HIL and RCP capabilities of real time digital simulators for MMC and other power converter applications

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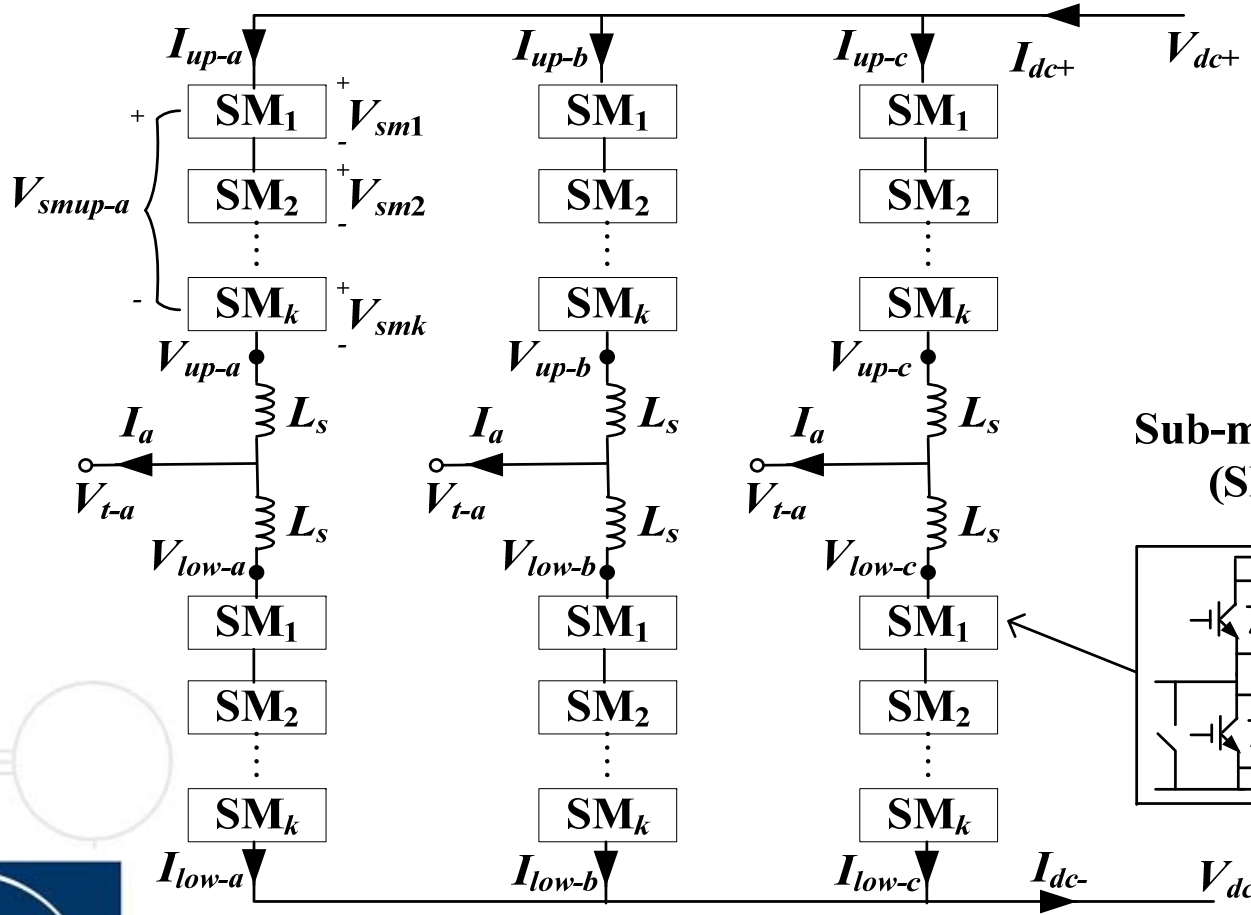
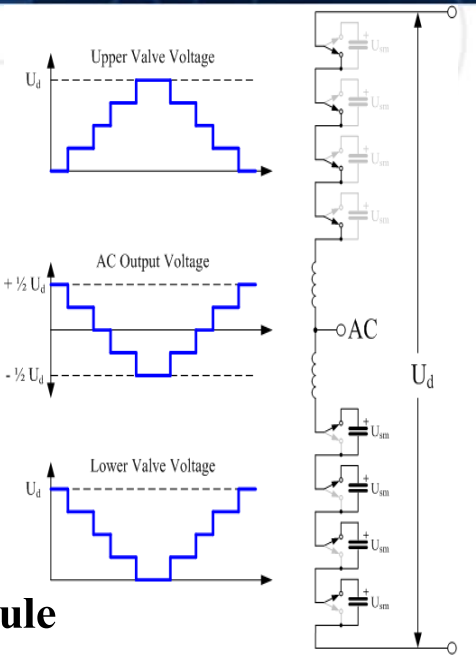
Contents

- MMC characteristics & advantages
- MMC projects and challenges
- Solutions to
  - Real time simulation of MMC systems
  - HIL test bench for MMC Control and protection system validation
- Industrial applications
- Conclusions

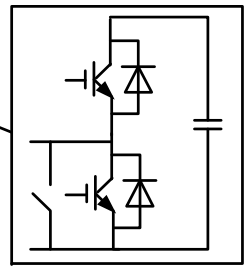
MMC HB ac-dc Converter

- Modular Multilevel Converter



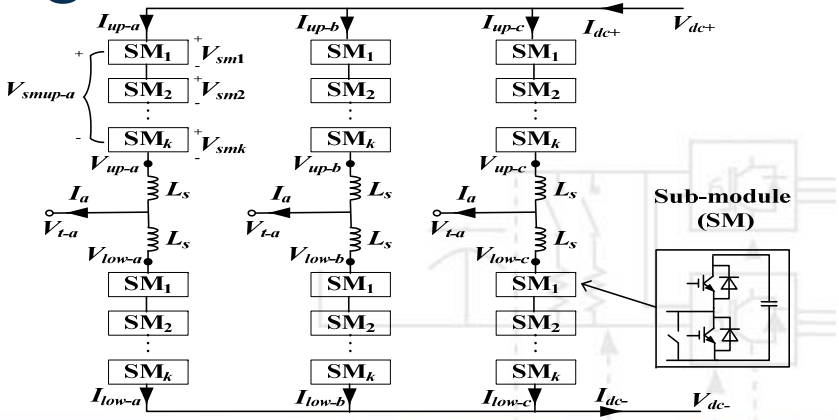


Sub-module (SM)



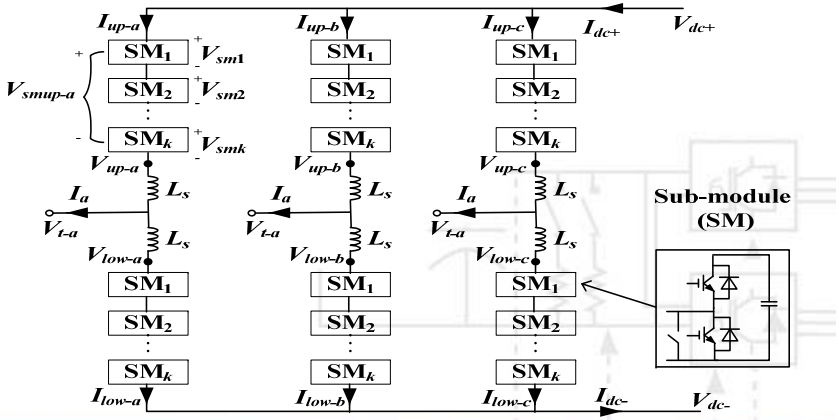
MMC Characteristics

- Commutating inductors are in arms
- Arm currents are continuous
- Capacitors in each cell (energy storage in MMC)
- SM capacitor voltage has to be balanced (on a larger time scale)
- Circulation current among arms



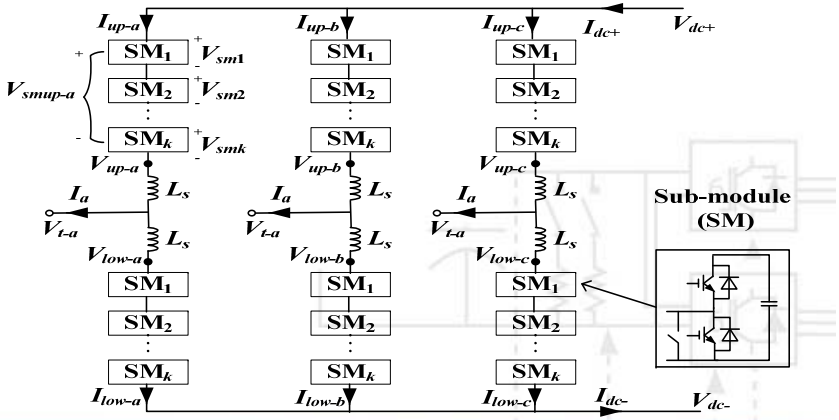
MMC Advantages

- Reduced stress on converter and grid component
- Low switching frequency – reduced switch losses
- Low ac harmonic content – no need for a filter
- Continuous currents in MMC arm and DC link - dc link capacitor omitted
- Fast recovery from AC-bus short-circuit (Better fault ride-through capacity)



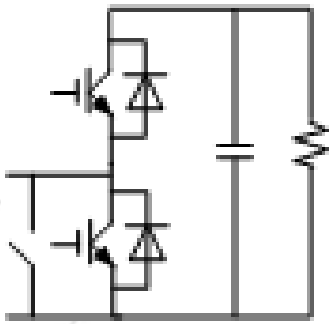
MMC Advantages (continued)

- Fast recovery from DC-bus short-circuit, but DC breaker or FB or CDSM topologies are needed
- Improved reliability due to modular design and redundancy in SM- system can remain operating for a certain period even when a few SM are out of order
- Can feed loads without any generators (no limit on short-circuit ratio)
- Easy start-up
- Smaller foot print

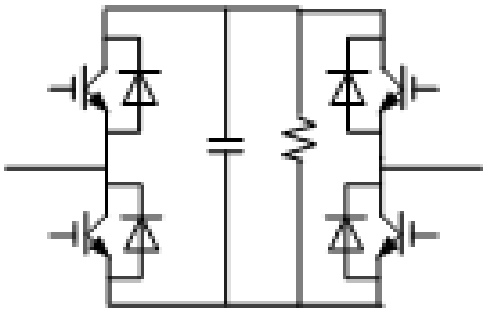


MMC and Sub-module

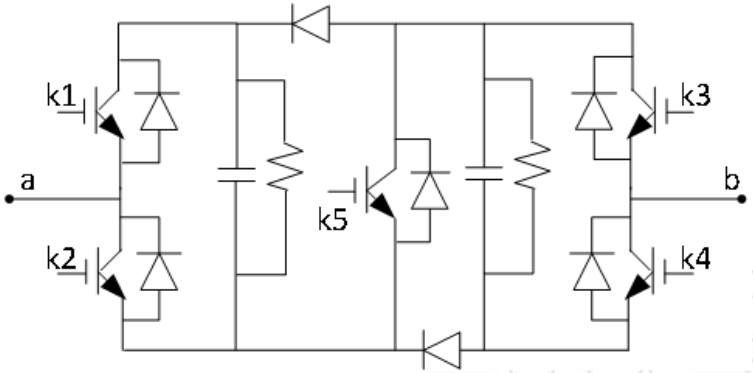
- Sub-module (SM) topologies
  - Half-bridge (HB): with 2 IGBT and 1 Capacitor
  - Full-bridge (FB): with 4 IGBT and 1 Capacitor
  - Clamp Double (CD): with 5 IGBT and 2 Capacitors
  - others



HB SM

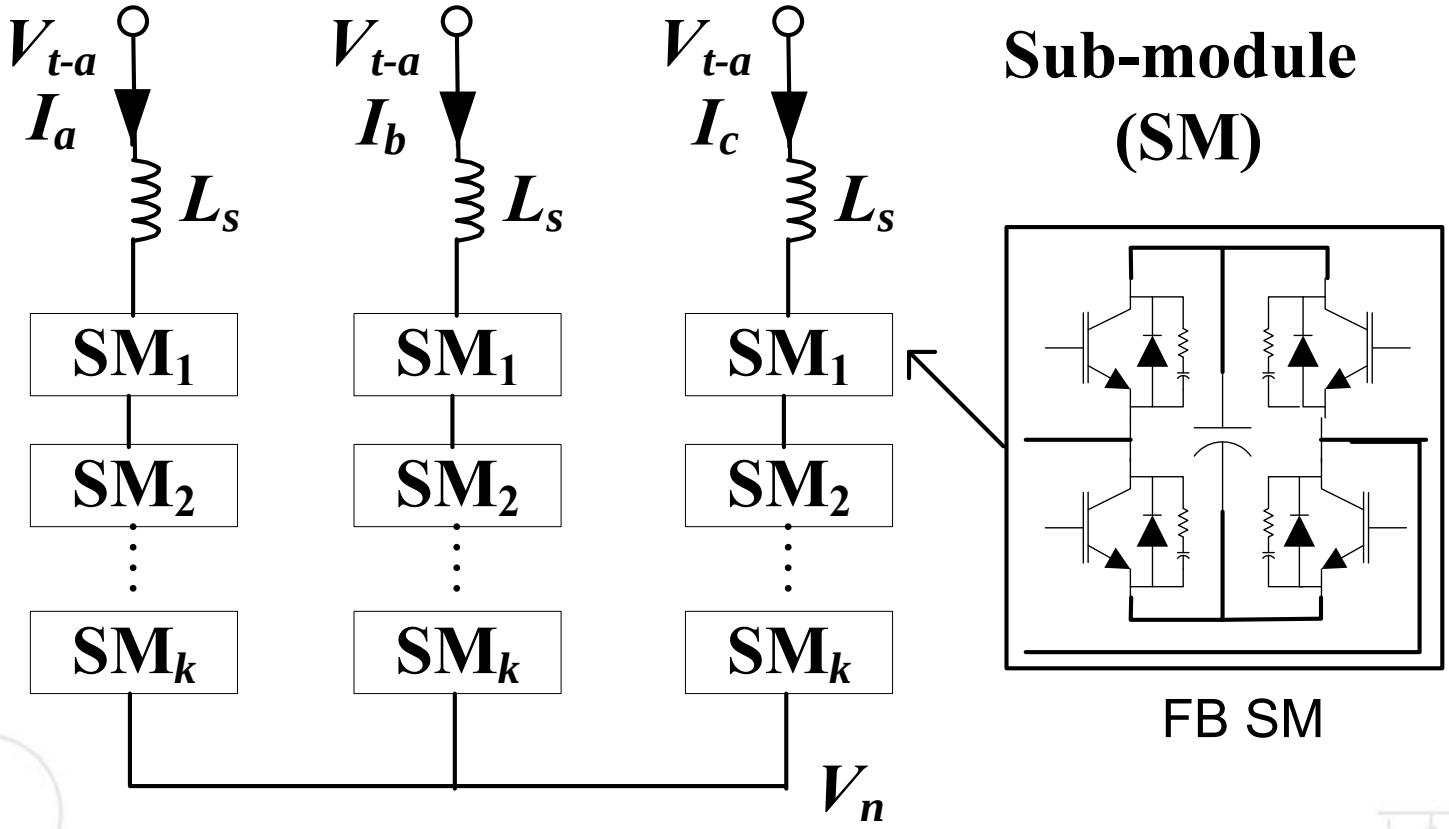


FB SM

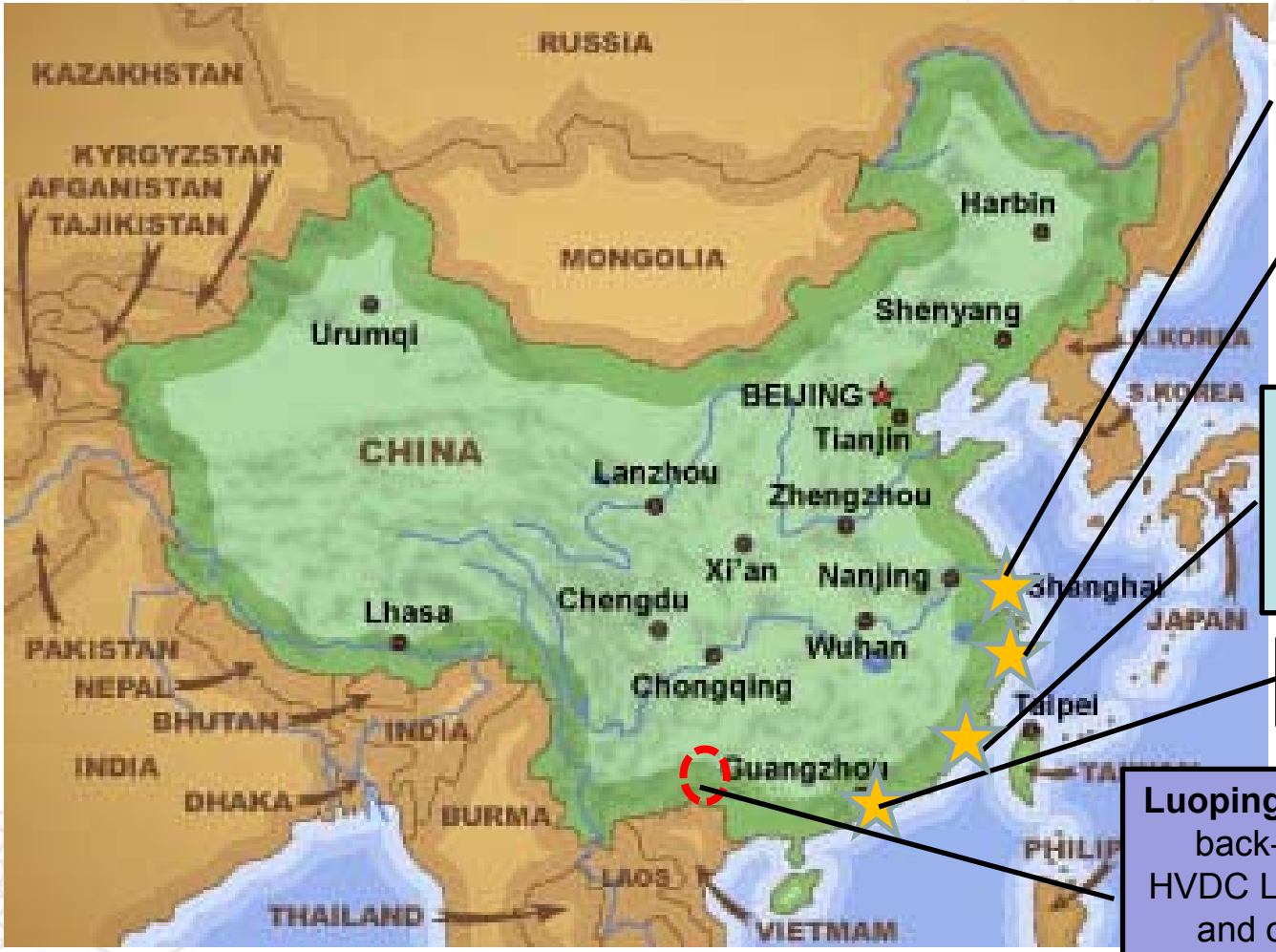


CDSM

MMC FBSM STATCOM



Recent MMC HVDC projects in China



Nanhui, 2011

Zhoushan, 2014

Xiamen 2015 (State grid): Bi-pole MMC ±320 kV, 1000MVA HVDC for city power supply

Nanao, 2013

Luoping (CSG) : MMC-LCC combined back-to-back ±350kV, 2000 MVA HVDC Links (one 1000 MVA MMC link and one 1000 MVA LCC link) for asynchronous network coupling

MMC Project in operation

MMC Project under construction

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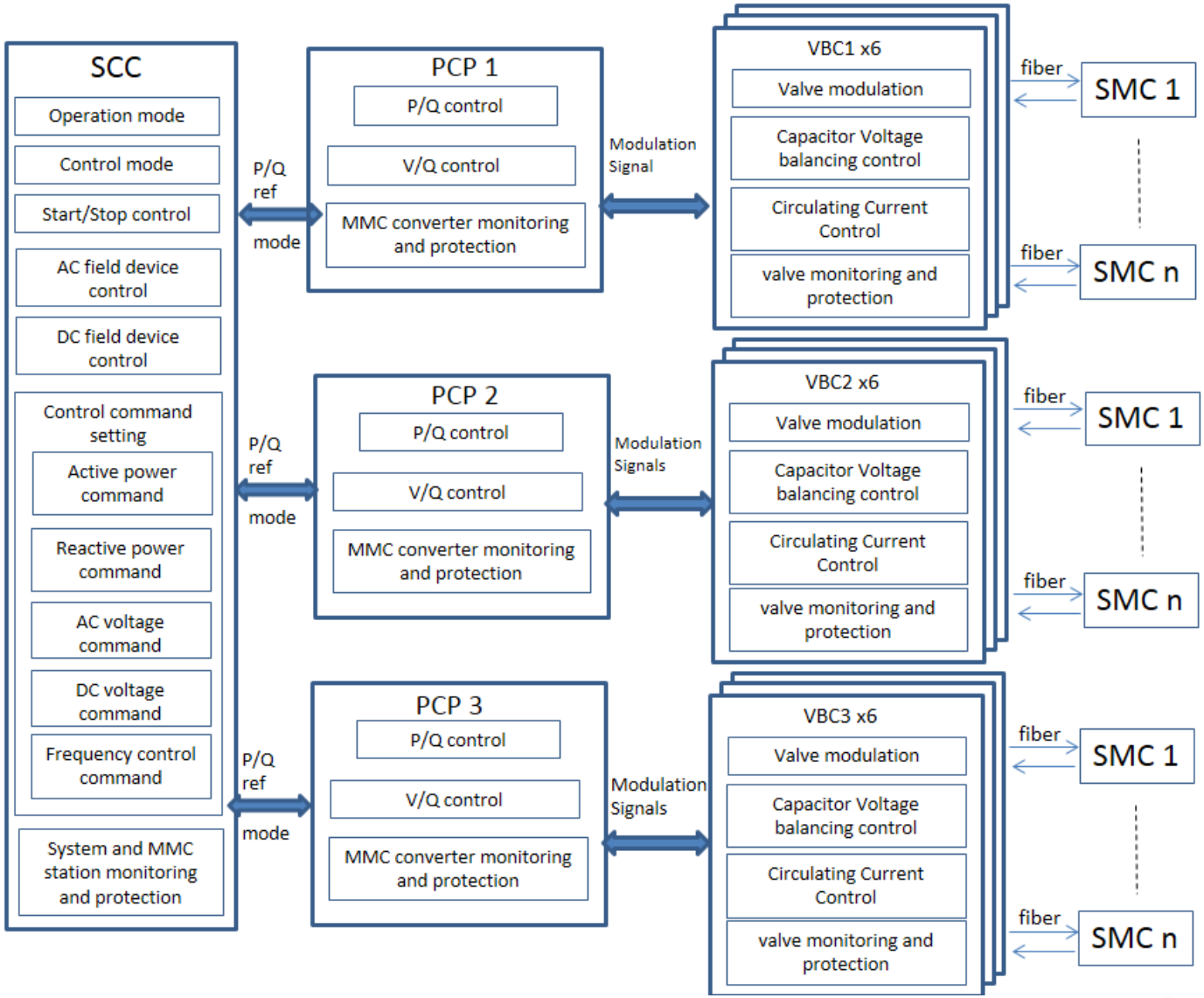
Recent MMC HVDC projects in China

Project	Year in operation	Nb. of terminals	Nb. of SM per valve	Rated DC Voltage	Capacity	Application
Nanhui	2011	2	50	60 kV	18 MVA	Wind Energy Integration
Nanao	2013	3	200	320 kV	200 MVA	Wind Energy Integration
Zhoushan	2014	5	250	400 kV	400 MVA	Power supply for islands
Luoping	2016	2	400	±350kV	1GVA	Asynchronous Networks Coupling
Xiamen	2015	2	400	±320 kV	1GVA	Power supply for large cities

MMC challenges

- New technologies and little engineering experience from existing projects
- Complex control and protection systems
  - Which could be supplied by different manufacturers in multi-terminal systems
- Expensive to make and maintain a physical test bench

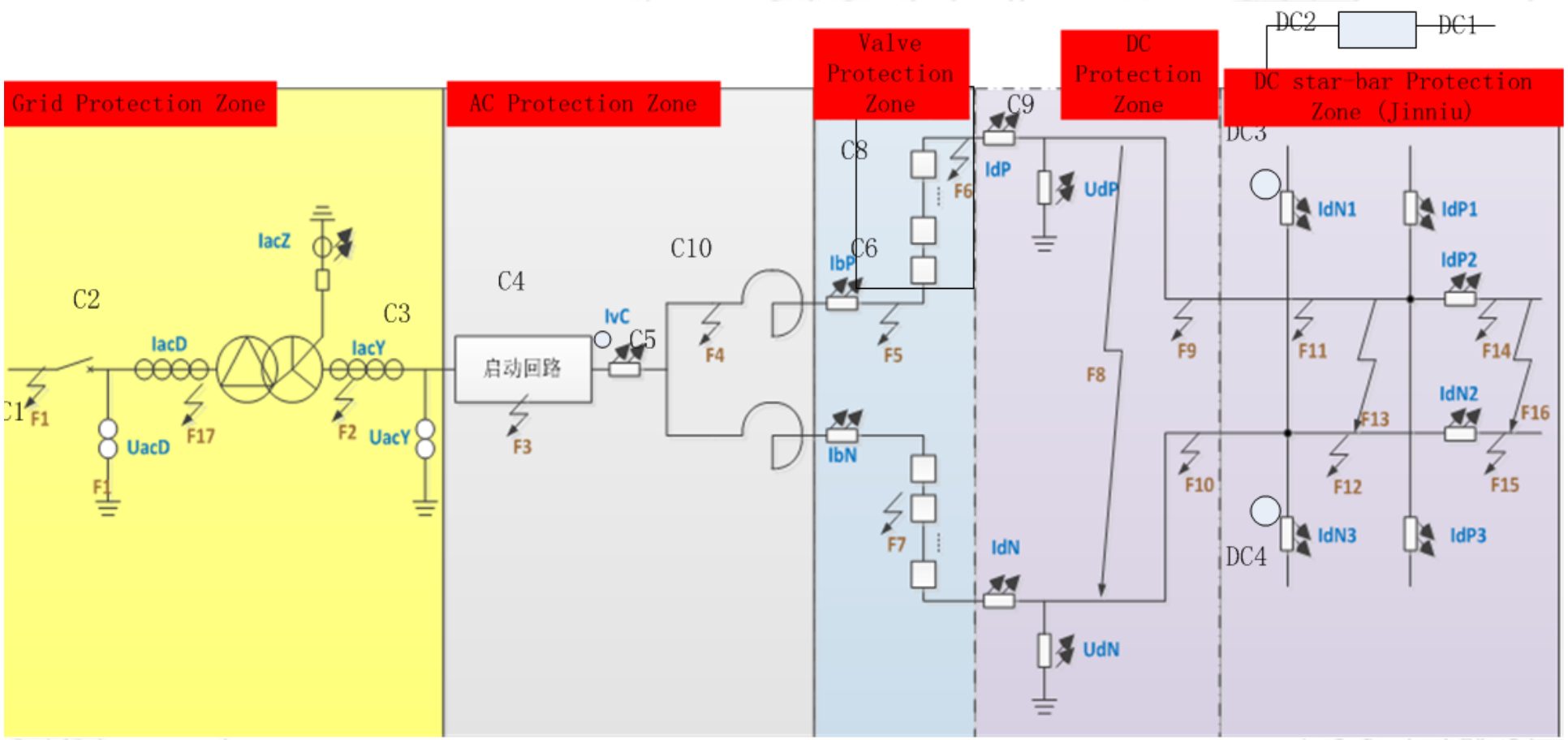
Challenges – Structure of MMC C&P system



Challenges – Test matrix and sequence

STATCOM operation	AC & HVDC Operation	Pure DC Operation
• Auto Start sequence • Power step command • PCP redundancy • Internal communication failure • AC faults • DC faults • Valve faults	• Auto Start sequence • Power step command • PCP redundancy • Operation with and without substation communication • AC faults • DC faults • Valve faults	• Auto Start sequence • Power step command • PCP redundancy • Operation with and without substation communication • AC faults • DC faults • Valve faults

Challenges – AC and DC faults assignment



MMC challenges and solution

- Solutions to validation of MMC C&P systems: Hardware-in-the-loop (HIL) test bench
  - Lower cost
  - Shorter time for R&D cycle and validation test
  - Wider range of tests: steady states, transients, & faults

Challenges for real time simulation of MMC

- challenges for real time simulation and HIL test bench
  - Large number of components
  - Large number of switches, frequent change of switch states
  - Non-linear elements, e.g. MOV
  - Large number of I/Os to interface with controllers

Solutions to real time simulation of MMC

- Circuit simplification [1,2]
  - Using one equivalent capacitor for a valve. Loss of details.
- Norton equivalent using Dommel's algorithm[4,5]
  - Dommel's algorithm[3]: switch ← $R_{on/off}$, C ←R//I_s.
- Norton equivalent + SSN parallel calculation[7]
  - SSN[6]: state space nodal method for parallel calculation.
- Surrogate networks with Thevenin equivalent[8]
  - SM grouped according to states (insert, bypass, block)
- General MMC valve equivalent circuit [9]
  - for all SM topologies, parallel calculation

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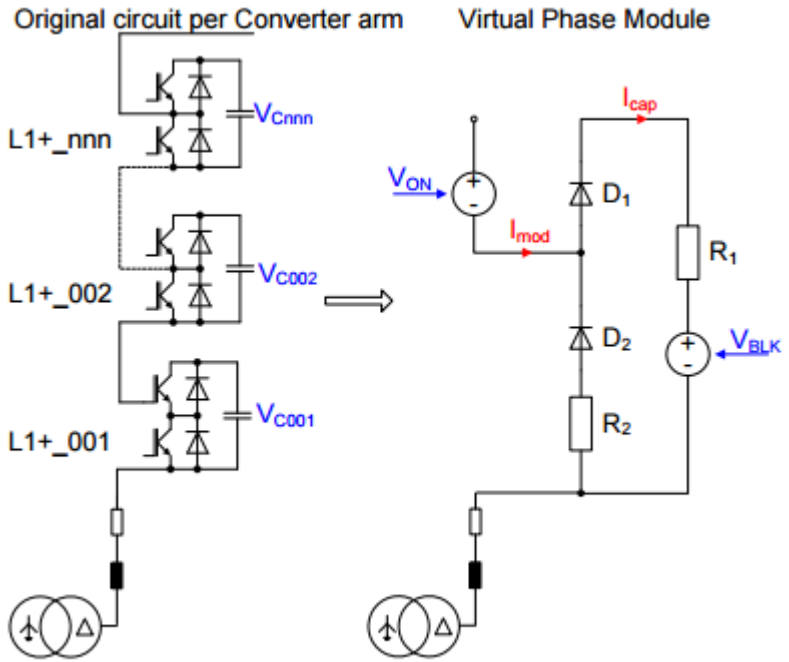


Fig. 2. Original electric circuit and Virtual Phase module electric circuit

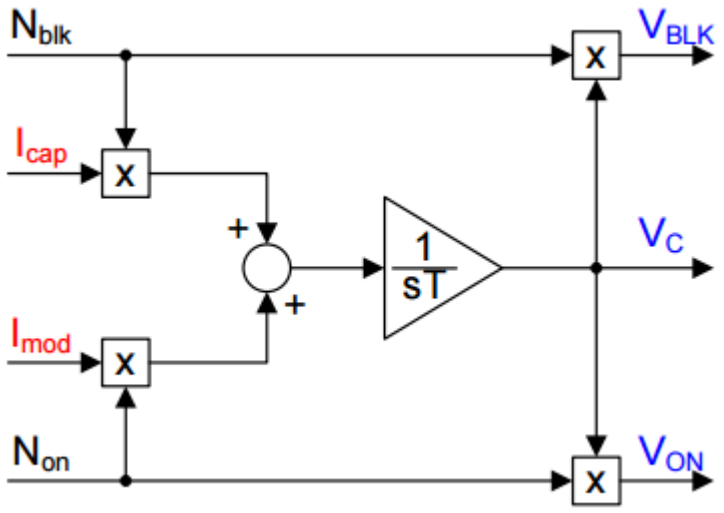


Fig. 3. Capacitor Voltage Calculation

Figures from reference [2] by O. Venjakob et al.

Solutions to real time simulation of MMC

- Norton equivalent using Dommel's algorithm[4,5]
  - Dommel's algorithm[3]: switch ← $R_{on/off}$, C ←$R//I_s$.

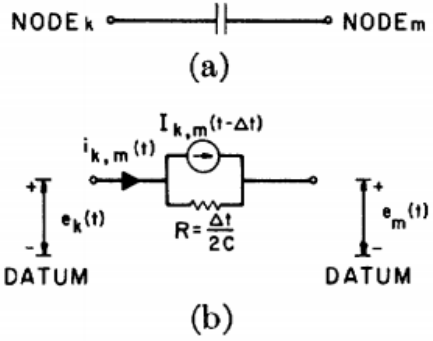


Fig. 3. (a) Capacitance. (b) Equivalent impedance network.

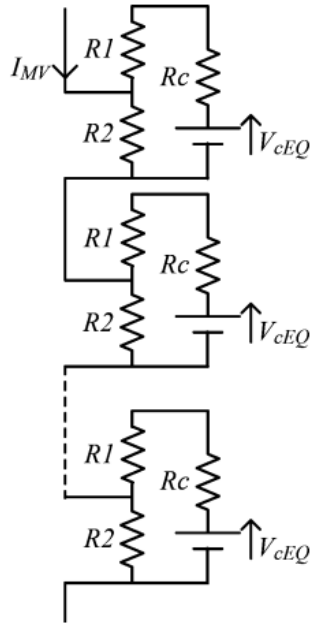


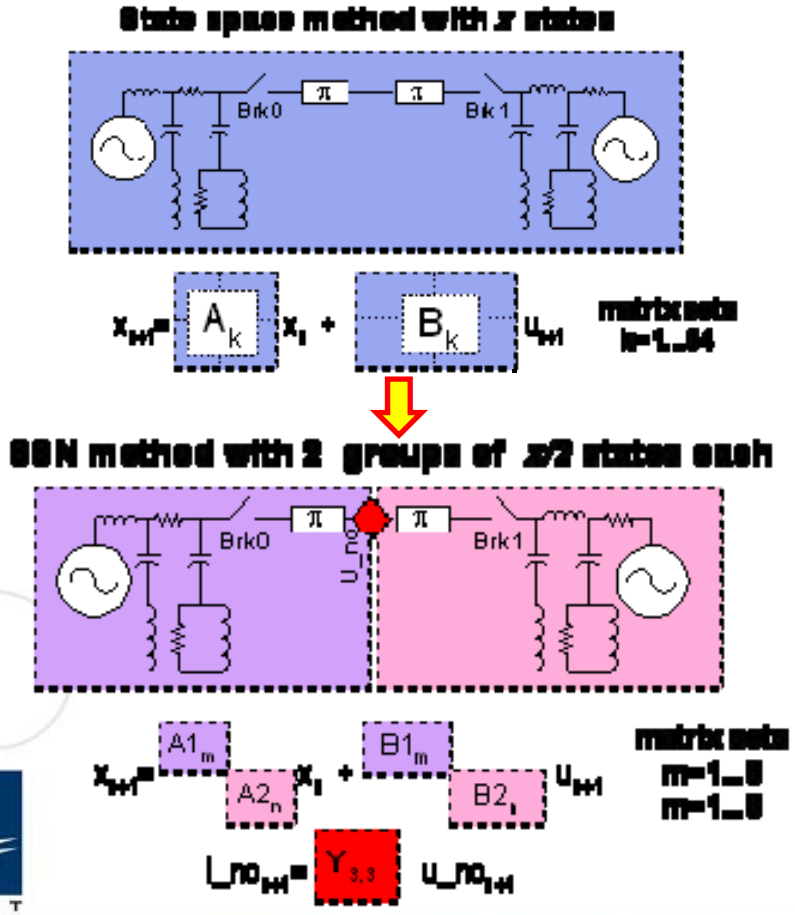
Fig. 7. Equivalent circuit representation for a multivalve.

Fig.3. from reference [3] by H. W. Dommel.

Fig.7. from reference [4] by U. N. Gnanarathna et al.

Solutions to real time simulation of MMC

- Norton equivalent + SSN parallel calculation[7]
  - SSN[6]: state space nodal method for parallel calculation.



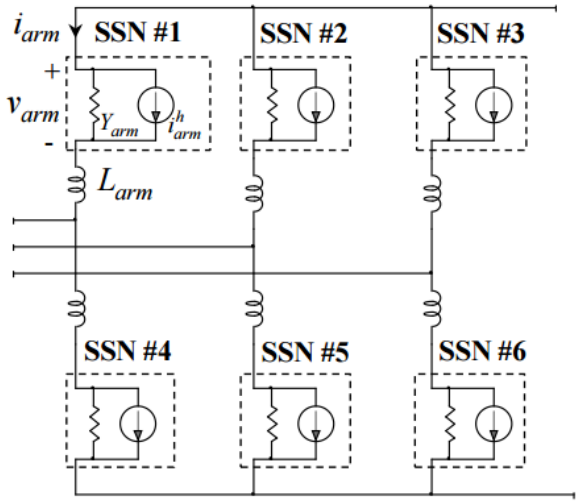


Fig. 6 SSN-MMC model

Figures from reference [7] by H. Saad et al.

Solutions to real time simulation of MMC

- Surrogate networks with Thevenin equivalent[8]
  - SM grouped according to states (insert, bypass, block)

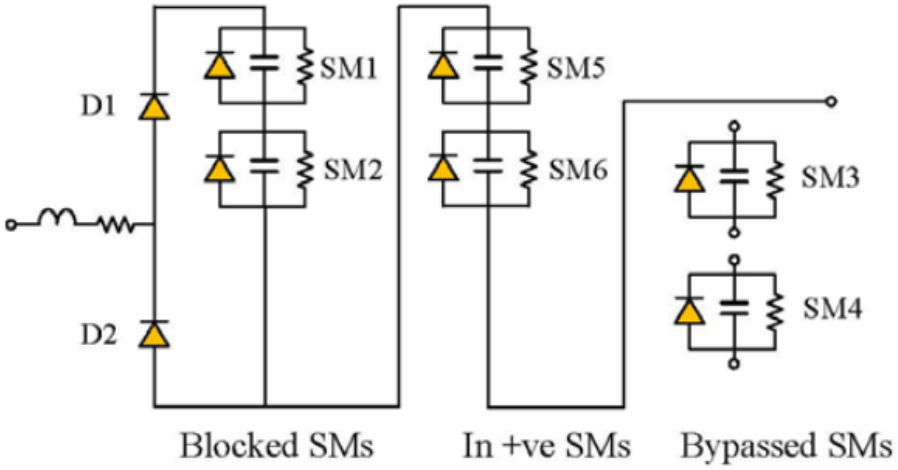


Figure 2. Half-bridge surrogate network topology

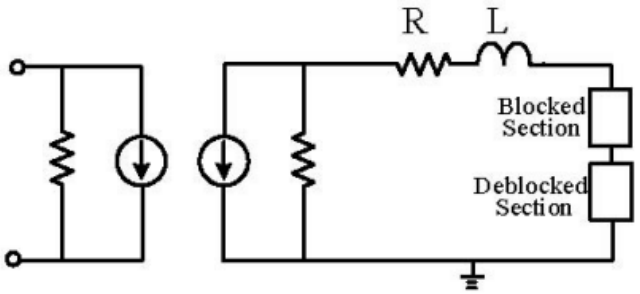
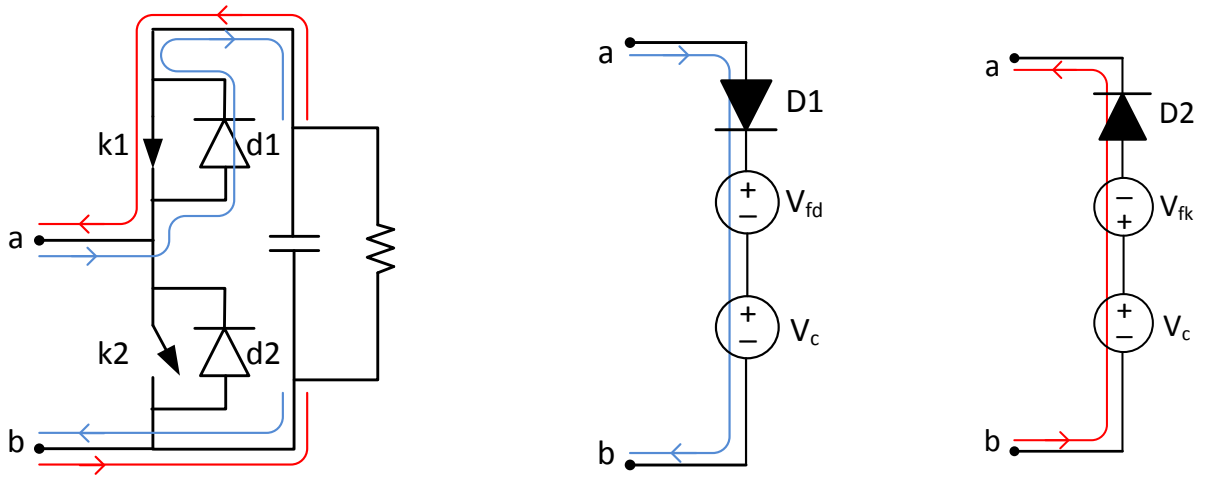


Figure 5. The T-Line Interface in the surrogate network topology

Figures from reference [8] by T. L. Maguire et al.

OPAL-RT Solution for MMC Simulation

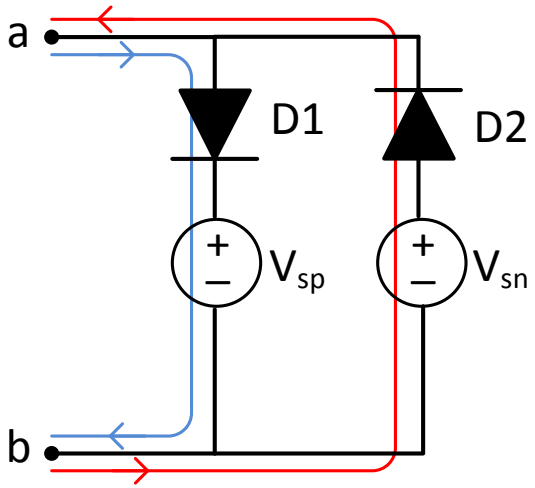
- General MMC valve equivalent circuit [9]
  - for of all SM topologies, parallel calculation



(a) HB SM in insert mode and equivalent circuits for (b) positive and (c) negative current directions

OPAL-RT Solution for MMC Simulation

- General MMC valve equivalent circuit [9]
  - for of all SM topologies, parallel calculation



A general SM equivalent circuit for all operating conditions

Table I Source voltages in HB SM Equivalent Circuit

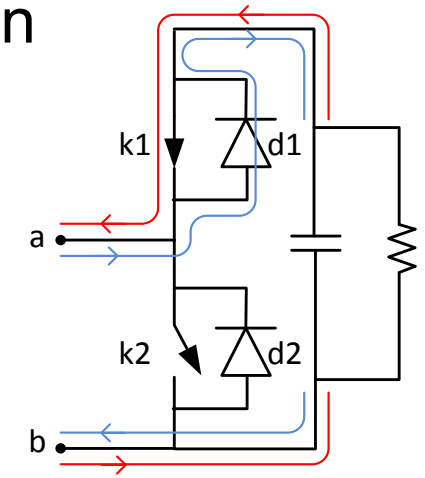
Mode	k1	k2	V_{sp}	V_{sn}
Insert	1	0	$V_c + V_{fd}$	$V_c - V_{fk}$
Bypass	0	1	V_{fk}	$- V_{fd}$
Diode	0	0	$V_c + V_{fd}$	$- V_{fd}$
Fault	1	1	V_{fk}	$- V_{fk}$

OPAL-RT Solution for MMC Simulation

- General MMC valve equivalent circuit [9]
  - for of all SM topologies, parallel calculation

Capacitor voltage:

$$V_c(t+T_s) = V_c(t) + \frac{T_s}{C_{SM}}\left(k(t)i_{val}(t) - \frac{V_c(t)}{R_{disc}}\right)$$



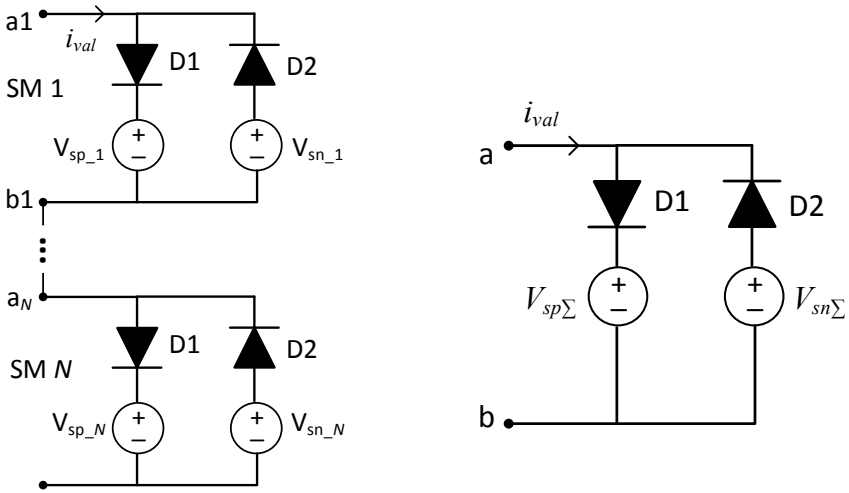
VARIABLE k IN CAPACITOR VOLTAGE EQUATION FOR HB SM

Mode	k1	k2	Valve current direction	k
Insert	1	0	either	1
Bypass	0	1	either	0
Diode	0	0	positive	1
			negative	0

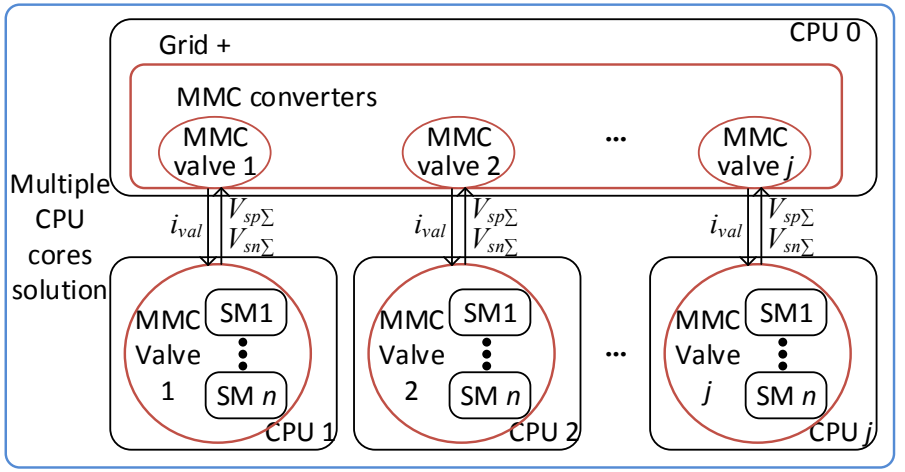
OPAL-RT Solution for MMC Simulation

❖ General MMC valve equivalent circuit [9]

- ➢ for of all SM topologies, parallel calculation

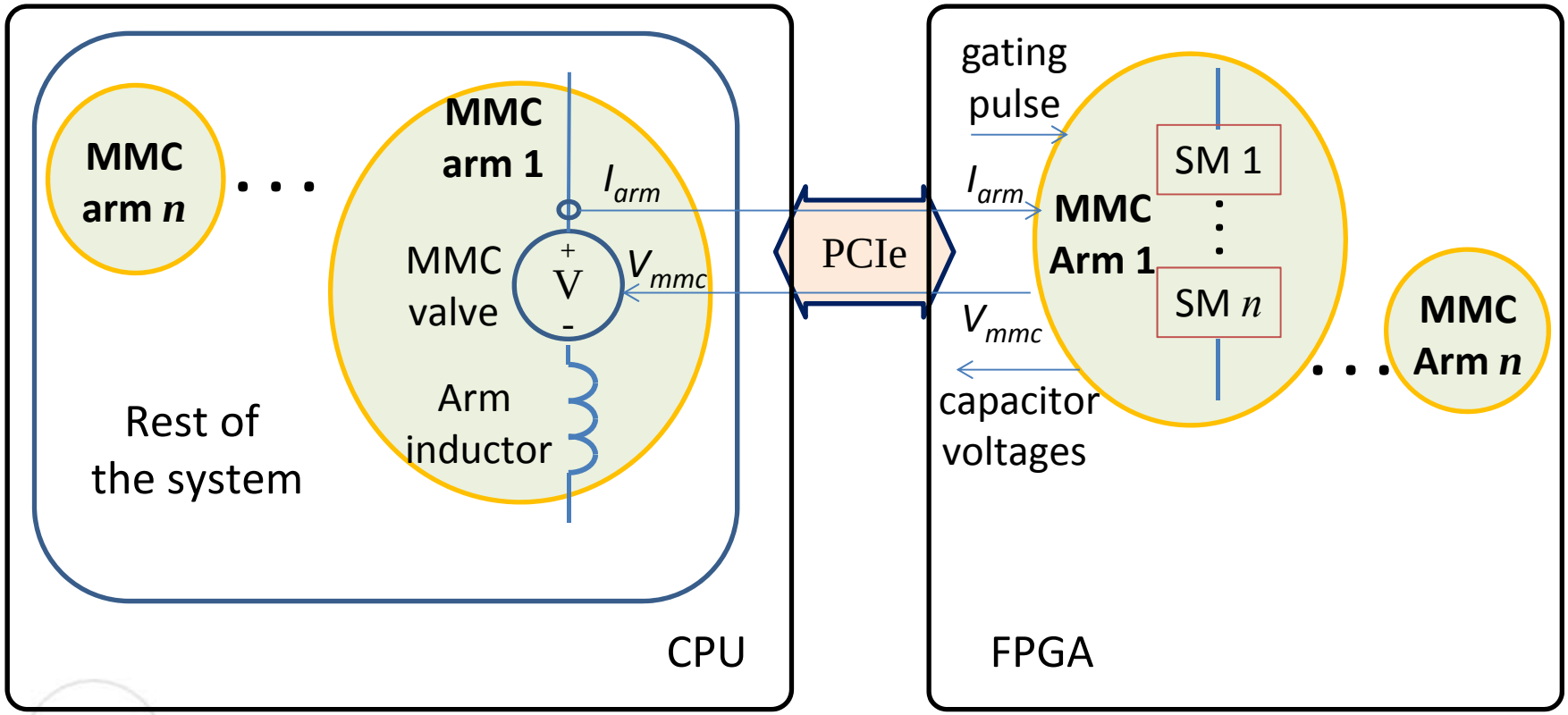


Equivalent circuits of (a) a stack of SM and (b) an MMC valve for all operating conditions.



Parallel solving grid and MMC valves

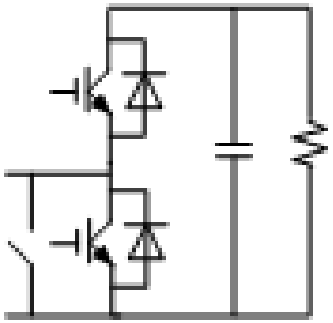
Multi-rate MMC Model

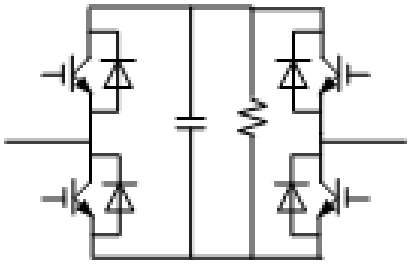


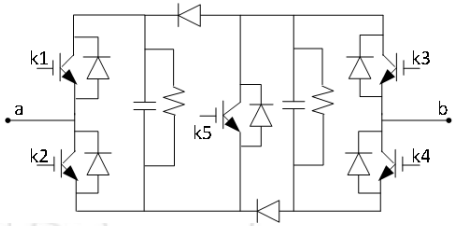
OPAL-RT Solution for MMC Simulation

- **Multi-rate MMC model in FPGA (T_{fpga}=250 ns) and CPU (Ts: tens of μs)**
- **Optional MMC models on CPU (25 μs)**
- Different SM topologies, HB, FB, CDSM, and other
- For HVDC, STATCOM, other Applications.
- Real time or fast simulation.
- HIL and RCP (rapid control prototyping)
- Hardware IO: Copper wiring or optical fibers
- Example MMC controller
- In RT-LAB or Hypersim platform

Detailed Model of Individual SM







Each of Individual SM is simulated	yes

In each SM

Each capacitor voltage controlled individually	yes
Discrepancy of SM capacitance values	yes
Discharge resistance is simulated	yes
Resolution of firing signal	250 ns
Simulation of dead time	yes
Cell short circuit and other faults	yes
Forward voltage of diodes	yes
Diode non linearity	no
Dynamic of IGBT and diode Turn-on and -off	Not yet

Implementation MMC model in FPGA

- Small calculation time step of 250 ns
- Large number of SM
  - up to 256 SM/valve * 6 valve in VIRTEX 6 (OP7000, ML605) and 256 SM/valve * 6 valve *2 converter in Kintex 7 (OP4500)
  - 512 SM * 6 valve * 2 or more converters in VIRTEX 7(op7020, op5607) (6,000 cells total) including 16 SFP (5 Gbits/s) with AURORA interface protocol
- MMC VBC (low-level controller) and communication protocol could be implemented in same FGPA
- Support multiple FPGAs for HVDC grids

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Implementation MMC in FPGA (continued)

- CPU resources is free to simulate larger AC network because no CPU resource is required
  - to calculate the MMC cell models
  - to manage I/O data communication with external controller
- Individual control of each IGBT and SM capacitor voltage
- Providing SM V_{cap} debugging mode to help user developing their controller
- Supporting both RT-LAB and Hypersim Platform

Implementation MMC Model in CPU

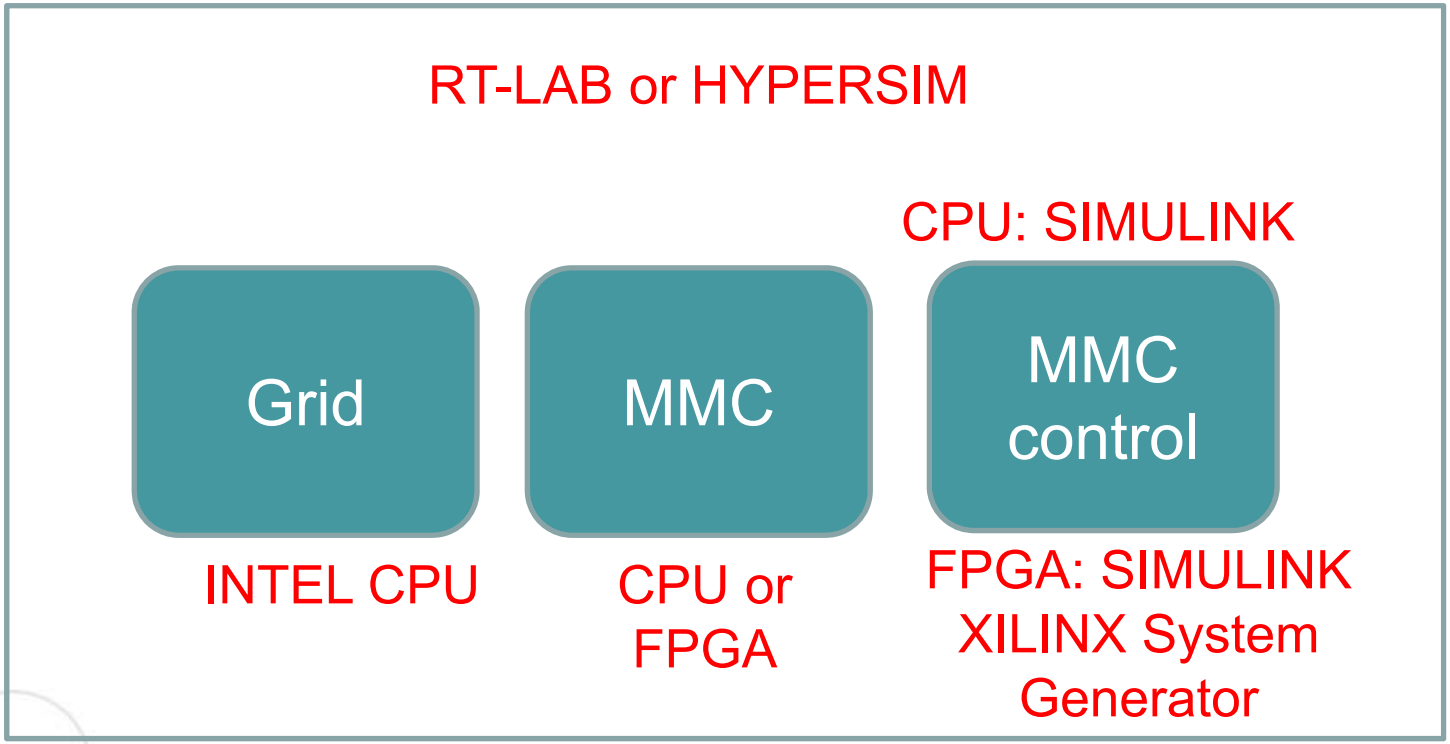
- Useful for off-line simulation of simple system (no FPGA needed) and algorithm development with SIMULINK
- Supporting MMC HB, FB, and CDSM topologies
- Unlimited number of SM per valve
- Several CPU cores are used to calculate the MMC and grid models
- 1 CPU can solve 300 SM with a time step of 25µs
- Providing SM *Vcap* debugging mode to help user developing their controller

Connectivity with External Controller

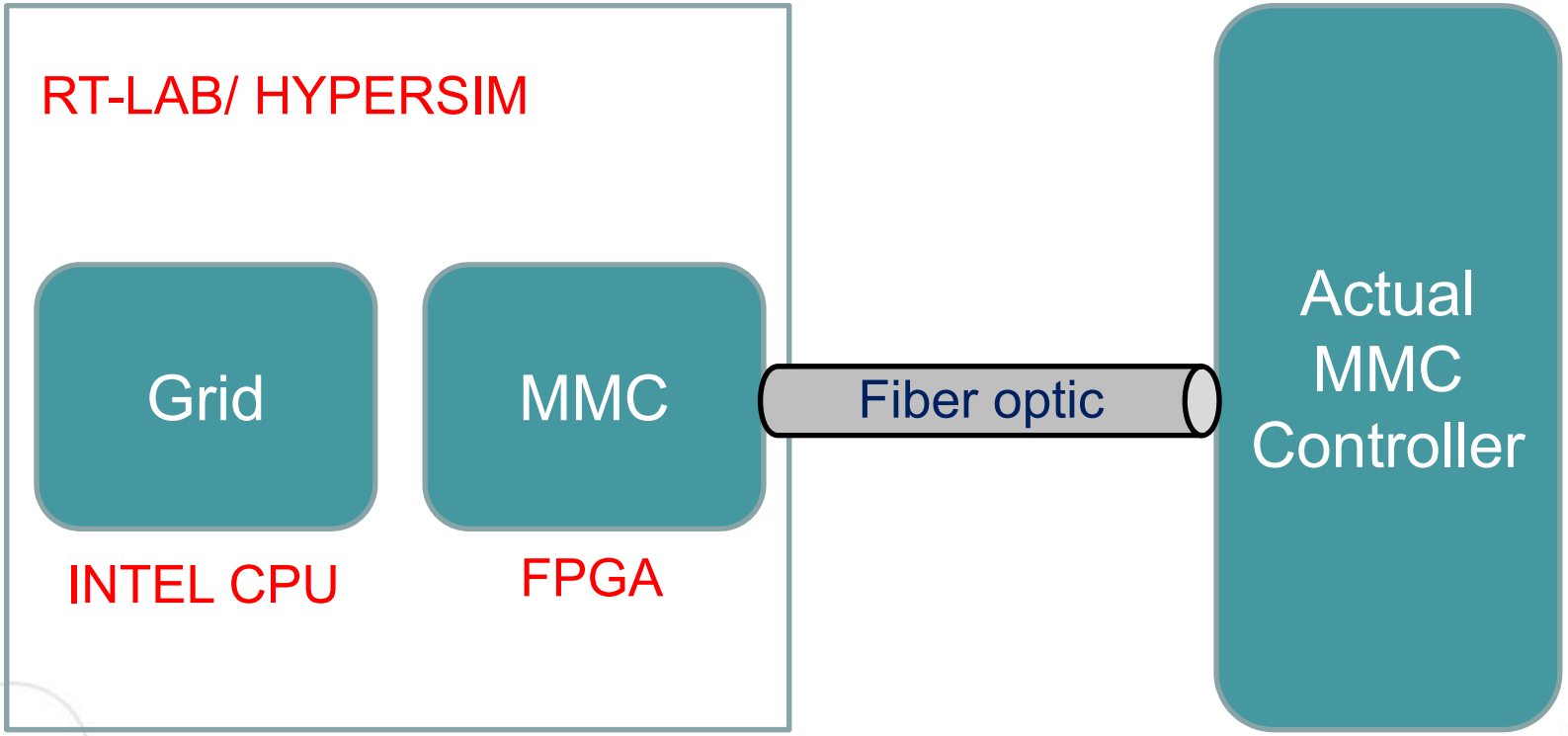
- Analog and digital I/Os for *Vcap*, currents, and gating pulses
- SFP optical fiber with Aurora protocol at 1 to 5 Gbits/s (16 links per VIRTEX-7 FPGA)
- SFP optical fiber with Gigabit Ethernet protocol
- Updating interval at a few µs depending on the number of optical fibers, number of cells and controller manufacturer requirements

The small form-factor pluggable (SFP) is a compact, hot-pluggable transceiver used for both telecommunication and data communications applications

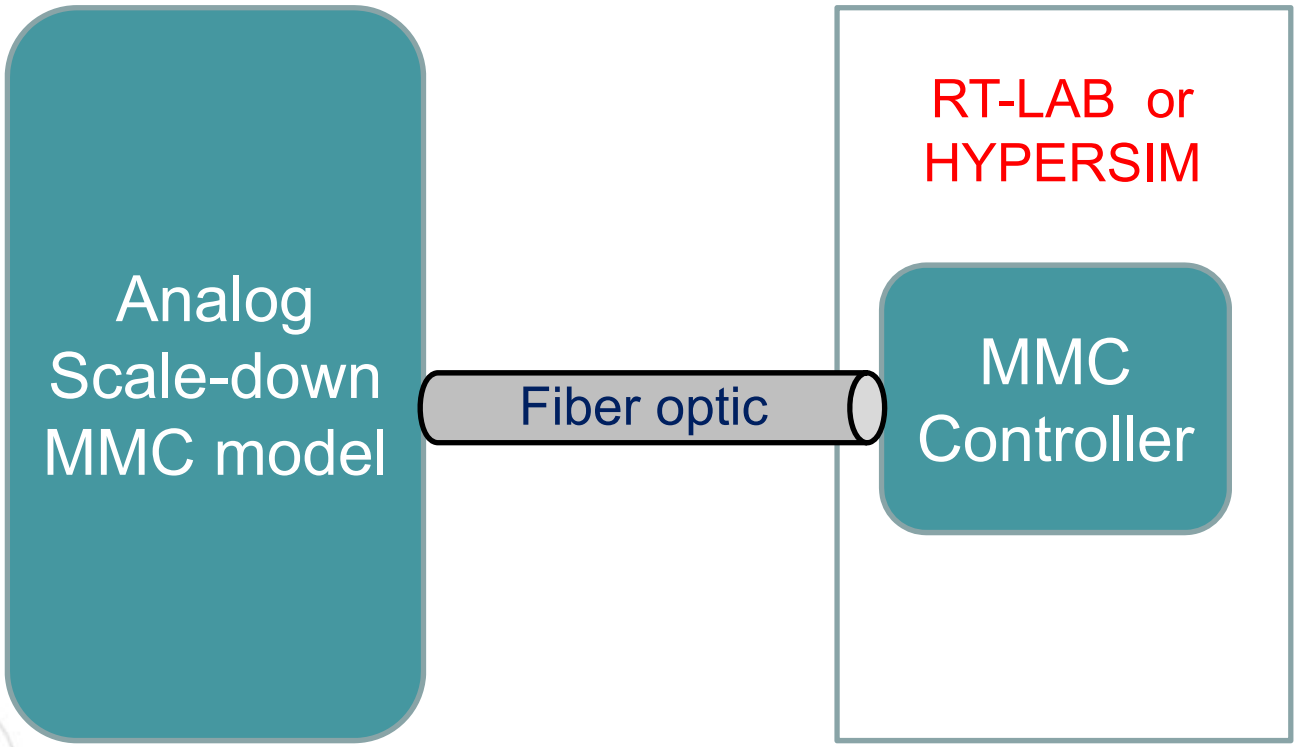
Digital Simulating of MMC System



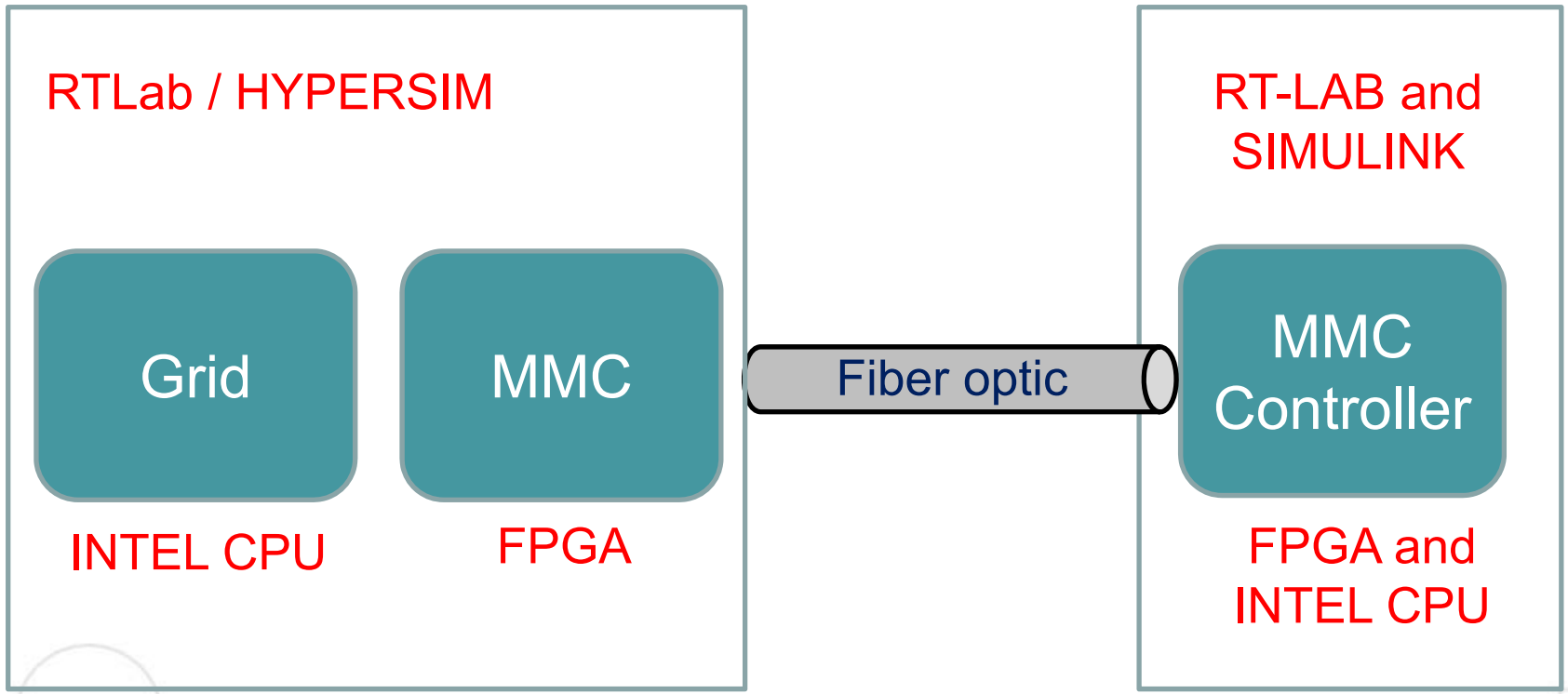
HIL Testing of Actual MMC Controller



MMC Rapid Control Prototyping (RCP)



MMC RCP with Virtual MMC plant and AC grid

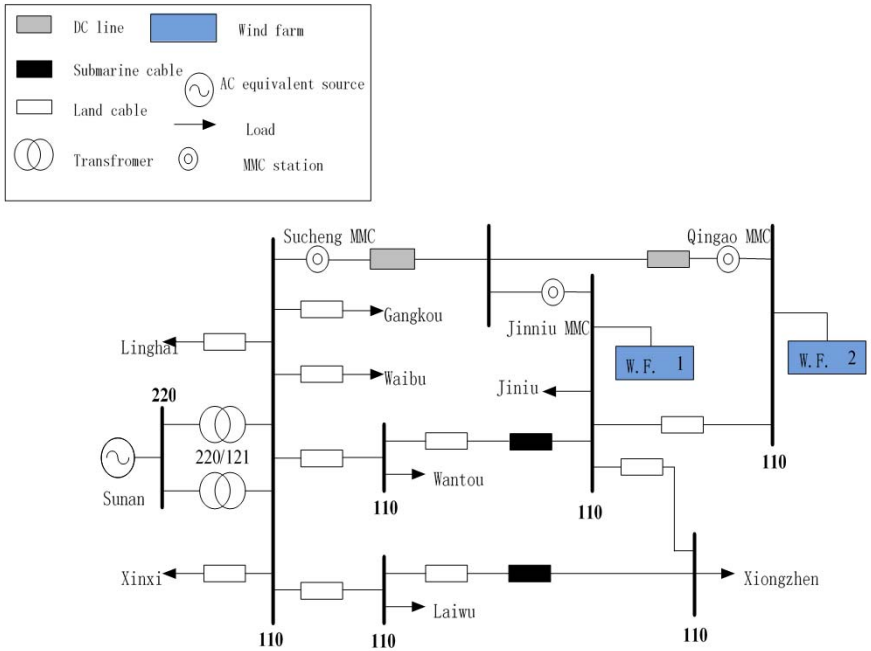


Very convenient setup for MMC controller development
Fast interactivity – fast batch-mode optimization

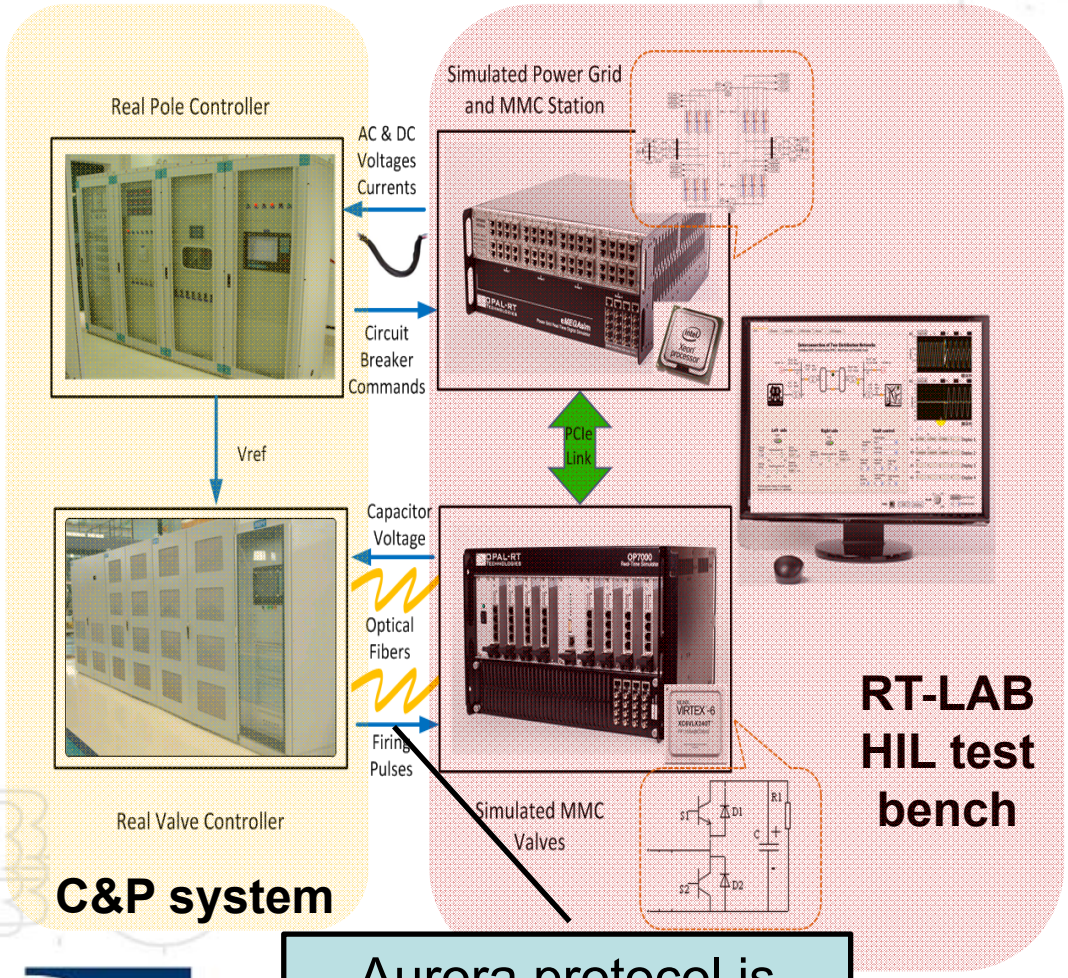
System model of Nanao project

Parameters	Sucheng station	Jinniu station	Qingao station
Transfomre connection	Yn/D11	Yn/D11	Yn/D11
Rated power (MVA)	240	120	63
Primary voltage (kV)	110	110	110
Secondary voltage (kV)	166	166	166
Primary impedance (pu) [R1,L1]	[0.0025 0.06]	[0.0025 0.06]	[0.0025 0.05]
Secondary impedance (pu) [R2,L2]	[0.0025 0.06]	[0.0025 0.06]	[0.0025 0.05]
Grounding resistance (kΩ)	5	5	5
MMC capacity(MVA)	200	100	50
Number of SMs in an arm	147	220	220
Number of redandant SMs	14	20	20
Rated SM voltage(kV)	2.4	1.6	1.6

The three multi-terminal VSC HVDC project



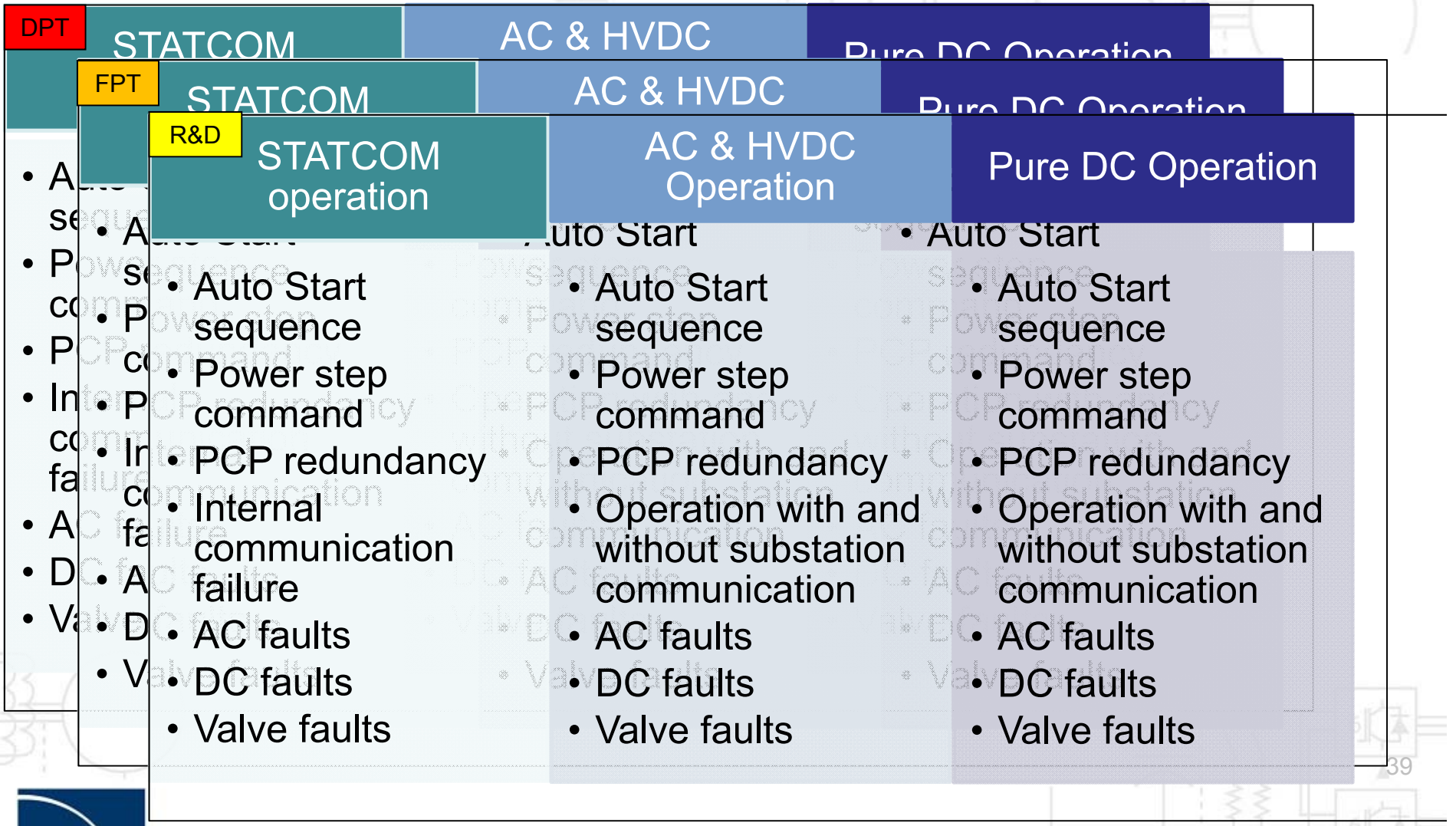
HIL testing system



Time Step	28 us
CPU #	6 (3 cpu for 3 Converters 1 cpu for ac grid 1 cpu for wind farm 1 cpu for data acquisition and logging)
FPGA #	3 Virtex-6
IO	32*3 AO 32*3 DI 32*3 DO

Aurora protocol is used to connect the VBC to the simulator

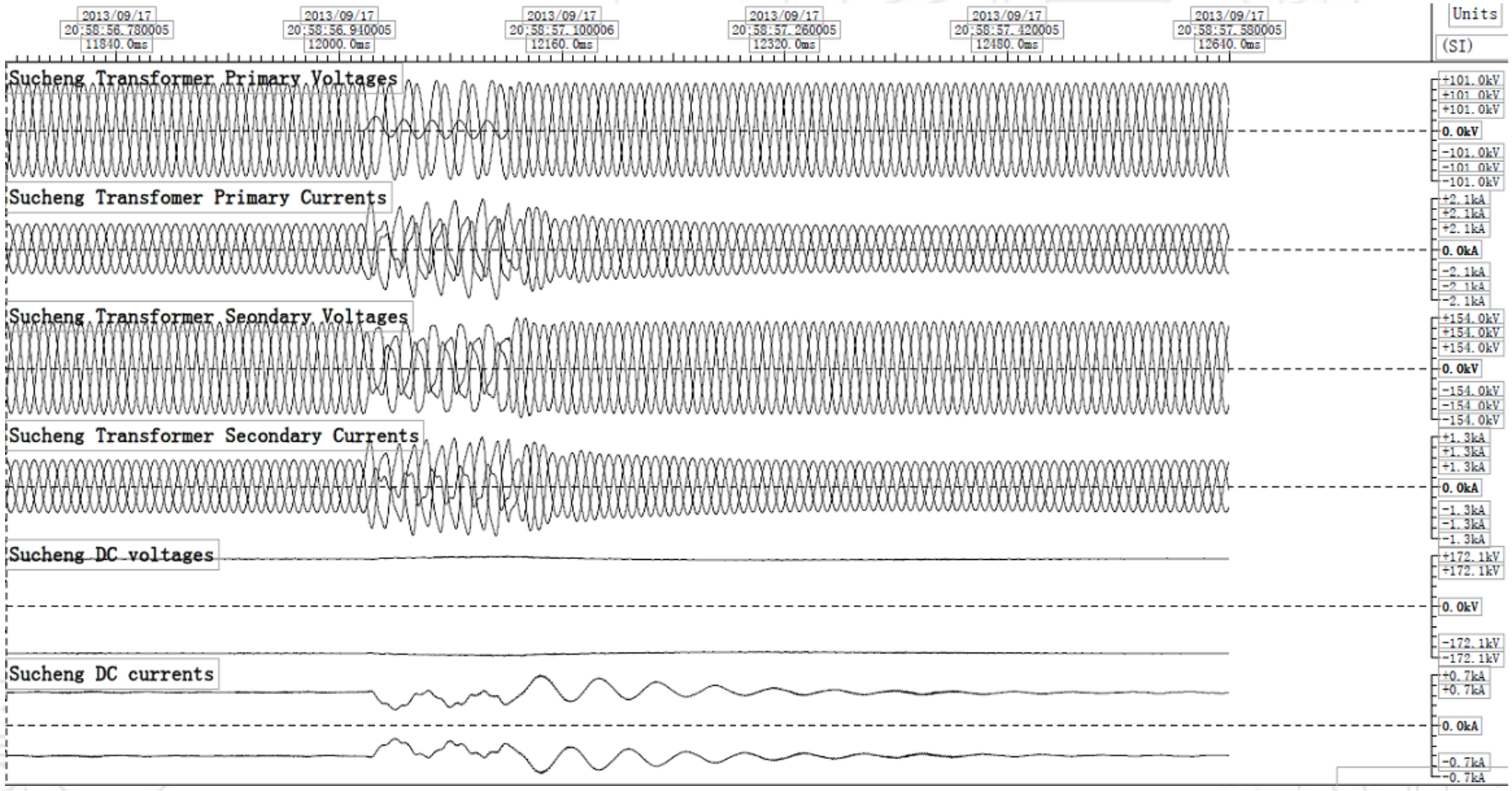
Test matrix and sequence



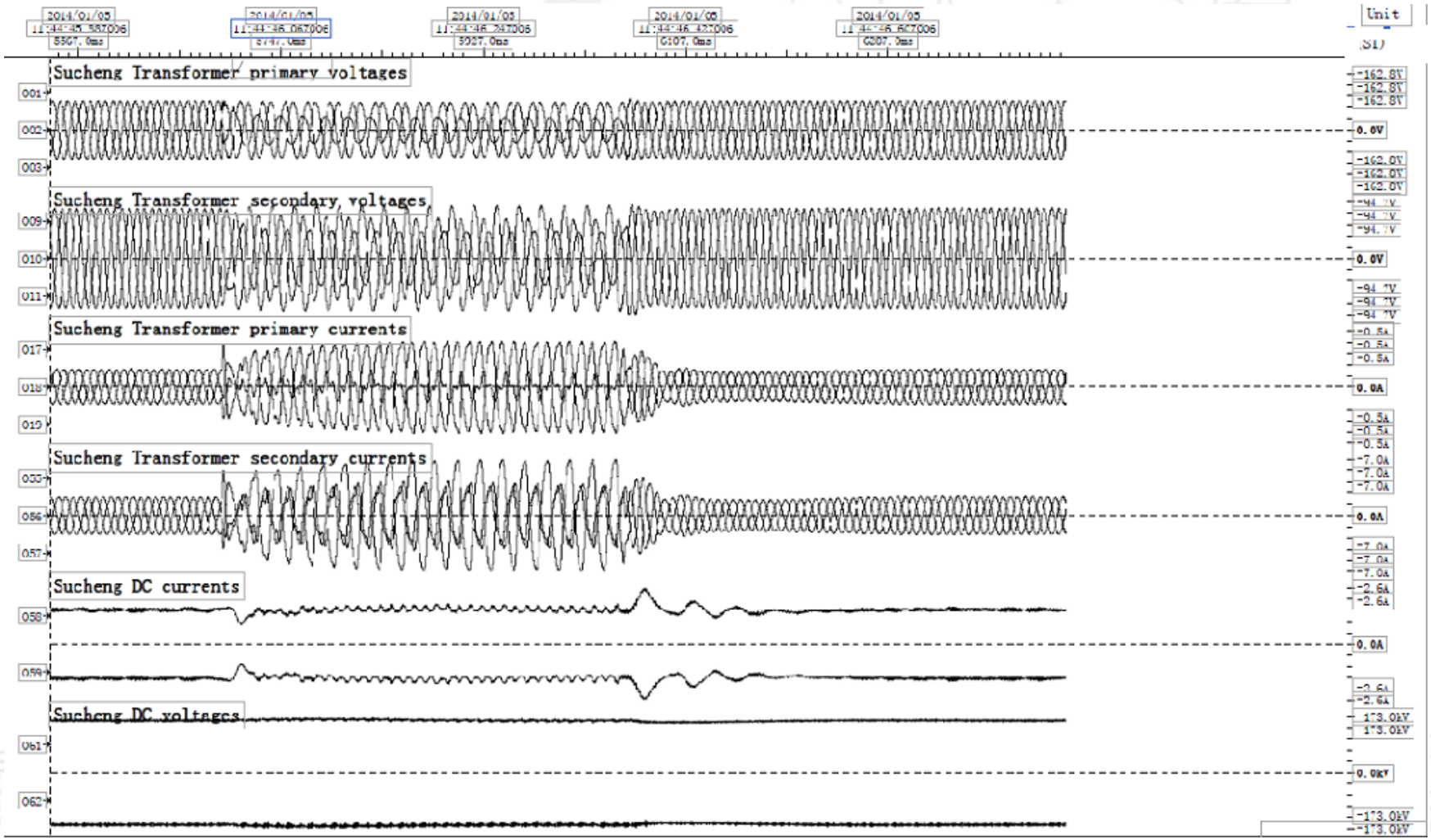
The same test scenarios are repeated at different stage of production.

* FPT: Functional performance test; DPT: Dynamic performance test

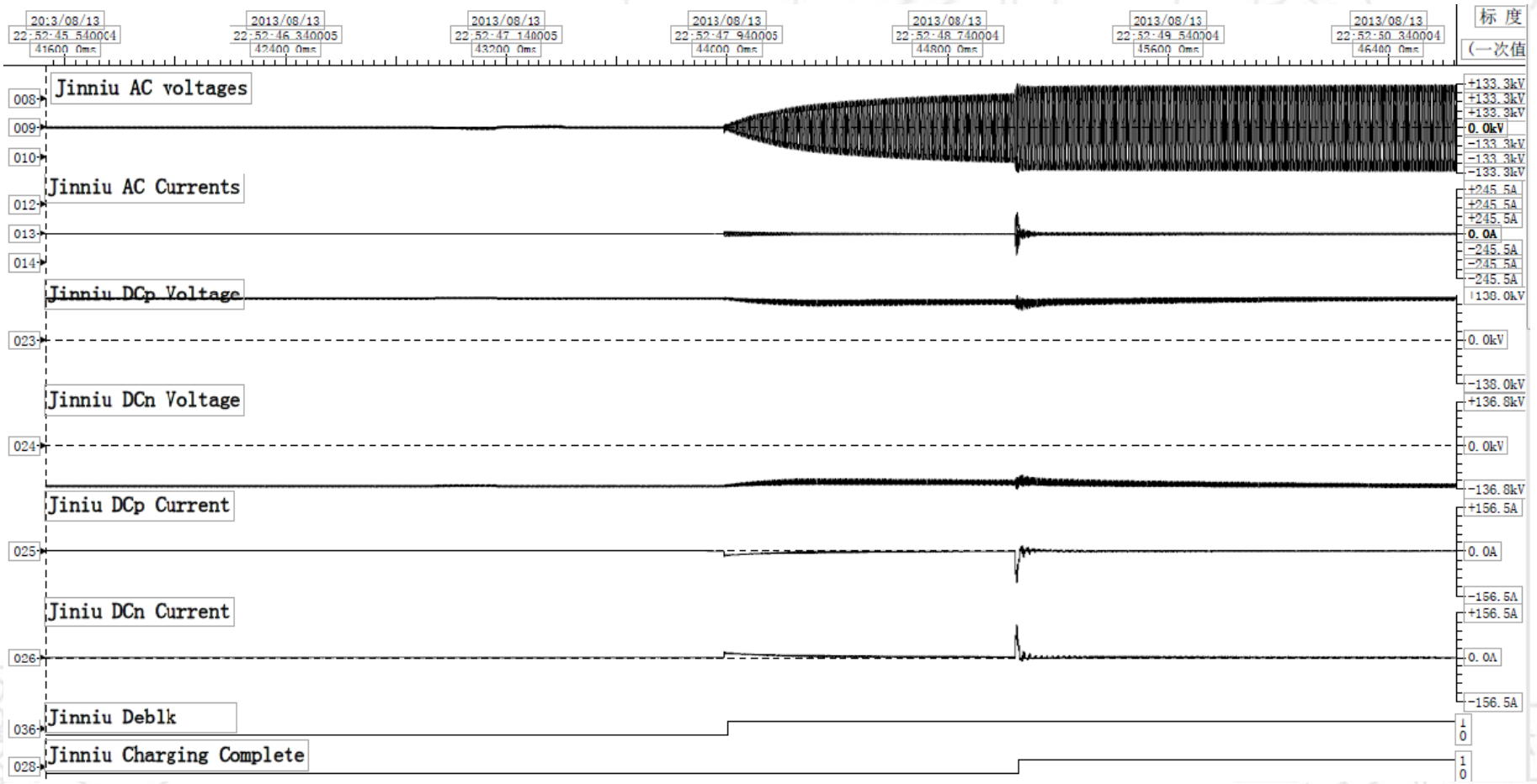
HIL Test results (F1) - Nanao project



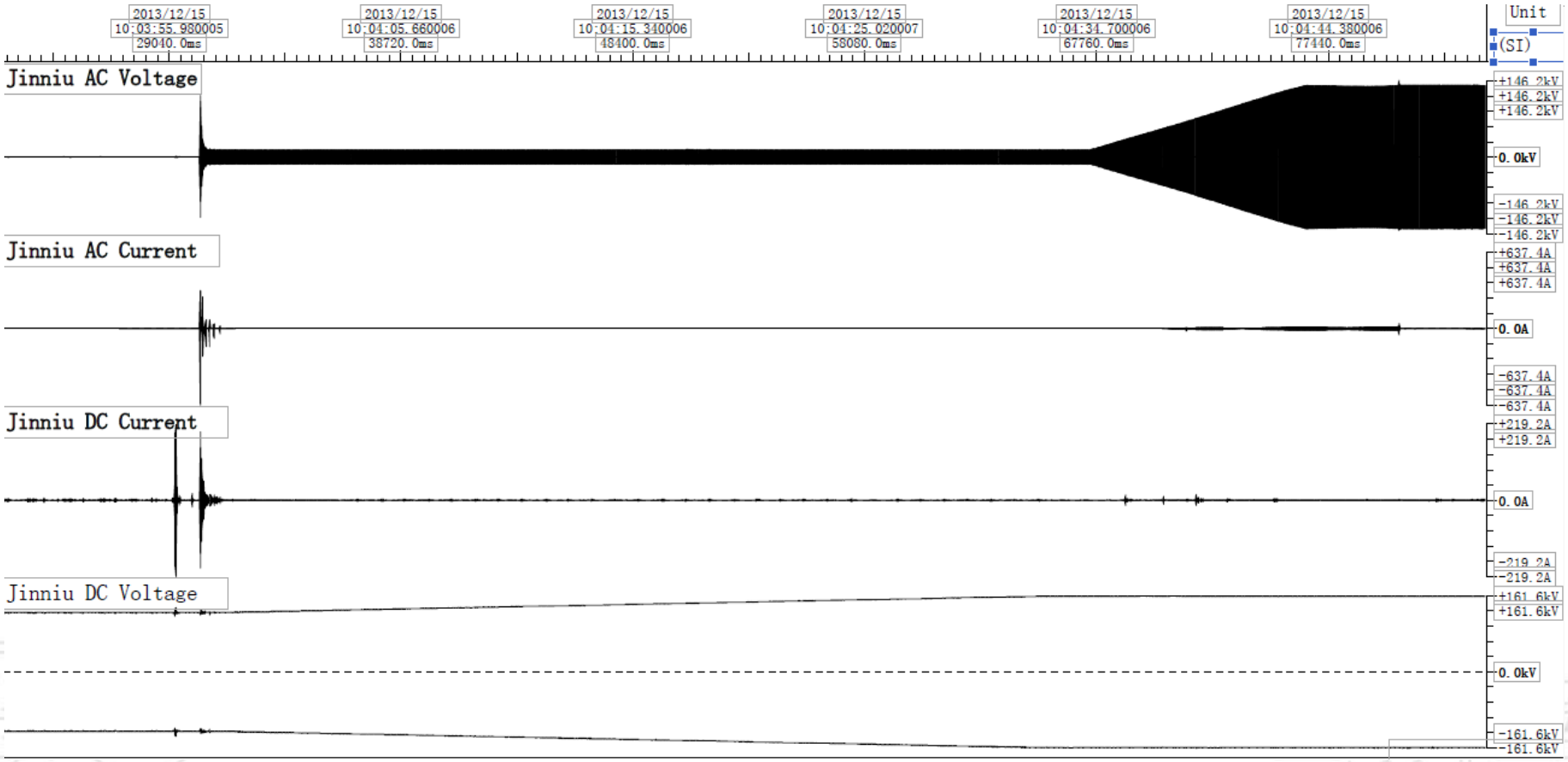
Field Test results (F1) - Nanao project



HIL results (DC charging) – Nanao project



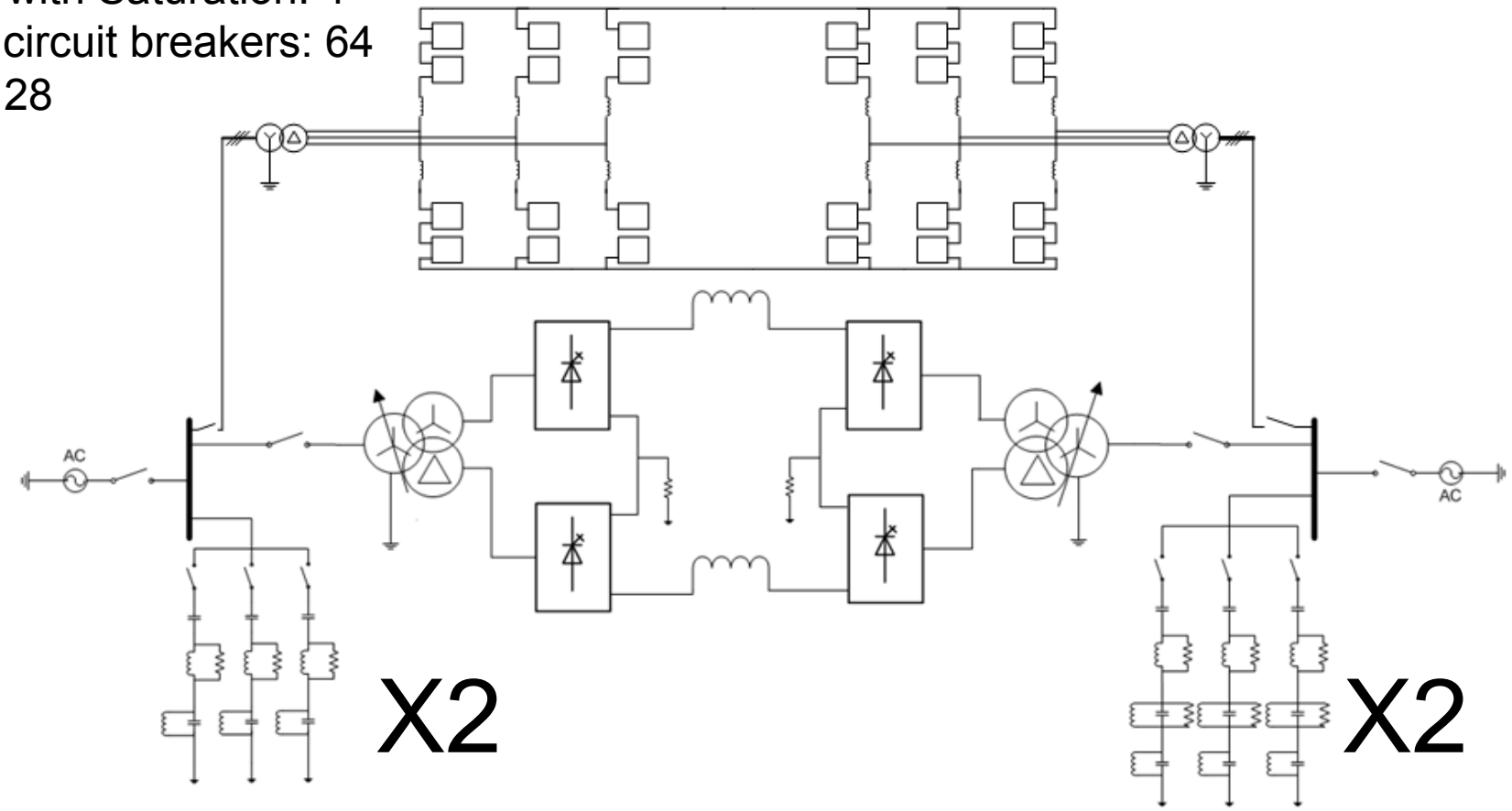
Field Test Results (DC charging) – Nanao project



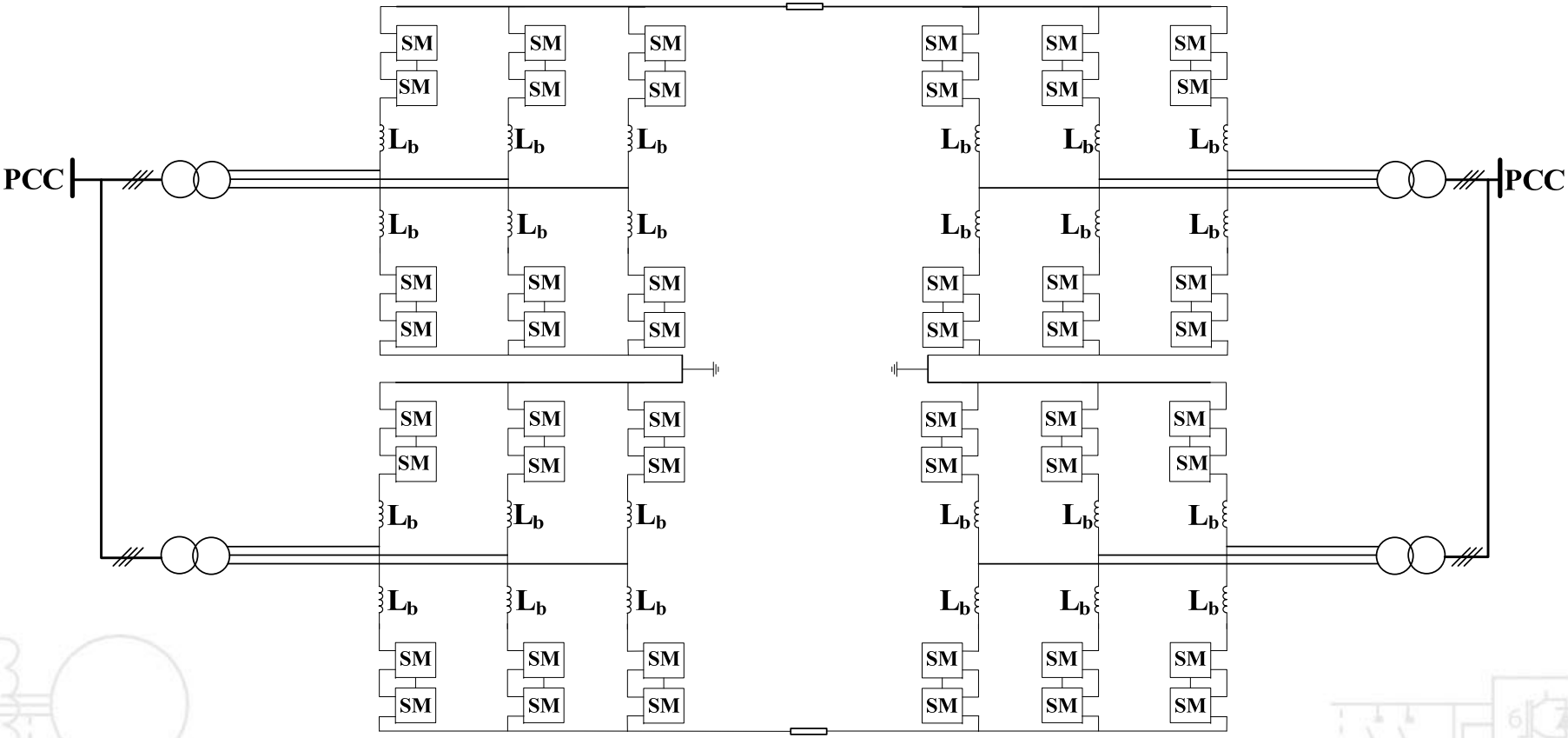
OPAL-RT

Luoping (Yunnan Project)

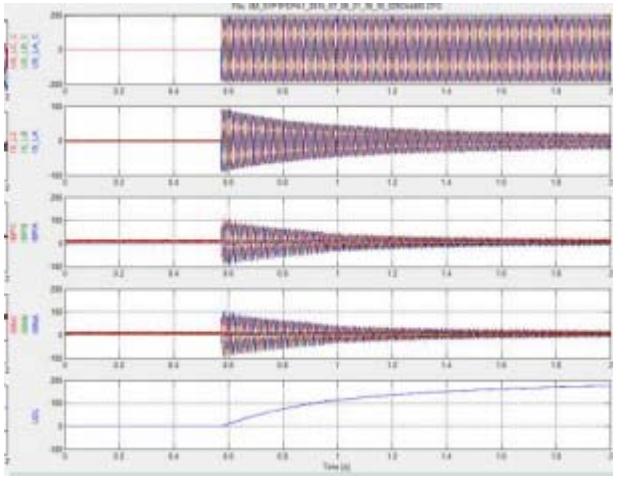
- MMC: 2 converters with 400 half-bridge submodules per valve (or 800 per arm)
- LCC: 2 converters with 12 thyristor each
- Passive filters with circuit breakers: 6 at each terminal
- OLTC with Saturation: 4
- Other circuit breakers: 64
- MOV: 28



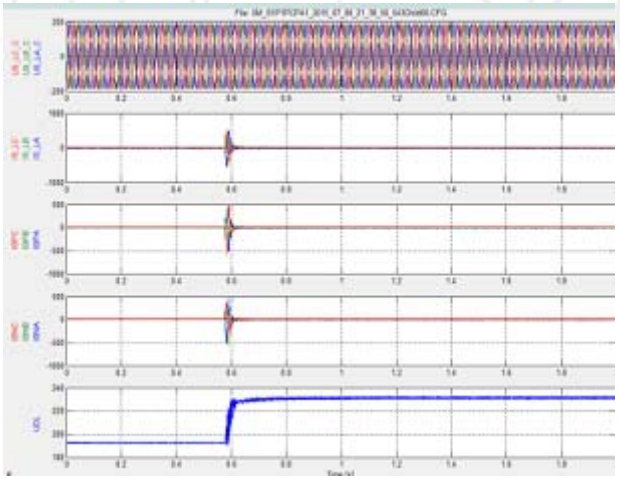
Xiamen MMC-based Bi-pole HVDC



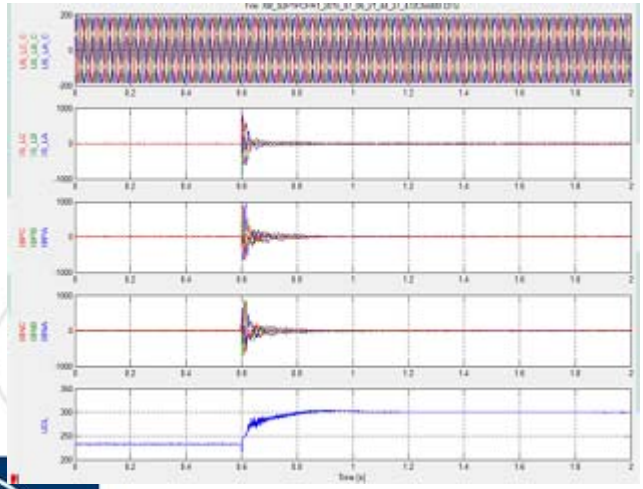
HIL results (start-up) – Xiamen project



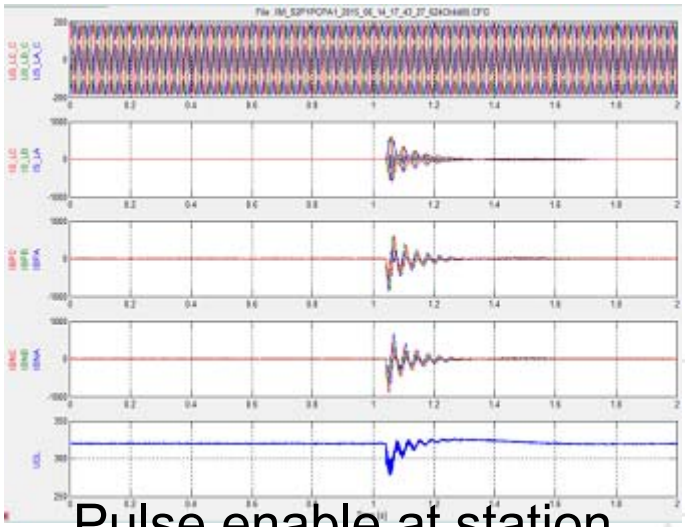
Closing Ac breaker



Closing charging resistor bypass breaker

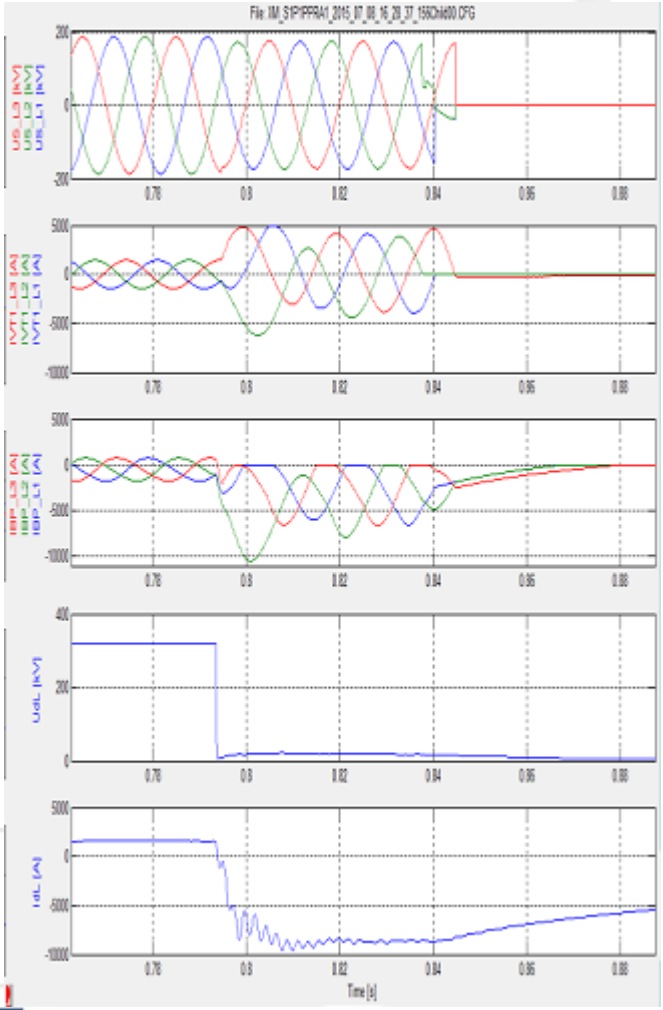


Pulse enable at station controlling Vdc

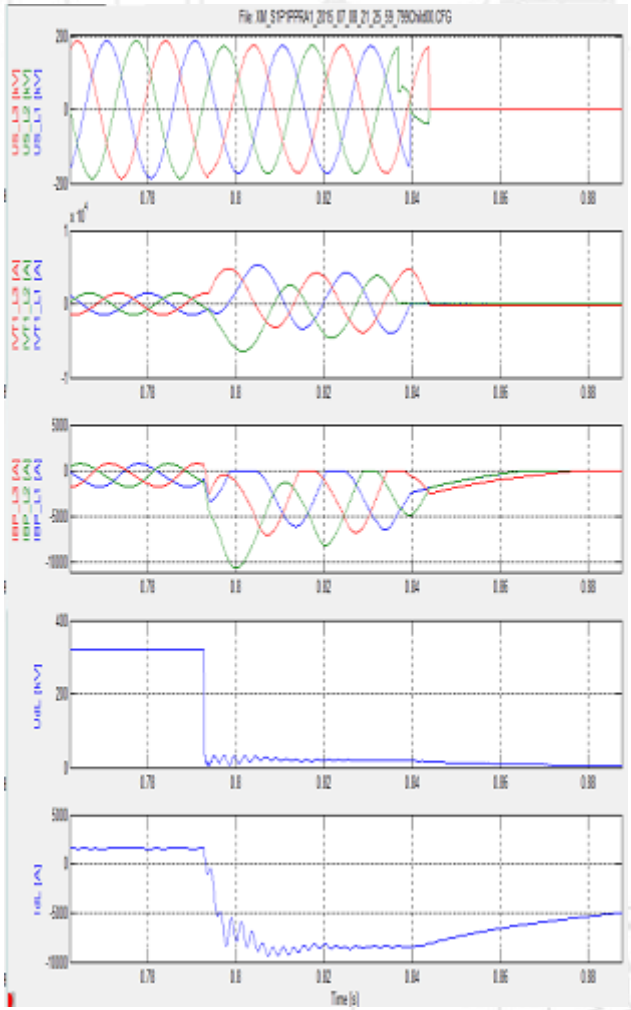


Pulse enable at station controlling active power

HIL results (faults) – Xiamen project



Positive dc pole to ground fault



Positive-to-negative dc fault

MMC Lab-scale test bench for RCP

OP1200 - Rapid control prototyping for Power Electronics Converters Modular, flexible, configurable

Configurable for different type of converter, topology, number of level (11, 21, 31…), DC Voltage (400V, 700V…), frequency (50Hz, 60Hz) and the output power (6kW, 10kW, 20kW…)

Specifications for a 3-Phases MMC Test Bench with 6kW 400V 11-Level for a total of 60 H-bridge cells in one cabinet

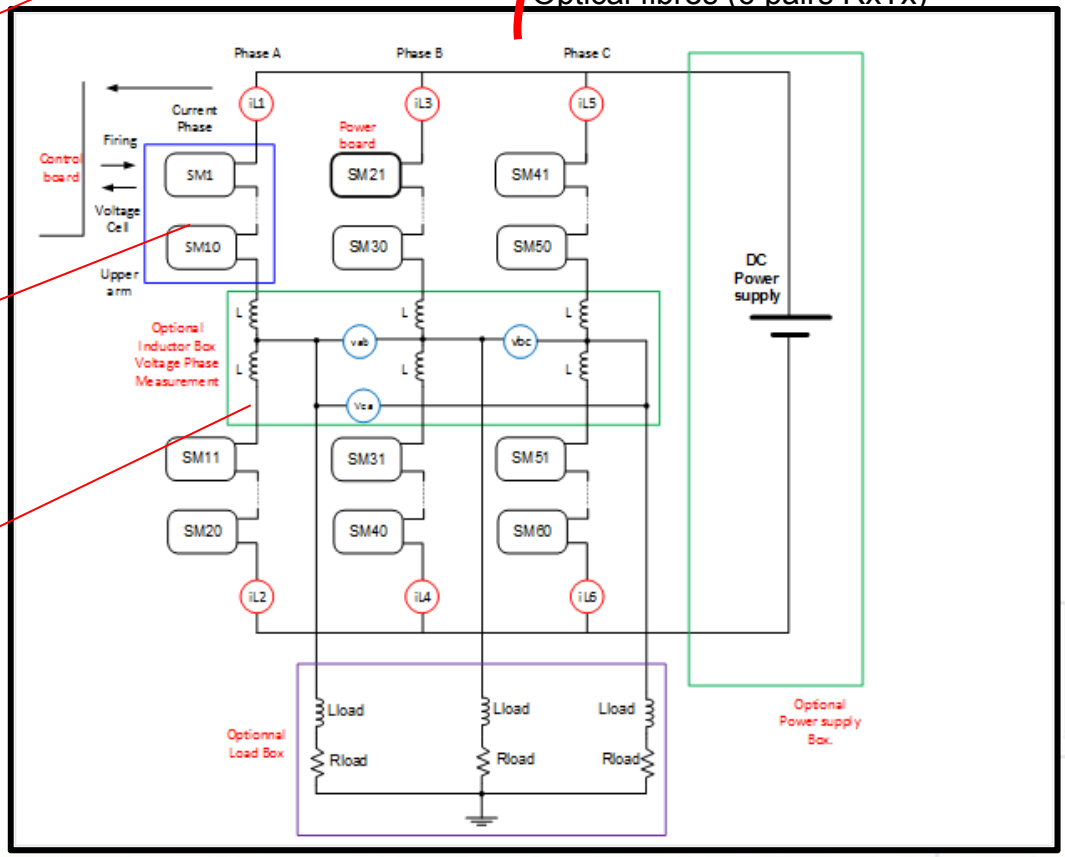
Technical specifications	Value (6 Arm / 11 levels)
DC Maximum Voltage per 10 cell	400 V
DC Maximum Current by arm, I phase	15 Arms (1800VA)
Maximum Output Power	6 KW
Max AC Voltage for each phase (with index modulation at 0.9)	120/208 V 3ph
Max AC RMS current at fundamental frequency	16.7 A
MOSFET Switching Frequency	0-10 kHz
Number of levels	11
Maximum Cell Voltage	40 V
Cell Capacitor	6 mF
Arm inductor	1.75 mH

MMC Lab-scale test bench for RCP

Example for a 3-Phases MMC Test Bench with 10 cells per arm, for a total of 60 H-bridge cells

OP4510 Real-Time Simulator
Intel Xeon Processor and Xilinx FPGA

Optical fibres (6 pairs RxTx)

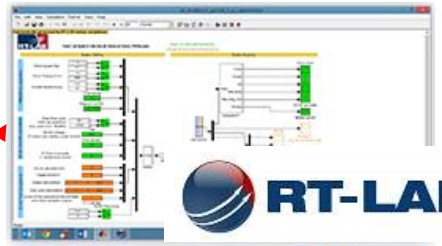


OP1200
OPAL-RT Lab-Scale MMC Test Bench

The **OP1200**, OPAL-RT Lab-Scale MMC Test Bench, includes:

OP1200 – Fully integrated MMC Test Bench

RT-LAB MATLAB/Simulink® and XILINX System Generator
FPGA IP and SIMULINK demo controller for AC-DC 3-phase MMC, 11 level



OP4510 - Real-time Simulator, Intel Xeon Processor and Xilinx FPGA with basic MMC controller Simulink and FPGA IP

OP1210 - 10 H-bridge cells MMC Converter 2U module with OP1211 control board and 10 OP1212 cell modules

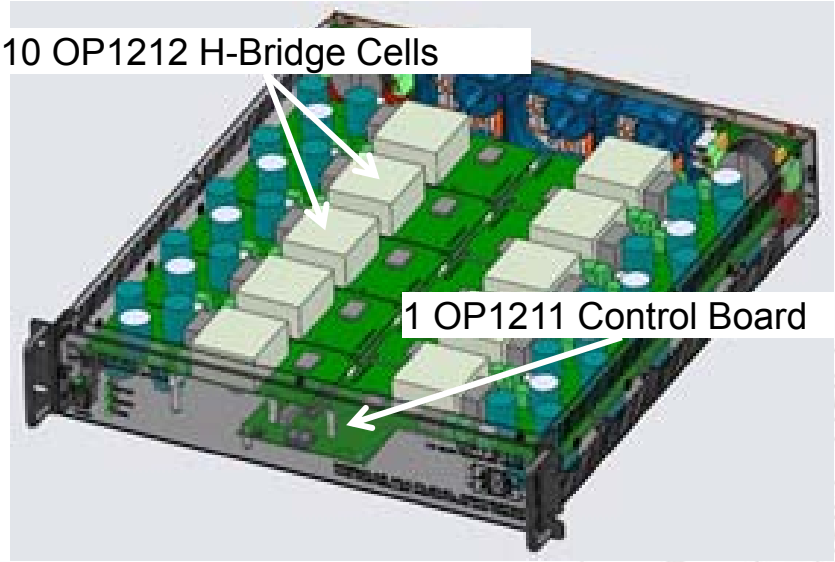
OP1211 – Valve Based Electronic control board

OP1212 - IGBT H-bridge Capacitor Switch Sub-Module

OP1210 - 10 H-bridge cells MMC Converter Specifications

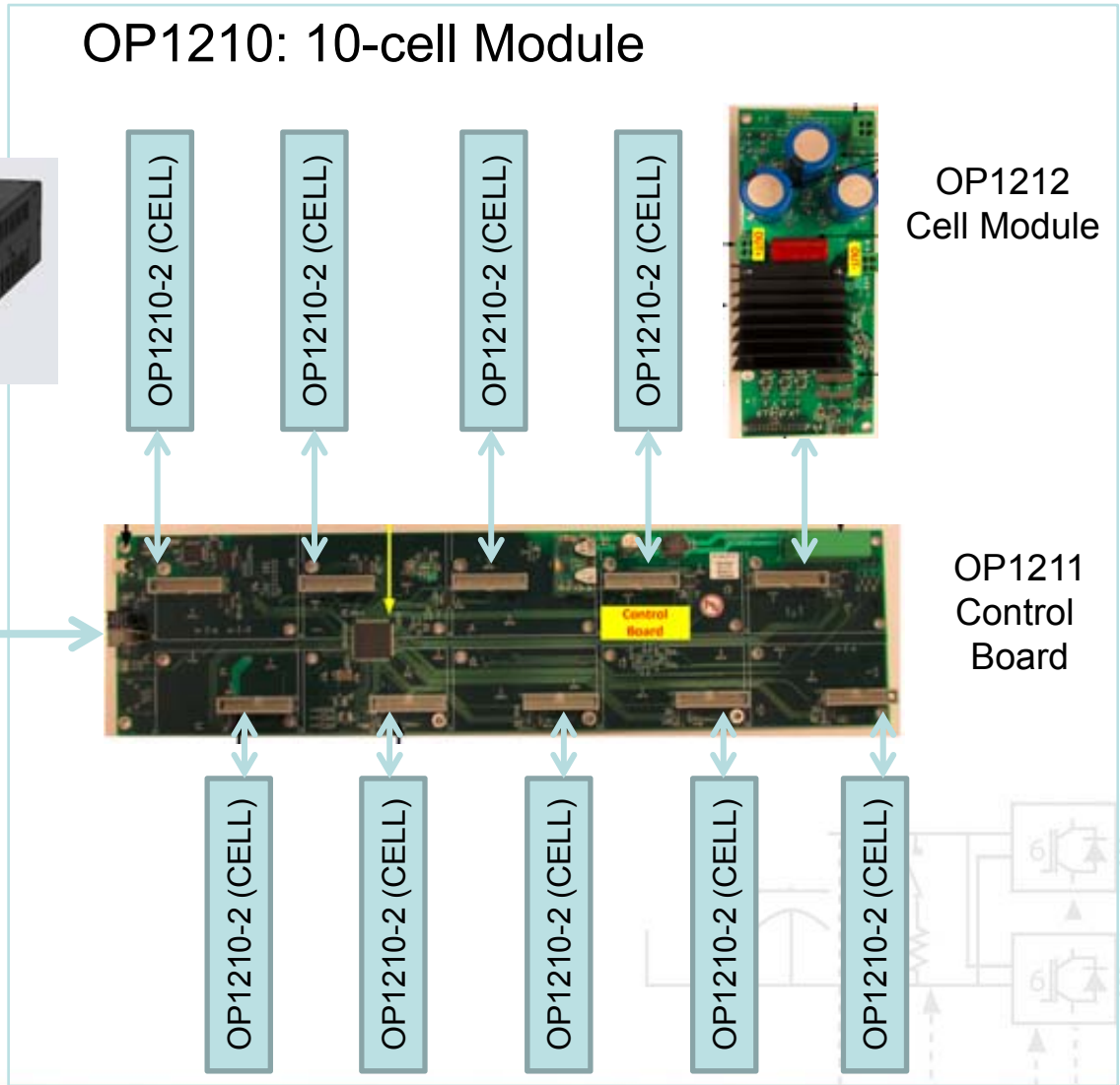
Opal-RT provides a lab **M**odular **M**ultilevel **C**onverter (OP1210) 2U module
Scalable up to 10 H-bridge cells. The OP1210 is designed for 2KW (Rail or Shelves)

Technical specifications	Values
Power Supply	48V
Total Number of H-Bridge Cells	10
Number of power output connectors	2
Max DC Voltage per cell	40 VDC
Max RMS current per arm	15 A
Serial Communication (Tx/Rx Fiber Optic)	50/10 Mbps
Switch status refresh rate	500 ns
ADC sample rate (Cell voltage and current)	50 kHz
Desktop/Rack (Rail or Shelves)	Height 2U Depth 20"
Weight	10Kg

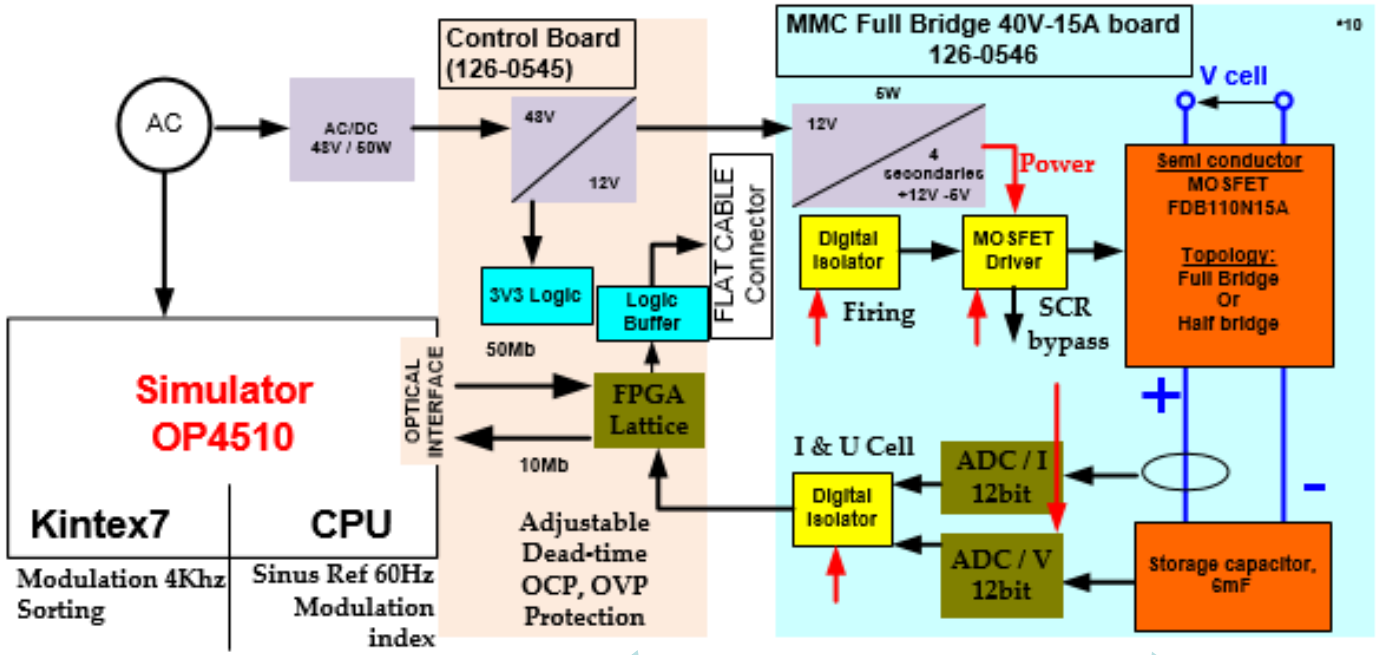


OP1210 - 10 H-bridge cells MMC Converter Module Bloc Diagram

OP4510 - Real-time Simulator
Intel Xeon Processor (4 cores)
Xilinx FPGA (Kintex7 325T)

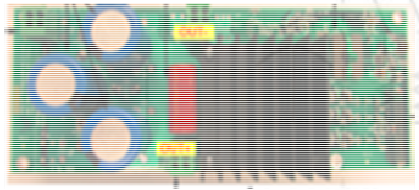


OP1210 - 10 H-bridge cells MMC Converter Module
Detailed Block Diagram



OP1211 Control board for 10 cells

OP1212 H-Bridge Cell



Summary

- MMC C&P systems is very complex, making complete integration test before commissioning is extremely important
- HIL complements off-line simulation tools:
  - -To increase simulation speed to meet tight development schedule
  - -To increase testing coverage by doing more tests in less time
  - -To increase fidelity by interfacing with actual hardware
  - -To perform large integration tests with several controllers
  - -All of the above are to reach the goal of better MMC C&P system quality by thorough validation of real life situation
- Multi-levels converter with multi-terminals require continues improving of the HIL tools

Summary

Challenges	OPAL-RT Solutions
Very small time step for SM	250 ns or 500 ns
Small time step for AC grid, arm inductors and transformer	20 to 60 micros using ARTEMIS-SSN or HYPERSIM nodal solver
Very small time step for arm inductor and transformer models	500 ns to 1 us using eHS FPGA nodal solver (Q4 2014)
Large number of SM per converter	1500 to 6000 cells per FPGA
Large number of terminal for HVDC grids	Use several FPGA boards (systems with up to 10 FPGA have been delivered)
Connection to controller with fast rate and small latency	Aurora or Gigabit Ethernet 1 to 5 us update depending on number of optical fiber links and number of cells
Accuracy for non-linear elements, e.g. MOV for fault simulation and other large disturbances	Iterative solver
Tested reliability	Several projects

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Thanks.