ETH zürich

Workshop

Smart Transformers for
Traction and Future Grids

Solid-State Transformers (SST)
Concepts, Challenges and Opportunities

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

Outline

- ► Transformer (XFMR) Basics
- ► Solid-State Transformer (SST) History
- ► Traction / Smart Grid Applications
- ► Derivation of Topologies
- ► Demonstrator Systems
- ► Evaluation / Challenges
- ► Conclusions

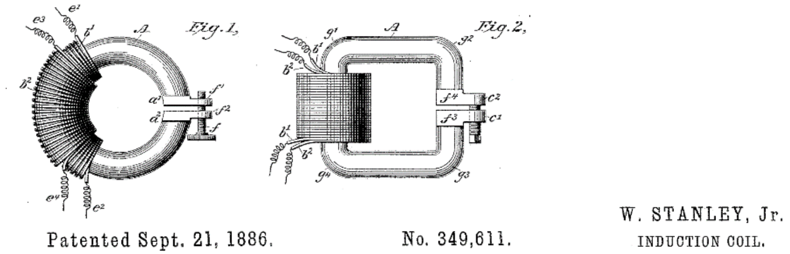
Acknowledgement
Dr. G. Ortiz
Th. Guillod
D. Rothmund

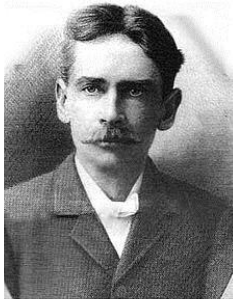
History

Transformer
"Electronic" Transformer

► Classical Transformer (XFMR) – History (1)

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





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

► Classical Transformer – History (2)

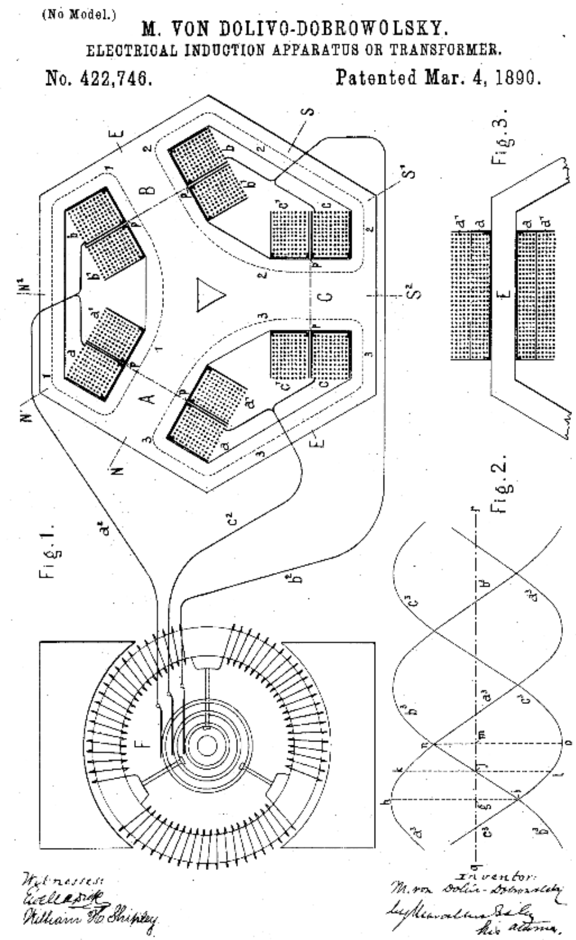
UNITED STATES PATENT OFFICE.

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

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

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

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



* 1889 - Dobrovolski → 3-Phase Transformer

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

United States Patent Office

3,517,300
Patented June 23, 1970

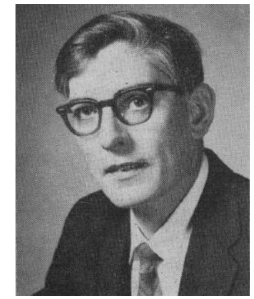
1

3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK

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

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

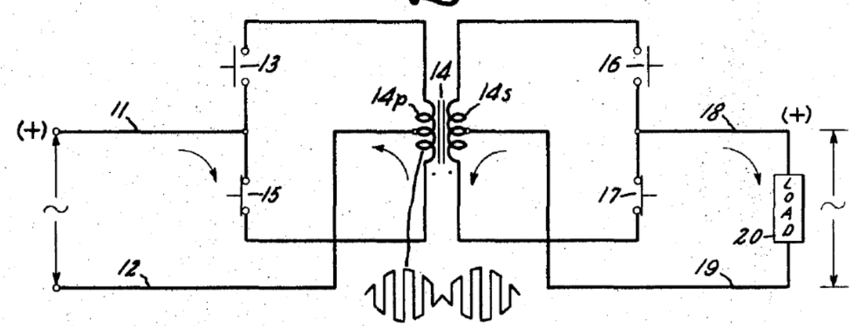
1968 !



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

Filed April 16, 1968

Fig. 1a



ABSTRACT OF THE DISCLOSURE

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

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

▶ Electronic Transformer

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

Fig. 3.

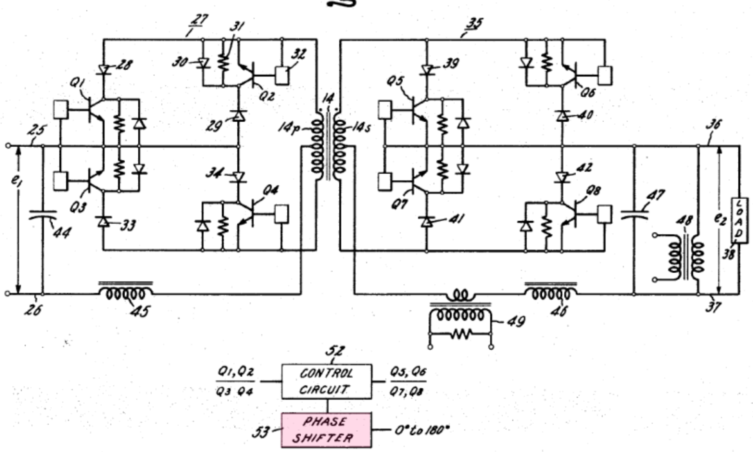
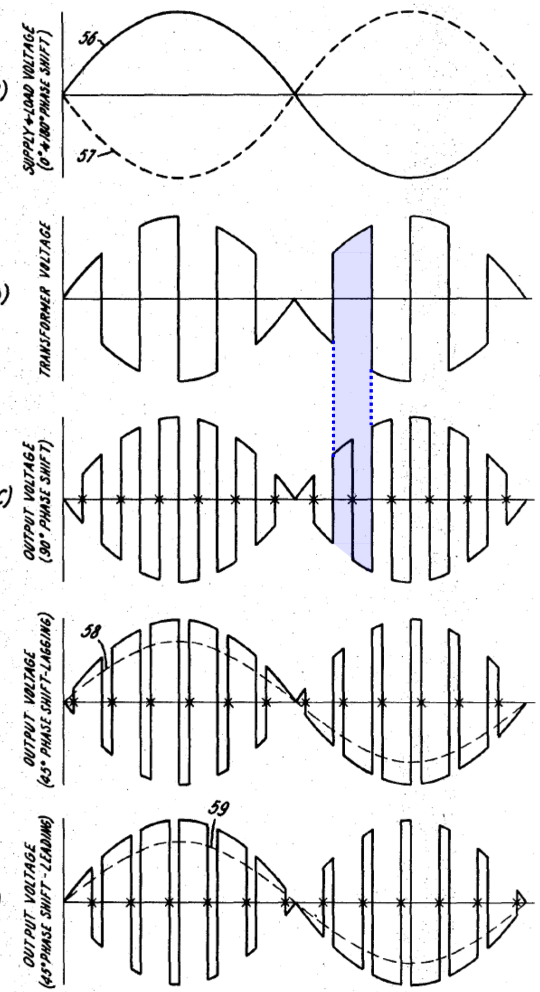


Fig.4(a)
Fig.4(b)
Fig.4(c)
Fig.4(d)
Fig.4(e)



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

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

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

WILLIAM McMURRAY, SENIOR MEMBER, IEEE

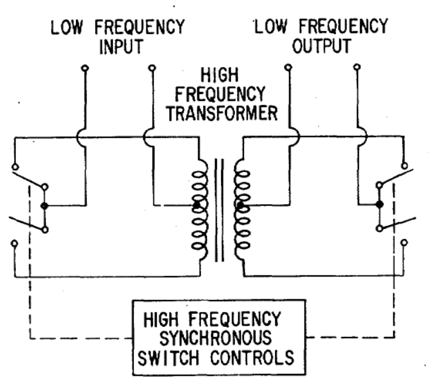


Fig. 1. Principle of electronic transformer.

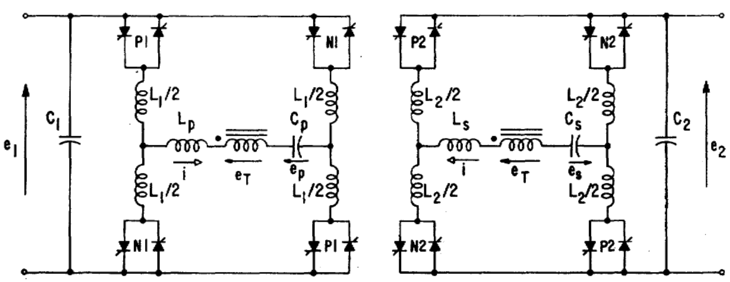


Fig. 5. Double-bridge electronic transformer; arrows define positive polarity of voltages and currents.

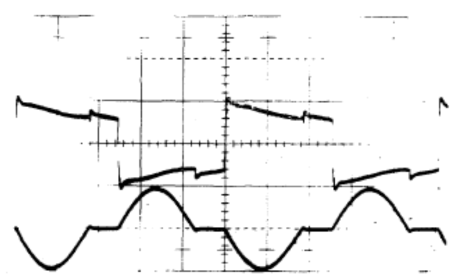


Fig. 8. Transformer waveforms, dc load 10 A; search-coil voltage—72 V/div; primary current—50 A/div; time—20 µs/div.

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

United States Patent [19]

Brooks et al.

[11] 4,347,474

[45] Aug. 31, 1982

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

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

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

[21] Appl. No.: 188,419

[22] Filed: Sep. 18 1980 ← 1980 !

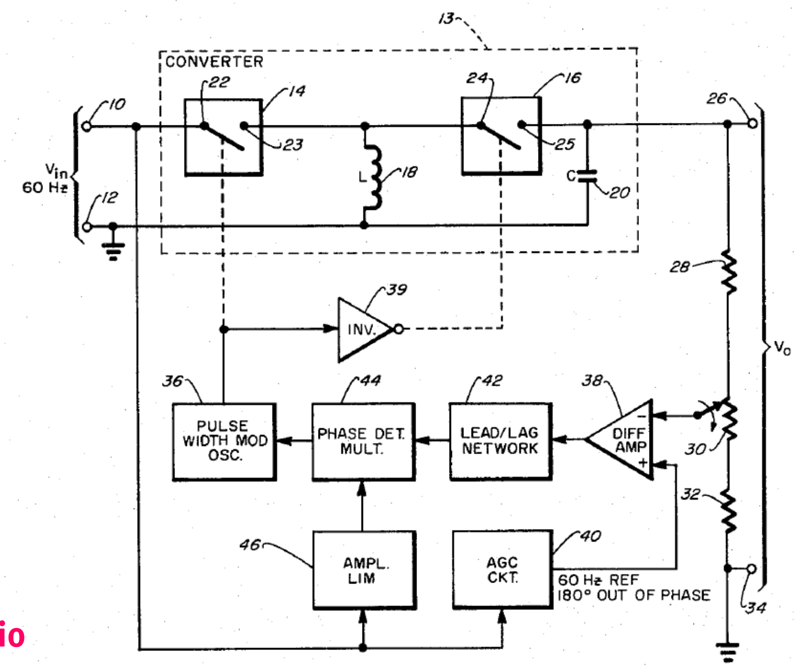


Fig. 1.

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

OTHER PUBLICATIONS

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

United States Patent [19] — **DeDoncker et al.**

[11] **Patent Number:** 5,027,264

[45] **Date of Patent:** Jun. 25, 1991 ← 1991

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

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

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

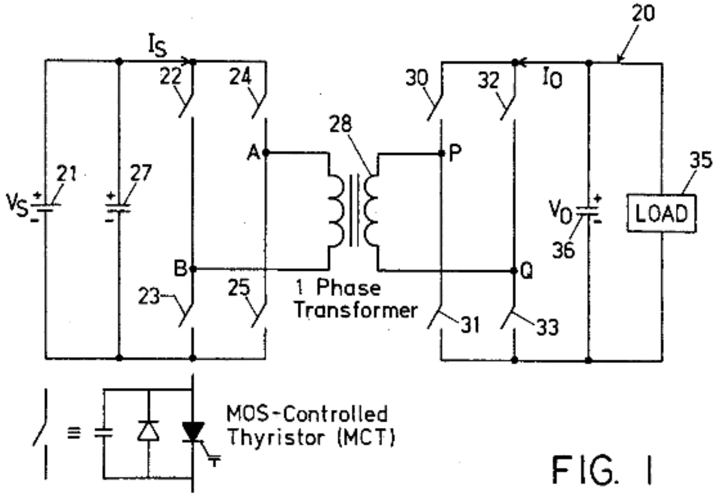


FIG. 1

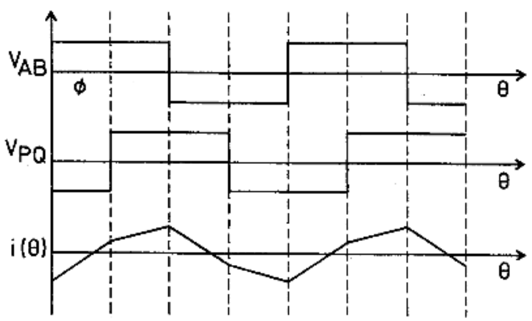


FIG. 2

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

"Solid-State" Transformer (SST)

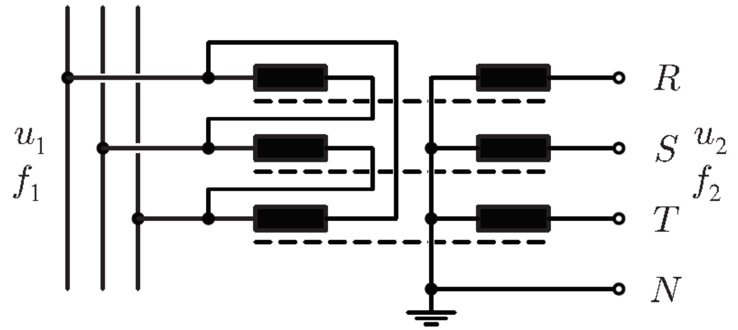
XFMR Scaling Laws
SST Application Areas / Concept

▶ Classical Transformer – Basics (1)

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

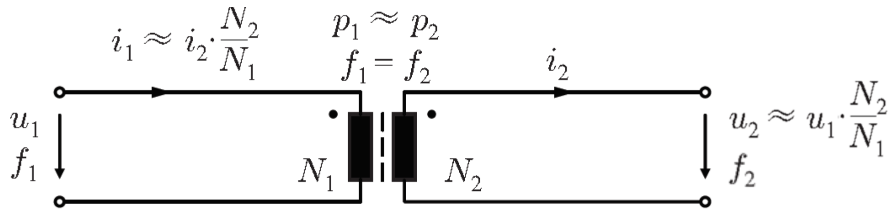
- Operating Frequency * 50/60Hz (El. Grid, Traction) or $16^2/_3$ Hz (Traction)
- Operating Voltage * 10kV or 20 kV (6…35kV)
  * 15kV or 25kV (Traction)
  * 400V

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



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

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



▶ Classical Transformer – Basics (2)

- Advantages

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

- Weaknesses

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

• Construction Volume

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

↑ ↑ ↑

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

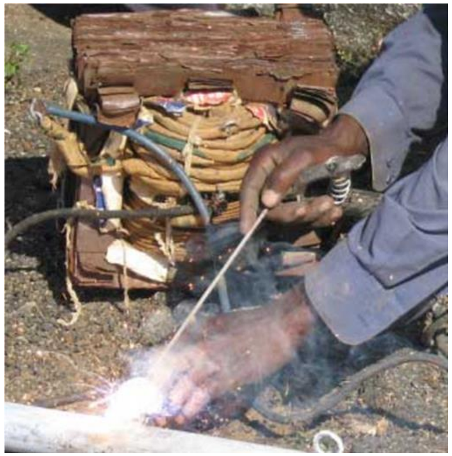
• Low Frequency → Large Weight / Volume

► Classical Transformer – Basics (3)

- Advantages

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

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

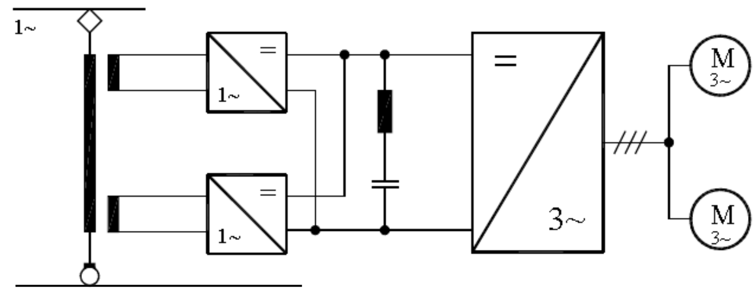


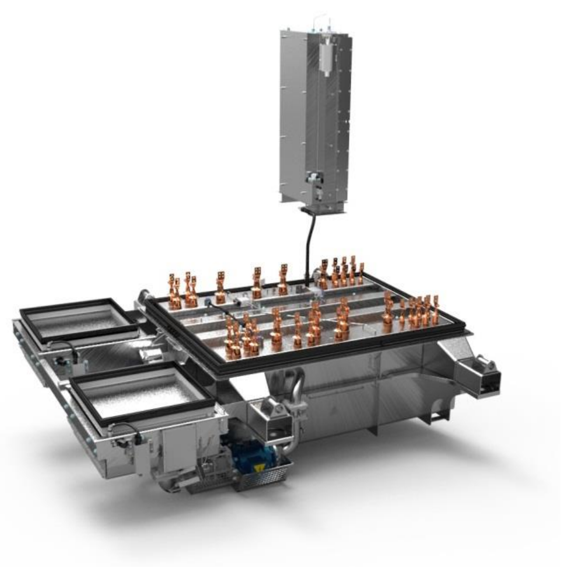
SST Motivation

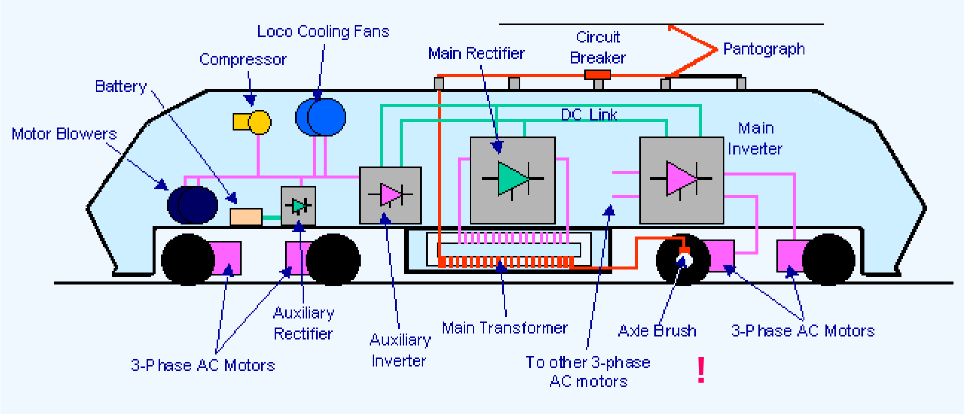
Next Generation Traction Vehicles

▶ Classical Locomotives

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







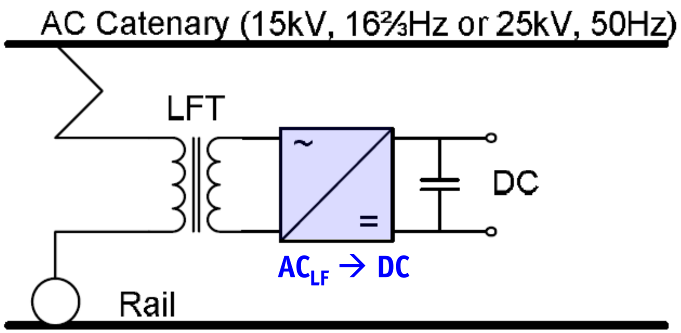
- **Transformer:**

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

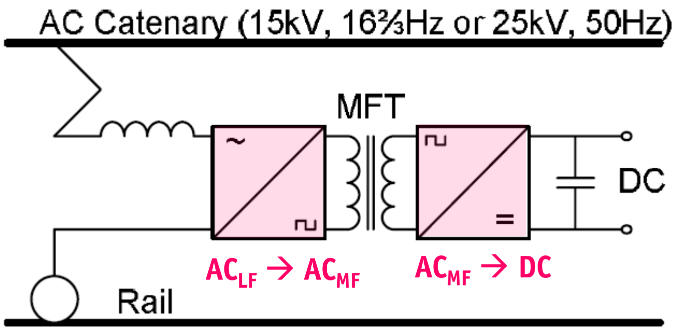
▶ Next Generation Locomotives

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

Source: ABB



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

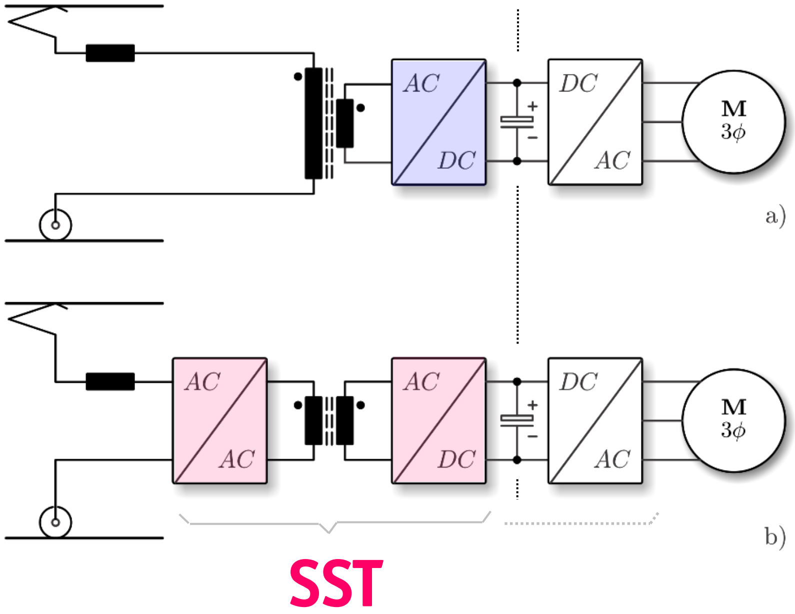


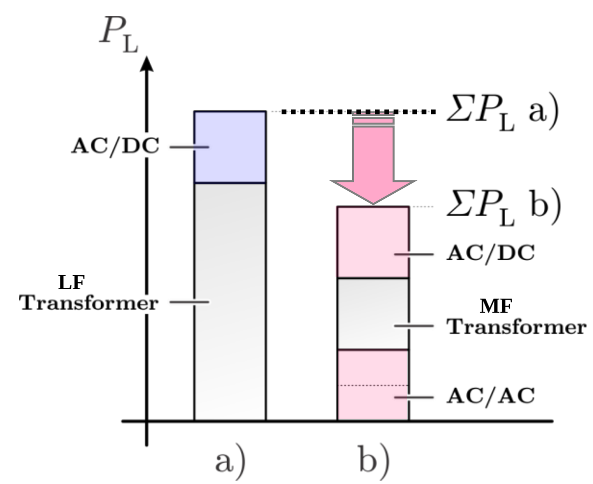
AC-DC conversion with medium frequency transformer (MFT).

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

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives





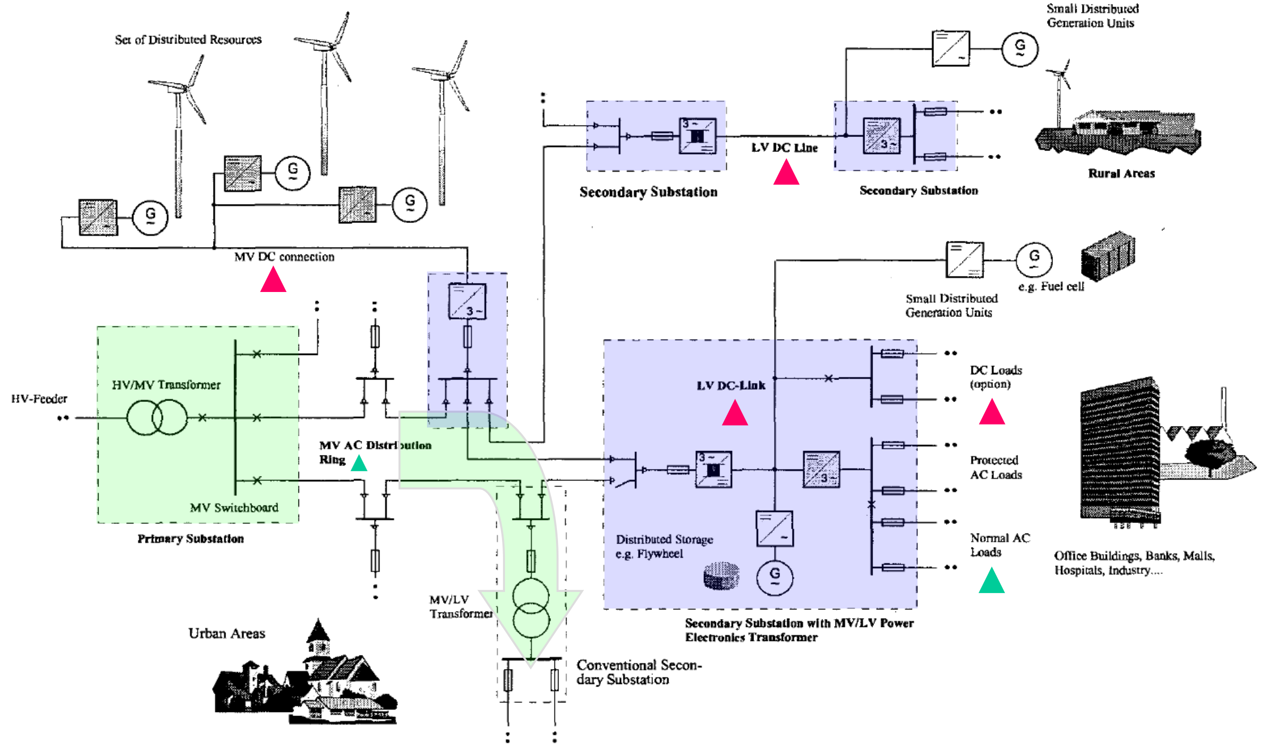
- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

Future Smart EE Distribution

Source: TU Munich

▶ 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

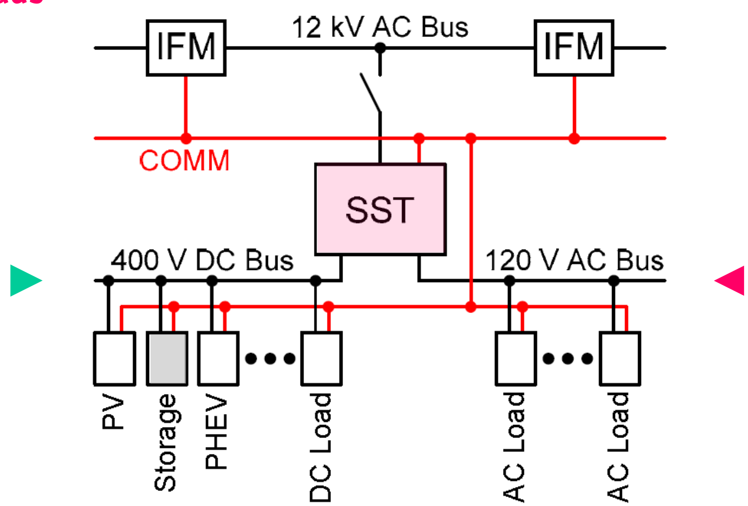
▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

IFM = Intellig. Fault Management

- SST as Enabling Technology for the "Energy Internet"

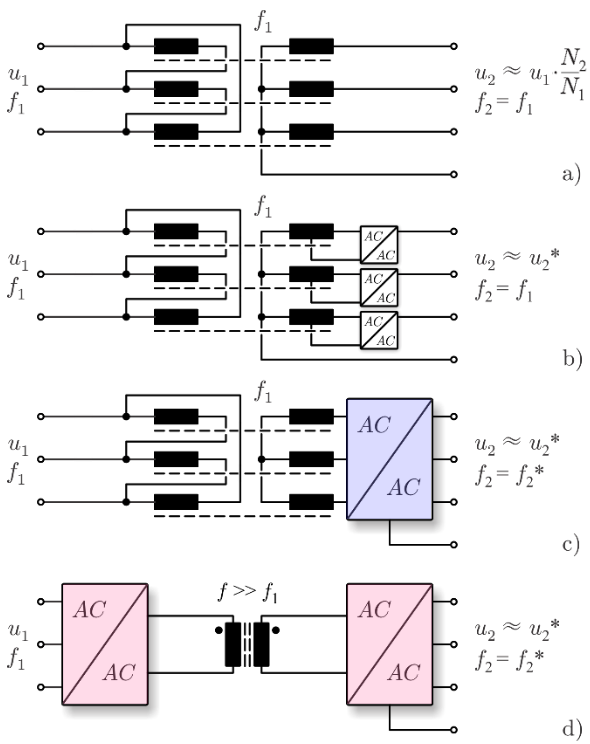
- Full Control of the Power Flow
- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Protects Power Syst. From Load Disturbances
- Protects Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.
- etc.



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

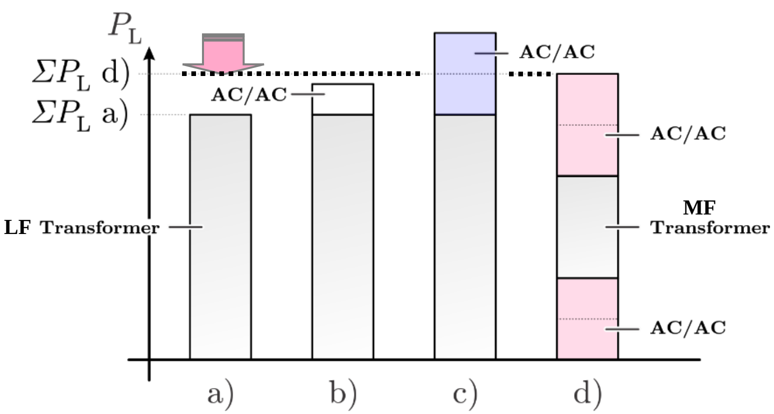
▶ Passive Transformer → SST

- Efficiency Challenge



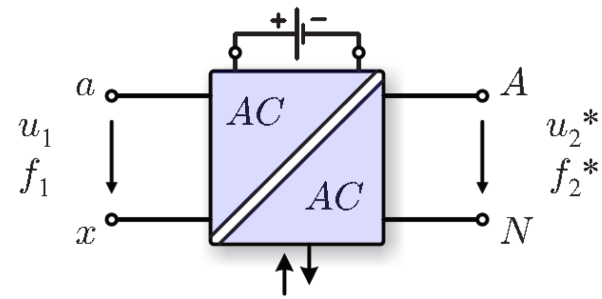
LF Isolation
Purely Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

MF Isolation
Active Input & Output Stage (d)

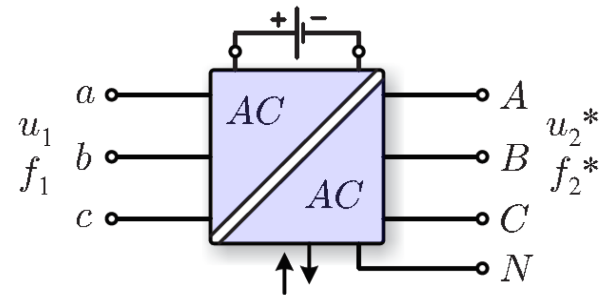


- Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses
- Medium Freq. → Low Volume, High Control Dynamics

▶ Terminology



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

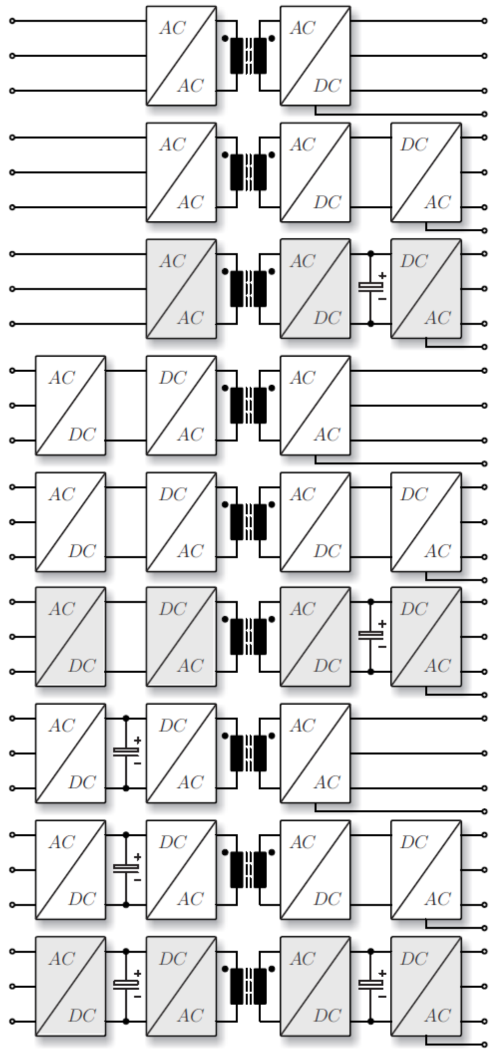


Classification of SST Topologies

▶ Basic SST Structures (1)

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

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



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

► Basic SST Structures (1)

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

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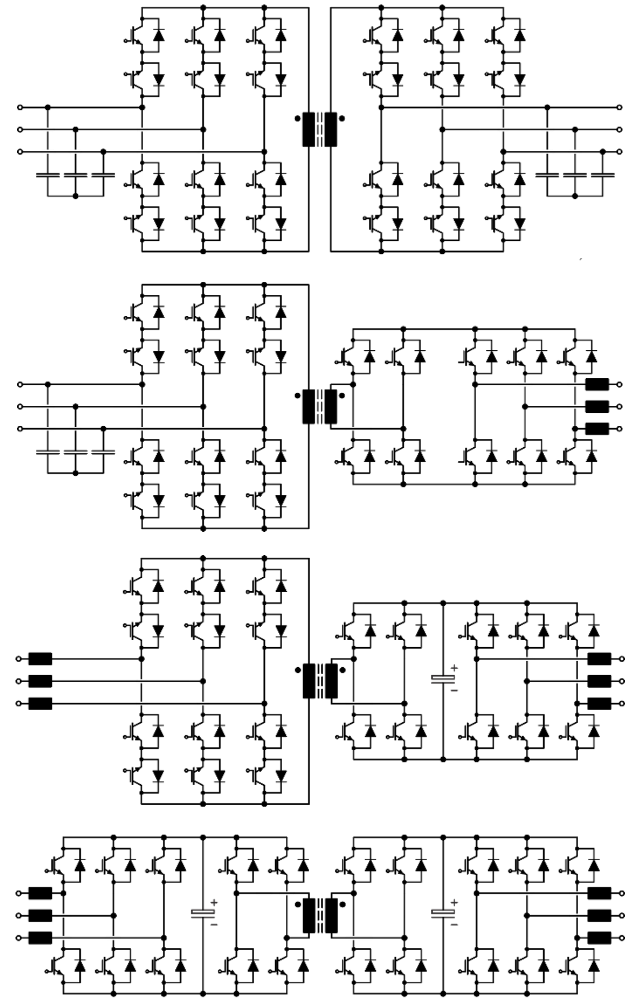
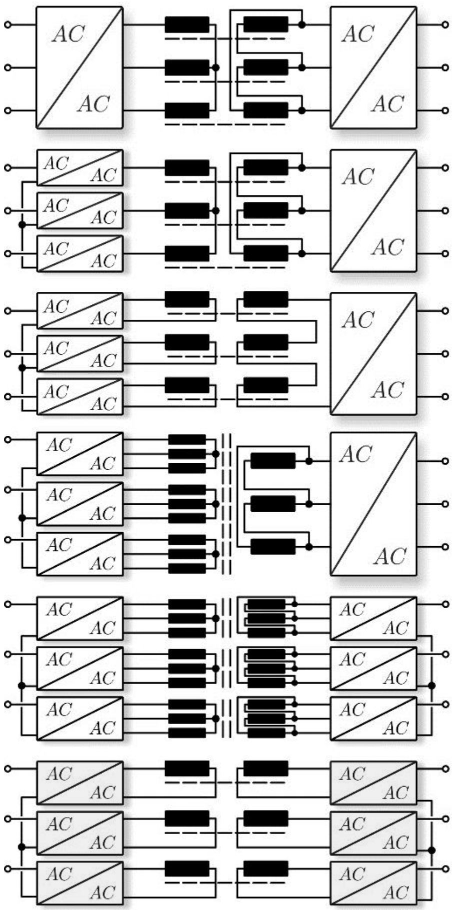


- 3-Stage Power Conversion with MV and LV DC Link
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 2-Stage with MV DC Link (Connection to HVDC System)
- 1-Stage Matrix-Type Topologies

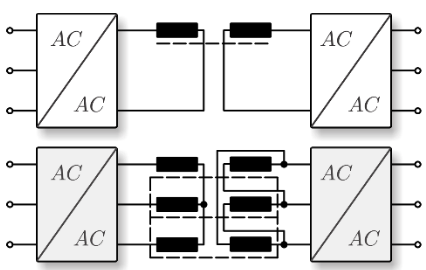
▶ Basic SST Structures (2)

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

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



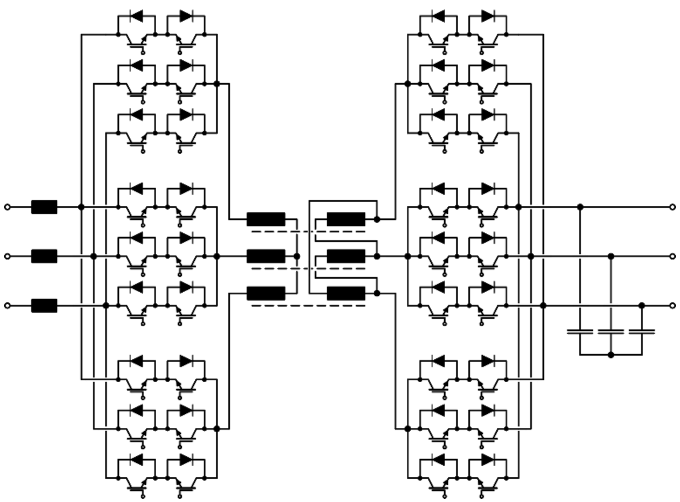
* Phase-Integrated SST



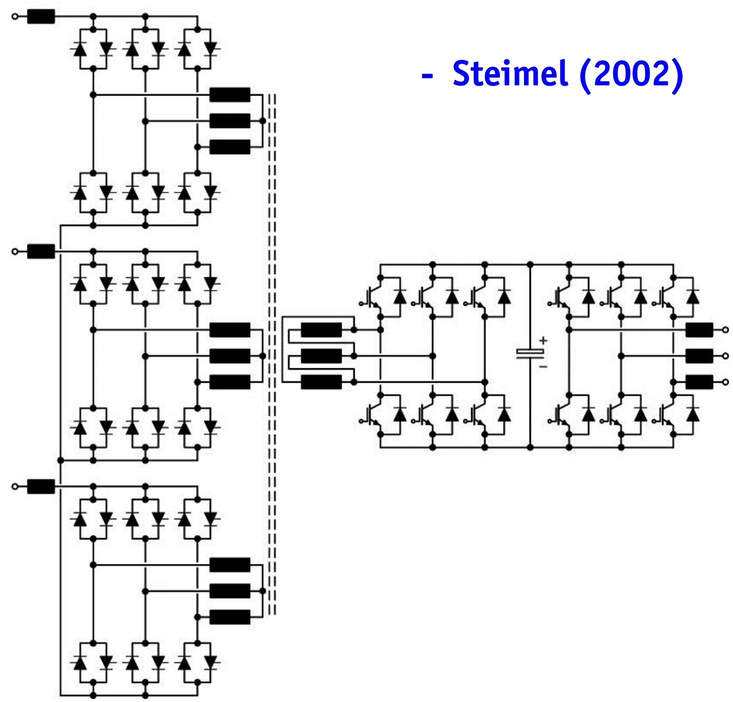
▶ Basic SST Structures (2)

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

- Enjeti (1997)



- Steimel (2002)



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

- Example of Partly Phase-Modular SST

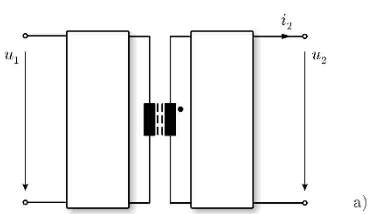
▶ Basic SST Structures (3)

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

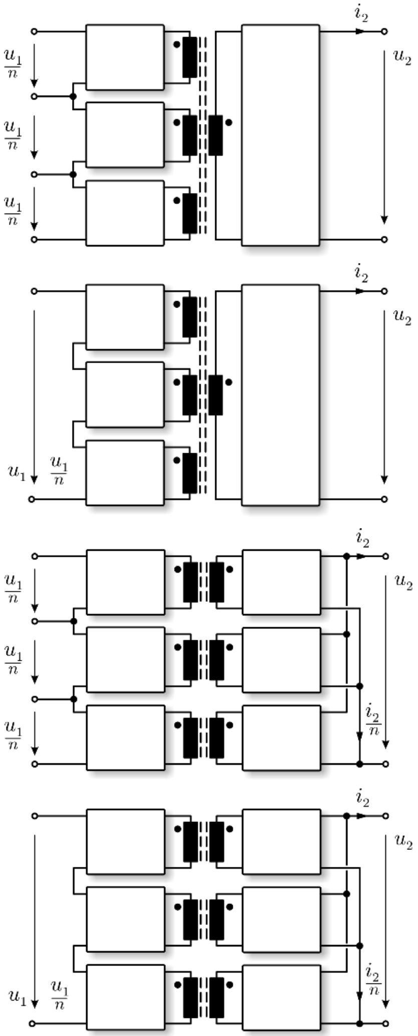
- Multi-Cell and Multi-Level Approaches

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

* Single-Cell / Two-Level Topology



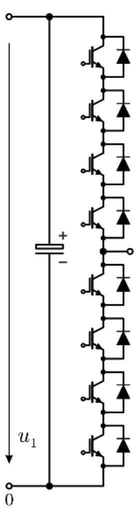
ISOP = Input Series / Output Parallel Topologies



▶ Basic SST Structures (3)

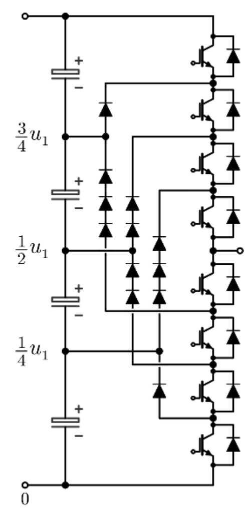
■ 3rd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

● Multi-Cell and Multi-Level Approaches

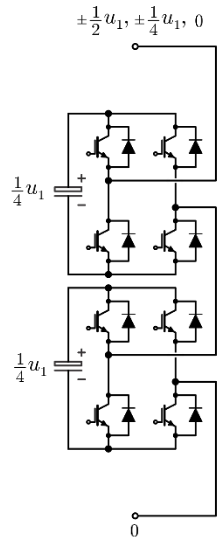


* Two-Level Topology

Akagi (1981)

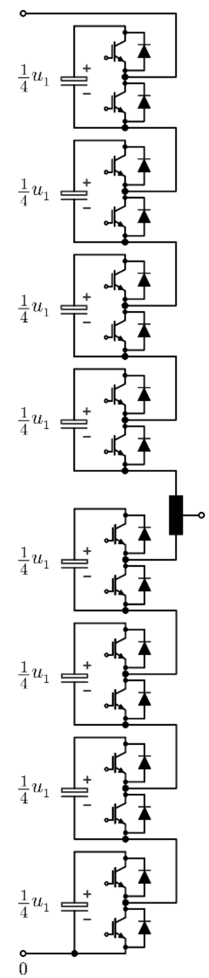


McMurray (1969)



Marquardt

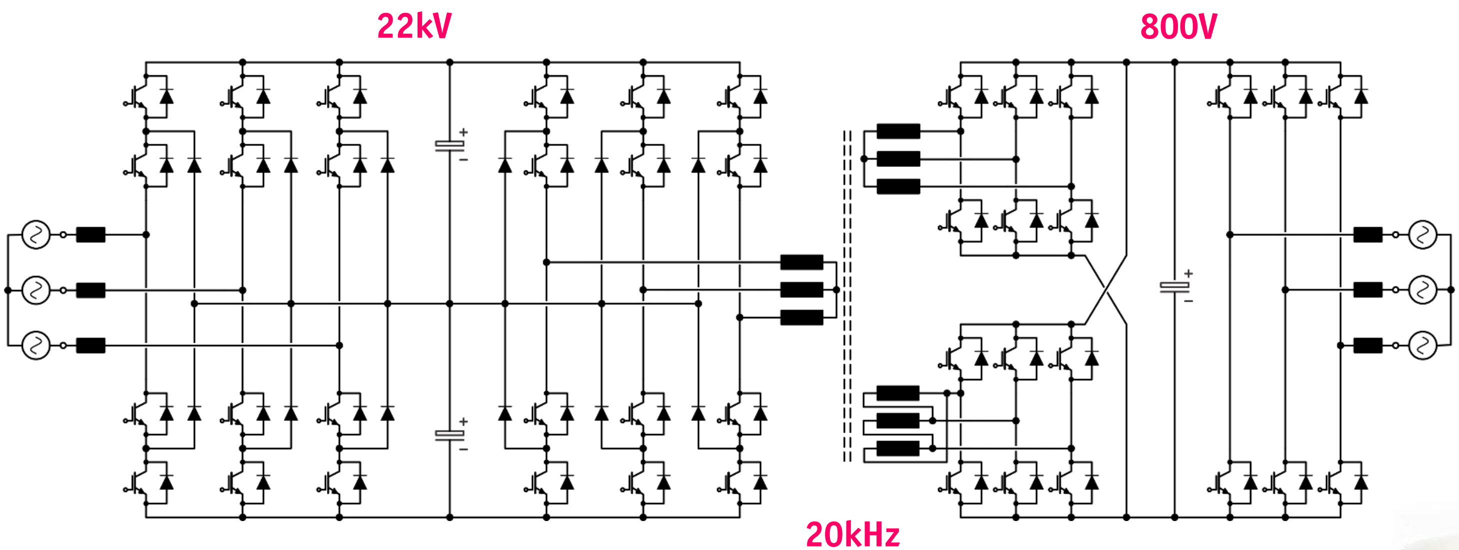
Alesina/ Venturini (1981)



* Multi-Level/ Multi-Cell Topologies

▶ Basic SST Structures (3)

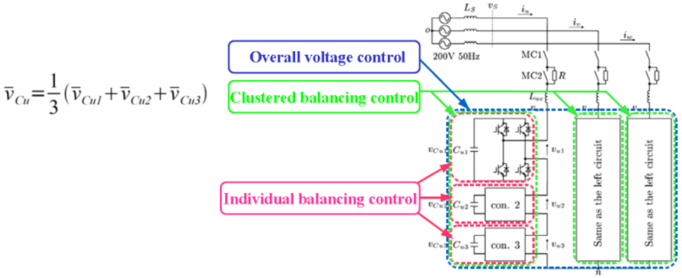
- Bhattacharya (2012)

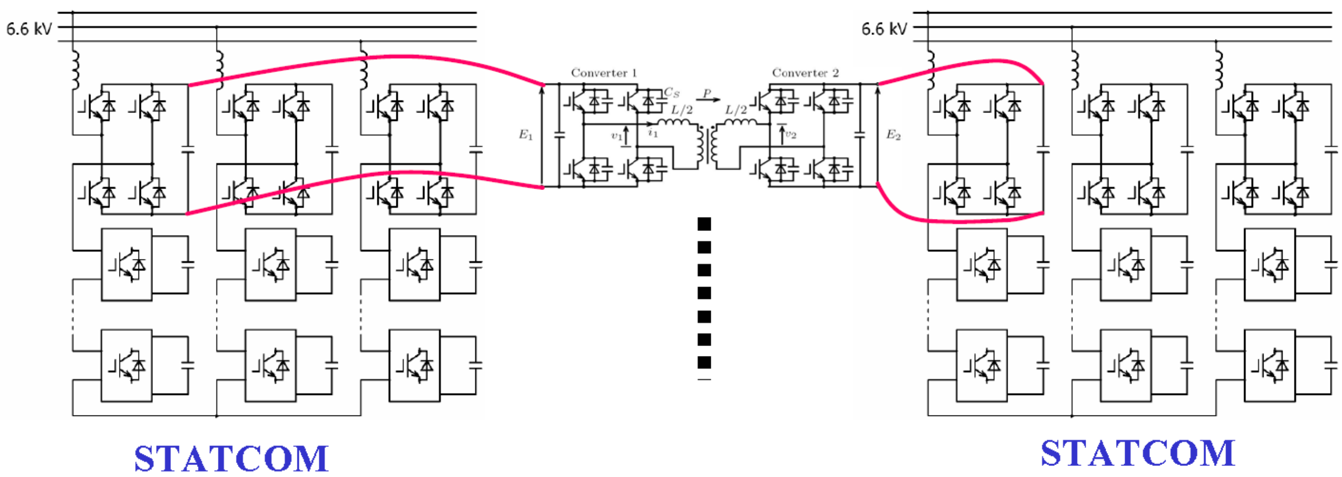


- 13.8kV → 480V
- 15kV Si-IGBTs, 1200V SiC MOSFETs
- Scaled Prototype

▶ Basic SST Structures (3)

- Akagi (2005)

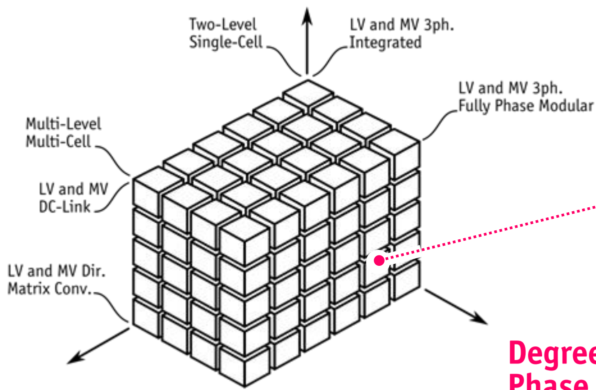




- Back-to-Back Connection of MV Mains by MF Coupling of STATCOMs
- Combination of Clustered Balancing Control with Individual Balancing Control

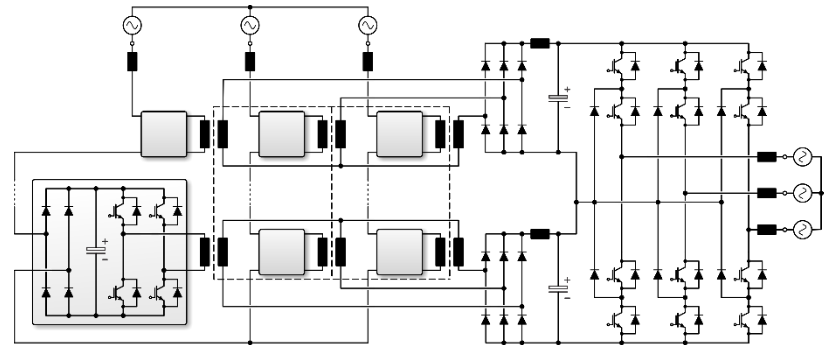
▶ Classification of SST Topologies

Degree of Power
Conversion Partitioning



Number of Levels
Series/Parallel Cells

Degree of
Phase Modularity



\- Enjeti (2012)

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

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

Functional Partitioning of AC/DC Power Conversion

Required Functions

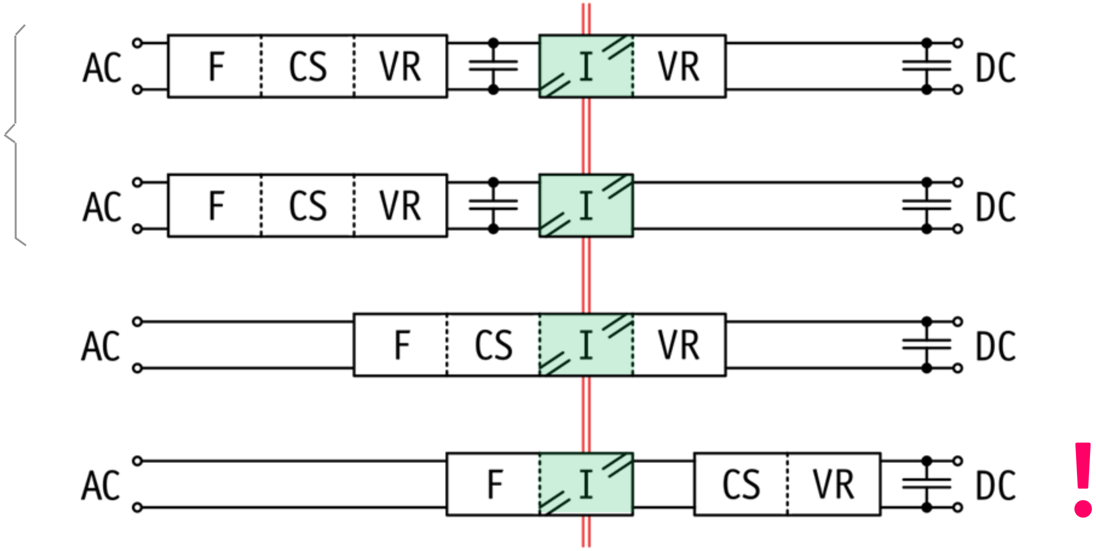
- F: Folding of the AC Voltage into a |AC| Voltage
- CS: Input Current Shaping
- I: Galvanic Isolation & Voltage Shaping
- VR: Output Voltage Regulation

Alternative Sequences of Equal Overall Functionality

Isolated Back End (IBE) →

Fully Integrated →

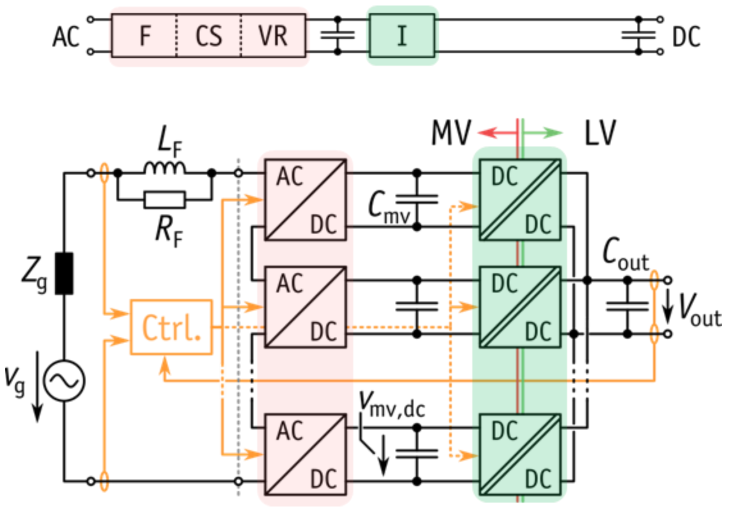
Isolated Front End (IFE) →



▶ Isolated Back/Front-End Topology

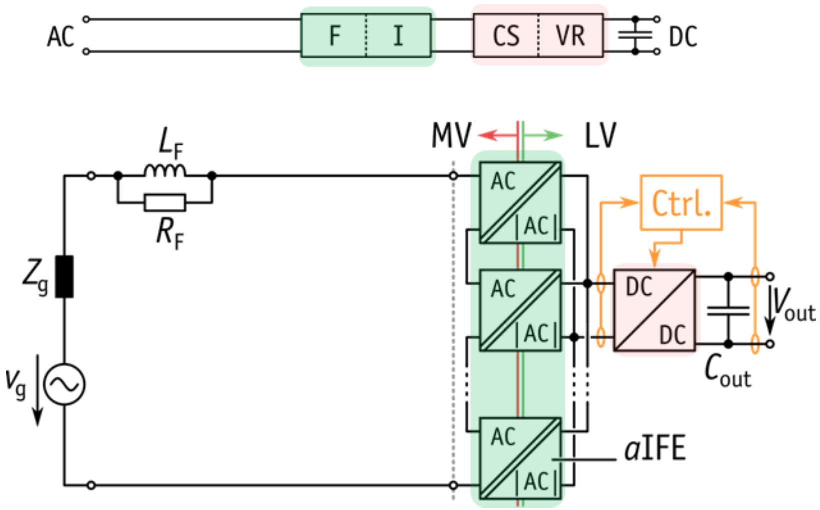
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
70 NRP Energy Turnaround
National Research Programme

■ Isolated DC/DC Back End



- Typical Multi-Cell SST Topology
- Two-Stage Multi-Cell Concept
- Direct Input Current Control
- Indirect Output Voltage Control
- High Complexity at MV Side

■ Isolated AC/ | AC | Front End



- Swiss SST (S3T)
- Two-Stage Multi-Cell Concept
- Indirect Input Current Control
- Direct Output Voltage Control
- Low Complexity on MV Side

Take Note!

SST Demonstrator Systems

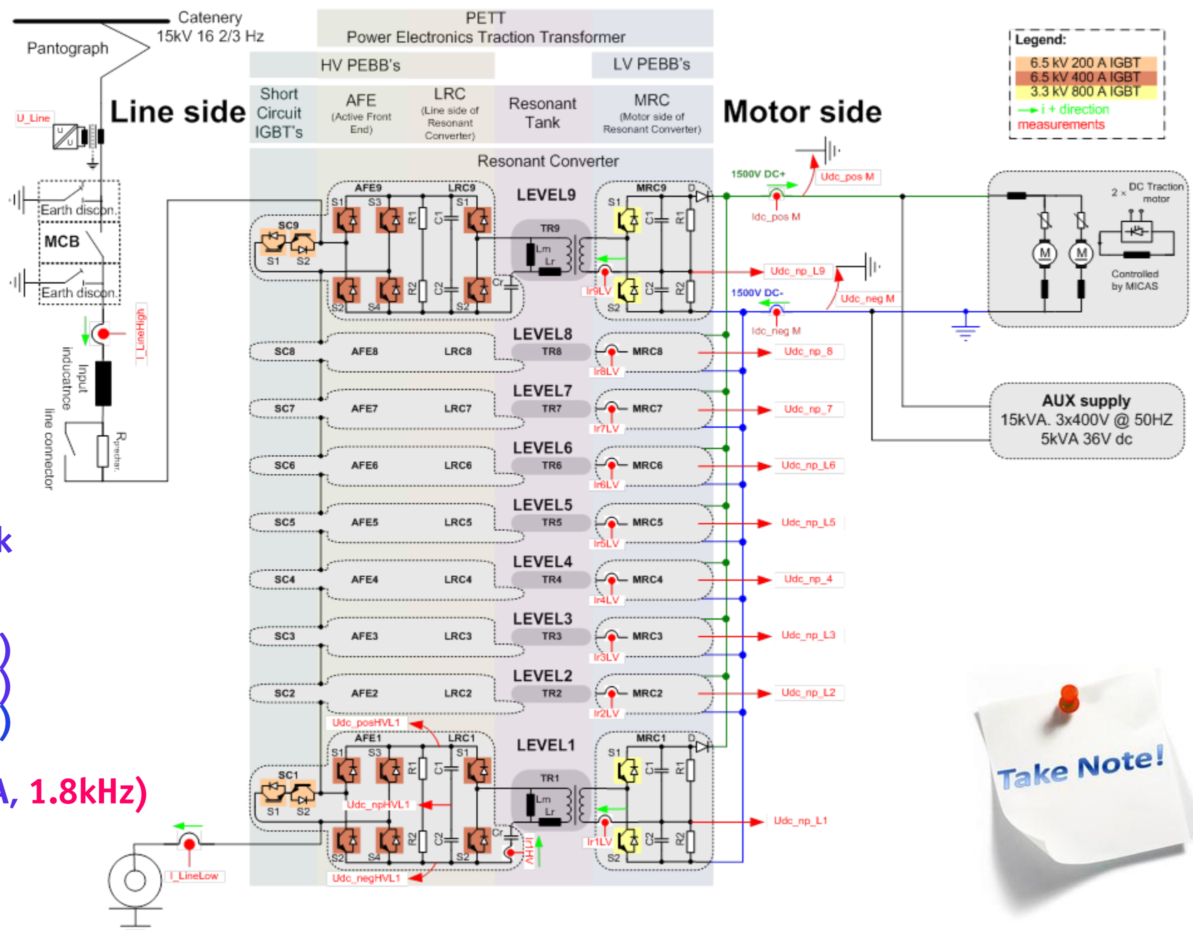
Future Locomotives
Smart Grid Applications

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

ABB

- Dujic et al. (2011)

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



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

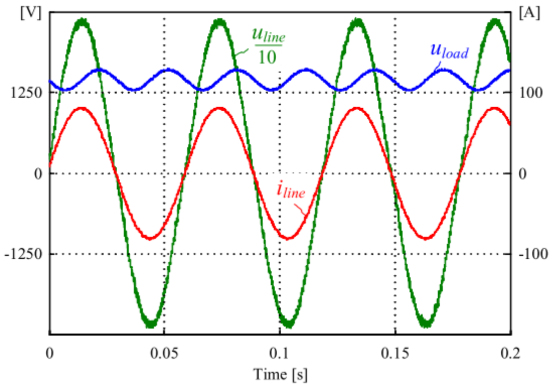
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

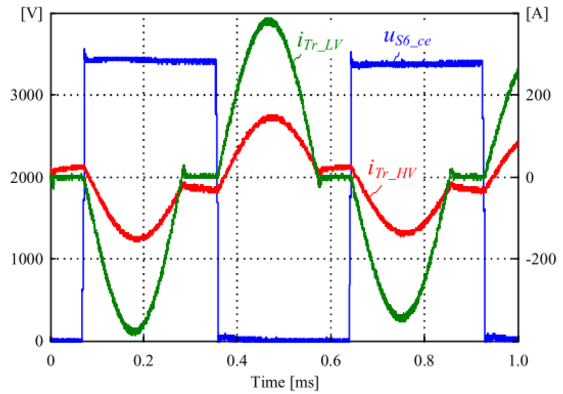
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

Take Note!

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

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





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

- Cascaded H-Bridges – 9 Cells
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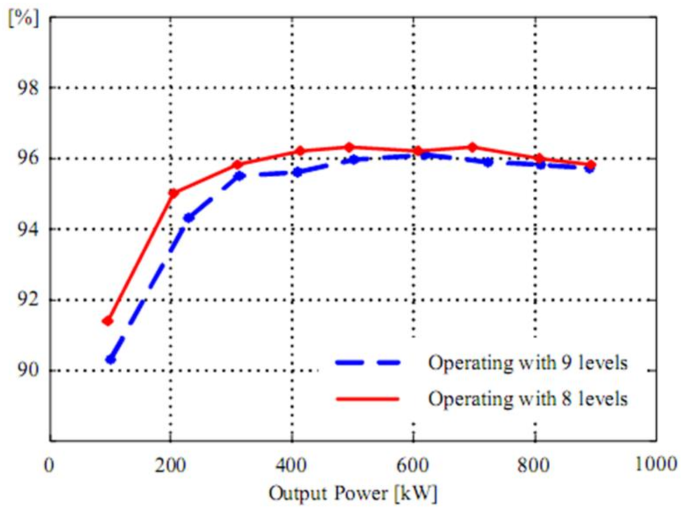
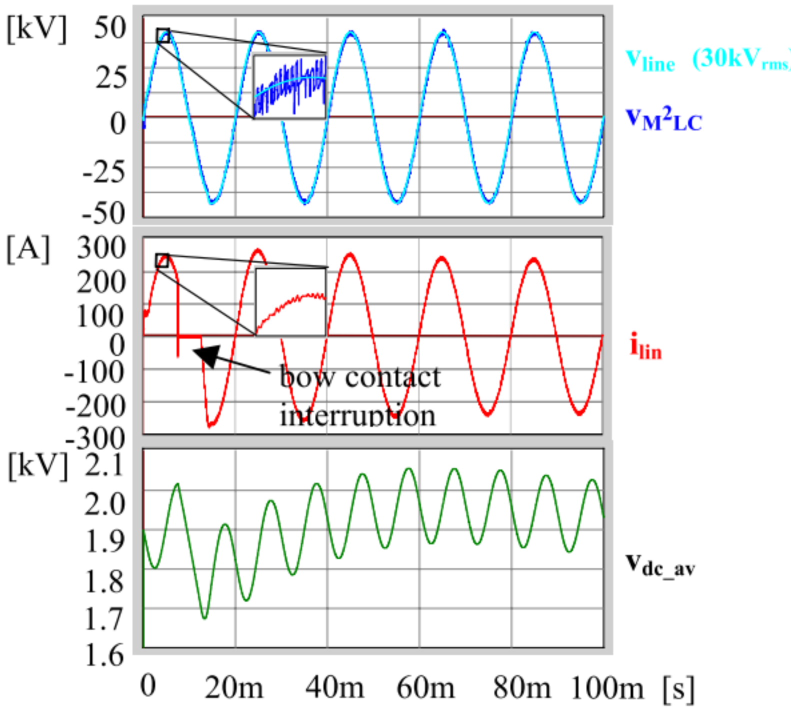
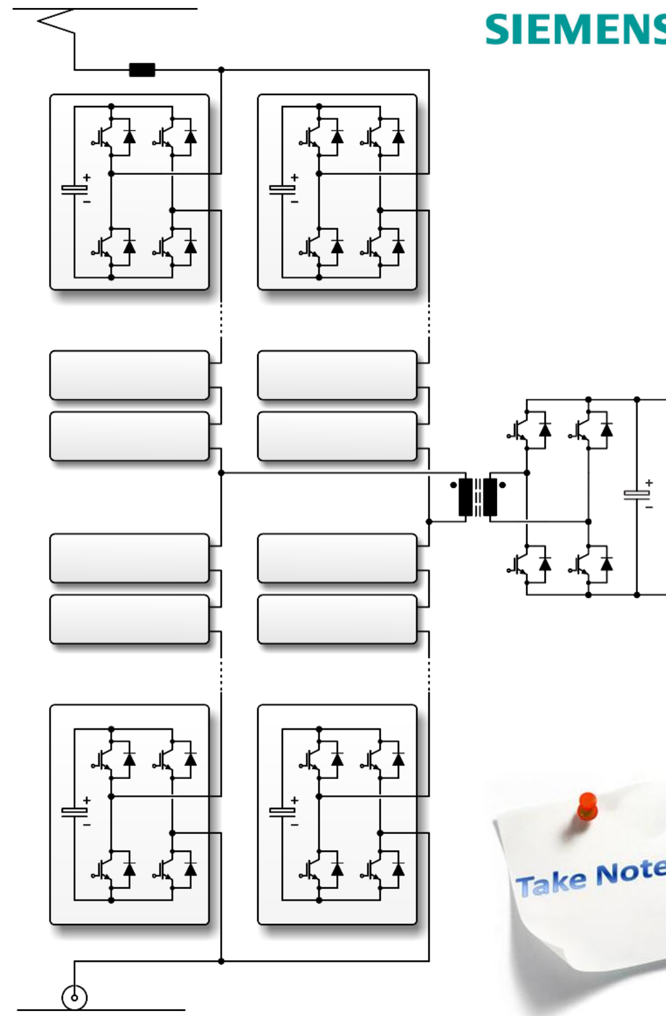
Efficiency



▶ Modular Multilevel Converter

- Marquardt (2003)



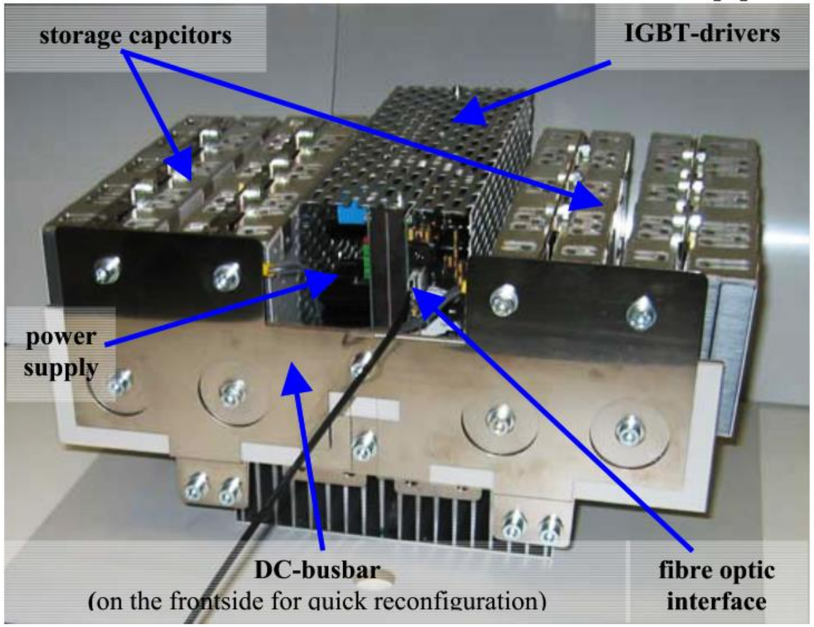


SIEMENS

Modular Multilevel Converter

- Marquardt (2003)

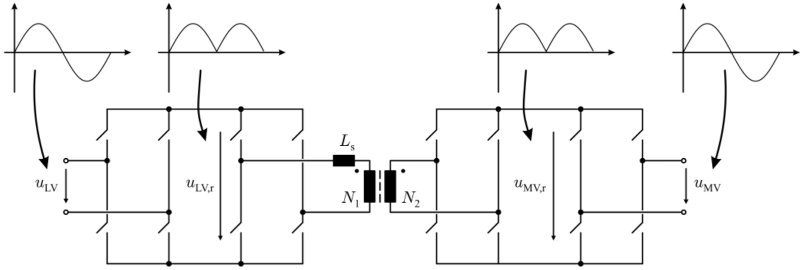
- Module Power 270kW
- Module Frequency 350Hz

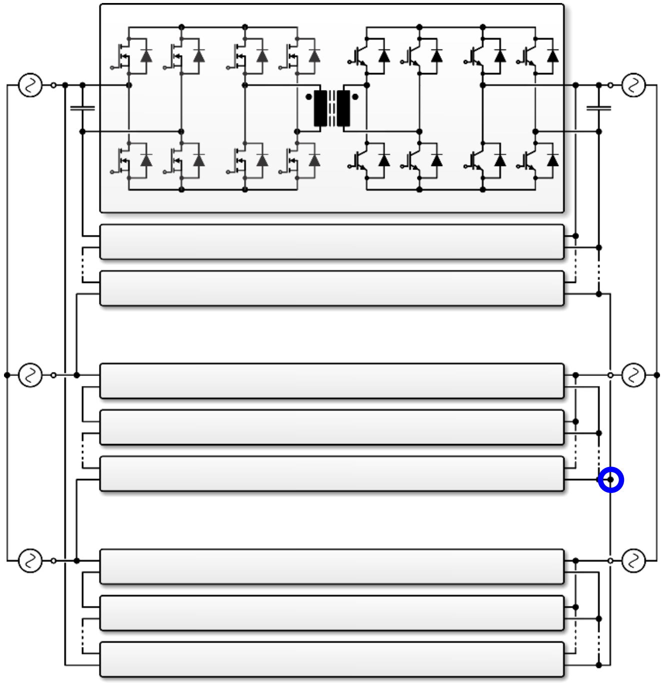


► SiC-Enabled Solid-State Power Substation

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

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





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

► SiC-Enabled Solid-State Power Substation

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- Fully Phase Modular System
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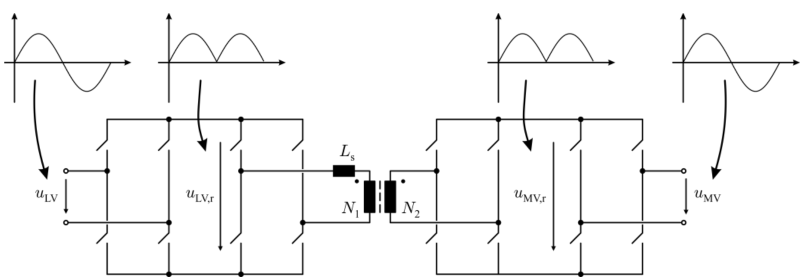
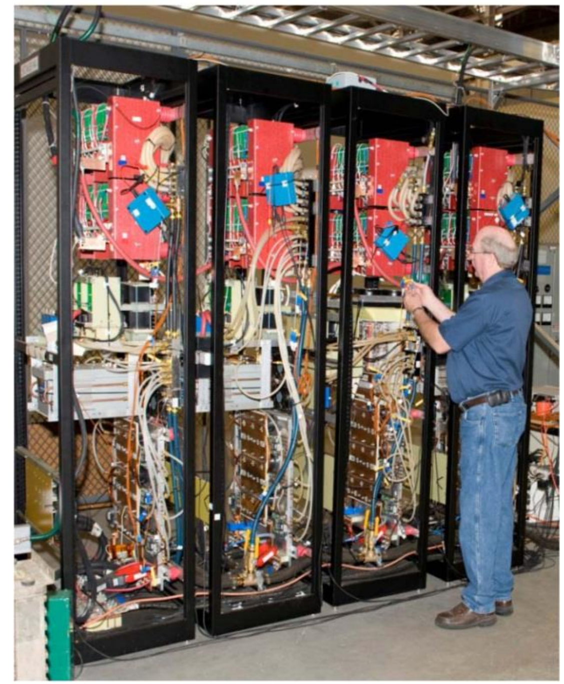
- LV Y-Connection (465V/√3, Modules in Parallel)



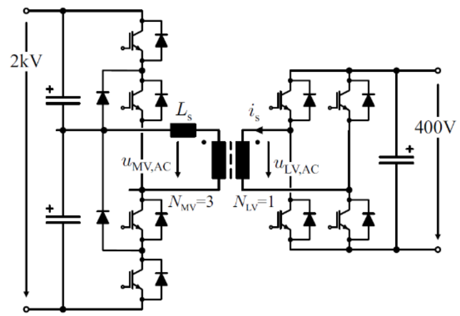


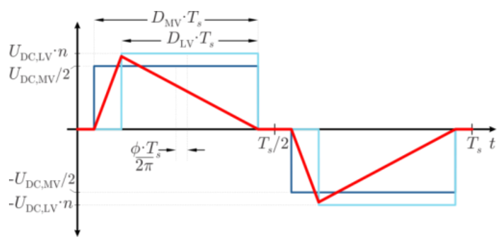
- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency / 25% Weight / 50% Volume Reduction (Comp. to 60Hz)

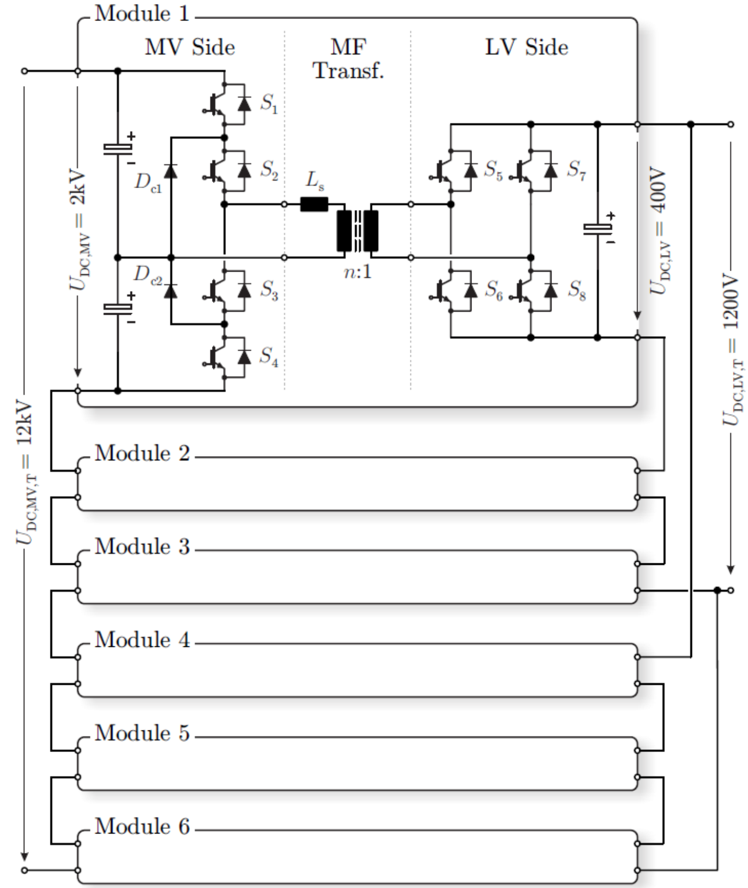
▶ MEGA Cube

- Rated Power 1MW
- Frequency 20kHz
- Input Voltage $12kV_{DC}$
- Output Voltage $1.2kV_{DC}$

- Efficiency Goal 97%





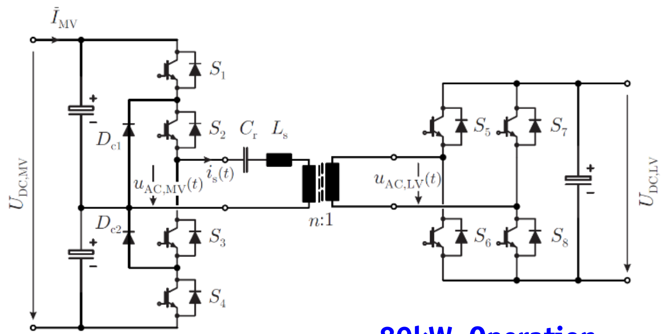


■ ISOP Topology – 6/2x3 - Input / Output

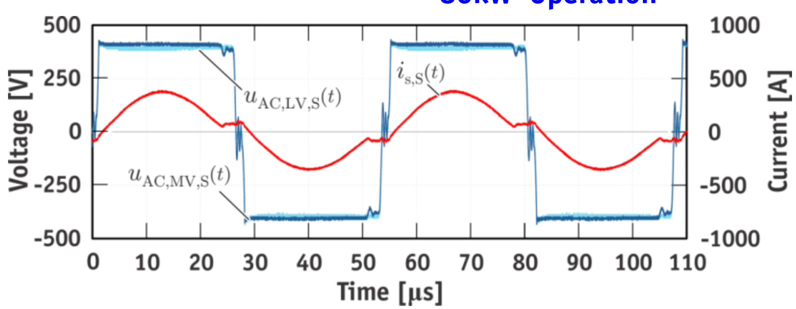
▶ 166kW / 20kHz DC-DC Converter Cell

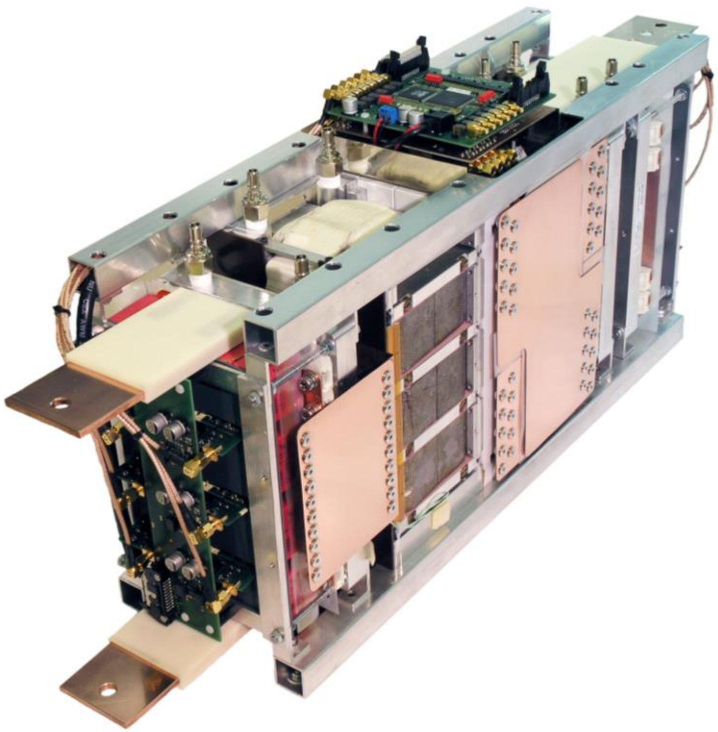
- **Half-Cycle DCM Series Resonant DC-DC Converter**

- **Medium-Voltage Side** 2kV
- **Low-Voltage Side** 400V



80kW Operation

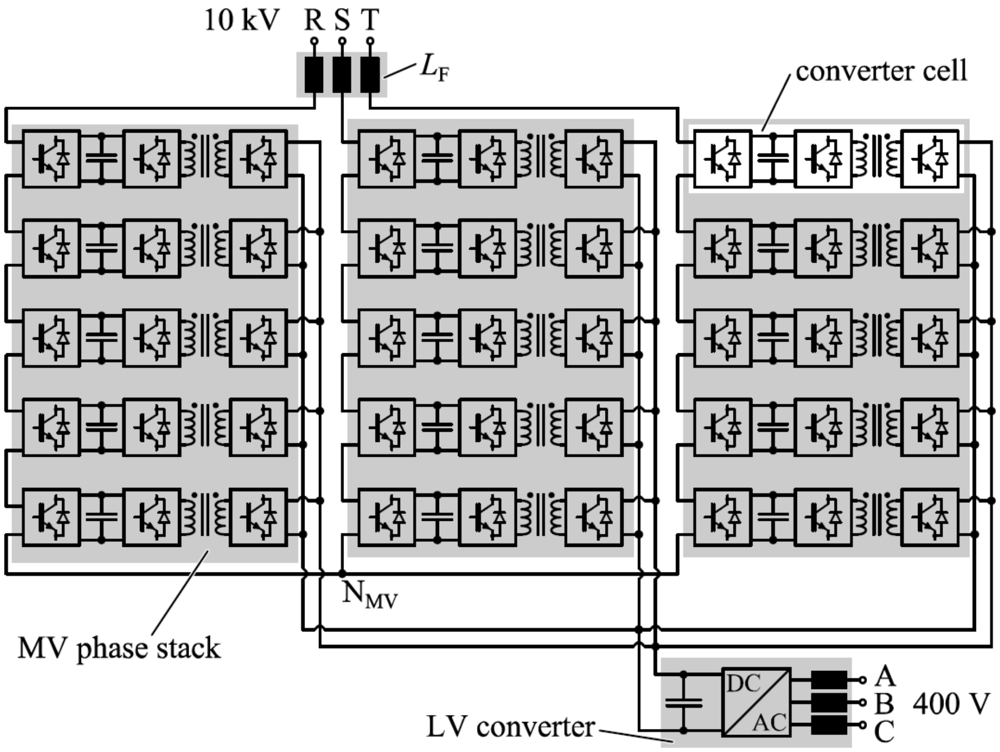




MEGA Link

▶ MEGALink @ ETH Zurich

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

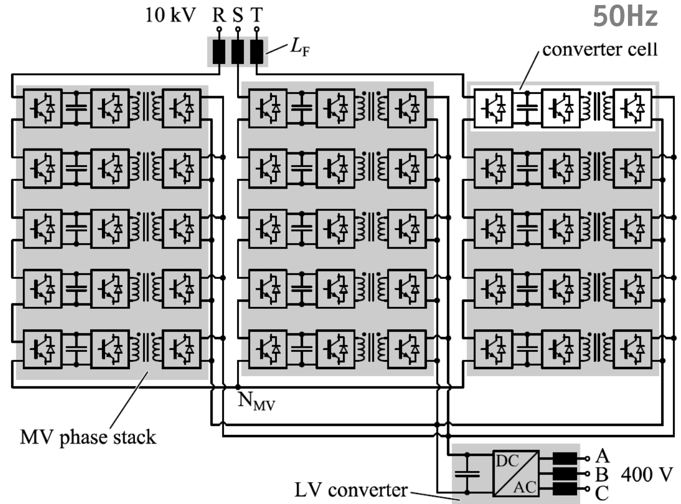


- 2-Level Inverter on LV Side / HC-DCM-SRC DC-DC Conversion / Cascaded H-Bridge MV Structure

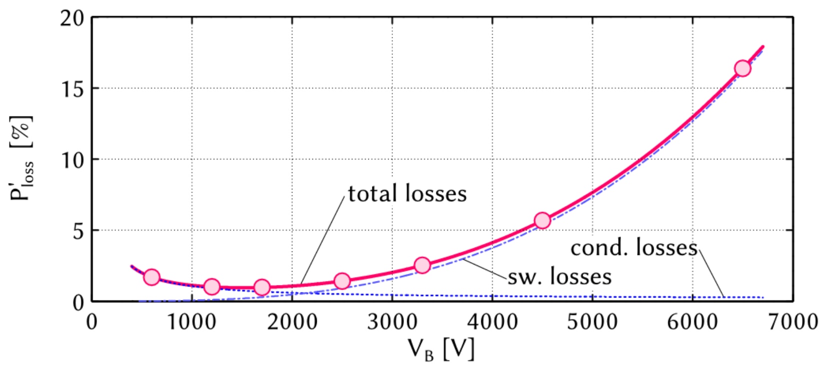
▶ Optimum Number of Converter Cells

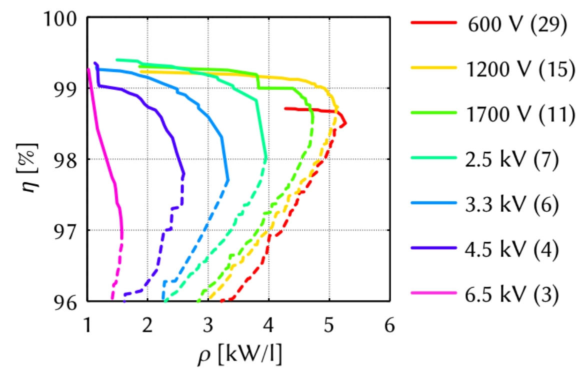
- Trade-Off High Number of Levels → High Conduction Losses/ Low Cell Switchg Frequ./Losses (also because of Device Char.)

1 MVA
10kV → 400V
50Hz



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



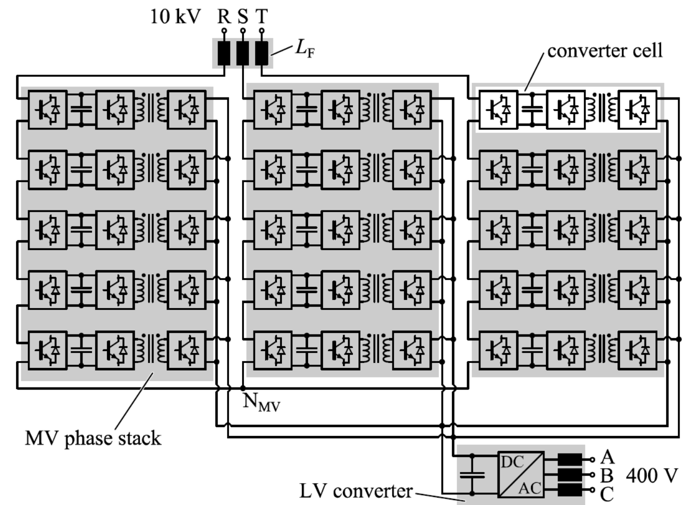


- 1200V ... 1700V Power Semiconductors best suited for 10kV Mains (No Advantage of SiC)

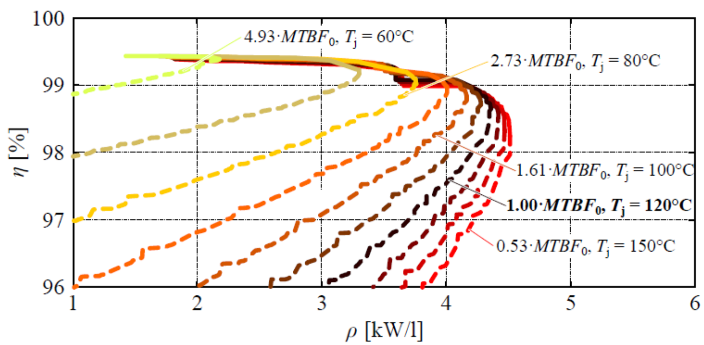
▶ Optimum Number of Converter Cells

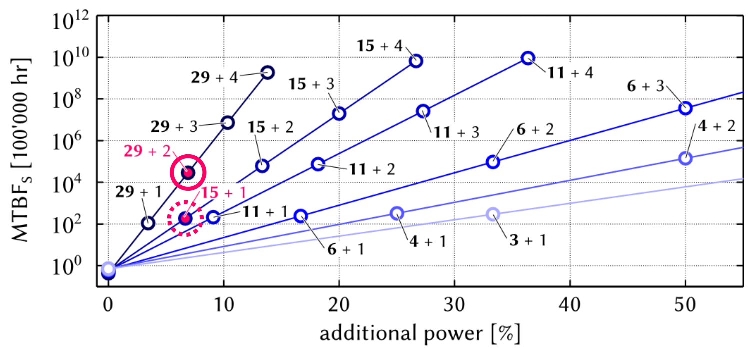
■ Trade-Off → Mean-Time-to-Failure vs. Efficiency / Power Density

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



No Redundancy
1700V IGBTs, 60% Utilized





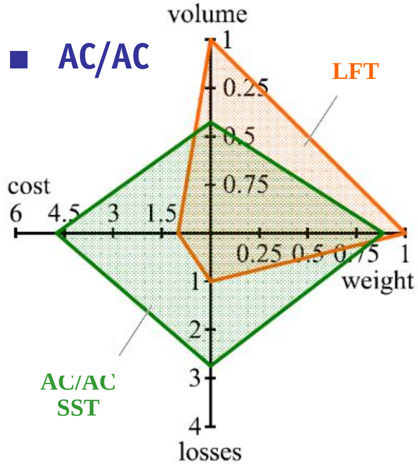
■ High MTBF also for Large Number of Cells (Repairable) / Lower Total Spare Cell Power Rating

► SST vs. LF Transformer + AC/AC or AC/DC Converter

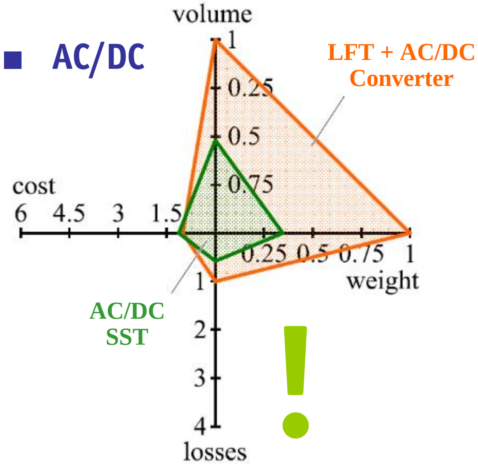
- **Specifications** 1MVA
  10kV Input
  400V Output
  1700V IGBTs (1kHz/8kHz/4kHz)

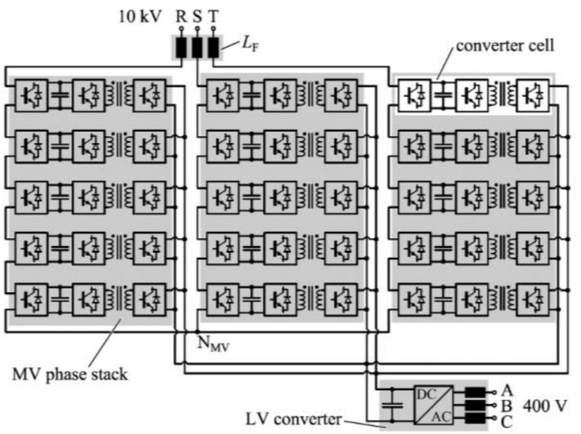
- **LF Transformer** 98.7 %
  16.2 kUSD
  2600kg (5700lb)

■ AC/AC



■ AC/DC

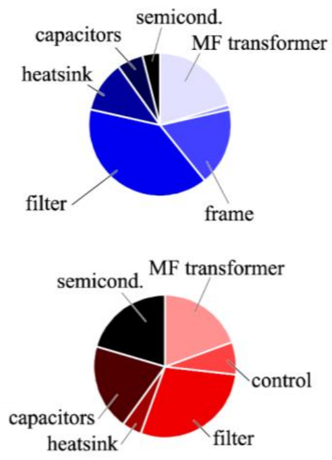


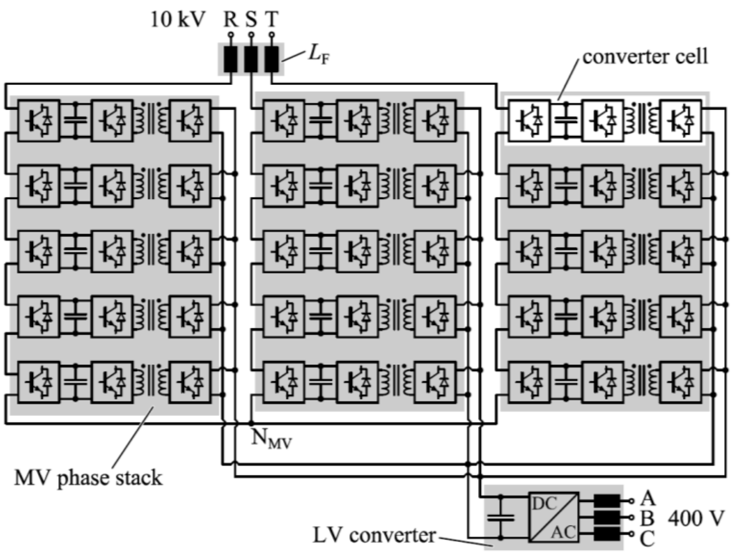


■ Clear Efficiency/Volume/Weight Advantage of SST for DC Output (98.2%)
■ Weakness of AC/AC SST vs. Simple LF Transformer (98.7%) - 5 x Costs, 2.5 x Losses

Efficiency Advantage of Direct MV AC – LV DC Conversion

- Comparison to LF Transformer & Series Connected PFC Rectifier (1MVA)
  - MV AC/DC Stage Weight (Top) and Costs (Bottom) Breakdown





CHARACTERISTIC PERFORMANCE INDICES FOR 1000 kVA LFTS AND SSTS IN AC/AC OR AC/DC APPLICATIONS.

	AC/AC LFT	AC/AC factor	AC/AC SST	AC/DC LFT	AC/DC factor	AC/DC SST
losses [W/kVA]	13.0	×2.75	35.7	30.9	×0.58	17.9
costs [USD/kVA]	16.2	×4.75	77.0	43.9	×1.12	49.3
volume [l/kVA]	3.43	×0.57	1.96	3.64	×0.48	1.75
weight [kg/kVA]	2.59	×0.89	2.30	3.63	×0.35	1.26

PERFORMANCE CHARACTERISTICS OVERVIEW.

	SST MV	SST LV	SST	LFT
efficiency	98.2 %	98.2 %	96.5 %	98.7 %
volume	1.751 m^3	0.211 m^3	1.962 m^3	3.427 m^3
weight	1262 kg	1036 kg	2298 kg	2591 kg
cost	49.3 kUSD	27.7 kUSD	77.0 kUSD	16 kUSD

Potential Future
SST Application Areas

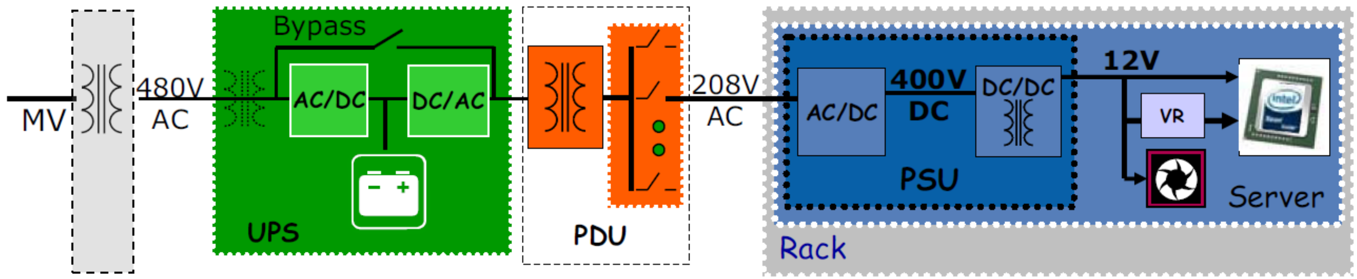
Datacenters
Oil and Gas Industry
Power-to-Gas
Distributed Propulsion Aircraft
More Electric Ships

▶ AC vs. Facility-Level DC Systems for Datacenters

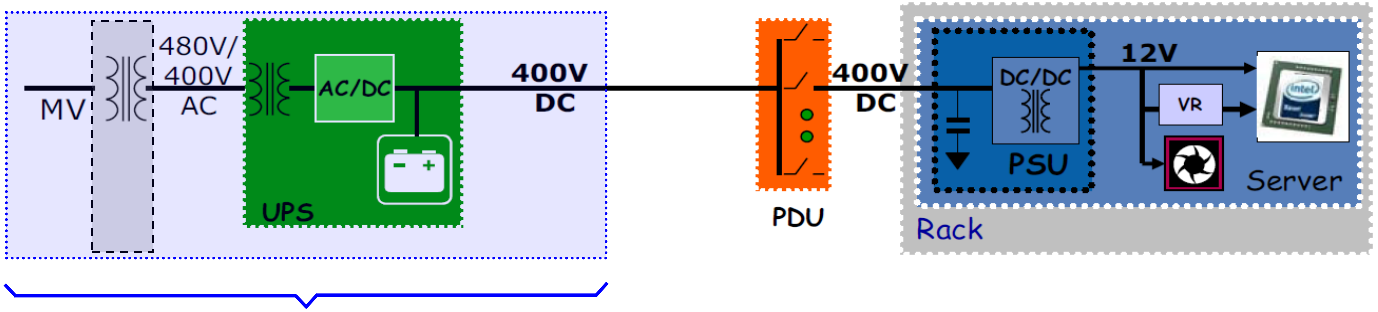
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US 480V_{AC} Distribution

Source: intel 2007



— Facility-Level 400 V_{DC} Distribution



- Future Concept: Unidirectional SST / Direct 6.6kV AC → 400V DC Conversion

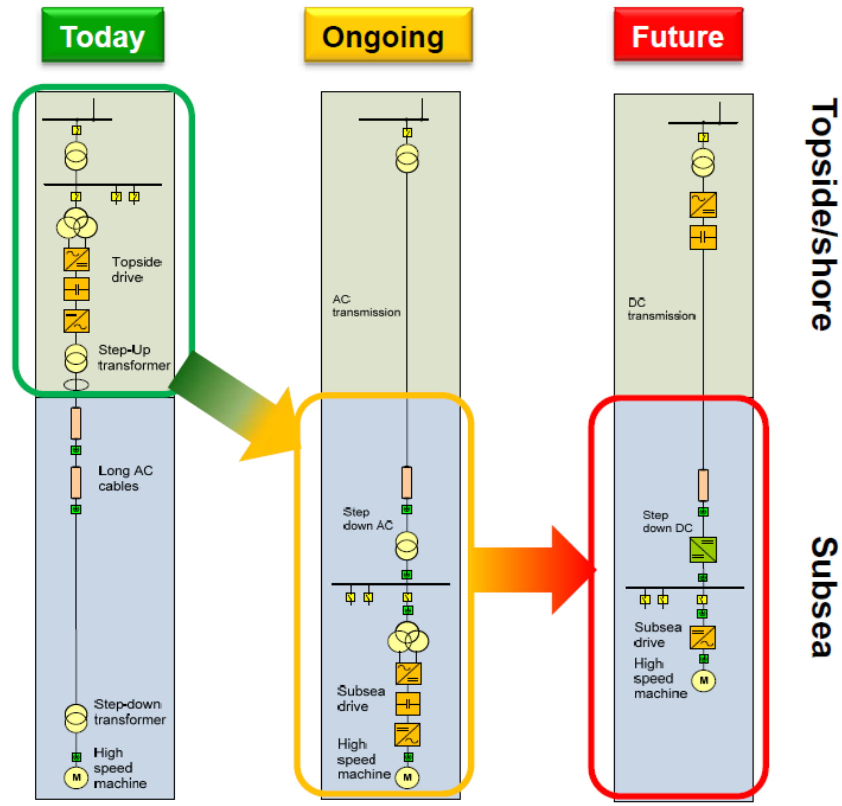
▶ Future Subsea Distribution Network – O&G Processing

- Devold (ABB 2012)

Today		Future

O&G processing		
Platform/floaters based	→	Subsea
Power supply		
Platform based power generation or power from shore	→	Long distance power from shore

ABB investing in subsea electrification & automation solutions to enable future subsea processing



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

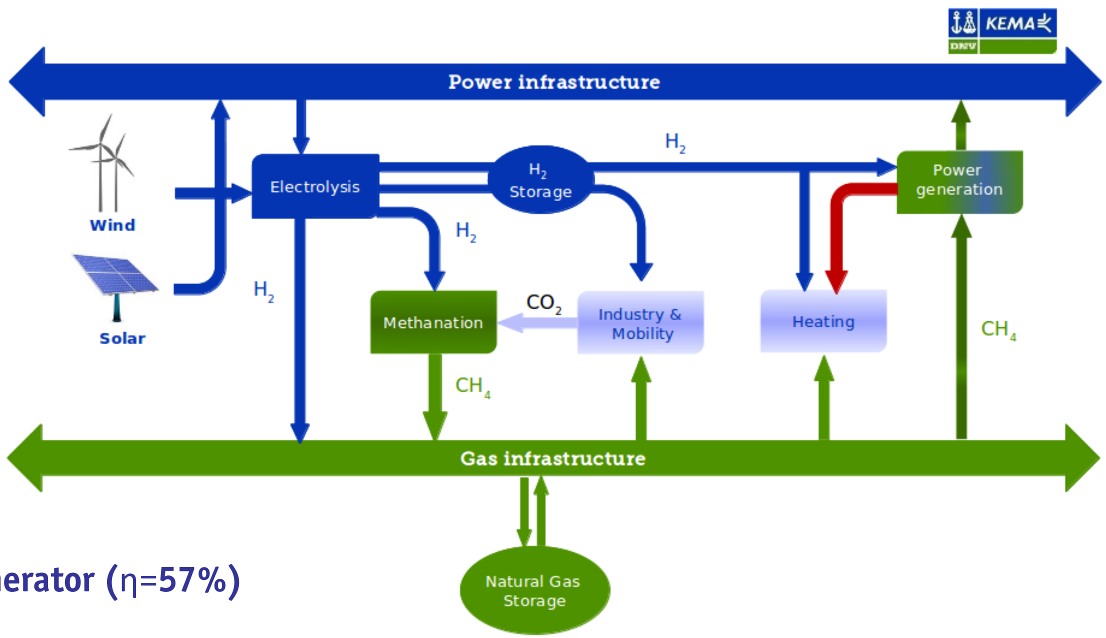
- Weight Optimized Power Electronics

► Power-to-Gas

- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen
  → Fuel-Cell Powered Cars
  → Heating

- High-Power @ Low DC Voltage (e.g. 220V)
- Very Well Suited for MV-Connected SST-Based Power Supply

– Hydrogenics 100 kW H_2-Generator (η=57%)



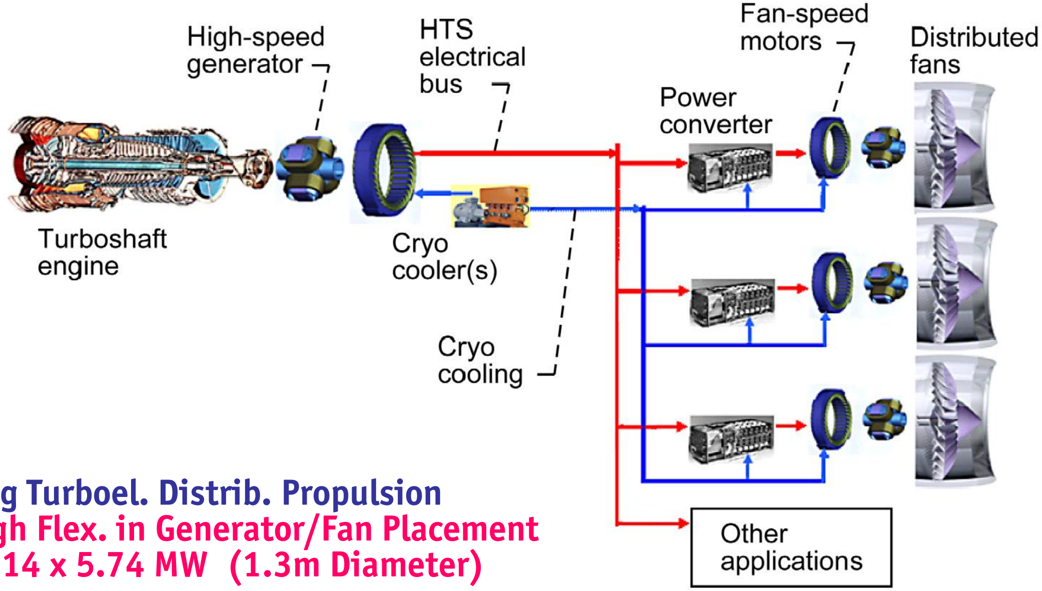
► Future Hybrid Distributed Propulsion Aircraft

Source: EADS

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- Until 2050: Cut CO_2 Emissions by 75%, NO_x by 90%, Noise Level by 65%

▶ Future Distributed Propulsion Aircraft

Source: NASA

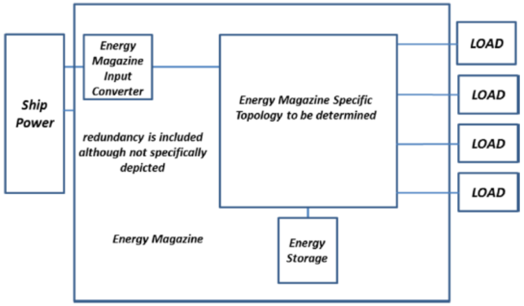


- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

Future Military Applications

- MV Cellular DC Power Distribution on Future Combat Ships etc.

Source:
General Dynamics

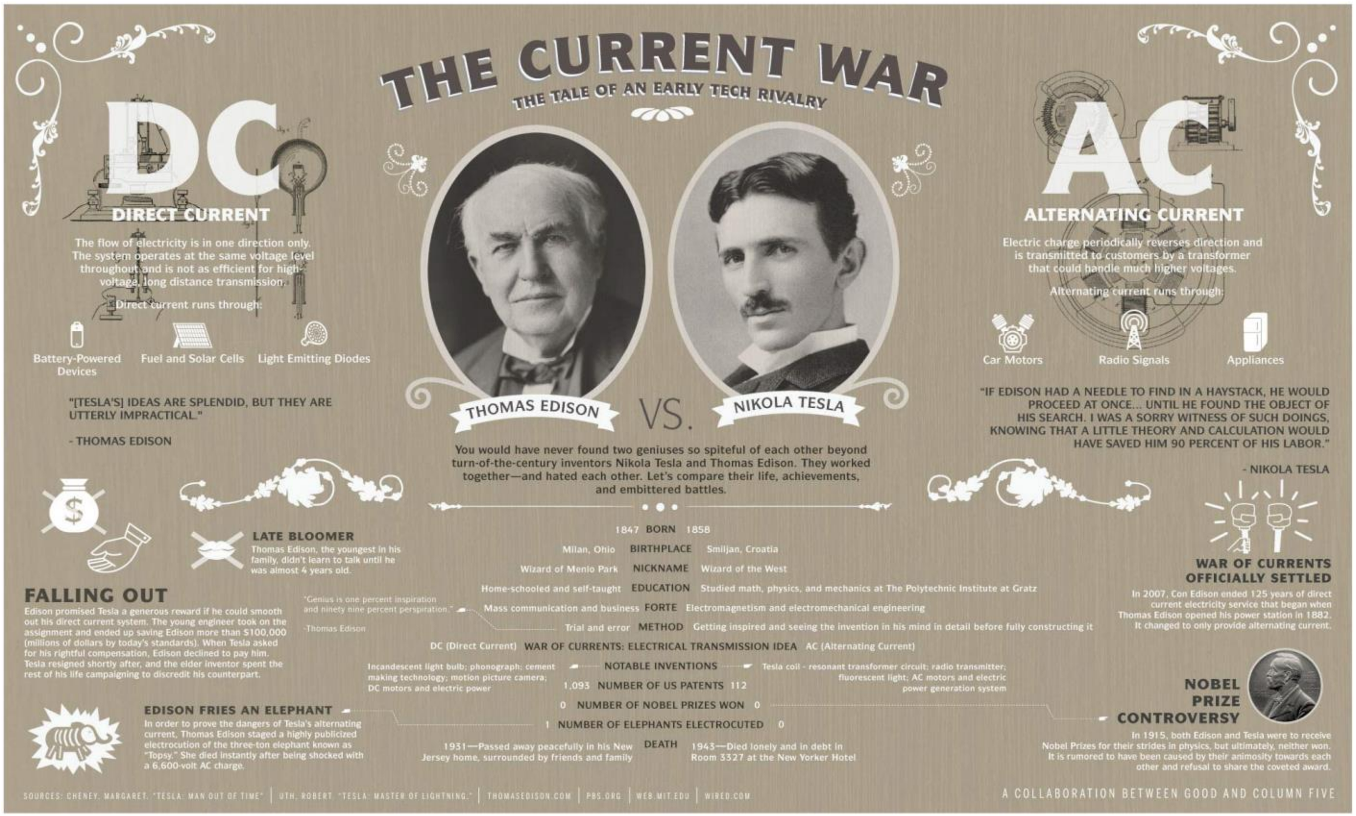


- "Energy Magazine" as Extension of Electric Power System / Individual Load Power Conditioning
- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements

Conclusions

SST Limitations / Concepts
Research Areas

► SST Ends the "War of Currents"



- No "Revenge" of T.A. Edison but Future "Synergy" of AC and DC Systems !

▶ Key Messages #1/3

■ **Basis SST Limitations**

— Efficiency (Rel. High Losses of 2-4%)
— High Costs (Cost-Performance Adv. still to be Clarified)
— Limited Weight/ Volume Reduction vs. Conv. Transf. (Factor 2-3)
— Limited Overload Capability
— Limited Overvoltage Tolerance
— (Reliability)

■ **Potential Application Areas**

▶ MV Grid/Load-Connected AC/DC and DC/DC Converter Systems
▶ Volume/Weight Limited Systems where 2-4 % of Losses Could be Tolerated

— Traction Vehicles

— MV Distribution Grid Interface
  * DC Microgrids (e.g. Datacenters)
  * Renewable Energy (e.g. DC Collecting Grid for PV, Wind; Power-to-Gas)
  * High Power Battery Charging (E-Mobility)
  * More Electric Ships
  * etc.

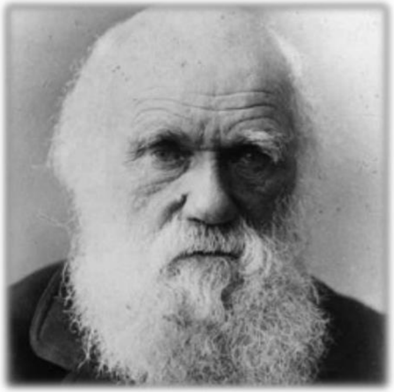
— Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
— Temporary Replacement of Conv. Distribution Transformer
— Military Applications

▶ Key Messages #2/3

■ Advantageous Circuit Approaches

▶ **Fully Modular Concepts**

— Resonant Isolated Back-End Topology (ABB)
— Resonant Isolated Front-End Topology (Swiss-SST)



"It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is the most adaptable to change."

Charles Darwin

* Redundancy (!)
* Scalability (Voltage / Power)
* Natural Voltage / Current Balancing
* Economy of Scale

▶ **Alternatives**

— Single Transformer Solutions (MMLC-Based)
— HV-SiC Based Solutions (SiC NPC-MV-Interface)

► Key Messages #3/3

■ Main Research Challenges

— Multi-Level vs. Two-Level Topologies with HV SiC Switches
— Low-Inductance MV Power Semiconductor Package
— Mixed-Frequ./Voltage Stress on Insul. Materials
— Low-Loss High-Current MF Interconnections / Terminals
— Thermal Mangmnt (Air and H_2O Cooling, avoiding Oil)
— SST Protection
— SST Monitoring
— SST Redundancy (Power & (!) Control Circuit)
— SST vs. FACTS (Flexible AC Transmission Systems)
— System-Oriented Analysis → Clarify System-Level Benefits (Balancing the Low Eff. Drawback)

■ SST Design for Production → Multi-Disciplinary Challeng

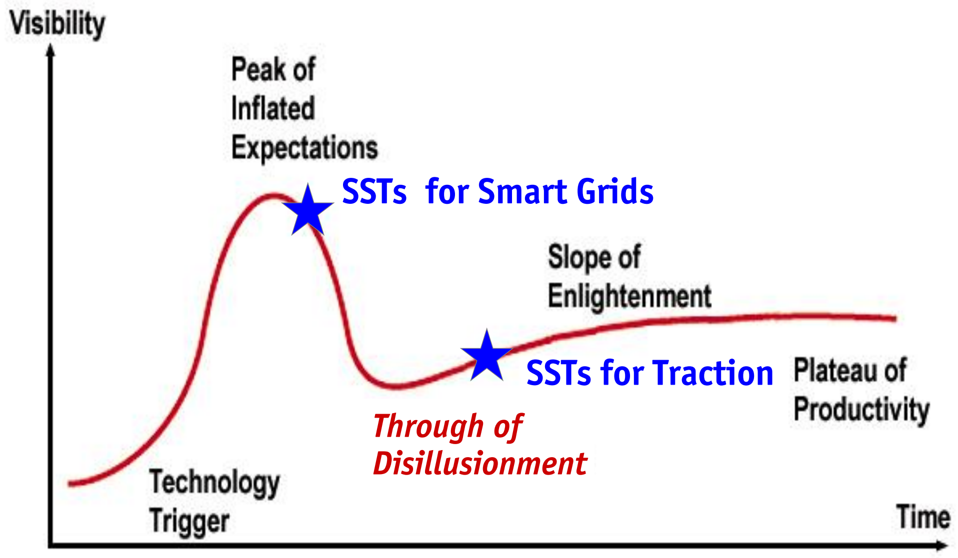
► Required Competences

— MV (High) Power Electronics incl. Testing
— Digital Signal Processing (DSP & FPGA)
— MF High Power Magnetics
— Isolation Coordination / Materials
— Power Systems
— etc.

► 50/60Hz XFRM Design Knowledge is NOT (!) Sufficient

▶ SST Technology Hype Cycle

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



Thank You!

Questions