UTILISING RT BOXES TO SUPPORT THE DEVELOPMENT OF MEDIUM VOLTAGE MODULAR MULTILEVEL CONVERTERS

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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	Liverpoool John Moores University, Liverpool, United Kingdom
2003 – 2006	University of Novi Sad, Novi Sad, Serbia

Education

2008	PhD, Liverpoool 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

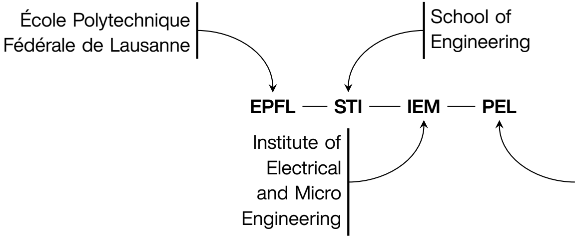
INDUSTRIAL RESEARCH PROJECTS

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



- Active since February 2014
- Currently: 10 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

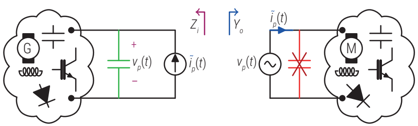
▲ Power Electronics Laboratory

PEL RESEARCH FOCUS

MVDC Technologies and Systems

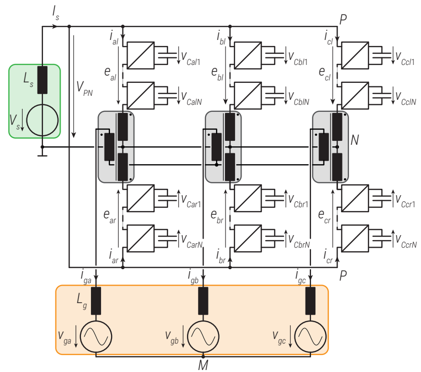
- System Stability
- Protection Coordination
- Power Electronic Converters

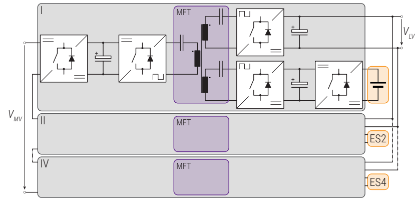
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS



High Power Electronics

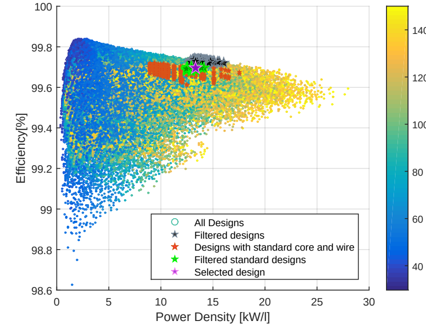
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion

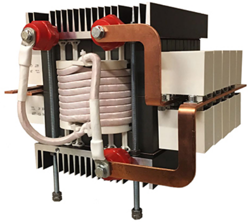




Components

- Semiconductor devices
- Magnetics
- Modeling, Characterization





MMC RESEARCH PLATFORM

High power university lab prototype and versatile HIL system

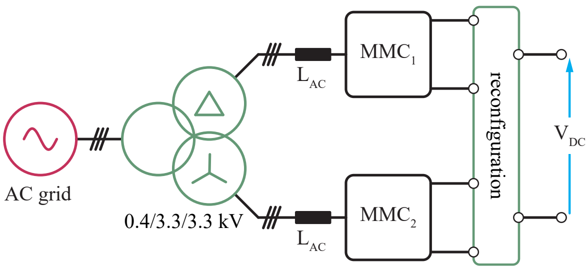
Pump Hydro Storage Research Platform

- MMC based AC/AC converter
- Interface between SG and local AC grid

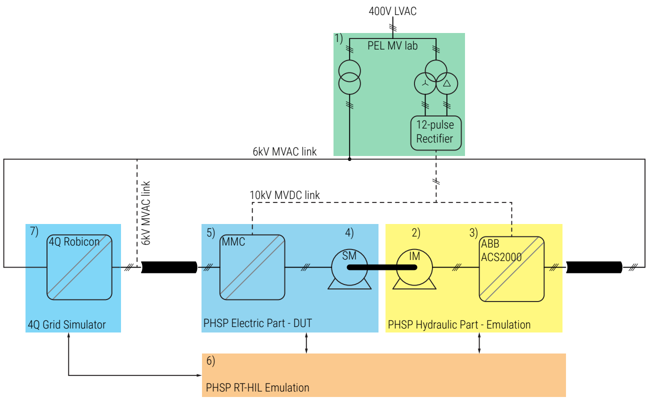
▲ MMC-Based AC/AC Converter for Pump Hydro Applications

Flexible DC Source (FlexDCS)

- MMC Based DC Source rated at 0.5 MVA
- Reconfiguration unit allows series/parallel operation
- Four quadrant operation
- Flexible voltage source in a range ±10 kV DC
- Flexible current source in a range ±100 A DC



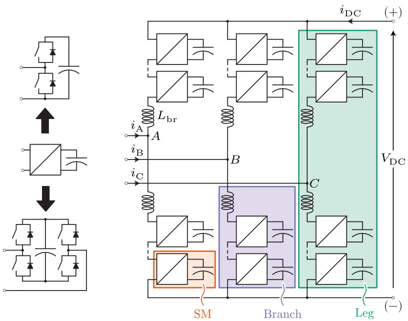
▲ Flexible DC Source Topology [1]



▲ Pumped Hydro Storage Plants - Research Platform

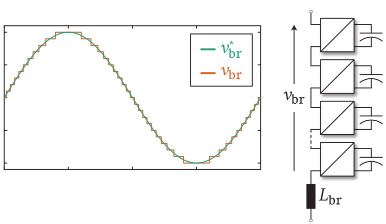
[1] M. Utvić, S. Milovanović, and D. Dujić. "Flexible Medium Voltage DC Source Utilizing Series Connected Modular Multilevel Converters." *2019 21st European Conference on Power Electronics and Applications (EPE '19 ECCE Europe)*. 2019, pp. 1–9

MODULAR MULTILEVEL CONVERTER



▲ Modular Multilevel Converter

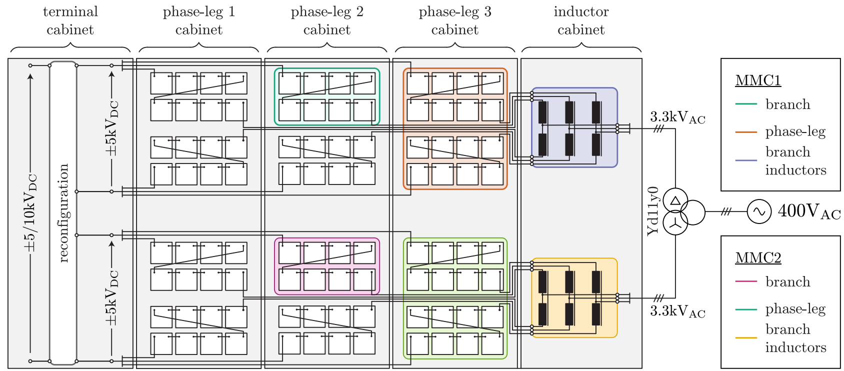
- Series connection of HB/FB Submodules (SMs)
- Flexible in terms of voltage scaling
- High quality voltage waveforms



▲ Branch with its voltage waveform

MMC demonstrator ratings

- 500 kVA or 2 x 250 kVA rated MMCs
- 2 x 3.3 kV$_{ac}$ $\longleftrightarrow$ ± 10 kV$_{dc}$
- 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

⇒ **The need for HIL**

Complex control structure requiring flexible and safe means of testing

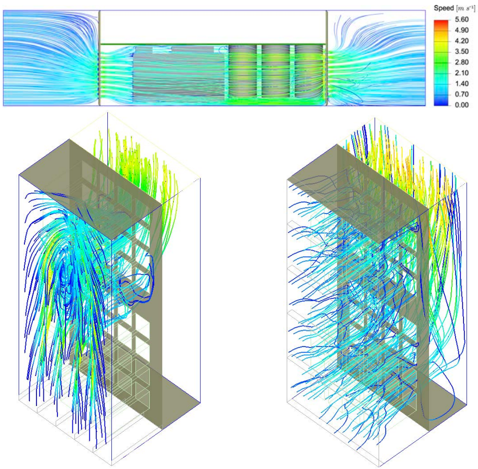
MMC – SUBMODULE OPTIMIZATION

Submodule

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

Thermal design

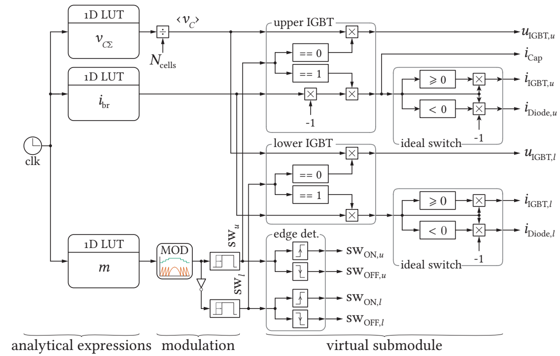
- Cell level: detailed FEM
- Cabinet level: simplified FEM

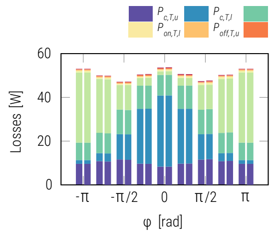


▲ CFD simulations

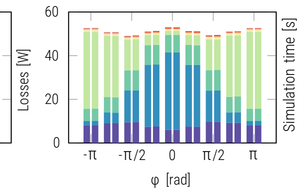
Semiconductor losses

- Virtual Submodule concept has been utilized [2]
- Closed-loop waveforms are approached by analytical waveforms

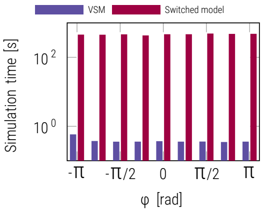




▲ PS-PWM, DC circ



▲ PS-PWM, DC+2nd circ

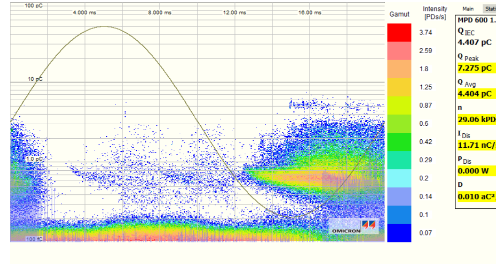


▲ Time benchmark

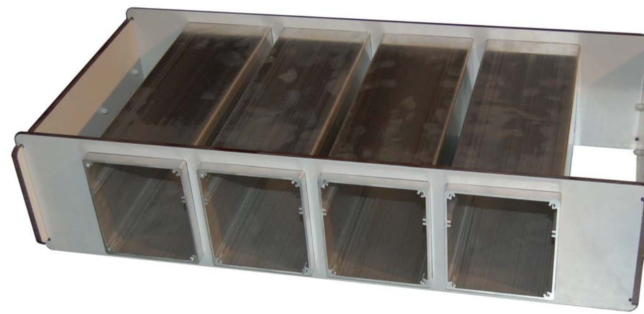
[2] A. Christe and D. Dujic. "Virtual Submodule Concept for Fast Semi-Numerical Modular Multilevel Converter Loss Estimation." *IEEE Transactions on Industrial Electronics* 64.7 (July 2017), pp. 5286–5294

- ✓ MV MMC converter laboratory prototype layout compliant with:
  - UL840 (for cell)
  - IEC 61800-5-1
- ✓ Complete AC dielectric withstand tests on real prototype [3]

▲ Cabinet of one phase-leg (32 cells) in Faraday cage during insulation coordination testing



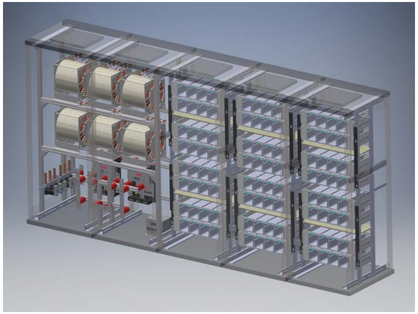
▲ AC dielectric withstand test result



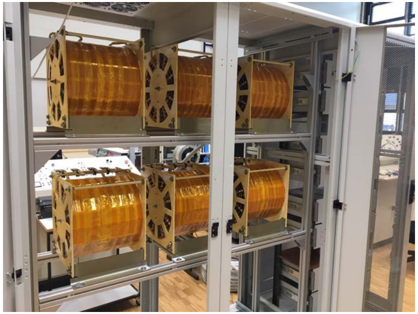
▲ Drawer holding 4 cell (MKHP material)

[3] 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

MMC MECHANICS

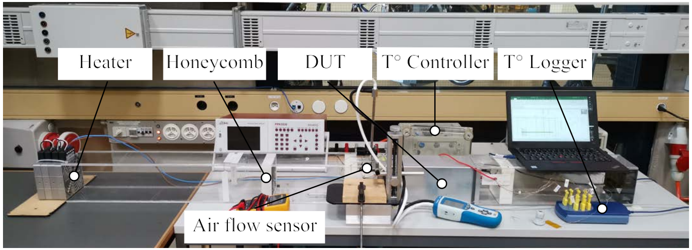


▲ MMC CAD development



▲ MMC coupled air-core branch inductors

▲ MMC - Actual mechanical assembly



▲ MMC Submodule thermal heat-run test setup [4]

[4] 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

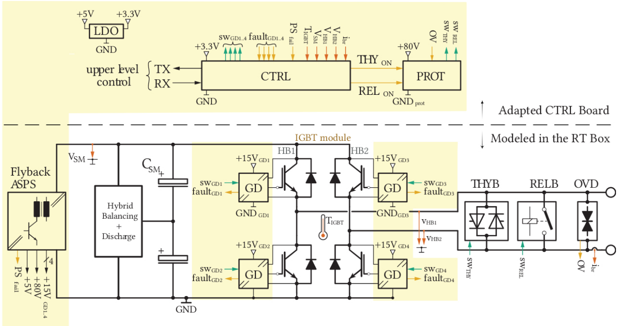
MMC SUB-MODULE

Low voltage based sub-module including cell controller

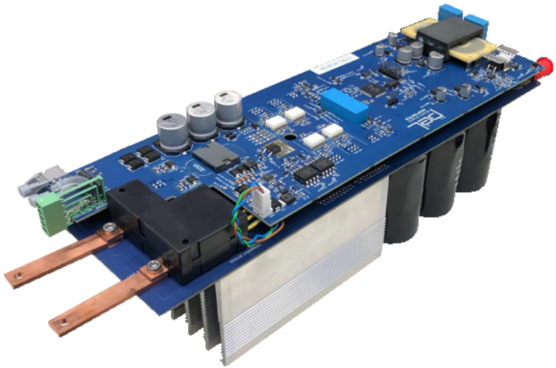
MMC SUB-MODULE – STRUCTURE

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**

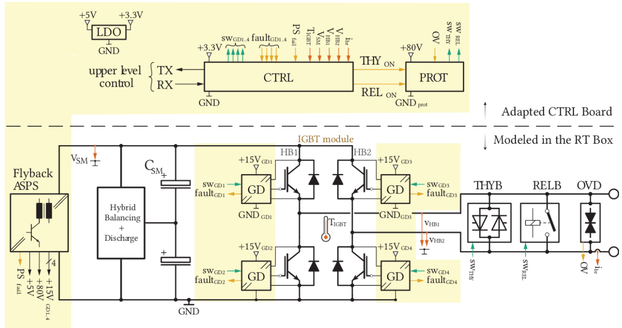


▲ MMC Sub-module Structure: Yellow parts - Control PCB

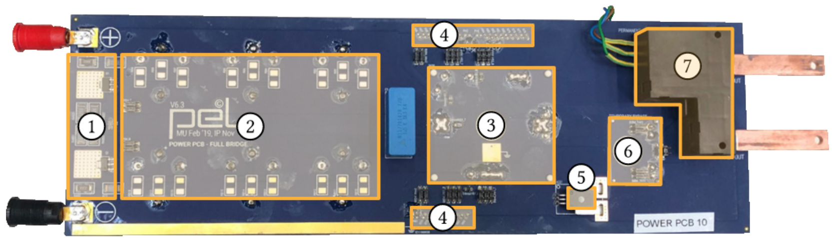


▲ Developed MMC FB sub-module based on the 1.2kV IGBTs

- 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



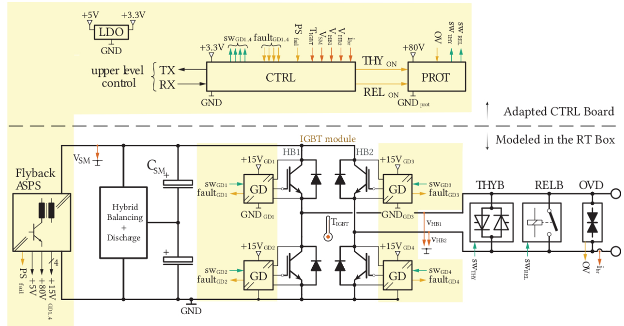
▲ MMC Sub-module Structure: Yellow parts - Control PCB



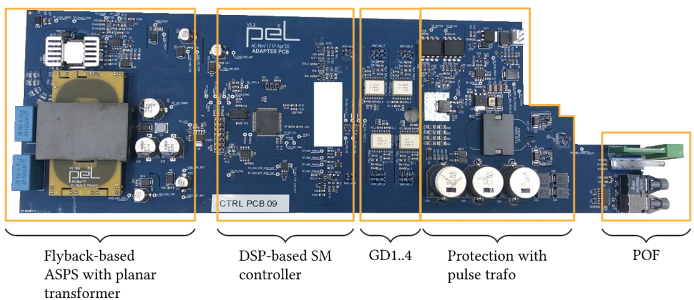
1 - Balancing Circuitry
2 - SM Capacitors
3 - IGBT Module
4 - Voltage Dividers
5 - Current Sensor
6 - Thyristor Module
7 - Bypass Relay

▲ Overview of the Power PCB

- Flyback based auxiliary power supply [5]
  - +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



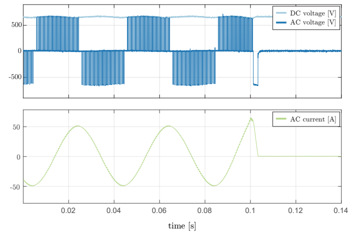
▲ Overview of the Control PCB

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

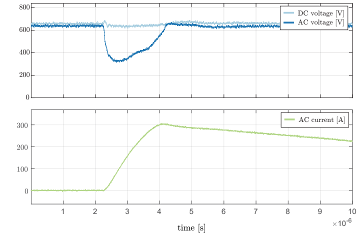
MMC SUB-MODULE POWER TESTS

Extensive testing has been done:

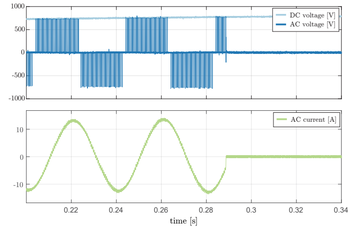
- Power tests
- Thermal heat-runs
- Over current tests
- Loss of power supply
- DC link over voltage
- Terminal over voltage
- Short-circuit tests
- ...



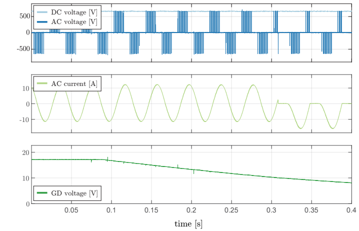
▲ MMC SM over current test



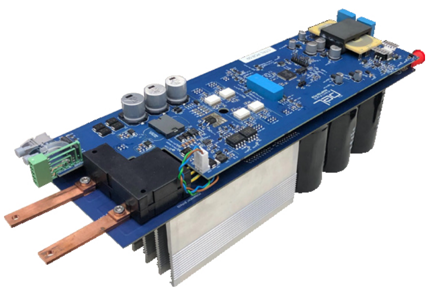
▲ Short circuit test (Desat detection)



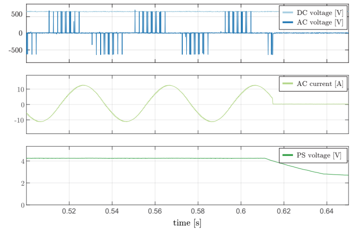
▲ MMC SM over voltage test



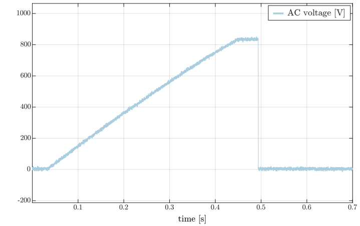
▲ Gate Driver failure



▲ Developed MMC FB sub-module



▲ Power supply under voltage detection



▲ AC terminals over voltage detection

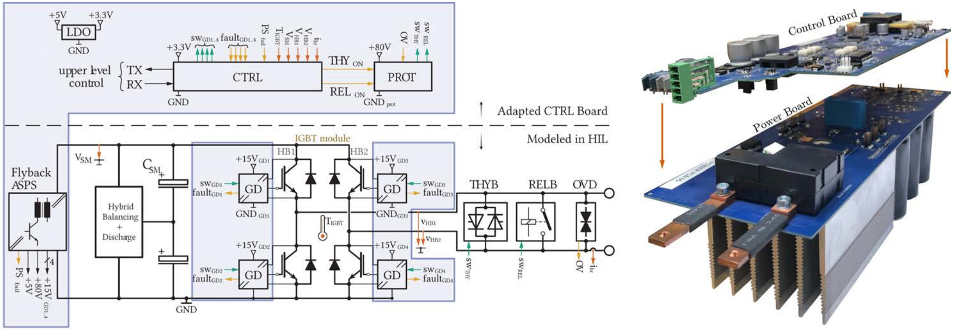
MMC DIGITAL TWIN

RT-Box based distributed HIL system

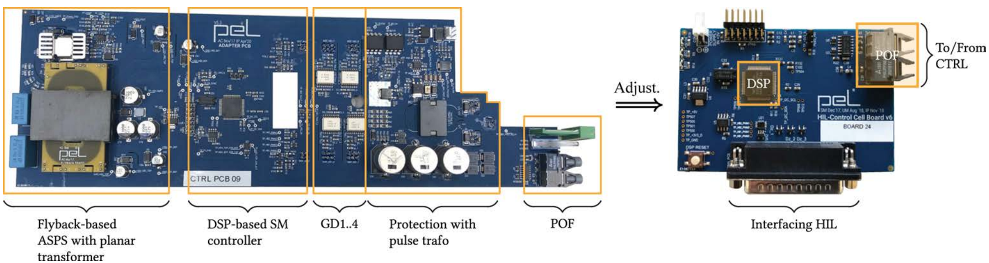
MMC SUBMODULE AND HIL-RELEVANT ADAPTATIONS

Key features

- LV power components (1.2 kV IGBTs)
- Full-bridge submodule structure
- Submodule rated voltage - 625 V
- Submodule insulation coordination - 900 V
- Two interconnected PCBs:
  - **Power PCB**
  - **Control PCB**



▲ MMC SM structure; Parts highlighted in purple belong to the Control PCB



▲ Control PCB adjustments needed for HIL real-time simulations

⇒ **Virtual Power Processing**

Power parts of the SM get modeled in the simulator, while parts of the Control PCB must be retained to match the real scenario.

DSP outputs governing the SM power part

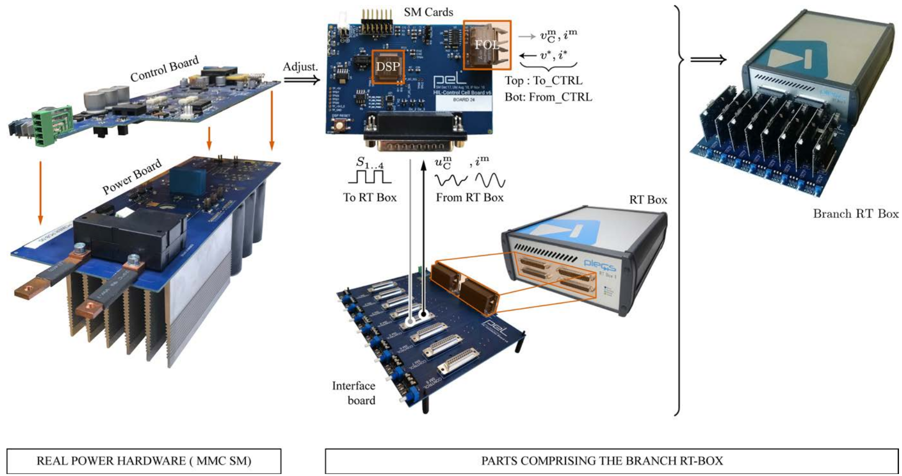
- Four switching signals $S_1 \dots S_4$
- Protection triggering (THY_ON and REL_ON)

Signals sent from the SM to PEC:

- SM cap. voltage (V_{SM})
- SM current (i_{SM})
- SM AC terminal voltages (V_{AC1} and V_{AC2})
- IGBT module temp T_{IGBT}

▲ Channels available on the RT Box 1

Description	No. of channels/ connectors	Voltage range
Analog Inputs	16	$-10\mathrm{V} \dots 10\mathrm{V}$
Analog Output	**16**	$-10\mathrm{V} \dots 10\mathrm{V}$
Digital Inputs	**32**	3.3V or 5V
Digital Outputs	32	3.3V or 5V
SFP Connectors	4	N.A.



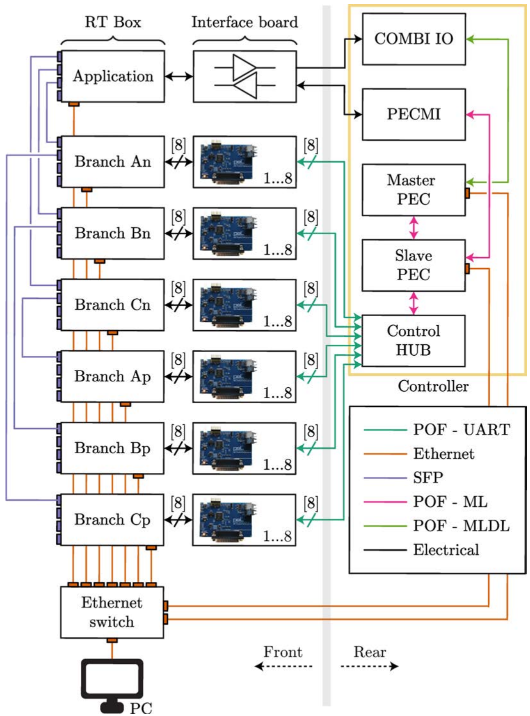
▲ Transformation of MMC cell into digital twin equivalent system [6]

Limitation in the number of RT Box DIs and AOs

One RT Box hosts up to 8 SMs ⇒ 6 x Branch RT Box for the real-time simulation of MMC branches + 1 RT Box for Application (e.g. AC grid/AC machine/etc.)

[6] 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 (II)



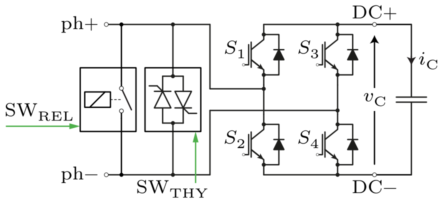
▲ Digital Twin - Realized RT-HIL system for control verification purpose: (left) front view; (middle) wiring scheme; (right) back view.

RT-HIL MODELING

Managing complexity of modular converters

MMC REAL-TIME MODELING (I)

Switched model of an SM



▲ FB SM with protection circuitry

In a circuit with N switches, the number of distinct topologies equals 2^N.

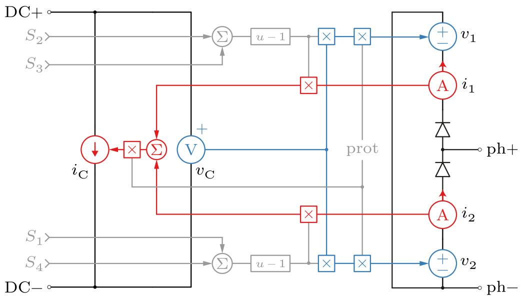
- Every state is described with its own state-space matrix
- Matrices need to be stored in the simulator memory
- Real-time code size and execution times

The number of switching devices in the model must be minimized to the highest possible extent

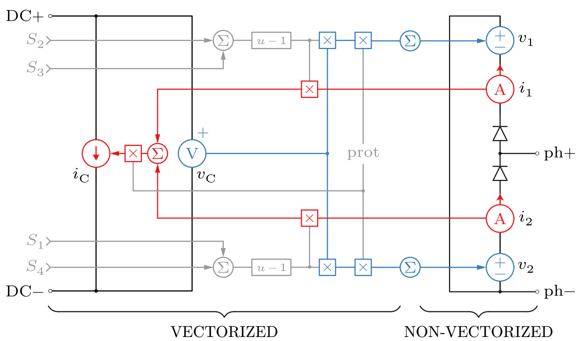
Sub-cycle average models

⇒ Mathematical equivalents retaining all physical properties of the switched model

Sub-cycle average models

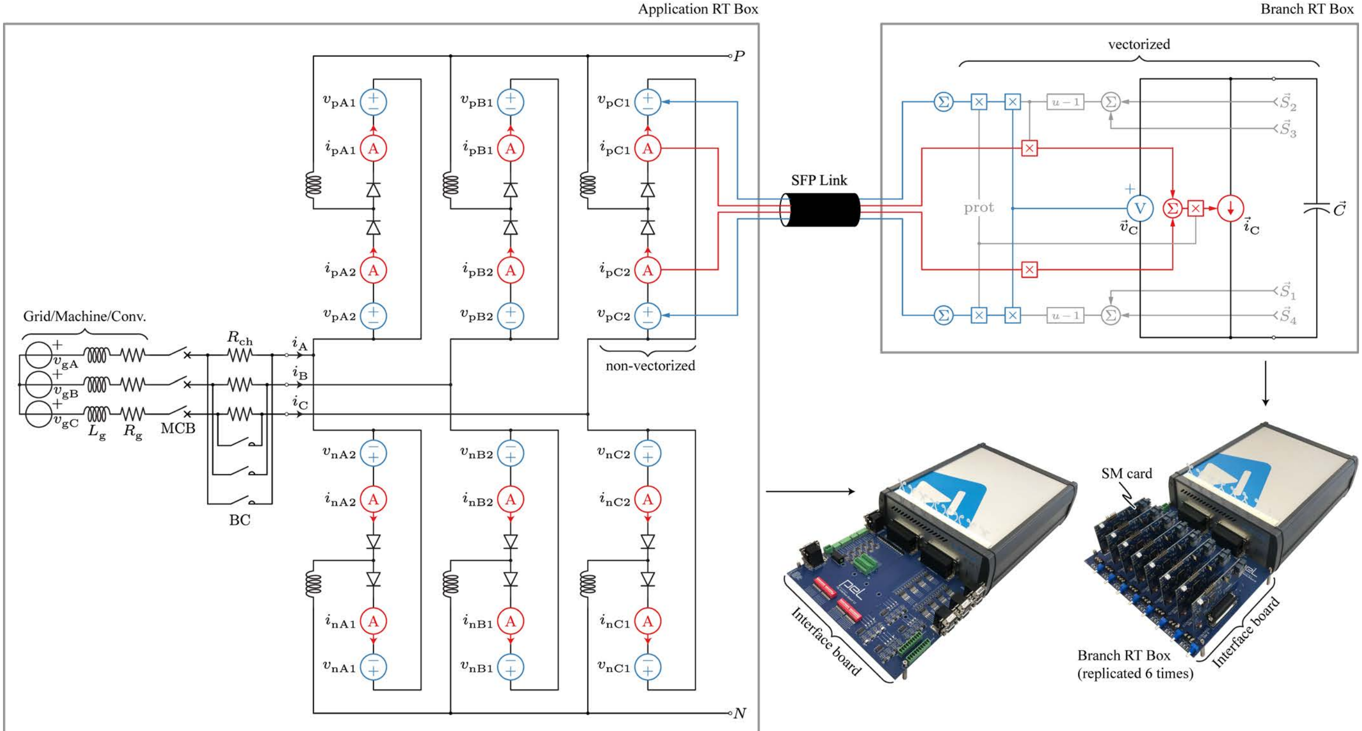


▲ Sub-cycle average model of the FB SM ($\text{prot} = \text{SW}_{\text{REL}} \wedge \text{SW}_{\text{THY}}$)



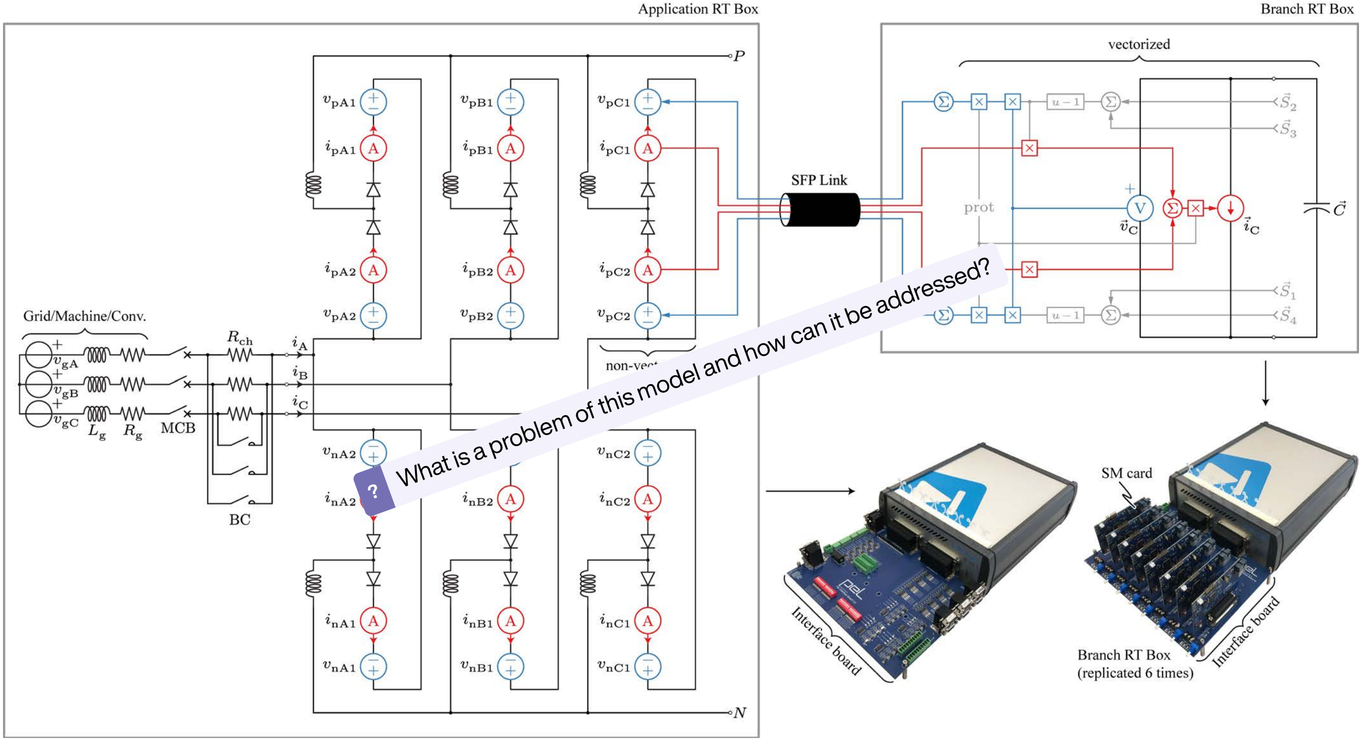
▲ Sub-cycle average model of a cluster of FB SMs

MMC REAL-TIME MODELING (II)



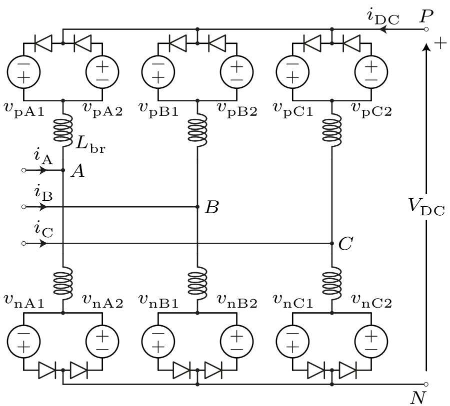
▲ Splitting of the branch model required for proper emulation of the MMC behavior in various operating regimes.

MMC REAL-TIME MODELING (II)



▲ Splitting of the branch model required for proper emulation of the MMC behavior in various operating regimes.

CIRCUIT SPLITTING



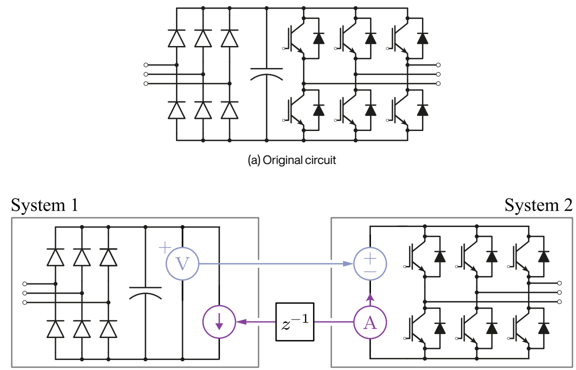
▲ MMC model running on the Application RT Box

- 12 diodes ⇒ 2^{12} circuits (state-space matrices)
- Step-size $T_{\text{step}} > 75\mu$s
- Code generation > 2min

Simulation step-size is unacceptably large

The circuit must be sectioned into several independent parts

Circuit splitting - General idea



(a) Original circuit

(b) Two circuits obtained after the splitting

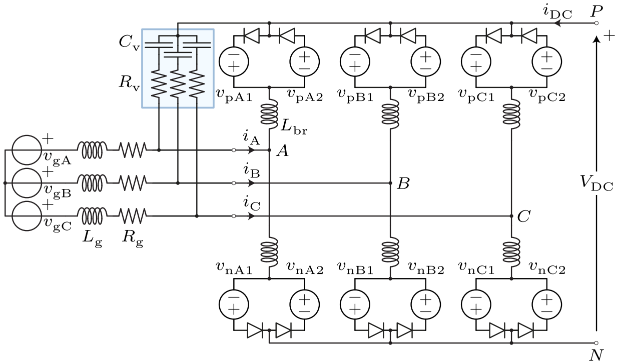
▲ An example of possible circuit splitting.

- Artificial delay is introduced between newly formed circuit parts
- Systems 1 and 2 are treated independently
- The number of state-space matrices is reduced from 2^{12} to 2×2^6
- Reduction of the simulation step-size
- Splitting should be done at a place containing either capacitor or inductor

? The analyzed model does not have a concentrated DC link

VIRTUAL CAPACITOR CONCEPT APPLIED TO THE MMC MODEL (I)

- "Virtual" $\Longleftrightarrow$ these elements do not exist in reality [7]
- Virtual elements do not conduct current components relevant for control testing
- Virtual elements can be used for circuit splitting!

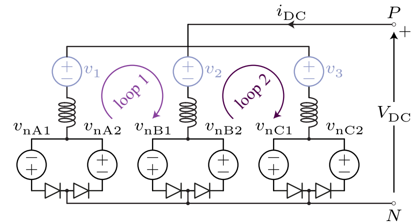


▲ Extension of the original MMC by the so-called virtual capacitor highlighted in blue.

- Virtual capacitors $\Rightarrow$ Circuit splitting
- Virtual resistors $\Rightarrow$ Numeric stability

Separating lower branches from the MMC model

Upper branches $\equiv$ a set of voltage sources.



▲ Separating the set of lower branches from the original MMC model

The role of voltage sources v_1, v_2 and v_3:

1. Preservation of the KVL equations
2. What is seen from the DC terminal must be equivalent to the original circuit.

Therefore, one can conclude that

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} = \begin{bmatrix} v_{PA} \\ v_{PB} \\ v_{PC} \end{bmatrix}.$$

[7] 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

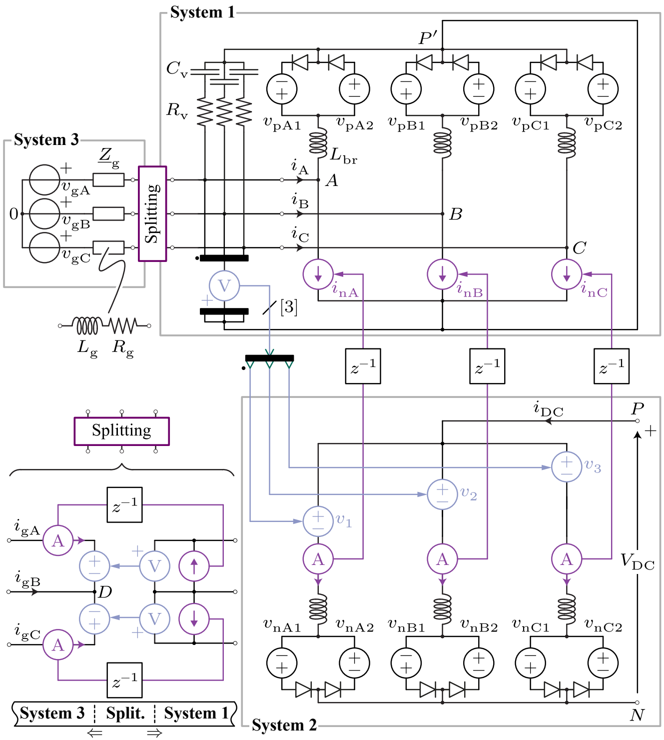
VIRTUAL CAPACITOR CONCEPT APPLIED TO THE MMC MODEL (II)

- Lower branches ≡ a set of current sources
- Three independent systems
  - System 1 ⇒ Upper branches including VCs and VRs
  - System 2 ⇒ Lower branches
  - System 3 ⇒ AC grid (or AC machine, etc.)
- Seen from the AC terminals, branches operate in parallel
- The number of state-space matrices is 2×2^6
- Step-size $T_{\text{step}} = 7\mu s$
- Code generation ≈ 10s

⇒ **Circuit splitting benefits**

More than a ten fold reduction in the simulation step-size!

? Is model functionality preserved?



▲ Model of the MMC relying on the use of three independent systems.

▼ Parameters of the converter used for further analyses

Rated power (S^*)	Output voltage (V_{DC})	Grid voltage (v_g)	Number of SMs per branch (N)	Nominal SM voltage (V_{SM})	SM capacitance (C_{SM})	Branch inductance (L_{br})	Branch resistance (R_{br})	PWM carrier frequency (f_c)	Fundamental frequency (f_o)	Virtual capacitance (C_v)	Virtual resistance (R_v)
250kVA	5kV	3.3kV	8	650V	2.25mF	2.5mH	60mΩ	1kHz	50Hz	360nF	45Ω

- Converter with parameters provided above
- Real industrial ABB PEC800 controller
  - Master & Slave PECs (flexibility in reconfiguration)
  - PECMI (v and i measurements)
  - Control HUB (SM signals aggregation and reference processing)
  - COMBIO (Relays/Switches/Monitoring)
- Application RT Box step-size → 7μs
- Branch RT Box step-size → 3.5μs

⇒ Control structure identical to the real prototype

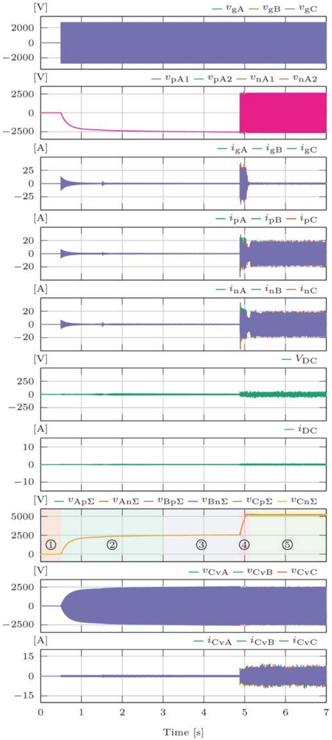
(a) Front view

(b) Rear view

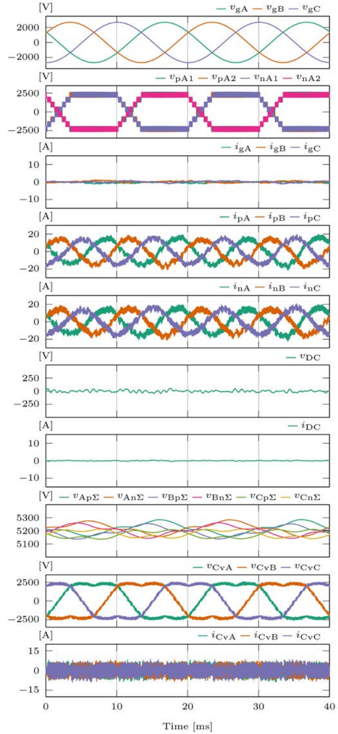
▲ HIL system used for result verification purpose.

Test scenarios

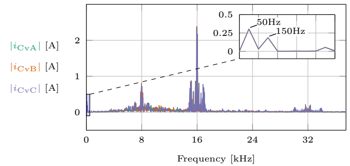
- Converter charging
  1. Converter OFF
  2. Passive charging
  3. Timeout
  4. Active charging
  5. Timeout
- No load operation



▲ Converter charging process.



▲ No load operation.

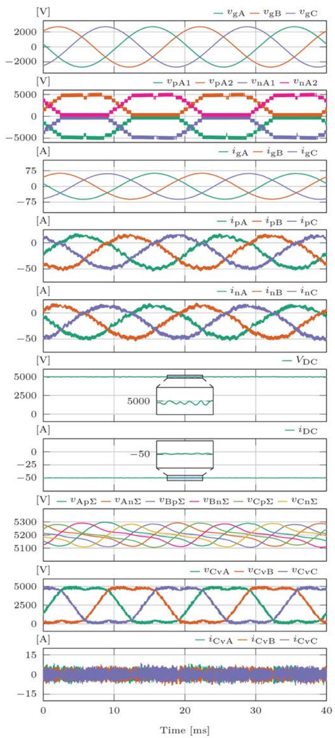


▲ Spectral content of VC currents ($P_{DC} = 0$).

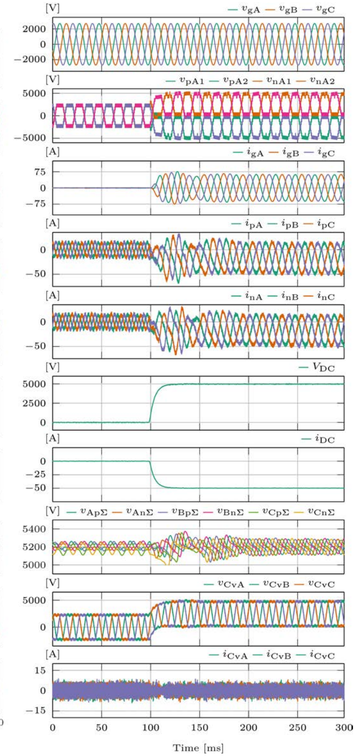
MODEL VERIFICATION (I)

Test scenarios

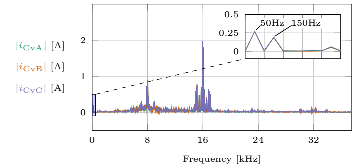
- Full load
  - $\hat{P}_{DC} = 250\text{kW}$
  - Rect. op. mode
- Load change $0 \rightarrow \hat{P}_{DC}$



▲ Operation at full load.



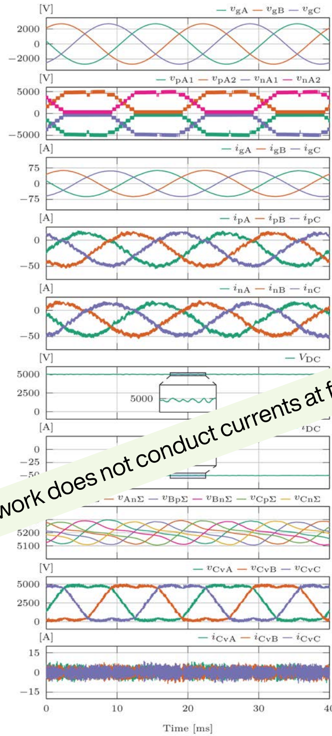
▲ Load change.



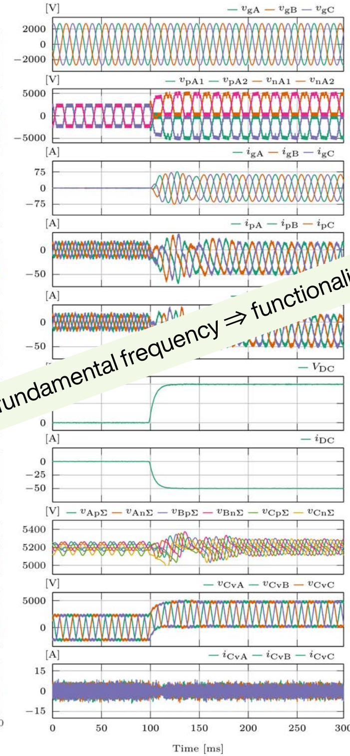
▲ Spectral content of VC currents ($P_{DC} = 250\text{kW}$).

Test scenarios

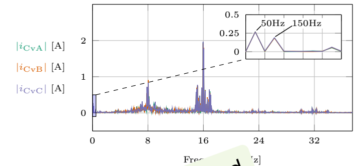
- Full load
  - $\hat{P}_{DC} = 250$kW
  - Rect. op. mode
- Load change $0 \rightarrow \hat{P}_{DC}$



▲ Operation at full load.



▲ Load change.



▲ Spectral conten ($P_{DC} = 250$kW).

⇒ Virtual network does not conduct currents at fundamental frequency ⇒ functionality of the model is not altered

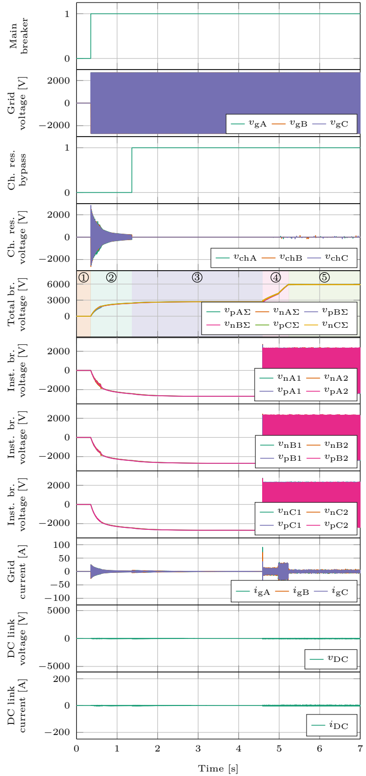
CONTROL SW TESTING

Results recorded from the HIL platform

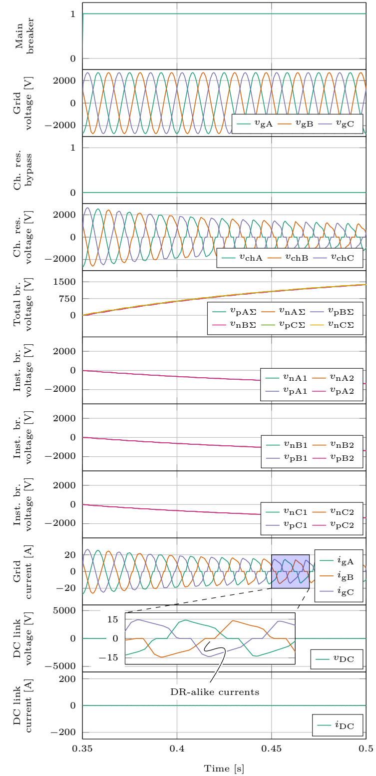
MMC OPERATION (I)

▲ 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

▲ 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
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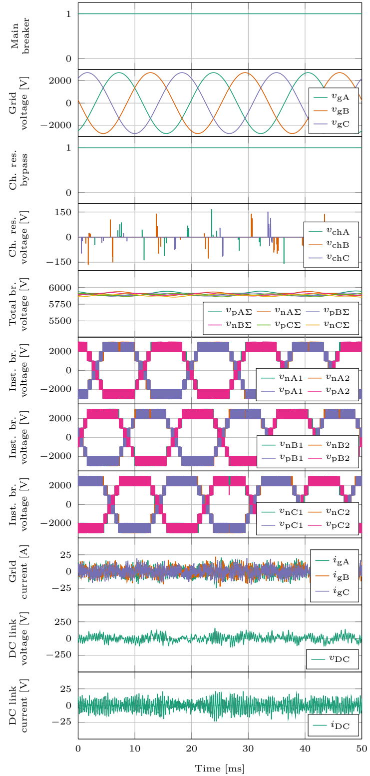
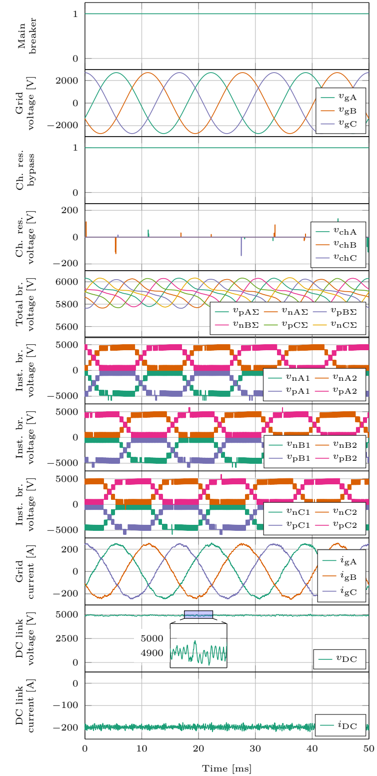


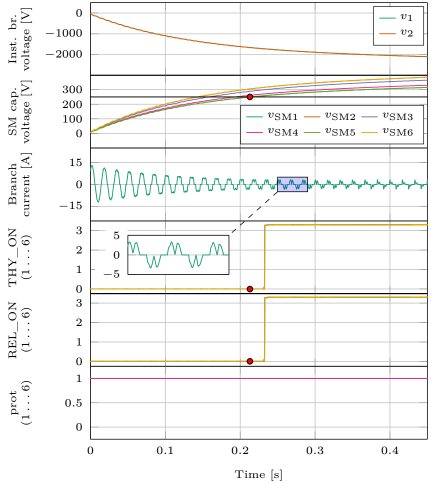
▲ Converter operation at no load ($P_{DC} = 0$)



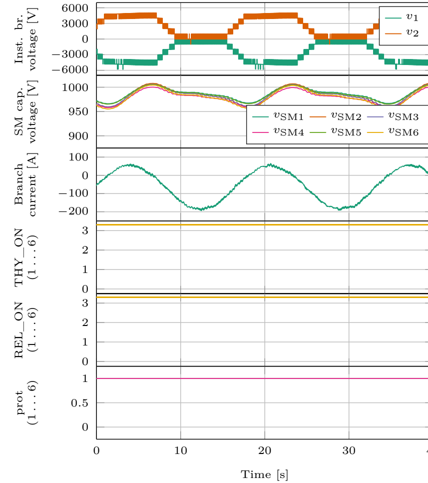
▲ Converter operation at full load ($P_{DC} = 1MW$)

▲ 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

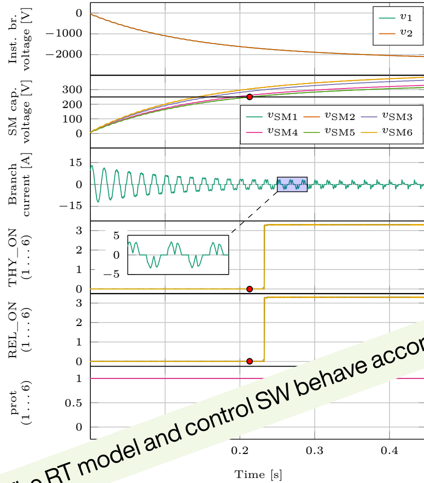


▲ Branch operation at full load

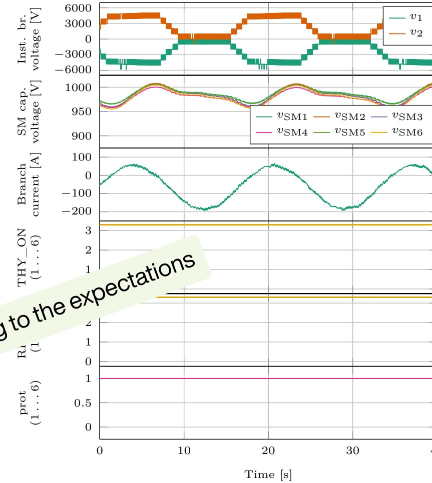
MMC OPERATION (III)

▲ 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



▲ ...sive charging of a branch



▲ Branch operation at full load

⇛ The RT model and control SW behave according to the expectations

MMC RELATED WORKS

Using developed platform to drive research forward…

Ignacio Polanco

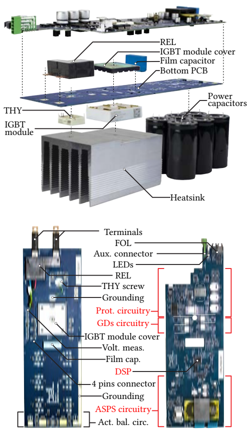
09.2018 – 08.2022

MSc: UDC, Chile

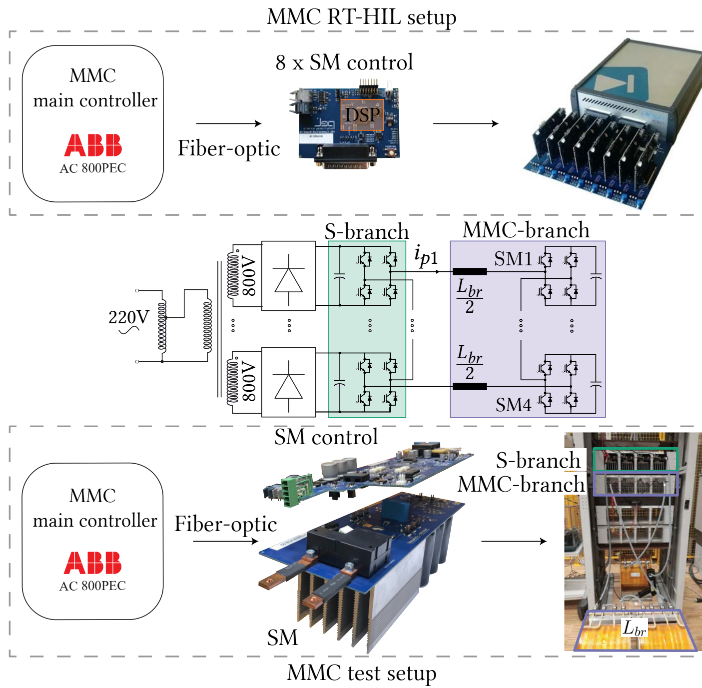
PhD: Condition health monitoring for MMC

Objectives

- to develop new MMC SM CHM strategies [8]
- to explore new approaches to integrate existing MMC SM component-level CHM indicators



▲ PEL SM - exploded view



▲ MMC testing platform

[8] Ignacio Polanco and Dražen Dujić. "Condition Health Monitoring of Modular Multilevel Converter Submodule Capacitors." *IEEE Transactions on Power Electronics* 37.3 (2022), pp. 3544–3554

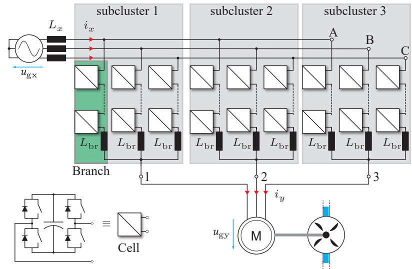
DIRECT MMC FOR HYDROPOWER APPLICATIONS

Philippe Bontemps

09.2019 – 08.2023

MSc: EPFL, Switzlerand

PhD: Direct MMC for hydro applications



Funding

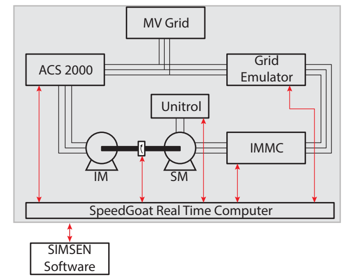
- EU project - XFLEX Hydro

Partners

- ALPIQ, ANDRITZ, ARMINES, CEA, EPFL, GE Renewable Energy, EDF, EDP, NEW, HES-SO, INESCTEC, IHA, PVE, MINES ParisTech, SuperGrid Institute, Universität Stuttgart, UPC, VOITH, Zabala

Objectives

- Flexibility enhancements of Pumped Hydro Storage Power Plant (PHSP) through variable speed drives
- Explore benefits in providing grid services
- Investigate impact on life expectancy of electric and hydraulic machinery
- RT HIL model of the direct-MMC in a PHSP application [9]
- Power-in-the-Loop test on a 500kVA/6kV test rig



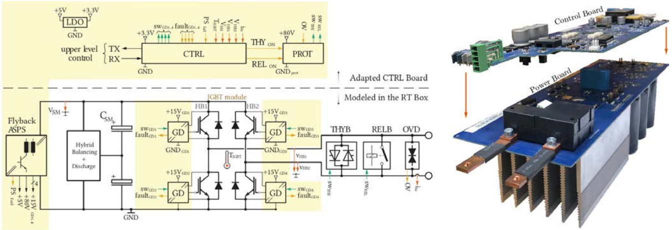
▲ RT-HIL for Direct MMC and experimental MV test rig

[9] 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* 2 (2021), pp. 603–613

SUMMARY

MMC research platform

- Electrical and mechanical design
- Insulation coordination
- Control development
- Testing independently HW and SW
- RT-HIL support for modeling and development
- Achieving flexibility for various applications
- Platform for future research activities



▲ PEL developed MMC sub-module

▲ MMC - Actual mechanical assembly

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

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[1] M. Utvić, S. Milovanović, and D. Dujić. “Flexible Medium Voltage DC Source Utilizing Series Connected Modular Multilevel Converters.” *2019 21st European Conference on Power Electronics and Applications (EPE ’19 ECCE Europe)*. 2019, pp. 1–9.

[2] 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.

[3] 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.

[4] 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.

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

[6] 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.

[7] 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.

[8] Ignacio Polanco and Dražen Dujić. “Condition Health Monitoring of Modular Multilevel Converter Submodule Capacitors.” *IEEE Transactions on Power Electronics* 37.3 (2022), pp. 3544–3554.

[9] 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* 2 (2021), pp. 603–613.

Acknowledgement:

- Dr. Alexandre Christe
- Dr. Stefan Milovanovic
- Dr. Ignacio Polanco
- Dr. Min Luo
- Dr. Emilien Coulinge
- Dr. Miodrag Basic
- Mr. Milan Utvic
- Mr. Philippe Bontemps

THANK YOU FOR YOUR ATTENTION