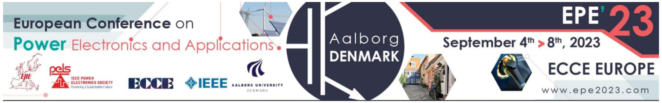


HIGH POWER MEDIUM VOLTAGE RESEARCH AT EPFL POWER ELECTRONICS LABORATORY

Prof. Dražen Dujić

École Polytechnique Fédérale de Lausanne (EPFL)
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

ABB Medium Voltage Drives

2013–2014 R&D Platform Manager ACS 6000

ABB Corporate Research

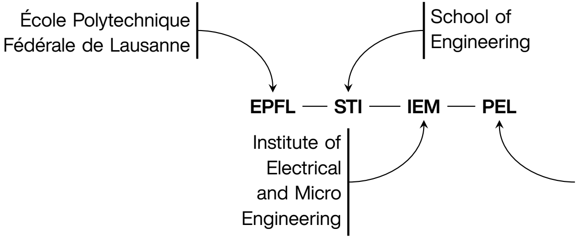
2011 – 2013 Voltage Isolation Voltage Adaptation - VIVA

2010 – 2011 Power Electronics Traction Transformer - PETT

2009 – 2010 Advanced Power Supply Technology - APST

2009 – 2010 New Hardware Platform for Robotics - YuMi

POWER ELECTRONICS LABORATORY AT EPFL



- Active since February 2014
- Currently: 11 PhD students, 4 Post Docs, 1 Administrative 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

PHD STUDENTS (11)

Xiaotong Du
10.2019 – 09.2023
MSc: Xi'an Yiaotong, China
PhD: Inductive power transfer

Renan Pillon Barcelos
02.2021 – 03.2024
MSc: UFSC, Brasil
PhD: DC system modeling and stability

Tianyu Wei
05.2020 – 04.2024
MSc: Tsinghua Uni., China
PhD: Solid State Transformers

Daniel Biner
02.2020 – 07.2024
MSc: HES-SO, Switzerland
PhD: Hydropower modelling

Jules Mace
09.2020 – 08.2024
MSc: SNU, Korea
PhD: Hybrid AC/DC networks

Yanick Frei
10.2021 – 09.2025
MSc: KTH, Sweden
PhD: SiC-based Direct MMC

Stefan Subotic
11.2022 – 10.2026
MSc: ETF, Serbia
PhD: DC-DC converter design optimisation

Max Dupont
03.2023 – 02.2027
MSc: EPFL
PhD: MMC control

Israel Yepez Lopez
09.2023 – 08.2027
MSc: UoSPL, Mexico
PhD: IPT

Gaia Petrillo
09.2023 – 08.2027
MSc: UNINA, Italy
PhD: IPT

Celia Hermoso Diaz
10.2023 – 09.2027
MSc: KTH, Sweden
PhD: PE for data centers

NN
??.2024 – ??.202?
MSc:
PhD:

POST DOCS (4), COLLABORATORS (1)

Post Doctoral Researchers

Dr. Andrea Cervone

PhD: 2021, Napoli, Italia

Expertise:
- power electronics
- electric machines

Dr. Chengmin Li

PhD: 2019, Zhejiang, China

Expertise:
- power electronics
- SiC devices

Dr. Chang-Hwan Park

PhD: 2021, Busan, Korea

Expertise:
- power electronics
- embedded systems

Dr. Rui Wang

PhD: 2023, Aalborg, Denmark

Expertise:
- power electronics
- SiC devices

Collaborators

Jonathan Braun

Engineer at PEL

Expertise:
- power electronics
- anything that must be done

GRADUATED PHD STUDENTS (16)

Dr. Alexandre Christe

04.2014 – 03.2018

PhD: Galvanically isolated modular converter

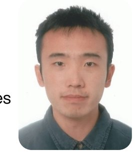
Job: HITACHI Energy, Turgi, Switzerland

Dr. Uzair Javaid

04.2014 – 03.2018

PhD: MVDC distribution fed high power multi-motor drives

Job: HITACHI Energy, Turgi, Switzerland



Dr. Min Luo

07.2014 – 07.2018

PhD: Dynamic modeling of magnetic components...

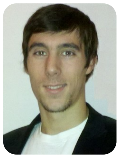
Job: Ekarus Engines, Basic, Zurich, Switzerland

Dr. Yan-Kim Tran

10.2014 – 04.2019

PhD: Multiport energy gateway

Job: EPFL, Lausanne Switzerland



Dr. Marko Mogorovic

10.2015 – 06.2019

PhD: High power MFT design optimization

Job: HITACHI Energy, Geneva, Switzerland

Dr. Stefan Milovanovic

03.2017 – 03.2020

PhD: MMC for MVDC applications

Job: Comel, Belgrade, Serbia

Dr. Dragan Stamenkovic

04.2016 – 03.2020

PhD: IGCT solid state resonant conversion

Job: ABB Medium Voltage Drives, Turgi, Switzerland

Dr. Emilien Coulinge

04.2016 – 03.2020

PhD: Superconducting magnet power supplies

Job: ABB Traction, Turgi, Switzerland

Dr. Seongil Kim

01.2017 – 09.2020

PhD: MVDC protection coordination

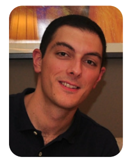
Job: HYUNDAI Research Center, Korea

Dr. Marko Petkovic

08.2017 – 03.2021

PhD: System identification for MV applications

Job: HITACHI Energy, Turgi, Switzerland



Dr. Miodrag Basic

12.2018 – 11.2021

PhD: Hybrid MMC for pumped hydropower..

Job: HITACHI Energy, Turgi, Switzerland

Dr. Gabriele Ulissi

09.2018 – 06.2022

PhD: High frequency IGCT operation for DC transformers

Job: Roland Berger, Zurich, Switzerland

Dr. Ignacio Polanco

09.2018 – 07.2022

PhD: Condition health monitoring for MMC

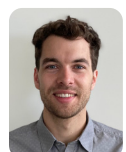
Job: Hydrogenics, Belgium

Dr. Milan Utvic

02.2018 – 01.2023

PhD: MMC Energy Control

Job: H55, Switzerland



Dr. Philippe Bontemps

09.2019 – 06.2023

PhD: M3C for Hydropower

Job: Maxon, Switzerland

Dr. Nikolina Djekanovic

04.2019 – 06.2023

PhD: MFT Design Optimization

Job: ABB Traction, Switzerland

PEL RESEARCH FOCUS

MVDC Technologies and Systems

- System Stability
- Protection Coordination
- Power Electronic Converters

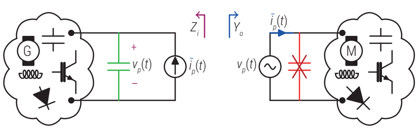
High Power Electronics

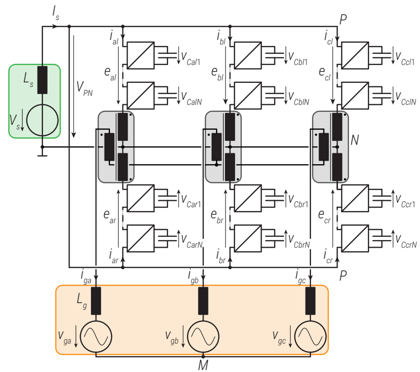
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

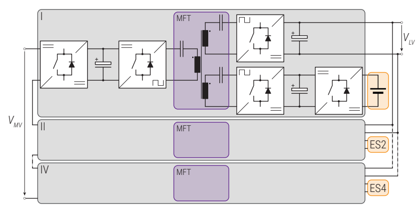
Components

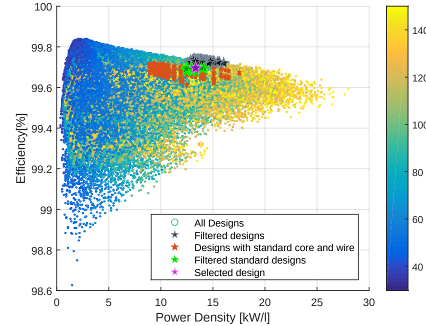
- Semiconductor devices
- Magnetics
- Modeling, Characterization

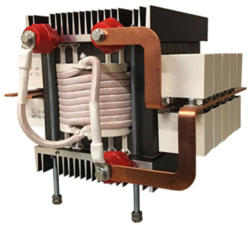
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS











RESEARCH FUNDING AND PARTNERS

Agencies

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN

Energy Turnaround
National Research Programme NRP 70

FNSNF

SCCER - FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

In cooperation with the CTI

Energy funding programme
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Commission for Technology and Innovation CTI

erc

Industry

plexim

ABB

GE

widap

Hitachi Energy

CERN

LEMSYS

SuperGrid Institute
Shaping power transmission

ECPE

HYUNDAI

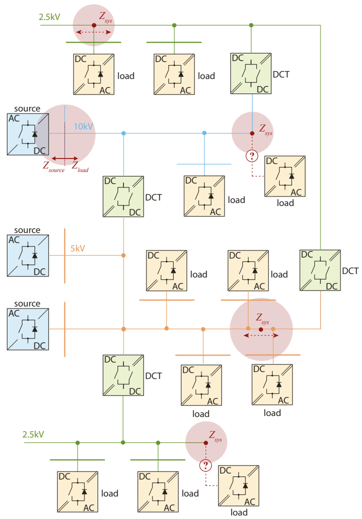
SEMIKRON
innovation + service

HUAWEI

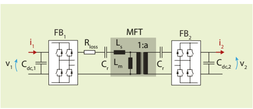
VW

HYOSUNG

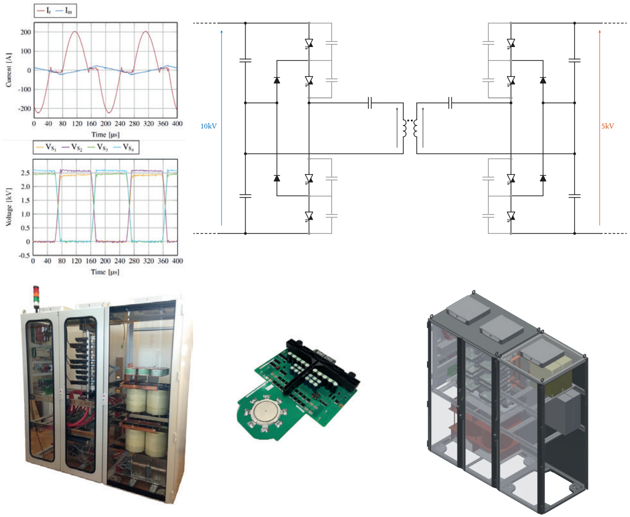
ERC COG - MVDC DIRECT CURRENT TRANSFORMER (I)



Direct Current Transformer



Prototypes



▲ Exemplary MVDC power distribution network with multiple DC Transformers

▲ 5 kV IGCT test setup and 10 kV DCT demonstrator under construction

[1] Renan Pillon Barcelos and Dražen Dujić. "Direct Current Transformer Impact on the DC Power Distribution Networks." *IEEE Transactions on Smart Grid* (2022), pp. 1–1

[2] Renan Pillon Barcelos, Jakub Kucka, and Drazen Dujic. "Power Reversal Algorithm for Resonant Direct Current Transformers for DC Networks." *IEEE Access* 10 (2022), pp. 127117–127127

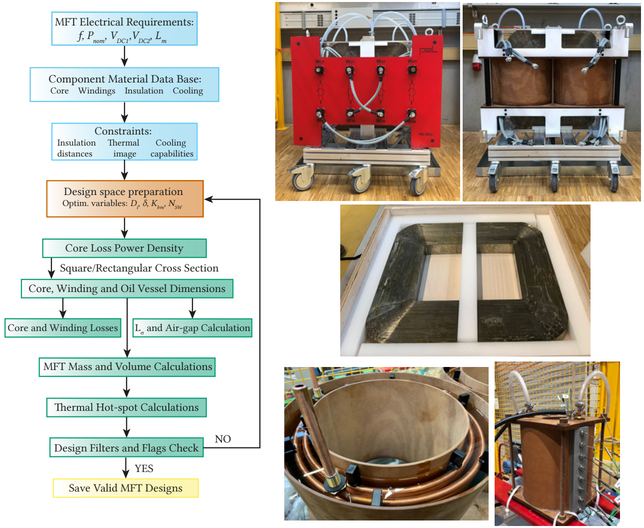
[3] R. Pillon Barcelos and D. Dujic. "On Features of Direct Current Transformers." *The 11th International Conference on Power Electronics - ICPE - ECCE Asia*. May 2023, pp. 1912–1918

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

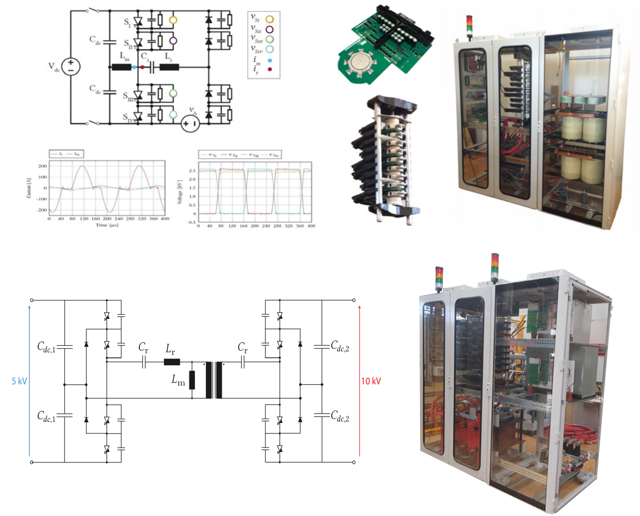
[5] Gabriele Ulissi et al. "High Frequency Operation of Series-Connected IGCTs for Resonant Converters." *IEEE Transactions on Power Electronics* (2021), pp. 1–1

[6] Gabriele Ulissi et al. "Resonant IGCT Soft-Switching: ZVS or ZCS." *IEEE Transactions on Power Electronics* (2022), pp. 1–1

ERC COG - MVDC DIRECT CURRENT TRANSFORMER (II)



▲ MFT design optimization and 1 MW 5kHz MFT prototype



▲ 1 MW DCT demonstrator under construction

[7] N. Djekanovic, M. Luo, and D. Dujic. "Thermally-Compensated Magnetic Core Loss Model for Time-Domain Simulations of Electrical Circuits." *IEEE Transactions on Power Electronics* (2021), pp. 1–1

[8] N. Djekanovic and D. Dujic. "Modeling and Characterization of Natural-Convection Oil-Based Insulation for Medium Frequency Transformers." *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2022

[9] N. Djekanovic and D. Dujic. "Design Optimization of a MW-level Medium Frequency Transformer." *PCIM Europe 2022; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of*. May 2022, pp. 735–744

[10] Nikolina Djekanovic and Drazen Dujic. "Copper Pipes as Medium Frequency Transformer Windings." *IEEE Access* 10 (2022), pp. 109431–109445

[11] R.P. Barcelos and D. Dujic. "Parallel Operation of Direct Current Transformers." *PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of*. May 2023, pp. 87–96

Construction

- Core Type

Electrical Ratings

- Power: 100kW
- Frequency: 10kHz
- Input Voltage: $\pm 750V$
- Output Voltage: $\pm 750V$

Core Material

- SiFerrite (UU9316 - CF139)
- U cores

Windings

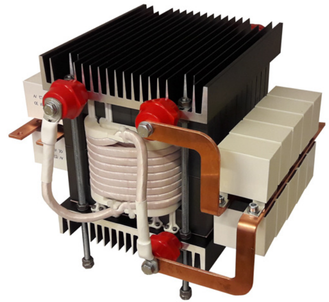
- Square Litz Wire

Cooling

- Winding - Air
- Core - Air cooled heatsink

Insulation

- Air



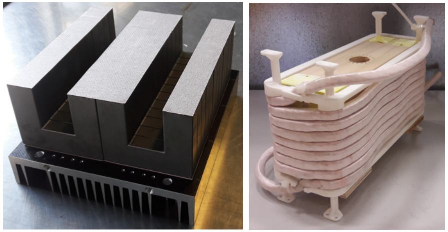
▲ 100kW MFT by EPFL

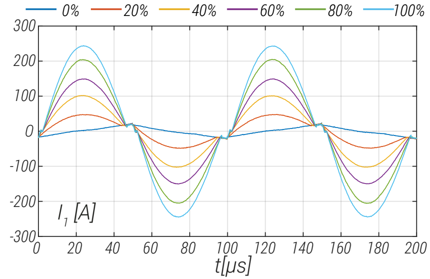
MFT dimensions

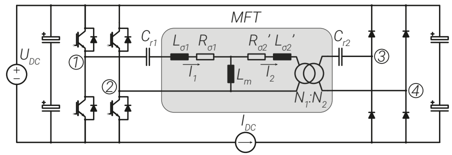
- Volume: ≈ 12.2 l
- V-Density: ≈ 8.2 kW/l
- Weight: ≈ 28 kg
- W-Density: ≈ 3.6 kW/kg

Insulation Tests

- PD: 6kV, 50Hz
- BIL: not performed







▲ MFT by EPFL

[12] M. Mogorovic and D. Dujic. "100kW, 10kHz Medium Frequency Transformer Design Optimization and Experimental Verification." *IEEE Transactions on Power Electronics* PP (2018)
[13] M. Mogorovic and D. Dujic. "Sensitivity Analysis of Medium Frequency Transformer Designs for Solid State Transformers." *IEEE Transactions on Power Electronics* PP (2018)

Construction

- Planar type

Electrical ratings

- Power: 100kW
- Frequency: 10kHz
- Input Voltage: $\pm 750V$
- Output Voltage: $\pm 750V$

Core material

- Nanocrystalline VITROPERM 500F
- U cores

Windings

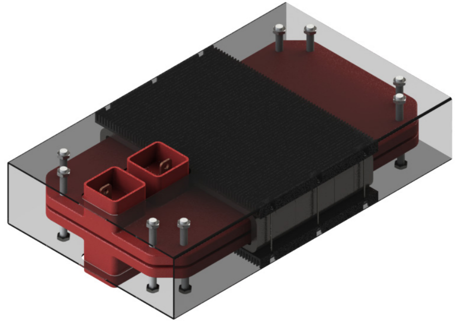
- Copper
- Litz wire

Cooling

- Winding - Forced air
- Core - Heatsinks (Forced air)

Insulation

- Solid - Cast resin



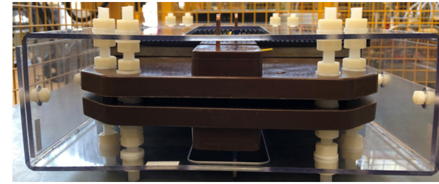
▲ 100kW Planar MFT by PEL.

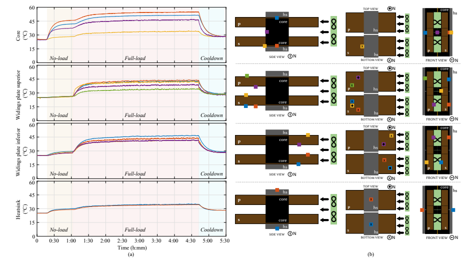
MFT dimensions

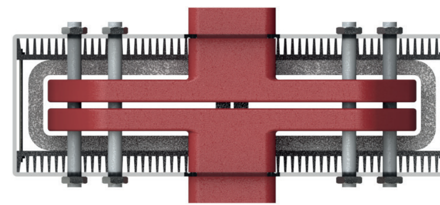
- Volume: 18.5l
- V-Density: 5.4kW/l
- Weight: 26.3kg
- W-Density: 3.8kW/kg

Insulation tests

- PD: 5kV, 50Hz
- BIL: not reported







▲ MFT by PEL.

MFT DESIGN OPTIMIZATION - EPFL PEL HYOSUNG MFT - 2020

Construction

- Core type

Electrical ratings

- Power: 300kW
- Frequency: 20kHz
- Input Voltage: ± 1.7kV
- Output Voltage: ± 4kV

Core material

- Nanocrystalline
- UU cores

Windings

- Copper
- Litz wire

Cooling

- Winding -Forced air
- Core - Forced air

Insulation

- Winding - Solid, cast resin
- Core - Air

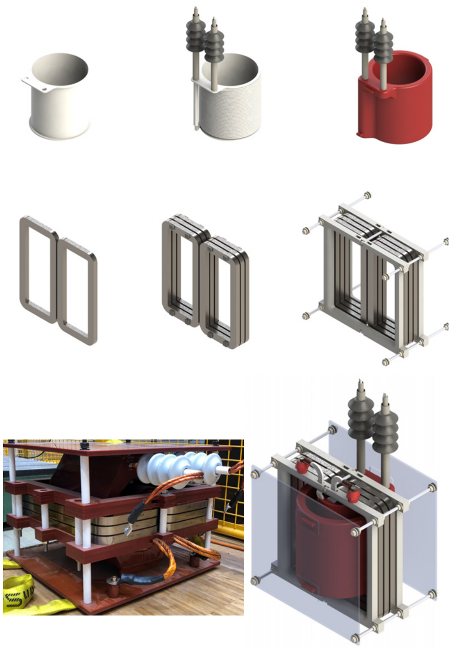
▲ 300kW Planar MFT by PEL and Hyosung.

MFT dimensions

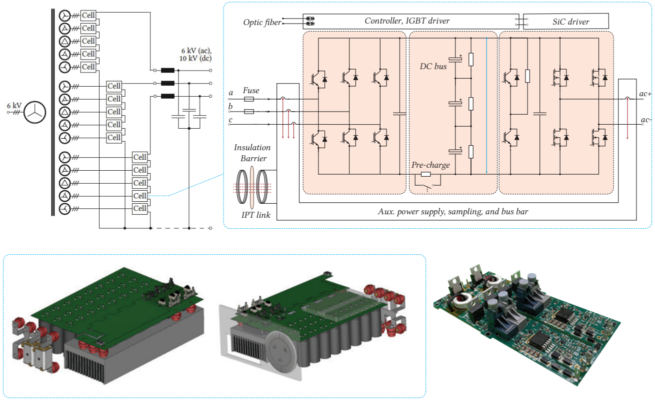
- Volume: 62l
- V-Density: 4.8kW/l
- Weight: 39.7kg
- W-Density: 7.55kW/kg

Insulation tests

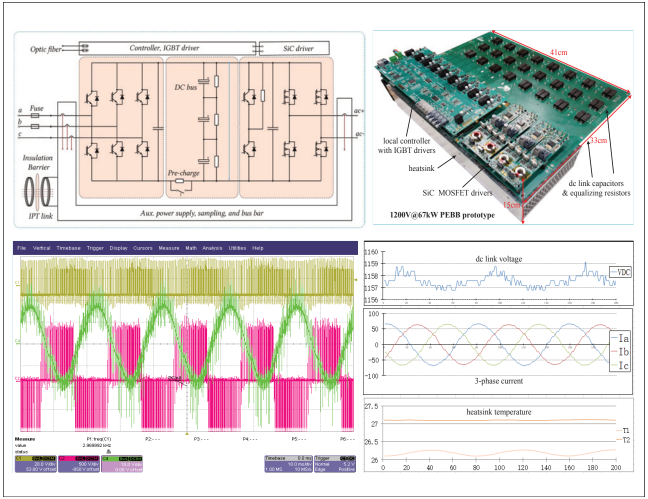
- PD: not reported
- BIL: not reported



▲ MFT by PEL and Hyosung.



▲ Concept of PEBB for 4Q Cascaded H-bridge converter

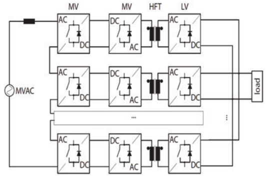


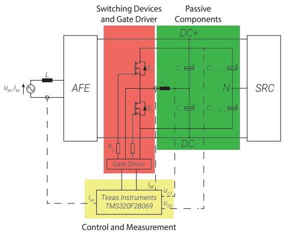
▲ Implementation and test of PEBB for 4Q Cascaded H-bridge converter

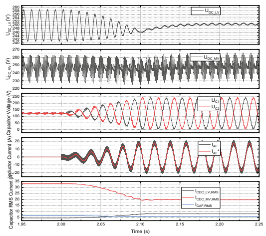
[14] N. Hildebrandt, M. Luo, and D. Dujic. "Robust and Cost Effective Synchronization Scheme for a Multicell Grid Emulator." *IEEE Transaction on Industrial Electronics* (2020), pp. 1–1

[15] Chengmin Li, Jing Sheng, and Drazen Dujic. "Reliable Gate Driving of SiC MOSFETs With Crosstalk Voltage Elimination and Two-Step Short-Circuit Protection." *IEEE Transactions on Industrial Electronics* (2022), pp. 1–10

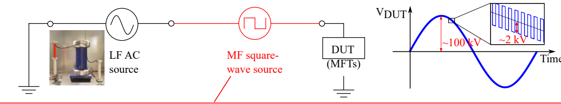
[16] C. Li and D. Dujic. "Crosstalk Voltage Suppression of SiC MOSFET With An Auxiliary Bidirectional Switch." *The 11th International Conference on Power Electronics - ICPE - ECCE Asia*. May 2023, pp. 381–386

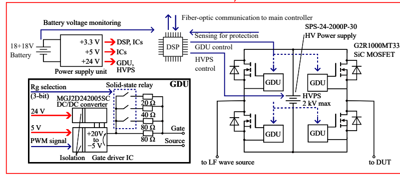


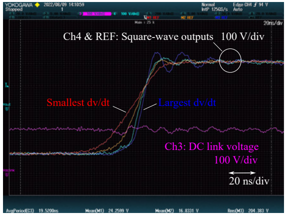


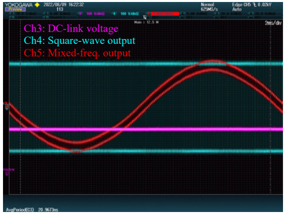


▲ ISOP SST with active filter for second-order harmonic ripple suppression









▲ Flexible SiC-based square wave source

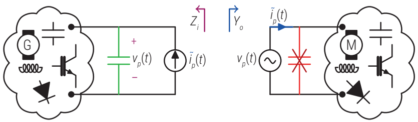
[17] T. Wei, A. Cervone, and D. Dujic. “Second Harmonic Ripple Voltage Suppression for Single-Phase ISOP Solid-State Transformer by Active Power Decoupling.” *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2023
[18] H. Takayama et al. “Square-Wave Source with Adjustable dv/dt for Insulation Testing under Mixed-Frequency Stresses.” *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2023

PEL RESEARCH FOCUS

MVDC Technologies and Systems

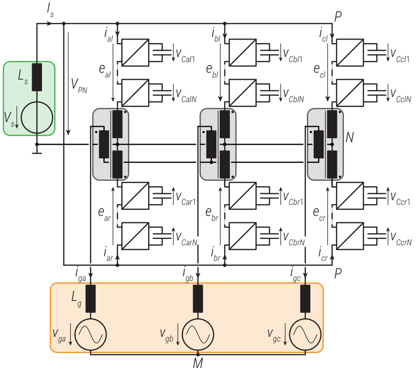
- System Stability
- Protection Coordination
- Power Electronic Converters

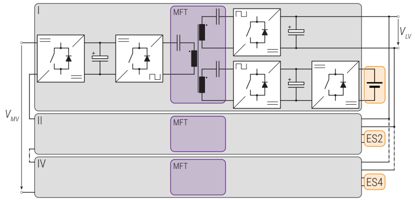
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics

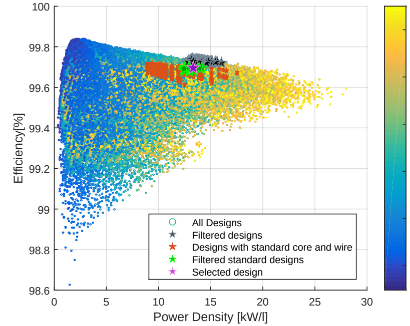
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

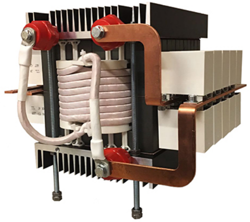




Components

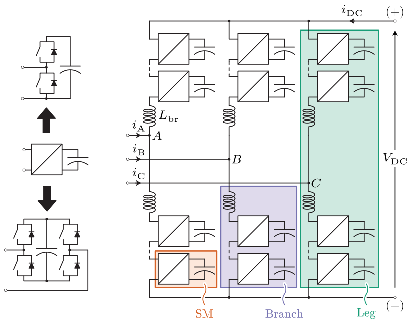
- Semiconductor devices
- Magnetics
- Modeling, Characterization





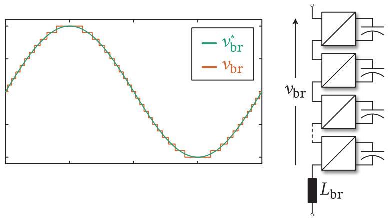
MMC RESEARCH PLATFORM

High power university lab prototype and versatile HIL system



▲ Modular Multilevel Converter

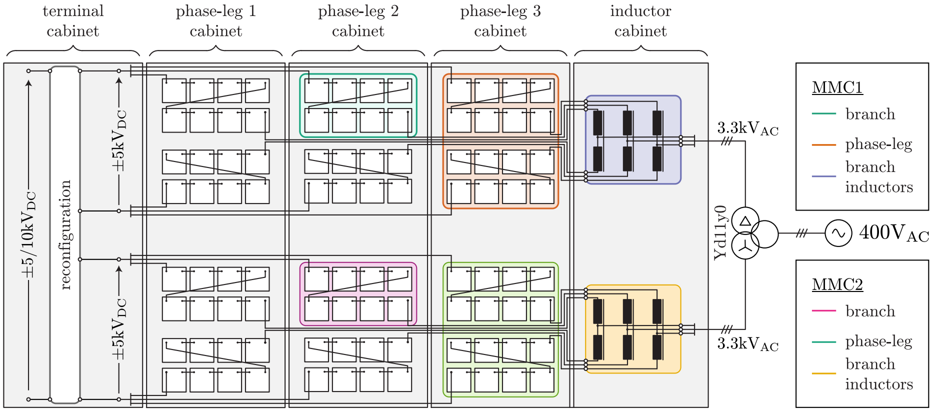
- Series connection of HB/FB Submodules (SMs)
- Flexible in terms of voltage scaling
- High quality voltage waveforms



▲ Branch with its voltage waveform

MMC demonstrator ratings

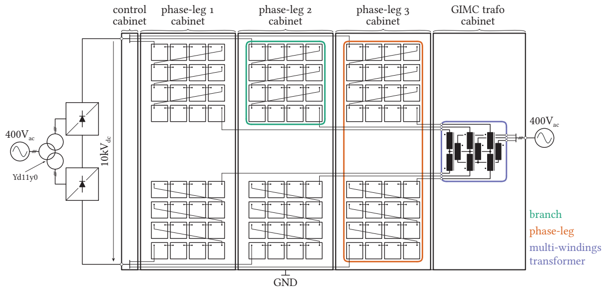
- 500 kVA
- 10 kV_{dc} ⟷ 400 V_{ac} or 2 x 3.3 kV_{ac}
- 8 low voltage cells per branch ⇒ 16 cells per phase (half a cabinet) ⇒ 48 cells per MMC ⇒ 96 cells in total
- Industrial central controller and communication (ABB AC PEC 800)



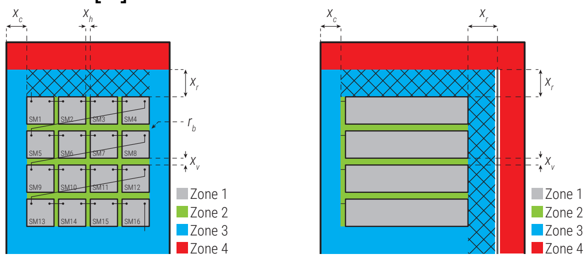
▲ PEL MMC layout

DIELECTRIC DESIGN - INSULATION COORDINATION (I)

System partitioning



Zones definition [19]



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$_{ac}$

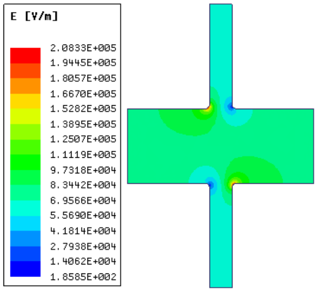
Zone 4 (ins. coord. for LV circuits) system voltage: 0.4 kV$_{ac}$

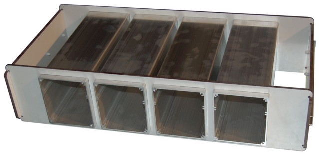
Standards

- 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

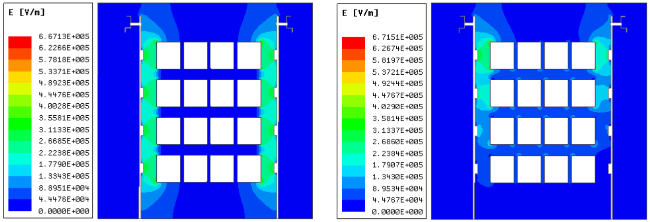
- Box at dc- cell's potential (floating)
- Box corner radius: 3 mm
- MKHP (high CTI material) drawer holding 4 cells





▲ E-field FEM simulations for drawer design

Zone 3 (2 out of 2^{16} combinations)

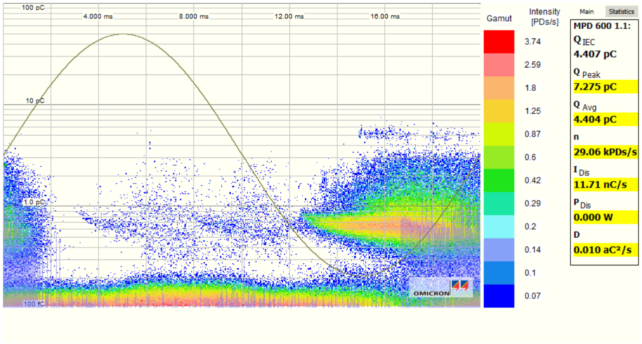


▲ E-field FEM simulations at cabinet level

Design recap

Variable	Minimal value [mm]	Actual design value [mm]
r_b		3
$d_{L,h}$	6.8	15
$d_{C,h}$	3.2	15
$d_{L,v}$	30	50
$d_{C,v}$	12.5	275
$d_{L,c}$	60	81.5
$d_{C,c}$	60	93
$d_{L,r}$	102	120

AC dielectric withstand test

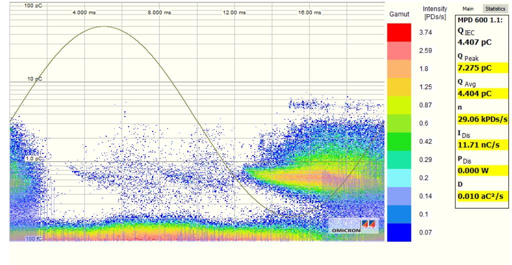


▲ PD testing at cabinet level

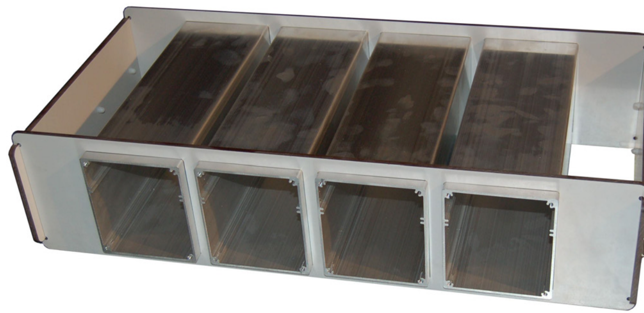
DIELECTRIC DESIGN - INSULATION COORDINATION (III)

- MV MMC converter laboratory prototype layout compliant with:
  - UL840 (for cell)
  - IEC 61800-5-1
- Complete AC dielectric withstand tests on real prototype [19]

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



▲ AC dielectric withstand test result



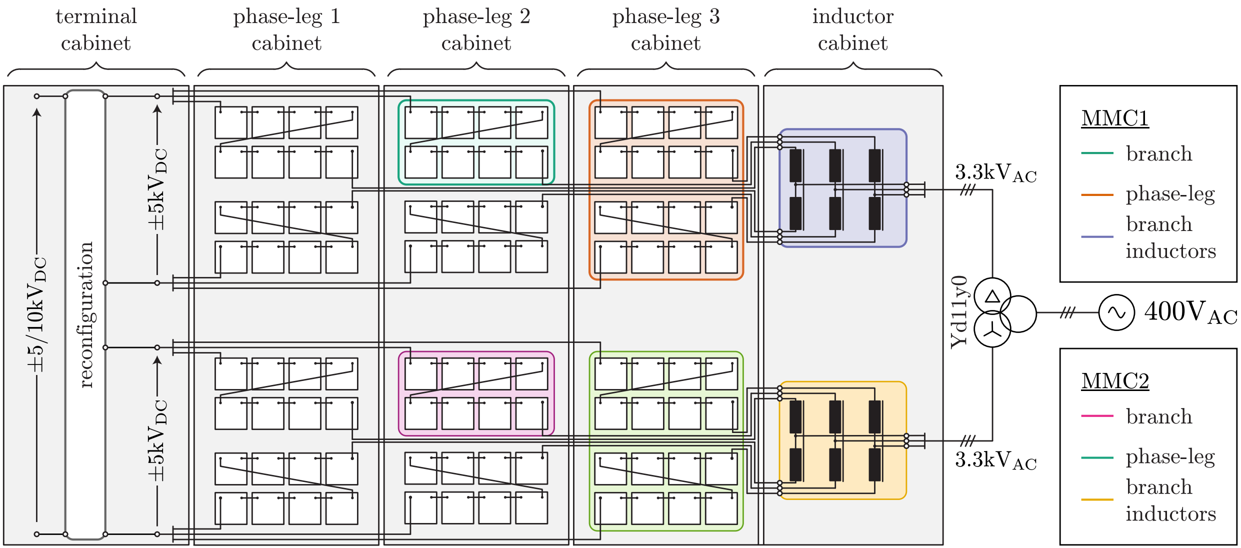
▲ Drawer holding 4 cell (MKHP material)

[19] A. Christe, E. Coulinge, and D. Dujic. "Insulation coordination for a modular multilevel converter prototype." *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe).* Sept. 2016, pp. 1–9

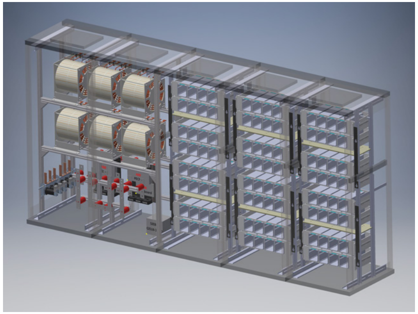
MECHANICAL DESIGN - MMC LAYOUT

MMC demonstrator ratings are:

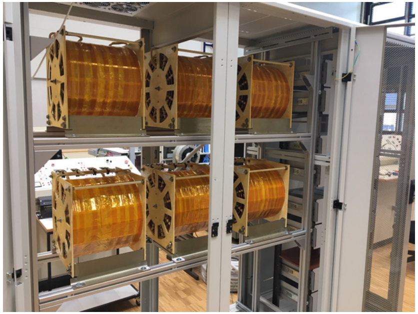
- 500 kVA (2 x 250 kVA)
- $\pm$ 10 $kV_{dc} \longleftrightarrow$ 2 x 3.3 kV_{ac}
- 8 low voltage cells per branch $\Rightarrow$ 16 cells per MMC phase $\Rightarrow$ 48 cells in total - per MMC
- Industrial central controller and communication (ABB AC PEC 800)



▲ Flexible DC Source Converter Layout

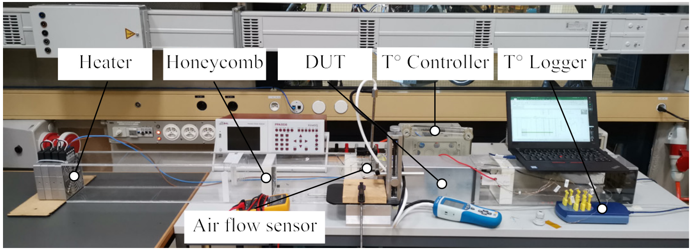


▲ MMC CAD development



▲ MMC coupled air-core branch inductors

▲ MMC - Actual mechanical assembly



▲ MMC Submodule thermal heat-run test setup [20]

[20] I. Polanco and D. Dujic. "Thermal Study of a Modular Multilevel Converter Submodule." *PCIM Europe digital days 2020; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. 2020, pp. 1–8

MMC SUB-MODULE

Low voltage based sub-module including cell controller

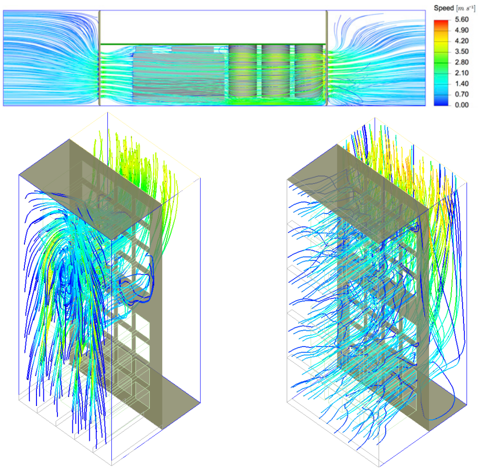
MMC – SUBMODULE OPTIMIZATION

Submodule

- 1.2 kV / 50 A full-bridge IGBT module
- $C_{cell} = 2.25\,\text{mF}$

Thermal design

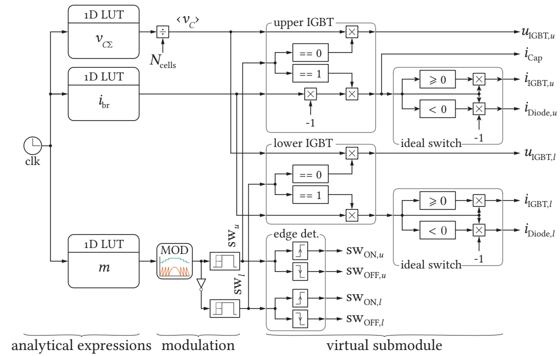
- Cell level: detailed FEM
- Cabinet level: simplified FEM

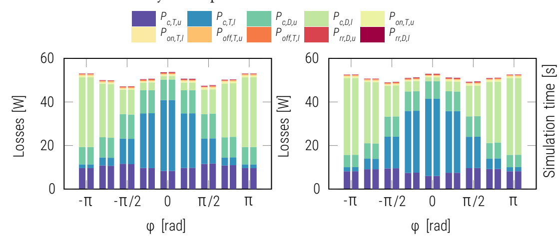


▲ CFD simulations

Semiconductor losses

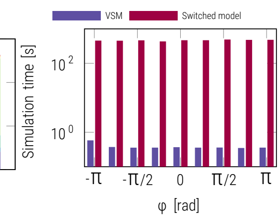
- Virtual Submodule concept has been utilized
- Closed-loop waveforms are approached by analytical waveforms





▲ PS-PWM, DC circ

▲ PS-PWM, DC+2nd circ



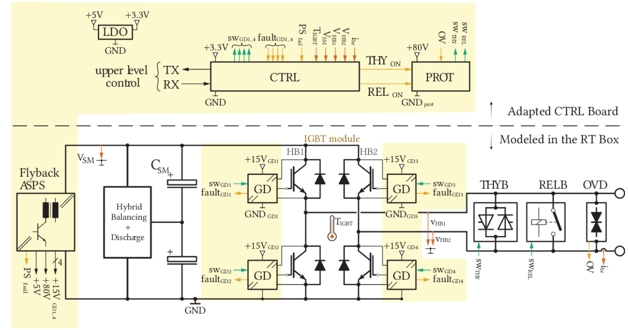
▲ Time benchmark

[21] E. Coulinge, A. Christe, and D. Dujic. "Electro-Thermal Design of a Modular Multilevel Converter Prototype." *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. May 2016, pp. 1–8

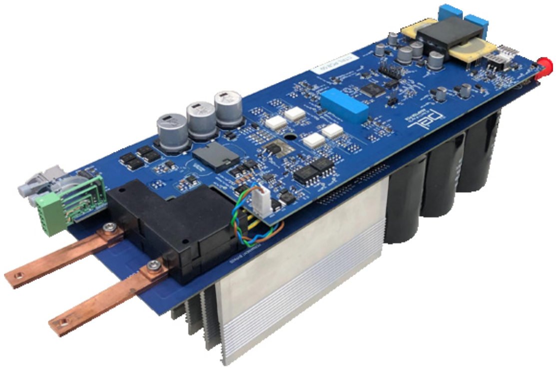
[22] A. Christe and D. Dujic. "Virtual Submodule Concept for Fast Semi-Numerical Modular Multilevel Converter Loss Estimation." *IEEE Transactions on Industrial Electronics* 64.7 (July 2017), pp. 5286–5294

Key Features

- Low voltage power components
- Full-bridge sub-module structure
- Sub-module rated voltage - 625 V
- Sub-module insulation coordination - 900 V
- Two interconnected PCBs: **Power PCB** and **Control PCB**

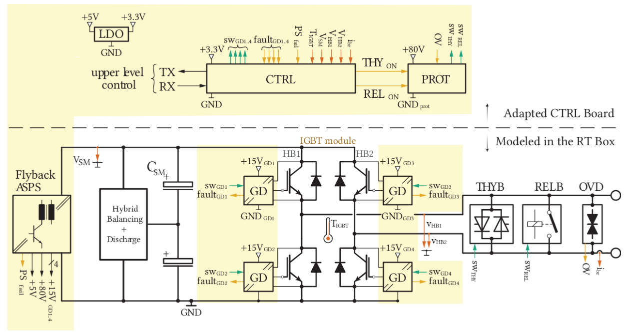


▲ MMC Sub-module Structure: Yellow parts - Control PCB

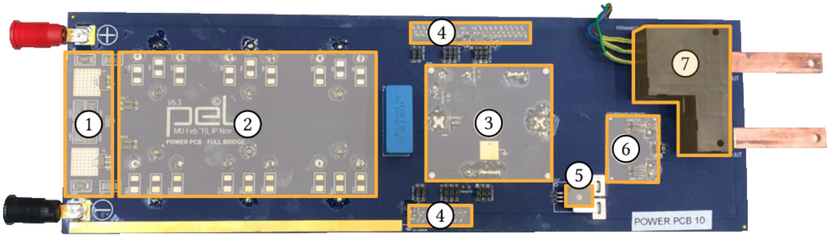


▲ Developed MMC FB sub-module based on the 1.2kV IGBTs

- Power processing part
- Semikron full-bridge IGBT module 1.2 kV/50 A
- Bank of electrolytic capacitors C_{sm} = 2.25 mF
- Protection devices: Bypass thyristor, relay and OVD
- Current and voltage measurements
- Hybrid balancing circuitry
- Hardware reconfiguration (HR)

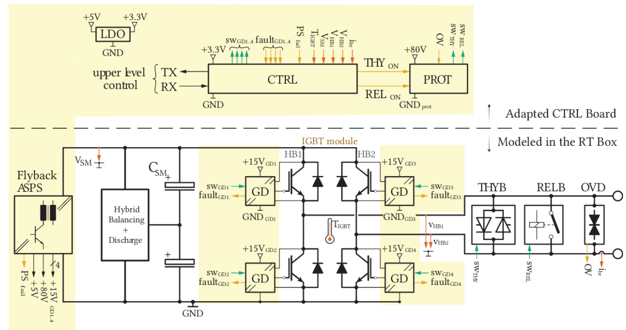


▲ MMC Sub-module Structure: Yellow parts - Control PCB

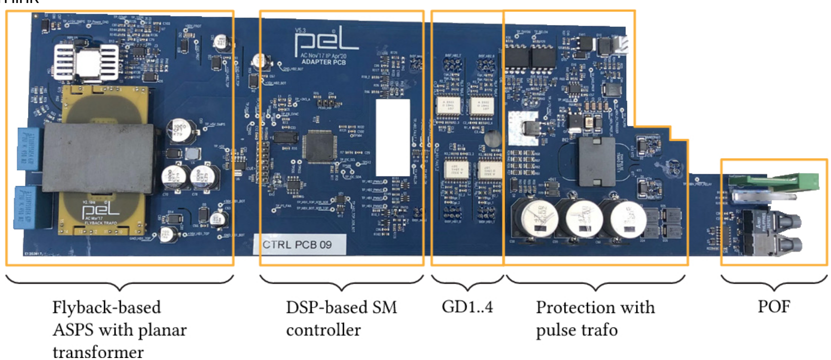


▲ Overview of the Power PCB

- Flyback based auxiliary power supply
  - +5V Output, used as a control feedback
  - +80V Protection supply
  - +15V Gate drivers supplies
  - +15V Self-supply output
- DSP based main SM Controller
  - Communication with upper level control
  - Voltage and current measurements
  - Monitoring the SM condition
  - Decentralized modulation
- Gate drivers
- Protection logic
  - Protection activation from upper level control
  - Protection activation from DSP
  - Protection activation by overvoltage detection
- Fiber-optical communication link



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



▲ Overview of the Control PCB

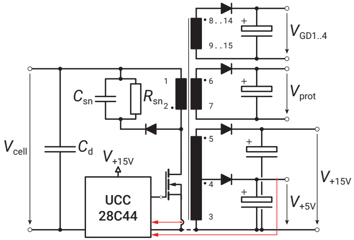
AUXILIARY SUB-MODULE POWER SUPPLY (I)

Possible concepts

- Externally supplied
  - Single wire loop
  - Siebel
  - Inductive power transfer
- Internally supplied
  - Tapped inductor Buck
  - Flyback

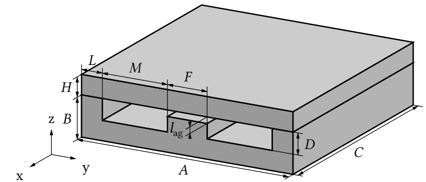
Choice

- Flyback with 6 isolated secondaries
  - 1× 5 V, 4 W for the controller supply (V_{+5V}). This output is tightly regulated in closed-loop.
  - 4× 15 V, 1.5 W for the IGBT gate drivers ($V_{GD1..4}$)
  - 1× 80 V, 15 W for 15 s operation when activated for the protection circuit (V_{prot})



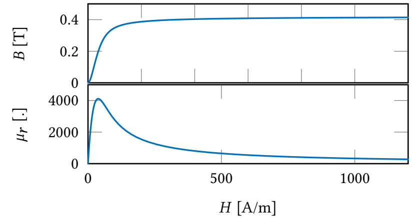
Planar trafo design

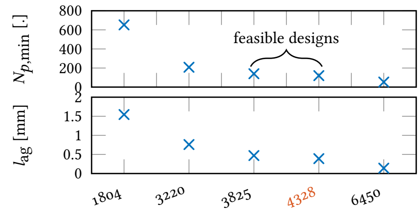
- PCB windings (isolation requirements!)
- Planar ferrite cores with custom gapping (COSMO ferrites)



Matlab design tool

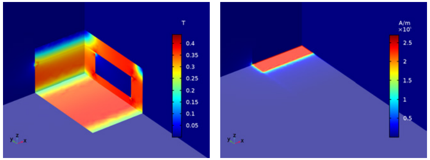
- Account for flux fringing
- BH curve for CF297
- Jiles-Atherton parametrization

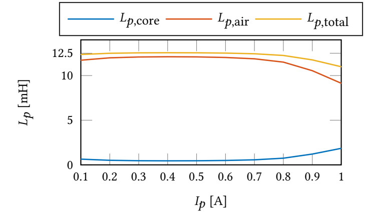




FEM

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

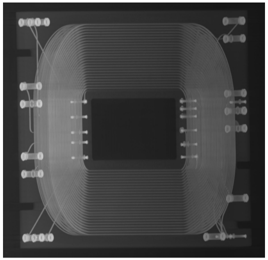


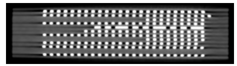


AUXILIARY SUB-MODULE POWER SUPPLY (II)

Transformer assembly

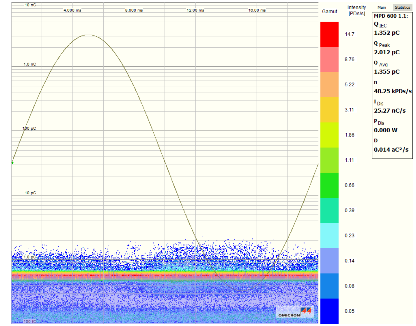
- 14 copper layers PCB
- Custom gapped ferrite E+I core



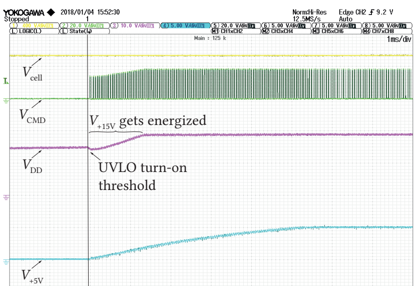


AC dielectric withstand test

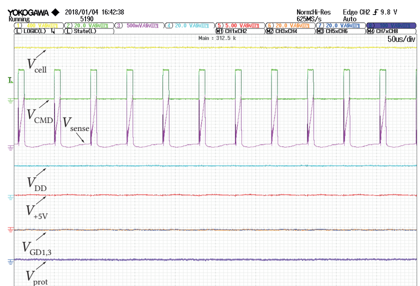
- Way below threshold level of 10pC



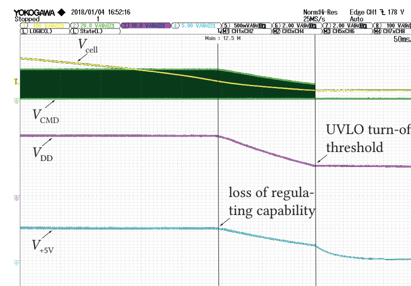
Tests



▲ Start-up



▲ Steady-state operation



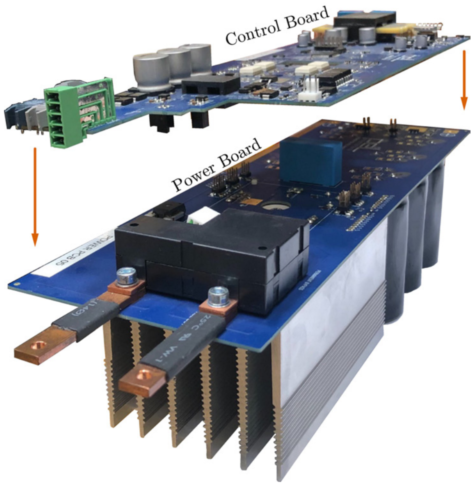
▲ Shut-down (slow dv/dt from Delta power-supply used to emulate the cell)

[23] A. Christe et al. "Auxiliary submodule power supply for a medium voltage modular multilevel converter." *CPSS Transactions on Power Electronics and Applications* 4.3 (Sept. 2019), pp. 204–218

MMC SUB-MODULE TESTING

How to validate hardware and software?

MMC SUBMODULES



▲ In-house built MMC cell

▲ Production of the MMC cells

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

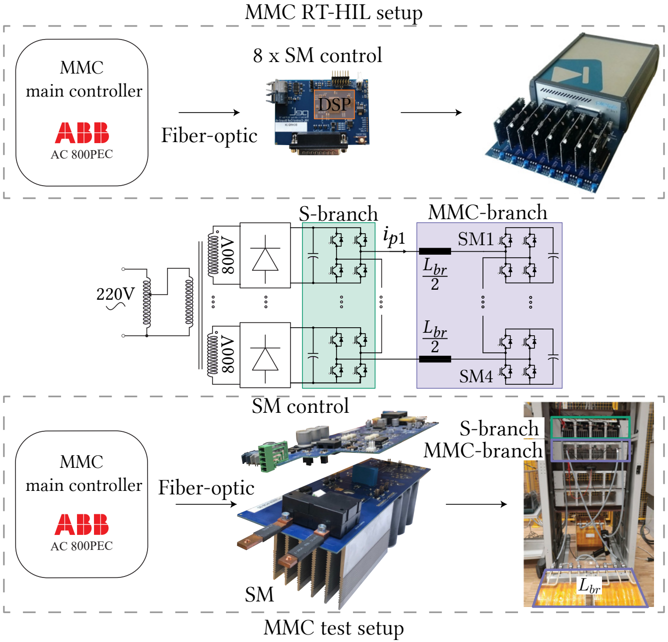
Each and every unit must be thoroughly tested!!!

MMC testing platform: RT-HIL & reduced branch

- Industrial level main controller
- Control cards: SM controller replica ⟹
- RT Box: SM power components simulation

- Operation as in full converter
- S-branch: ac source, made of four SMs ⟹
- MMC-branch: $SM_{1..4}$ (DUT) following branch current ref.

- Industrial level main controller
- 4xSMs (S-branch) + 4xSMs (MMC-branch) ⟹
- Wide range of operation. Serves other purposes (SM HW/SW testing, calibration,...)

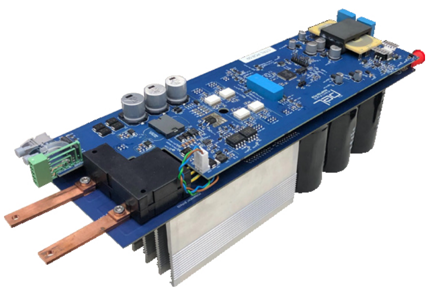


▲ MMC testing platform

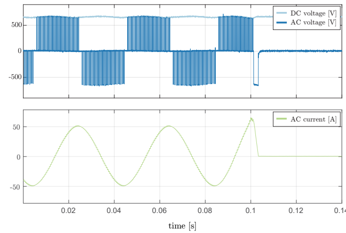
MMC SUB-MODULE FUNCTIONAL POWER TESTS

Extensive testing has been done:

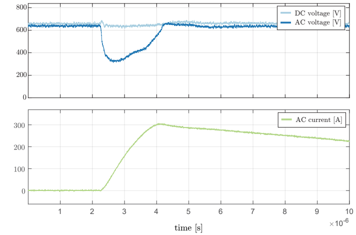
- Power tests
- Thermal heat-runs
- Over current tests
- Loss of power supply
- DC link over voltage
- Terminal over voltage
- Short-circuit tests
- ...



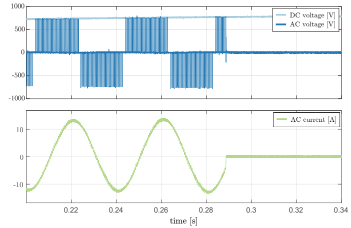
▲ Developed MMC FB sub-module



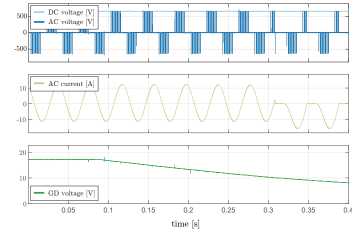
▲ MMC SM over current test



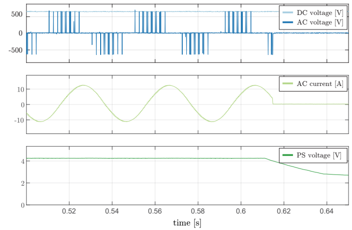
▲ Short circuit test (Desat detection)



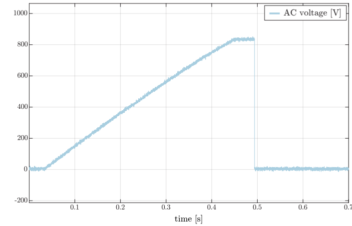
▲ MMC SM over voltage test



▲ Gate Driver failure



▲ Power supply under voltage detection



▲ AC terminals over voltage detection

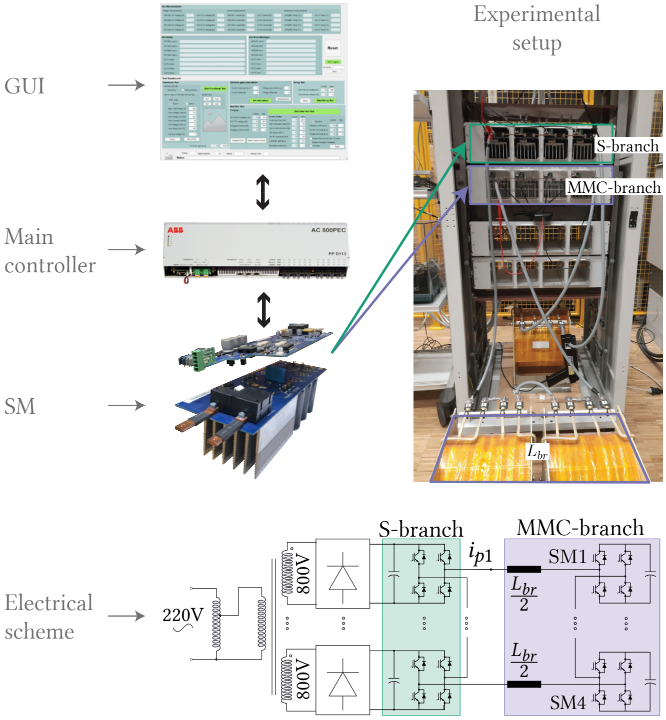
MMC SUB-MODULE HEAT RUN TESTING

MMC testing platform: Heat Run Test setup details

- Custom made GUI
- Monitoring and setting main variables/parameters
- Logging function

- Industrial level AC 800PEC controller
- Simulink-based programming
- FOL communication to each SM

- 16kVA, 70A, 650V SM (8x)
- 3600V, 70A branch
- up to 1kHz sw. freq., 40kHz samp. freq.

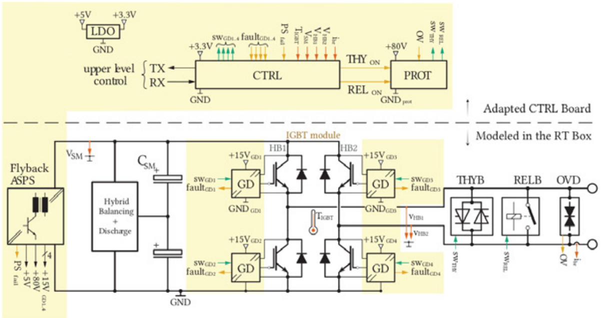


▲ MMC testing platform detail

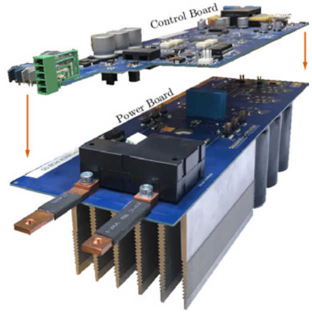
MMC DIGITAL TWIN

RT-Box based distributed HIL system

MMC – RT-HIL SYSTEM (I)



▲ Submodule layout

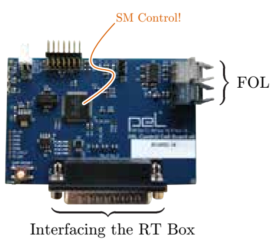


Submodule

- Full-Bridge IGBT module
- Capacitor bank
- Protection circuitry
- Balancing circuit
- Auxiliary power supply

ABB controller

- 2 × PEC 800 (Master/Slave config.)
- PECMI (measurements)
- COMBIO (relays, switches, etc.)
- HUB (data gateway)

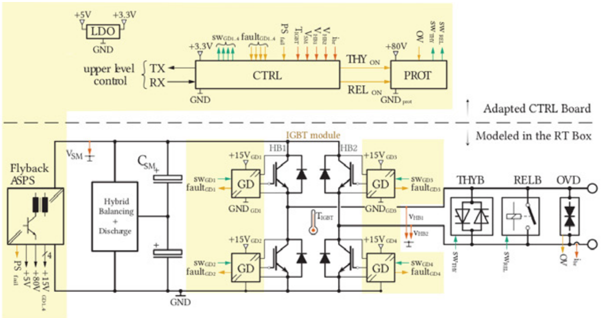


▲ SM control board adapted for HIL testing

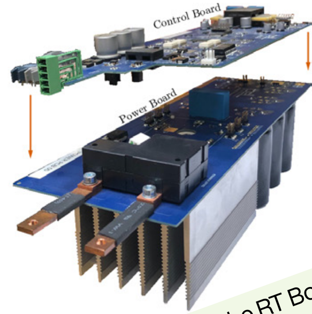
▲ RT Boxes used to host up to eight MMC control cards

▲ Application (Grid) RT Box

[24] S. Milovanovic and D. Dujic. “Upscaling Small Real-Time Simulators for Large Power Electronic Systems.” *Bodo’s Power Systems* 5 (2021), pp. 72–74



▲ Submodule layout



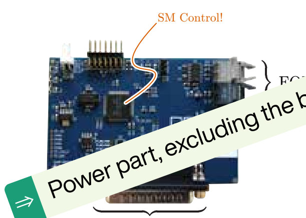
Submodule

- Full-Bridge IGBT module
- Capacitor bank
- Protection circuitry
- Balancing circuit
- Auxiliary power s

ABB contr

- 500 (Master/Slave config.)
- PECMI (measurements)
- COMBIO (relays, switches, etc.)
- HUB (data gateway)

⇒ Power part, excluding the balancing circuitry and power supply, is modeled in the RT Box ⇒ **VIRTUAL POWER PROCESSING**

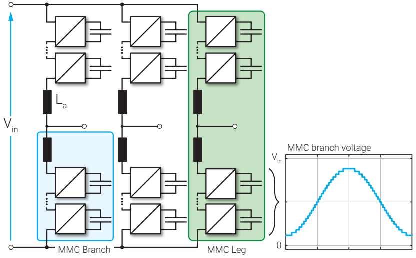


▲ SM control board adapted for HIL testing

▲ RT Boxes used to host up to eight MMC control cards

▲ Application (Grid) RT Box

[24] S. Milovanovic and D. Dujic. "Upscaling Small Real-Time Simulators for Large Power Electronic Systems." *Bodo's Power Systems* 5 (2021), pp. 72–74



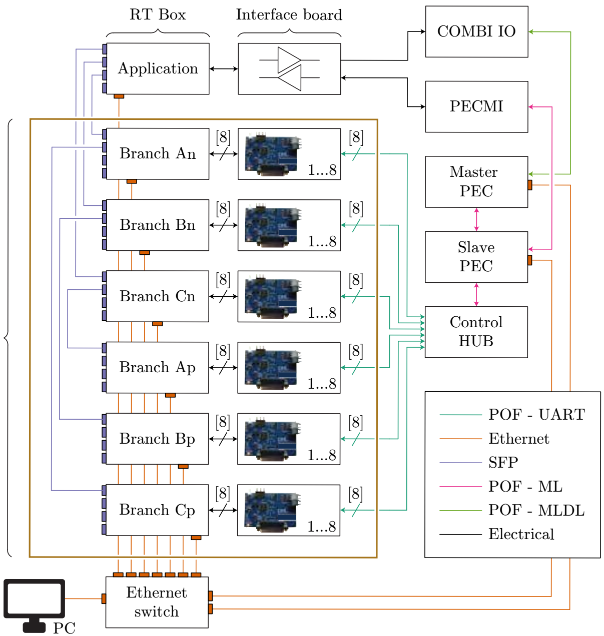
▲ Modular Multilevel Converter

▲ Channels available on the RT Box

Description	No. of channels/ connectors	Voltage range
Analog Inputs	16	−10V . . . 10V
Analog Output	16	−10V . . . 10V
Digital Inputs	**32**	3.3V or 5V
Digital Outputs	32	3.3V or 5V
SFP Connectors	4	N.A.

Limitation in the number of DIs

One RT Box hosts up to 8 SMs!



▲ Wiring communication scheme of a system comprising one MMC serving an arbitrary application

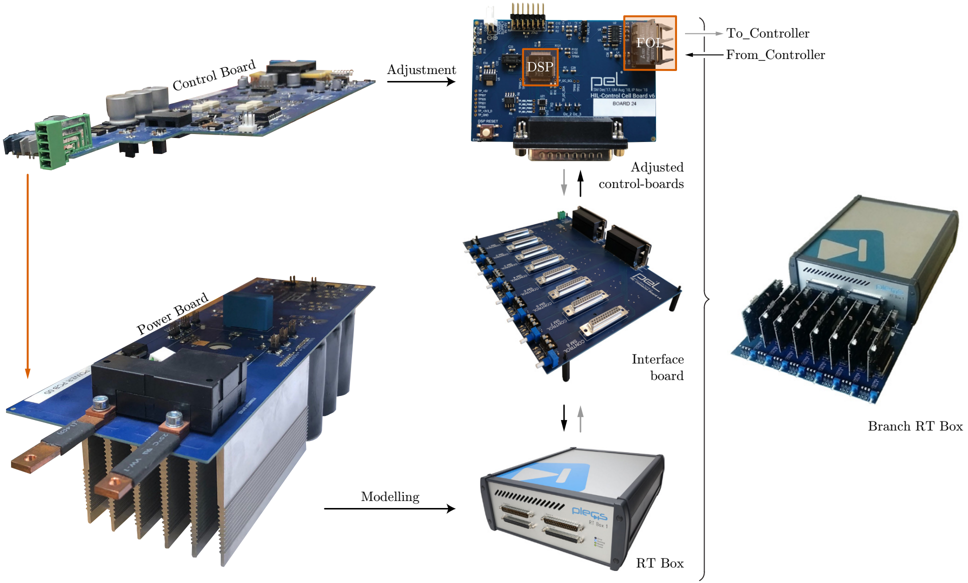
[25] Stefan Milovanovic et al. “Flexible and Efficient MMC Digital Twin Realized With Small-Scale Real-Time Simulators.” *IEEE Power Electronics Magazine* 8.2 (2021), pp. 24–33

MMC – RT-HIL SYSTEM (III)

System summary

- 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

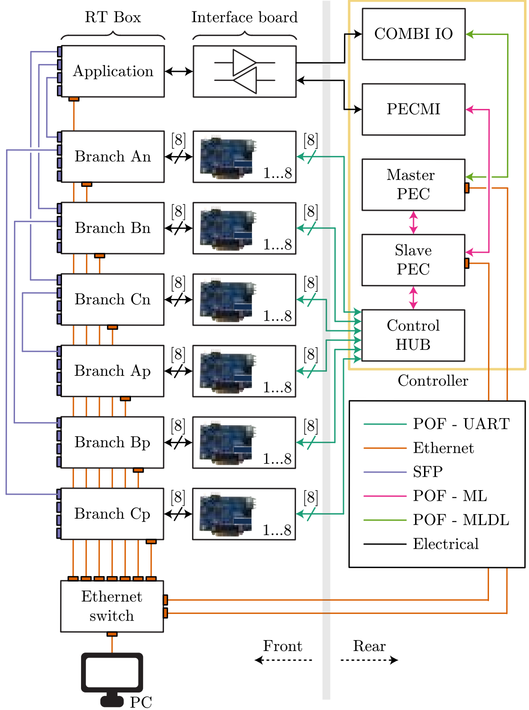
▲ Application (Grid) RT Box

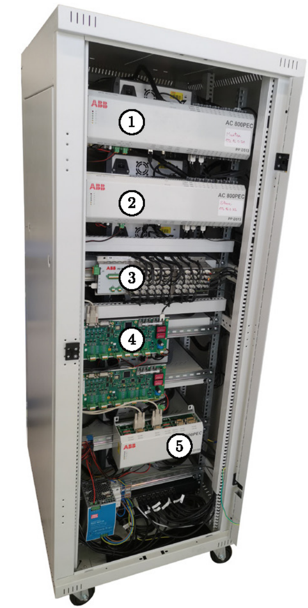


▲ Transformation of MMC cell into digital twin equivalent system

[26] Stefan Milovanović, Min Luo, and Dražen Dujić. "Virtual Capacitor Concept for Computationally Efficient and Flexible Real-Time MMC Model." *IEEE Access* 9 (2021), pp. 144211–144226
[27] S. Milovanovic, M. Luo, and D. Dujic. "Virtual Capacitor Concept for Effective Real-Time MMC Simulations." *PCIM Europe Digital Days 2021*. May 2021, pp. 437–444
[28] Stefan Milovanović et al. "Hardware-in-the-Loop Modeling of an Actively Fed MVDC Railway Systems of the Future." *IEEE Access* 9 (2021), pp. 151493–151506

1- Grid RT Box
2 - Interface board
3 - Branch RT Box
4 - Adjusted control cards





1 - Master PEC 2 - Slave PEC 3 - CHUB
4 - PECMI 5 - COMBI IO

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

MMC RT-HIL extended version

- 4 RT-HIL cabinets - one per MMC
- 48 cells per one RT-HIL cabinet
- Various reconfigurations are possible

▲ RT Box hosting application

▲ RT Box hosting eight MMC sub-modules

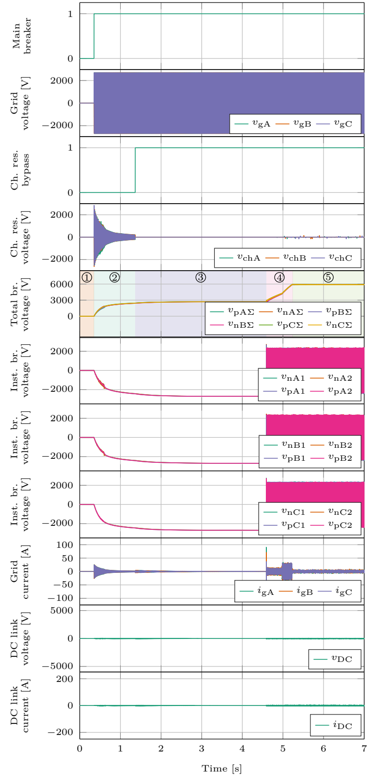
▲ Digital Twins - Four RT-HIL systems allowing for various topological reconfigurations

CONTROL SW TESTING

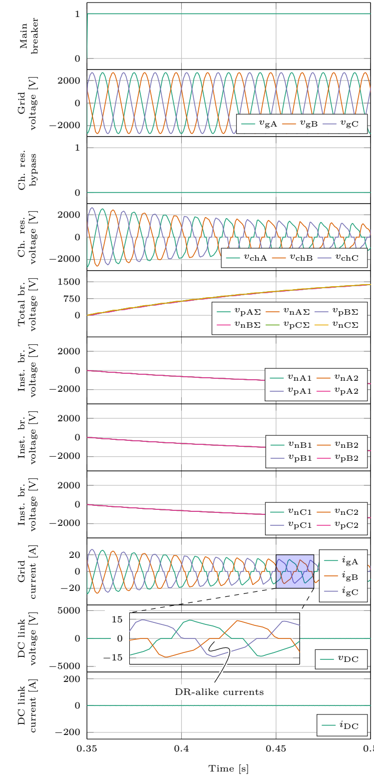
Results recorded from the HIL platform

▲ Simulated converter param.

Rated power (S^*)	1MVar
Output voltage (V_{DC})	5kV
Grid voltage (v_g)	3.3kV
No. of SMs per branch (N)	6
SM capacitance (C_{sm})	3.36mF
Branch inductance (L_{br})	2.5mH
Brach resistance (R_{br})	60mΩ
PWM carrier frequency (f_{pwm})	1kHz
Fudamental frequency (f_o)	60Hz
Charging resistors (R_{ch})	210Ω



▲ Converter charging process presented through several stages

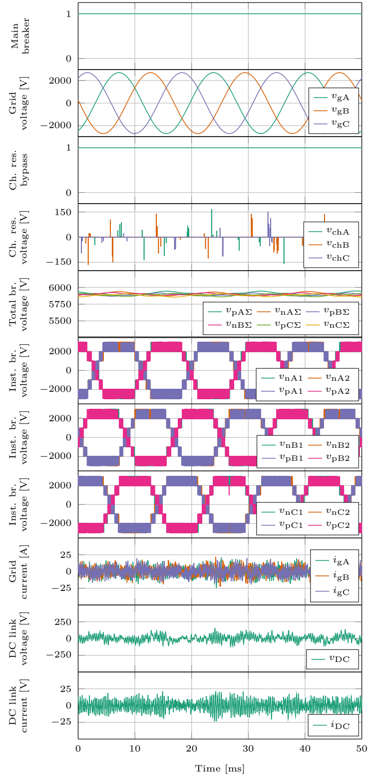


▲ A fraction of the interval referred to as the passive charging

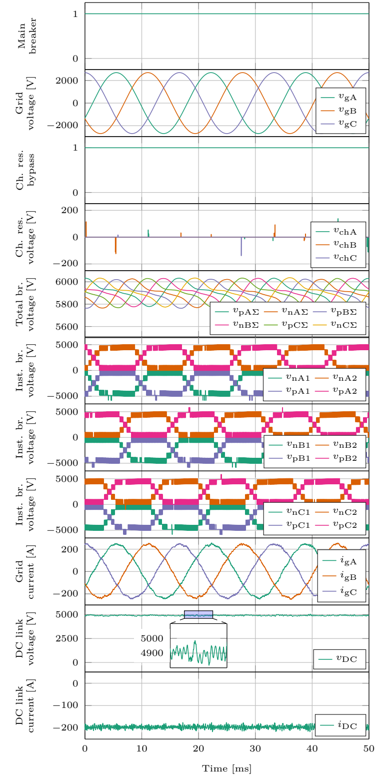
RECORDED WAVEFORMS (II)

▲ Simulated converter param.

Rated power (S^*)	1MVar
Output voltage (V_{DC})	5kV
Grid voltage (v_g)	3.3kV
No. of SMs per branch (N)	6
SM capacitance (C_{sm})	3.36mF
Branch inductance (L_{br})	2.5mH
Brach resistance (R_{br})	60mΩ
PWM carrier frequency (f_{pwm})	1kHz
Fudamental frequency (f_o)	60Hz
Charging resistors (R_{ch})	210Ω



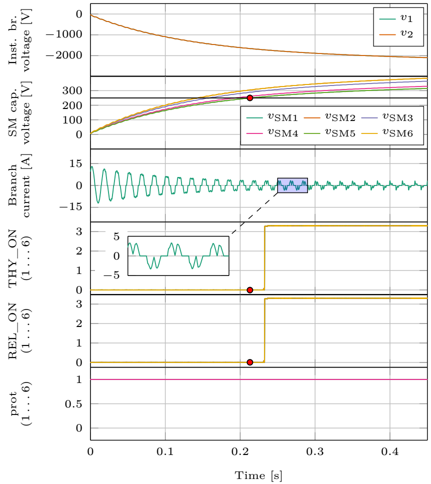
▲ Converter operation at no load ($P_{DC} = 0$)



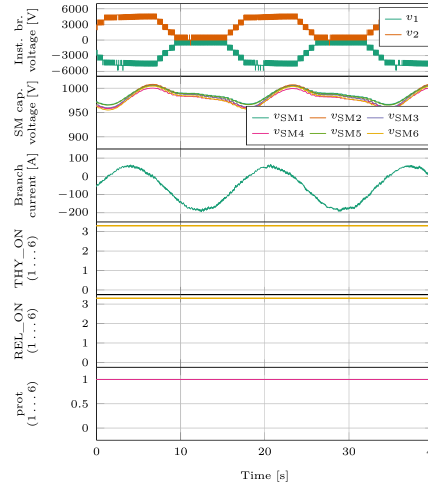
▲ Converter operation at full load ($P_{DC} = 1$MW)

▲ Simulated converter param.

Rated power (S^*)	1MVar
Output voltage (V_{DC})	5kV
Grid voltage (v_g)	3.3kV
No. of SMs per branch (N)	6
SM capacitance (C_{sm})	3.36mF
Branch inductance (L_{br})	2.5mH
Brach resistance (R_{br})	60mΩ
PWM carrier frequency (f_{pwm})	1kHz
Fudamental frequency (f_o)	60Hz
Charging resistors (R_{ch})	210Ω



▲ Passive charging of a branch



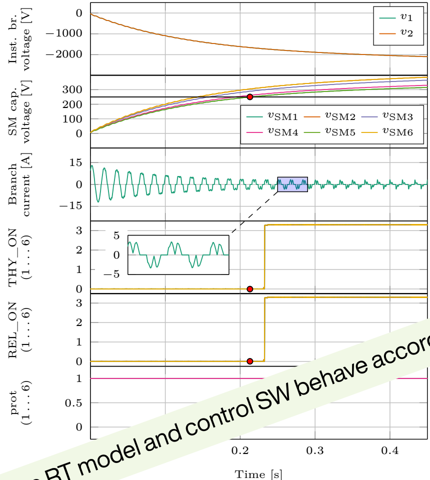
▲ Branch operation at full load

[29]S. Milovanovic and D. Dujic. "Comprehensive Comparison of Modular Multilevel Converter Internal Energy Balancing Methods." *IEEE Transactions on Power Electronics* (2021), pp. 1–1

RECORDED WAVEFORMS (III)

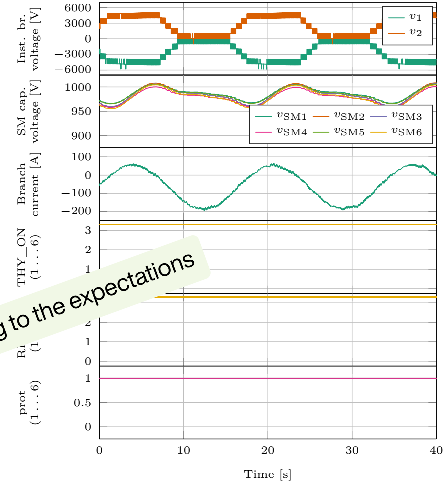
▲ Simulated converter param.

Rated power (S^*)	1MVar
Output voltage (V_{DC})	5kV
Grid voltage (v_g)	3.3kV
No. of SMs per branch (N)	6
SM capacitance (C_{sm})	3.36mF
Branch inductance (L_{br})	2.5mH
Brach resistance (R_{br})	60mΩ
PWM carrier frequency (f_{pwm})	1kHz
Fudamental frequency (f_o)	60Hz
Charging resistors (R_{ch})	210Ω



The RT model and control SW behave according to the expectations

…sive charging of a branch



▲ Branch operation at full load

[29]S. Milovanovic and D. Dujic. "Comprehensive Comparison of Modular Multilevel Converter Internal Energy Balancing Methods." *IEEE Transactions on Power Electronics* (2021), pp. 1–1

MMC RELATED WORKS

Using developed platform to drive research forward...

Motivation:

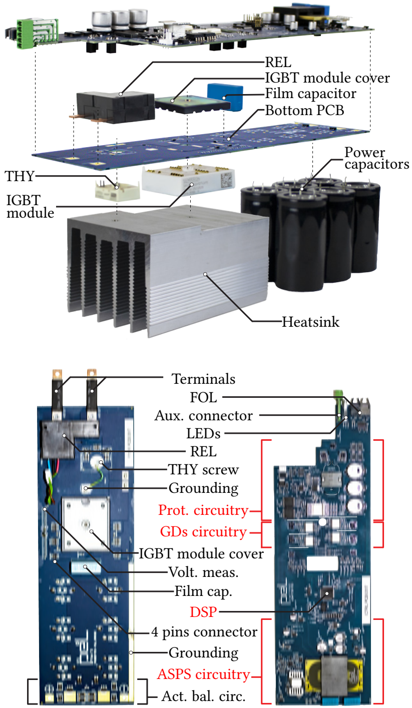
- SM is a simple topology but complex in practice ⟶ large number of components
- Opportunity/tool to prevent failure
- Asset management ⟶ reliability ↑ - availability ↑

Challenges:

- Narrowed to a few components
- Complex existing algorithms
- Limited measurement capability (sensors, accuracy, precision, volume, cost...)
- Limited computational power (at least at SM-level)

Vision:

- Methods simplification
- Wider monitoring using existing measurements
- Healt Index integration ⟶ asset management improvement

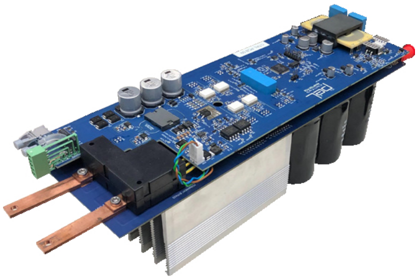


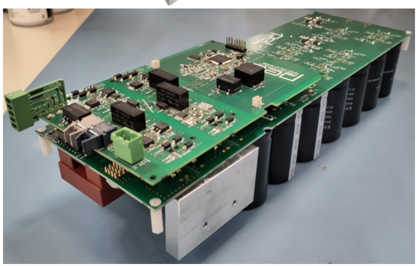
▲ PEL SM - exploded view

[30]Ignacio Polanco Lobos and Drazen Dujic. "Condition Health Monitoring of Modular Multilevel Converter Submodule Capacitors." *IEEE Transactions on Power Electronics* (2021), pp. 1–1

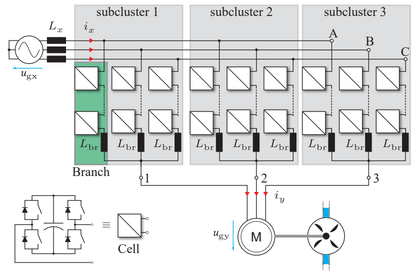
New MMC SM

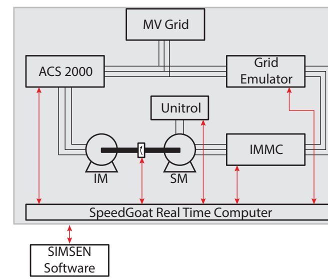
- 2kV DC link
- 3.3kV discrete semiconductors
- 9 branches with 8 sub-modules
- 72 SM needed





▲ Ongoing MMC sub-module redesign...





▲ RT-HIL for Direct MMC and experimental MV test rig

[31] Philippe Bontemps, Stefan Milovanovic, and Drazen Dujic. "Distributed Real-Time Model of the M3C for HIL Systems Using Small-Scale Simulators." *IEEE Open Journal of Power Electronics* (2021), pp. 1–1

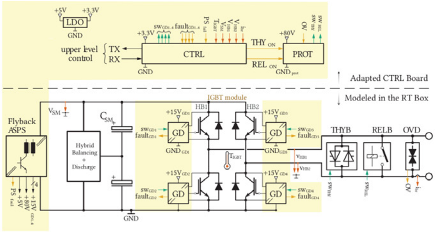
[32] Philippe Bontemps, Stefan Milovanovic, and Drazen Dujic. "Performance Analysis of Energy Balancing Methods for Matrix Modular Multilevel Converters." *IEEE Transactions on Power Electronics* (2022), pp. 1–15

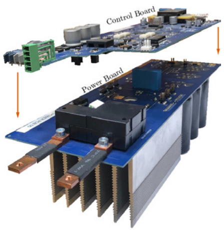
SUMMARY

...

Medium Voltage Power Electronics Research at University

- 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
- Control development - RT HIL tools are great asset
- It takes time, money and a lot of patience...





▲ PEL developed MMC sub-module

▲ MMC - Actual mechanical assembly

▲ Digital Twins - Four RT-HIL systems allowing for various topological reconfigurations

[1] Renan Pillon Barcelos and Dražen Dujić. "Direct Current Transformer Impact on the DC Power Distribution Networks." *IEEE Transactions on Smart Grid* (2022), pp. 1–1.

[2] Renan Pillon Barcelos, Jakub Kucka, and Drazen Dujic. "Power Reversal Algorithm for Resonant Direct Current Transformers for DC Networks." *IEEE Access* 10 (2022), pp. 127117–127127.

[3] R. Pillon Barcelos and D. Dujic. "On Features of Direct Current Transformers." *The 11th International Conference on Power Electronics - ICPE - ECCE Asia*. May 2023, pp. 1912–1918.

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

[5] Gabriele Ulissi et al. "High Frequency Operation of Series-Connected IGCTs for Resonant Converters." *IEEE Transactions on Power Electronics* (2021), pp. 1–1.

[6] Gabriele Ulissi et al. "Resonant IGCT Soft-Switching: ZVS or ZCS." *IEEE Transactions on Power Electronics* (2022), pp. 1–1.

[7] N. Djekanovic, M. Luo, and D. Dujic. "Thermally-Compensated Magnetic Core Loss Model for Time-Domain Simulations of Electrical Circuits." *IEEE Transactions on Power Electronics* (2021), pp. 1–1.

[8] N. Djekanovic and D. Dujic. "Modeling and Characterization of Natural-Convection Oil-Based Insulation for Medium Frequency Transformers." *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2022.

[9] N. Djekanovic and D. Dujic. "Design Optimization of a MW-level Medium Frequency Transformer." *PCIM Europe 2022; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of*. May 2022, pp. 735–744.

[10] Nikolina Djekanovic and Drazen Dujic. "Copper Pipes as Medium Frequency Transformer Windings." *IEEE Access* 10 (2022), pp. 109431–109445.

[11] R.P. Barcelos and D. Dujic. "Parallel Operation of Direct Current Transformers." *PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of*. May 2023, pp. 87–96.

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

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

[14] N. Hildebrandt, M. Luo, and D. Dujic. "Robust and Cost Effective Synchronization Scheme for a Multicell Grid Emulator." *IEEE Transaction on Industrial Electronics* (2020), pp. 1–1.

[15] Chengmin Li, Jing Sheng, and Drazen Dujic. "Reliable Gate Driving of SiC MOSFETs With Crosstalk Voltage Elimination and Two-Step Short-Circuit Protection." *IEEE Transactions on Industrial Electronics* (2022), pp. 1–10.

[16] C. Li and D. Dujic. "Crosstalk Voltage Suppression of SiC MOSFET With An Auxiliary Bidirectional Switch." *The 11th International Conference on Power Electronics - ICPE - ECCE Asia*. May 2023, pp. 381–386.

[17] T. Wei, A. Cervone, and D. Dujic. "Second Harmonic Ripple Voltage Suppression for Single-Phase ISOP Solid-State Transformer by Active Power Decoupling." *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2023.

[18] H. Takayama et al. "Square-Wave Source with Adjustable dv/dt for Insulation Testing under Mixed-Frequency Stresses." *2023 IEEE Applied Power Electronics Conference and Exposition (APEC)*. Mar. 2023.

[19] A. Christe, E. Coulinge, and D. Dujic. "Insulation coordination for a modular multilevel converter prototype." *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*. Sept. 2016, pp. 1–9.

[20] I. Polanco and D. Dujic. "Thermal Study of a Modular Multilevel Converter Submodule." *PCIM Europe digital days 2020; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. 2020, pp. 1–8.

[21] E. Coulinge, A. Christe, and D. Dujic. "Electro-Thermal Design of a Modular Multilevel Converter Prototype." *PCIM Europe 2016; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*. May 2016, pp. 1–8.

[22] A. Christe and D. Dujic. "Virtual Submodule Concept for Fast Semi-Numerical Modular Multilevel Converter Loss Estimation." *IEEE Transactions on Industrial Electronics* 64.7 (July 2017), pp. 5286–5294.

[23] A. Christe et al. "Auxiliary submodule power supply for a medium voltage modular multilevel converter." *CPSS Transactions on Power Electronics and Applications* 4.3 (Sept. 2019), pp. 204–218.

[24] S. Milovanovic and D. Dujic. "Upscaling Small Real-Time Simulators for Large Power Electronic Systems." *Bodo's Power Systems* 5 (2021), pp. 72–74.

[25] Stefan Milovanovic et al. "Flexible and Efficient MMC Digital Twin Realized With Small-Scale Real-Time Simulators." *IEEE Power Electronics Magazine* 8.2 (2021), pp. 24–33.

[26] Stefan Milovanović, Min Luo, and Dražen Dujić. "Virtual Capacitor Concept for Computationally Efficient and Flexible Real-Time MMC Model." *IEEE Access* 9 (2021), pp. 144211–144226.

[27] S. Milovanovic, M. Luo, and D. Dujic. "Virtual Capacitor Concept for Effective Real-Time MMC Simulations." *PCIM Europe Digital Days 2021*. May 2021, pp. 437–444.

BIBLIOGRAPHY

[28] Stefan Milovanović et al. “Hardware-in-the-Loop Modeling of an Actively Fed MVDC Railway Systems of the Future.” *IEEE Access* 9 (2021), pp. 151493–151506.

[29] S. Milovanovic and D. Dujic. “Comprehensive Comparison of Modular Multilevel Converter Internal Energy Balancing Methods.” *IEEE Transactions on Power Electronics* (2021), pp. 1–1.

[30] Ignacio Polanco Lobos and Drazen Dujic. “Condition Health Monitoring of Modular Multilevel Converter Submodule Capacitors.” *IEEE Transactions on Power Electronics* (2021), pp. 1–1.

[31] Philippe Bontemps, Stefan Milovanovic, and Drazen Dujic. “Distributed Real-Time Model of the M3C for HIL Systems Using Small-Scale Simulators.” *IEEE Open Journal of Power Electronics* (2021), pp. 1–1.

[32] Philippe Bontemps, Stefan Milovanovic, and Drazen Dujic. “Performance Analysis of Energy Balancing Methods for Matrix Modular Multilevel Converters.” *IEEE Transactions on Power Electronics* (2022), pp. 1–15.

THANK YOU FOR YOUR ATTENTION