









WP9 T9.7/T9.8 Demonstration of Non-selective strategies for Meshed HVDC networks

03-04/09/2020



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North Sea Grid for the European New Deal

How to unlock Europe's Offshore Wind potential - a deployment plan for meshed HVDC grid



Laurent CHEDOT

Research group leader

laurent.chedot@supergrid-institute.com +33 (0) 6 69 31 69 38



• EXPERIENCE

- PhD in electrical engineering with Valeo, research on starter-alternator control
- 10-years with Alstom Transport as motor control expert
- 6-years with SuperGrid Institute as power converter control engineer and then modelling and simulation group leader

• PROJECT ROLE

- Coordination of the real-time simulation platform of SuperGrid Institute
- Technical review of specifications and test results



CONTENT

- 5' CONTEXT
 - Objectives
 - Roadmap

25' - NON-SELECTIVE PROTECTION STRATEGIES

- Generalities
- Non-selective fault clearing strategies
 - Focus on CBS: Converter breaker strategy
 - Focus on FBS: Full-bridge converter-based strategy



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HARDWARE-IN-THE-LOOP DEMONSTRATION

- 40' Scope
- 30' Results
- 5' CONCLUSION
- 15' Q&A session







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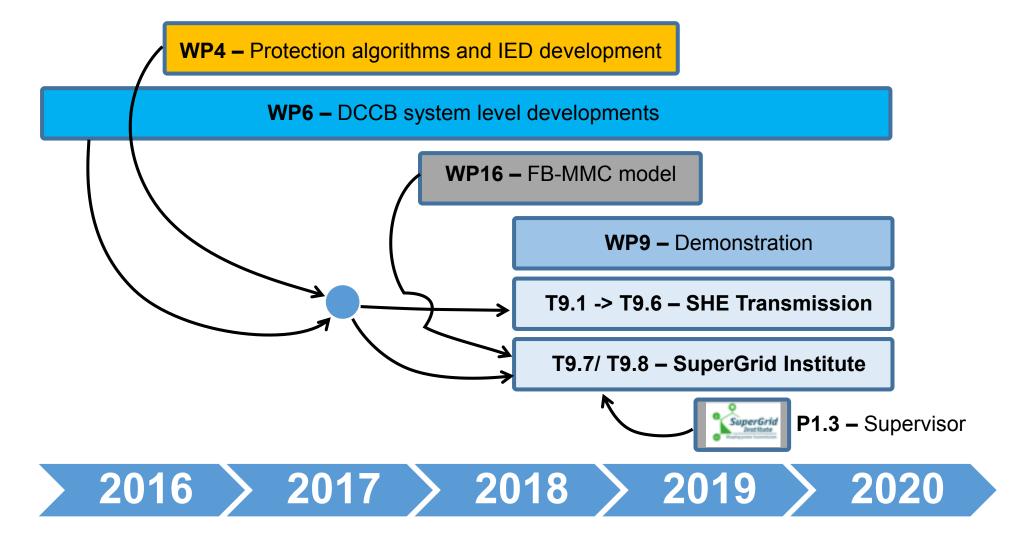
WP9 Objectives

- Integrate IED prototypes (from WP4) and DCCB models (from WP6) in RTS environments
- Develop DC grid benchmark models and test procedures for protection system testing
- Demonstrate protection system performance using HIL testing
 - Primary sequence
 - Backup sequences
 - System level consequences of protection failure
- Demonstrate equipment interoperability
 - Different DCCB technologies (HSS, DCCB)
 - Different MMC technologies (HB-MMC or FB-MMC)
 - Prototyped IEDs
 - Standard communication protocol (IEC61850)
- Demonstrate DC grid restoration performance (after fault clearing process)
 - DC grid control (station and central supervisors)
 - IEDs (Hardware-In-the-Loop) or in the simulation (Software-In-the-Loop)



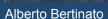


CONTEXT WP9 Framework













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NON-SELECTIVE PROTECTION STRATEGIES





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Alberto Bertinato



Research Group Leader - Supergrid Architecture Principles

Alberto.bertinato@supergrid-institute.com +33 (0)6 98 67 24 42

• EXPERIENCE

- DC grid protection
- DC grid operation
- AC high voltage substation equipment

- PROJECT ROLE
- Lead of Deliverable 4.3
- Support to WP4, WP9, WP12
- Support for Short Term Project Clean Stream Energy Hub Bornholm



SuperGrid Institute

Alberto Bertinato

INTRODUCTION TO DC PROTECTION STRATEGIES

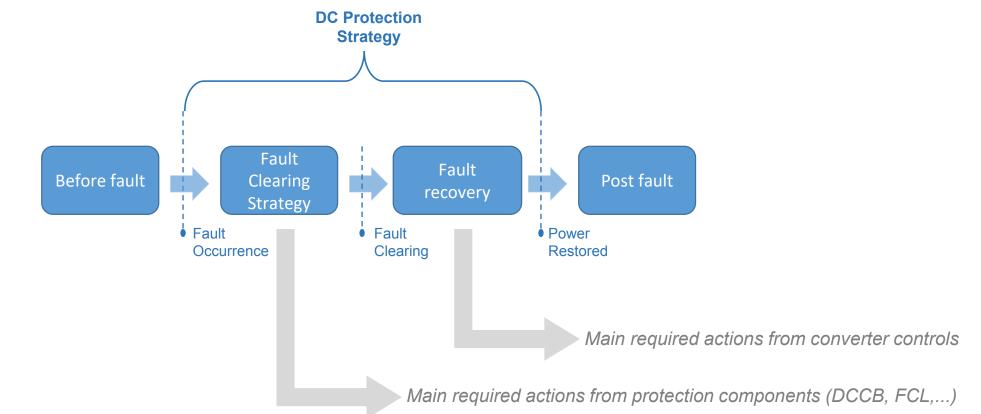


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NON-SELECTIVE PROTECTION STRATEGIES DC Protection Strategy Generalities

• What is meant by DC protection strategy ?

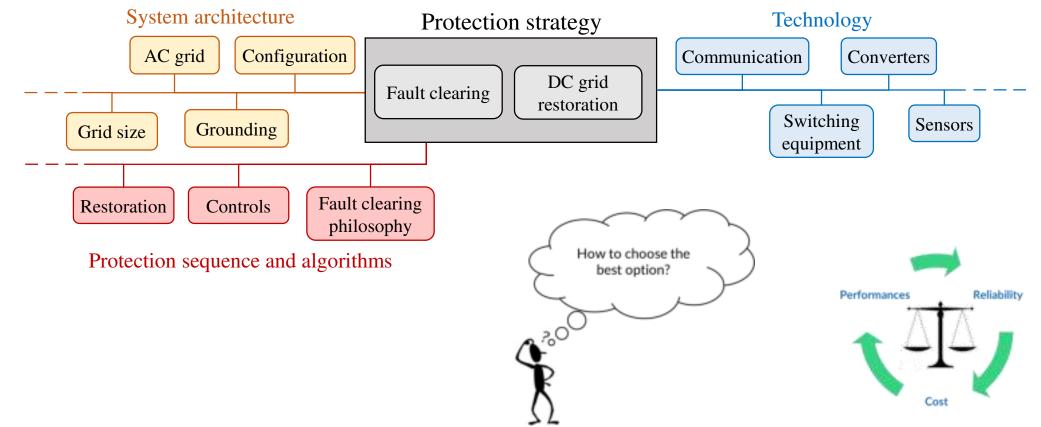






NON-SELECTIVE PROTECTION STRATEGIES **DC Protection Strategy Generalities**

• The DC protection strategy is the combination of three key elements:

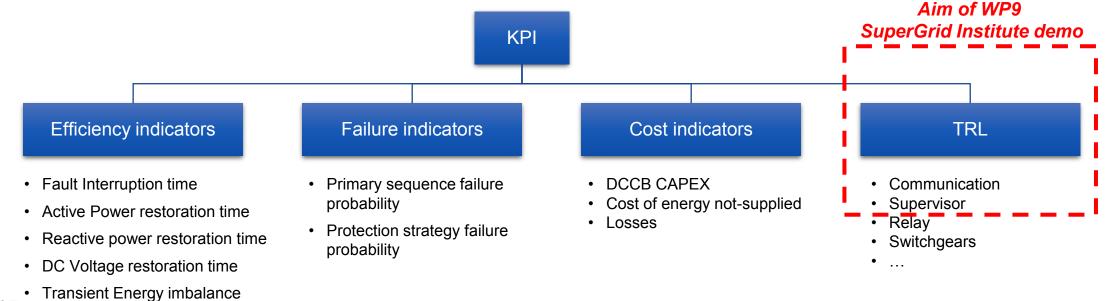






NON-SELECTIVE PROTECTION STRATEGIES **DC Protection Strategy Generalities**

- Proposal of KPIs families
 - $\checkmark\,$ Measure the impact a protection strategy can cause to the DC system
 - ✓ Measure the reliability of the protection strategy
 - $\checkmark\,$ Find the optimum from a techno-economic point of view
 - ✓ Technological Readiness Level of protection equipment





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How to unlock Europe's Offshore Wind potential - a deployment plan for meshed HVDC grid



Pascal TORWELLE

PhD candidate | Research engineer pascal.torwelle@supergrid-institute.com +33 (0) 7 51 32 36 63



• EXPERIENCE

- M.Sc. Electrical Power Engineering, LUH Hannover
- Currently: Last year of PhD at Supergrid Institute in cooperation with University Grenoble Alpes, research interest: HVDC grid protection

- PROJECT ROLE
- Support to WP4, Task T4.3



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Converter Breaker Strategy



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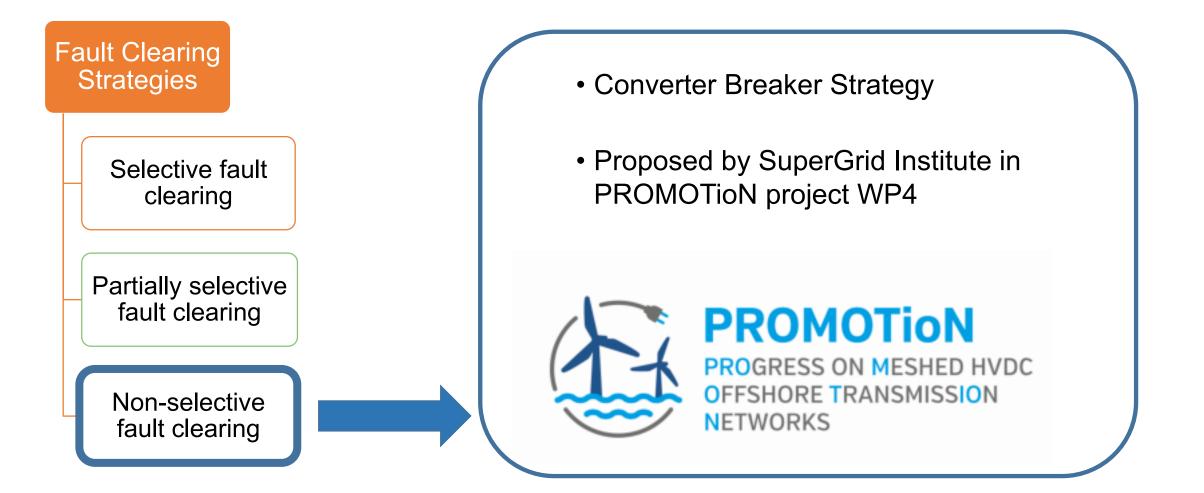


Converter Breaker Strategy **OUTLINE**

- Introduction
- Protection components and layout
- Primary sequence
- Backup sequence
- Switchgear requirements
- Conclusions



CONVERTER BREAKER STRATEGY





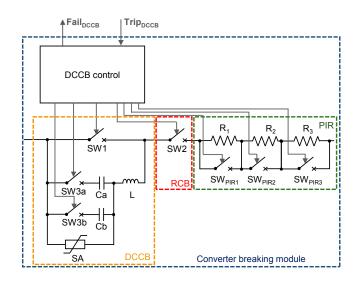




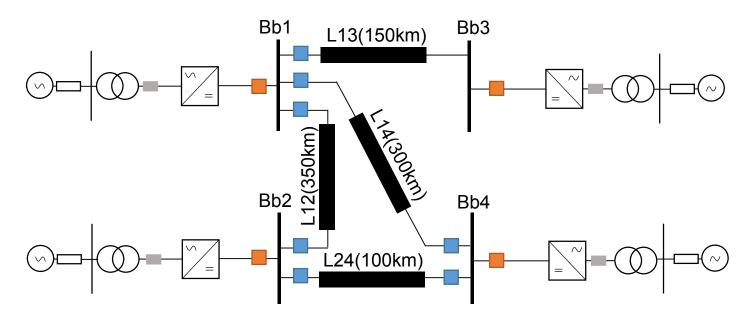
CONVERTER BREAKER STRATEGY Protection components and layout

Line breaker module <u>LB</u> installed at each line end

Converter breaker module <u>CB</u> installed at each converter output



DCCB: DC circuit breaker RCB: Residual current breaker

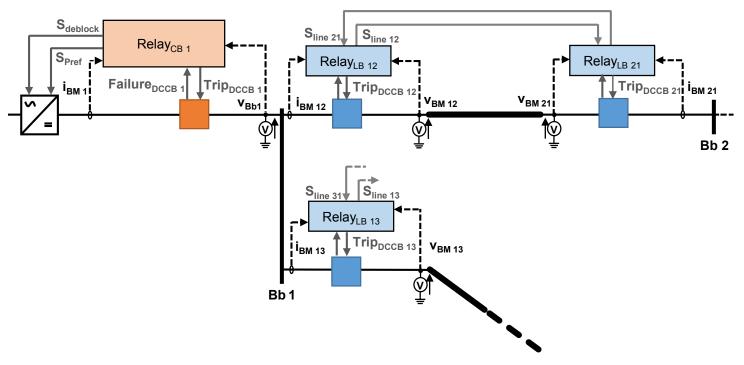






CONVERTER BREAKER STRATEGY Protection components and layout

Sensor measurement and relay communications



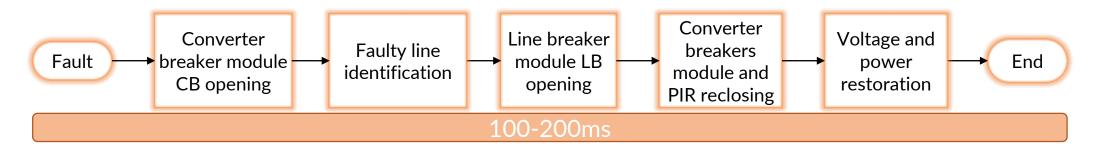
CB relay

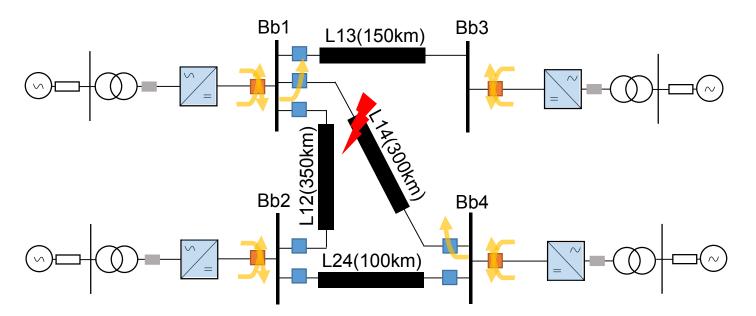
- Voltage and current measurements
- Communication with breaking module
- Communication with MMC
- LB relay
 - Voltage and current measurements
 - Communication with breaking module
 - Communication with remote line end





CONVERTER BREAKER STRATEGY **Primary sequence**

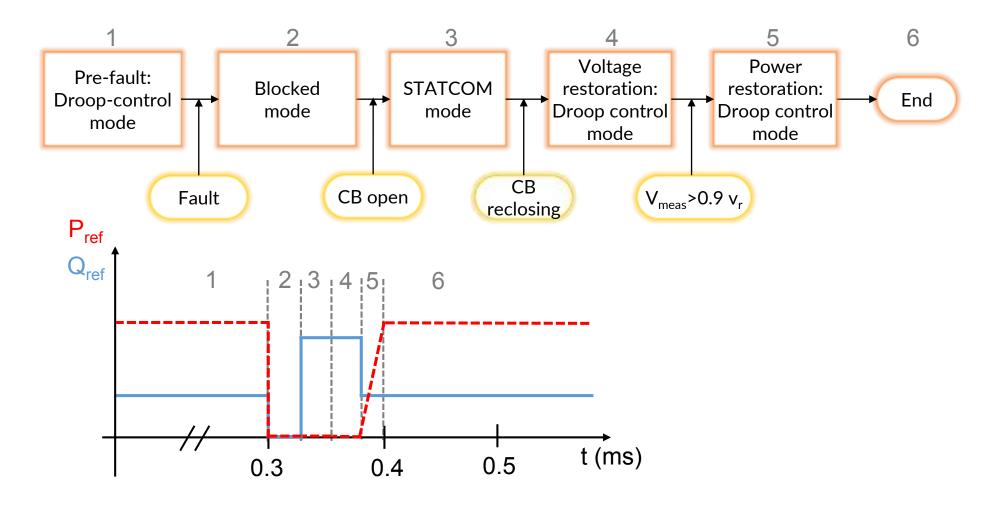








CONVERTER BREAKER STRATEGY MMC fault ride through operation modes

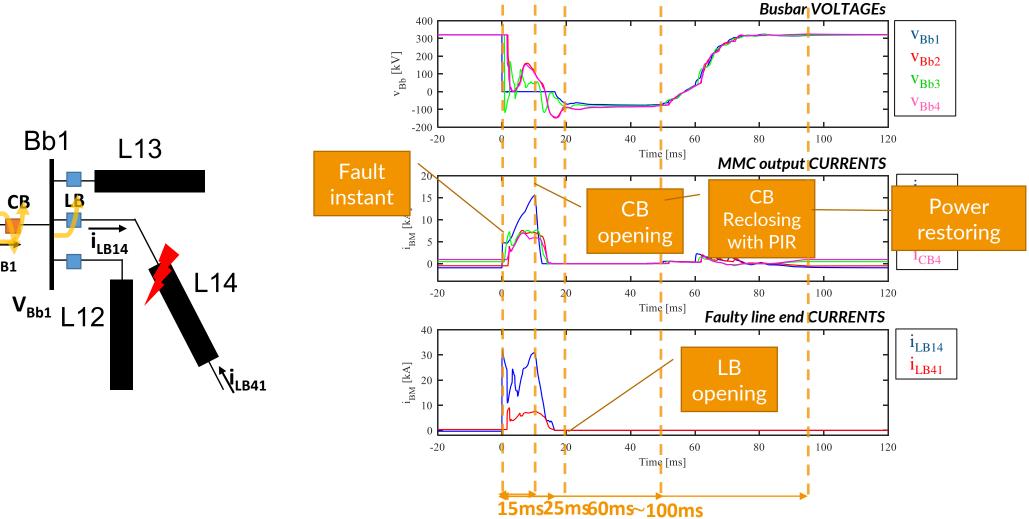




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CONVERTER BREAKER STRATEGY Simulation of the primary sequence





 \mathbf{P}_{AC}

 \sim

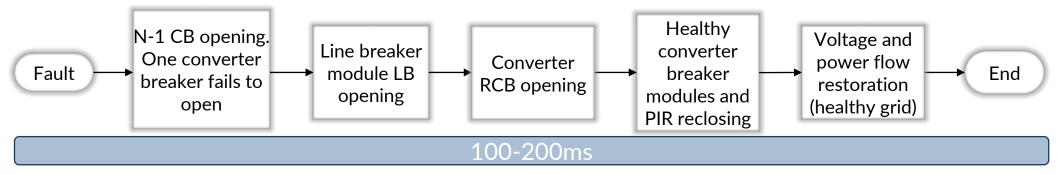
CB

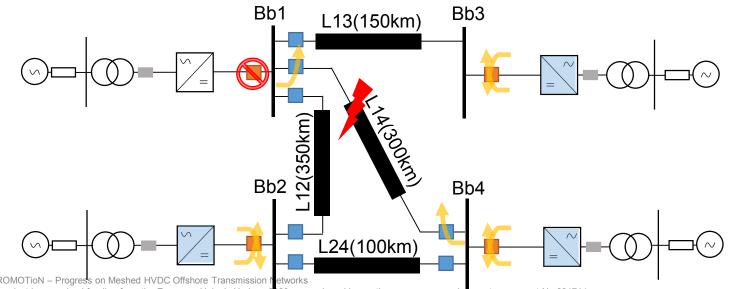
I_{CB1}



CONVERTER BREAKER STRATEGY BACKUP SEQUENCES

• Case 1: Converter Breaker failure





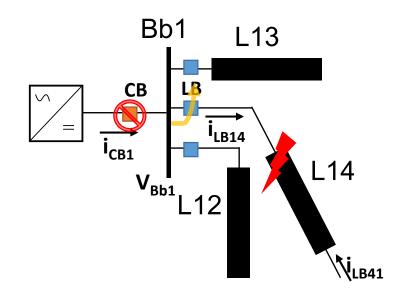


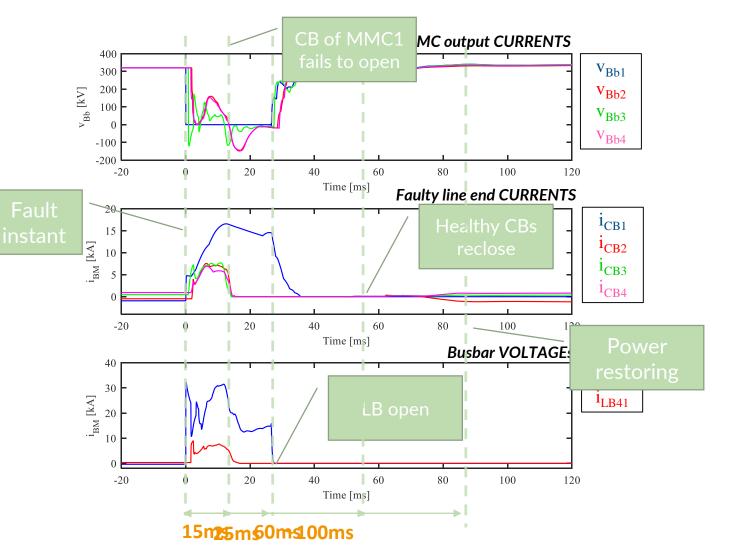
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CONVERTER BREAKER STRATEGY BACKUP SEQUENCES

Case 1: Converter Breaker failure



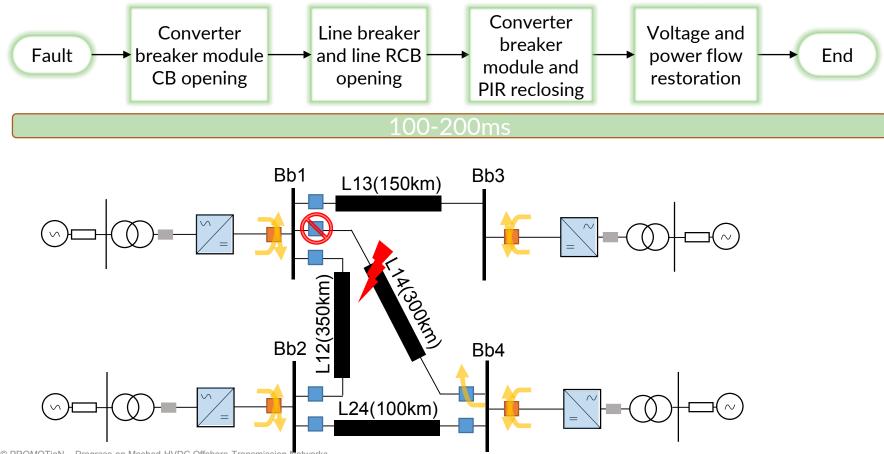






CONVERTER BREAKER STRATEGY BACKUP SEQUENCES

• Case 2: Line Breaker failure



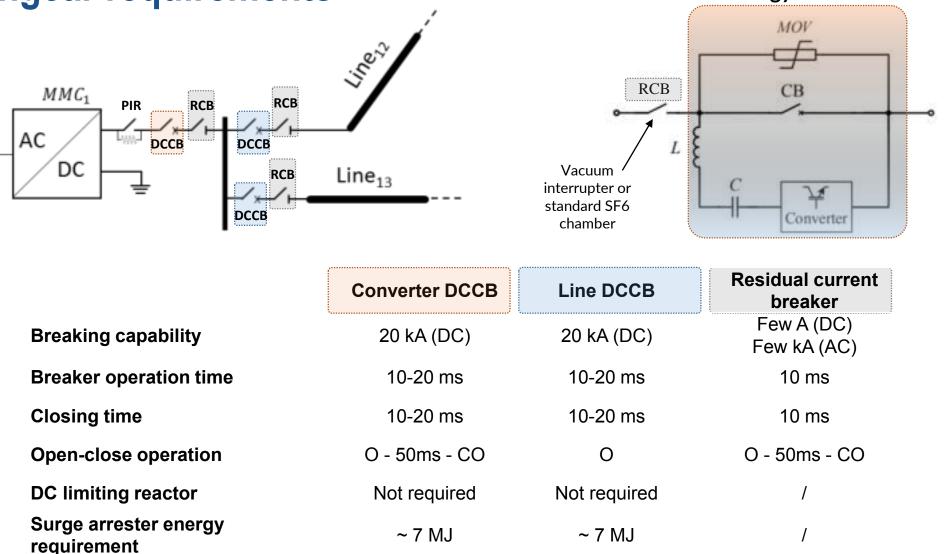


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CONVERTER BREAKER STRATEGY Switchgear requirements

Example of possible technology for DCCB





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CONVERTER BREAKER STRATEGY CONCLUSIONS

- Advantages of the Converter breaker strategy
 - No need to use ultra-fast hybrid DC breaker
 - Mechanical DC breaker is a suitable solution
 - Reduced energy dissipation required within DC breaker
 - No need to use limiting inductor
 - No need to use ultra fast fault discrimination algorithms
 - Communication protocols for protection equipment can be based on IEC61850
- MMC can work in STATCOM mode to support the AC side \sim 40ms after fault inception
- Power restoring within 100-200ms for primary and backup sequences
 - No risk of transient instability when considering an AC inertia coefficient of 4 with reasonable DC power exchange





✓ Multivendor
✓ Cost
✓ Interoperability

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Philipp RUFFING

Team Leader DC Systems

p.ruffing@iaew.rwth-aachen.de +49 (0) 241 / 80 92948

Patrick DÜLLMANN

Research Associate

p.duellmann@iaew.rwth-aachen.de +49 (0) 241 / 80 93033



EXPERIENCE

- Team Leader DC Systems @ RWTH Aachen since 2019
- Research Associate
 @ RWTH Aachen since
 2016
- M.Sc. Electrical Engineering @ RWTH Aachen in 2015

PROJECT ROLE

- Work package lead of WP16
- Model development in WP2
- Development a DC grid protection strategy based on fault-blocking converters in WP2/WP4

EXPERIENCE

- Research Associate
 @ RWTH Aachen since
 2018
- M.Sc. Electrical Engineering @ RWTH Aachen in 2018

PROJECT ROLE

- Development of MATLAB/Simulink® and Hypersim® Models in WP9
- Research on DC grid protection based on fault-blocking converters in WP2/WP4/WP16

FULL-BRIDGE MMC BASED STRATEGY



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Non-Selective Protection

Fault separation at near-zero current and voltage

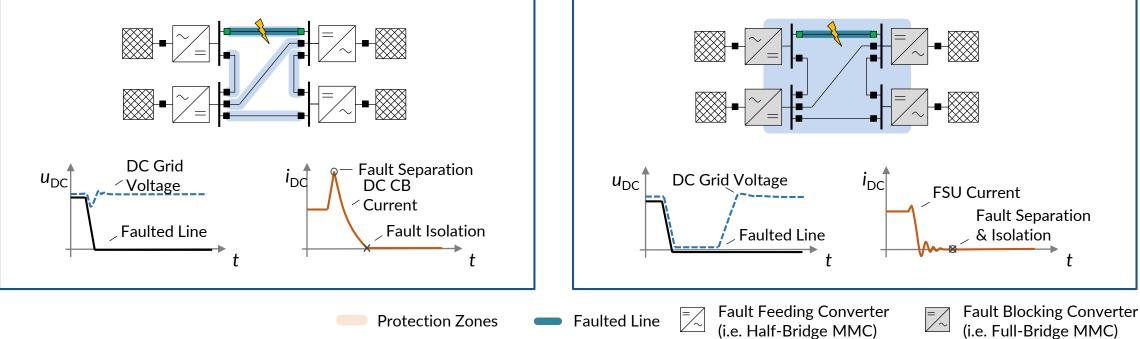
Entire DC network as protection zone

Fast de-energisation of the protection zone

FULL-BRIDGE MMC BASED STRATEGY HVDC Grid Protection Philosophies

Fully Selective Protection

- Every DC line as an individual protection zone
- Fault separation by fast DC circuit breakers
- High requirements on DC switchgear

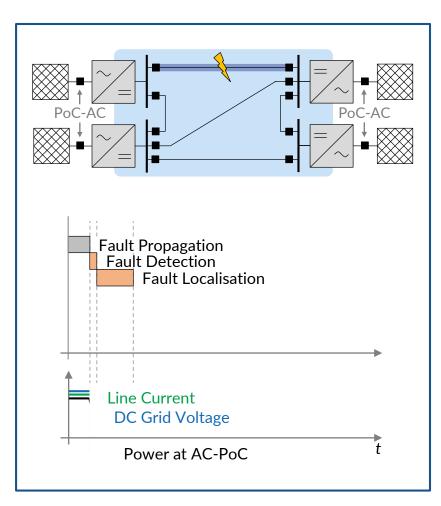






FULL-BRIDGE MMC BASED STRATEGY

Protection Strategy – Detection and Localisation



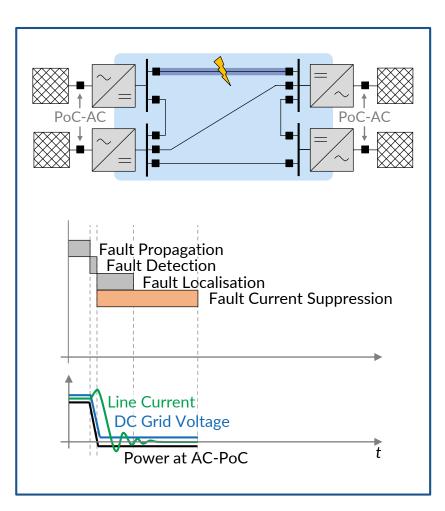
Fault Detection

- Fault detection by every converter within the network
- Initiate the fault current suppression of each converter within the protection zone
- ≻High-speed fault detection
- Fault Localisation
 - · Localization of the line to be separated
 - Required for the fault separation after the deenergization of the network
 - Low-speed fault localization based on communication is sufficient for the protection strategy

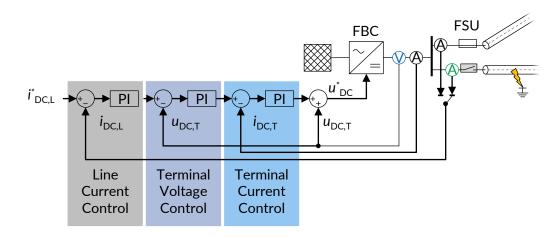




FULL-BRIDGE MMC BASED STRATEGY Protection Strategy – DC Fault Control



- Fast reduction of the energy injected into the DC system
- Enable a fast fault separation under near-zero current and voltage conditions
 - Discharge the DC network
 - Reduce the current flowing through the fault separation units
- Cascaded fault control approach

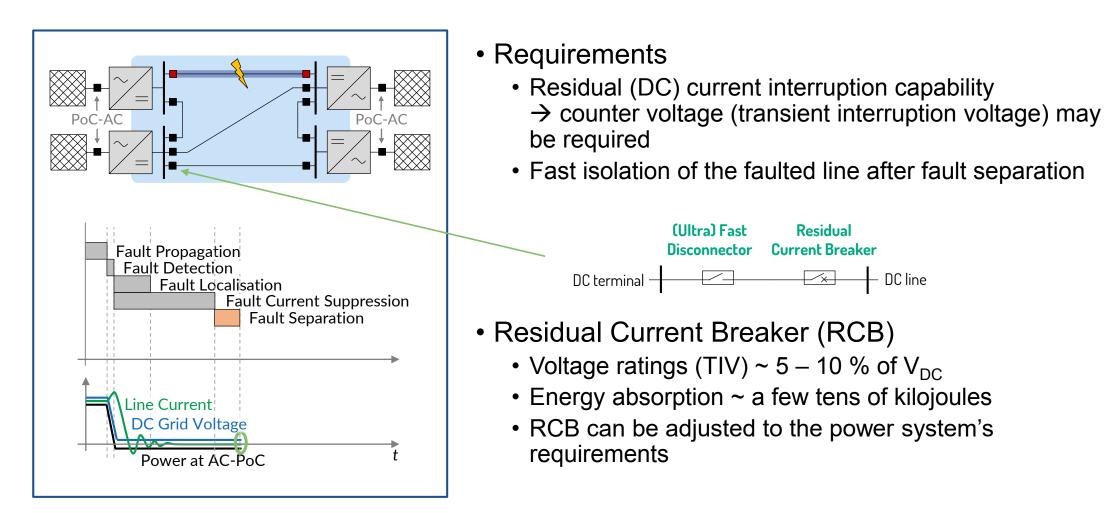






FULL-BRIDGE MMC BASED STRATEGY

Protection Strategy – Fault Separation Unit

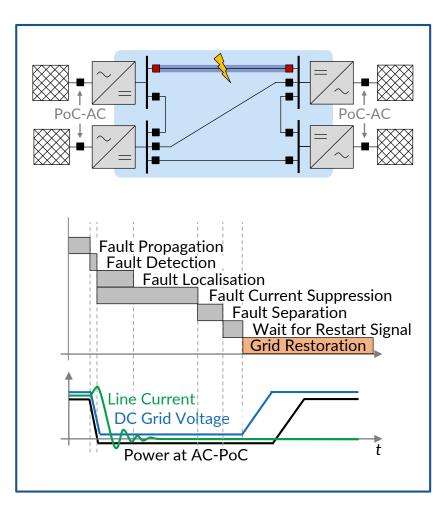






FULL-BRIDGE MMC BASED STRATEGY

Protection Strategy – Grid Restoration

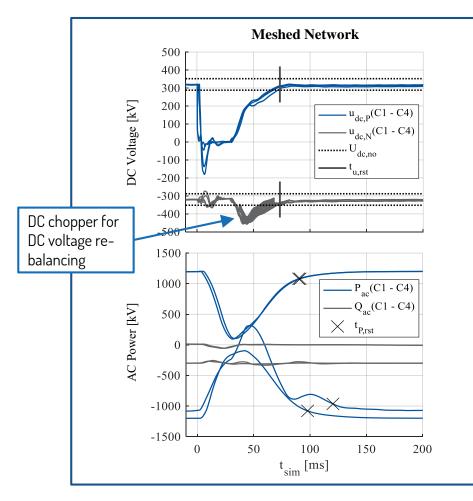


- DC Voltage Restoration
 - Symmetrical monopole configuration
 - Pole-voltage rebalancing required
 - By: DC choppers, AC-side zero-sequence grounding or converter-controlled rebalancing
 - Bipole configuration
 - No pole-voltage rebalancing required
- Active Power Restoration
 - Fast active power restoration since no line inductors are required for the protection strategy





FULL-BRIDGE MMC BASED STRATEGY Protection Strategy – Performance



- Key Performance Indicators (4-terminal HVDC network):
 - Fault Separation Time: 20 50 ms
 - DC Voltage Restoration Time: 50 100 ms
 - Active Power Restoration Time: 70 150 ms
 - Transient Energy Imbalance: 20 70 MJ
 - Reactive Power: No outage, since MMCs are continuously controlled

FBC-based protections systems can be competitive alternative to DC circuit breaker based HVDC grid protection systems for "small" networks





William Leon-Garcia

SCOPE OF THE HARDWARE-IN-THE-LOOP DEMONSTRATION



SuperGrid



Antoine Ghyselinck



North Sea Grid for the European New Deal

How to unlock Europe's Offshore Wind potential - a deployment plan for meshed HVDC grid



William LEON GARCIA

Research engineer

william.leongarcia@supergrid-institute.com +33 (0) 6 69 28 48 63



• EXPERIENCE

- PhD in electrical engineering research on HVDC grid protection and applied superconductivity
- 3-years in HIL testing, real-time simulation and prototyping at SuperGrid Institute

- PROJECT ROLE
- Technical leader of tasks T9.7 and T9.8 in WP9:

Demonstration of non-selective fault clearing strategies for meshed HVDC networks



William Leon Garcia

SuperGrid Institute

SCOPE OF THE DEMONSTRATION System layout



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OVERVIEW Demonstration of two kinds of non-selective protection strategies

> Converter Breaker Protection Strategy (CBS)



Bipole

Half Bridge MMC

Converter Breaker

Mechanical DC Circuit Breakers

Full Bridge converter based protection Strategy (FBS)



Asymmetric Monopole

Full Bridge MMC

Fault current control

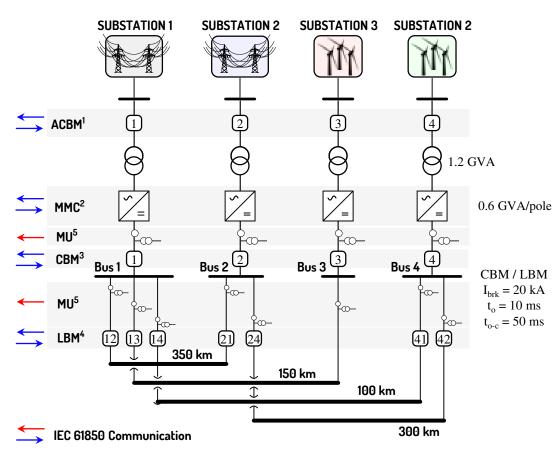
High Speed Switch





SCOPE OF THE DEMONSTRATION - System layout

PLANT – CONVERTER BREAKER PROTECTION STRATEGY Four-terminal meshed HVDC network

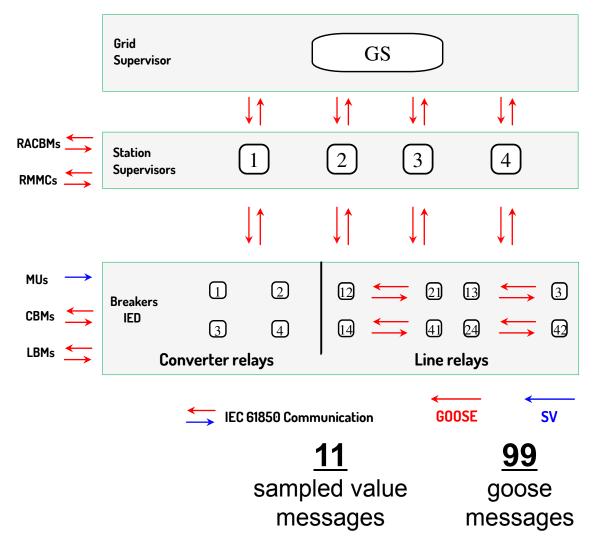


¹AC breaker module ²Modular multi-level converter ³Converter breaker module ⁴Line breaker module ⁵Merging Unit

- Bipole (one pole represented)
- A lot of communication is needed
- One pole simulated
 - Lighter for :
 - The simulation target
 - The ethernet network (one switch)



SCOPE OF THE DEMONSTRATION - System layout DEVICES UNDER TEST – CONVERTER BREAKER PROTECTION STRATEGY - Communication architecture

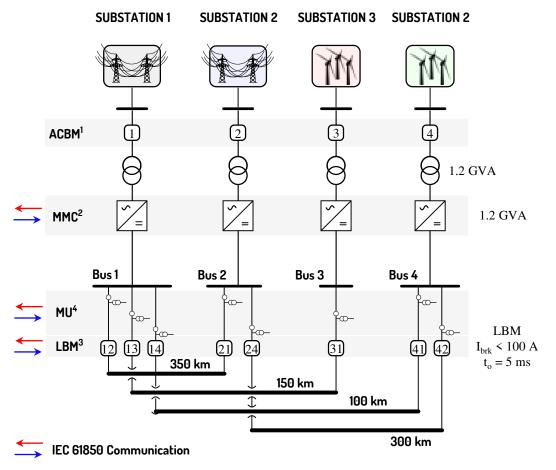


- 4 layers of communication :
 - Network <-> Relays
 - Relay <-> Relay
 - Relays <-> Station Supervisors
 - Station Supervisors <-> Grid Supervisor
- RLBMs on the same line communicate to give current direction information.

SCOPE OF THE DEMONSTRATION - System layout



PLANT – FULL BRIDGE CONVERTER PROTECTION STRATEGY Four-terminal meshed HVDC network



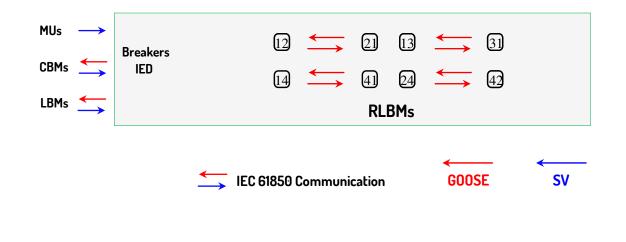
¹AC breaker module ²Modular multi-level converter ³Line breaker module ⁴Merging Unit Asymmetric monopole

- The full-bridge converter has fault current controlling capability
 - Converter breaker not needed
 - Line breaker module:
 - Residual current breaker +
 - High speed switches
- Model can startup without supervision, and supervision is not needed by protection



SCOPE OF THE DEMONSTRATION - System layout

DEVICES UNDER TEST – FULL BRIDGE CONVERTER PROTECTION STRATEGY - Communication Architecture

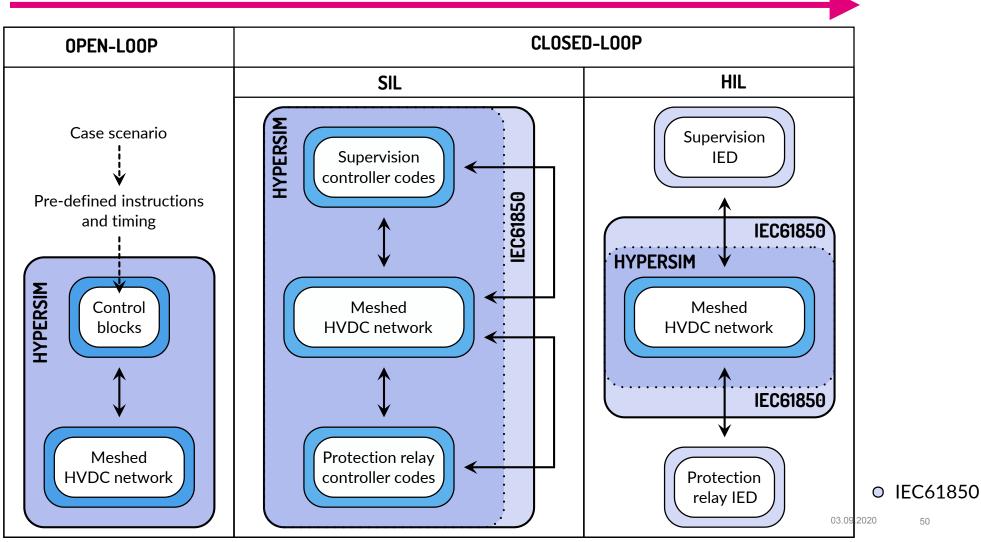


<u>8</u> <u>43</u> sampled value goose messages messages

- Full-bridge converter supervision included in simulation model
 - Communication simplified: less signals and layers.
- 2 layers of communication :
 - Network <-> Relays
 - Relay <-> Relay
- RLBMs on the same line communicate to exchange current direction information.



SCOPE OF THE DEMONSTRATION - System layout HARDWARE-IN-THE-LOOP **Demonstration workflow**



50

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Antoine GHYSELINCK

Research engineer

antoine.ghyselinck@supergrid-institute.com +33 (0) 7 63 66 19 06



• EXPERIENCE

- Engineer degree in power systems
- Internship on AC/DC grid stability
- 1 year on HIL testing and real-time simulation at Supergrid Institute

- PROJECT ROLE
- Implementation of the Demonstration of non-selective fault clearing strategies for meshed HVDC networks



















Antoine Ghyselinck

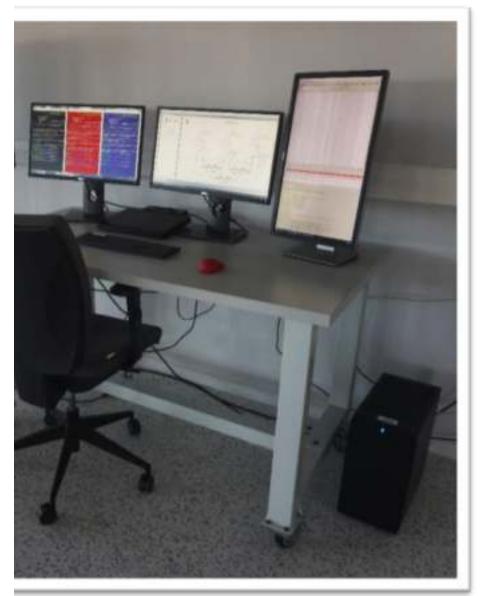




SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup USER'S WORKSPACE

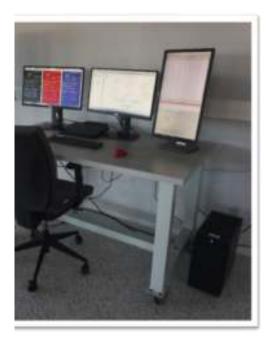
• Good grade desktop PC with all the softwares needed for HIL set up.

• Several monitors to display results from the different softwares.















Opal-RT OP5700 Target

Items Quantity		Description		
Operating System	1	Redhat v2.6.29.6-opairt-6.1		
Chassis Type	1	OP5700		
CPU	2	Intel Xeon E5, 8Cores, 3.2 GHz, 20M Cache		
Total Core *	16			
Memory	4	8 GB		
Motherboard		X10DRL-I Supermicro Motherboard Dual Intel® Xeon (E5) processor		
IP Address		192.168.10.101 (eth 0) - PF616171S01 192.168.10.103 (eth 0) - PF616171S03 - see Figure 1 for Ethernet port identifications		
AC Input		115-230V, 60-50Hz		
FPGA Board Index		00		

*Our license can run up to 10 cores on a simulation

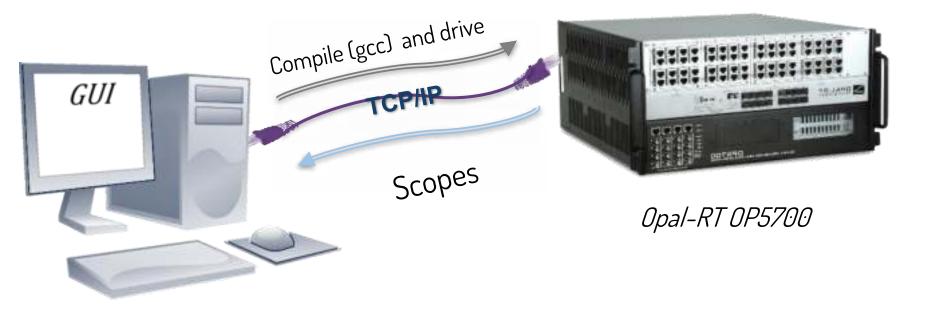
OPAL-RT OP5700 Target Hardware

ld 📥	Exec	Exec Max	Sim	Sim Max	IO Out Max	IO In Max	Last in Sync	Stretched Step
1	16.76	40.0	49.99	50.66	0.06	0.08	109428	0
2	1.57	2.51	46.71	60.65	0.61	13.72	0	0
3	1.25	2.0	44.06	65.35	9.07	13.0	0	0
4	1.98	5.5	47.7	59.69	0.11	13.81	0	0
5	4.17	5.12	46.99	66.28	11.43	12.21	19	0
6	1.82	4.97	49.96	60.85	0.06	13.61	0	0
7	1.98	6.62	52.66	59.73	0.6	13.86	0	0
8	5.17	12.3	53.96	62.06	0.18	14.43	0	0
9	10.55	19.0	50.03	51.06	0.26	0.44	0	0
10	6.94	18.81	50.01	50.92	0.32	0.47	0	0

Hyperview during a simulation (Target Analyzer)

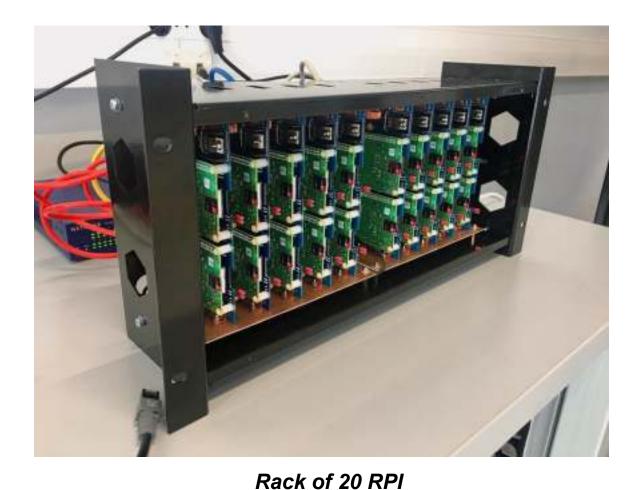








SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup INTELLIGENT ELECTRONIC DEVICES





System on Chip	64-bit quad-core Cortex-A72 processor
Clock speed	1.5 GHz
RAM	4GB LPDDR4 SDRAM
Communication	Native Gigabit Ethernet port
Operating System	Debian
Dev tools	Text editor, gcc (compiler) , gdb (debugger)

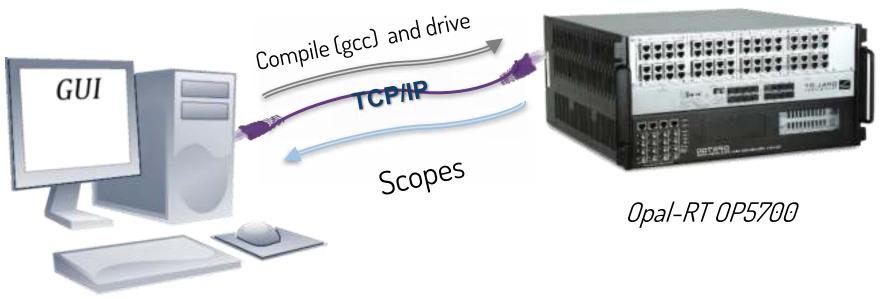
Raspberry PI 4B Overview

CBS : 11 Relays, 5 Supervisors FBS : 8 Relays



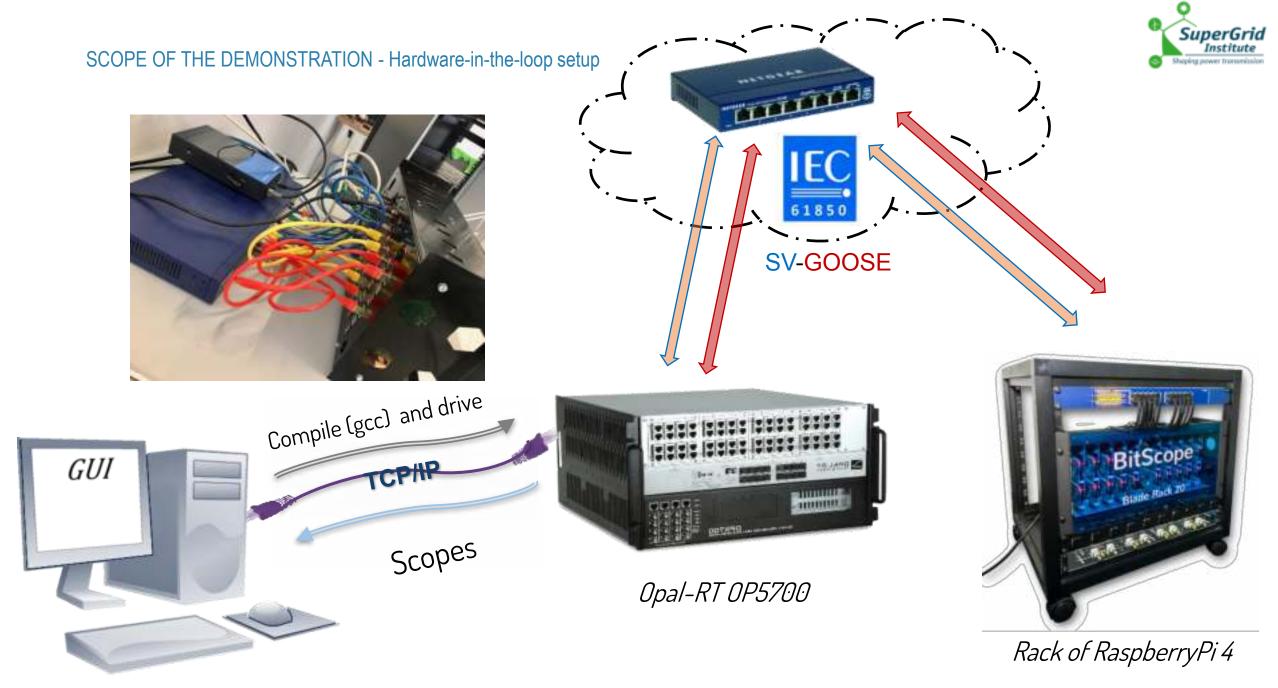


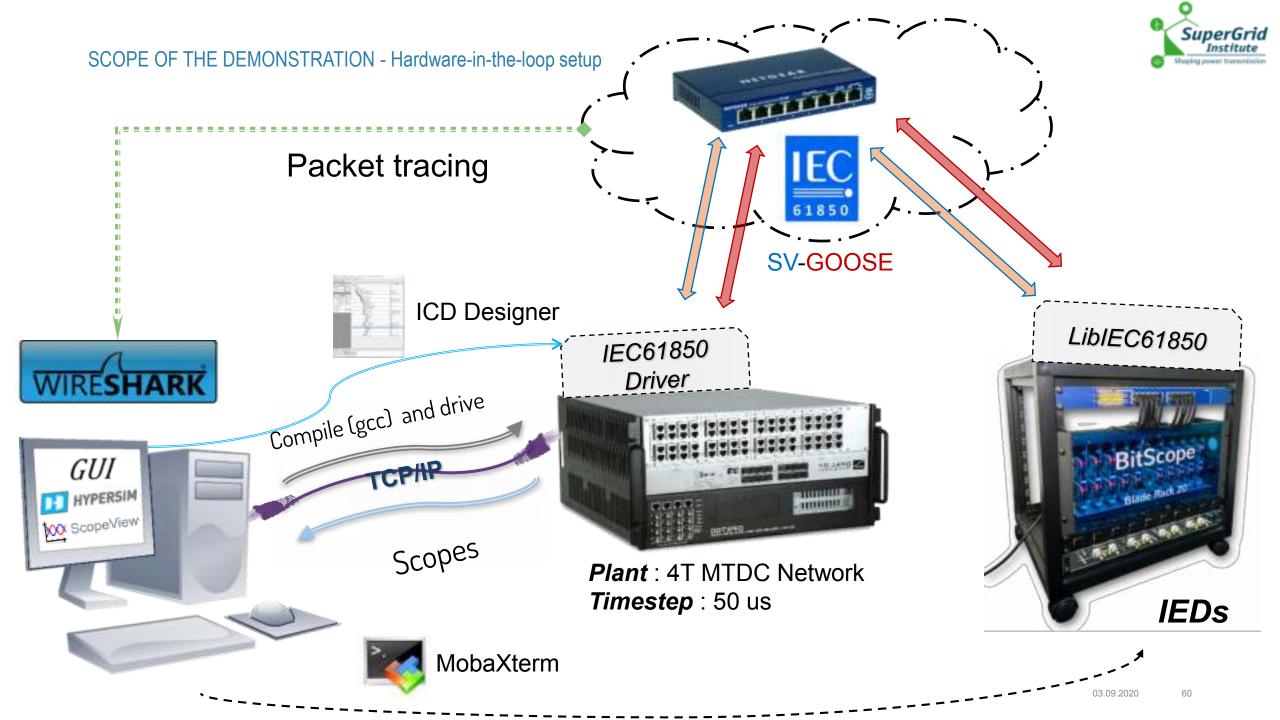






Rack of RaspberryPi 4







SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup THE BIG STEPS

	CBS	FBS
Build HYPERSIM models	X	
Collaboration with RWTH for model and		X
Real time implementation and validation 🧿	X	X
Implement protection relays	X	Χ
Implement supervisors	X	
IED prototype development	X	Χ
Set up communication with IEC61850	X	Χ





William Leon-Garcia

SuperGrid Institute

SCOPE OF THE DEMONSTRATION Real-time simulation models

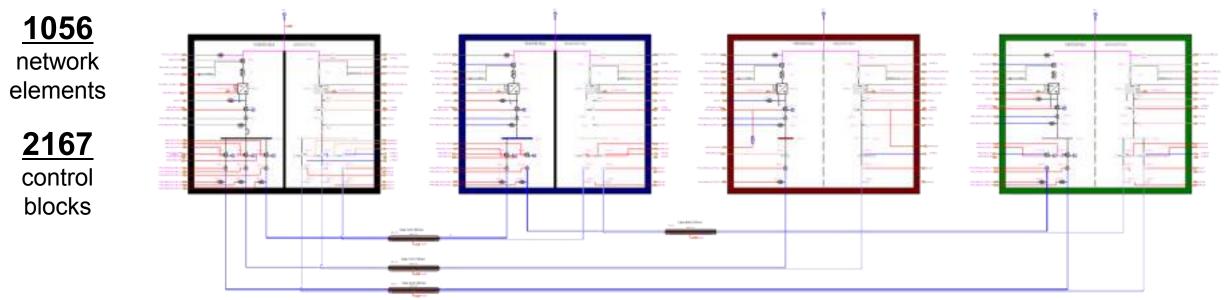


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SCOPE OF THE DEMONSTRATION - Real-time simulation models BUILD HYPERSIM MODELS Four-terminals meshed HVDC network for CBS protection strategy

- Real-time models developed in other PROMOTioN workpackages are compatible with RTDS.
 - We needed to built them from scratch for OPAL-RT solutions.
- Main models required : MMC , DC Breakers, Cable
 - These models were created based on documents from other workpackages' and know-how in modeling of HVDC technologies.

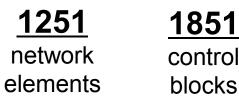


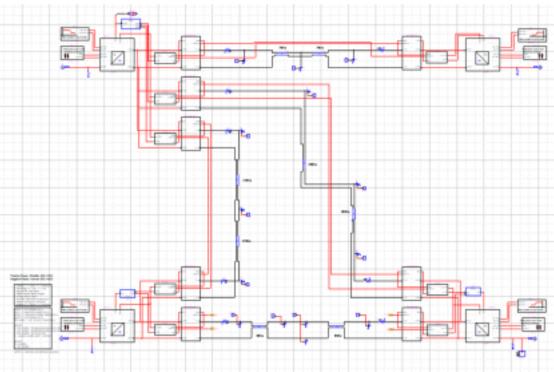




BUILD HYPERSIM MODELS Score of the DEMONSTRATION - Real-time simulation models Four-terminals meshed HVDC network for FBS protection strategy

- The model was given by RWTH with a full documentation (☺)
 - Depth Understanding of the FBS (literature, documentation, collaboration with RWTH)
 - Handling of the model
- Real time implementation tasks:
 - Task managing
 - Decoupling if necessary







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SCOPE OF THE DEMONSTRATION - Real-time simulation models

BUILD HYPERSIM MODELS

Semi-analytical average model of Modular Multilevel Converter

Physica	al Model	Control		
 i.e. Average Model Valve in the HYPE Arm Topology IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII		 HB-MMC control (ZAMA Ahmed, SuperGrid Institute) in Simulink imported in HYPERSIM via Hyperlink. FB-MMC control (RUFFING P, DÜLLMANN P) From model MMC control module GUI for control tuning For model GUI for control tuning 		

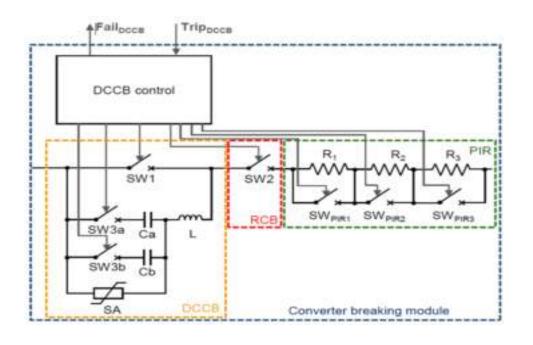
Average Model reduction of the MMC's arm



SCOPE OF THE DEMONSTRATION - Real-time simulation models BUILD HYPERSIM MODELS DC circuit breakers

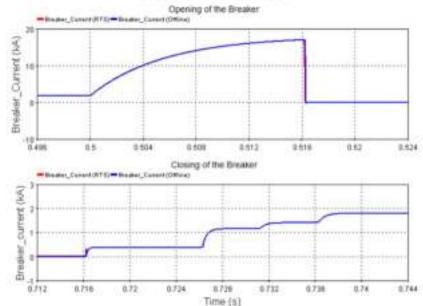
• CBS

- Active resonant DC breaker made from the WP6 literature
- Breaker model validation



FBS

- Residual current breaker
- Ultra fast disconnector
- Models are simplified but follow the specifications (ideal switch with adapted delays, current and voltage operating threshold)
 Breaker Validation in RTS

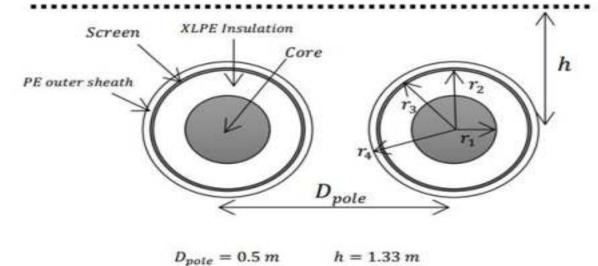






SCOPE OF THE DEMONSTRATION - Real-time simulation models BUILD HYPERSIM MODELS DC Cable

• Wideband cable model



DC Cable Description

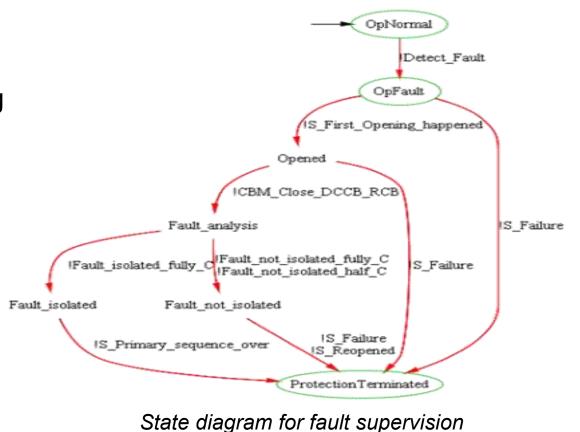
- Heavy computation, some assumptions has been made:
 - Screen grounded at both ends (limit number of sections)
 - Screen effect neglectable -> reducing number of conductors (4 to 2)





SCOPE OF THE DEMONSTRATION - Real-time simulation models BUILD HYPERSIM MODELS Supervisors design

- Discrete events controllers which will coordinate the associated system according to its inputs
- The associated system can be a station or the entire network
- Defined by two types of technical specifications :
 - A state diagram
 - A list of I/O
- Board to IED :
 - Extraction to C functions (SUPREMICA)











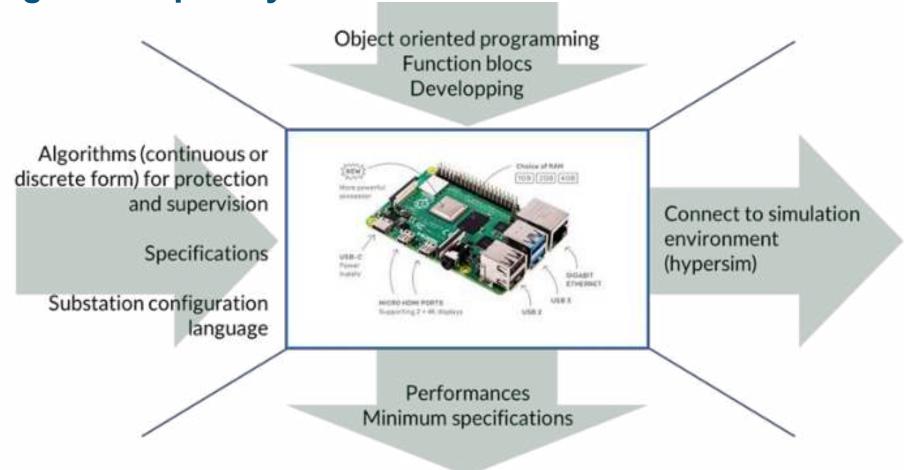
Antoine Ghyselinck



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SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup INTELLIGENT ELECTRONIC DEVICE (IED) Prototyping on Raspberry Pi 4b





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SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup IED PROTOTYPING C code algorithms

- Why C code ?
 - Low level langage, achieving speed requirements
 - IEC61850 Library is made for C code
- In depth C code learning required to :
 - Translate algorithms in a structured way
 - Meet the specifications







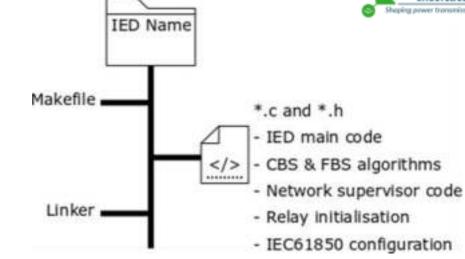
© PROMOTION – Prc C code translating workflow

main.c embedded on RPI



SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup IED PROTOTYPING Structure

- Object Oriented thanks to structure
 - Relays are structures containing several attributes
 - Algorithms are C code methods designed :
 - From scratch based on specifications (ex : WP4)
 - From a third party software
- Communication managed by different C files using IEC61850 library
- In the end, the executable file is a reusable "skeleton" for our IEDs
 - Initialize relay and communications
 - Execution Loop (constant time step) :
 - Call different methods
 - Publish results







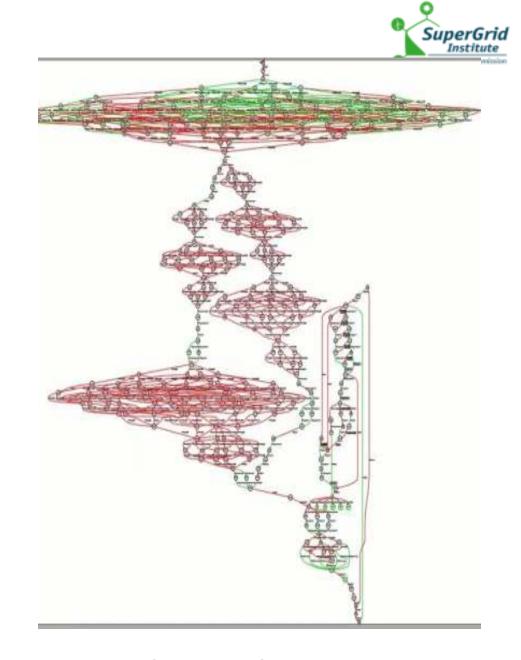
Full-brige converter based protection algorithms implementation

- Collaboration to understand the protection algorithm and its specs :
 - RWTH explainations about the different I/O
 - Simulink model given
- C code achievements :
 - Time based events translated into C functions (delays, ...)



SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup IED PROTOTYPING Supervisors: Implementation

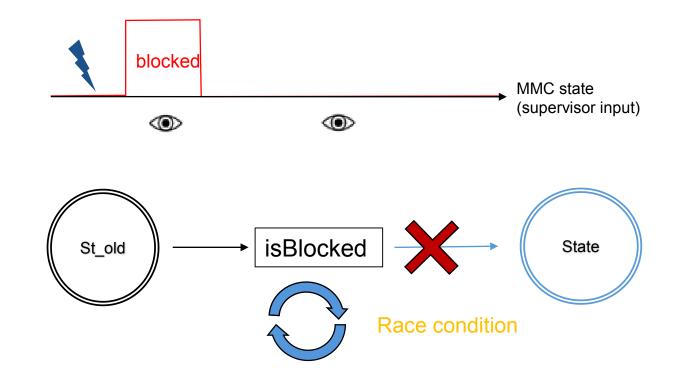
- Board to IED :
 - Extraction to C functions (SUPREMICA)
 - Integrate to the IED
 - Structure I/O
 - Align to IED prototyping workflow





SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup IED PROTOTYPING Supervisors : Race condition

- Issue raised by HIL testing
- The supervisor is outside the simulation :
 - Not synchronized anymore









SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup IED PROTOTYPING Supervisors : Race condition fix

- Make the impulse long enough to make sure the supervisor see it.
 - Quick fix, but not robust
 - How do we choose the time ? What if there is a time delay non predictible ?



- Next step example : « Acknowledgement » :
 - Keep the pulse going and wait for an « Ok » answer from the supervisor.
 - Deeper research needed



SCOPE OF THE DEMONSTRATION Application of the IEC61850 communication standard





Antoine Ghyselinck

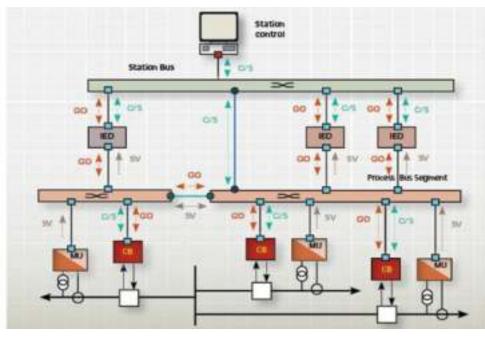


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- Norm to transfer data between intelligent devices
- It was made for interoperability and rapidity. IEDs from different constructors can exchange data via IEC61850



Application layer	MMS	SV	GOOSE	SNTP
Presentation layer				
Session layer	Oriented Connection			Ļ
Transport layer	TCP			UDP TCP
Network layer	IP			IP
Data link layer	Ethernet			
Physical layer	Optical Fiber			

IEC61850 in the OSI* model

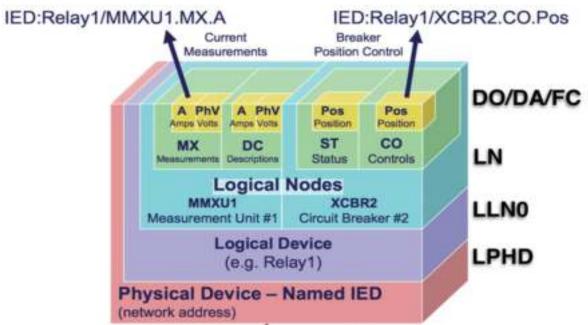


IEC61850 Example Architecture



SCOPE OF THE DEMONSTRATION - Application of the IEC61850 communication standard IEC61850: SEMANTICS

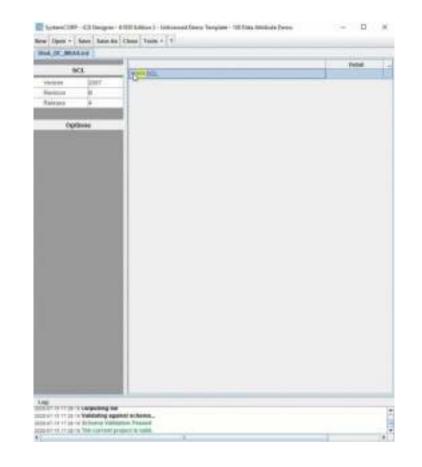
- Understanding semantics of the protocol
 - Object Oriented protocol
 - Messages :
 - Sampled Values (SV)
 - Generic Object Oriented Substation Event (GOOSE)



SCOPE OF THE DEMONSTRATION - Application of the IEC61850 communication standard IEC61850: IMPLEMENTATION

- Making HYPERSIM and RPI communicate with IEC61850
 - IED capability description (ICD) files :
 - ICD Designer from SYSTEMCORP
 - Used in HYPERSIM to feed the IEC driver
 - LibIEC61850 :
 - Open source C library
 - Used by the RPI

Data for one pole		
	CBS	FBS
Data points	234	104





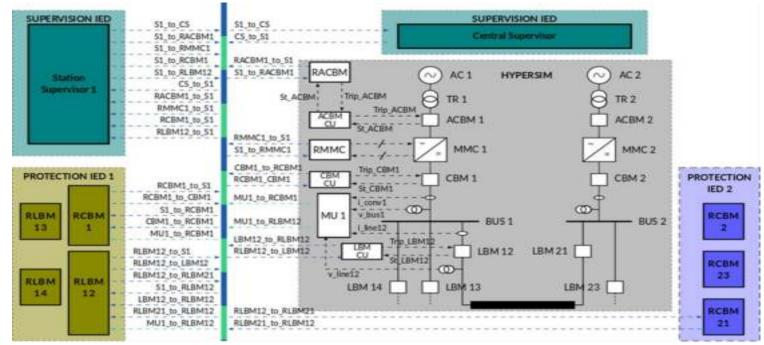






SCOPE OF THE DEMONSTRATION - Application of the IEC61850 communication standard IEC61850: INTEGRATION

- Build the communication architecture :
 - Naming
 - Linking
 - Identification (MAC Address)

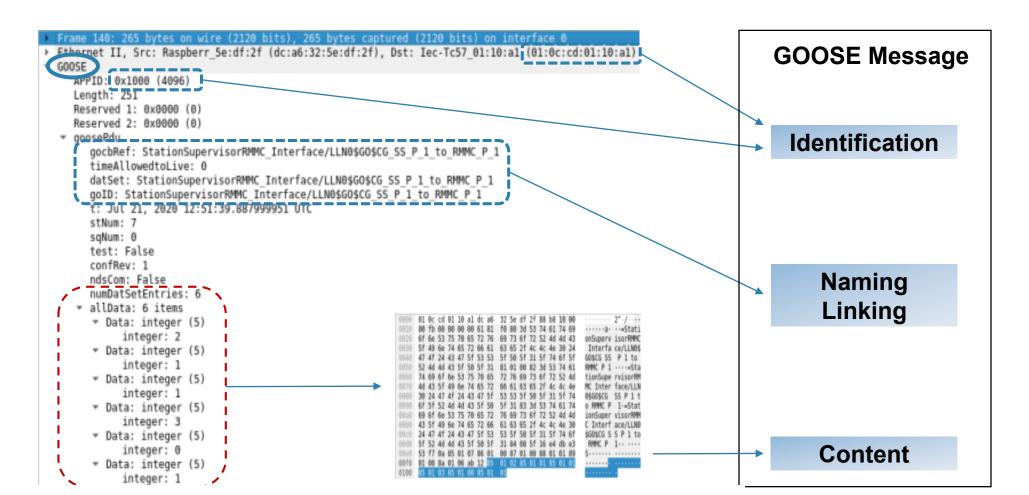




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SCOPE OF THE DEMONSTRATION - Application of the IEC61850 communication standard WIRESHARK : THE PACKET TRACER





SuperGrid Institute

Shaping power transmission



William Leon-Garcia

RESULTS OF THE HARDWARE-IN-THE-LOOP DEMONSTRATION



SuperGrid Institute



Antoine Ghyselinck

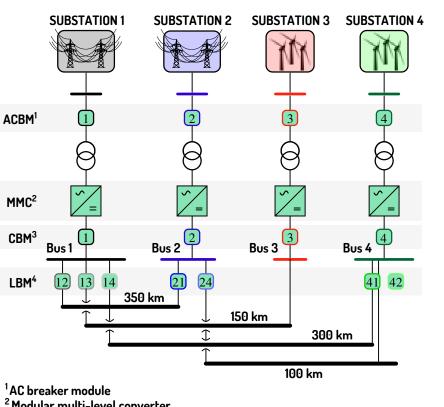


VIRTUAL DEMO CONVERTER BREAKER PROTECTION STRATEGY

Startup

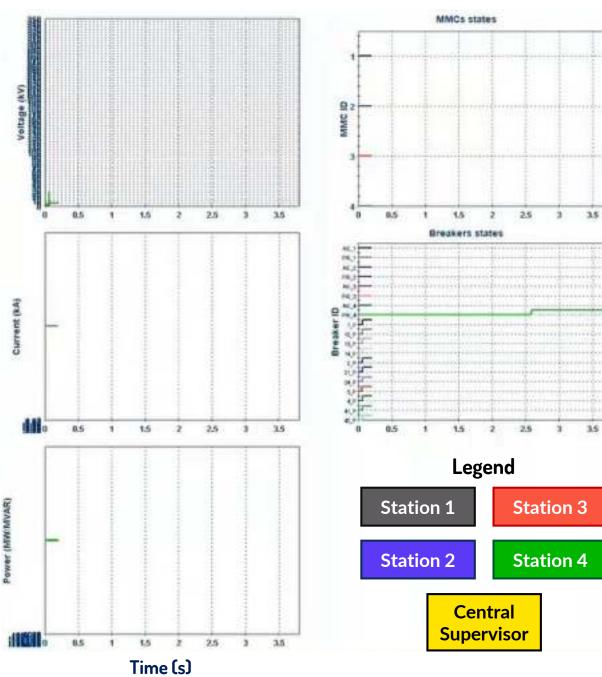


RESULTS OF THE HIL DEMONSTRATION FOUR-TERMINAL HVDC NETWORK Half-bridge MMC converters Startup



² Modular multi-level converter ³ Converter breaker module

⁴Line breaker module



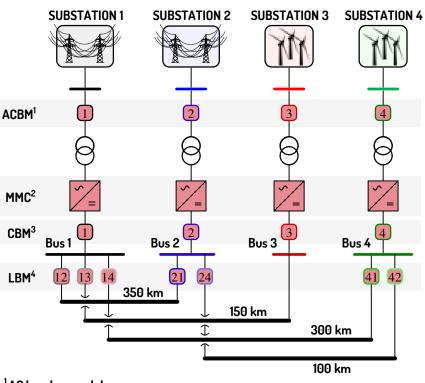
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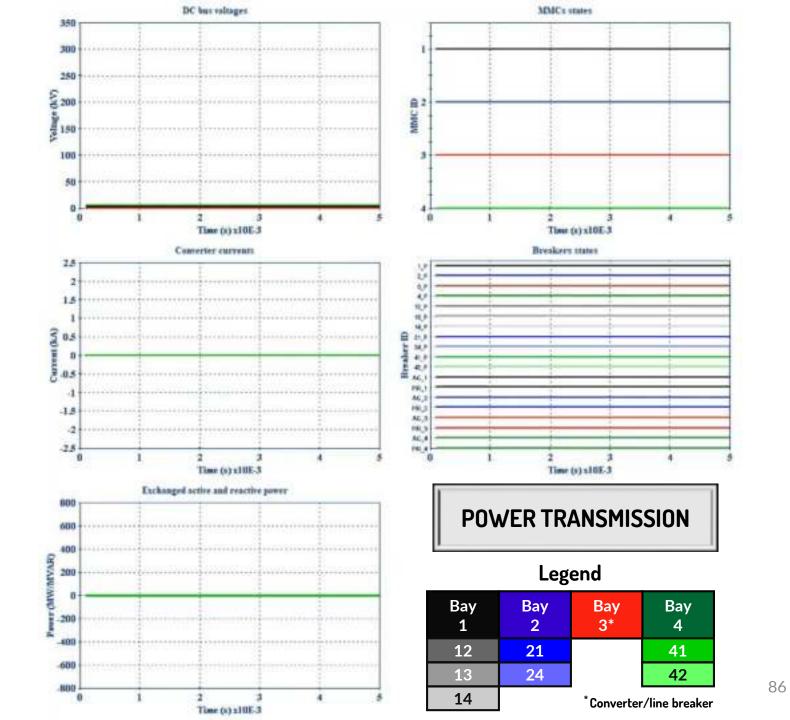
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Protoce

RESULTS OF THE HIL DEMONSTRATION FOUR-TERMINAL HVDC NETWORK Half-bridge MMC converters Startup



¹AC breaker module ² Modular multi-level converter ³ Converter breaker module ⁴ Line breaker module



VIRTUAL DEMO CONVERTER BREAKER PROTECTION STRATEGY

Pole-to-ground fault in cable 24



RESULTS OF THE HIL DEMONSTRATION CONVERTER BREAKER PROTECTION STRATEGY Pole-to-ground fault: cable 24 (@50km)

400 350

380 250

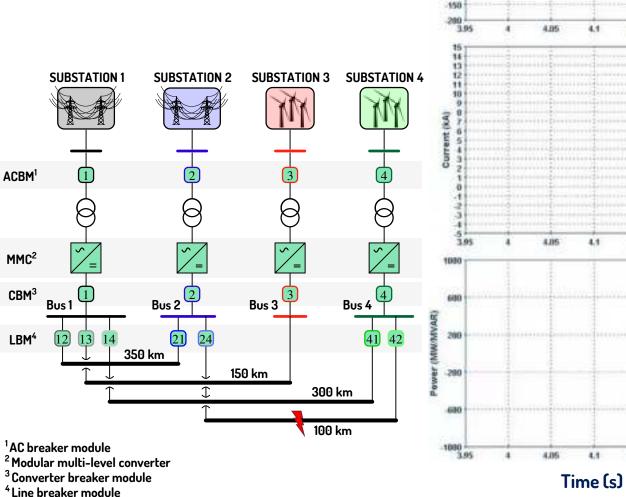
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4.1



MMCs states MINC ID 4.2 4.25 3.95 4.05 4.15 4.2 4.15 4.1 Breakers states 1.11 12.3 13.5 14.5 0 2 \$21.1 B 24 33 4.5 41.1 42.0 4.15 4.2 4,75 3.46 4,05 \$2 Legend Station 1 Station 3 Station 2 Station 4 Central **Supervisor** 4.15 4.2 4.75

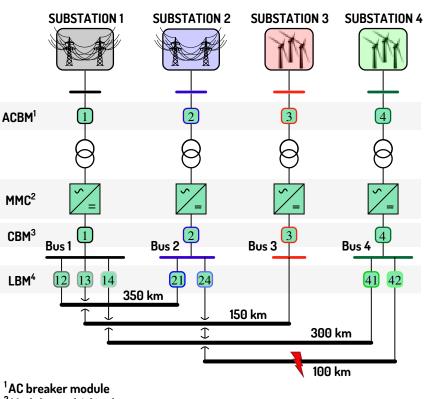
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0.061272026	Raspberr 59:0a	11 GODSE
0.001582612	Raspberr Seide	:4c G005E
0.002123007		
0.062691939	Raspherr 73:92	:6d G005E
0.062736888	Raspberr 73:92	07 6005E
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0.007783305		11 GOOSE
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0.009607597		120 GOOSE
0.009741223	Raspberr_S8:40	19 60058
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8.010093197	Raspberr 23:92	52 GODSE
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0.010093197 0.010299998 0.010881942 0.011033674	Raspberr 73:92 Raspberr 58 eff Raspberr 73:92 Raspberr 73:92	52 GODSE 11 GODSE 61 GODSE 61 GODSE
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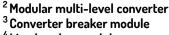
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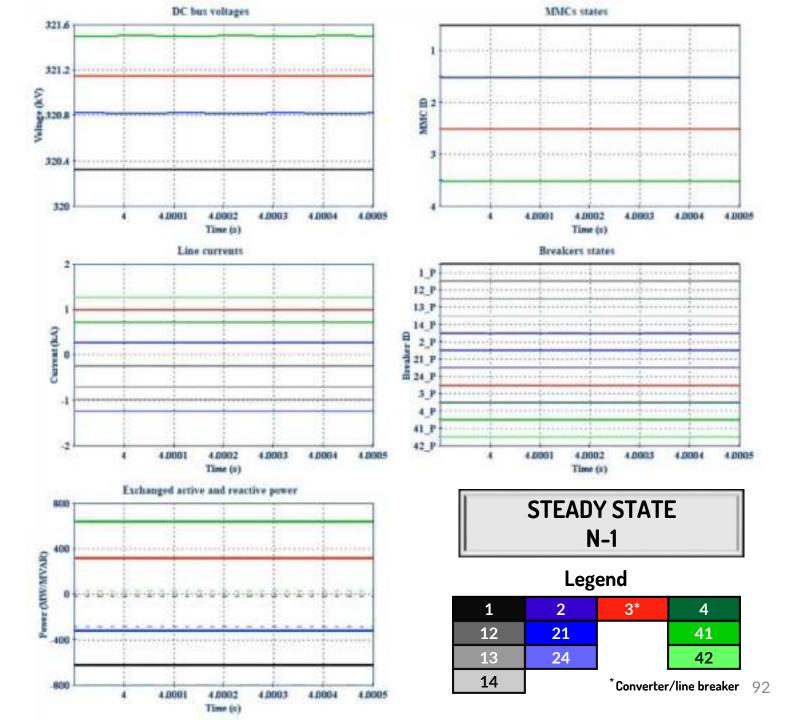
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RESULTS OF THE HIL DEMONSTRATION CONVERTER BREAKER PROTECTION STRATEGY Pole-to-ground fault: cable 24 (@50km)





⁴Line breaker module

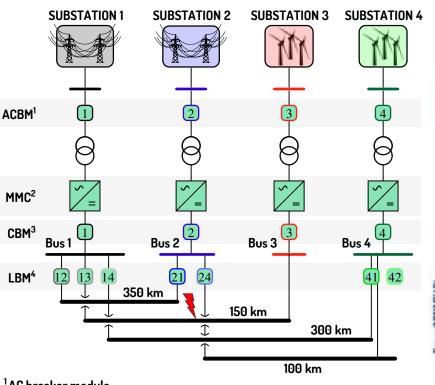


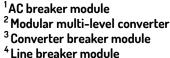
VIRTUAL DEMO CONVERTER BREAKER PROTECTION STRATEGY

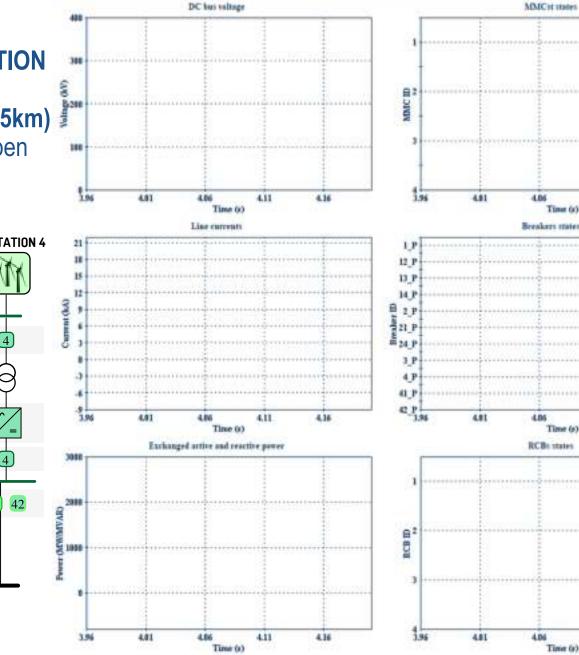
Pole-to-ground fault in cable 13 Backup sequence: CBM1 fails to open



RESULTS OF THE HIL DEMONSTRATION CONVERTER BREAKER PROTECTION STRATEGY Pole-to-ground fault: cable 13 (@75km) Backup sequence: CBM1 fails to open







Time	Source	Protoco
0.00000000	Raspherr 73:92:67	GDDSE
0.000333881	Raspbern Setde:4c	GDOSE
0.000357895	Raseberr 73:92:07	GOOSE
0.000856351	Raspbern Seider4c	GOOSE
0.002004516	Raspbern 59:9a:20	COOSE .
0.002745143	Raspberr 73:92:64	DOOSE
0.003570617	Raspberr Seidfigt	00055
0.003130056	Raspberr 59:0a:20	00058
0.003766098	Batabare 73-03-64	- DDD5E-
0.004791319	Raspberr 59:0a:11 Raspberr 73.92:6d	ODDSE
0.886637519	Raspherr 73:92.6d	GOOSE
0.888791864	Raspberr 73:92:19	0005E
0.003661021	Ratubers //1102207	COOSE
0.00954686I	Raspberr 58.e7:43	LIN
0.009340001	Respect Seren 45	10003C
0.009548652	Rasphere, 73192107	GDODE
0.010315475	Rasphert 73:52:56 Rasphert 73:52:07 Rasphert 73:52:07	00058
9.010414564	Maspherr 75:12:50	10054
0.011267139	Respberr 73:92:76	
	Bestaters to an It.	10 mil
0.011573873	Raspberr 5e:df:2f	COOSE
0.011268050	Raspberr 50:0a 20	CODEE
0.012210933 0.013458498	Raspberr 73:92:64	GOOSE
0.013430400	Haspberr 56:e7:43	GARSE
0.016338360	Raspherr 73:92:19	GD05E
0.019373885	Raspberr 59:0a:23	
0.019403736	Raspberr 59:0a:23	
0.019430310	Raspherr 59:0a:23	
0.019453385	Raspbert 59:0a:23	
0.019571751	Raspherr 73192150 Raspherr 581e7/43	
0.020102013 0.020211440		
0.020367677	Raspberr 73:92:19 Raspberr 59:6a:11	00055
0.820531740	Raspherr 73:82.61	6005E
8,022238951	Raspherr Seidf:21	GOOSE
0.823192888	Raspherr 56:e7:43	6005E
0.823563950	Raspberr 73:07:19	GD05E
0.023719288	Raspherr 59:60:11	GOOSE
0,823894488	Rasoberr 73192161	GODSE
0.825123591	Raspberr 73:92:6d	GOOSE
0.031995142	Raspherr Se:de:4c	GODSE
	Ratoberr 73:97:64	6005E
0.034188260 0.034269618	Raspberr 73:92:64 Raspberr 59:0a:20	GOOSE
0.035382382	Raspberry Secdec4c	0005E
0.037270303	Raspherr Se:df:2f	GOOSE
0.038271484	Raspherr 73:92:6d	
0.838335575	Raspherr Seidf:21	
0.839451662	Raspberr Seidf:2f	GOOSE
0.041592614 0.041860590	Raspberr Se:df:2f Raspberr 73:92:6d	
0.843157876	Raspherr 73:92:6d Raspherr 73:92:6d	
0.943960321	Rospherr 73192:6d	
0.872800814	Raspherr 59:0a:23	GD05E
0.072822088	Raspberr 59:0a:23	
0.072839421	Raspberr_59:0a:23	
0.072863272	Raspberr 59(0a:23	
0.073178099	Raspherr 73:97:6d	
0.073961711	Raspbern Seidf:21	GOOSE

4.11

4.11

4.11

Time (a)

Time (s)

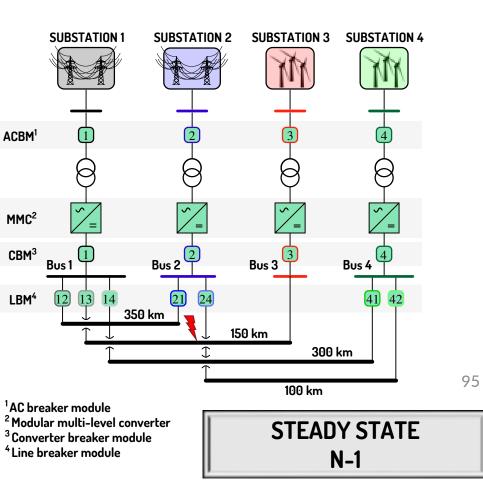
Time (c)

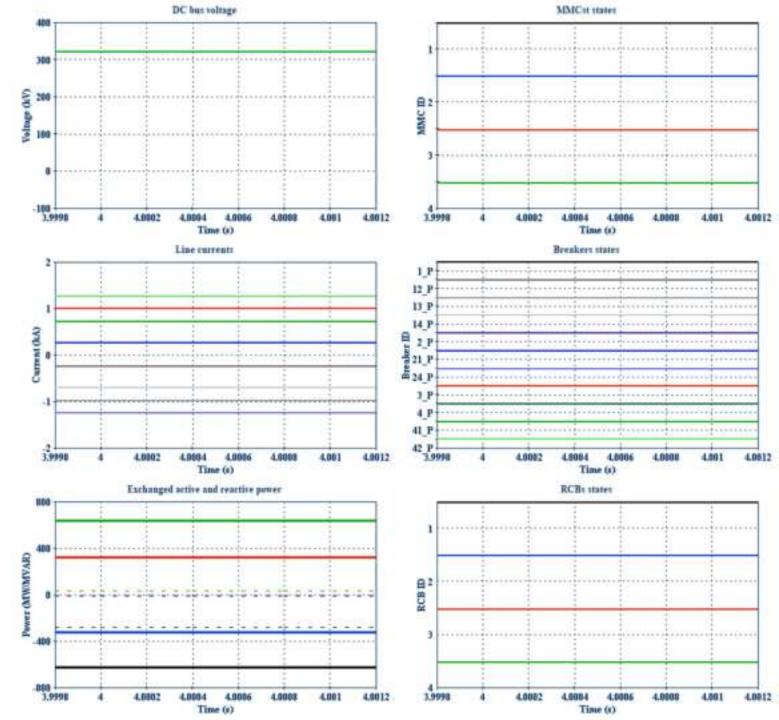
4.16

4.16

4.16

RESULTS OF THE HIL DEMONSTRATION CONVERTER BREAKER PROTECTION STRATEGY Pole-to-ground fault: cable 13 (@75km) Backup sequence: CBM1 fails to open





VIRTUAL DEMO FULL-BRIDGE CONVERTER PROTECTION STRATEGY

Pole-to-ground fault in cable 13



RESULTS OF THE HIL DEMONSTRATION FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY Pole-to-ground fault: cable 13 (@50km)

SUBSTATION 2

2

 $\left| \right\rangle$

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Bus 3

150 km

Bus 2

350 km

21

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SUBSTATION 1

[1]

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Bus 1

1213

¹AC breaker module

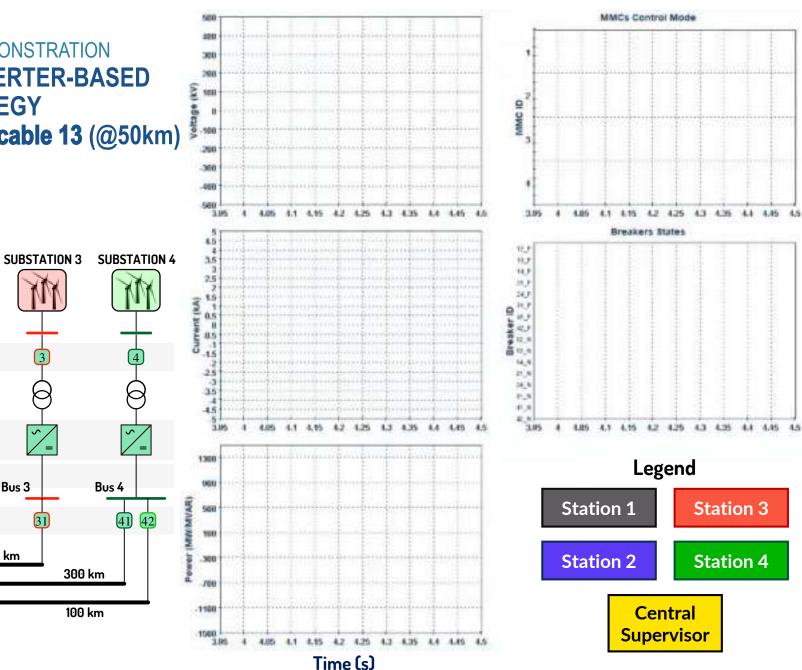
³Line breaker module

² Modular multi-level converter

ACBM¹

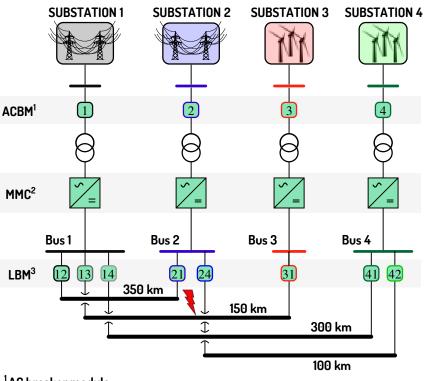
MMC²

LBM³

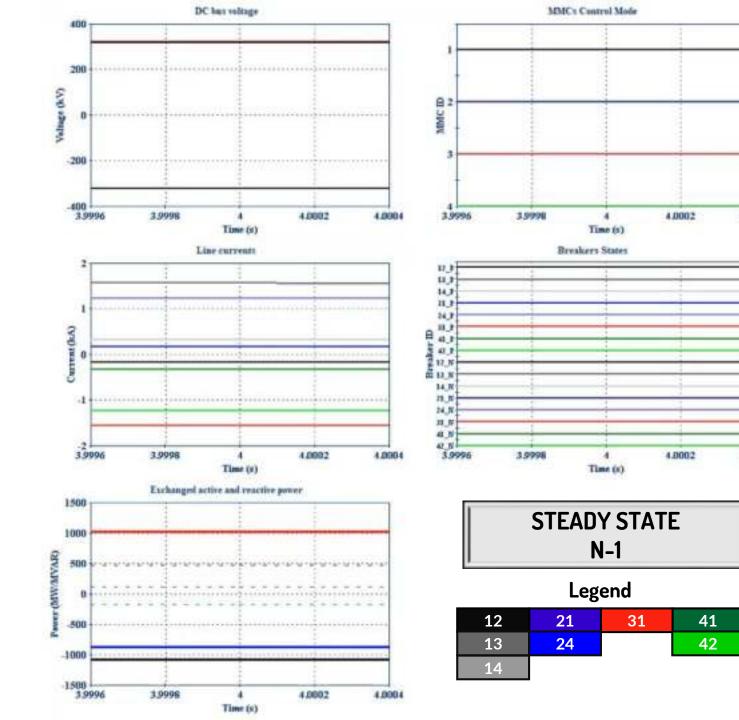


Time *	Source	Protocol
0.00000000	Raspberr 73:92:58	600SE
0.000094238	Raspberr 73:92:67	GOOSE
0.000220532	Raspberr 58:e7:43	GOOSE
0.000231846	Raspberr 73:92:19	GOOSE
0.001089845	Respberr 73:91:fb	600SE
0.001335673	Raspberr 73:92:52	GOOSE
0.001632333	Raspberr 73:92:76	GOOSE
0.001778626	Raspberr 58:e8:19	GOOSE
0.010589463	Raspberr 73:92:76	GOOSE
8.010678986	Raspberr 73:91:fb	GOOSE
0.010696980	Raspberr 73:92:07	GOOSE
0.010817032	Raspberr 58:e8:19	GOOSE
0.010932993	Raspberr 58:e7:43	GOOSE
0.011667106	Raspberr 73:92:19	GOOSE
0.012063060	Raspberr 73:92:52	GOOSE
0.014131865	Raspberr 73:92:58	GOOSE
0.014203937	Raspberr 73:92:58	GOOSE
0.015043937	Raspberr 73:92:87	GOOSE
8.859985716	Raspberr 73:92:58	GOOSE
0.051322188	Raspberr 73:92:07	GOOSE
0.051919100	Raspberr 73:92:07	GOOSE
0.052534735	Raspberr 73:92:07	GOOSE
0.063897903	Baspberr_73:92:58	GODSE
0.065013557	Raspberr_73:92:58	GOOSE
0.066158611	Raspberr 73192:58	GOOSE
0.166236583	Raspberr_73:92:58	GOOSE

RESULTS OF THE HIL DEMONSTRATION FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY Pole-to-ground fault: cable 13 (@50km)



¹AC breaker module ²Modular multi-level converter ³Line breaker module



4,0004

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VIRTUAL DEMO FULL-BRIDGE CONVERTER PROTECTION STRATEGY

Pole-to-pole fault in cable 24



RESULTS OF THE HIL DEMONSTRATION FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY Pole-to-pole fault: cable 24 (@50km)

SUBSTATION 2

2

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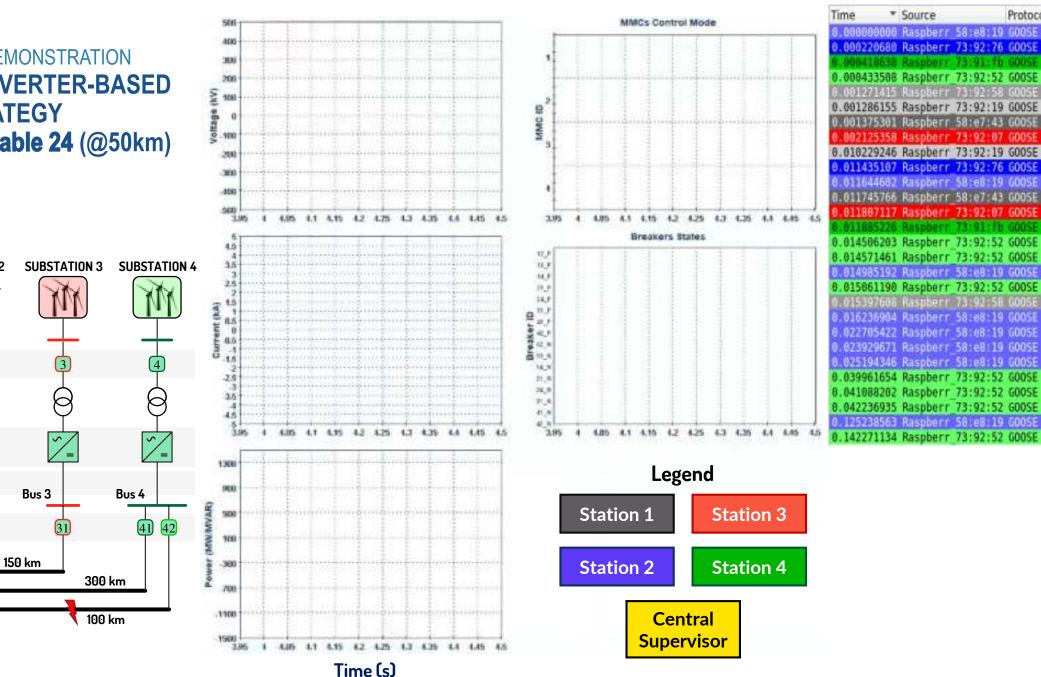
Bus 2

350 km

21

24

T



¹AC breaker module ² Modular multi-level converter ³Line breaker module

SUBSTATION 1

[1]

 $\left| \right\rangle$

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13

Bus 1

12

ACBM¹

MMC²

LBM³

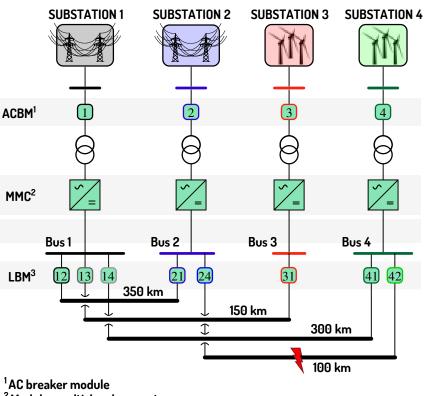
10303

Protoco

GOOSE

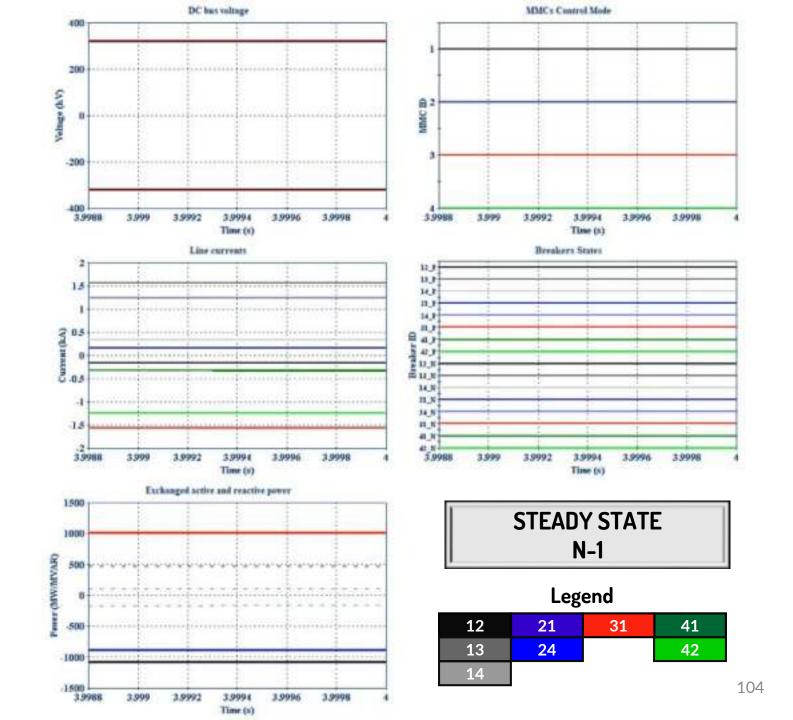
GOOSE

RESULTS OF THE HIL DEMONSTRATION **FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY Pole-to-pole** fault: **cable 24** (@50km)



²Modular multi-level converter

³Line breaker module



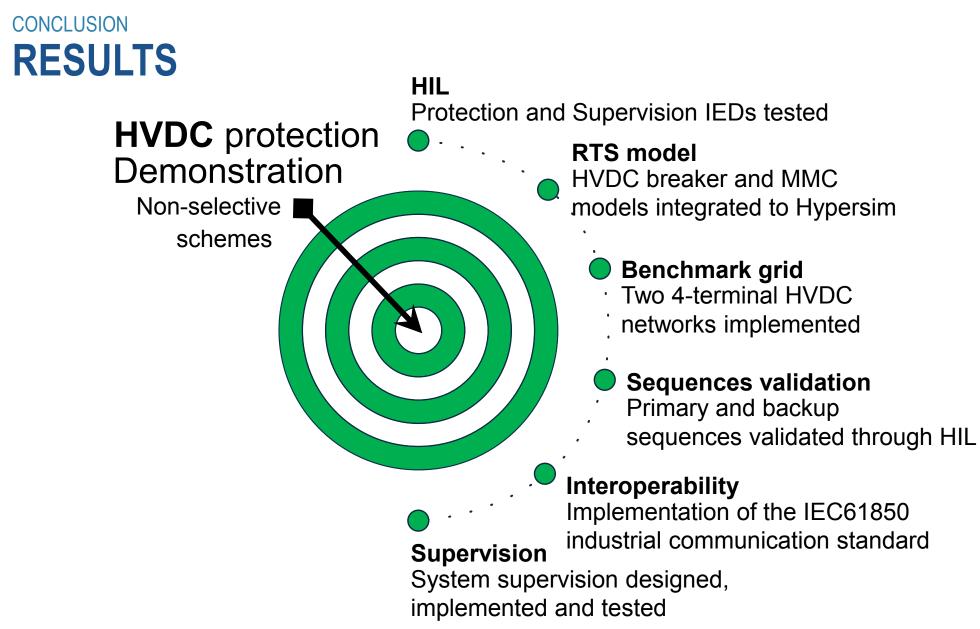


SuperGrid Institute

Laurent Chédot

CONCLUSION









CONCLUSION NEXT STEPS

- KPI calculation
- Extensive testing
- IEDs maintenance
 - Protection
 - Supervision
- Benchmark grid evolution
- Robustness studies
 - Communication network
 - Restoration backup sequence \rightarrow DC grid control upgrade







Co-funded by the Horizon 2020 programme of the European Union

Thank you for your attention. For further questions, don't hesitate to contact me.

Check the demonstration at: <u>www.promotion-offshore.net</u>

North Sea Grid for the European New Deal How to unlock Europe's Offshore Wind potential – a deployment plan for meshed HVDC grid

William LEON GARCIA

william.leongarcia@supergrid-institute.com +33 (0) 6 69 28 48 63

