ETH zürich

SGRE 2019

Solid-State-Transformer (SST) Applications - A Glimpse Into the Future

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Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Nov. 19, 2019

ETH Zurich

21	Nobel Prizes
530	Professors
6100	T&R Staff
2	Campuses
136	Labs
35%	Int. Students
90	Nationalities
36	Languages
150th	Anniv. in 2005

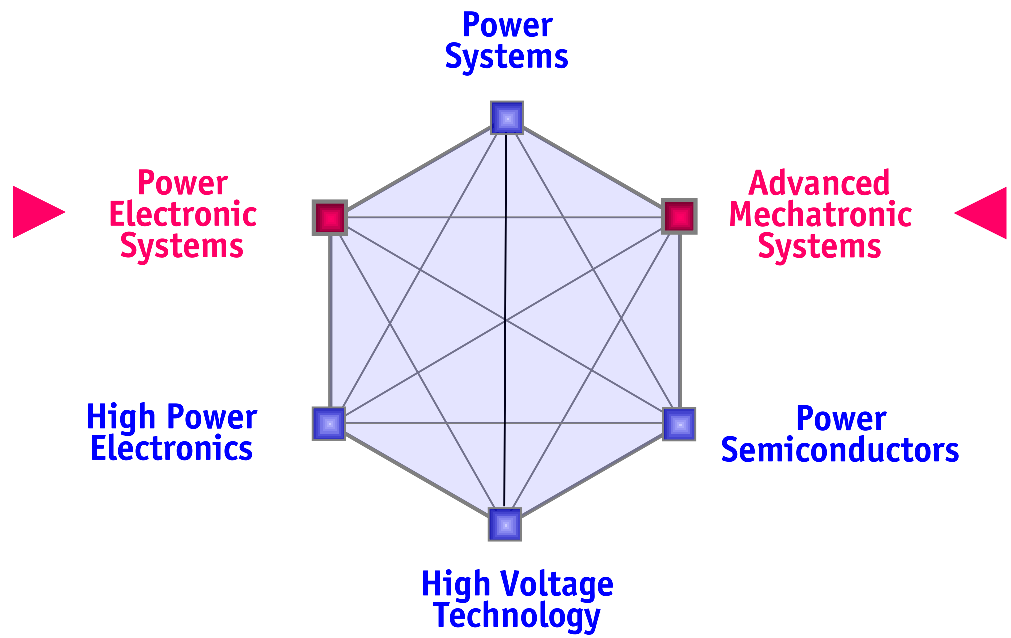
Departments

ARCH	Architecture
BAUG	Civil, Environmental and Geomatics Eng.
BIOL	Biology
BSSE	Biosystems
CHAB	Chemistry and Applied Biosciences
ERDW	Earth Sciences
GESS	Humanities, Social and Political Sciences
HEST	Health Sciences, Technology
INFK	Computer Science
ITET	Information Technology and Electrical Eng.
MATH	Mathematics
MATL	Materials Science
MAVT	Mechanical and Process Engineering
MTEC	Management, Technology and Economy
PHYS	Physics
USYS	Environmental Systems Sciences

Students ETH in total

21'000	B.Sc.+M.Sc.-Students
4'300	Doctoral Students

ITET – Research in E-Energy



Systems

Technologies

- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Measurement Technology	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	**D. Bortis**	**F. Krismer**		**D. Bortis**	**D. Bortis**
M. Heller Y. Li D. Menzi D. Neumayr D. Zhang	J. Azurza P. Czyz M. Haider	P. Bezerra T. Guillod G. Knabben J. Schäfer	M. Antivachis J. Böhler M. Guacci	P. Papamanolis	P. Niklaus	E. Hubmann R. Giuffrida	Th. Holenstein P. Püntener S. Miric

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

22 Ph.D. Students
1 PostDoc
2 Sen. Researchers

ECPE Competence Centre

EPSMA

Leading Univ. in Europe

SGRE

Outline

- SST Origins
  - Traction
  - Smart Grids
- Key Characteristics
- *MEGATRENDS* → Future SST Application Areas
  - Datacenter
  - Smart Cities / Buildings
  - High Power EV Charging
  - More Electric/Hybrid Aircraft
  - More Electric/Hybrid Ships
  - Renewable Energy – Wind / Solar
  - Deep Sea Exploration etc.
- Key Topologies
- Industry / ETH Demonstrators
- Conclusions

Acknowledgement: P. Czyz
T. Guillod
J. Huber
G. Ortiz
D. Rothmund

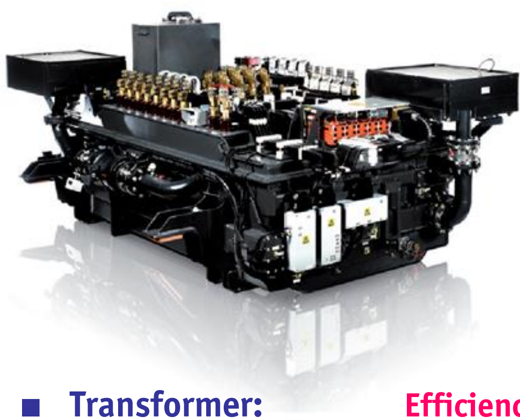
SST Origins

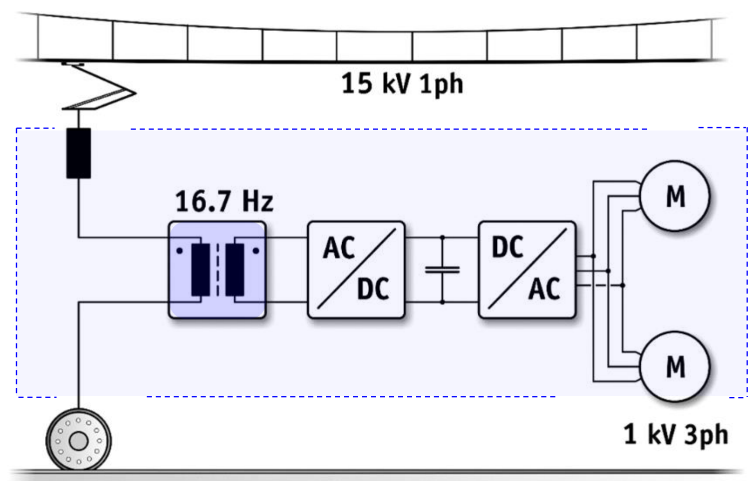
Next Generation
Traction Vehicles

▶ Classical Locomotives

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

Source: www.abb.com





■ Transformer:

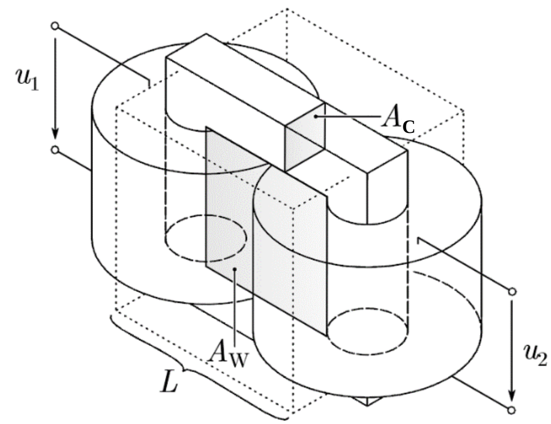
Efficiency	90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
Power Density	2...4 kg/kVA (0.5...0.25 kVA/kg)

Passive Transformer

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

$$A_{Core} A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{rms} \hat{B}_{max} f} \sim L^4$$

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

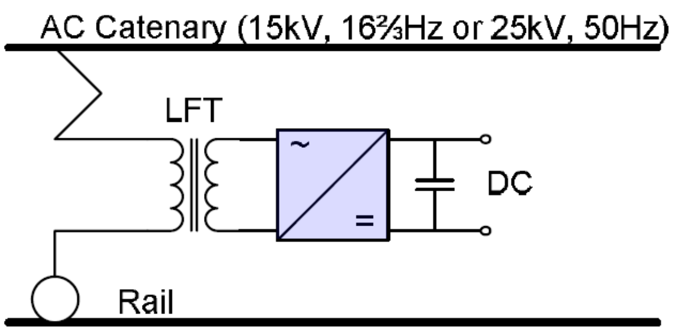


- Low Frequency → Large Weight / Volume
- Trade-off → Volume vs. Efficiency

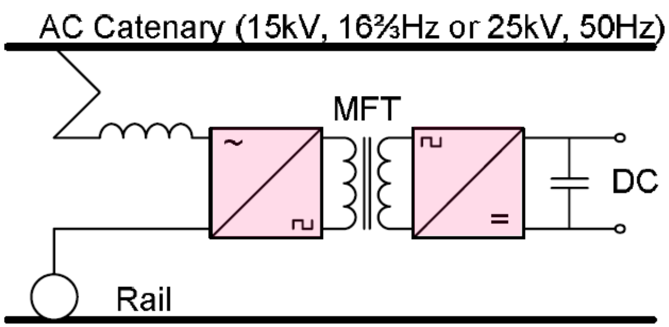
→ Next Generation Locomotives (1)

- **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).

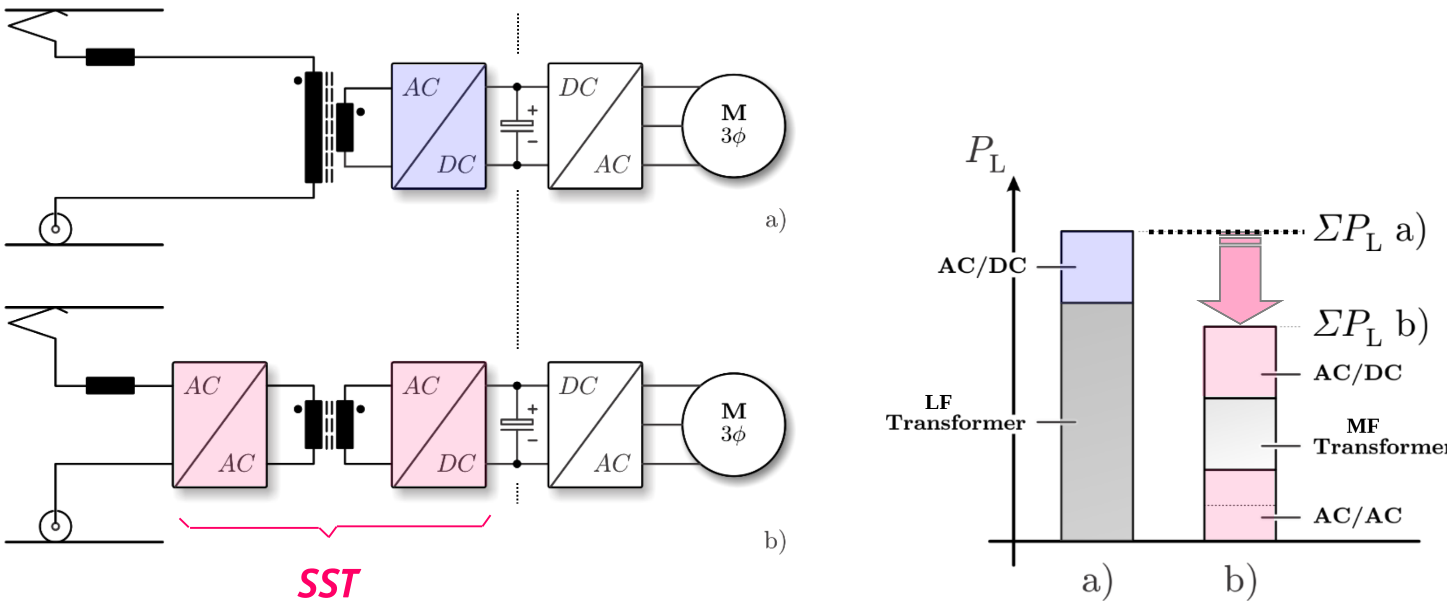


AC-DC conversion with medium frequency transformer (MFT).

- Replace LF Transformer with *MF Transformer & Power Electronics Interface* → *SST*
- Medium-Frequency Allows *Reduction* of *Volume* & *Losses*

→ Next Generation Locomotives (2)

■ Loss Distribution of Conventional & Next Generation Locomotives



- *MF Provides Degree of Freedom → Reduction of Volume & Losses (!)*

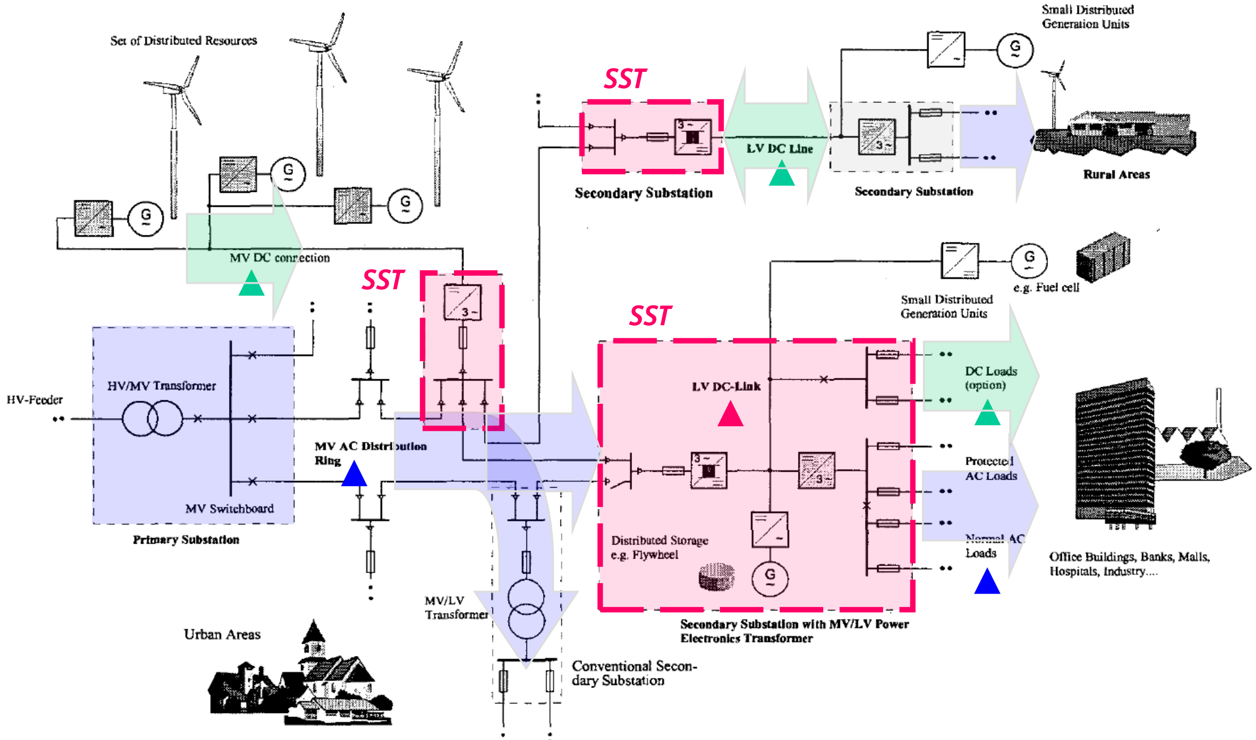
SST Motivation

Future Smart EE Distribution

Source: TU Munich

► Advanced (High Power Quality) Grid Concept

- Heinemann / ABB (2001)



- MV AC Distribution with DC Subsystems (LV and MV) and Distributed AC & DC Sources /Loads
- 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.

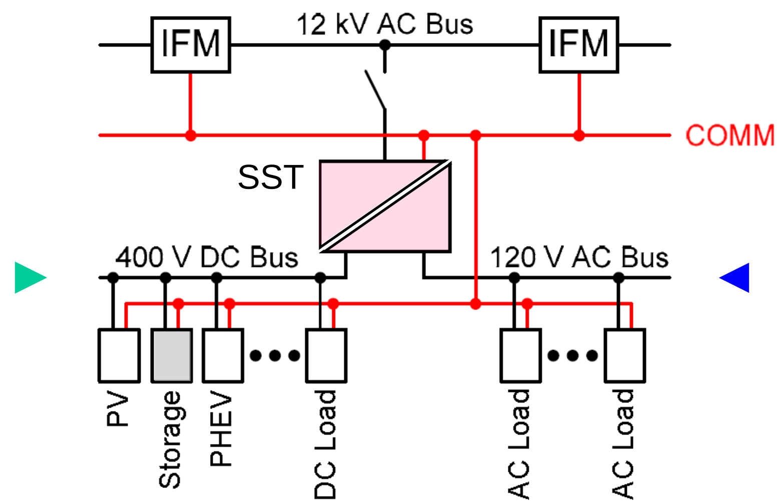
- Huang et al. (2008)

- SST as Enabling Technology for the "Energy Internet"

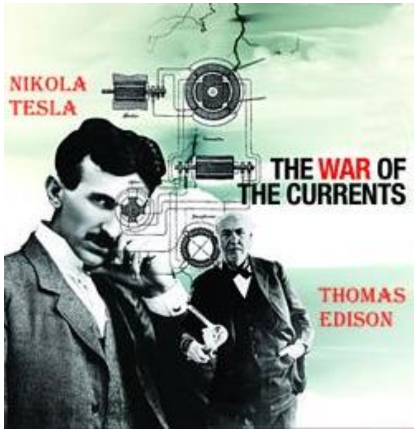
- Full Control of the Power Flow
- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Protects Power Syst. From Load Disturbances
- Protects Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.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

FREEDM systems center

IFM = Intellig. Fault Management



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



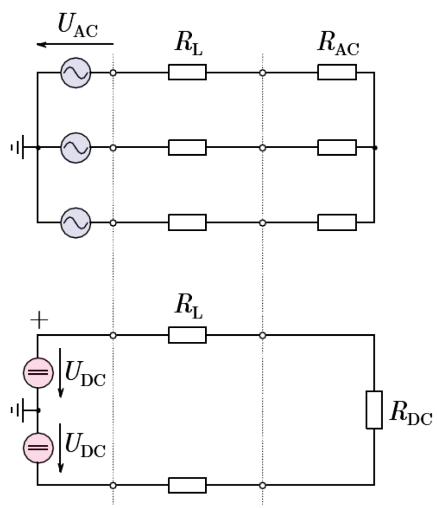
Source: www.yacht-chartercroatia.com

▶ 3-Φ AC vs. DC Power Systems

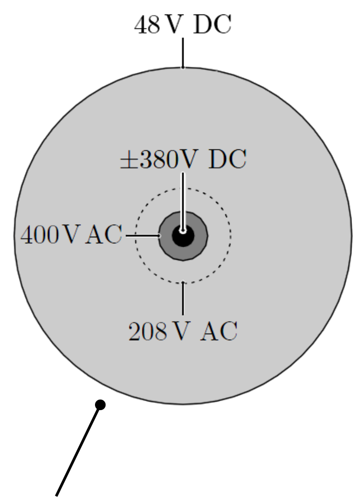
- DC Voltage Ensures Max. Utiliz. of Isol. Voltage → Highest Voltage RMS Value / Lowest Current (!)
- Quadratic Dependency of Losses on Voltage Level → Reduction of Conductor Cross Section

$$P_{V,AC} = 3 \cdot \left(\frac{\frac{1}{3}P}{U_{AC}}\right)^2 \cdot R_L$$

$$P_{V,DC} = 2 \cdot \left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L$$



$$\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2} \cdot \left(\frac{U_{AC}}{U_{DC}}\right)^2 \Bigg|_{U_{DC}=\sqrt{2}\,U_{AC}} = 0.75$$

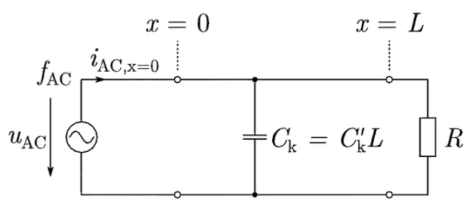


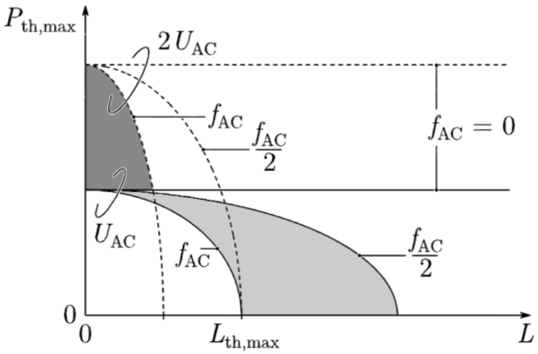
Conductor Cross Sections for Same Losses

- DC Voltage Level Transformation Requires Power Electronics Interfaces
- DC Fault Current Clearing is Challenging (Missing Regular Current Zero Crossing)

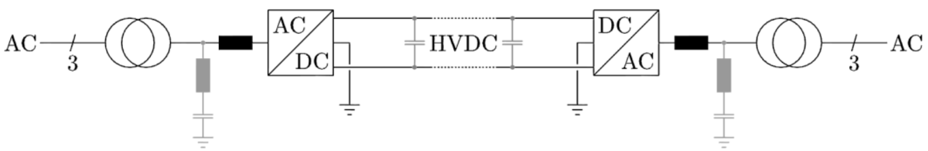
▶ AC vs. DC Power Transmission

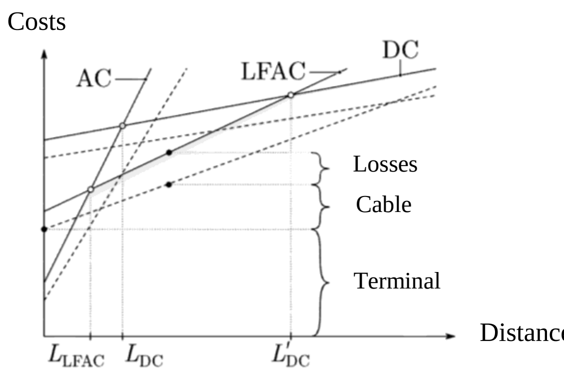
■ AC Cable – Thermal Limit Due to Cap. Current @ L = 0





■ HVDC Transmission – Advantageous for Long Distances

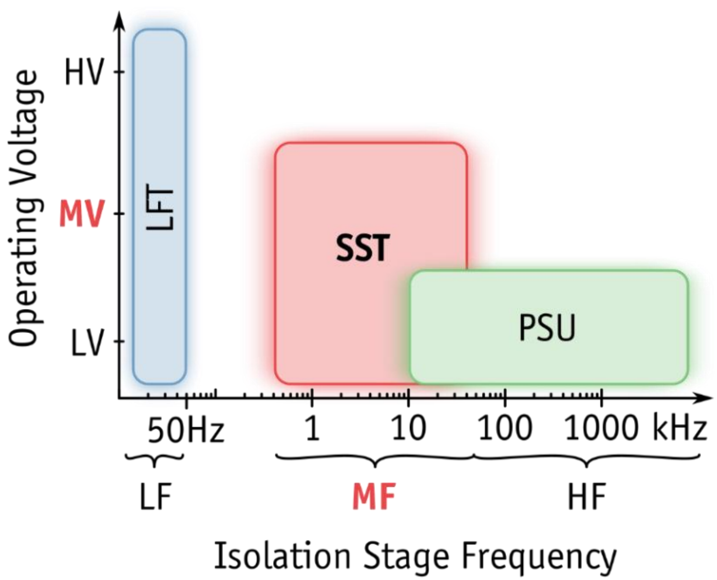


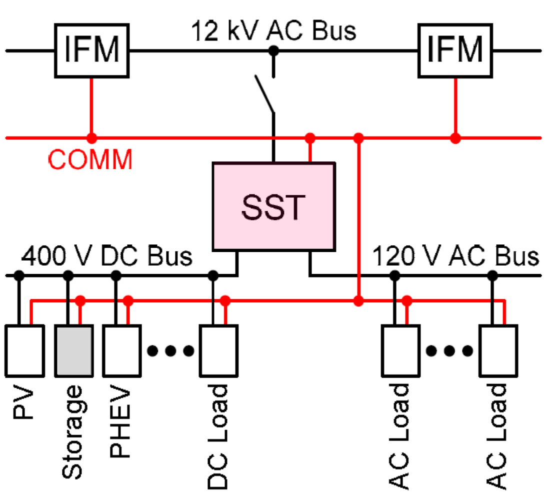


■ Low-Frequency AC (LFAC) as Possible (Purely Passive) Solution for Medium Transmission Distances

► SST Key Characteristics

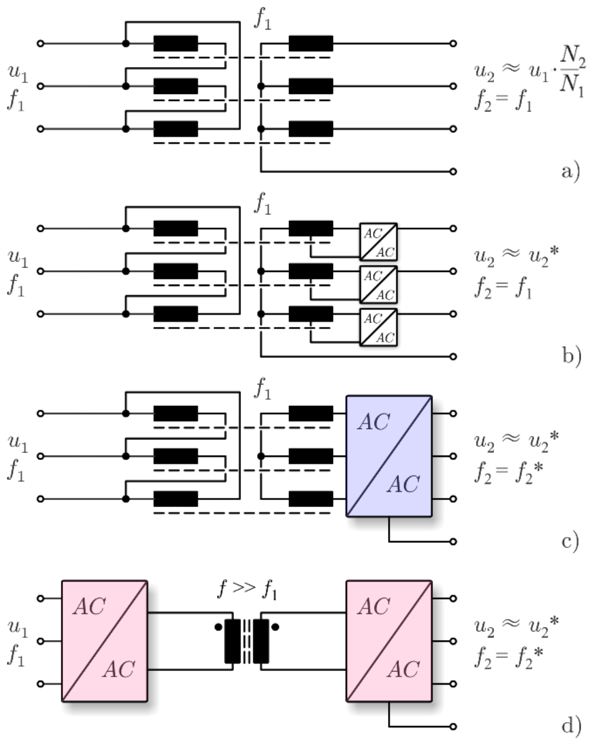
McMurray — Electronic Transformer (1968)
Brooks — Solid-State Transformer (SST, 1980)
EPRI — Intelligent Universal Transformer (IUT™)
ABB — Power Electronics Transformer (PET)
Wang — Energy Router
etc.





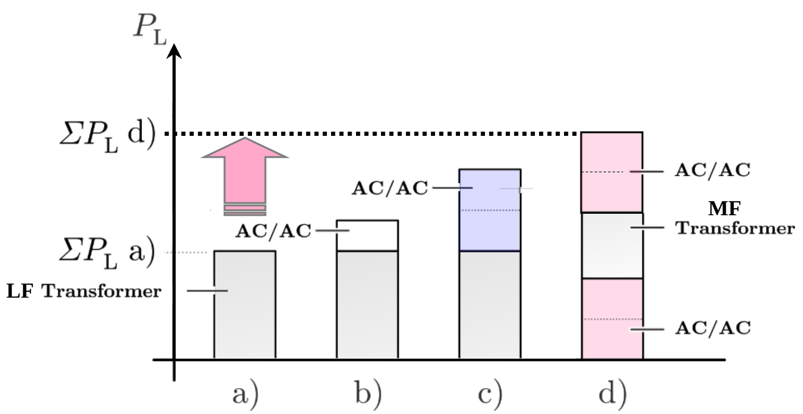
- Interface to Medium-Voltage / Medium-Frequency Isolation / AC or DC Input and/or Output

Remark Trade–Off - Controllability vs. Efficiency



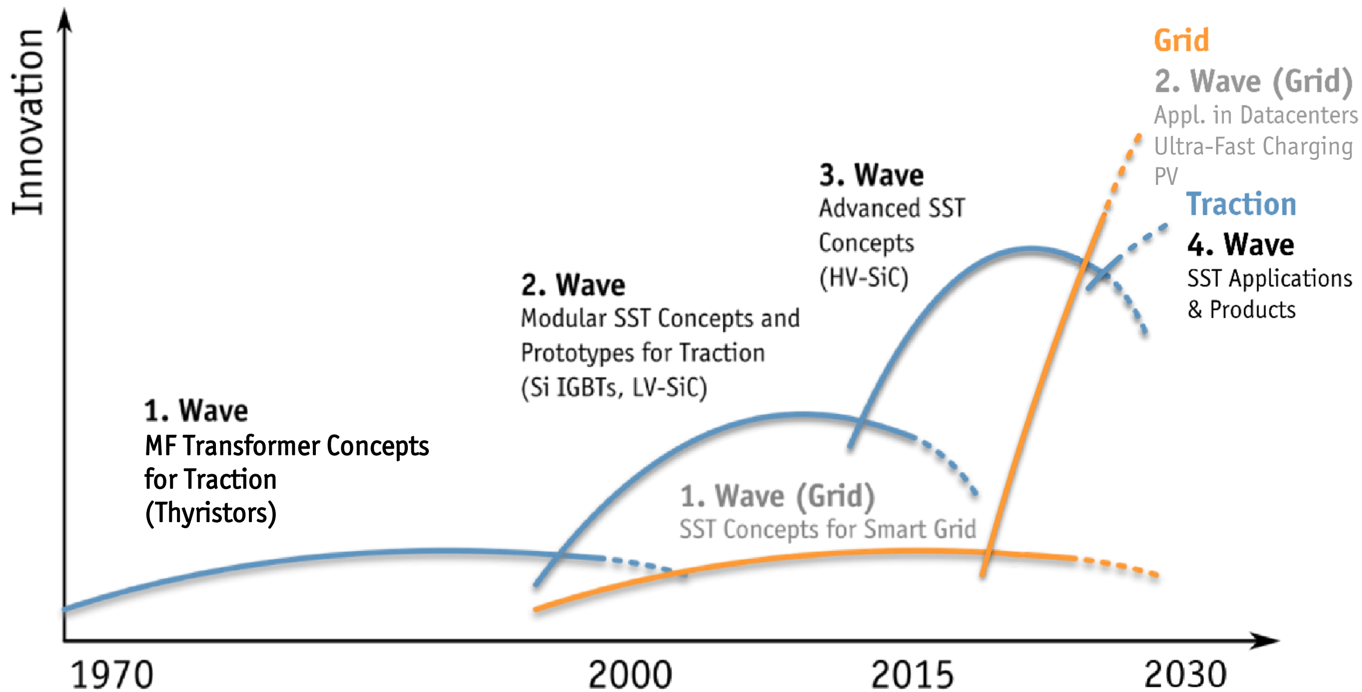
LF Isolation
Purely Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

MF Isolation
Active Input & Output Stage (d)



- Lower Efficiency of SST Compared to “Grid-Type” Passive Transformer
- Medium Freq. → Higher Transf. Efficiency only Partly Compensates Converter Stage Losses

SST Development Cycles



- **Development Cycles Reaching Over Decades – Matched to "Product" Life Cycle**

Global Megatrends

Digitalization
Urbanization
Sustainable Mobility
Renewable Energy
Etc.

Global Megatrends

Digitalization →
Urbanization
Sustainable Mobility
Renewable Energy
Etc.

▶ Deep Green / Zero CARBON Datacenters

— Ranging from Medium Voltage to Power-Supplies-on-Chip
— Short Power Supply Innovation Cycles
— Modularity / Scalability

— Higher Availability
— Higher Efficiency
— Higher Power Density
— Lower Costs

Server-Farms
up to **450 MW**
99.9999%/<30s/a
$1.0 Mio./Shutdown

Since 2006
Running Costs >
Initial Costs

Source: REUTERS/Sigtryggur Ari

33 Watts

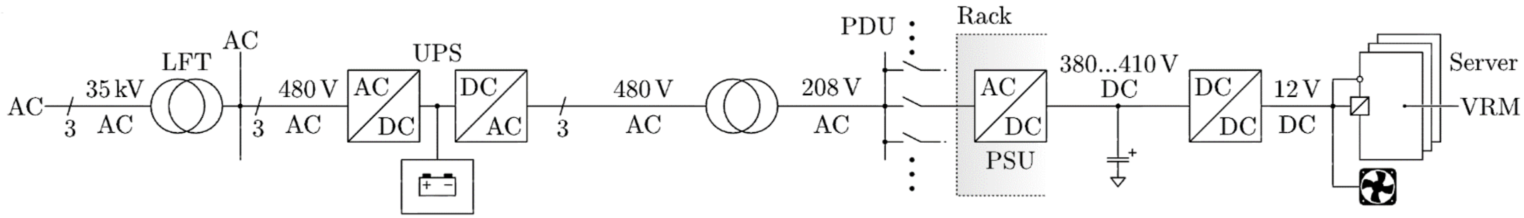
→

60 Watts

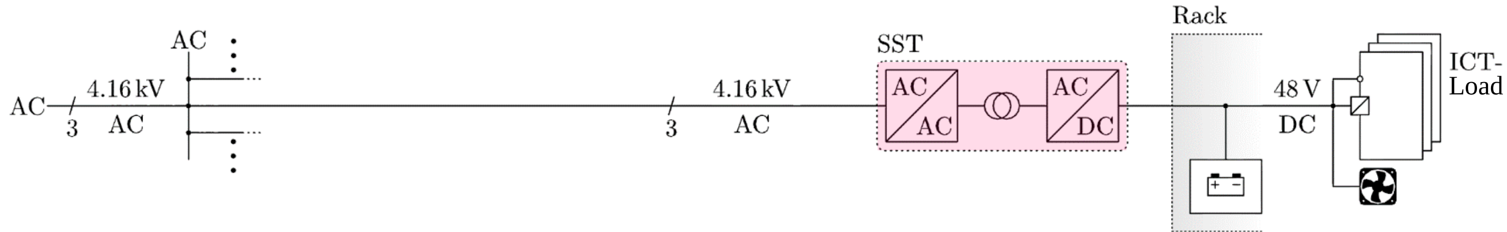
→ Future *Modular* SST-Based Power Distribution

- 5...7% Reduction in Losses & Smaller Footprint
- Improves Reliability & Power Quality

— Conventional



— Direct 3-Φ 6.6kV AC → 48V DC Conversion / Unidirectional SST



- *MV → 48V → 1.2V - Only 2 Conversion Stages from MV to CPU-Level (!)*

Global Megatrends

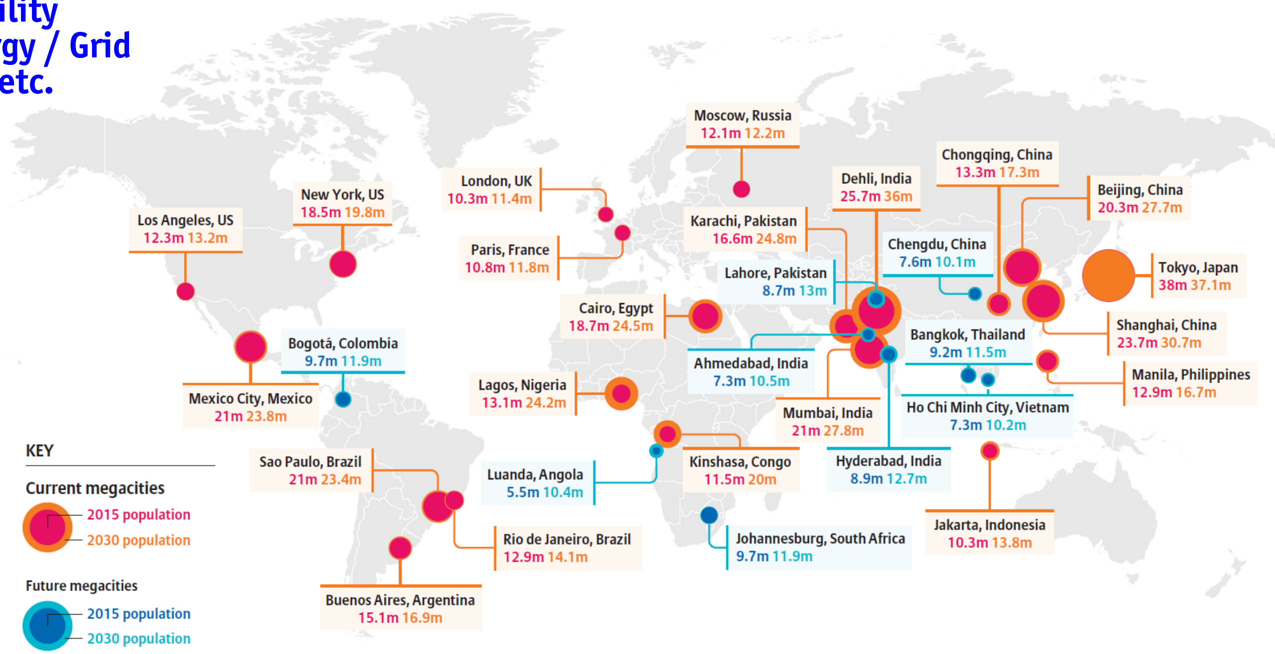
Digitalization
Urbanization →
Sustainable Mobility
Renewable Energy
Etc.

▶ Urbanization

- 60% of World Population Exp. to Live in Urban Cities by 2025
- 30 MEGA Cities Globally by 2023

— Smart Buildings
— Smart Mobility
— Smart Energy / Grid
— Smart ICT, etc.

Source: World Urbanization Prospects: The 2014 Revision



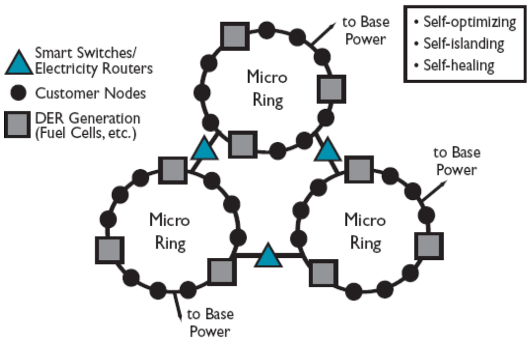
▶ *Selected Current & Future MEGA Cities 2015 → 2030*

→ Smart Cities / Grids / Buildings (1)

— *Masdar = "Source"*
— **Fully Sustainable Energy Generation**
  * Zero CO_2
  * Zero Waste
— **EV Transport / IPT Charging**
— **to be finished 2025**

Masdar CITY
www.masdar.ae

Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

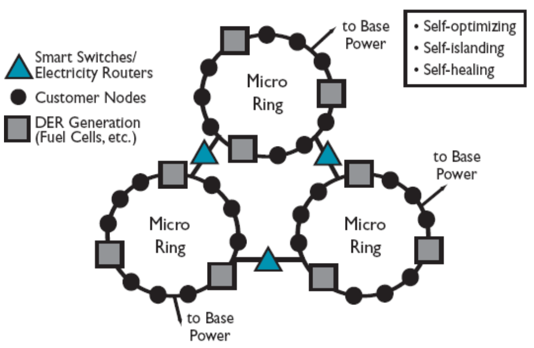


→ Smart Cities / Grids / Buildings (2)

— *Masdar = "Source"*
— Fully Sustainable Energy Generation
  * Zero CO_2
  * Zero Waste
— EV Transport / IPT Charging
— to be finished 2025

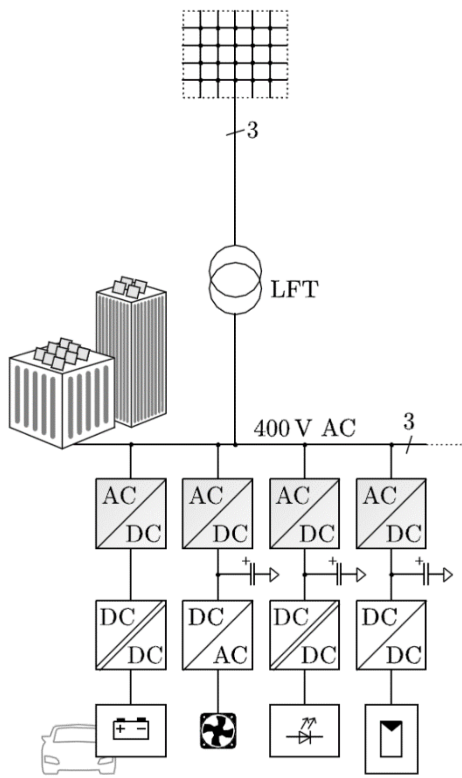
Masdar CITY
www.masdar.ae

Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

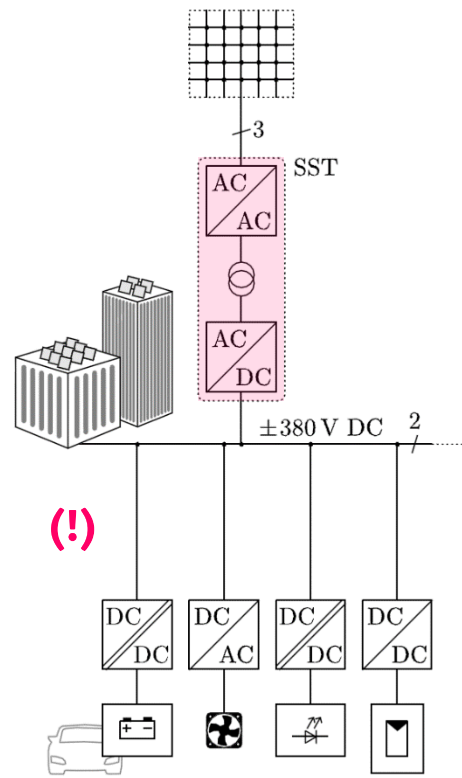


→ DC Microgrids

- Local DC Microgrid Integrating Loads/Ren. Sources/Storage
- No Low-Voltage AC/DC Conversion → Higher Efficiency & Lower Realization Effort



— Conventional



— *Future SST-Based Concept*

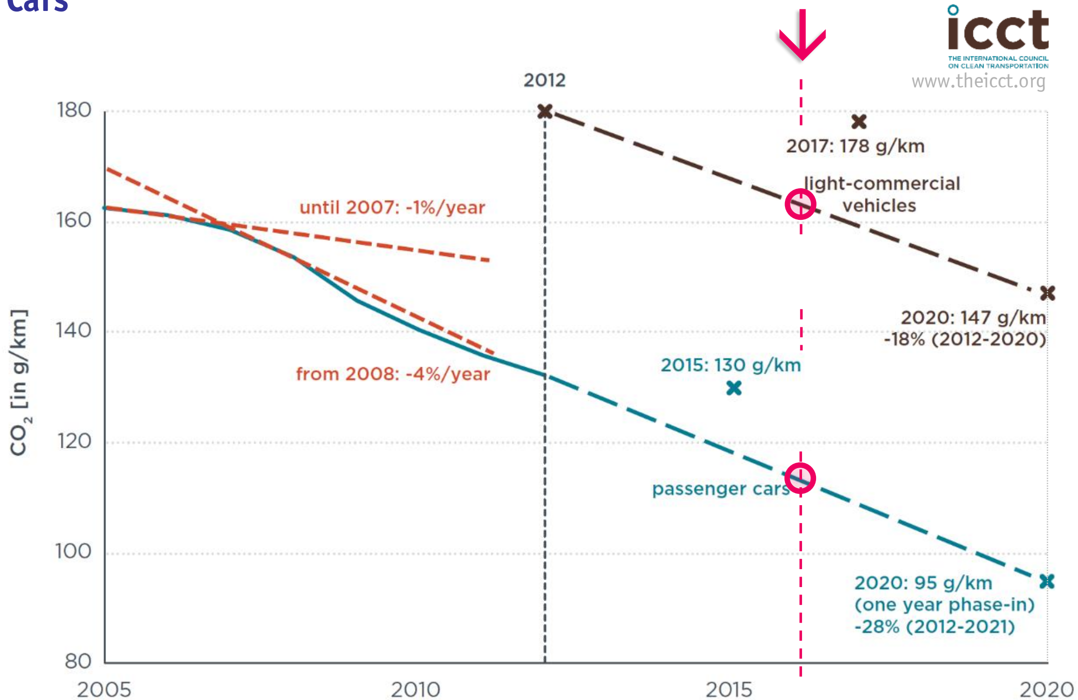
Global Megatrends

Digitalization
Urbanization
Sustainable Mobility →
Renewable Energy
Etc.

▶ Sustainable Mobility

■ **EU Mandatory 2020 CO_2 Emission Targets for New Cars**

— 147g CO_2/km for Light-Commercial Vehicles
— 95g CO_2/km for Passenger Cars
— 100% Compliance in 2021



▶ Hybrid Vehicles
▶ Electric Vehicles

→ *Ultra-Fast / High-Power EV Charging*

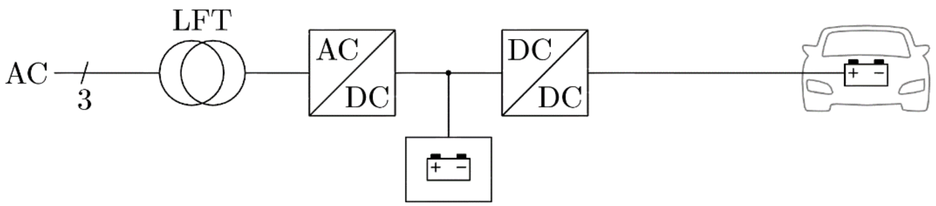
- *Medium Voltage Connected* Modular Charging Systems
- Very Wide Output Voltage Range (200...800V)

Source: Porsche Mission-E Project

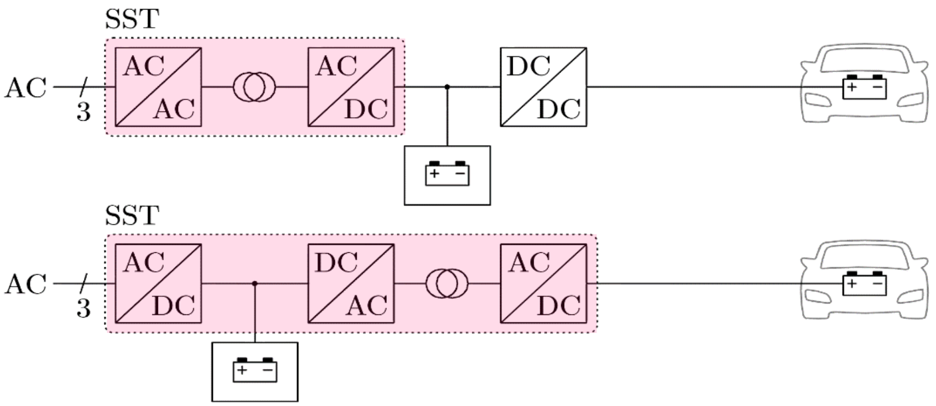
- E.g., Porsche *FlexBox* incl. Cooling
- Local Battery Buffer (140kWh)
- 320kW → 400km Range in 20min

→ *Bidirectional SST-Based MV Interface*

- **Conventional**



- ***Future SST-Based Concept***



- **On-Site Power / Energy Buffer → „Energy-Hub“**
- **Power / Energy Management → Peak Load Shaving & Grid Support / Stabilization**

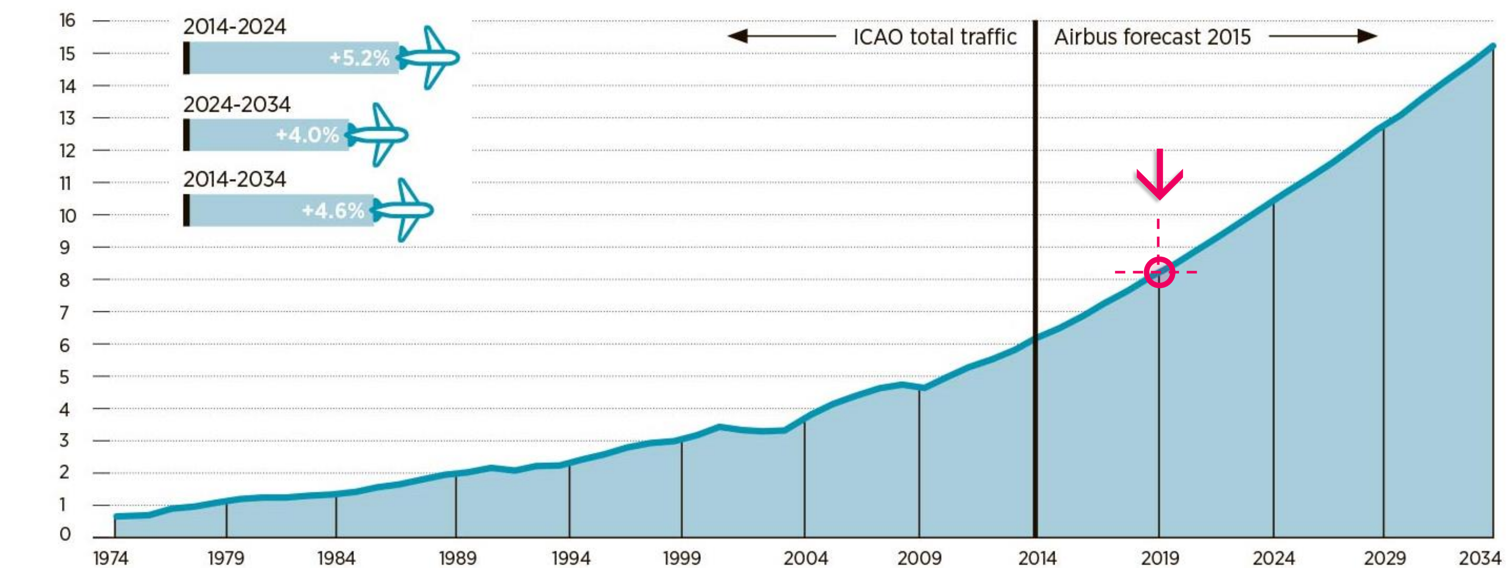
▶ Sustainable Air Transportation

- **Massive Steady Increase of Global Air Traffic Over the Next Decades**

— **Need for 70´000 New Airliners over the Next 20 Years (Boeing & Airbus)**
— **Stringent *Flightpath 2050 Goals* of ACARE → Reduction of CO_2/NO_x/Noise Emissions**

GLOBAL AIR TRAFFIC (TRILLION REVENUE PASSENGER KILOMETRES)

→ Traffic is expected to double in the next 15 years



Source: International Civil Aviation Organization (ICAO)/Airbus 2015

→ *Future Distributed Propulsion Aircraft*

- **Cut Emissions Until 2050**
  - **CO_2 by 75%,**
  - **NO_x by 90%,**
  - **Noise Level by 65%**

Source:

NASA N3-X Vehicle Concept

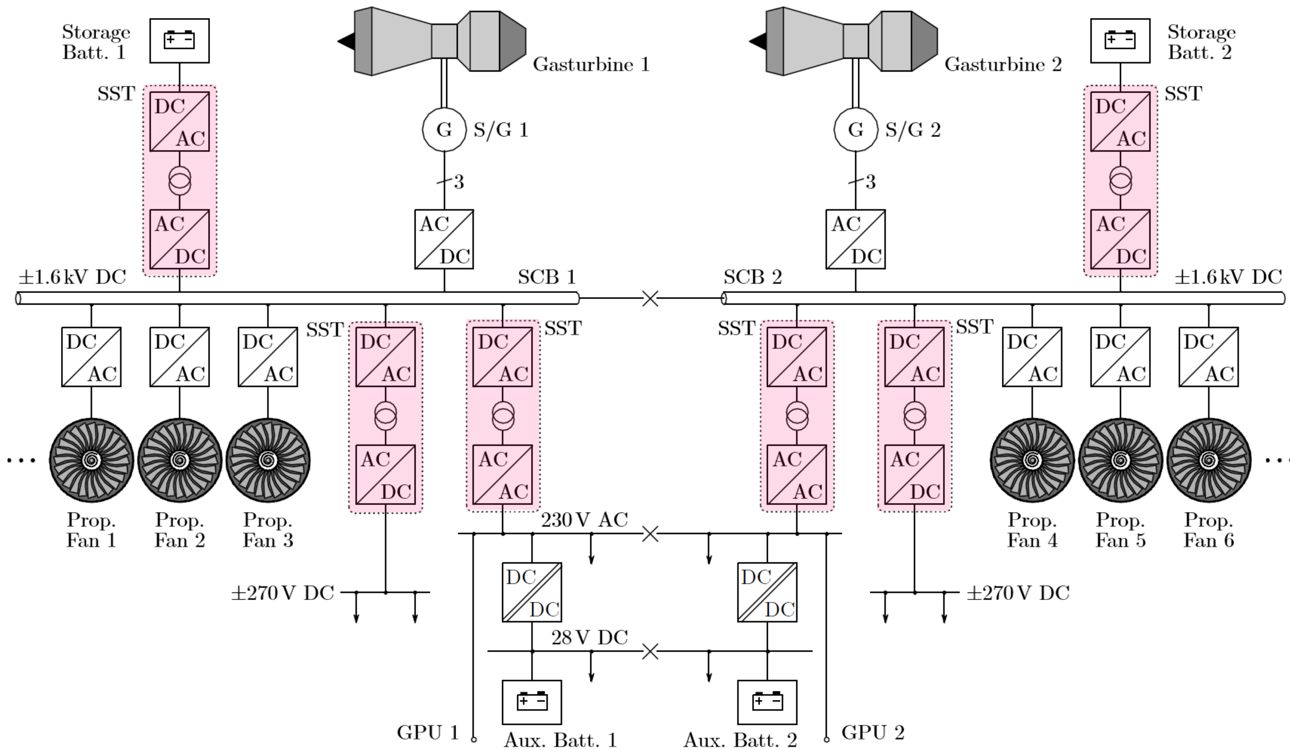
Turbo Generators

E-Fans / Continuous Nacelle

- **Wing-Tip Mounted Eff. Optimized Gas Turbines & Distributed E-Fans ("E-Thrust")**
- **MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)**

Future Aircraft Electric Power System

▶ MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)



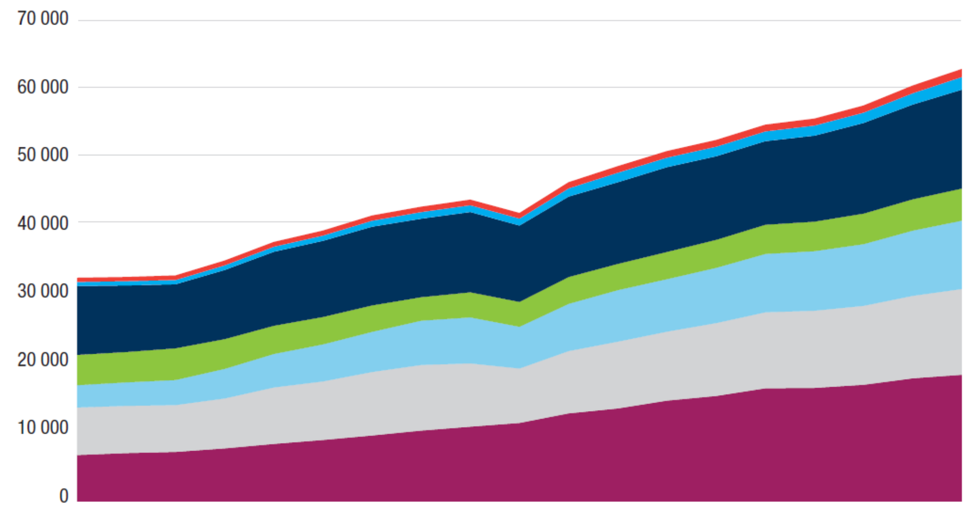
- Generators — 2 x 40.2MW (NASA)
- E-Fans — 14 x 5.7 MW (1.3m Diameter)

▶ Sustainable Maritime Transportation

■ 80% of All Globally Traded Goods Transported by Ships

— IMO → Ship Energy Eff. Management Plan (SEEMP) & Energy Eff. Design Index (EEDI)
— Crude Oil → New Fuel Types (LNG)
— Fully-Electric Port Infrastructure

Source: UNCTAD 2018



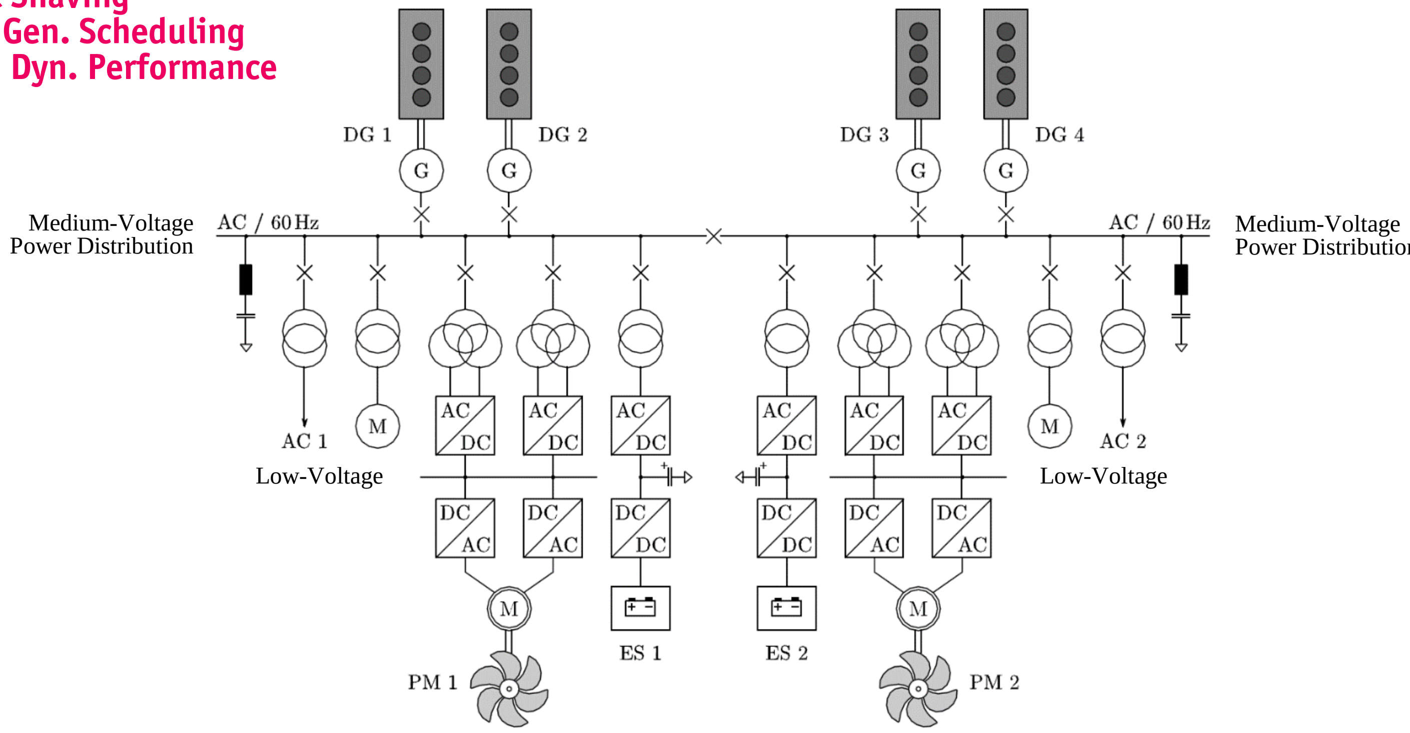
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017[a]	2018[b]
Chemicals	580	589	620	632	650	676	713	747	759	783	848	888	903	925	920	961	993	1 058	1 111
Gas	576	591	611	662	717	735	833	913	956	958	1 148	1 344	1 333	1 337	1 381	1 421	1 462	1 595	1 766
Oil	9 614	9 303	8 938	9 665	10 348	10 654	10 984	10 981	11 211	10 679	11 255	11 420	11 831	11 657	11 659	11 993	12 657	13 216	13 809
Other dry cargo	4 233	4 245	4 414	4 150	3 920	3 818	3 712	3 257	3 517	3 481	3 723	3 645	3 795	3 923	4 065	4 139	4 242	4 384	4 497
Containers	3 111	3 279	3 512	4 124	4 687	5 158	5 601	6 178	6 431	5 815	6 588	7 206	7 352	7 712	8 157	8 290	8 635	9 117	9 535
Minor dry bulks	6 638	6 573	6 538	6 965	7 876	8 170	8 852	9 160	8 817	7 586	8 705	9 312	9 624	10 172	10 617	10 775	11 018	11 510	11 967
Main Bulks	6 509	6 793	6 937	7 448	8 061	8 626	9 245	9 941	10 476	11 006	12 336	13 019	14 099	14 764	15 828	15 897	16 314	17 217	17 729

▶ Worldwide Seaborne Trade in Billions of Cargo Ton-Miles

→ Hybrid Diesel-Electric Propulsion

- No Mech. Coupling of Propulsion & Prime Movers (DGs) → Eff. Optim. Load Distrib. to the DGs
- Energy Storage (Batt., Fuel Cell, etc.)

— Peak Shaving
— Opt. Gen. Scheduling
— High Dyn. Performance

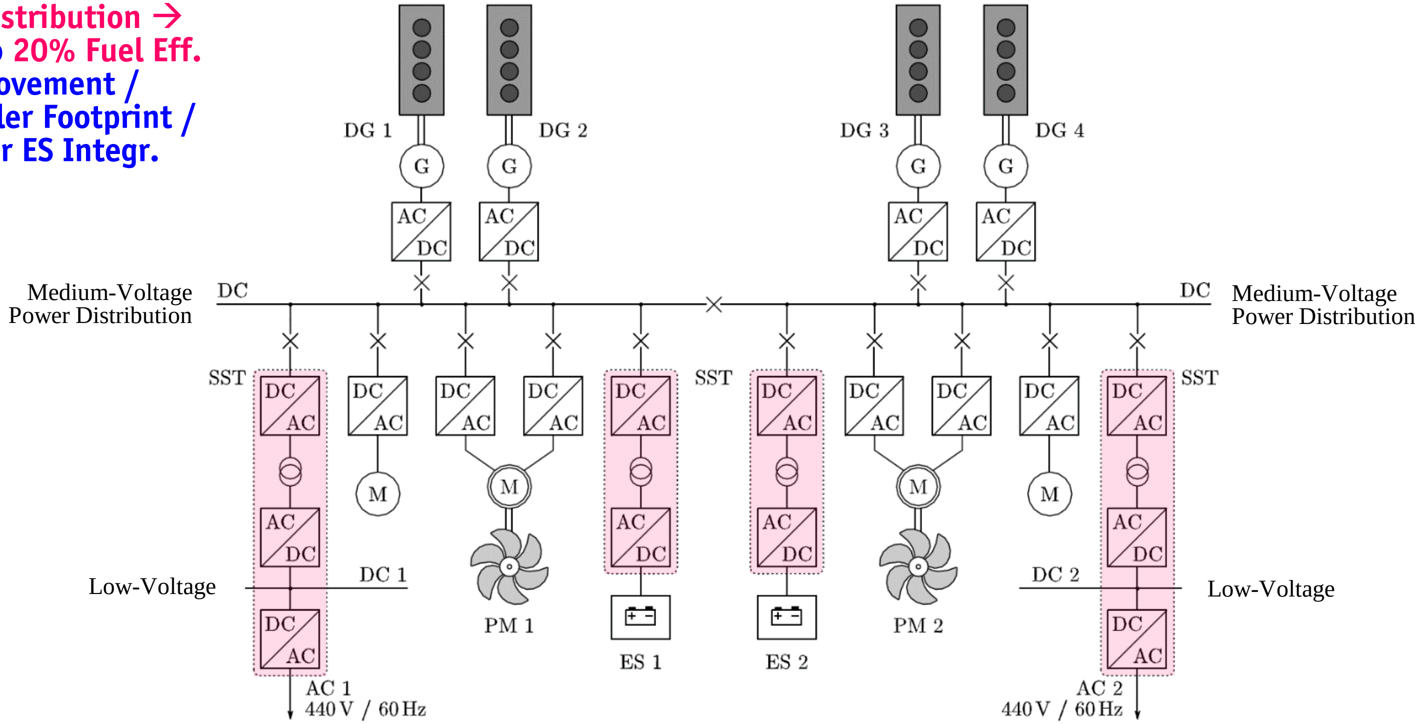


- Conv. AC Power Distrib. Network → Disadvantage of Const. Prime Mover / Generator Speed

→ Shipboard DC Power Distribution

- Future DC/AC-SST Interface to Low-Voltage AC & DC Grid
- Future DC/DC-SST Interface to Energy Storage (ES)

— DC Distribution →
Up to 20% Fuel Eff.
Improvement /
Smaller Footprint /
Easier ES Integr.

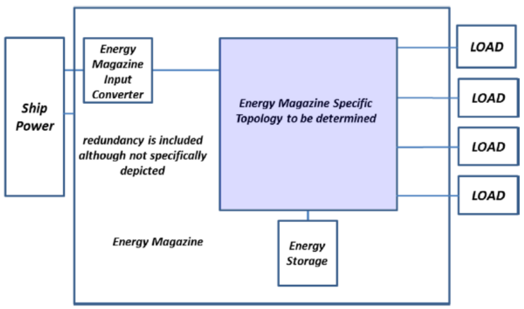


- 1kV/< 20MW or 1...35kV/20...100MW DC Distribution (Radial or Ring, Central. or Distrib.)

→ Future Combat Ships (1)

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

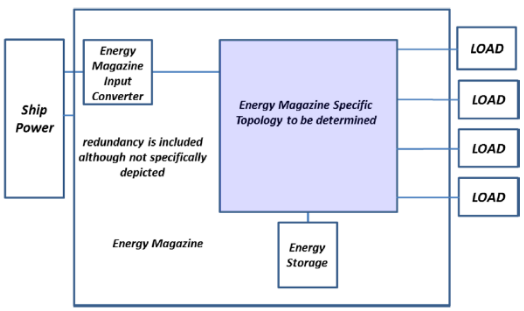
Source:
General Dynamics



- ► "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

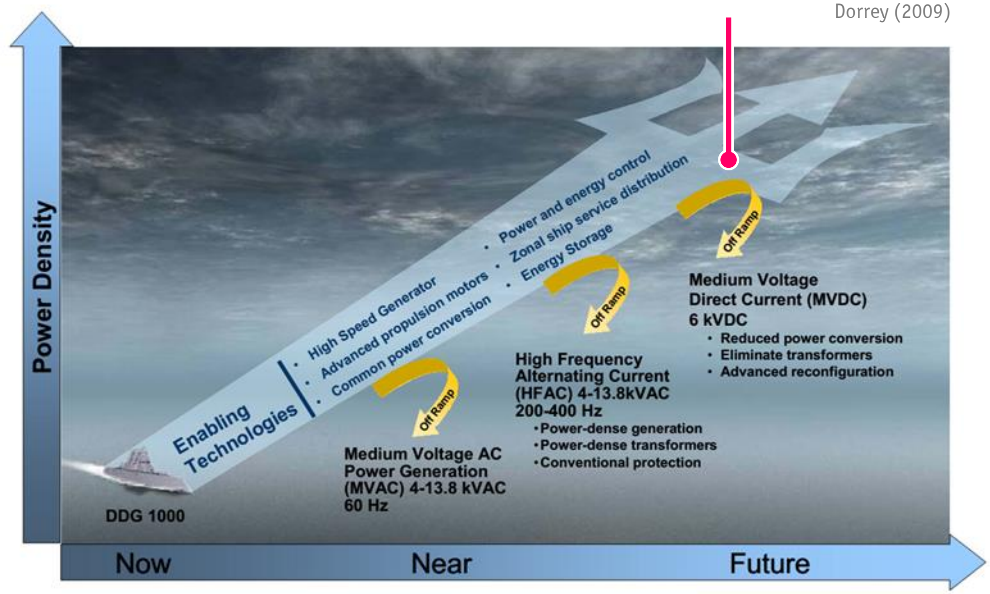
→ Future Combat Ships (2)

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



6kV DC/DC SST for Size/Weight Reduction

Dorrey (2009)



► "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

Global Megatrends

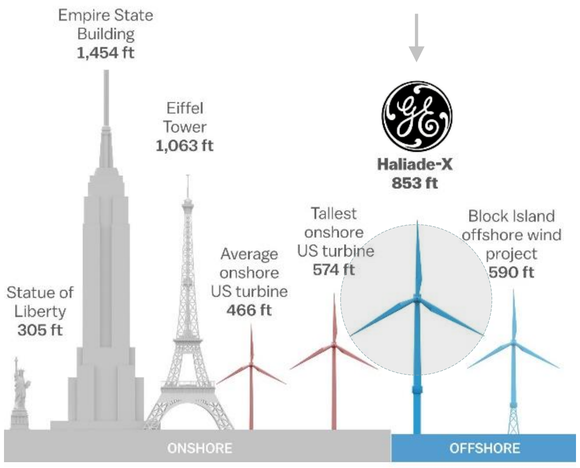
Digitalization
Urbanization
Sustainable Mobility
Renewable Energy →
Etc.

▶ Wind Energy

- *Power* prop. D^2 → "Bigger is Better" / Lower Relative Costs
- 50kW (D = 15m) in 1980 → Up to 20MW (D = 250m) in Future

12MW

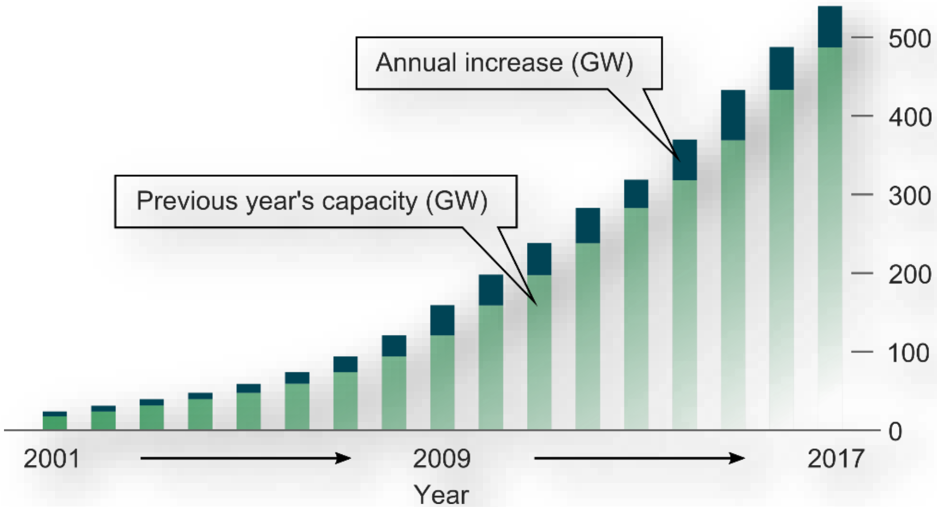
Under Development



Source: GE, Vox research

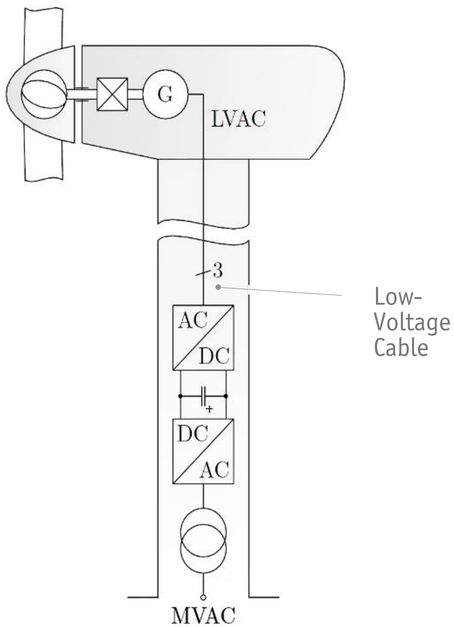
Source: gwec.net / Blaabjerg

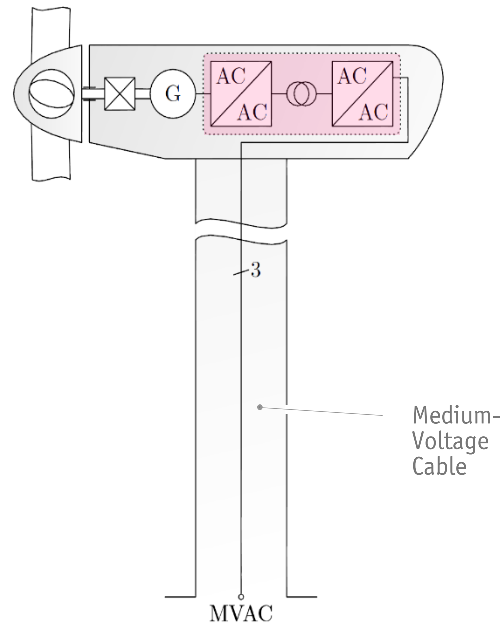
540 GW



→ Wind Turbine Electrical System

- Current 690V Electrical System → Significant Cabling Weight/Costs & Space Requirement
- Future Local Medium-Frequency Conv. to Medium-Voltage AC or DC

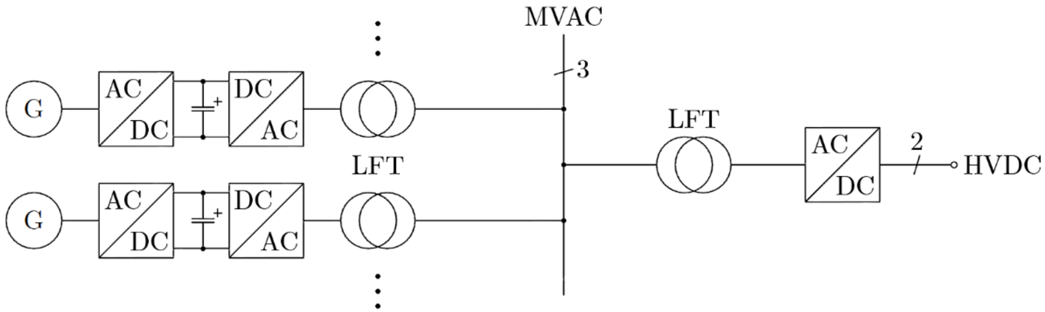




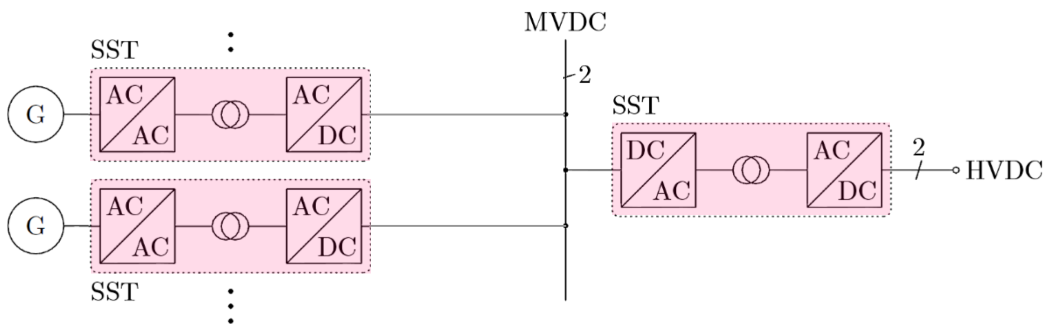
▶ On-Shore Wind Power System

▶ Future Off-Shore System

→ Off-Shore Collector-Grid Concepts



- Conventional AC Collector-Grid



- DC/DC-SST Interface — Wind Turbine DC Link to MVDC Collector Grid → Lower Losses (1%) & Volume
- DC/DC-SST Interface — MVDC Grid to HVDC Transmission → Lower Losses (1%) & Volume

► Utility-Scale Solar Power Plants

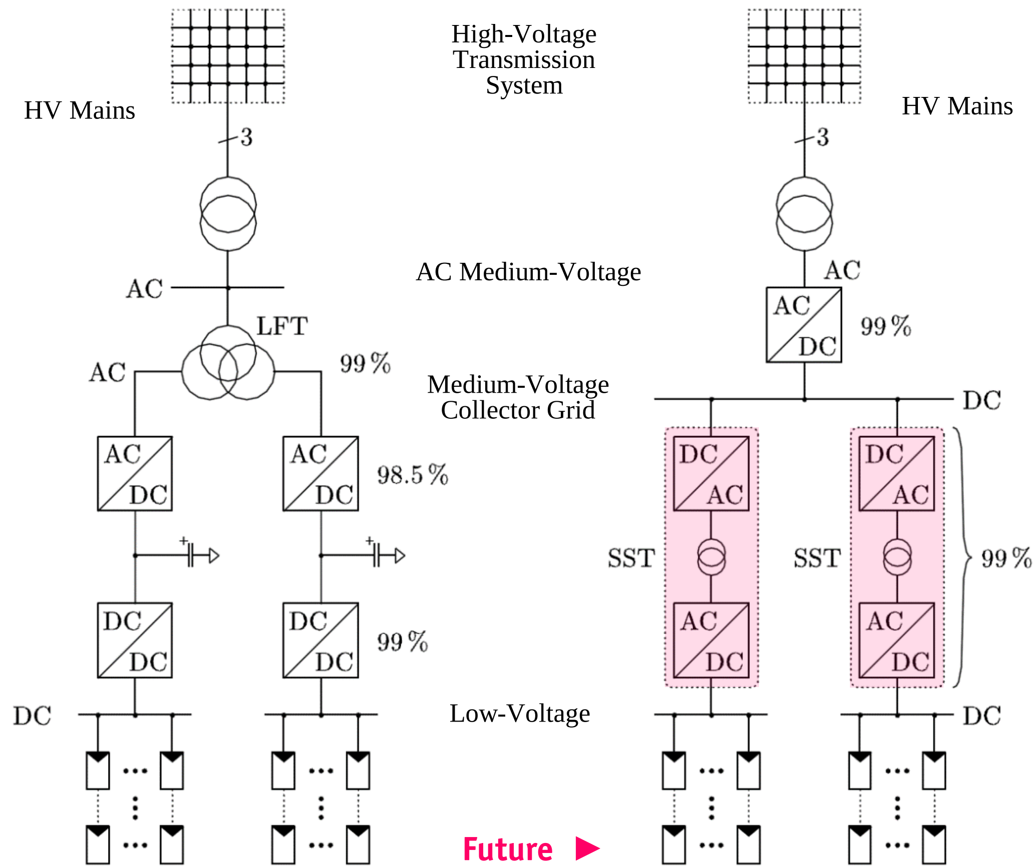
■ Medium-Voltage Power Collection and Transmission

Source: REUTERS/Stringer

■ Globally Installed PV Capacity Forecasted to 2.7 Terawatt by 2030 (IEA)

→ Future DC Collector Grid

- DC/DC SST for MPPT & Direct Interfacing of PV Strings to MV Collector Grid
- 1.5% Efficiency Gain Compared to Conv. AC Technology

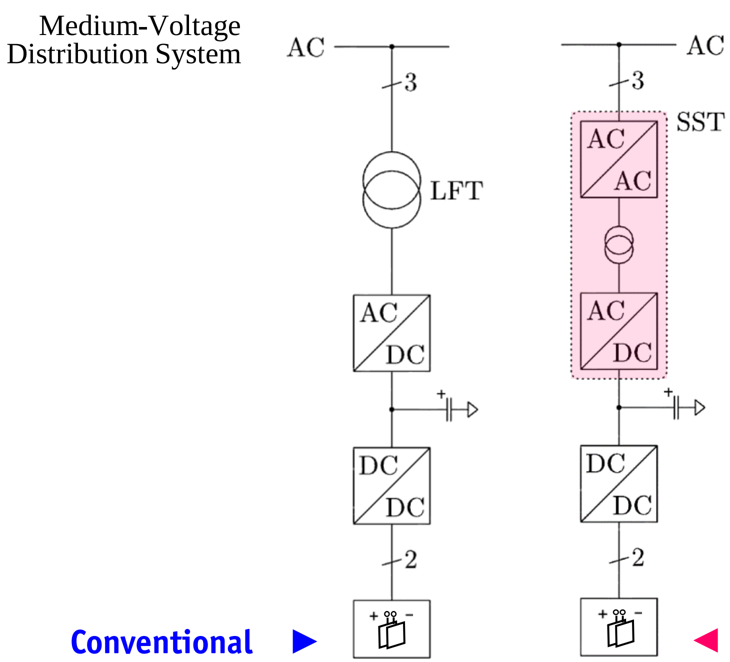


▶ Power-to-Gas

- 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
- SST Allows Direct Interfacing to DC Collector Grid

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

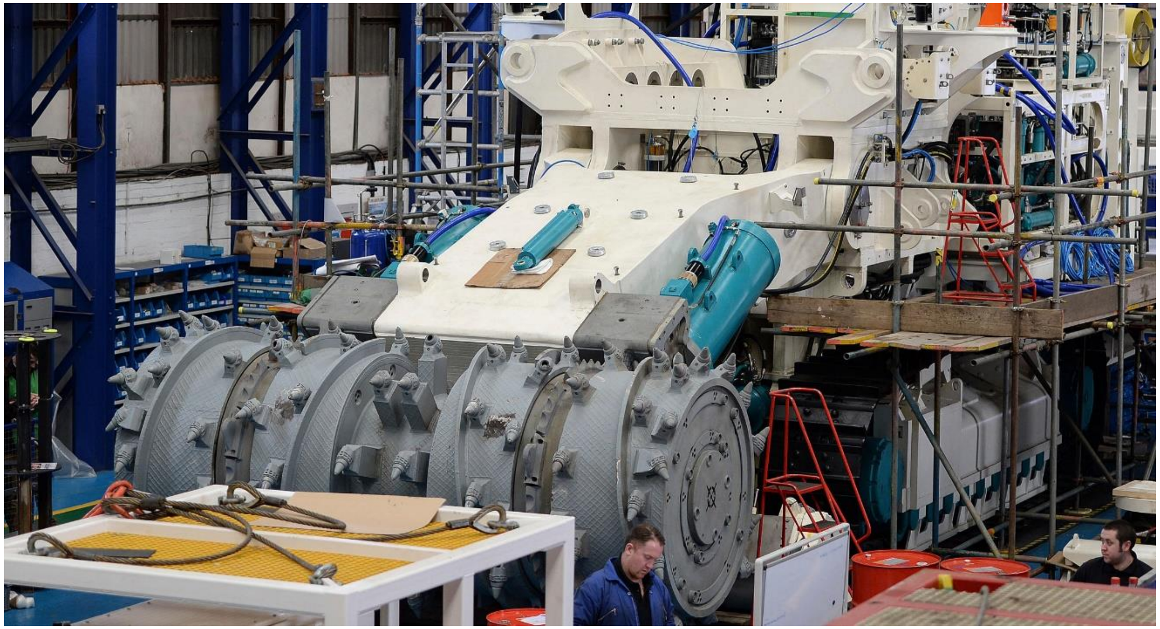


Global Megatrends

Digitalization
Urbanization
Sustainable Mobility
Renewable Energy
Etc. →

▶ Future Deep Sea Mining

- "Subsea Factories" / Subsea Power Grid → Long-Distance MV Power Supply from Shore
- Subsea Mining Machines / ROVs / Pumps / Compressors etc.



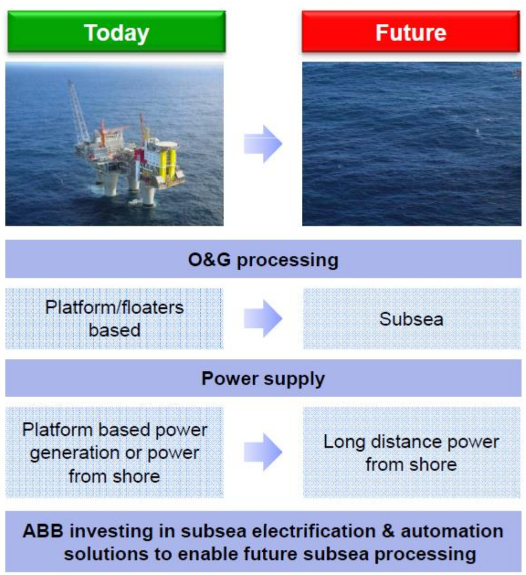
Source: SMD - Specialist Machine Developments

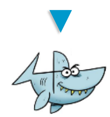
- Demand for Highly Compact / Efficient / Reliable Systems

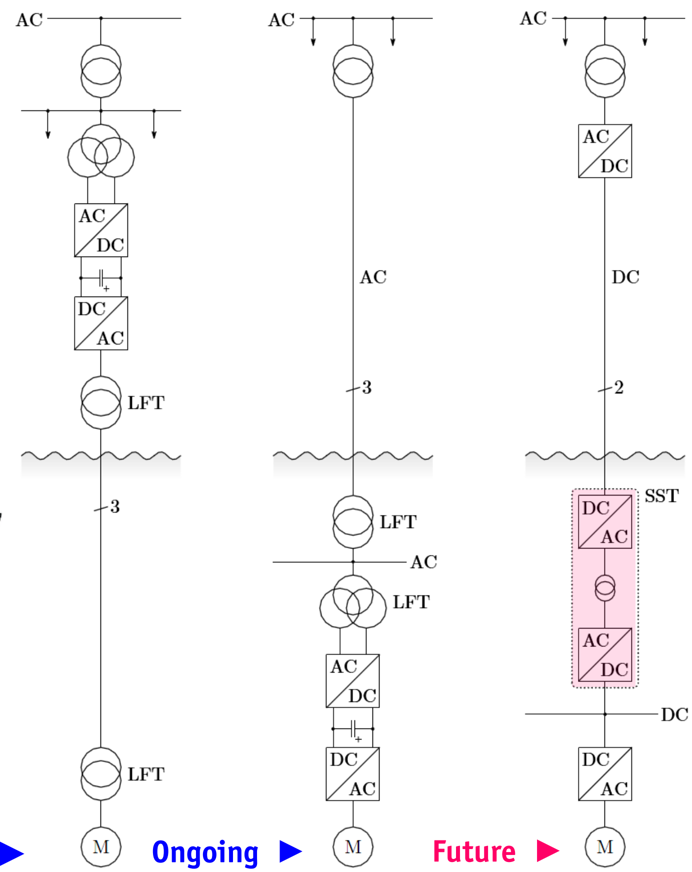
→ Future Power Supply of Subsea Systems

- DC Transmission from Shore
- No Platforms/Floaters

Source: Devold (ABB 2012)

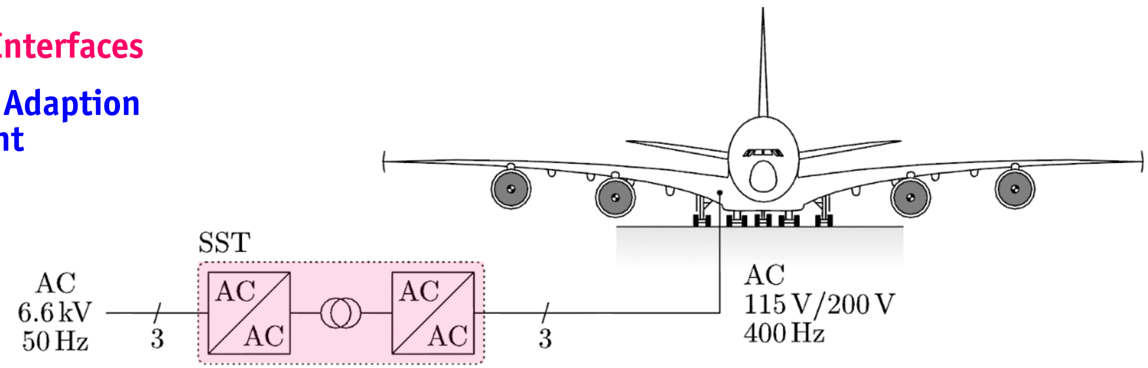




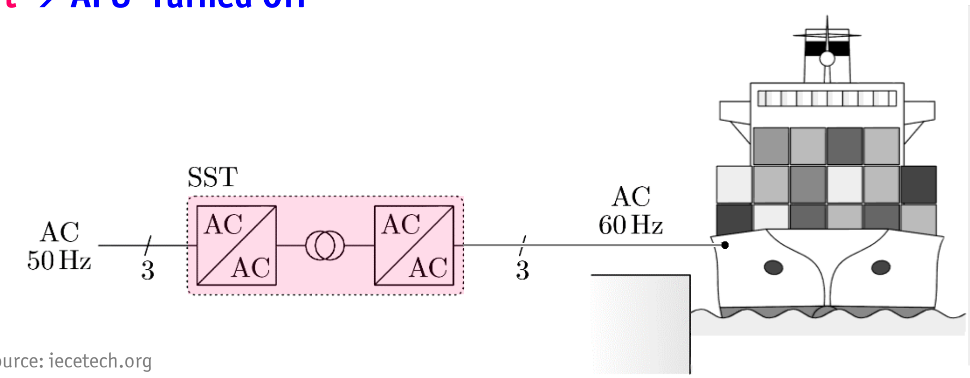


→ *Cutting Emissions & Noise in Airports / Harbours*

- **SST Medium-Voltage Interfaces**
  - **Voltage Level / Frequ. Adaption**
  - **Low Space Requirement**



- **Ground Power Supply of Aircraft → APU Turned Off**



Source: iecetech.org

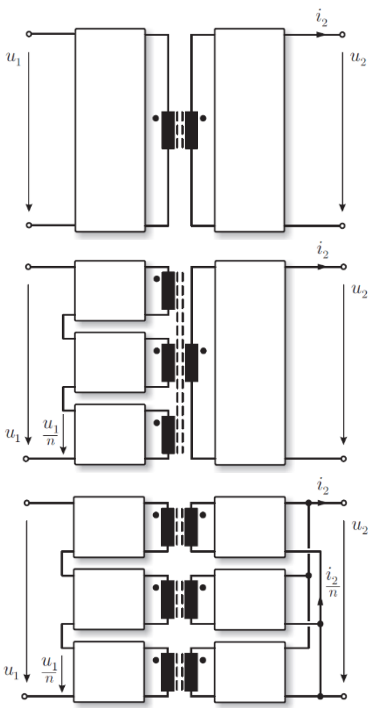
- **MV-Level Shore-Side Power to Docked Ships ("Cold-Ironing") → Diesel Aux. Engines Turned Off**

SST Concept Implementation

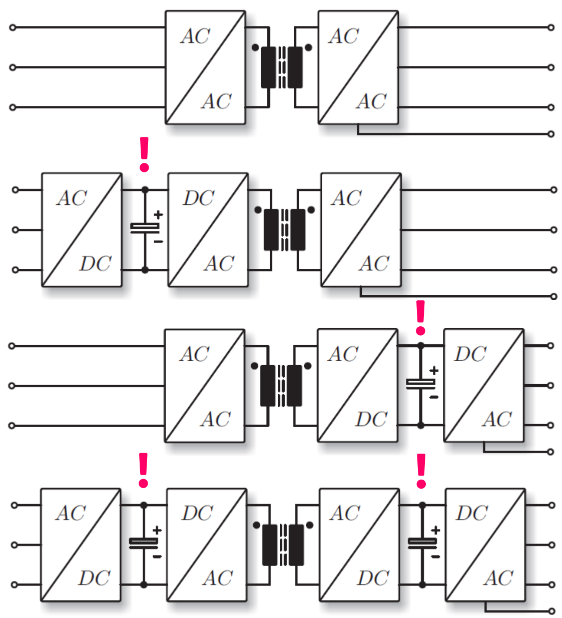
Creation of MV → LV SST Topologies

▶ Classification of SST Topologies (1)

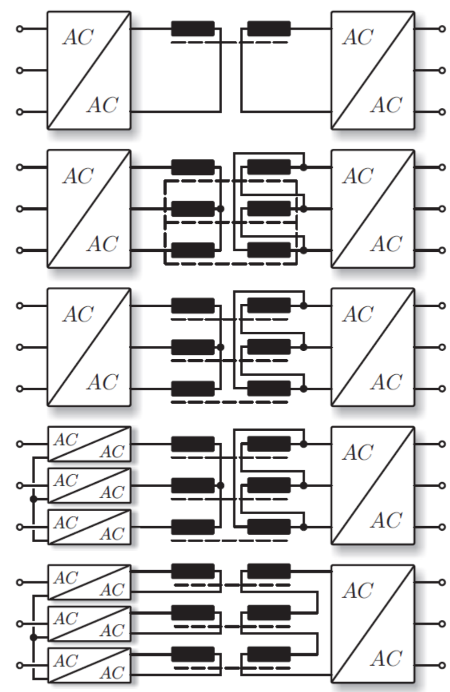
- **Number of Levels Series/Parallel Cells**



- **Degree of Power Conversion Partitioning**

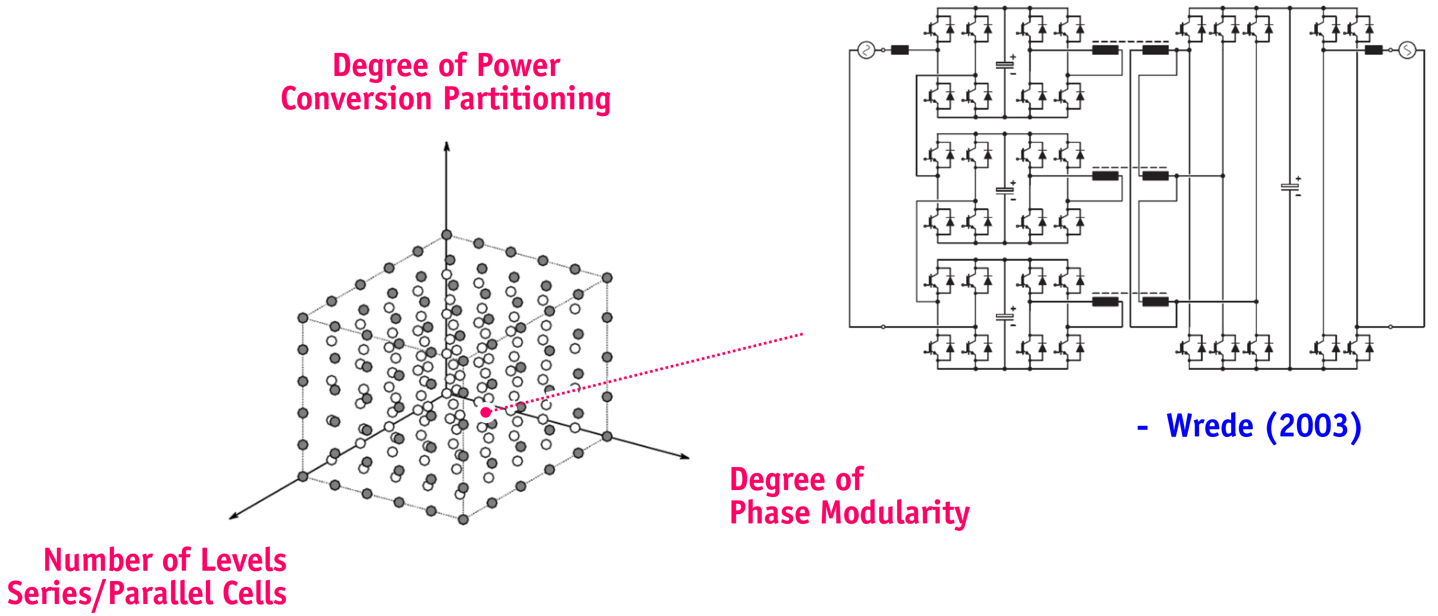


- **Degree of Phase Modularity**



▶ **3-Dimensional Topology Selection Space**

► Classification of SST Topologies (2)

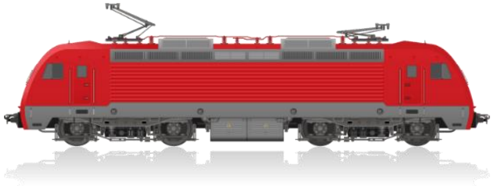


■ **Very (!) Large Number of Possible Topologies**

- 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

Combining the
Basic Concepts I

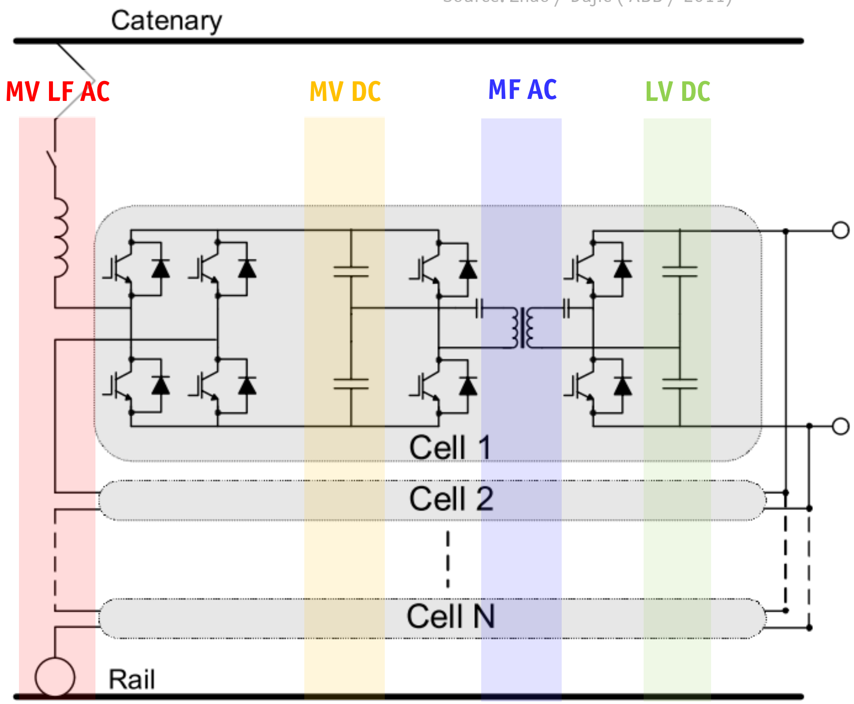
Single-Phase AC-DC Conversion /
Traction Applications

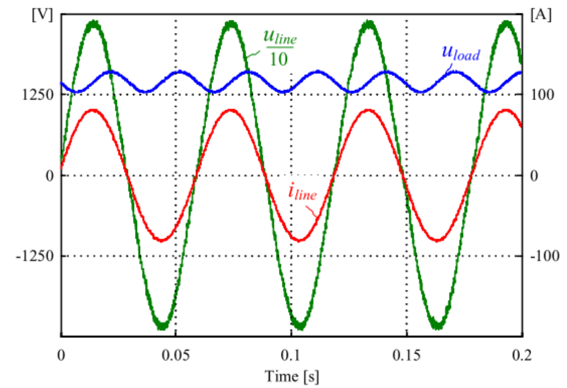


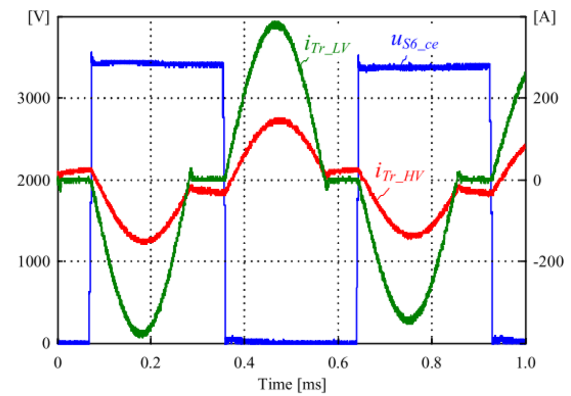
▶ Cascaded H-Bridges w. Isolated Back End

- Multi-Cell Concept (AC/DC Front End & Soft-Switching Resonant DC//DC Converter)
- Input Series / Output Parallel Connection – Self Symmetrizing (!)
- Highly Modular / Scalable
- Allows for Redundancy
- High Power Demonstrators: ABB BOMBARDIER the evolution of mobility ALSTOM etc.

Source: Zhao / Dujic (ABB / 2011)

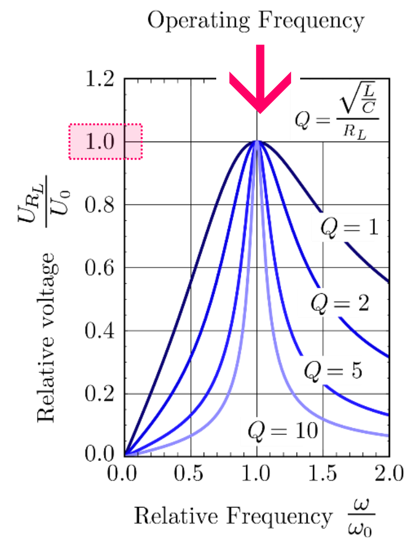


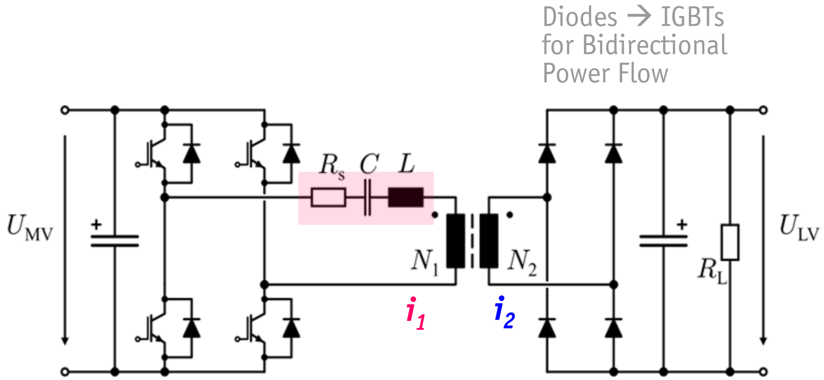


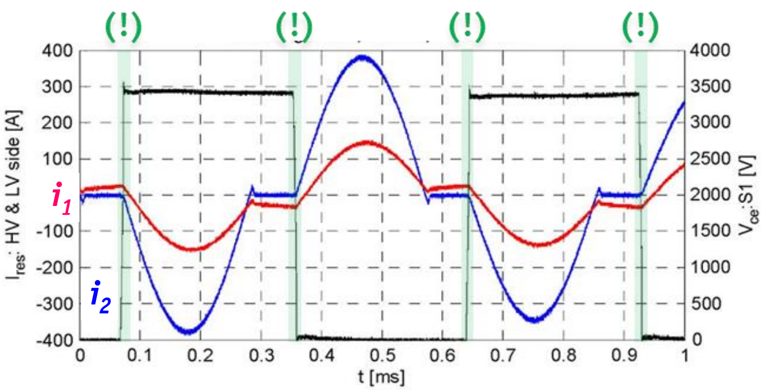


▶ DCX — "DC Transformer"

- $f_S \approx$ Resonant Frequency → "Unity Gain" ($U_2/U_1=N_2/N_1$)
- Fixed Voltage Transfer Ratio Independent of Transferred Power (!)
- Power Flow Level & Direction Self-Adjusting
- No Controllability / No Need for Control
- ZCS of All Devices

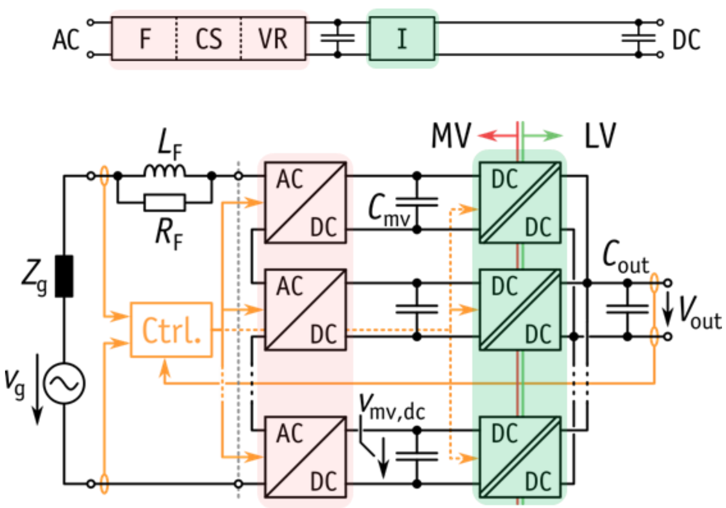






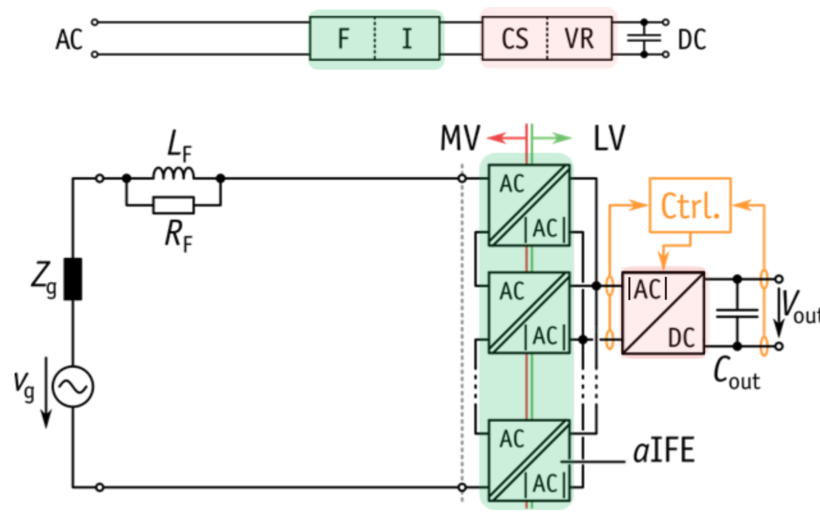
► Current Shaping & Isolation → Isolation & Current Shaping

■ 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



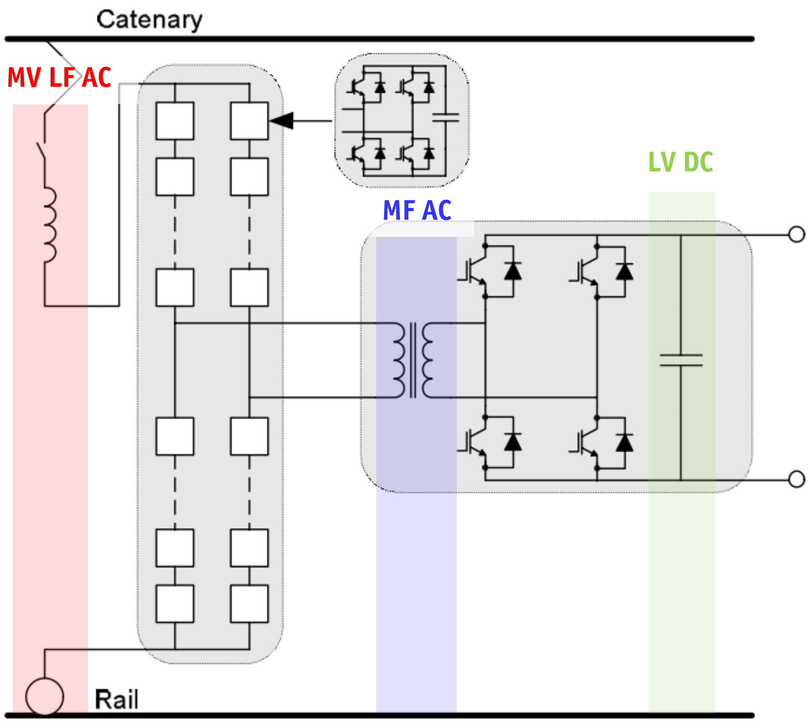
- **Swiss SST (S3T)**
- Two-Stage Multi-Cell Concept
- Indirect Input Current Control
- Direct Output Voltage Control
- **Low Complexity** on MV Side

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

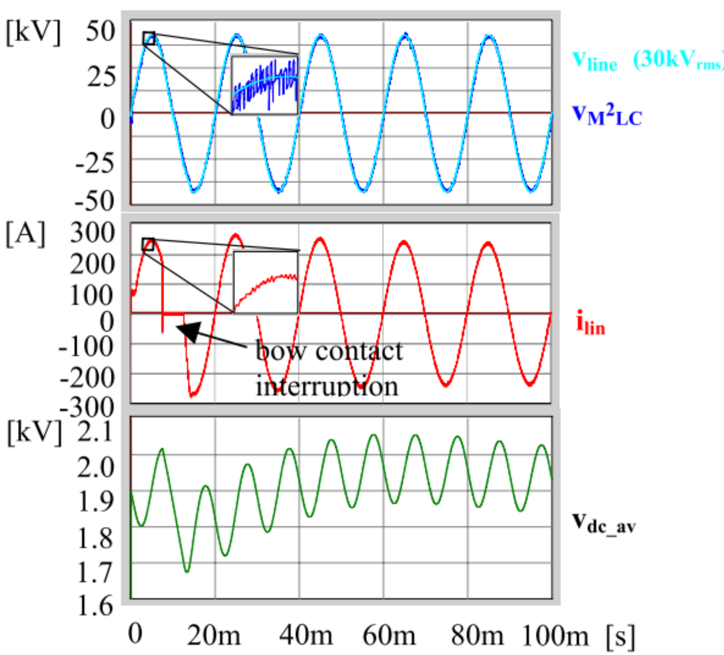
▶ Modular Multilevel Converter

- Single Transformer Isolation
- Highly Modular / Scalable
- Allows for Redundancy
- Challenge of Balancing the Cell DC Voltages

SIEMENS
- Marquardt/Glinka (2003)

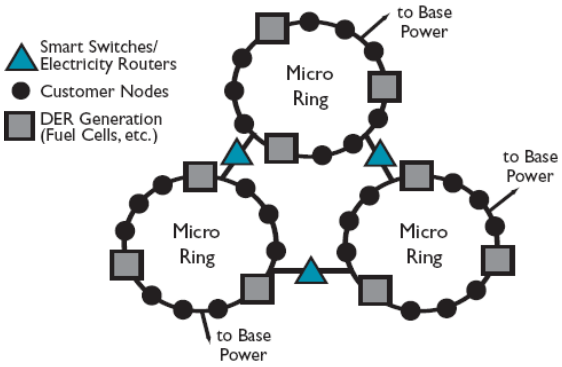


Source: Zhao / Dujic (ABB / 2011)



Combining the Basic Concepts II

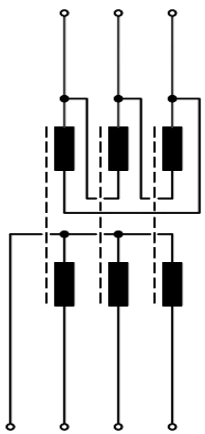
Three-Phase AC-AC Conversion / Smart Grid Applications



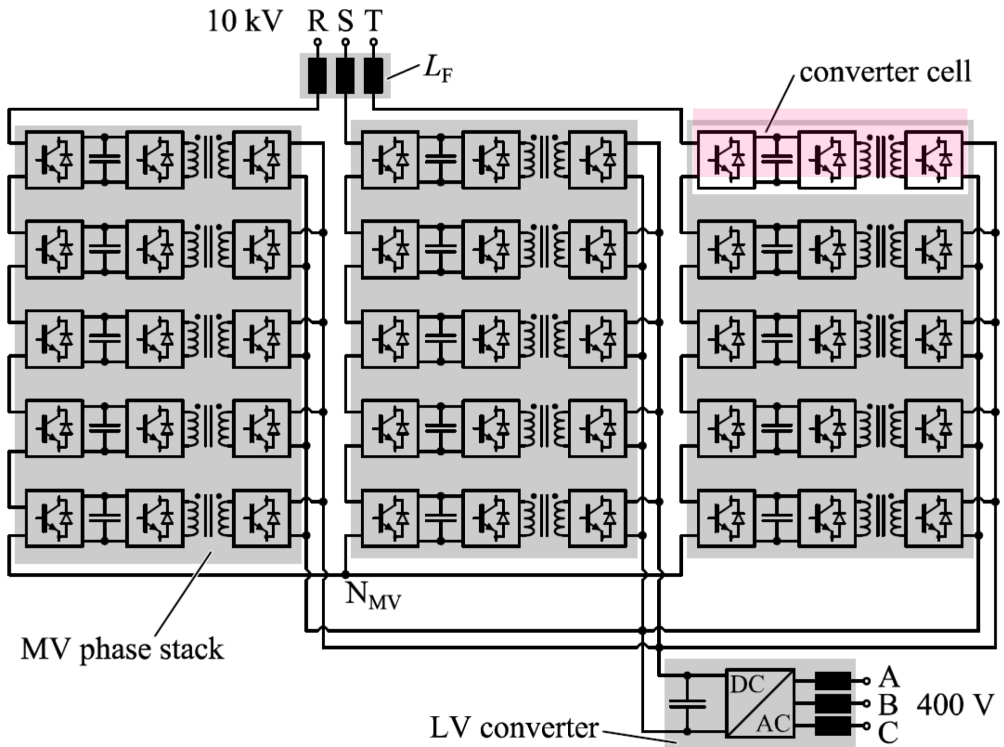
Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

▶ MEGALink @ ETH Zurich

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



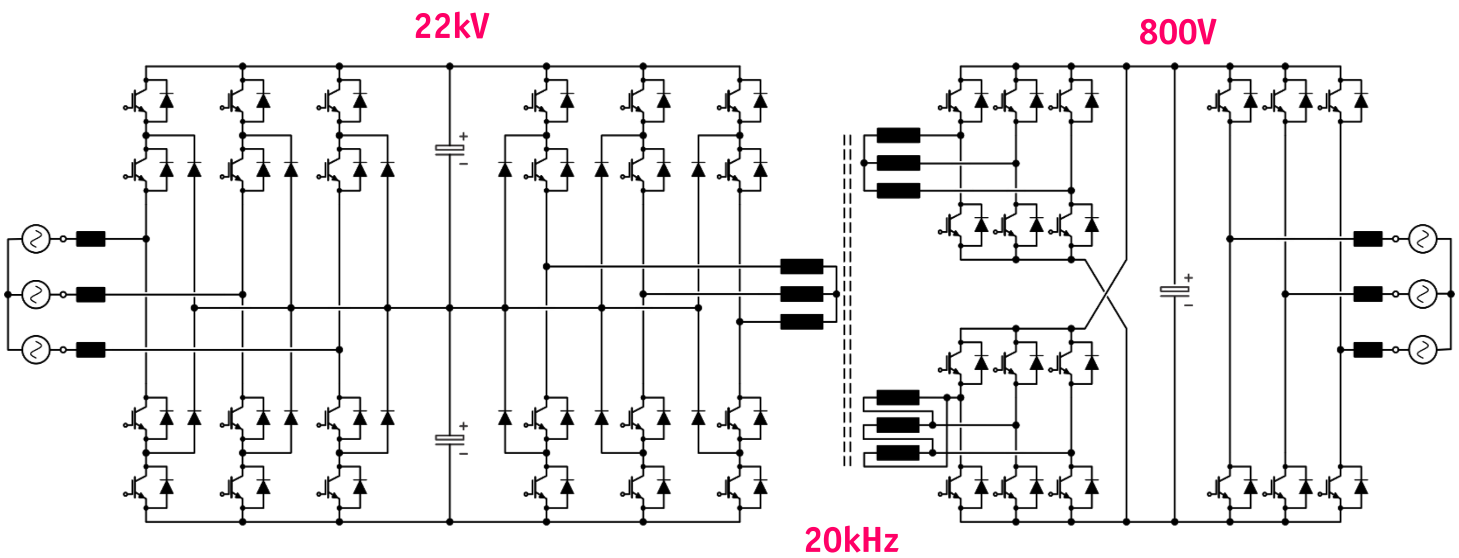
→



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

▶ Non-Cascaded Structure (SiC)

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



- Redundancy Only for Series-Connection of Power Semiconductors (!)

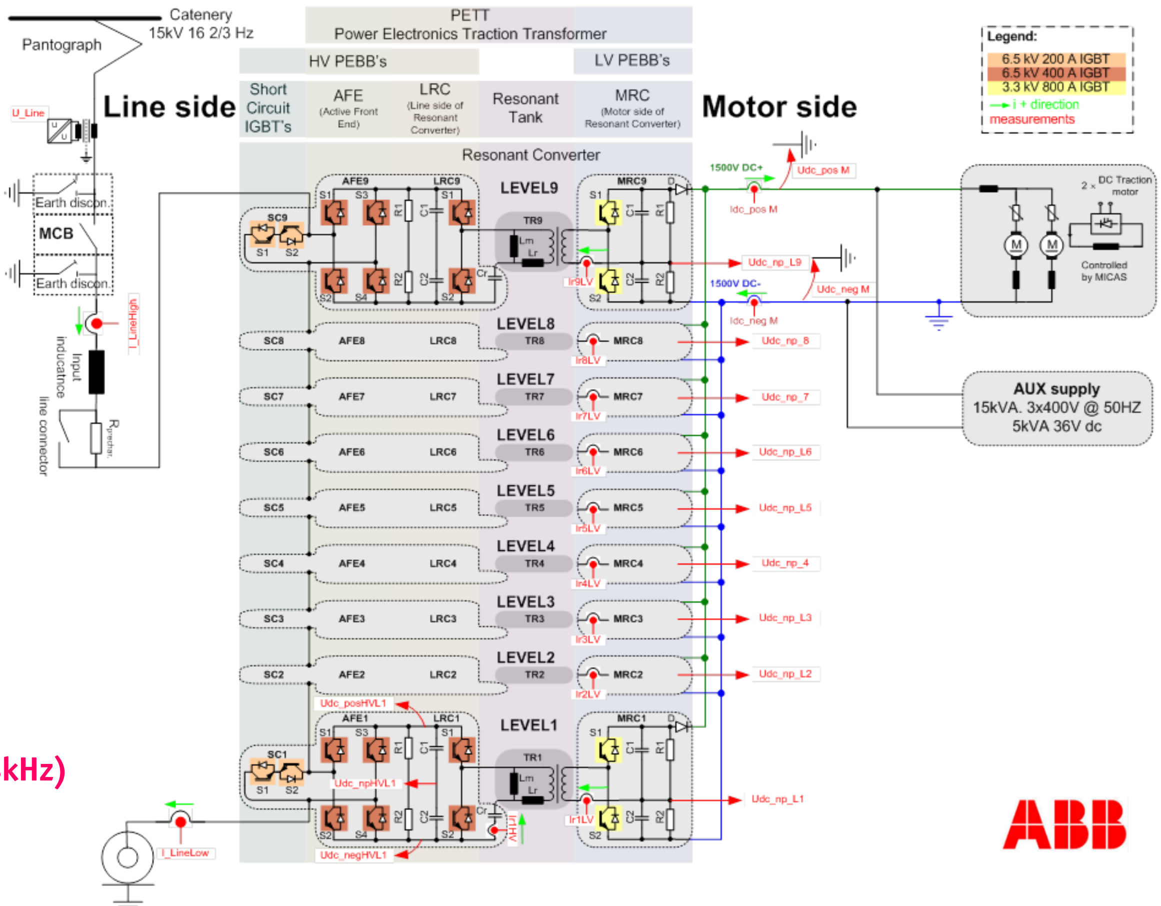
SST Demonstrator Systems

Future Locomotives
Smart Grid Applications

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

- Dujic et al. (2011)

- Heinemann (2002)
- Steiner/Stemmler (1997)
- Schibli/Rufer (1996)



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

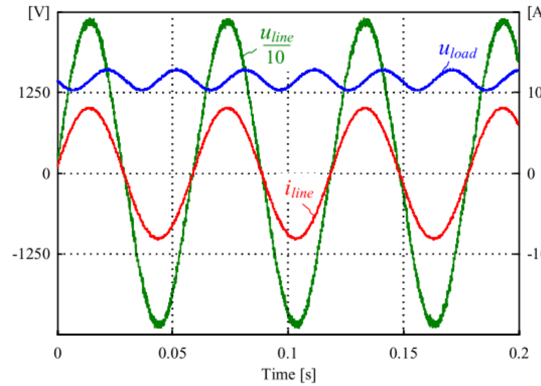
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

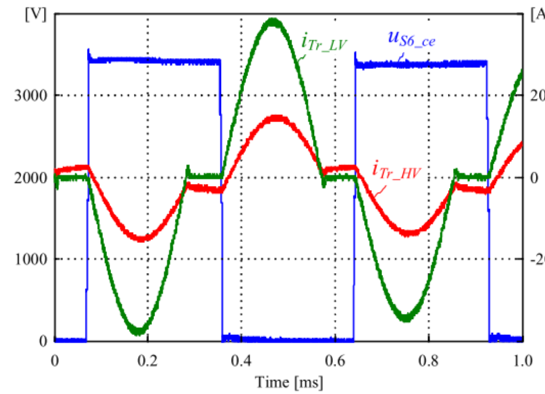
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

ABB

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

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



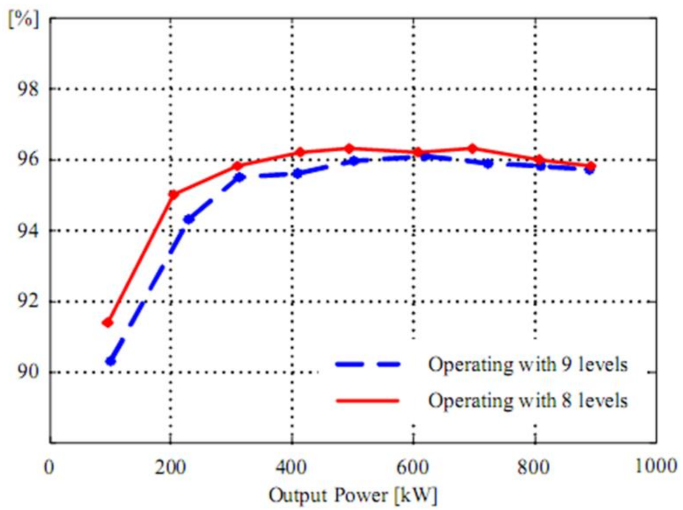


- Same Overall Volume as Conventional System
- Future Development Targets Half Volume

▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer (2)

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

Efficiency

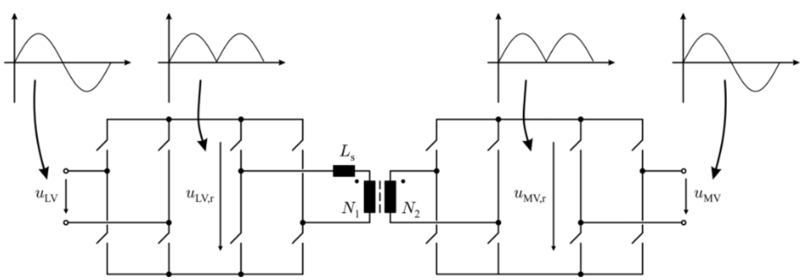


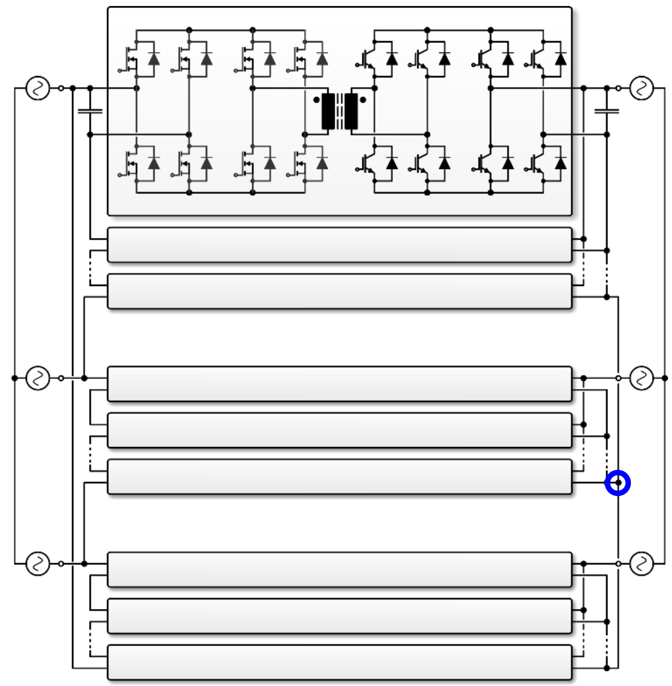
- Same Overall Volume as Conventional System
- Future Development Targets Half Volume

▶ SiC-Enabled Solid-State Power Substation (1)

- 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$_{\text{l-l}}$, 4 Modules in Series)
- LV Y-Connection (265V, Modules in Parallel)



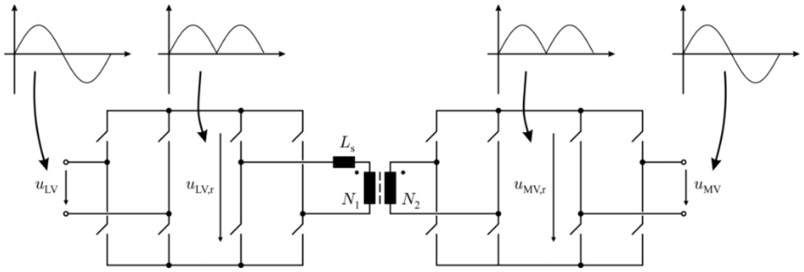


- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)

▶ SiC-Enabled Solid-State Power Substation (2)

- Das et al. (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 (265V, Modules in Parallel)

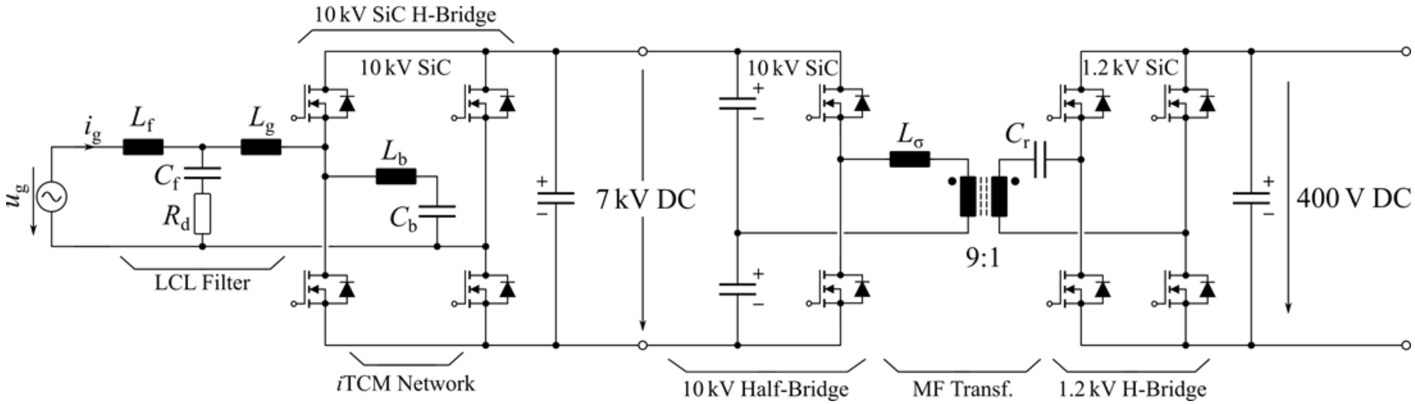


- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)

25kW SwiSS-Transformer @ ETH Zurich

- *Bidirectional 1-Φ 3.8 kV$_{rms}$ AC → 400V DC Power Conversion*
- *Based on 10kV SiC MOSFETs*
- *Full Soft-Switching*

★ 3.3 kW/dm³



★ 3.8 kW/dm³

▶ *35...75kHz iTCM Input Stage*

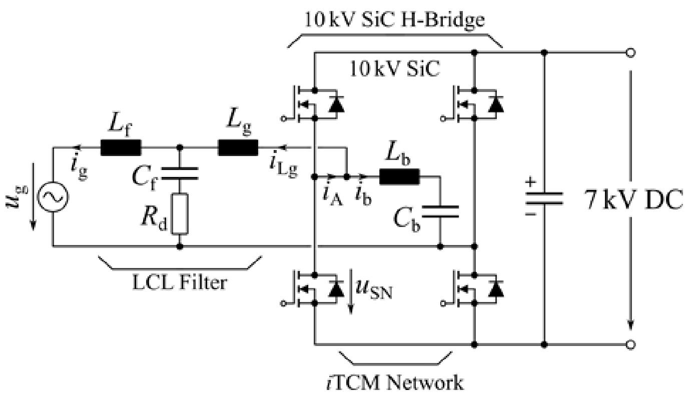
▶ *48kHz DC-Transformer Output Stage*

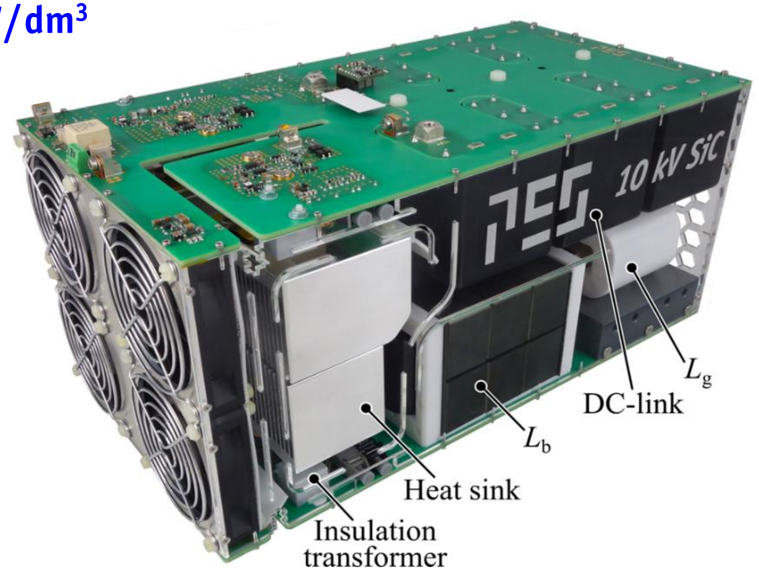
▶ 3.8kV → 7kV ZVS AC/DC Stage

- *Full-Bridge iTCM – integrated Triang. Current Mode Operation Enables ZVS*

— ZVS Requires Change of Sw. Current Direction in Each Sw. Period
— Open-Loop Variation of Sw. Frequency for Const. ZVS Current (35...75kHz)
— Separate Optim. of ZVS and Input Inductor Possible
— No Large Ripple Input Current

★ 3.3 kW/dm³





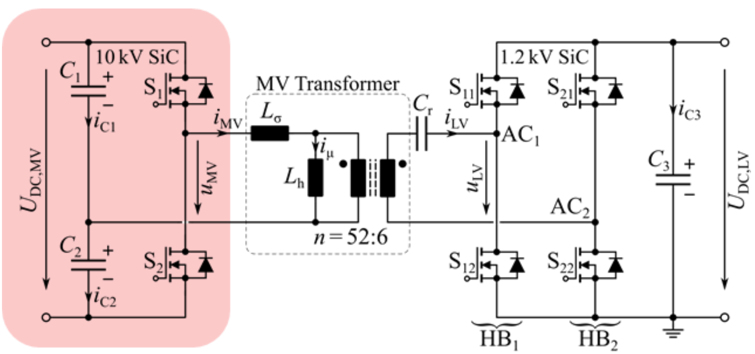
▶ Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)

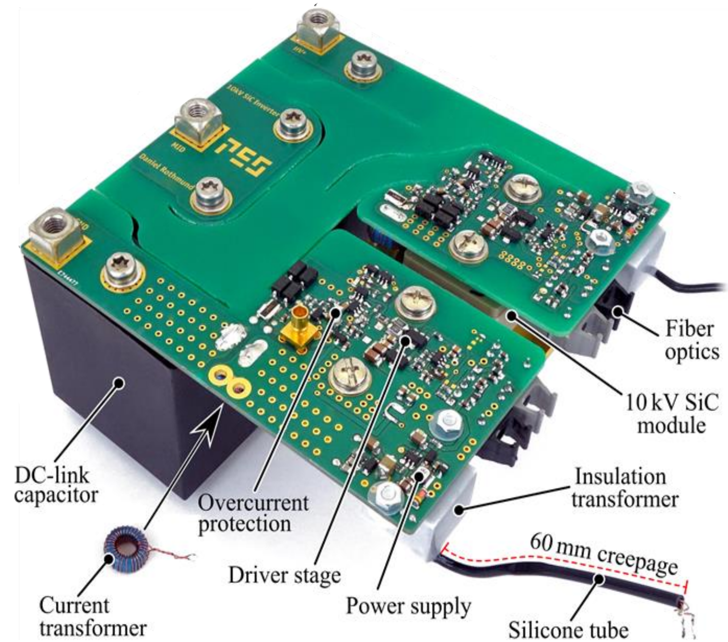
▶ 7kV → 400V DC/DC Stage (1)

■ *MV-Side Half-Bridge*

— 48kHz Sw. Frequency, ZVS
— Cooling of Power Semicond. by Floating Heatsinks (Not Shown)
— Creepage Distances Ensured by PCB Slots

★ 3.8 kW/dm³



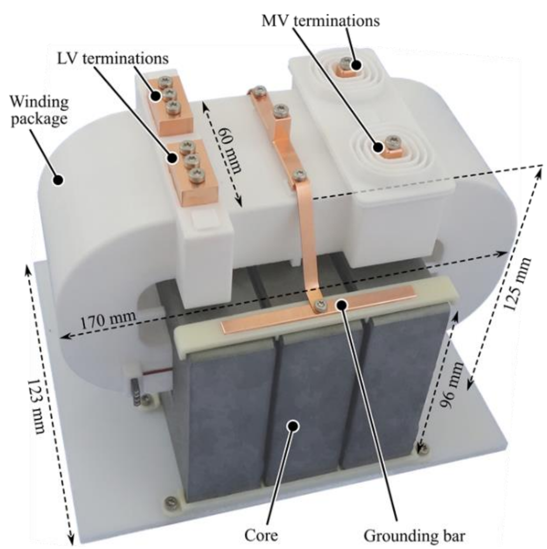


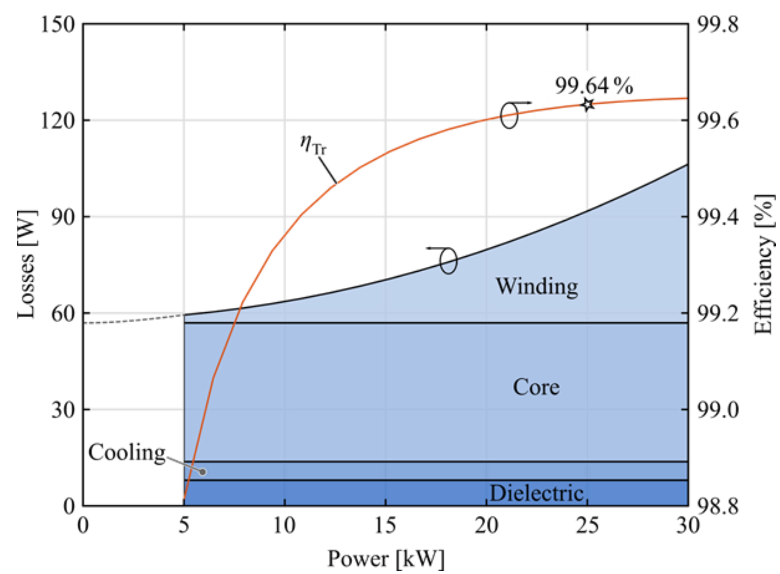
▶ Half-Bridge for Cutting Voltage in Half / Lower Switch Count

▶ 7kV → 400V DC/DC Stage (2)

■ *MF-Transformer Measurement*

— Fully Tested @ 25kW / 7 kV
— Calorimetric Loss Measurement
— 99.64% Efficiency

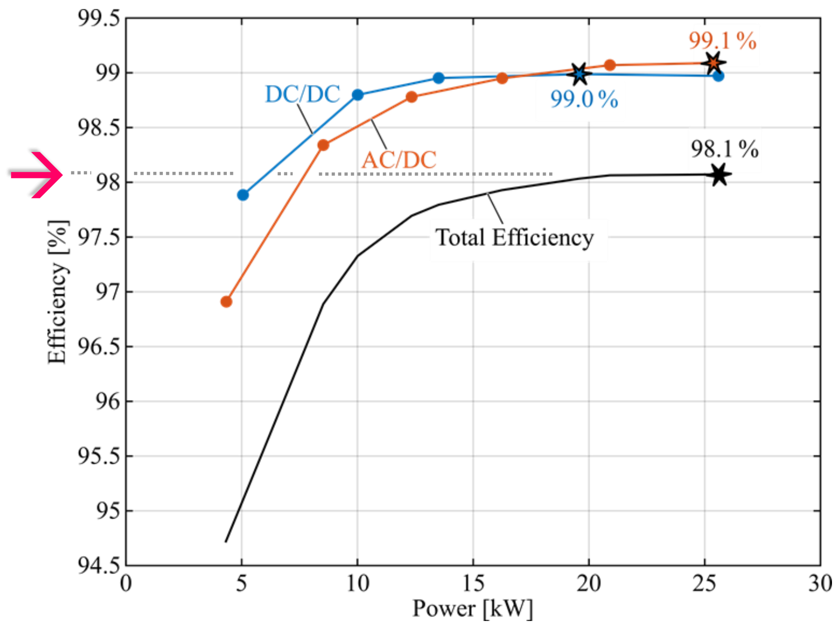




▶ Transformer Prototype / Loss Distribution / Efficiency

▶ Overall Performance

- *Full Soft-Switching*
- *98.1% Overall Efficiency @ 25kW*
- *1.8 kW/dm³ (30W/in³)*

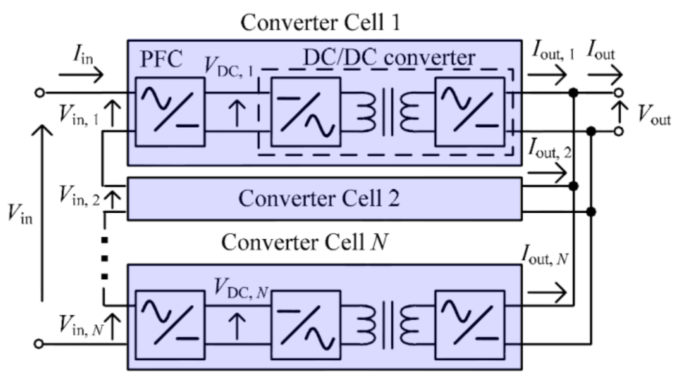


▶ *Red. of Losses & Volume by Factor of >2 Comp. to Alternative Approaches (!)*
▶ *Significantly Simpler Compared to Multi-Module SST Approach*

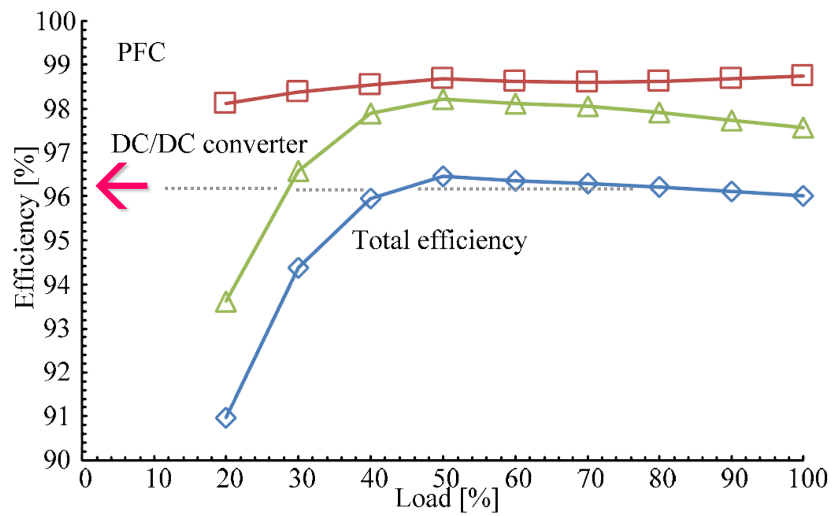
Remark 1-Φ 2.4 kV$_{rms}$ AC → 54V DC

Fuji Electric

- Published @ IEEE APEC 2017
- N=5 Series-Connected Cells @ MV-Side / Cost Optimum
- Input Stage Module → Boost PFC Half Contr. Thyr. Rect. / 1.2kV IGBTs & SiC Diodes
- Output Stage Module → 3-Level DC/DC Conv. - 600V SJ & 100V MOSFETs



Multi-cell converter.

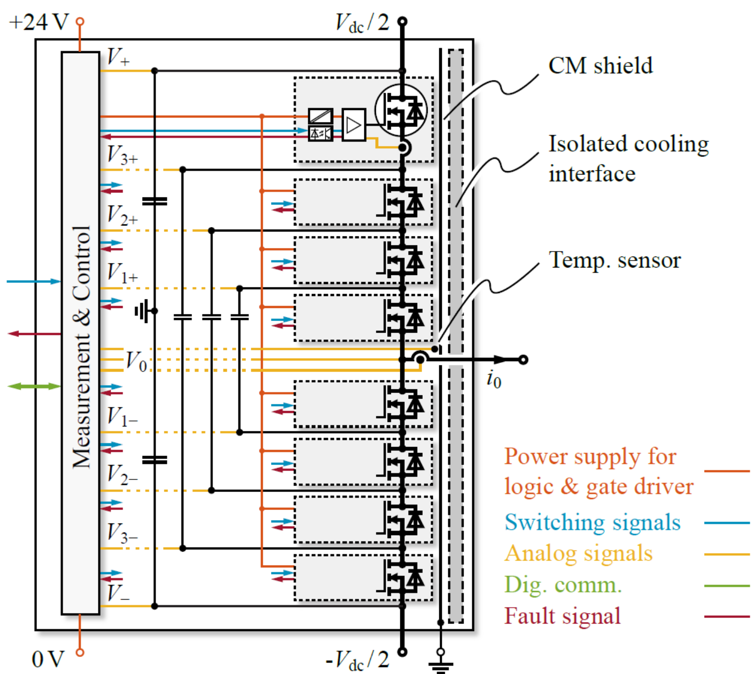


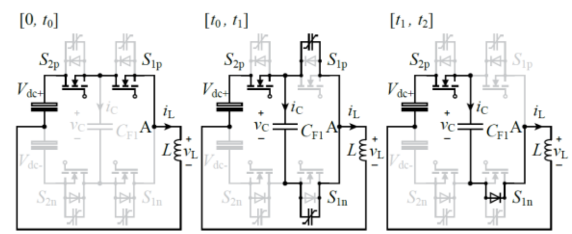
Efficiency of the prototype.

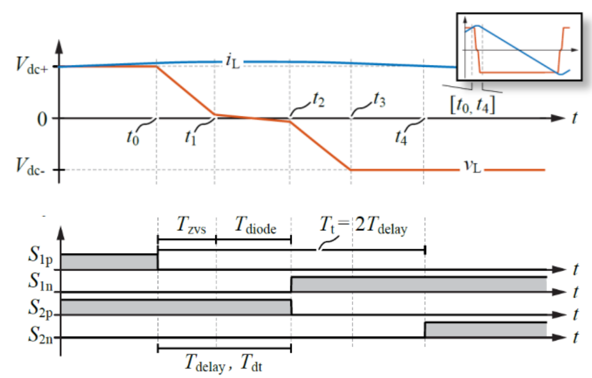
- Power Density of 0.4kW/dm³ (6.6W/in³)
- 96% Overall Efficiency @ 25kW

▶ 40kV SiC Super-Switch @ ETH Zurich

- *Cascaded 10kV SiC MOSFETs*
- *Quasi-X-Level (Staggered) Switching*
- *Intellig. Power Module — Two-Level Bridge-Leg Appearance*



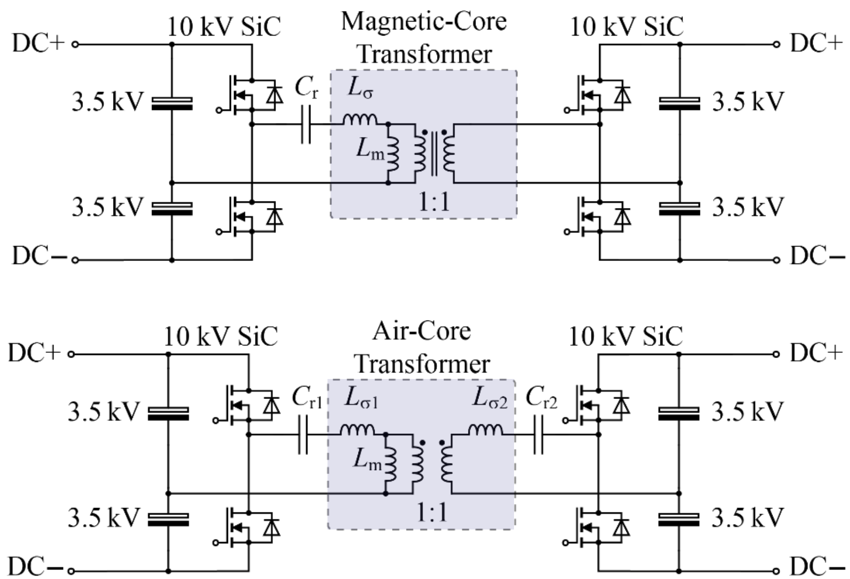


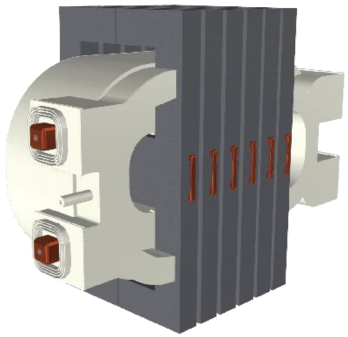


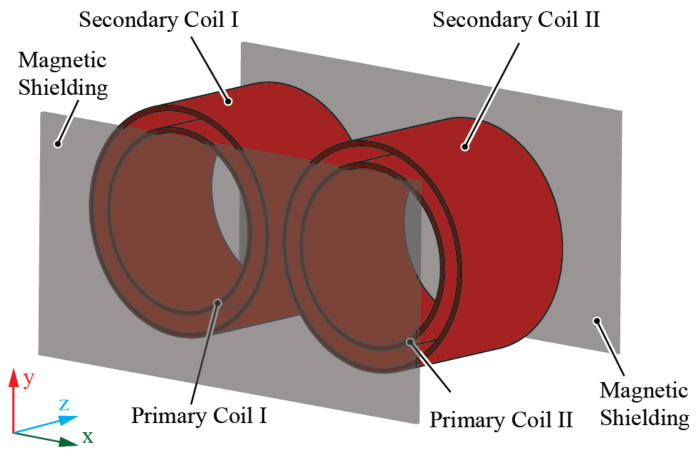
- *Integrated Gate Drive / Voltage Balancing / Protection / Isol. Cooling Surface etc.*

▶ SST — Air-Core vs. Magnetic-Core XFRM (1)

- Rated Power 166kW
- DC/DC Conversion 7kV / 7kV

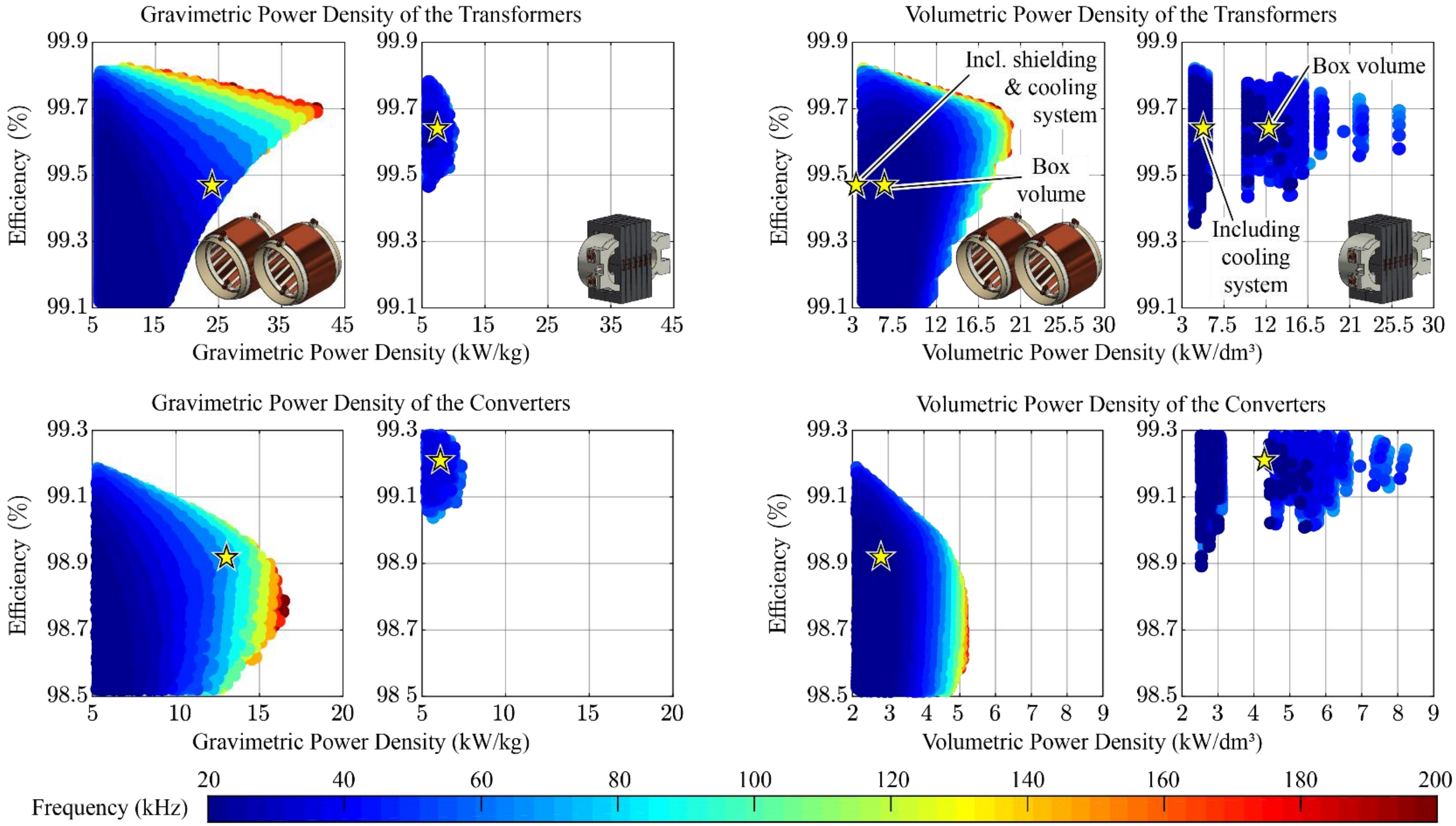






▶ Clarify Weight / Efficiency Trade-Off

► SST — Air-Core vs. Magnetic-Core XFRM (2)

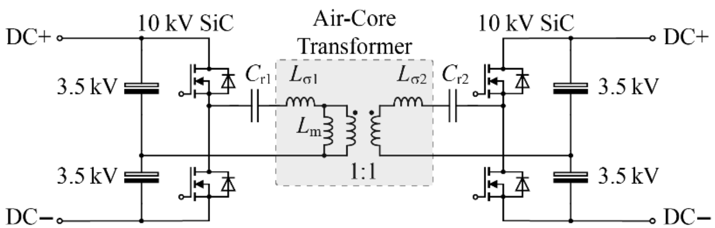


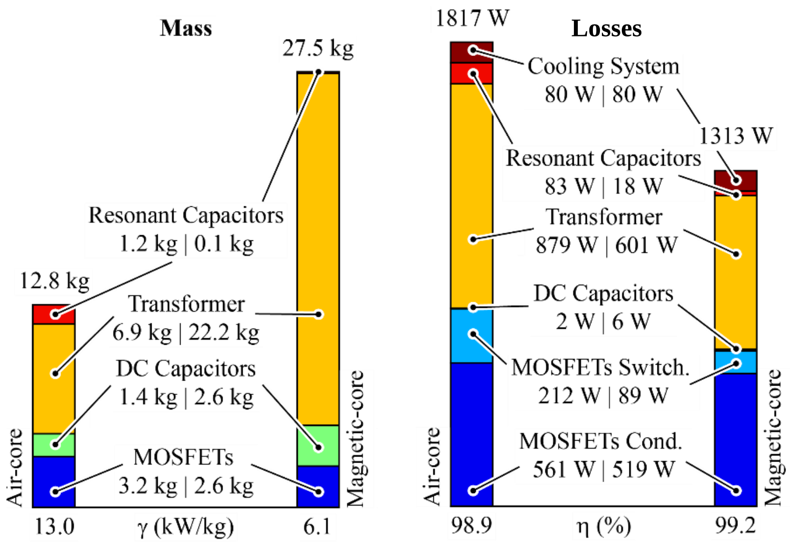
■ *η-γ-ρ-Pareto Fronts of Transformers & Converters*

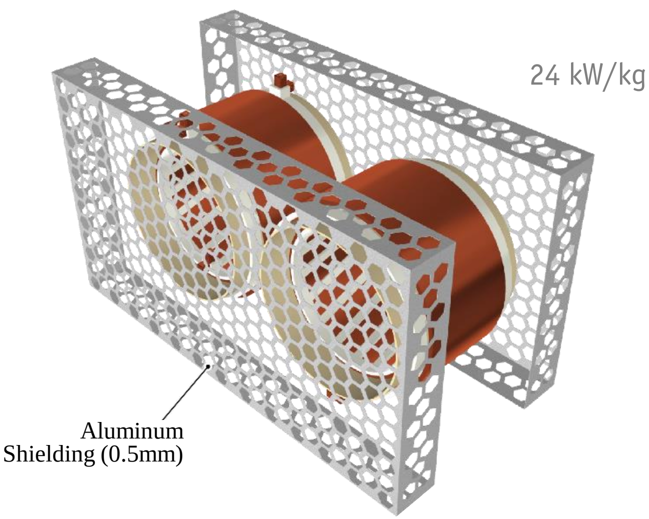
▶ SST — Air-Core vs. Magnetic-Core XFRM (3)

- **Air Core SST** → 98.9% / 12.8kg (77kHz)
- **Mag. Core SST** → 99.2% / 27.2kg (40kHz)

★ 13 kW/kg







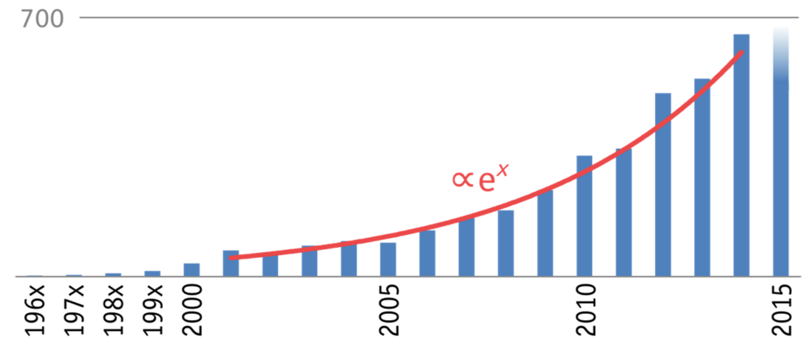
▶ **Weight / Efficiency Trade-Off**

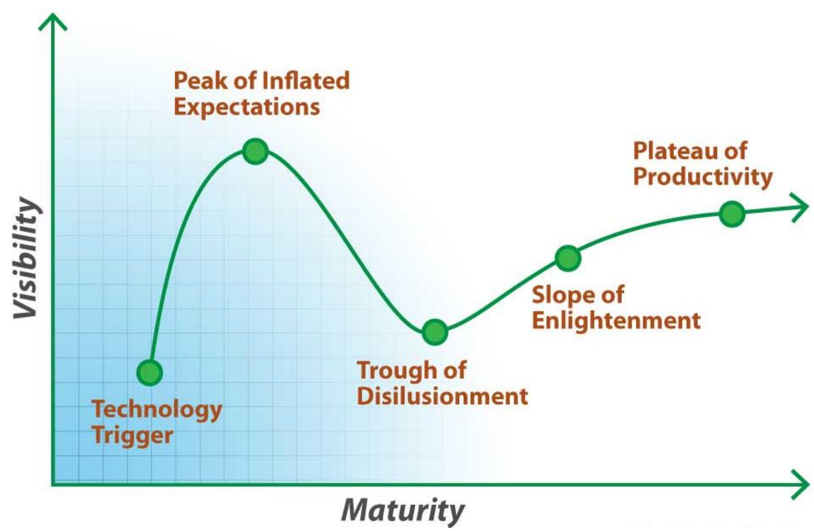
Conclusions

SST Limitations / Concepts
Research Areas

▶ The Solid-State Transformer Hype

- Large # of Publications !
- Research on Main Application Challenges Currently Largely Missing





Source: And Update My Website AndUpdateMyWebsite.com

- ▶ Protection (?)
- ▶ Control in Active Grids (?)
- ▶ System Level Adv. (?)

► SST Applications → *The Road Ahead*

■ NOT (!) Weight / Space Limited
■ Smart Grid, Stationary Applications

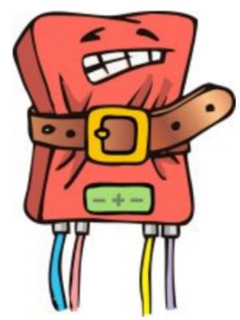
● AC/AC
- Efficiency Challenge
- More Eff. Voltage Control by
  * Tap Changers
  * Series Regulators (Partial Power)
- Not Compatible w. Existing Infrastr.
- Cost / Robustness / Reliability

● AC/DC
- Efficiency Challenge more Balanced
- "Local" Applic. (Datacenters, DC Distr.)
- Cost / Robustness / Reliability

● DC/DC
- No Other Option (!)
- MV DC Collection Grids (Wind, PV)
- Sw. Frequ. as DOF of Design

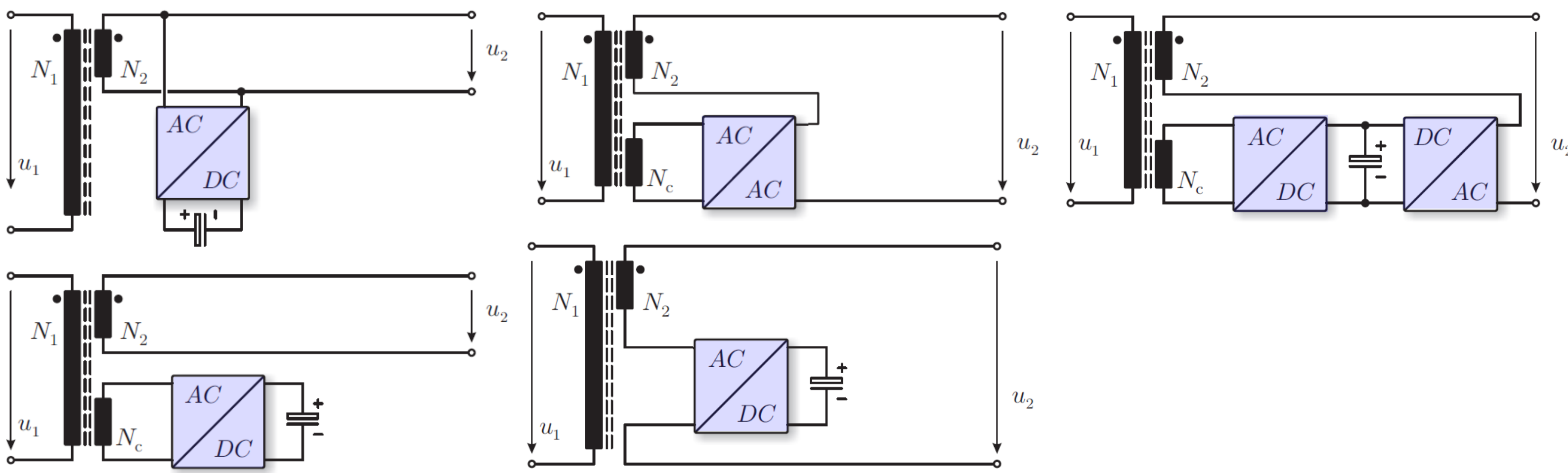
■ Weight / Space Limited
■ Traction Applic. etc.

● DC/DC
● AC/DC
● AC/AC
- Sw. Frequ. as DOF of Design
- Low Weight/Volume @ High Eff.
- Local Applic. (Load/Source Integr.)



Remark "Hybrid" Transformers

- Combination of Mains-Frequ. Transformer & SST
- Fractional Power Processing → High Efficiency
- Low Blocking Voltage Requirement
- Simplified Protection

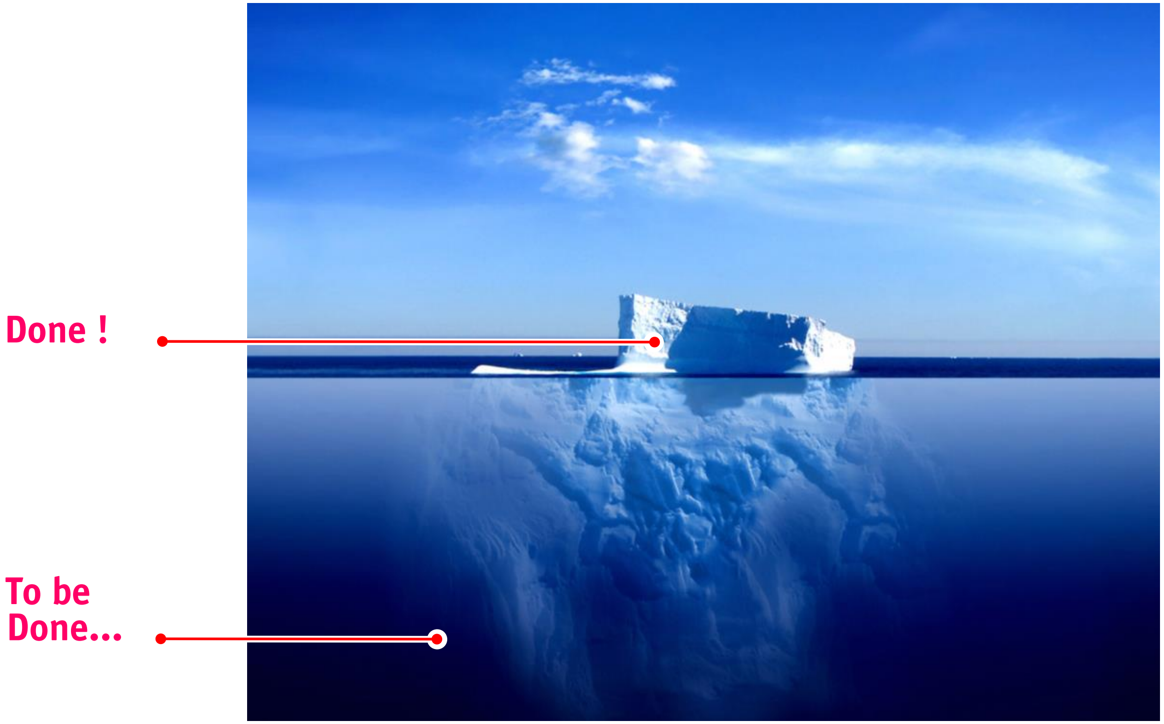


▶ **Shunt Connection**
— Reactive Current Inj.
— Harm. Curr. Inj.

▶ **Series Connection**
— Reactive Voltage Inj.
— Phase Shiftg / Volt. Cntrl

▶ **Combined Connection**
— Reactive / Harm. Curr. Inj.
— Volt. Cntrl / Phase Shiftg

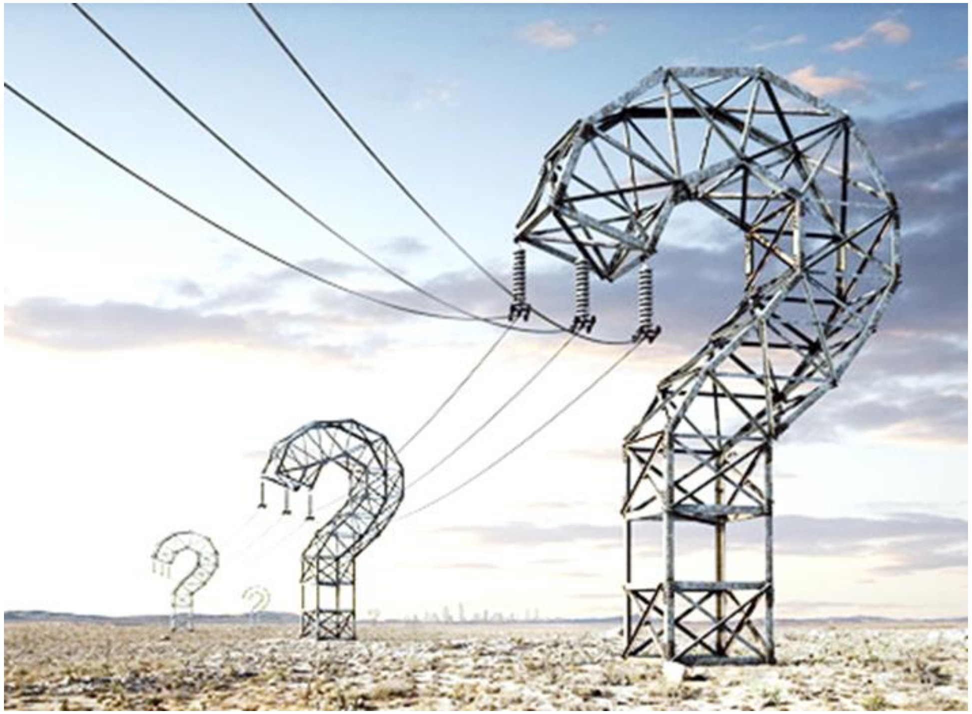
▶ Current SST Research Status



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

Thank You!

Questions



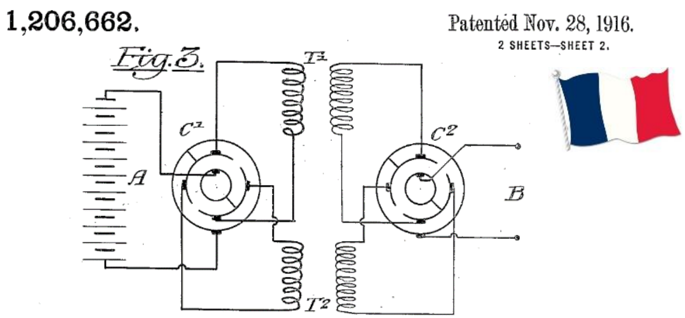
Source: P. Aylward

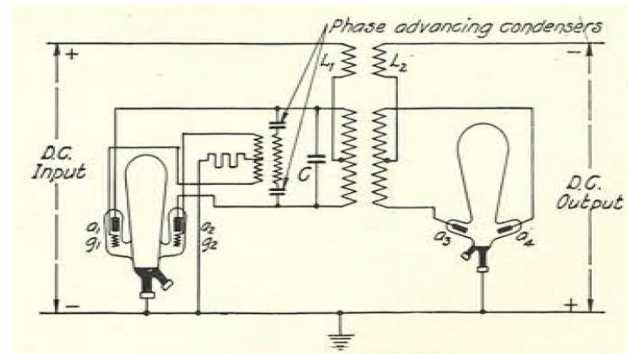
www.pes.ee.ethz.ch/publications.html


BACKUP

Electronic Transformer - History

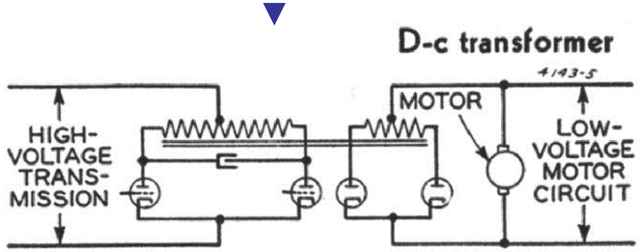
- System Using Mech. Switches *Patented Already in 1913* (!)
- Mechanical Sw. → Tubes → Mercury Arc Valves → Solid State Switches

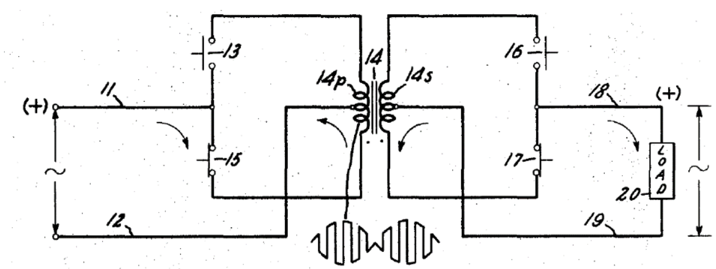




▲
1913 — *P.M.J. Boucherot*
1944 — *E.F.W. Alexanderson et al.*
▼

1928 — *D.C. Prince* ▲
1968 — *W. McMurray* ▼





- “Transformer of Cont. Current” / “DC Transformer” / “Electronic Transformer”

United States Patent Office

3,517,300
Patented June 23, 1970 ← 1970 !

1

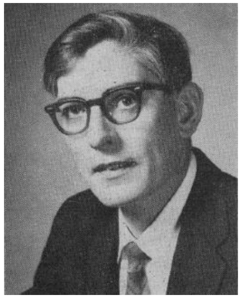
3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK

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

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

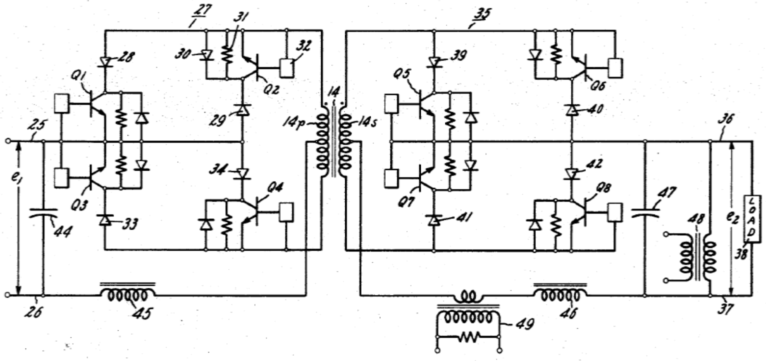
ABSTRACT OF THE DISCLOSURE

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



Inventor:
William McMurray,
by
His Attorney.

Fig. 3.



- Transistor/Diode-Based "Electronic Transformer"
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption