WP9 T9.7/T9.8

Demonstration of Non-selective strategies for Meshed HVDC networks

03-04/09/2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

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- 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

HARDWARE-IN-THE-LOOP DEMONSTRATION

- 40’ - Scope
- 30’ - Results

5’ - CONCLUSION

15’ - Q&A session

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CONTEXT

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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)

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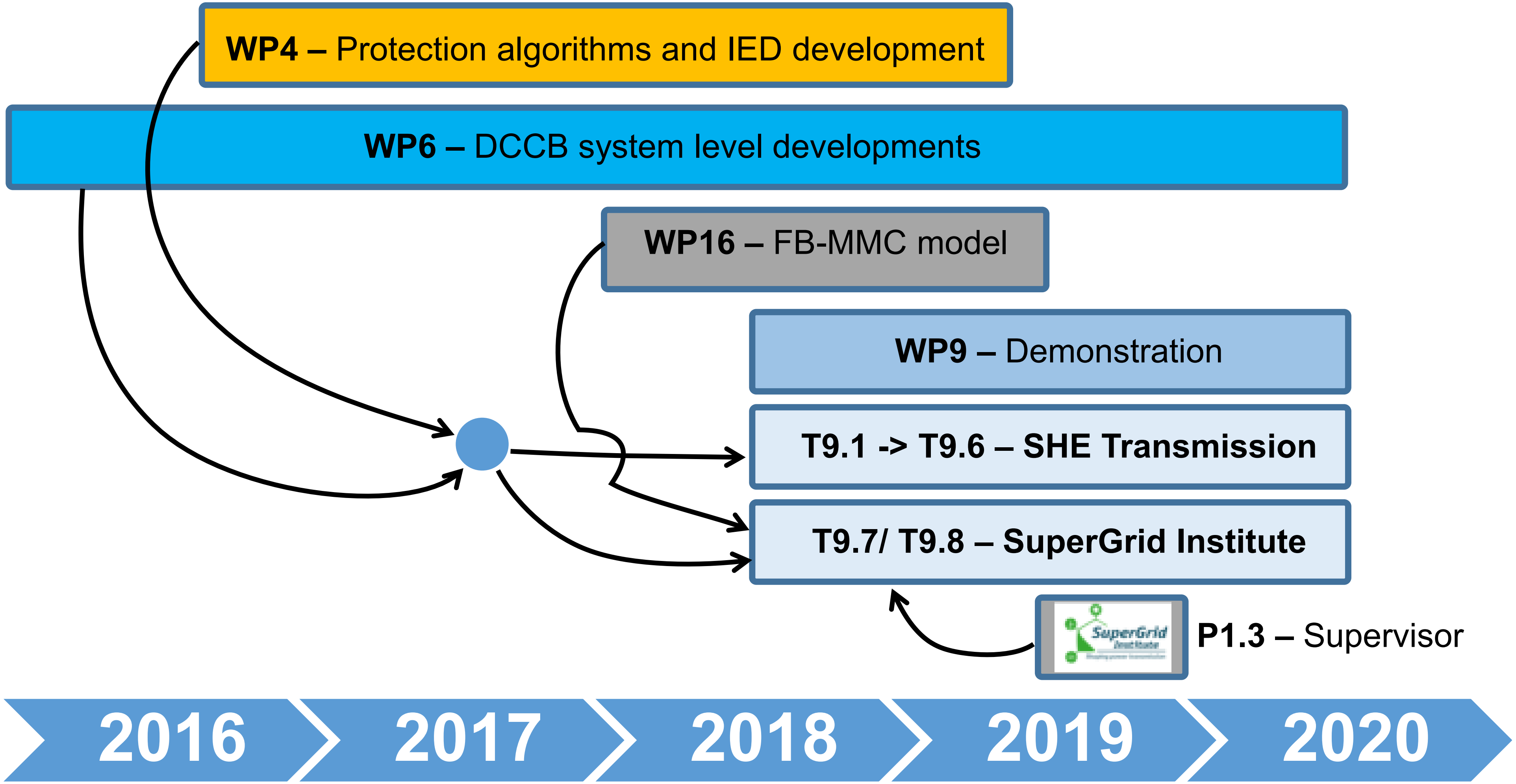
CONTEXT

WP9 Framework



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NON-SELECTIVE PROTECTION STRATEGIES

Alberto Bertinato

Pascal Torwelle

Philipp Ruffing

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- 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
Shaping power transmission

Alberto Bertinato

INTRODUCTION TO DC PROTECTION STRATEGIES

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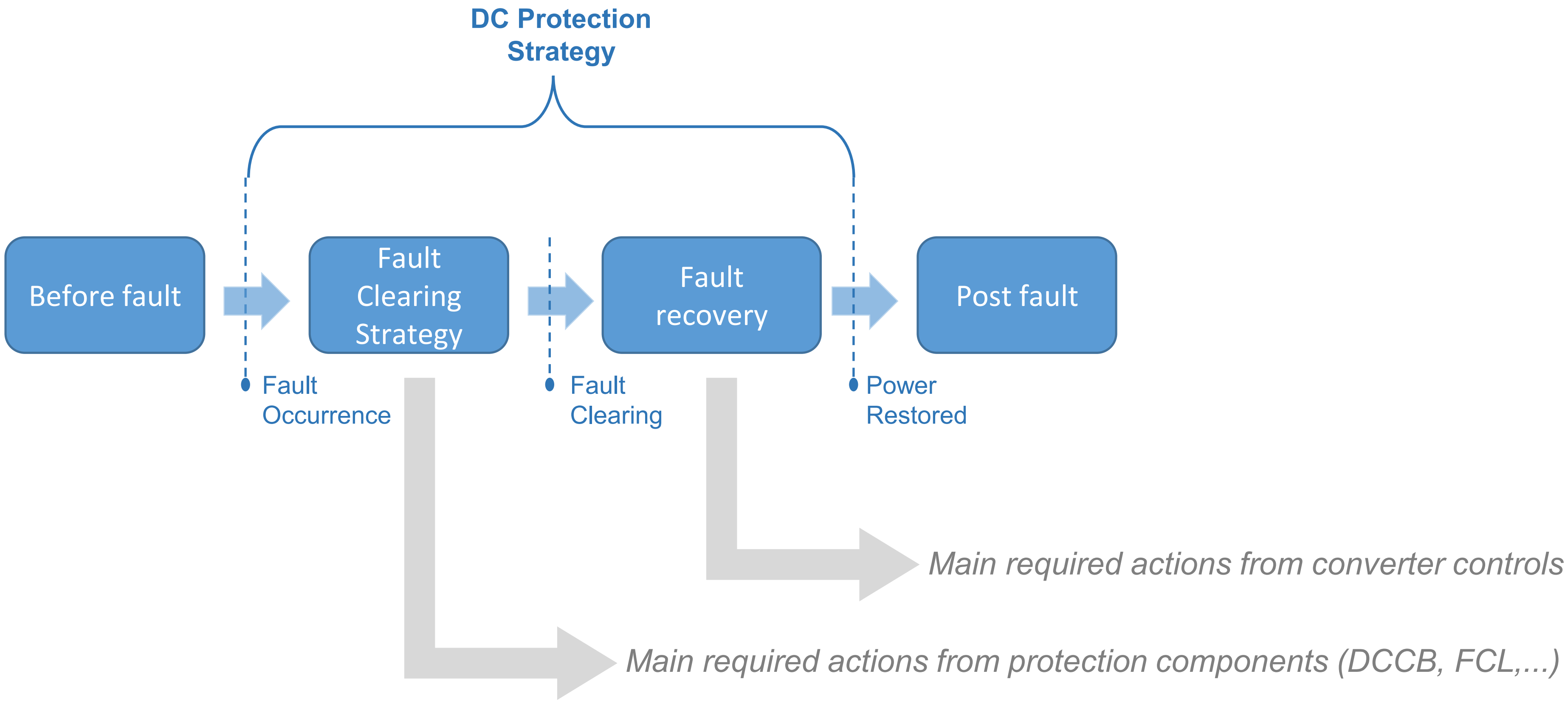
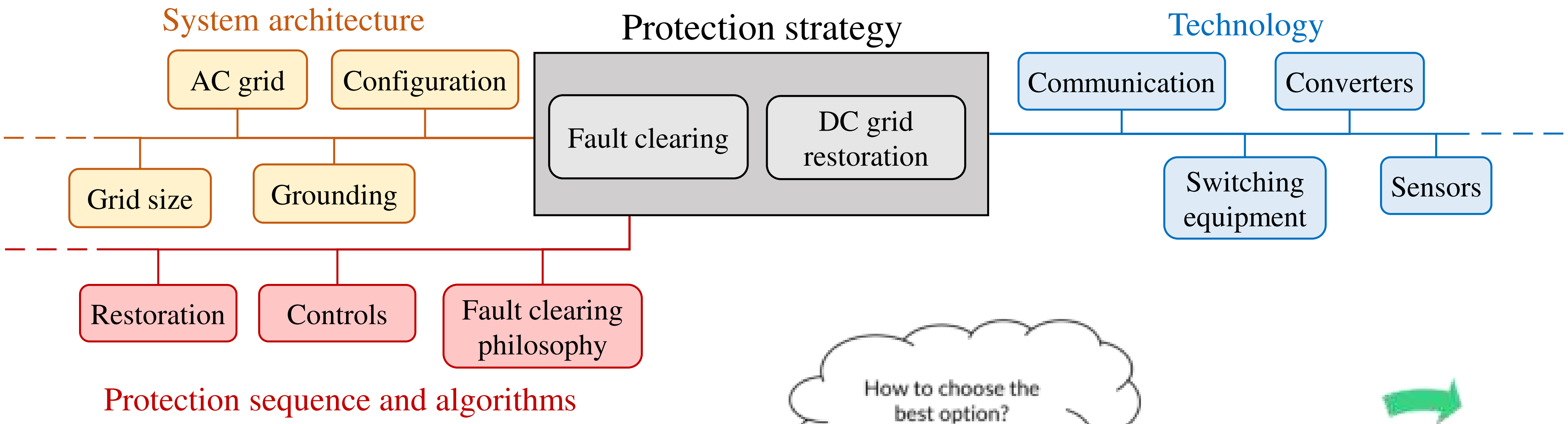
DC Protection Strategy Generalities

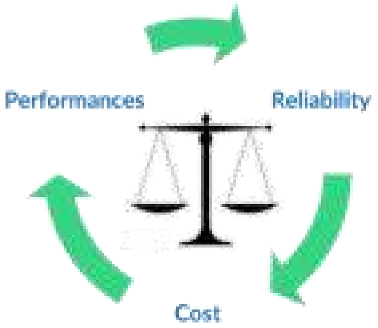
- What is meant by DC protection strategy ?



DC Protection Strategy Generalities

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





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DC Protection Strategy Generalities

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

Aim of WP9
SuperGrid Institute demo

KPI

Efficiency indicators

- Fault Interruption time
- Active Power restoration time
- Reactive power restoration time
- DC Voltage restoration time
- Transient Energy imbalance

Failure indicators

- Primary sequence failure probability
- Protection strategy failure probability

Cost indicators

- DCCB CAPEX
- Cost of energy not-supplied
- Losses

TRL

- Communication
- Supervisor
- Relay
- Switchgears
- …

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- 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

Pascal Torwelle

Converter Breaker Strategy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

OUTLINE

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

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Introduction

Fault Clearing Strategies

- Selective fault clearing
- Partially selective fault clearing
- Non-selective fault clearing

• Converter Breaker Strategy

• Proposed by SuperGrid Institute in PROMOTioN project WP4

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

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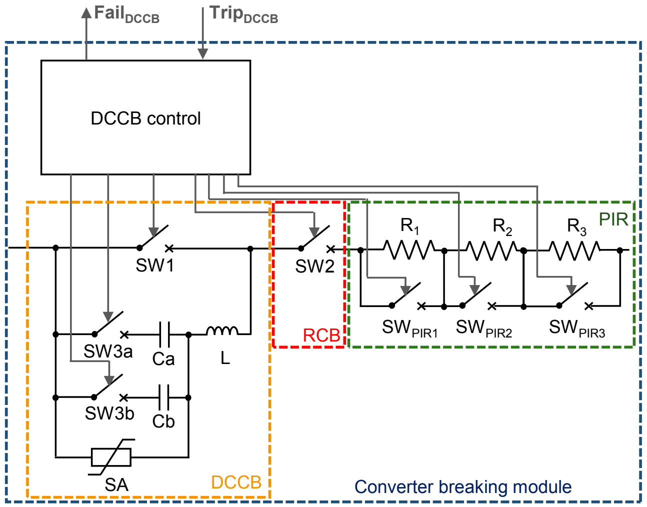
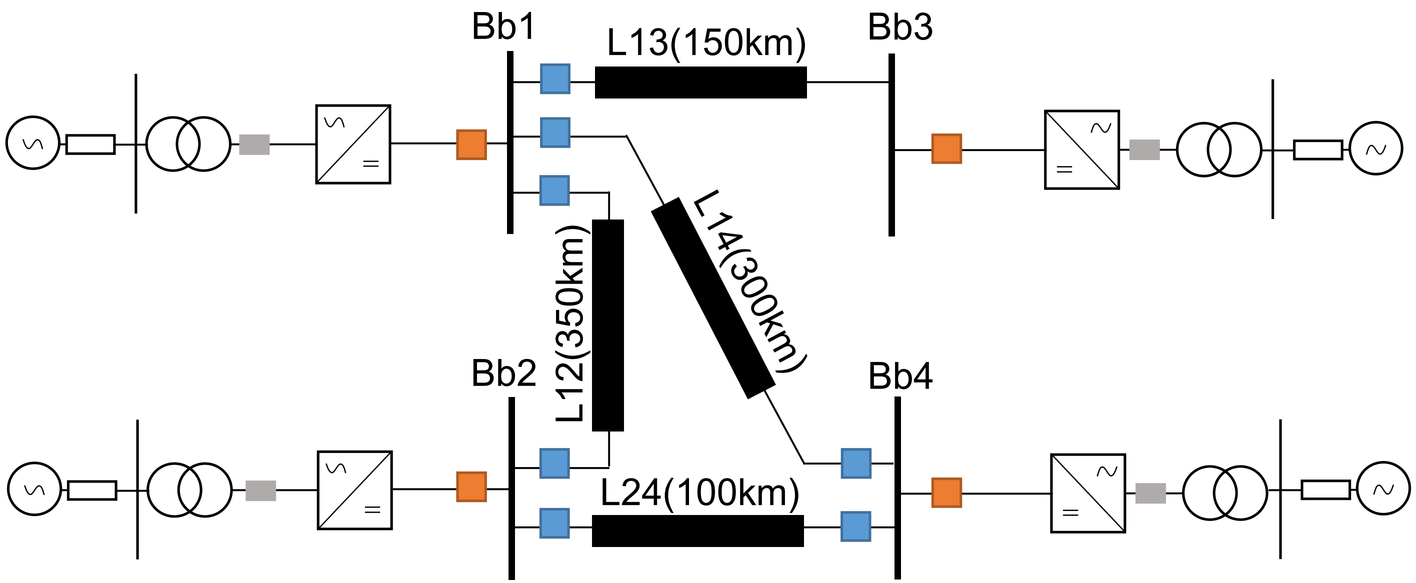
Protection components and layout

Line breaker module LB installed at each line end

Converter breaker module CB installed at each converter output



DCCB: DC circuit breaker
RCB: Residual current breaker



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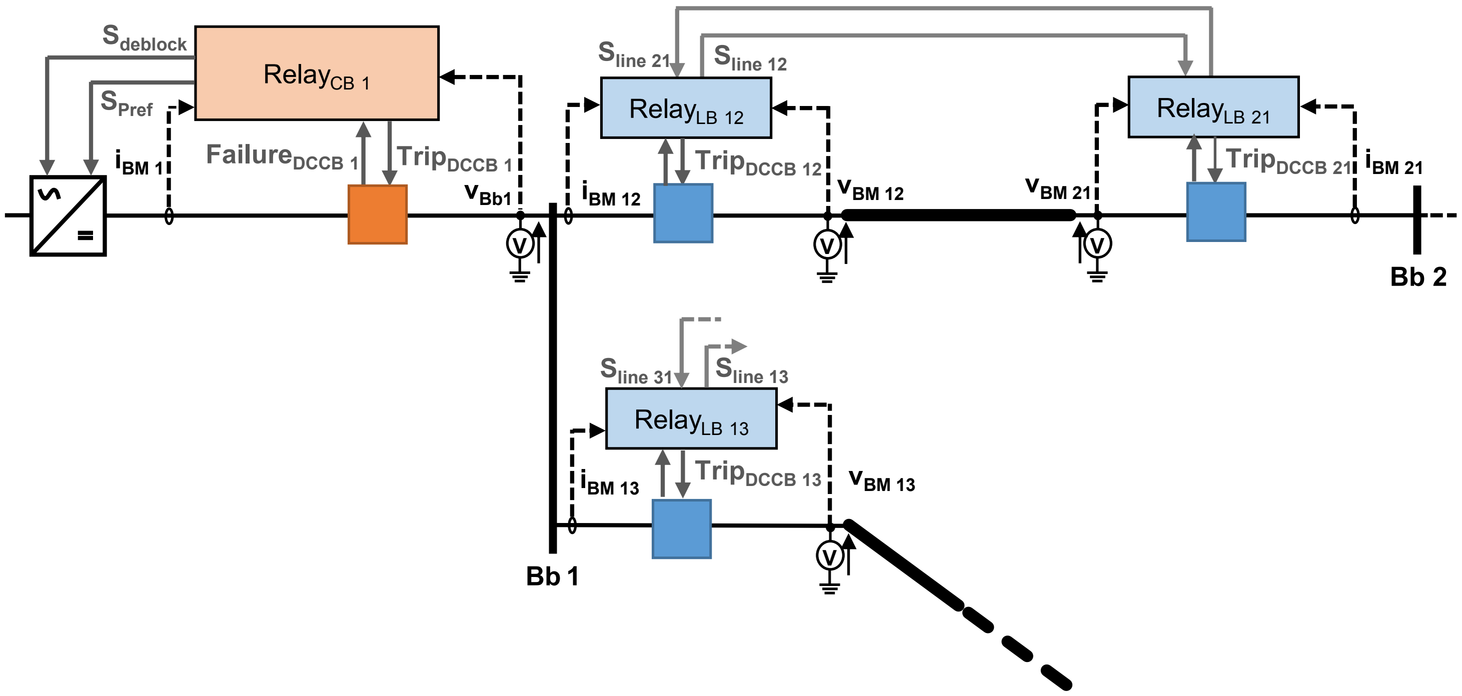
Protection components and layout

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

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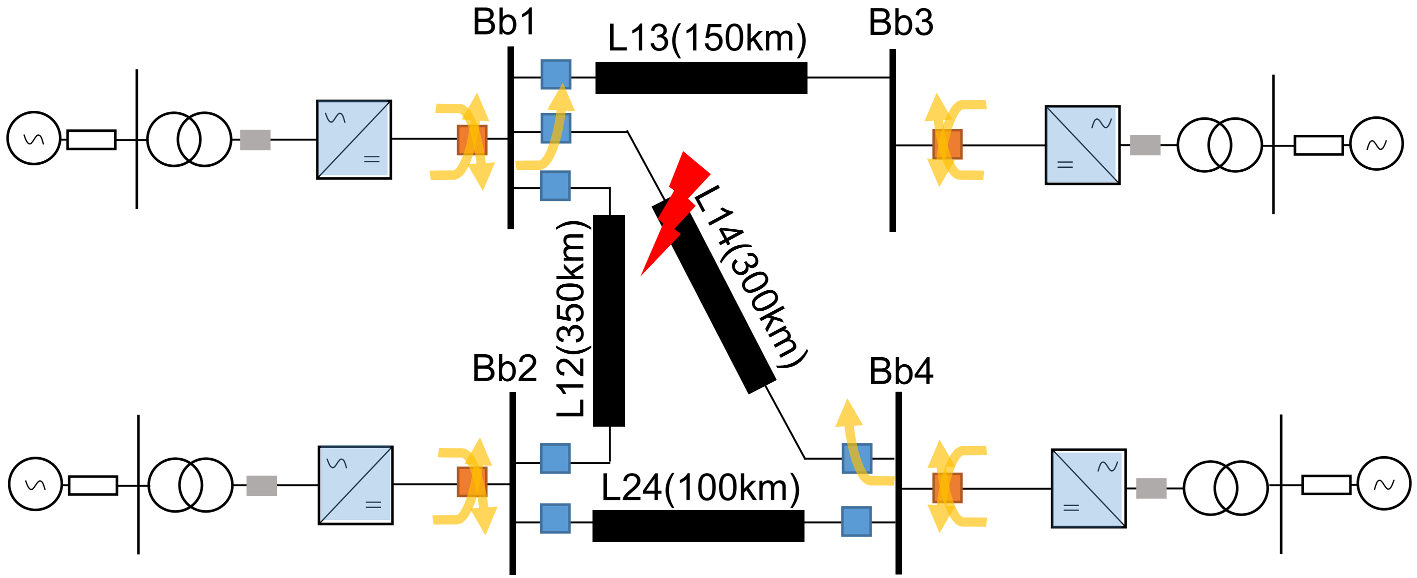
Primary sequence

Fault → Converter breaker module CB opening → Faulty line identification → Line breaker module LB opening → Converter breakers module and PIR reclosing → Voltage and power restoration → End

100-200ms



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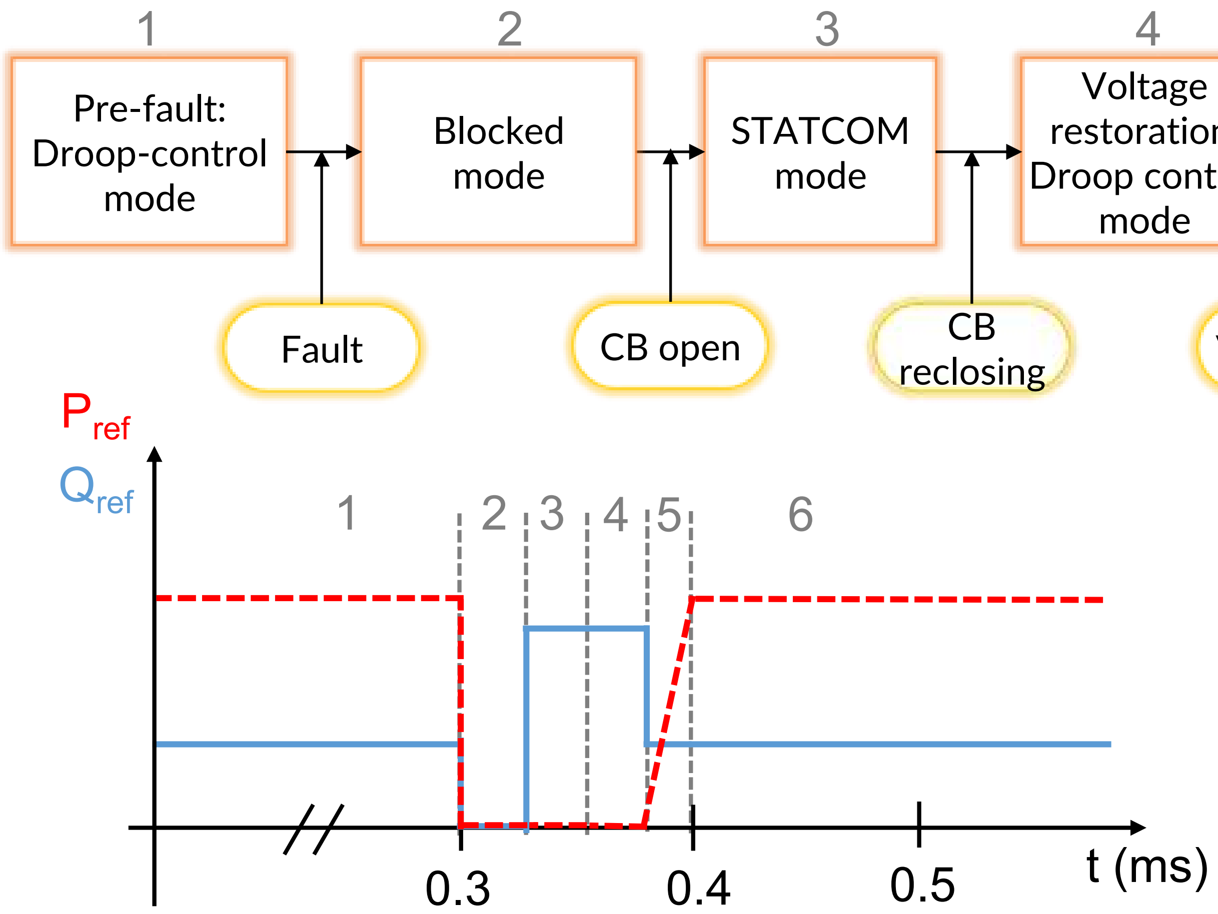
MMC fault ride through operation modes



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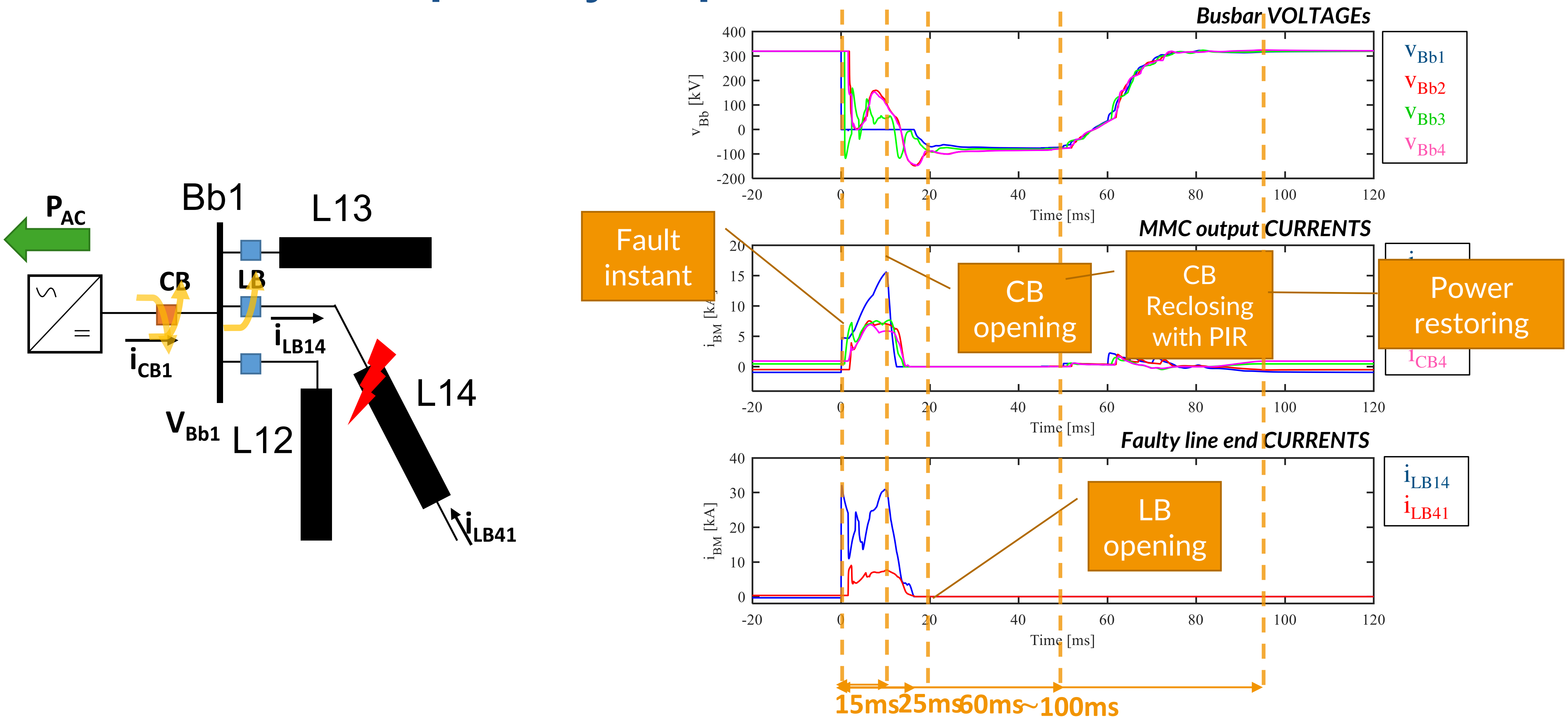
Simulation of the primary sequence



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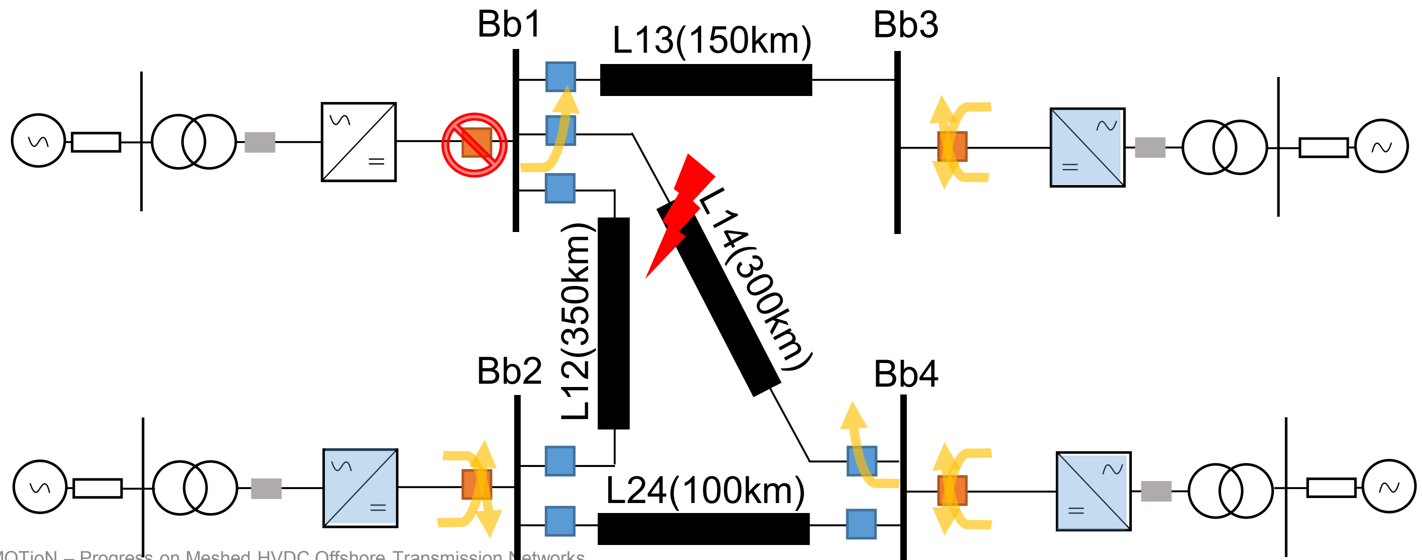
BACKUP SEQUENCES

- Case 1: Converter Breaker failure

Fault → N-1 CB opening. One converter breaker fails to open → Line breaker module LB opening → Converter RCB opening → Healthy converter breaker modules and PIR reclosing → Voltage and power flow restoration (healthy grid) → End

100-200ms



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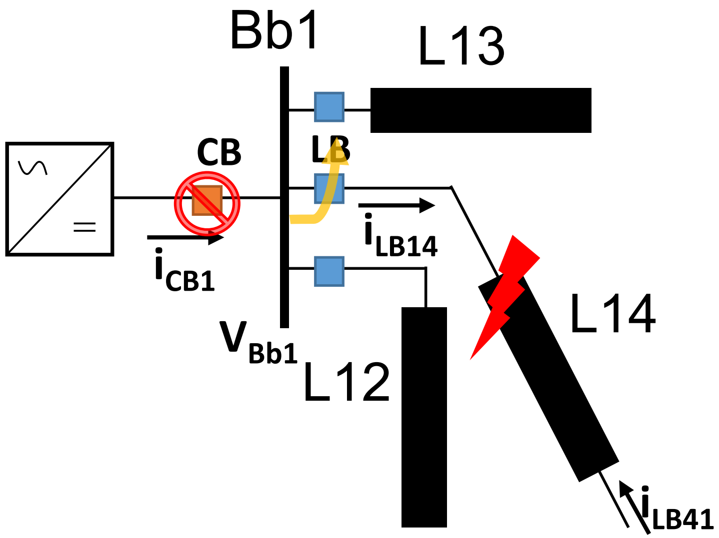
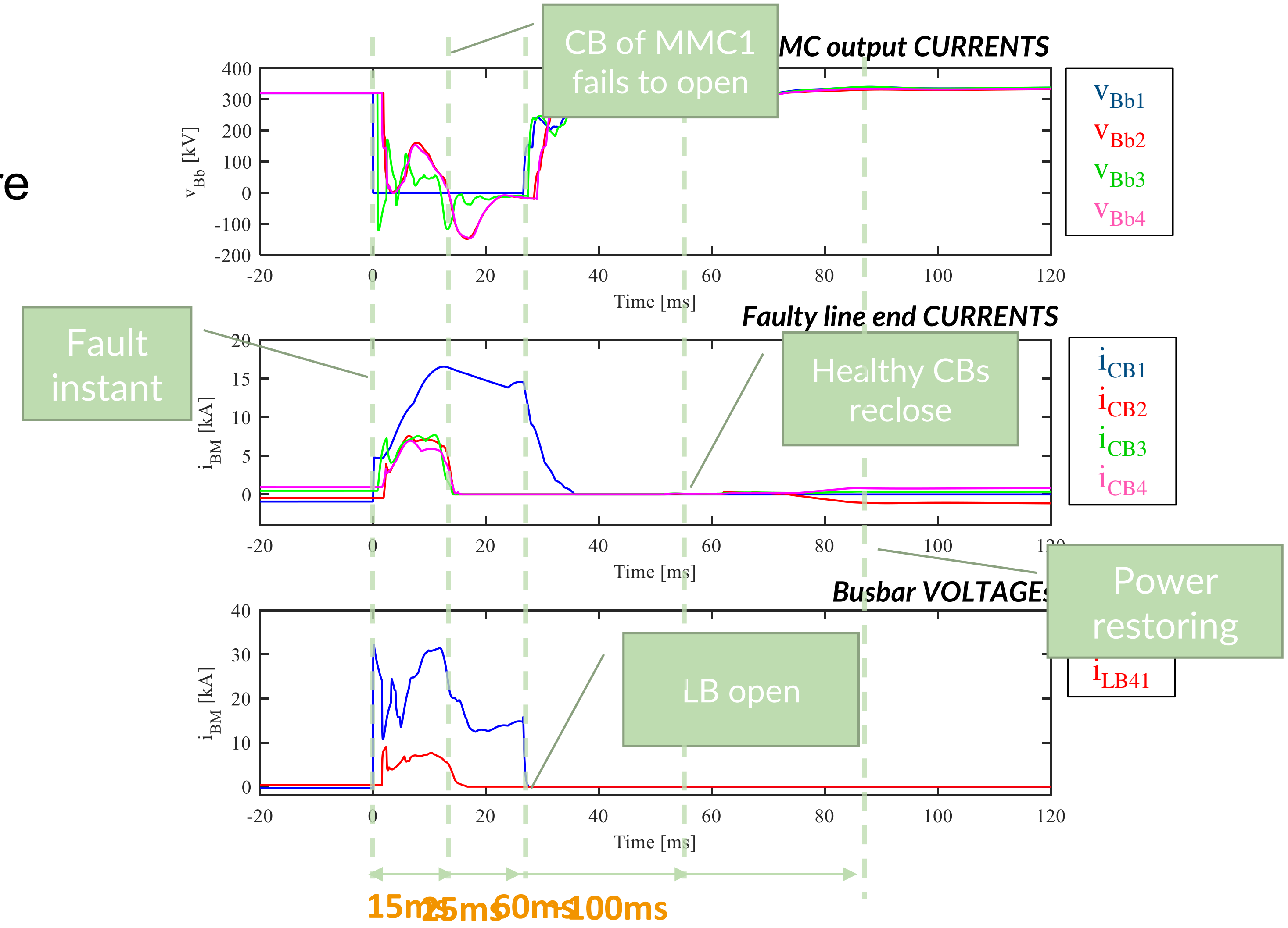
BACKUP SEQUENCES

- Case 1: Converter Breaker failure





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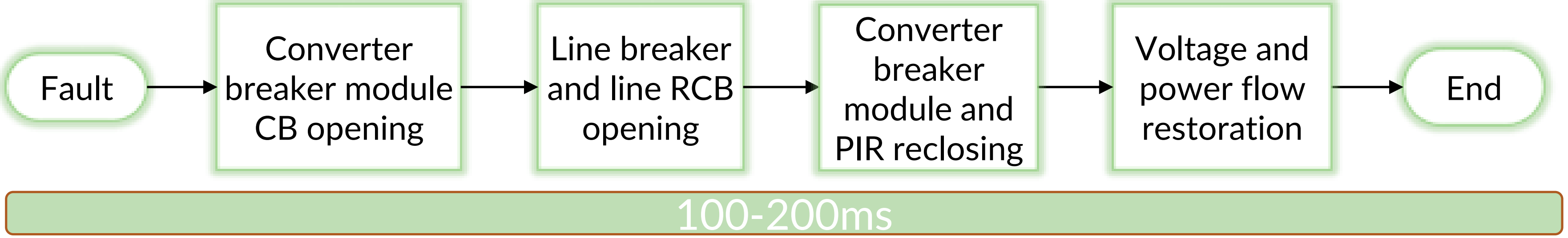
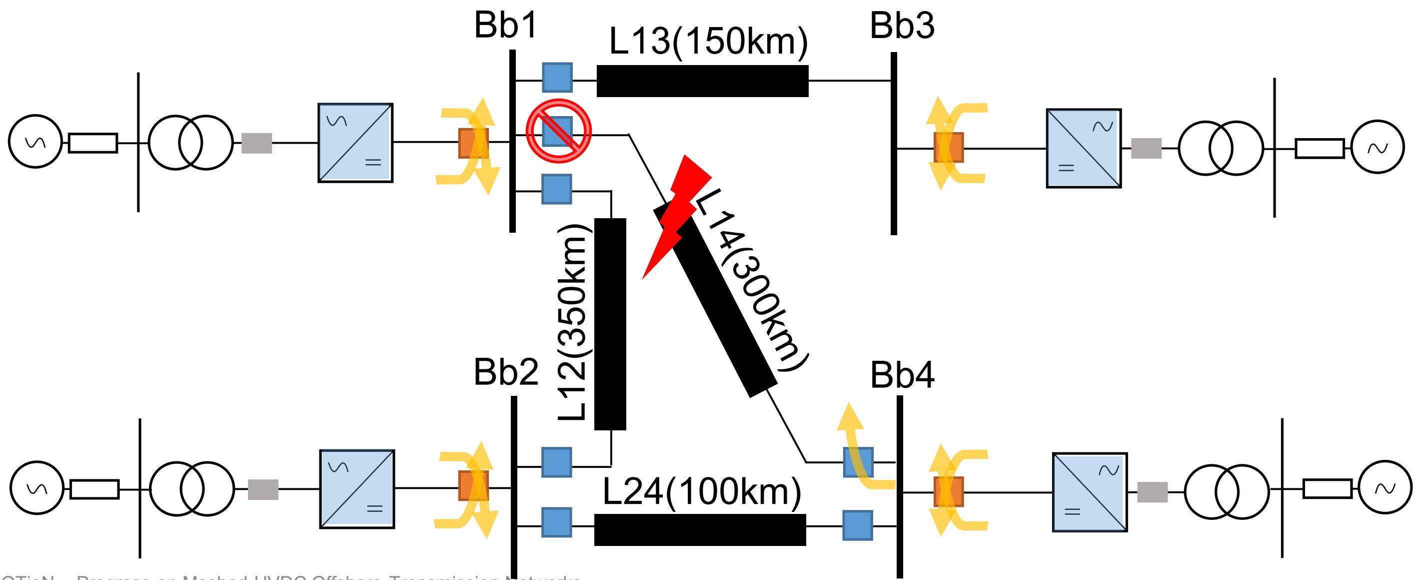
CONVERTER BREAKER STRATEGY

BACKUP SEQUENCES

- Case 2: Line Breaker failure





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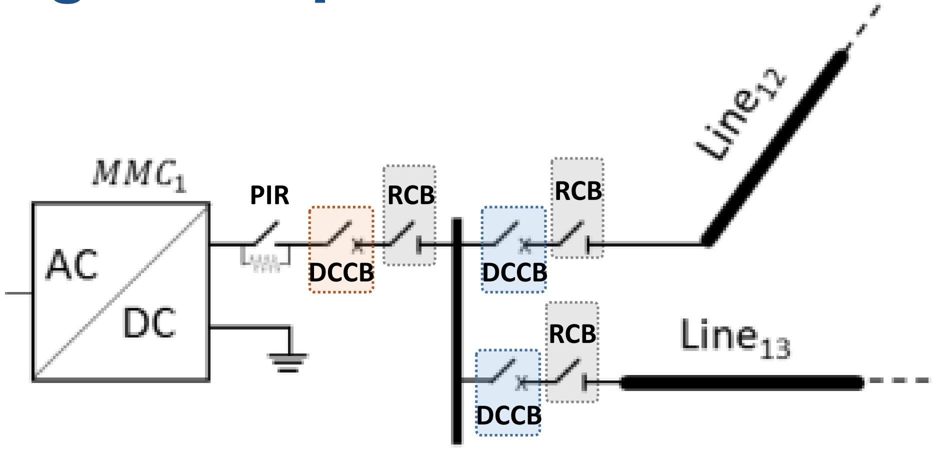
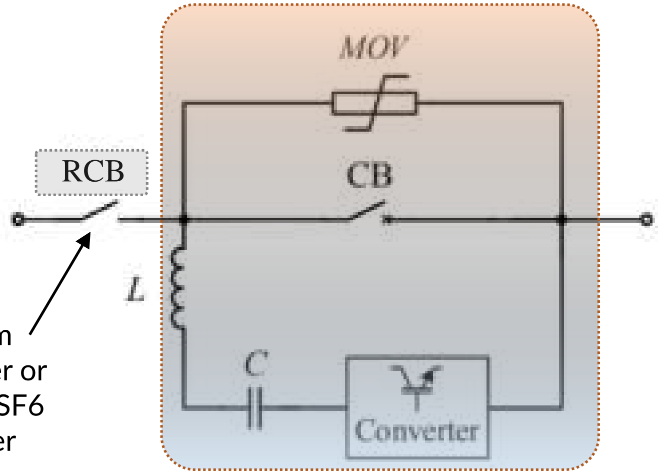
Switchgear requirements



Example of possible technology for DCCB



	Converter DCCB	Line DCCB	Residual current breaker
Breaking capability	20 kA (DC)	20 kA (DC)	Few A (DC) Few kA (AC)
Breaker operation time	10-20 ms	10-20 ms	10 ms
Closing time	10-20 ms	10-20 ms	10 ms
Open-close operation	O - 50ms - CO	O	O - 50ms - CO
DC limiting reactor	Not required	Not required	/
Surge arrester energy requirement	~ 7 MJ	~ 7 MJ	/

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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 ~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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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

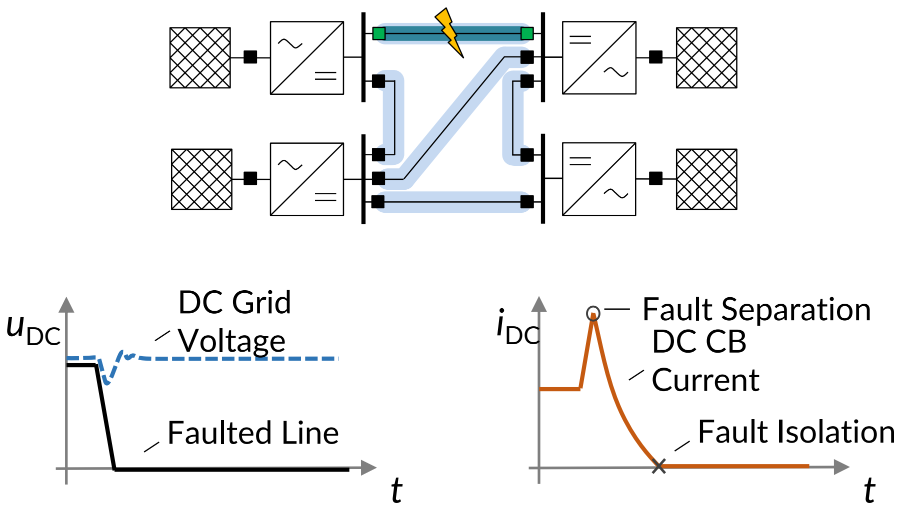
Philipp Ruffing

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

HVDC Grid Protection Philosophies

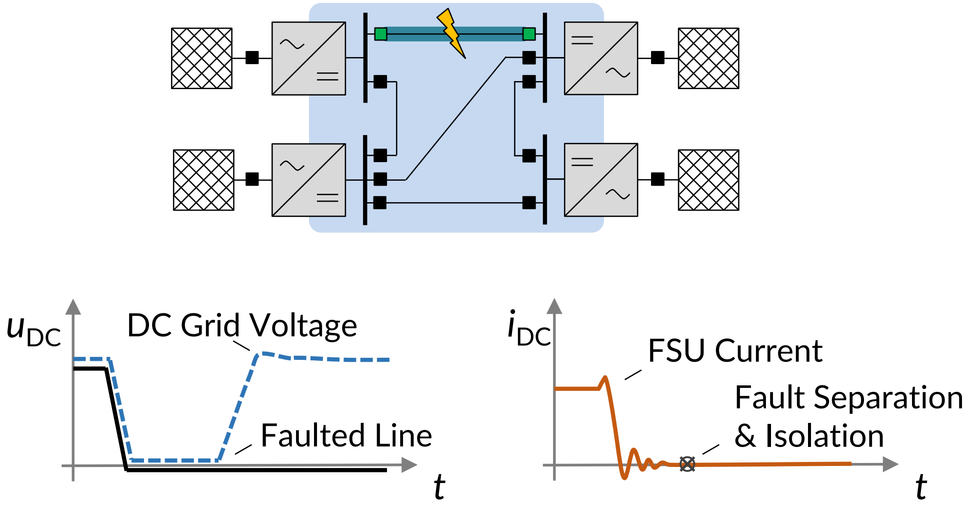
Fully Selective Protection

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



Non-Selective Protection

- Entire DC network as protection zone
- Fast de-energisation of the protection zone
- Fault separation at near-zero current and voltage



Protection Zones | Faulted Line | Fault Feeding Converter (i.e. Half-Bridge MMC) | Fault Blocking Converter (i.e. Full-Bridge MMC)

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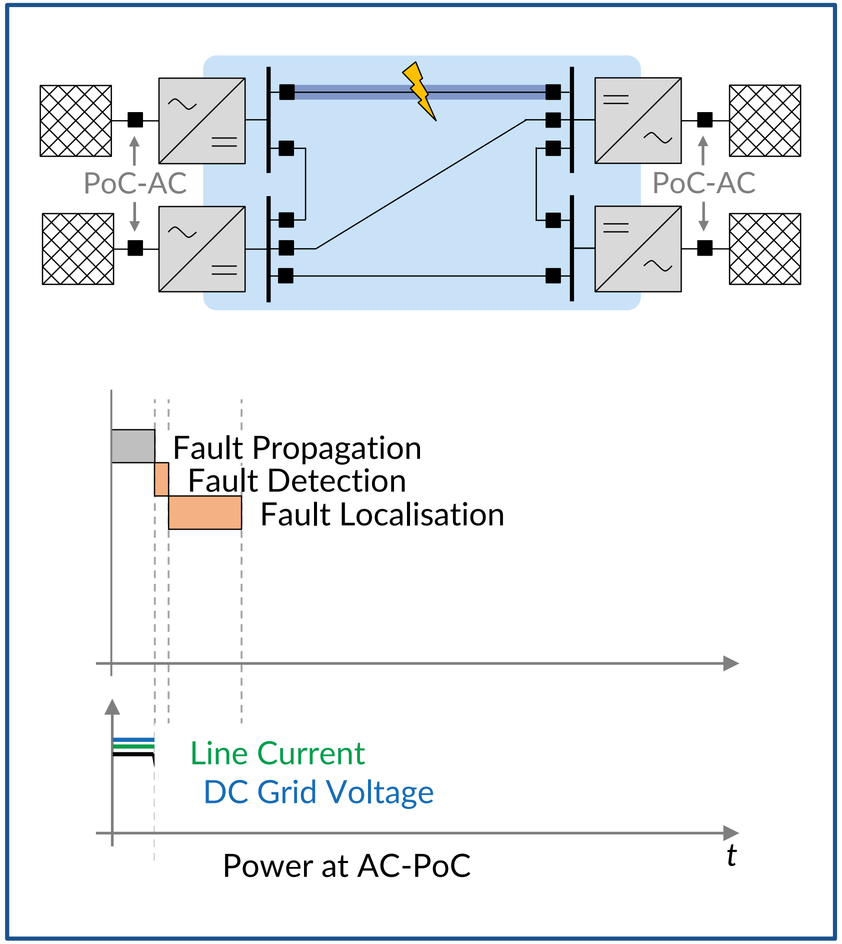
Protection Strategy – Detection and Localisation



- 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 de-energization of the network
  - ➢Low-speed fault localization based on communication is sufficient for the protection strategy

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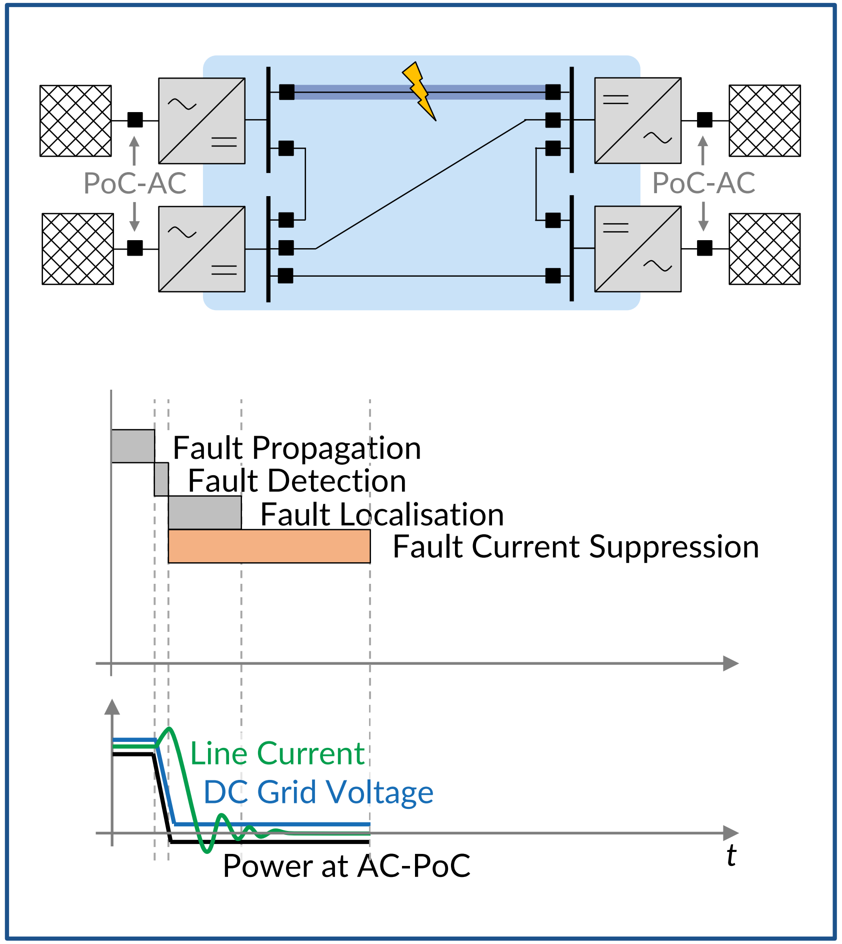
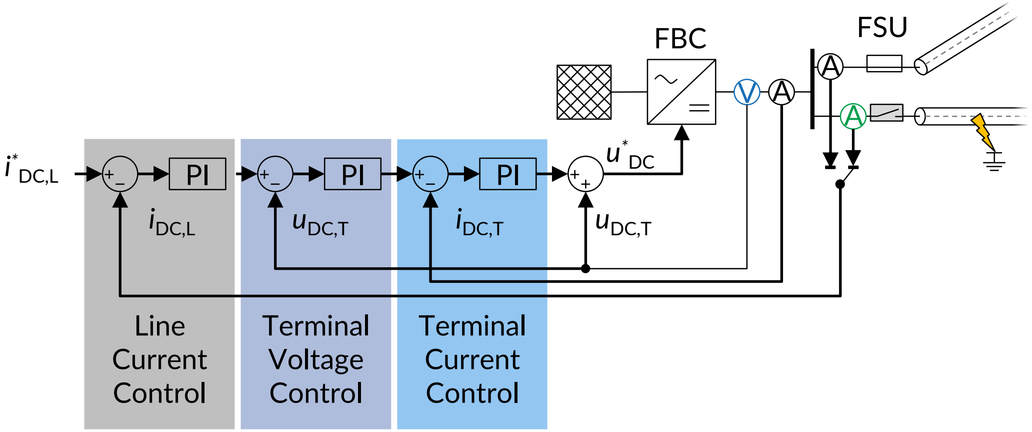
Protection Strategy – DC Fault Control



- 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



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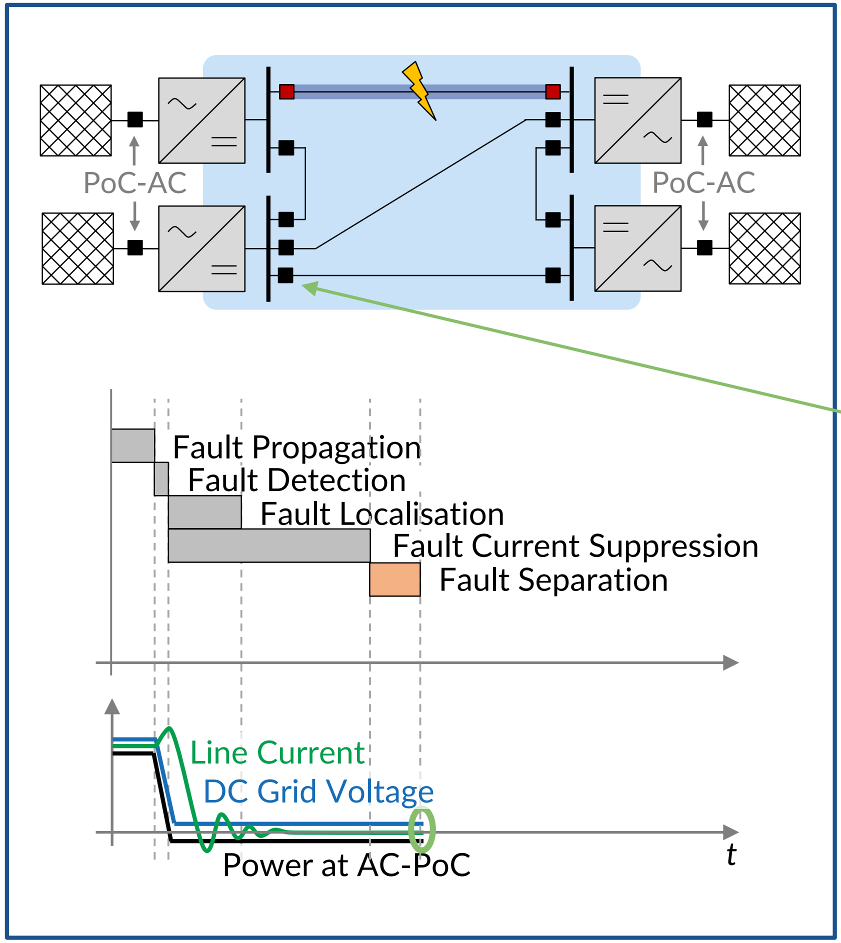
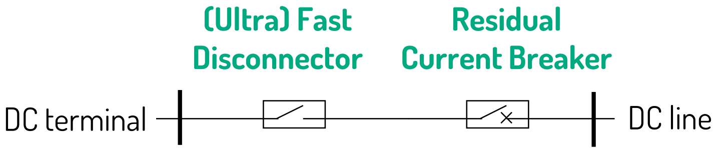
Protection Strategy – Fault Separation Unit



- Requirements
  - Residual (DC) current interruption capability → counter voltage (transient interruption voltage) may be required
  - Fast isolation of the faulted line after fault separation



- Residual Current Breaker (RCB)
  - Voltage ratings (TIV) ~ 5 – 10 % of V_{DC}
  - Energy absorption ~ a few tens of kilojoules
  - RCB can be adjusted to the power system's requirements

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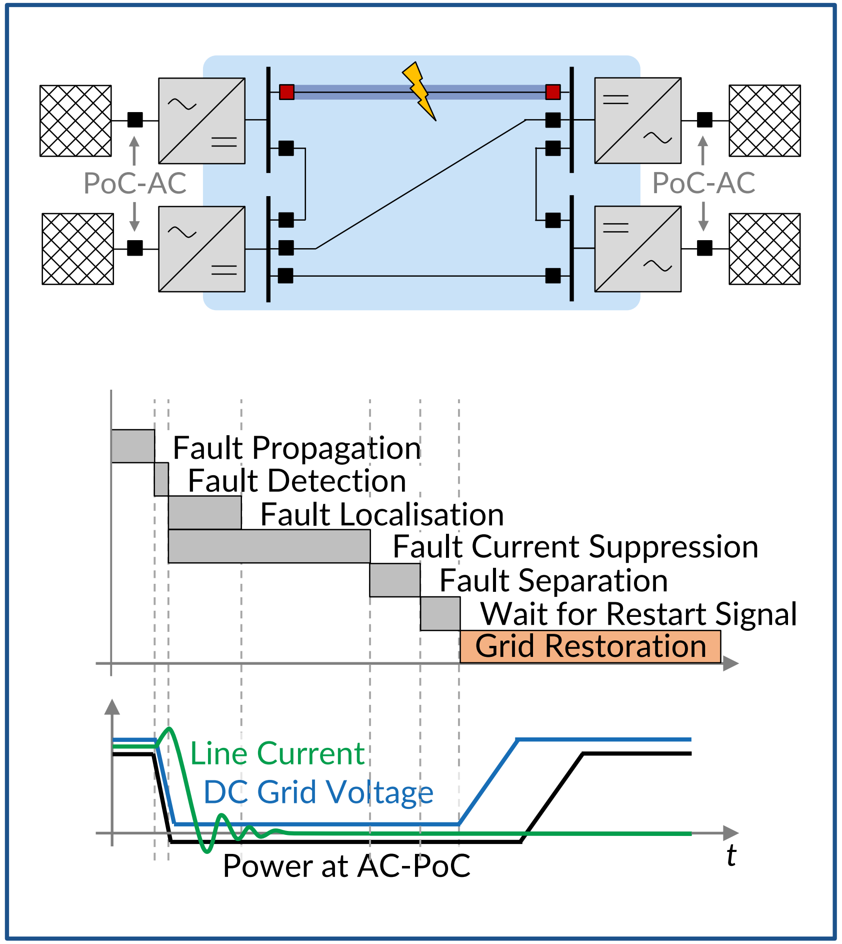
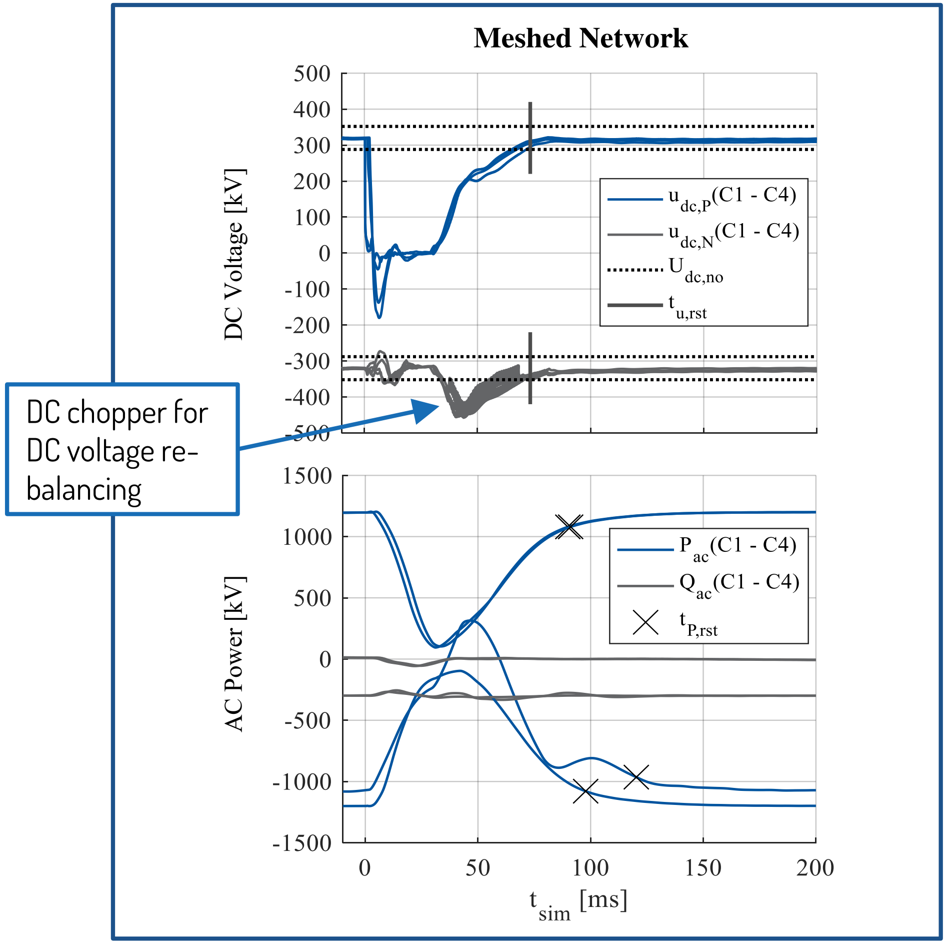
Protection Strategy – Grid Restoration



- 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

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

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SCOPE OF THE HARDWARE-IN-THE-LOOP DEMONSTRATION

William Leon-Garcia

Antoine Ghyselinck

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- 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

SCOPE OF THE DEMONSTRATION
System layout

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

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

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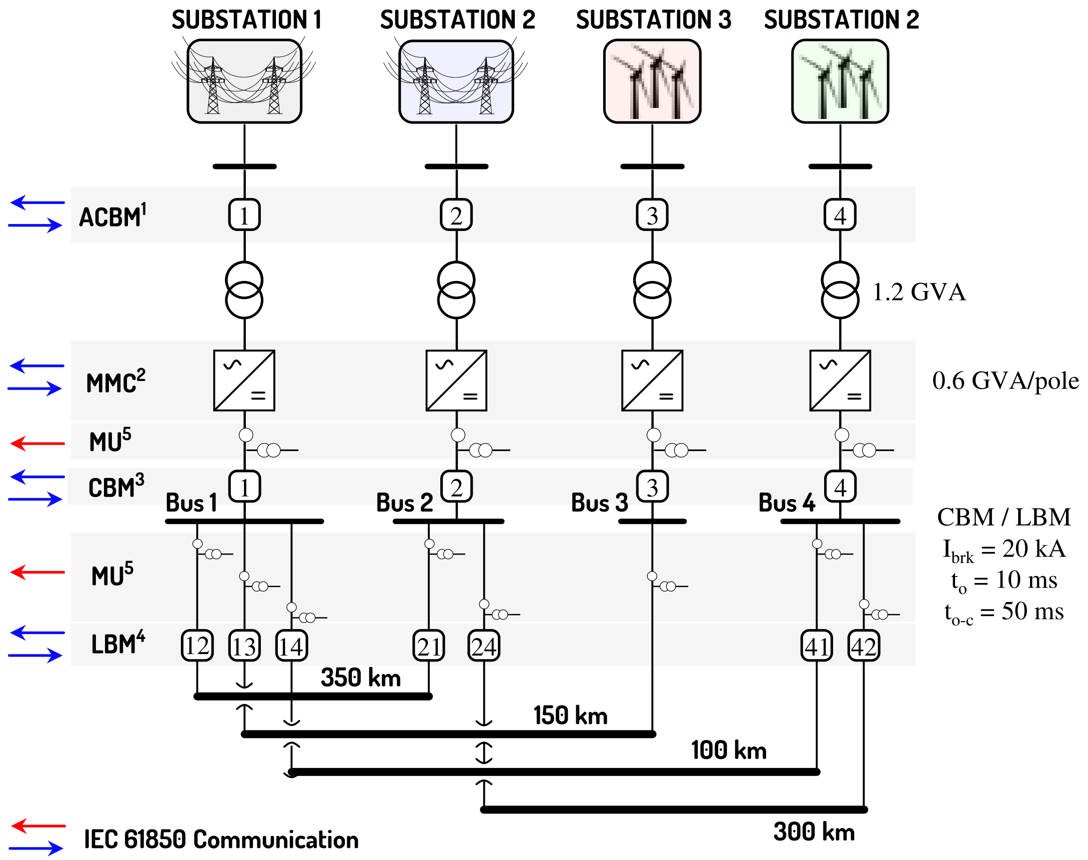
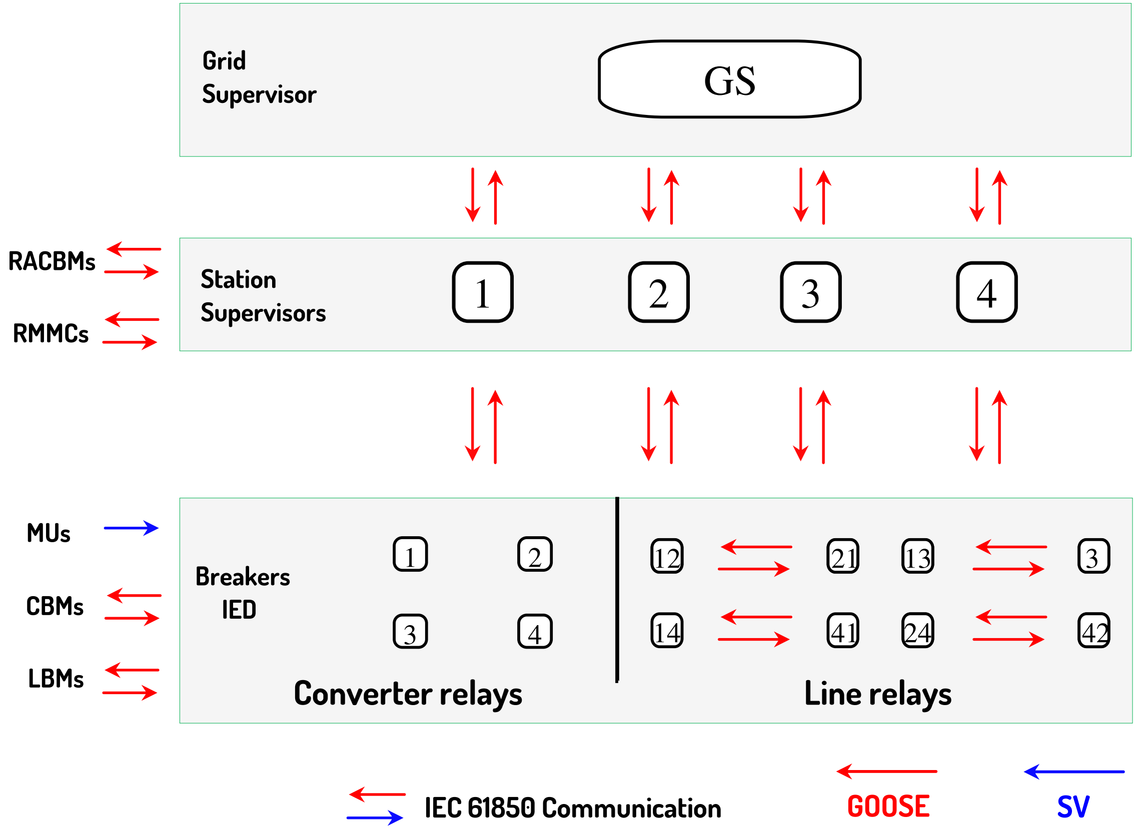
PLANT – CONVERTER BREAKER PROTECTION STRATEGY
Four-terminal meshed HVDC network



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

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

DEVICES UNDER TEST – CONVERTER BREAKER PROTECTION STRATEGY - Communication architecture

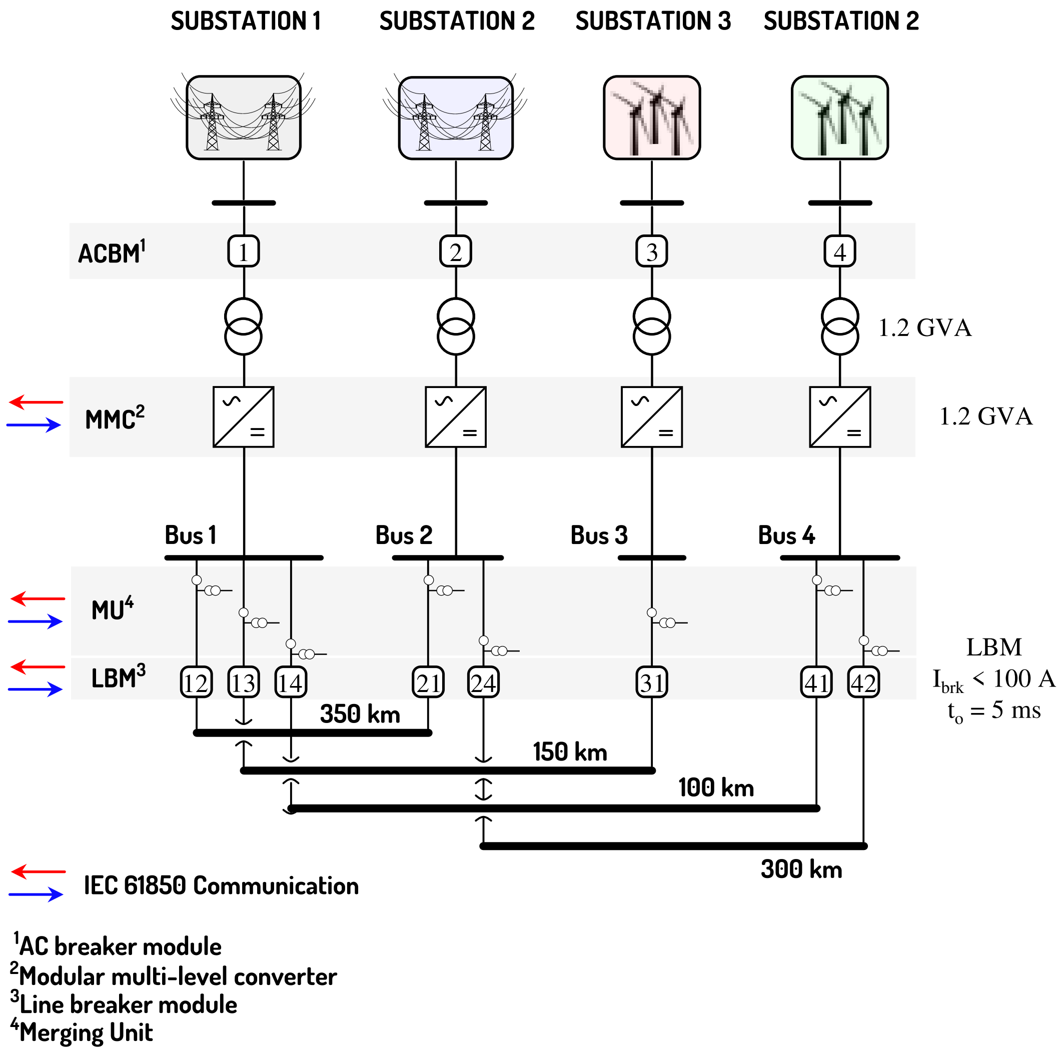


11
sampled value messages

99
goose messages

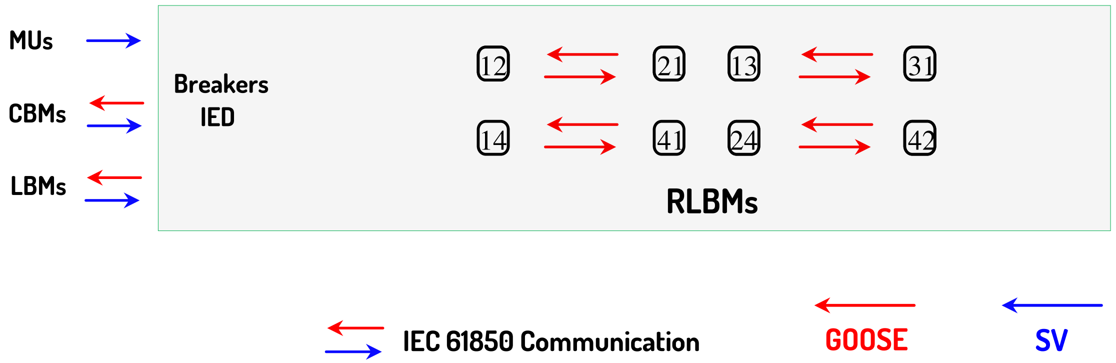
- 4 layers of communication :
  - Network <-> Relays
  - Relay <-> Relay
  - Relays <-> Station Supervisors
  - Station Supervisors <-> Grid Supervisor
- RLBMs on the same line communicate to give current direction information.

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



- 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

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

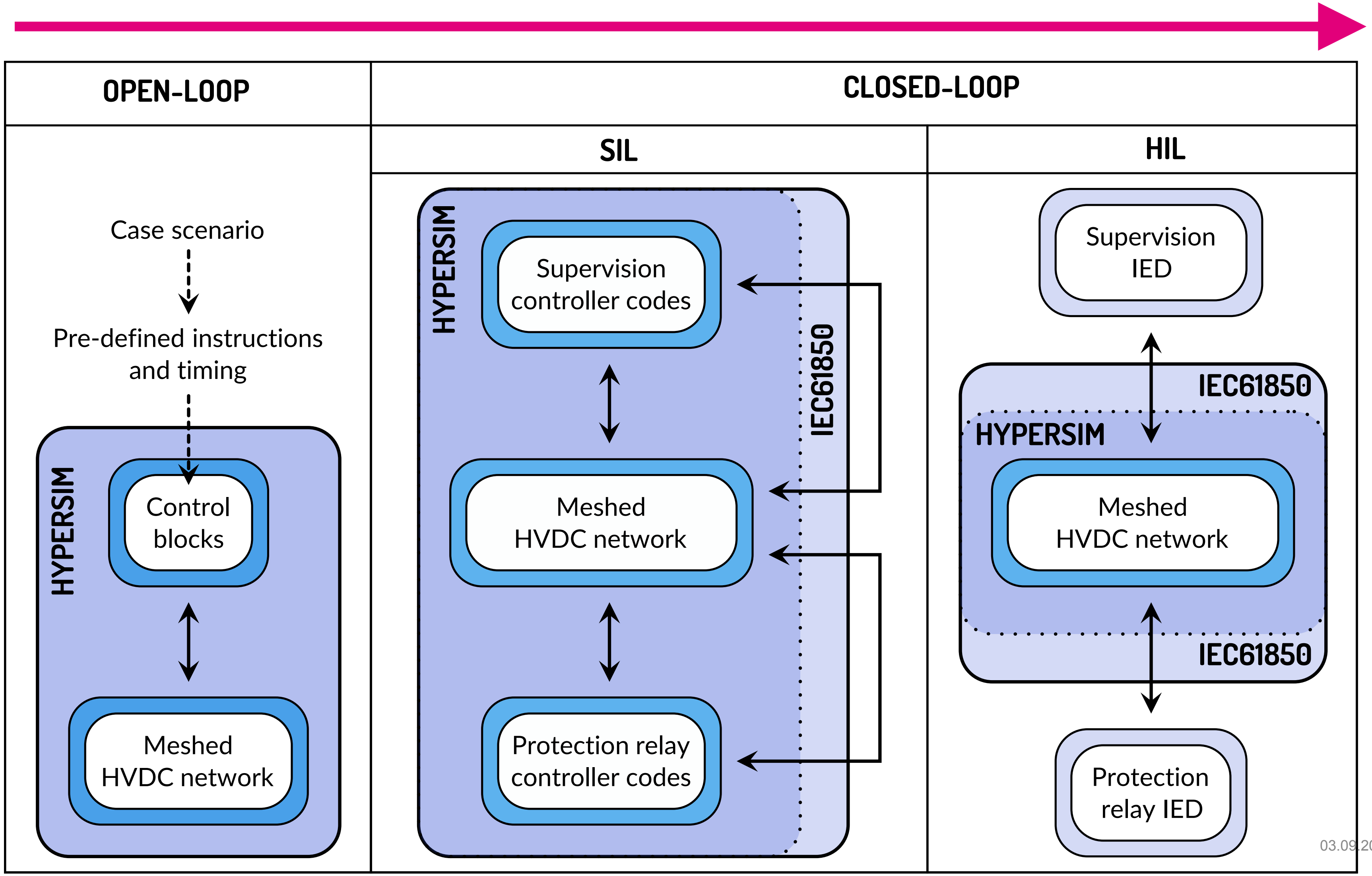


8
sampled value messages

43
goose 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.

HARDWARE-IN-THE-LOOP
Demonstration workflow



IEC61850

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Research engineer

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- 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

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

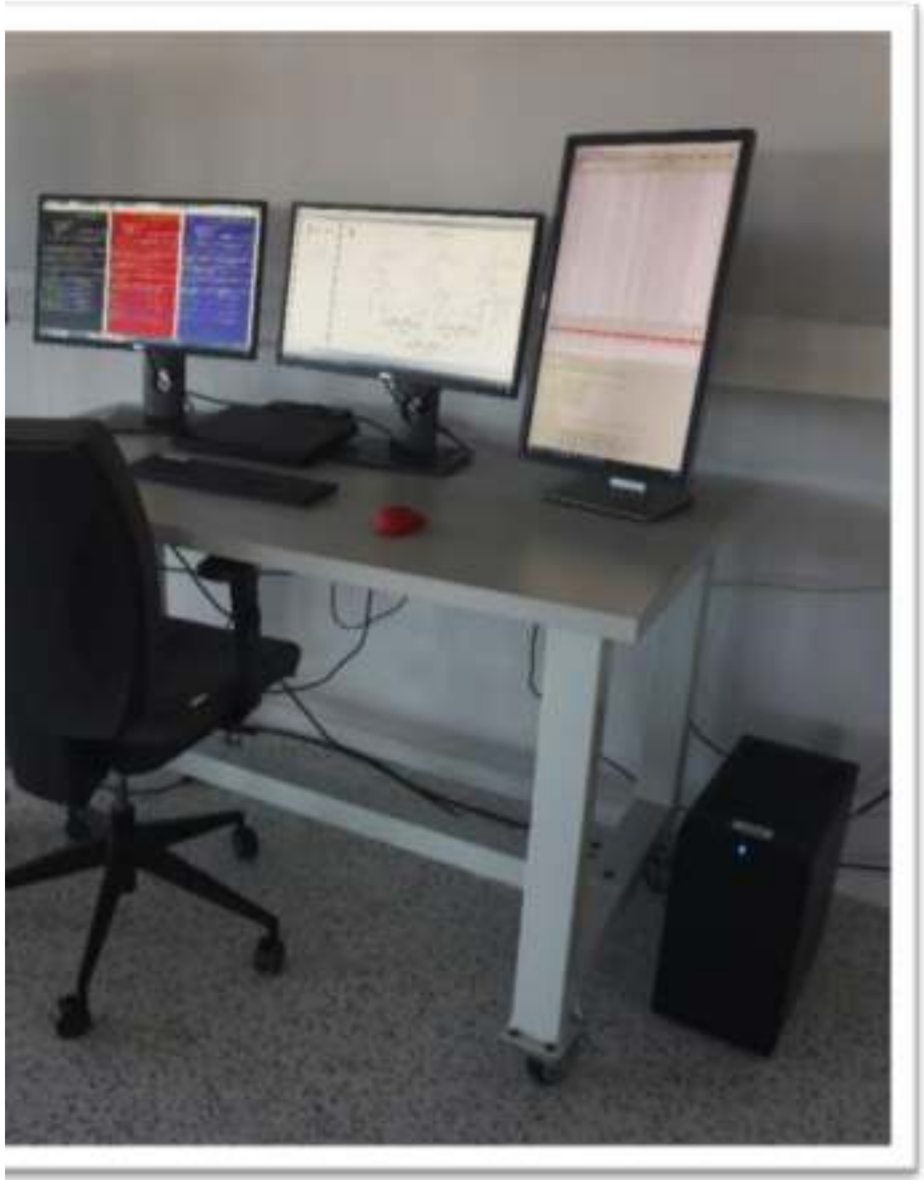
Antoine
Ghyselinck

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

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.



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

Opal-RT OP5700 Target

Items	Quantity	Description
Operating System	1	Redhat v2.6.29.6-opalrt-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

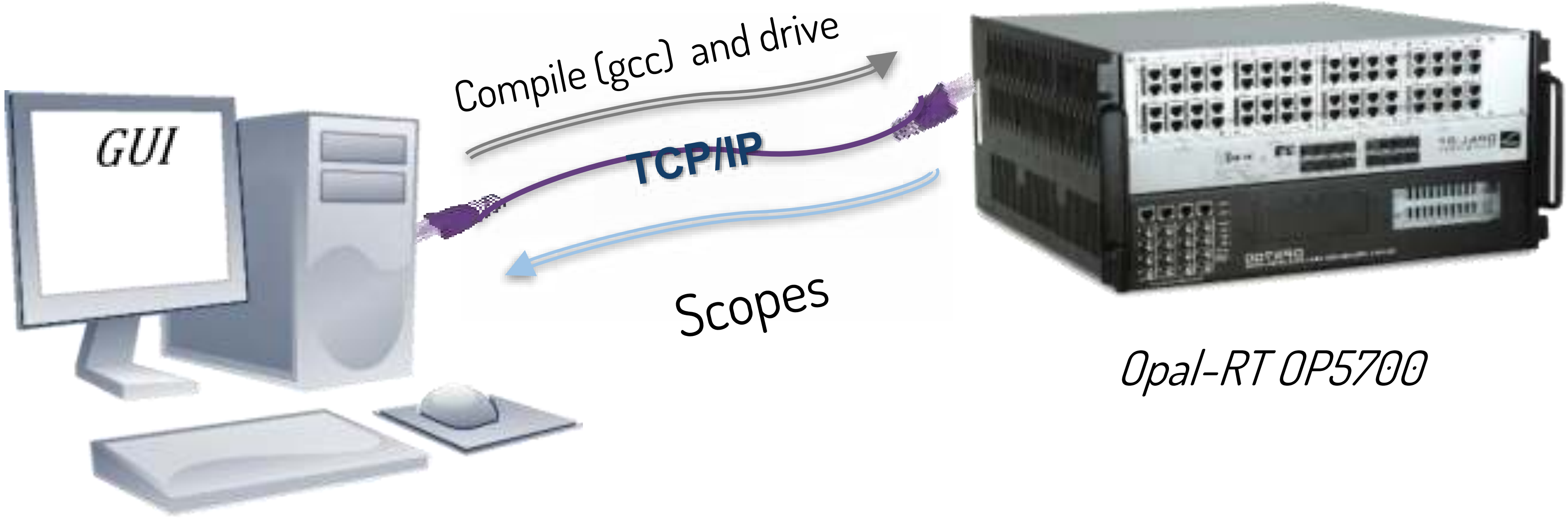
***Our license can run up to 10 cores on a simulation**

OPAL-RT OP5700 Target Hardware

Id	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

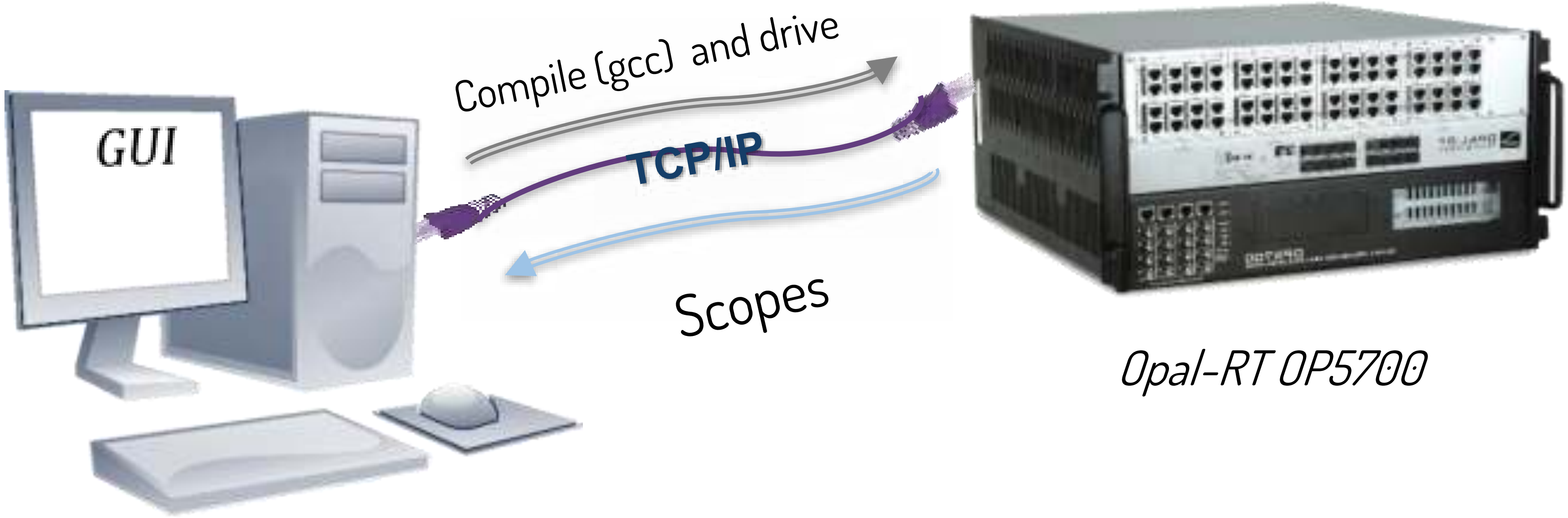
Rack of 20 RPI

CBS : 11 Relays, 5 Supervisors
FBS : 8 Relays

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

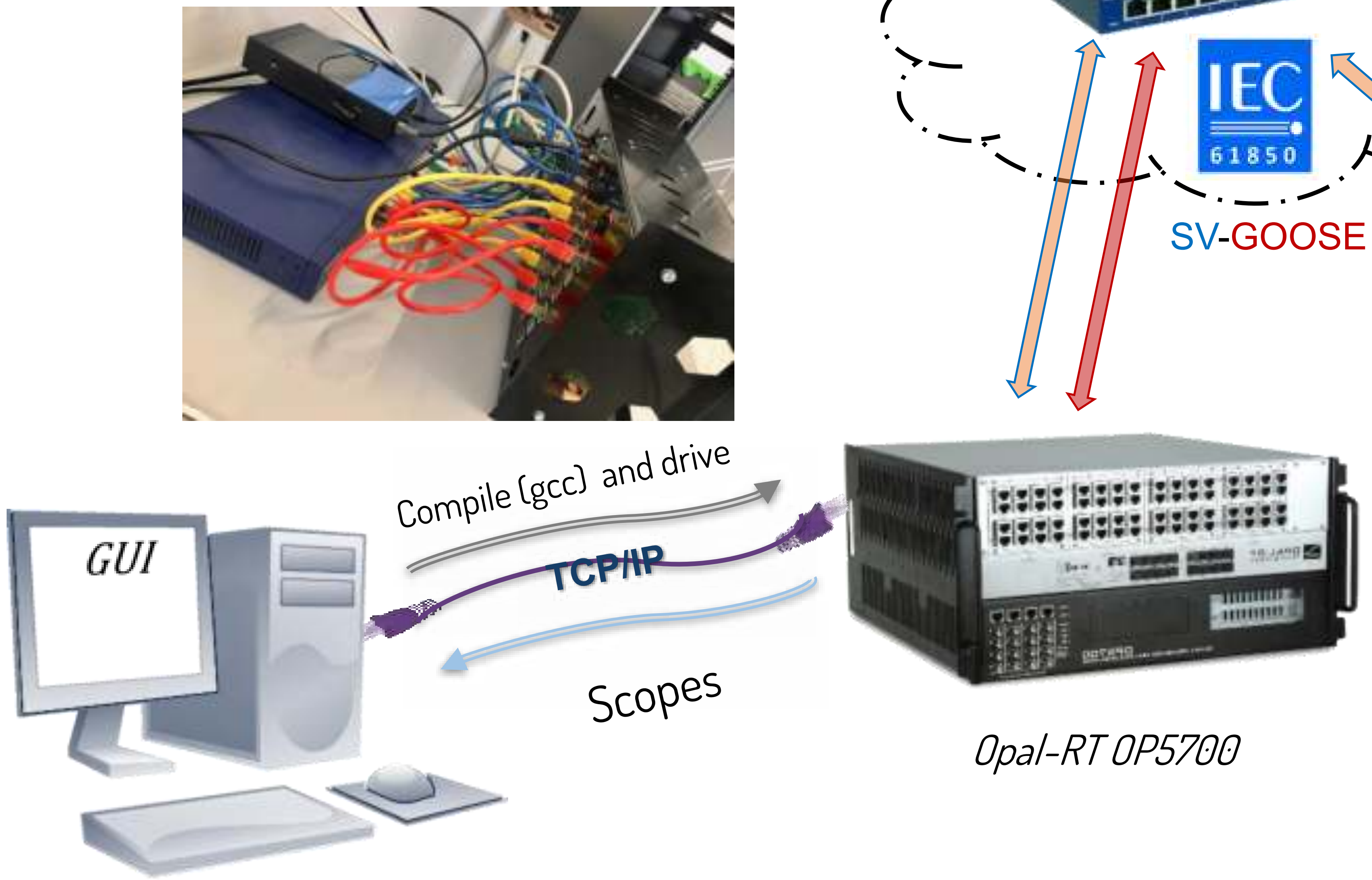
SCOPE OF THE DEMONSTRATION - Hardware-in-the-loop setup

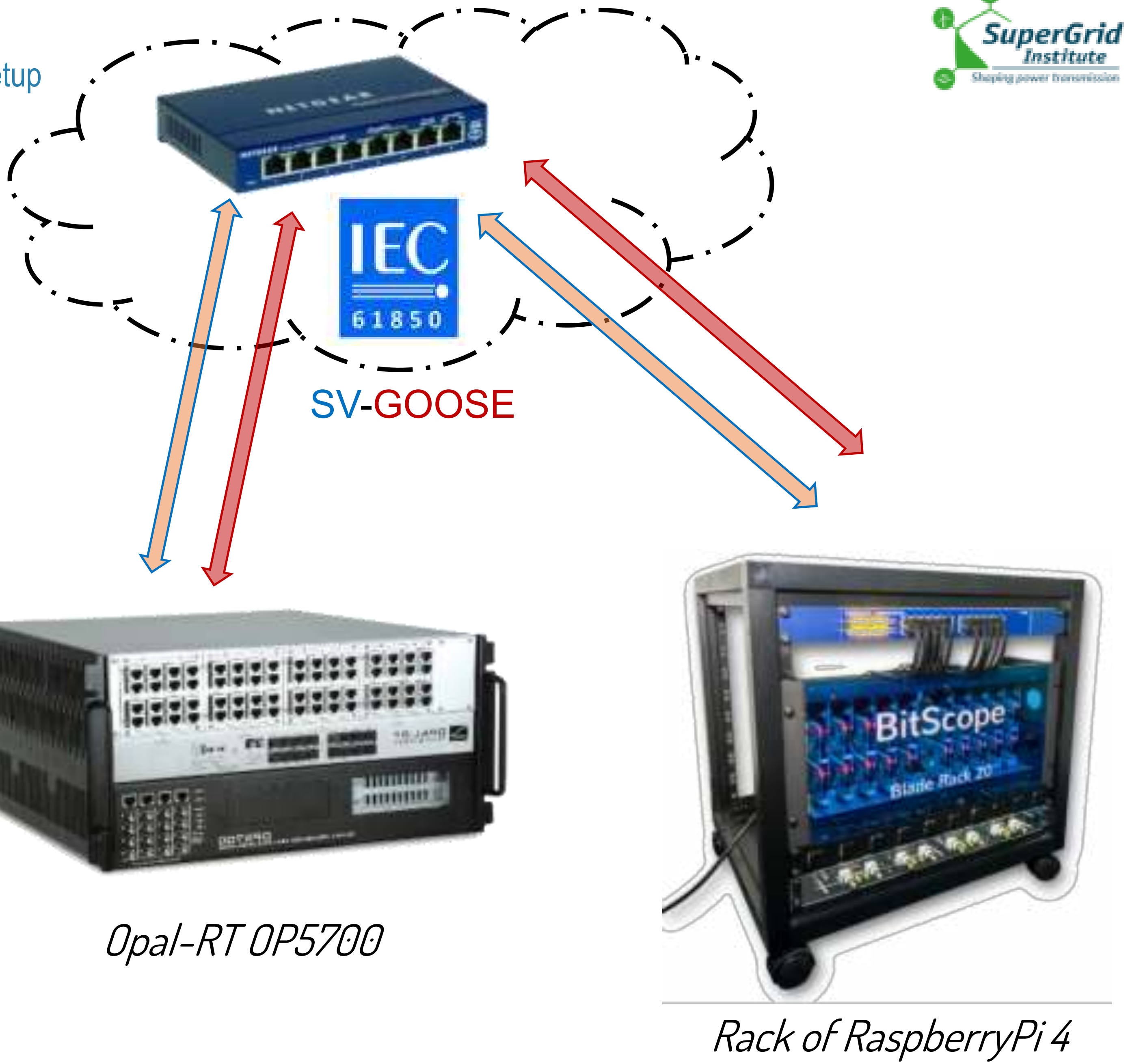


Opal-RT OP5700

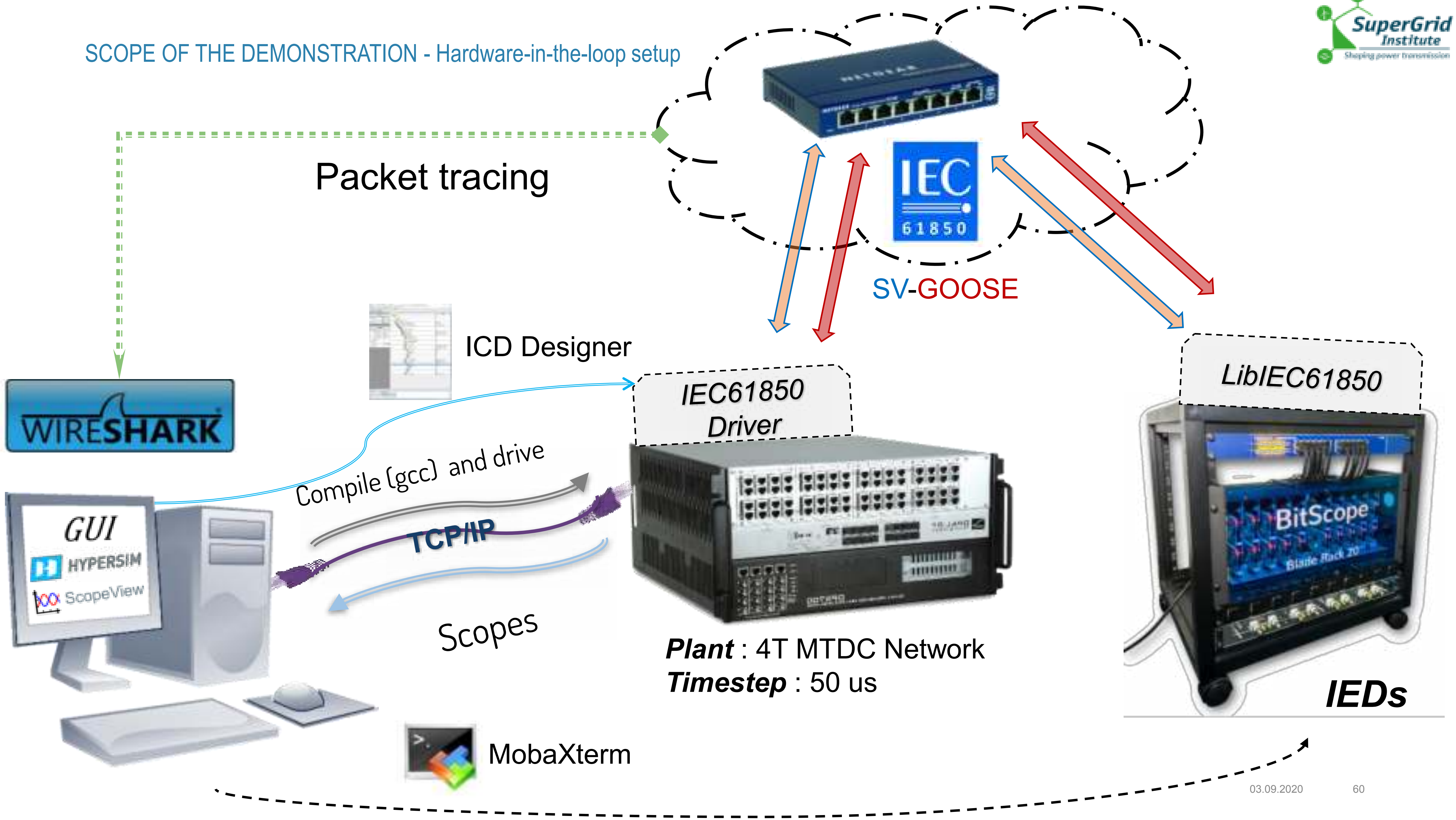
Rack of RaspberryPi 4

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





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



THE BIG STEPS

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

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

William Leon-Garcia

SCOPE OF THE DEMONSTRATION
Real-time simulation models

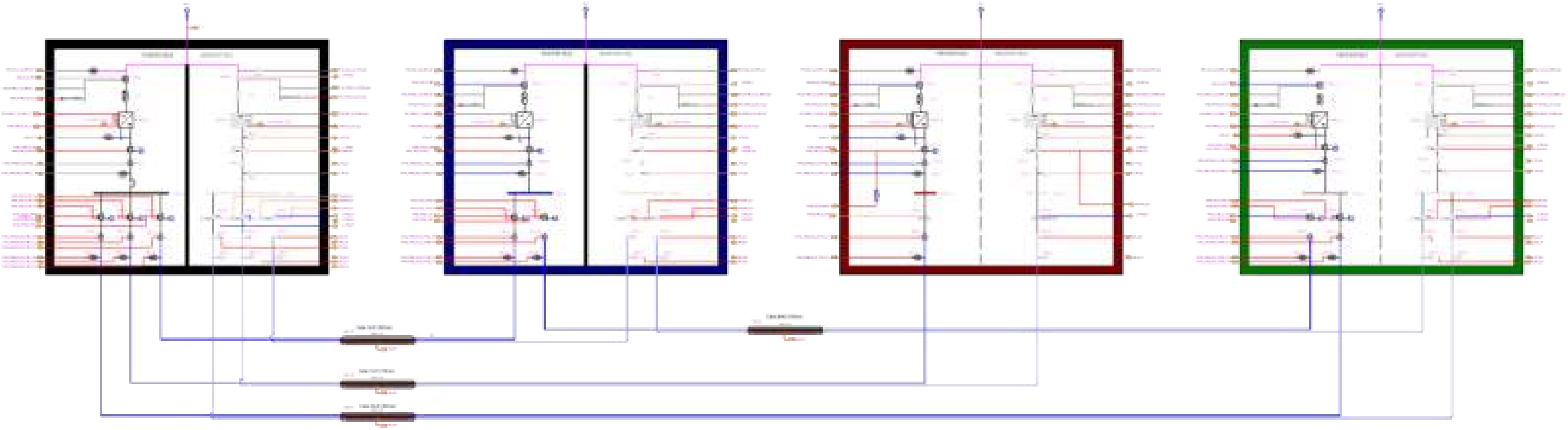
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

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.
- <u>Main models required : MMC , DC Breakers, Cable</u>
  - These models were created based on documents from other workpackages' and know-how in modeling of HVDC technologies.

<u>1056</u>
network elements

<u>2167</u>
control blocks



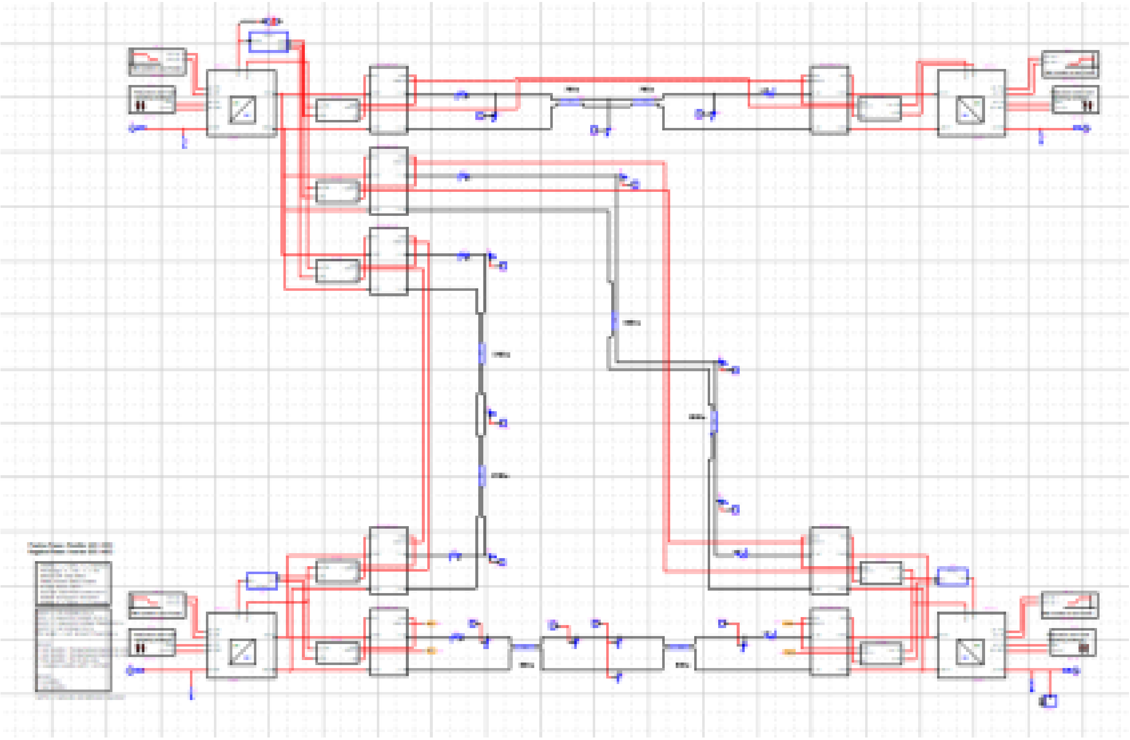
4T MTDC Plant for CBS on HYPERSIM

BUILD HYPERSIM 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

1251 network elements

1851 control blocks



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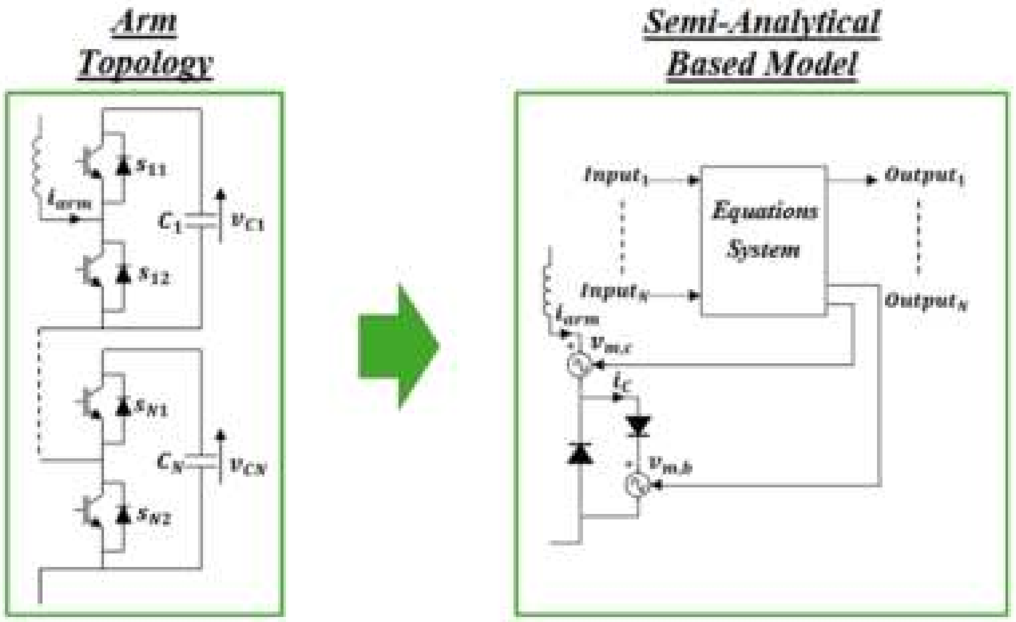
BUILD HYPERSIM MODELS
Semi-analytical average model of Modular Multilevel Converter

Physical Model

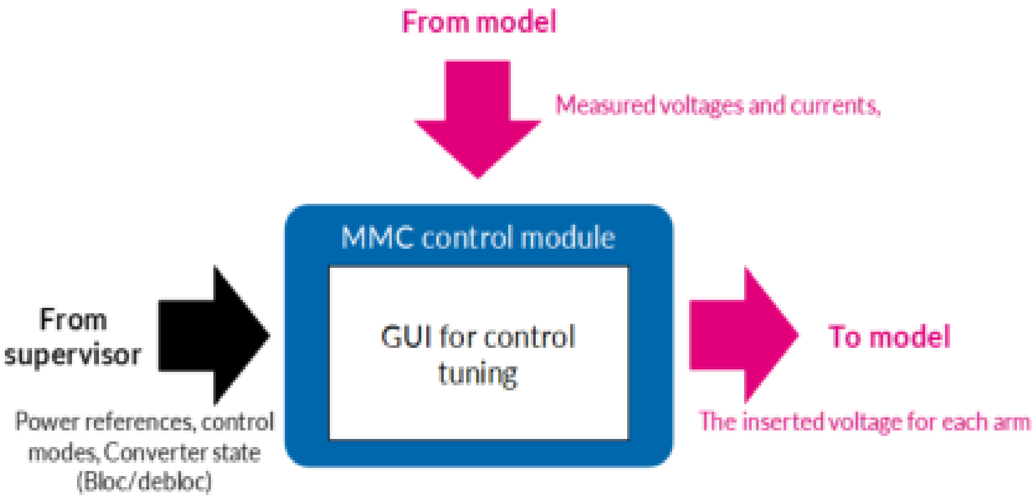
- i.e. Average Model based on the HB Valve in the HYPERSIM library.



Average Model reduction of the MMC's arm

Control

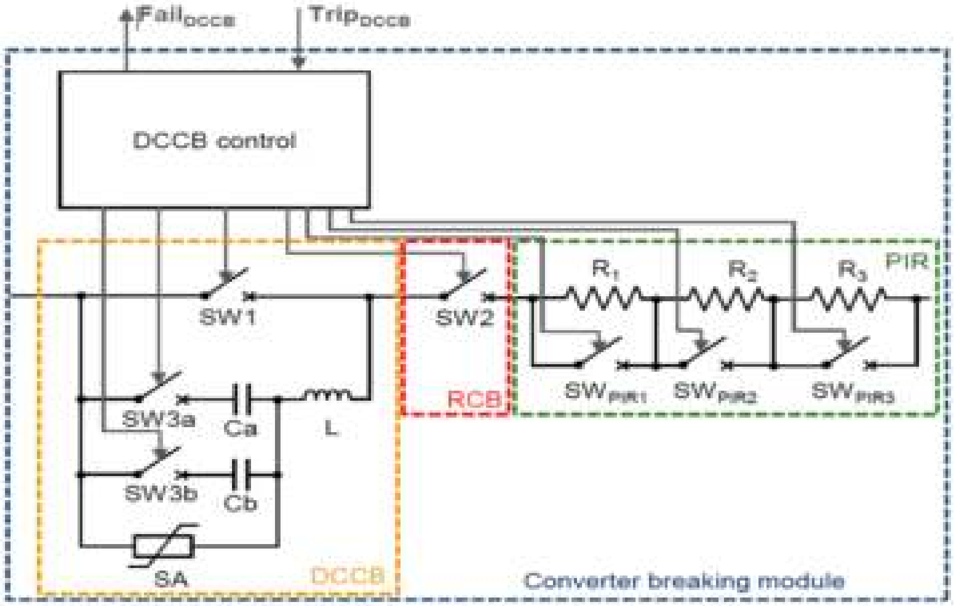
- HB-MMC control (ZAMA Ahmed, SuperGrid Institute) in Simulink imported in HYPERSIM via Hyperlink.
- FB-MMC control (RUFFING P, DÜLLMANN P)



MMC Control Integration

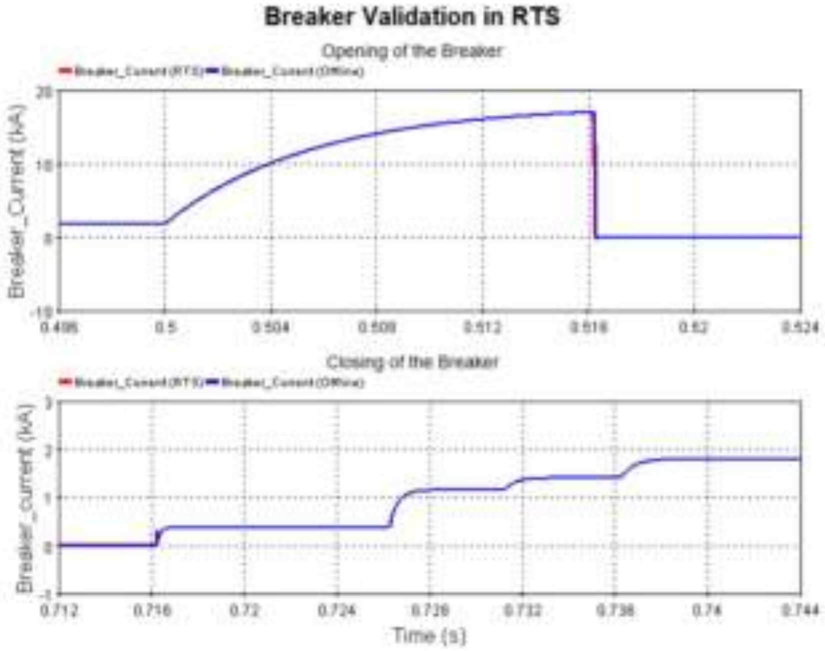
BUILD HYPERSIM MODELS
DC circuit breakers

- **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)



© PROMOTioN – Progress on Meshed HVDC Offshore Transmission Networks
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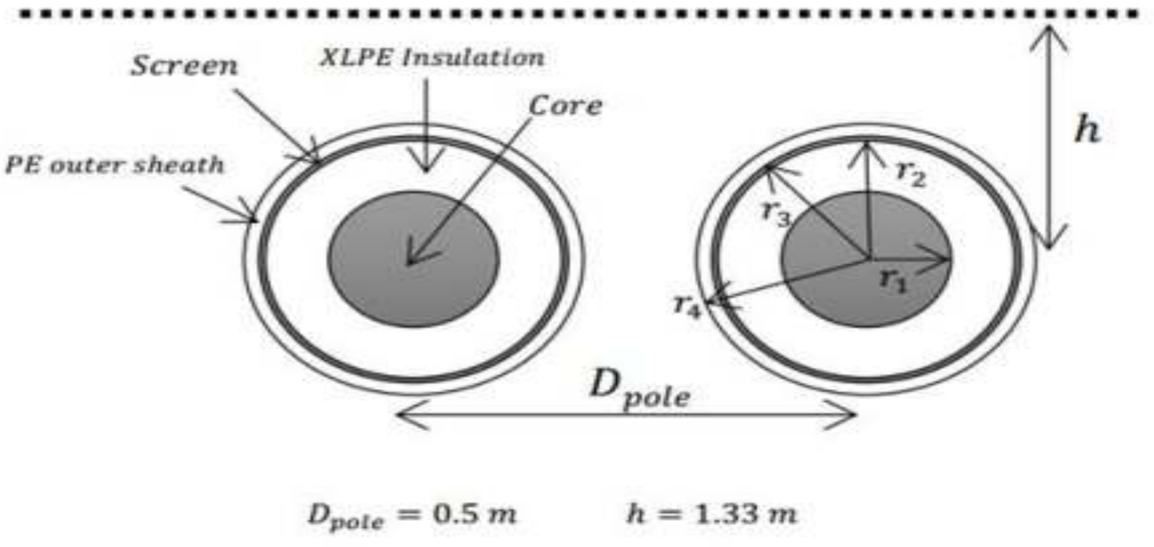
BUILD HYPERSIM MODELS
DC Cable

- 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)

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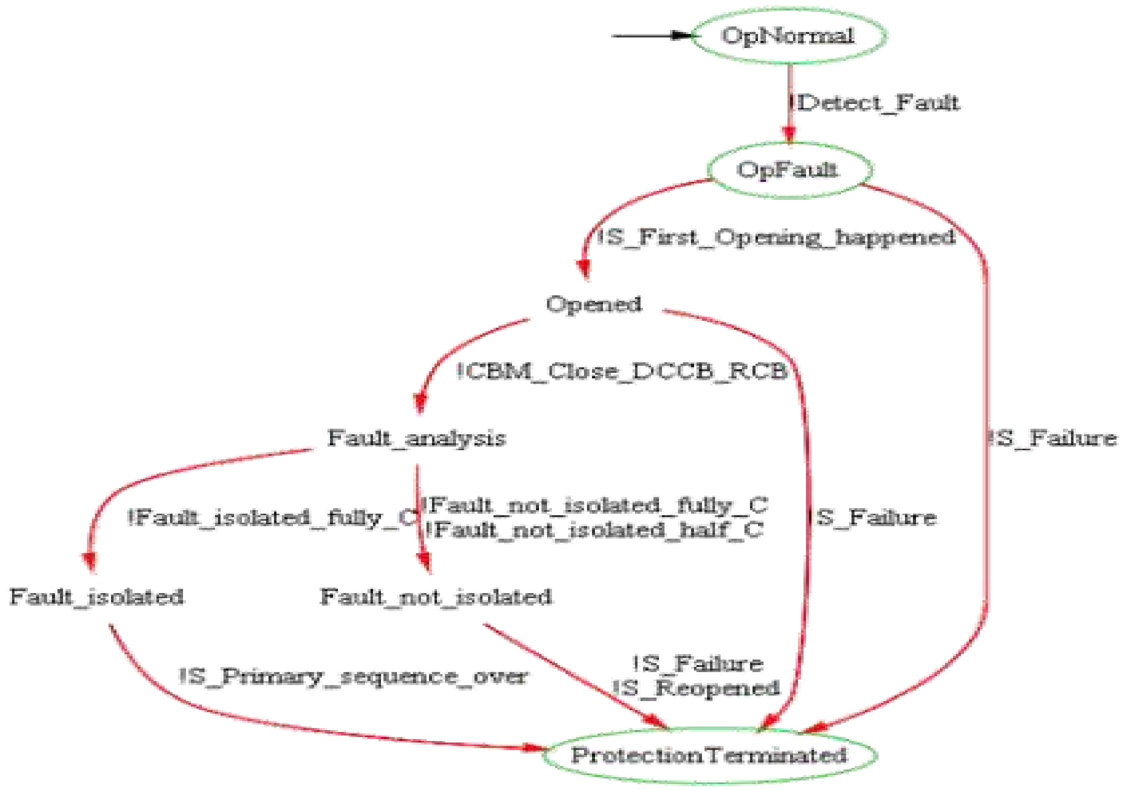
BUILD HYPERSIM MODELS
Supervisors design

- 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)



State diagram for fault supervision

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SCOPE OF THE DEMONSTRATION

Hardware-in-the-loop setup

Antoine Ghyselinck

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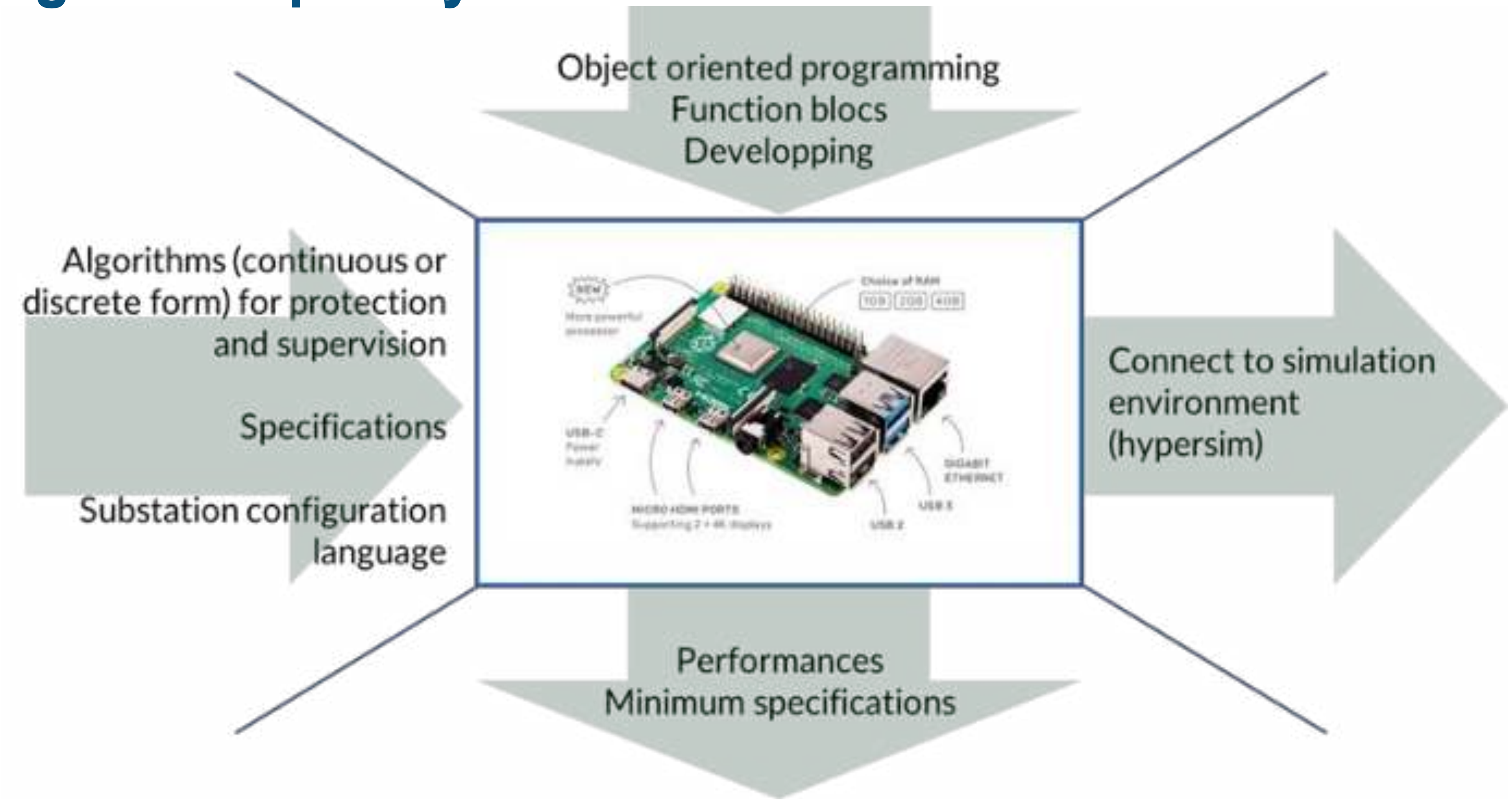
INTELLIGENT ELECTRONIC DEVICE (IED)
Prototyping on Raspberry Pi 4b



Workflow to prototype IED

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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

C code translating workflow

main.c embedded on RPI

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IED PROTOTYPING
Structure

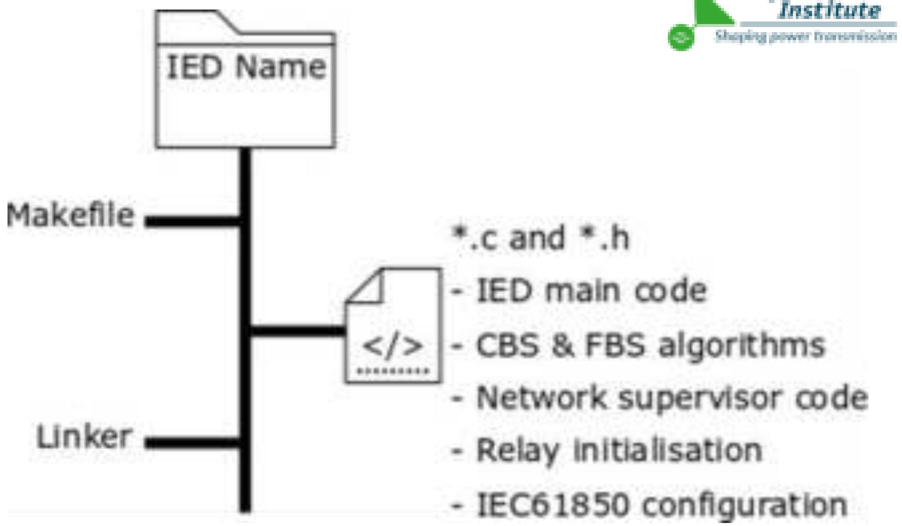
- Object Oriented thanks to structure

  - 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



IED PROTOTYPING
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, …)

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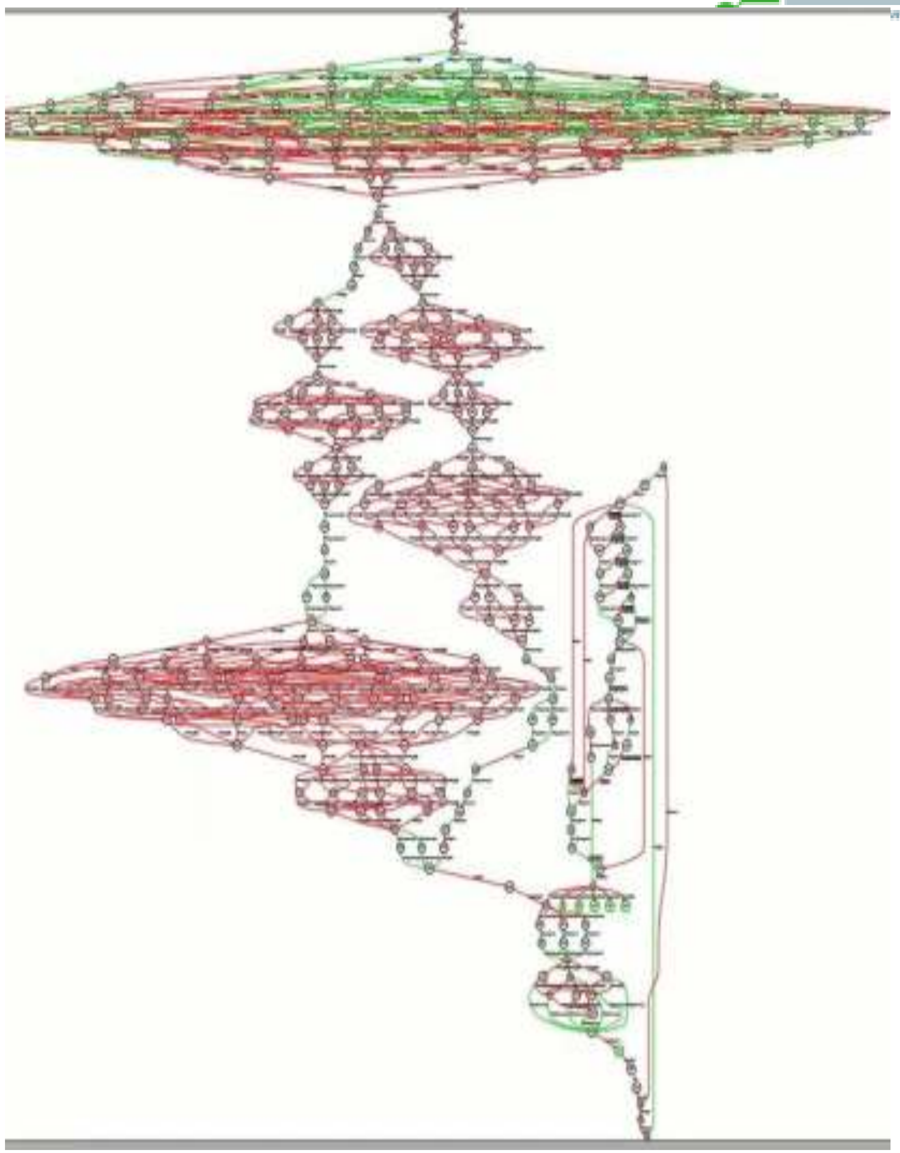
IED PROTOTYPING
Supervisors: Implementation

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



Supervisor State Diagram

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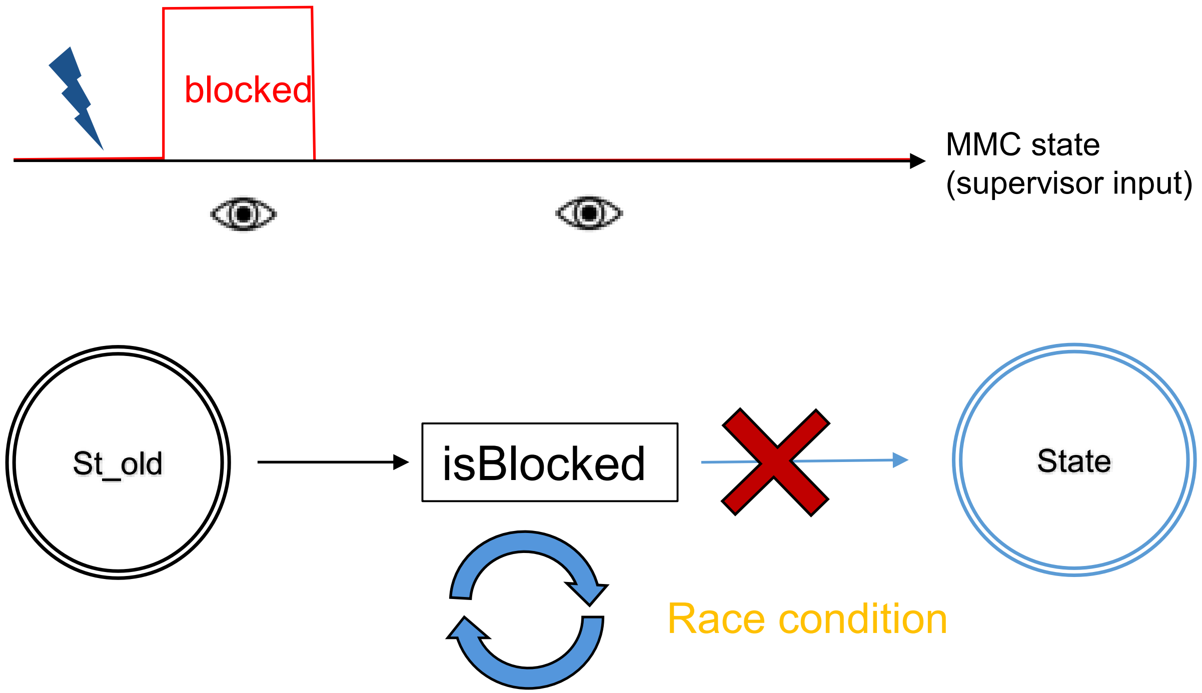
IED PROTOTYPING
Supervisors : Race condition

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



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

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SCOPE OF THE DEMONSTRATION

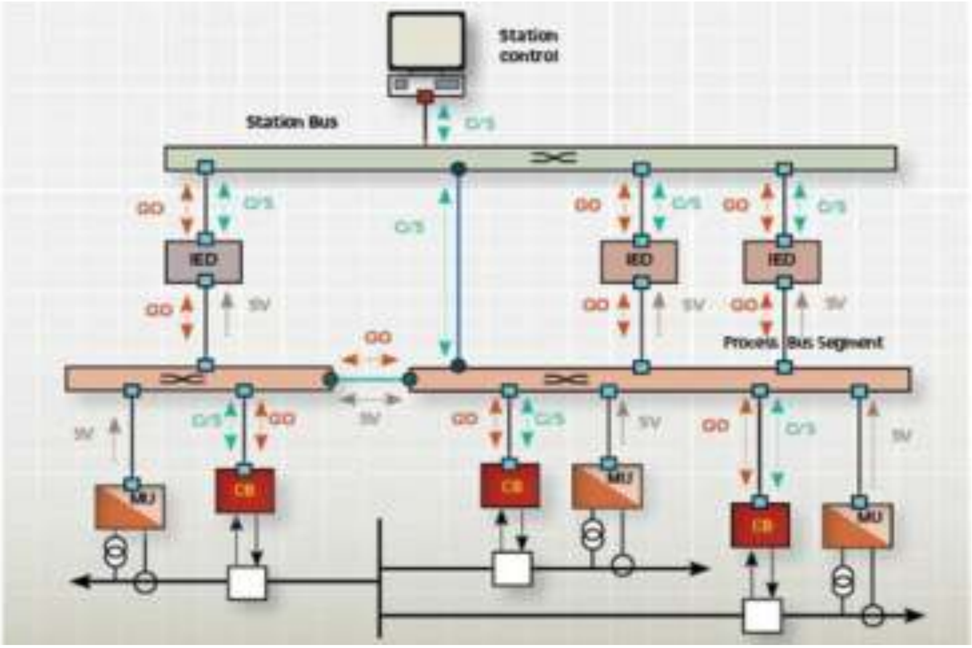
Application of the IEC61850 communication standard

Antoine
Ghyselinck

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

IEC 61850

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



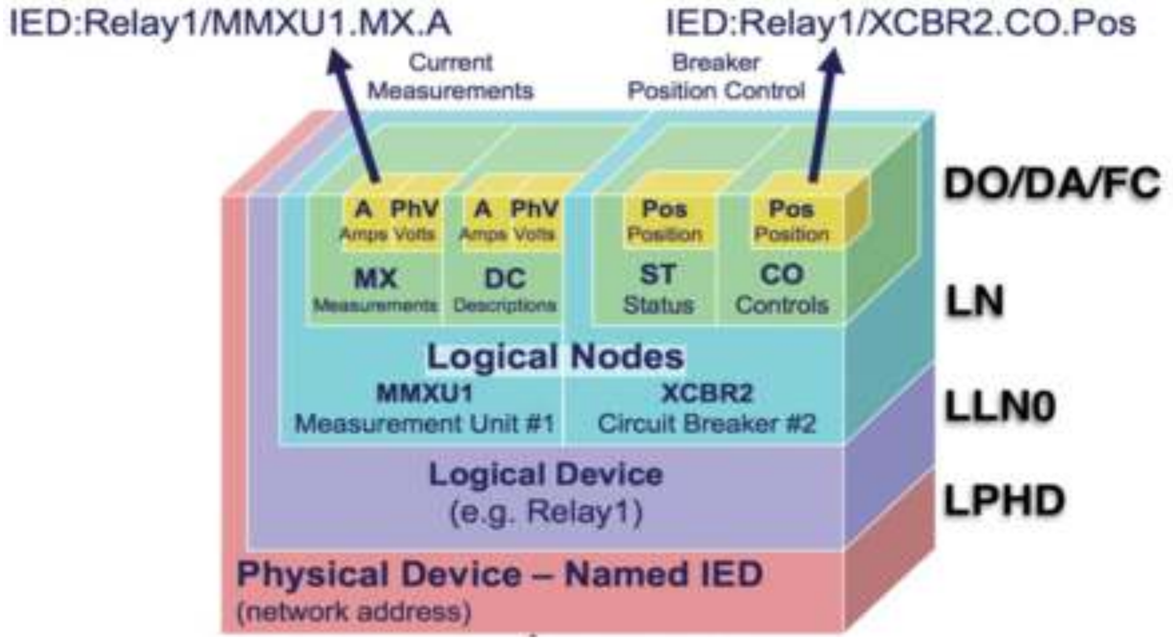
IEC61850 Example Architecture

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

IEC61850 in the OSI model*

IEC61850: SEMANTICS

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

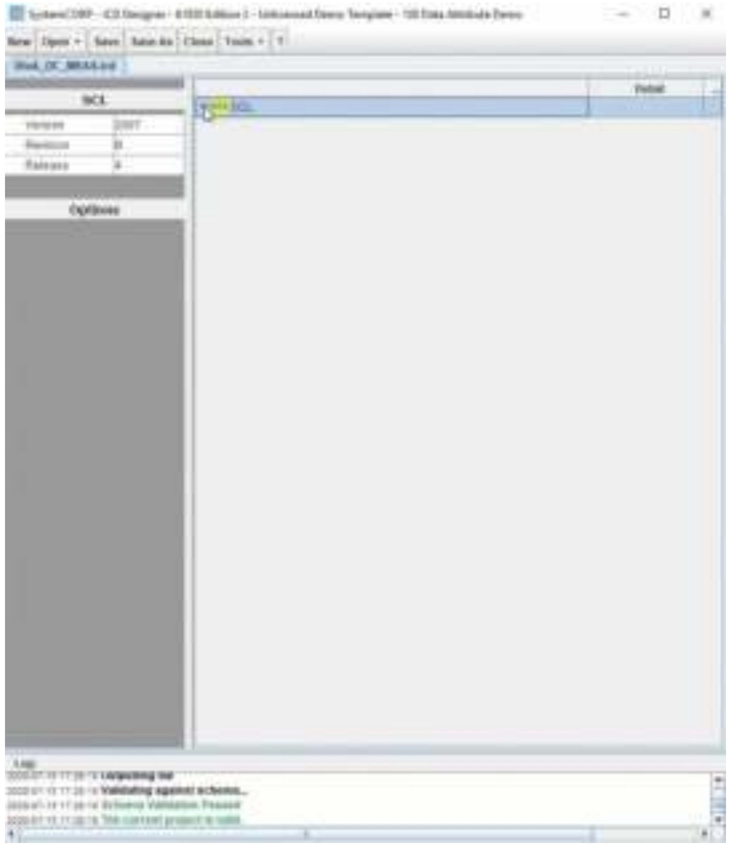


IEC61850 Class Oriented Semantics

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



ICD Designer

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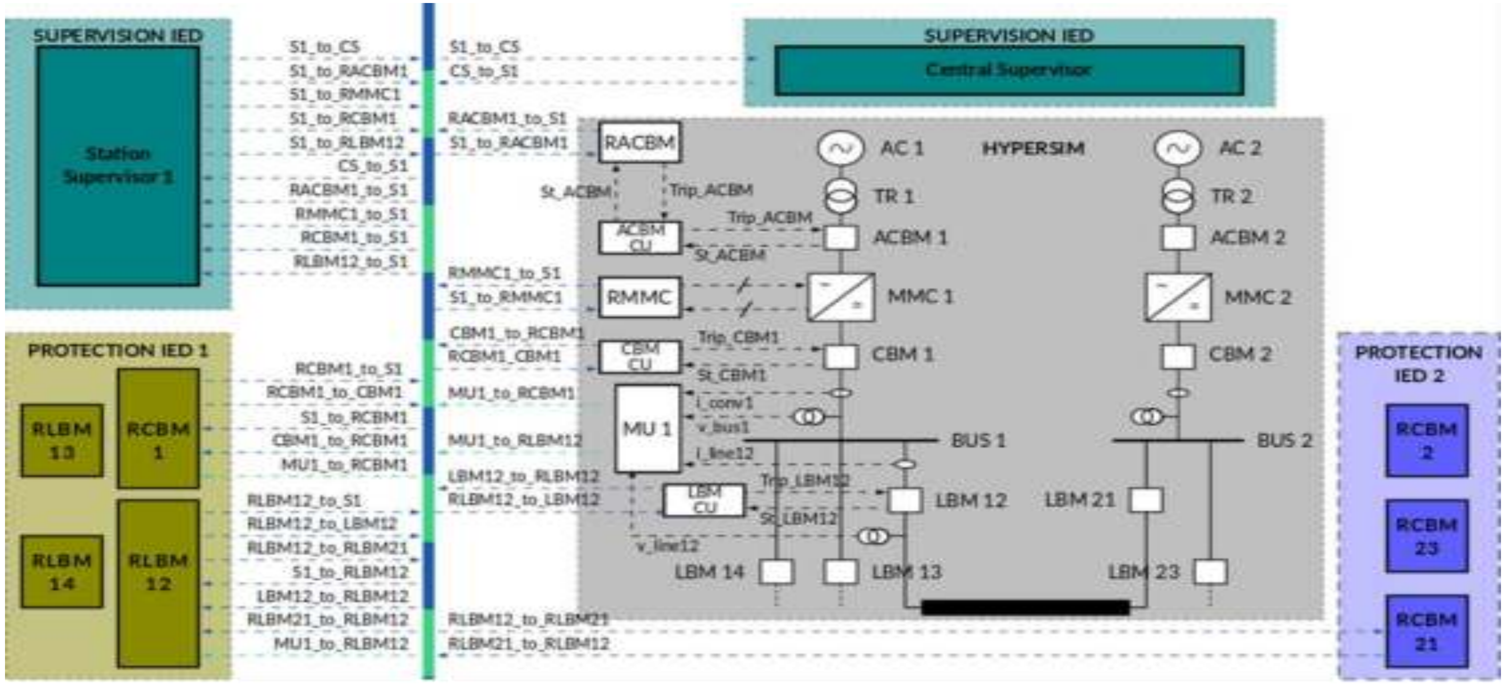
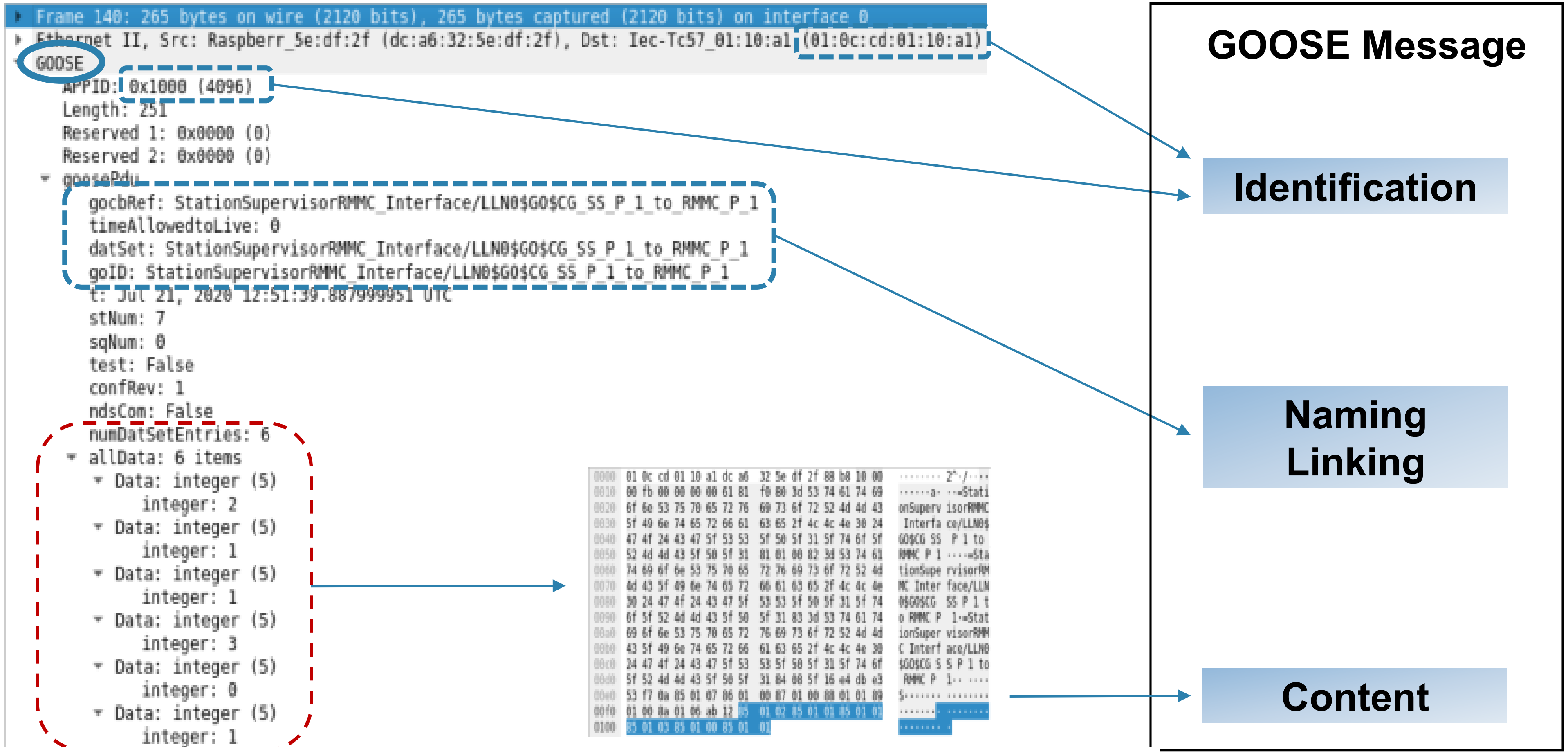
IEC61850: INTEGRATION

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



Part of the CBS IEC61850 Architecture

WIRESHARK : THE PACKET TRACER



RESULTS OF THE HARDWARE-IN-THE-LOOP DEMONSTRATION

William Leon-Garcia

SuperGrid Institute

Antoine Ghyselinck

SuperGrid Institute

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

VIRTUAL DEMO CONVERTER BREAKER PROTECTION STRATEGY

Startup

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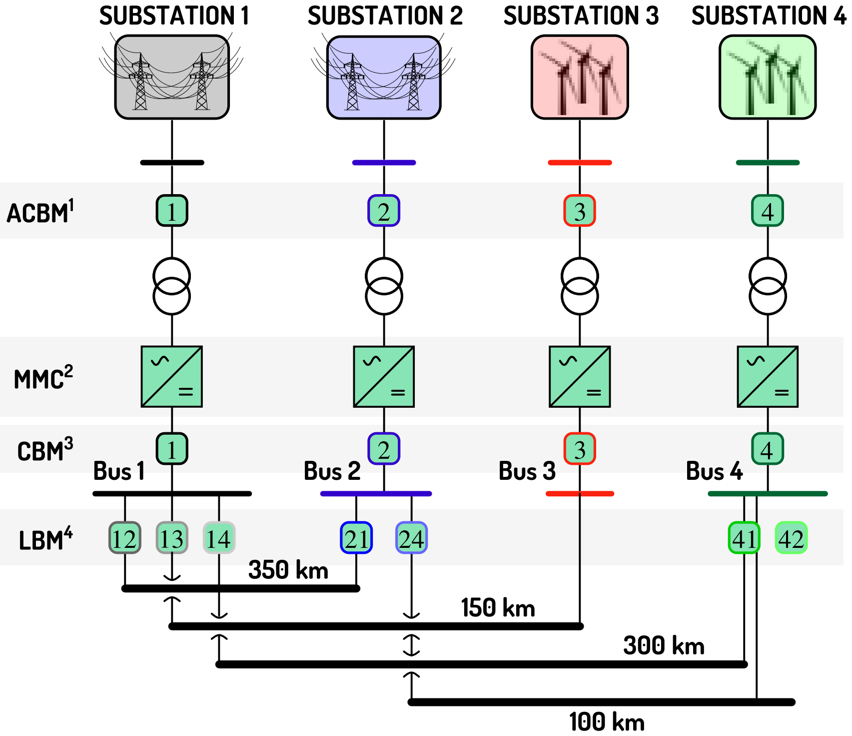
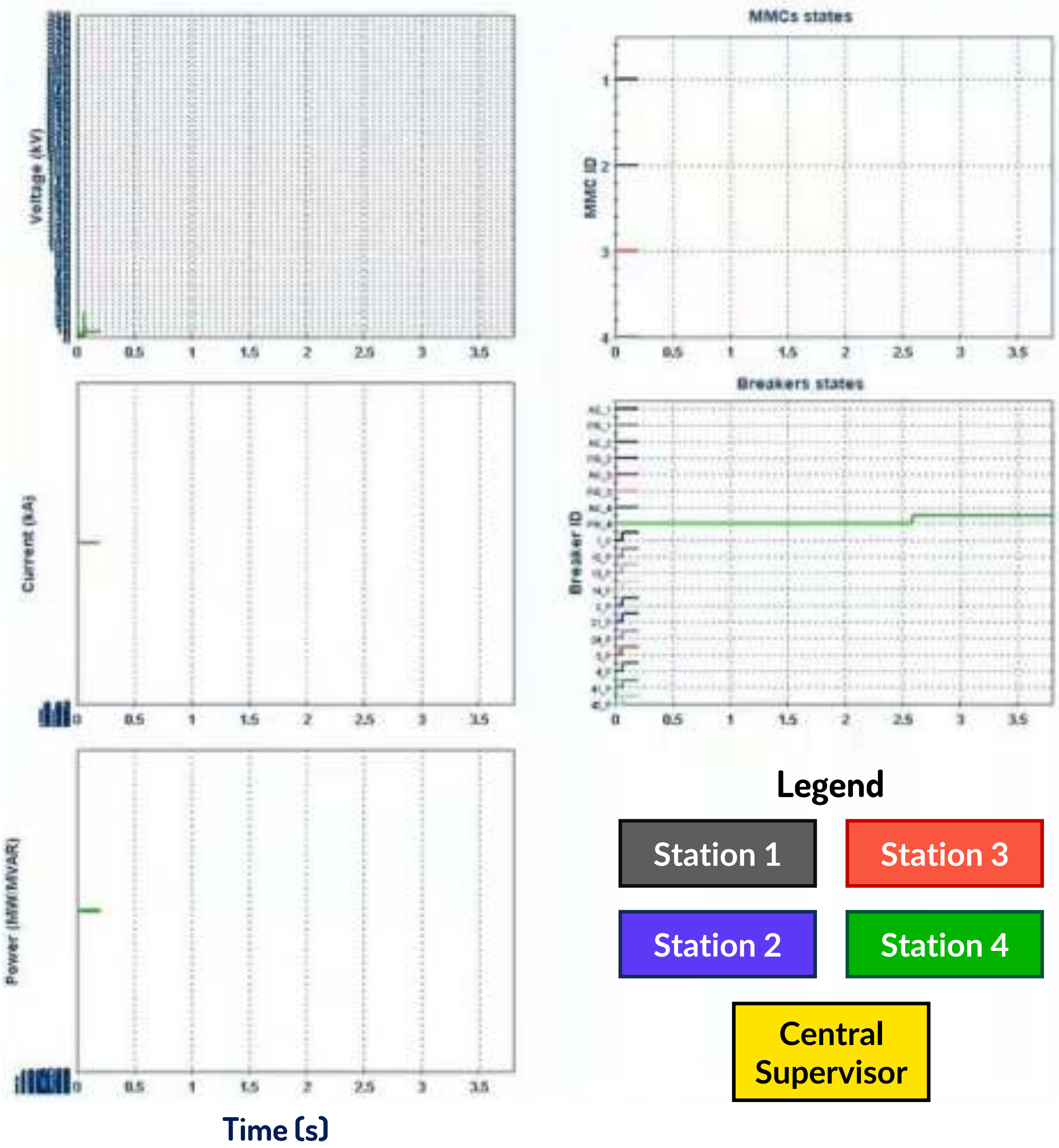
RESULTS OF THE HIL DEMONSTRATION

FOUR-TERMINAL HVDC NETWORK
Half-bridge MMC converters
Startup

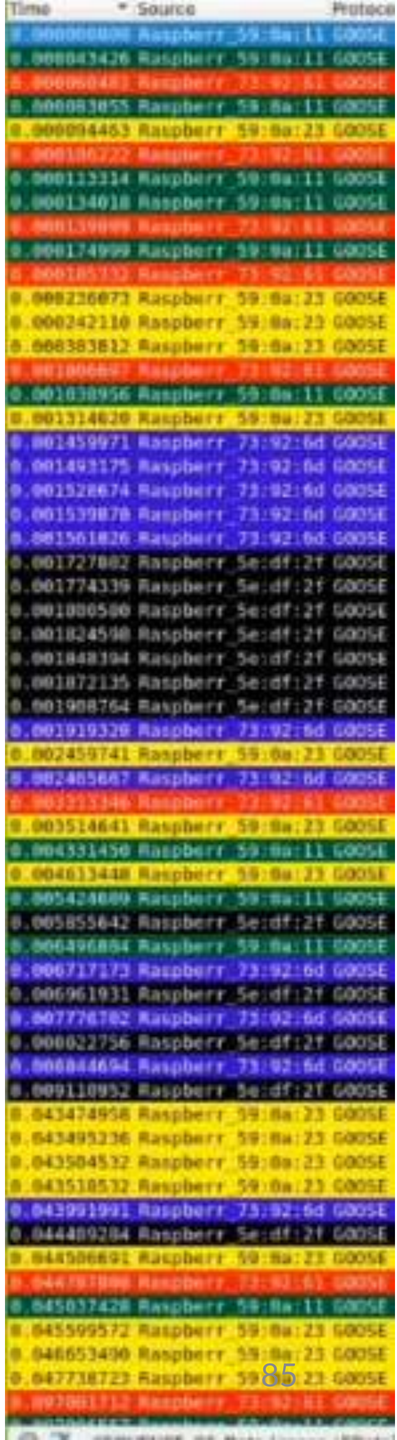


[1] AC breaker module
[2] Modular multi-level converter
[3] Converter breaker module
[4] Line breaker module



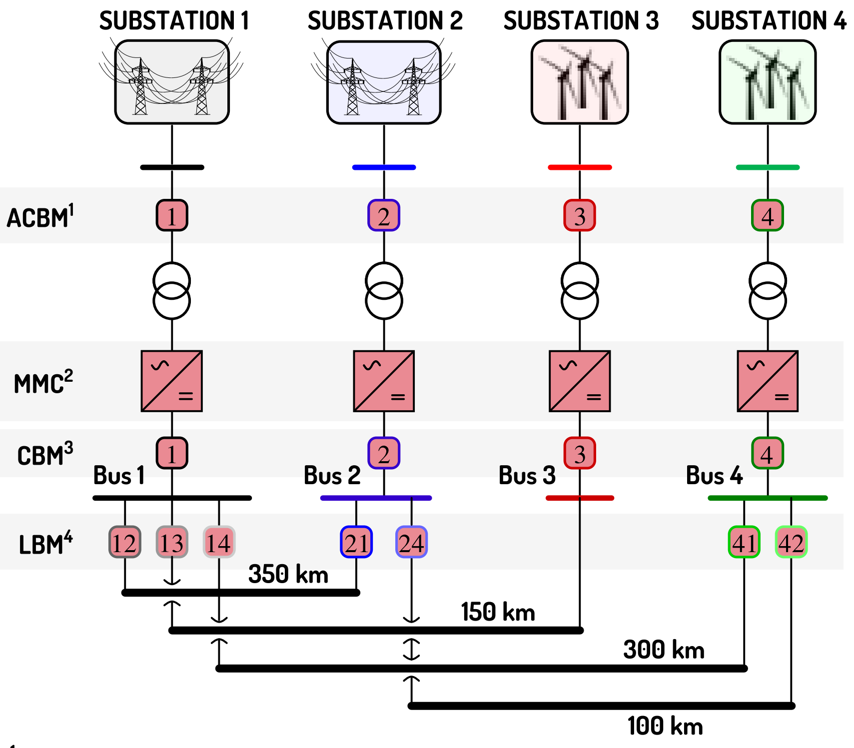
Legend

Station 1
Station 3
Station 2
Station 4
Central Supervisor



RESULTS OF THE HIL DEMONSTRATION

FOUR-TERMINAL HVDC NETWORK
Half-bridge MMC converters
Startup



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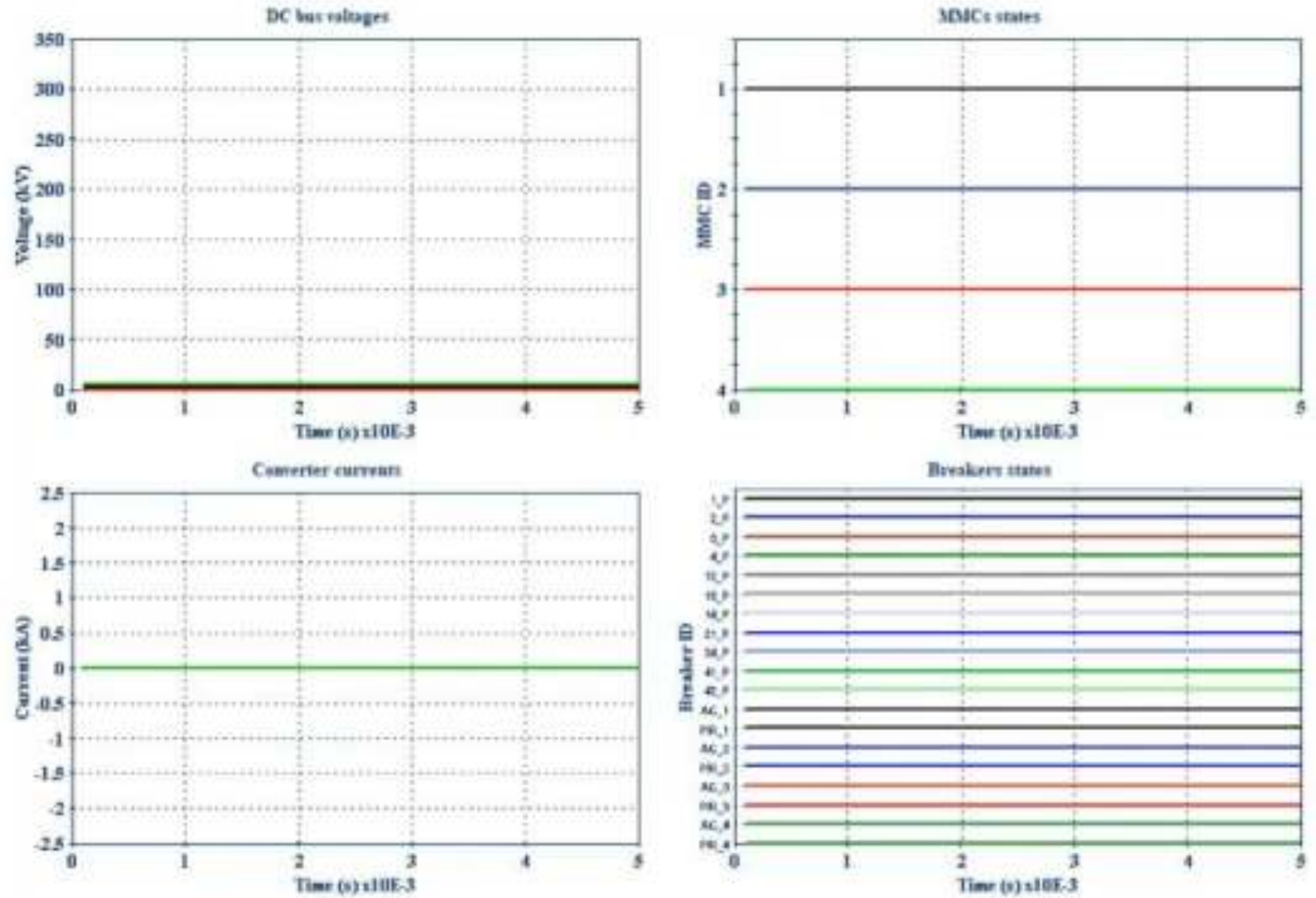
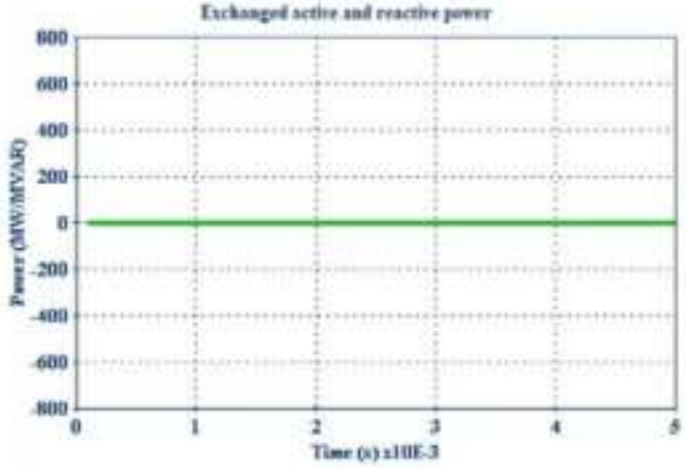




POWER TRANSMISSION

Legend

Bay 1	Bay 2	Bay 3*	Bay 4
12	21		41
13	24		42
14			

*Converter/line breaker

VIRTUAL DEMO
CONVERTER BREAKER PROTECTION STRATEGY

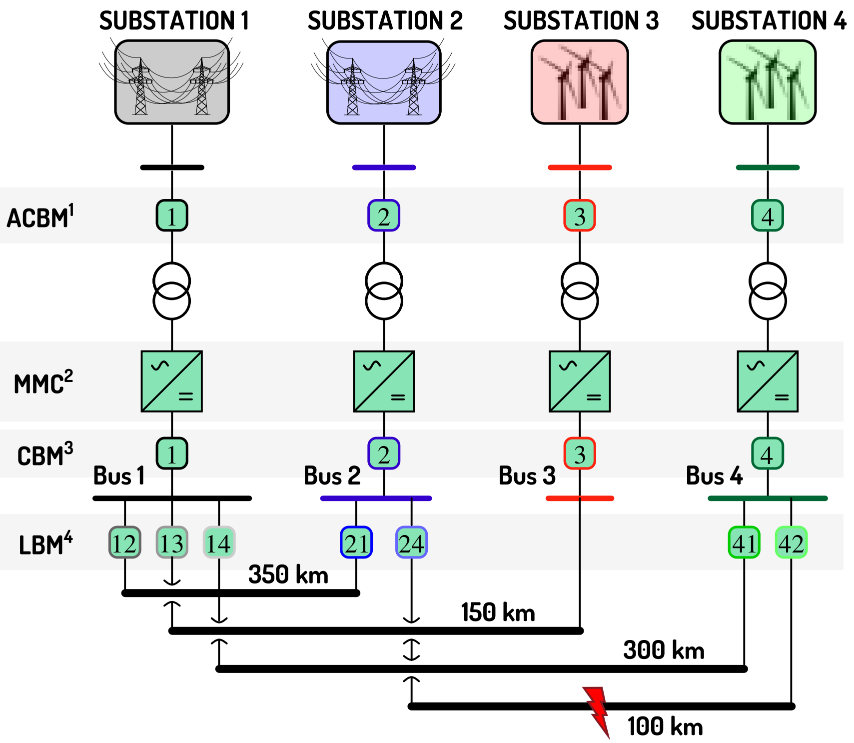
Pole-to-ground fault in cable 24

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

RESULTS OF THE HIL DEMONSTRATION

CONVERTER BREAKER PROTECTION STRATEGY

Pole-to-ground fault: cable 24 (@50km)



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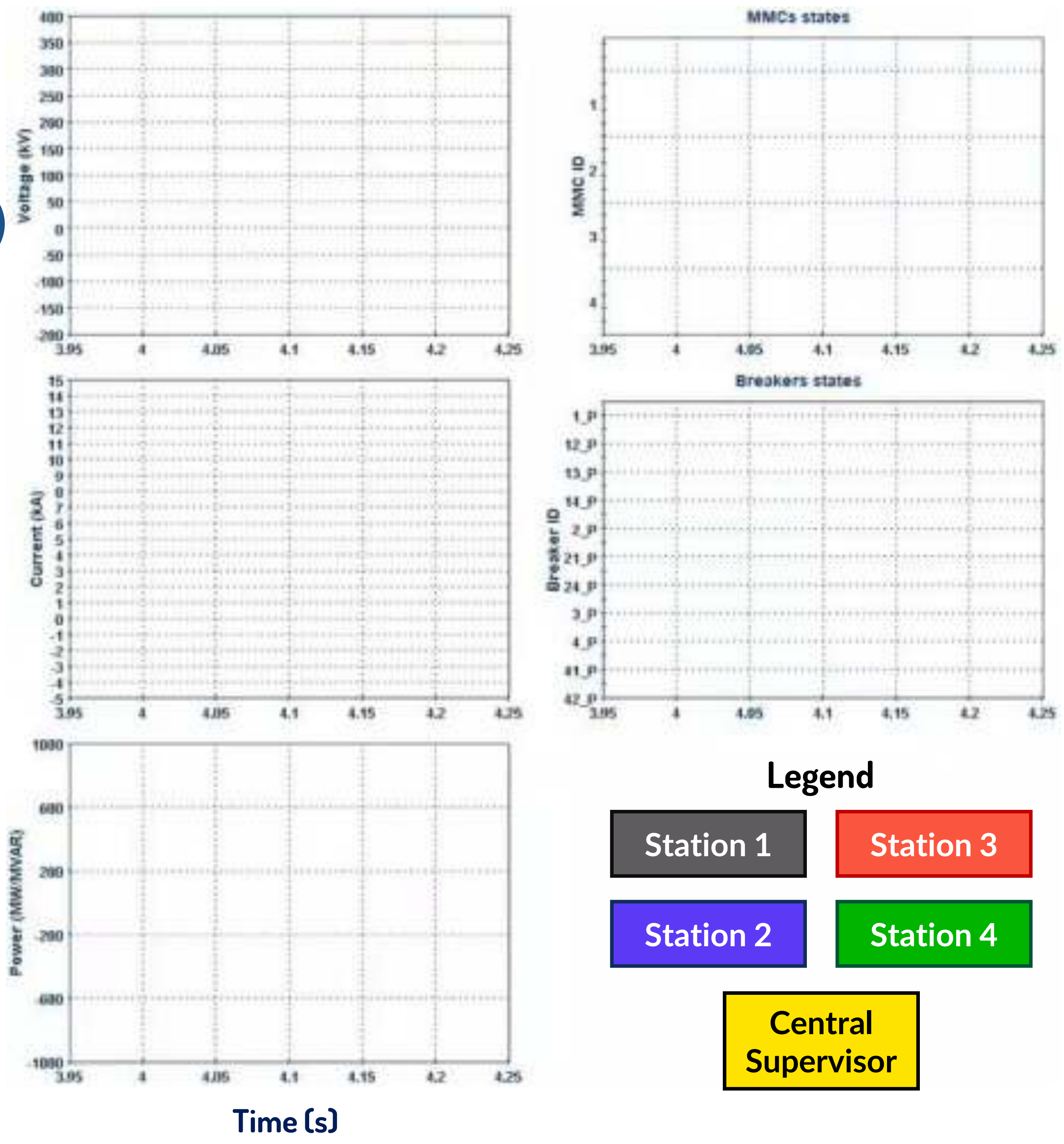

Time	Source	Protocol
0.0000000…	Raspberr_73:92:64	GOOSE
0.000017165	Raspberr_59:0a:20	GOOSE
0.000547302	Raspberr_73:92:64	GOOSE
0.000553228	Raspberr_59:0a:20	GOOSE
0.001272026	Raspberr_59:0a:11	GOOSE
0.001582612	Raspberr_5e:de:4c	GOOSE
0.002123087	Raspberr_5e:de:4c	GOOSE
0.002691939	Raspberr_73:92:6d	GOOSE
0.002736808	Raspberr_73:92:07	GOOSE
0.003266777	Raspberr_73:92:07	GOOSE
0.003573530	Raspberr_5e:df:2f	GOOSE
0.004461157	Raspberr_73:92:61	GOOSE
0.006585665	Raspberr_59:0a:23	GOOSE
0.006614627	Raspberr_59:0a:23	GOOSE
0.006636497	Raspberr_59:0a:23	GOOSE
0.006655478	Raspberr_59:0a:23	GOOSE
0.007718547	Raspberr_73:92:61	GOOSE
0.007783305	Raspberr_59:0a:11	GOOSE
0.007870062	Raspberr_5e:df:2f	GOOSE
0.008020818	Raspberr_73:92:6d	GOOSE
0.008646285	Raspberr_58:e8:19	GOOSE
0.008893094	Raspberr_73:92:76	GOOSE
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[illegible]	[illegible]	GOOSE
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0.009607597	Raspberr_59:0a:20	GOOSE
0.009741223	Raspberr_58:e8:19	GOOSE
0.010079049	Raspberr_59:0a:11	GOOSE
0.010088826	Raspberr_5e:df:2f	GOOSE
0.010093197	Raspberr_73:92:52	GOOSE
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0.011139432	Raspberr_5e:de:4c	GOOSE
0.011212356	Raspberr_73:92:6d	GOOSE
0.011258170	Raspberr_73:92:6d	GOOSE
0.011265948	Raspberr_59:0a:11	GOOSE
0.011479962	Raspberr_73:92:19	GOOSE
0.011991154	Raspberr_73:92:07	GOOSE
0.013092406	Raspberr_73:92:07	GOOSE
0.013118295	Raspberr_73:92:07	GOOSE
0.013523508	Raspberr_5e:df:2f	GOOSE
0.014398451	Raspberr_73:92:6d	GOOSE
0.014585206	Raspberr_5e:df:2f	GOOSE
[illegible]	[illegible]	GOOSE
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[illegible]	[illegible]	GOOSE
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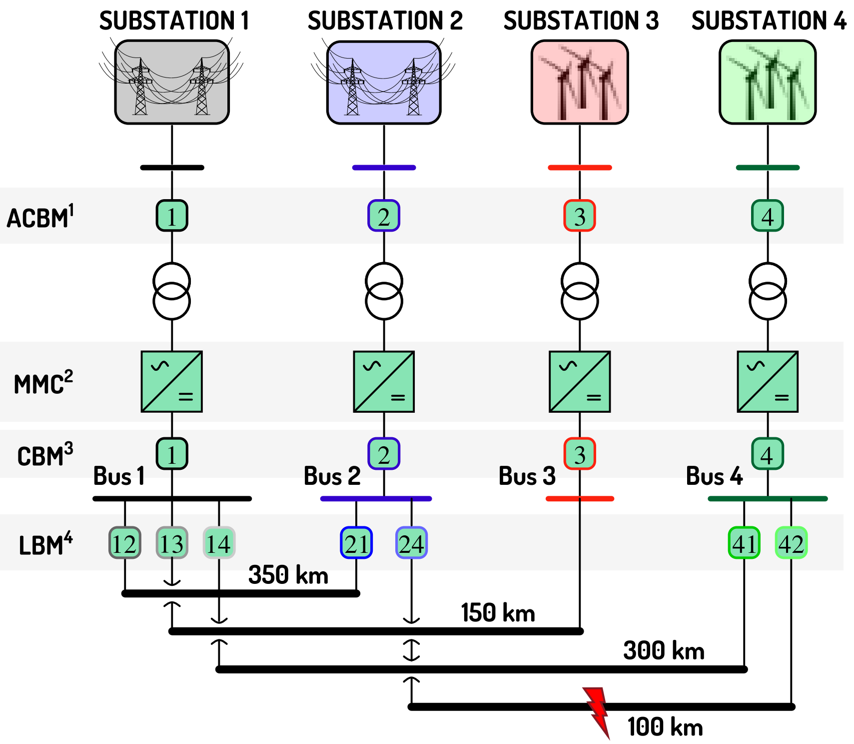
0.032981233	Raspberr_5e:de:4c	GOOSE
0.034229686	Raspberr_73:92:07	GOOSE
0.050417782	Raspberr_59:0a:23	GOOSE
[illegible]	Raspberr_59:0a:23	GOOSE

RESULTS OF THE HIL DEMONSTRATION

CONVERTER BREAKER PROTECTION STRATEGY

Pole-to-ground fault: cable 24 (@50km)



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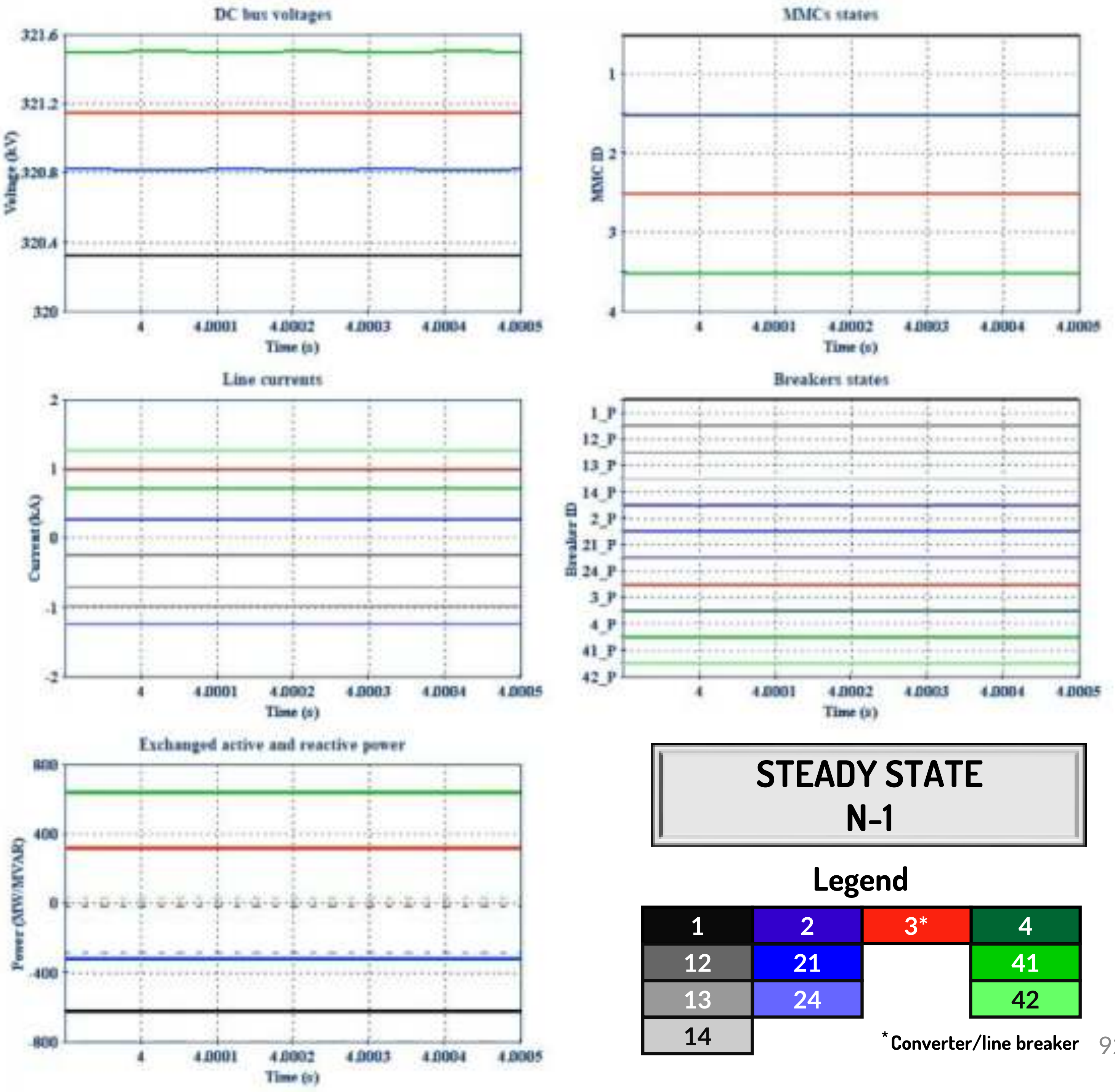
[3] Converter breaker module
[4] Line breaker module



STEADY STATE
N-1

Legend

1	2	3*	4
12	21		41
13	24		42
14			

* Converter/line breaker

VIRTUAL DEMO
CONVERTER BREAKER PROTECTION STRATEGY

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

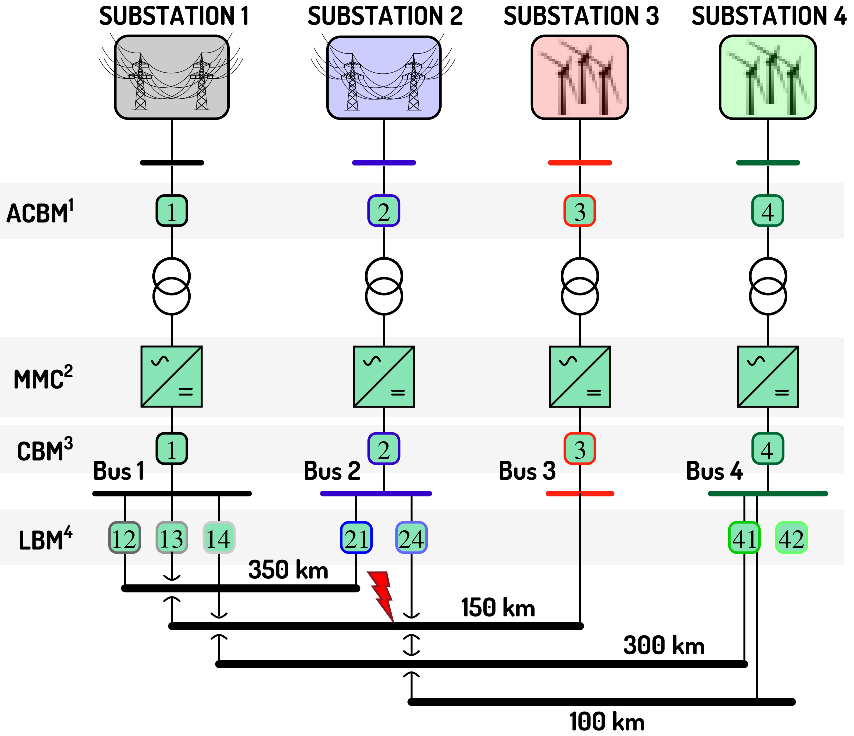
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

RESULTS OF THE HIL DEMONSTRATION

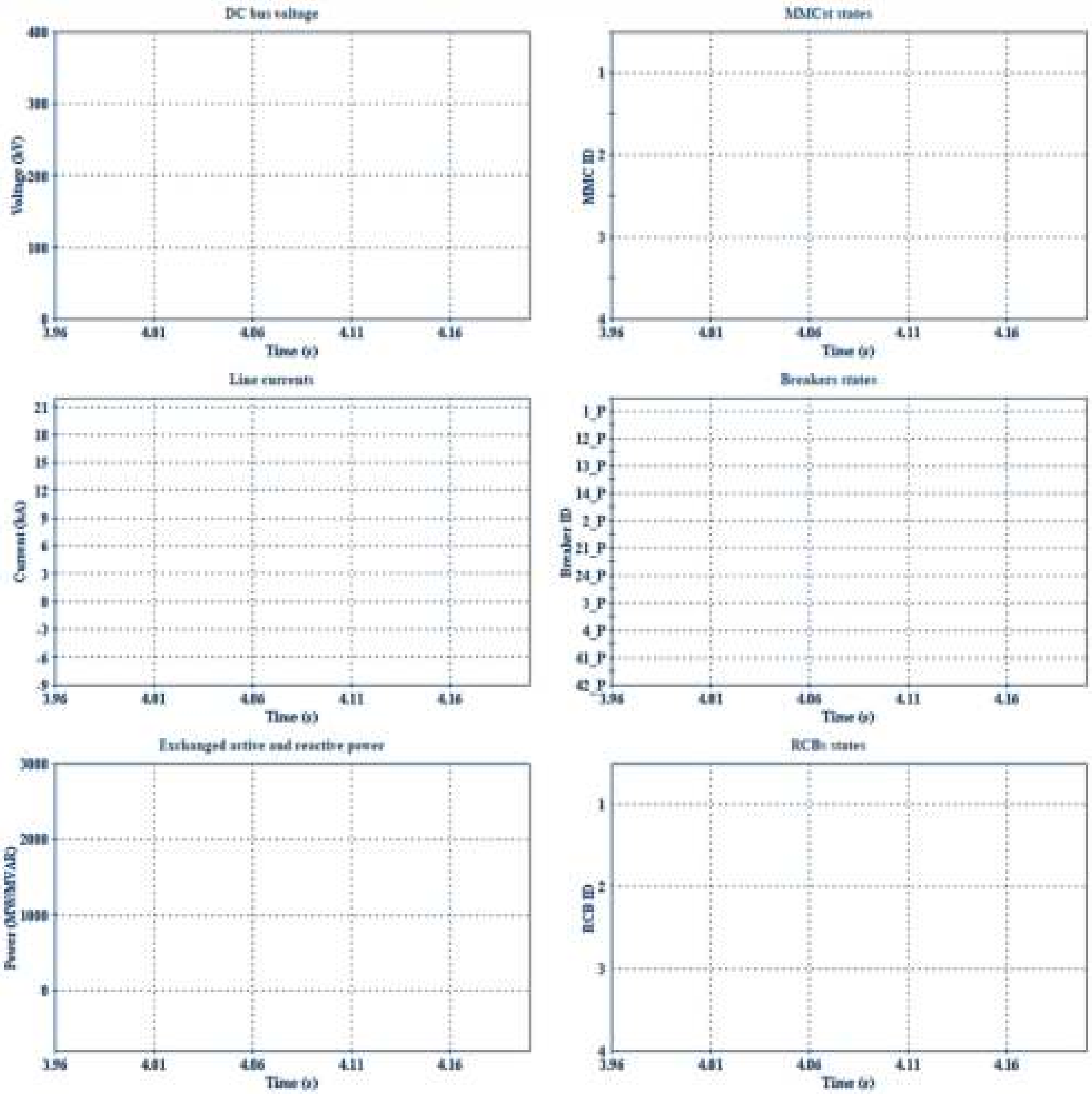
CONVERTER BREAKER PROTECTION STRATEGY

Pole-to-ground fault: cable 13 (@75km)

Backup sequence: CBM1 fails to open



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



Time	Source	Protocol
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0.000557095	Raspberr_73:92:07	GOOSE
0.000858351	Raspberr_5e:de:4c	GOOSE
0.001334211	Raspberr_73:92:61	GOOSE
0.002004516	Raspberr_59:0a:20	GOOSE
0.002745143	Raspberr_73:92:64	GOOSE
0.003070617	Raspberr_5e:df:2f	GOOSE
0.003130056	Raspberr_59:0a:20	GOOSE
0.003766098	Raspberr_73:92:64	GOOSE
0.004791319	Raspberr_59:0a:11	GOOSE
0.006637519	Raspberr_73:92:6d	GOOSE
0.008791064	Raspberr_73:92:19	GOOSE
0.009061021	Raspberr_73:92:07	GOOSE
0.009313664	Raspberr_73:92:58	GOOSE
0.009540862	Raspberr_58:e7:43	GOOSE
0.009840053	Raspberr_73:92:58	GOOSE
0.010290027	Raspberr_73:92:07	GOOSE
0.010315475	Raspberr_73:92:07	GOOSE
0.010414564	Raspberr_73:92:58	GOOSE
0.011267139	Raspberr_73:92:76	GOOSE
[illegible]	[illegible]	[illegible]
0.011573873	Raspberr_5e:df:2f	GOOSE
0.011968660	Raspberr_73:92:61	GOOSE
0.012210933	Raspberr_59:0a:20	GOOSE
0.013458498	Raspberr_73:92:64	GOOSE
0.016333712	Raspberr_58:e7:43	GOOSE
0.016338360	Raspberr_73:92:19	GOOSE
0.019373885	Raspberr_59:0a:23	GOOSE
0.019403736	Raspberr_59:0a:23	GOOSE
0.019430310	Raspberr_59:0a:23	GOOSE
0.019453383	Raspberr_59:0a:23	GOOSE
0.019571751	Raspberr_73:92:58	GOOSE
0.019811460	Raspberr_58:e7:43	GOOSE
0.020102013	Raspberr_5e:df:2f	GOOSE
0.020211440	Raspberr_73:92:19	GOOSE
0.020387677	Raspberr_59:0a:11	GOOSE
0.020511749	Raspberr_73:92:61	GOOSE
0.022238951	Raspberr_5e:df:2f	GOOSE
0.023192800	Raspberr_58:e7:43	GOOSE
0.023503960	Raspberr_73:92:19	GOOSE
0.023719288	Raspberr_59:0a:11	GOOSE
0.023894488	Raspberr_73:92:61	GOOSE
0.025123591	Raspberr_73:92:6d	GOOSE
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0.031995142	Raspberr_5e:de:4c	GOOSE
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0.034209610	Raspberr_59:0a:20	GOOSE
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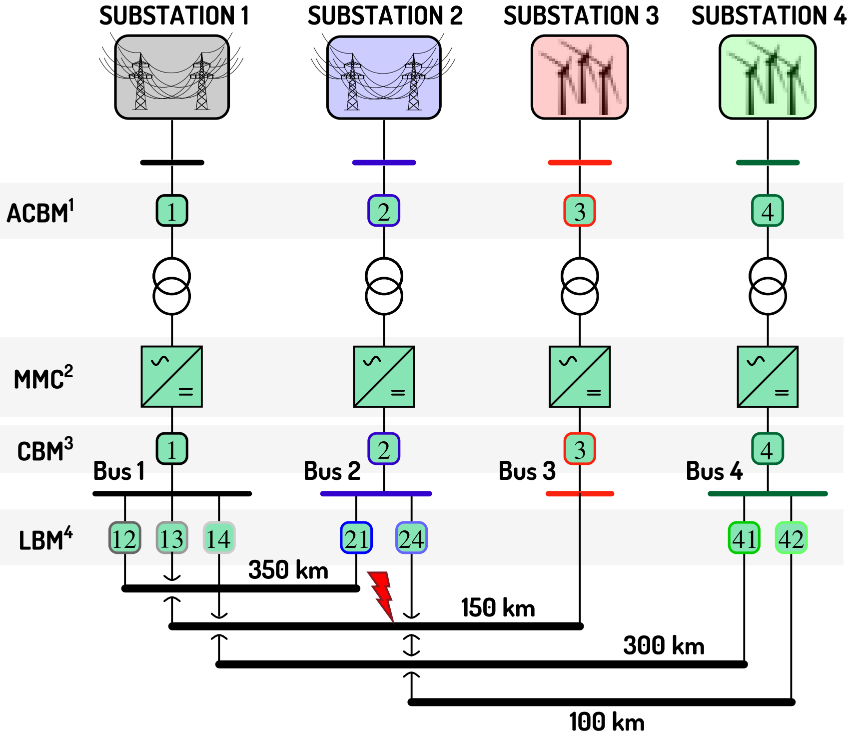
0.037270303	Raspberr_5e:df:2f	GOOSE
0.038271404	Raspberr_73:92:6d	GOOSE
0.038335575	Raspberr_5e:df:2f	GOOSE
0.039451662	Raspberr_5e:df:2f	GOOSE
0.041592614	Raspberr_5e:df:2f	GOOSE
0.041860590	Raspberr_73:92:6d	GOOSE
0.043157876	Raspberr_73:92:6d	GOOSE
0.043960321	Raspberr_73:92:6d	GOOSE
0.072800014	Raspberr_59:0a:23	GOOSE
0.072822088	Raspberr_59:0a:23	GOOSE
0.072839421	Raspberr_59:0a:23	GOOSE
0.072863272	Raspberr_59:0a:23	GOOSE
0.073178099	Raspberr_73:92:6d	GOOSE
0.073961711	Raspberr_5e:df:2f	GOOSE

RESULTS OF THE HIL DEMONSTRATION

CONVERTER BREAKER PROTECTION STRATEGY

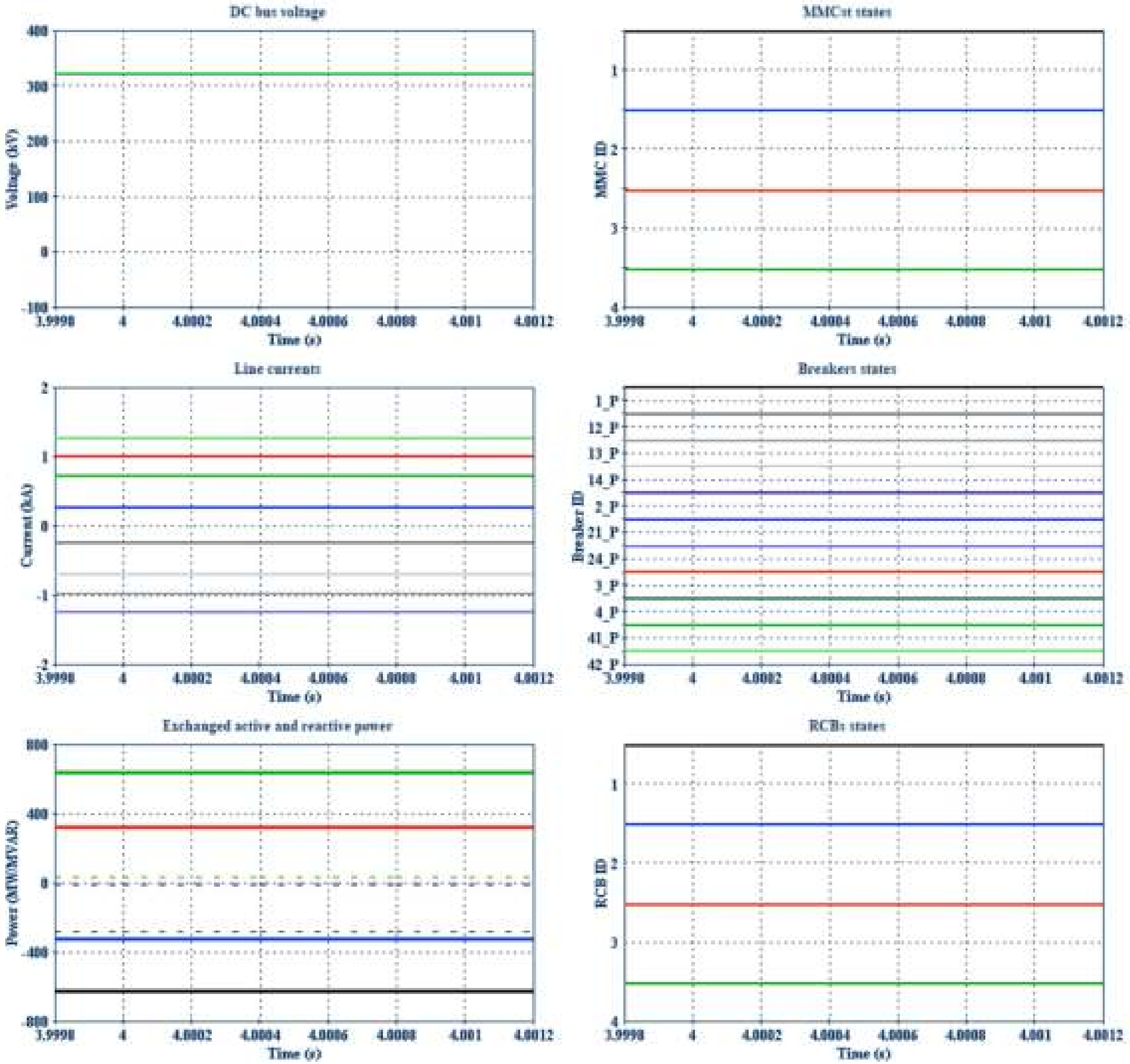
Pole-to-ground fault: cable 13 (@75km)

Backup sequence: CBM1 fails to open



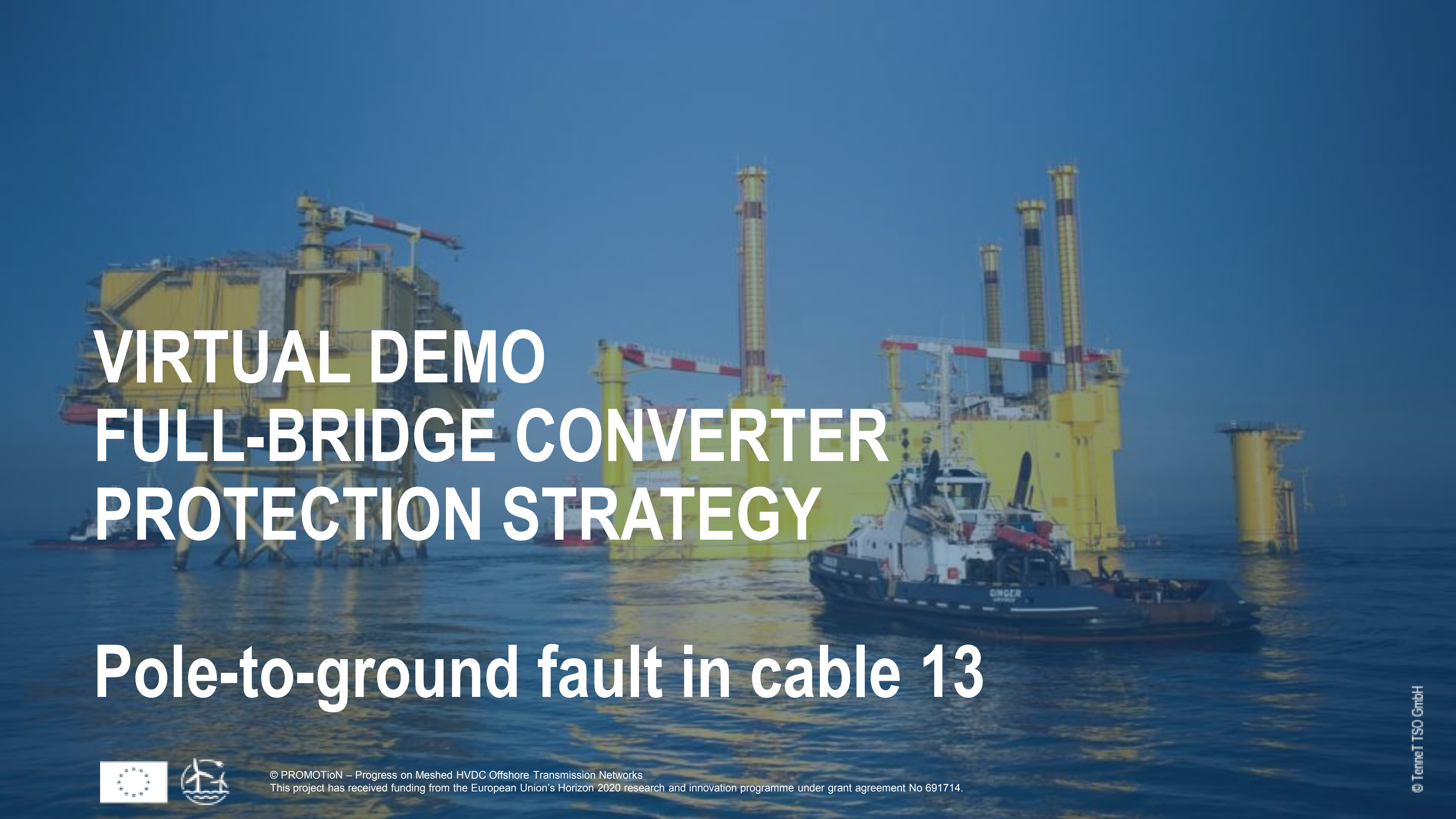
[1] AC breaker module
[2] Modular multi-level converter
[3] Converter breaker module
[4] Line breaker module

STEADY STATE
N-1



VIRTUAL DEMO
FULL-BRIDGE CONVERTER PROTECTION STRATEGY

Pole-to-ground fault in cable 13



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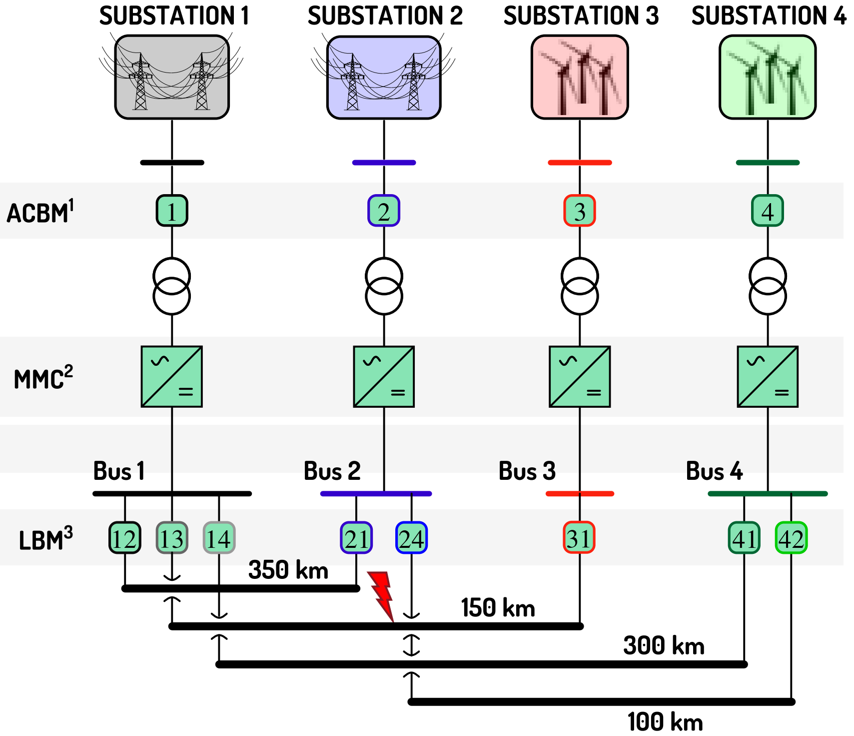
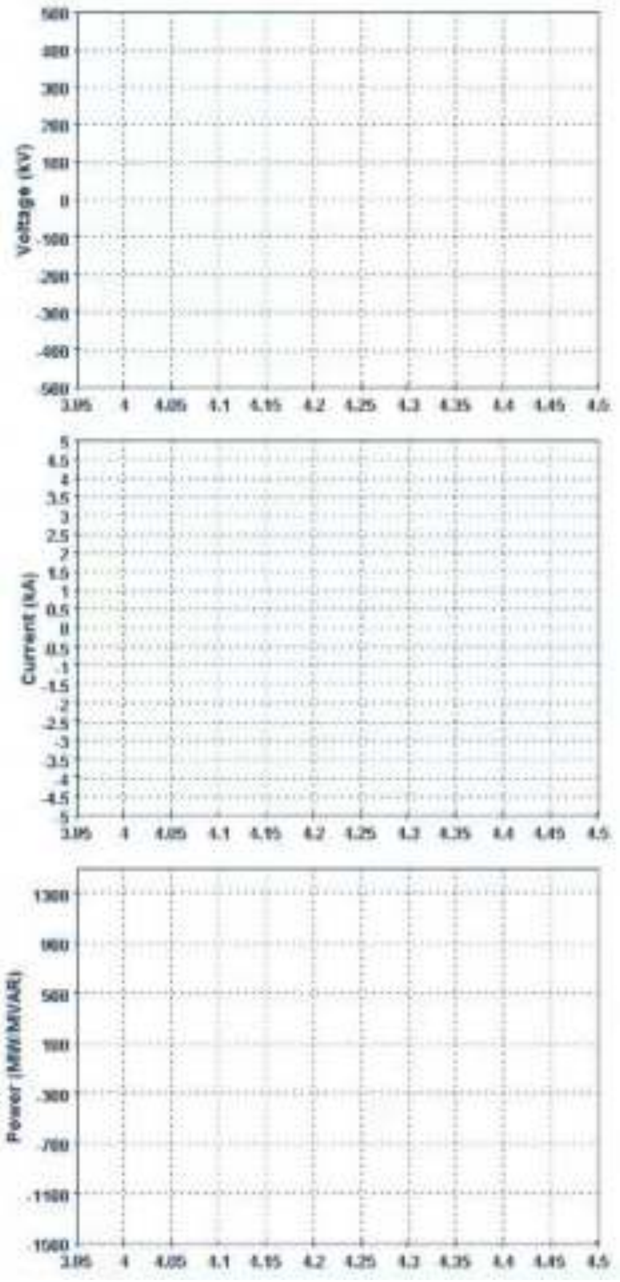
RESULTS OF THE HIL DEMONSTRATION

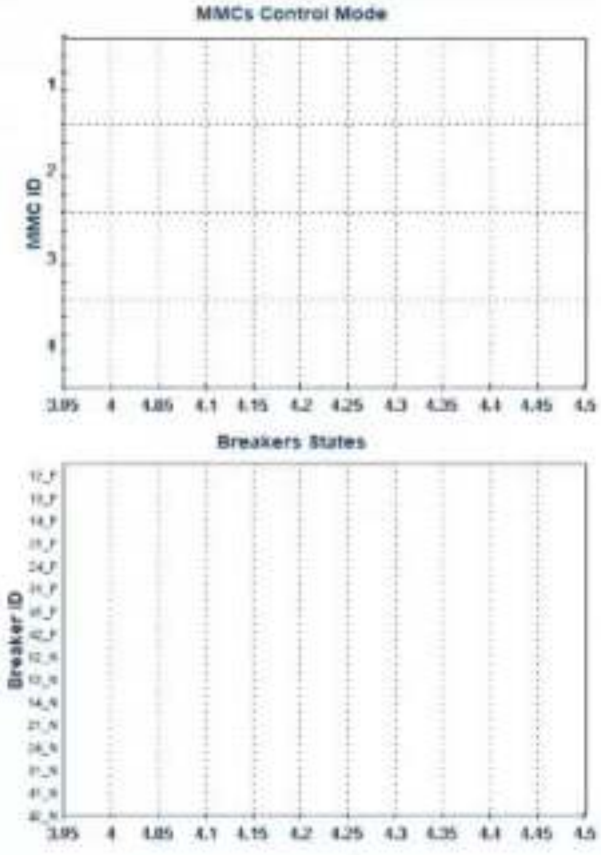
FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY

Pole-to-ground fault: cable 13 (@50km)



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





Time	Source	Protocol
0.000000000	Raspberr_73:92:58	GOOSE
0.000094238	Raspberr_73:92:07	GOOSE
0.000220532	Raspberr_58:e7:43	GOOSE
0.000231046	Raspberr_73:92:19	GOOSE
0.001089045	Raspberr_73:91:fb	GOOSE
0.001335673	Raspberr_73:92:52	GOOSE
0.001632333	Raspberr_73:92:76	GOOSE
0.001770626	Raspberr_58:e8:19	GOOSE
0.010589463	Raspberr_73:92:76	GOOSE
0.010678906	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_73:92:07	GOOSE
0.050905716	Raspberr_73:92:58	GOOSE
0.051322108	Raspberr_73:92:07	GOOSE
0.051919100	Raspberr_73:92:07	GOOSE
0.052534735	Raspberr_73:92:07	GOOSE
0.063897903	Raspberr_73:92:58	GOOSE
0.065013507	Raspberr_73:92:58	GOOSE
0.066150611	Raspberr_73:92:58	GOOSE
0.166230583	Raspberr_73:92:58	GOOSE

Legend

Station 1

Station 3

Station 2

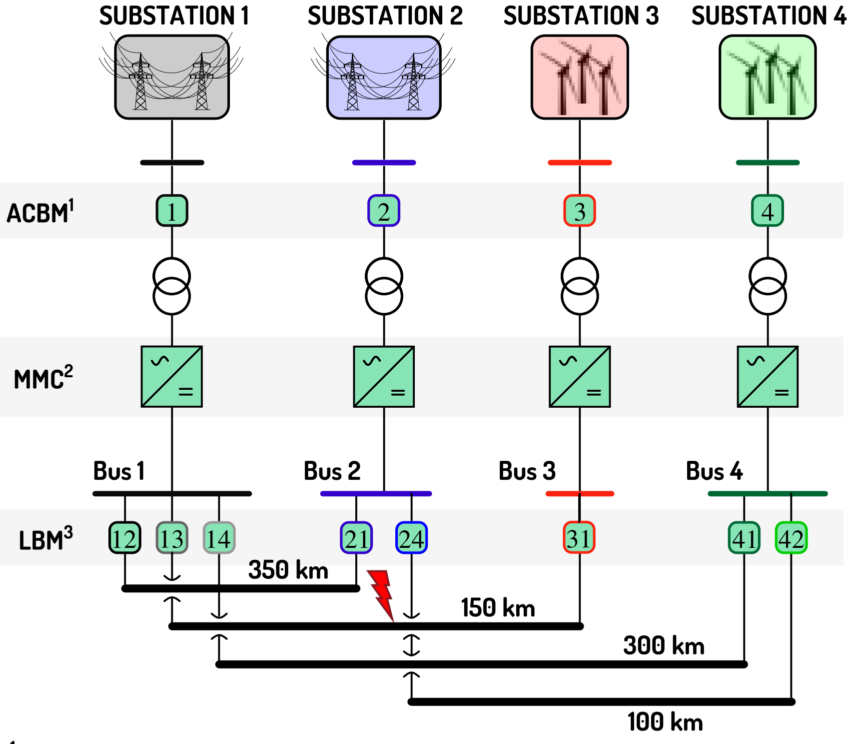
Station 4

Central Supervisor

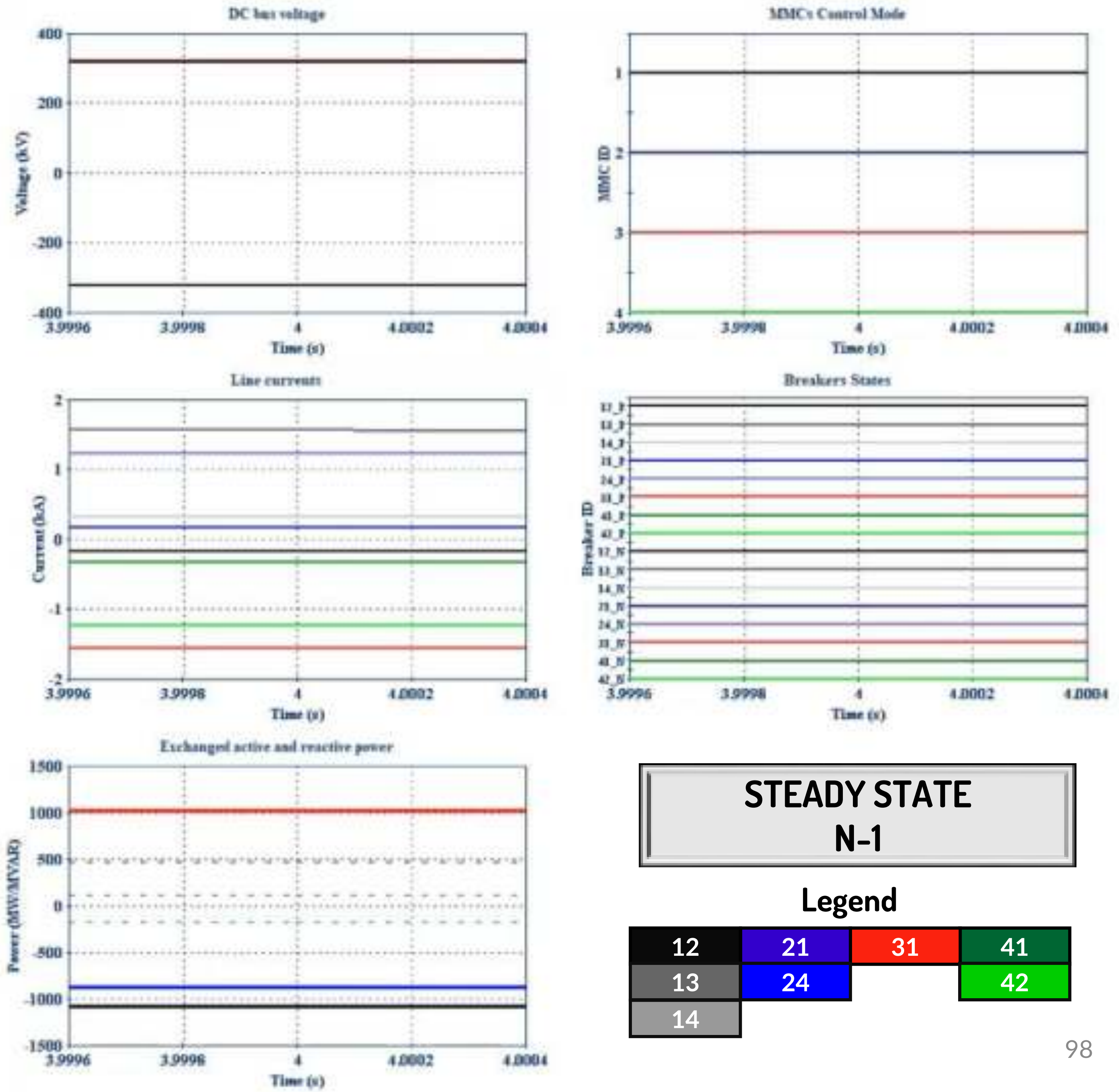
RESULTS OF THE HIL DEMONSTRATION

FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY

Pole-to-ground fault: cable 13 (@50km)



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



STEADY STATE
N-1

Legend

12	21	31	41
13	24		42
14			

VIRTUAL DEMO
FULL-BRIDGE CONVERTER PROTECTION STRATEGY

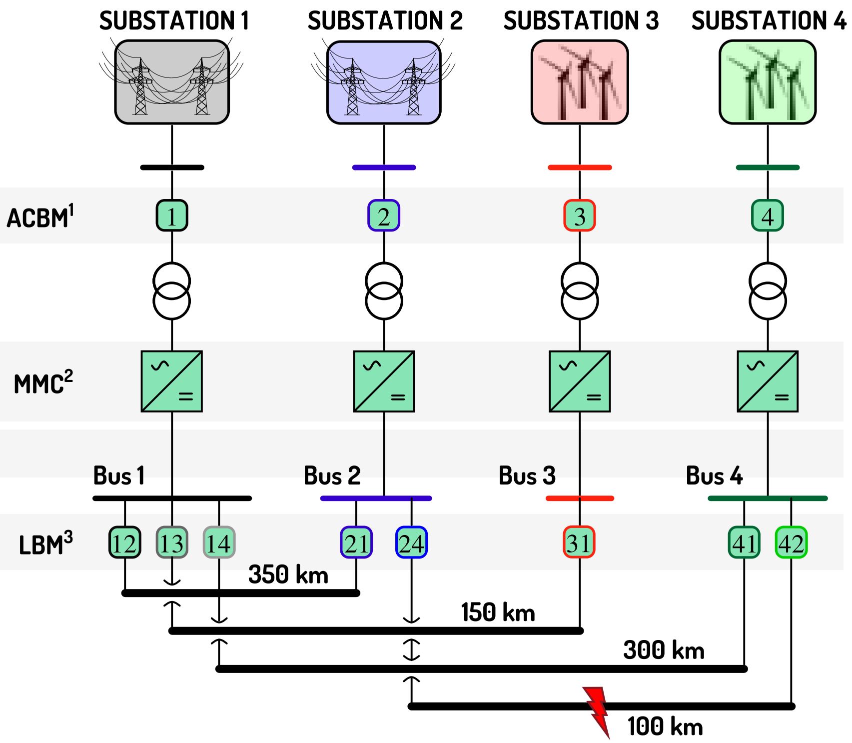
Pole-to-pole fault in cable 24

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691714.

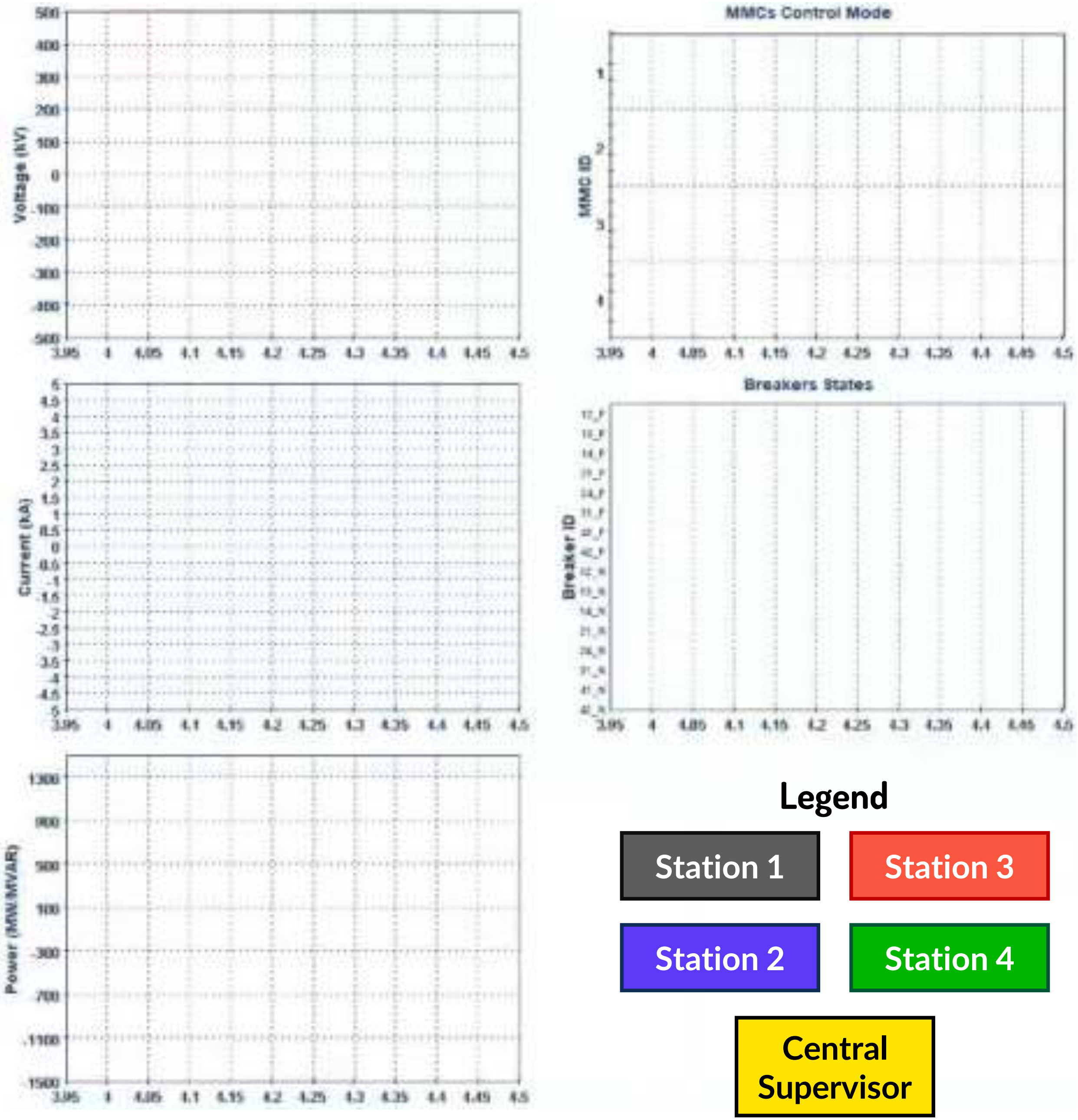
RESULTS OF THE HIL DEMONSTRATION

FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY

Pole-to-pole fault: cable 24 (@50km)



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



Legend

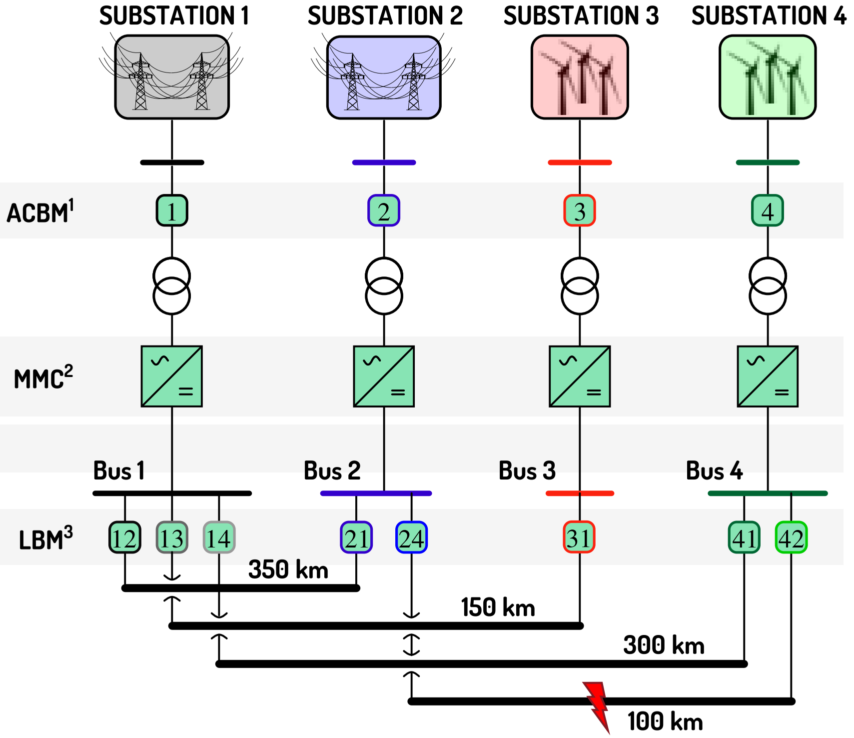
Station 1
Station 3
Station 2
Station 4
Central Supervisor

Time	Source	Protocol
0.000000000	Raspberr_58:e8:19	GOOSE
0.000220680	Raspberr_73:92:76	GOOSE
0.000410638	Raspberr_73:91:fb	GOOSE
0.000433508	Raspberr_73:92:52	GOOSE
0.001271415	Raspberr_73:92:58	GOOSE
0.001286155	Raspberr_73:92:19	GOOSE
0.001375301	Raspberr_58:e7:43	GOOSE
0.002125358	Raspberr_73:92:07	GOOSE
0.010229246	Raspberr_73:92:19	GOOSE
0.011435107	Raspberr_73:92:76	GOOSE
0.011644602	Raspberr_58:e8:19	GOOSE
0.011745766	Raspberr_58:e7:43	GOOSE
0.011807117	Raspberr_73:92:07	GOOSE
0.011885226	Raspberr_73:91:fb	GOOSE
0.014506203	Raspberr_73:92:52	GOOSE
0.014571461	Raspberr_73:92:52	GOOSE
0.014985192	Raspberr_58:e8:19	GOOSE
0.015061190	Raspberr_73:92:52	GOOSE
0.015397608	Raspberr_73:92:58	GOOSE
0.016236904	Raspberr_58:e8:19	GOOSE
0.022705422	Raspberr_58:e8:19	GOOSE
0.023929671	Raspberr_58:e8:19	GOOSE
0.025194346	Raspberr_58:e8:19	GOOSE
0.039961654	Raspberr_73:92:52	GOOSE
0.041088202	Raspberr_73:92:52	GOOSE
0.042236935	Raspberr_73:92:52	GOOSE
0.125238563	Raspberr_58:e8:19	GOOSE
0.142271134	Raspberr_73:92:52	GOOSE

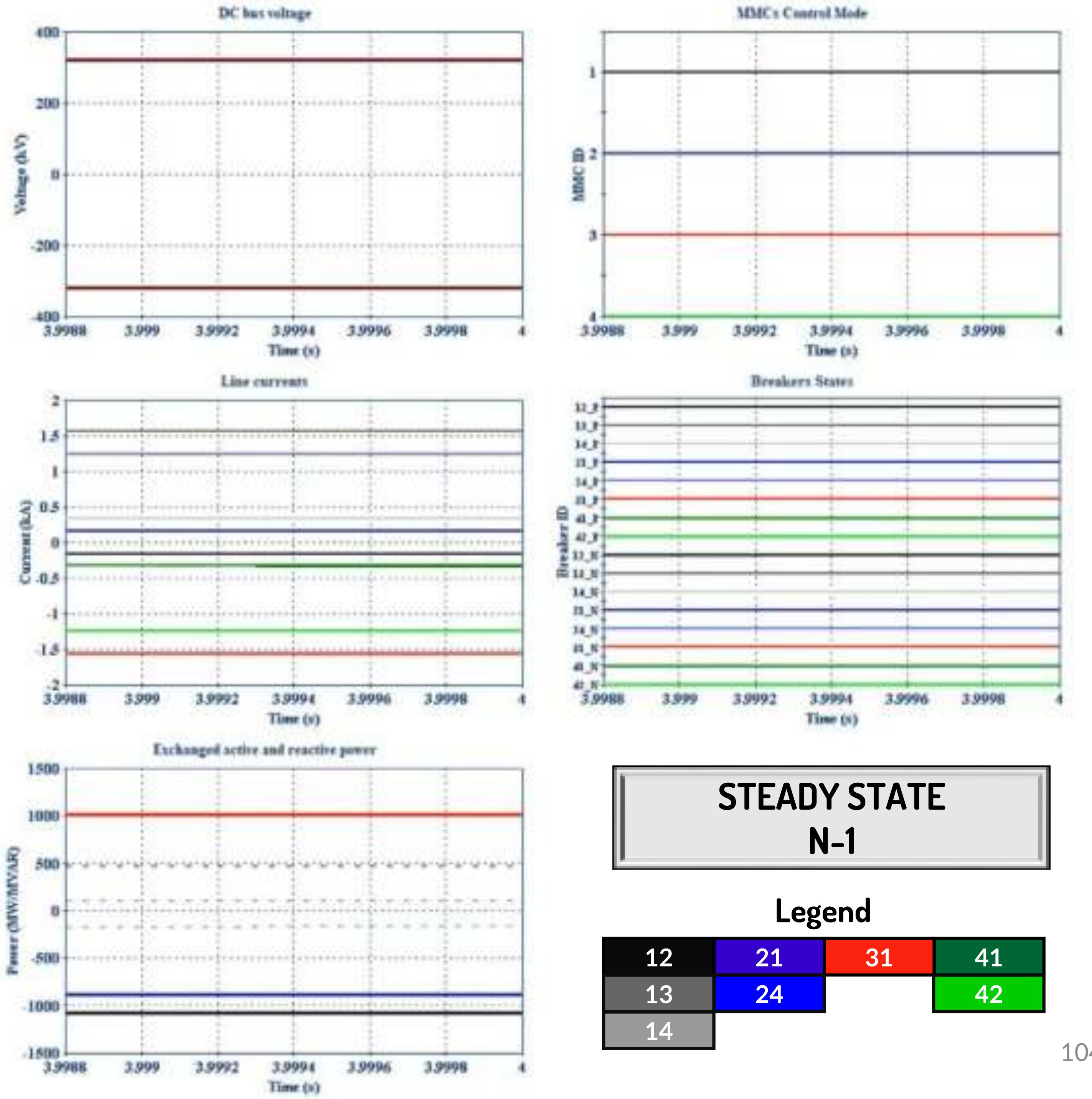
RESULTS OF THE HIL DEMONSTRATION

FULL-BRIDGE CONVERTER-BASED PROTECTION STRATEGY

Pole-to-pole fault: cable 24 (@50km)



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



STEADY STATE
N-1

Legend

12	21	31	41
13	24		42
14			

Laurent Chédot

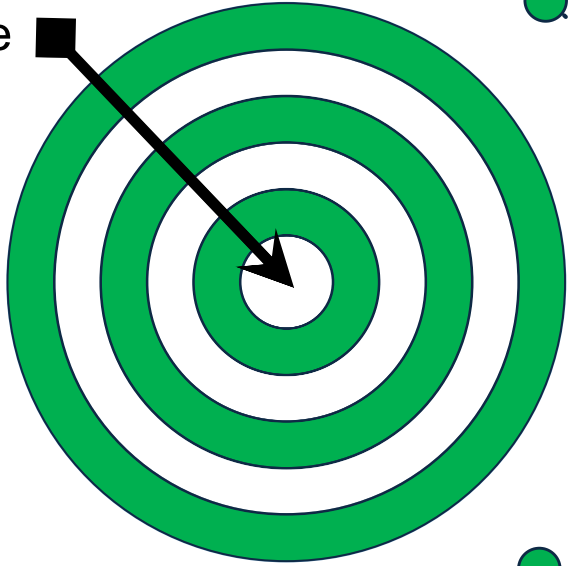
CONCLUSION

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691714.

RESULTS

HVDC protection
Demonstration

Non-selective schemes



HIL
Protection and Supervision IEDs tested

RTS model
HVDC breaker and MMC models integrated to Hypersim

Benchmark grid
Two 4-terminal HVDC networks implemented

Sequences validation
Primary and backup sequences validated through HIL

Interoperability
Implementation of the IEC61850 industrial communication standard

Supervision
System supervision designed, implemented and tested

NEXT STEPS

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

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PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

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: www.promotion-offshore.net

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

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