The Essence of Solid-State Transformers

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www.pes.ee.ethz.ch

Outline

Acknowledgement: D. Bortis
Th. Guillod
F. Krismer
G. Ortiz
D. Rothmund

Transformer Basics

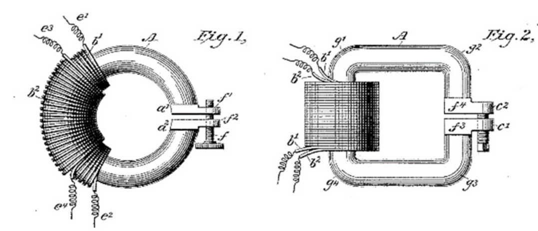
History
Scaling Laws
Efficiency / Power Density Trade-off

▶ Classical Transformer (XFMR) – History (1)

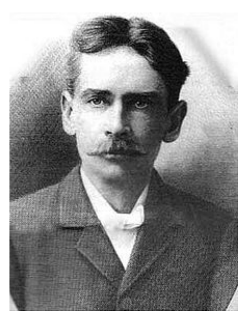
* 1830 - Henry/Faraday → Property of Induction
* 1878 - Ganz Company (Hungary) → Toroidal Transformer (AC Incandescent Syst.)
* 1880 - Ferranti → Early Transformer
* 1882 - Gaulard & Gibbs → Linear Shape XFMR (1884, 2kV, 40km)
* 1884 - Blathy/Zipernowski/Deri → Toroidal XFMR (inverse type)

Europe

USA



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



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

► Classical Transformer – History (2)

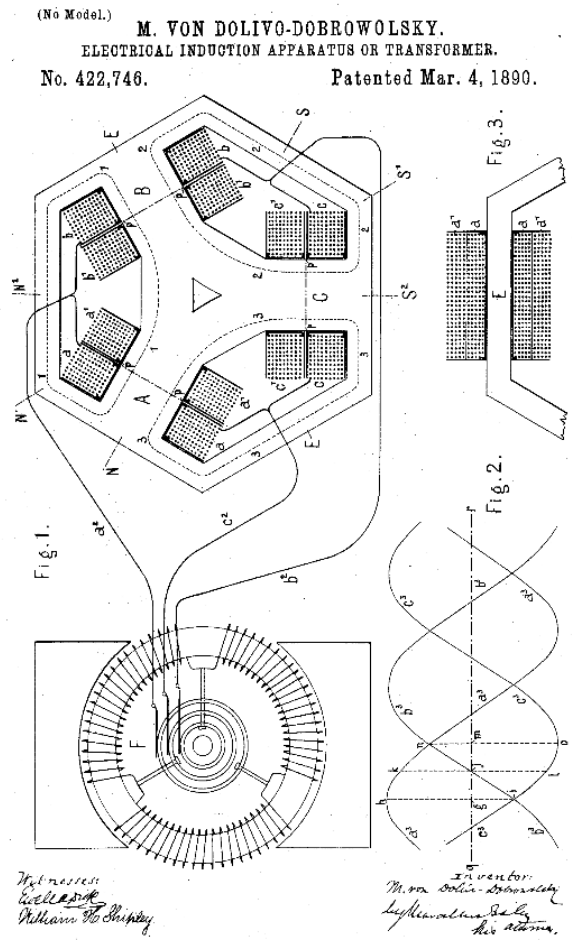
UNITED STATES PATENT OFFICE.

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.)



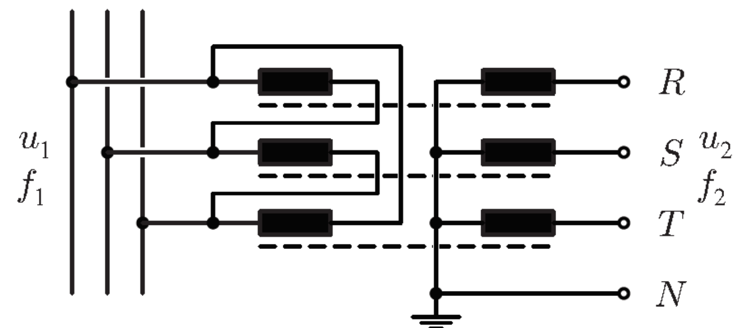
* 1889 - Dobrovolski → 3-Phase Transformer

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

► Classical Transformer – Basics (1)

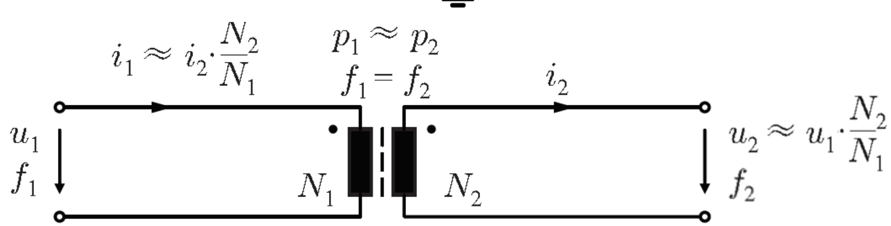
- Magnetic Core Material * Silicon Steel / Nanocrystalline / Amorphous / Ferrite
- Winding Material * Copper or Aluminium
- Insulation/Cooling * Mineral Oil or Dry-Type

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



▶ Classical Transformer – Basics (2)

Source: www.faceofmalawi.com

■ Advantages

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

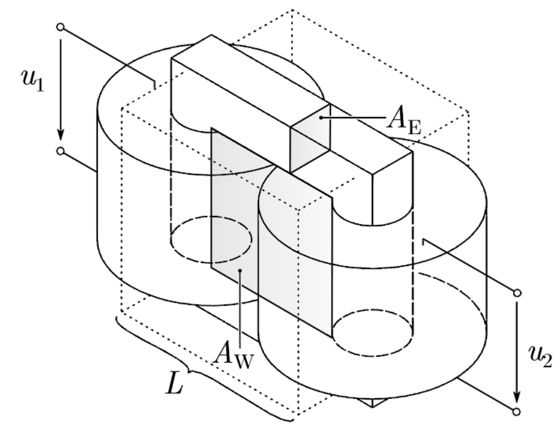
▶ Classical Transformer – Basics (3)

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

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

↑ ↑ ↑

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

Classical Transformer – Basics (4)

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

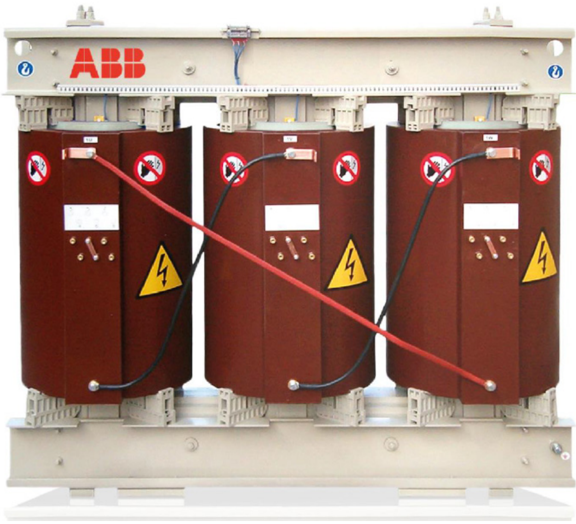
$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

↑ ↑ ↑

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

▶ Classical Transformer – Basics (5)

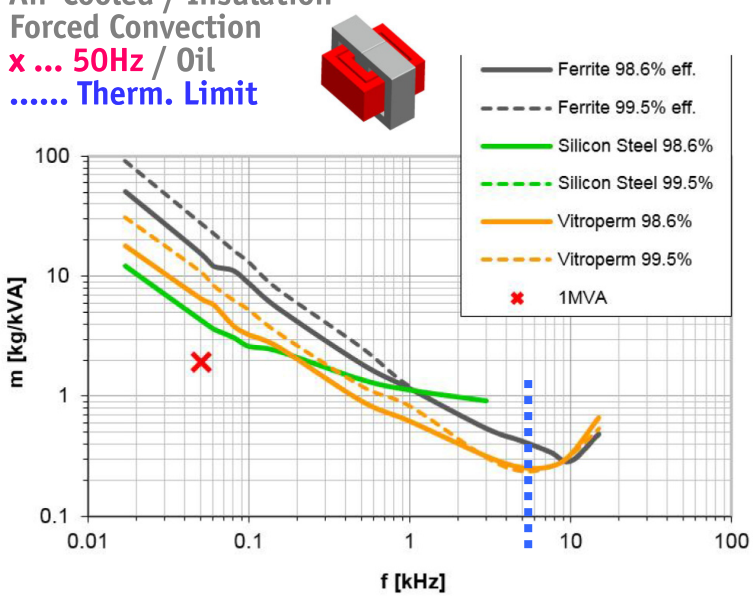
- **Construction Volume**

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

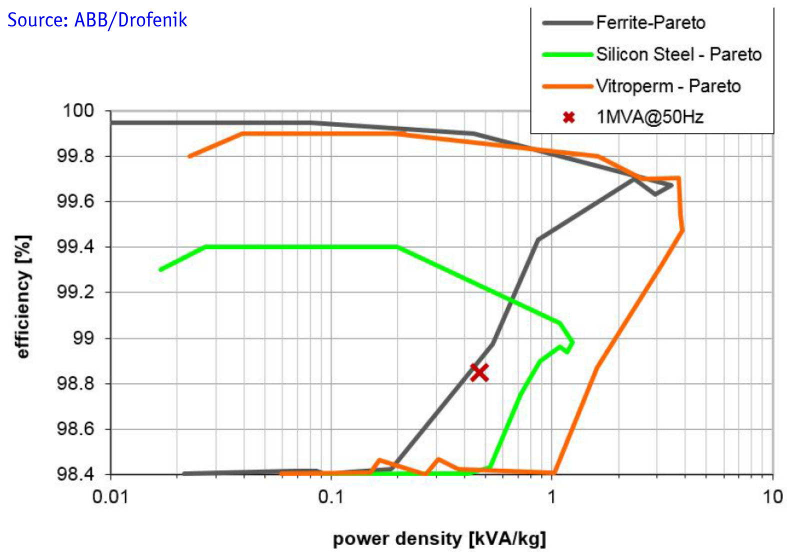
↑ ↑ ↑

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

180kVA
Weight-Optimized
Air-Cooled / Insulation
Forced Convection
x ... 50Hz / Oil
...... Therm. Limit



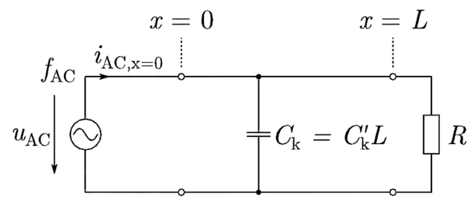
Source: ABB/Drofenik

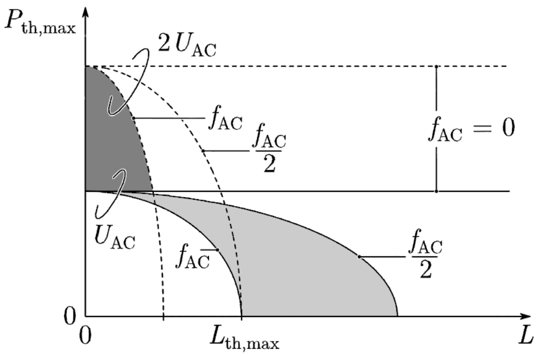


- Higher Frequency → Lower Weight / Volume
- Higher Volume → Higher Efficiency

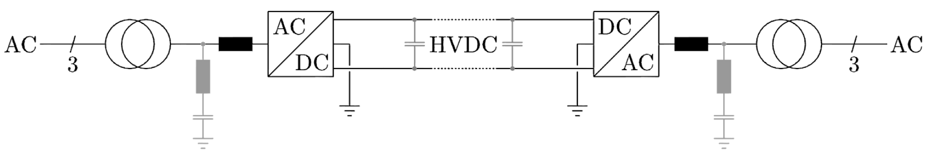
▶ AC vs. DC Power Transmission (1)

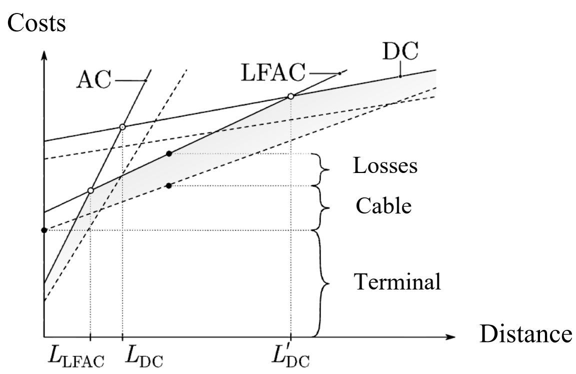
- **AC Cable** – Thermal Limit Due to Cap. Current @ L = 0





- **HVDC Transmission** – Advantageous for Long Distances





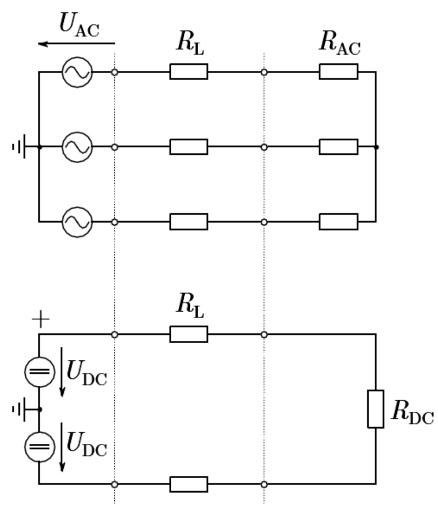
- **Low-Frequency AC (LFAC) as Possible (Purely Passive) Solution for Medium Transmission Distances**

► AC vs. DC Power Transmission (2)

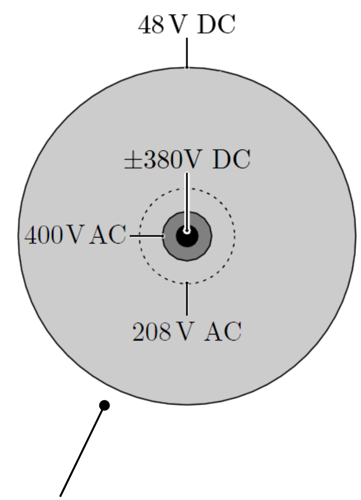
- **Quadratic Dependency of Losses on Voltage Level** → **Reduction of Conductor Cross Section**
- **DC Voltage Ensures Max. Utiliz. of Isol. Voltage** → **Highest RMS Value / Lowest Current**

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

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



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



Conductor Cross Sections
for Same Losses

- **Fault Current Clearing** as Main Challenge of DC Distr. Systems (Missing Regular Current Zero Crossing)

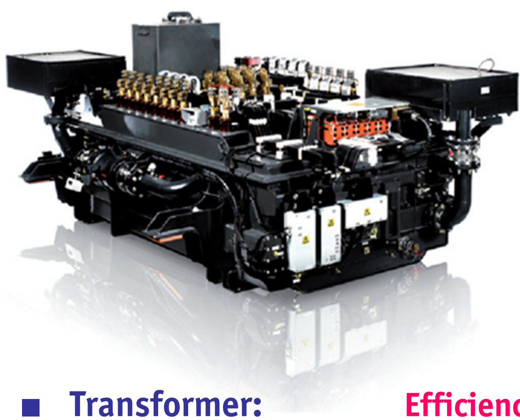
SST Motivation

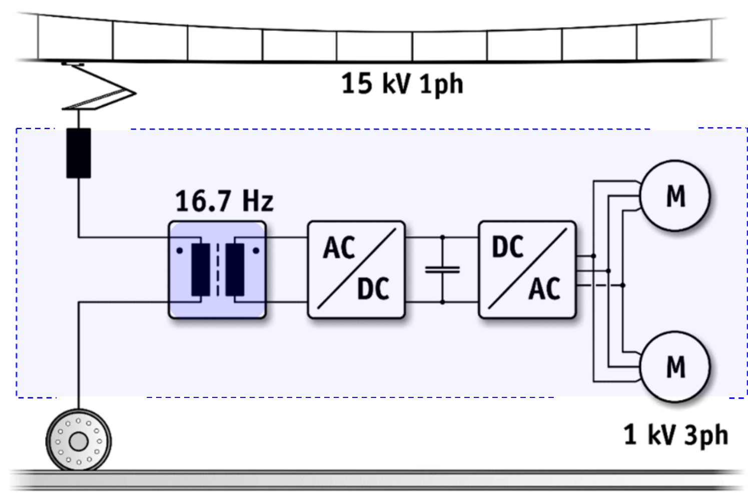
Next Generation Traction Vehicles

Classical Locomotives

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

Source: www.abb.com





- **Transformer:**

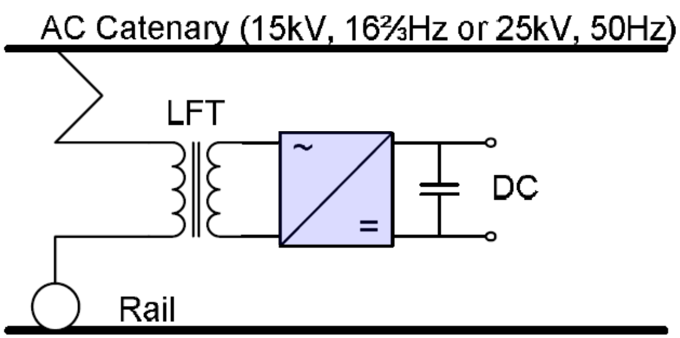
Efficiency	90...95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
Power Density	2...4 kg/kVA

▶ Next Generation Locomotives

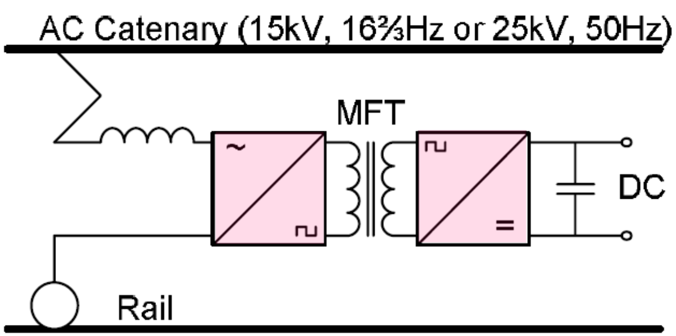
■ **Trends**

* 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).

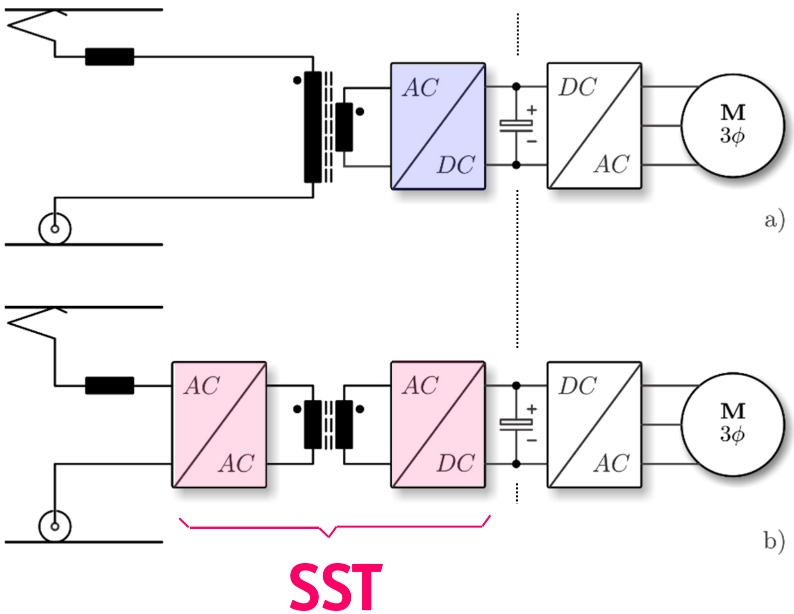


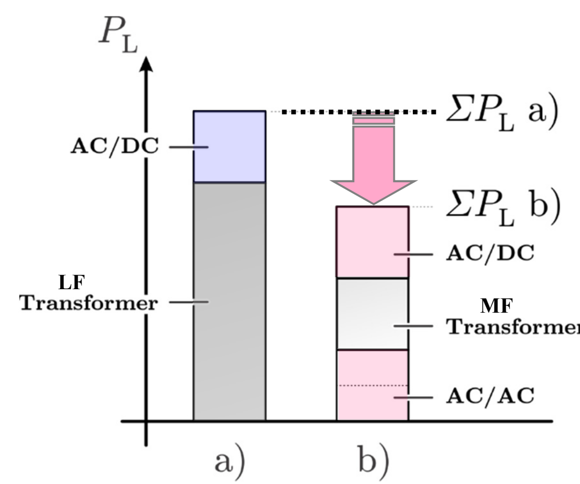
AC-DC conversion with medium frequency transformer (MFT).

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

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives





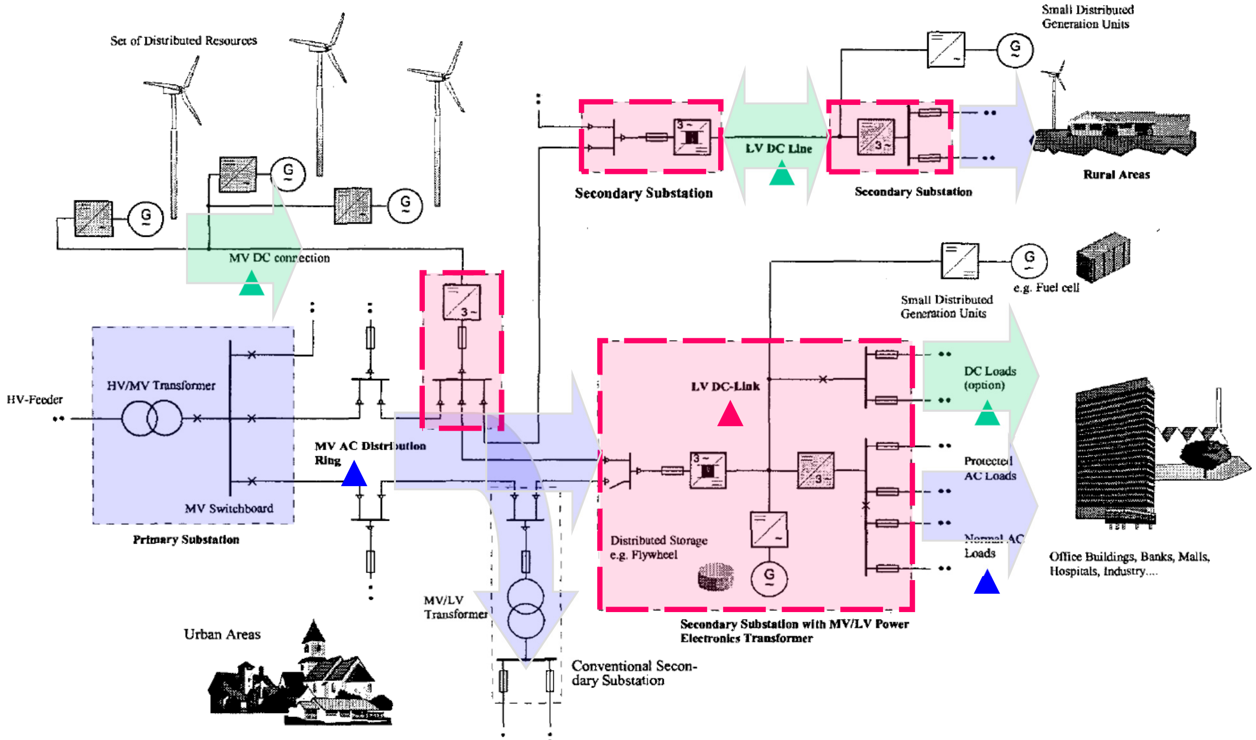
- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

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.

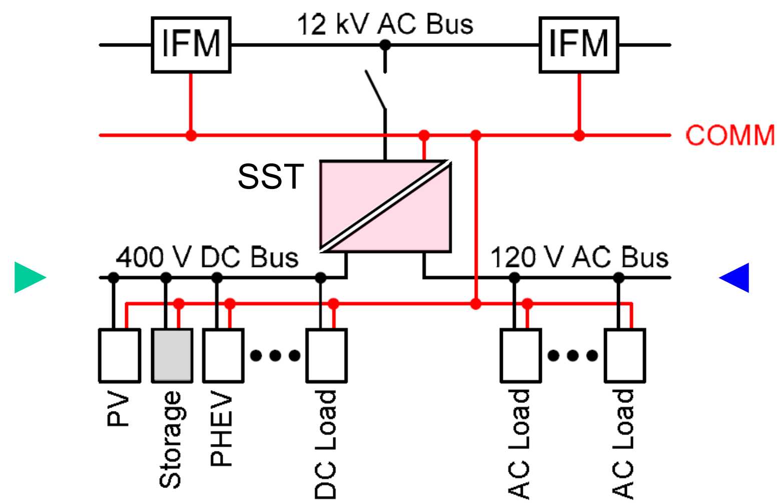
- Huang et al. (2008)

- 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.

FREEDM systems center

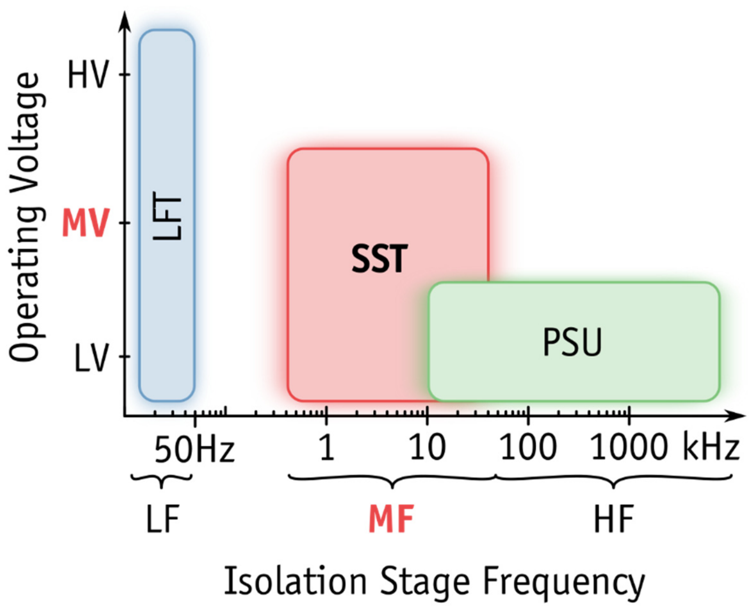
IFM = Intellig. Fault Management

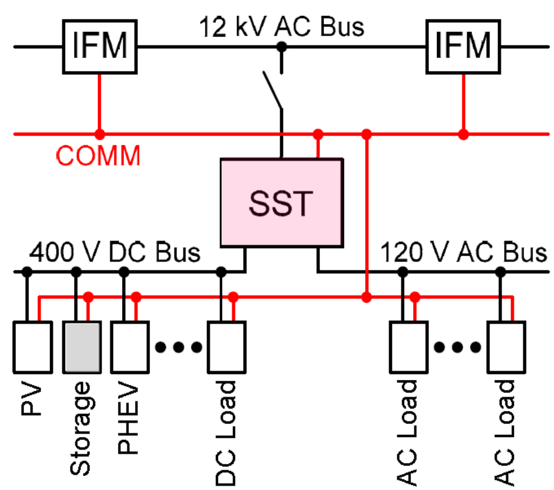


- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl

▶ Terminology (1)

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.





▶ Terminology (2)

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 ← "… Solid State Regulated Power Transformer …"

[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**

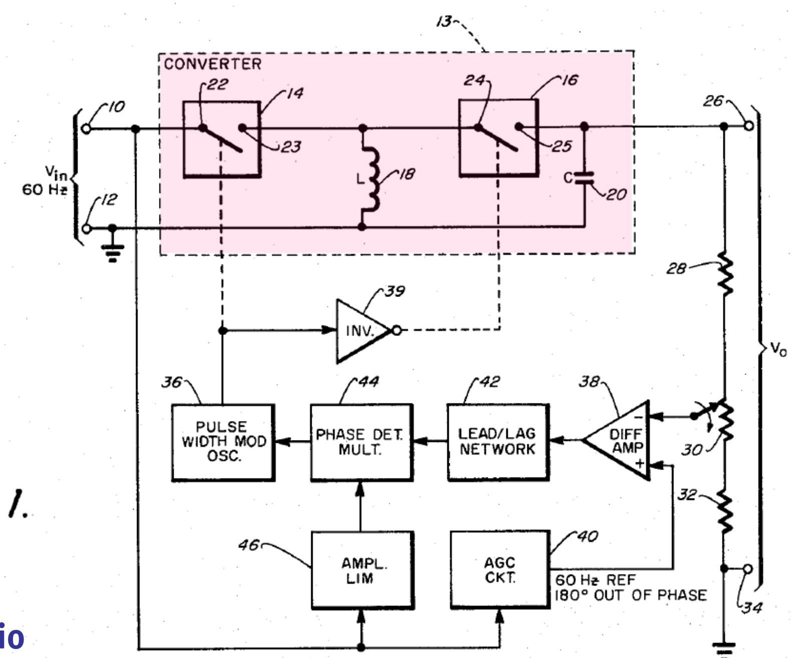
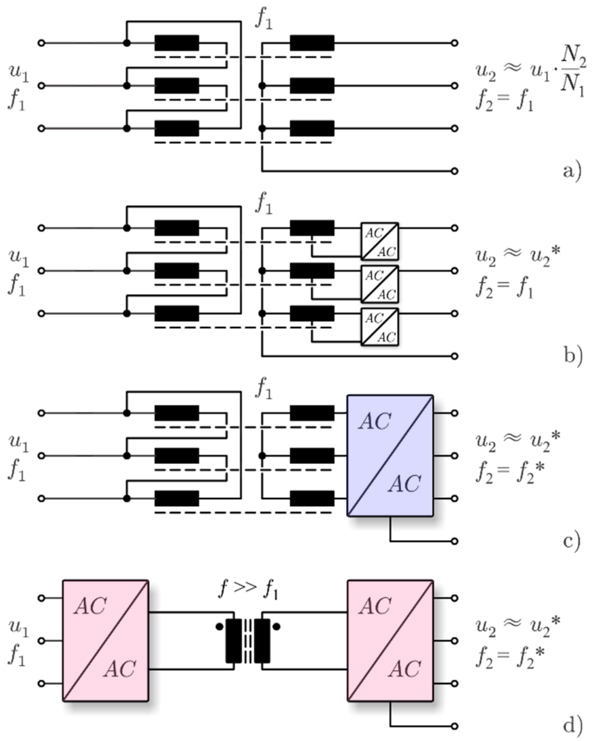


Fig. 1.

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

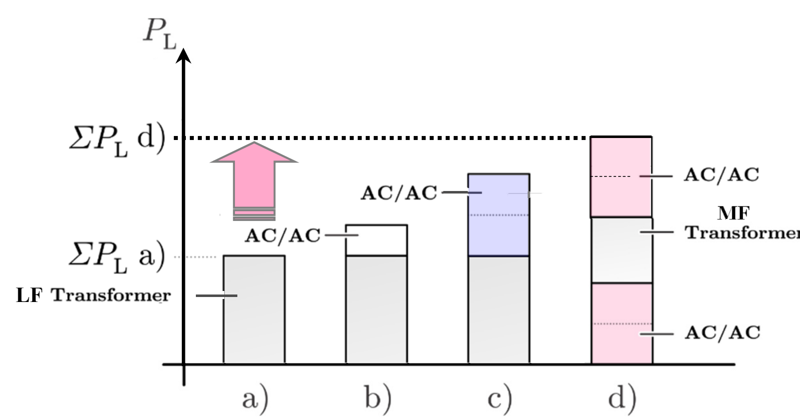
► Passive Transformer → SST

■ 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

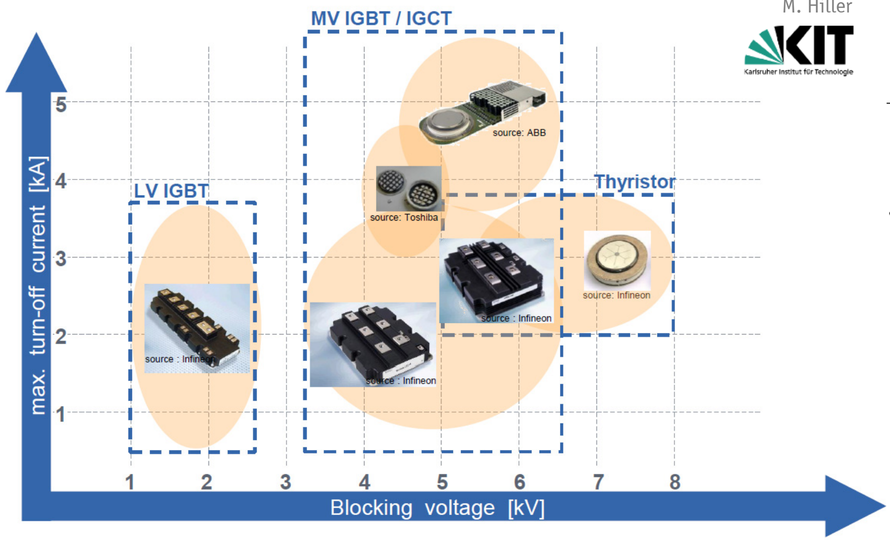
Availability / Selection of Power Semiconductors

▶ Available Si Power Semiconductors

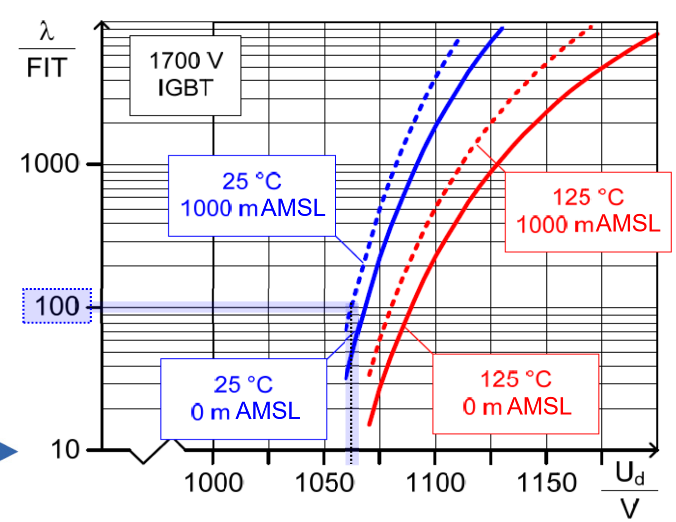
- 1200V/1700V Si-IGBTs Most Frequently Used in Industry Applications

- Derating Requirement due to Cosmic Radiation 1700V Si-IGBTs → ≈1000V max. DC Voltage

Source: M. Doppelbauer M. Hiller



Source: H.-G. Eckel Univ. Rostock

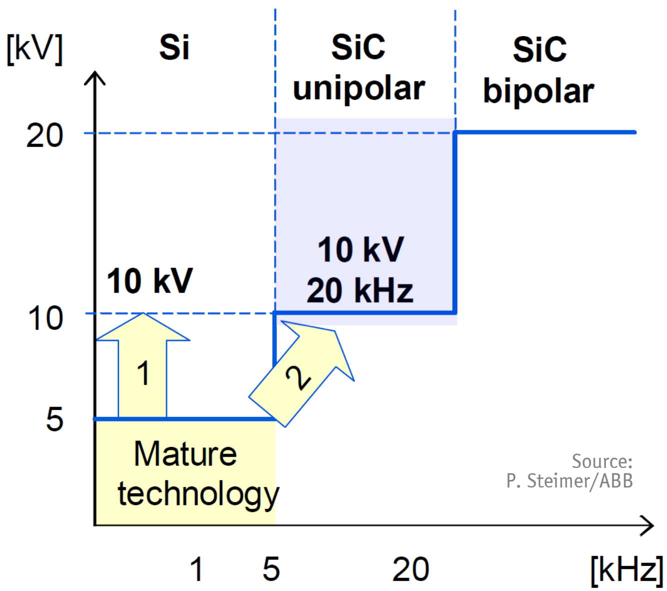


- Interfacing to Medium Voltage → Multi-Level Converter Topologies

▶ SiC Power Semiconductors

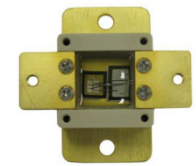
- **Samples**

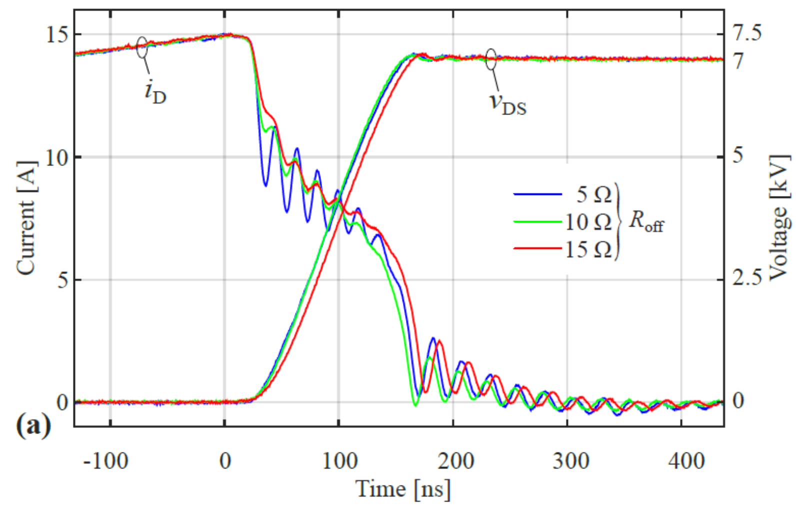
* 10kV & 15kV / 10A MOSFETs
* 10kV & 15kV / 8A JBS Diodes
* 15kV / 20A IGBTs



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

Wolfspeed





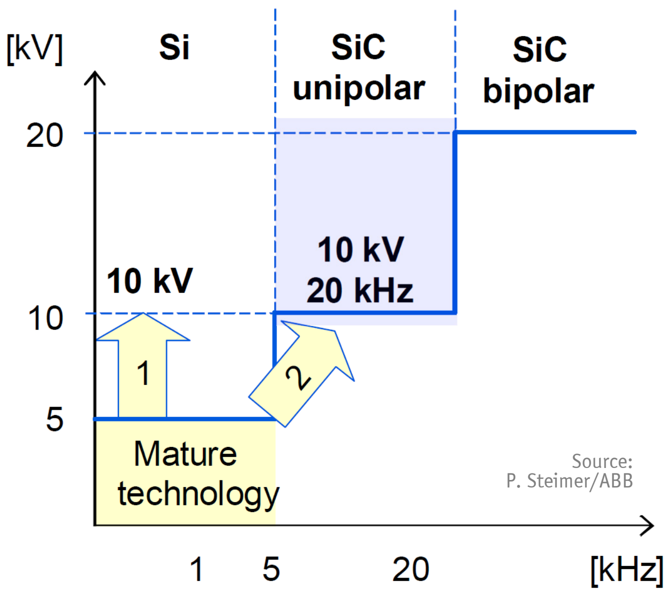
■ **Interfacing to Medium Voltage → Two-Level *OR* Multi-Level Converter Topologies**

▶ SiC Power Semiconductors

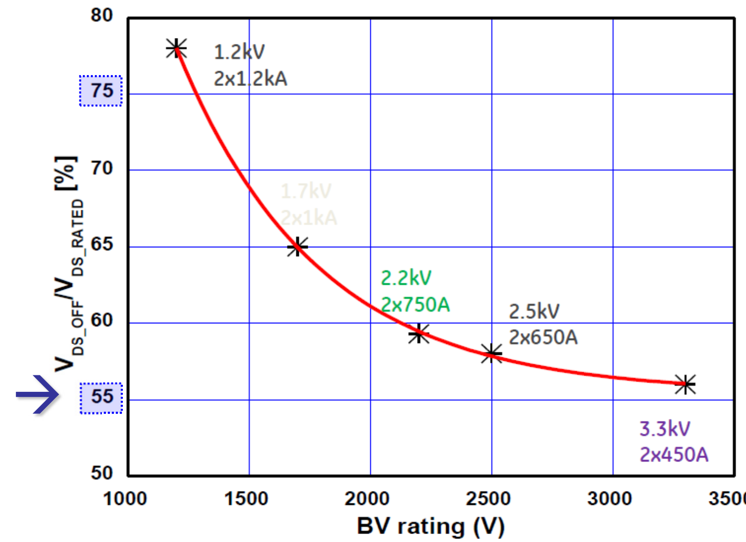
- **Samples** Wolfspeed

* 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



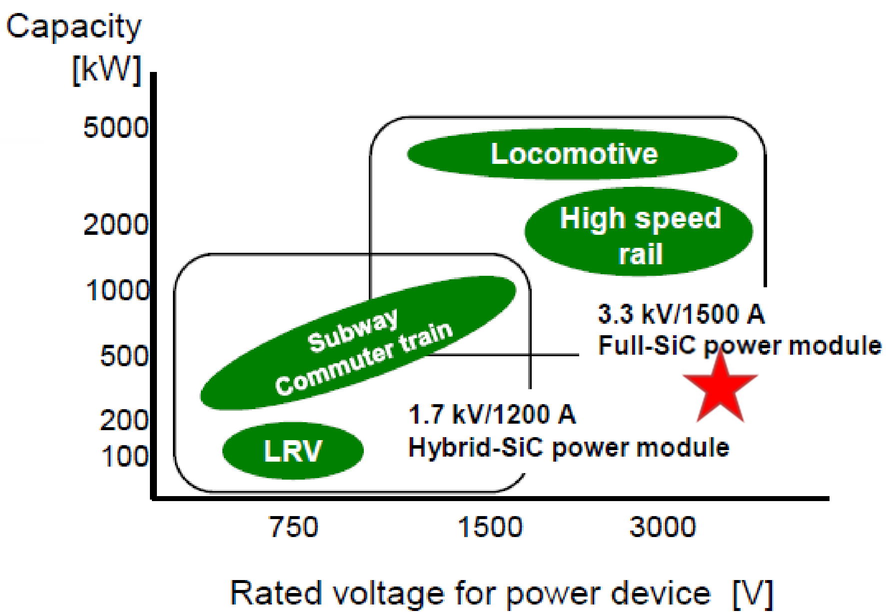
Source: P. Sandvik
R. Datta

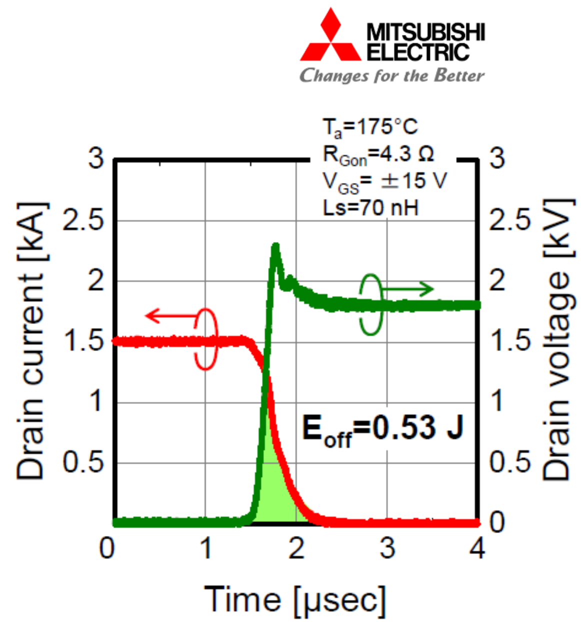


- **Interfacing to Medium Voltage → Two-Level *OR* Multi-Level Converter Topologies**

▶ Commercially Available SiC Power Semiconductors

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





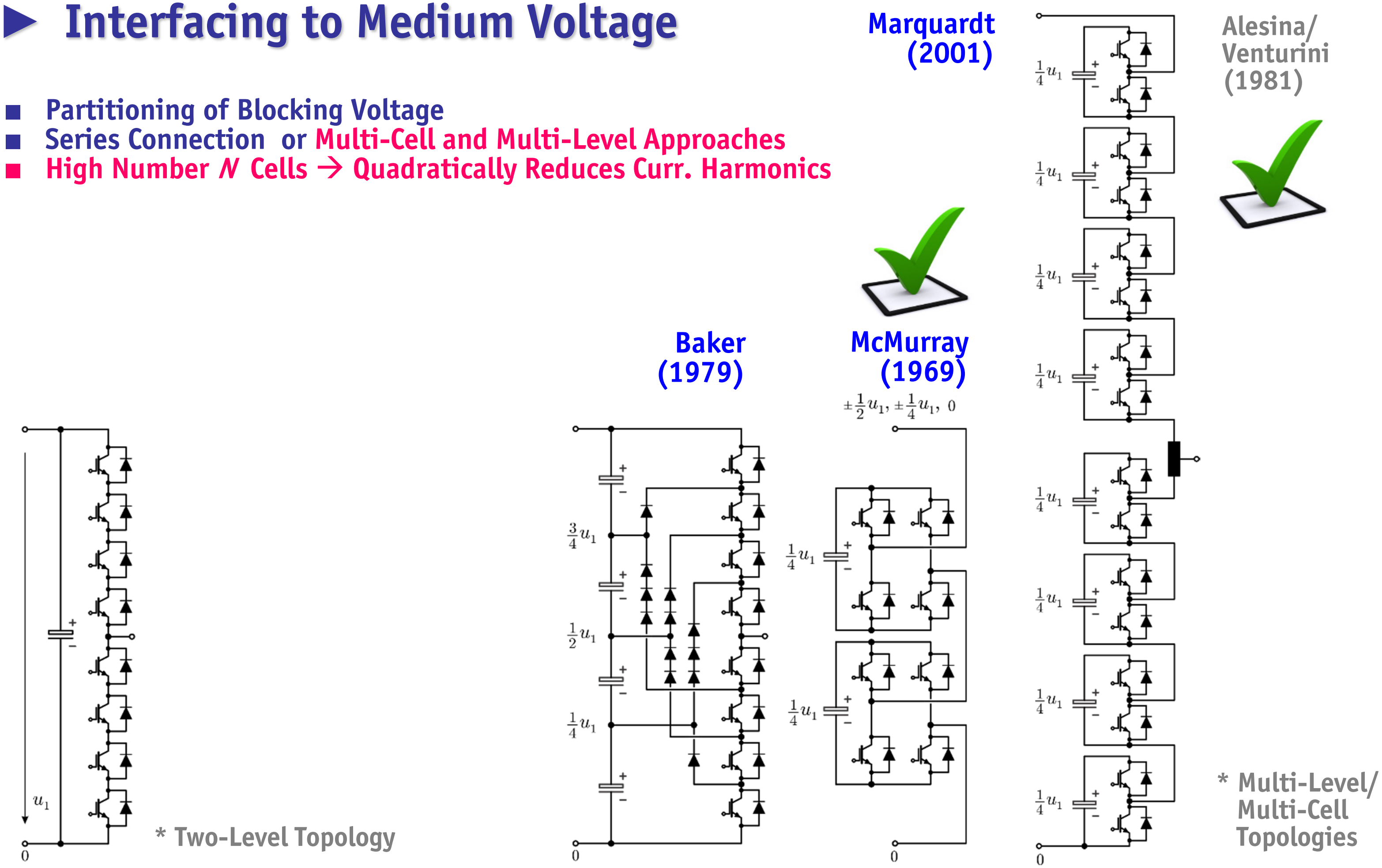
- 6.5kV Samples Available

Challenge #2/5

*Creation of MV → LV
SST Topologies*

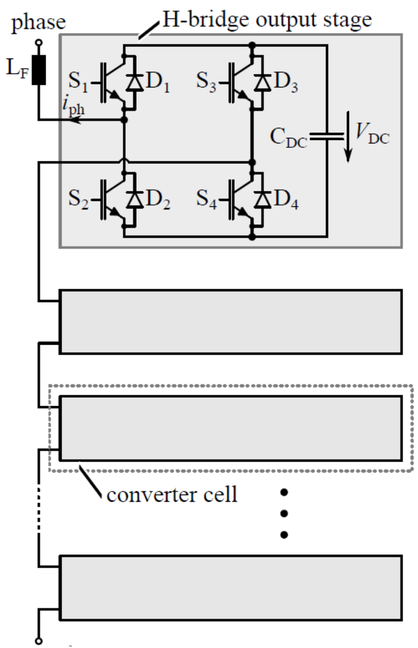
▶ Interfacing to Medium Voltage

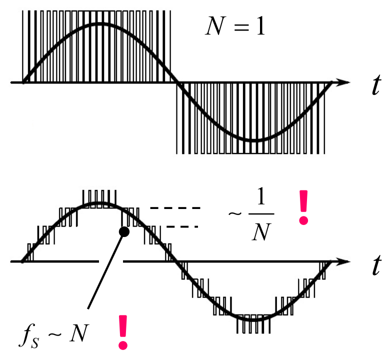
- Partitioning of Blocking Voltage
- Series Connection or Multi-Cell and Multi-Level Approaches
- High Number *N* Cells → Quadratically Reduces Curr. Harmonics

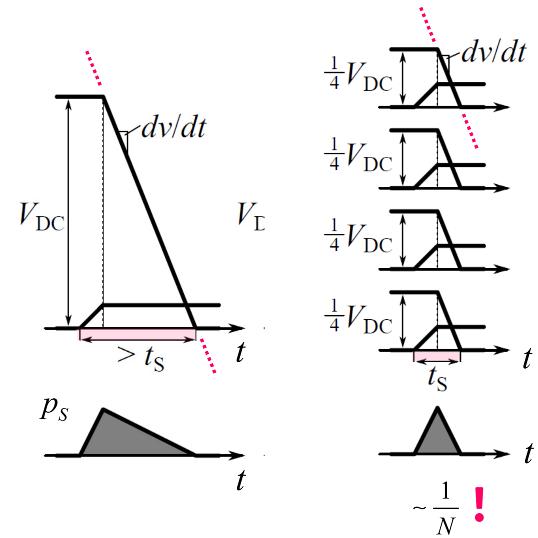


▶ Scaling of Series Interleaving of Converter Cells

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







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

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

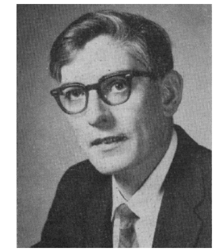
■ **Converter Cells Could Operate at VERY Low Switching Frequency**
■ **Minimization of Passives (Filter Components)**

United States Patent

[11] **3,581,212**

[54] **FAST RESPONSE STEPPED-WAVE SWITCHING POWER CONVERTER CIRCUIT**
18 Claims, 13 Drawing Figs.

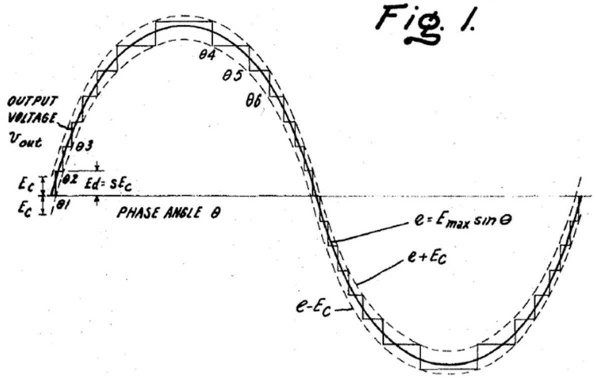
Inventor:
William McMurray
by Donald R. Campbell
His Attorney.

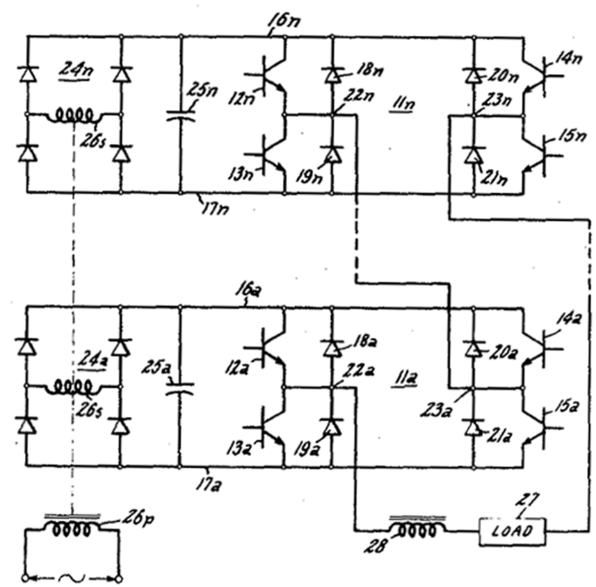


[72]	Inventor	**William McMurray** **Schenectady, N.Y.**
[21]	Appl. No.	**846,354**
[22]	Filed	**July 31, 1969**
[45]	Patented	**May 25, 1971**
[73]	Assignee	**General Electric Company**

← **1969 !**

Fig. 1.

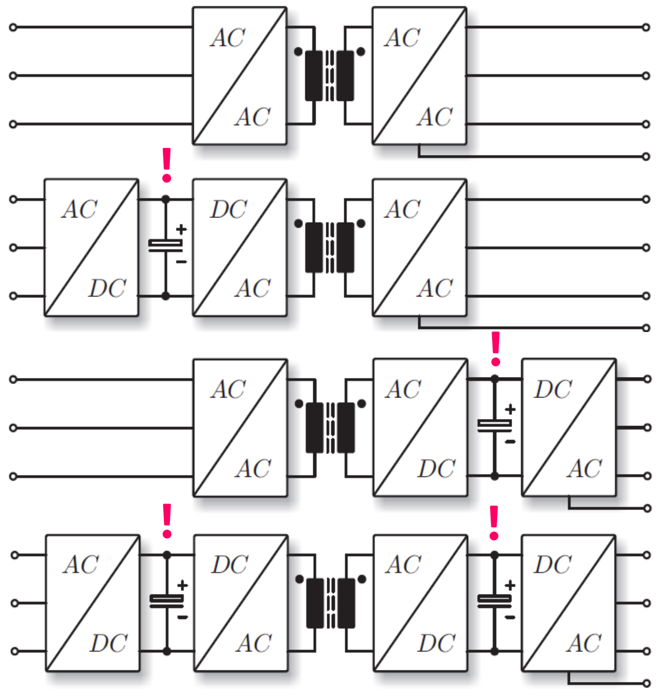




- **Cascaded H-Bridge Multi-Cell Converter (1-Φ AC/AC SST)**

Partitioning of AC/AC Power Conversion

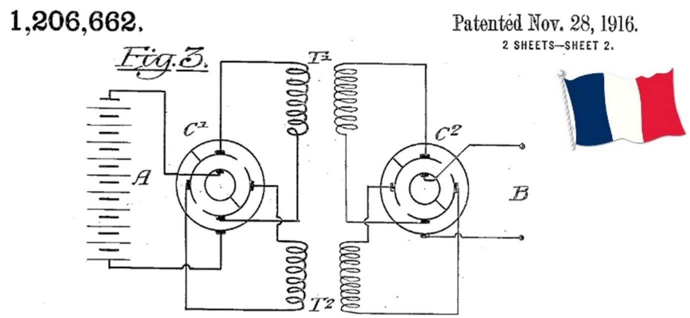
- Introduction of Intermediate DC-Links
  - Connection to DC Distribution Lines
  - Basic Converter Building Blocks
  - Integration of Energy Storage

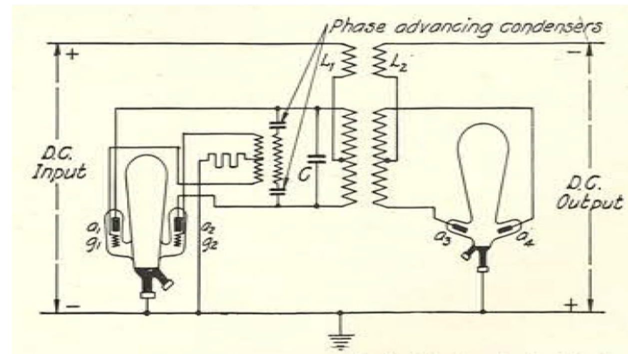


- Direct AC/AC Conversion – Isolated Back End – Isolated Front End - DC/DC Conv. Isolation

▶ Electronic Transformer - History

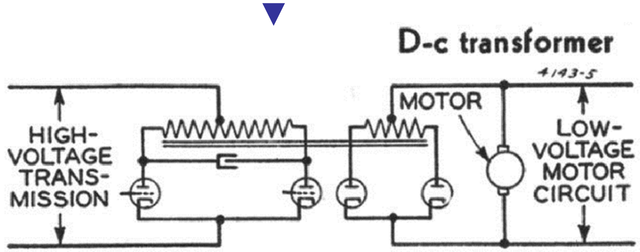
- System Using Mech. Switches *Patented Already in 1913* (!)
- Mechanical Sw. → Tubes → Mercury Arc Valves → Solid State Switches

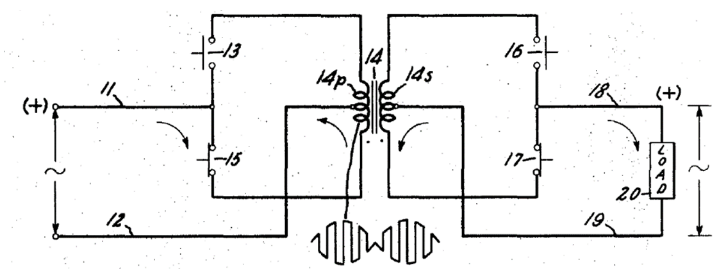




▲
1913 — *P.M.J. Boucherot*
1944 — *E.F.W. Alexanderson et al.*
▼

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

1

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

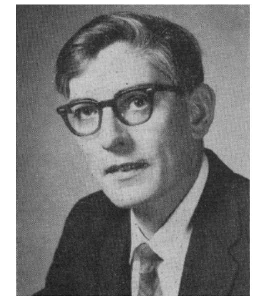
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York

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.

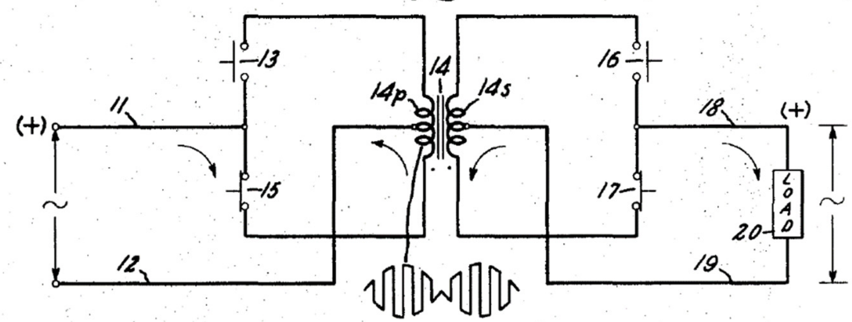
1968 !



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

Filed April 16, 1968

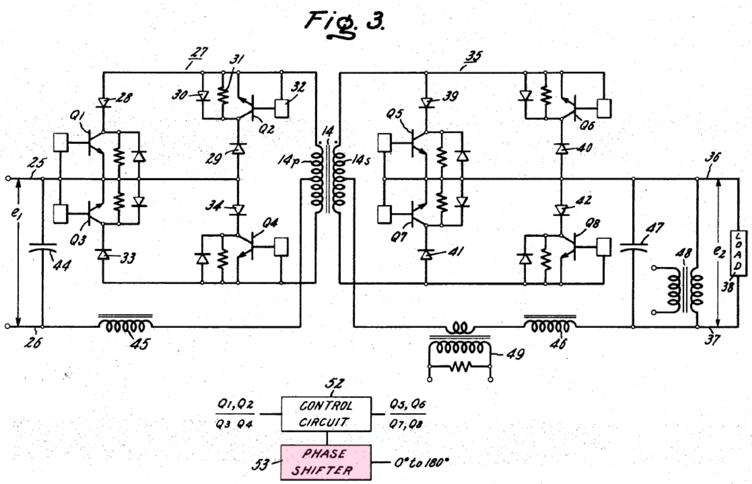
Fig. 1a



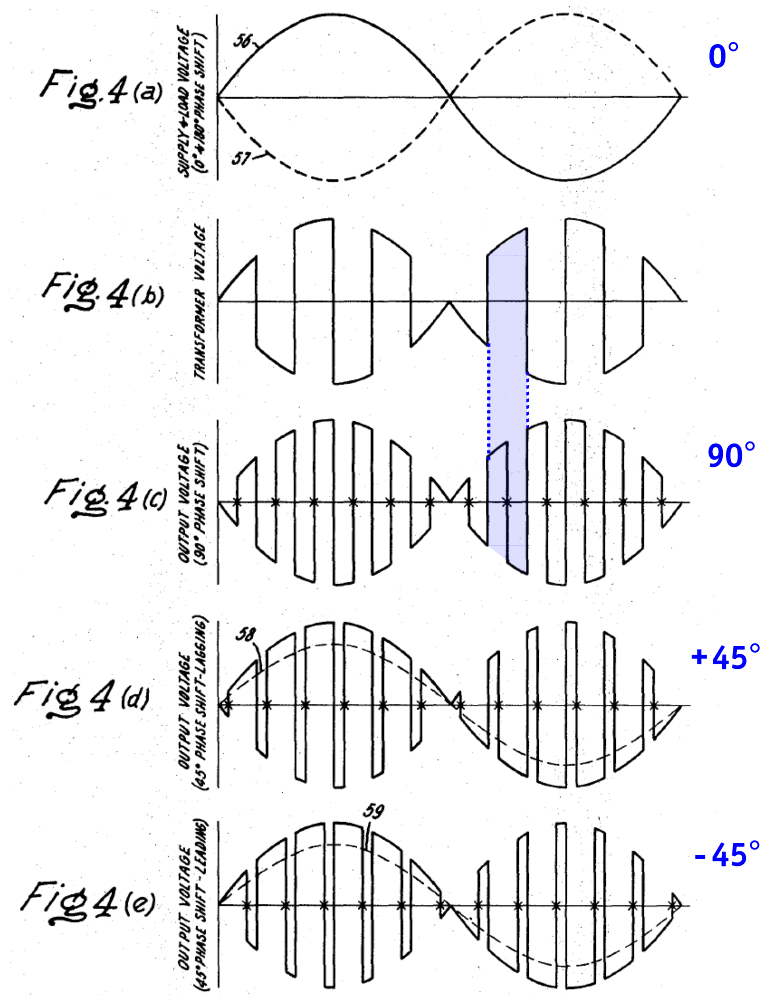
- Electronic Transformer ($f_1 = f_2$)
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption

► Electronic Transformer

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



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



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** ← "… 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**

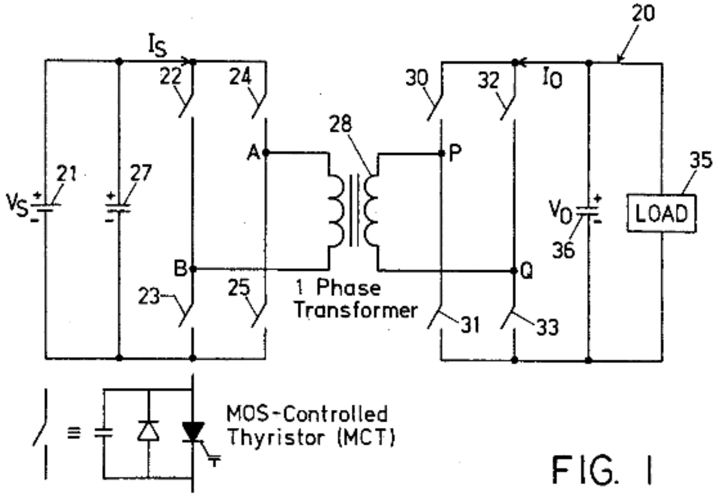


FIG. 1

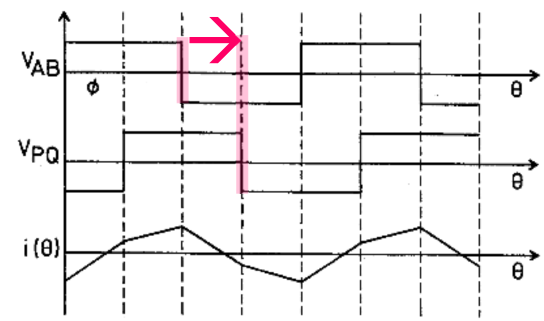


FIG. 2

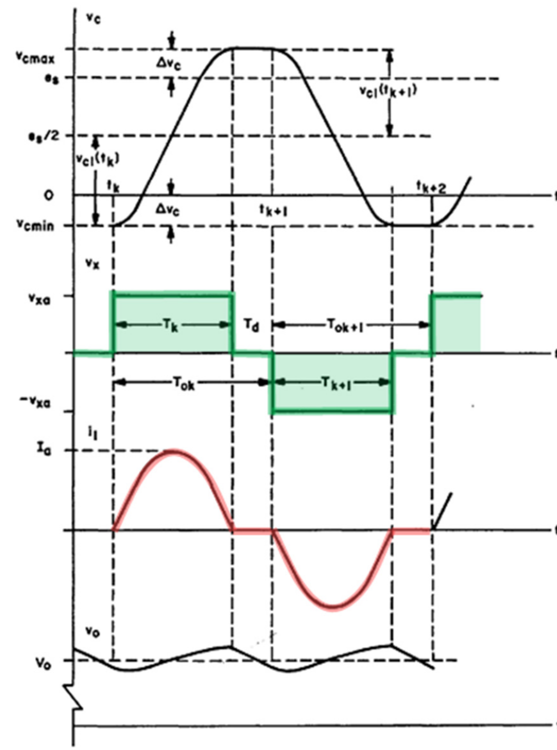
- Soft Switching in a Certain Load Range
- Power Flow Control by Phase Shift between Primary & Secondary Voltage

IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS AND CONTROL INSTRUMENTATION VOL. IECI-17, NO. 3, MAY 1970 ← 1970 !

A Method of Resonant Current Pulse Modulation for Power Converters

FRANCISC C. SCHWARZ, SENIOR MEMBER, IEEE

- **Load-Insensitive DCM Series Resonant *Thyristor* Converter**



- Transformer Voltage
- Transformer Current

- Resonant Tank

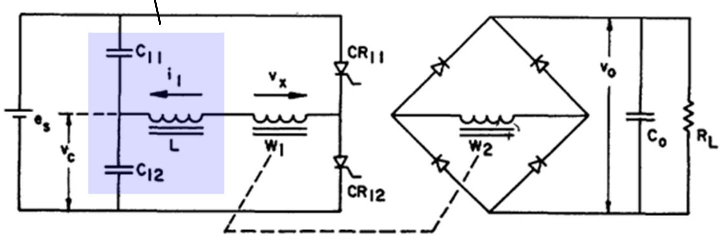
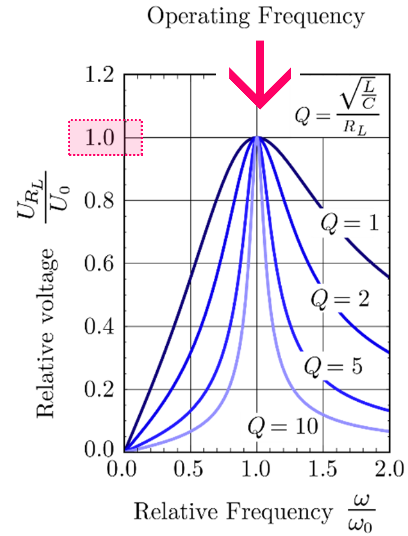
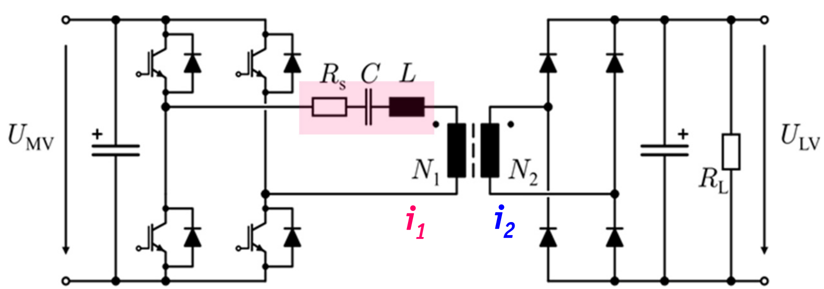


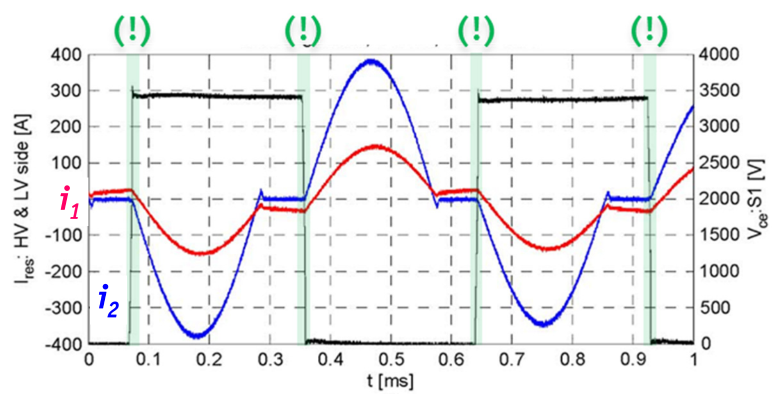
Fig. 4. Alternative simplified schematic of a controllable and load-insensitive series capacitor dc converter with transfer of inductive energy to the load.

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

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



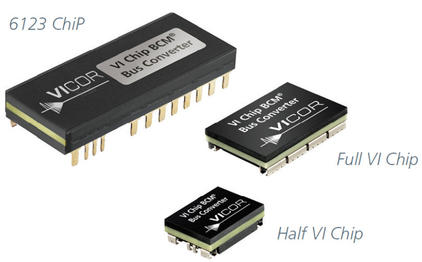


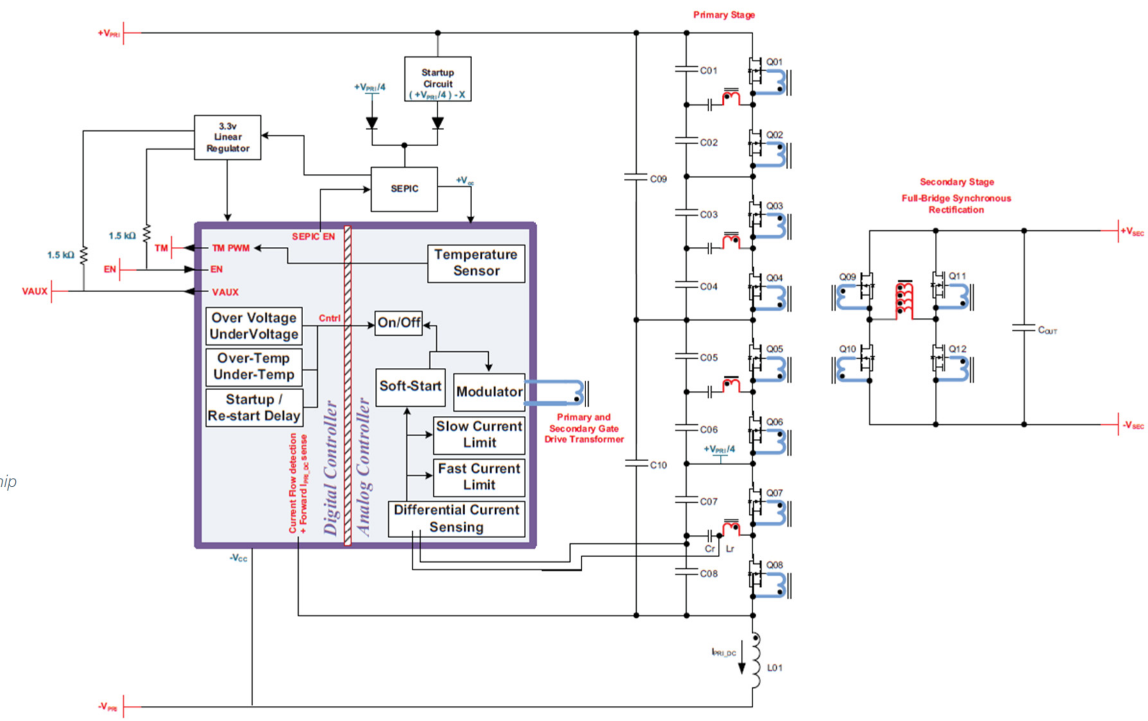


Remark – Concept also Used for Low-Power

- BCM Bus Converter Family
- Sine Amplitude Converter (SAC)
- Fixed Voltage Conversion Ratio DC/DC Converter

VICOR

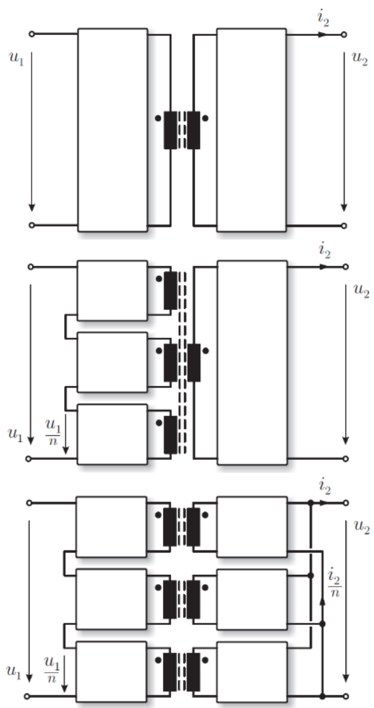




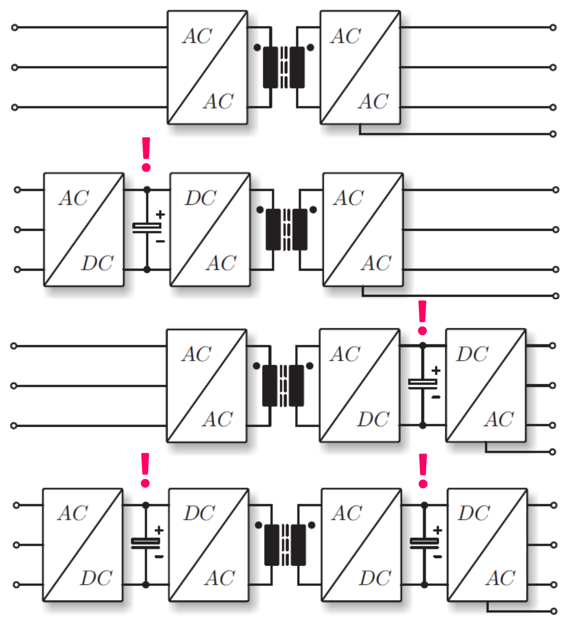
- Very High Power Density
- Very High Efficiency

▶ Classification of SST Topologies

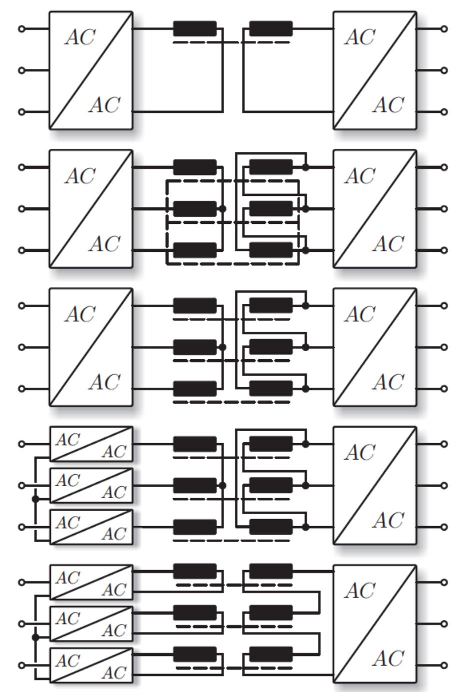
- **Number of Levels Series/Parallel Cells**



- **Degree of Power Conversion Partitioning**

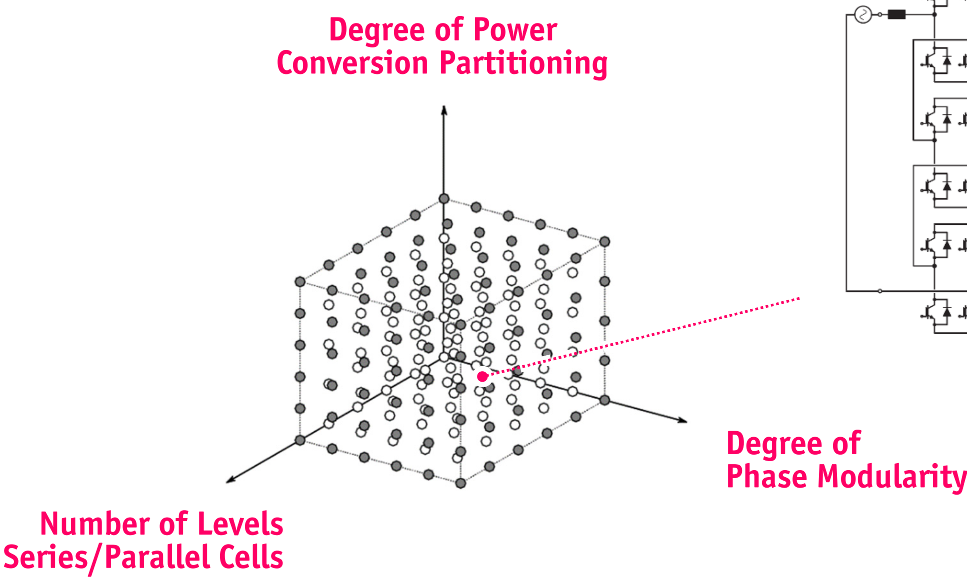


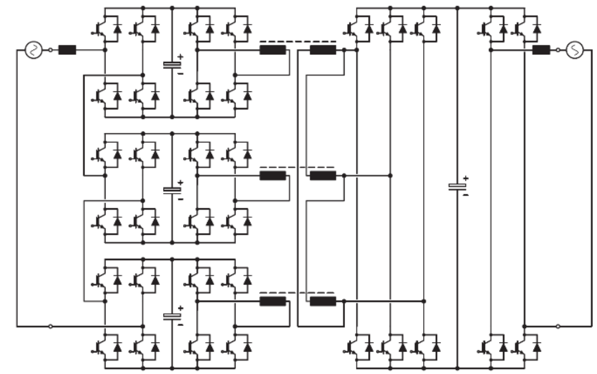
- **Degree of Phase Modularity**



▶ **3-Dimensional Topology Selection Space**

► Classification of SST Topologies





- Wrede (2003)

■ **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

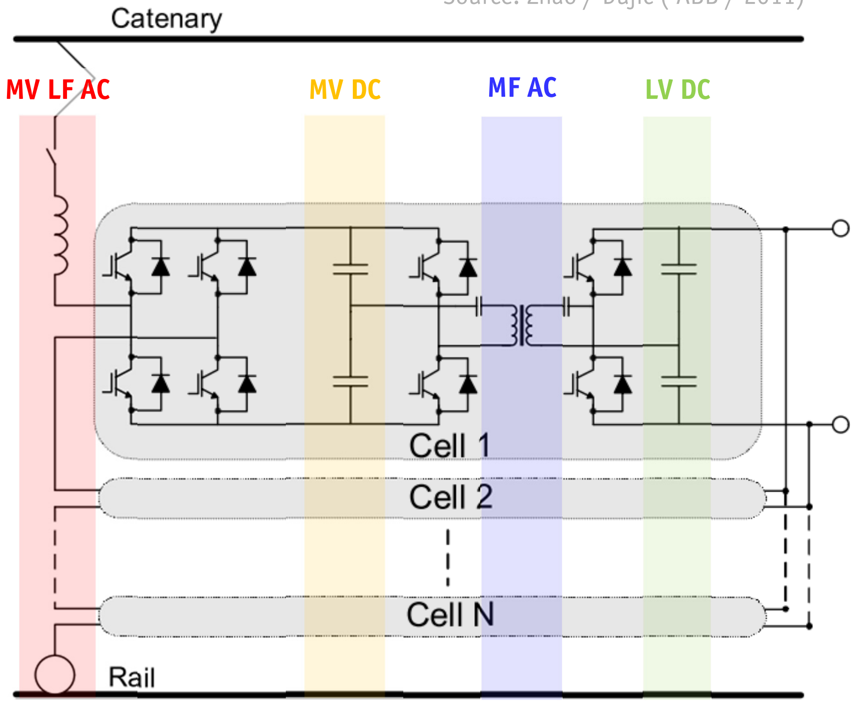
Combining the Basic Concepts I

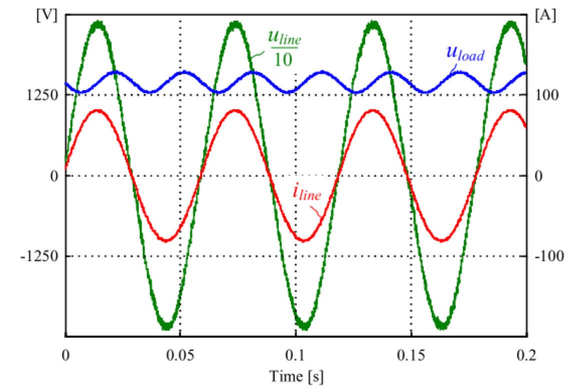
Single-Phase AC-DC Conversion / Traction Applications

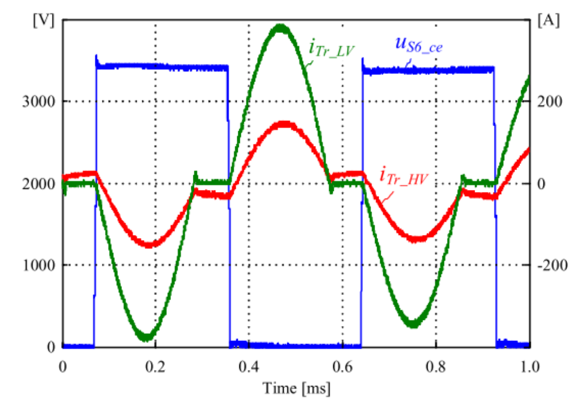
► Cascaded H-Bridges w. Isolated Back End

- 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)

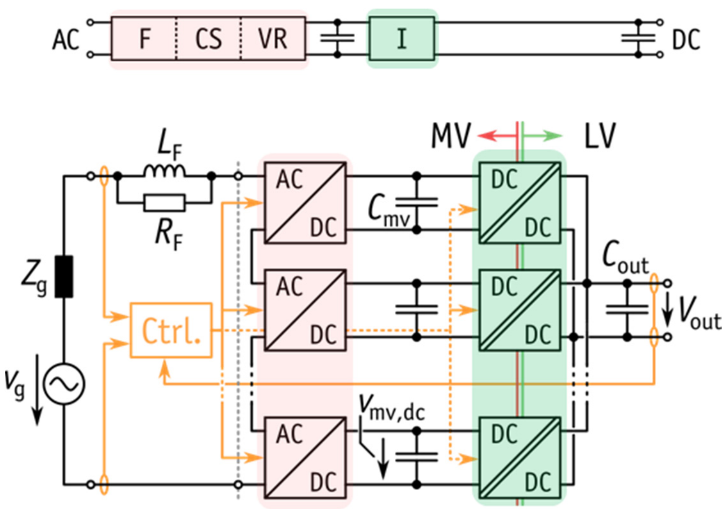






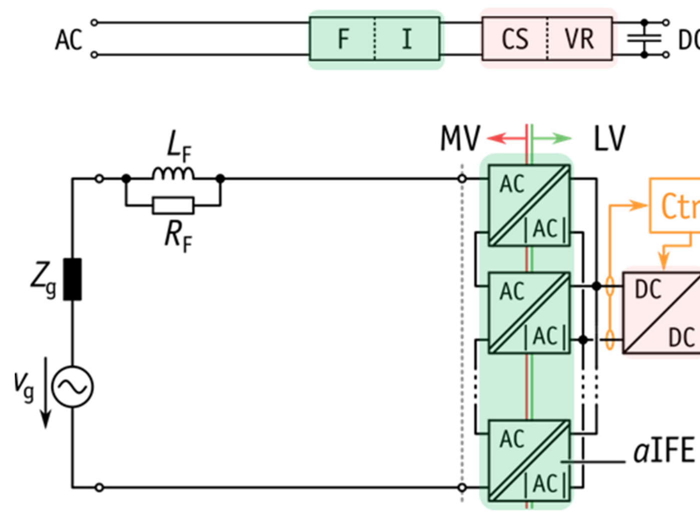
▶ Current Shaping & Isolation → Isolation & Current Shaping

■ 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

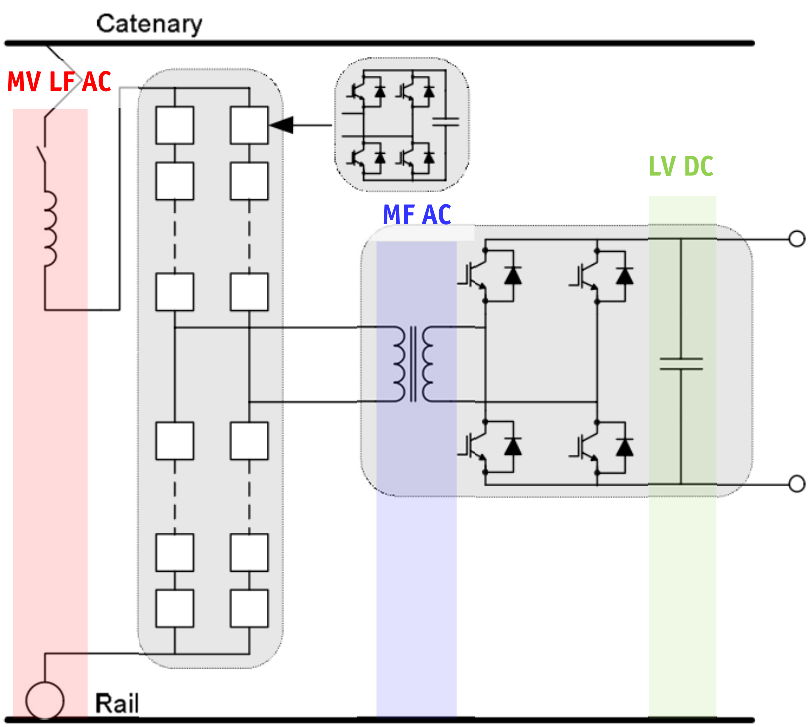


- Swiss SST (S3T)
- Two-Stage Multi-Cell Concept
- Indirect Input Current Control
- Direct Output Voltage Control
- Low Complexity on MV Side

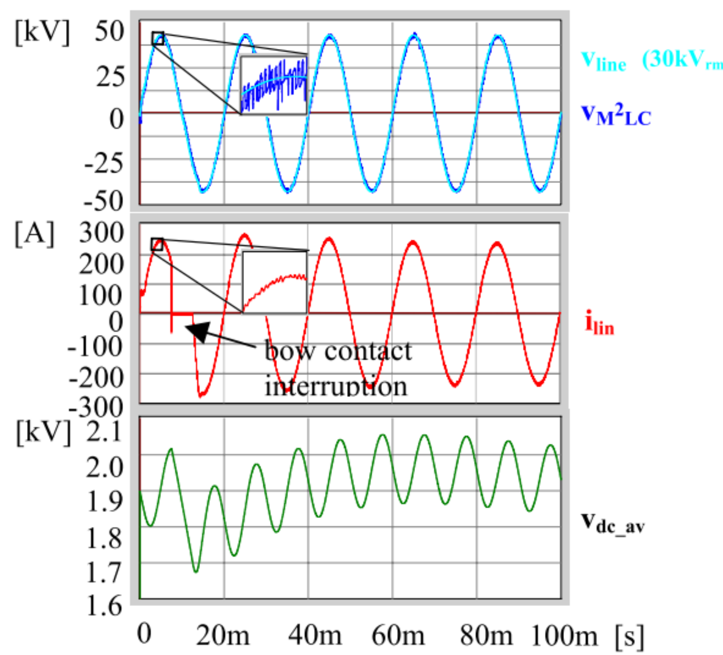
▶ Modular Multilevel Converter

- Single Transformer Isolation
- Highly Modular / Scalable
- Allows for Redundancy
- Challenging Balancing on Cell DC Voltages

SIEMENS
- Marquardt/Glinka (2003)

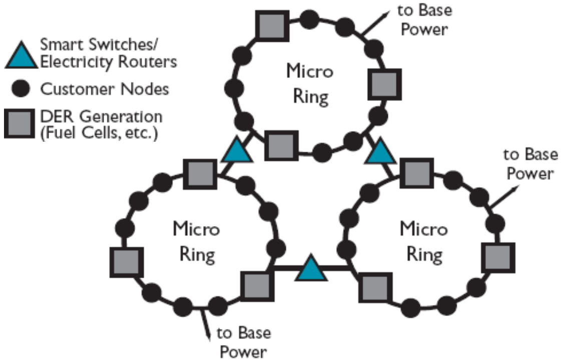


Source: Zhao / Dujic (ABB / 2011)



Combining the Basic Concepts II

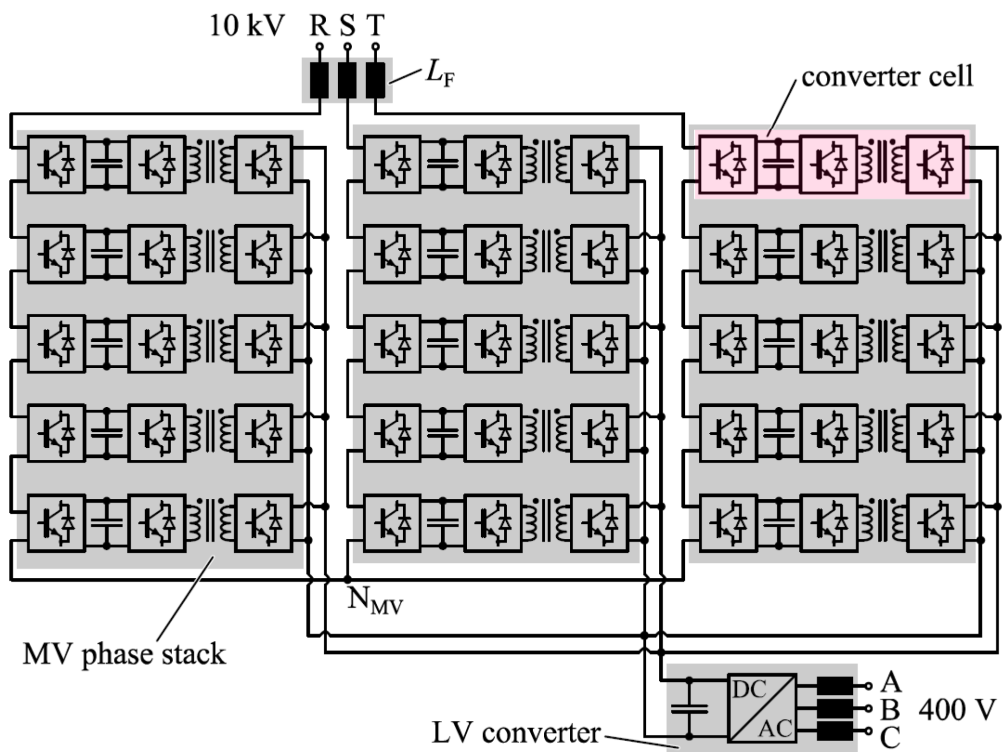
Three-Phase AC-AC Conversion / Smart Grid Applications



Source: EPRI ELECTRIC POWER RESEARCH INSTITUTE

▶ MEGALink @ ETH Zurich

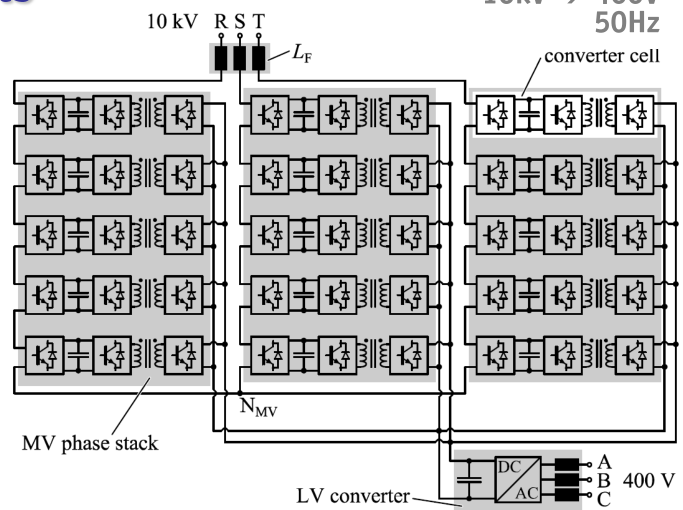
S_N = 630kVA
U_{LV} = 400 V
U_{MV} = 10kV



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

▶ Optimum Number of Converter Cells

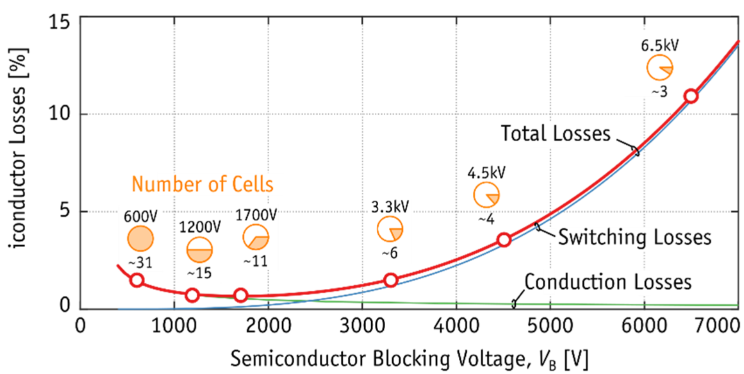
1 MVA
10kV → 400V
50Hz

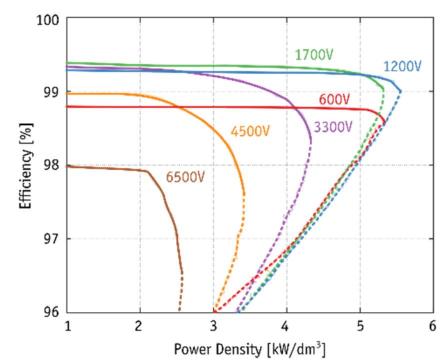


- **Trade-Off** High Number of Levels →
  High Conduction Losses/
  Low Cell Sw. Frequ./Losses
  (also because of Device Char.)

- Opt. Device Voltage Rating for Given MV Level
- ηρ-Pareto Opt. (Compliance to IEEE 519 @ Eff. Sw. Frequ., only Cascaded H-Bridges, i.e. DC/DC Converter Stages Not Considered)

L_F=10%
$\Delta i_{pp}/\hat{I}_N$=1%



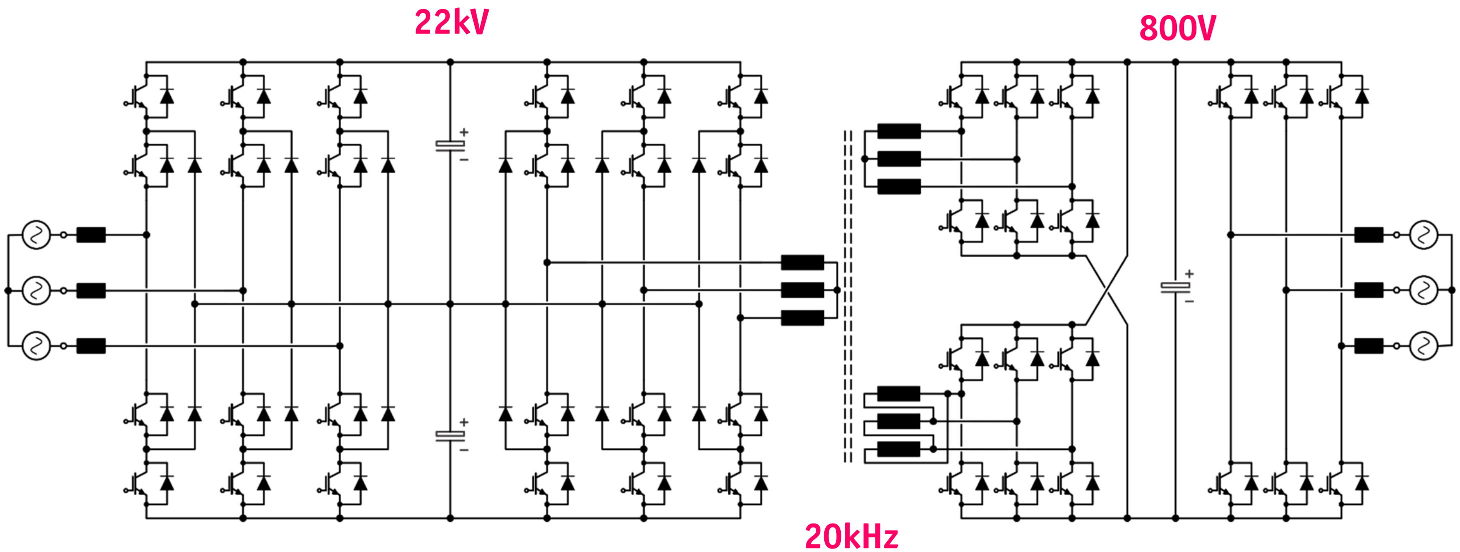


- **1700V Power Semiconductors Best Suited for 10kV Mains → 10kV or Higher SiC Not Required (!)**

▶ Single-Cell Structure (SiC)

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

FREEDM systems center



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

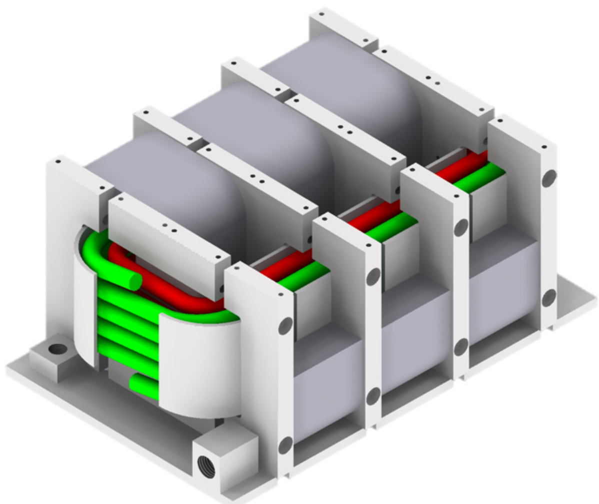
Challenge #3/5

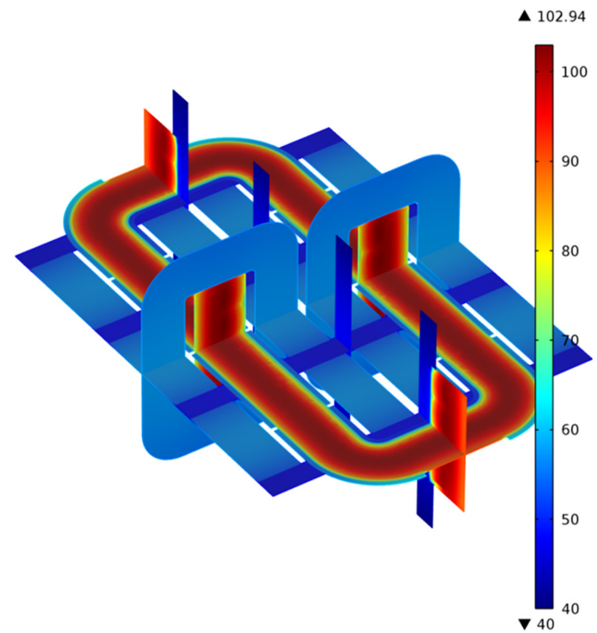
Medium-Frequency Transformer Design

- *Heat Management*
- *Isolation*

▶ MF Transformer Design – Cold Plates/ Water Cooling

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





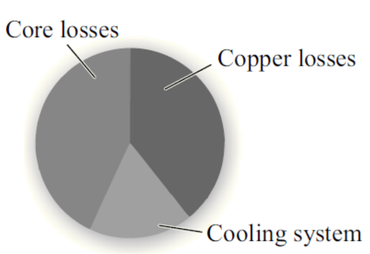
- Combination of Heat Conducting Plates and Top/Bottom Water-Cooled Cold Plates
- FEM Simulation Comprising Anisotropic Effects of Litz Wire and Tape-Wound Core

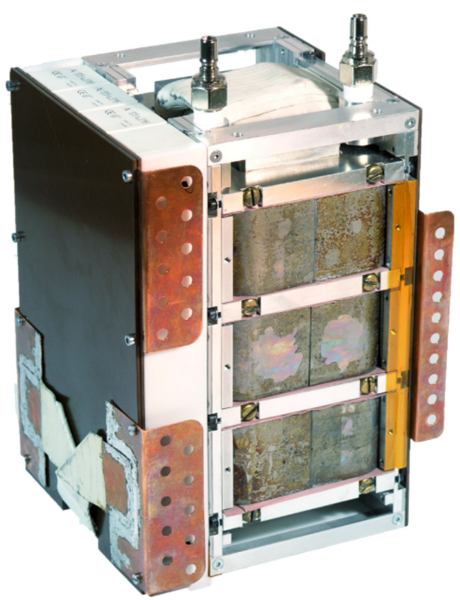
▶ Water-Cooled 20kHz Transformer

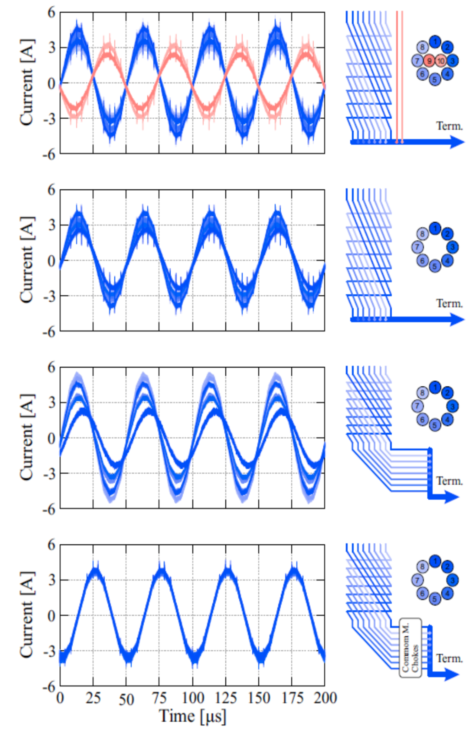
- Power Rating 166 kW
- Efficiency 99.5%
- Power Density 32 kW/dm^3

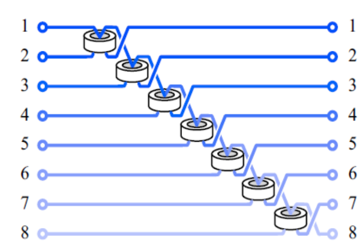
- Nanocrystalline Cores with 0.1mm Airgaps between Parallel Cores for Equal Flux Partitioning

- Litz Wire (10 Bundles) with CM Chokes for Equal Current Partitioning





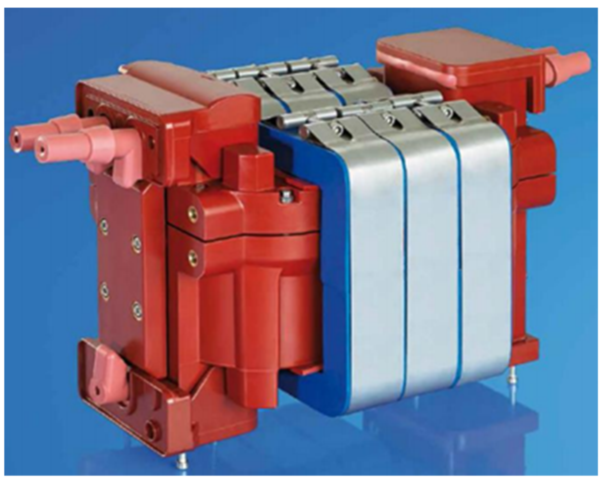




Further MF Transformer Examples

- Coaxial Windings – Shell Type
- Tunable Leakage Inductance
- Simple Terminations

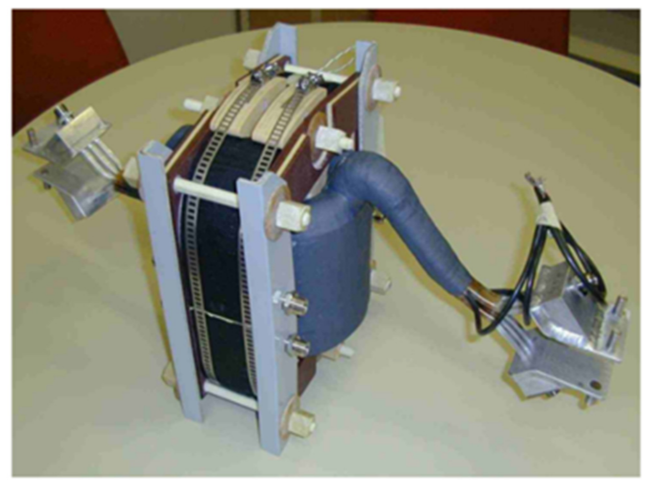
- 450kW @ 8 kHz / 50kg
- 99.7% Efficiency
- Dry Type / Liquid Isolation for 34.5kV



STS (2014)
www.sts-trafo.com

- 350kW @ 8 kHz
- Water Cooling / Hollow Conductors
- Isolation for 33kV

Steiner (2007)



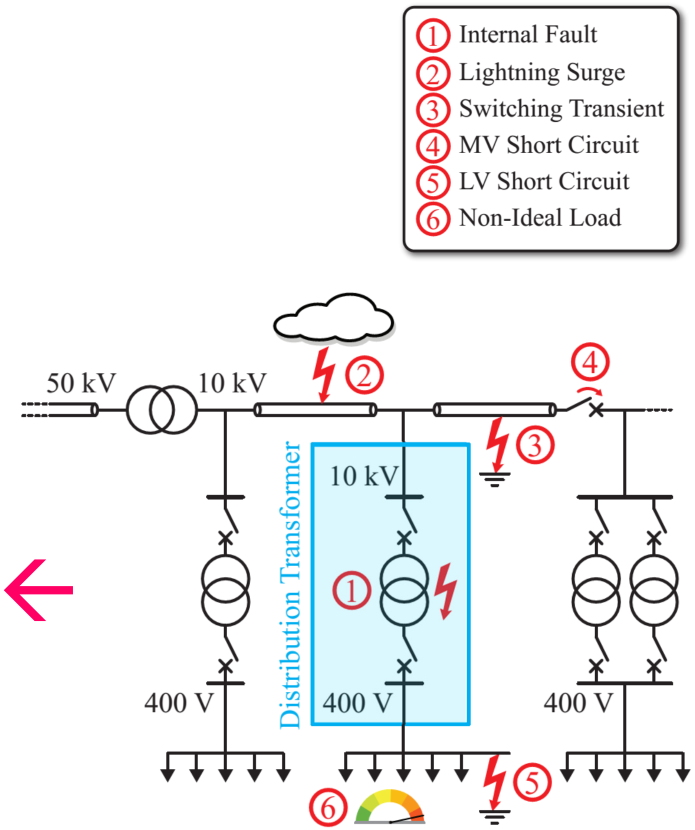
- 1 MVA @ 50Hz → 2600kg / 99% Efficiency @ Rated Load (!)

Challenge #4/5

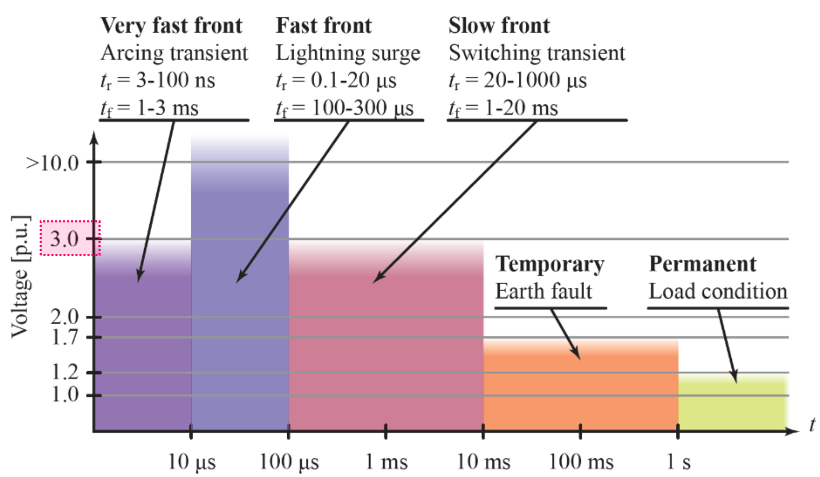
Mains ← SST → Load
Protection

▶ Conv. MV→LV XFRM – Overvoltage Requirements

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



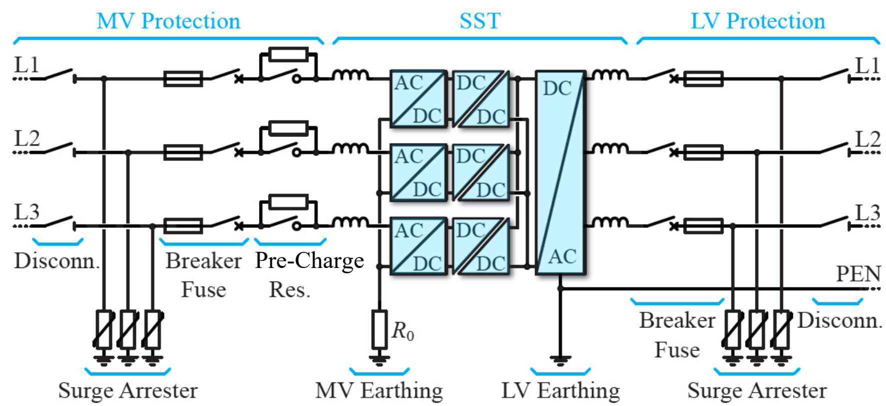
- **Conv. MV Grid Time-Voltage Characteristic**



▶ Overvoltage Protection of SST

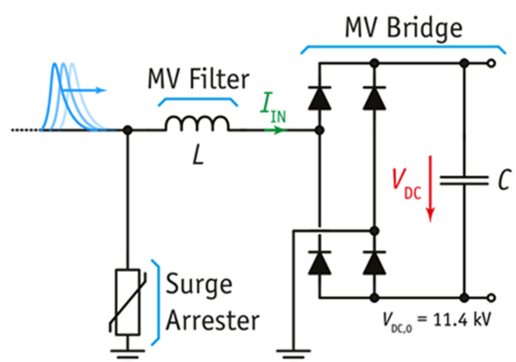
■ Missing Analysis of SST Faults (Line-to-Line, Line-to-Gnd, S.C., etc.) & Protection Schemes

- Proposed SST Protection Scheme with Minimum # of Protection Devices



- Overvoltage Protection (Lightning Strike)

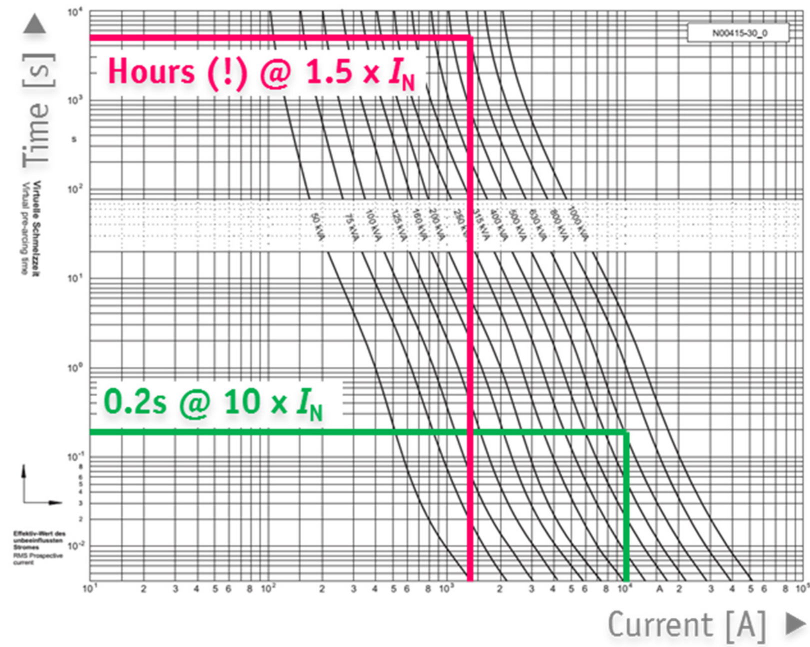
  * High Arrester Clamping Voltage
  * Filter Inductor > 8% for Current Limiting
  * Requires Min. DC Link Capacitance
  * Sufficient Blocking Capability
  * Grounding – Lower Stress if Unearthed



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

▶ Conv. MV→LV XFRM – Overcurrent Requirements

400V Fuse / 630kVA XFRM



- Very High Currents Required to Trip Fuses OR Protection Relays

- Low-Frequ. XFRM must Provide Short-Circuit Currents of up to 10 Times Nominal Current for 200 ms

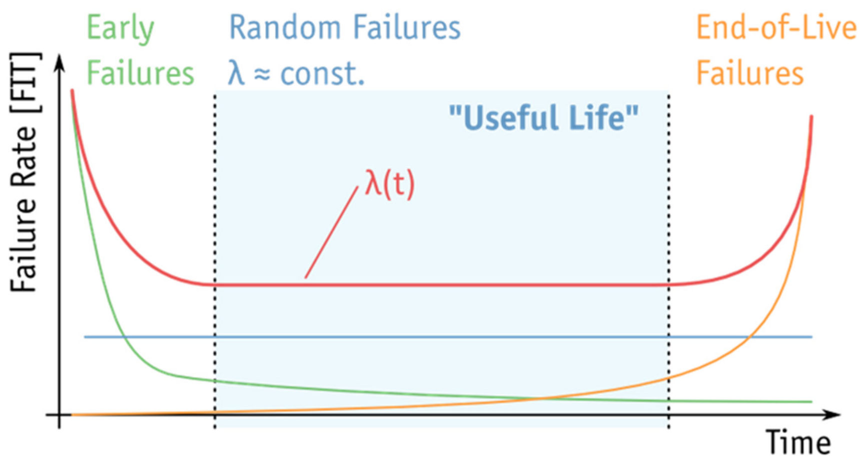
■ Lower Grid Voltage Levels → Higher Relative Short Circuit Currents
■ SST is NOT (!) a 1:1 Replacement for a Conventional Low-Frequency XFRM

Challenge #5/5

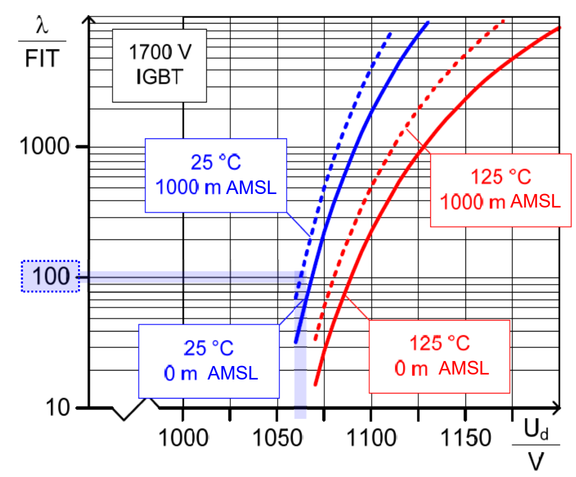
Ensuring Reliability of Highly Complex
Multi-Cell Converter Topologies

▶ Reliability Model (1) – Failure Rate

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



Source: H.-G. Eckel
Univ. Rostock



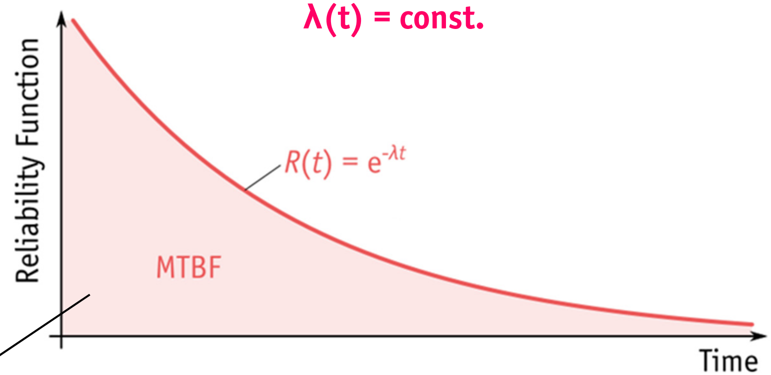
- Sources for Empirical Component Failure Rate Data : MIL-HDBK-217F, IEC Standard 62380, etc.

► 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.

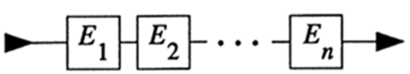


- **Mean Time Between Failures**

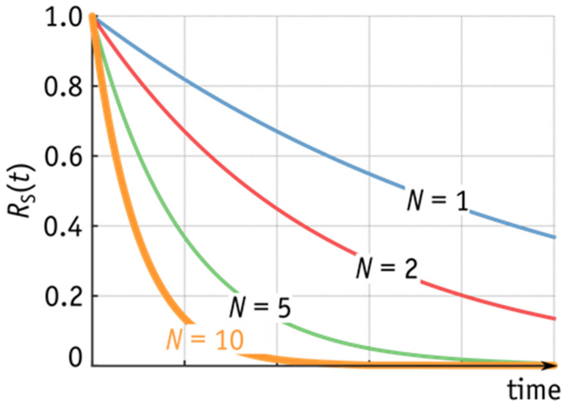
$$\text{MTBF} = \int_0^\infty R(t)\,dt = \int_0^\infty e^{-\lambda t}\,dt = \frac{1}{\lambda}$$

- **Series Structure**

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



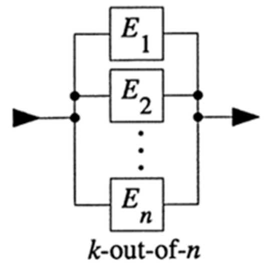
Independent Cells with Equal Failure Rate

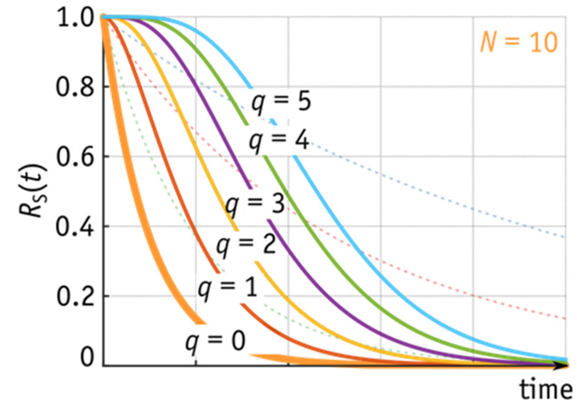


▶ Redundancy in Multi-Cell Converter Systems

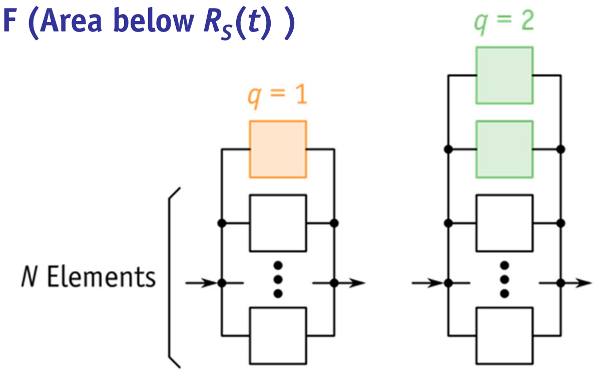
- ***k*-out-of-*n* Redundancy**
  Redundancy of Cells in Phase Stack

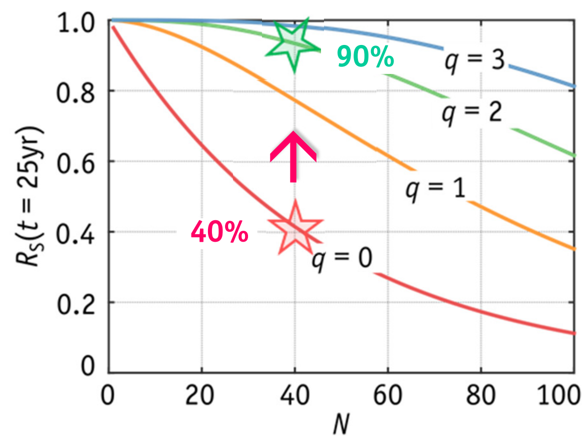
  ***System is Operational as Long as at Least k-out-of-n* Subsystems are Working**





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





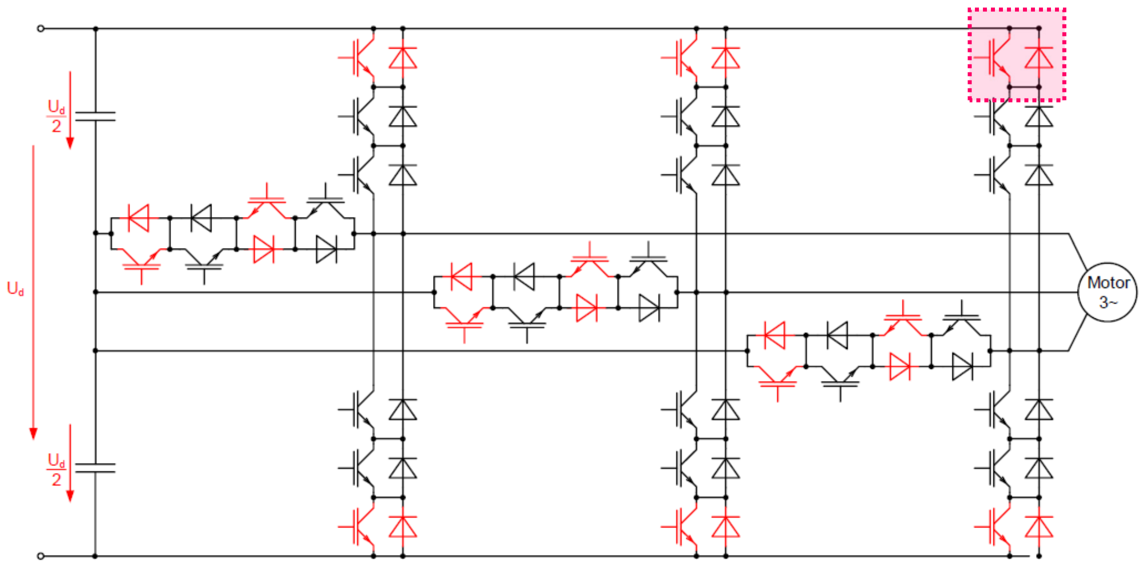
- **Redundancy Significantly Improves System Level Reliability (!)**

▶ Redundancy in Single-Cell Converter Systems

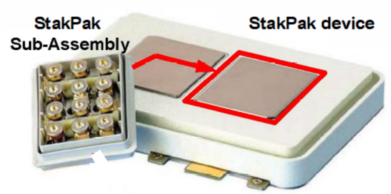
Source: M. Doppelbauer
M. Hiller

■ Example: Three-Level MV Motor Drive

■ Redundant Series Device



Press-Pack
NPC Phase Module



- Fail-to-Short Behavior Required (!)
- Only Feasible with Press-Pack Modules

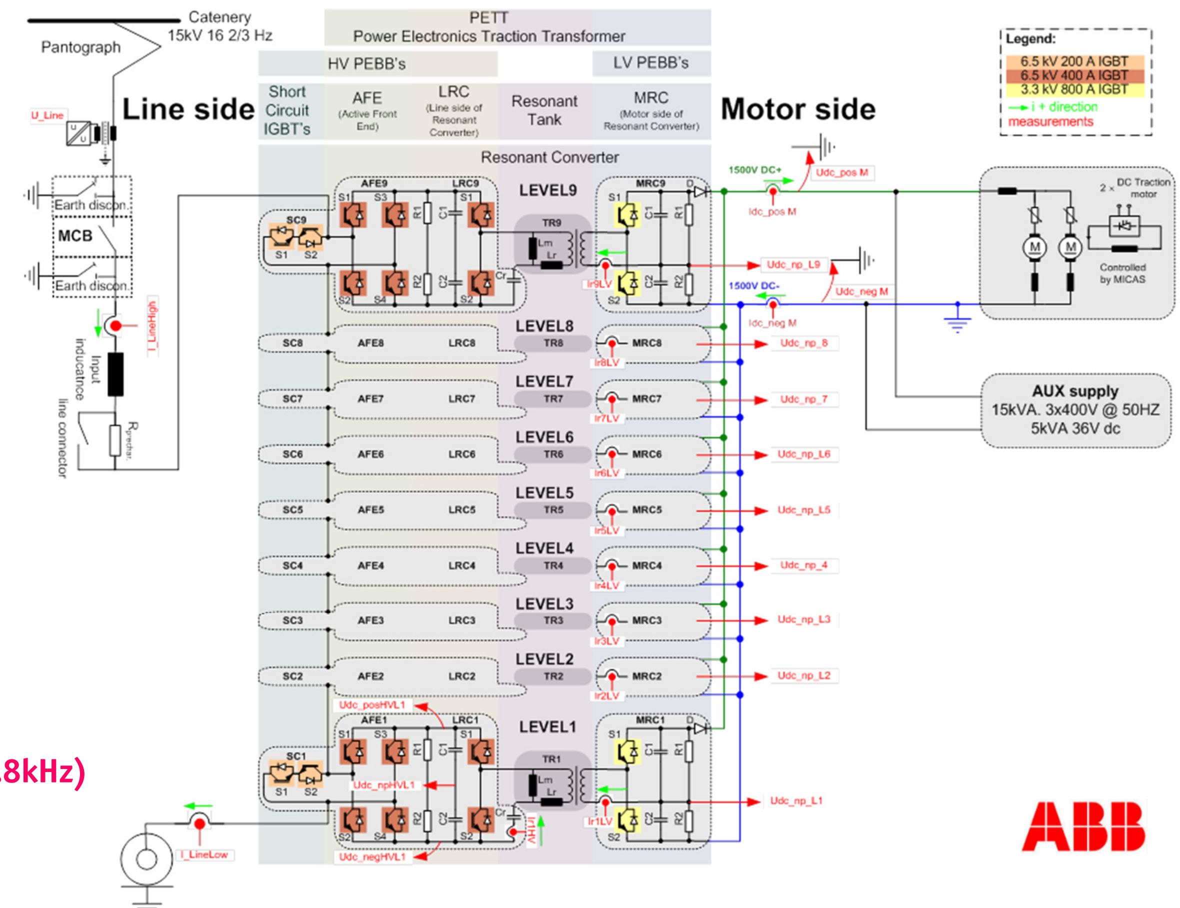
SST Demonstrator Systems

Future Locomotives
Smart Grid Applications

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

- Dujic et al. (2011)

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



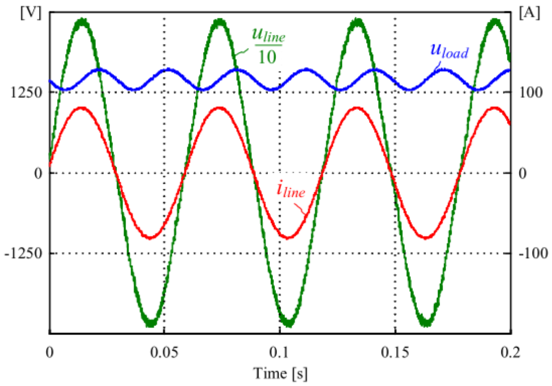
P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

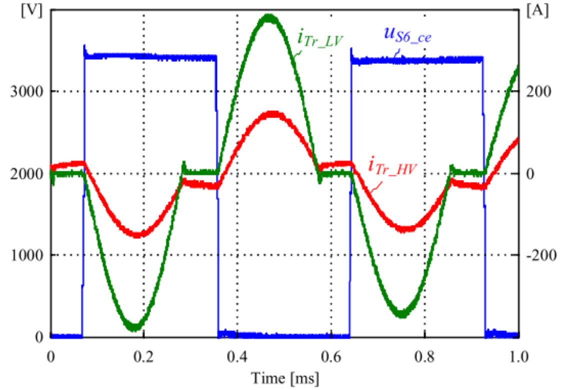
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

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



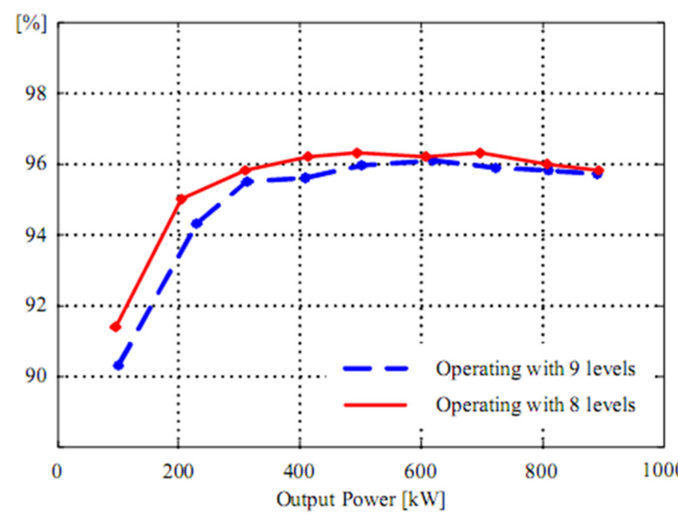


- Same Overall Volume as Conv. System
- Future Development Targets Cutting Volume in Half

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

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

Efficiency

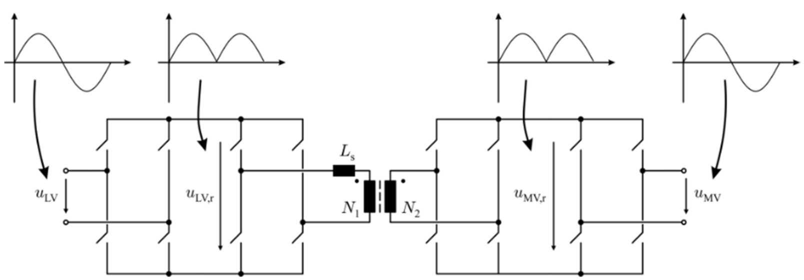


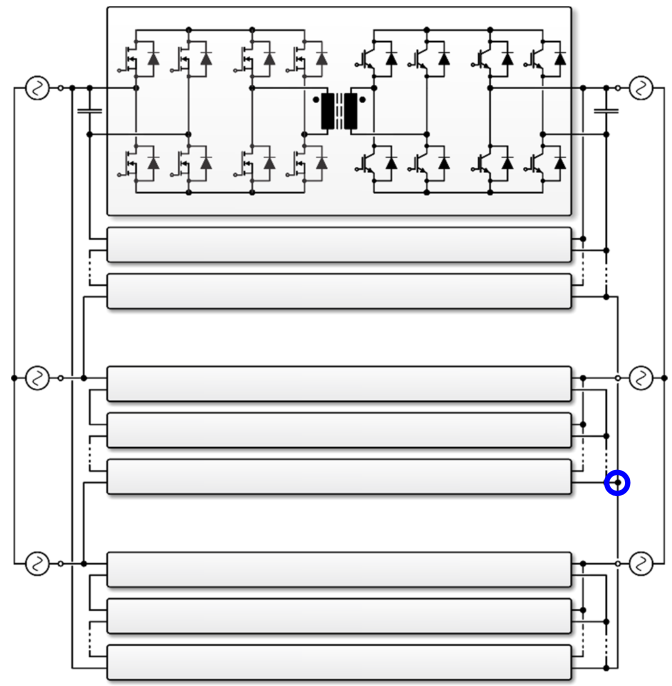
- Same Overall Volume as Conv. System
- Future Development Targets Cutting Volume in Half

► 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 (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

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- Fully Phase Modular System
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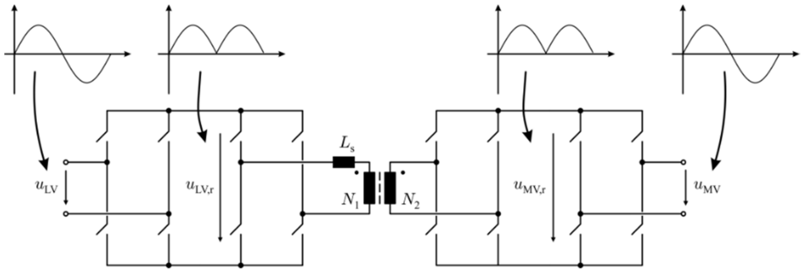


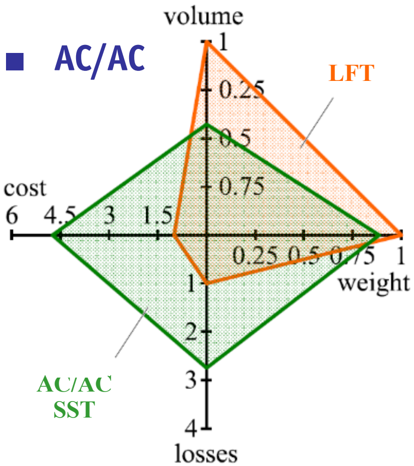
- SiC Enabled 20kHz/1MVA "Solid State Power Substation"
- 97% Efficiency @ Full Load / 1/3rd Weight / 50% Volume Reduction (Comp. to 60Hz)

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

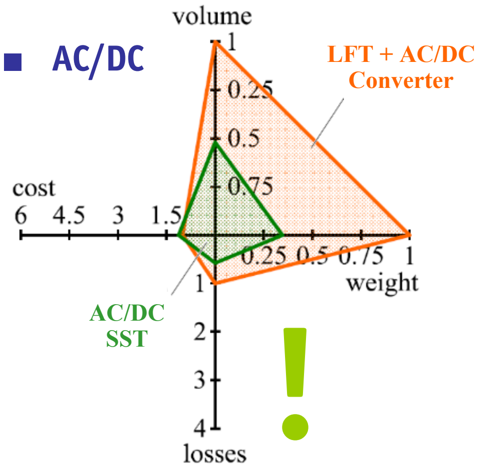
- Specifications: 1MVA
  10kV Input
  400V Output
  1700V IGBTs (1kHz/8kHz/4kHz)

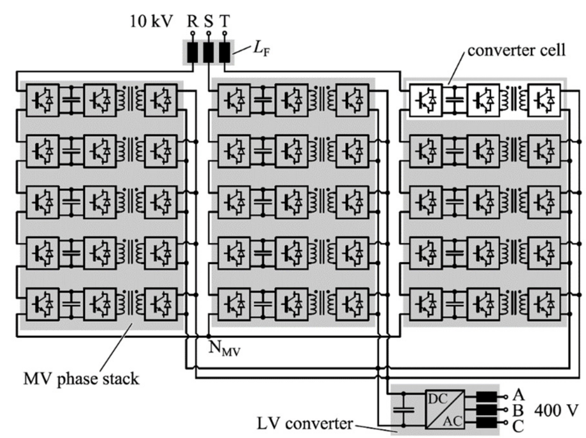
- LF Transformer: 98.7 %
  16.2 kUSD
  2600kg (5700lb)

■ 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
High Power/Fast EV Charging
Off-Shore Wind
Oil and Gas Industry
Power-to-Gas
Distributed Propulsion Aircraft
More Electric Ships

▶ Green / Zero CARBON Datacenters

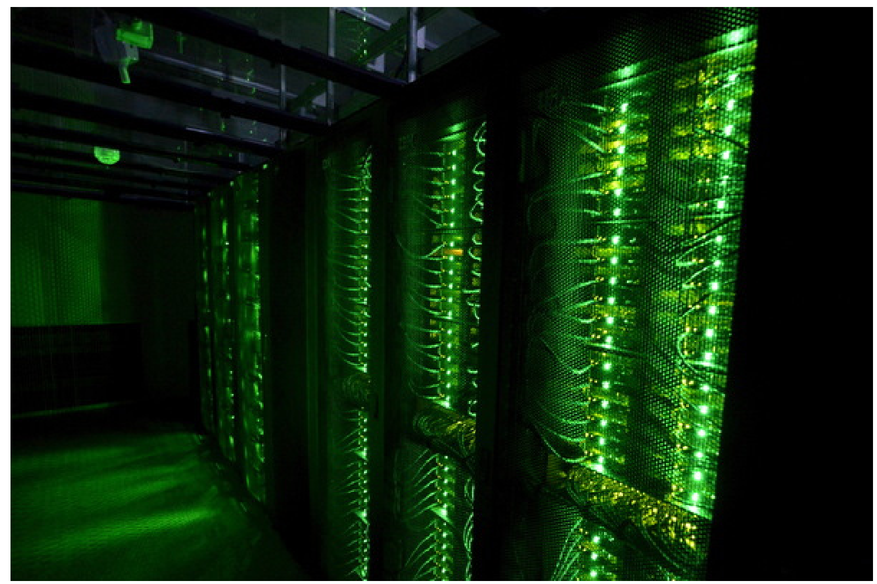
— Ranging from Medium Voltage to Power-Supplies-on-Chip
— Short Power Supply Innovation Cycles
— Modularity / Scalability

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

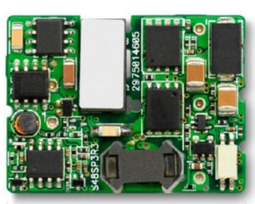
Server-Farms
up to 450 MW
99.9999%/<30s/a
$1.0 Mio./Shutdown

Since 2006
Running Costs >
Initial Costs

Source: REUTERS/Sigtryggur Ari



33 Watts



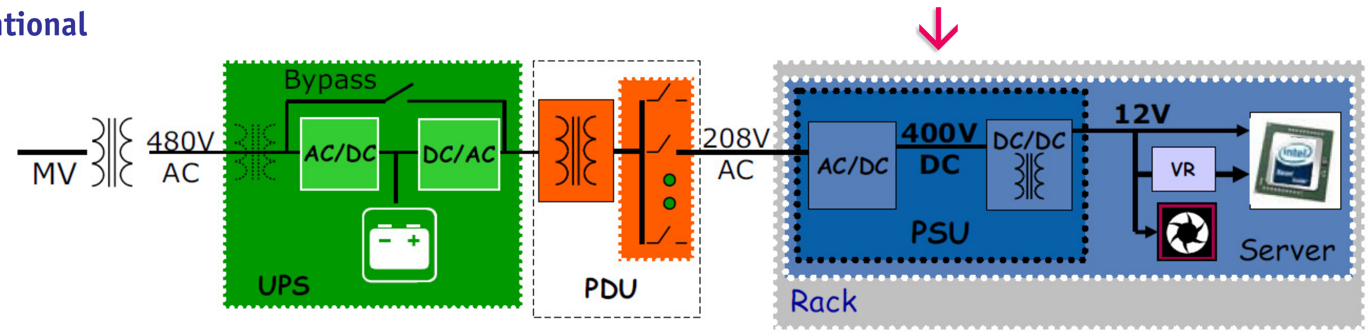
→

60 Watts

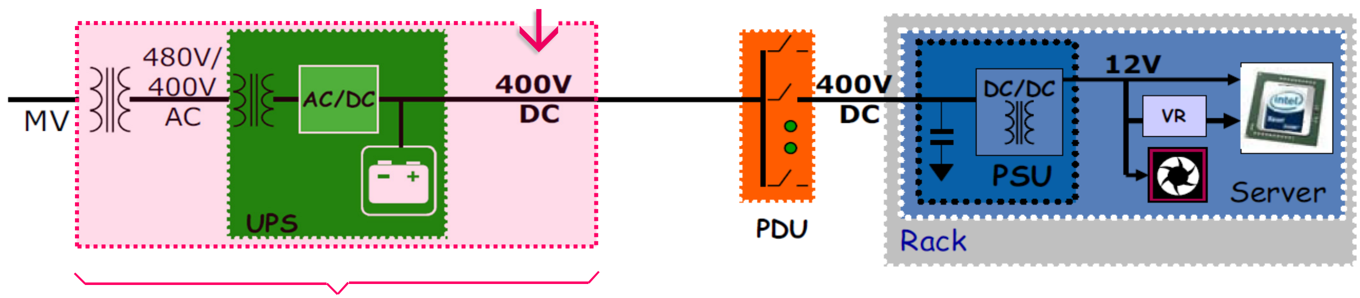
▶ SST-Based 400V DC-Distribution System

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

— Conventional



— Facility-Level 400 V_{DC} Distribution → Gain in Efficiency / Complexity

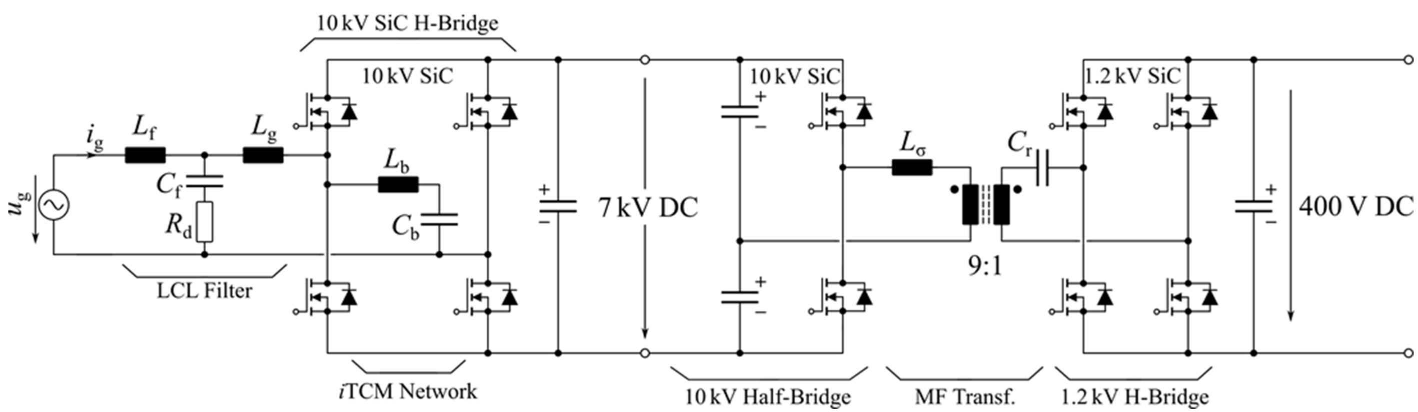


- Direct 3-Φ 6.6kV AC → 400V DC Conversion / Unidirectional SST

25kW SwiSS-Transformer

- *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

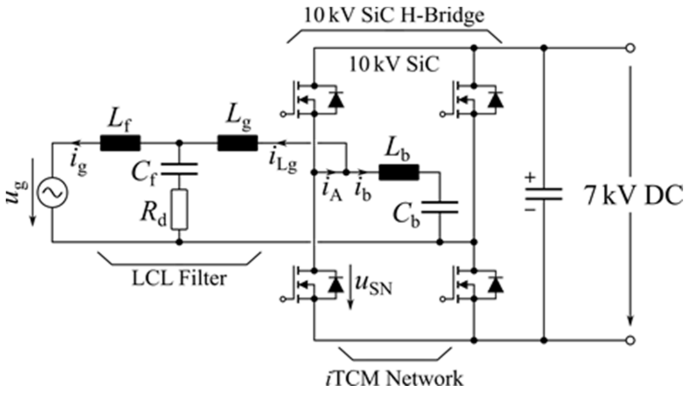
▶ *35...75kHz iTCM Input Stage*

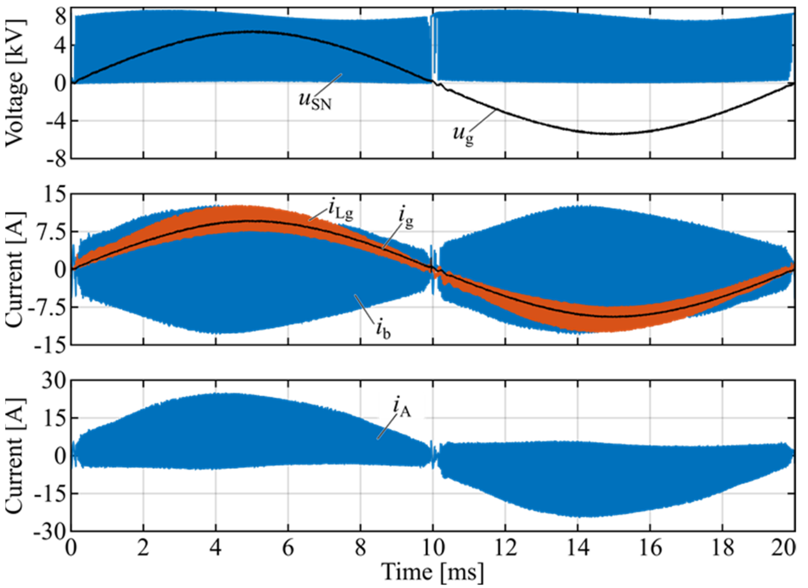
▶ *48kHz DC-Transformer Output Stage*

▶ 3.8kV → 7kV ZVS AC/DC Converter

■ *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 ZVS (35…75kHz)
— Separate Optim. of ZVS and Input Inductor Possible
— No Large Ripple Input Current





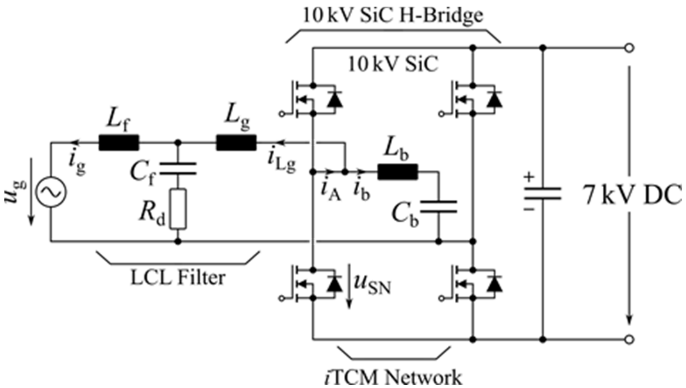
▶ Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)

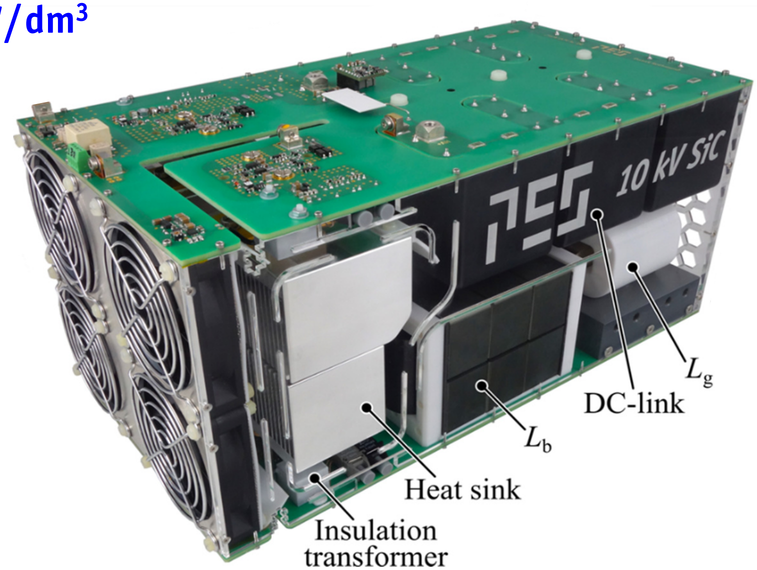
▶ 3.8kV → 7kV ZVS AC/DC Converter

■ *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





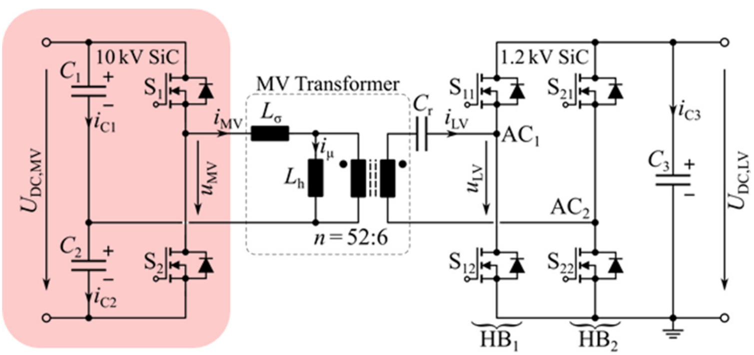
▶ Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)

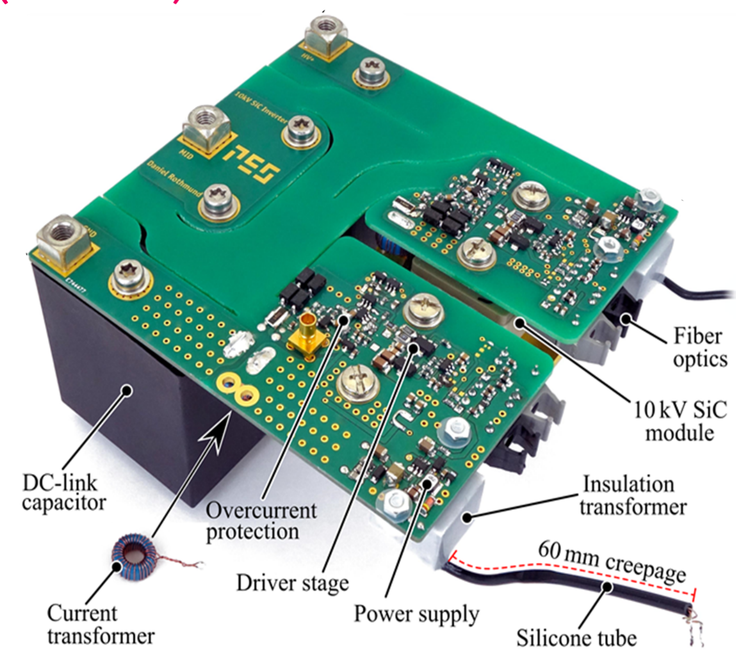
▶ 7kV → 400V DC/DC Converter

■ *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



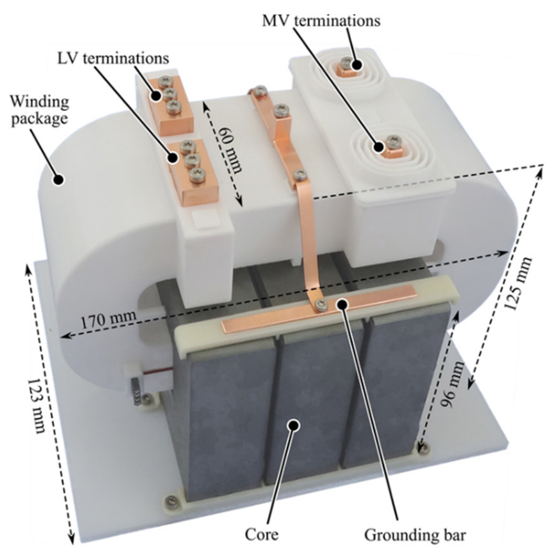


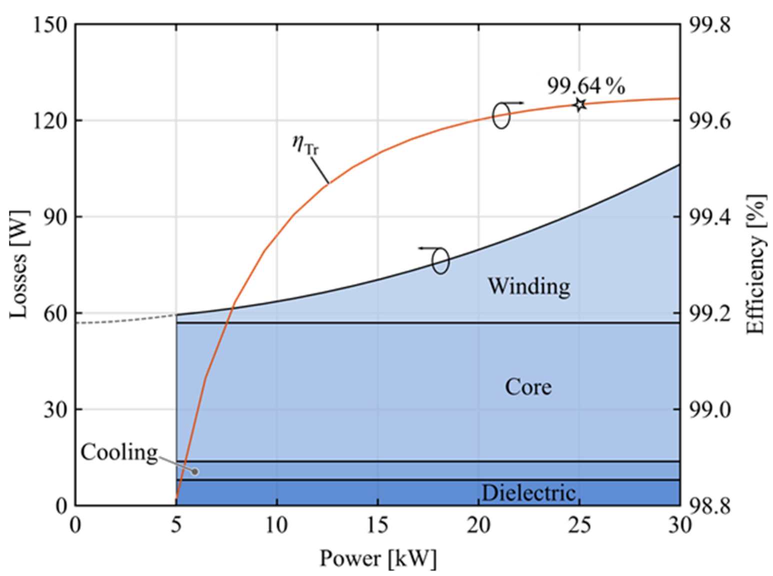
▶ Half-Bridge for Cutting Voltage in Half / Lower Switch Count

▶ 7kV → 400V DC/DC Converter

■ *MF-Transformer Measurement*

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

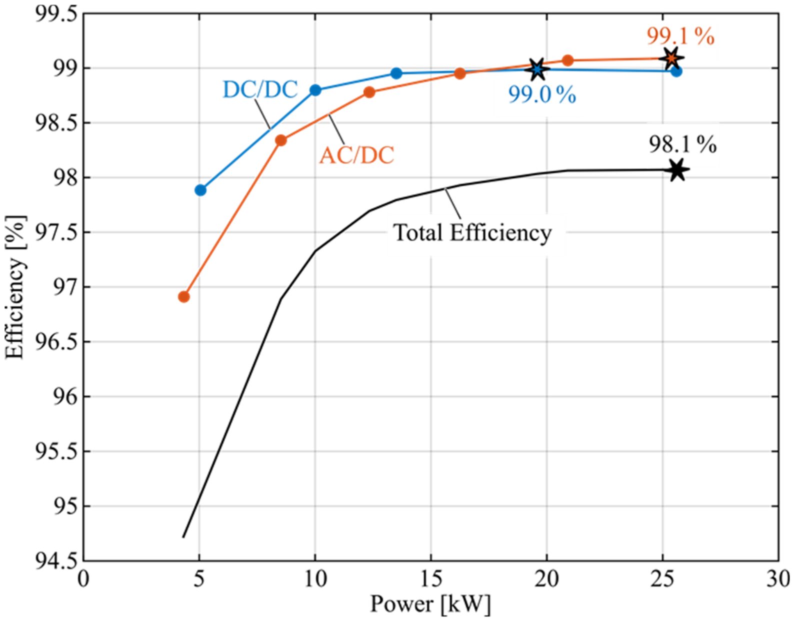




▶ Transformer Prototype / Loss Distribution / Efficiency

▶ Overall Performance

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

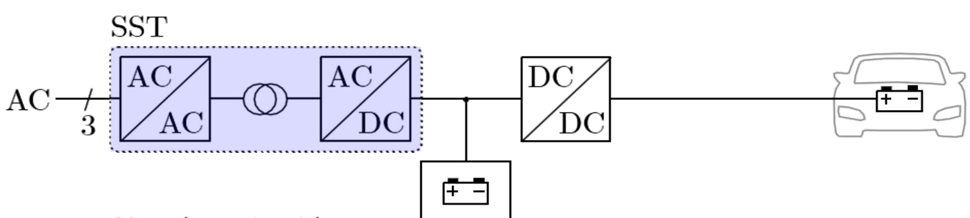


▶ *Red. of Losses & Volume by Factor of >2 Comp. to Alternative Approaches (!)*
▶ *Significantly Simpler Compared to Multi-Module SST Approach*

▶ Ultra-Fast / High-Power EV Charging

— Medium Voltage Connected Modular Charging Systems (e.g. Porsche *FlexBox* incl. Cooling)
— Very Wide Output Voltage Range (200...800V)

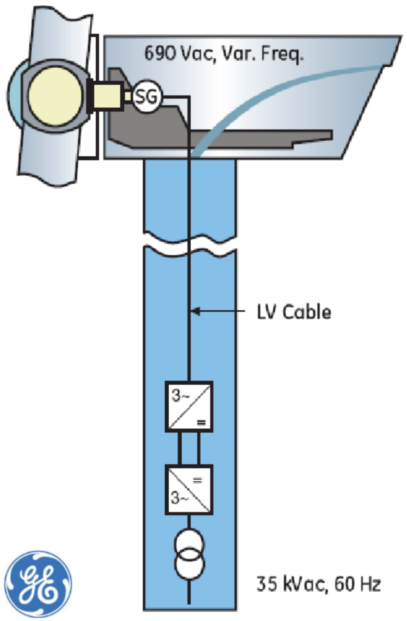
Source: Porsche
Mission-E Project



— Local Battery Buffer (140kWh)
— 320kW → 400km Range in 20min

▶ On-Shore/Off-Shore Windfarms

— 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

Source: M. Prahm / Flickr

▶ On-Shore/Off-Shore Windfarms

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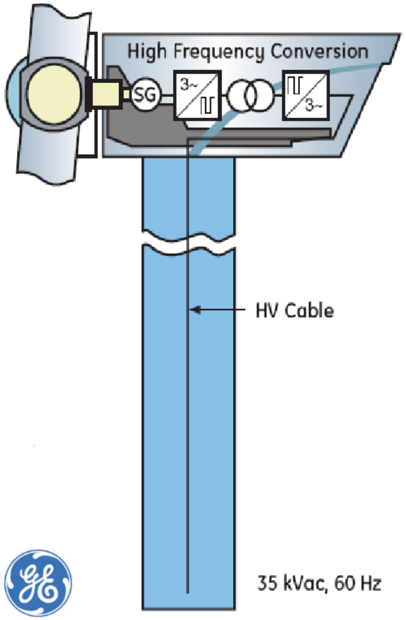
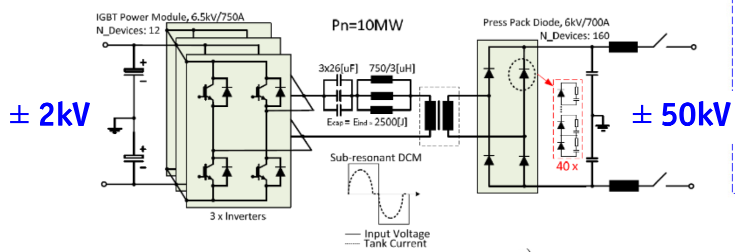


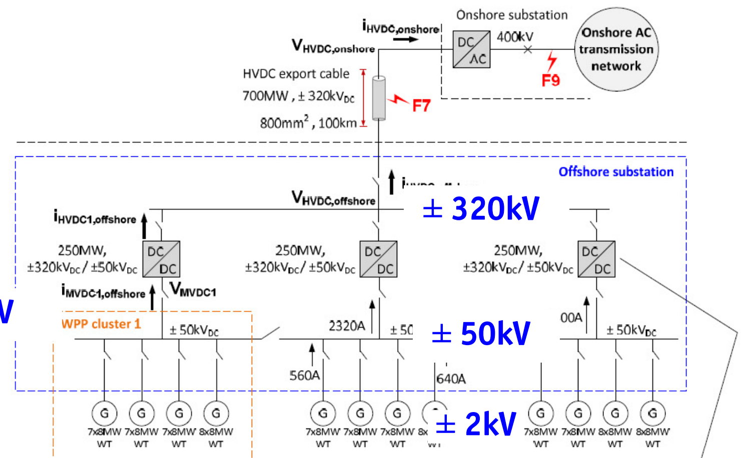
▶ Future Off-Shore System

Source: M. Prahm / Flickr

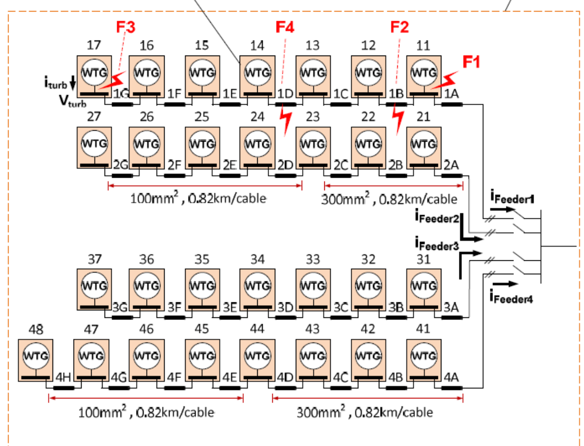
DC Collection Grids

- ± 50kV DC Offshore Collection Grid
- ± 50kV / ± 320kV DC/DC Offshore Substation
- ± 320kV HVDC Transmission to Shore

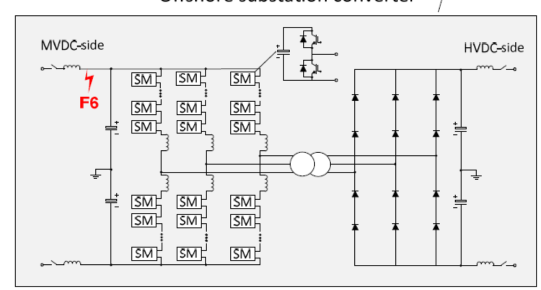




- Unidirectional Series Resonant MF DC→MVDC Conversion in Each Wind Turbine



Offshore substation converter



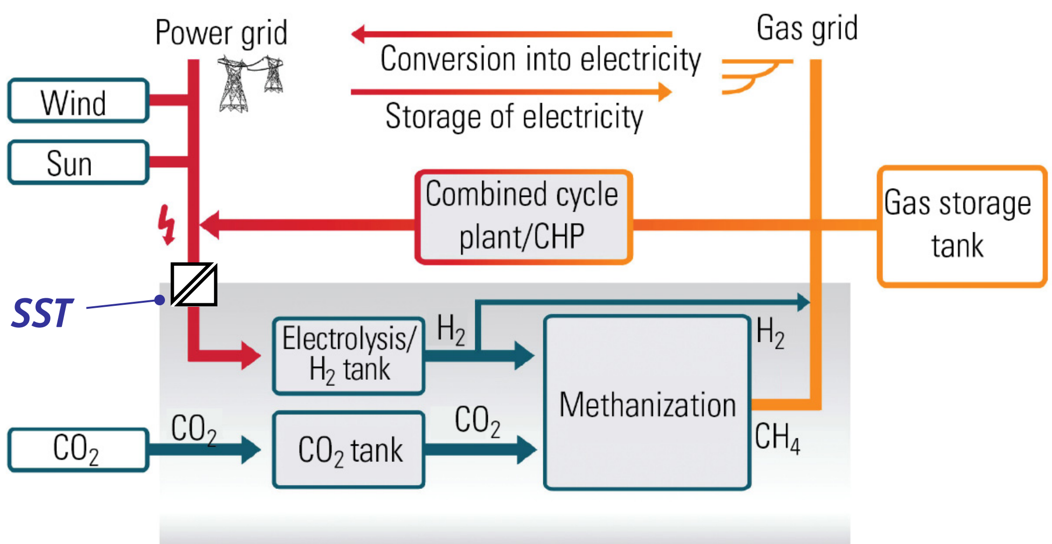
- MMLC-Based MF Isolation

Source: Kjaer/2016

▶ Power-to-Gas

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

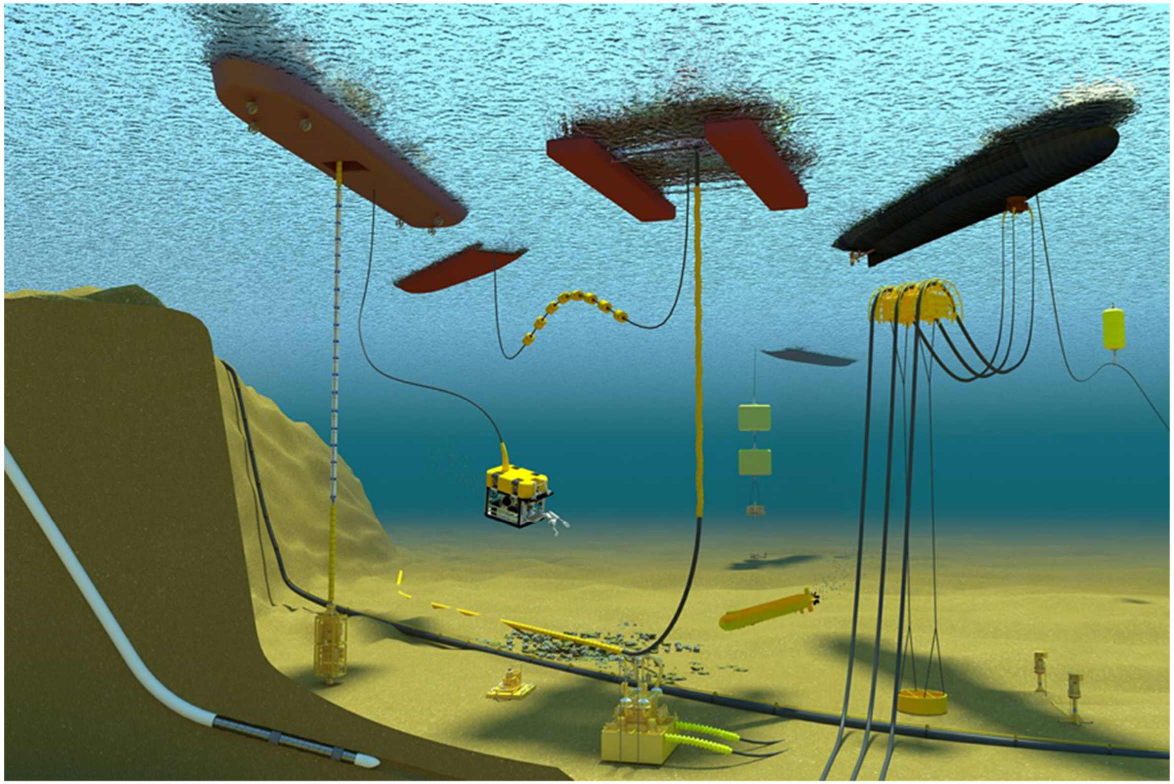
- High-Power @ Low DC Voltage (e.g. 220V)
- Very Well Suited for MV-Connected SST-Based Power Supply



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

Source: www.r-e-a.net

► 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

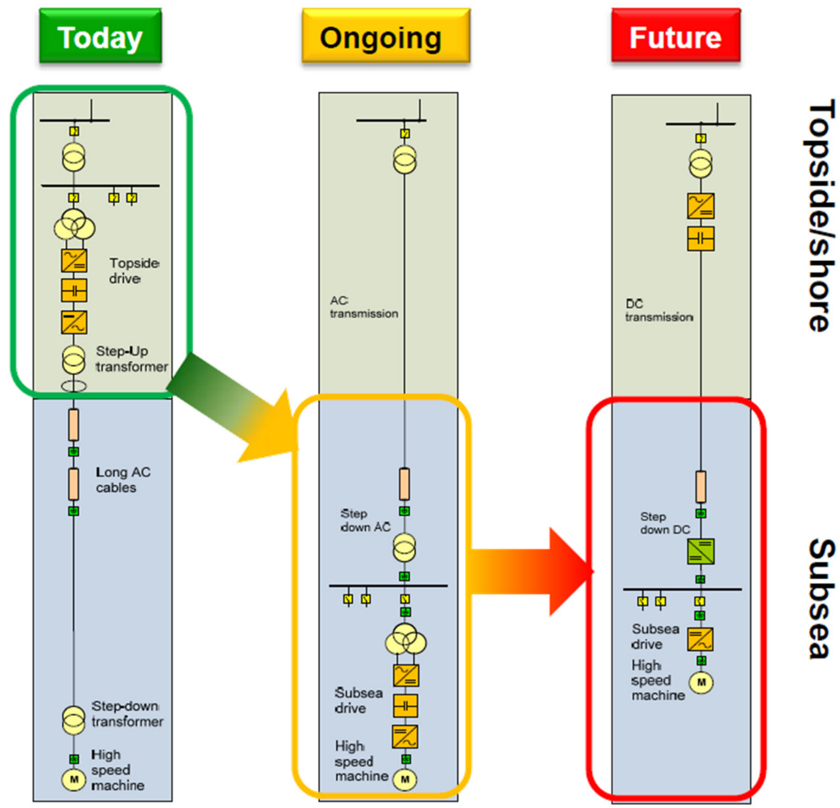
Source: Devold (ABB 2012)

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



▶ Future Hybrid & Distributed Propulsion Aircraft

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

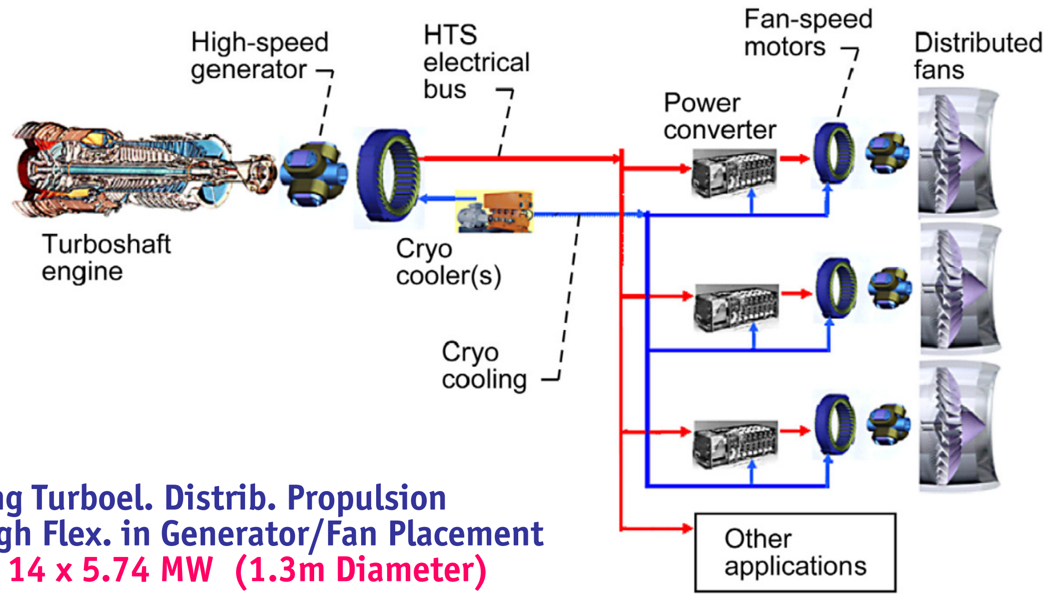
Source: EADS
Future Hybrid
Distributed Propulsion Aircraft

- ▶ Eff. Optim. Gas Turbine
- ▶ Distrib. Fans (E-Thrust)
- ▶ 1000Wh/kg Batteries

- ▶ Supercond. Motors
- ▶ MV Power Distribution

▶ Future Distributed Propulsion Aircraft

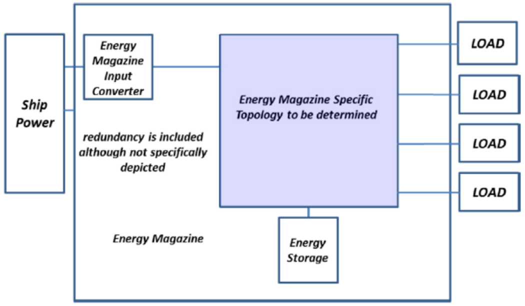
Source: NASA



- 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 Naval Applications

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



Source:
General Dynamics

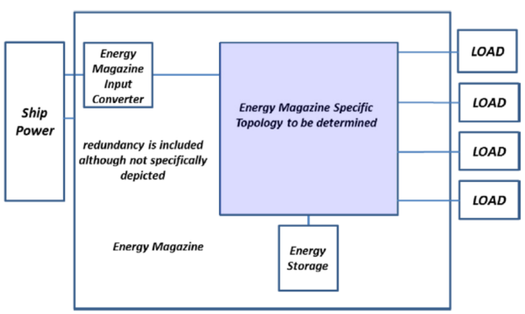
▶ "Energy Magazine" as Extension of Electric Power System / Individual Load Power Conditioning
▶ Bidirectional Power Flow for Advanced Weapon Load Demand
▶ Extreme Energy and Power Density Requirements

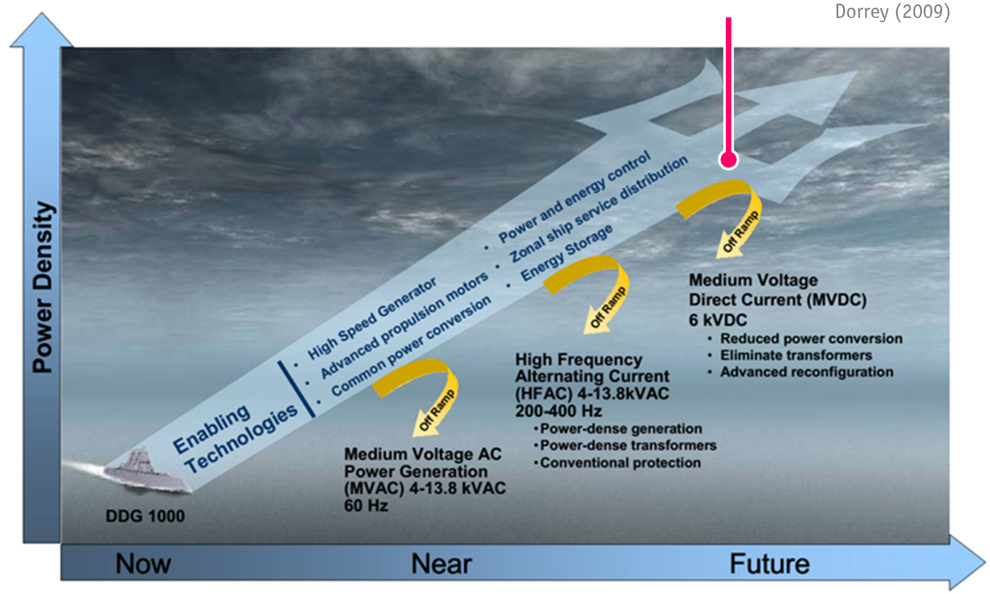
▶ Future Naval Applications

■ 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

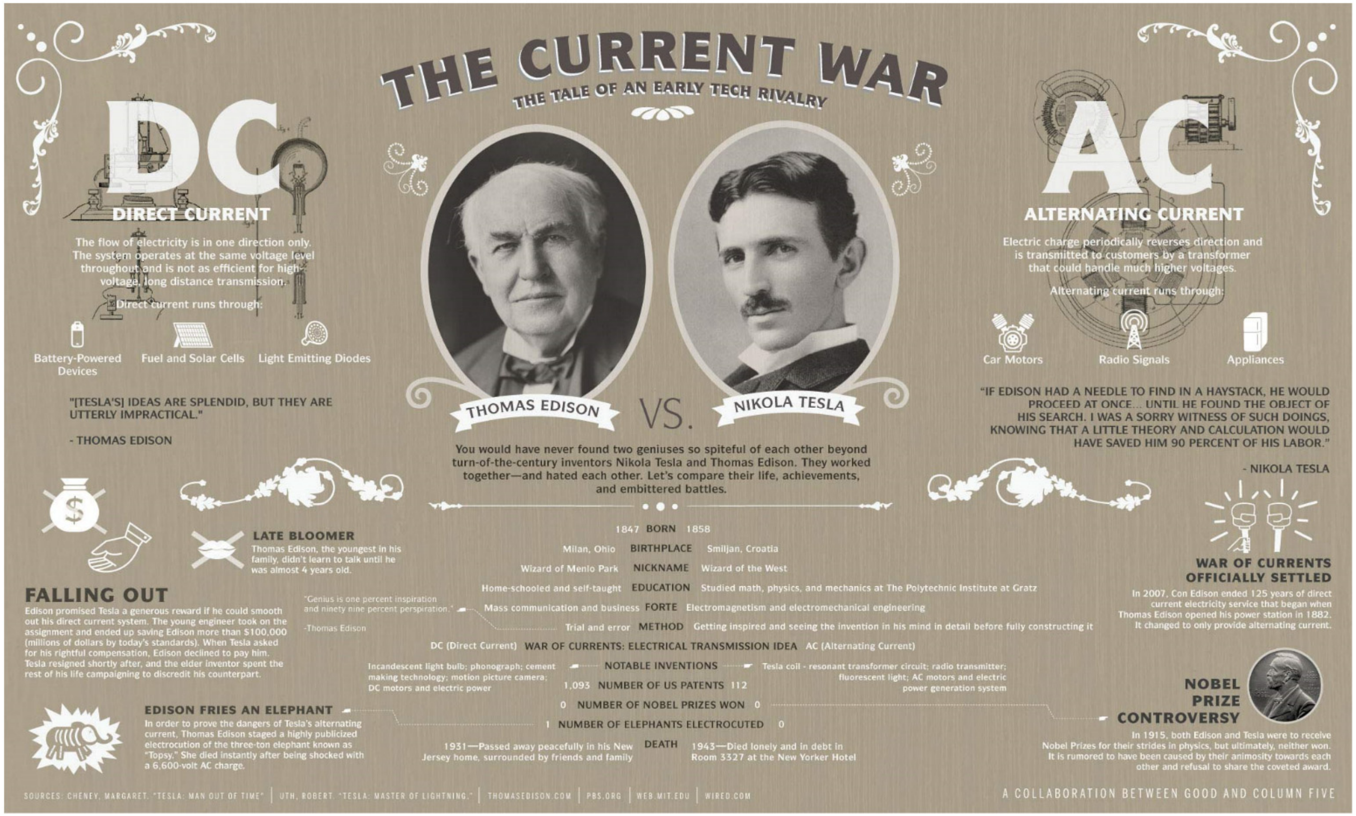
▶ Bidirectional Power Flow for Advanced Weapon Load Demand

▶ Extreme Energy and Power Density Requirements

Conclusions

SST Limitations / Concepts
Research Areas

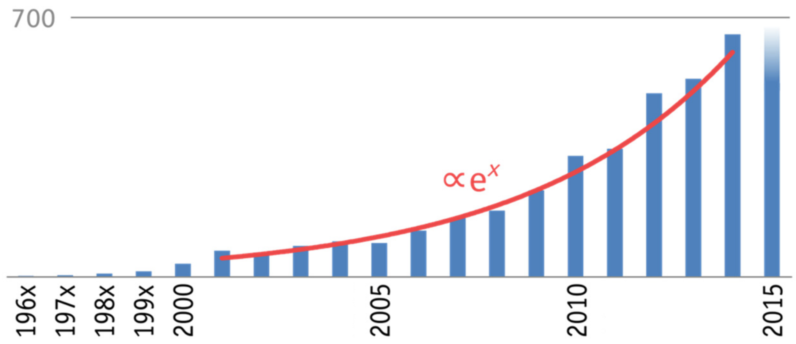
▶ SST Ends the “War of Currents”

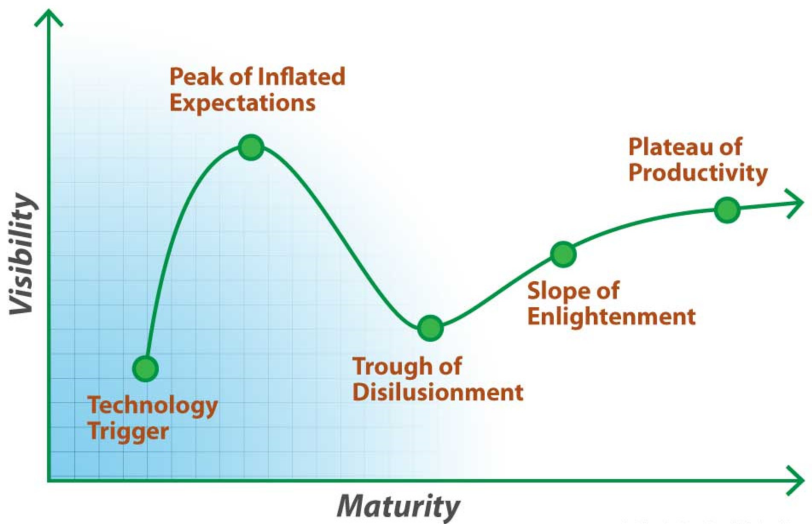


- No “Revenge” of T.A. Edison but Future “Synergy” of AC and DC Systems !

► 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

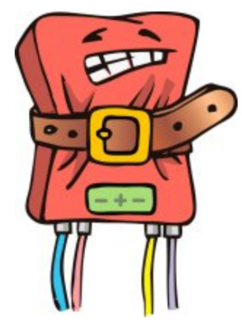
● DC/DC

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

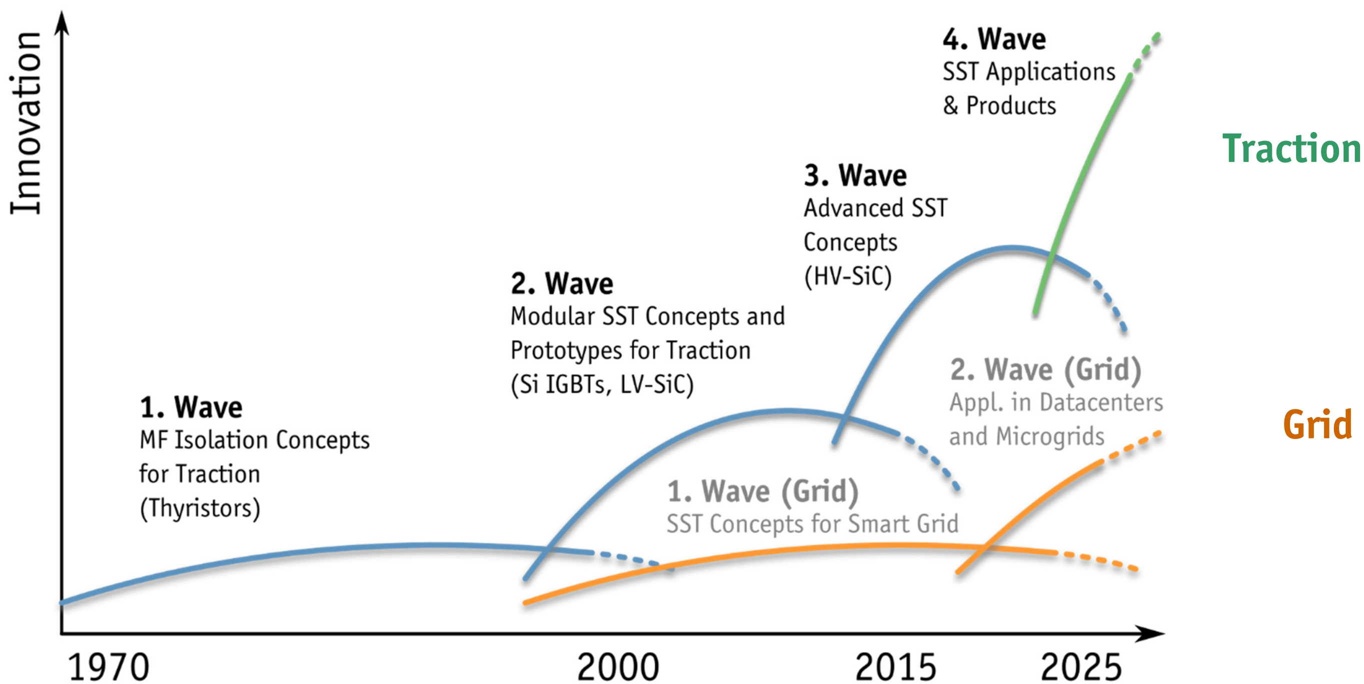
■ Weight / Space Limited
■ Traction Applic. etc.

● DC/DC
● AC/DC
● AC/AC

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



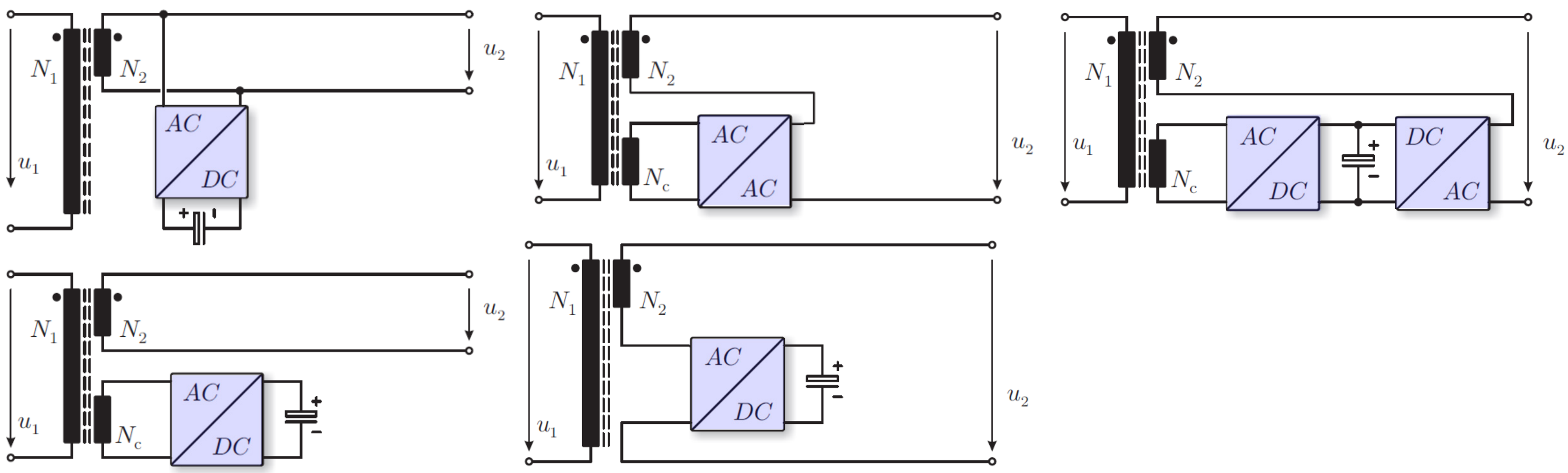
► SST Development Cycles - Outlook



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

Remark "Hybrid" Transformers

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

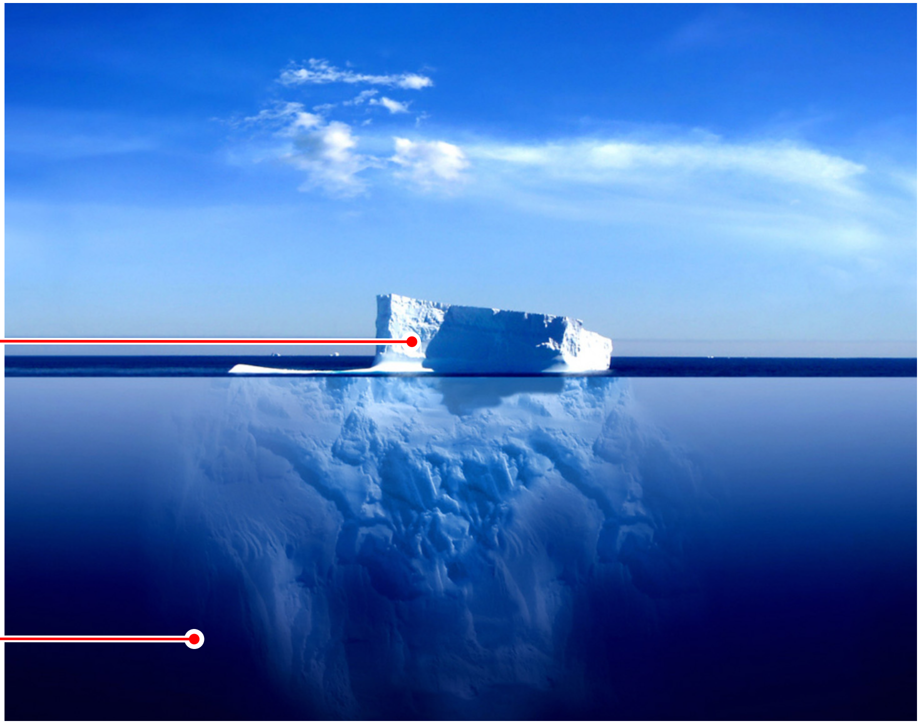


▶ **Shunt Connection**
— Reactive Current Inj.
— Harm. Curr. Inj.

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

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

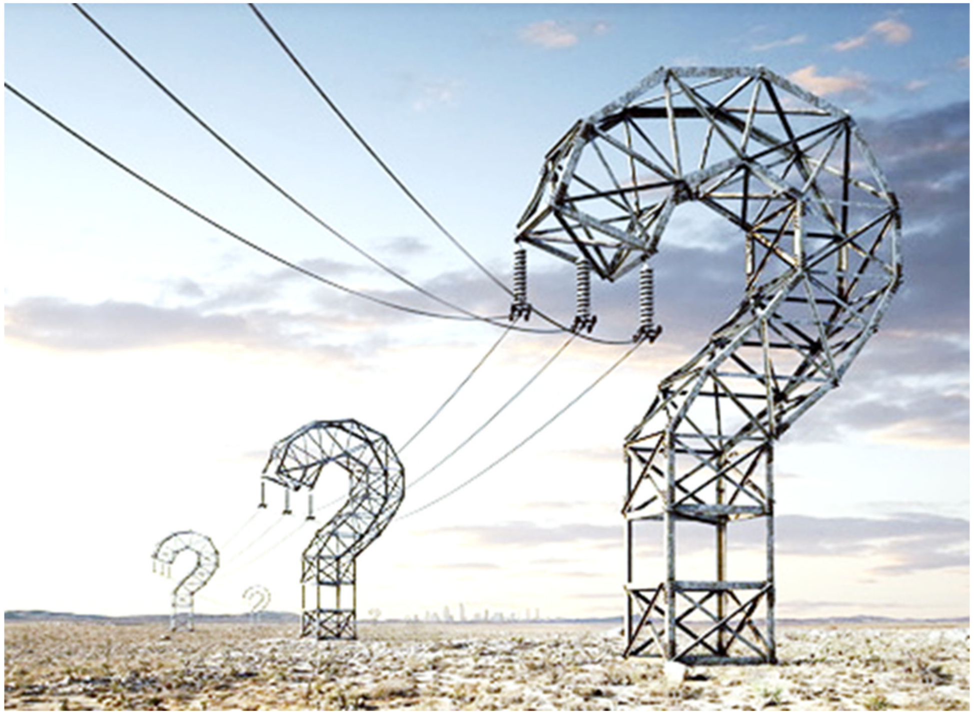
▶ Current SST Research Status



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

Thank You!

Questions



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