SOLID STATE TRANSFORMERS FOR HIGH-POWER MEDIUM-VOLTAGE APPLICATIONS

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École Polytechnique Fédérale de Lausanne → EPFL

School of Engineering → STI

Institute of Electrical Engineering → IEL

EPFL — STI — IEL — PEL

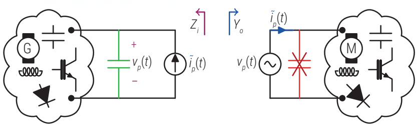
- Online since February 2014
- Currently: 12 PhD students, 3 Post Docs, 1 Administrative Ass.
- Funding CH: SNSF, SFOE, Innosuisse
- Funding EU: H2020, S2R JU, ERC CoG
- Funding: Industry OEMs
- `https://www.epfl.ch/labs/pel/`

Competence Centre

▲ Power Electronics Laboratory - Research facilities

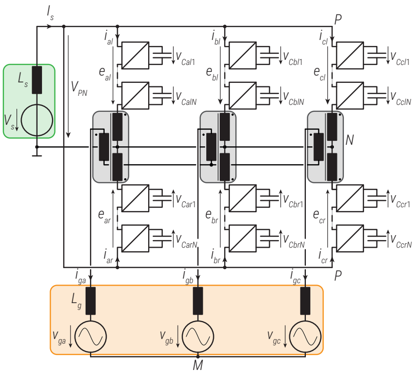
MVDC Technologies and Systems

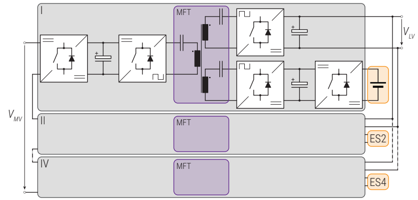
- System Stability
- Protection Coordination
- Power Electronic Converters



High Power Electronics

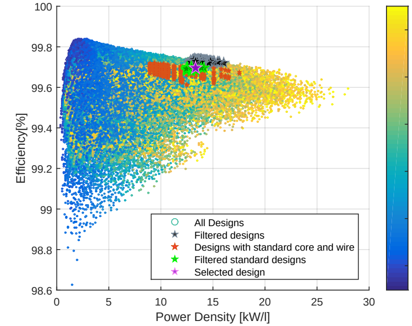
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion





Components

- Semiconductor devices
- Magnetics
- Modeling, Characterization



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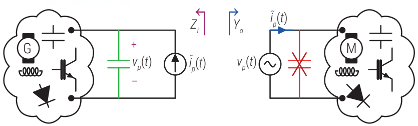
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



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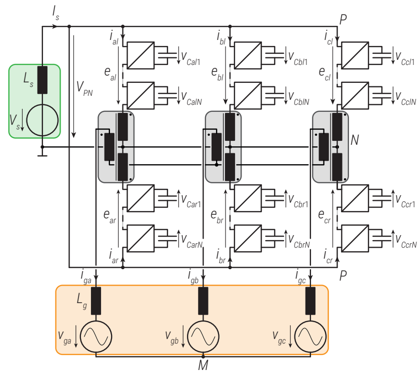

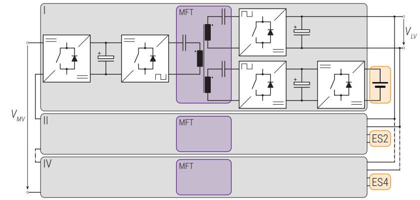

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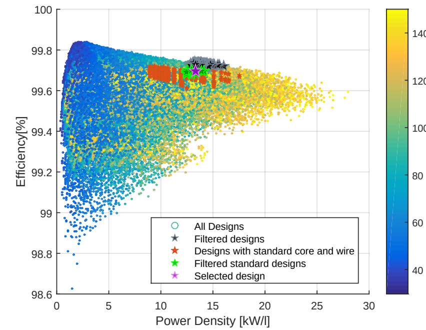
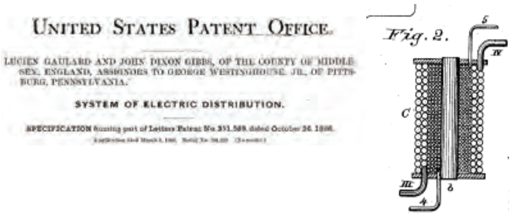


⇒ Medium Voltage High Power Electronics!

SOLID STATE TRANSFORMERS

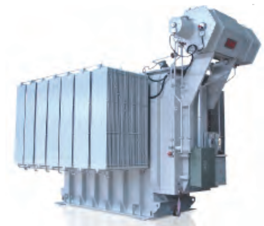
What is it all about?

IEC 60076-1 definition - Power Transformer: *A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.*



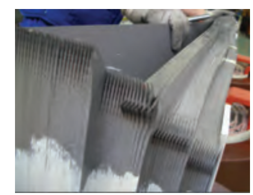
Line Frequency Transformers

- Around for more than 100 of years
- Operated at low (grid) frequencies: 16.7Hz, 25Hz, 50/60Hz
- Standardized shapes and materials
- Cheap: ≈ 10kUSD / MW at MV level
- Efficient: routinely above 99 % for utility applications
- Simple and reliable device



What are the problems?

- Bulky - for certain applications
- Inefficient - for certain applications
- Uncontrollable power flow
- Fixed transformation (power, voltage, current, frequency)
- Performs only AC-AC conversion
- Frequency is defined by the surrounding network



▲ Source: www.abb.com

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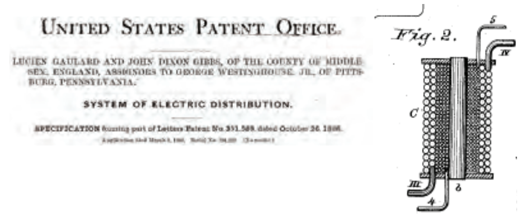

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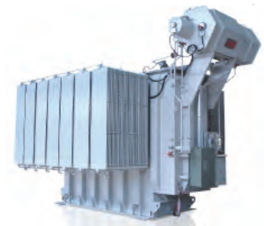

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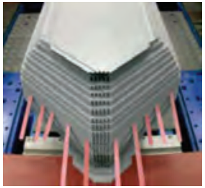
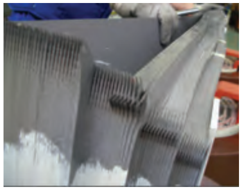


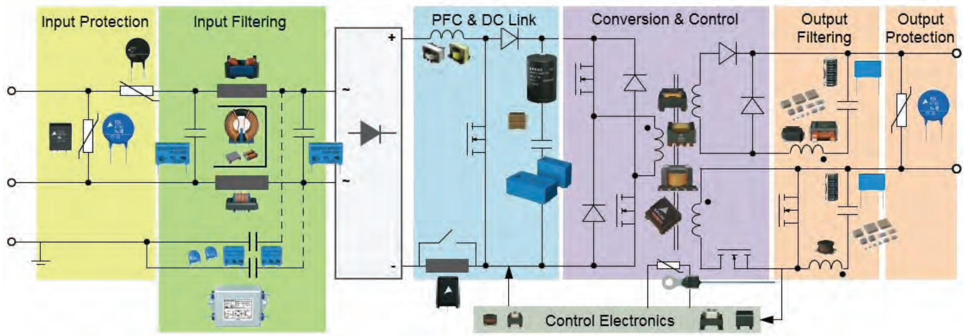


⇒ Can we do better?

▲ Source: www.abb.com

Switched Mode Power Supply (SMPS) technologies (Low Voltage

- Medium or High frequency conversion is not a new thing!
- Widely deployed in low voltage/power applications
- High efficiency thanks to semiconductors
- Galvanic isolation at high frequency (standardized core sizes and shapes)
- Increased (high) power density (e.g. laptop chargers)
- Cost savings



▲ SMPS technologies; Source: www.mouser.ch/new/tdk/epcos-smps/

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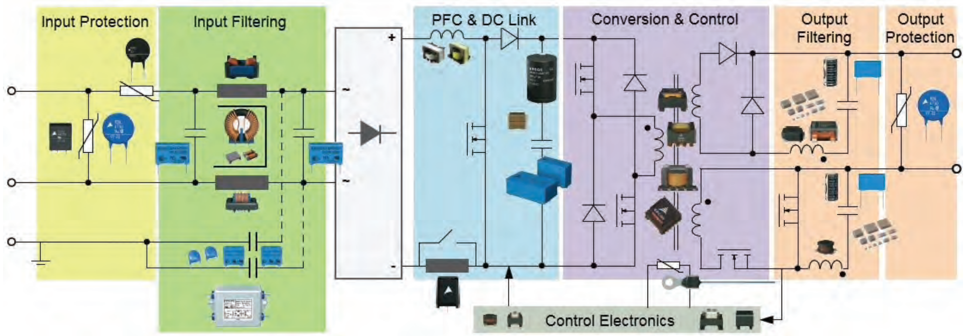

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⇒ Solid State Transformers should provide that for a High Power Medium Voltage Applications!

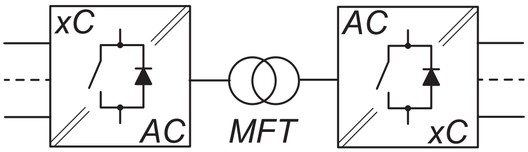
SOLID STATE TRANSFORMERS?

What not is a Solid State Transformer?

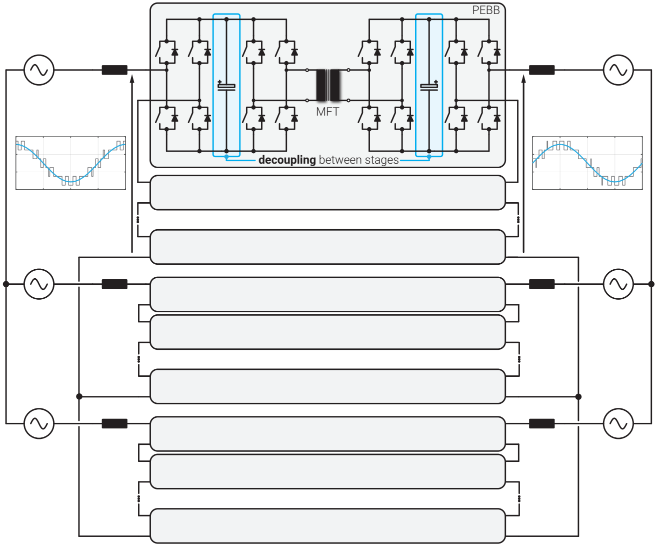
- Not a transformer replacement?
- Should not be compared against 50/60 Hz transformer!

What is it?

- A **converter**
- A converter with **galvanic isolation**
- Can be designed for **DC** and **AC** (1-ph, 3-ph) grids
- Can be used in **LV, MV** and **HV** applications
- Can be made for **AC-AC, DC-DC, AC-DC, DC-AC** conversion
- Has direct **power electronic terminals**
- Transformer **high frequency** is design variable (kHz)



▲ Simplified SST concept



▲ SST employed with the aim of interfacing two AC systems [1], [2]

SST DEMONSTRATORS

Few selected examples with relevant applications and ratings...

HUST - 500KVA ELECTRONIC POWER TRANSFORMER - EPT

Ratings

- Power: 500kVA
- Input AC voltage: 10kV, 50Hz
- Output AC voltage: 400V, 50Hz
- Efficiency: 93.72% (at 105 kW)
- Cost: 10x conv. transformer

Topology

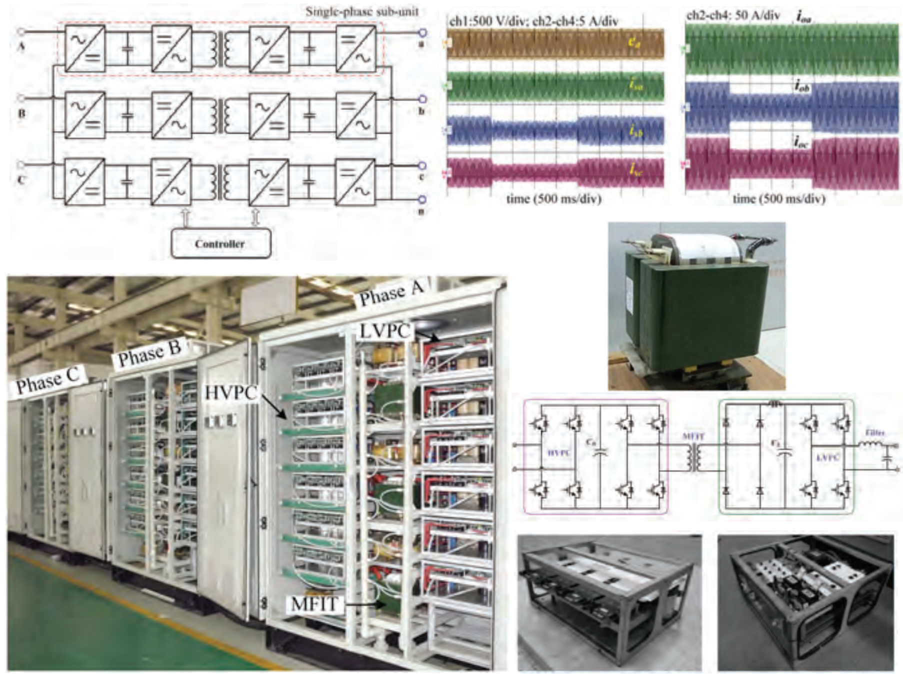
- AC-DC + DC-DC + DC-AC
- 6 cascaded stages per phase
- Unidirectional

Semiconductor Devices

- HV side: 3.3kV IGBTs
- LV side: 1.2kV IGBTs?

MFT

- Power: 30kW per MFT
- Frequency: 1kHz
- Core: Iron-based amorphous alloy
- Insulation / Cooling: solid /air



▲ HUST reported EPT [3]

CHINESE ACADEMY OF SCIENCE (I) - 1.15 MW SST

Ratings

- Power: 1.15MVA
- Input AC voltage: 10kV, 50Hz
- Output DC voltage: 750V
- Efficiency: ?
- Cost: ?

Topology

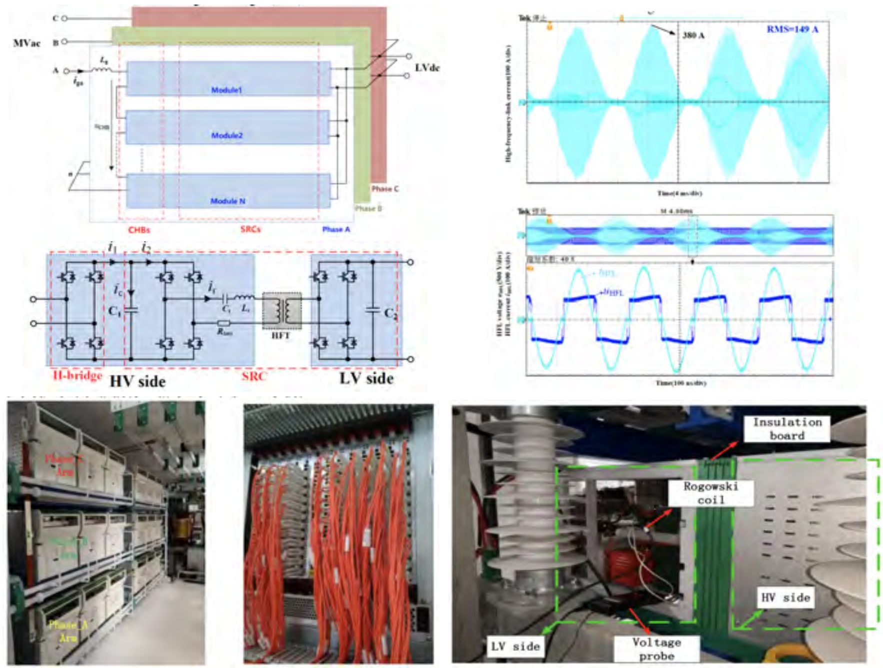
- AC-DC + DC-DC
- (5+1) cascaded stages per phase
- Bidirectional

Semiconductor Devices

- HV side: 3.3kV IGBTs (ABB)
- LV side: 1.2kV IGBTs (Infineon)

MFT

- Power: 75kW per MFT
- Frequency: 5.1kHz
- Core: ?
- Insulation / Cooling: ?



▲ 1.15 MW Solid State Transformer, ISOP AC-DC + DC-DC

CHINESE ACADEMY OF SCIENCE (II) - 1 MW SST

Ratings

- Power: 1MVA
- Input AC voltage: 10kV, 50Hz
- Output DC voltage: 750V
- Volume: 30 m^3
- Efficiency: ?
- Cost: ?

Topology

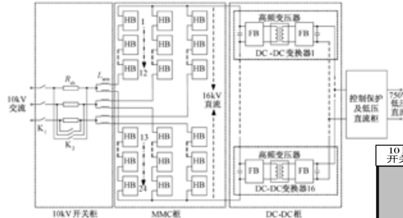
- AC-DC (MMC) + DC-DC (ISOP)
- 12 cells per branch, 16 DC-DC stages
- Bidirectional

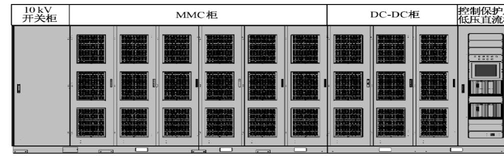
Semiconductor Devices

- MMC side: 3.3kV IGBTs (ABB)
- HV side: 1.7kV IGBTs (Infineon)
- LV side: 1.2kV IGBTs (Infineon)

MFT

- Power: 70kW per MFT
- Frequency: 8.3kHz
- Core: ?
- Insulation / Cooling: Air insulation / cooling



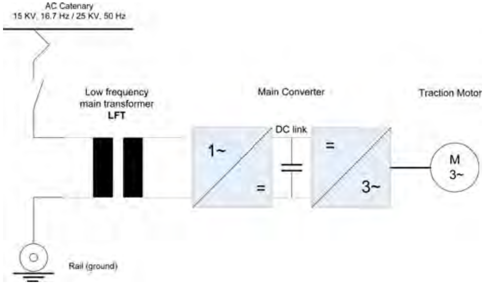


▲ 1 MW Solid State Transformer, MMC + DC-DC

Seen as early adopters and motivated by:

- Weight decrease
- Volume decrease
- Efficiency increase

▲ Your daily SSB commute...



▲ Typical (conventional) traction on-board power supply chain

▲ Various realization of traction transformers, Source: www.abb.com

WORLD'S FIRST - 1.2 MW SST TOPOLOGY

Characteristics

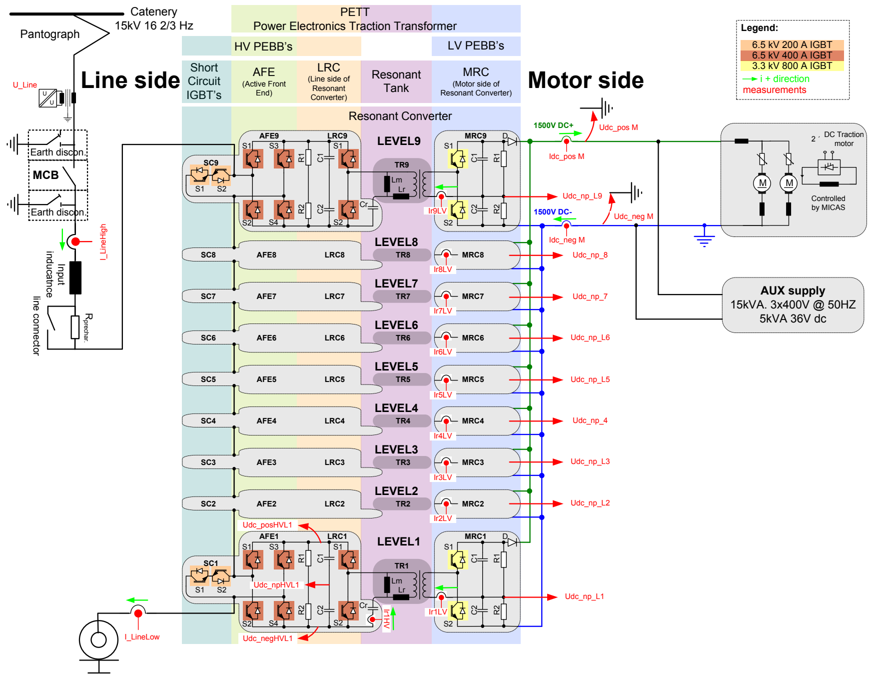
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- Input-Series Output-Parallel (ISOP)
- Double stage conversion

99 semiconductor devices

- HV PEBB: 9 x (6 x 6.5kV IGBT)
- LV PEBB: 9 x (2 x 3.3kV IGBT)
- Bypass: 9 x (2 x 6.5kV IGBT)
- Decoupling: 9 x (1 x 3.3kV Diode)

9 MFTs

- Power: 150kW
- Frequency: 1.75kHz
- Core: Nanocrystalline
- Winding: Litz
- Insulation / Cooling: oil



▲ Power Electronics Traction Transformer topology [4], [5]

[1] D. Dujic et al. "Power Electronic Traction Transformer-Low Voltage Prototype." *IEEE Transactions on Power Electronics* 28.12 (Dec. 2013), pp. 5522–5534

WORLD'S FIRST - 1.2 MW SST PROTOTYPE

Retrofitted to shunting locomotive

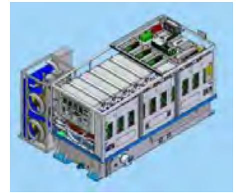
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies

- Standard 3.3kV and 6.5kV IGBTs
- De-ionized water cooling
- Oil cooling/insulation for MFTs
- n + 1 redundancy
- IGBTs used for bypass switch

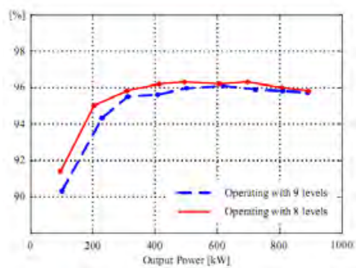
Can be seen now at:

- Swiss Museum of Transport
- https://www.verkehrshaus.ch









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[2] C. Zhao et al. "Power Electronic Traction Transformer-Medium Voltage Prototype." *IEEE Transactions on Industrial Electronics* 61.7 (July 2014), pp. 3257–3268

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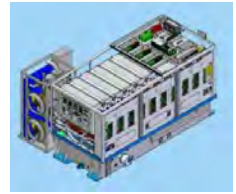





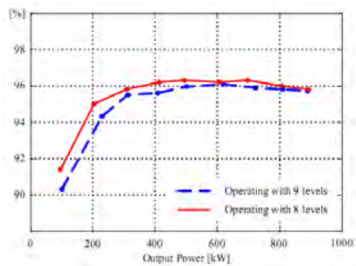

⇒ Why? What are the challenges?

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SOLID STATE TRANSFORMER CHALLENGES

Applications
- Feasibility
- Benefits
- Business case

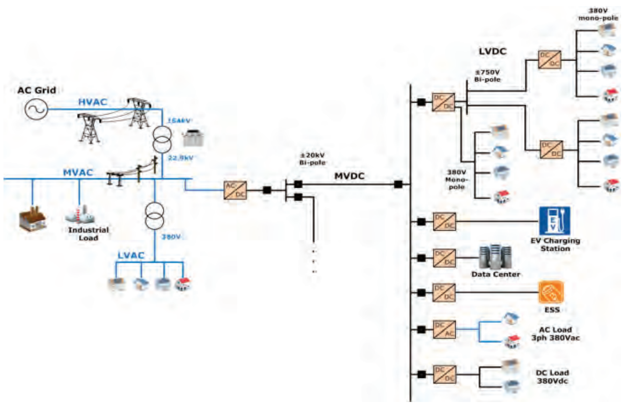
Topology
- Complexity
- Modularity
- Scalability

Semiconductors
- Efficiency
- Si, SiC, GaN?
- Reliability

Magnetics
- Efficiency
- Power density
- Customization

Control
- Performances
- Protection
- Integration

▲ Power electronics constituents



▲ SST enabling future MVDC grids and and linking it with existing AC grids

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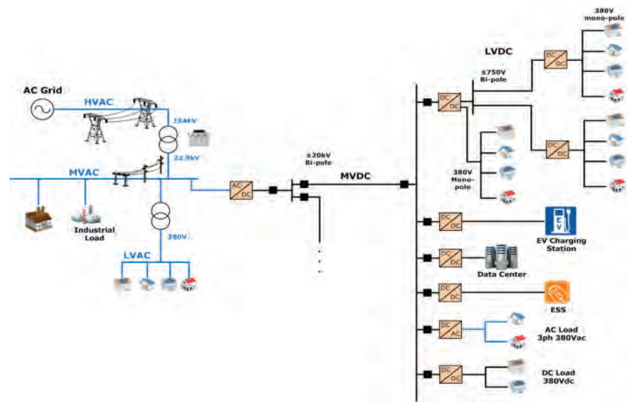


▲ SST enabling future MVDC grids and and linking it with existing AC grids

⇒ A number of technology gaps are driving research in this domain, but busines case is strongly linked to application!

SST APPLICATIONS: MVDC, MVAC

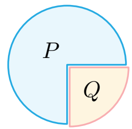
A new breed of power distribution networks...

WHY DC?

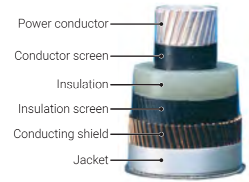
- No reactive power

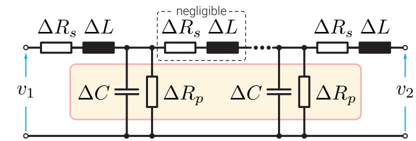
  Example: @ $cos(\varphi) = 0.95$

  $$\frac{P}{Q} \approx \frac{3}{1}$$

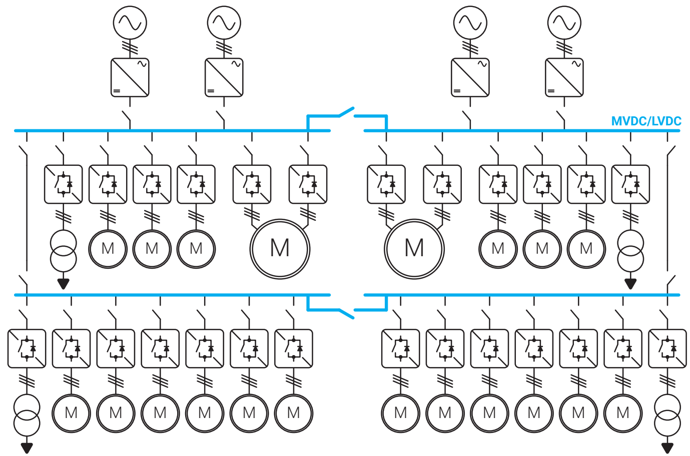


  - No constraints imposed upon transmission distance
  - Transmission capacity increase
  - Lower transmission losses
  - Alleviated stability problems
- No skin effect ($R_\gamma \downarrow \Rightarrow P_\gamma \uparrow$)
- Cheaper solution ("Break-even distance")
- Underwater cable transmission
- No need for synchronization (Marine applications)
- Direct integration of Renewable Energy Sources
- Challenges $\Rightarrow$ DC Transformer/Protection?

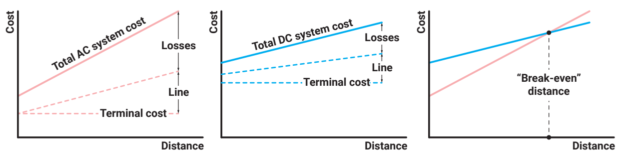




▲ High voltage cable



▲ DC Ship distribution system - frequency decoupling through a DC distribution



▲ Cost comparison between AC and DC systems

[3] U. Javaid et al. "Stability Analysis of Multi-Port MVDC Distribution Networks for All-Electric Ships." *IEEE Journal of Emerging and Selected Topics in Power Electronics* (2019), pp. 1–1

EMERGING MVDC APPLICATIONS

Installations

- ABB HVDC Light demo: 4.3 km/$\pm$9 kV$_{dc}$ [7]
- Tidal power connection: 16 km/10 kV$_{dc}$ (based on MV3000 & MV7000) [8]

- Unidirectional oil platform connection in China: 29.2 km/$\pm$15 kV$_{dc}$ [9]

Projects

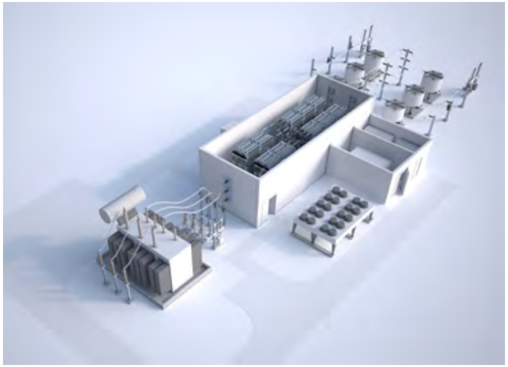
- Angle DC: conversion of 33 kV MVac line to $\pm$27 kV MVdc [10]

Universities

- Increased number of laboratories active in high power domain
- China, Europe, USA,...

Products

- Siemens MVDC Plus
  - 30 - 150 MW
  - $<$ 200 km
  - $< \pm$50 kV$_{dc}$



- RXPE Smart VSC-MVDC
  - 1 - 10 MVAr
  - ± 5 - $\pm$50 kV$_{dc}$
  - 40 - 200 km

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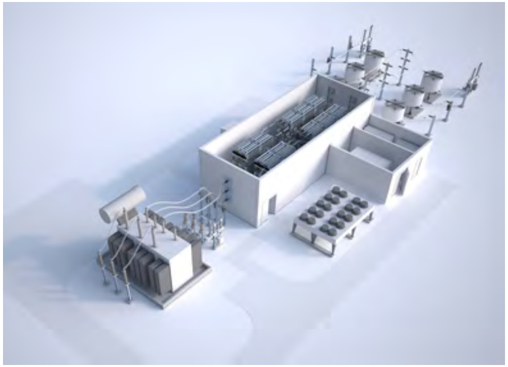

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  - 1 - 10 MVAr
  - $\pm$5 - $\pm$50 kV_{dc}
  - 40 - 200 km

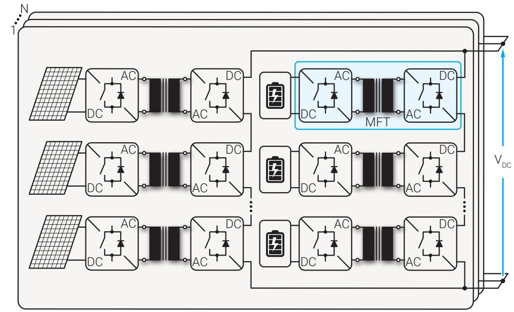
⇒ Several demonstrations of MVDC power distribution networks around the world!

MVDC DC-DC CONVERTERS

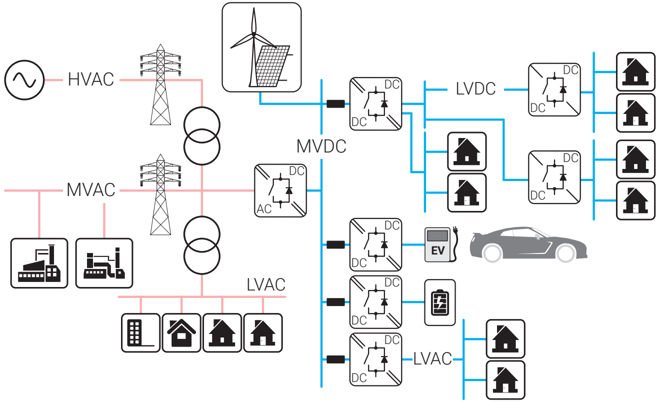
Building blocks of Solid State Transformers

MVDC DC-DC SST

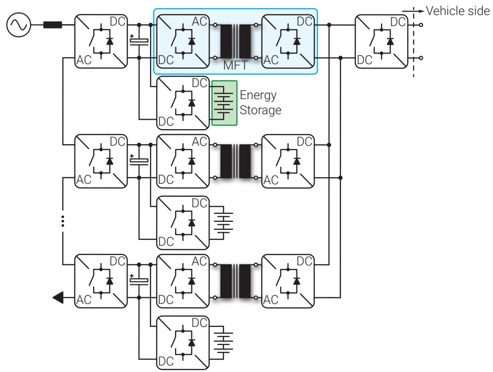
- Inherent part of the AC-AC SST
- Expansion of the existing power system
- Enabling technology for MVDC
- Penetration of renewable energy sources
- Fast / Ultra Fast EV charging
- **Medium Frequency** conversion



▲ Employment of a DC-DC SST within RES-based systems



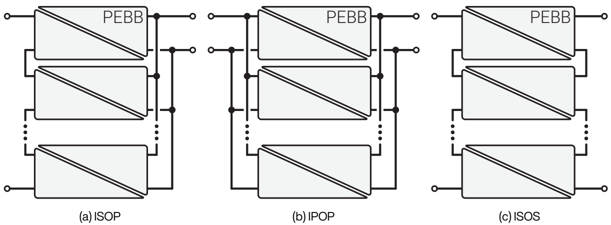
▲ Power electronics dominated power system



▲ Fast EV charging concept

Fractional power processing

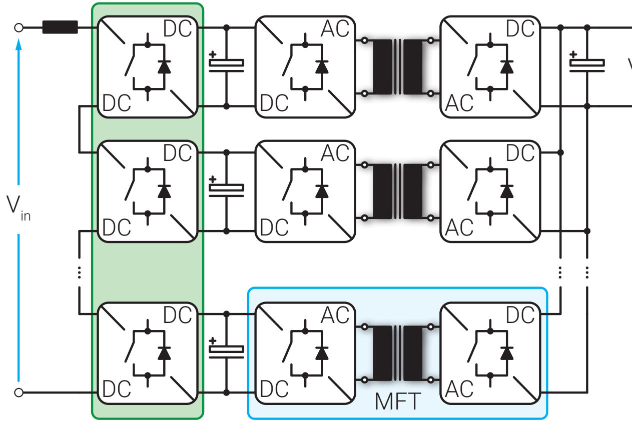
- Multiple MFTs
- Equal power distribution among PEBBs
- MFT isolation?
- Various PEBB configurations



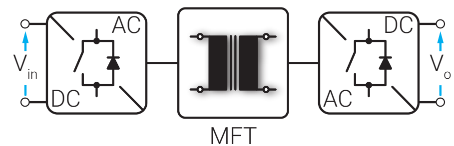
▲ Different structures employed depending upon the voltage level

Bulk power processing - Monolithic converter structures

- Single MFT
- Isolation solved only once
- Various configurations/operating principles
- **PEBB** = Power Electronics Building Block



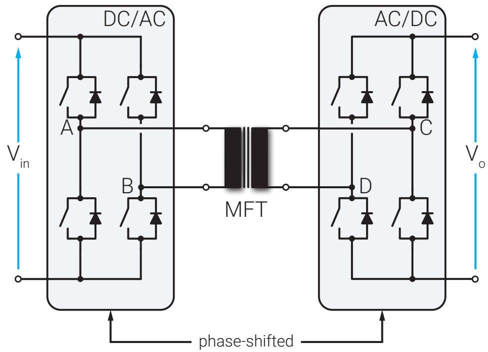
▲ Fractional power processing - ISOP converter structures

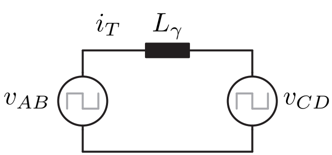


▲ Bulk power processing concept

COMMON PEBB CONFIGURATIONS

Dual-Active Bridge

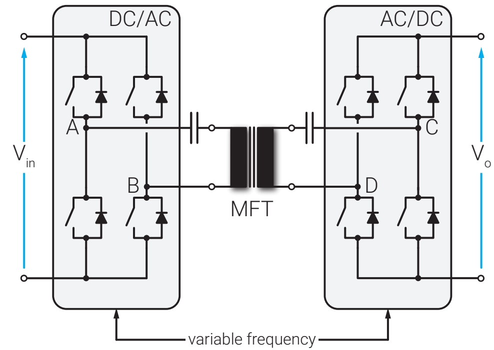


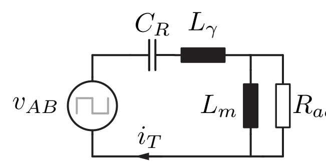


$$P = P(\varphi)$$

▲ Dual Active Bridge [11]

Resonant Converters





$$f_{r1} = \frac{1}{2\pi\sqrt{C_R L_\gamma}}$$

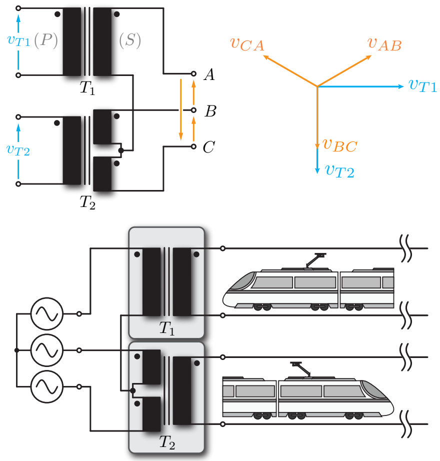
$$f_{r2} = \frac{1}{2\pi\sqrt{C_R (L_\gamma + L_m)}}$$

$$Q = Q(R_{ac})$$

$$G = G\left(\frac{f_{sw}}{f_{r1}}, \frac{L_m}{L_\gamma}, Q\right)$$

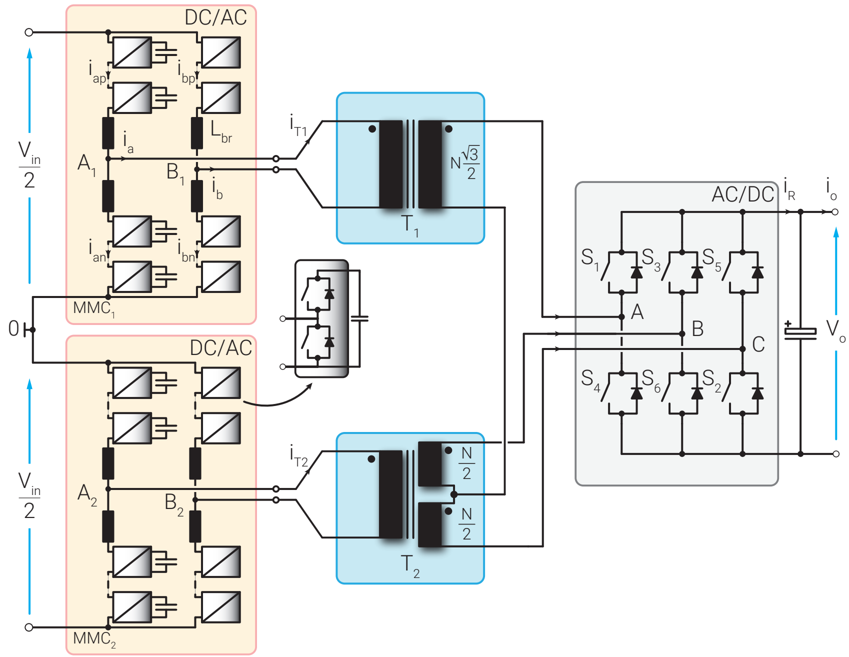
▲ LLC Resonant Converter

MMC-BASED BIDIRECTIONAL DC-DC CONVERTER EMPLOYING STC



▲ Scott Transformer Connection

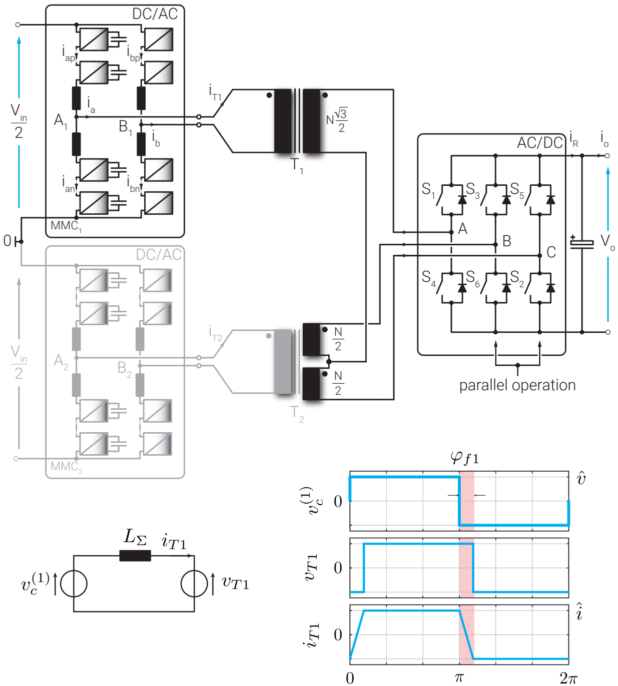
- 3PH 3W Tx ⟹ 2 x 1PH Tx
- Number of MMC branches reduction ($N_L \downarrow$)
- Ability to operate in a pure rectifier mode
- Medium frequency operation



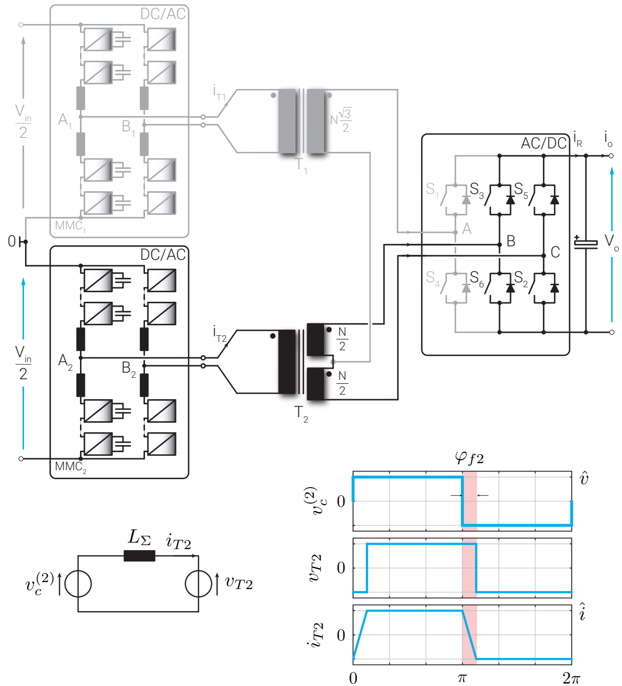
▲ MMC-Based High Power DC-DC Converter Employing Scott Transformer Connection [12]

[8] S. Milovanovic and D. Dujic. "High-Power DC–DC Converter Utilising Scott Transformer Connection." *IET Electric Power Applications* (2019)

OPERATION UNDER FAULTS



▲ Converter operation in the case of "Minus" DC pole malfunction



▲ Converter operation in the case of "Plus" DC pole malfunction

SOLID STATE RESONANT CONVERSION

Benefiting from soft switching...

TYPICAL HIGH POWER SEMICONDUCTORS (MW CONVERTERS

IGBT Plastic Modules

▲ IGBT modules: (left) Single 6.5kV IGBT; (middle) Dual 6.5kV IGBT; (right) Dual IGBT module (cut view)

IGBT Press-Pack Modules

▲ IGBT press-pack modules: (left) Single 4.5kV press-pack IGBT; (middle) Press-pack IGBT - cut view; (right) Short circuit failure design

IGCT

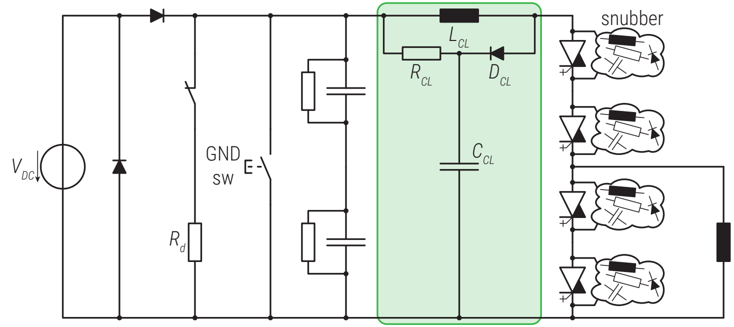
▲ IGCT: (left) Wafer; (middle) 4.5kV, 5.2kA Reverse Blocking IGCT; (right) 6.5kV, 3.8kA Assymetric IGCT

Motivation

- Bulk power conversion
- IGCT characterization
- IGCT optimization
- High power magnetics design

▲ Multifunctional IGCT test setup

Characterization setup



▲ One test setup configuration

Objectives

- IGCT soft switching
- DC-DC resonant conversion
- High power SST

[11] D. Stamenkovic et al. "IGCT Low-Current Switching, TCAD and Experimental Characterization." *IEEE Transactions on Industrial Electronics* (2019), pp. 1–1

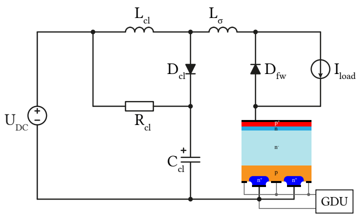
[12] D. Stamenkovic and D. Dujic. "Application of the IGCT for Resonant Conversion with Low Switching Losses." *IEEJ Journal of Industry Applications* 9.3 (2020), pp. 1–10

▲ IGCT characterization test setup

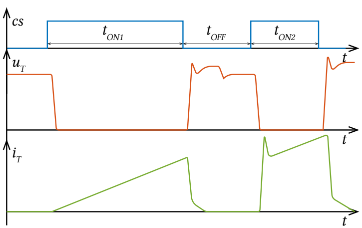
IGCT SOFT (LOW CURRENT) SWITCHING

IGCT low current turn-off?

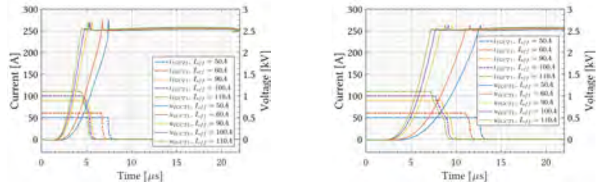
- Not a part of data sheet
- Very important for resonant converters
- How low can we go?



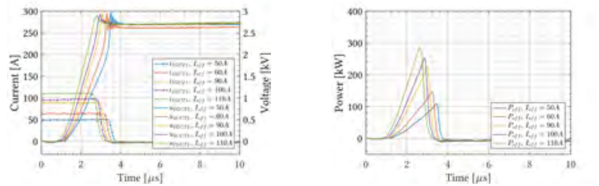
▲ TCAD single-pulse and double-pulse simulation circuit



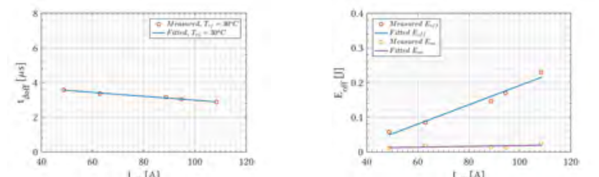
▲ Typical double-pulse test waveform



▲ TCAD simulated turn-off at $30^{\circ}C$ (left) and $115^{\circ}C$ (right)



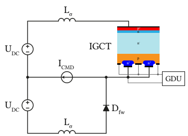
▲ Experimental turn-off at $30^{\circ}C$ (left) and transient power loss (right)



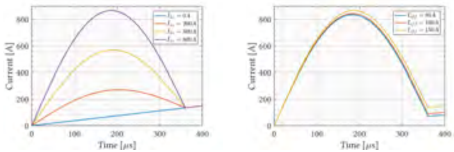
▲ Experimental turn-off delay (left) and turn-off energy (right)

IGCT resonant pulse pre-flooding?

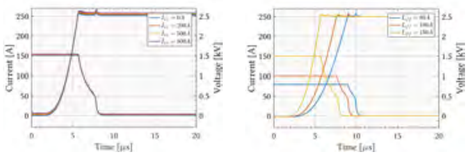
- High resonant peak current, low turn-off current



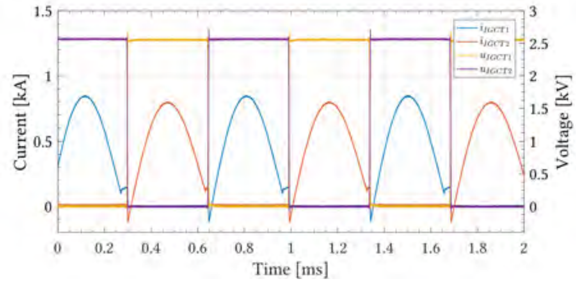
▲ TCAD single resonant-pulse circuit



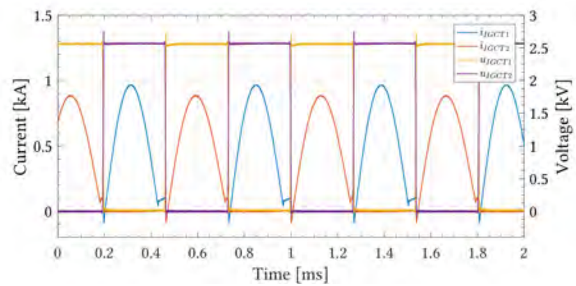
▲ IGCT pre-flooding with high resonant current



▲ IGCT constant current turn-off



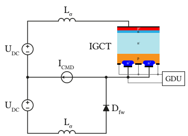
▲ Experimental waveforms for continuous operation at 1440Hz



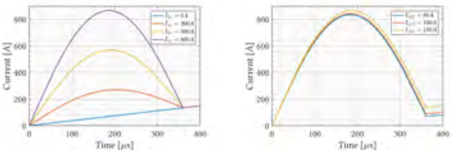
▲ Experimental waveforms for continuous operation at 1860Hz

IGCT resonant pulse pre-flooding?

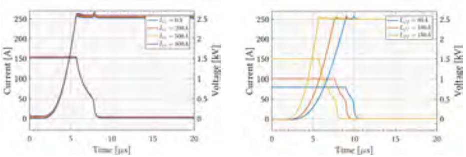
- High resonant peak current, low turn-off current



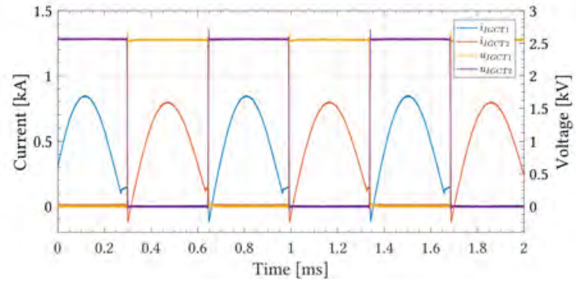
▲ TCAD single resonant-pulse circuit



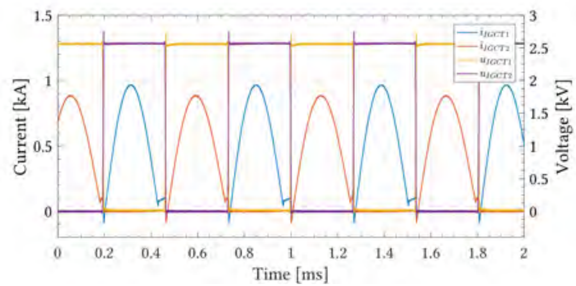
▲ IGCT pre-flooding with high resonant current



▲ IGCT constant current turn-off



▲ Experimental waveforms for continuous operation at 1440Hz



▲ Experimental waveforms for continuous operation at 1860Hz

⇒ Two 4.5kV, 3kA IGCT devices in half-bridge configuration can process 1 MW of power - Beauty of Bulk Power processing!

MFT DESIGN OPTIMIZATION

Increasing power density through high frequency switching...

MFT CHALLENGES.

Transformer scaling law:

$$V_T \propto \underbrace{A_w \cdot A_e}_{A_p} = \frac{P_t}{k_f k_u J_m f_{sw} B_m} \quad \Rightarrow V_T \propto \frac{1}{f_{sw}} \quad \Rightarrow V_T \propto \frac{1}{J_m} \quad \Rightarrow V_T \propto \frac{1}{B_m}$$

- P_t - MFT power
- A_p - core area product
- A_w - window area
- A_e - core cross-section area
- k_f - converter waveform coefficient
- k_u - core window utilization coefficient
- B_m - limited by material
- J_m - limited by cooling
- f_{sw} - limited by power electronics and losses

Multiphysics design optimization problem:

Electrical design

- Managing HF losses
- Accurate electric parameter design
- ...

Magnetic design

- Non-sinusoidal excitation
- Core losses (hysteresis and eddy current losses)
- ...

Dielectric design

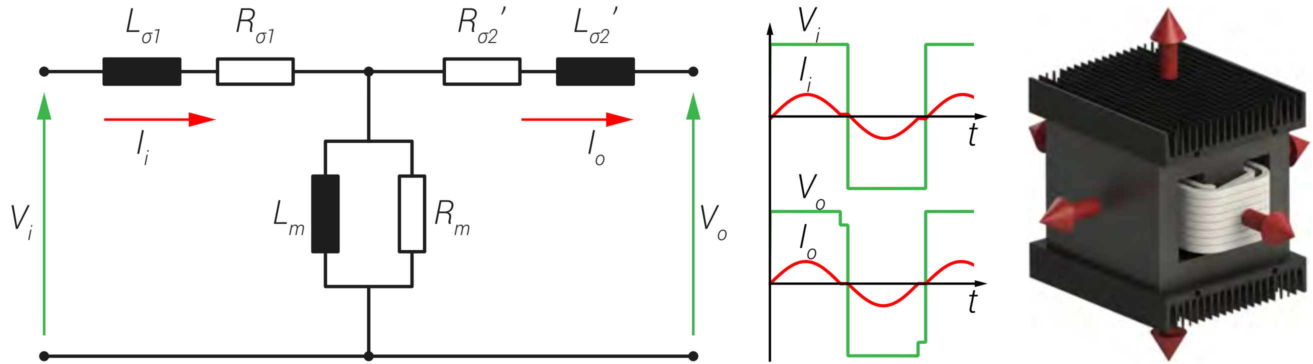
- Insulation coordination
- High dV/dt characteristic of the square voltage waveform
- ...

Thermal design

- Thermal anisotropy of different materials
- System integration
- ...

MFT CHALLENGES..

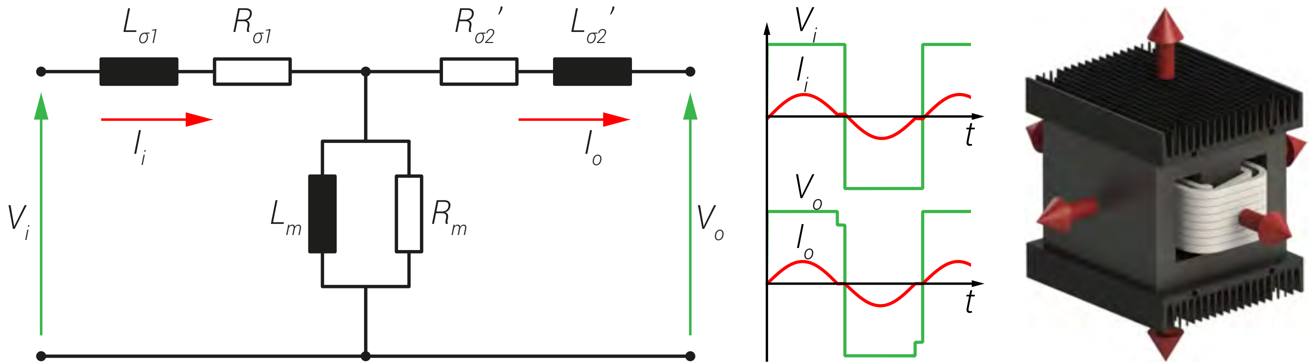
- **Skin and proximity effect losses:** impact on efficiency and heating
- **Cooling:** increase of power density ⇒ decrease in size ⇒ less cooling surface ⇒ higher R_{th} ⇒ higher temperature gradients
- **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- **Insulation:** coordination and testing taking into account high $\frac{dV}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control:** especially in case of resonant converter applications



▲ Medium Frequency Transformer challenges

MFT CHALLENGES..

- **Skin and proximity effect losses:** impact on efficiency and heating
- **Cooling:** increase of power density $\Rightarrow$ decrease in size $\Rightarrow$ less cooling surface $\Rightarrow$ higher R_{th} $\Rightarrow$ higher temperature gradients
- **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- **Insulation:** coordination and testing taking into account high $\frac{dV}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control:** especially in case of resonant converter applications



▲ Medium Frequency Transformer challenges

$\Rightarrow$ MFT design requires multiphysics considerations and multiobjective optimization!

MFT VARIETY OF DESIGNS...

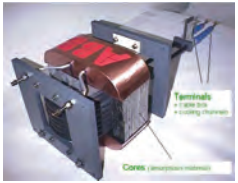
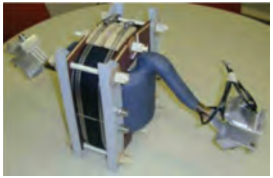
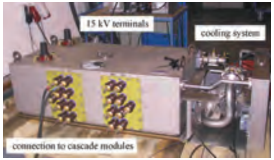


ABB: 350kW, 10kHz

ABB: 3x150kW, 1.8kHz

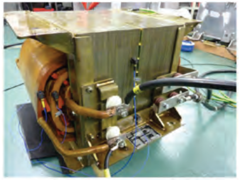


BOMBARDIER: 350kW, 8kHz



ALSTOM: 1500kW, 5kHz

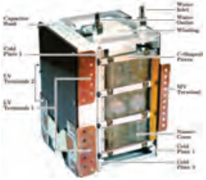
IKERLAN: 400kW, 5kHz



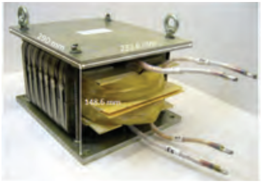
IKERLAN: 400kW, 1kHz

FAU-EN: 450kW, 5.6kHz

CHALMERS: 50kW, 5kHz

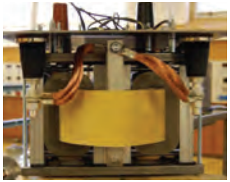


ETHZ: 166kW, 20kHz

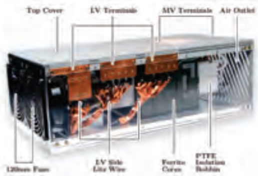


EPFL: 300kW, 2kHz

STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz

EPFL: 100kW, 10kHz

?

ACME: ???kW, ???kHz

MFT VARIETY OF DESIGNS...

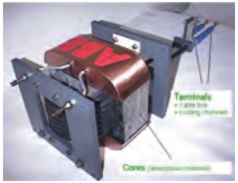
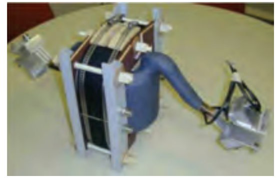
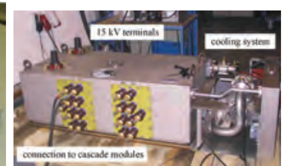


ABB: 350kW, 10kHz

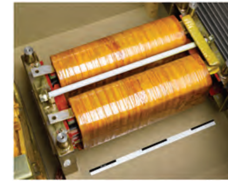
ABB: 3x150kW, 1.8kHz



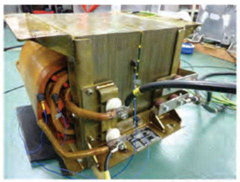
BOMBARDIER: 350kW, 8kHz



ALSTOM: 1500kW, 5kHz

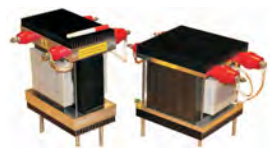


IKERLAN: 400kW, 5kHz

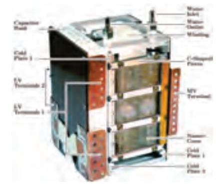


IKERLAN: 400kW, 1kHz

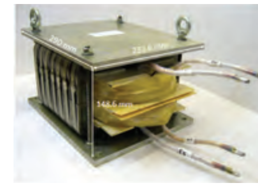
FAU-EN: 450kW, 5.6kHz



CHALMERS: 50kW, 5kHz

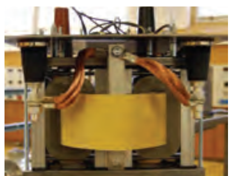


ETHZ: 166kW, 20kHz

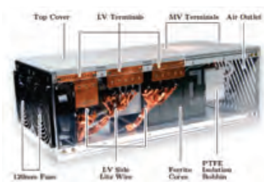


EPFL: 300kW, 2kHz

STS: 450kW, 8kHz



KTH: 170kW, 4kHz



ETHZ: 166kW, 20kHz

EPFL: 100kW, 10kHz

?

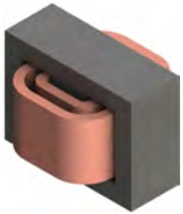
ACME: ???kW, ???kHz

⇒ Many design degrees of freedom are available!

MATERIALS, TECHNOLOGIES, DESIGN CHOICES

Construction choices:

- MFT Types



Shell Type

Core Type

C-Type

Coaxial Type

- Winding types

Litz Wire

Foil

Coaxial

Hollow

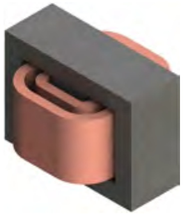
Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water

MATERIALS, TECHNOLOGIES, DESIGN CHOICES

Construction choices:

- MFT Types



Shell Type

Core Type

C-Type

Coaxial Type

- Winding types

Litz Wire

Foil

Coaxial

Hollow

Materials:

- Magnetic Materials
  - Silicon Steel
  - Amorphous
  - Nanocrystalline
  - Ferrites
- Windings
  - Copper
  - Aluminum
- Insulation
  - Air
  - Solid
  - Oil
- Cooling
  - Air natural/forced
  - Oil natural/forced
  - Water

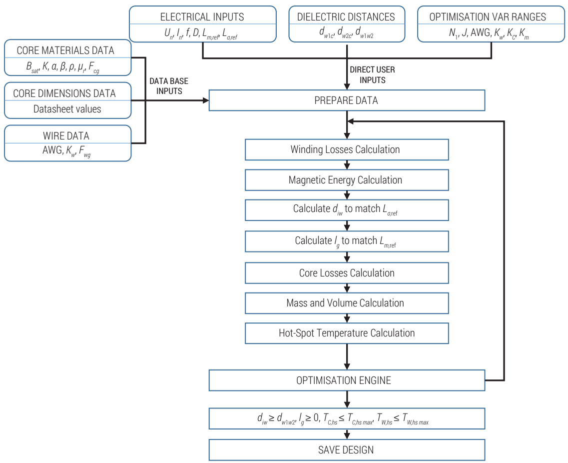
⇒ Any combination can produce reasonably performing MFT. Optimization problem!

MFT DESIGN & OPTIMIZATION

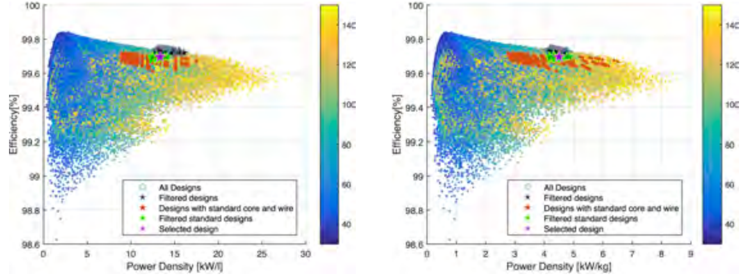
Challenges

- High voltage MFT design - insulation coordination
- Precise parameter control - resonant operation
- High power conversion - thermal design
- Characterization of magnetic materials

Design algorithm



Design optimization results



Prototype as proof of concept

- P = 100 kW
- $V_p = V_s$ = 750 V
- f_{sw} = 10 kHz

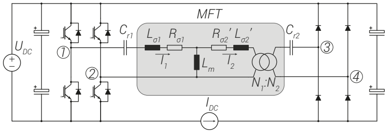
[13] M. Mogorovic and D. Dujic. "100kW, 10kHz Medium Frequency Transformer Design Optimization and Experimental Verification." *IEEE Transactions on Power Electronics* PP (2018)

[14] M. Mogorovic and D. Dujic. "Sensitivity Analysis of Medium Frequency Transformer Designs for Solid State Transformers." *IEEE Transactions on Power Electronics* PP (2018)

MFT POWER TESTS

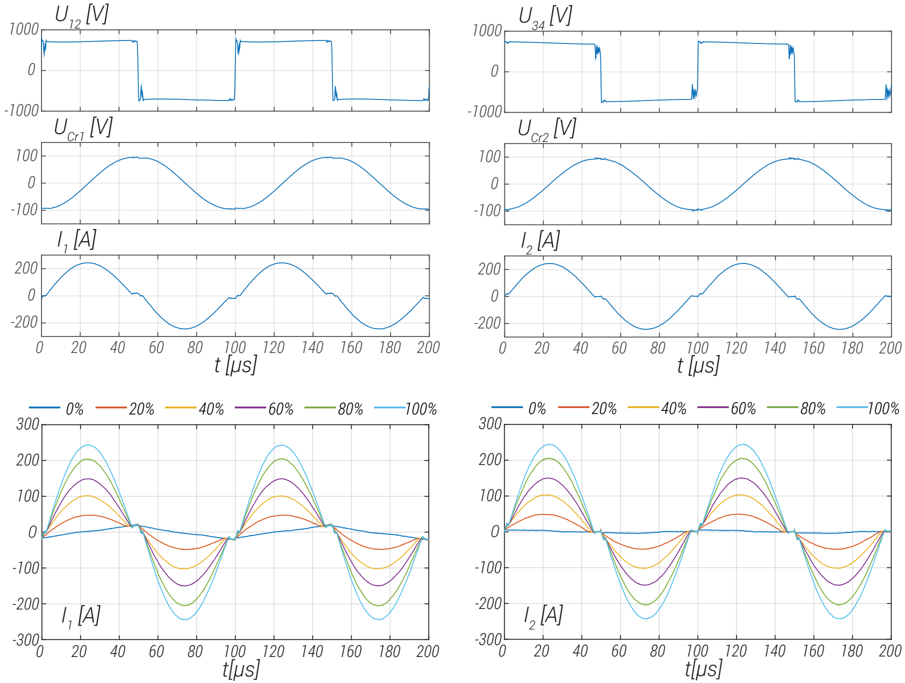
Test setup topology:

- B2B resonant converter
- Input voltage maintained by U_{DC}
- Power circulation via I_{DC}
- Open loop power tests



Test setup:

Measurement results:



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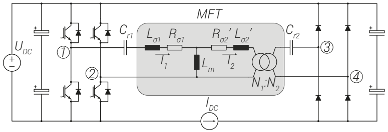
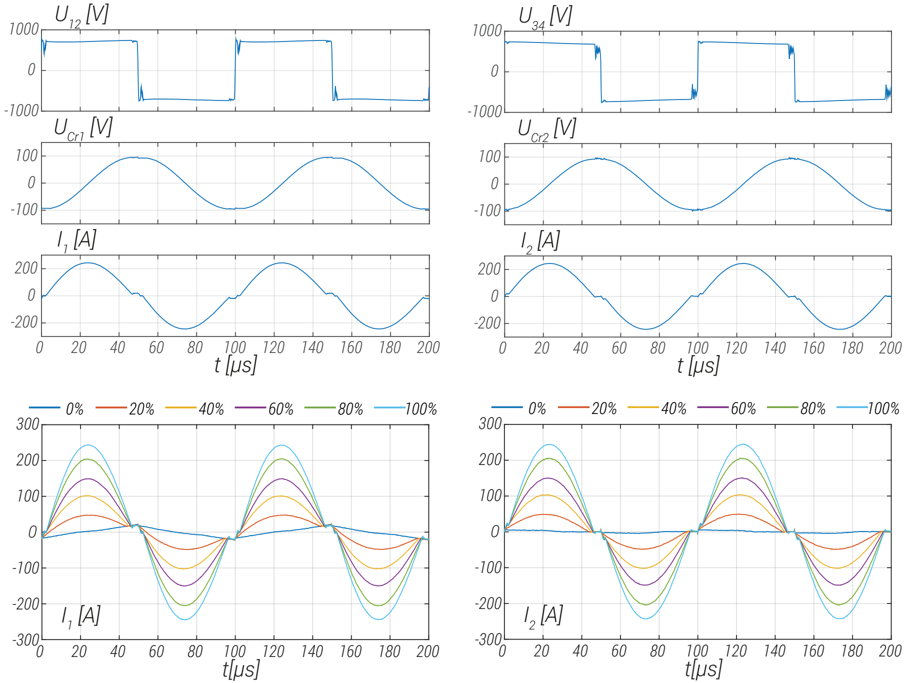


Test setup:

Measurement results:



⇒ Medium Frequency Transformers are essential technology for Solid State Transformers!

SUMMARY

SOLID STATE TRANSFORMER TECHNOLOGY

Applications
- Feasibility
- Benefits
- **Business case**

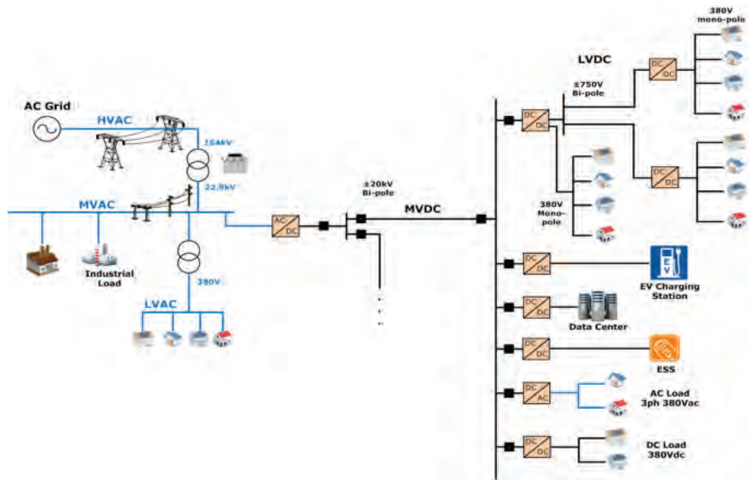
Topology
- **Complexity**
- Modularity
- Scalability

Semiconductors
- Reliability
- Si, SiC, GaN?
- **Cost**

Magnetics
- Efficiency
- Power density
- **Customization**

Control
- **Performances**
- Protection
- Integration

▲ Power electronics constituents



▲ Possible future MVDC grids and its links with existing grids

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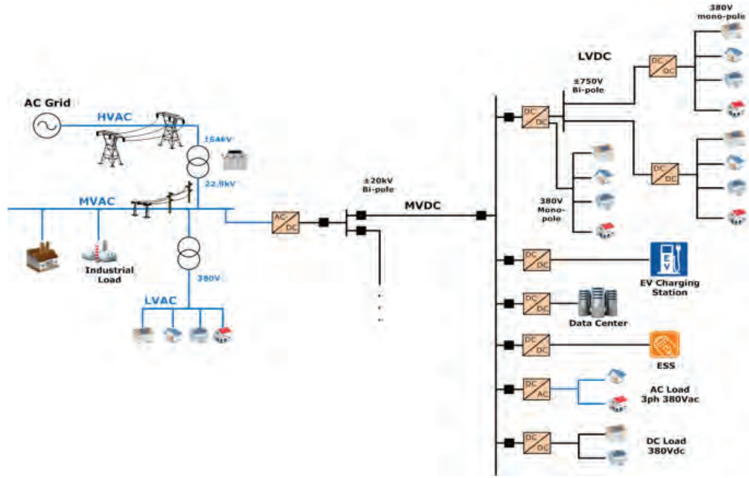

▲ Possible future MVDC grids and its links with existing grids

⇒ SST is expected to transform future energy systems? It proves to be not that simple! There is work ahead for all of us!

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THANK YOU FOR YOUR ATTENTION