


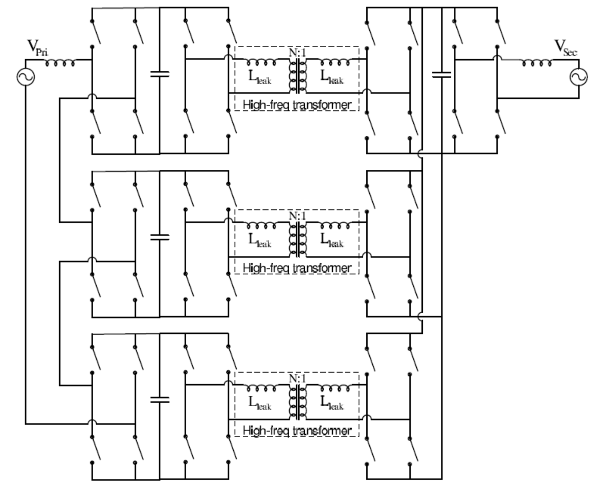
... controlled via v_S according to the MV system load state

- **Multi-Loop Control Structure of the Electronic Power Transformer**

▶ 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

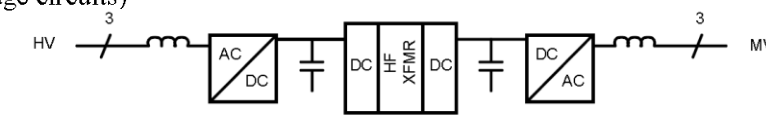
- Clare/Wheeler et al. (2001)

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

Side A Side B

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

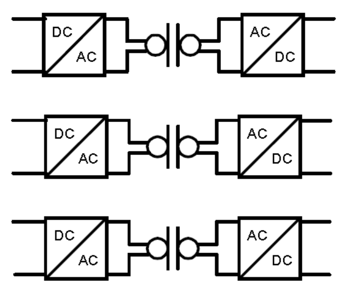
X, number of DC links on Side A (equal to number of Side A AC/DC bridge circuits)
Y, number of DC links on Side B (equal to number of Side B AC/DC bridge circuits)
L, number of HF transformers
M, windings per HF transformer (Side A)
N, windings per HF transformer (Side B)



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

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

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

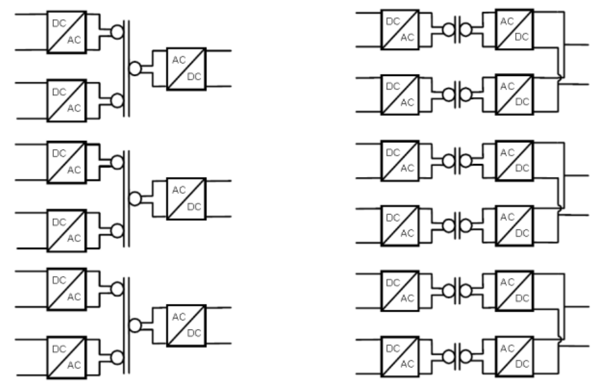


- **Transformer Classification Independent of Number of DC Links**

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

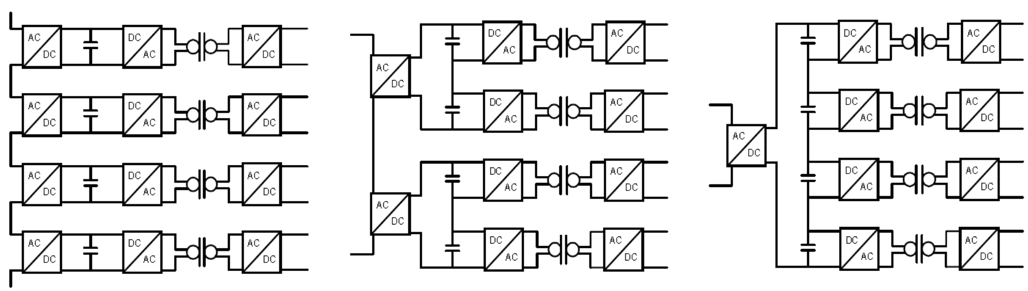
- **Structure of HF Transformer Defined by L,M,N**

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



- **Structure of the DC Links**

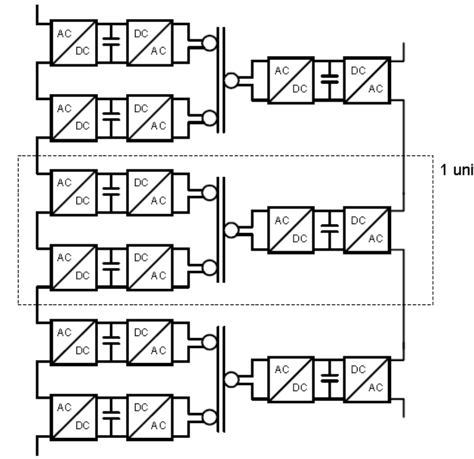
$X\,{}^{M}L^{N} = 4\,{}^{1}4^{1}$ $\quad$ $X\,{}^{M}L^{N} = 2\,{}^{1}4^{1}$ $\quad$ $X\,{}^{M}L^{N} = 1\,{}^{1}4^{1}$

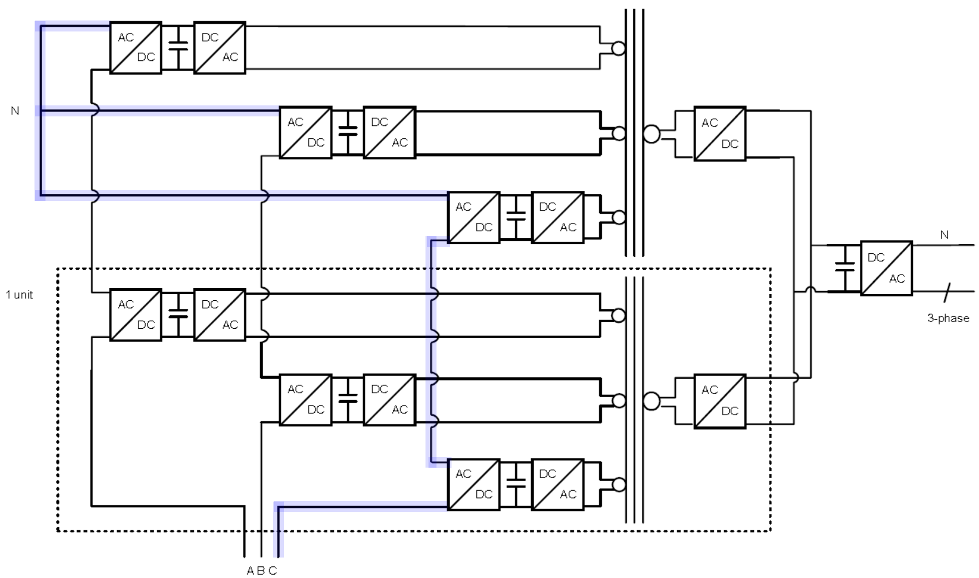


▶ Classification System for Multi-Level & Multi-Cell Power Converters

- **Complete Converter Structures**

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

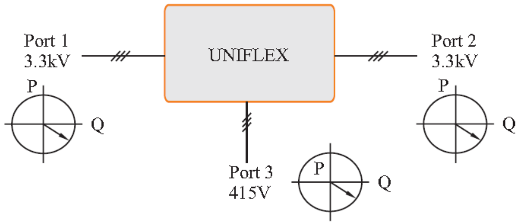


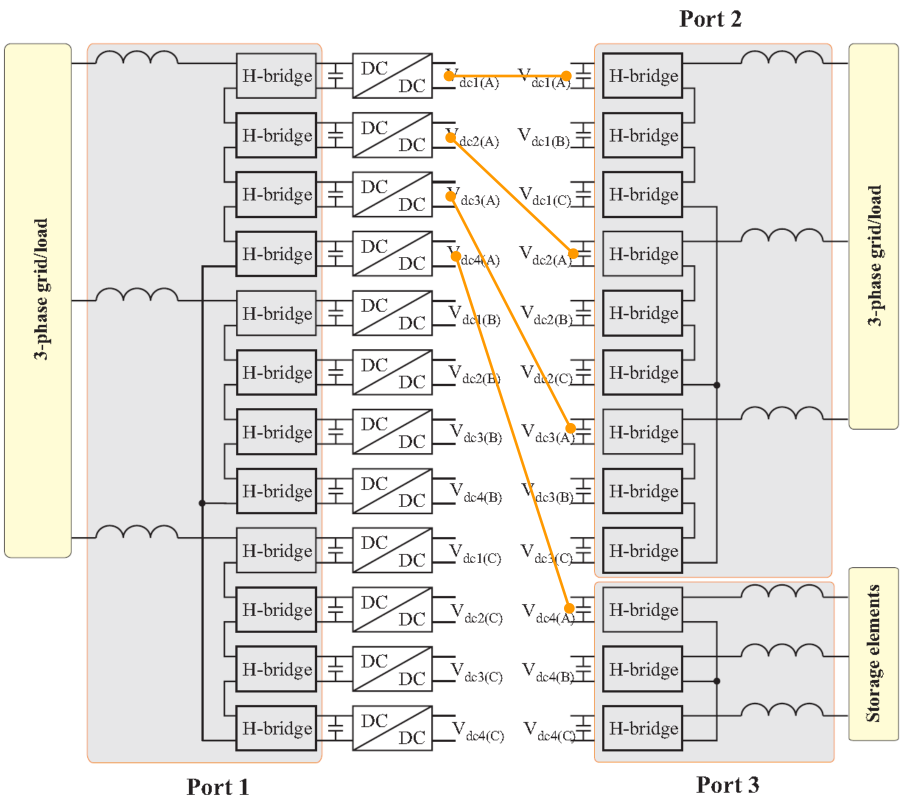


$$X^{M}L^{N}Y = 6^{3}2^{1}1$$

▶ UNIFLEX Project

- EU Project (2009)

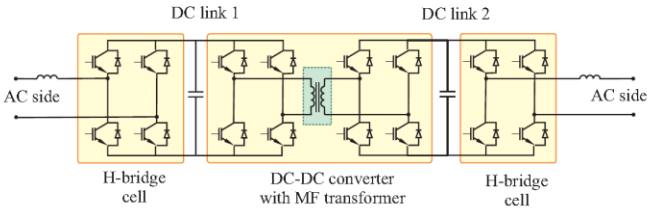


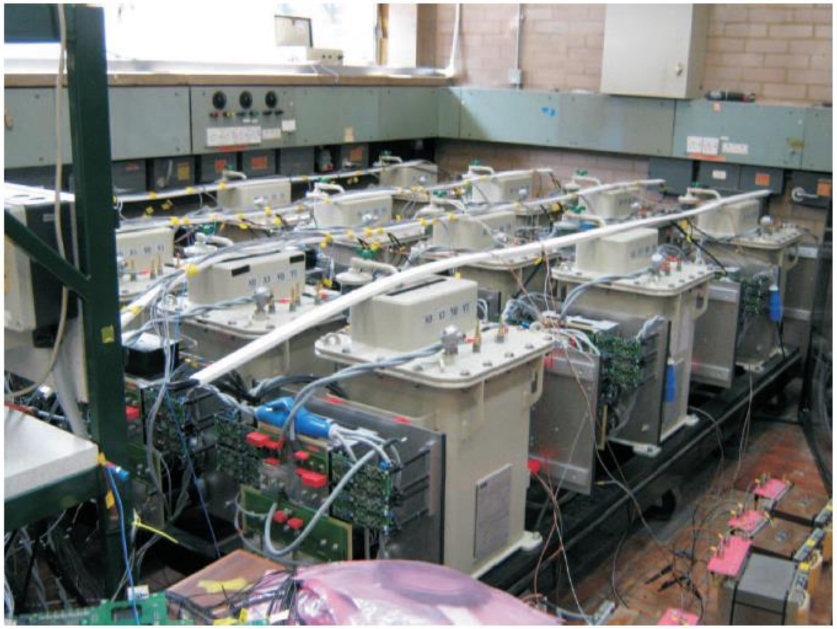


- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- Cellular 300kVA Demonstrator of 3-Port Topology for 3.3kV Distr. System & 415V LV Grid Connection

▶ UNIFLEX Project

- EU Project (2009)



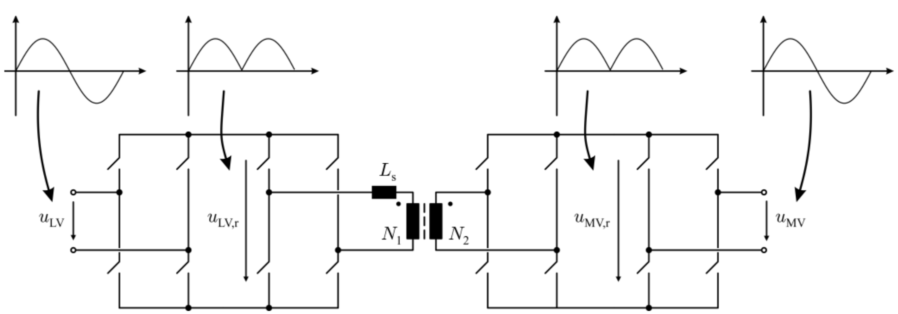


- AC/DC-DC//DC-DC/AC Module (MF Isolation, 1350V DC Link) and Prototype @ Univ. of Nottingham

▶ SiC-Enabled Solid State Power Substation

- Das (2011)

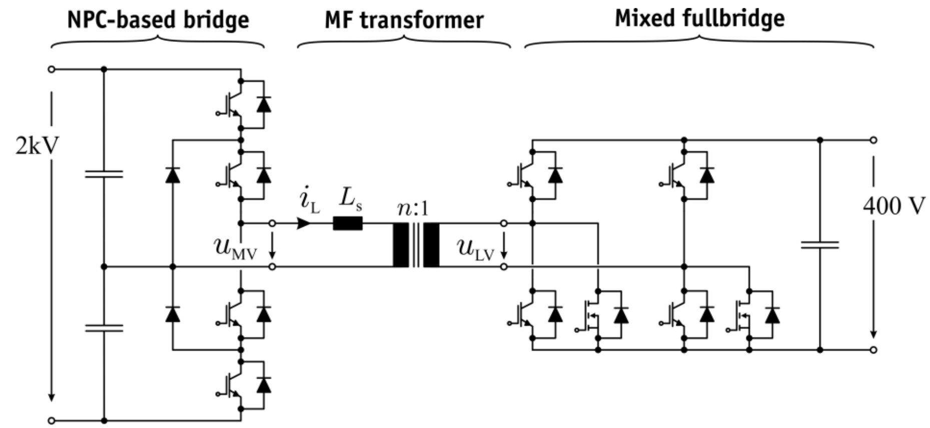
- Fully Phase Modular System
- Indirect Matrix Converter Modules ($f_1 = f_2$)
- MV Δ-Connection (13.8kV$_{l-l}$, 4 Modules in Series)
- LV Y-Connection (465V/√3, Modules in Parallel)

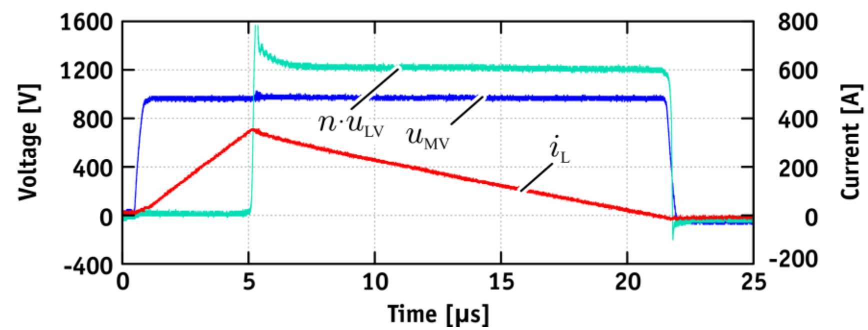


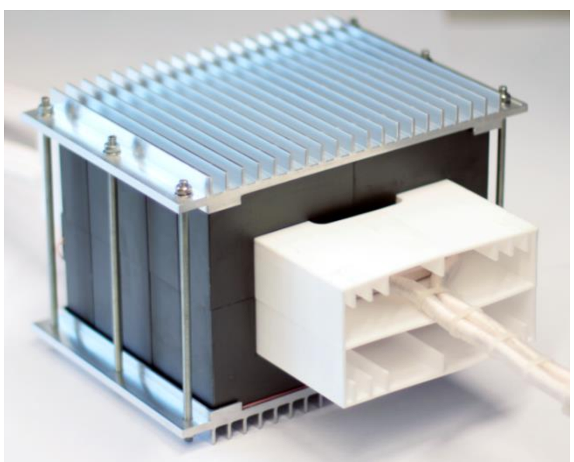
- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

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

Module 1

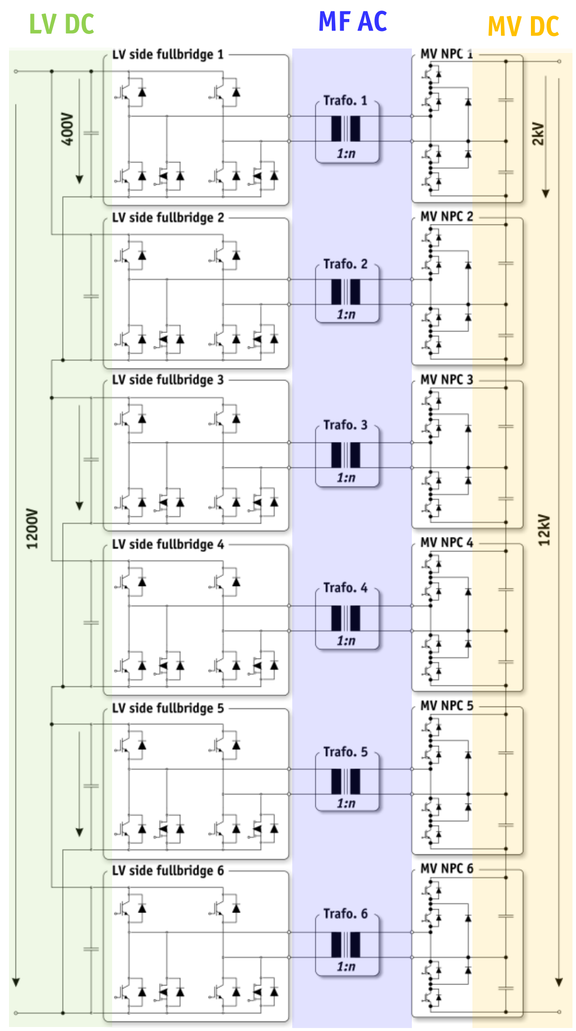
Module 2

Module 3

Module 4

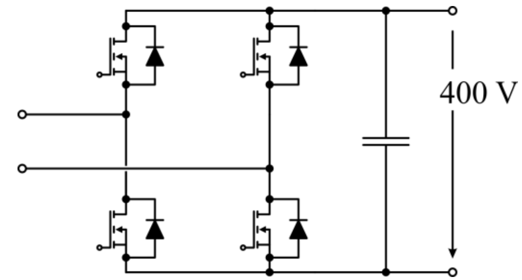
Module 5

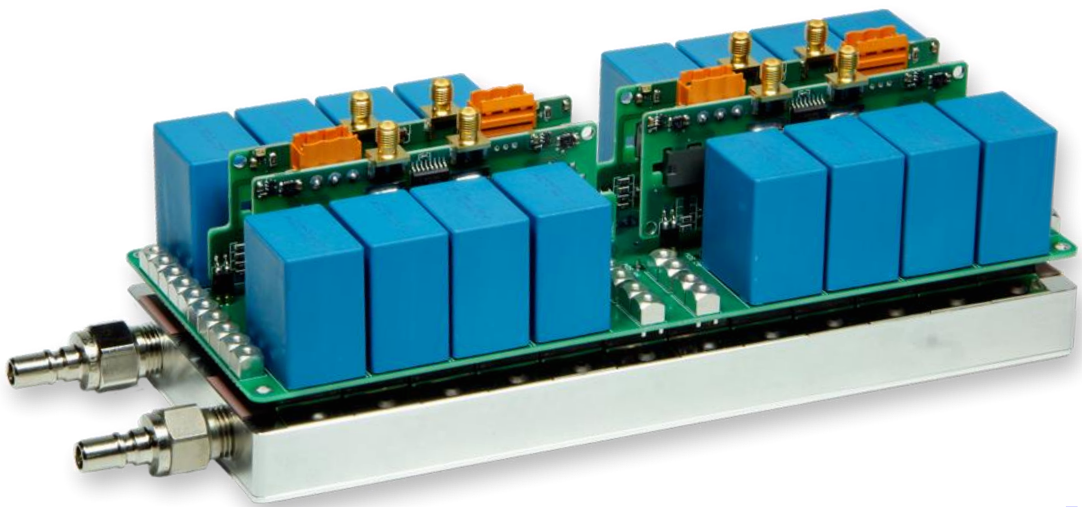
Module 6



▶ The MEGACube - MOSFET-based LV Full-Bridge

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

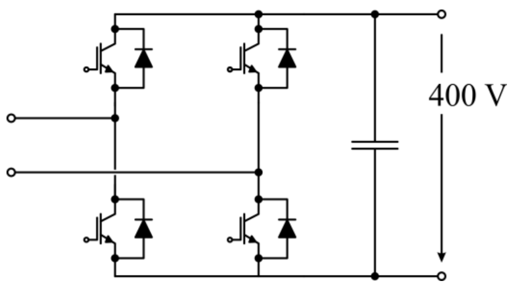




▲ **55 kW Water-Cooled LV Full-Bridge**
Utilized for MOSFET/IGBT Arrangement

▶ The MEGACube - IGBT-Based LV Full-Bridge

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

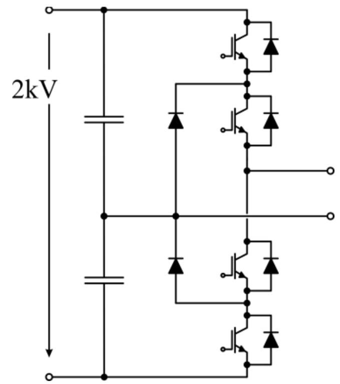


▶ 83 kW Water-Cooled LV Full-Bridge

Based on IGBT ECONOdual Modules

▶ The MEGACube - MV NPC Module

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



166 kW Water-Cooled MV NPC Module ▶
Based on ECONOdual IGBTs

▶ The MEGACube - Air-Cooled Ferrite Core Transformer

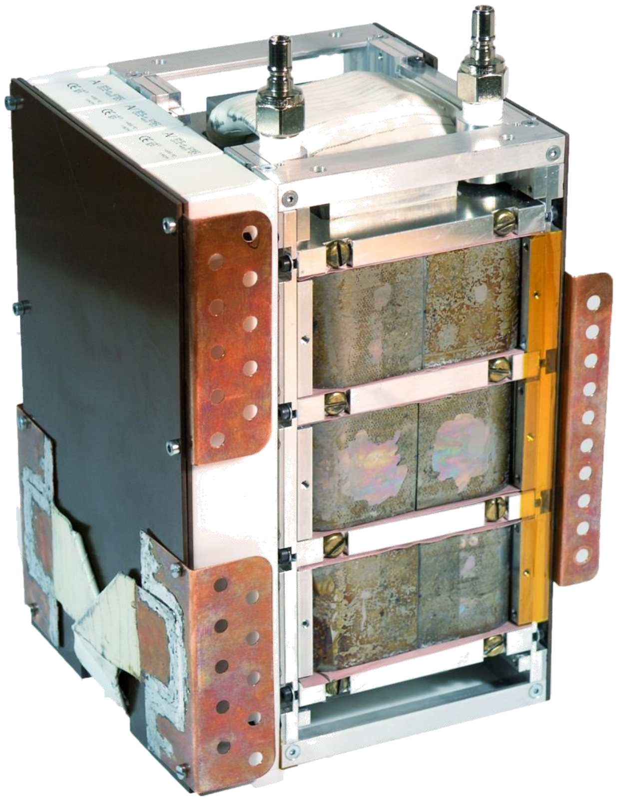
- Power Rating 166 kW
- Estimated Losses (incl. Fan Power) 0.59 kW
- Forced-Air-Cooled

▲ 166 kW Air-Cooled Ferrite Core Transformer

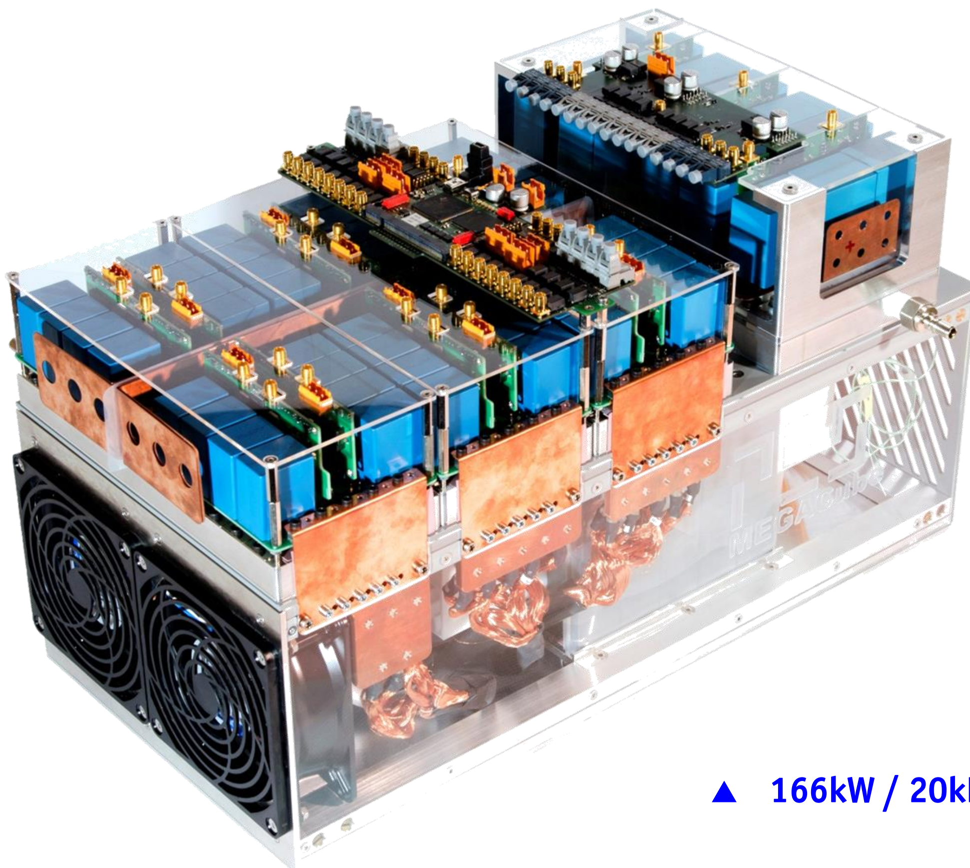
▶ The MEGACube - Water-Cooled Nanocrystalline Transformer

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

166 kW Water-Cooled
Nanocrystalline Core Transformer
Resonant Cap. Directly Attached ▶

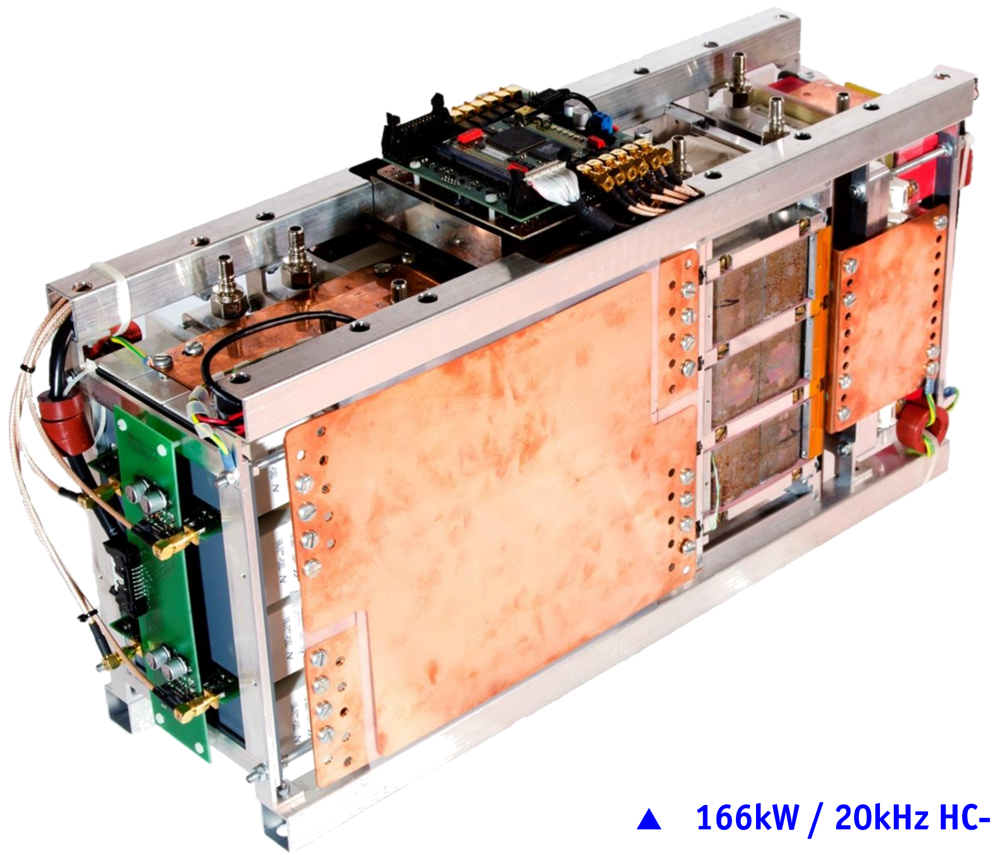


► The MEGACube 166kW / 20kHz Module



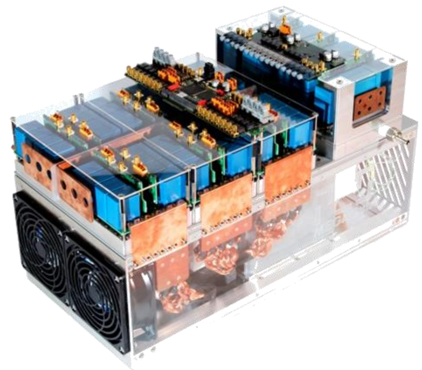
▲ **166kW / 20kHz TCM DC-DC Converter**
400V LV-Side / 2kV MV-Side

▶ The MEGACube - Resonant 166kW / 20kHz Converter

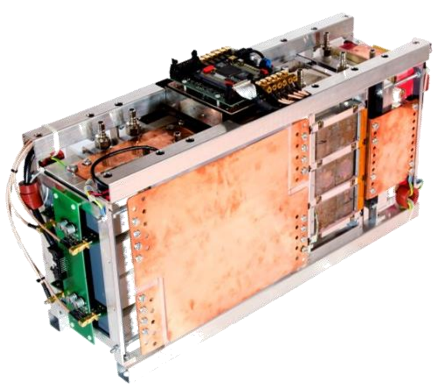


▲ **166kW / 20kHz HC-DCM-SRC DC-DC Converter**
400V LV-Side / 2kV MV-Side

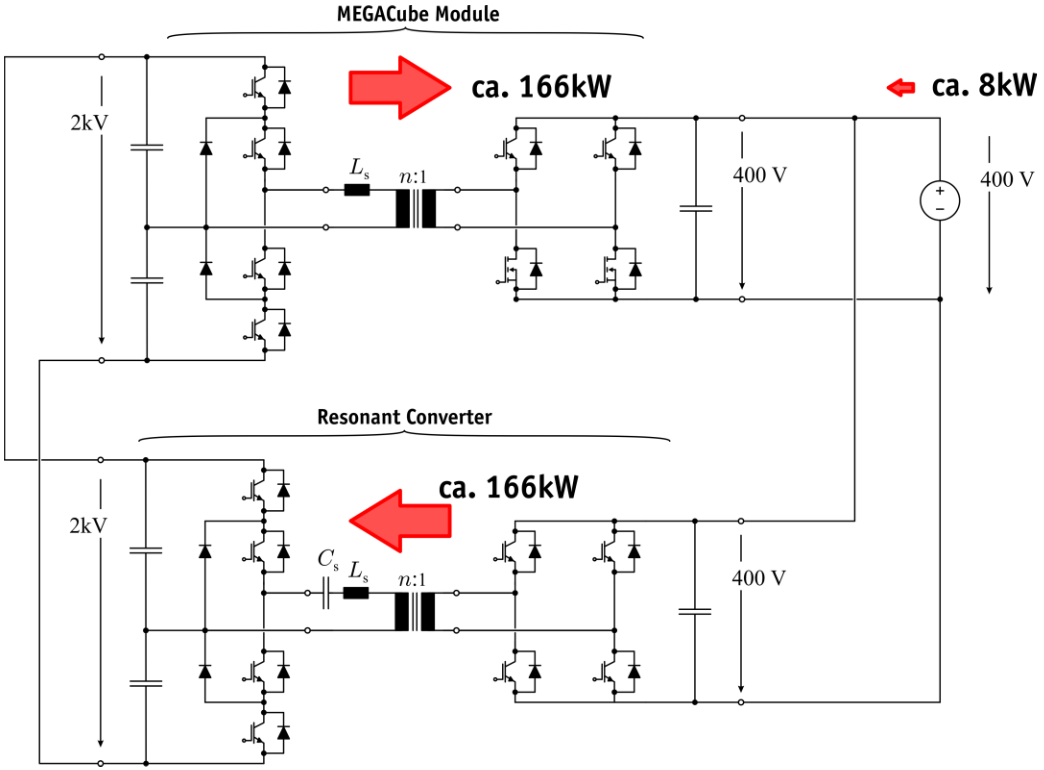
▶ The MEGACube – Back-to-back Testbench



▲ TCM DC-DC Converter

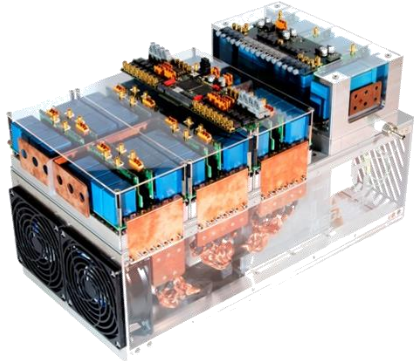


▲ Resonant DC-DC Converter

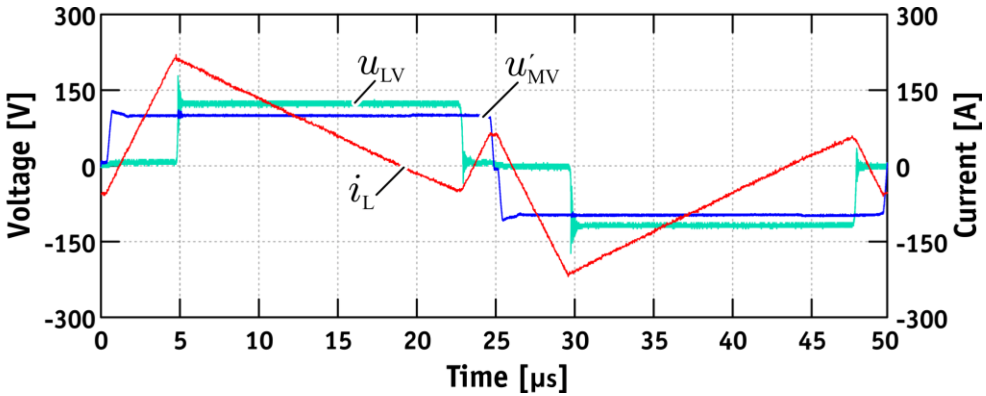


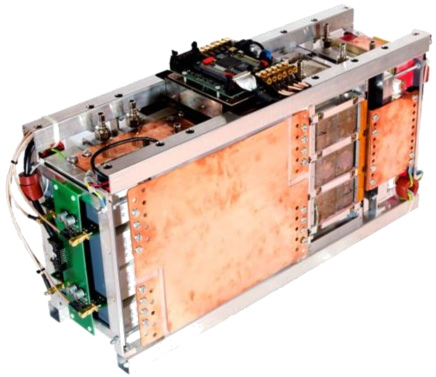
▲ Back-to-Back Arrangement

▶ The MEGACube – Back-to-back Testbench

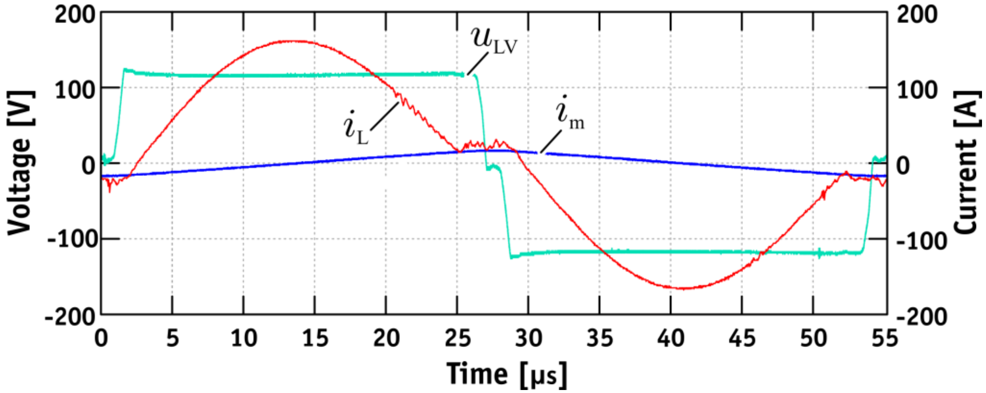


▲ TCM DC-DC Converter

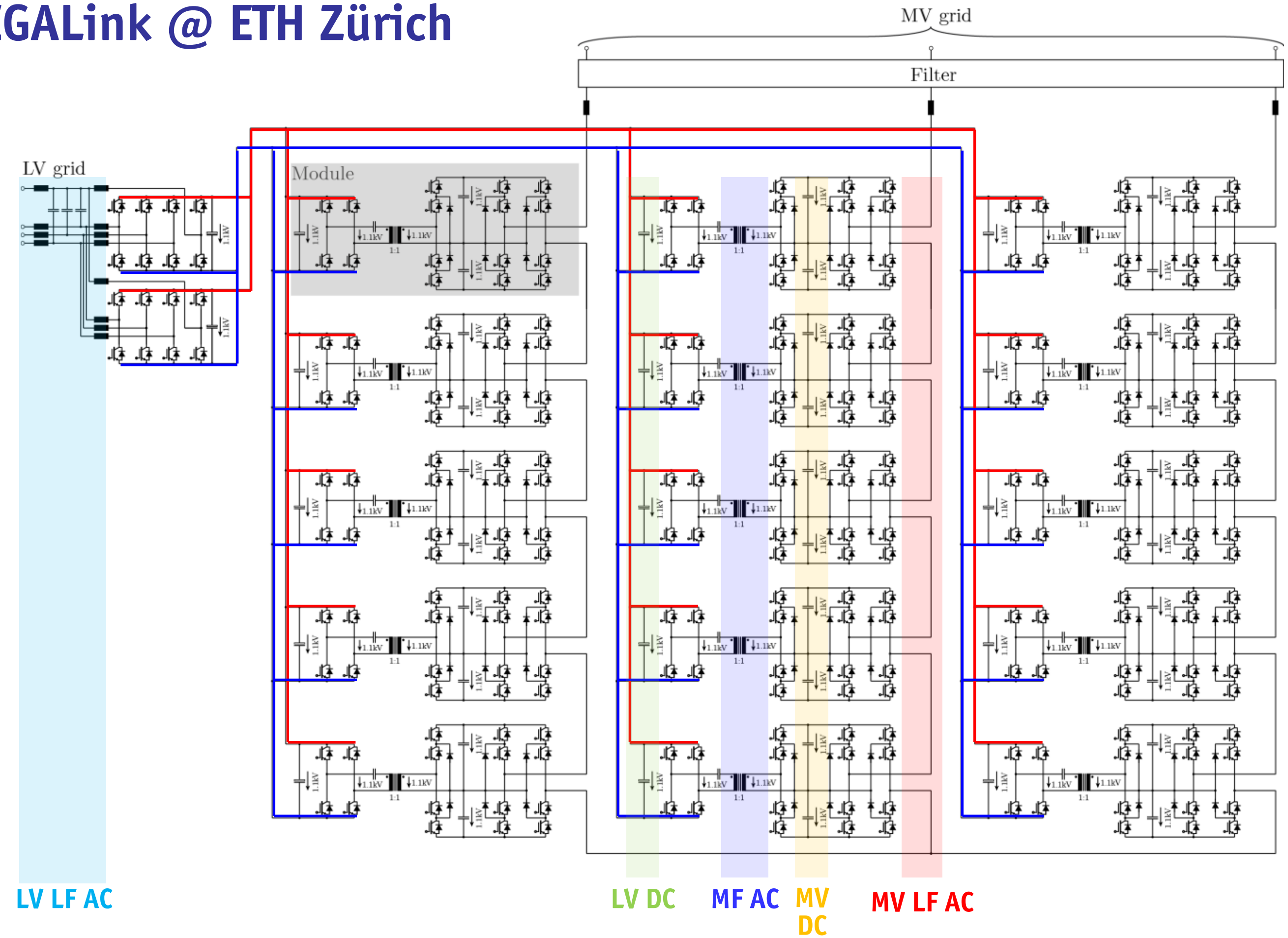




▲ Resonant DC-DC Converter



▶ The MEGALink @ ETH Zürich

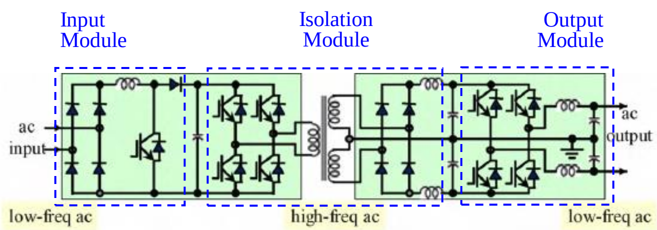


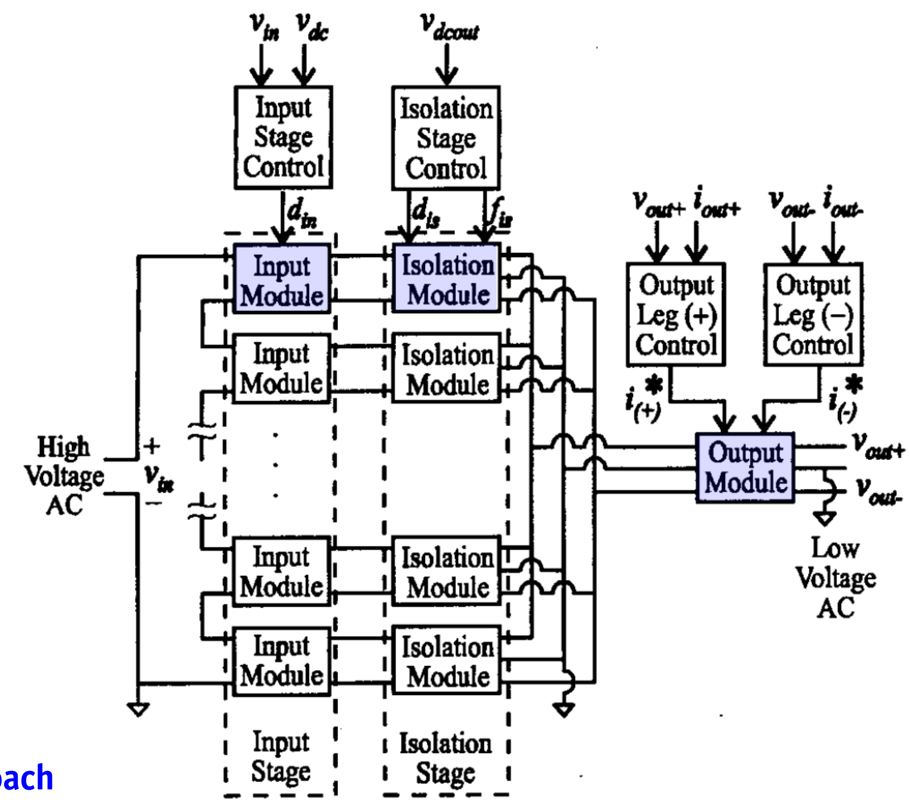
- **2-Level VSI on LV Side / HC-DCM-SRC DC-DC Conversion / Multilevel MV Structure**

▶ Unidirectional DC-Link Based SST Structures

- Ronan et al. (2000)

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



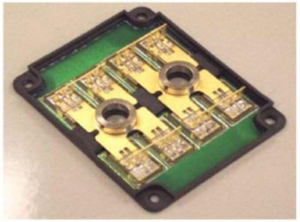


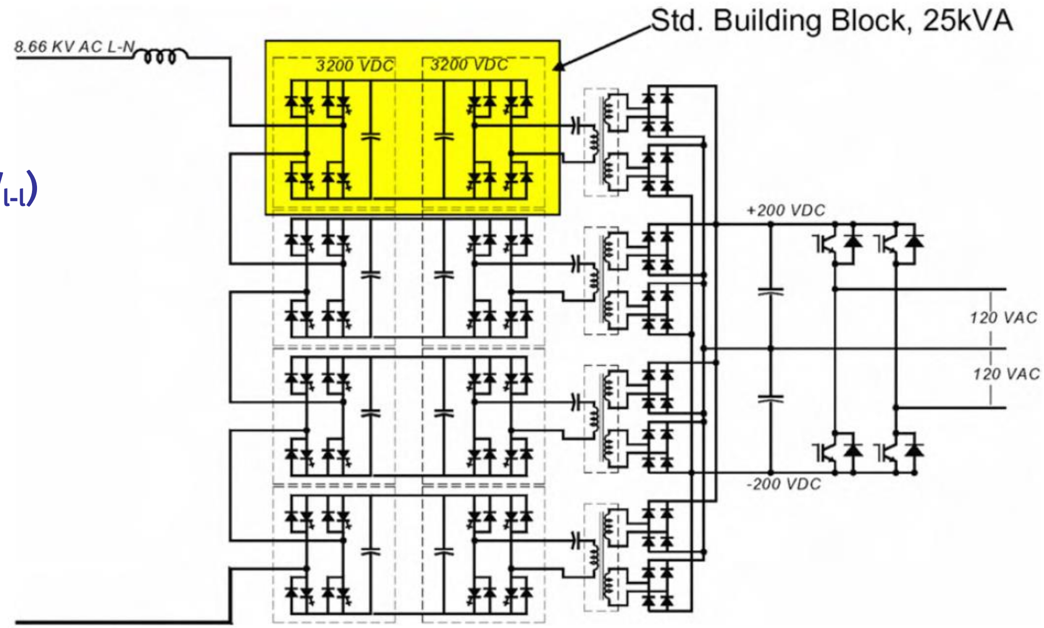
- ISOP Modular Topology
- Three-Stage (AC/DC-DC/DC-DC/AC) Approach

▶ Unidirectional DC-Link Based SST Structures

- EPRI (2009)

- AC Input 8.6kV (15kV$_{l-l}$)
- DC/DC 3.5kV/400V
- AC Output 120V/240V

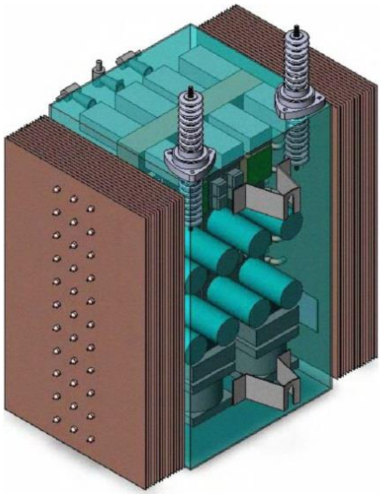


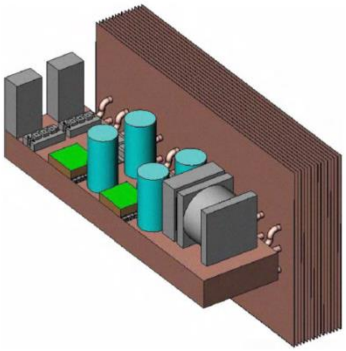


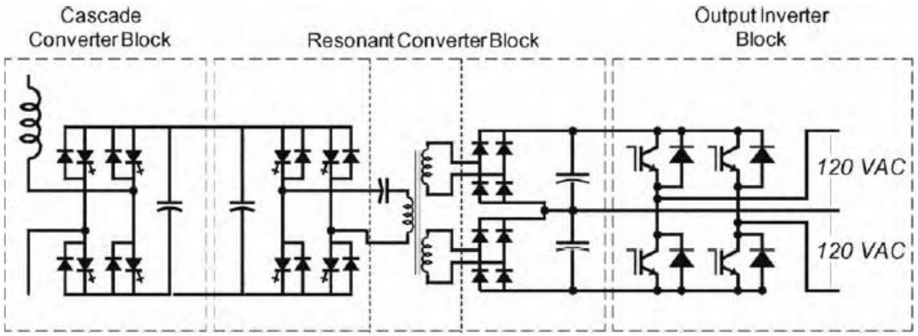
- 100kVA 15kV Class Intelligent Universal Transformer (IUT™)
- Development of HV Super GTO (S-GTO) as MV Switching Device / SiC Secondary Diodes
- 20kHz Series Resonant DC/DC Converter Utilizing Transformer Stray Inductance

▶ Unidirectional DC-Link Based SST Structures

- EPRI (2009)



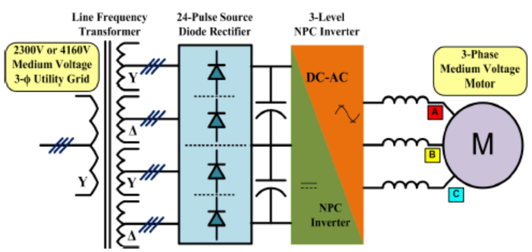


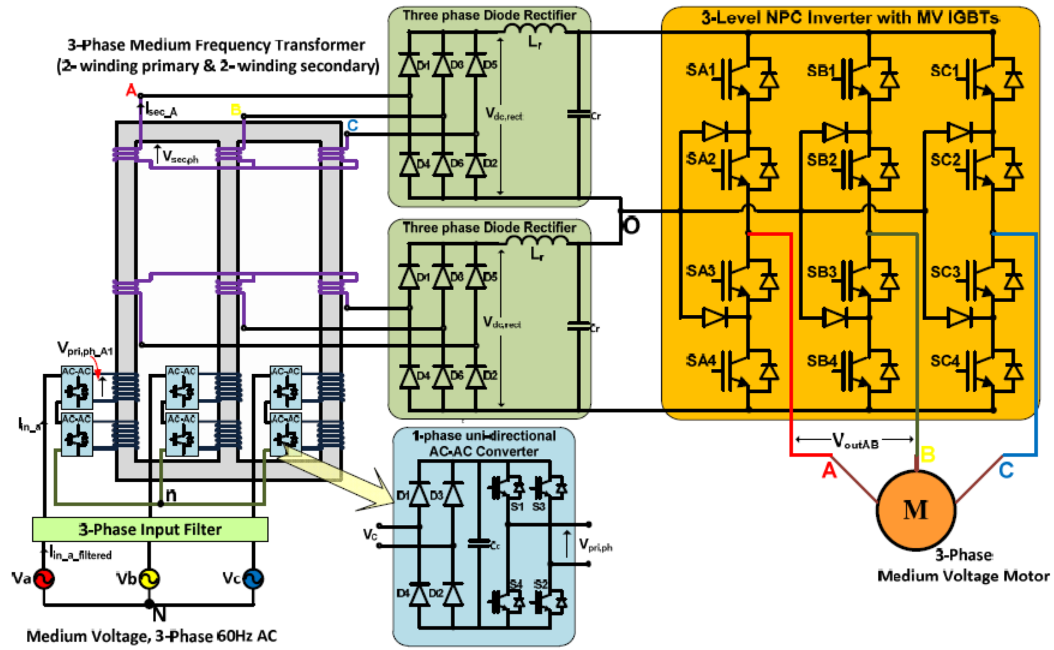


- Outline of 100kVA (4x25kVA) IUT (Pole Mount Layout, 35"H 35"W 20"D, 1050 lbs)
- Natural Air Cooling / S-GTO Module (No Wire Bonds, 50kHz Switching Frequency Target)

▶ Unidirectional DC-Link Based SST Structures

- Enjeti (2012)

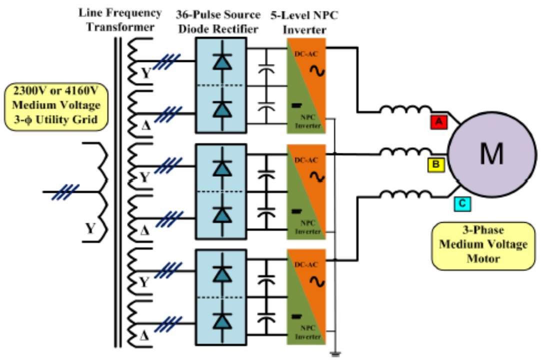


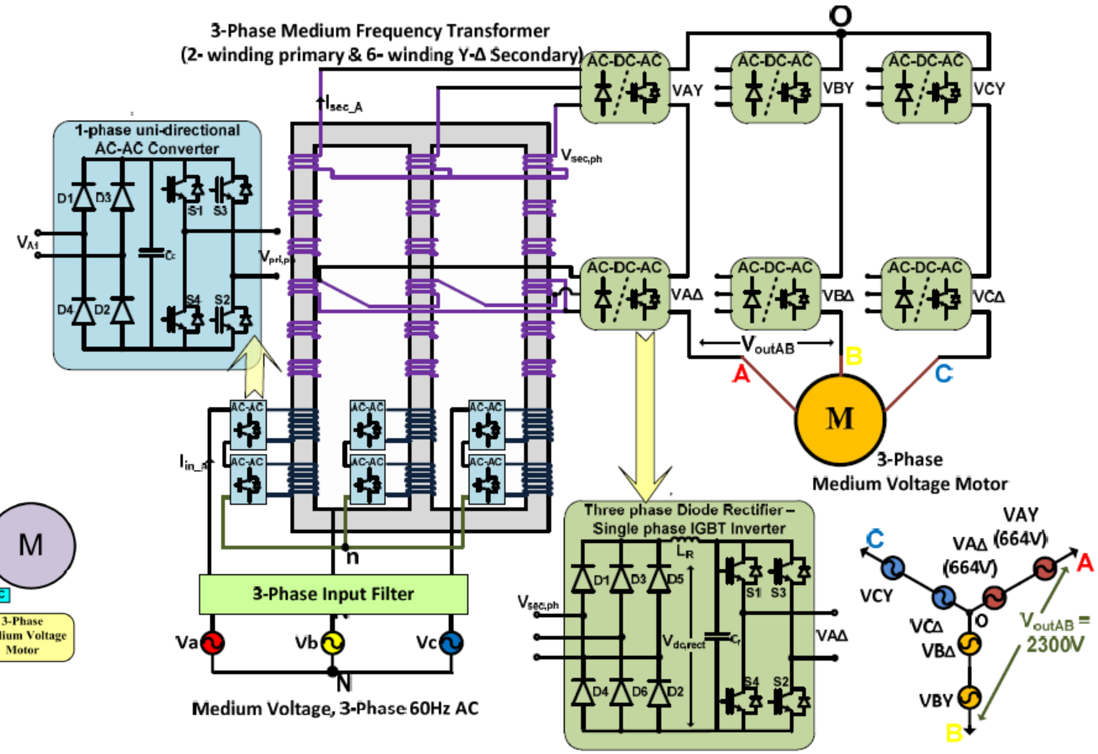


- SST Application for MV Adjustable Speed Drive (Unidirectional AC/AC Front End / 3L NPC Inverter)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

▶ Unidirectional DC-Link Based SST Structures

- Enjeti (2012)

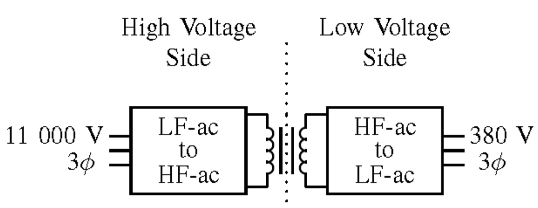


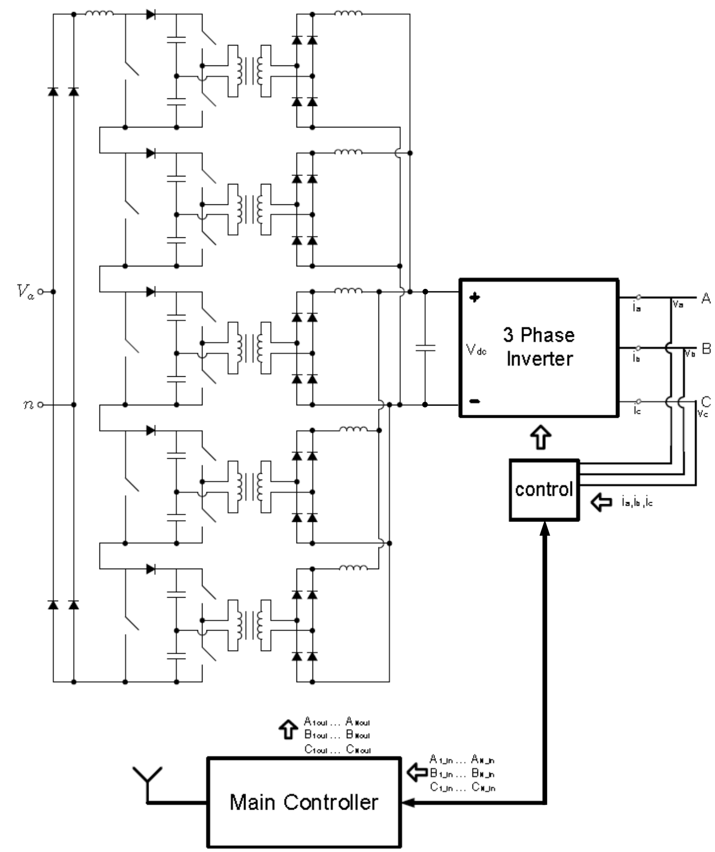


- SST Appl. for MV Adjustable Speed Drive (Unidir. AC/AC Front End / Cascaded 2L 1ph.-Inverters)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

▶ Unidirectional DC-Link Based SST Structures

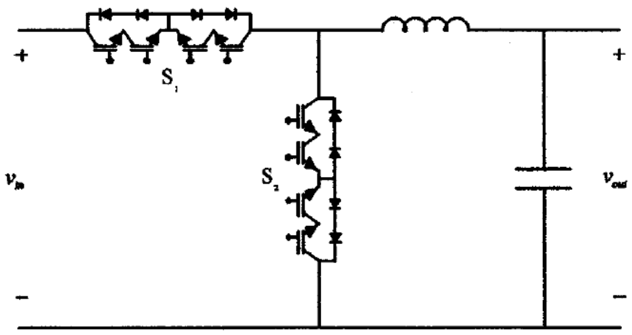
- van der Merwe (2009)





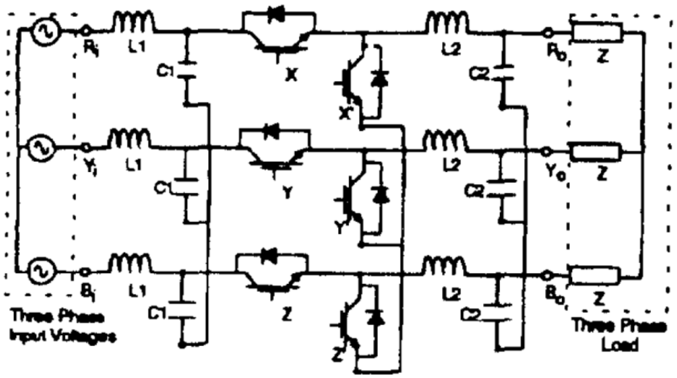
- **5-Level Series Stacked Unidir. Boost Input Stage**

► 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)

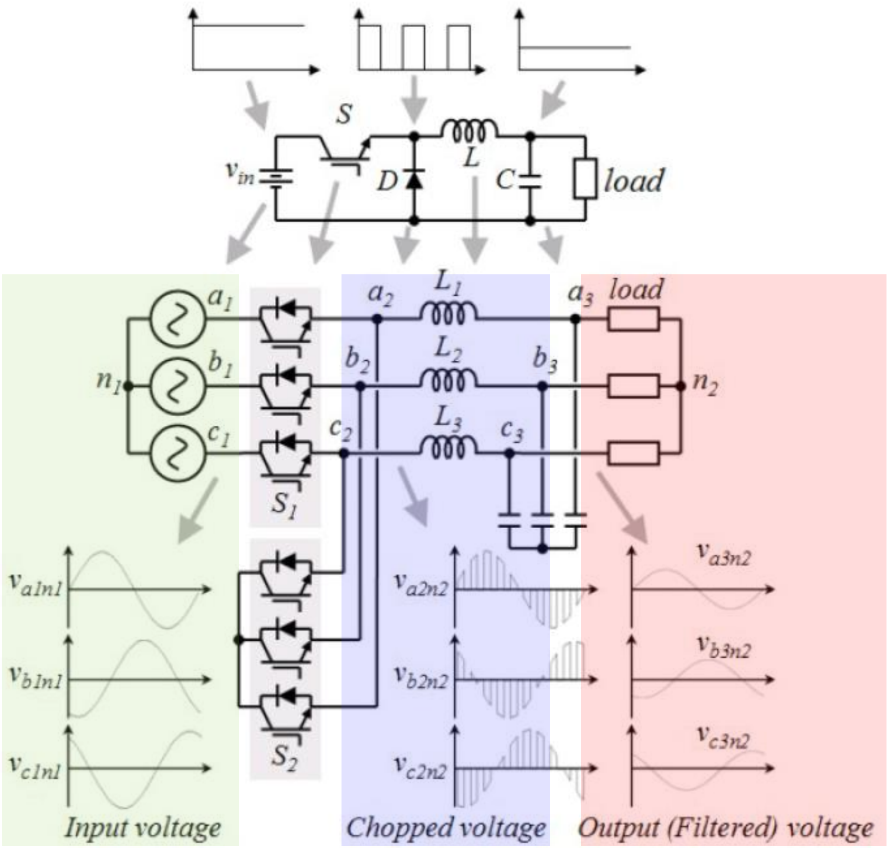
- 3ph AC Version – G. Venkataramanan (1995)
- No 4-Quadrant Switches Required
- Isolation with LF Transformer (Not Shown)



Three Phase Buck Converter with input filters

▶ Full Power SST Employing LF Transformers

- **Derived from DC Buck Converter**

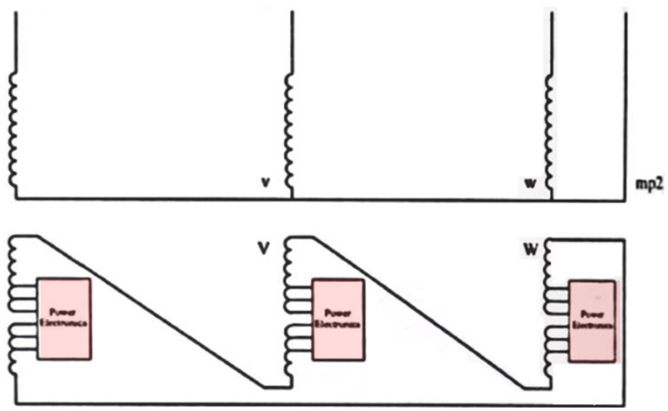


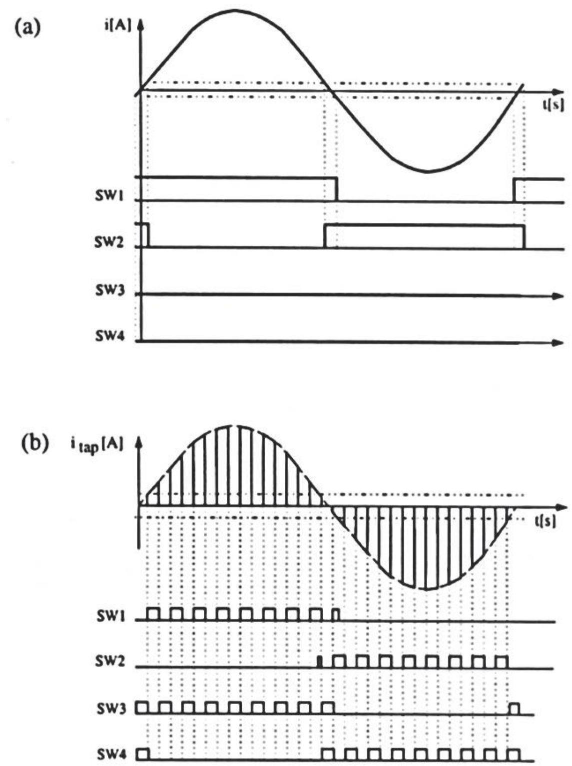
- **J. C. Rosas-Caro (2010)**

▶ Partial Power SST Employing LF Transformers

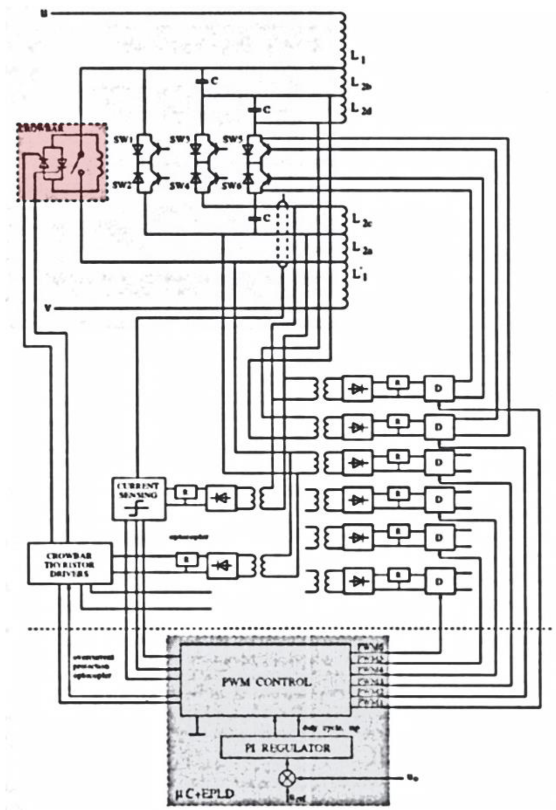
- P. Bauer (1997)

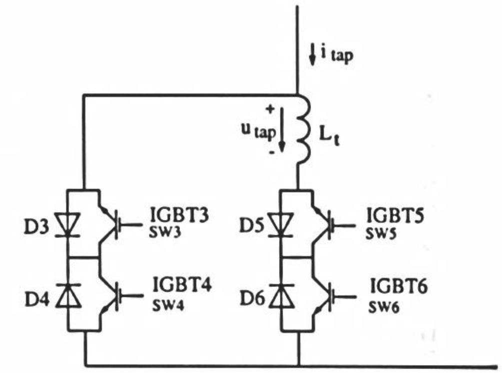
- Electronic Tap Changer of LF Transformer
- MV Winding with Power Electronic Switched Tap.
- Two Modes of Operation:
  - Single Tap Position   (a)
  - PWM Modulated Tap (b)



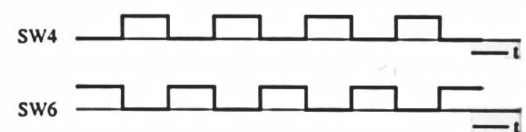


▶ Partial Power SST Employing LF Transformers





Switching cell of the tap switching.

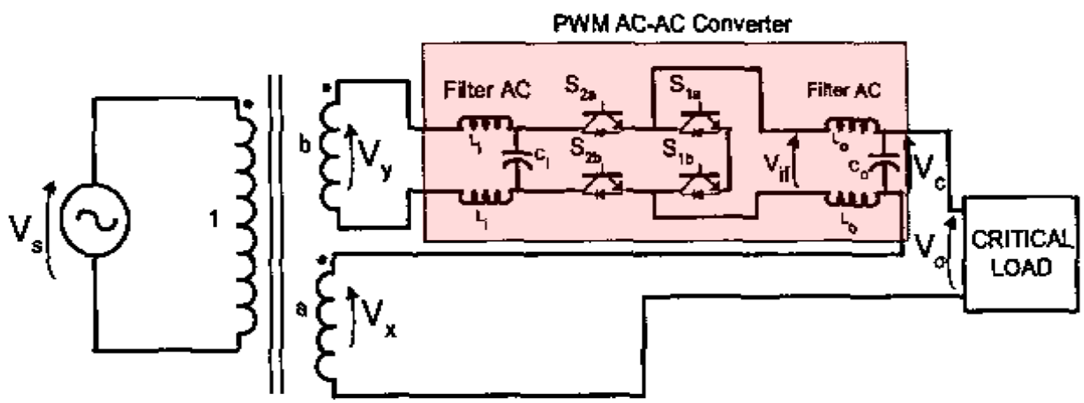


- Electronic Tap Changer – Complex Control Circuit
- Crowbar for Emergency Ride-Through

- Commutation Sequence of the 4-Quadrant Switches

▶ Partial Power SST Employing LF Transformers

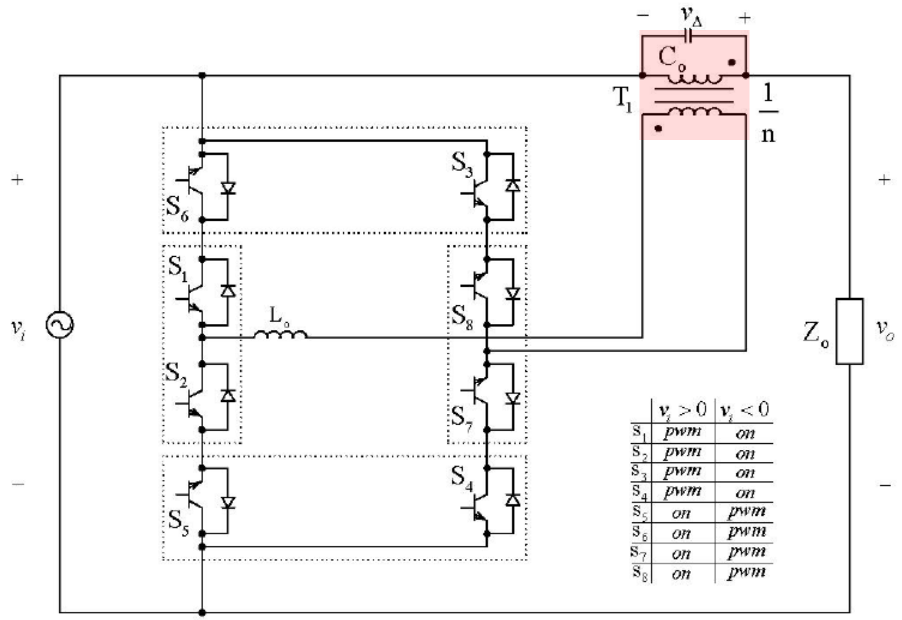
- Enjeti (2003)



- Controlled Output Voltage: $V_o = V_x + V_c$
- LF Isolation Transformer

▶ Partial Power SST Employing LF Transformers

- Barbi (2006)



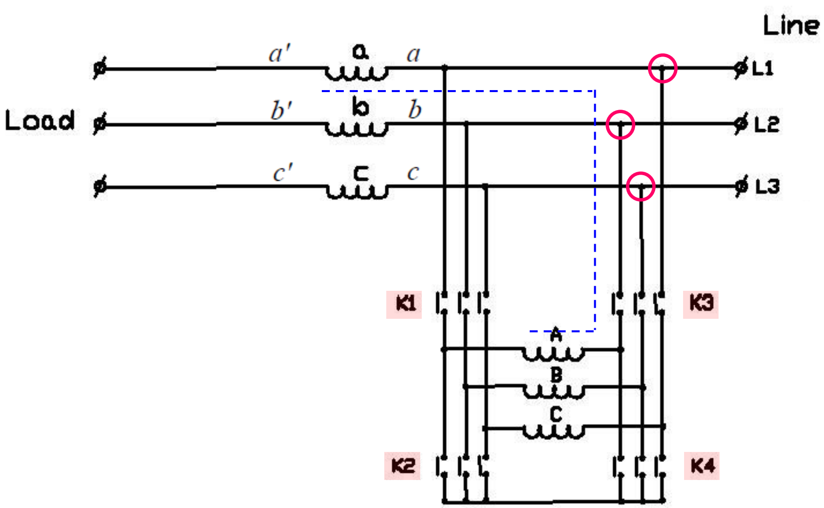
	$v_i > 0$	$v_i < 0$
S_1	*pwm*	*on*
S_2	*pwm*	*on*
S_3	*pwm*	*on*
S_4	*pwm*	*on*
S_5	*on*	*pwm*
S_6	*on*	*pwm*
S_7	*on*	*pwm*
S_8	*on*	*pwm*

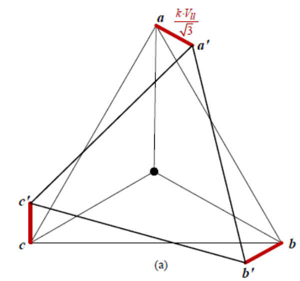
$$\frac{V_o}{V_i} = 1 + \frac{2D-1}{n}\bigg|_{2\text{ levels}} \qquad \frac{V_o}{V_i} = 1 + \frac{D}{n}\bigg|_{3\text{ levels}}$$

- Controlled Output Voltage: $v_o = v_i + \Delta v$
- Isolation Provided with LF Transformer (Not Shown)

▶ Partial Power SST Employing LF Transformers

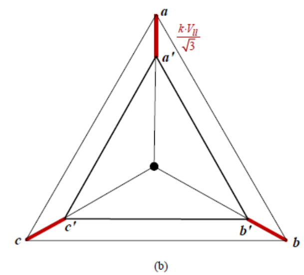
- Shmilovitz (2011)





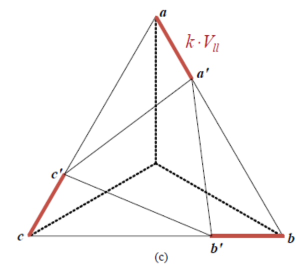
- K2 and K3 = ON

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



- K1 and K4 = ON

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



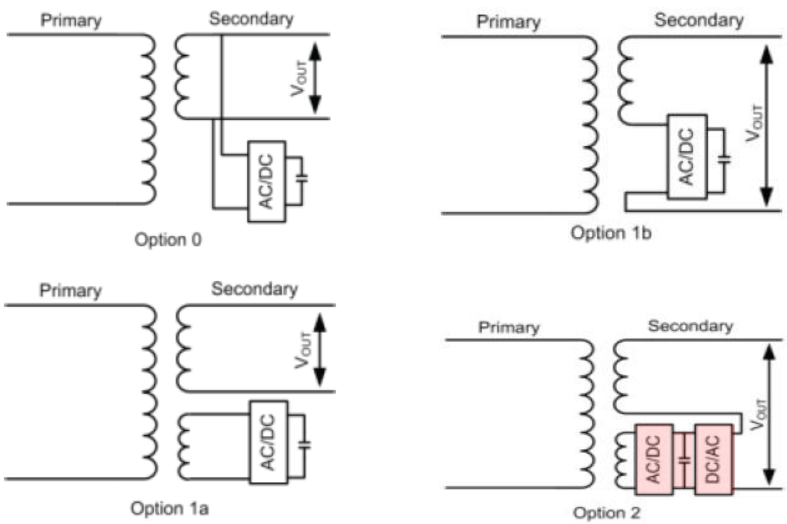
- K1 and K3 = ON

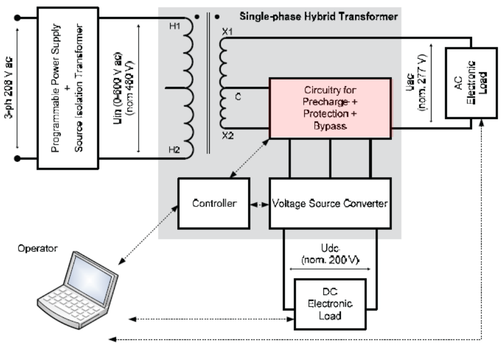
$$V_{ll-motor} = \sqrt{1-3k+3k^2} \cdot V_{line}$$

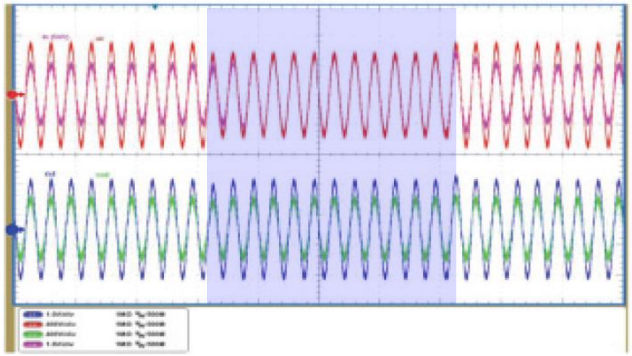
- Reconfigurable Auto-Transformer
- Switches K1, K2, K3 and K4 Used to Modify Output Voltage

▶ Partial Power SST Employing LF Transformers

- Bala (ABB 2012)



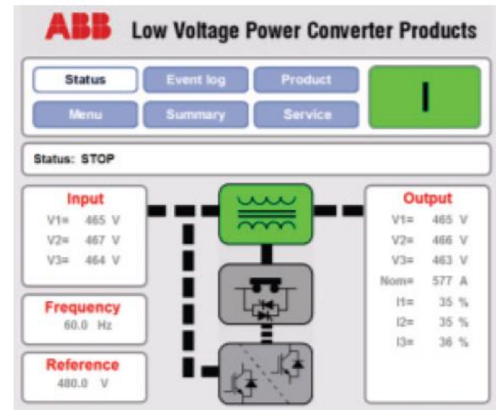


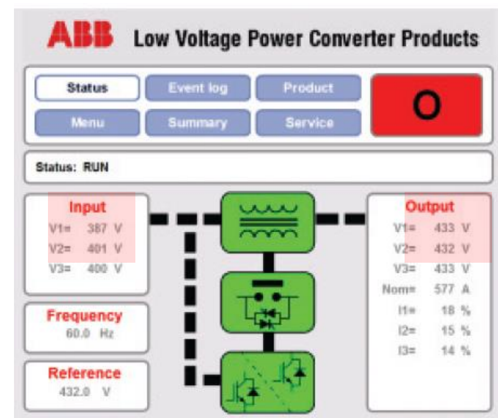


- Reactive Power Compensation (PFC, Active Filter, Flicker Control)
- Available DC Port (Isolated in Option 1a)
- Option 2: Controlled Output Voltage

▶ 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

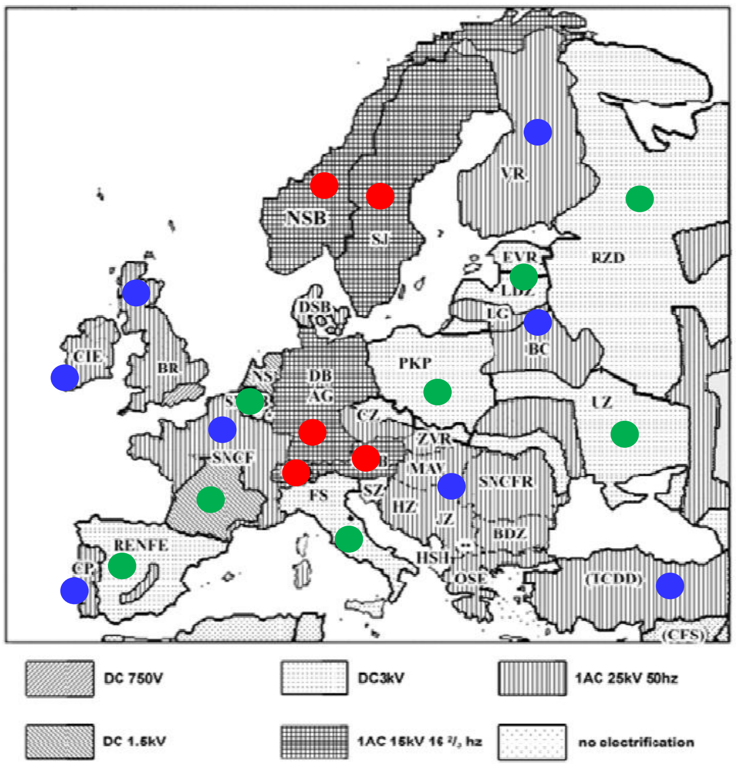
Railway Systems Voltage/Freq.
Modern Railway Systems' Requirements
SST Concepts for Traction

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)

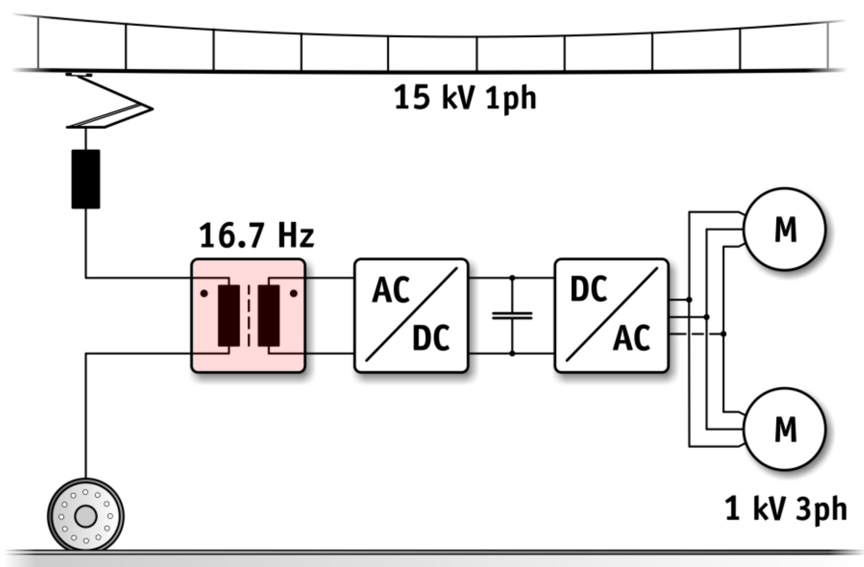
Network line lengths and proportion of electrical railway systems (2003)

DC 1500 V	15,320 km	6.5 %
DC 3000 V	72,105 km	30.3 %
AC 15 kV/16^2/$_3$ 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 %

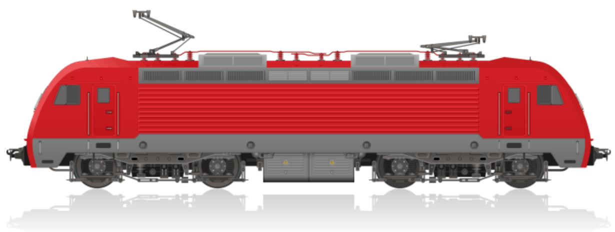
≈ 6 Turns Around the Earth

▶ Electric Railway Systems – Today's Drive Scheme

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



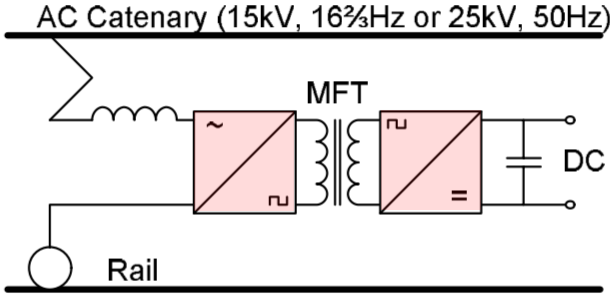
- Low Frequency Transformer
  - 15% Weight of Locomotive
  - e.g. for 2MW ca. 3000kg
  - 90-92% Efficiency



▶ Trends in Modern Railway Systems

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

- Weight Reduction
- Energy Efficient Railways

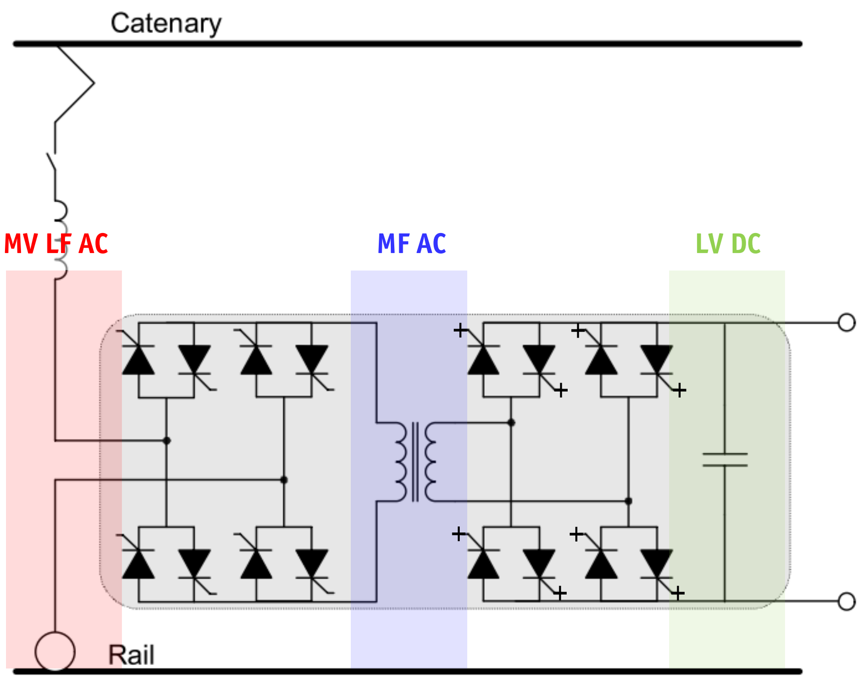


AC-DC conversion with medium frequency transformer (MFT)

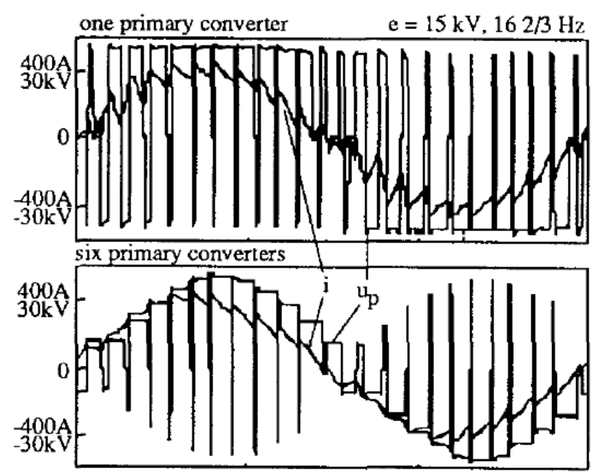
- All Goals Lead to a Medium-Frequency Isolation / Conversion Syst. (Dujic 2011)

▶ VSI Commutated Primary Converter

- Menniken (1978)
- Östlund (1992)

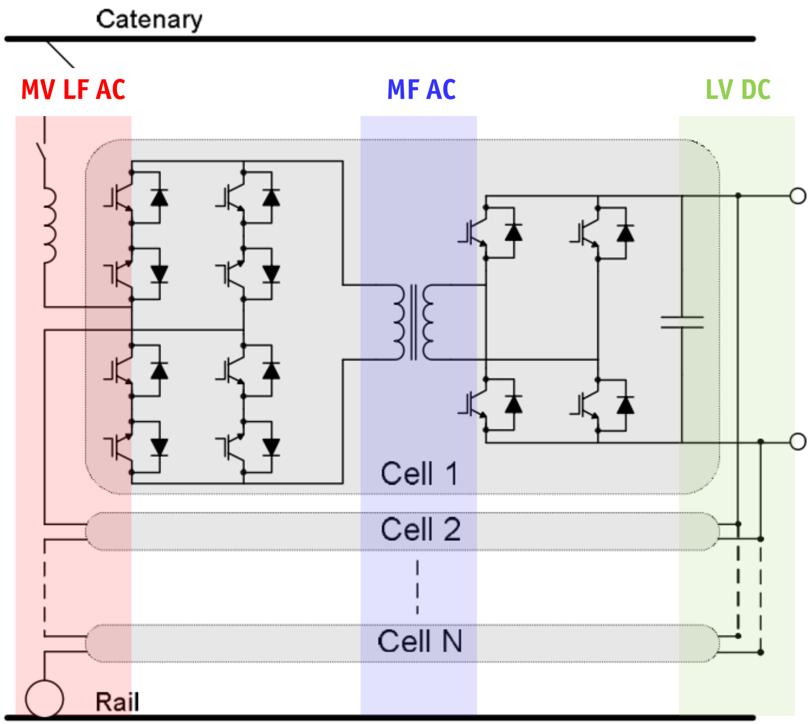


PET topology with source commutated primary converter

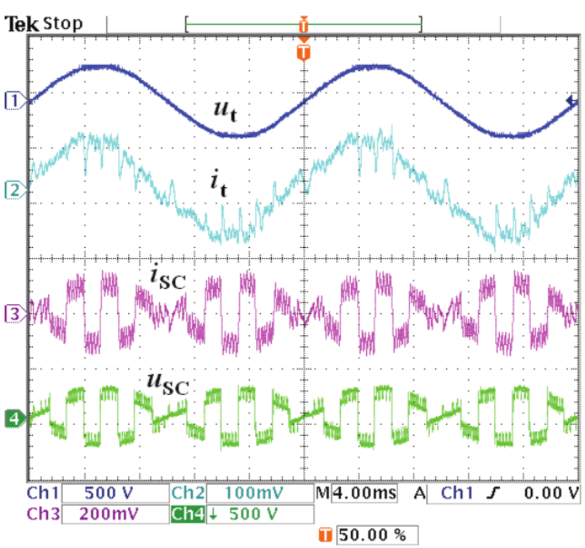


▶ Cascaded VSI Commutated Primary Converter

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

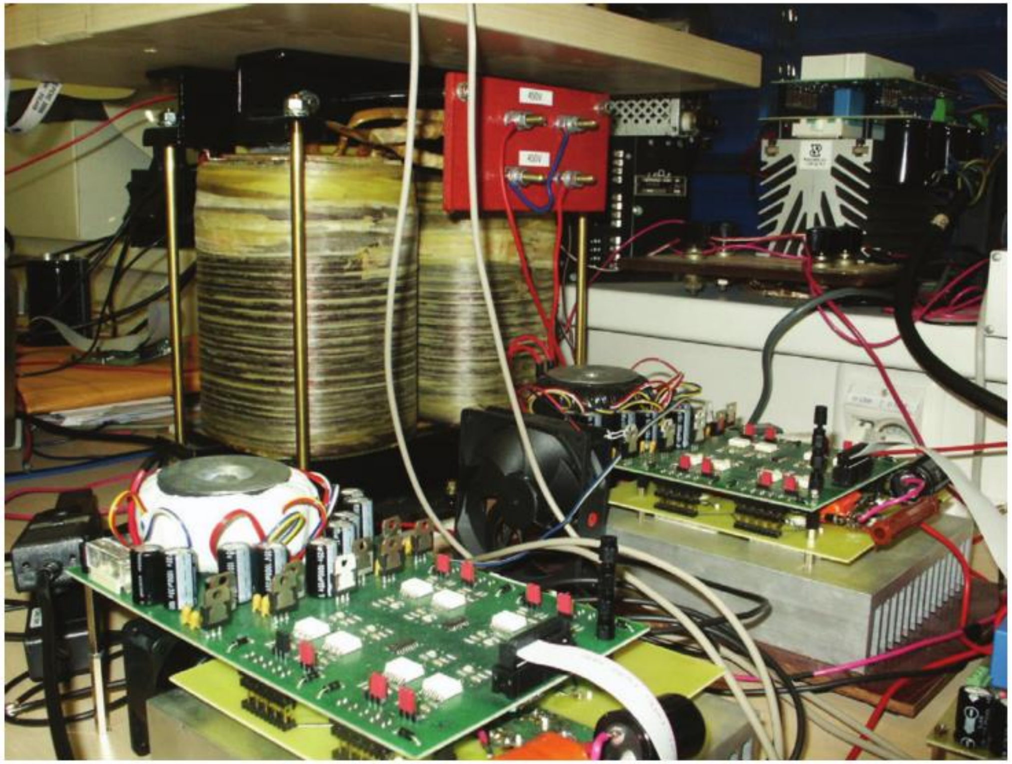


PET topology with cascaded source commutated primary converters



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

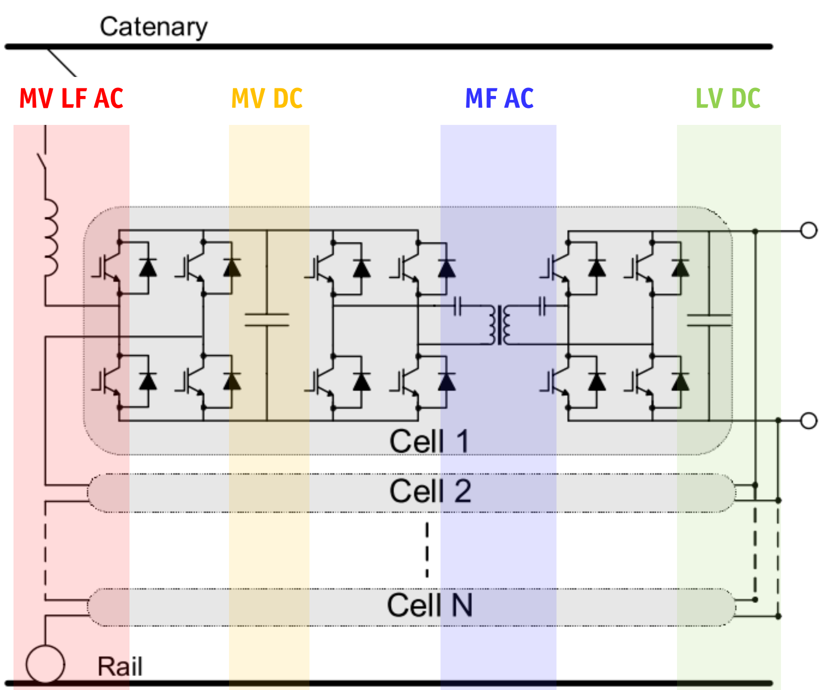
► Cascaded Source Commutated Primary Converter

- Hugo (ABB, 2006)

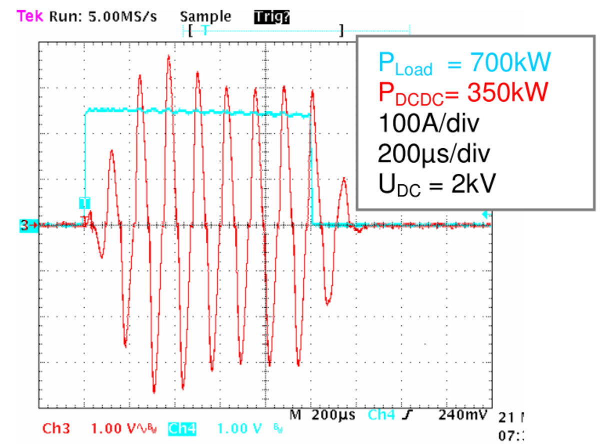
- Total Power 1.2MVA/15kV
- Module Power 75kW
- Frequency 400Hz

▶ 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.

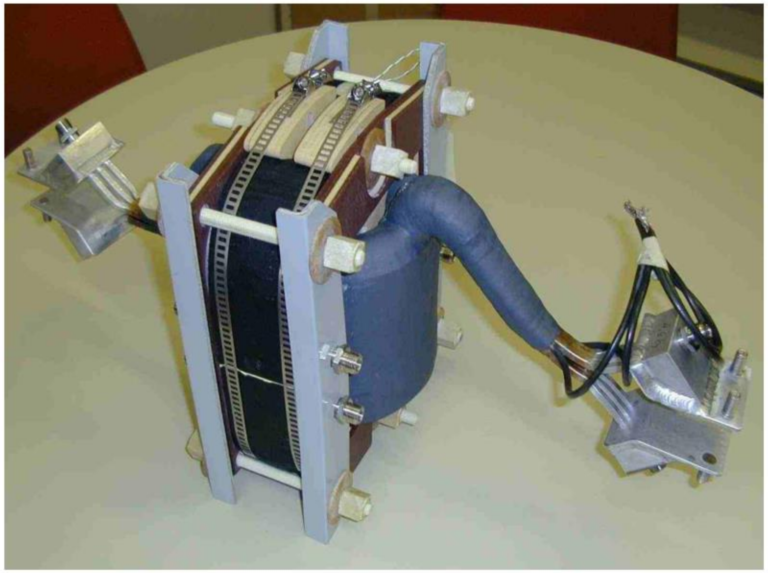


Dynamic behavior of DC-DC converter

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

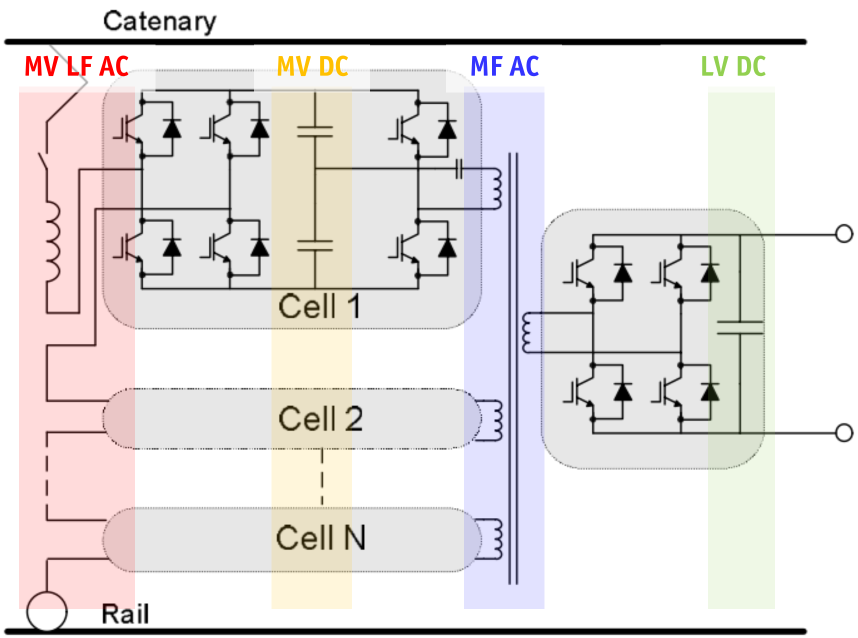
- Weigel (SIEMENS, 2009)
  - Module Power 450kW
  - Frequency 5.6kHz

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

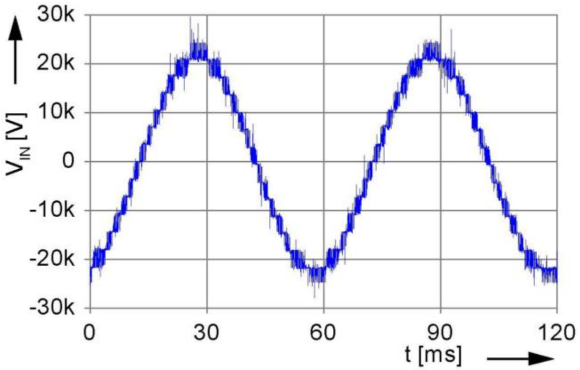


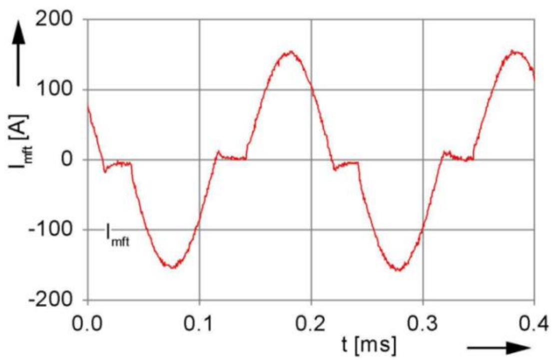
▶ Cascaded H-Bridges with Multi-Winding MF Transformer

- **Engel (ALSTOM, 2003)**

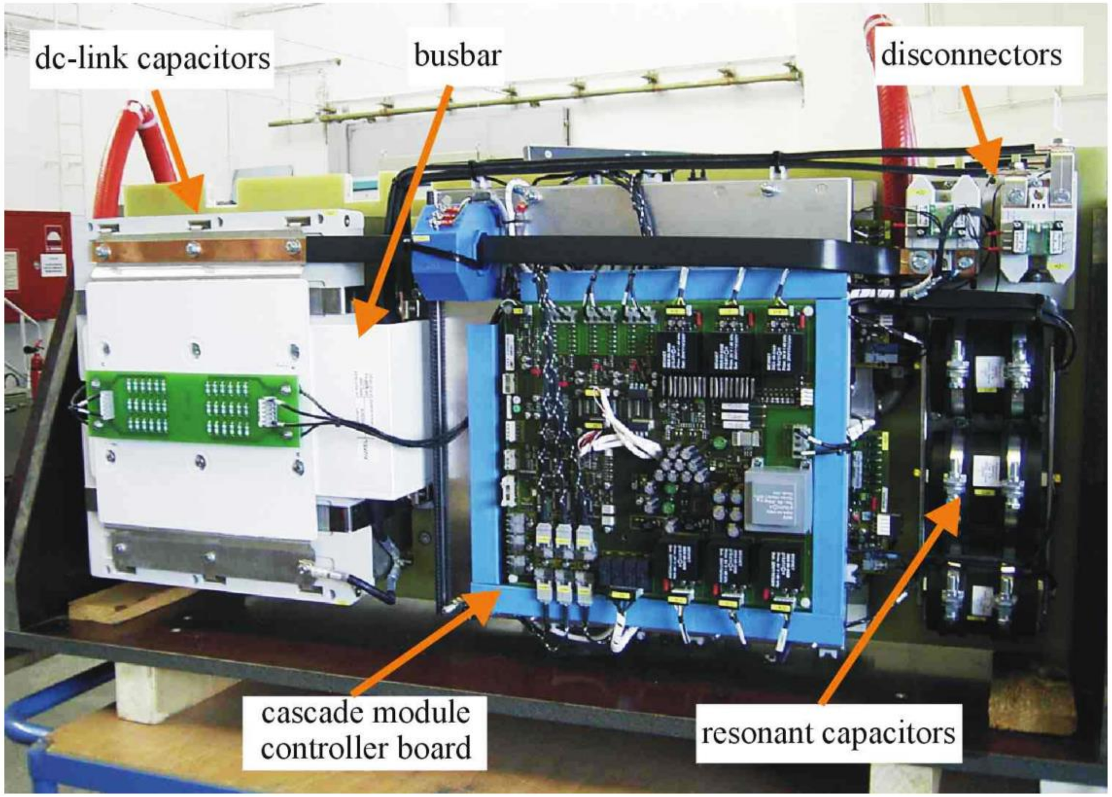


PET topology with cascaded H-bridges and multi-winding MFT





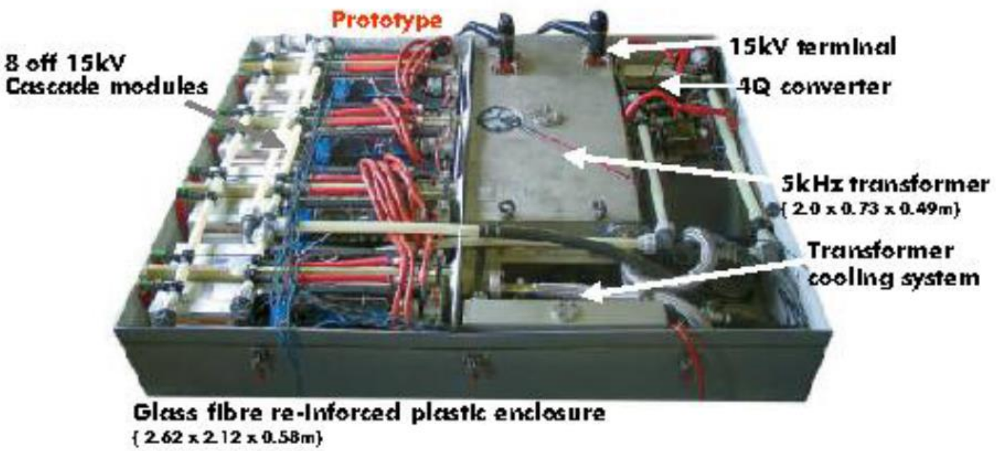
▶ Cascaded H-Bridges with Multi-Winding MF Transformer



- Engel (ALSTOM, 2003)

- Module Power 180kW
- Frequency 5kHz

▶ Cascaded H-Bridges with Multi-Winding MF Transformer

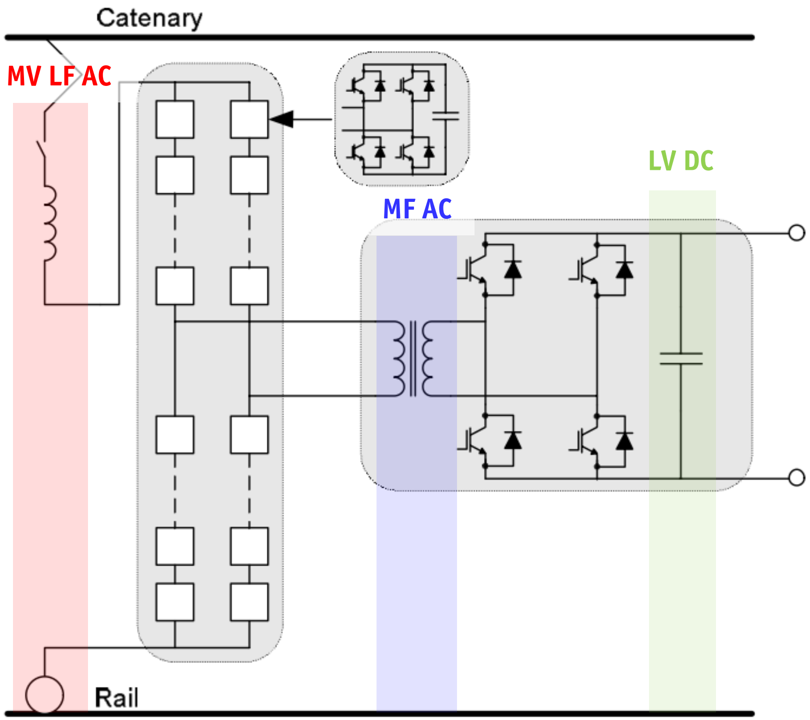


- Taufiq (ALSTOM, 2007)

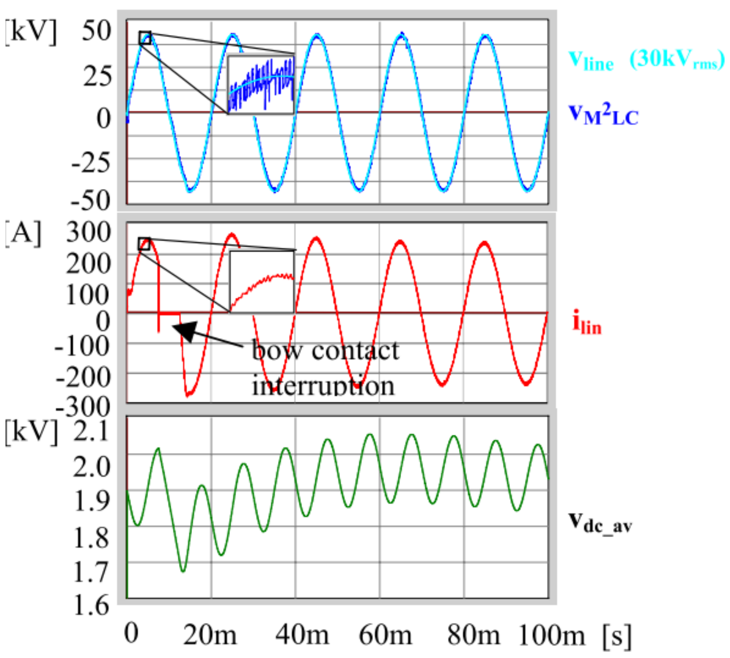
- Module Power 180kW
- Frequency 5kHz

▶ Modular Multilevel Converter

- Marquardt/Glinka (SIEMENS, 2003)



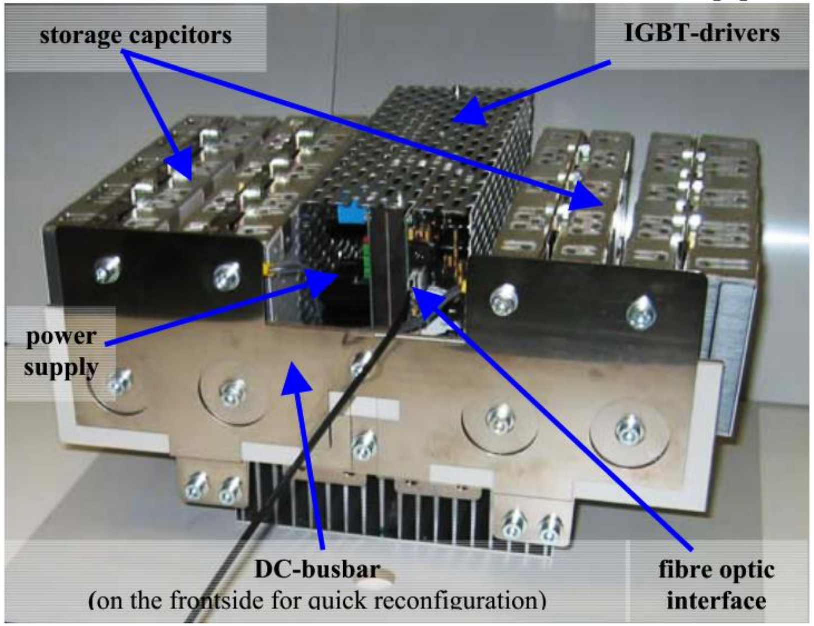
PET topology using M2LC converter



▶ Modular Multilevel Converter

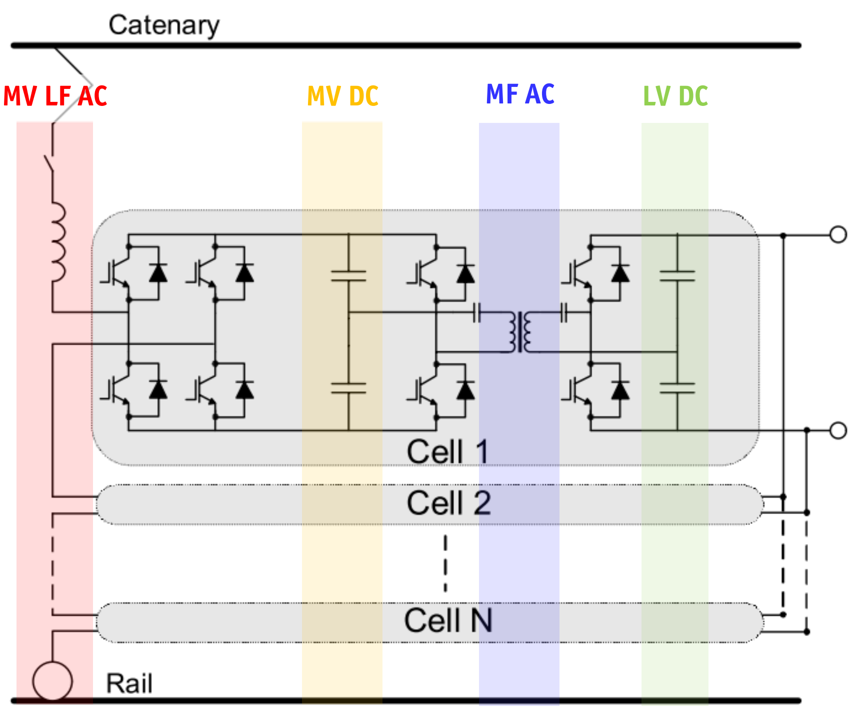
- Marquardt/Glinka (SIEMENS, 2003)

- Module Power 270kW
- Module Frequency 350Hz

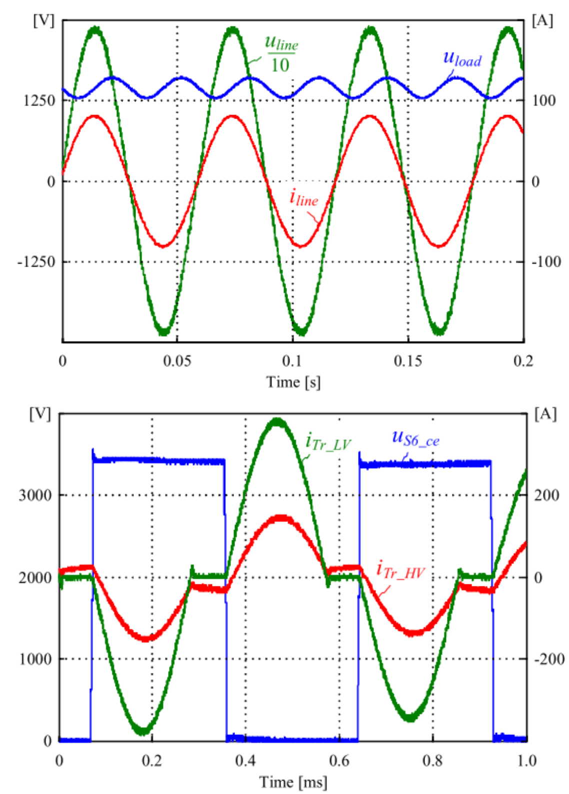


▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages

- **Zhao et al. (ABB, 2011)**



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



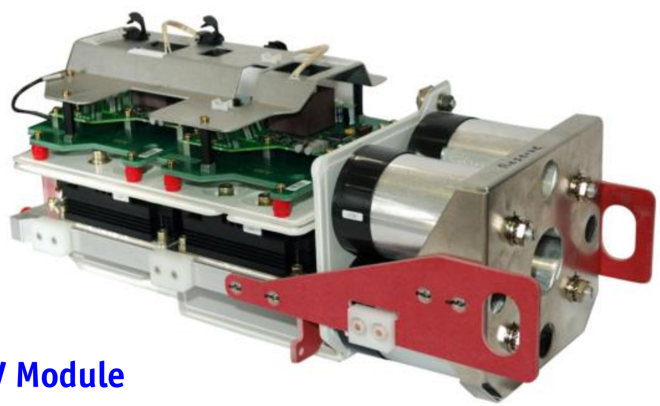
▶ Cascaded H-Bridges and Resonant LLC DC-DC Stages

- Zhao et al. (ABB, 2011)

MV Module

Assembled Converter

- Module Power 170 kW
- Frequency 2kHz



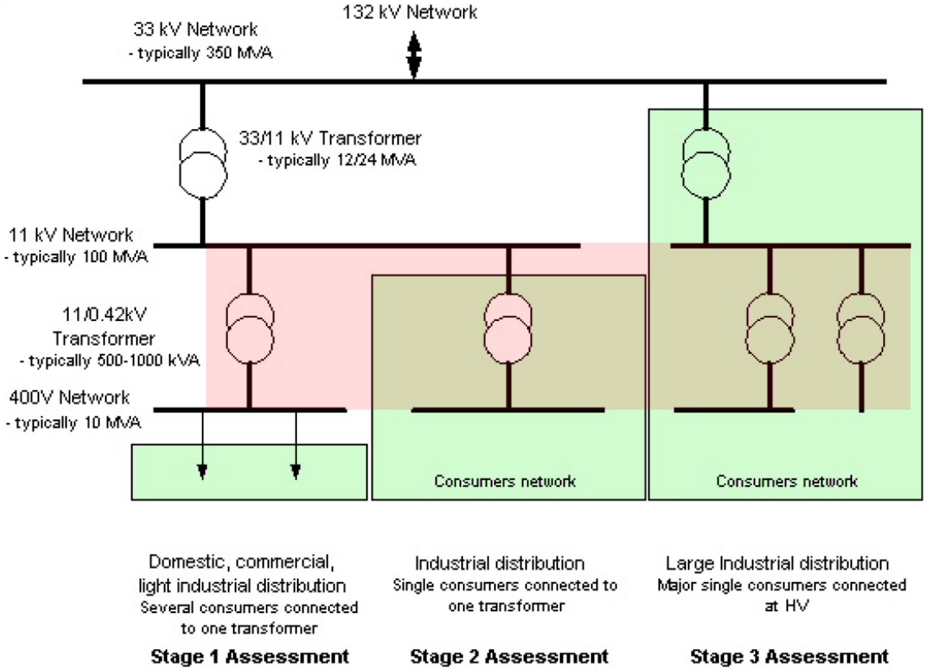
LV Module

SST Design Remarks

Current Ratings
Cooling Considerations
MF Transformer Design
Flux Balancing

▶ Current Ratings – Overcurrent Requirements

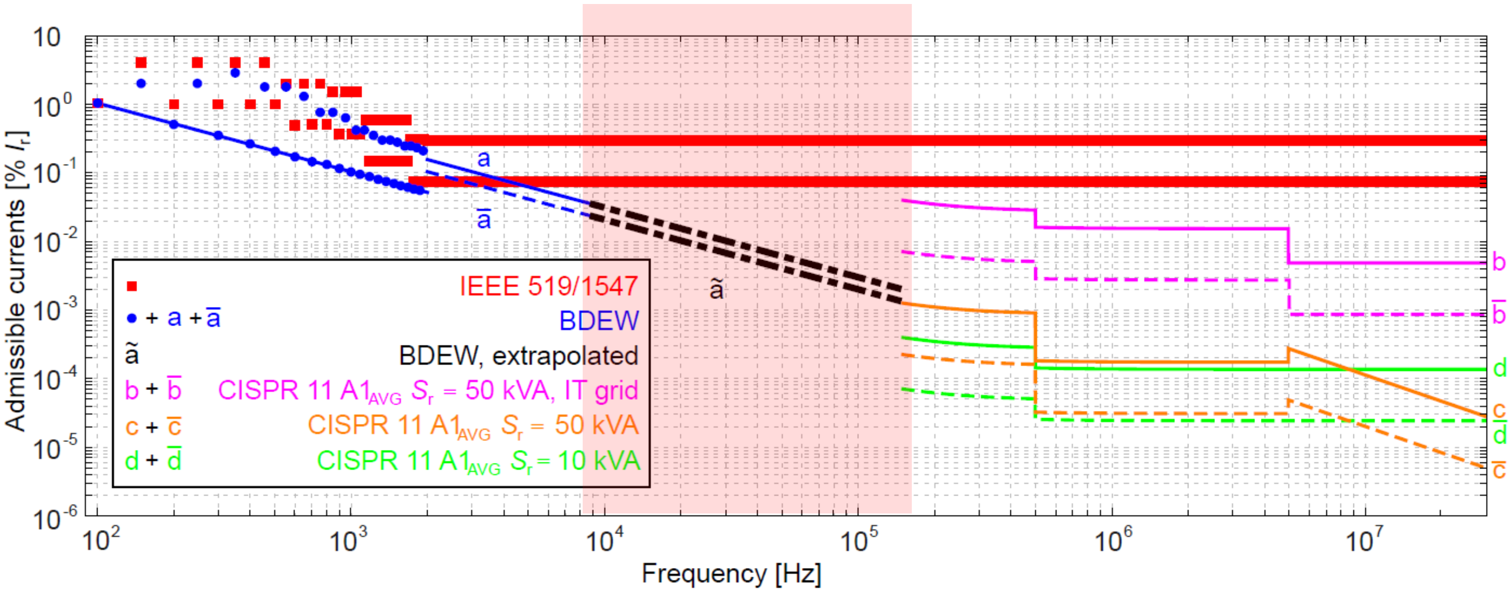
- MV Transformers must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)
- Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)
- Power Electronics: Very Short Time Constants !



▶ Grid Harmonics and EMI Standards

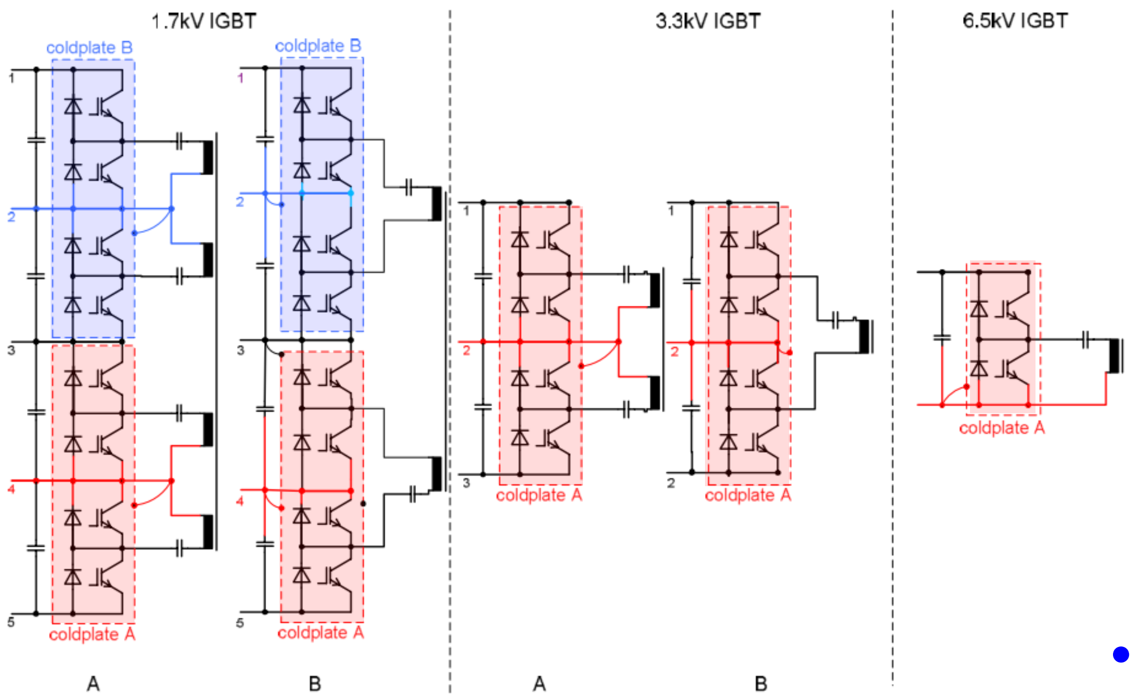
- **Medium Voltage Grid Considered Standards (Burkart, 2012)**
  - IEEE 519/1547
  - BDEW
  - CISPR

- **Requirements on Switching Frequency and EMI Filtering**



▶ Semiconductor Cooling and Isolation

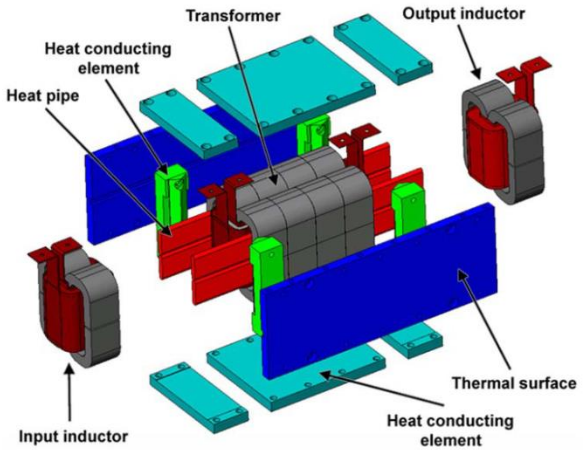
- **1.7kV IGBTs → Semiconductor Modules on Coldplates/Heatsinks Connected to Different Potentials (CM Voltage Problems)**
- **3.3kV or 6.5kV IGBTs → Isolation Provided by the Modules' Substrate, No Splitting of the Cooling System Necessary.**

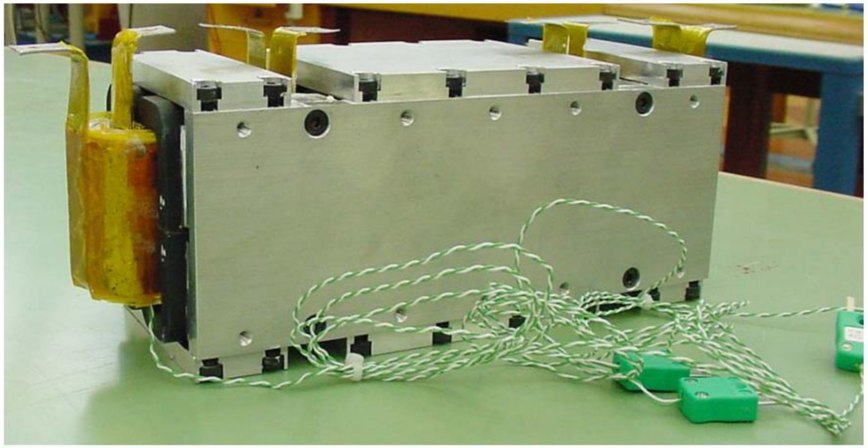


- **Hoffmann (2009)**

▶ MF Transformer Design – Cold Plates Cooling

- **Heat Conducted from Inner Parts (Winding/Cores) to Outer Actively Cooled Coldplates**





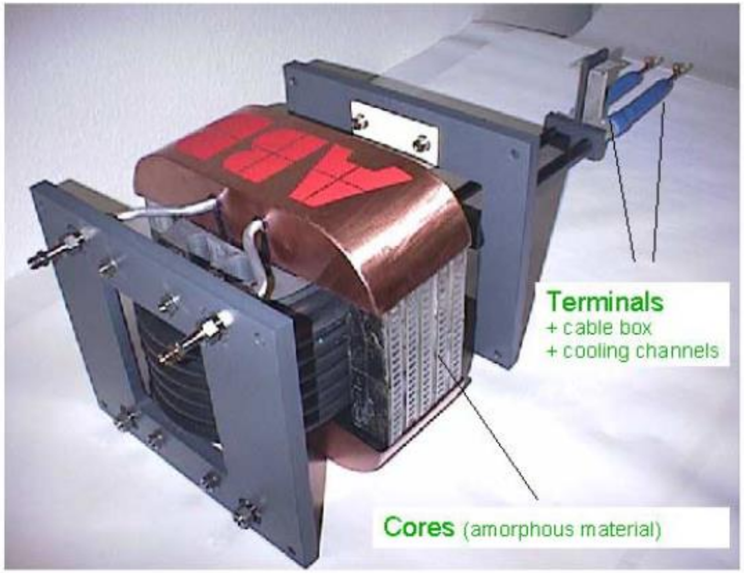
- **Pavlovsky (2005)**

MF Transformer Design – Water Cooling

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

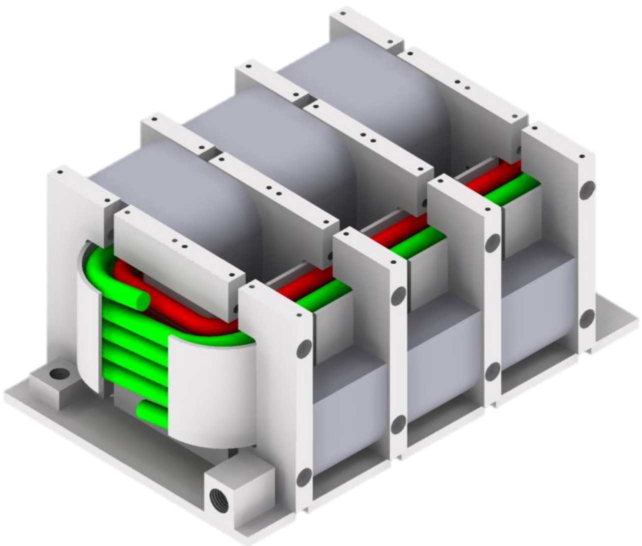
- **Hoffmann (SIEMENS, 2011)**

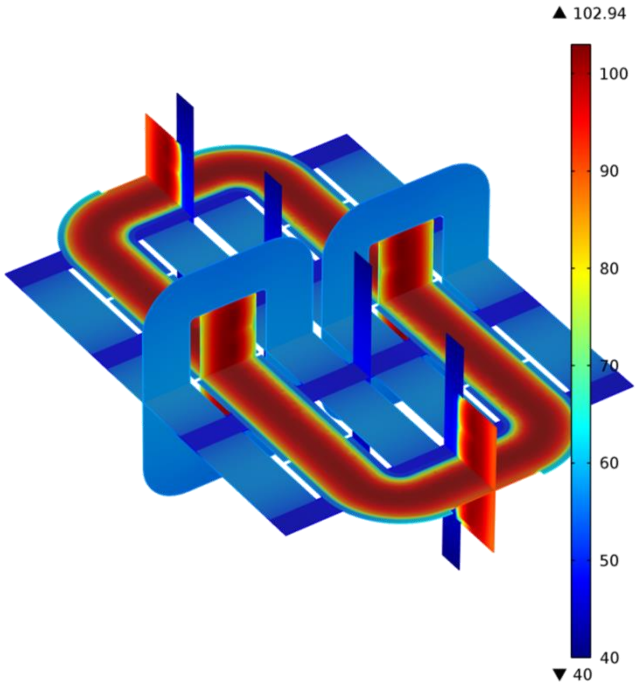
- **Heinemann (ABB, 2002)**



▶ MF Transformer Design – Cold Plates/ Water Cooling

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



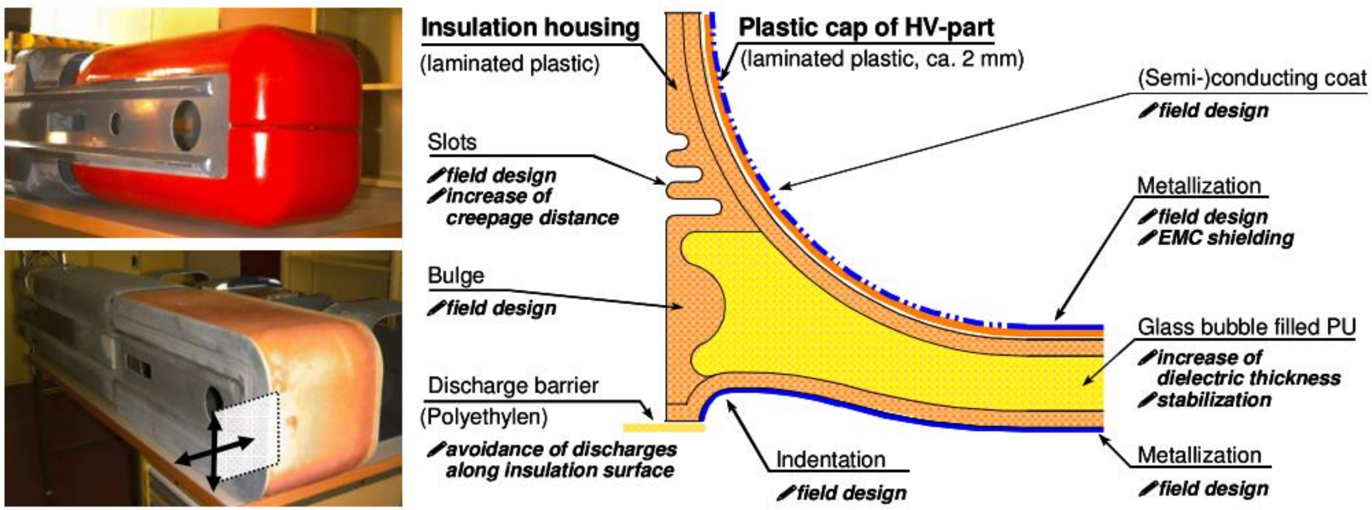


- **Combination of Heat Conducting Plates and Top/Bottom Water-cooled Cold Plates**
- **FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core**

▶ MF Transformer Design - Isolation

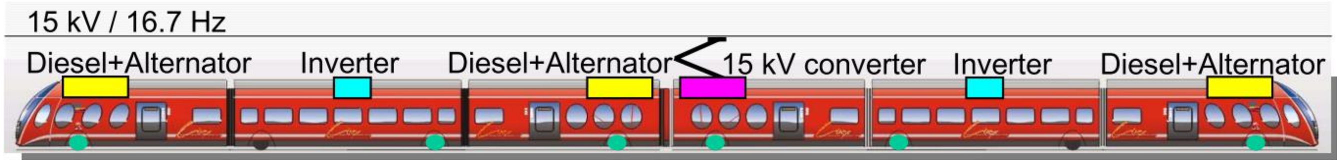
- Specially Designed Isolated Housing for High Isolation to Ground

- Steiner (Bombardier, 2007)



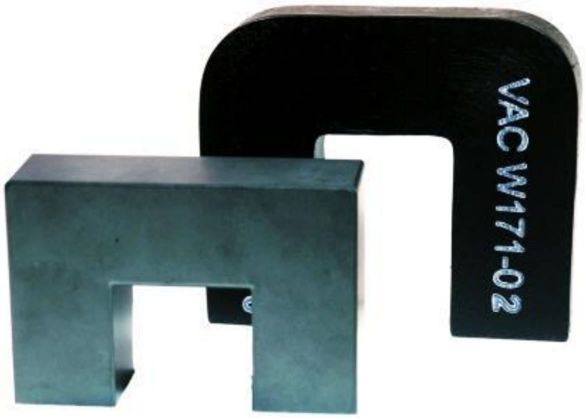
MF Transformer Design - Isolation

- **Glass-Fiber Container**
  Engel (ALSTOM, 2003)



MF Transformer Design – 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



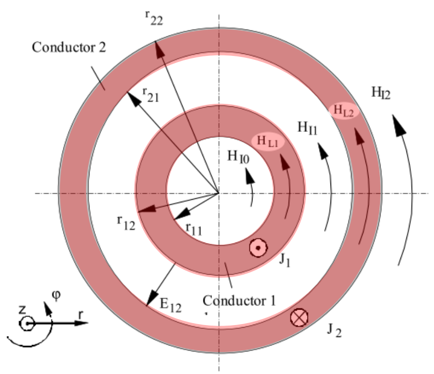
- Acoustic Noise Emitted at $2 \cdot f_s$ (!)

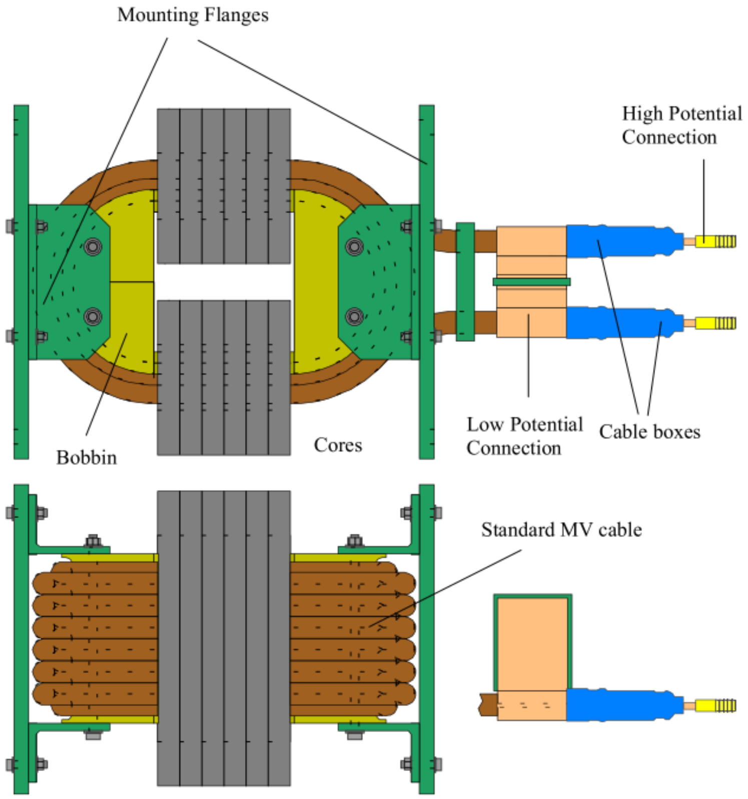
MF Transformer Design – Winding Arrangements

- **Coaxial Cable Winding**

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

  - Low Flexibility on Turns Ratio
  - Complex Terminations

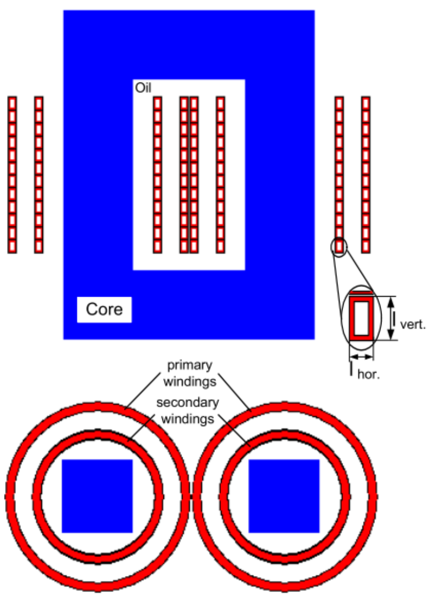




- **Heinemann (2002)**

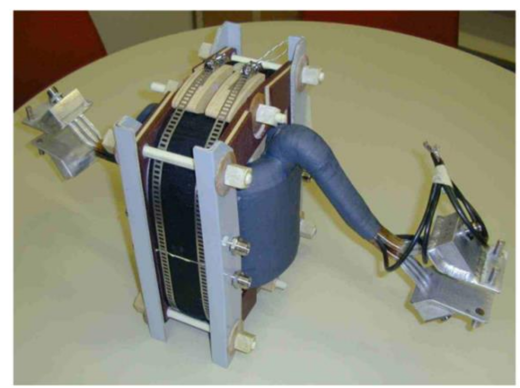
MF Transformer Design – Winding Arrangements

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



- Hoffmann (2011)

- Steiner (2007)

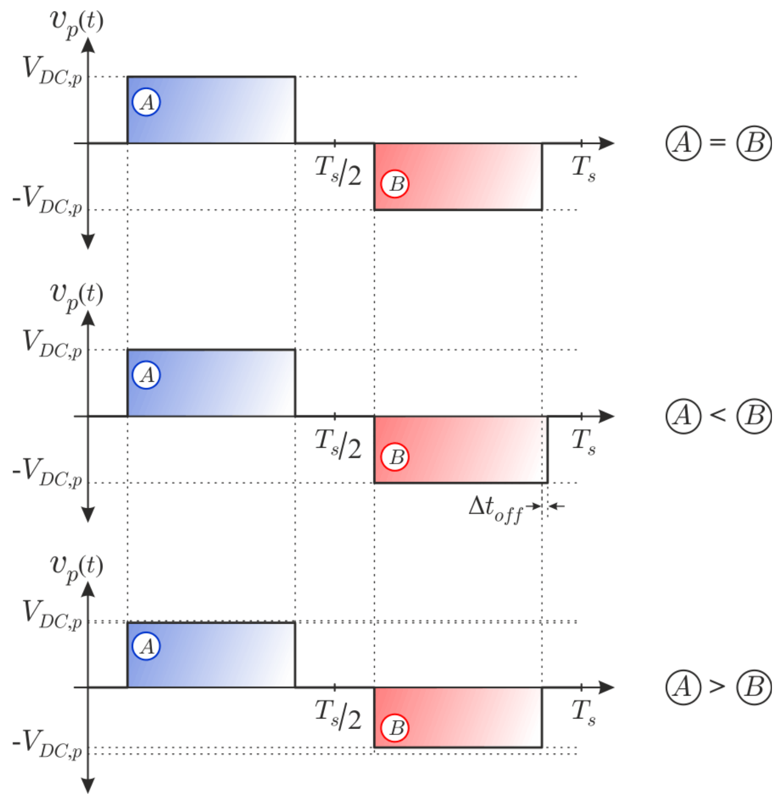


Flux Balancing - DC Magnetization

- Higher Losses
- Overcurrents
- Audible Noise

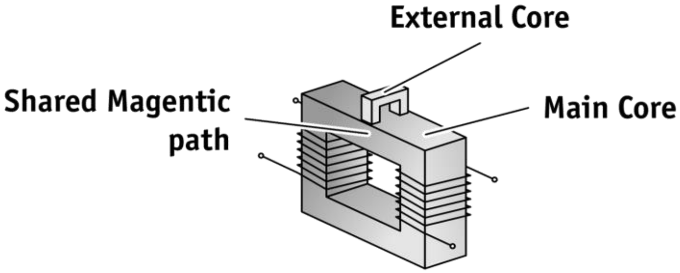
- Diff. Turn-on/Turn-off Times

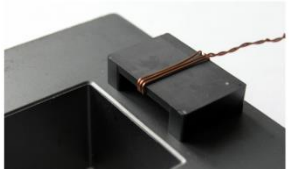
- Diff. Switch On-Characteristics

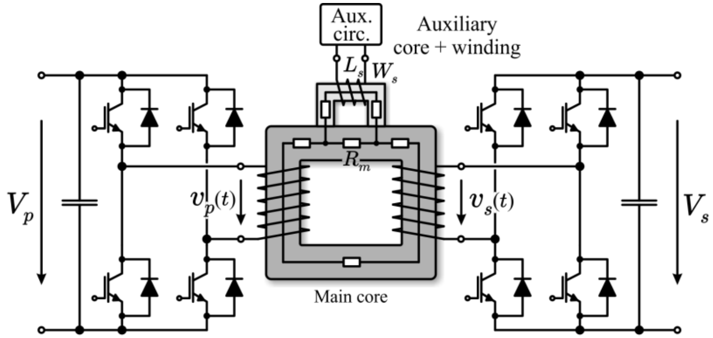


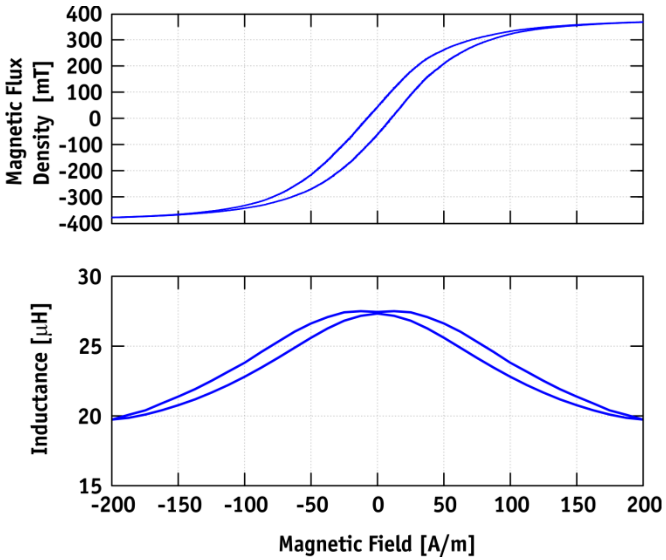
▶ Flux Density Transducer – The Magnetic Ear

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



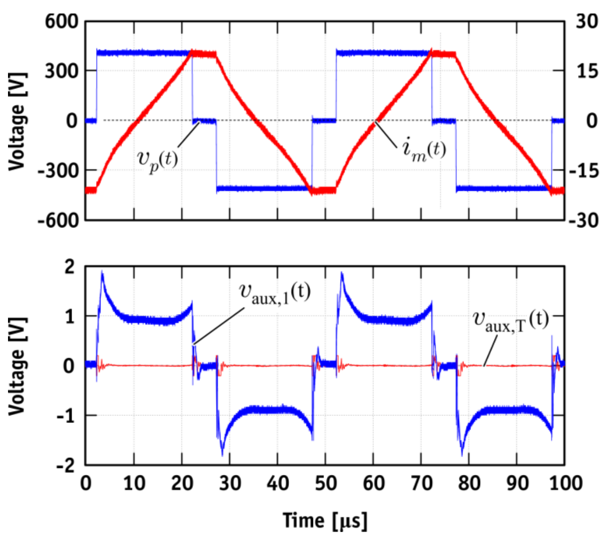


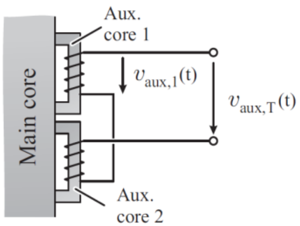


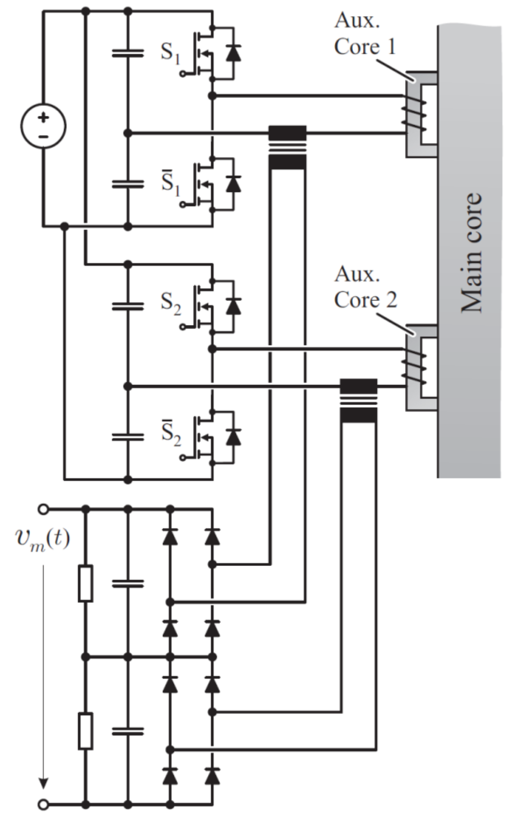


▶ Flux Density Transducer – The Magnetic Ear

- Compensation Network to
  Decouple Main and Auxiliary Flux



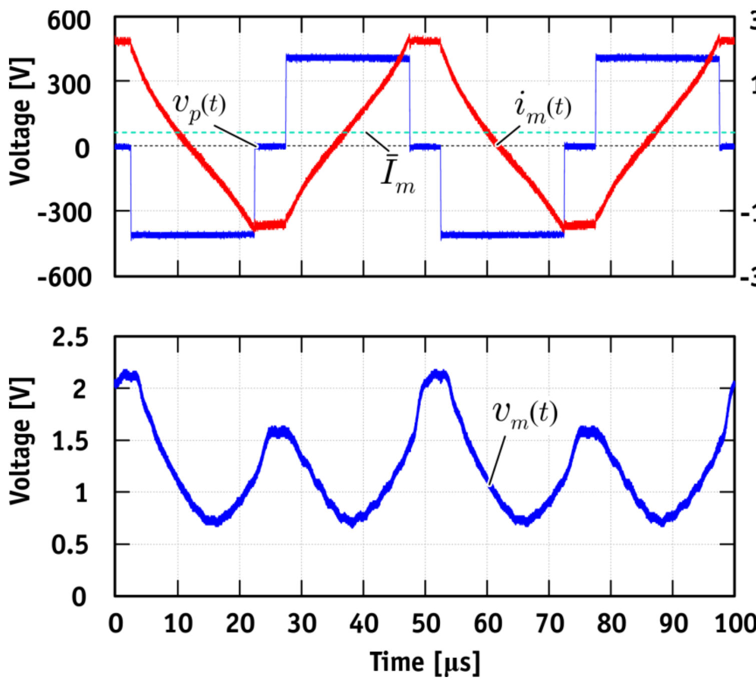




- Interleaved Operation for
  Maximum Bandwidth (ETH/Ortiz, 2013)

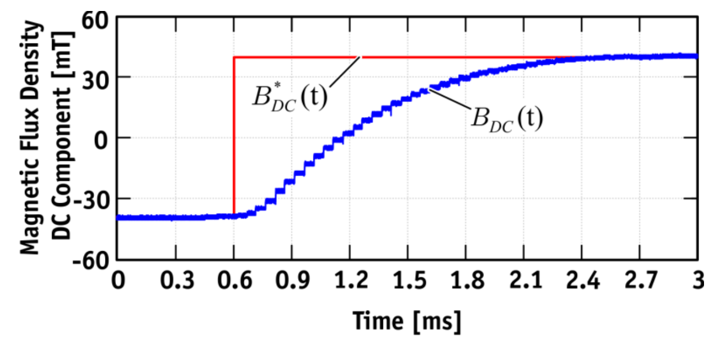
▶ Flux Density Transducer – The Magnetic Ear

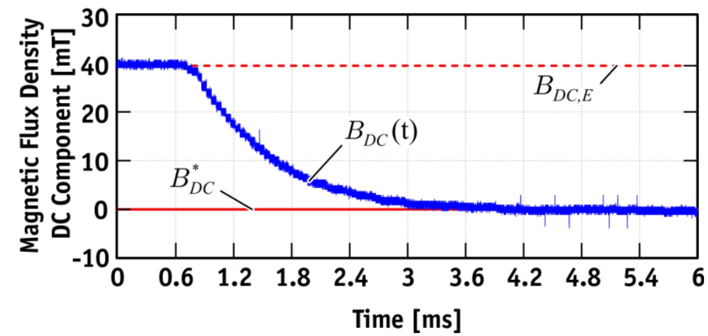
▸ **Transducer Output for Biased Magnetic Operation**



▸ **Closed Loop Response**

- Reference Step
- Disturbance Rejection



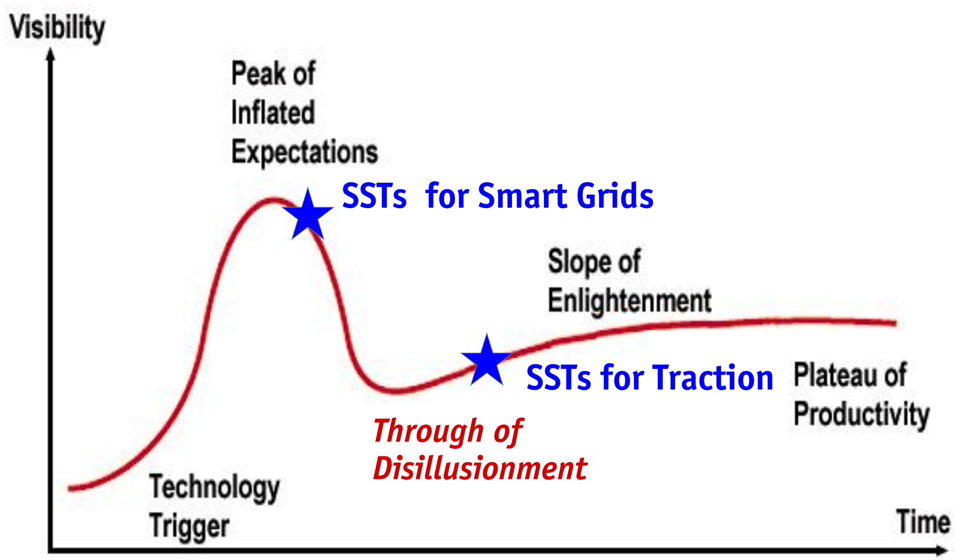


Conclusions

SST Limits / Application Areas
Optimization Potential
Future Research Areas
General Remarks

▶ Technology Hype Cycle

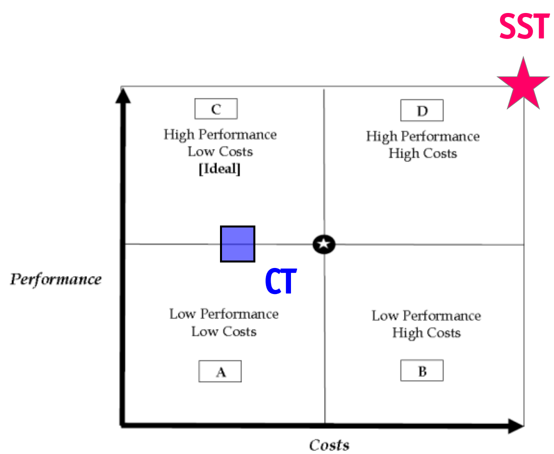
- **Different State of Development of SSTs for Smart Grid and Traction Applications**



▶ 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)

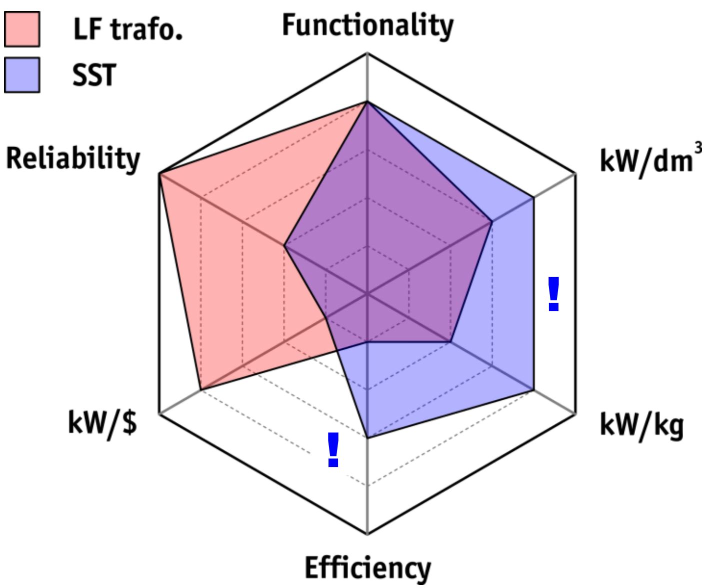


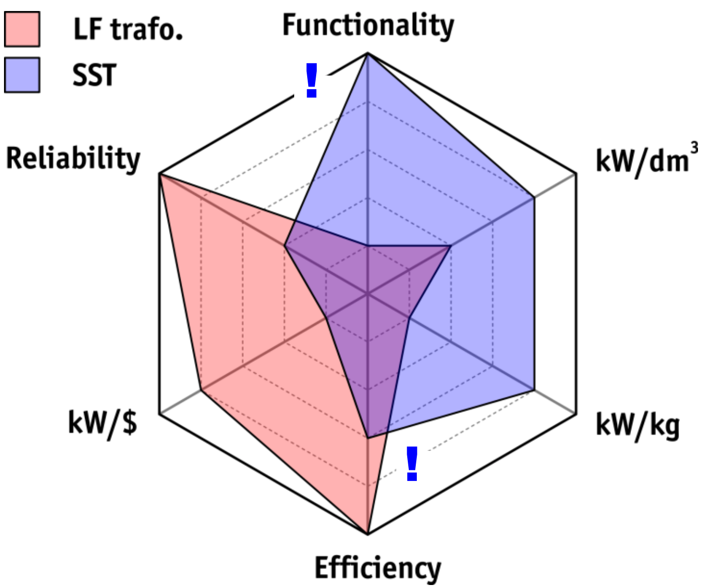
■ Potential Application Areas

▶ 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)

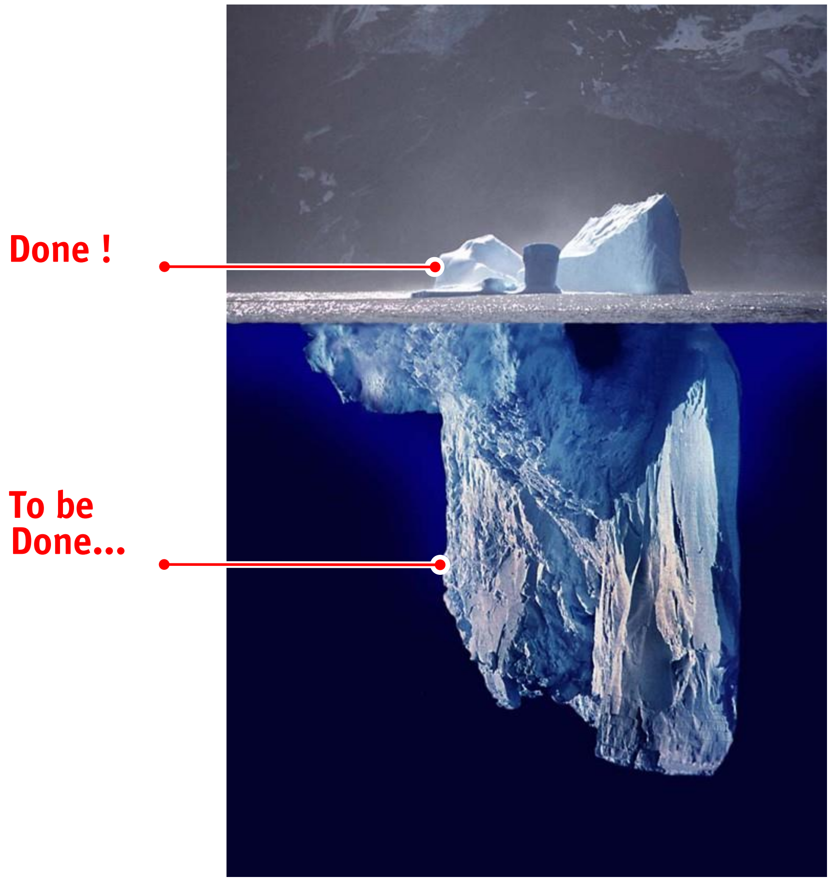
▶ Future Research Topics

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- MF Transformer Construction featuring High Insulation Voltage
- Thermal Management (Air and H_2O 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



► 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 Clearly Reflecting the Actual Functionality → EEnergy Router (?)

Thank You!

Questions ?

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► Introduction

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About the Instructors

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.

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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.