ETH zürich

TGZ
TECHNISCHE GESELLSCHAFT ZÜRICH

Intelligente Transformatoren für das Energienetz der Zukunft

Konzepte – Herausforderungen – Anwendungen

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Industry Relations
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ECPE Competence Centre

EPSMA

Leading Univ. in Europe

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Outline

- Transformer Basics
- Solid-State Transformer (SST) Concept
- Key SST Realization Challenges
  - #1 Power Semiconductors
  - #2 Topologies
  - #3 Medium Frequency Transformer
  - #4 Protection
  - #5 Reliability
- Industry Demonstrator Systems
- Potential Future Applications
- Conclusions

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

Transformer Basics

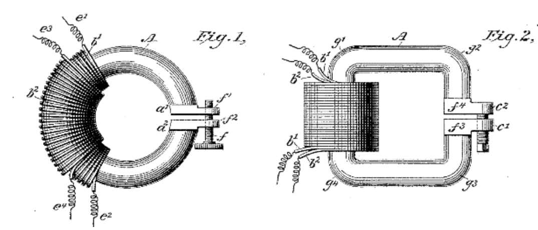
History
Scaling Laws
Efficiency / Power Density Trade-off

► Classical Transformer (XFMR) – History (1)

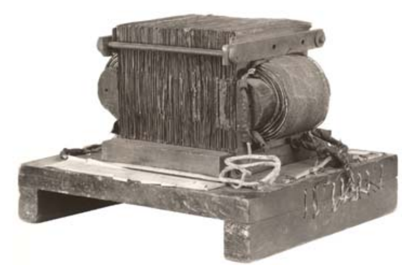
* 1830 - Henry/Faraday → Property of Induction
* 1878 - Ganz Company (Hungary) → Toroidal Transformer (AC Incandescent Syst.)
* 1880 - Ferranti → Early Transformer
* 1882 - Gaulard & Gibbs → Linear Shape XFMR (1884, 2kV, 40km)
* 1884 - Blathy/Zipernowski/Deri → Toroidal XFMR (Inverse Type)

Europe

USA

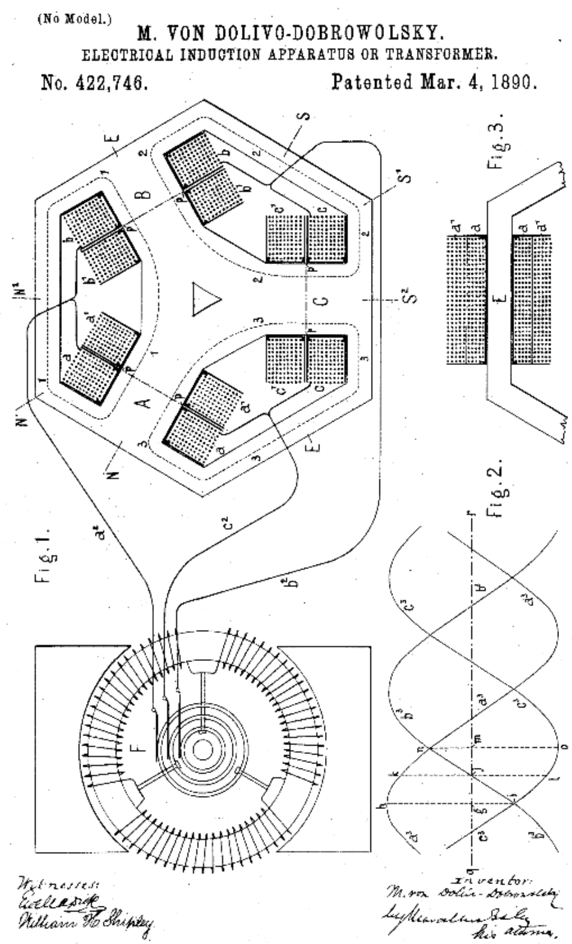


W. STANLEY, Jr.
INDUCTION COIL.
No. 349,611. Patented Sept. 21, 1886.



* 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.)

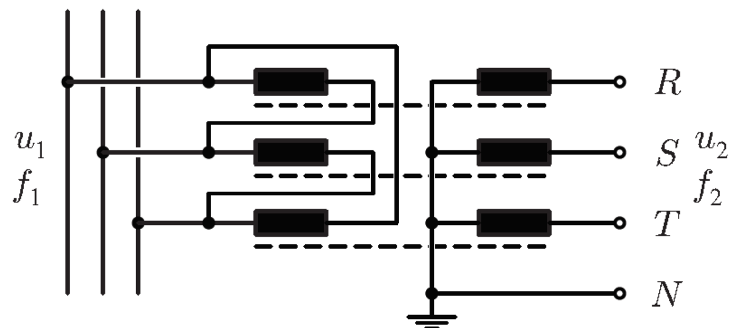
* 1890 - Dobrovolski → 3-Phase Transformer
* 1891 - 1st Complete AC System (Gen.+XFMR+Transm.+El. Motor+Lamps, 40Hz, 25kV, 175km)

▶ 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 ($f_1 = f_2$)

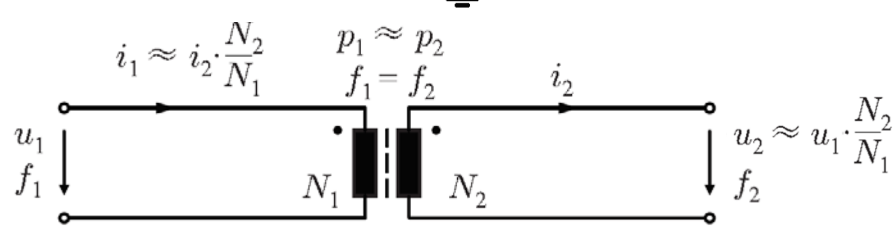


- Magnetic Core Cross Section

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

- Winding Window

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



▶ Classical Transformer – Basics (2)

Source: www.faceofmalawi.com

■ Advantages

- Relatively Inexpensive
- Highly Robust / Reliable
- Highly Efficient
- Short Circuit Current Limitation

▶ Classical Transformer – Basics (3)

■ 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
- Not Directly Controllable
- Dependency of Weight / Volume on Frequency
- Sensitivity to DC Offset Load Imbalances
- Sensitivity to Harmonics

- Construction Volume

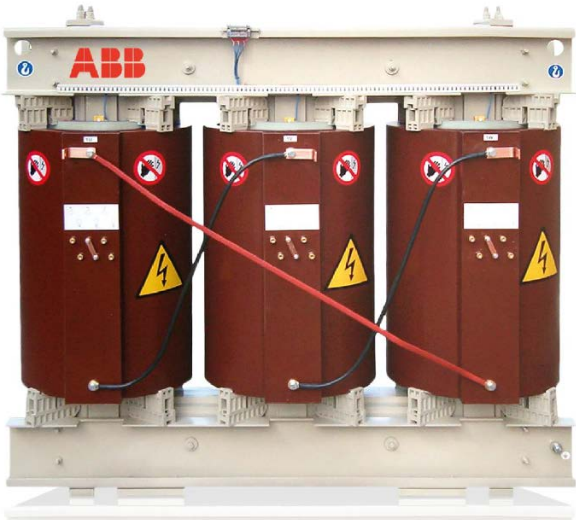
$$A_{Core} A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

↑ ↑ ↑

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

- Low Frequency → Large Weight / Volume

Vacuum Cast Coil Dry-Type
Distribution Transformer



1 MVA – 12kV/400V @ 2600kg
0.2%/1% Losses @ No/Rated Load

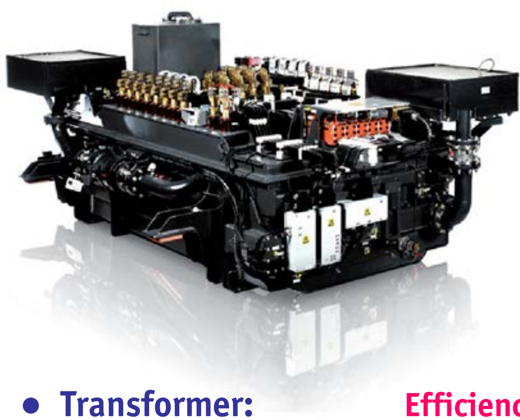
SST Motivation

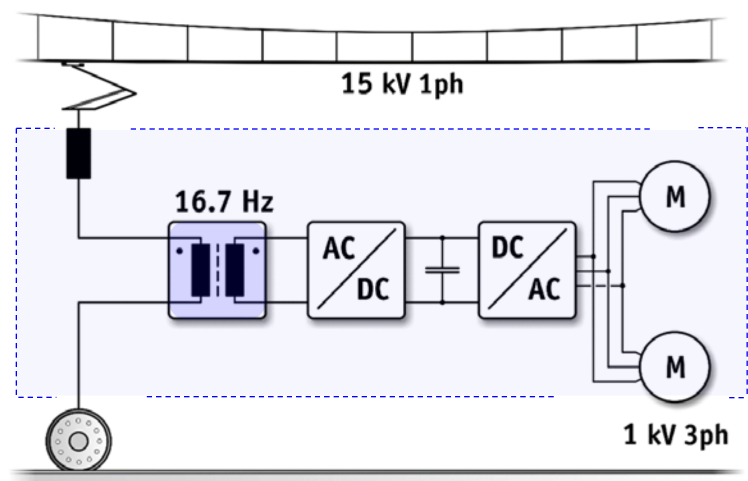
Next Generation
Traction Vehicles

▶ Classical Locomotives

- Catenary Voltage 15kV or 25kV
- Frequency $16^{2}/_{3}$Hz or 50Hz
- Power Level 1...10MW typ.

Source: www.abb.com



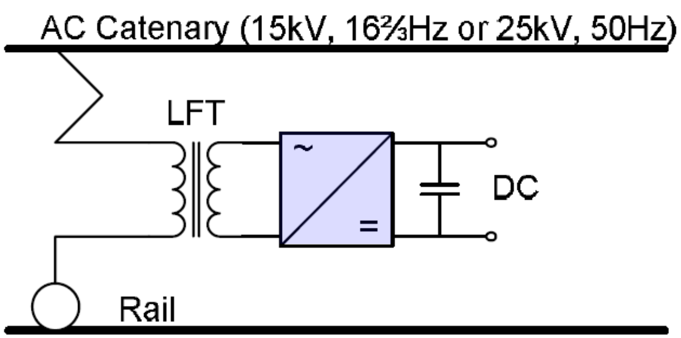


- Transformer: Efficiency 90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
  Current Density 6 A/mm² (2A/mm² typ. Distribution Transformer)
  Power Density 2...4 kg/kVA

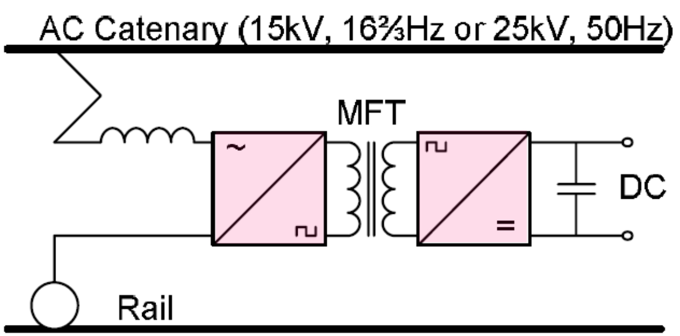
▶ Next Generation Locomotives

- **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).

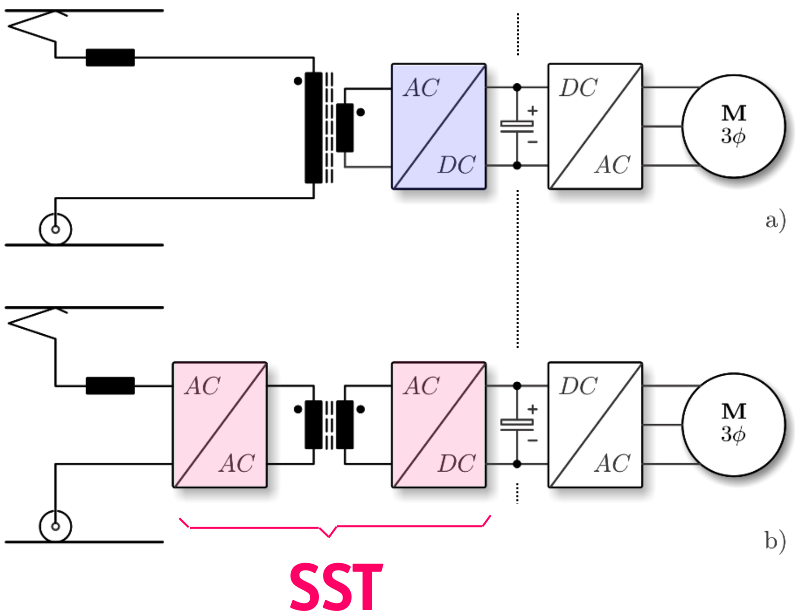


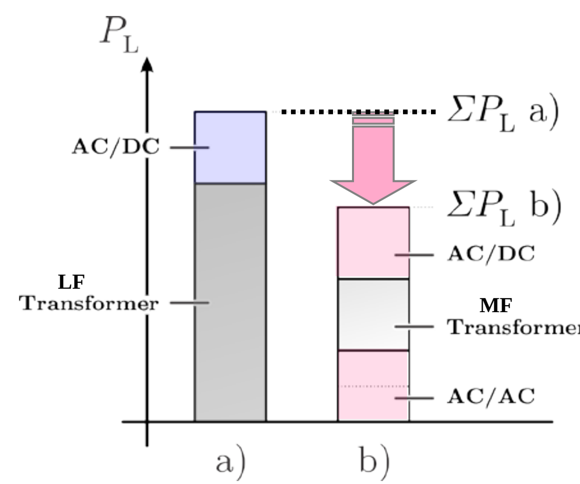
AC-DC conversion with medium frequency transformer (MFT).

- 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





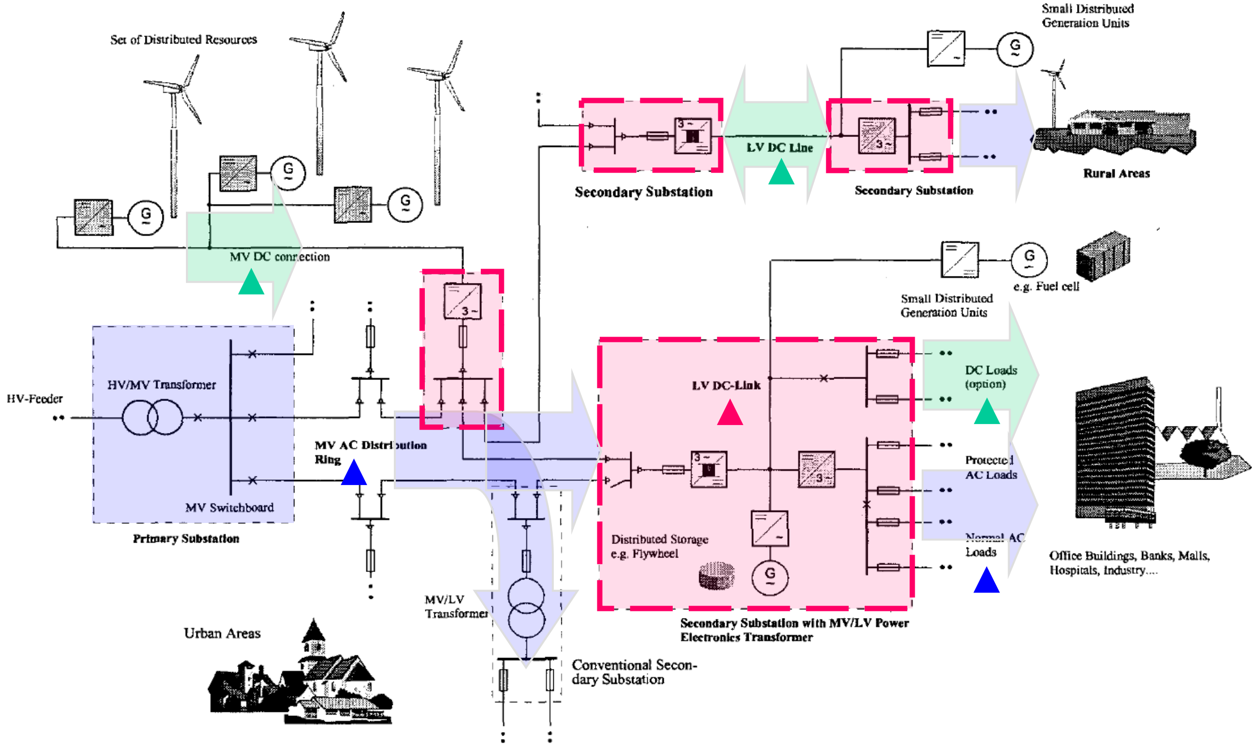
- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

Future Smart EE Distribution

Source: TU Munich

▶ Advanced (High Power Quality) Grid Concept

- Heinemann / ABB (2001)



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

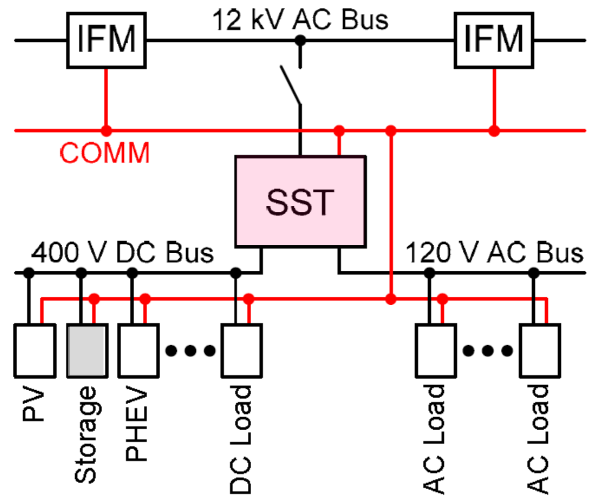
► Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

- Huang et al. (2008)

● SST as Enabling Technology for the "Energy Internet"

- 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.

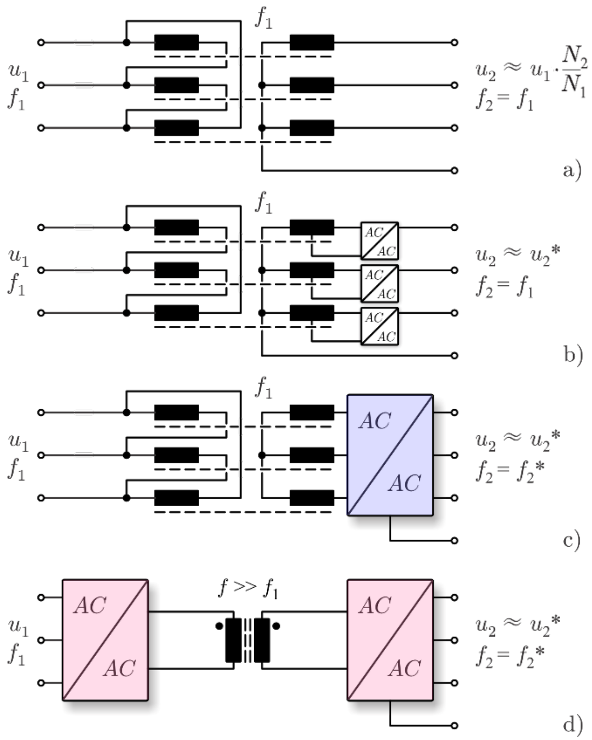
IFM = Intellig. Fault Management



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

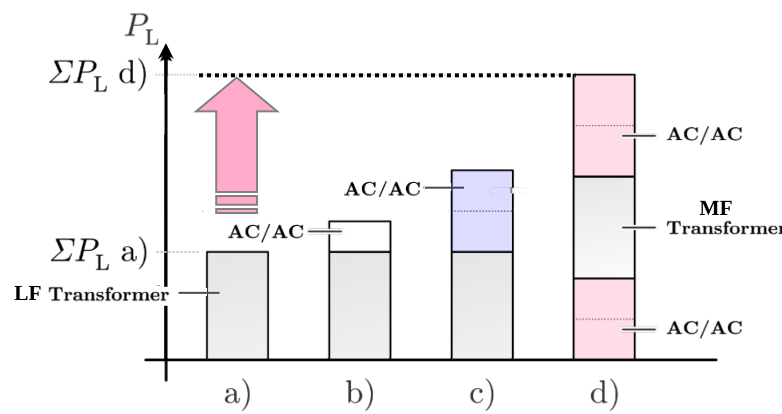
► Passive Transformer → SST

- 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

SST Concept Implementation

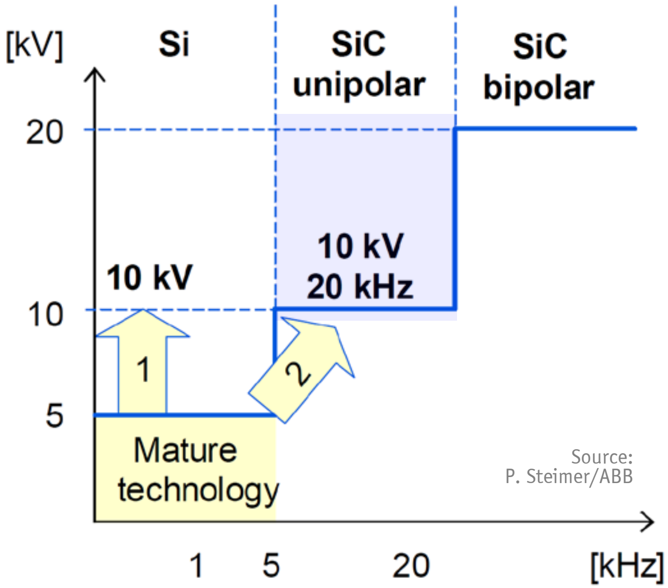
Challenge #1/5

Availability / Selection of Power Semiconductors

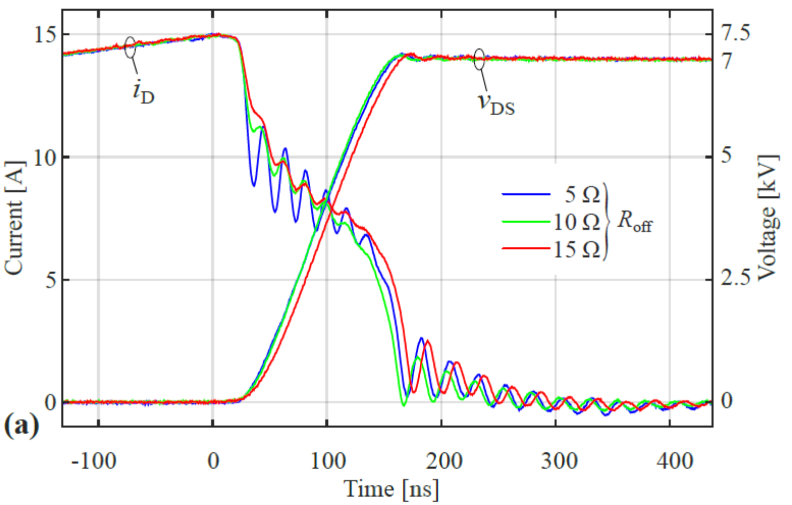
▶ SiC Power Semiconductors

- **Samples**

* 10kV & 15kV / 10A MOSFETs
* 10kV & 15kV / 8A JBS Diodes
* 15kV / 20A IGBTs



- **Soft-Switching (ZVS) Performance**
10kV MOSFET @ 15A
(250uJ)



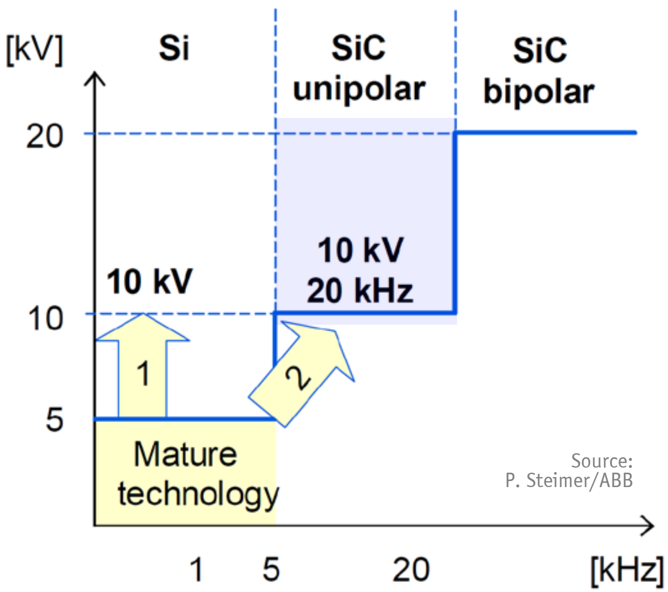
■ **Interfacing to Medium Voltage → Two-Level *OR* Multi-Level Converter Topologies**

▶ SiC Power Semiconductors

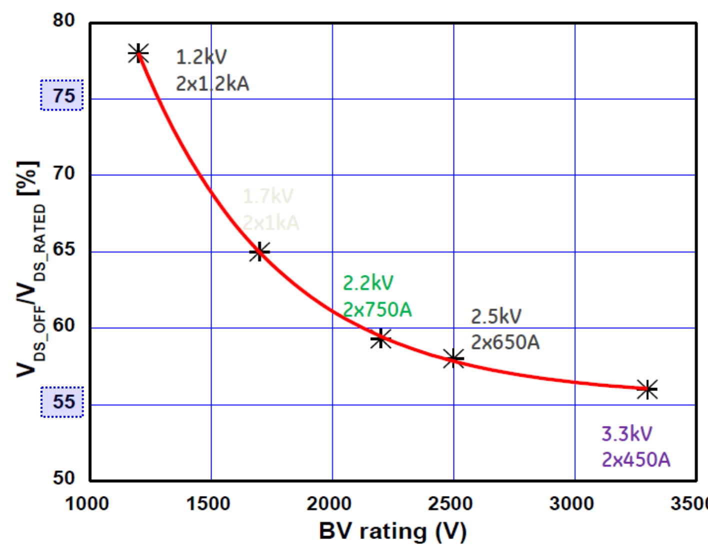
- **Samples** Wolfspeed

* 10kV & 15kV / 10A MOSFETs
* 10kV & 15kV / 8A JBS Diodes
* 15kV / 20A IGBTs

- **Derating Requirement due to Cosmic Radiation for 100 FIT @ 25°C & 0 m AMSL** A_{act}=7.2cm²



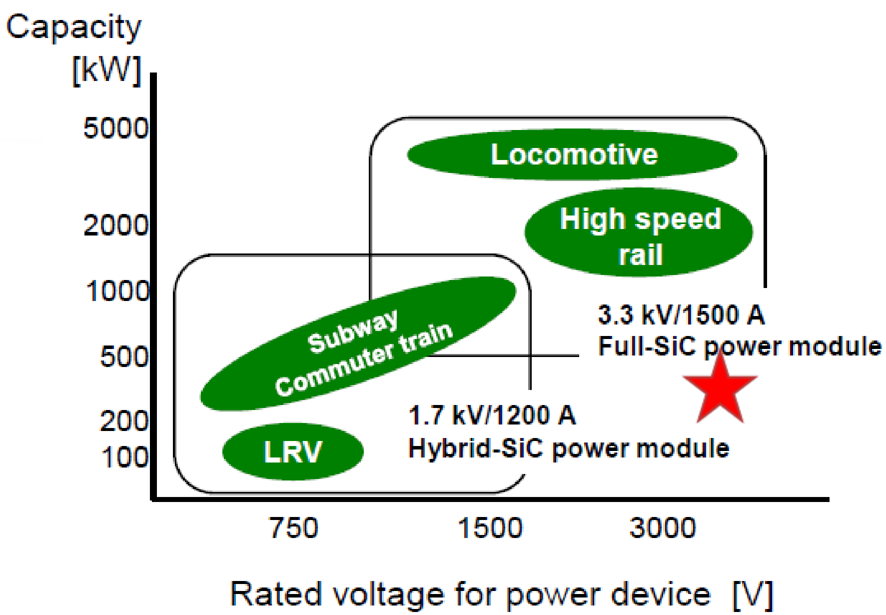
Source: P. Sandvik
R. Datta

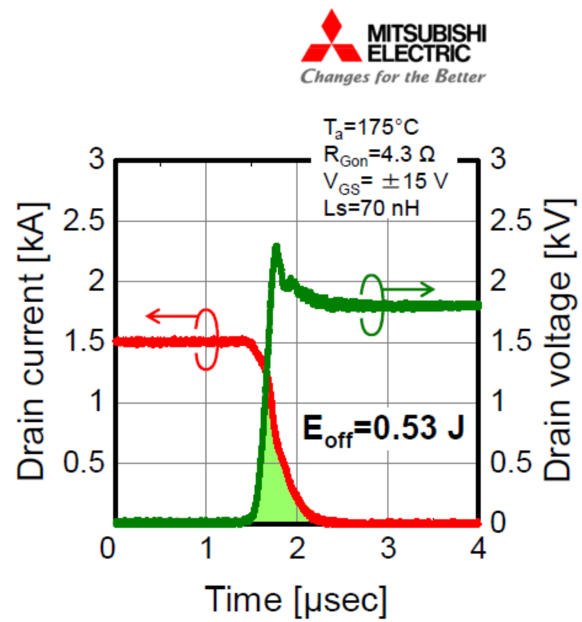


- **Interfacing to Medium Voltage → Two-Level *OR* Multi-Level Converter Topologies**

▶ Commercially Available SiC Power Semiconductors

- High Current 3.3kV / 1.7kV / 1.2 kV Power Modules
- Mitsubishi (CREE, ROHM, GE, etc.)



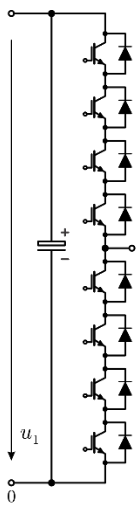


Challenge #2/5

Creation of MV → LV SST Topologies

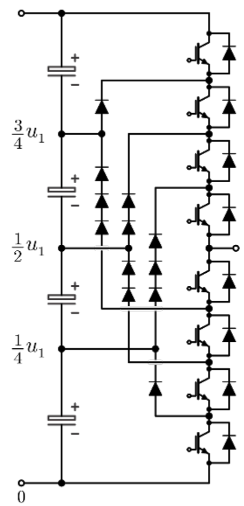
▶ Interfacing to Medium Voltage

- Partitioning of Blocking Voltage
- Series Connection or Multi-Cell and Multi-Level Approaches
- High Number *N* Cells → Quadratically Reduces Curr. Harmonics



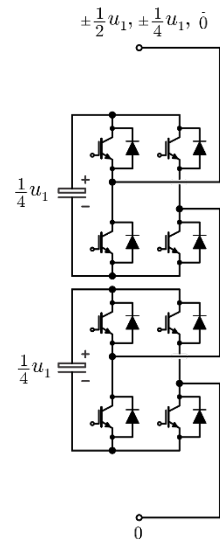
* Two-Level Topology

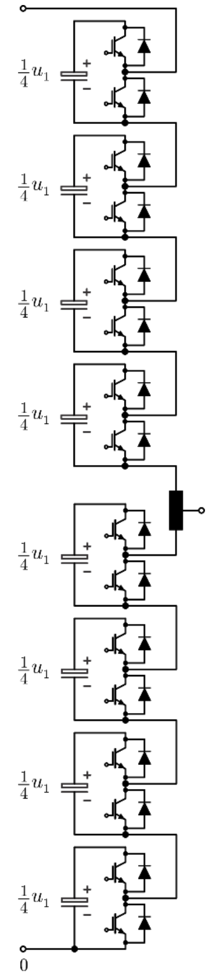
Akagi (1981)



Marquardt

McMurray (1969)



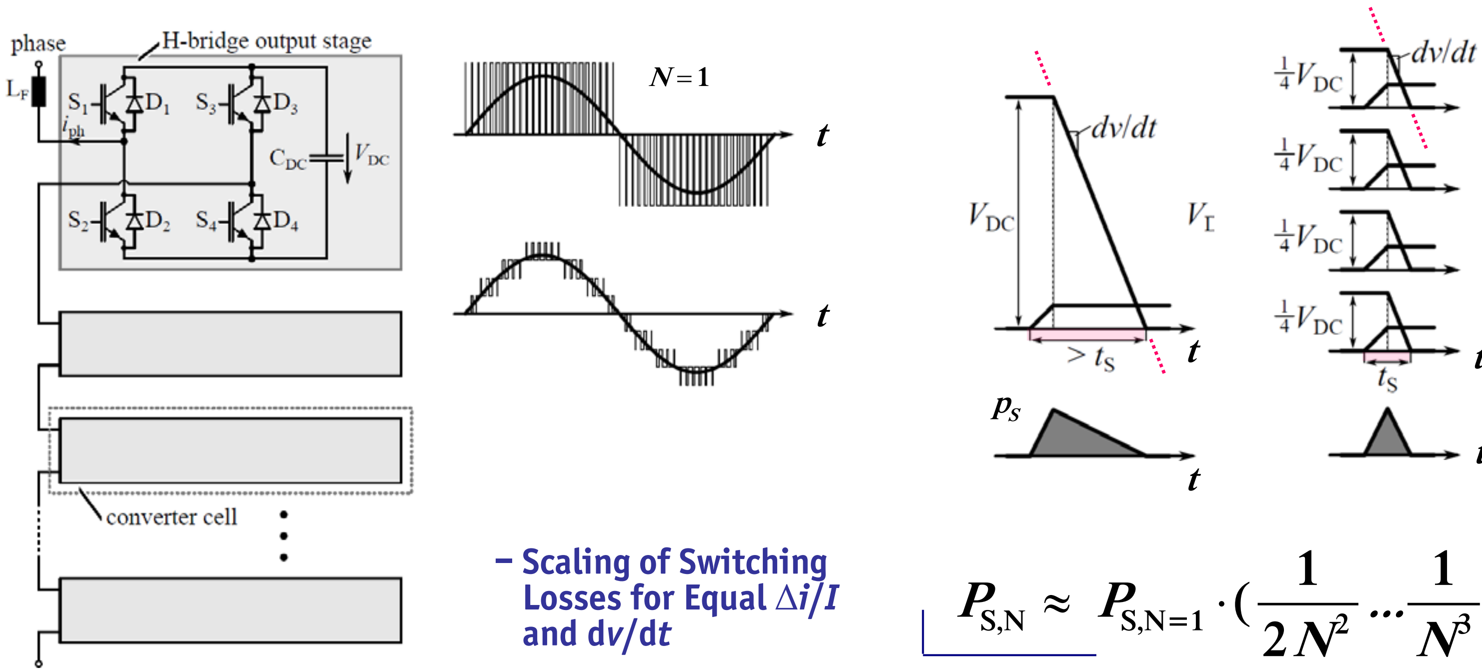


Alesina/ Venturini (1981)

* Multi-Level/ Multi-Cell Topologies

► Scaling of Series Interleaving of Converter Cells

■ Interleaved Series Connection Dramatically Reduces Switching Losses (or Harmonics)



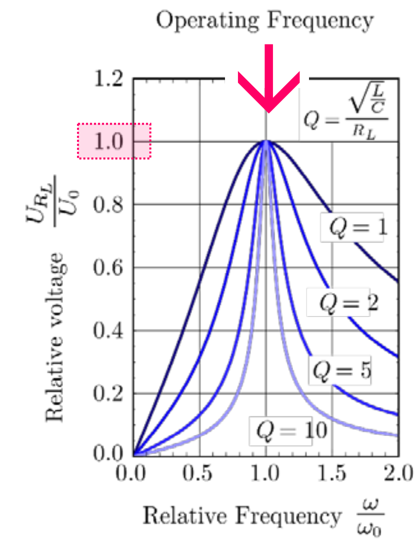
– Scaling of Switching Losses for Equal $\Delta i/I$ and dv/dt

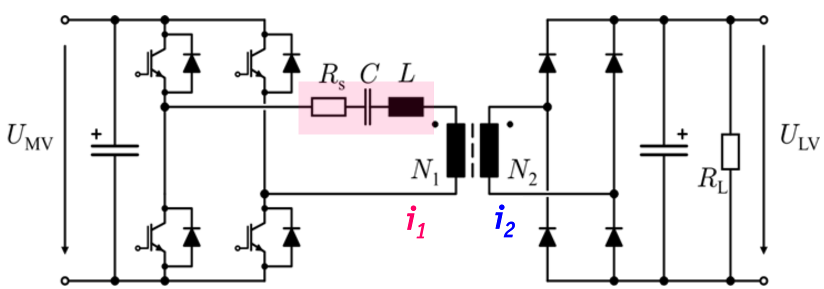
$$P_{S,N} \approx P_{S,N=1} \cdot \left(\frac{1}{2N^2} \dots \frac{1}{N^3}\right)$$

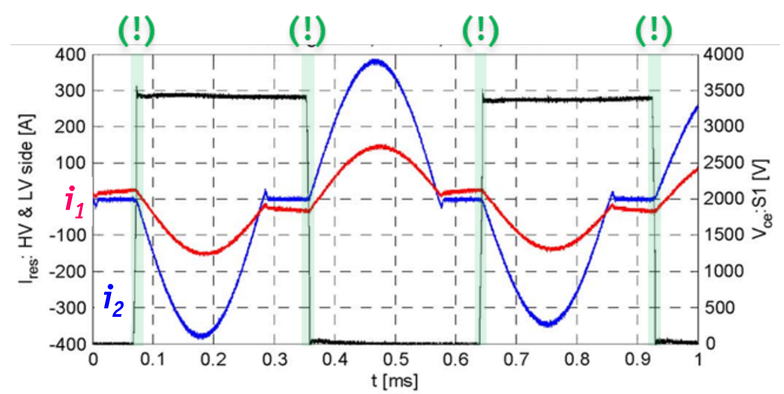
■ Converter Cells Could Operate at VERY Low Switching Frequency
■ Minimization of Passives (Filter Components)

► Half-Cycle DCM Series Resonant Converter (HC-DCM-SRC)

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







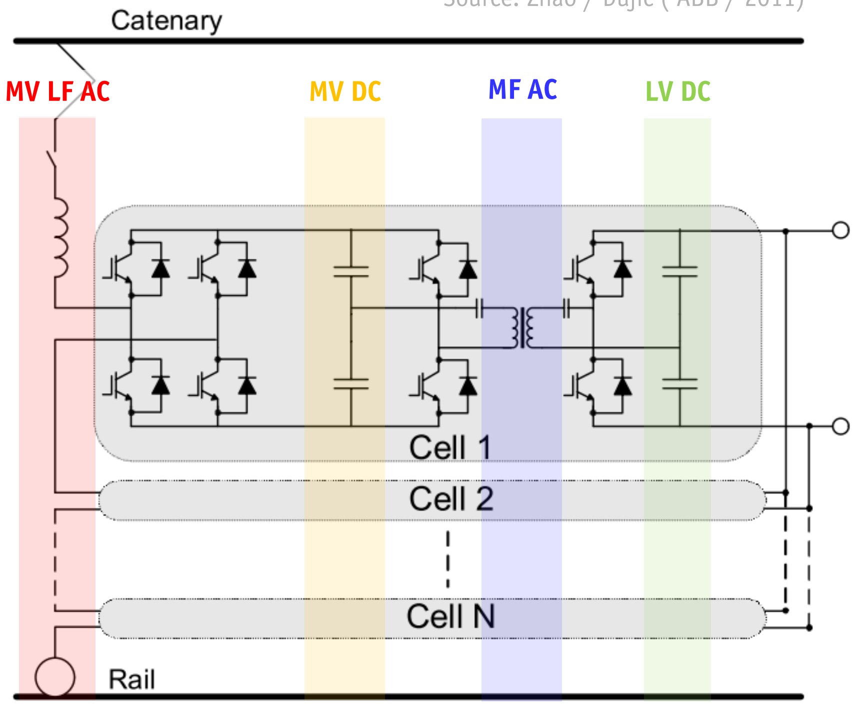
Combining the Basic Concepts I

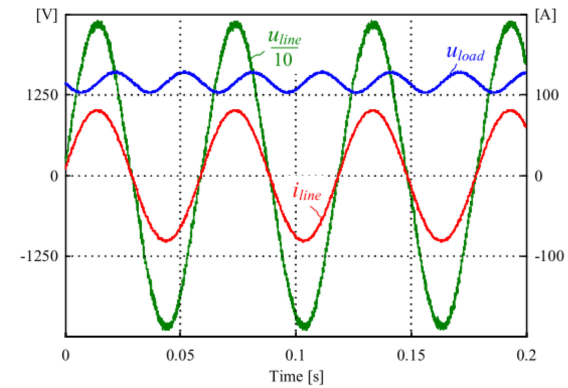
Single-Phase AC-DC Conversion / Traction Applications

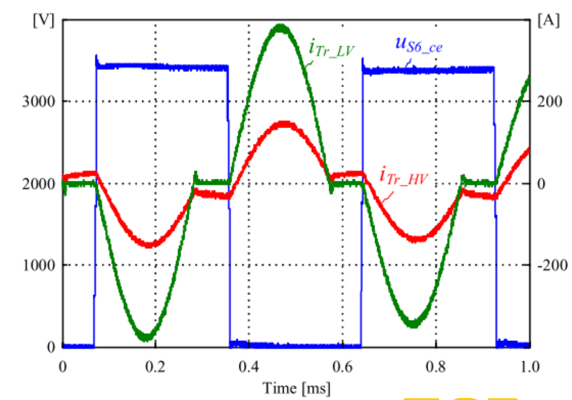
Cascaded H-Bridges w. Isolated Back End

- 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)

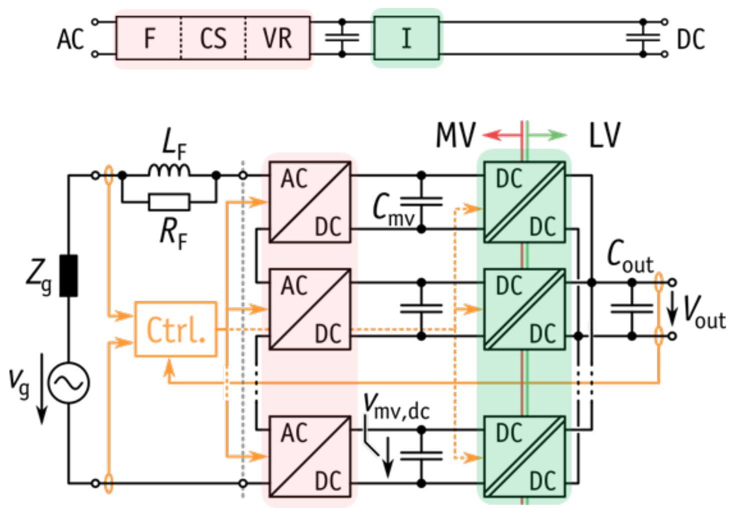






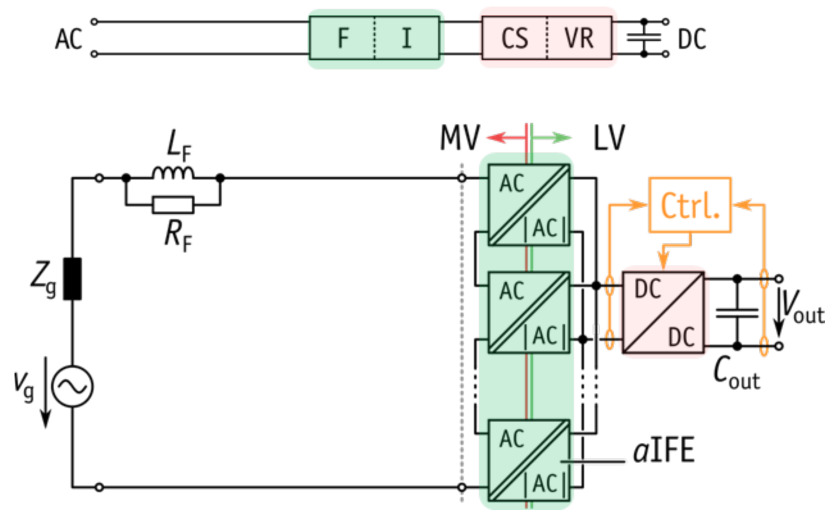
▶ Reversal of the Sequence of Current Shaping & Isolation

■ 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

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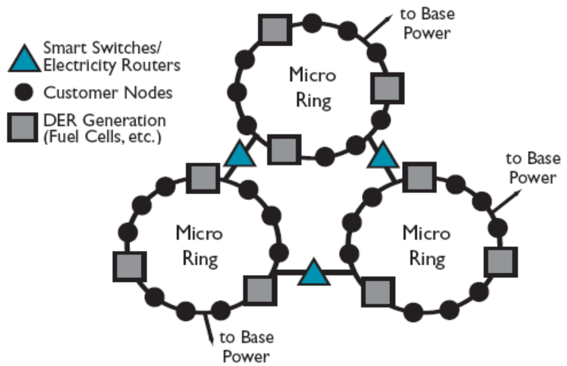
Combining the
Basic Concepts II

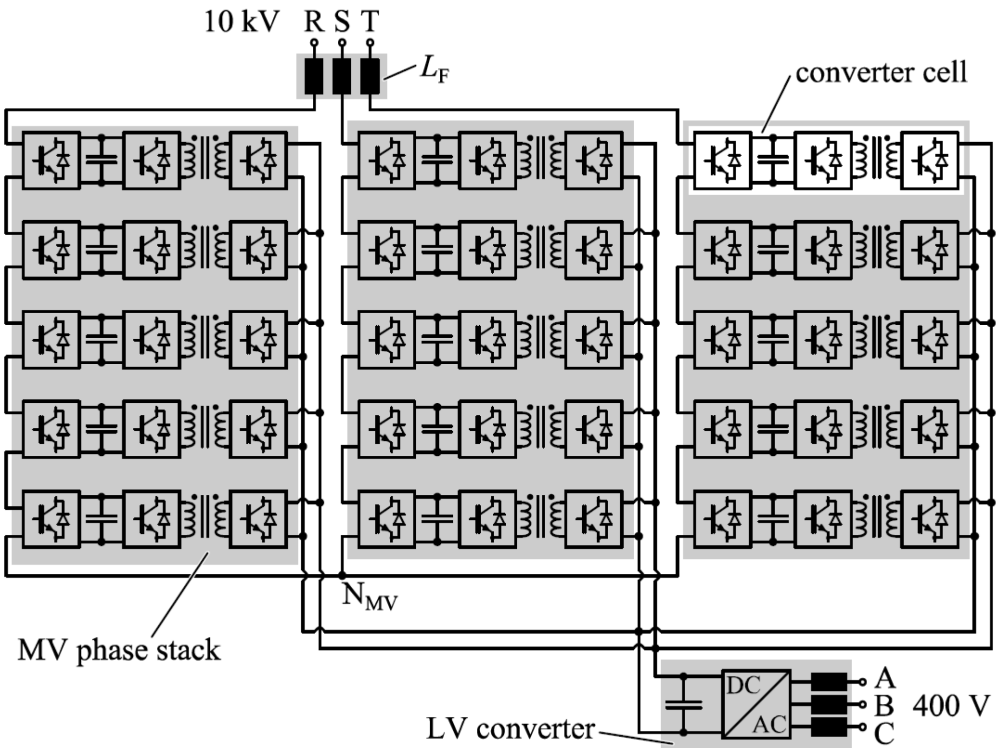
Three-Phase AC-AC Conversion /
Smart Grid Applications



Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

▶ MEGALink @ ETH Zurich

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

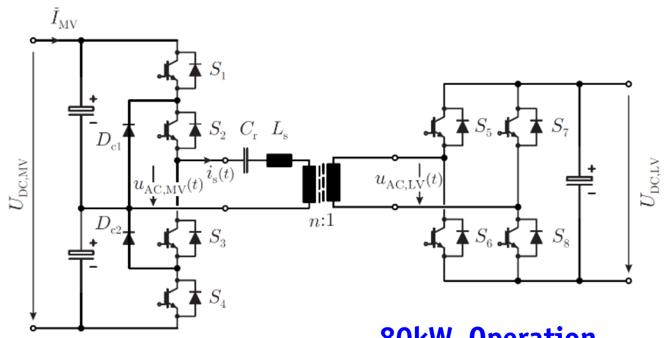


- 2-Level Inverter on LV Side
- HC-DCM-SRC DC//DC Conversion
- Cascaded H-Bridge MV Structure – ISOP Topology

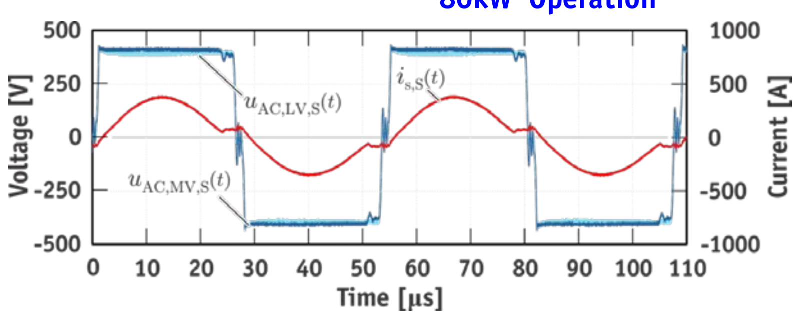
▶ 166kW / 20kHz HC-DCM-SRC DC-DC Converter Cell

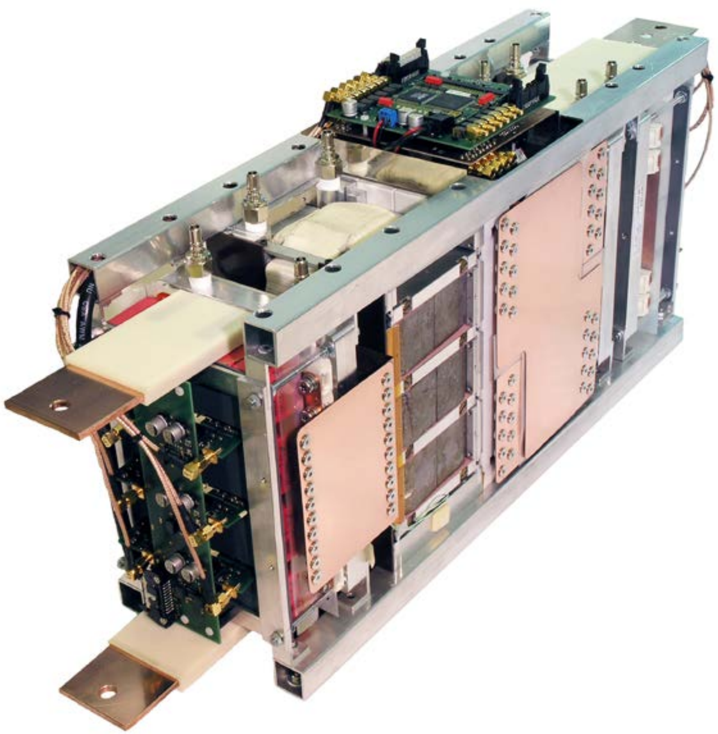
- Half-Cycle DCM Series Resonant DC-DC Converter

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



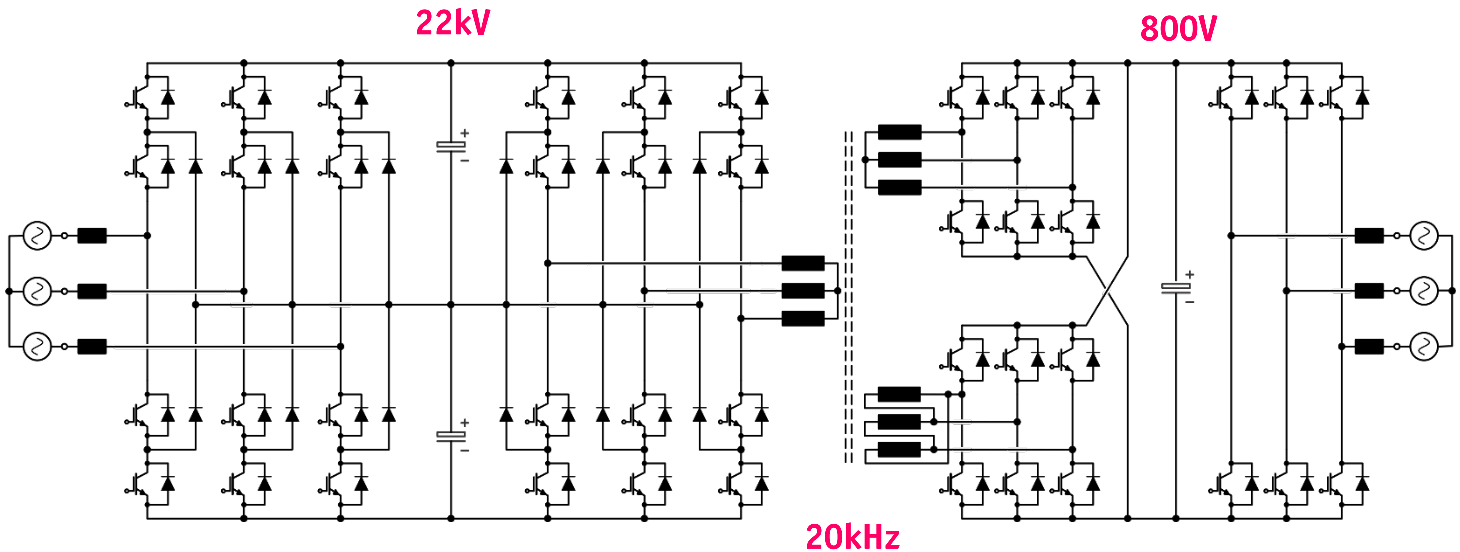
80kW Operation





▶ Single-Cell Structure

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



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

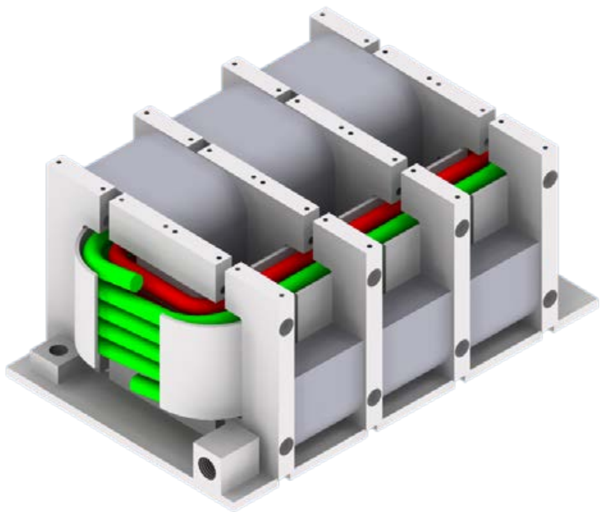
Challenge #3/5

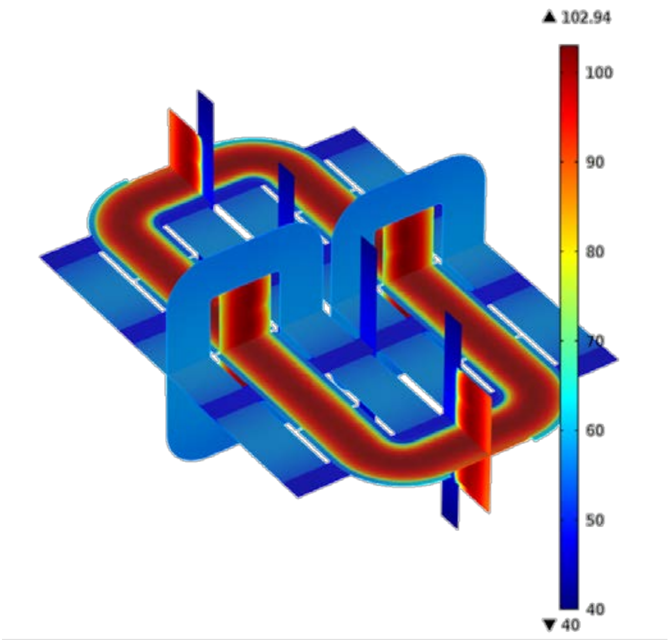
Medium-Frequency
Transformer Design

- *Heat Management*
- *Isolation*

▶ MF Transformer Design – Cold Plates/ Water Cooling

■ Nano-Crystalline 160kW/20kHz Transformer (ETH, Ortiz 2013)



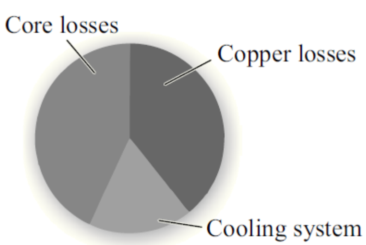


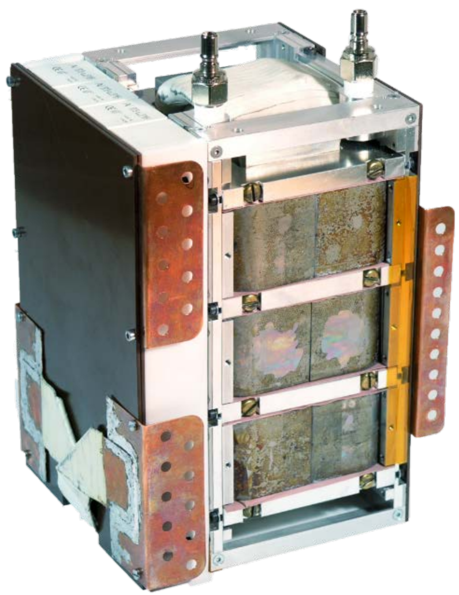
- Combination of Heat Conducting Plates and Top/Bottom Water-Cooled Cold Plates
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

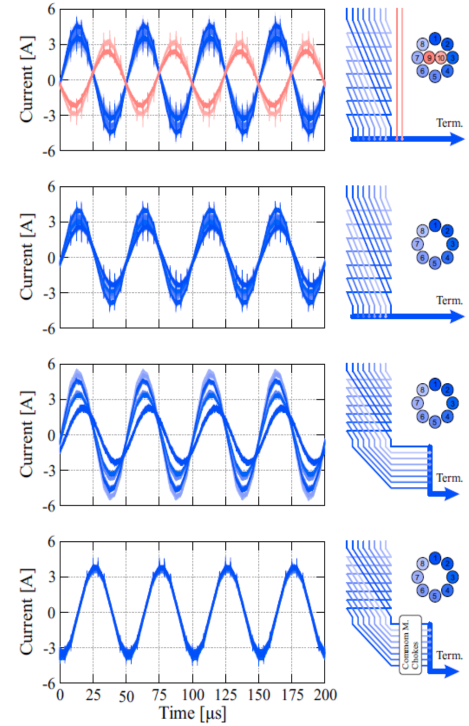
▶ Water-Cooled 20kHz Transformer

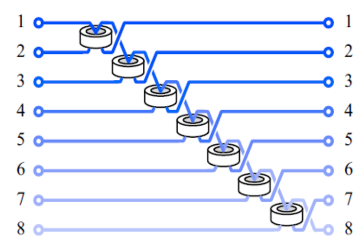
- Power Rating 166 kW
- Efficiency 99.5%
- Power Density 32 kW/dm^3

- Nanocrystalline Cores with 0.1mm Airgaps between Parallel Cores for Equal Flux Partitioning
- Litz Wire (10 Bundles) with CM Chokes for Equal Current Partitioning









Challenge #4/5

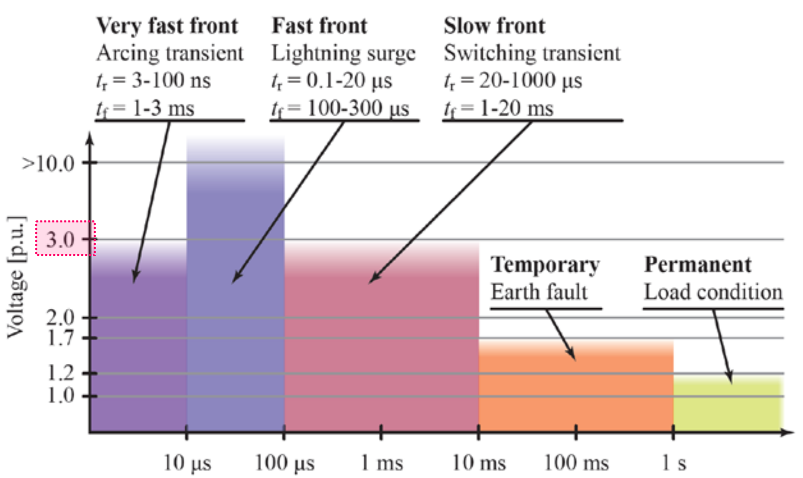
Mains ← SST → Load
Protection / Grid Codes

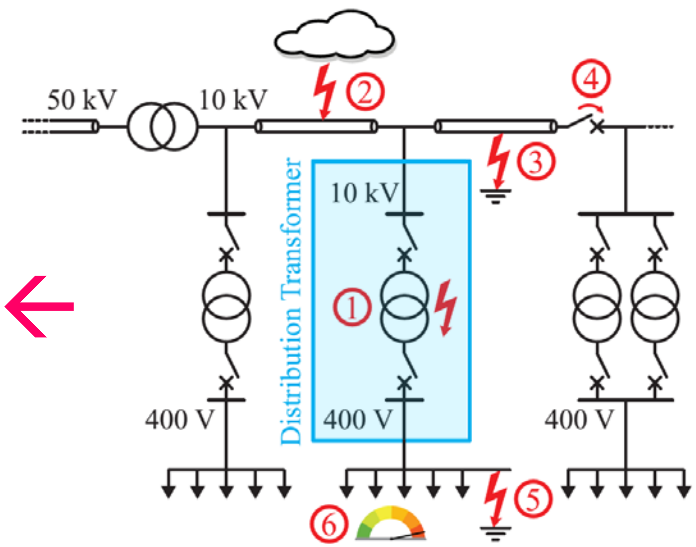
▶ Potential Faults of MV/LV Distribution-Type SSTs

- Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids
- SST more Appropriate for Local Industrial MV Grids

1. Internal Fault
2. Lightning Surge
3. Switching Transient
4. MV Short Circuit
5. LV Short Circuit
6. Non-Ideal Load

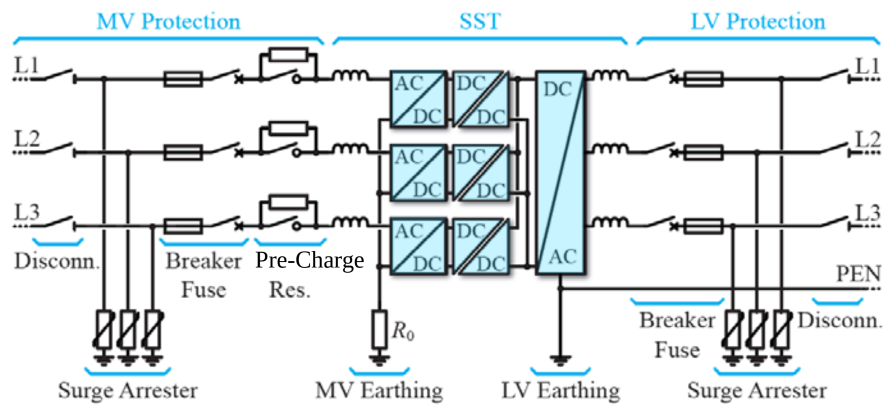
- Conv. MV Grid Time-Voltage Characteristic



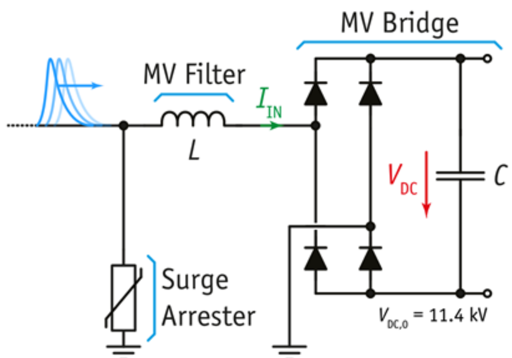


▶ Protection of LF-XFRM vs. SST Protection

■ Missing Analysis of SST Faults (Line-to-Line, Line-to-Gnd, S.C., etc.) and Protection Schemes



- Proposed SST Protection Scheme with Minimum # of Protection Devices

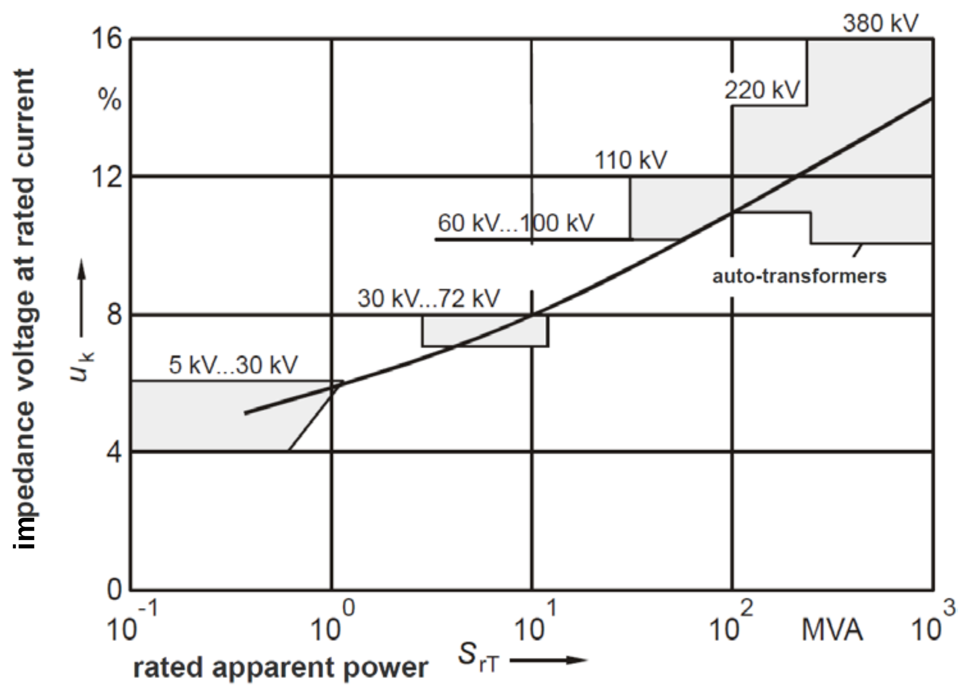


- Overvoltage Protection (Lightning Strike)

  * High Arrester Clamping Voltage
  * Filter Inductor > 8% for Current Limiting
  * Min. DC Link Capacitance
  * Sufficient Blocking Capability
  * Grounding – Lower Stress if Unearthed

■ Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed /Safety /Reliability

▶ Distribution Transformer Overcurrent Requirements



- Low-Frequ. XFRM 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)

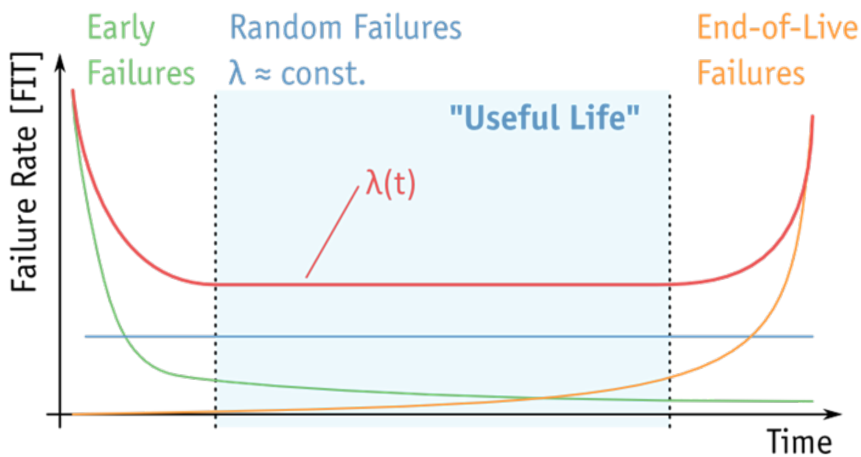
- Lower Grid Voltage Levels → Higher Relative Short Circuit Currents
- SST is NOT (!) a 1:1 Replacement for a Conventional Low-Frequency XFRM

Challenge #5/5

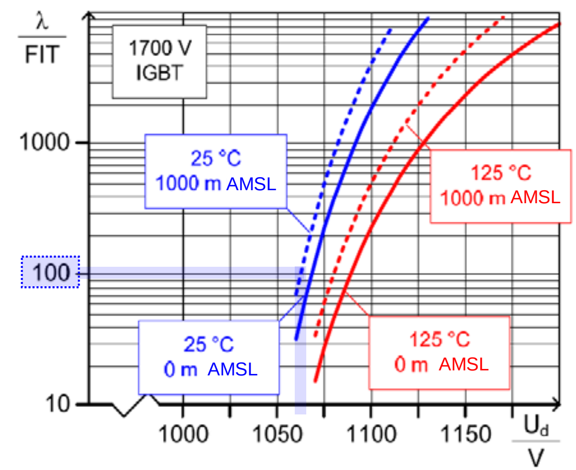
*Ensuring Reliability of Highly Complex
Multi-Cell Converter Topologies*

▶ Reliability Model (1) – Failure Rate

- Failure Rate $\lambda(t)$ is a Function of Time – „Bathtub Curve“
- Useful Life Dominated by Random Failures → $\lambda(t)$ = const.
- $[\lambda]$ = 1 FIT (1 Failure in 10^9 h)
- Typ. Value for IGBTs: 100 FIT



Source: H.-G. Eckel
Univ. Rostock



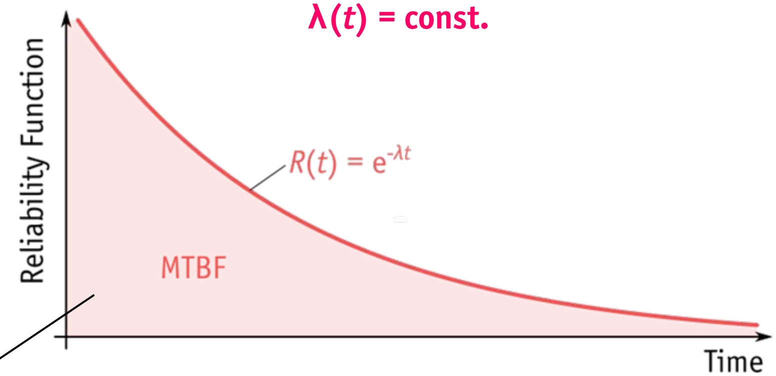
- Sources for Empirical Component Failure Rate Data : MIL-HDBK-217F, IEC Standard 62380, etc.

Reliability Model (2) – Reliability Function

- **Reliability Function:** Probability of System being Operational after t:

$$R(t) = e^{-\int_0^t \lambda(x)\,dx} = e^{-\lambda t}$$

$\lambda(t)$ = const.



- **Mean Time Between Failures**

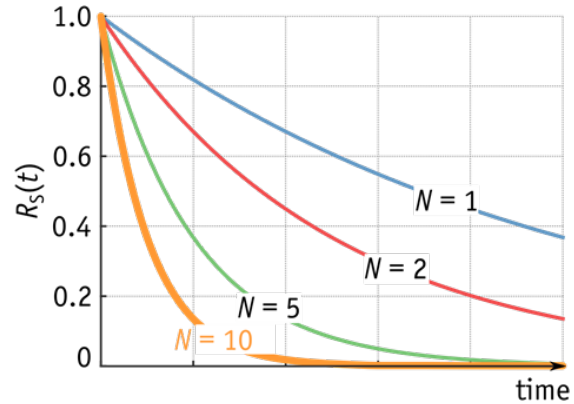
$$\mathrm{MTBF} = \int_0^\infty R(t)\,dt = \int_0^\infty e^{-\lambda t}\,dt = \frac{1}{\lambda}$$

- **Series Structure**

$$\lambda_S = \sum_{i=1}^{n} \lambda_i$$

E_1 E_2 … E_n

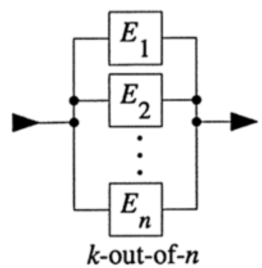
Independent Cells
with Equal Failure Rate

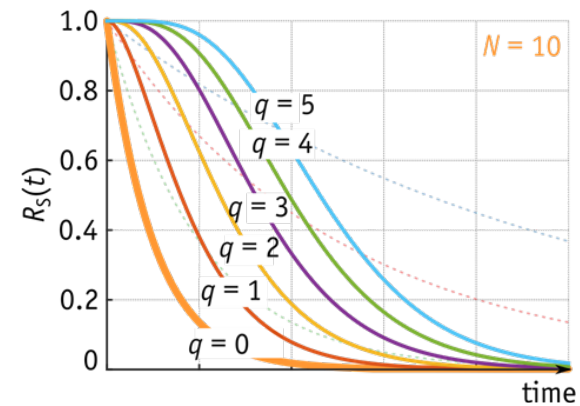


▶ Redundancy in Multi-Cell Converter Systems

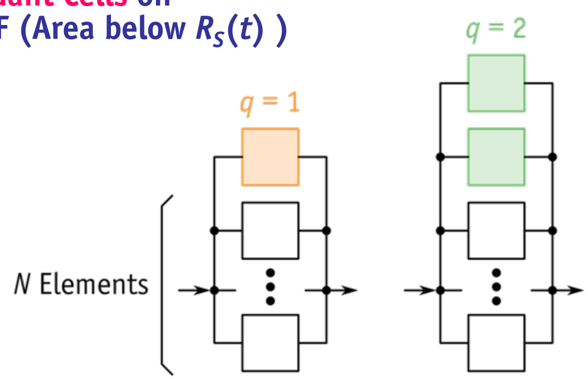
- ***k*-out-of-*n* Redundancy**
  Redundancy of Cells in Phase Stack

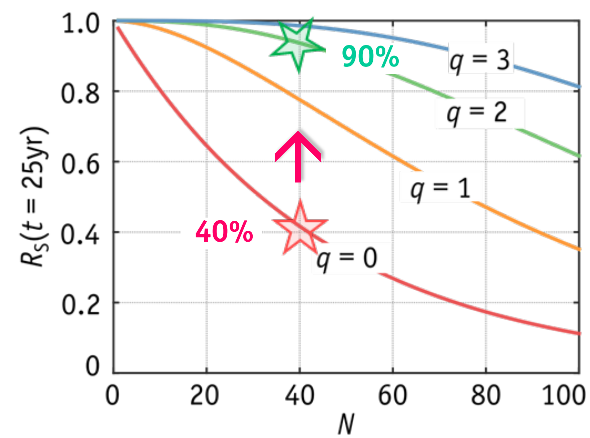
  System is Operational as Long as at Least k-out-of-*n* Subsystems are Working





- **Effect of *q* Redundant Cells on $R_S(t)$ and/or MTBF (Area below $R_S(t)$)**





- **Redundancy Significantly Improves System Level Reliability (!)**

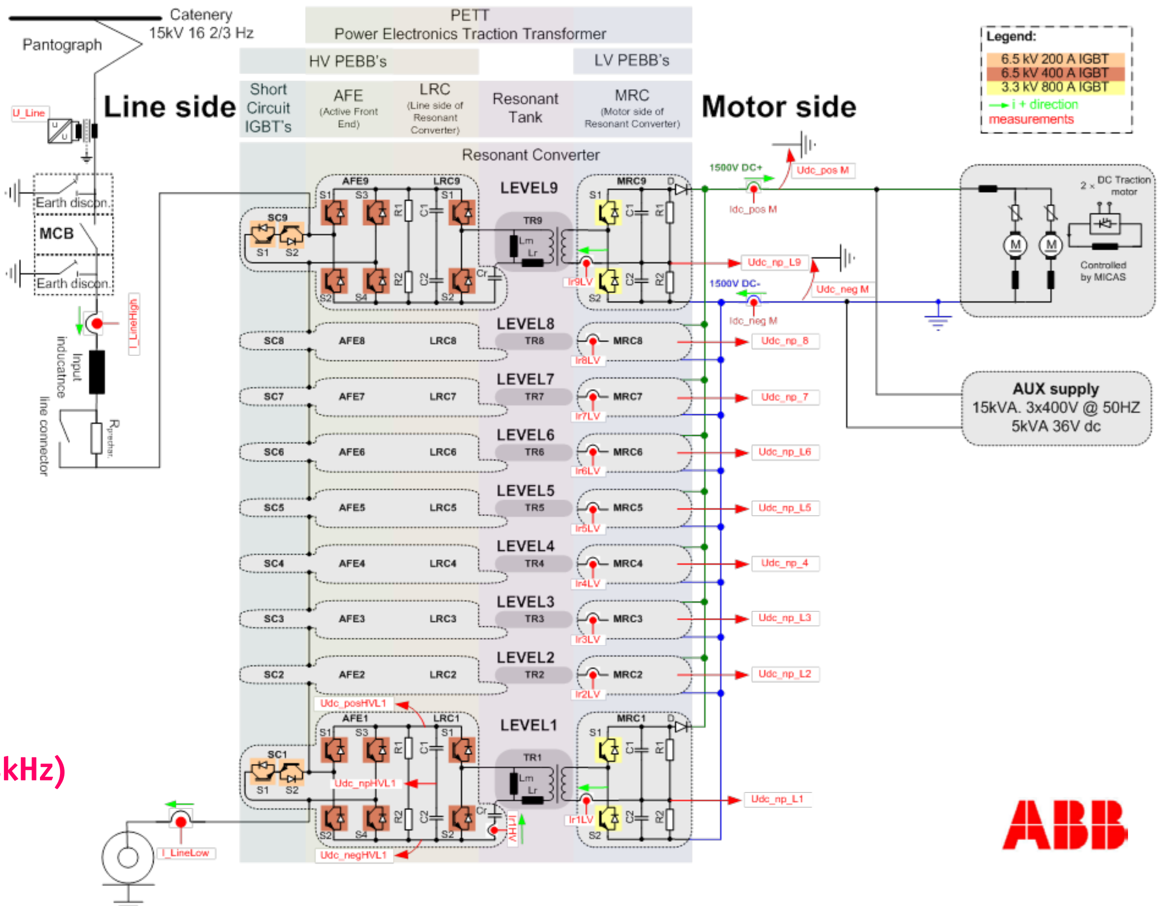
SST Demonstrator Systems

Future Locomotives
Smart Grid Applications

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

- Dujic et al. (2011)

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



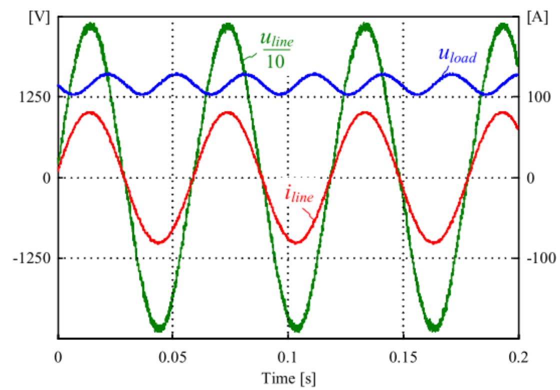
P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

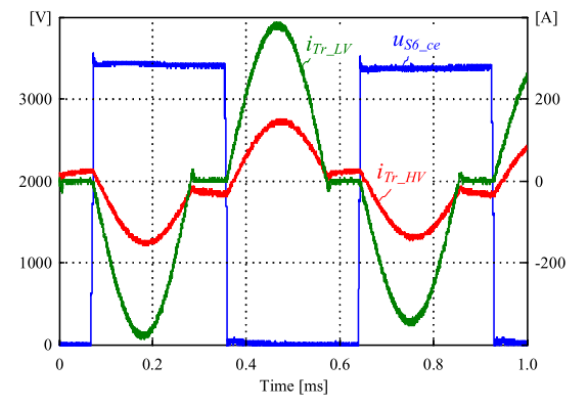
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

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

▶ 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

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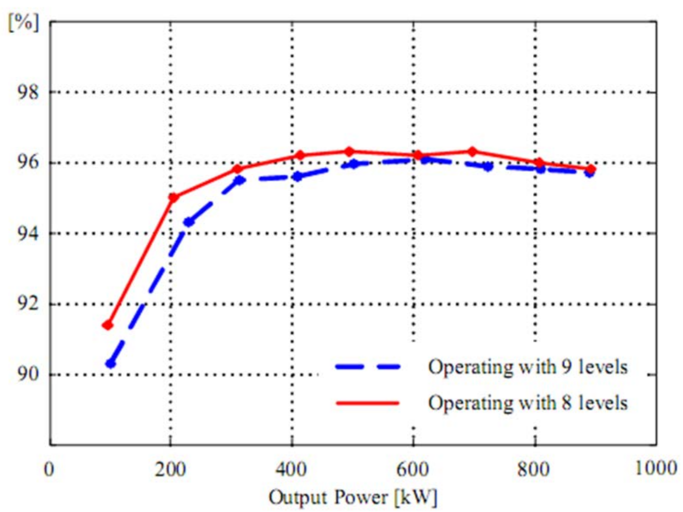
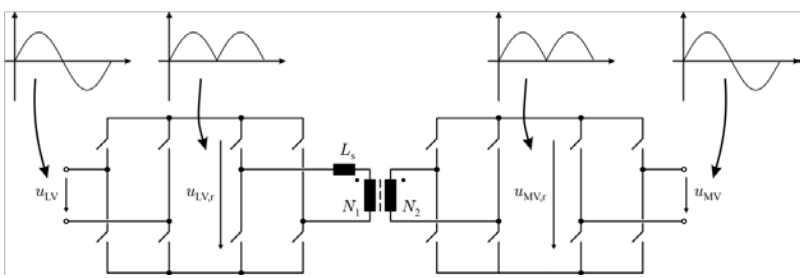
Efficiency

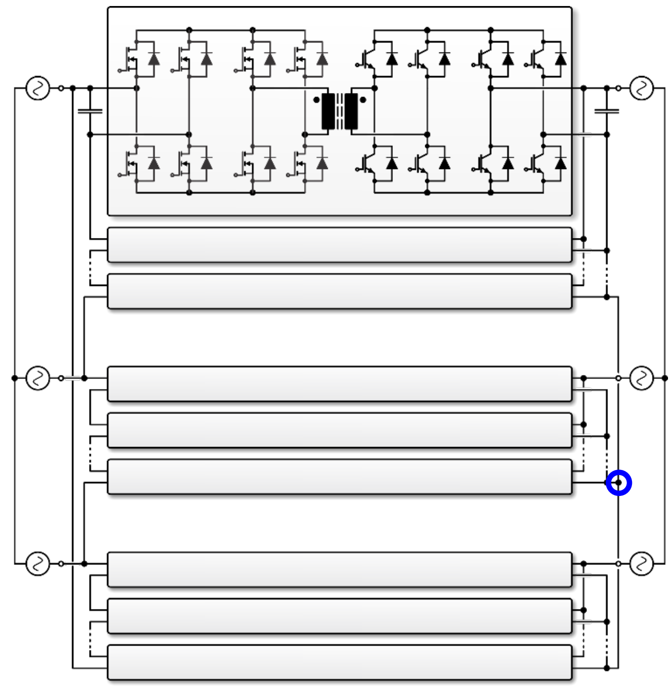


► SiC-Enabled Solid-State Power Substation

- 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$_{\text{l-l}}$, 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)

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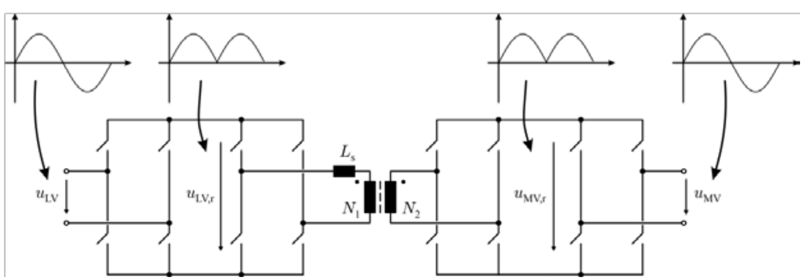
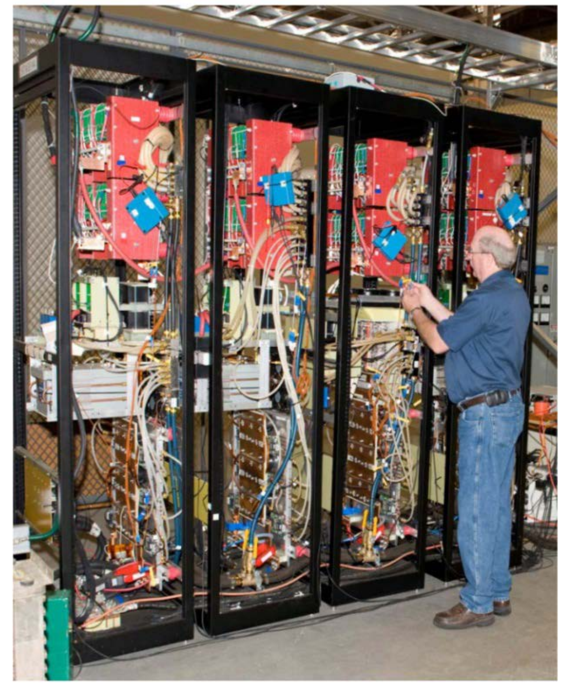




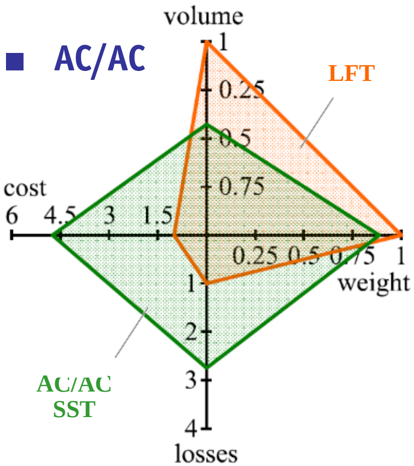
- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)

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

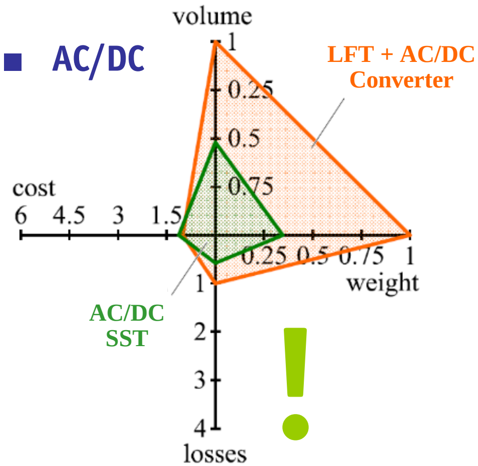
- Specifications — 1MVA
  10kV Input
  400V Output
  1700V IGBTs (1kHz/8kHz/4kHz)

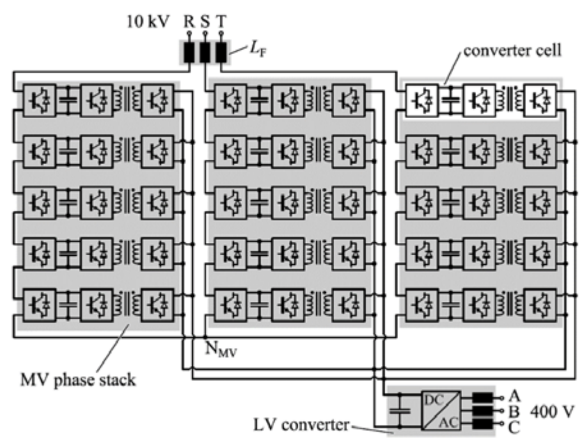
- LF Transformer — 98.7 %
  16.2 kUSD
  2600kg (5700lb)

■ 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

Potential Future SST Application Areas

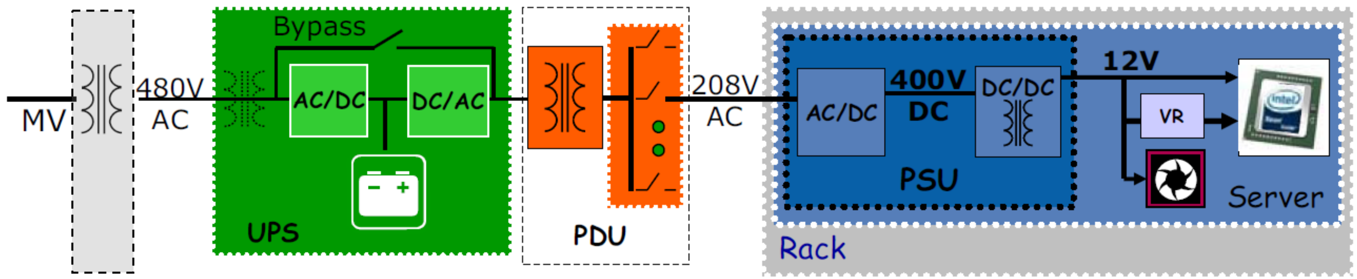
Datacenters
Off-Shore Wind
Oil and Gas Industry
Power-to-Gas
All Electric Aircraft

▶ AC vs. Facility-Level DC Systems for Datacenters

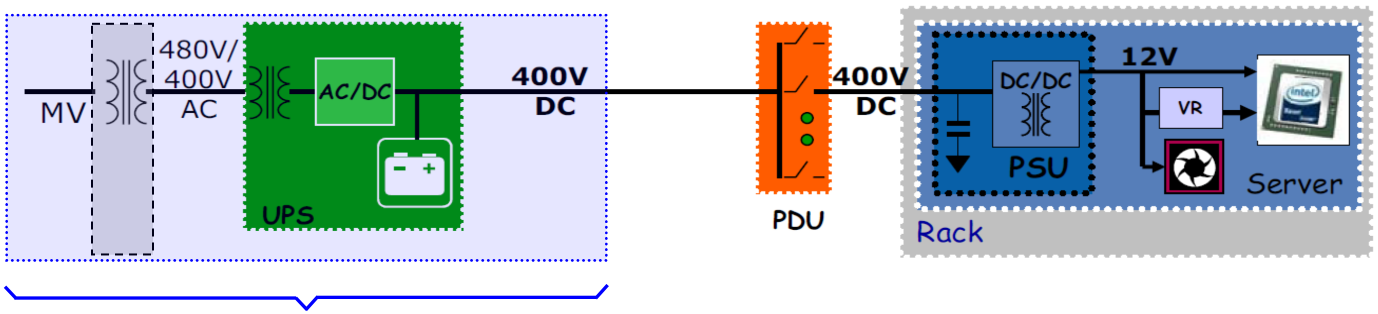
- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional US 480V_{AC} Distribution

Source: intel 2007



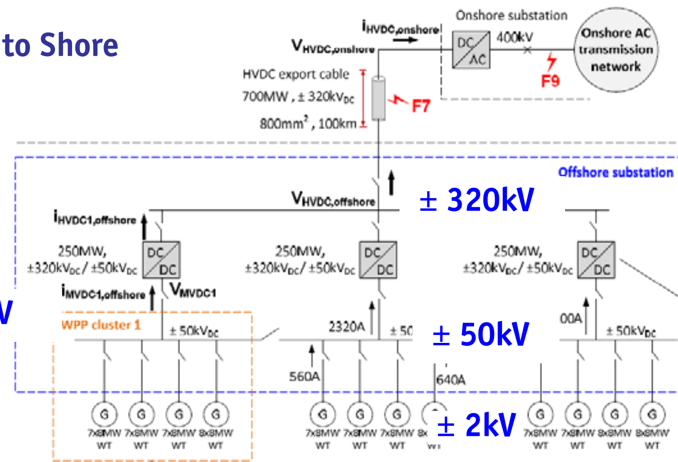
— Facility-Level 400 V_{DC} Distribution



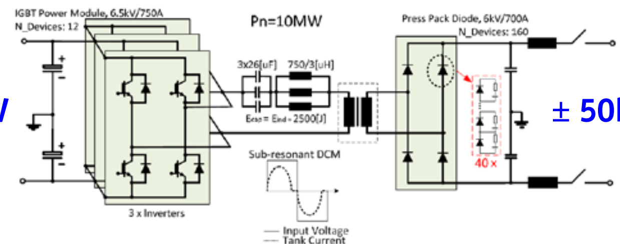
- Future Concept: Unidirectional SST / Direct 6.6kV AC → 400V DC Conversion

▶ DC Collection Grids for Offshore Wind Parks

■ ± 320kV HVDC Transmission to Shore

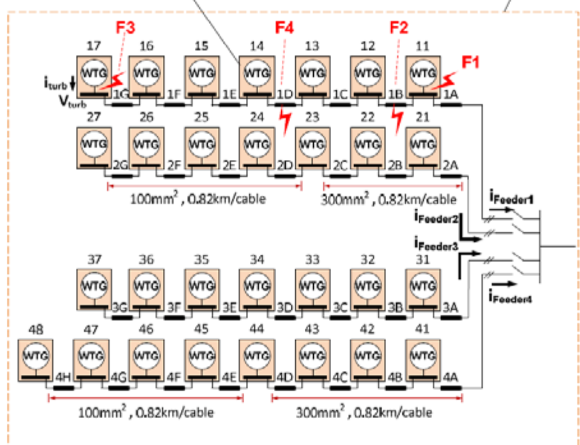


± 2kV

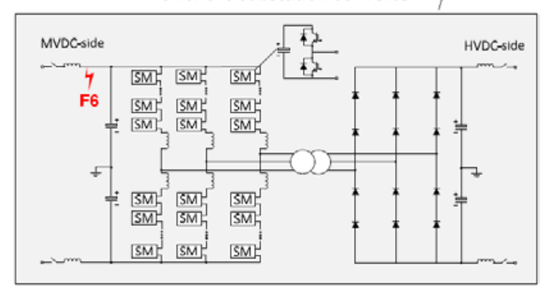


± 50kV

■ Unidirectional
MF Series Resonant
DC→MVDC
Conversion in Each
Wind Turbine



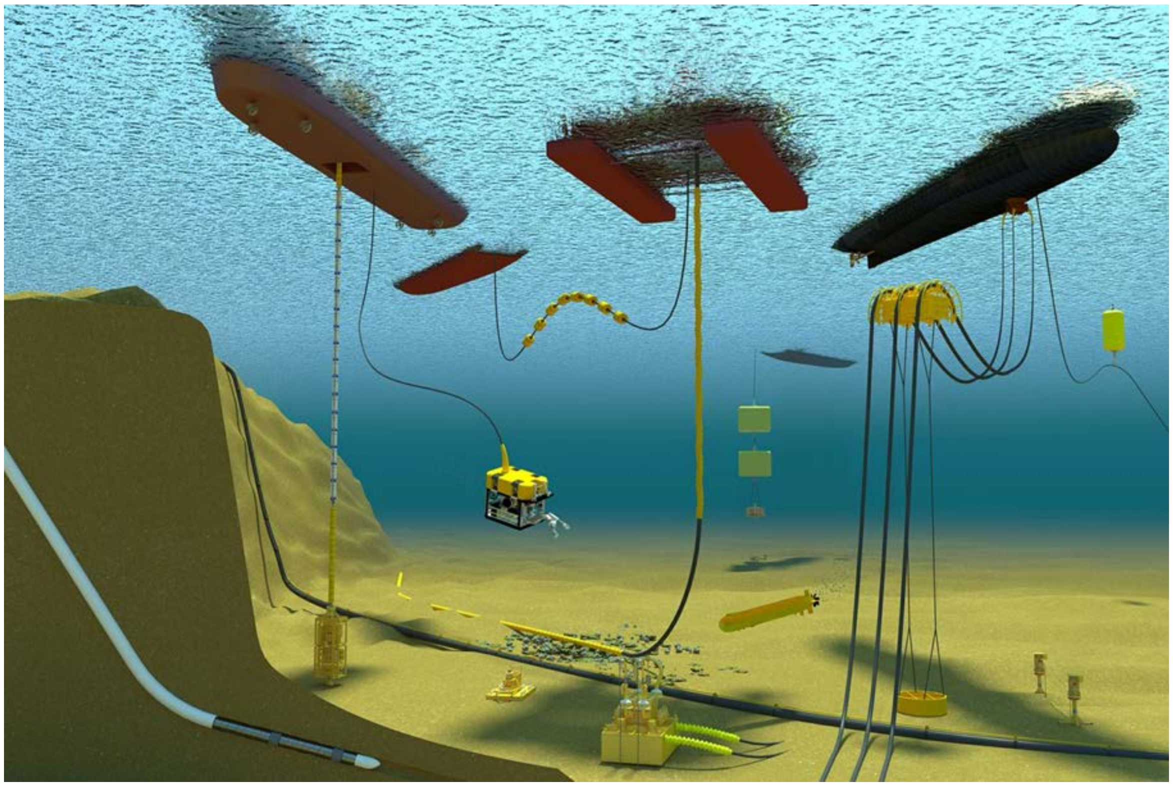
Offshore substation converter



■ ± 50kV Offshore Collection Grid
■ ± 50kV / ± 320kV Offshore Substation
■ MMLC-Based MF Isolation

Source: Kjaer/2016

▶ Subsea Applications – Oil & Gas Processing



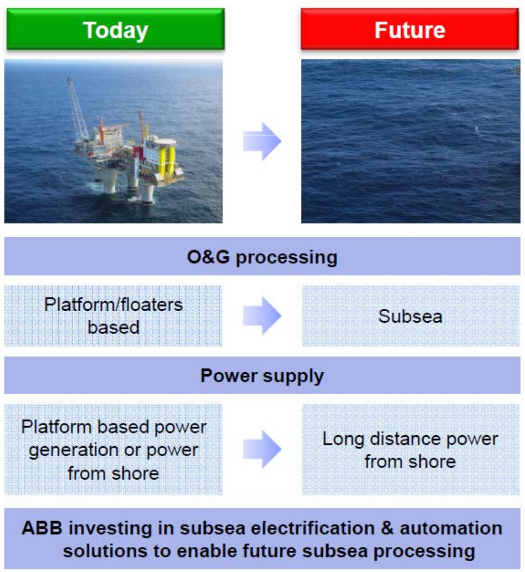
- ABB´s Future Subsea Power Grid → "Develop All Elements for a Subsea Factory"

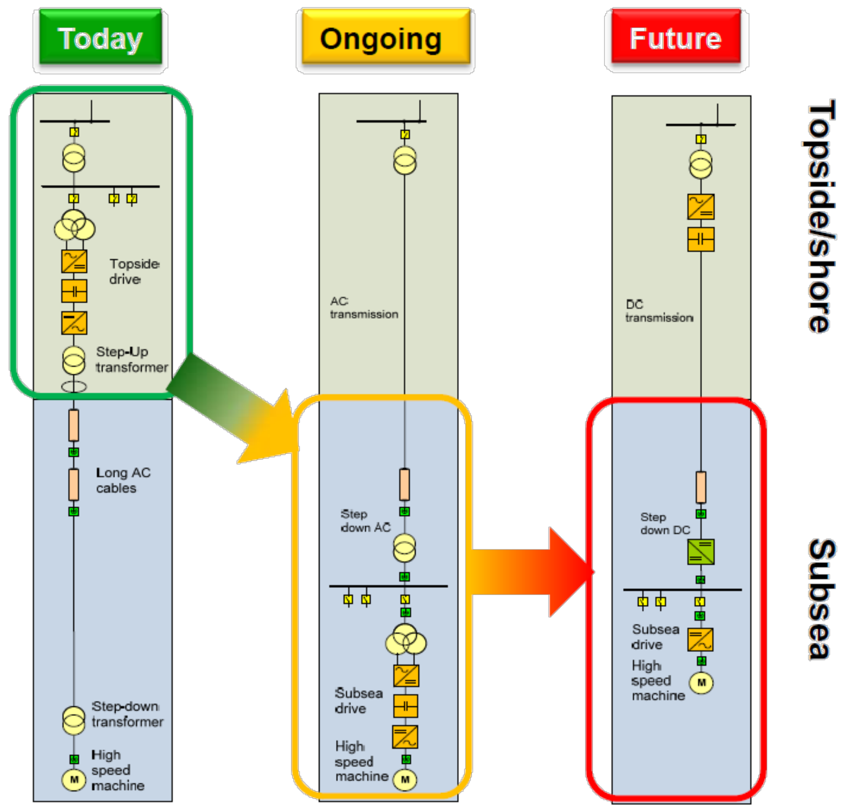
▶ Future Subsea Distribution Network

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

- Weight Optimized Power Electronics

Source: Devold (ABB 2012)

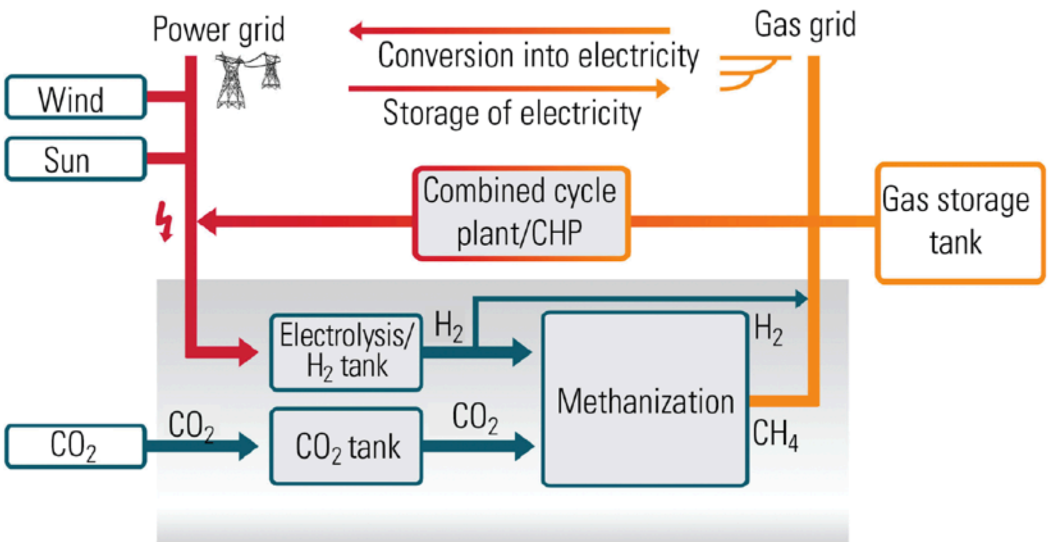




► Power-to-Gas

- 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%)

Source: www.r-e-a.net

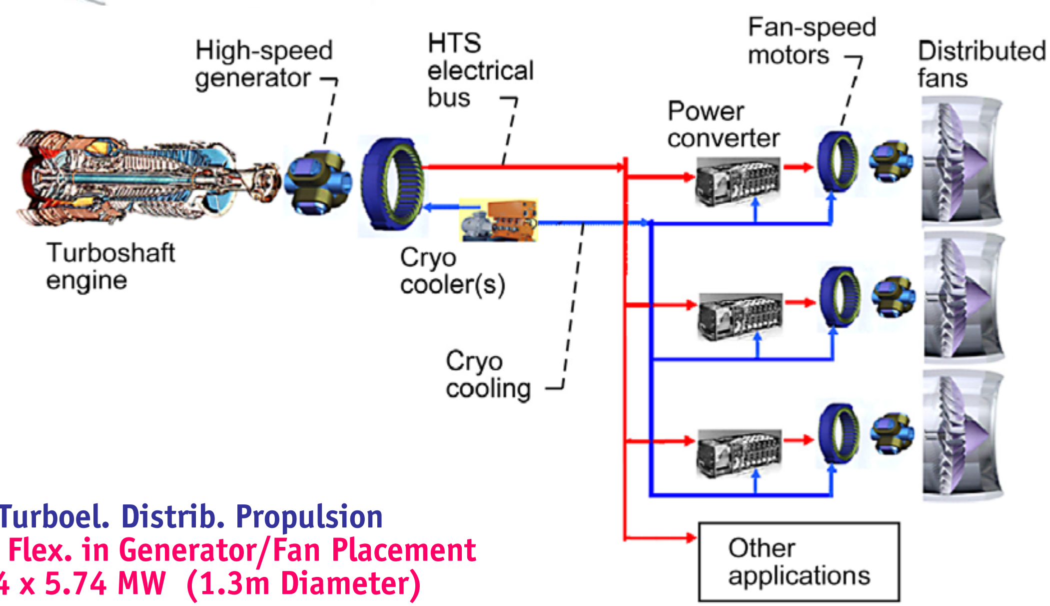
▶ Future Hybrid Distributed Propulsion Aircraft

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

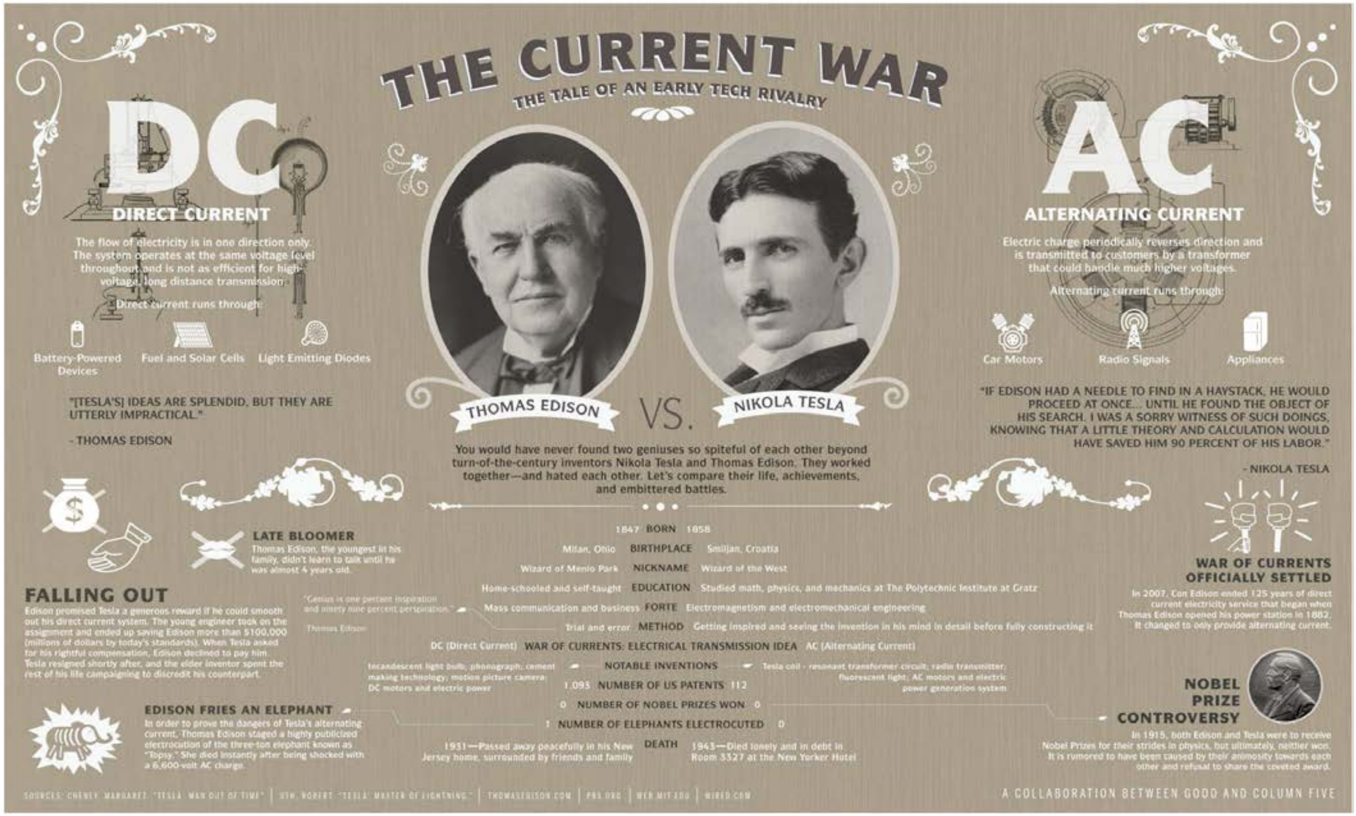


- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

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 !

SST Applications - The Road Ahead

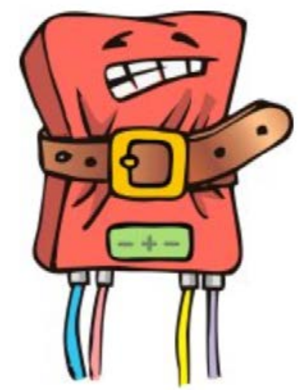
- NOT (!) Weight / Space Limited
- Smart Grid, Stationary Applications

- AC/AC
  - Efficiency Challenge
  - Controllability also by More Efficient Alternatives
    * Tap Changers
    * Series Regulators (Partial Power Processing)
  - Not Compatible w. Existing Infrastr.
  - Cost / Robustness / Reliability

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

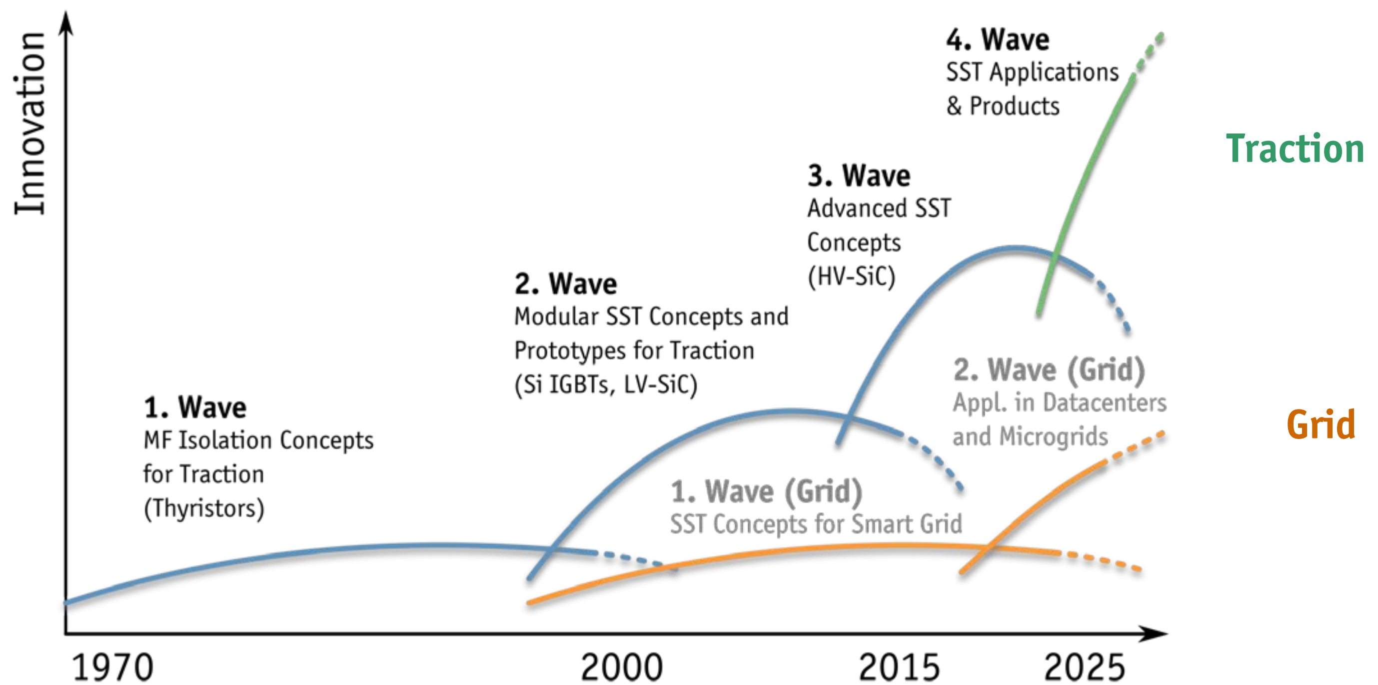
- DC/DC
  - No Other Option (!)
  - MV DC Collection Grids (Wind, PV)
  - Sw. Frequ. as DOF of Design

- 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.)

► SST Development Cycles - Outlook



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

Thank You!

Questions