MEDIUM VOLTAGE DIRECT CURRENT TECHNOLOGIES

Prof. Dražen Dujić

École Polytechnique Fédérale de Lausanne (EPFL)
Power Electronics Laboratory (PEL)
Lausanne, Switzerland

INTRODUCTION

Power Electronics Laboratory at EPFL

École Polytechnique Fédérale de Lausanne

School of Engineering

EPFL — STI — IEM — PEL

Institute of Electrical and Micro Engineering

- Online since February 2014
- Currently: 10 PhD students, 3 Post Docs, 1 Administrative Assistant
- Funding CH: SNSF, SFOE, Innosuisse
- Funding EU: H2020, S2R JU, ERC CoG
- Funding Industry: OEMs
- `https://www.epfl.ch/labs/pel/`

ECPE

Competence Centre

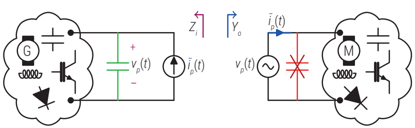
▲ PEL Medium Voltage Laboratory

RESEARCH FOCUS

MVDC Technologies and Systems

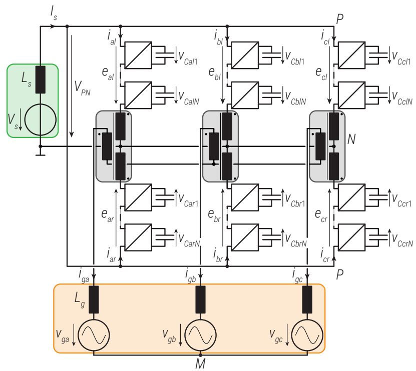
- System Stability
- Protection Coordination
- Power Electronic Converters

MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



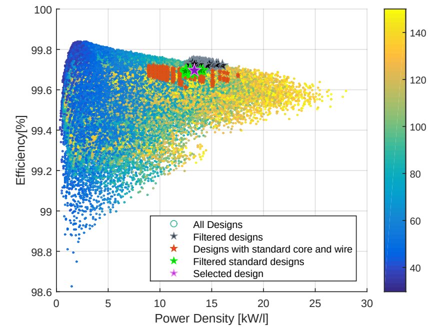
High Power Electronics

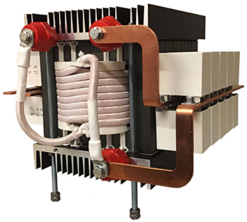
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion



Components

- Semiconductor devices
- Magnetics
- Modeling, Characterization



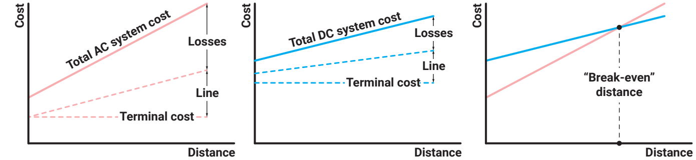


WHY DC? WHY MVDC?

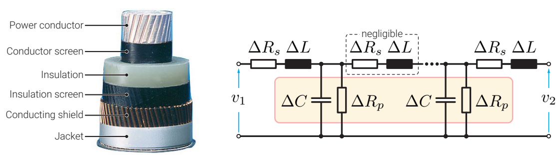
What are driving forces?

GENERAL NOTES OR CLAIMS ON DC

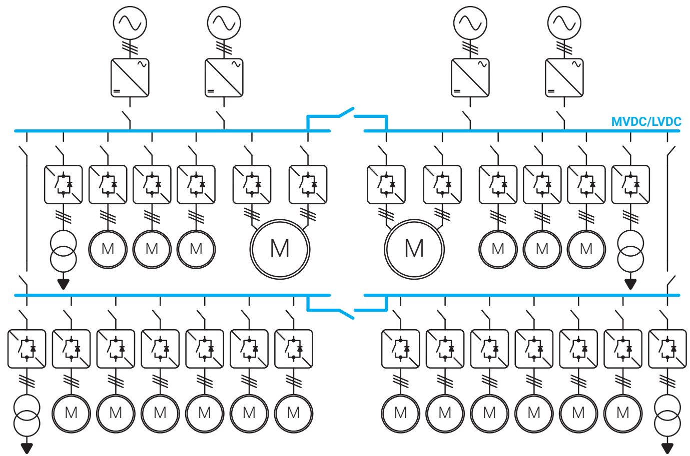
- No reactive power
- No skin effect problems
- No constraints imposed upon transmission distance
- Transmission capacity increase
- Lower transmission losses
- Alleviated stability problems
- Cheaper solution ("Break-even distance")
- Underwater cable transmission
- No need for synchronization
- Direct integration of Renewable Energy Sources
- Challenges $\Rightarrow$ Protection?



▲ Cost comparison between AC and DC systems

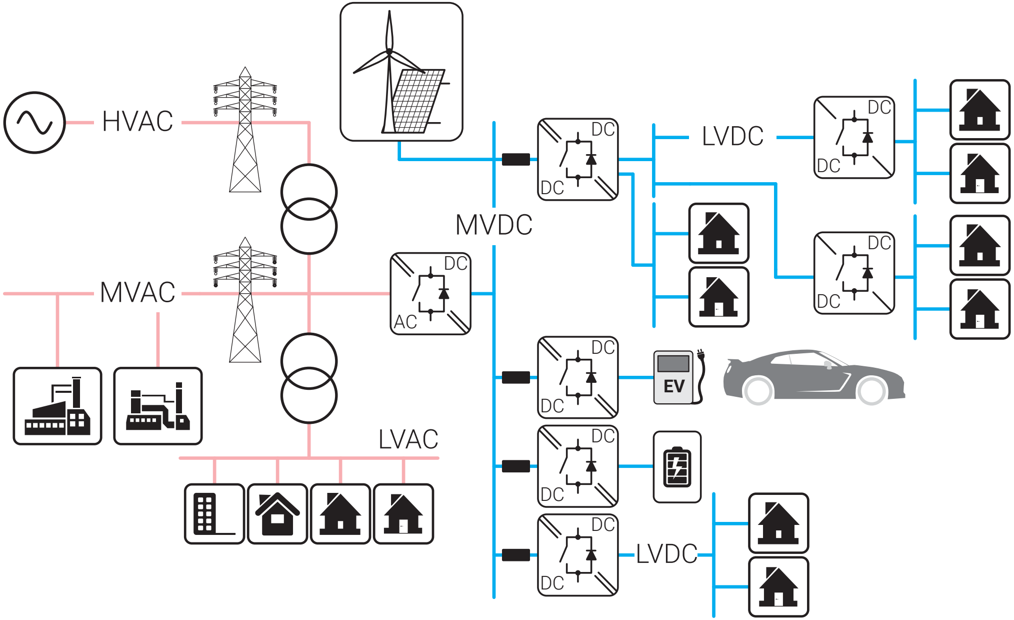


▲ High voltage cable



▲ DC Ship distribution system - frequency decoupling through a DC distribution [1]

A NEW POWER SYSTEM



▲ A modern power system with many DC technologies

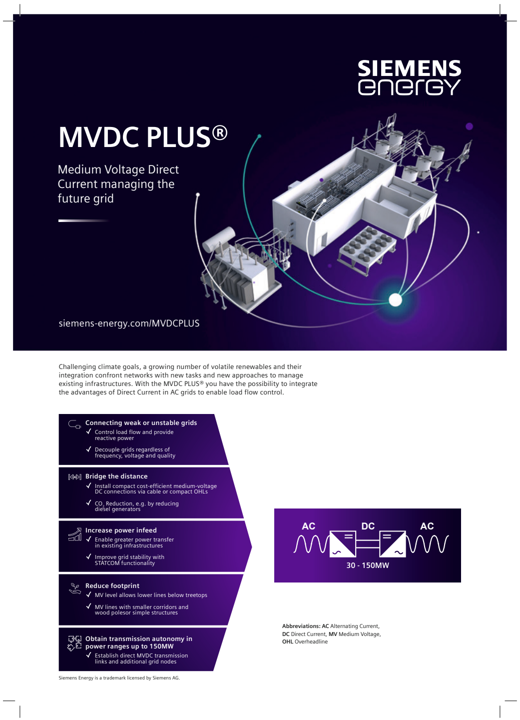
ABB

MEDIUM VOLTAGE PRODUCTS

Technical Application Papers No. 24

Medium voltage direct current applications

▲ ABB - MVDC Application Note



SIEMENS energy

MVDC PLUS®

Medium Voltage Direct Current managing the future grid

siemens-energy.com/MVDCPLUS

Challenging climate goals, a growing number of volatile renewables and their integration confront networks with new tasks and new approaches to manage existing infrastructures. With the MVDC PLUS® you have the possibility to integrate the advantages of Direct Current in AC grids to enable load flow control.

Connecting weak or unstable grids
- ✓ Control load flow and provide reactive power
- ✓ Decouple grids regardless of frequency, voltage and quality

Bridge the distance
- ✓ Install compact cost-efficient medium-voltage DC connections via cable or compact OHLs
- ✓ CO_2 Reduction, e.g. by reducing diesel generators

Increase power infeed
- ✓ Enable greater power transfer in existing infrastructures
- ✓ Improve grid stability with STATCOM functionality

Reduce footprint
- ✓ MV level allows lower lines below treetops
- ✓ MV lines with smaller corridors and wood polesor simple structures

Obtain transmission autonomy in power ranges up to 150MW
- ✓ Establish direct MVDC transmission links and additional grid nodes

AC DC AC
30 - 150MW

Abbreviations: AC Alternating Current, **DC** Direct Current, **MV** Medium Voltage, **OHL** Overheadline

Siemens Energy is a trademark licensed by Siemens AG.

▲ SIEMENS ENERGY - MVDC PLUS flyer

MVDC IN REALITY - PILOTS AND DEMOS

- Tjaereborg ABB HVDC Light demo: 7.2 MW, 4.3 km, $\pm 9\,kV_{dc}$ [2]
- Paimol-Brehat tidal power connection: 4 MW, 16 km, $10\,kV_{dc}$ [3]
- Wenchang offshore platform connection: 8 MW, 29.2 km, $\pm 15\,kV_{dc}$ [4]
- ...

▲ EDF's OpenHydro deployment of the 2nd Turbine

▲ Wenchang offshore platform

- Siemens MVDC Plus: 30 - 150 MW, < 200 km, $< \pm 50\,kV_{dc}$
- RXPE (RXHK) Smart VSC-MVDC: 1 - 10 MW, ± 5 - $\pm 50\,kV_{dc}$, 40 - 200 km
- ...

▲ Angle DC project details at (https://www.spenergynetworks.co.uk)

MVDC CHALLENGES

Standardization

- IEC, IEEE, CIGRE
- DC INDUSTRIE
- CURRENT OS

Power Distribution Networks

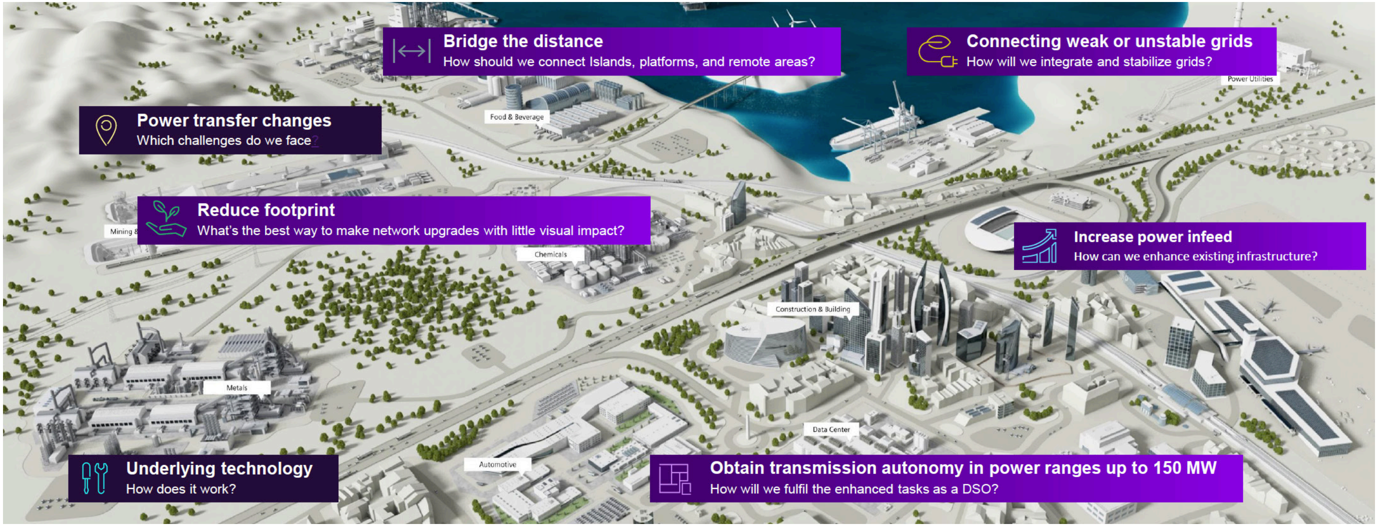
- Business case
- Applications
- Feasibility

Protection

- DC Breaker?
- Protection Coordination
- The role of Converters?

Conversion

- Efficiency, Reliability
- Flexible, Modular, Scalable
- Topology



▲ Source: SIEMENS MVDC PLUS

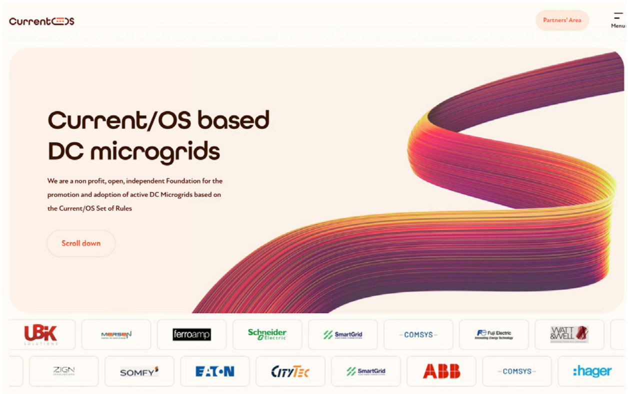
TOWARDS STANDARDIZATION

Current OS

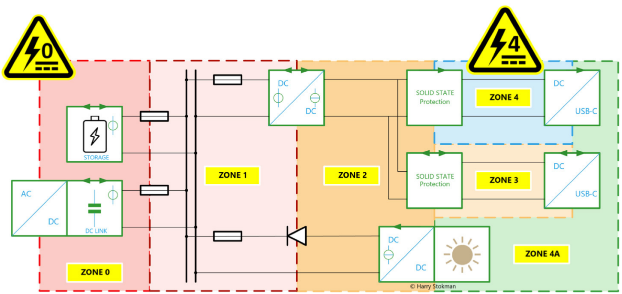
- Foundation (fee-based subscription)
- Current OS: Set-of-Rules
- Large number of industrial members

System										
Current/OS values										
	U_{DC}	† B6	AC Line	U_{DC}	† B6	AC Line	U_{DC}	U_{DC}		
									Dead band	Transients
U6	540			1080			270	2160	OVP Protection band	
U5	420			840			210	1680		
	410			820			205	1640	Over voltage	Bleed
U4	400			800			200	1600	Overshoot	
	390			780			195	1560		
U3	380			760			190	1520		
	375			750			187.5	1500	Over supplied	Normal operation
	370			740			185	1480		
	365			730			182.5	1460		
	360			720			180	1440		
	355			710			177.5	1420		
Nom.	350			700			175	1400		
	345			690			172.5	1380	Under supplied	
	340			680			170	1360		
	335			670			167.5	1340		
	330			660			165	1320		
	325			650			162.5	1300		
U2	320			640			160	1280		
	310	308	220	620	616	440	155	1240	Emergency	Emergency operation
	300	294	210	600	488	420	150	1200		
	290			580			145	1160		
	280	280	200	560	560	400	140	1120		
	270	266	190	540	532	380	135	1080		
	260			520			130	1040		
U1	250	252	180	500	504	360	125	1000		
	0			0			0	0	Blackout	Off

▲ Source: Current OS foundation - Voltage bands



▲ Source: Current OS foundation (https://currentos.foundation)

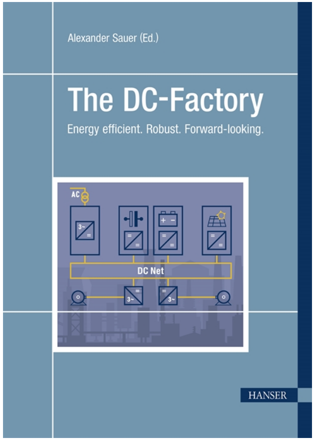


▲ Source: Current OS foundation - Zoning by risk level

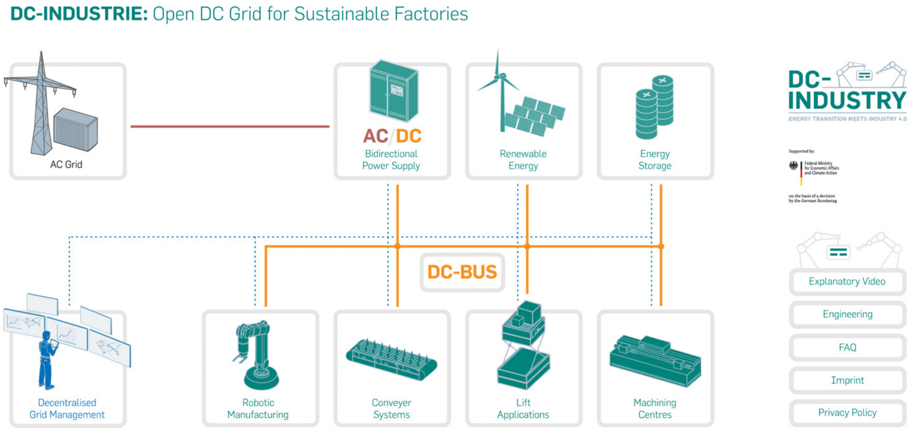
TOWARDS STANDARDIZATION

DC INDUSTRIE

- Funded by German government
- Focus on the industrial production plants
- 39 industrial and research partners
- ODCA - Open DC Alliance



▲ DC INDUSTRIE 1 details inside



▲ Source: DC INDUSTRIE 2 (https://www.ife-owl.de/en/research/projects/dc-industry-2)

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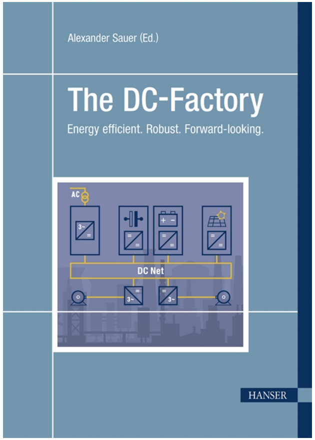

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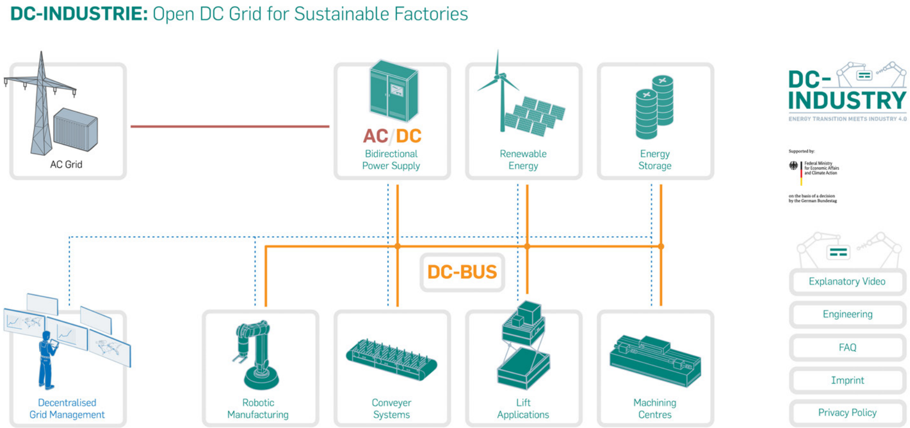
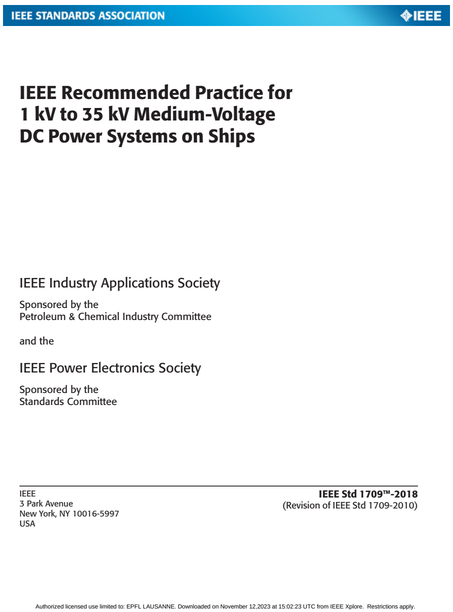


▲ Source: DC INDUSTRIE 2 (https://www.ife-owl.de/en/research/projects/dc-industry-2)

⇒ Current OS and DC INDUSTRIE focus is only on LVDC!

TOWARDS STANDARDIZATION

IEEE


IEEE STANDARDS ASSOCIATION ◈IEEE

IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships

IEEE Industry Applications Society

Sponsored by the
Petroleum & Chemical Industry Committee

and the

IEEE Power Electronics Society

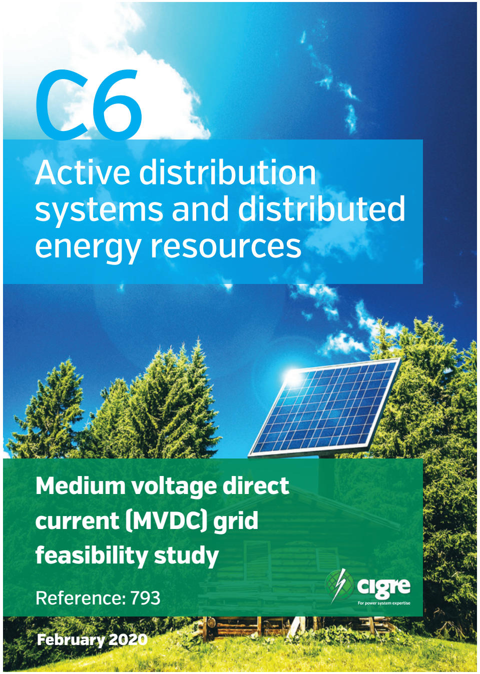
Sponsored by the
Standards Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1709™-2018
(Revision of IEEE Std 1709-2010)

▲ IEEE Recommended Practice for 1 kV to 35 kV MVDC Power Systems on Ships

CIGRE WG C6.31



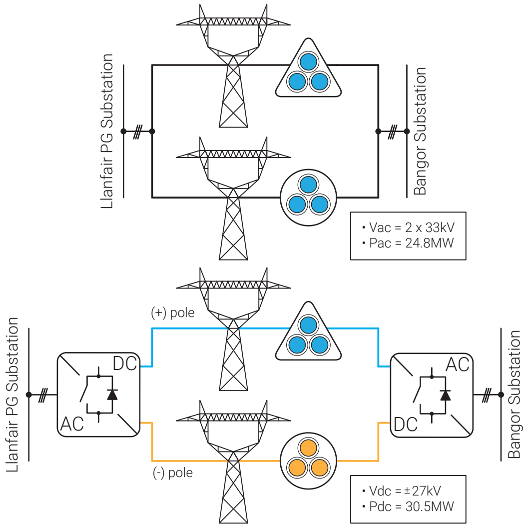
▲ Medium Voltage Direct Current (MVDC) Grid Feasibility Study

MVDC APPLICATIONS

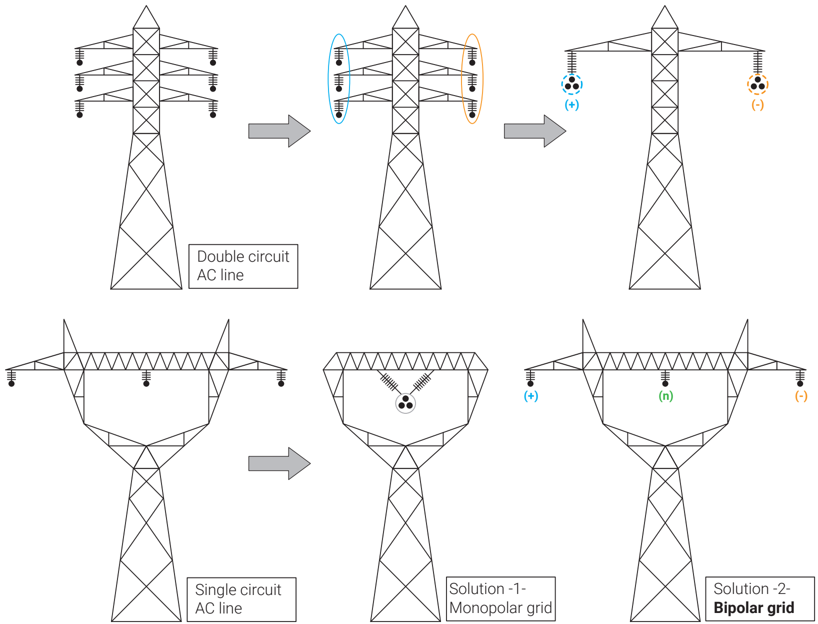
Power Distribution Networks for different applications

POWER GRIDS: CONVERSION OF AC LINES INTO DC LINES

- Transmission capacity increase
- Employment of the existing conductors
- No change in tower foundations
- Tower head adjustment
- Isolator's assemblies adjustment



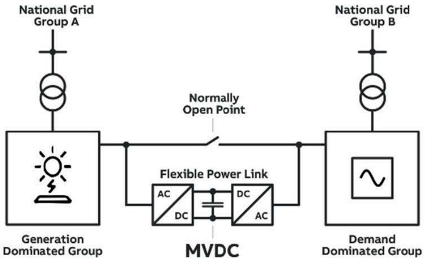
▲ Angle DC Project - UK



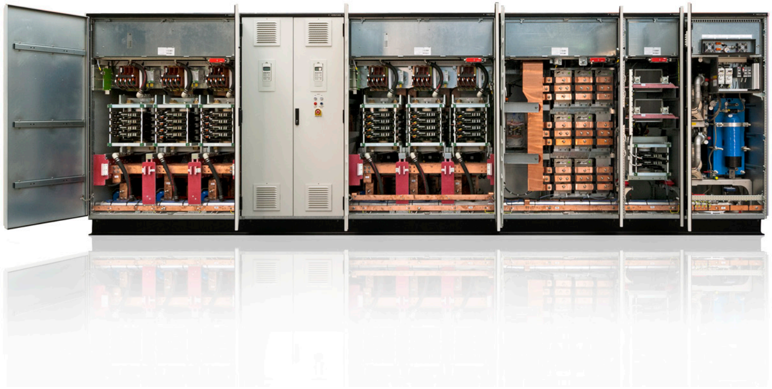
▲ Conversion of two typical AC lines into DC [5], [6], [7], [8]

POWER GRIDS: SOFT-OPEN POINT (MVDC)

- Connecting two AC grids (asynchronous)
- Short links - substation
- Long links - network
- Increasing operational flexibility
- Improving voltage profile
- No increase in short circuit current



▲ Flexible Power Link (FPL), Soft-Open Point (SOP) [9]



▲ ABB's ACS6000 Medium Voltage drive with 5kV DC link

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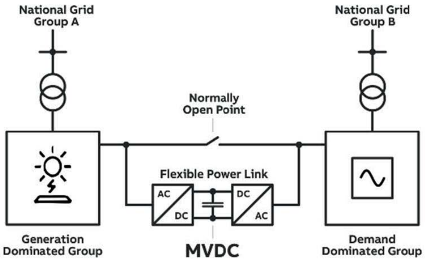

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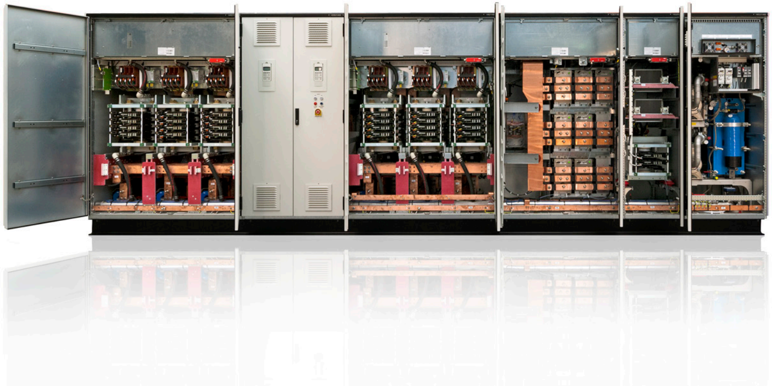
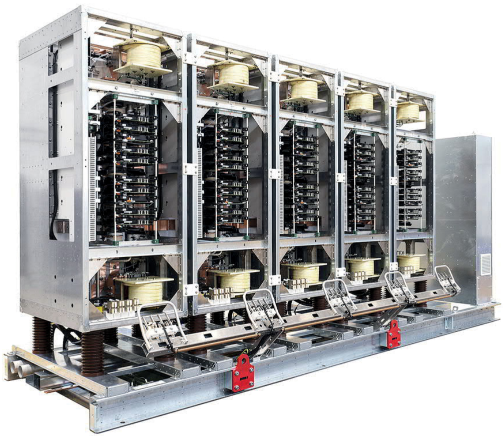


▲ ABB's ACS6000 Medium Voltage drive with 5kV DC link

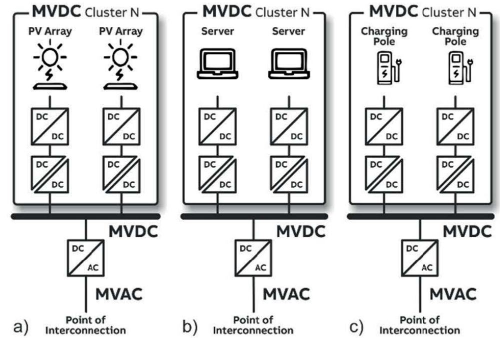
▲ ABB's ACS6000 multi-drive line up - around 33 meters long - done 20 years ago!

POWER GRIDS: MVDC COLLECTION NETWORKS

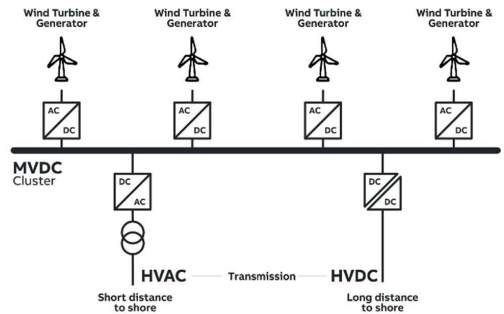
- MVDC collection
- Voltage level - case by case
- Efficiency driven
- Off-shore / On-shore
- DC-DC converters needed



▲ Assembly of 10 MMC full-bridge submodules - Building Blocks!

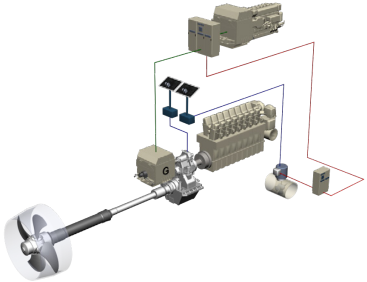


▲ MVDC collection networks for a) PV generation; b) high power data centers and c) Fast EV charging [9]

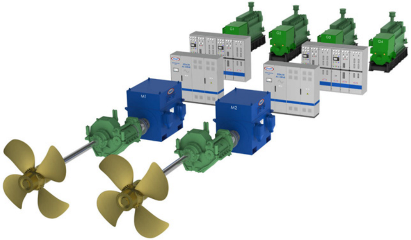


▲ MVDC collection network for wind application [9]

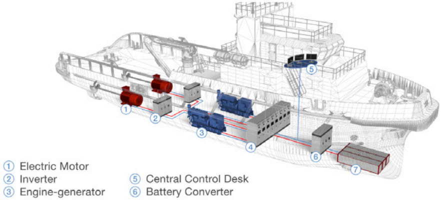
▲ Source: (http://www.cnae.co.kr/electric-propulsion-system/?ckattempt=1)



▲ Diesel propulsion system with shaft generator



▲ Diesel Electric propulsion system

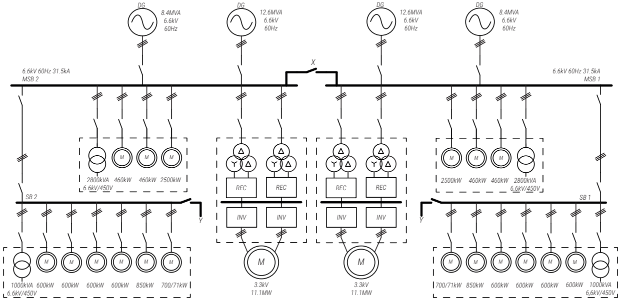


▲ Battery powered electric propulsion system

- Fuel savings with variable speed generators
- Efficiency of power distribution
- Smaller equipment footprint
- Easy integration of ESS
- Reduced greenhouse emissions

▲ Marine hybrid electric (www.MaritimeCyprus.com)

▲ LNG carrier Mraweh (only an illustrative image)



▲ LNG carrier - MVAC power distribution network (a real layout, 1/2)

MARINE MVDC POWER DISTRIBUTION NETWORKS

- Fuel savings with variable speed generators
- Efficiency of power distribution
- Smaller equipment footprint
- Easy integration of ESS
- Reduced greenhouse emissions

▲ Marine hybrid electric (www.MaritimeCyprus.com)

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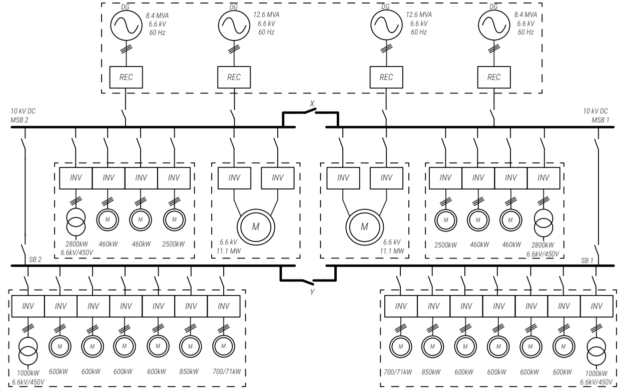
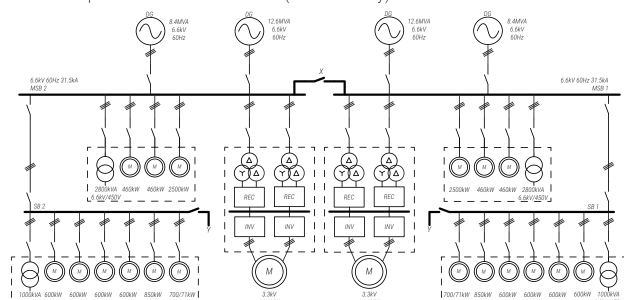


▲ LNG carrier - MVDC power distribution network (scenario only)



▲ LNG carrier - MVAC power distribution network (a real layout, 1/2)

MVDC PROTECTION

Protection coordination to achieve selectivity in safety critical applications

- Example: Traction circuit breaker UR26 (https://www.secheron.com)

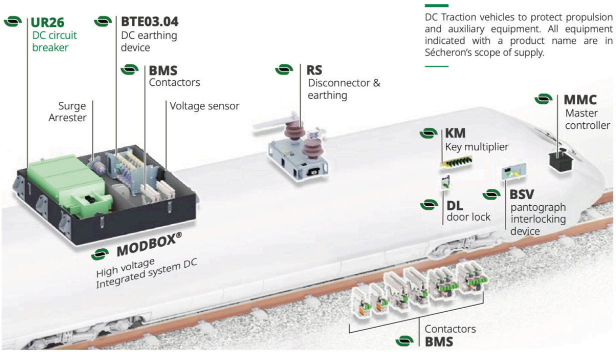
	Symbol	Unit	UR26				
Arch chute type			81	82	64	DV64	
MAIN HIGH VOLTAGE CIRCUIT							
Rated operational voltage	U_r	$[V_{DC}]$	900	1,800	3,600	1,800	3,600
Rated insulation voltage	U_{Nm}	$[V_{DC}]$	3,000		4,800		
Conventional free air thermal current (1)	I_{th}	[A]	2,300				
Rated operational current	I_r	[A]	2,300				

No Natural Current Zero-Crossing

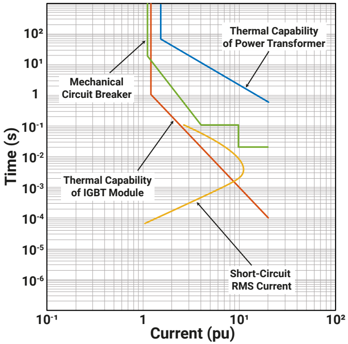
- Difficulty in fault interruption
- Mechanical, Hybrid, Solid-State Circuit Breaker

Low Overloading Capability of Power Converters

- AC protection: several hundreds of milliseconds
- DC protection: several milliseconds



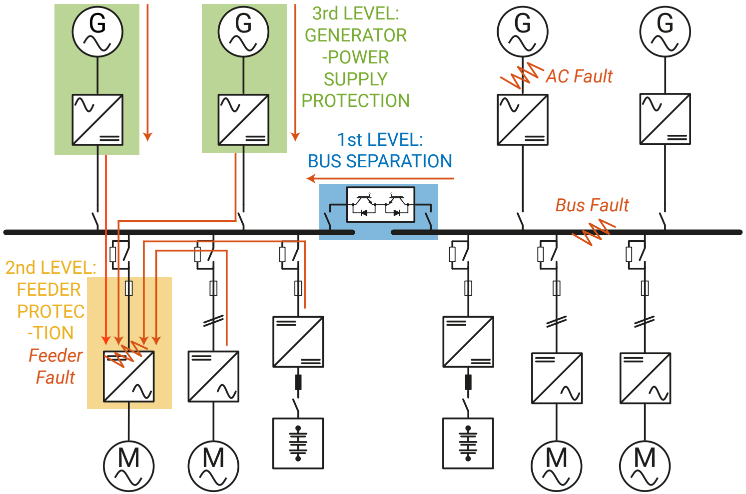
- DC Traction protection equipment (https://www.secheron.com)



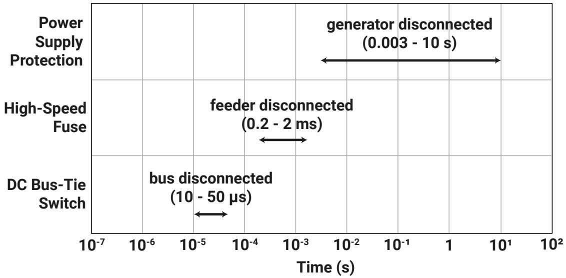
- Thermal capabilities against short-circuit current

THREE-LEVEL PROTECTION

- **Fast action:** Bus separation by solid state bus-tie switches
- **Medium action:** Feeder protection by high-speed fuses or solid state circuit breakers
- **Slow action:** Power supply protections - blocking fault current contribution of source



▲ Operational diagram of a three-level protection [10], [11], [12]

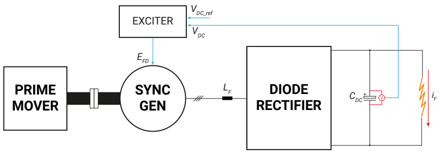


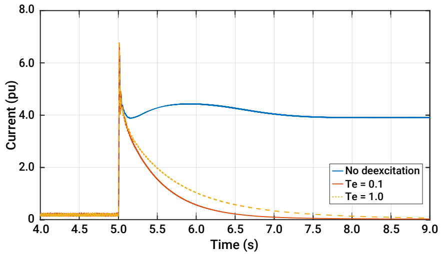
▲ Operational time frames of a three-level protection.

POWER SUPPLY PROTECTION METHODS

Diode Rectifier

- Deexcitation with high X_d'' [13]

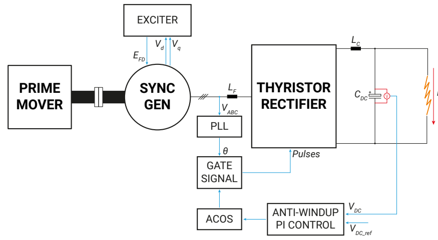


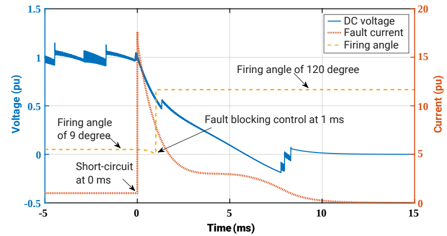


▲ Fault interruption by deexcitation

Thyristor Rectifier

- Fold-back protection control [14]

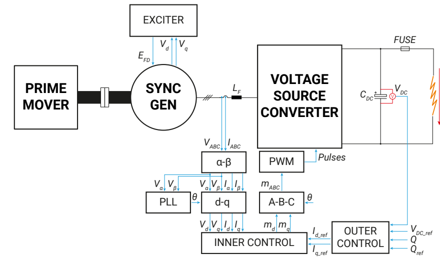


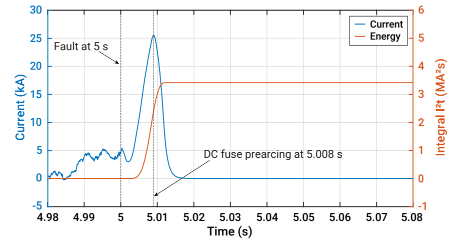


▲ Fold-back protection control

Voltage Source Converter

- High-speed fuse [12]





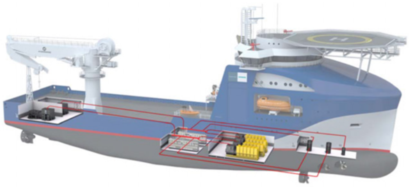
▲ Fault interruption by high-speed fuse

EMPLOYED PROTECTION SCHEMES - LVDC VESSELS

	Solution	Siemens BlueDrive PlusC	ABB Onboard DC Grid	Ingeteam E3-Ship	We Tech Hybrid DC Machinery	The Switch DC-Hub
Power supply	**Generator (AC voltage)**	SG (0.69 kV)	SG (N/A)	SG or PMSG (0.69 kV)	SG or PMSG (0.45 kV)	SG or PMSG (N/A)
	Rectifier (DC voltage)	Diode rectifier (0.93 kV)	Thyristor rectifier (1 kV)	VSC (1.5 kV)*	VSC (1 kV)	VSC (1 kV)
Protective device	**Bus separation**	Solid-state bus-tie switch				
	Feeder protection	Fuse	Fuse	Fuse	N/A	SSCB
	Power supply protection (Backup)	Deexcitation with high X_d''	Fault-blocking converter (Fuse)	Fuse	N/A	SSCB

[15], [12], [13], [16], [17] * Note: The voltage rating of the solid-state bus-tie switch in [12].

▲ ABB Onboard DC Grid [18]



▲ Siemens BlueDrive PlusC [19]

MVDC CONVERSION TECH...

Power electronics as enabling technology

POWER SEMICONDUCTORS: AN ABUNDANCE OF OPTIONS

IGBT

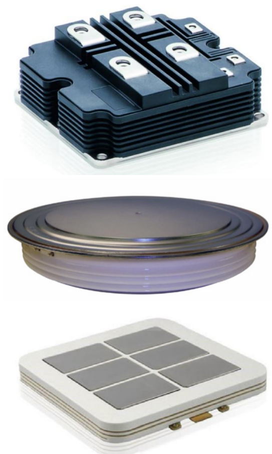
- Can be well controlled by gate driver
- Offers controllable di/dt
- Various packaging options
- Does not require external circuitry
- Several kHz easily achievable

IGCT

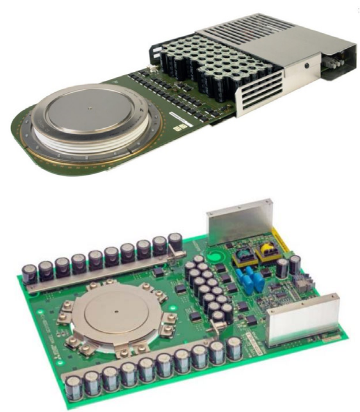
- Thyristor based device
- Lowest conduction loss
- External circuitry needed (clamp)
- Only available as press-pack
- Low frequency (<1 kHz)

SiC MOSFET

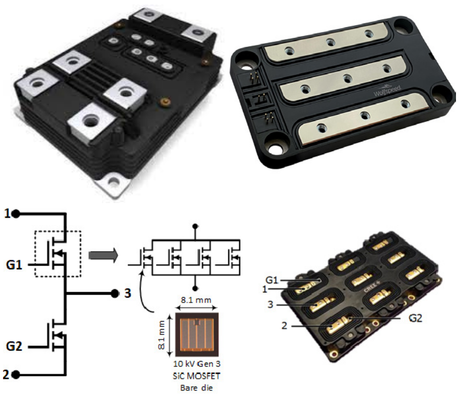
- 3.3kV (6.5kV) commercially available
- Significantly faster switching
- Significantly higher switching frequency
- Protection, Reliability, Cost
- High frequency (>10 kHz)



▲ IGBT devices in different packaging



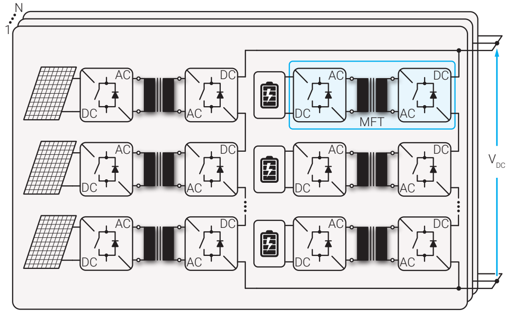
▲ The IGCT - Integrated Gate Commutated Thyristor



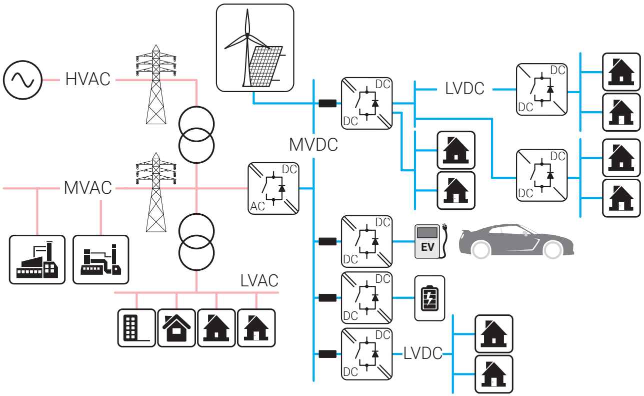
▲ SIC MOSFET: LinPak, WOLFSPEED [20]

DC-DC CONVERTERS, DC-DC SOLID STATE TRANSFORMERS

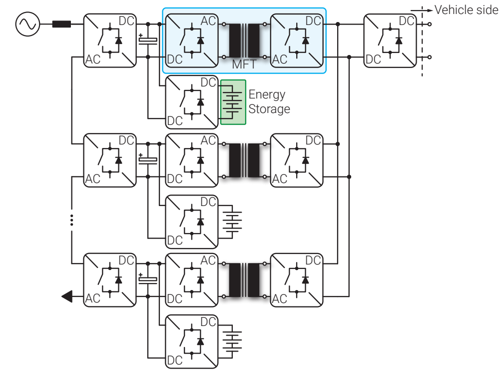
- Inherent building block of the almost all SST topologies
- Interface between different MVDC levels
- Enabling technology for MVDC
- Integration of renewable DC energy sources
- Integration of Fast / Ultra Fast EV charging
- Medium Frequency conversion with MFTs



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



▲ Concept of a modern power system

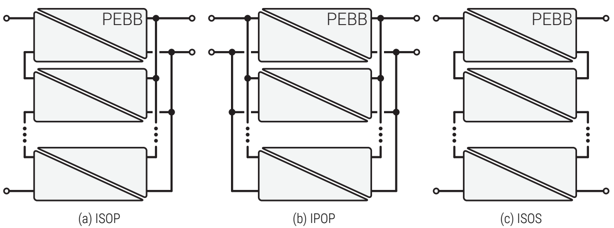


▲ Fast EV charging concept

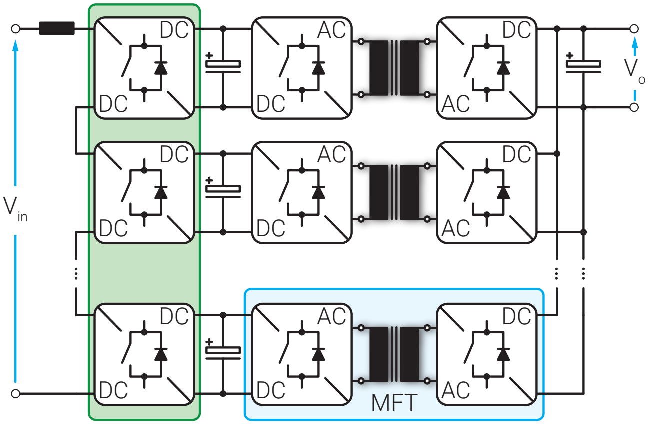
DC-DC SST - BASIC CONCEPTS

Fractional Power Processing

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



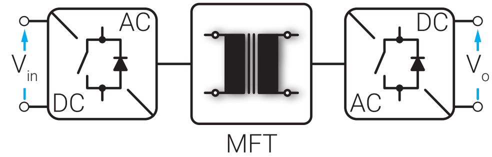
▲ Different and well known structures



▲ Fractional power processing with ISOP structure

Bulk Power Processing

- Single MFT
- Isolation problem solved only once
- Various configurations/operating principles

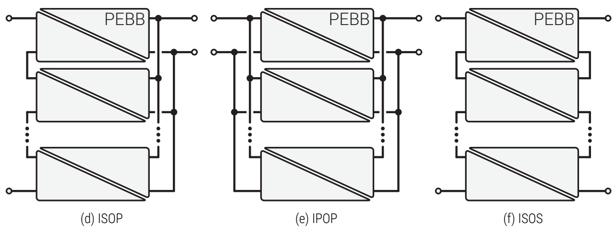


▲ Bulk power processing concept

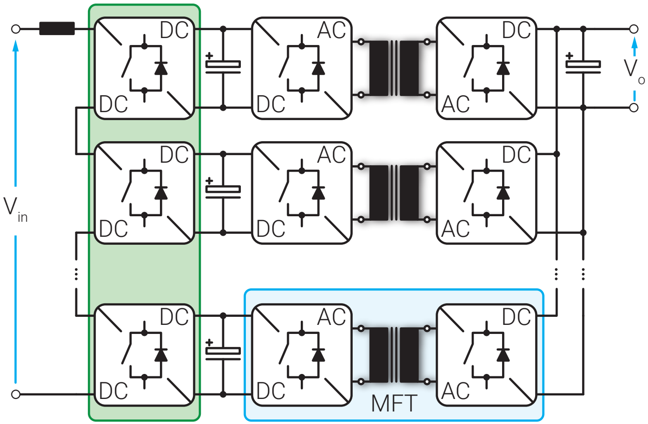
DC-DC SST - BASIC CONCEPTS

Fractional Power Processing

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



▲ Different and well known structures



▲ Fractional power processing with ISOP structure

Bulk Power Processing

- Single MFT
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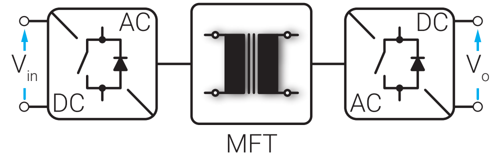
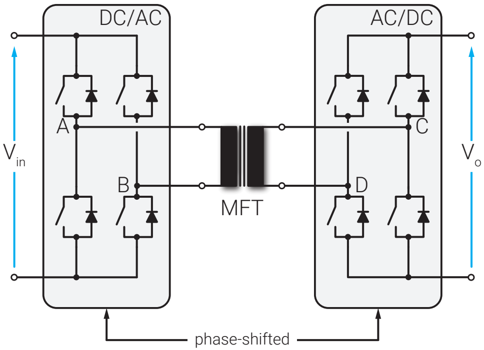


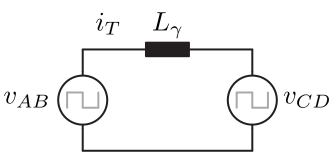
▲ Bulk power processing concept

⇒ Both design approaches are valid, and have their pros and cons! Many factors should be considered!

COMMON PEBB CONFIGURATIONS

Dual-Active Bridge

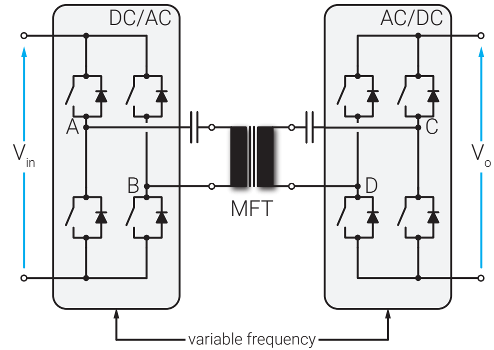


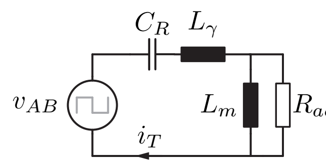


$$P = P(\varphi)$$

▲ Dual Active Bridge [21]

Resonant Converters





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

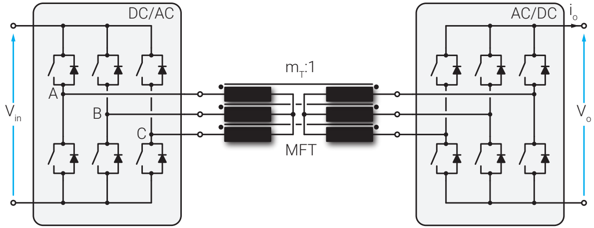
$$f_{r2} = \frac{1}{2\pi\sqrt{C_R(L_\gamma + L_m)}}$$

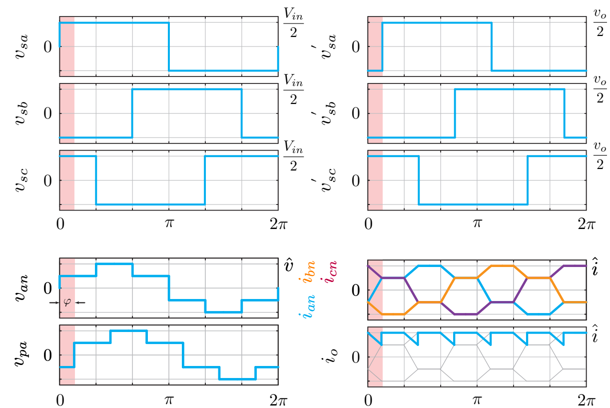
$$Q = Q(R_{ac})$$

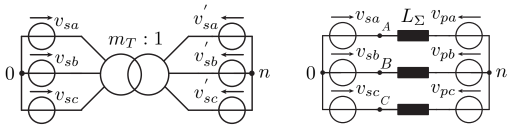
$$G = G\left(\frac{f_{sw}}{f_{r1}}, \frac{L_m}{L_\gamma}, Q\right)$$

▲ LLC Resonant Converter

THREE-PHASE (3PH) DAB

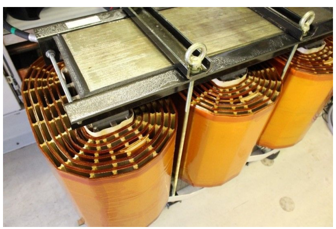






$$v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \qquad v_{pa} = m_T \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3}$$

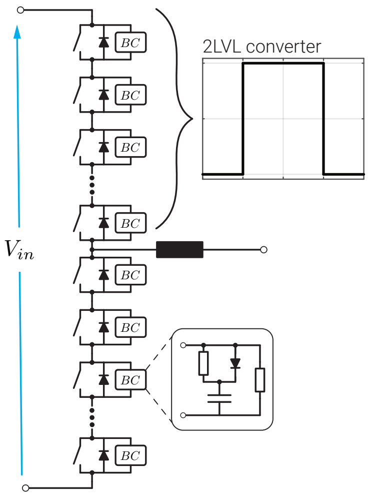
▲ 3PH-DAB with its relevant waveforms



▲ 5MW, 1kHz 3PH MFT by Schaffner

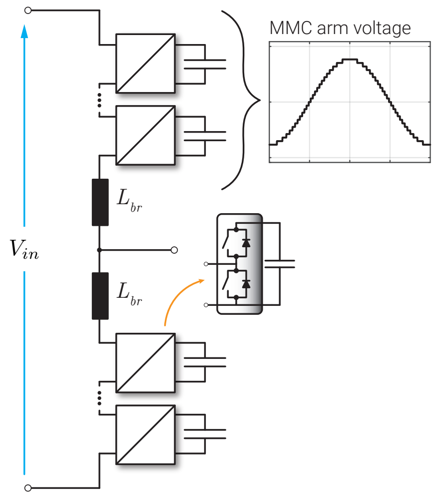
▲ 5MW, 1kHz 3PH DAB IGCT prototype at RWTH, Aachen

HOW TO HANDLE HIGH/MEDIUM VOLTAGES?



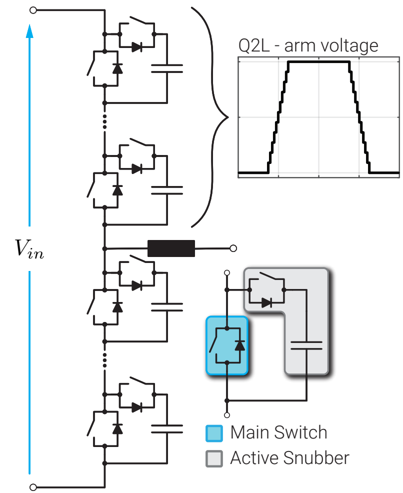
▲ Series connection of switches [22]

- Series connection of switches with snubbers
- Two-Level voltage waveforms



▲ Modular Multilevel Converter (MMC)

- Series connection of Submodules (SM)
- Arbitrary voltage waveform generation

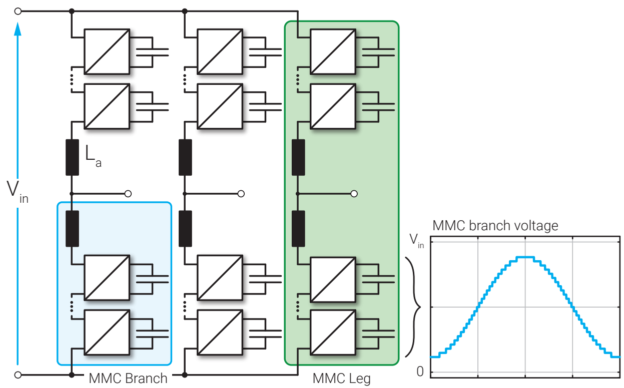


▲ Quasi Two-Level (Q2L) Converter [23], [24]

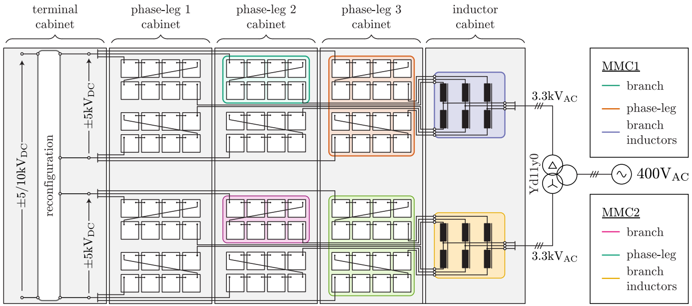
- Series connection of MMC-alike SMs
- Quasi Two-Level (trapezoidal) voltage waveform

MODULAR MULTILEVEL CONVERTER (MMC)

- Variety of conversion possibilities
- Variety of modulations
- Different types of submodules (SMs)
  - Half-Bridge (HB)
  - Full-Bridge (FB)
  - Others...
- Arbitrary voltage waveform generation



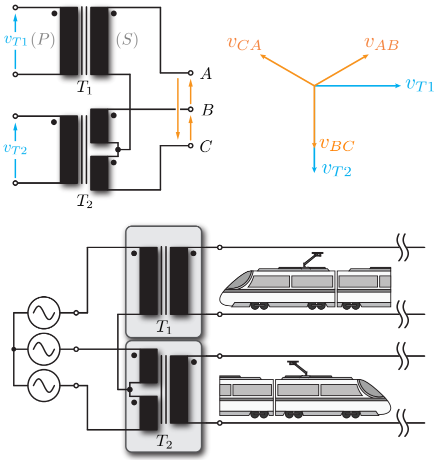
▲ Modular Multilevel Converter (MMC)



▲ EPFL PEL - Dual MMC-based MVDC source - layout

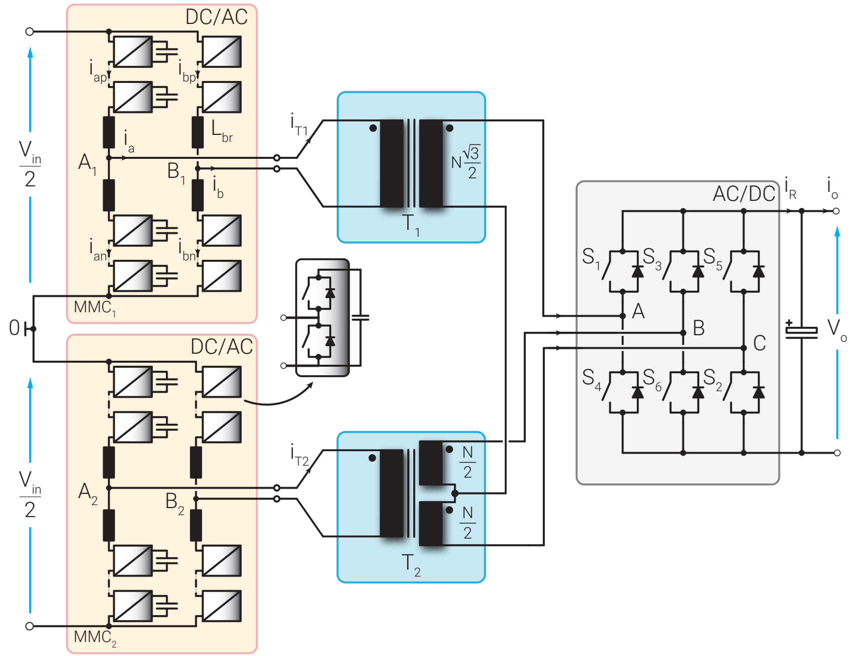
▲ EPFL PEL - Dual MMC-based MVDC source - realized 2 x 250kW system

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 ↓)
- Ability to operate in a pure rectifier mode
- Medium frequency operation



▲ MMC-Based High Power DC-DC Converter Employing Scott Transformer Connection [25]

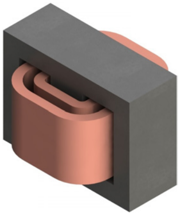
MEDIUM FREQ. TRANSFORMERS

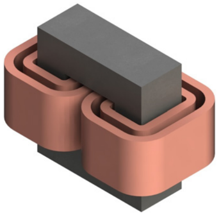
Designing for high power, high voltage, high frequency...

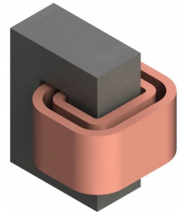
MFT: TECHNOLOGIES, MATERIALS, DESIGNS

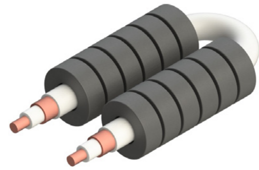
Construction Choices:

- MFT Types


Shell Type


Core Type

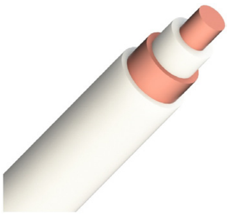

C-Type

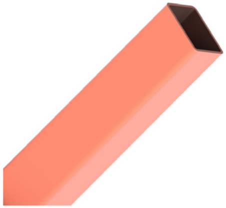

Coaxial Type

- Winding Types


Litz Wire


Foil


Coaxial


Hollow/Pipes

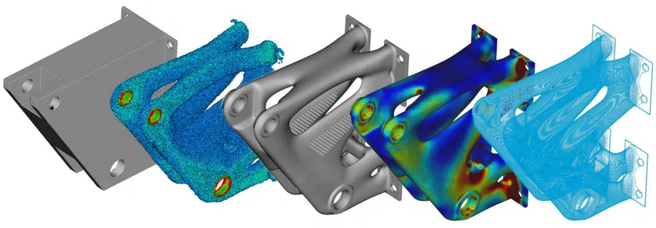
Materials:

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

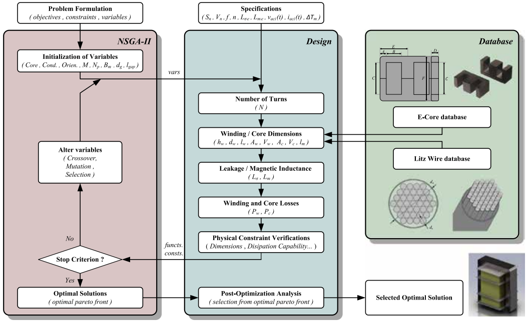
MFT DESIGN METHODS

- Multi-objective optimization problem
- Multiple competing objectives
- Meeting converter parameters
- Respecting constraints
- Manufacturability

▼ Source: (https://formlabs.com/ch/)



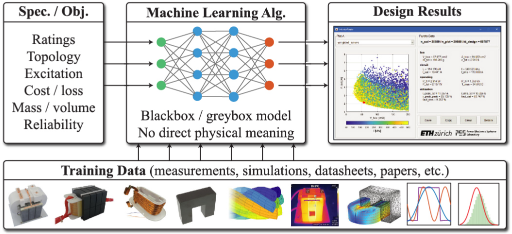
Genetic Algorithm



▲ Design flowchart using NSGA-II algorithm [26]

Neural Networks

- ANN must be trained somehow
- Measurements, simulations, FEM, datasheets

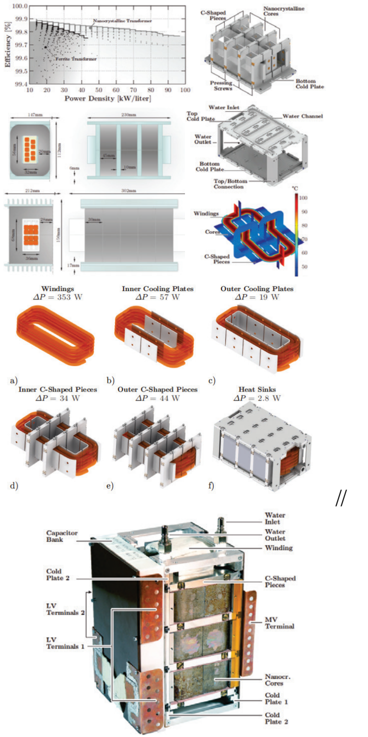


▲ Inductor design with the help of ANN [27]

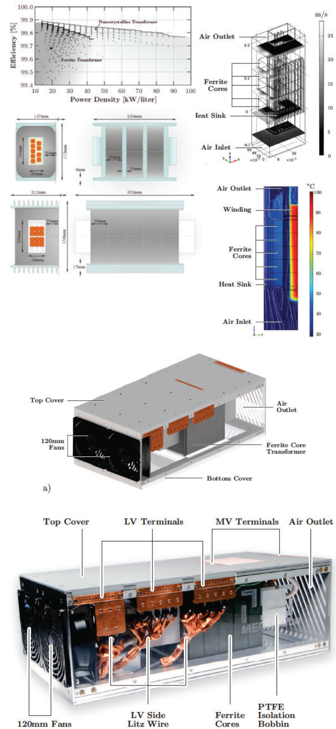
Brute Force

- Exhaustive search concept
- All possible combinations
- Computationally intensive
- Easy to implement

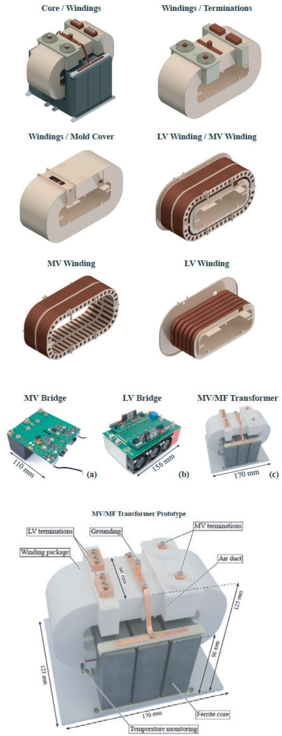
▲ 10'000 combinations



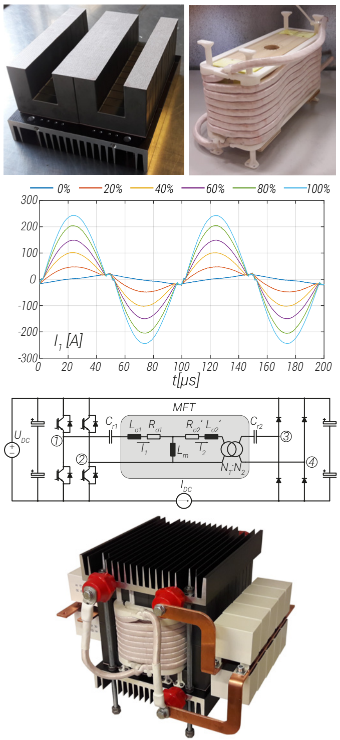
▲ Shell, 166kW, 20kHz, Nanocrystalline MFT [28], [29], [30]



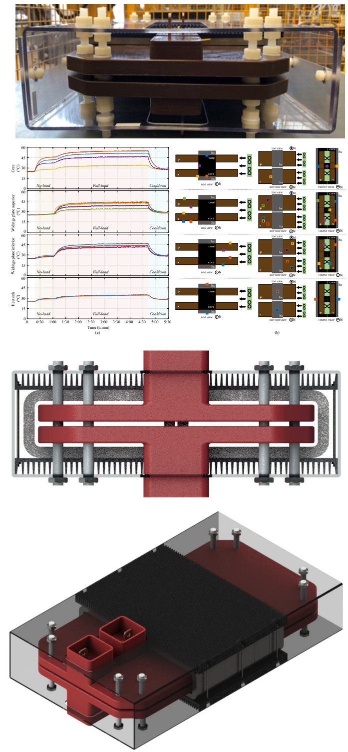
▲ Shell, 166kW, 20kHz, Ferrite MFT [28]



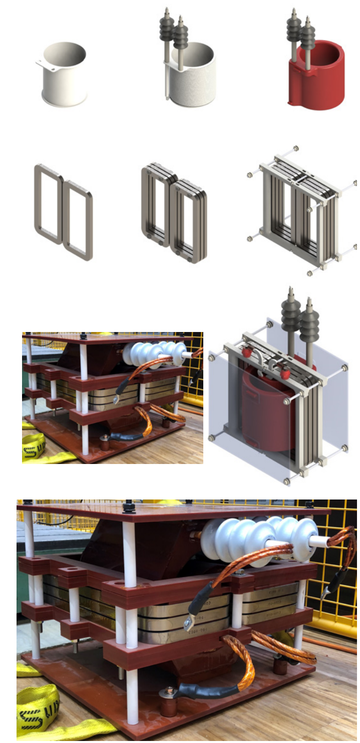
▲ Shell, 25kW, 48kHz, Ferrite MFT [31]



▲ Core, 100kW, 10kHz, Ferrite MFT [32], [33], [34]



▲ Planar, 100kW, 10kHz, Nanocrystalline MFT



▲ Core, 300kW, 20kHz, Nanocrystalline MFT

MFT DESIGN DIVERSITY

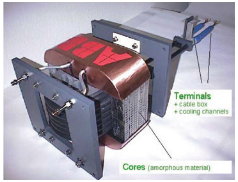


ABB: 350kW, 10kHz

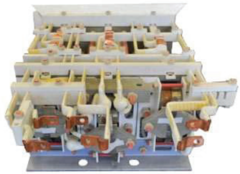
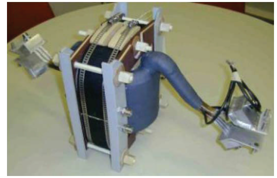
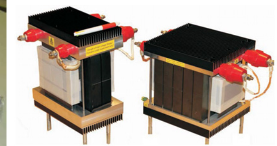
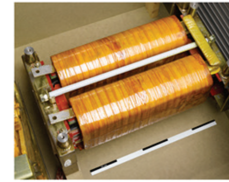
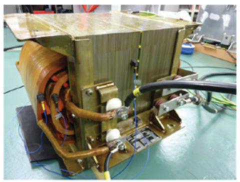


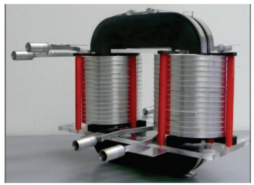
ABB: 3x150kW, 1.8kHz

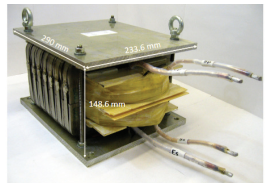

BOMBARDIER: 350kW, 8kHz


CHALMERS: 50kW, 5kHz

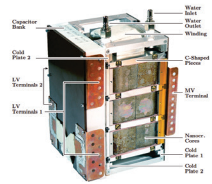

IKERLAN: 400kW, 5kHz


IKERLAN: 400kW, 1kHz

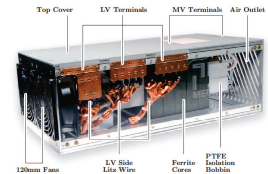

FAU-EN: 450kW, 5.6kHz



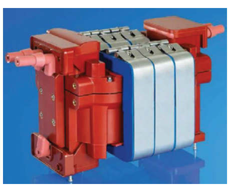
EPFL: 300kW, 2kHz

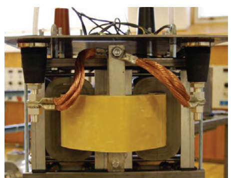


ETHZ: 166kW, 20kHz



ETHZ: 166kW, 20kHz


STS: 450kW, 8kHz


KTH: 170kW, 4kHz


EPFL: 100kW, 10kHz


SCHAFFNER: 5000kW, 1kHz

?

MFT DESIGN DIVERSITY

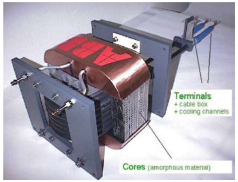


ABB: 350kW, 10kHz

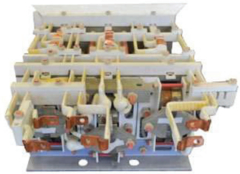
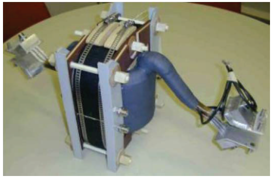


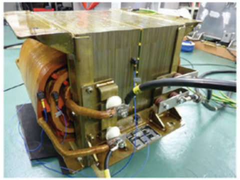
ABB: 3x150kW, 1.8kHz



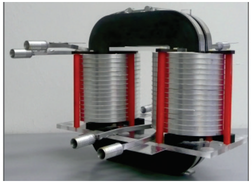
BOMBARDIER: 350kW, 8kHz

CHALMERS: 50kW, 5kHz

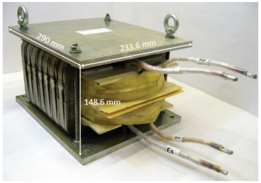
IKERLAN: 400kW, 5kHz



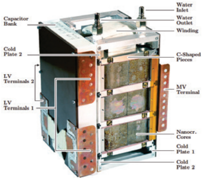
IKERLAN: 400kW, 1kHz



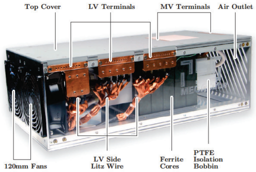
FAU-EN: 450kW, 5.6kHz



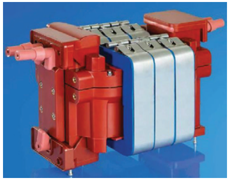
EPFL: 300kW, 2kHz



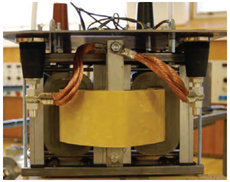
ETHZ: 166kW, 20kHz



ETHZ: 166kW, 20kHz

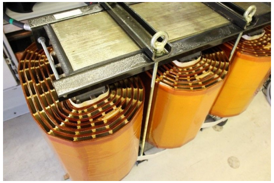


STS: 450kW, 8kHz



KTH: 170kW, 4kHz

EPFL: 100kW, 10kHz



SCHAFFNER: 5000kW, 1kHz

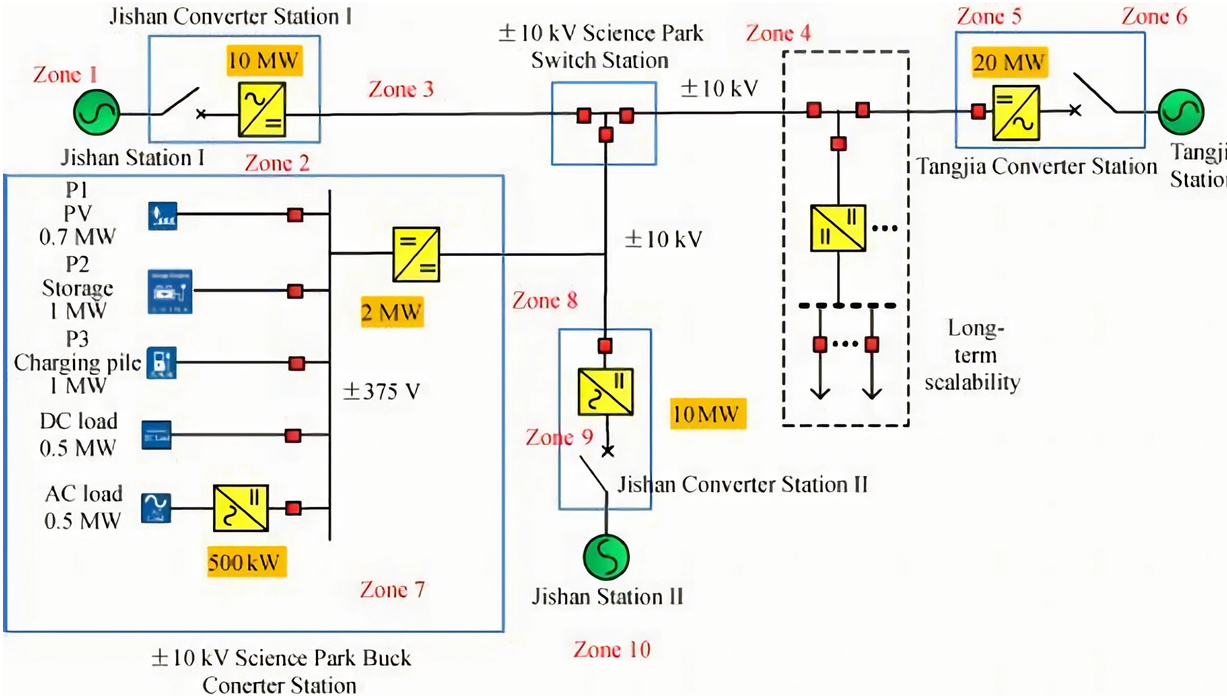
?

⇒ Design with Natural Intelligence or Artifical Intelligence? Choose wisely!

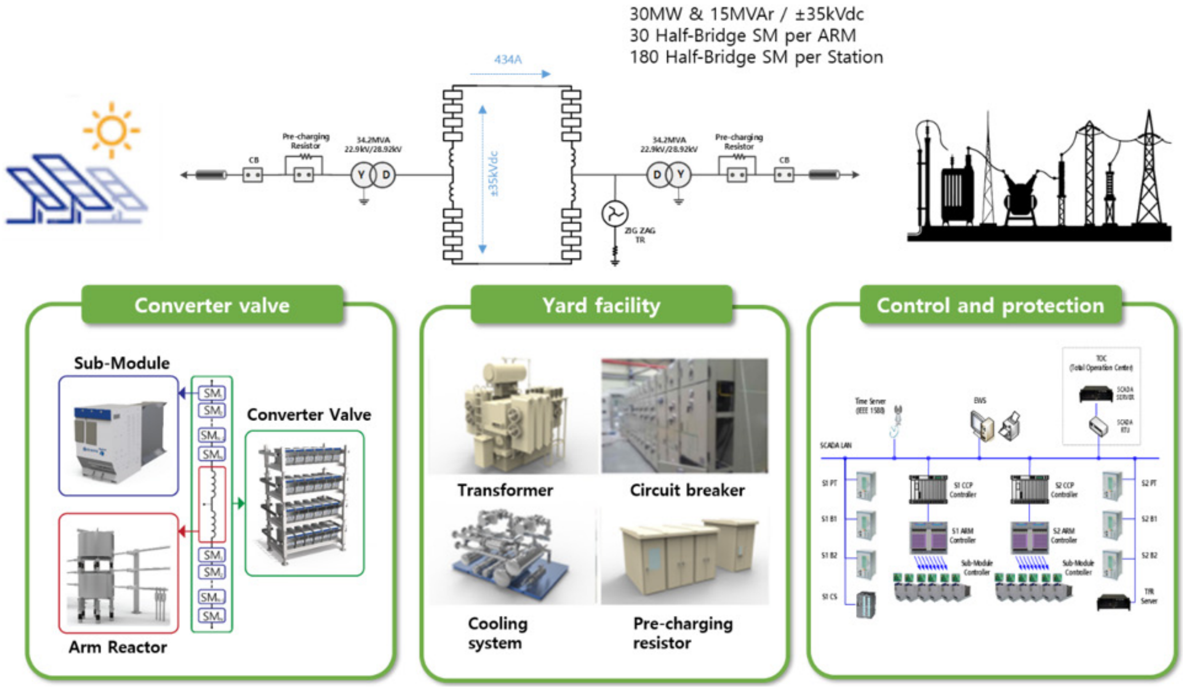
MVDC DEMONSTRATORS

Demonstration sites or project

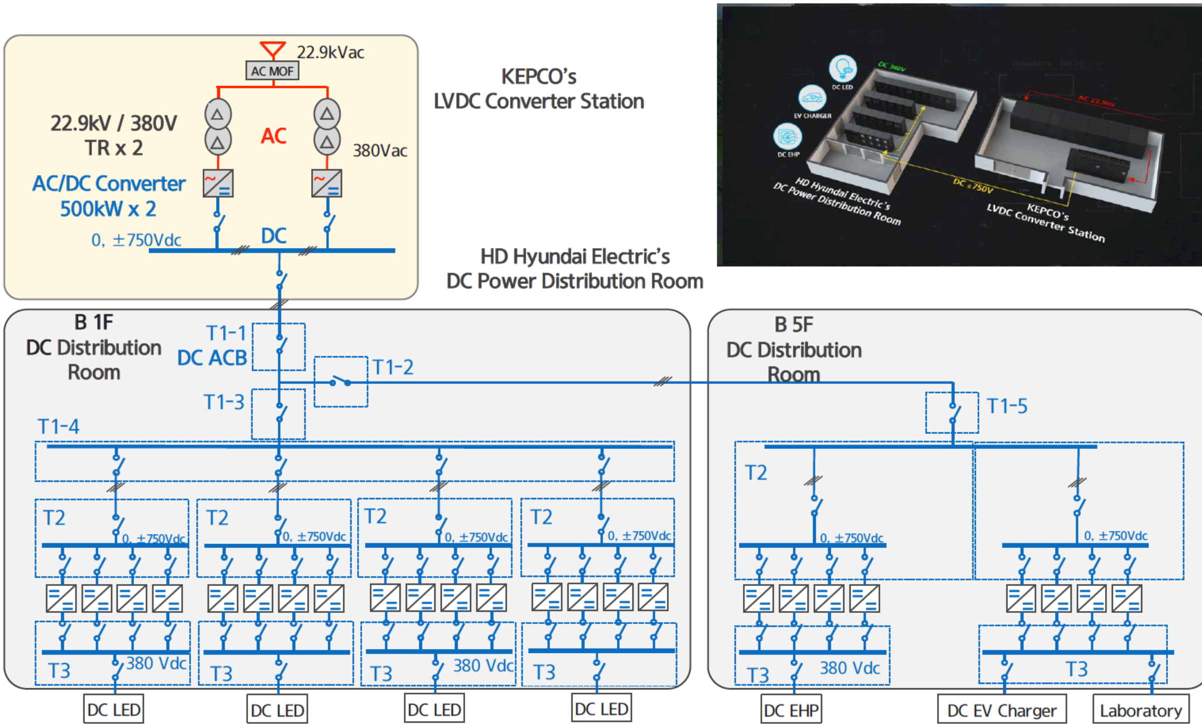
CHINA: ZHUHAI



▲ The MVDC distribution network in Zhuhai, China

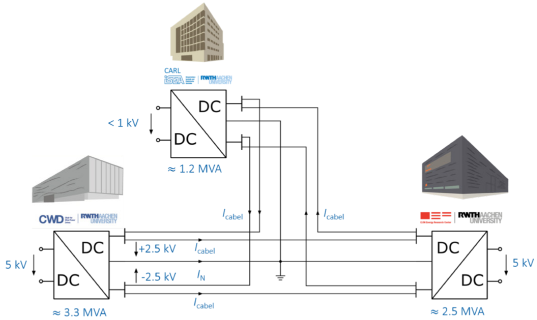


▲ The first MVDC station project in Korea



▲ HYUNDAI Global Research Center LVDC building, Korea

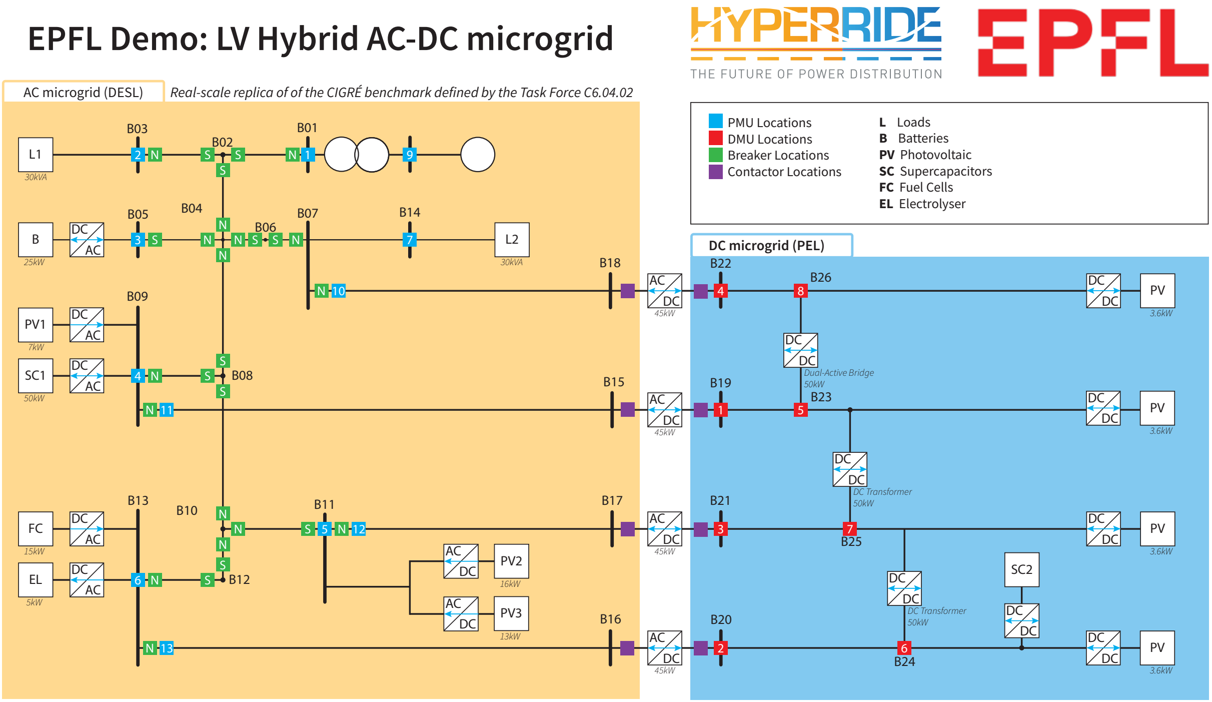
GERMANY: RWTH, AACHEN



▲ The MVDC campus connection at RWTH, Aachen, Germany

▲ FEN consortium efforts

EPFL Demo: LV Hybrid AC-DC microgrid



▲ Hybrid AC-DC microgrid at EPFL, Switzerland

EMPOWER

Medium Voltage Direct Current Transformer

MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS

▲ EMPOWER-ing the future energy systems

MVDC Grids

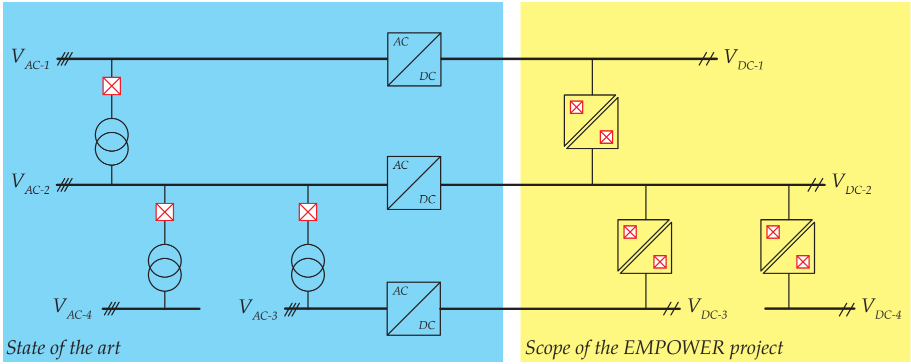
- DC Transformer
- Flexibility
- Stability

DC-DC Conversion

- Resonant principles
- Medium frequency conversion
- Absence of the control loops

DC Protection

- HV semiconductors
- Active protection
- Selectivity



▲ Today's AC and tomorrow's DC power distribution networks enabled by DC Transformers

▲ The EMPOWER - Holistic and Integrated

EMPOWER - AN EUROPEAN RESEARCH COUNCIL CONSOLIDATOR GRANT

▲ EMPOWER-ing the future energy systems

MVDC Grids

- DC Transformer
- Flexibility
- Stability

DC-DC Conversion

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- Medium frequency conversion
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DC Protection

- HV semiconductors
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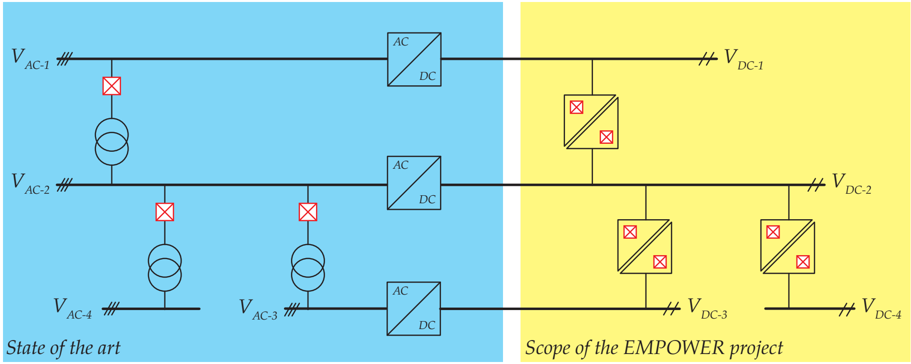


▲ Today's AC and tomorrow's DC power distribution networks enabled by DC Transformers

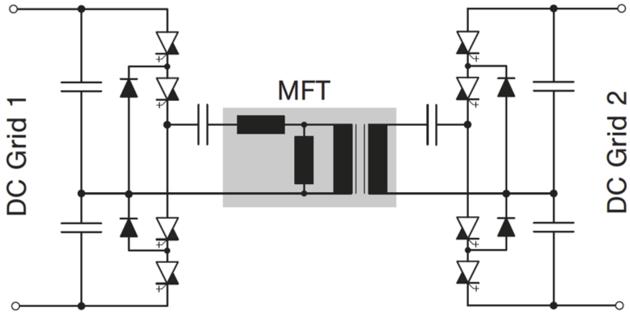
▲ The EMPOWER - Holistic and Integrated

⇒ Can we make a simple DC Transfomer behaving as much as possible as equivalent AC transformer?

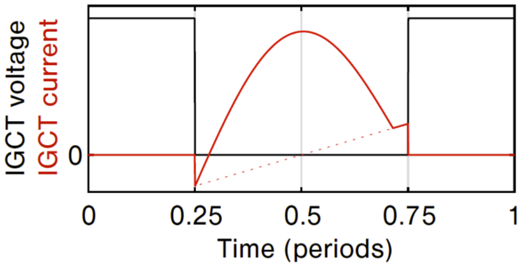
Key details

- 1MW, 5kHz, 5kV-10kV
- 3L-NPC + split-capacitors legs
- Resonant conversion
- 4.5kV and 10kV IGCTs
- Nanocrystalline MFT core
- Copper pipes as winding (oil insulated)

▲ Direct Current Transformer demonstrator



▲ IGCT based DC Transfomer

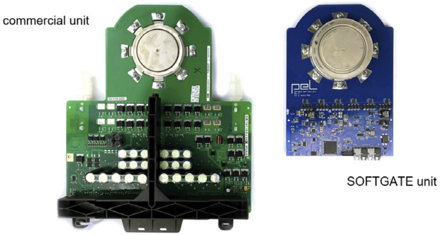


▲ Typical waveforms experienced by IGCT during operation

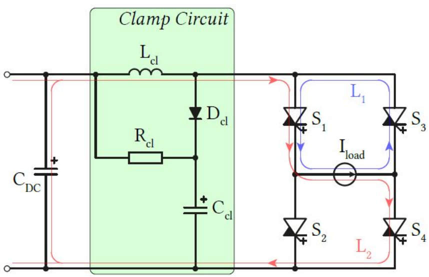
POWER SEMICONDUCTOR: IGCT

Objectives

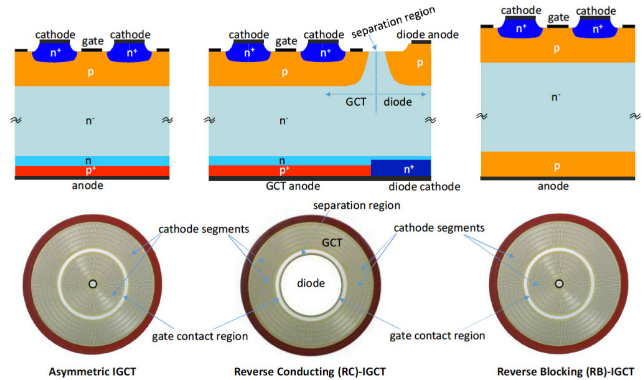
- 5kHz switching frequency
- Benefit from low conduction loss
- Benefit from ZVS
- Remove clamp circuit



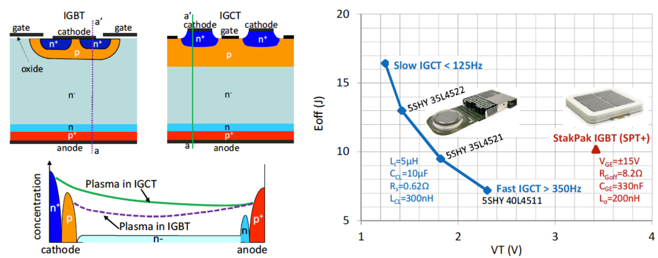
▲ Commercial vs SOFTAGE gate unit [35]



▲ Clamp circuit for hard switching operation



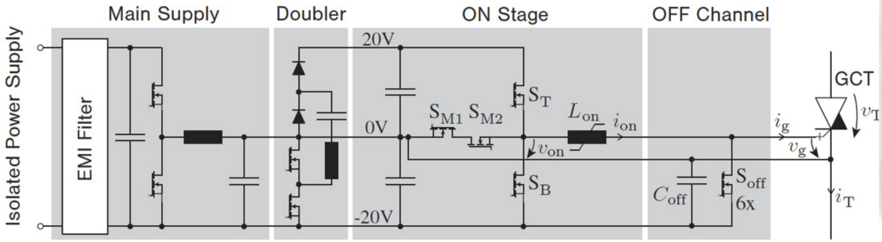
▲ State-of-the-art IGCT device types [36].



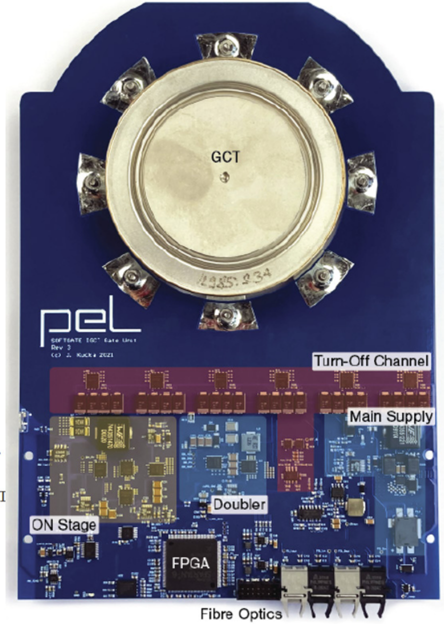
▲ IGCT vs. IGBT. Plasma distribution (conduction); technology curve at 2.8kV, 2kA, 125°C [36].

Multiple functions integrated in a single ON channel:

- Turn-ON function
- Retrigger function
- Backporch function
- Negative-Voltage Backporch functions

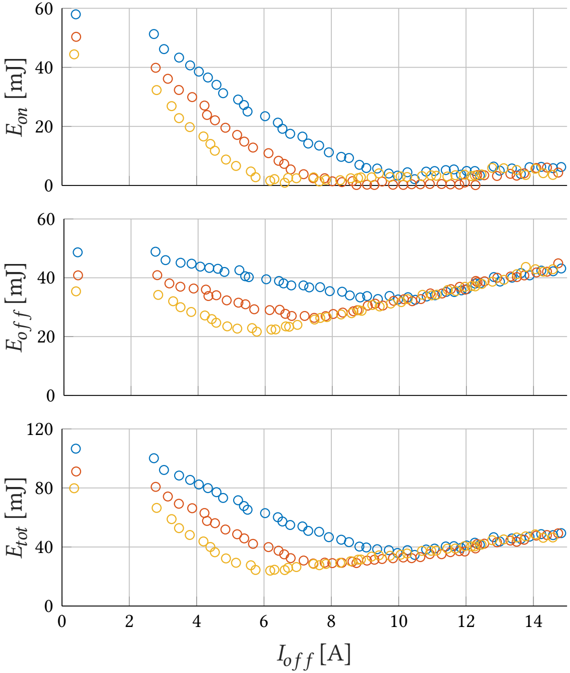


▲ Simplifed SOFTGATE circuitry



▲ Realized SOFTGATE gate unit [37]

IGCT: ZVS VERSUS ZCS?



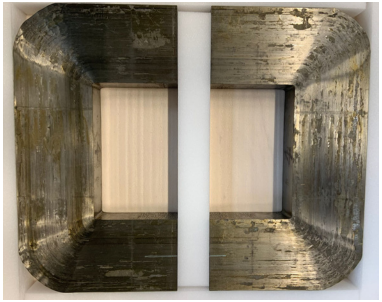
▲ Parametric sweep with different dead-times of o 10 μs, o 12 μs, and o 14 μs, respectively [38]

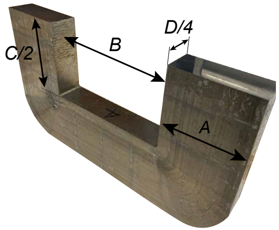
- Dead-time - from 10 μs to 14 μs
- Turn-off current - from 3 A to 15 A

▲ Flexible and reconfigurable IGCT test setup [39]

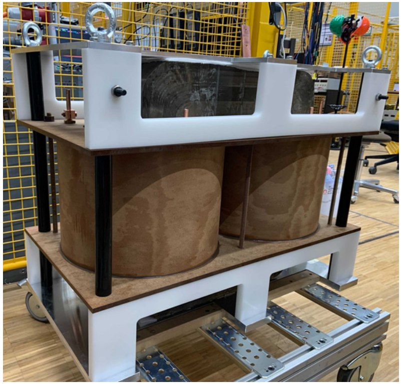
MFT PROTOTYPE

A	B	C	D	M_c
140 mm	256 mm	318 mm	232 mm	≈ 324 kg

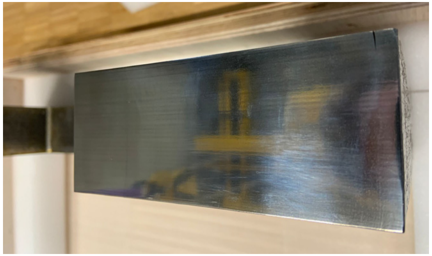


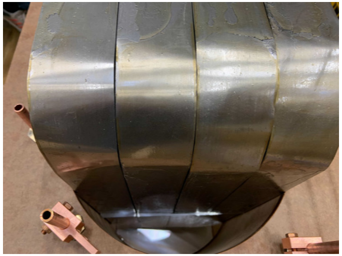


▲ Nanocrystalline C-cut cores - Hitachi Metals [40]



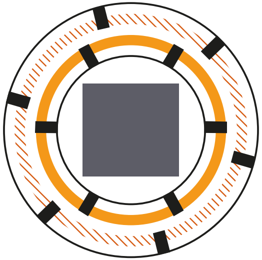
▲ Full-scale prototype of the 2-vessel MFT [41]





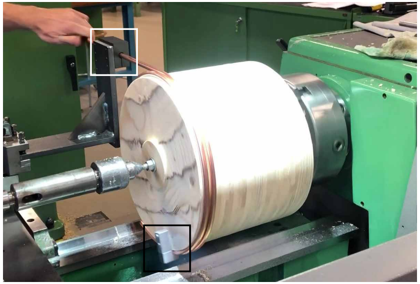
▲ MFT cores during assembly.

Pipe windings assembly:



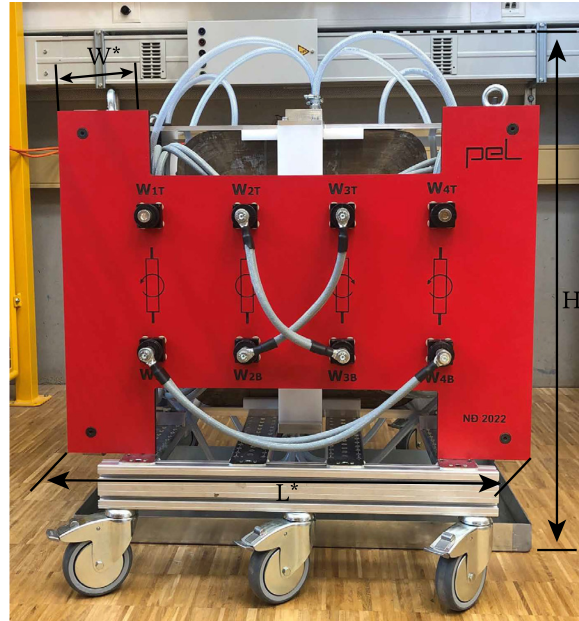
▲ Winding structure with the hollow pipe conductors

- Copper hollow conductors, made by Luvata [42]
- Spacers made of thermoplastic POM material
- Oil vessels from Etronit I and B66, produced by Elektro-Isola [43]
- Midel 7131 [44] insulation fluid used
- Air pockets in each vessel for oil expansion
- Air breathers with silica gel to keep moisture away

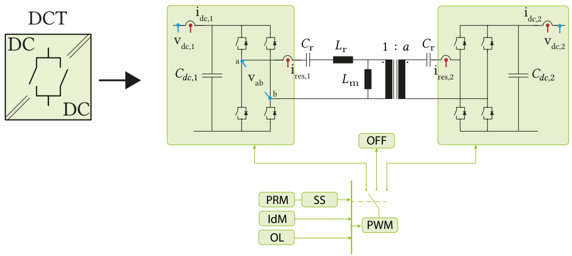


▲ Winding assembly details

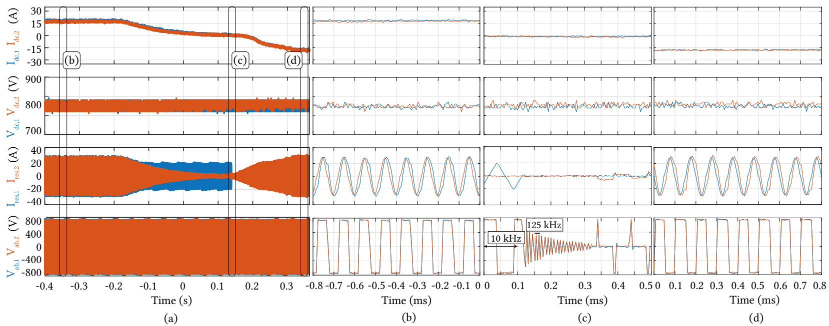
▲ 1 MW prototype of the 2-vessel MFT structure



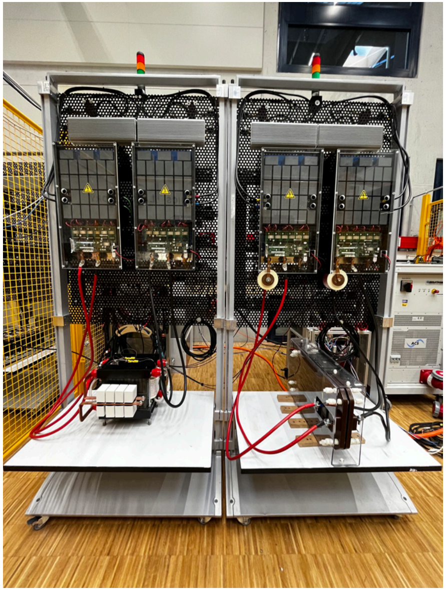
▲ Fully assembled prototype of the 2-vessel MFT



▲ Power Reversal Algorithm with Soft Start, Idling Mode, Overload protection

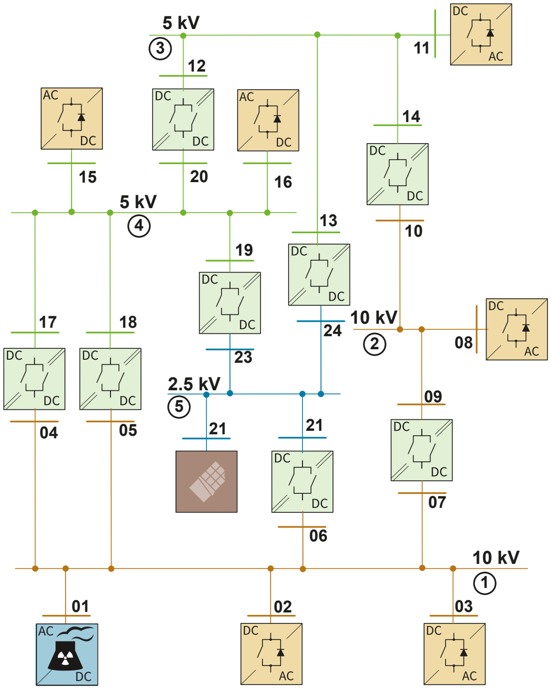


▲ Experimental results during the power reversal

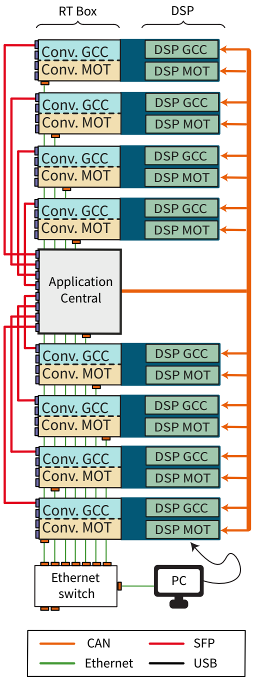


▲ Two low voltage DCTs for experimental validations (PEL's MFTs)

MVDC RT-HIL POWER DISTRIBUTION NETWORK



▲ MVDC PDN deployed on the RT-HIL system



▲ 8 x RT Box 1 + 1 x RT Box 3

▲ MVDC PDN RT HIL system

SUMMARY AND CONCLUSIONS

Why MVDC? How MVDC? and When MVDC?

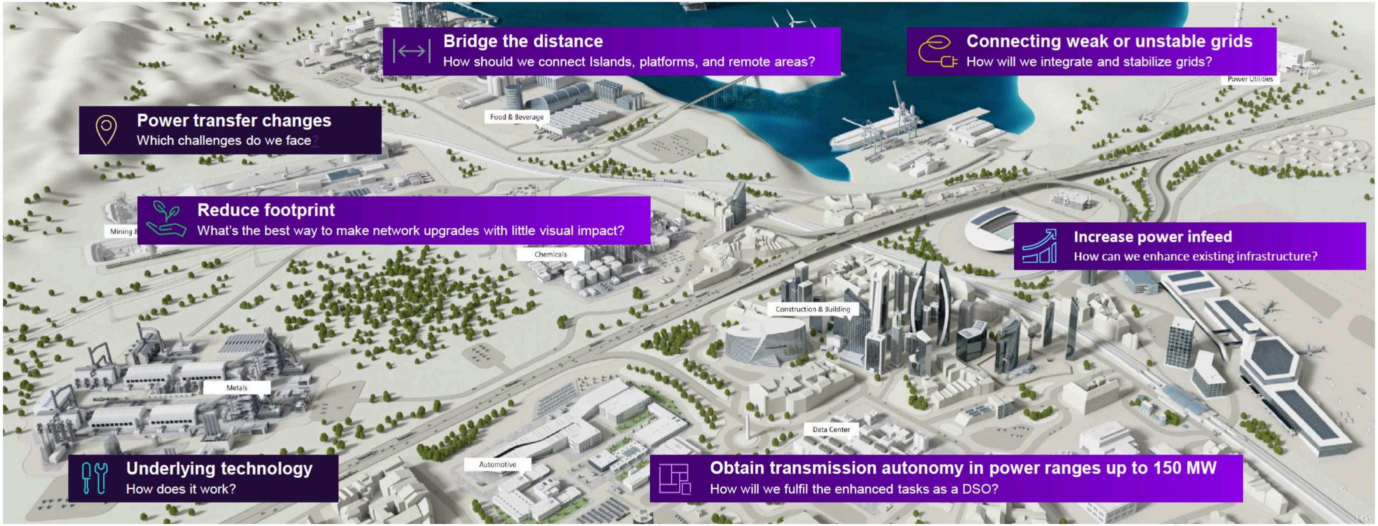
MVDC CHALLENGES

Standards
- We
- Need
- Standards

Power Distribution Networks
- Business case
- Business case
- Business case

Protection
- Standardized Voltages
- DC Breaker
- Protection Coordination

Conversion
- Flexible
- Modular
- Scalable



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Conversion
- Flexible
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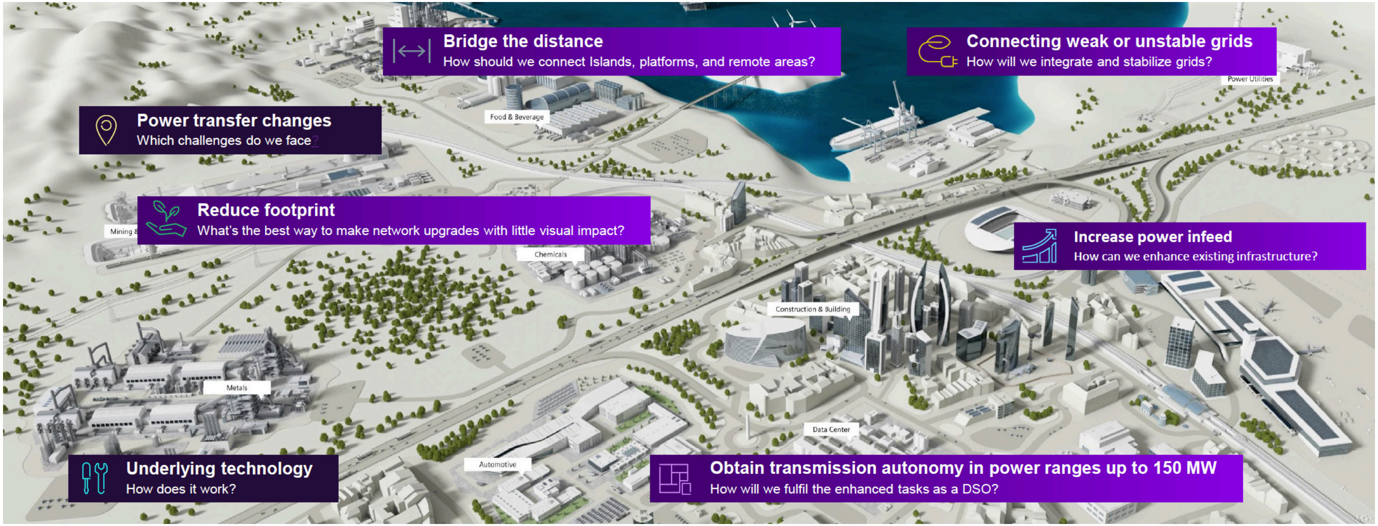
⇒ Many technology gaps need to be bridged. MVDC is great area for the research!



MVDC

ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS

Tutorial pdf can be downloaded from:

- https://www.epfl.ch/labs/pel/publications-2/publications-talks/

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