IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

MEDIUM VOLTAGE POWER ELECTRONICS RESEARCH: CHALLENGES AND OPPORTUNITIES

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Power Electronics Laboratory (PEL)
Switzerland

INTRODUCTION

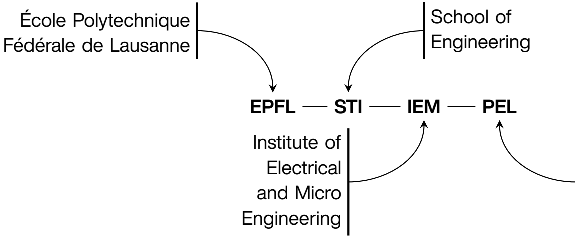
Non technical one...

Experience

2014 – today	École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
2013 – 2014	ABB Medium Voltage Drives, Turgi, Switzerland
2009 – 2013	ABB Corporate Research, Baden-Dättwil, Switzerland
2006 – 2009	Liverpool John Moores University, Liverpool, United Kingdom
2003 – 2006	University of Novi Sad, Novi Sad, Serbia

Education

2008	PhD, Liverpool John Moores University, Liverpool, United Kingdom
2005	M.Sc., University of Novi Sad, Novi Sad, Serbia
2002	Dipl. Ing., University of Novi Sad, Novi Sad, Serbia



- Active since February 2014
- Typically: 10-12 PhDs, 2-4 Post-Docs, 1 Eng, 1 Ass.
- Funding CH: SNSF, SFOE, Innosuisse
- Funding EU: H2020, S2R JU, ERC CoG
- Funding: Industry OEMs
- `www.epfl.ch/labs/pel/`

ECPE Competence Centre

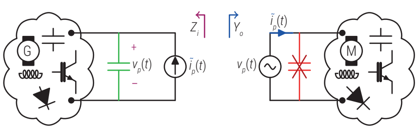
▲ Power Electronics Laboratory

PEL RESEARCH FOCUS

MVDC Technologies and Systems

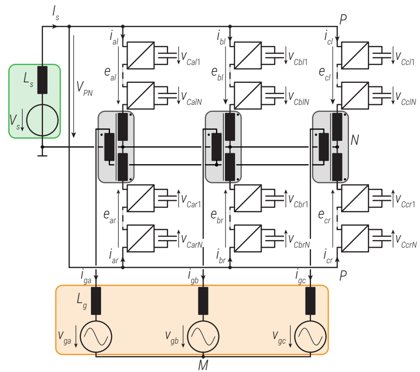
- System Stability
- Protection Coordination
- Power Electronics Converters

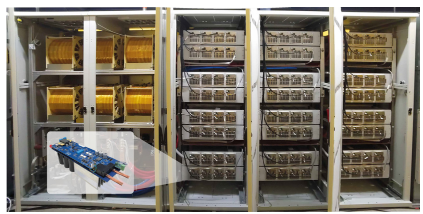
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics Converters

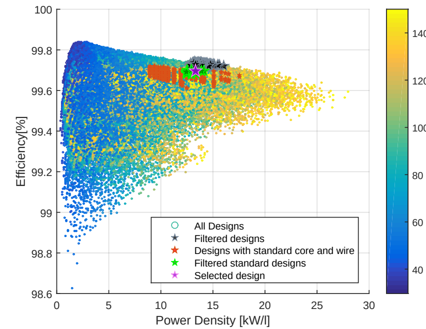
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

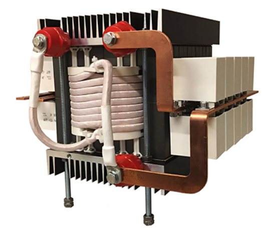




Components

- Semiconductors
- Magnetics
- Modeling, Characterization, Optimization





MEDIUM VOLTAGE APPLICATIONS

...and the role of the power electronics

Traditional MV application

- ≈ 65% of electricity goes into motors
- Efficiency gains with VSD
- Flexibility
- Standardized voltages

Typical ratings

- 1kV to 36kVac
- up to hundreds of MW

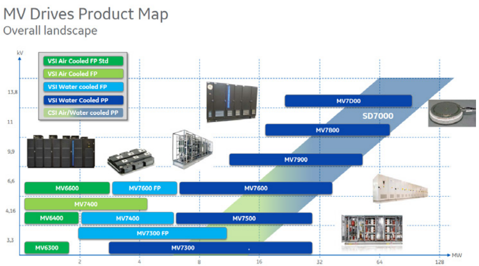
Industry segments

- Cement
- Oil and gas
- Marine and offshore
- Metals
- Mining
- Marine
- Power
- Pulp and paper
- Water and wastewater
- ...

▲ Source: ABB

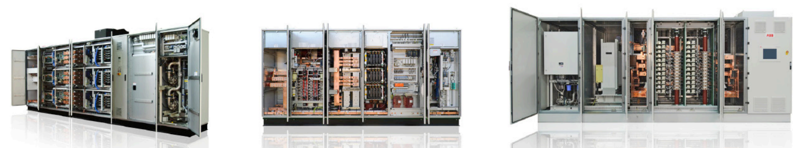
Continuous evolution since 80's:

- **Topologies:** NPC, FC, NPP, ANPC, CHB, MMC
- **Semiconductors:** SCR, GTO, IGCT, IGBT, (SiC?)
- **PWM:** SHE, OPP, SVPWM
- **Control:** Scalar, RFOC, DTC, MPC
- **Type:** Majority is VSI; few CSI



▲ Source: GE MV Drives

	General purpose medium voltage drives		
Type	ACS 1000	ACS 2000	ACS 5000
Output voltage	2.3 / 3.3 / 4.0 / 4.16kV Optional: 6.0 / 6.6kV with step-up transformer	4.0kV - 6.9kV	6.0–6.9kV Optional: 4.16 kV with step-down transformer

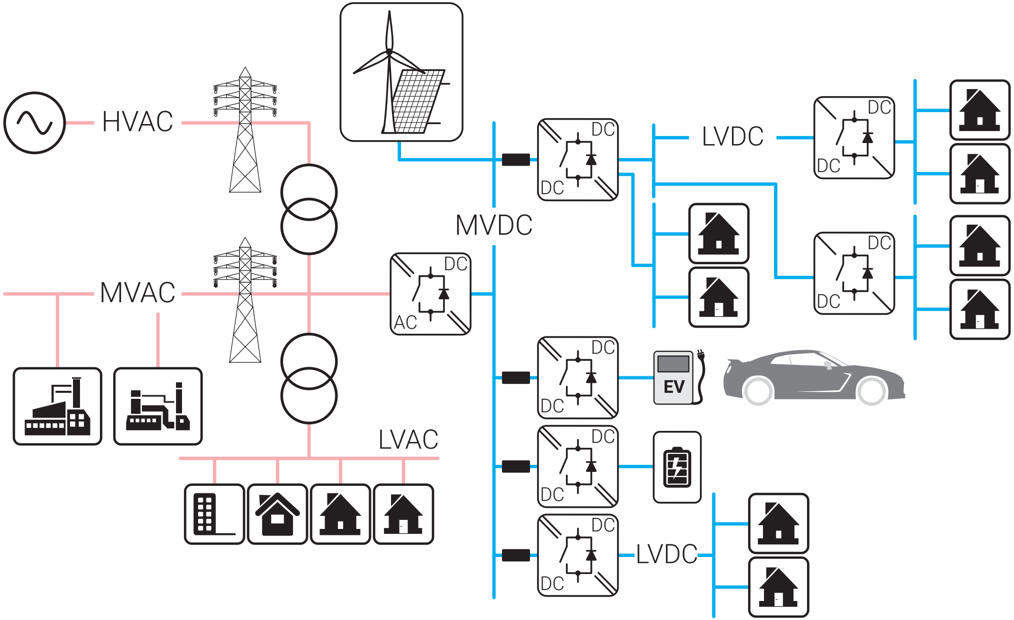


Special purpose medium voltage drives		
ACS 5000	ACS 6000	MEGADRIVE-LCI
6.0–6.9kV Optional: 4.16 kV with step-down transformer	3.0–3.3kV Optional: 2.3kV	2.1–10kV

▲ Source: ABB MV Drives

▲ Source: SIEMENS Sinamics MV Drives

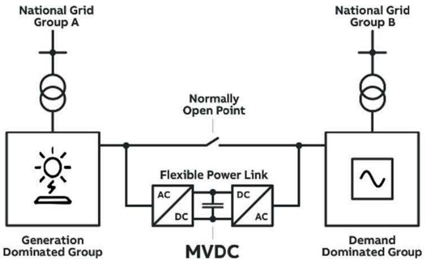
POWER ELECTRONICS DOMINATED POWER SYSTEM



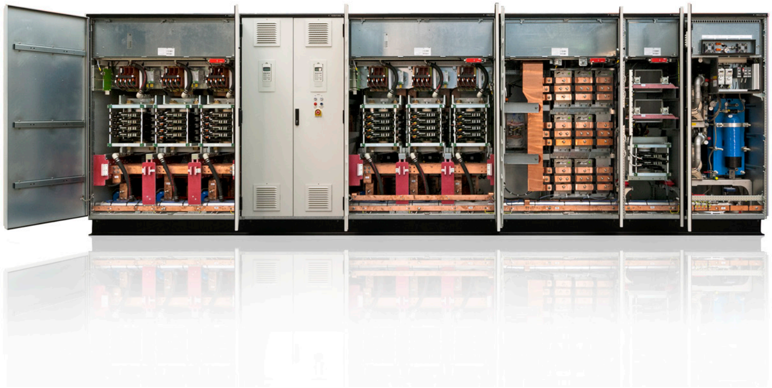
▲ A modern power system with many Inverter Based Resources (IBR) as DC technologies

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) [1]

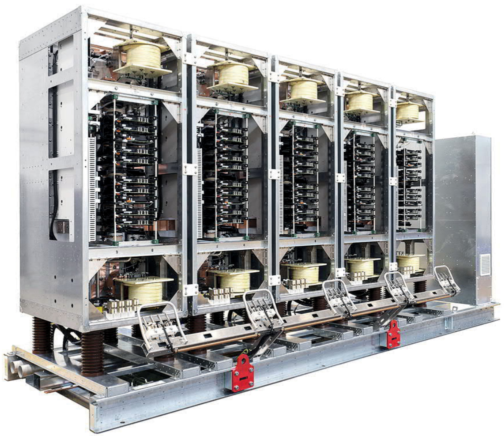


▲ ABB's ACS6000 Medium Voltage drive with 5kV DC link

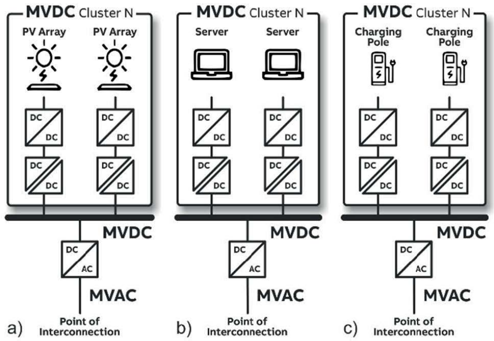
▲ ABB's ACS6000 multi-drive line up - around 33 meters long - modular design done 20 years ago!

MVDC Collection Networks

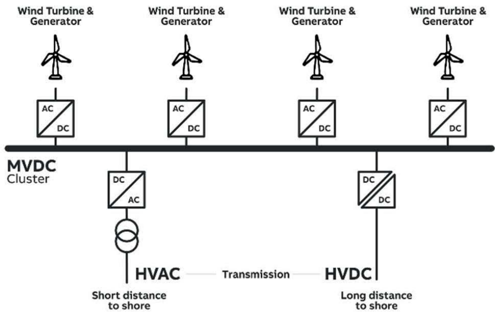
- MVDC collection
- Voltage level - case by case
- Efficiency driven
- Off-shore / On-shore
- AC-DC and DC-DC converters needed



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



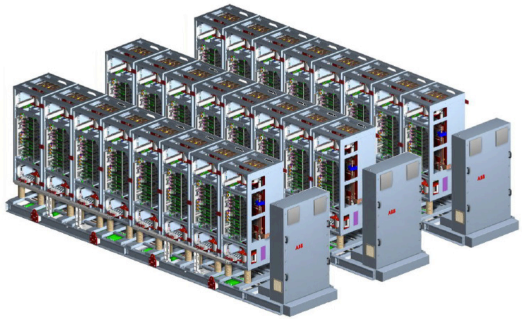
▲ MVDC collection networks for a) PV generation; b) high power **Data Centers** and c) Fast **EV Charging** [1]



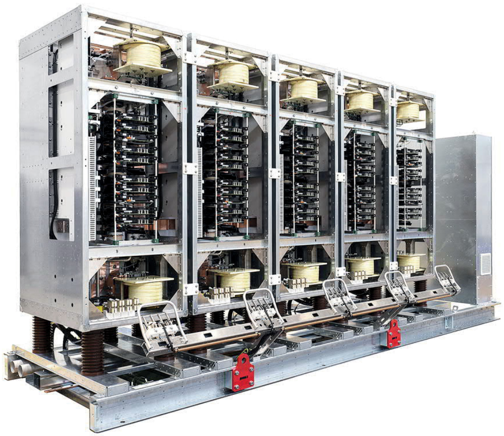
▲ MVDC collection network for wind application [1]

IGCT-based MMC

- Versatile hardware platform
- Half-Bridge/Full-Bridge
- Direct MMC for Hydropower CFSM
- Rail Inter-ties (3-ph to 1-ph)
- STATCOM



▲ HITACHI ENERGY: MV MMC layout: Source: M. Vasiladiotis,"DMMC for CFSM", PELS online workshop



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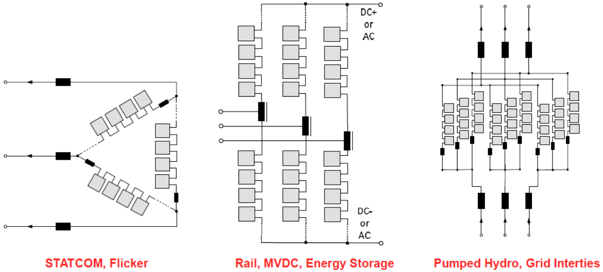


▲ HITACHI ENERGY: MV MMC Applications: Source: M. Vasiladiotis,"DMMC for CFSM", PELS online workshop

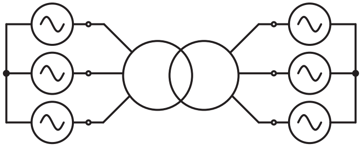
SST is just another converter

- Galvanically Isolated Modular Converter
- Power Electronic Building Blocks (PEBBs)
- Medium frequency transformer (MFT) for isolation
- Can be designed for any conversion
- AC-AC, AC-DC, DC-DC, DC-AC
- Endless topological variations

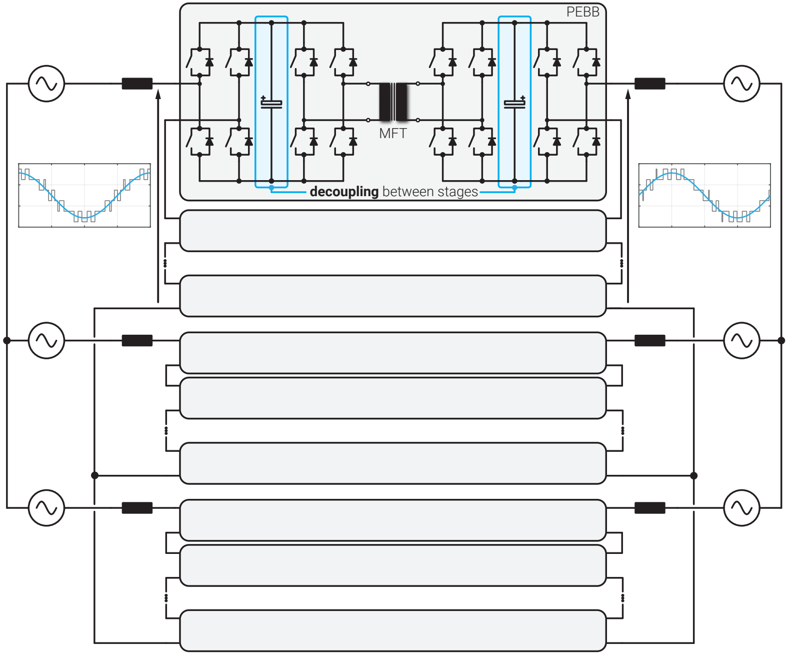
Conventional Transformer vs. SST

	Grid Tx	SST
Controlability	No	Yes
Efficiency	$\eta \geq 99\%$	$P_?$
Q compensation	No	Yes
Fault tolerance	No	Yes
Size	Bulky	Compact
Cost	Low	High

Direct comparison makes not much sense!



▲ Conventional AC grid transformer



▲ Solid-State Transformer interfacing two AC systems [2], [3]

POWER ELECTRONICS TRACTION TRANSFORMER (ABB)

Characteristics

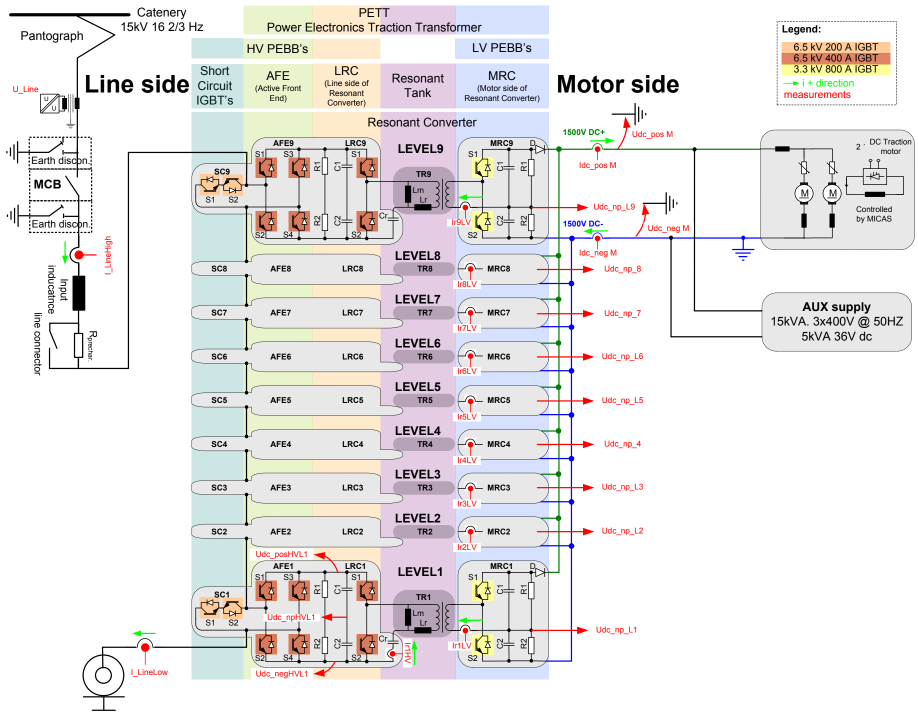
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- Input-Series Output-Parallel
- Double stage conversion

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



▲ ABB PETT scheme [4], [5]

Retrofitted to shunting locomotive

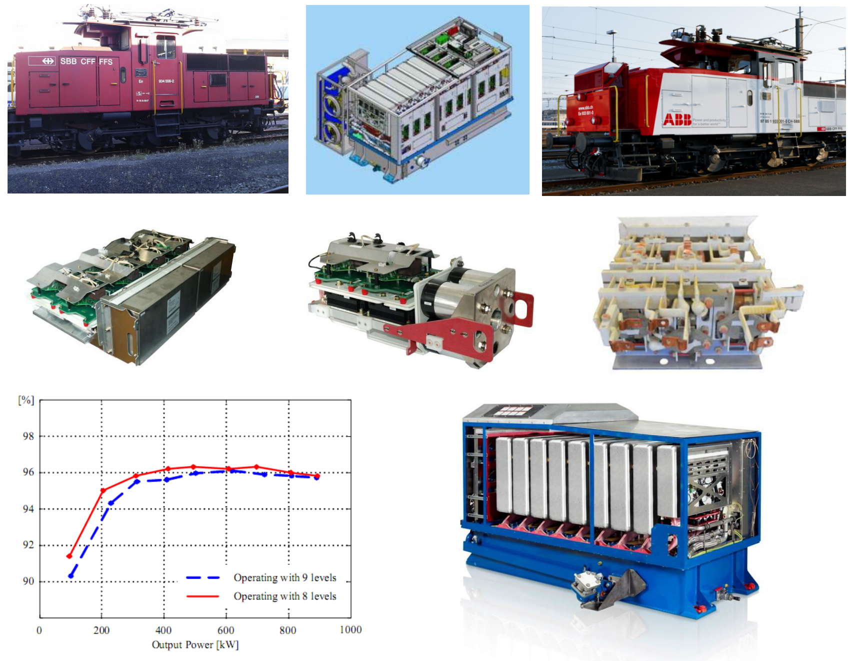
- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronics failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

Technologies

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

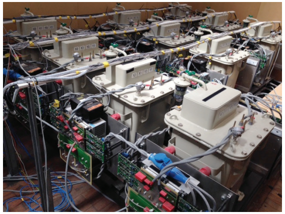
Reality

- No product development
- No early adopters
- No customers
- No business case



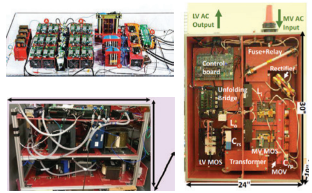
▲ ABB PETT prototype [4], [5]

UNIFLEX-PM



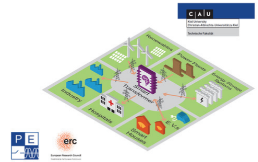
▲ Reduced scale prototype

FREEDM



▲ Reduced scale prototypes [7]

HEART (Kiel)



▲ Reduced scale prototypes

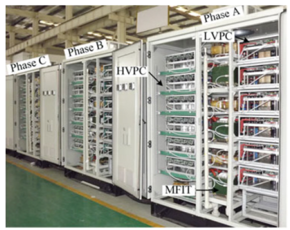
EMPOWER (EPFL)

▲ Full scale prototype

GE

▲ Full scale prototype [6]

HUST



▲ Full scale prototype [8]

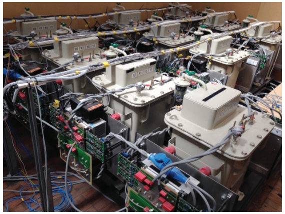
XD Electric Company

▲ Full scale prototype [9]

DELTA

▲ Full scale prototype

UNIFLEX-PM



▲ Reduced scale prototype

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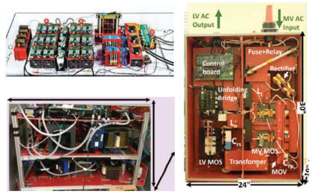

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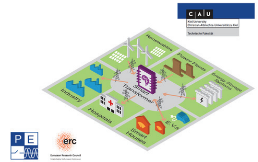

▲ Reduced scale prototypes

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▲ Full scale prototype

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▲ Full scale prototype [6]

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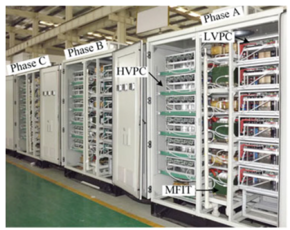


▲ Full scale prototype [8]

XD Electric Company

▲ Full scale prototype [9]

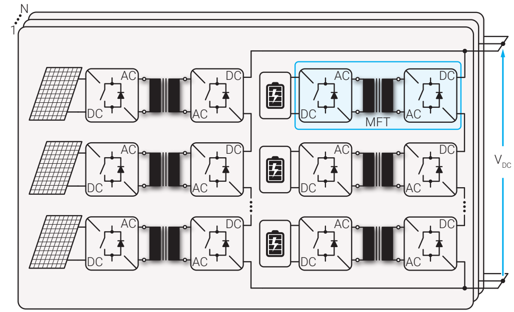
DELTA

▲ Full scale prototype

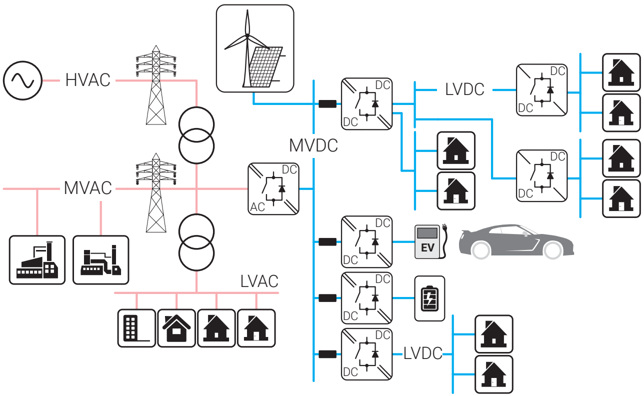
⇒ SST is an attractive research topic and many technology gaps need to be addressed before it becomes the commercial reality!

HIGH POWER DC-DC CONVERTERS

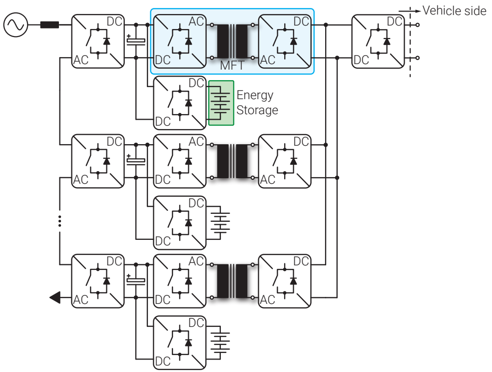
- Inherent building block of most SST topologies
- Interface between different MVDC levels
- Enabling technology for MVDC
- Integration of renewable DC energy sources
- Integration of Fast / Ultra Fast EV charging
- Medium Frequency conversion



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



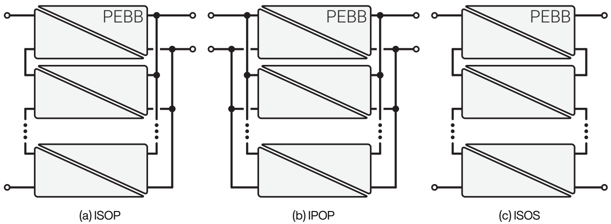
▲ Concept of a modern power system



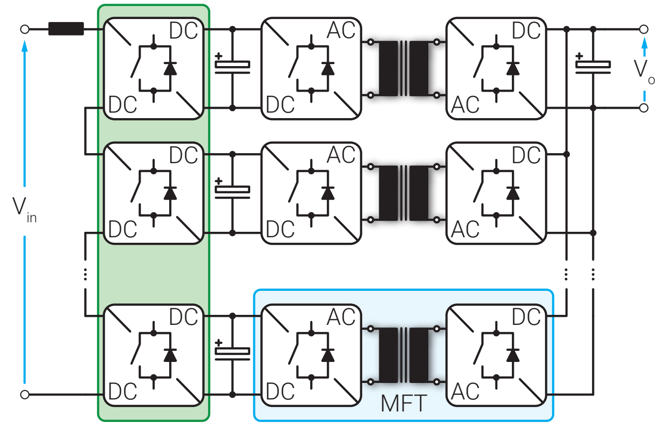
▲ Fast EV charging concept

Fractional Power Processing

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



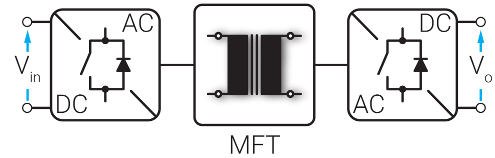
▲ Different and well known structures for modular designs



▲ 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

Fractional Power Processing

- Multiple MFTs
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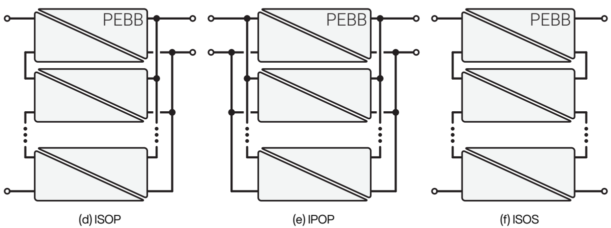
- Various PEBB configurations



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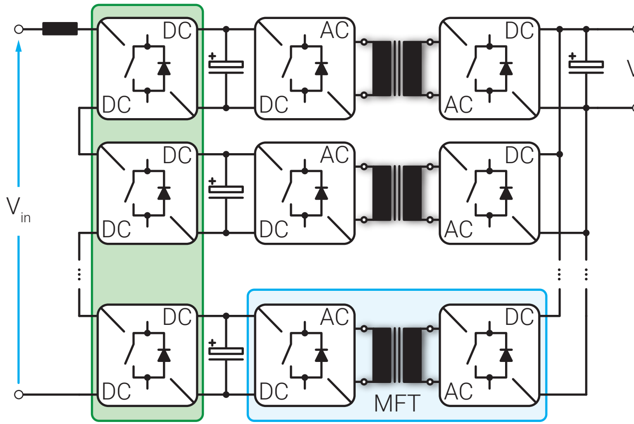

▲ Fractional power processing with ISOP structure

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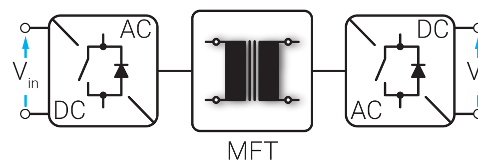


▲ Bulk power processing concept

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

MEDIUM VOLTAGE RESEARCH

...and how to do it at the University

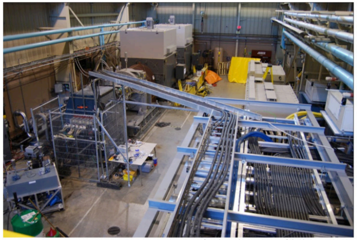
Doable with careful and strategic planning

- Infrastructure - surface and volume
- Protection - of personnel and equipment
- Safety - of personnel
- Training - of personnel
- Patience - of everyone involved
- Funding - a lot of it

▲ PEL Low Voltage and Medium Voltage switchgear

Testing Infrastructure (2)

- Significant Planning and Realization Effort
- Power Supply / Cooling / Control / Simulation (Integrated)

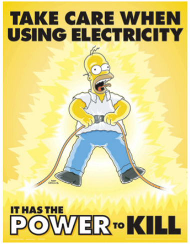


Img.:Center for Advanced Power Systems / Florida State University

- Large Space & Infrastructure Requirement / Considerable Investment (!)

Remark: Education and MV Power Electronics

- PhD Students are Missing Practical Experience / Underestimate the Risk
- High-Power-Density Power Electronics Differs from Conventional (Passive) HV Equipment
- Very Careful Training / Remaining Question of Responsibility



Source: www.safetyposters.com

... ESPECIALLY @ Medium Voltage (!)

- High Costs / Long Manufacturing Time of Test Setups
- Complicated Testing Due to Safety Procedures → Lower # of Publications/Time

▲ Source: PES, ETH

Versatile and Flexible Infrastructure

- AC voltages: up to 3.3kV, 6kV, 9kV, 11kV, 15kV, 20kV
- DC voltages: up to ± 5kV, ± 10kV
- MV electrical machines: IM, SM, DFIM (0.5MW, 6kV)
- PD test setup (100kV, 200mA)
- LVAC and LVDC power distribution
- Distributed and mobile cooling systems

▲ MV Power Electronics Laboratory

▲ MV Power Electronics Laboratory

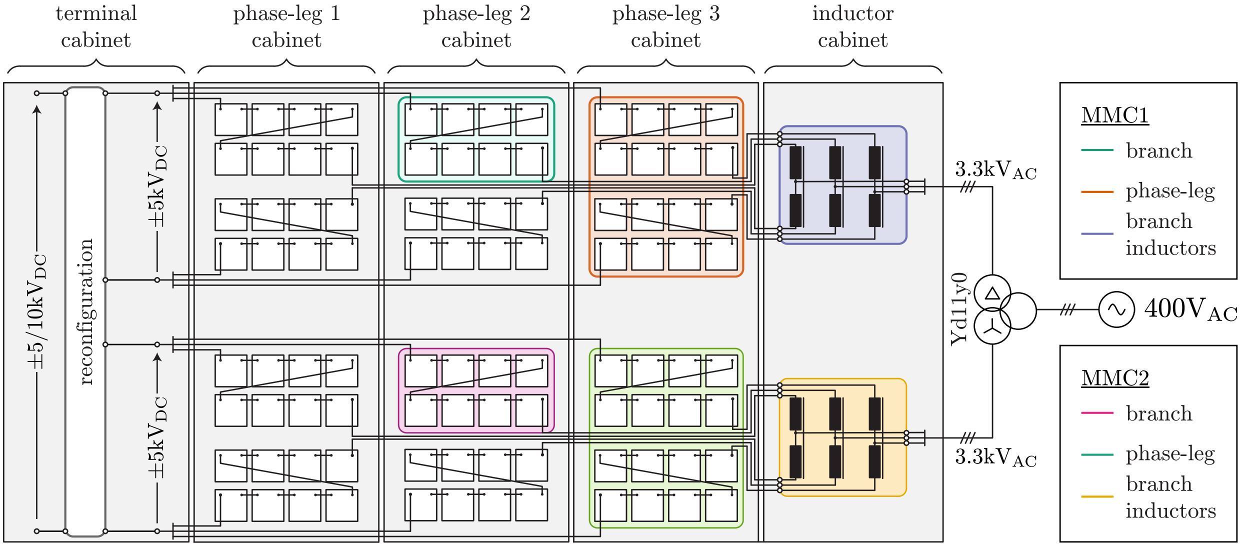
MMC RESEARCH PLATFORM

High power university lab prototype and versatile HIL system

DUAL MMC MVDC SUPPLY

MMC demonstrator ratings are:

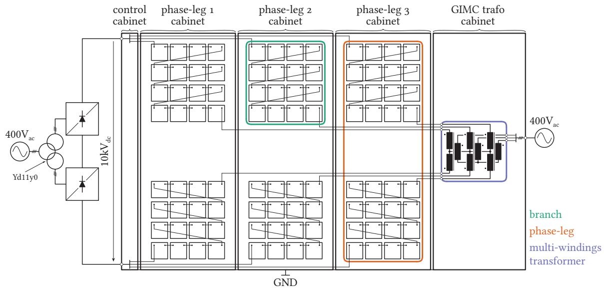
- 500 kVA (2 x 250 kVA)
- $\pm$ 10 $kV_{dc} \longleftrightarrow$ 2 x 3.3 kV_{ac}
- 8 low voltage cells per branch ⇒ 16 cells per MMC phase ⇒ 48 cells in total - per MMC
- Industrial central controller and communication (ABB AC PEC 800)



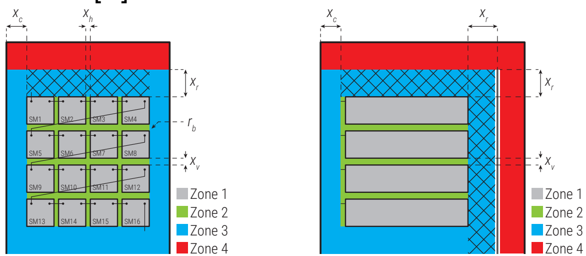
▲ Flexible Dual MMC Power Supply

DIELECTRIC DESIGN - INSULATION COORDINATION (I)

System partitioning



Zones definition [10]



Zone 1 (ins. coord. inside a SM's enclosure) system voltage: 1 kV$_{ac}$

Zone 2 (ins. coord. branch)

- Horizontal system voltage: 1 kV$_{ac}$
- Vertical system voltage: 3.6 kV$_{ac}$

Zone 3 (ins. coord. branch - cabinet (at GND)) system voltage: 6.6 kV$_{ac}$

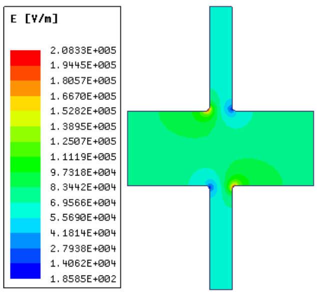
Zone 4 (ins. coord. for LV circuits) system voltage: 0.4 kV$_{ac}$

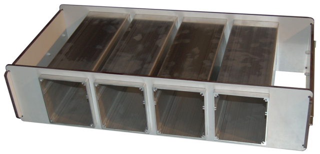
Standards

- UL840 for cell PCB (< 1 kV)
- IEC61800-5-1 (AC motor drives)
  - Pollution degree 2: "Normally, only non-conductive pollution occurs. Occasionally, however, a temporary conductivity caused by condensation is to be expected, when the PDS is out of operation."
  - Overvoltage category II: "Equipment not permanently connected to the fixed installation. Examples are appliances, portable tools and other plug-connected equipment."

Zone 2

- Box at dc- cell's potential (floating)
- Box corner radius: 3 mm
- MKHP (high CTI material) drawer holding 4 cells



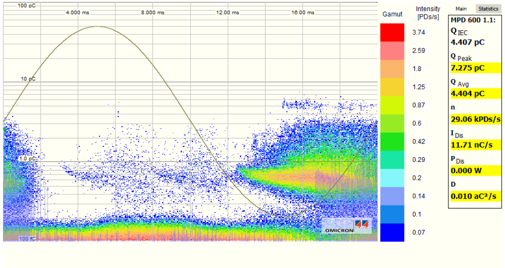


▲ E-field FEM simulations for drawer design

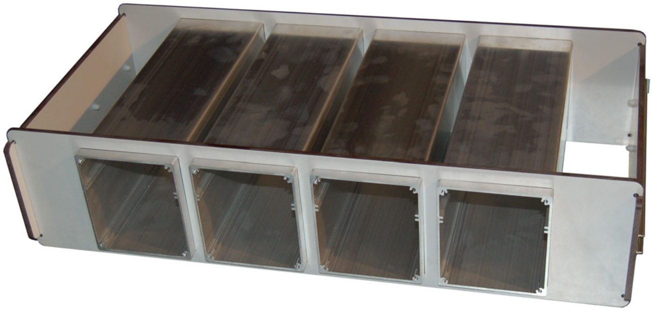
DIELECTRIC DESIGN - INSULATION COORDINATION (II)

- √ MV MMC converter laboratory prototype layout compliant with:
  - UL840 (for cell)
  - IEC 61800-5-1
- √ Complete AC dielectric withstand tests on real prototype [10]

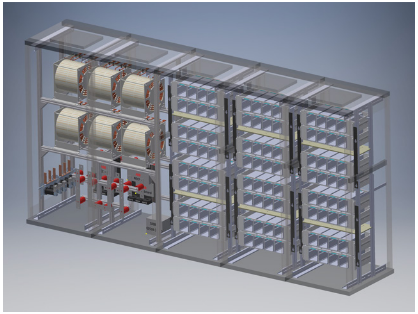
▲ Cabinet with 32 cells in Faraday cage during insulation coordination testing



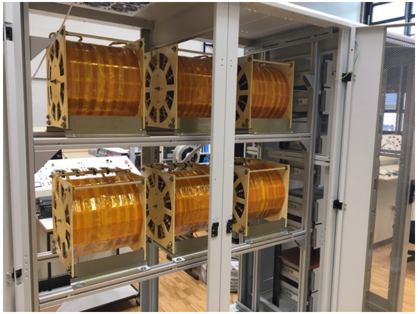
▲ AC dielectric withstand test result



▲ Drawer holding 4 cell (MKHP material)

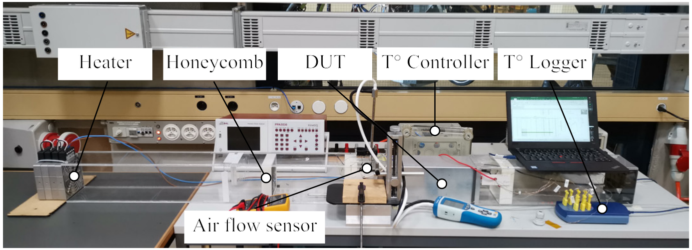


▲ MMC CAD development



▲ MMC coupled air-core branch inductors

▲ MMC - Actual mechanical assembly



▲ MMC Submodule thermal heat-run test setup [11]

MMC SUB-MODULE

Low voltage based sub-module including cell controller

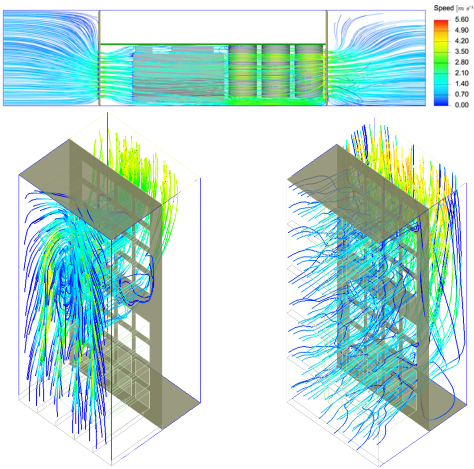
SUB-MODULE OPTIMIZATION

Submodule

- 1.2 kV / 75 A full-bridge IGBT module
- $C_{cell} = 2.25\,\text{mF}$

Thermal design [12]

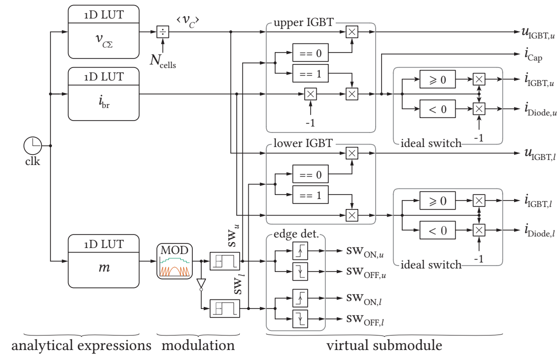
- Cell level: detailed FEM
- Cabinet level: simplified FEM

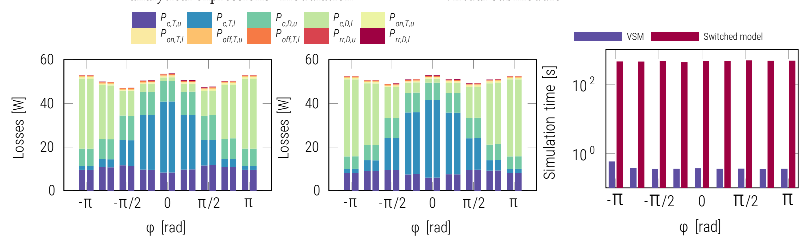


▲ CFD simulations

Semiconductor losses

- Virtual Submodule concept has been utilized [13]
- Closed-loop waveforms are approached by analytical waveforms





▲ PS-PWM, DC circ

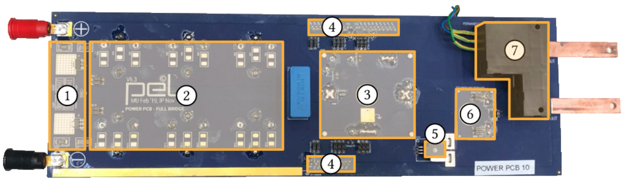
▲ PS-PWM, DC+2nd circ

▲ Time benchmark

SUB-MODULE

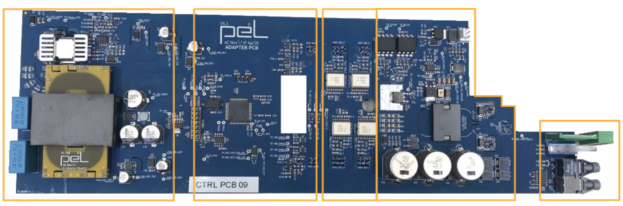
Key Features

- Low voltage power components
- Semikron full-bridge IGBT module 1.2 kV/75 A
- Bank of electrolytic capacitors C_{sm} = 2.25 mF
- Protection devices: Bypass thyristor, Relay and OVD
- Two interconnected PCBs: **Power PCB** and **Control PCB**
- Metalic enclosure



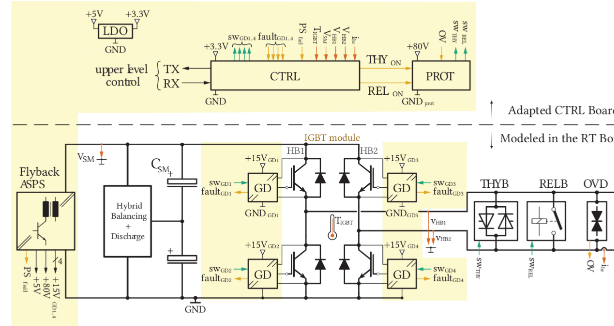
1 - Balancing Circuitry
2 - SM Capacitors
3 - IGBT Module
4 - Voltage Dividers
5 - Current Sensor
6 - Thyristor Module
7 - Bypass Relay

▲ Overview of the Power PCB

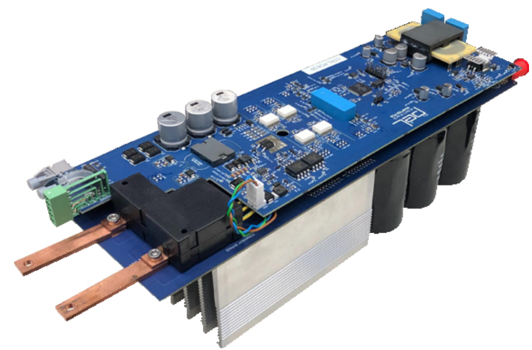


Flyback-based ASPS with planar transformer | DSP-based SM controller | GD1..4 | Protection with pulse trafo | POF

▲ Overview of the Control PCB



▲ MMC Sub-module Structure: Yellow parts - Control PCB



▲ Developed MMC FB sub-module based on the 1.2kV IGBTs

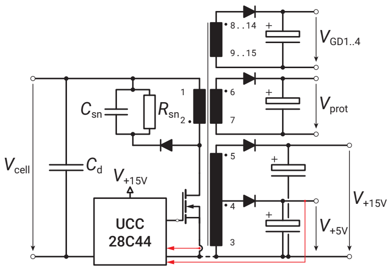
AUXILIARY SUB-MODULE POWER SUPPLY (I)

Possible concepts

- Externally supplied
  - Single wire loop
  - Siebel, GVA
  - Inductive Power Transfer
- Internally supplied
  - DC-DC step down of some sort
  - Flyback

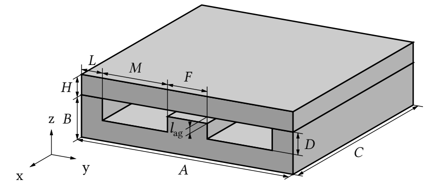
Choice

- Flyback with 6 isolated secondaries



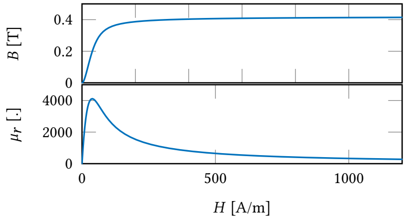
Planar design [14]

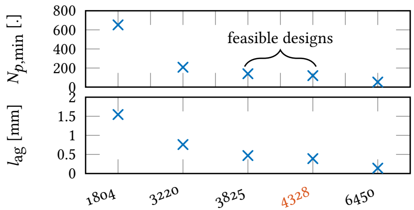
- PCB windings (isolation requirements!)
- Planar ferrite cores with custom gapping (COSMO ferrites)



Matlab design tool

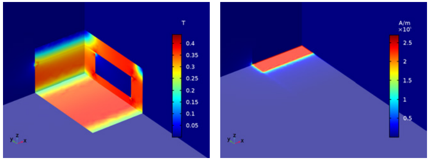
- Account for flux fringing
- BH curve for CF297
- Jiles-Atherton parametrization

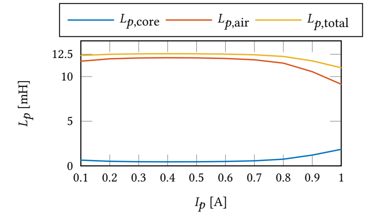




FEM

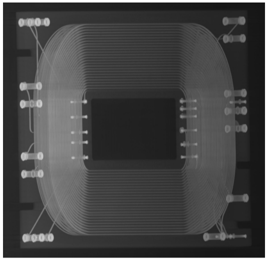
- Validate Matlab design
- 3D model for accurate leakage flux

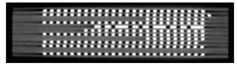




Transformer assembly

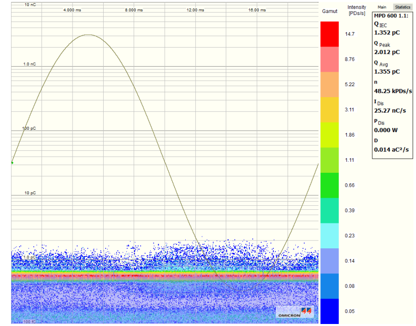
- 14 copper layers PCB
- Custom gapped ferrite E+I core



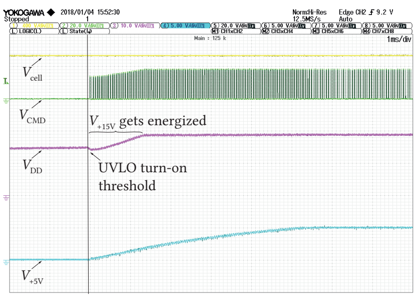


AC dielectric withstand test

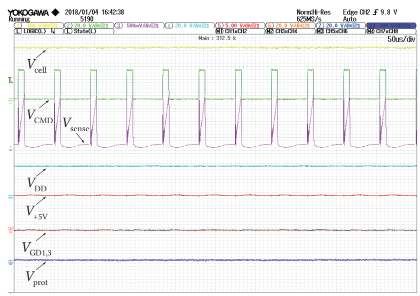
- Way below threshold level of 10pC



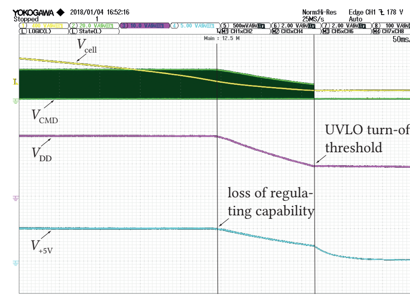
Tests



▲ Start-up



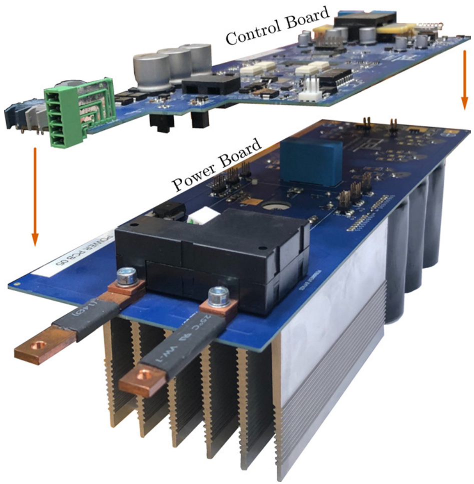
▲ Steady-state operation



▲ Shut-down sequence

MMC SUB-MODULE TESTING

How to validate hardware and software?



▲ In-house built MMC submodule

▲ Production of the MMC cells

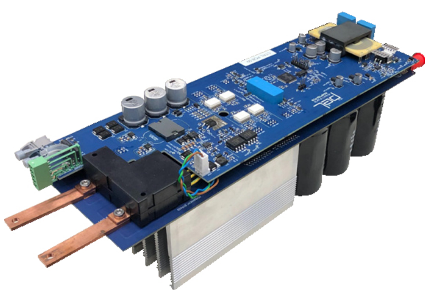
⇒ **120 MMC Submodules are produced in total**

Each and every unit must be thoroughly tested!!!

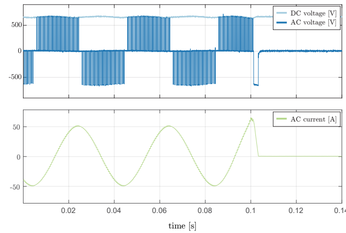
FUNCTIONAL SUBMODULE TESTS

Extensive testing of every sub-module

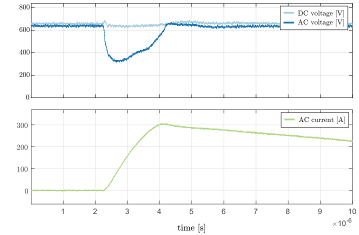
- Power tests
- Thermal heat-runs
- Over current tests
- Loss of power supply
- DC link over voltage
- Terminal over voltage
- Short-circuit tests
- ...



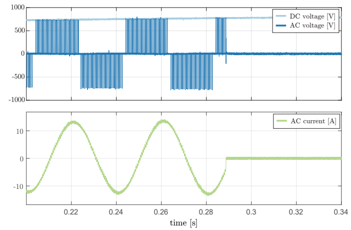
▲ Developed MMC FB sub-module



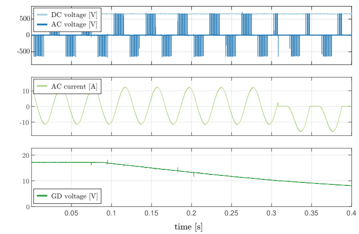
▲ MMC SM over current test



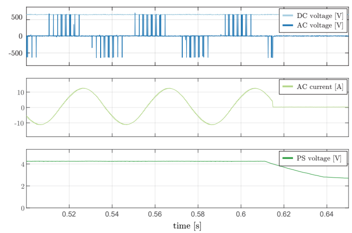
▲ Short circuit test (Desat detection)



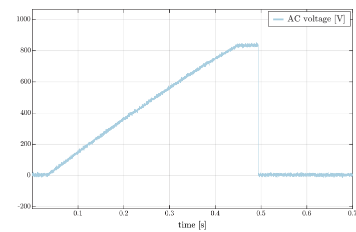
▲ MMC SM over voltage test



▲ Gate Driver failure



▲ Power supply under voltage detection

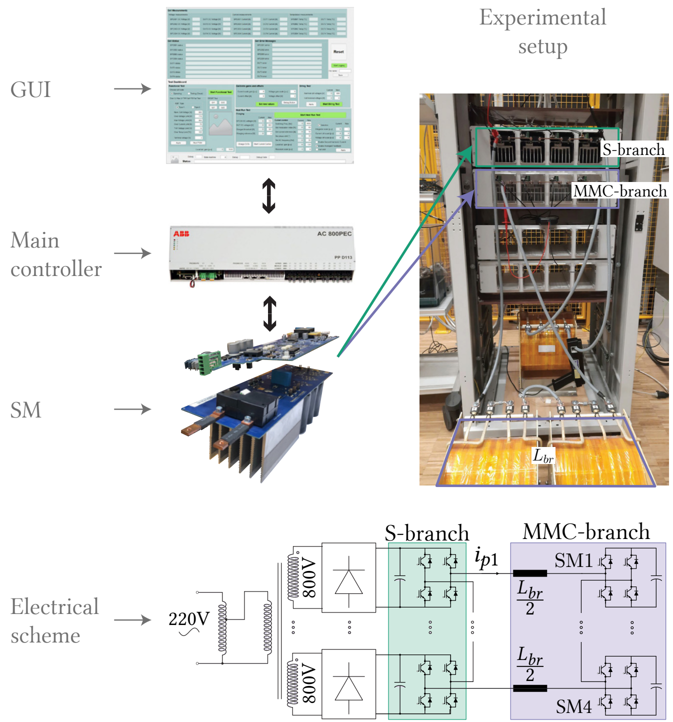


▲ AC terminals over voltage detection

Heat Run Test platform

- Custom made GUI
- Monitoring and setting main variables/parameters
- Logging function
- Simulink-based programming
- FOL communication to each SM

▲ MMC mini-RT-HIL



▲ MMC testing platform detail

Single MMC ratings:

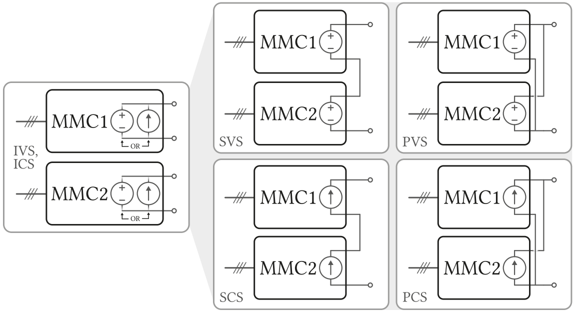
- 3.3kVac
- ±5kV
- 250kW

Single MMC as:

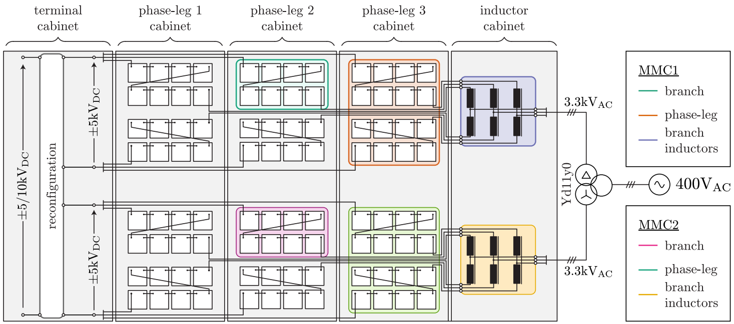
- Voltage source
- Source source

Two MMCs in:

- Series connection
- Parallel connection



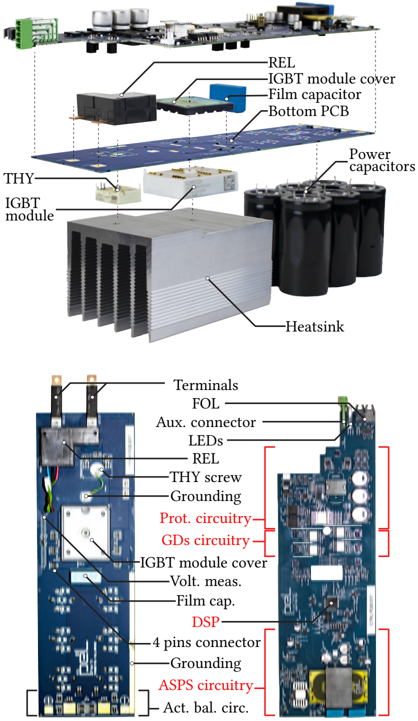
▲ Possible configurations with two MMCs



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

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

MEDIUM VOLTAGE POWER HARDWARE DESIGN



▲ PEL SM - exploded view [15]

Many design considerations

- Electrical
- Thermal
- Dielectric
- Mechanical
- Integration
- Manufacturing
- Testing
- Control
- ...

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

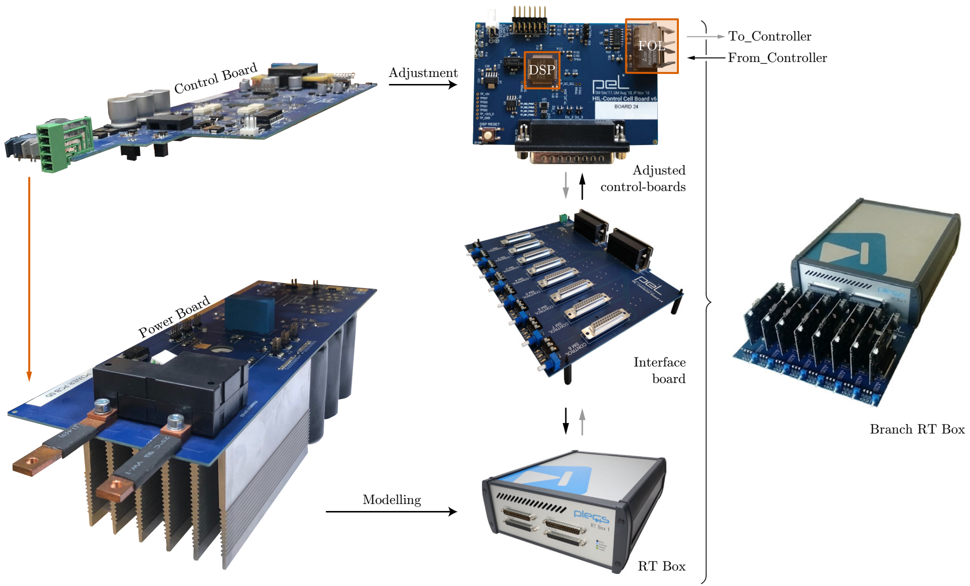
MMC DIGITAL TWIN

RT-Box based distributed HIL system

System summary [16], [17], [18], [19]

- 6 RT-Boxes - one per Branch of the MMC
- 1 RT-Box - Application (AC and DC side)
- ACS 800 PEC - ABB Industrial controller
- ABB other peripheral control boards
- Integrated into IT cabinet

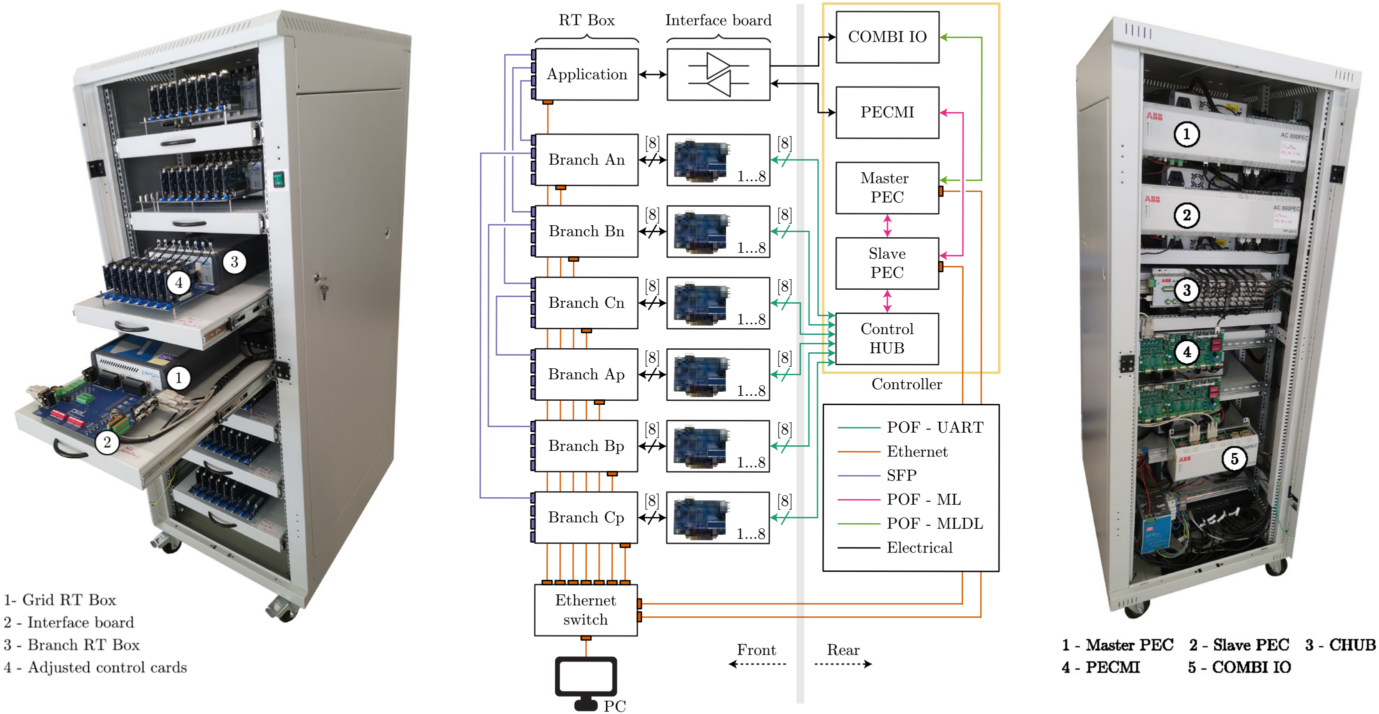
▲ Application (Grid) RT Box



▲ Transformation of MMC cell into digital twin equivalent system

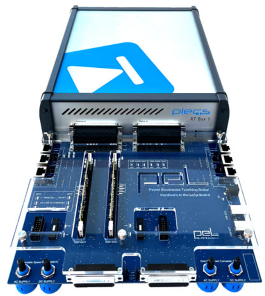
⇒ Significant effort and customization is needed to establish the RT-HIL system!

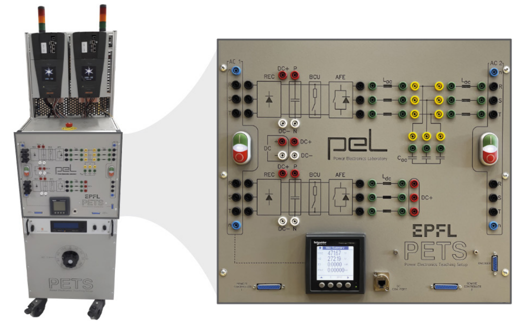
RT-HIL SYSTEM



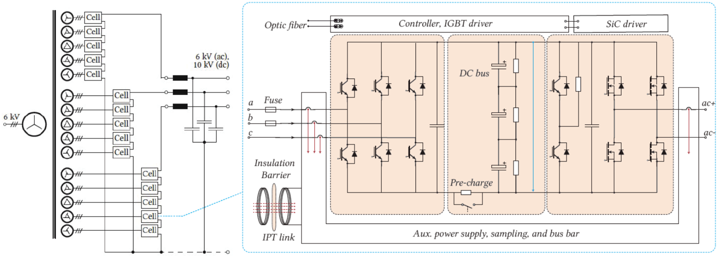
▲ Digital Twin - Realized RT-HIL system for control verification purpose: (left) front view; (middle) wiring scheme; (right) back view.

RT-HIL TOOLS





▲ Power Electronics Teaching Setup: RT-HIL system and the actual power hardware



▲ Analogue simulator: LV PETT vs. MV PETT

▲ Grid emulator: RT-HIL system and power HW under development (Semikron-Danfoss IGBTs, WOLFSPEED SiC MOSFETs)

⇒ RT-HIL tools are great asset to de-risk development and validate control software!

DIRECT CURRENT TRANSFORMER

EMPOWER-in the MVDC power distribution networks

EMPOWER - AN EUROPEAN RESEARCH COUNCIL CONSOLIDATOR GRANT

MVDC ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS

▲ EMPOWER-ing the future energy systems

MVDC Grids

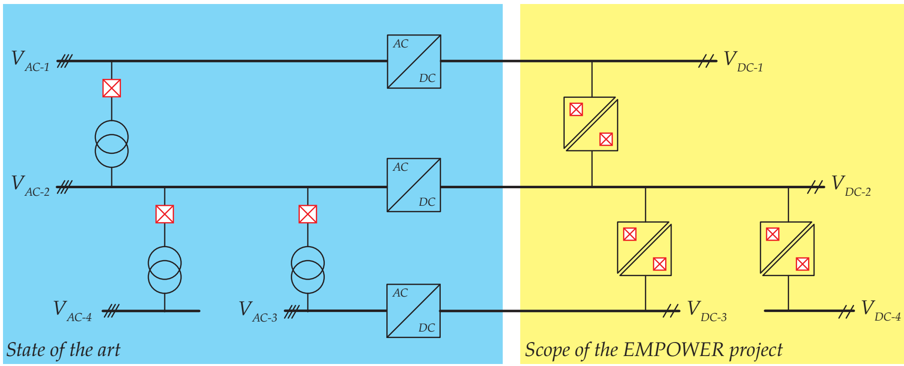
- DC Transformer
- Flexibility
- Stability

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

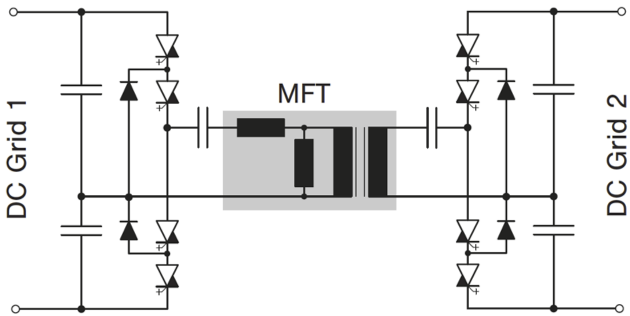
⇒ Can we make a simple DC Transfomer behaving as close as possible to an equivalent AC transformer?

DIRECT CURRENT TRANSFORMER

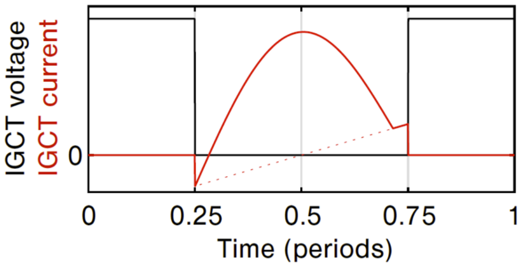
Key details

- 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

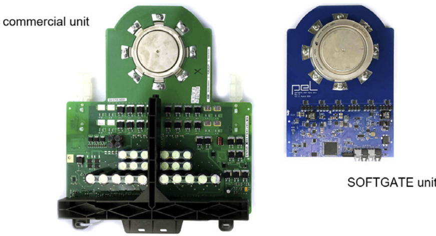


▲ Typical waveforms experienced by IGCT during operation

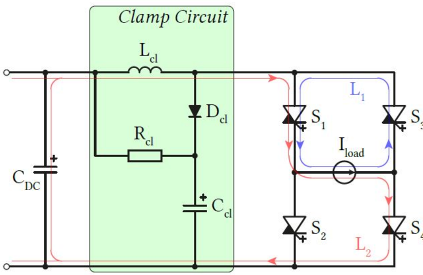
POWER SEMICONDUCTOR: IGCT

Objectives

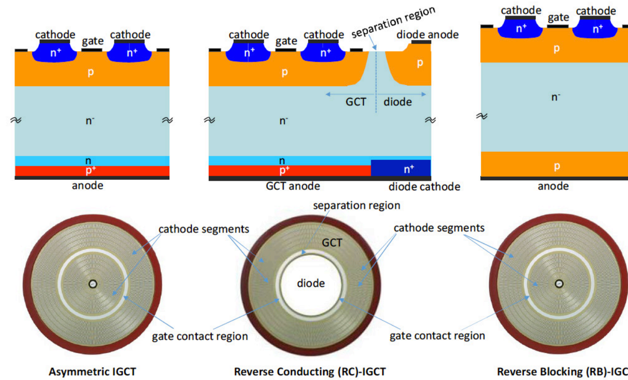
- 5kHz switching frequency
- Benefit from low conduction loss
- Benefit from ZVS
- Remove clamp circuit



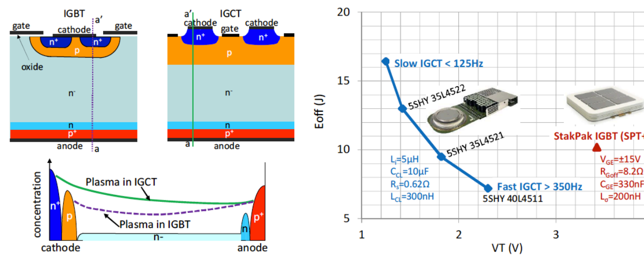
▲ Commercial vs SOFTAGE gate unit [20]



▲ Clamp circuit for hard switching operation



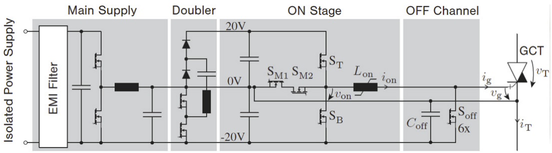
▲ State-of-the-art IGCT device types [21].



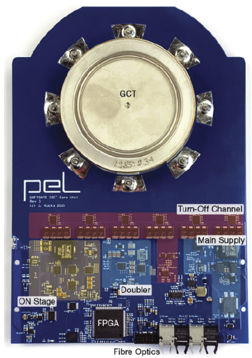
▲ IGCT vs. IGBT. Plasma distribution (conduction); technology curve at 2.8kV, 2kA, 125°C [21].

SOFTGATE IGCT gate unit

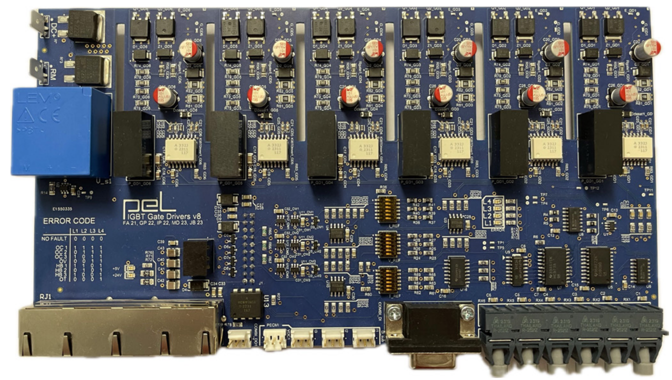
- Turn-ON function
- Retrigger function
- Backporch function
- Negative-Voltage Backporch functions



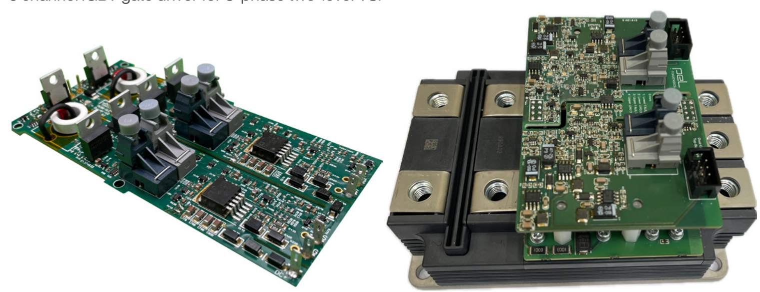
▲ Simplifed SOFTGATE circuitry



▲ Realized SOFTGATE gate unit [22]

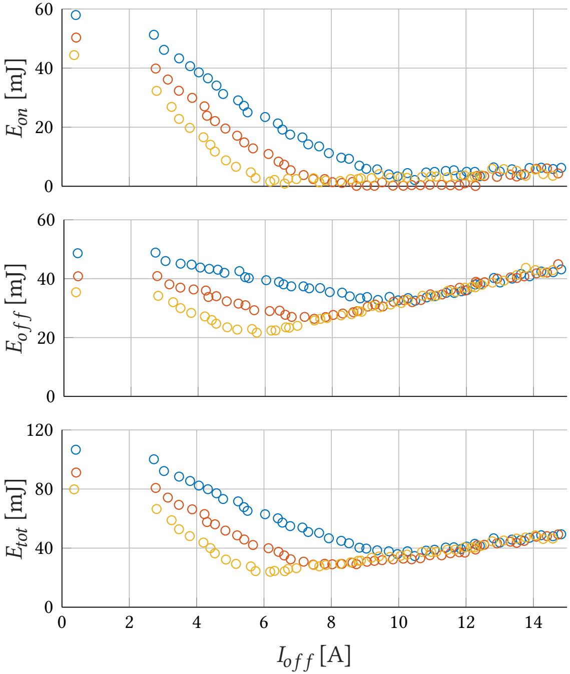


▲ 6 channel IGBT gate driver for 3-phase two-level VSI



▲ SiC MOSFET dual gate drivers: 1.7kV class [23], and 3.3kV class [24]

IGCT: ZVS VERSUS ZCS?



▲ Parametric sweep with different dead-times of o 10 µs, o 12 µs, and o 14 µs, respectively [25]

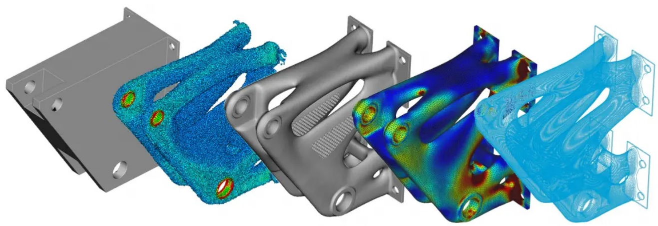
- Dead-time - from 10 µs to 14 µs
- Turn-off current - from 3 A to 15 A

▲ Flexible and reconfigurable IGCT test setup [26]

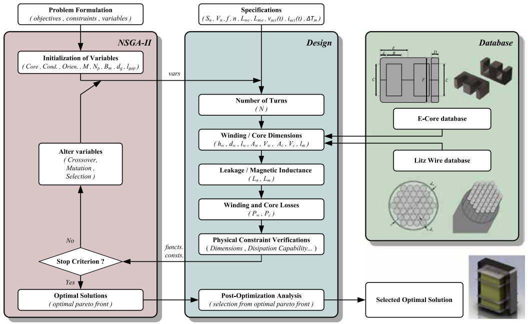
DESIGN OPTIMIZATION

- Multi-objective optimization problem
- Multiple competing objectives
- Meeting converter parameters
- Respecting constraints
- Manufacturability
- Artificial or Natural Intelligence?

▼ Source: (https://formlabs.com/ch/)



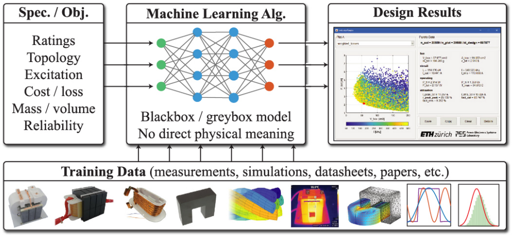
Genetic Algorithm



▲ Design flowchart using NSGA-II algorithm [27]

Neural Networks

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



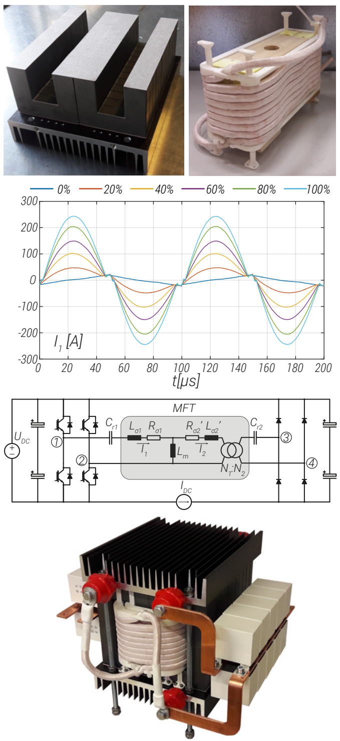
▲ Inductor design with the help of ANN [28]

Brute Force

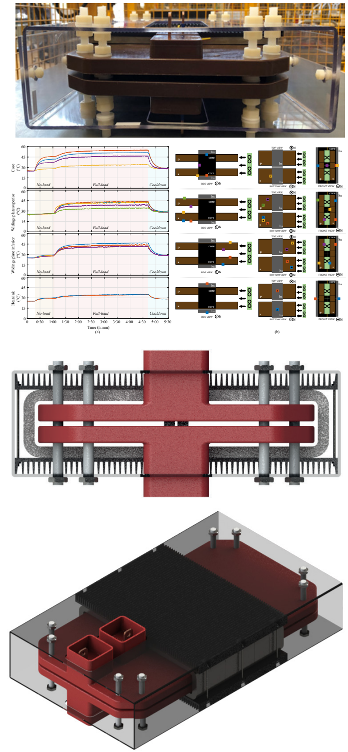
- Exhaustive search concept
- All possible combinations
- Computationally intensive
- Easy to implement

▲ 10'000 combinations

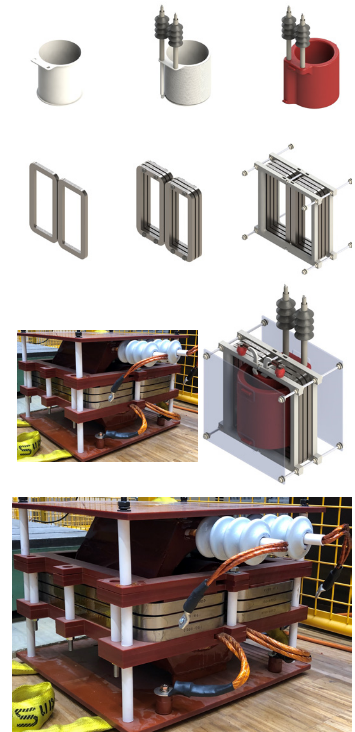
MEDIUM FREQUENCY TRANSFORMERS



▲ Core, 100kW, 10kHz, Ferrite MFT [29], [30], [31]

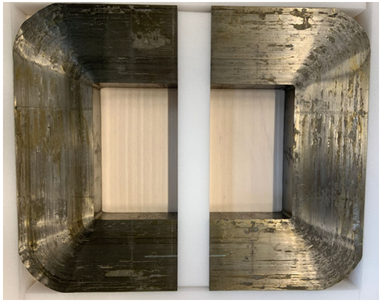


▲ Planar, 100kW, 10kHz, Nanocrystalline MFT

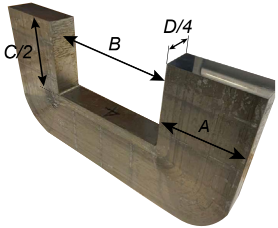


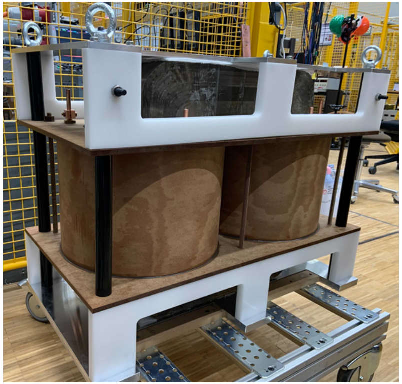
▲ Core, 300kW, 20kHz, Nanocrystalline MFT

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

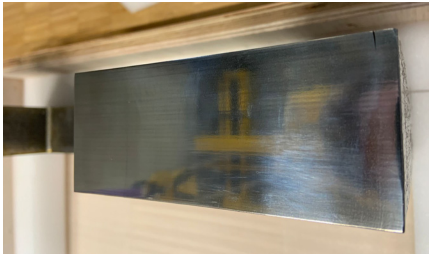


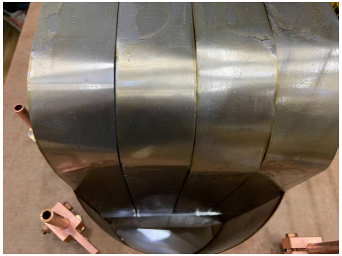
▲ Nanocrystalline C-cut cores - Hitachi Metals [32]





▲ Full-scale prototype of the 2-vessel MFT [33]

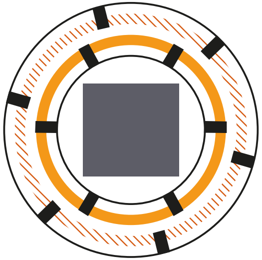




▲ MFT cores during assembly.

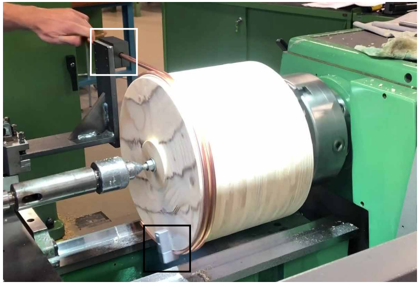
1MW MFT PROTOTYPE

Pipe windings assembly:



▲ Winding structure with the hollow pipe conductors

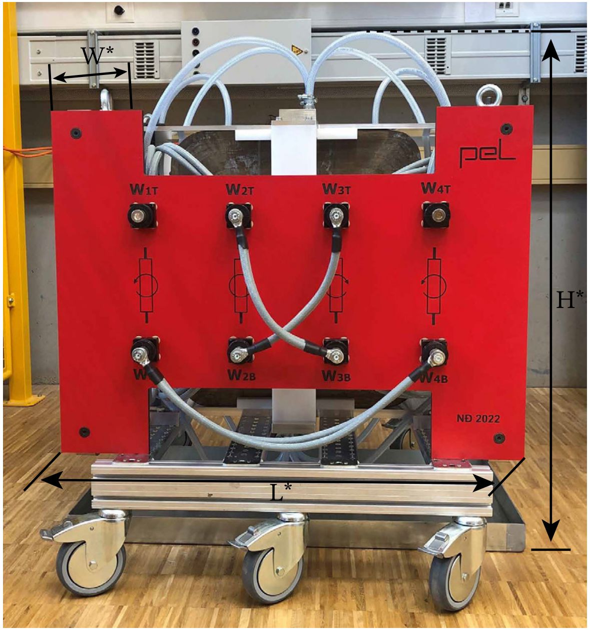
- Copper hollow conductors, made by Luvata [34]
- Spacers made of thermoplastic POM material
- Oil vessels from Etronit I and B66, produced by Elektro-Isola [35]
- Midel 7131 [36] insulation fluid used
- Air pockets in each vessel for oil expansion
- Air breathers with silica gel to keep moisture away



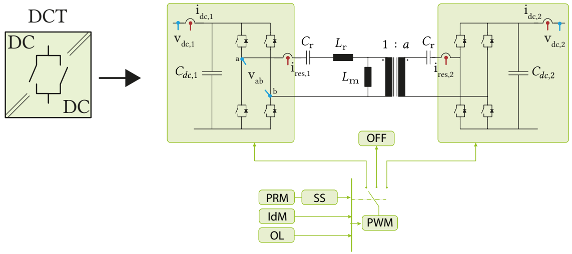
▲ Winding assembly details

1MW MFT PROTOTYPE

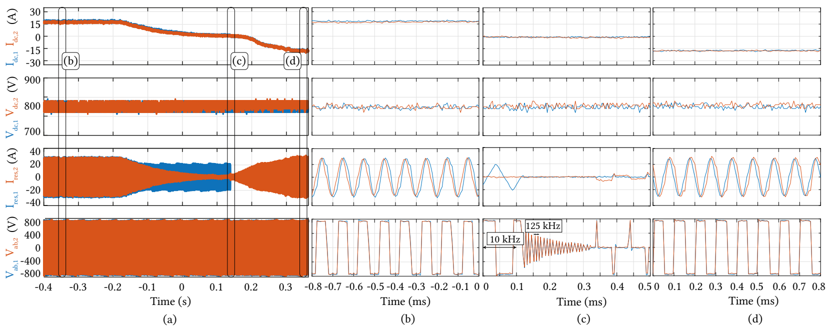
▲ 1 MW prototype of the 2-vessel MFT structure



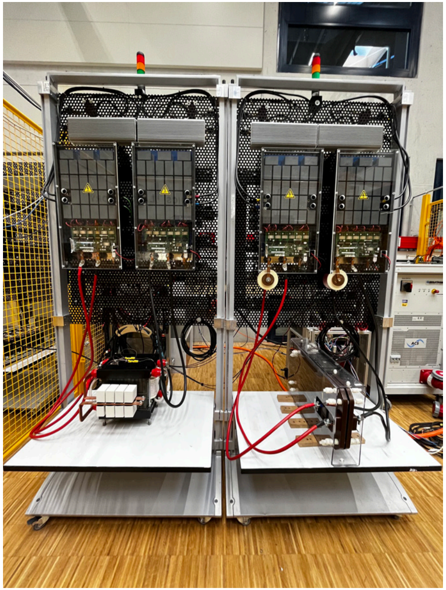
▲ Fully assembled prototype of the 2-vessel MFT



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



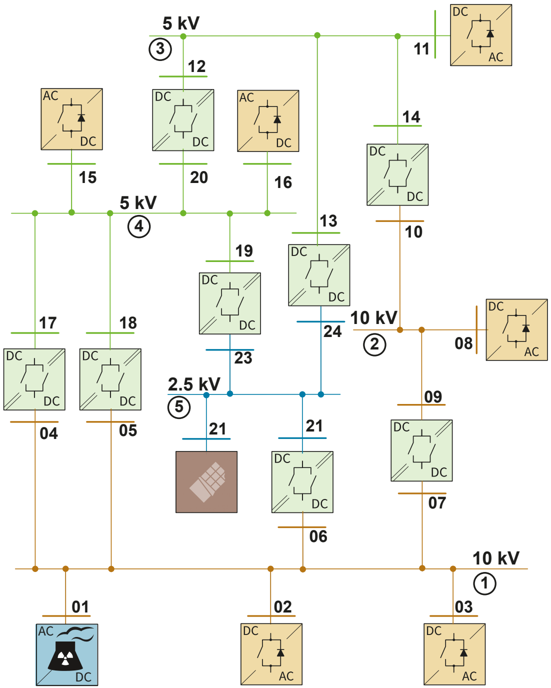
▲ Experimental results during the power reversal



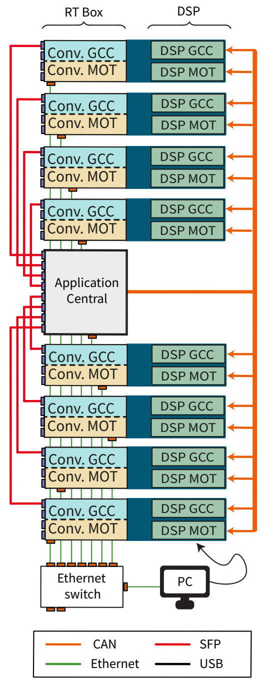
▲ Two low voltage DCTs for experimental validations (PEL's MFTs)

⇒ Scaled-down DCT prototypes are used due to their availability in the lab.

MVDC RT-HIL POWER DISTRIBUTION NETWORK



▲ MVDC PDN deployed on the RT-HIL system



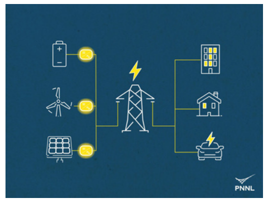
▲ 8 x RT Box 1 + 1 x RT Box 3

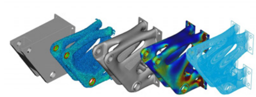
▲ MVDC PDN RT HIL system

SUMMARY

...

POWER ELECTRONICS DOMINATED POWER SYSTEM





École Polytechnique Fédérale de Lausanne

School of Engineering

EPFL — STI — IEM — PEL

Institute of Electrical and Micro Engineering

▲ Medium Voltage Power Electronics Laboratory

Few things to consider:

- Good infrastructure is a must - Investment of money
- Safety must be ensured - Investment of time
- Mechanical Design - Often more important than the Electrical design
- Dielectric Design - Insulation Coordination, Safety
- Electrical Design - Power Density is not a key here
- Thermal Design - Many technologies are available
- Control development - RT HIL tools are great asset
- It takes time, money and a lot of patience...

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