

IECON 2013

Solid State Transformer Concepts in Traction and Smart Grid Applications

J.W. Kolar, G.I. Ortiz

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



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



- Magnetic Core Material
 - * Silicon Steel / Nanocristalline / Amorphous / Ferrite

 u_1

 f_1

 u_1 f_1

- Winding Material * Copper or Aluminium
- Insulation/Cooling
- * Mineral Oil or Dry-Type
- Operating Frequency
- Operating Voltage

* 50/60Hz (El. Grid, Traction) or $16^2/_3$ Hz (Traction) * 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.)

 $i_1 \approx i_2 \cdot \frac{N_2}{N_1}$

* Fixed $(P_1 \approx P_2)$

* Fixed $(f_1 = f_2)$

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

 $A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$

* Fixed $(Q_1 \approx Q_2)$

* 400V

- Public LV Grid

 $p_1 \approx p_2$

 $f_1 = f_2$

- Voltage Transf. Ratio * Fixed * Fixed
- Current Transf. Ratio
- Active Power Transf.
- React. Power Transf.
- Frequency Ratio
- Magnetic Core **Cross Section**
- Winding Window



R

T

N•

 l_2

 S^{u_2}

 J_2

 $u_2 \approx u_1 \cdot \frac{N_2}{N_1}$

- Advantages
- **Relatively Inexpensive** ٠
- Highly Robust / Reliable
- Highly Efficient (98.5%...99.5% Dep. on Power Rating)
- Weaknesses
- Voltage Drop Under Load
- Losses at No Load ٠
- Sensitivity to Harmonics
- Sensitivity to DC Offset Load Imbalances ٠
- **Provides No Overload Protection** ٠
- **Possible Fire Hazard** ٠
- **Environmental Concerns**
- Construction Volume

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

- P₊ Rated Power k_{w} Window Utilization Factor (Insulation) B_{max}^{W} ... Flux Density Amplitude J_{rms}^{W} ... Winding Current Density (Cooling) f Frequency
- No Controllability
- Low Mains Frequency Results in Large Weight / Volume



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 $|u_2|$

 u_1

- Scaling of Core Losses



- 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/m³) Allow to Achieve Higher Efficiencies







- Higher Relative Volumes (Lower kVA/m³) Allow to Achieve Higher Efficiencies
 Higher Operating Frequency → Lower Volume & Higher Efficiency



Classical / Next Generation Locomotives



Classical Locomotives

- Catenary Voltage
 - e 15kV or 25kV
- FrequencyPower Level
- 16²/₃Hz or 50Hz 1...10MW typ.







• Transformer:

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



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Next Generation Locomotives

- * Distributed Propulsion System \rightarrow Weight Reduction (pot. Decreases Eff.) - Trends
 - **Energy Efficient Rail Vehicles** \rightarrow **Loss Reduction Red. of Mech. Stress on Track** \rightarrow **Mass Reduction** (would Reg. Higher Vol.)
 - (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 \rightarrow Allows Loss Reduction AND Volume Reduction
- El. Syst. of Next Gen. Locom. (1ph. AC/3ph. AC) represents Part of a 3ph. AC/3ph. AC SST for Grid Appl.



Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives



• Medium Frequ. Provides Degree of Freedom \rightarrow Allows Loss Reduction AND Volume Reduction



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Next Generation Locomotives





- Basic Front End Converter Topologies
- Direct Matrix Converter
- Indirect Matrix Converter
- DC Link AC-DC-AC Converter



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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 <u>Ren. Electric</u> <u>Energy</u> <u>Delivery</u> & <u>Management</u> (FREEDM) Syst.

- Huang et al. (2008)



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





Smart Grid Concept

- **Borojevic** (2010)
- Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids
- Distr. Syst. of Contr. Conv. Interfaces
- Source / Load / Power Distrib. Conv.
- Picogrid-Nanogid-Microgrid-Grid Structure
- Subgrid Seen as Single Electr. Load/Source
- ECCs provide Dyn. Decoupling
- Subgrid Dispatchable by Grid Utility Operator
- Integr. of Ren. Energy Sources
- ECC = Energy Control Center
- Energy Routers
- Continuous Bidir. Power Flow Control
- Enable Hierarchical Distr. Grid Control
- Load / Source / Data Aggregation
 Up- and Downstream Communic.
- Intentional / Unintentional Islanding for Up- or Downstream Protection
- etc.





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Future Subsea Distribution Network – O&G Processing

Devold (ABB 2012) -



- Transmission Over DC, No Platforms/Floaters Longer Distances Possible
- Subsea 0&G Processing ٠

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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 ightarrow Low Weight / Volume
- Definable Output Frequency
- High Efficiency
- No Fire Hazard / Contamination







Terminology



McMurray Brooks EPRI ABB Borojevic Wang etc.

Electronic Transformer (1968) Solid-State Transformer (SST, 1980) Intelligent Universal Transformer (IUT™) Power Electronics Transformer (PET) Energy Control Center (ECC) Energy Router





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Basic SST Structures

- Efficiency Challenge



• Medium Freq. \rightarrow Higher Transf. Efficiency Partly Compensates Converter Stage Losses



- 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







• Basic SST Topologies Including also Indirect Matrix Converters







• Examples of Direct and Partial Indirect Matrix-Type Converter Topologies







• Examples of Hybrid (Partial Matrix-Type) and DC-Link-Based Converter Topologies



- Partial or Full Phase Modularity
- * Modularity of Electric Circuit* Modularity of Magnetic Circuit











• Example of Partly Phase Modular SST





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Basic SST Structures

- Multi-Cell and Multi-Level Approaches
- * Medium Voltage Application → Partitioning of the Overall Voltage Required Due to Limited Blocking Capability of the Power Semiconductors



* Single-Cell / Two-Level Topology







- Multi-Cell and Multi-Level Approaches
- * Medium Voltage Application → Partitioning of the Overall Voltage Required Due to Limited Blocking Capability of the Power Semiconductors

u1 * Two-Level Topology







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- Classification



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





Degree of Phase Modularity $\lambda_{\rm F}$

- Classification



- Very Large Number of Possible Converter Topologies (!)
- * Partitioning of Power Conversion \rightarrow Matrix & DC-Link Topologies
- * Splitting of 3ph. System into Individual Phases \rightarrow Phase Modularity
- * Splitting of Medium Operating Voltage into Lower Partial Voltages ightarrow Multi-Level/Cell Approaches





Challenges of Semiconductor Control of Distribution-Class Devices

- Heydt (2010)

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- Losses / Efficiency Reliability -
- **Insulation Coordination** -
- Cost



| Phenomenon | Basic problem | Mitigation possibilities |
|---|---|---|
| Basic impulse level – insulation coordination | Voltage breakdown of typical semicon- ductor 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 strate- gies (e.g., zero voltage or zero current switching) |
| Bulk resistive losses in semi- conductors | <i>I²R</i> loss in semicon- ductors | Development of more suitable semiconductor materials Use of low current con- figurations |
| Cost of compo- nents | High cost of high power switches | Mass production Development of better manufacturing tech- niques |
| Cooling semi- conductor com- ponents | Losses in semicon- ductor switches | Oil and air cooled tech- nologies Reduce losses in semi- conductor switches |
| Isolation and safety | No ohmic isolation afforded by semi- conductor switches | Principle of 'insulation by isolation' Judicious use of circuit breakers to isolate cir- cuits Use a magnetic trans- former for isolation |
| Component life- time | Loss of life due to heat | Better coolingReduce 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



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

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



- 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



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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





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 $f_1 = f_2$











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Electronic Transformer

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









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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 !



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Direct Matrix-Type 1ph. AC/DC Converter

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





 Thyristor Converter Control Angle α= π/3



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







 Thyristor Converter Control Angle α= 2π/3



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



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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



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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



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





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



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





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



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





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





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





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Direct Matrix-Type 1ph. AC/DC Converter



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



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



- Alternate Commutation of VSC and CSC \rightarrow 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 V₀ vs. Three-Level Contr. (Norrga)



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





- $f_1 = f_2$

- 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

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- Enjeti (V-Input, V-Output, $\theta = 0$, 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 •



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





- $f_1 = f_2$
- Input Power = Output Power (and No Reactive Power Control)Negative Power Flow1ph. 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





input voltage

4000

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)





- 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





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



• Six Conduction States within a Pulse Period



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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)



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Direct Matrix-Type 1ph. AC/DC Converter



- 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





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





• Experimental Analysis





- 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



- 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



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



- AC/DC Input Stage (Bidir. Full-Wave Fundamental Frequ. GTO Rect. Bridge, No Output Capacitor)
- Subsequent DC/DC Conversion & DC/AC Conversion (Demodulation, f₁ = f₂)
 Output Voltage Control by Phase Shift of Primary and Secondary Side Switches (McMurray)
 Lower Number of HF HV Switches Comp. to Matrix Approach

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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 (G₁,G₃), (G₂,G₄), (G₅,G₇), (G₆,G₈)





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

- ۲
- 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)**



- 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)



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DAB – Common Bridge Configurations

Neutral-Point-Clamped (NPC) Configuration



■ NPC / Full-Bridge Configuration



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

• Suitable for Higher MV/LV Ratios



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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



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DAB – Phase-Shift Modulation

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







- Soft Switching Range



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DAB – Phase-Shift / Duty-Cycle Modulation

 Additional Degrees of Freedom can be Utilized to Optimize Targeted Criteria



• Not Possible in Half-Bridge Configuration



DAB – Triangular-Current Mode

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







Three-Phase DAB

- **De Doncker (1991)**





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

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



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



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



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





Equivalent Circuit for Transient Analysis (Esser, 1991)



• Output Voltage is $V_{LV} \approx V_{MV}$ n for Any Output Power









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

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- 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)













- 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

 $\begin{array}{c} \mathbf{S}_{1} \neq \mathbf{S}_{1} \\ \mathbf{S}_{2} \neq \mathbf{S}_{2} \\ \mathbf{S}_{2} \neq \mathbf{S}_{2} \\ \mathbf{S}_{4} \neq \mathbf{S}_{4} \\ \mathbf{S}$

MV side NPC Bridge

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



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Operation

NPC Bridge Applies Full Positive Voltage

As soon as the Current Reaches Zero, the NPC Bridge is Turned to Freewheeling, achieving ZCS on S₁



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





- NPC Bridge Applies Full Positive Voltage
- As soon as the Current Reaches Zero, the NPC Bridge is Turned to Freewheeling, achieving ZCS on S₁



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



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► 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



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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)



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



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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



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



| 4 |
|----------------|
| 38 |
| 22 |
| 16 |
| L4 38 22 |

A Summary of IGBTs' Parameters



▲ Experimental Stored Charge Dynamic Analysis on 1.7kV NPT IGBT



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• Quasi ZCS and ZVS: $MV \rightarrow LV$

- 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



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Quasi ZCS and ZVS: Switched Current Sweep



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



- 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

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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

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

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



- Frequently 1ph. AC/3ph. AC Converter Topologies Analyzed Instead of Full 3ph. Systems
- Frequently Unidir. (MV \rightarrow LV) Topologies Proposed/Analyzed Instead of Bidir. Systems
- 1ph. AC/3ph. AC Conv. Topologies are Directly Applicable for Traction Applications



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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 $f_{\rm P}\approx 200$ Hz (α =150°)
 - Reactive Power Demand of the Thyristor Cycloconverter
 - Implementation of Cycloconv. with (Turn-Off) RB IGCTs (6.5kV) allows $f_{\rm P}\approx$ 500Hz
- Enjeti: Three-Limb Core could be Employed for Realiz. of MF D-y-Transformer (Enjeti, 1997)





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

- Venkataramanan (2000)



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





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

- Mohan (2009)



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





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

- Mohan (2009)



- Equivalent Circuit of the Transformer for 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







- •
- •
- 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 •







- 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)
- •





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



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



- 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




- Akagi (2005)



- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs Combination of Clustered Balancing Control with Individual Balancing Control ٠







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





- Steimel et al. (2002)



- Electronic Power Transformer for 110/20kV and 110/10kV Applications Truck Movable Temporary Replacement of Failed Conventional Transformer ٠





- Steimel et al. (2002)



(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.)





- Steimel et al. (2002)



• 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 •
- •

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

- Clare/Wheeler et al. (2001)

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

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)

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

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

• Transformer Classification Independent of Number of DC Links

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MV DC

Side A Side B

 $X \stackrel{M}{L} N Y$









DC

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

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



• Structure of the DC Links





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





3-phase grid/load

Storage elements

Port 2

UNIFLEX Project

- EU Project (2009)



H-bridge

H-bridge

H-bridge

DC

÷

[Ť] DC

V{dc2(C)}

V{dc3(C)}

dc4(C)

V_{dc4(}A

V_{dc4(C)}±

V_{dc4(B)} H-bridge

H-bridge

H-bridge



Port 1

Port 3

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









- Advanced Power Conv. for <u>Universal and Flexible Power Management (UNIFLEX)</u> 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-1}, 4 Modules in Series) LV Y-Connection (465V/ $\sqrt{3}$, Modules in Parallel)





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





SiC-Enabled Solid State Power Substation

- Das (2011)
- Fully Phase Modular System
- Indirect Matrix Converter Modules $(f_1 = f_2)$ MV Δ -Connection (13.8kV_{I-l}, 4 Modules in Series) LV Y-Connection (465V/ $\sqrt{3}$, Modules in Parallel)





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





Transformerless Intelligent Power Substation (TIPS)

- Bhattacharya / FREEDM Center (2012)



- $13.8kV \rightarrow 480V$
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype





The MEGACube @ ETH Zürich

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





Structure of the 166kW Module and MV Side Waveforms





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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



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The MEGACube - IGBT-Based

LV Full-Bridge

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



83 kW Water-Cooled LV Full-Bridge **Based on IGBT ECONOdual Modules**







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► The MEGACube - MV NPC Module

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









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The MEGACube - Air-Cooled Ferrite Core Transformer

- 166 kW
- Power Rating
 Estimated Losses (incl. Fan Power)
 Based on ECONOdual IGBT Module 0.59 kW
- Forced-Air-Cooled



166 kW Air-Cooled Ferrite Core Transformer



The MEGACube - Water-Cooled Nanocrystalline Transformer

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

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► The MEGACube 166kW/20kHz Module







The MEGACube - Resonant 166kW / 20kHz Converter









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









- 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





- 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)





- 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)







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)











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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)

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







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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) u mp2 U





Partial Power SST Employing LF Transformers



- 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)



- Controlled Output Voltage: v₀ = v₁ + △v
 Isolation Provided with LF Transformer (Not Shown)





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Partial Power SST Employing LF Transformers



- 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 ۲
- ۲



Single-phase Hybrid Transformer

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)









ETH

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





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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 % |

\approx 6 Turns Around the Earth









- **16.7Hz 1ph.-Transformer Required to Step-Down the** Catenary Voltage to the Drive's Operating Voltage
- Electric Railway Systems Today's Drive Scheme
- **Power Electronic Systems** Laboratory



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





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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)



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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-ut, Ch2-it: 10A/100mV, Ch3-isc: 10A/100mV, Ch4- usc



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Cascaded Source Commutated Primary Converter



- Pittermann (2008)
- Module Power 2kW (downscaled)Frequency 800Hz
- Frequency



Cascaded Source Commutated Primary Converter



- Hugo (ABB, 2006)
- Total Power 1.2MVA/15kV Module Power 75kW
- 400Hz - Frequency





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 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 multiwinding MFT



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Cascaded H-Bridges with Multi-Winding MF Transformer



- Engel (ALSTOM, 2003)
- Module Power 180kW
- Frequency 5kHz



Cascaded H-Bridges with Multi-Winding MF Transformer



Glass fibre re-inforced plastic enclosure { 2.62 x 2.12 x 0.58m}

- Taufiq (ALSTOM, 2007)
- Module Power 180kW 5kHz
- Frequency





Modular Multilevel Converter

- Marquardt/Glinka (SIEMENS, 2003)





power supply

Modular Multilevel Converter

- Marquardt/Glinka (SIEMENS, 2003)
- Module Power 270kW

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- Module Frequency 350Hz

storage capcitors









IGBT-drivers

(63)

fibre optic

interface

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





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Cascaded H-Bridges and Resonant LLC DC-DC Stages

• Zhao et al. (ABB, 2011)







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





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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.





MF Transformer Design – Cold Plates Cooling

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









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)





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► MF Transformer Design - Isolation

• Glass-Fiber Container Engel (ALSTOM, 2003)









MF Transformer Design – Acoustic Noise Emissions

• Magnetostriction of Core Materials (Zhao, 2011)

- Nanocrystalline ~ Oppm

- 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

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- Extremely Low Leakage Inductance
 Reliable Isolation due to Homog. E-Field
- Low Flexibility on Turns RatioComplex Terminations



• Heinemann (2002)





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MF Transformer Design – Winding Arrangements

- Coaxial Windings

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



• Hoffmann (2011)

• Steiner (2007)







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Flux Balancing - DC Magnetization





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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







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Flux Density Transducer – The Magnetic Ear

 Compensation Network to Decouple Main and Auxiliary Flux







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



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Flux Density Transducer – The Magnetic Ear

 Transducer Output for Biased Magnetic Operation

- Closed Loop Response
 - Reference Step
 - Disturbance Rejection







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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 2-4 % 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)

Current/Future Research Topics

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- MF Transformer Construction featuring High Voltage Isolation
- Thermal Management (Air and H₂O Cooling, avoiding Oil)
 "Low" Voltage SiC Devices for Efficiency Improvement
- Multi-Level vs. Two-Level Topologies with SiC Switches \rightarrow "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 \rightarrow 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 Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations
- → SST Requires a Certain Application Environment (until Smart Grid is Fully Realized)
- \rightarrow 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.)

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

• "SST" is NOT AT ALL Clearly Reflecting the Actual Functionality \rightarrow EEnergy Router (?)





Thank You!



Questions ?





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About the Instructors



Johann W. Kolar (F¹10) 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 9 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.





About the Instructors (Cont'd)



Gabriel Ortiz (M¹0) 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.

