FUNCTIONAL TESTING OF HVDC PROTECTION SYSTEMS – TOWARDS MULTIVENDOR

GERAINT CHAFFEY

KU LEUVEN

Energy Ville

2023 EUROPEAN RTDS TECHNOLOGIES INC. USER'S GROUP MEETING 2023

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RTDS Technologies
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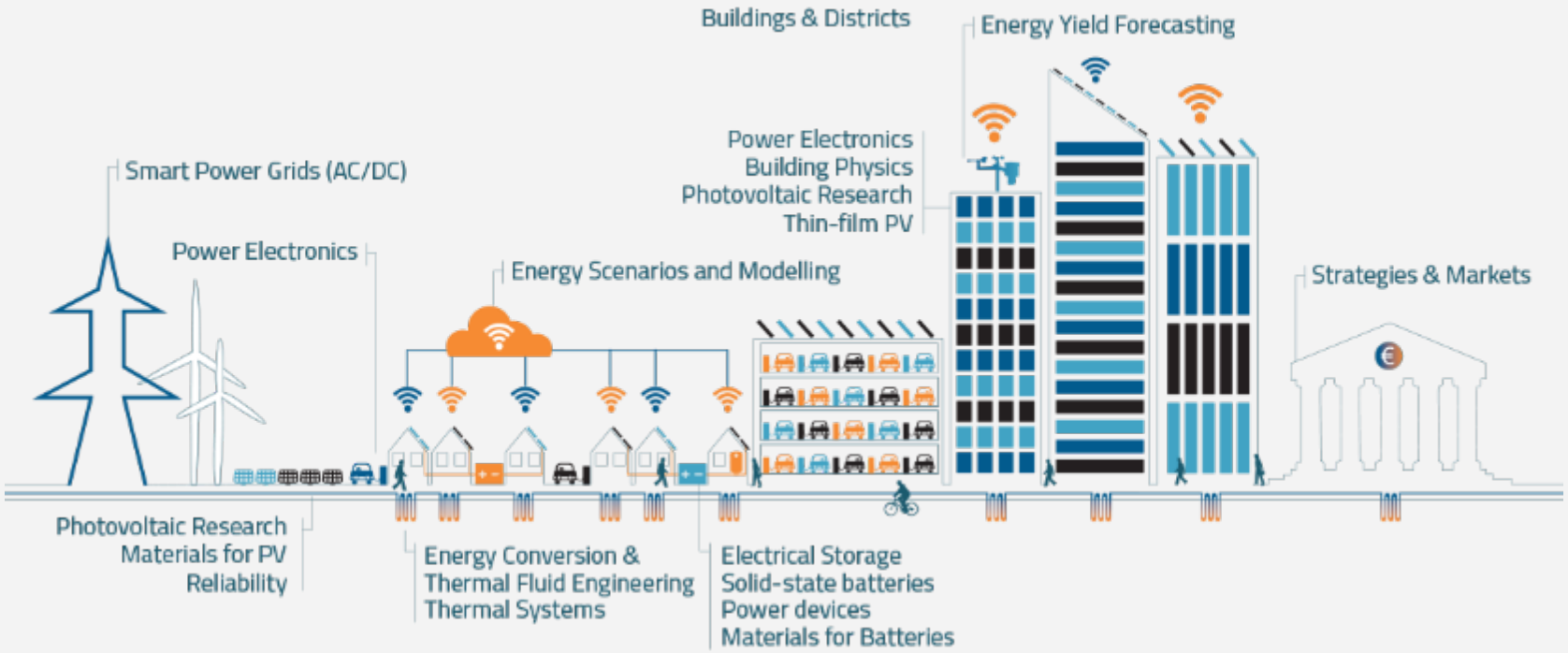
FUNCTIONAL TESTING OF HVDC PROTECTION SYSTEMS – TOWARDS MULTIVENDOR

Overview

- Introduction to HVDC protection and multivendor challenges
- Mitigation of interoperability challenges
- Testing of HVDC protection systems (IEDs)
  - Standalone testing
  - System-level testing
  - Towards standardisation and future type testing?
- Test methods for (HVDC) protection IEDs
- Future outlook

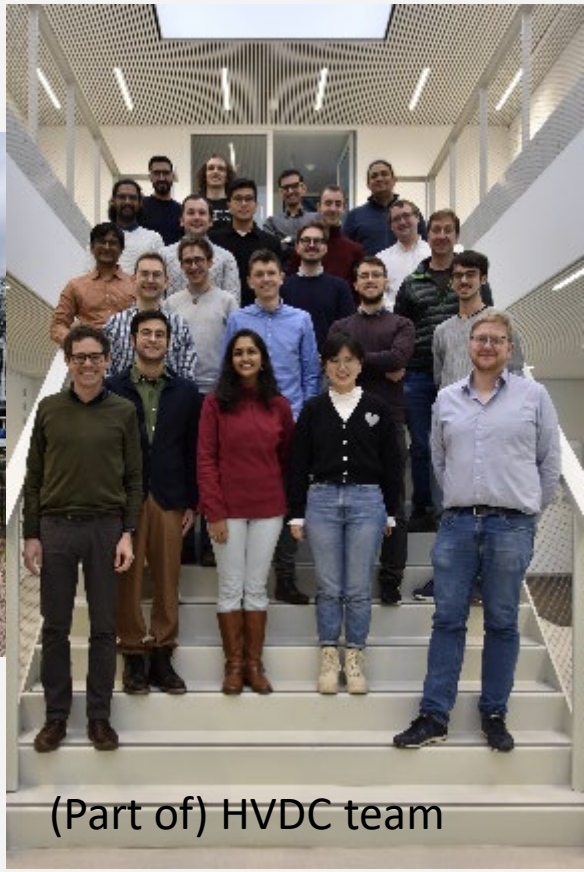
ENERGYVILLE

- A collaboration



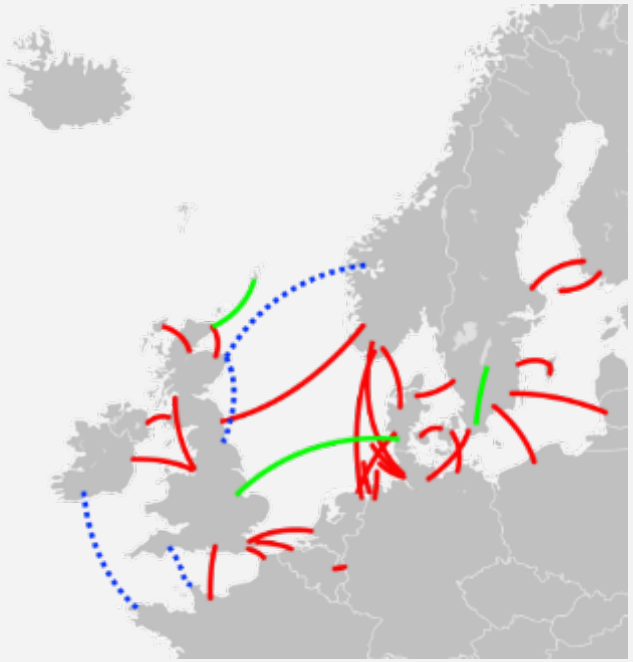
ELECTRICAL NETWORKS

HVDC, control, protection, planning …



(Part of) HVDC team

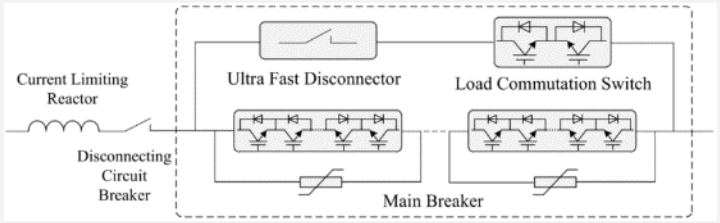
HVDC PROTECTION - INTRODUCTION



HVDC connections in EU - Wikipedia

EU supergrid concept - FOSG

HVDC PROTECTION - INTRODUCTION



HVDC CB concepts, CIGRE TB683

ABB DCCB Testing

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

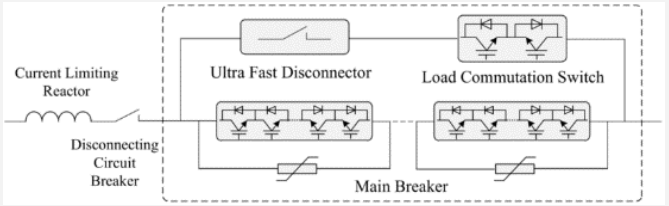
HVDC PROTECTION - INTRODUCTION

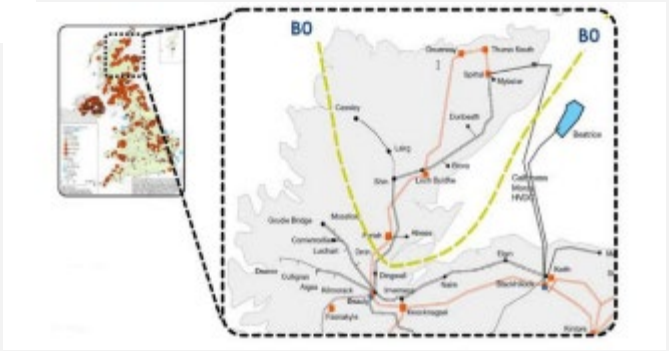
Nan'ao 3T, RXPE

Zhoushan 5T, NREC

Zhangbei - GEIRI, SGCC

Ultranet, Amprion

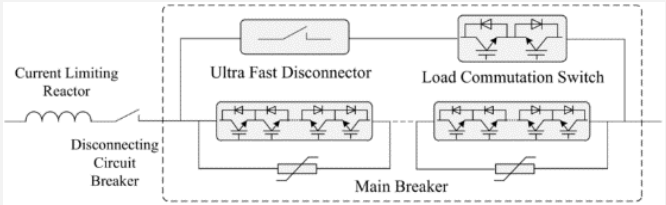




Caithness Moray Shetland, SSE

HVDC PROTECTION - INTRODUCTION

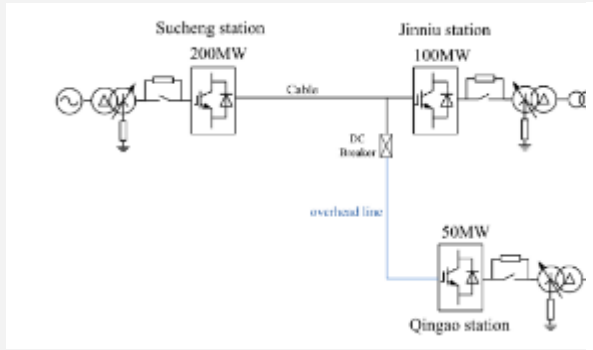
- Towards multiterminal, multivendor systems (VSC)
  - Requirement for DC-side protection
- Protection devices for future multiterminal HVDC systems
  - Novel, only recently demonstrated, expensive, …
- Advances made in recent HVDC systems
- Future outlook anticipates multivendor systems
  - Interoperability in protection systems also important!



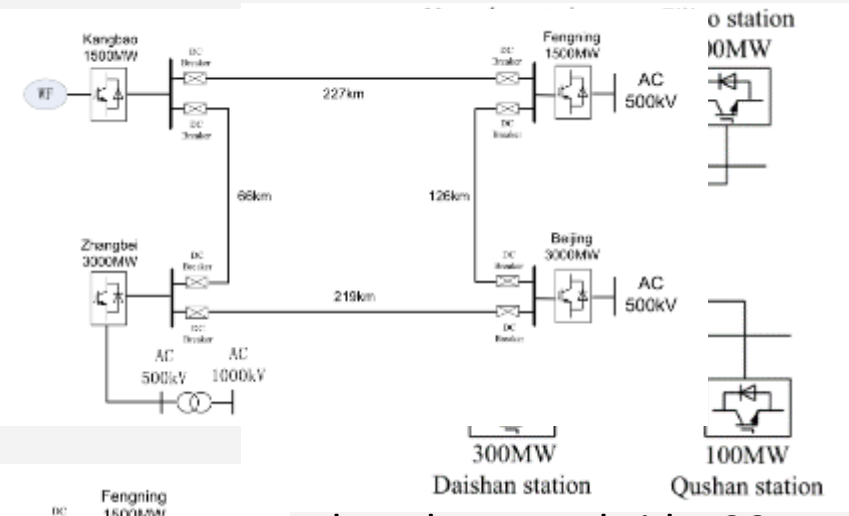
HVDC PROTECTION – DC CIRCUIT BREAKERS

Known devices:

- Operational
  - Nan'ao, Zhoushan, Zhangbei
- Demonstrated (lab)
  - Mitsubishi Electric, Hitachi Energy, SCiB
- (+ numerous conceptual / low power demo



Nan'ao – Mechanical DCCB



Zhoushan – Hybrid DCCB

Mitsubishi Electric DCCB testing

SCiBreak DCCB testing

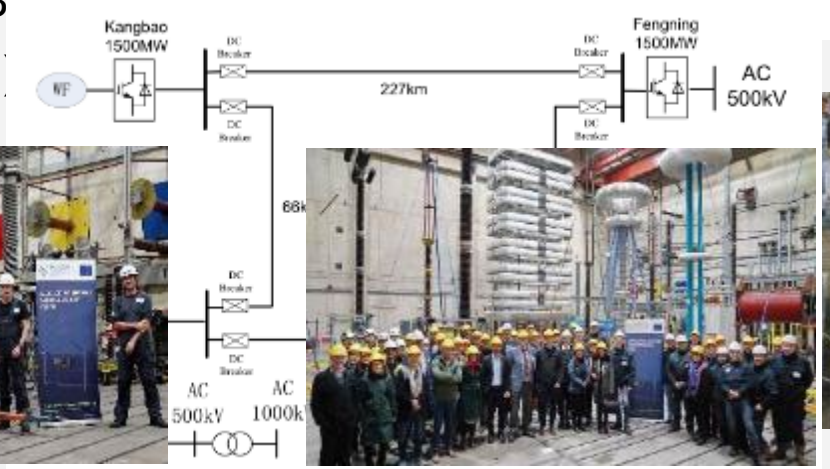


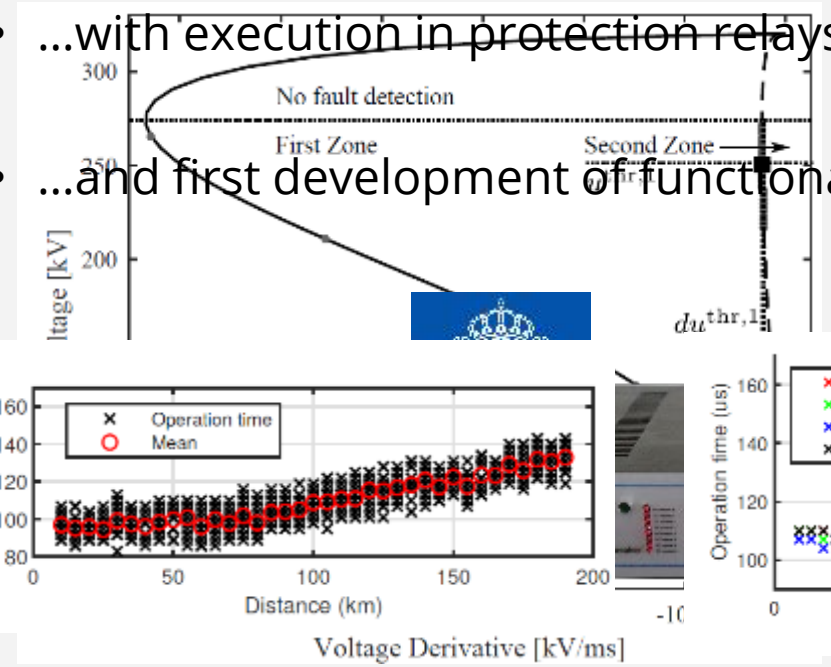
ABB – DCCB testing

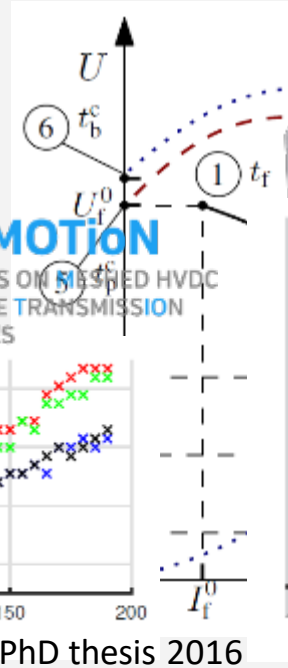
Zhangbei – Hybrid DCCB

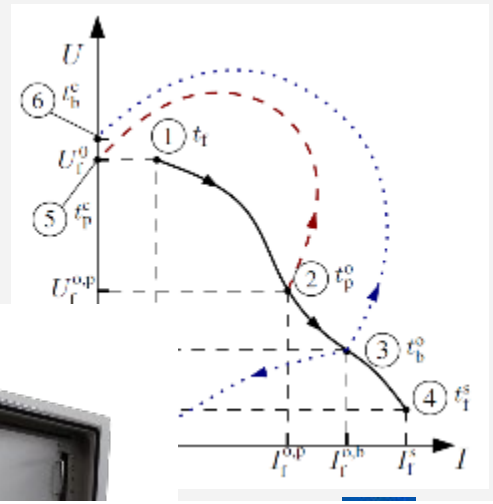
Figures: Jovcic et al., 2019

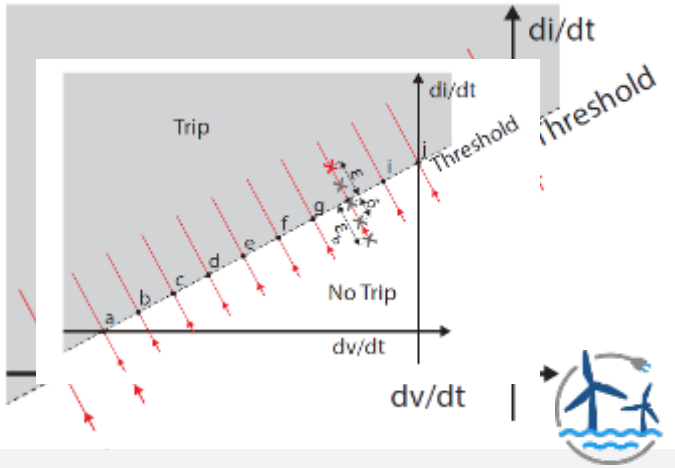
HVDC PROTECTION – IEDS (RELAYS)

- Functions (algorithms) detect/discriminate faults
- …with execution in protection relays (IEDs)
- …and first development of functional tests









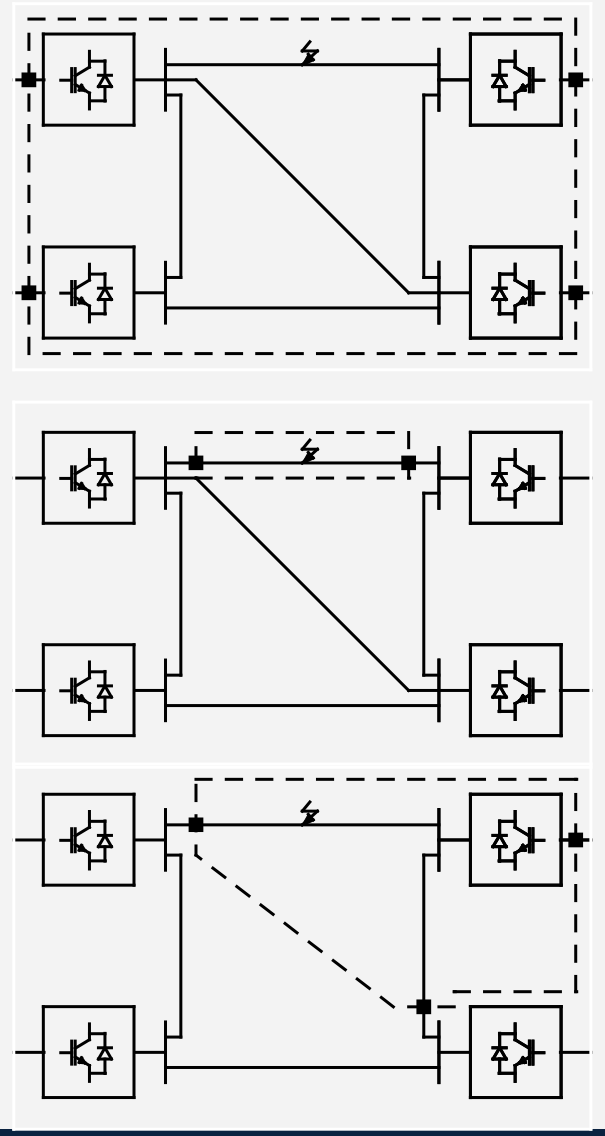
Willem Leterme, PhD thesis 2016

HVDC PROTECTION – STRATEGIES

Non-selective
- De-energize the entire grid
- Switch off the faulted line
- Energize the grid and resume power flow
- *Examples: Zhoushan, Caithness Moray Shetland, Ultranet,…*

Fully selective
- Protect every line and node individually
- *Example: Zhangbei*

Partially selective
- Allow larger sections of the grid to be disconnected in case of a fault
- *Example: Nan'ao*



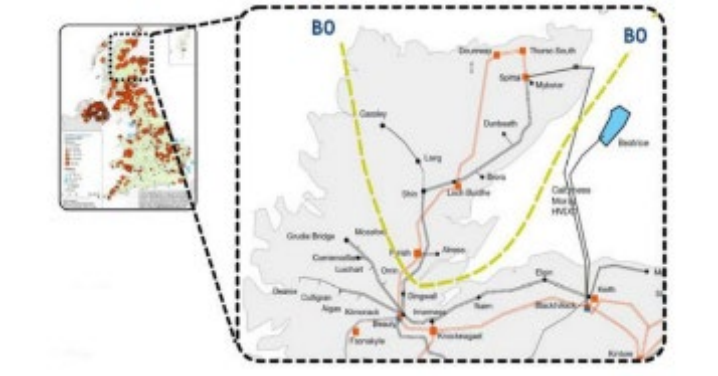
MULTIVENDOR INTEROPERABILITY

What is required?

- *Electrical interface* interoperability
- *Functional* interoperability
  - E.g. when one DCCB trips, the others remain stable
- *Communications* interoperability
  - E.g. protocols for control/configuration, intertrip, (differential)
- *Information* interoperability
  - E.g. signals required, also for system design – transfer of system properties / settings!
- System level *structures*
  - Splitting of functionality

-> Most aspects working in single vendor systems… but multivendor is key challenge

MULTIVENDOR IN TODAYS VSC HVDC GRIDS



Caithness Moray Shetland, SSE

Single vendor (system integrator)

MULTIVENDOR IN TODAYS VSC HVDC GRIDS

Zhangbei - GEIRI, SGCC

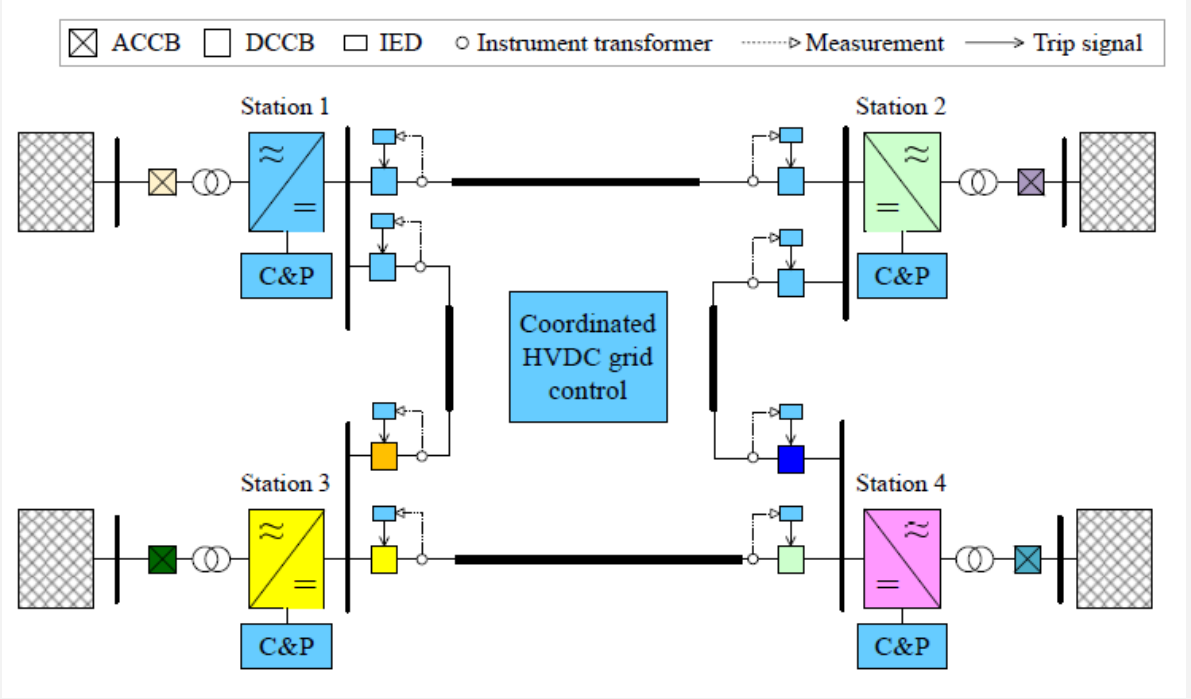
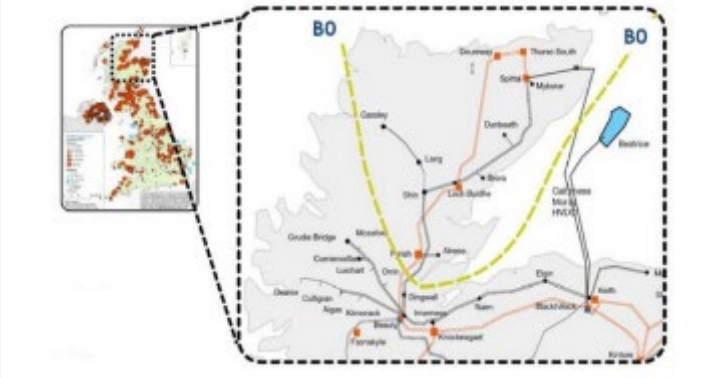


Figure: Wang, M., 2020. Multi-vendor Protection Systems for Meshed HVDC Grids

MULTIVENDOR IN TODAYS VSC HVDC GRIDS



Caithness Moray Shetland, SSE

Single vendor (system integrator)

Nan'ao 3T, RXPE

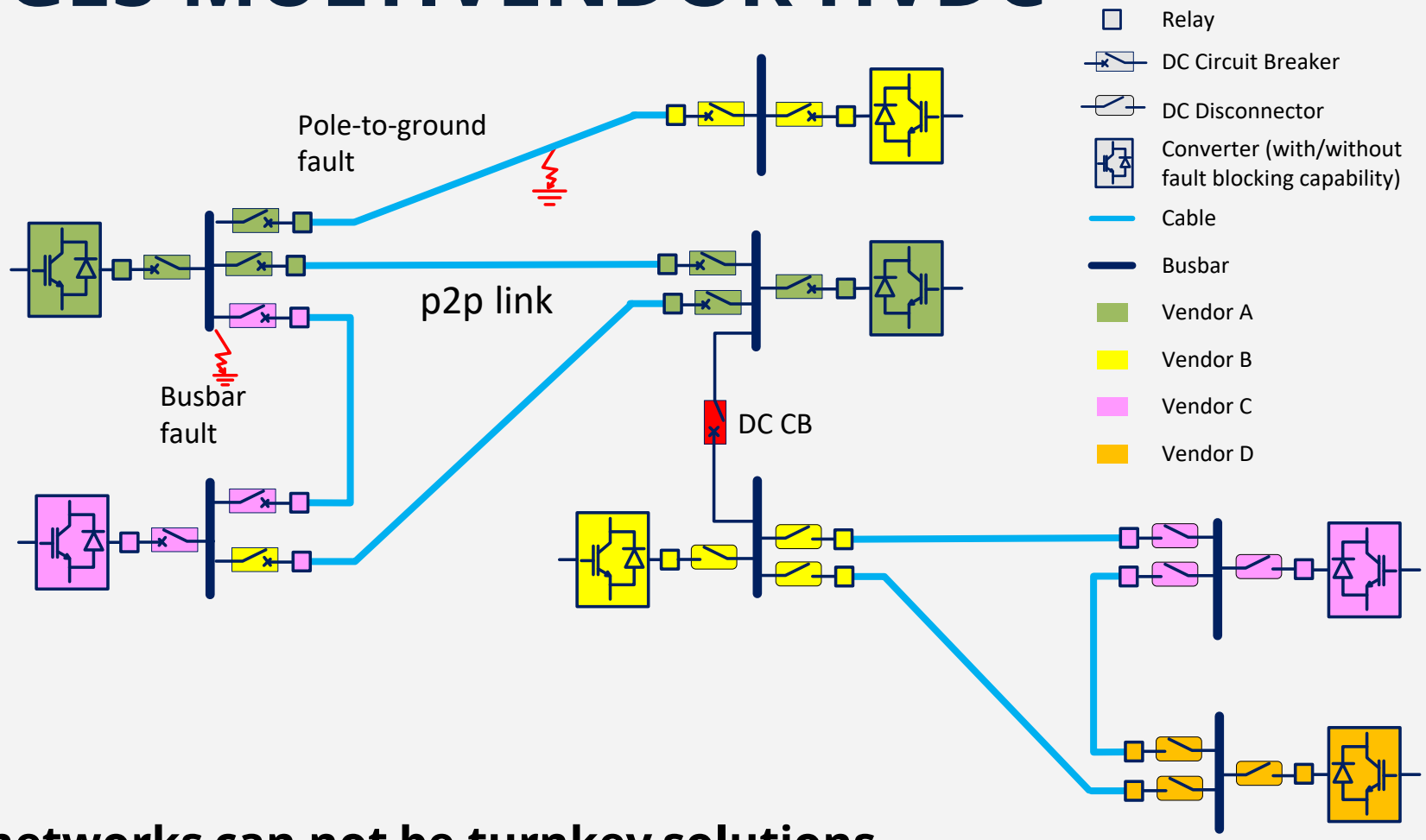
Zhoushan 5T, NREC

Single converter vendor, single system integrator

Zhangbei - GEIRI, SGCC

Many converter vendors, single vendor control, single system integrator

CHALLENGES MULTIVENDOR HVDC



Large scale HVDC networks can not be turnkey solutions…

Figure: Mian Wang

CHALLENGES MULTIVENDOR HVDC

- Towards AC system paradigm (moving away from turnkey)
- Overall multivendor challenges
- Key technical challenges for multivendor:
  - Interfaces
  - Performance expectations/validation
  - Structural (!)

DESIGNING FOR MULTIVENDOR PROTECTION

Key ways to enable interoperability

- Functional specification
- Functional testing
- System structure consensus (harmonisation)

-> Towards standardisation in HVDC protection…

FUNCTIONAL PERFORMANCE OF PROTECTION SYSTEMS

Protection IEDs – functional requirements and functional testing

- Protection IEDs in systems, line protection near market,…
- Need common definition of performance (functional specifications)
- Need common methodologies for determining functionality (functional testing)
- Example of common tests in AC systems (for comparison):

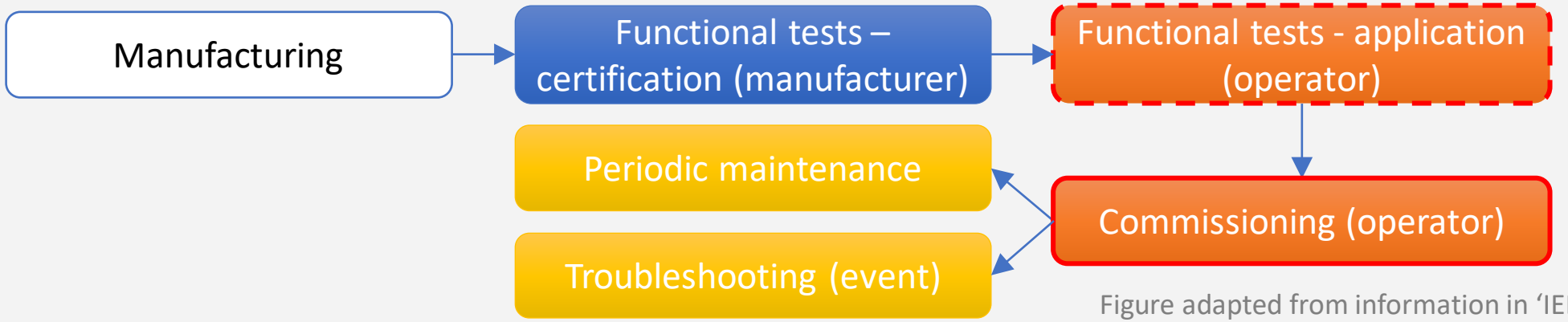


Figure adapted from information in 'IEEE Std C37.233-2009 - IEEE Guide for Power System Protection Testing'

TESTING OF (HVDC) PROTECTION SYSTEM EQUIPMENT

- Expected tests: functional testing (standalone, system-level), commissioning, maintenance,…

- Test configurations for design and validation of hardware performance
  - Real-time testing (RTDS, OPAL-RT,…)
  - IED test suite (without RTS)

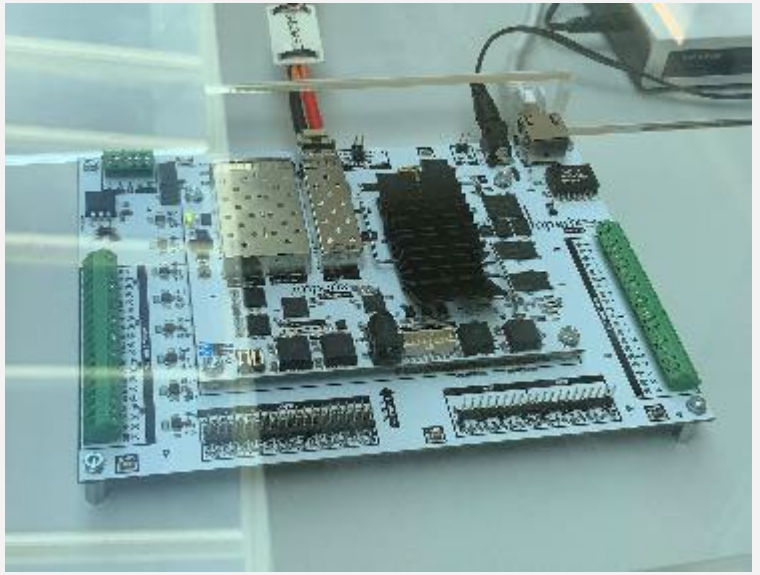
DUT: HVDC PROTECTION IEDS

Devices, interfaces,…

- PROMOTioN/KTH
  - Open source design for research and education
  - 6 functional units with flexible design (algorithms may be written by user)
- Mitsubishi Electric
  - Industrial prototype on industrial control hardware
  - 6 functional units (2 poles x 3 locations)
- And other devices e.g. 1MHz sampling (to be published)
- (+ AC protection IEDs)

References: *"An open-source protection IED for research and education in multiterminal HVDC grids,"* Jahn et al. 2020.

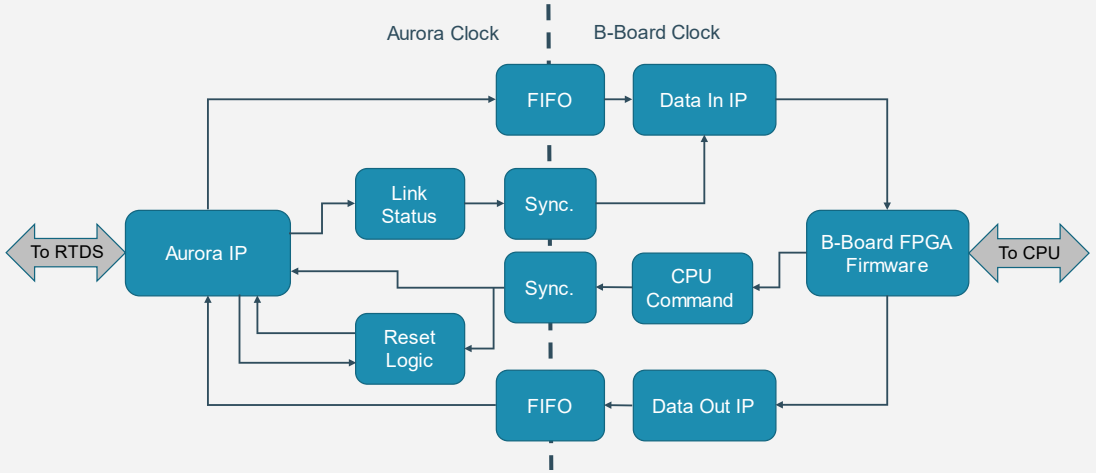
DUT: MMC CONTROL SYSTEM



Devices, interfaces,…

- Imperix B-Board PRO as MMC controller
  - Aurora implementation for interface to RTS

- Key applications:
  - Interaction studies with more realistic controls (MTDC)
  - Developing functional test procedures for MMC controls
  - Reducing computational burden in RTS

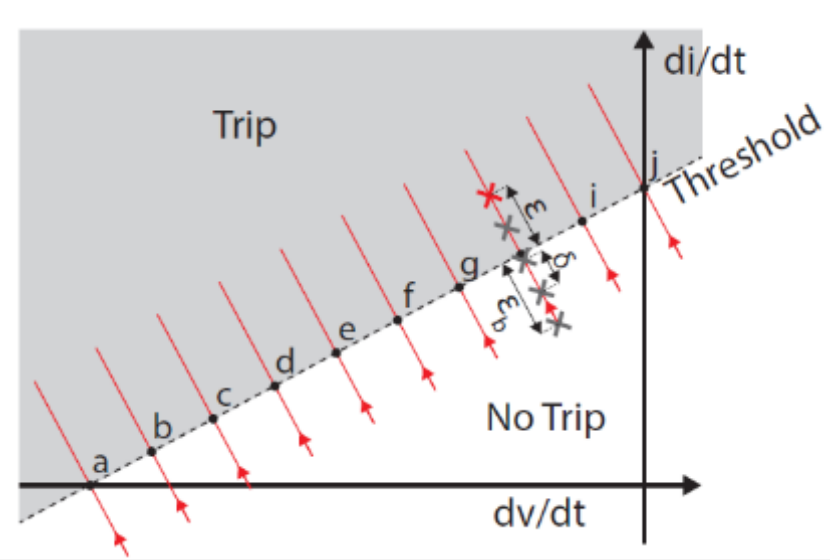


References: *"Real-time Testing and Analysis of an MMC Controller in a Hardware Implementation,"* Debree et al. IECON 2023

TESTING USING RTS

Standalone (type) testing (PB5 + GTFPGA + …)

- Basic characteristic accuracy test
  - Accuracy of the algorithm characteristic

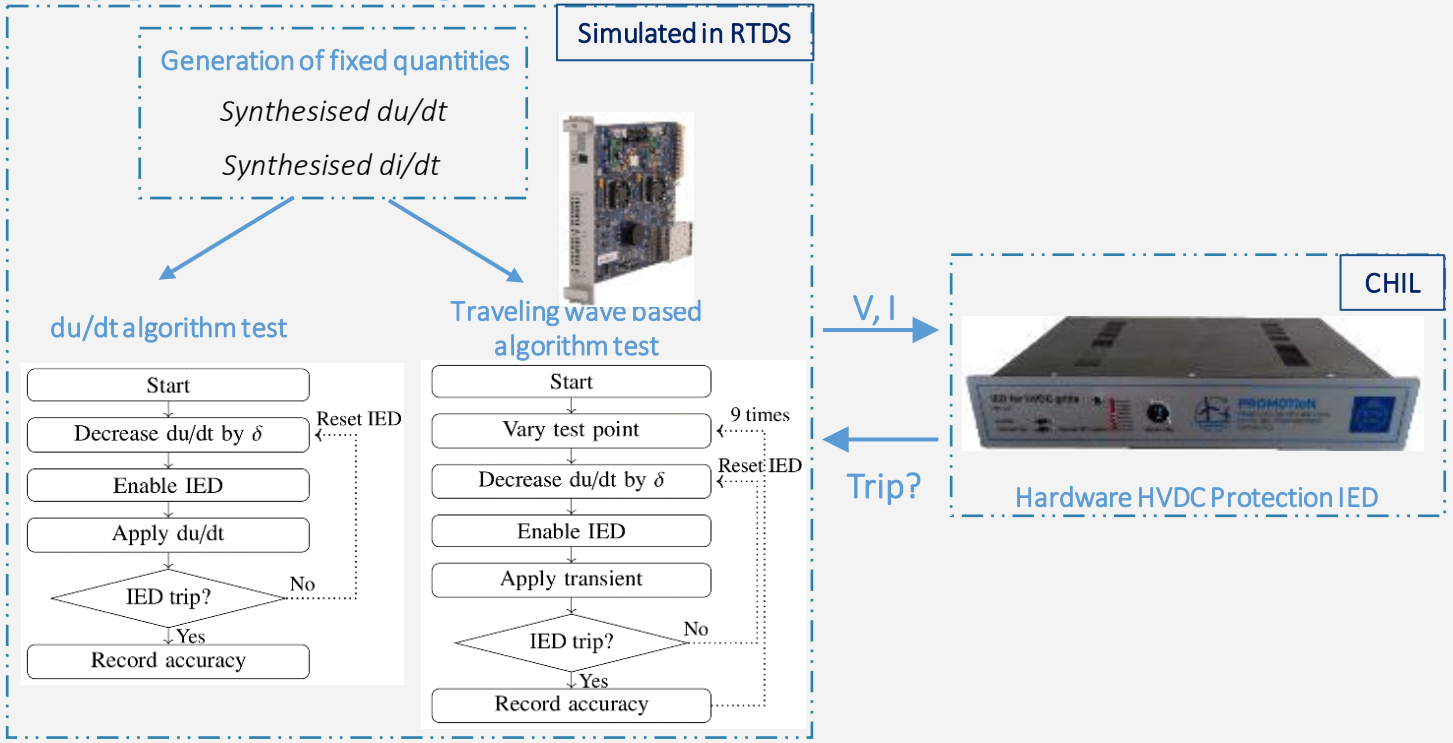


IED setting (kV/µs)	0.3	1.0
ε (%)	**4.2**	4.0

References: *"Requirements for functional testing of HVDC protection IEDs,"* Chaffey et al. 2019.

TESTING USING RTS

Standalone (type) testing (PB5 + GTFPGA + …)



References: *"Requirements for functional testing of HVDC protection IEDs,"* Chaffey et al. 2019.

TESTING USING RTS

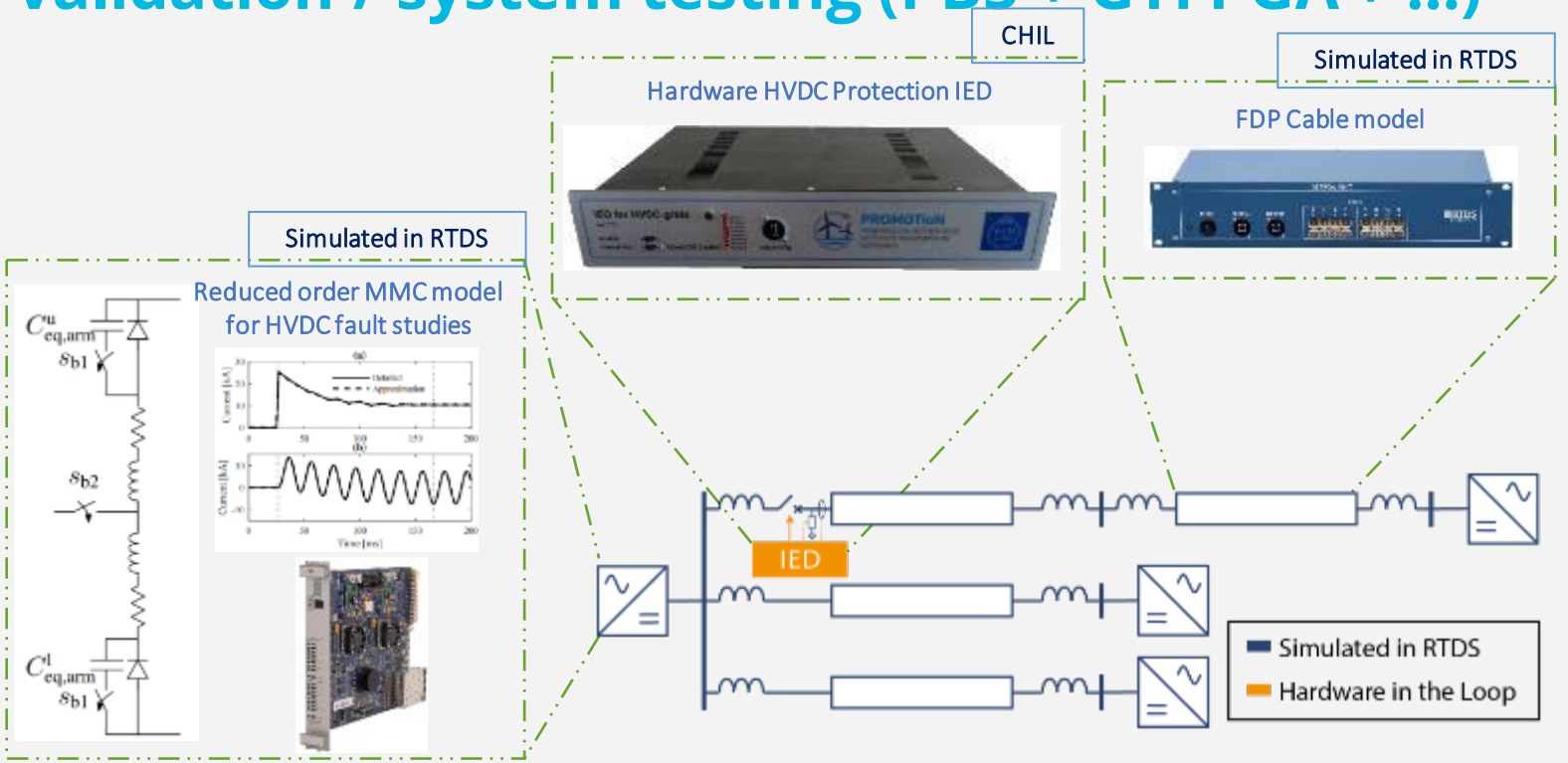
Dynamic validation / system testing (PB5 + GTFPGA + …)

- Several tests:
  - Standalone testing (dynamic validation)
    - Demonstration of dynamic performance of device
  - System-level testing
    - Interaction with other IEDs
    - Interaction with other devices (converter controls)
    - Validation of protection system performance

References: *"Requirements for functional testing of HVDC protection IEDs,"* Chaffey et al. 2019. "Demonstration of Partially and Fully Selective Protection for Multiterminal HVDC Systems," Chaffey and Rahman, RTDS UGM 2020. *"Multi-vendor interoperability tests of IEDs for HVDC grid protection,"* Wang et al. 2020.

TESTING USING RTS

Dynamic validation / system testing (PB5 + GTFPGA + …)



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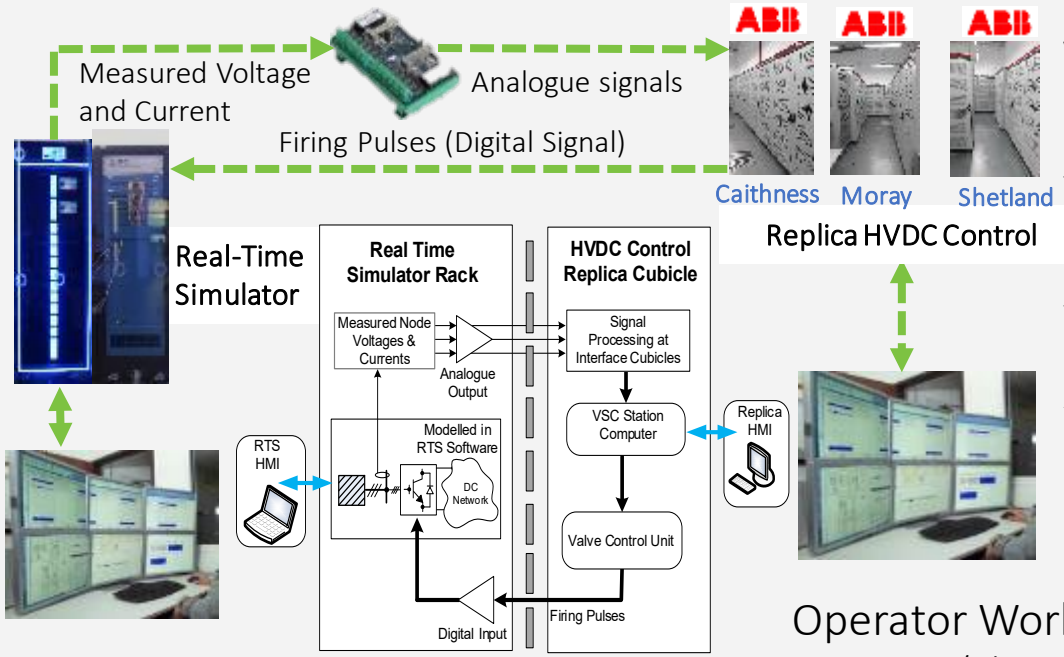
TESTING USING RTS

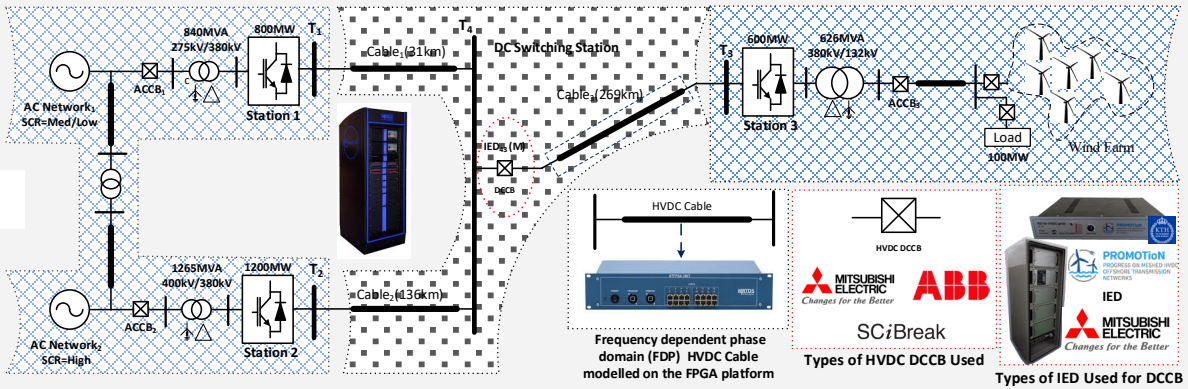


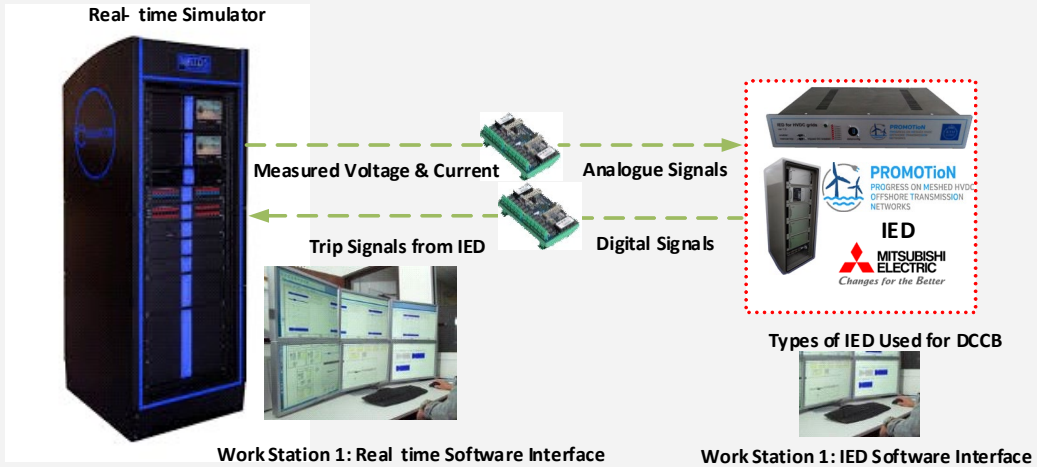
Real-time Simulator Runtime Interface

- Apply network faults
- Change generation dispatch

Operator Work Station

- Start up / shut down
- Change control mode
- Change set points



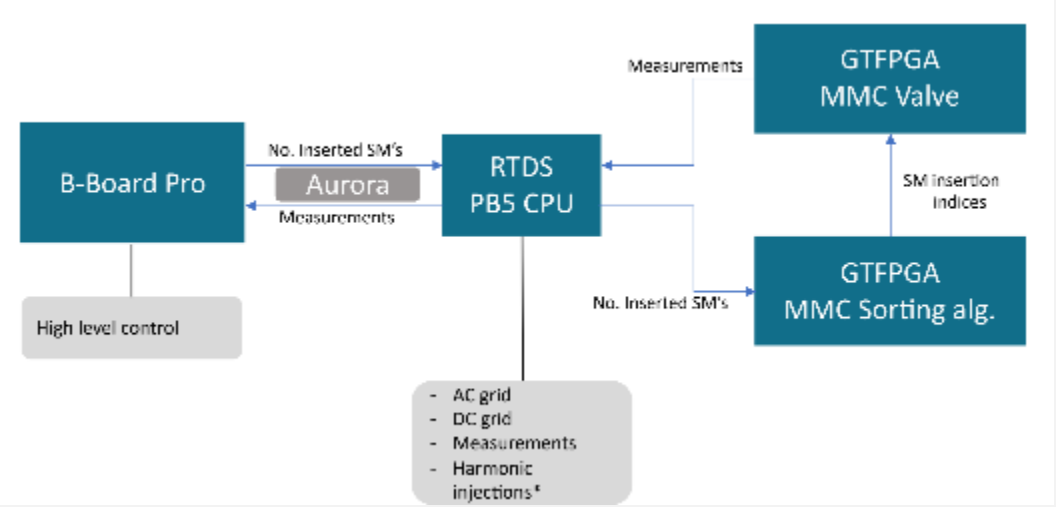


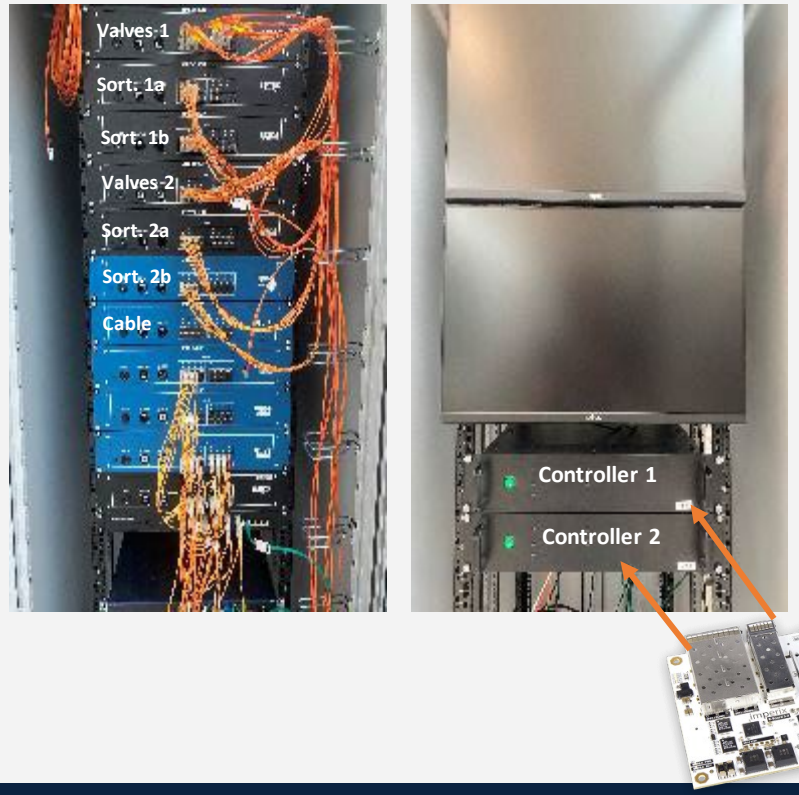
"Demonstration of Partially and Fully Selective Protection for Multiterminal HVDC Systems," Chaffey and Rahman, RTDS UGM 2020.

TESTING USING RTS

Dynamic validation / system testing (PB5 + GTFPGA + Imperix)

- Functional testing of MMC controllers
- Interaction testing in MTDC grid
- Test procedure development

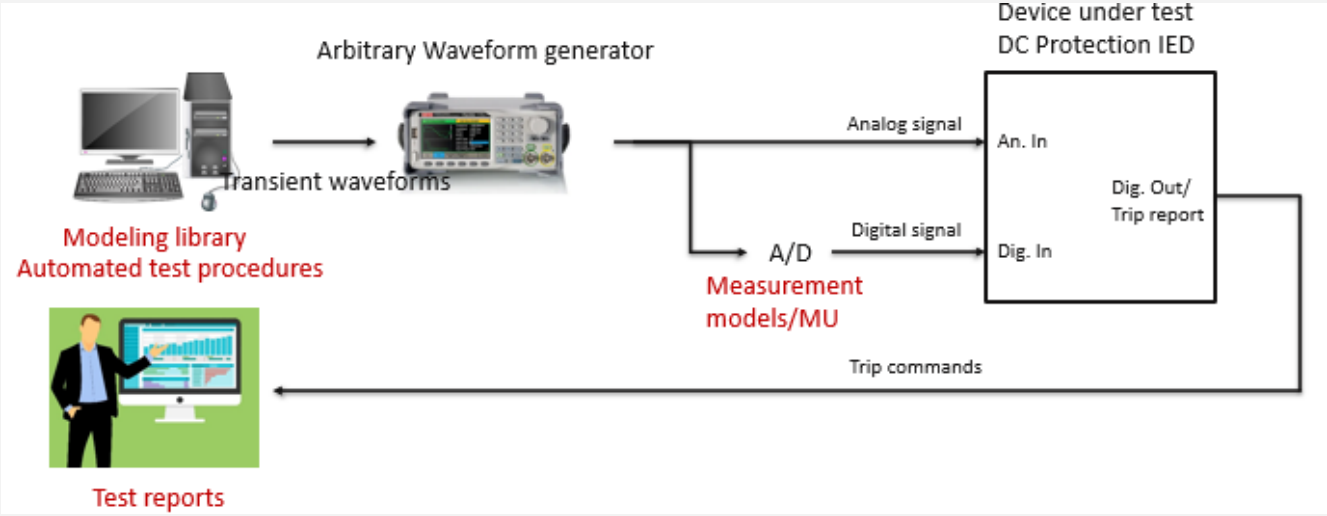




TESTING WITHOUT RTS

HVDC IED Test Suite

- Requirements of functional testing
  - High fidelity representation of system
    - Models
    - Time-step
  - Analysis tools
- Alternative test setup
  - Waveform playback with automated test procedures
  - Interface independent, simulation environment independent

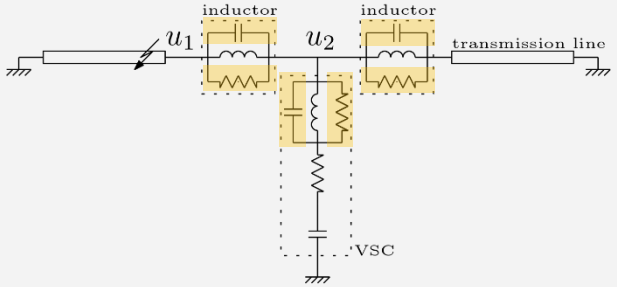


"Test Bench Development for Testing DC Protection Relays," Loenders et al. 2024.

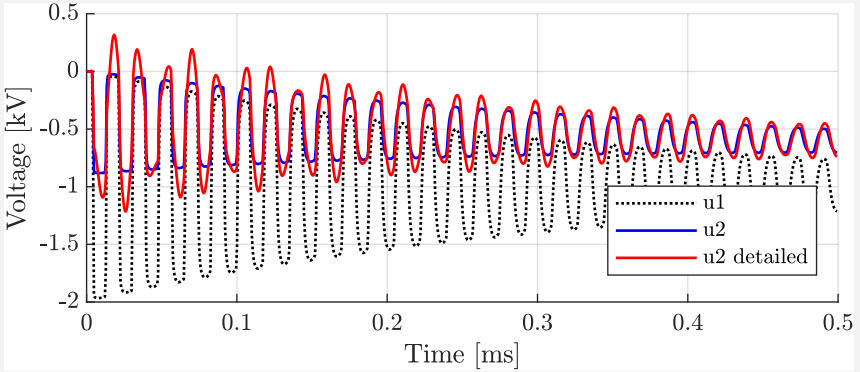
TESTING WITHOUT RTS

HVDC IED Test Suite

- Benefits of non-RT testing
  - Higher fidelity models
    - Environment independent
    - Not limited to EMT -> frequency domain modelling
  - Smaller time step



With and without parasitics…

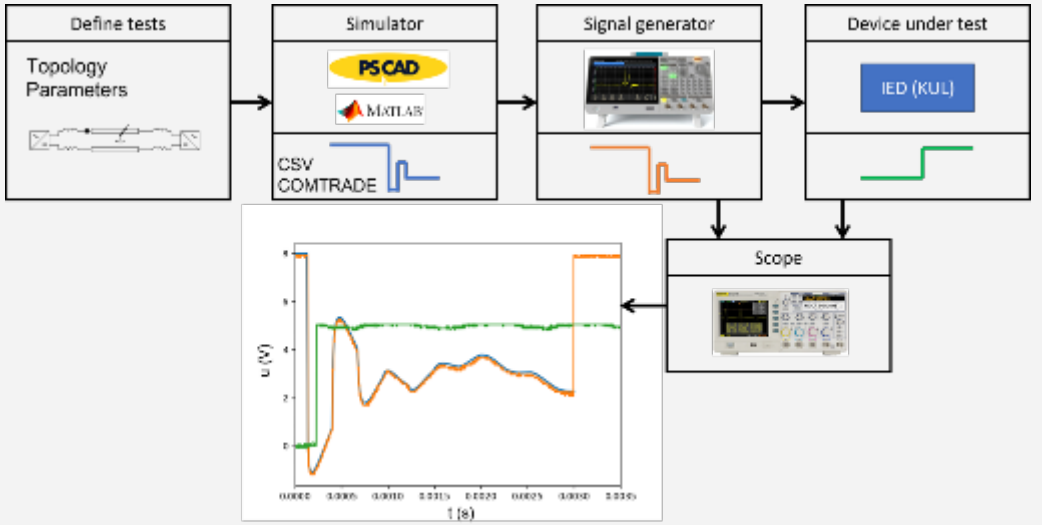


"Test Bench Development for Testing DC Protection Relays," Loenders et al. 2024. *"On HVDC protection IED testing: challenges and outlook,"* Nadeem et al. 2023. *"On modeling of air-core inductors for dc protection studies,"* Leterme et al. 2021

TESTING WITHOUT RTS

HVDC IED Test Suite

- Towards testing of higher bandwidth protection IEDs and other devices
  - HVDC protection IEDs
    - 1 MHz sampling
  - Travelling wave protection / fault location
    - Up to 10 MHz sampling
- Generic test structures
  - Towards functional testing
  - Towards testing of various interfaces



"Test Bench Development for Testing DC Protection Relays," Loenders et al. 2024.

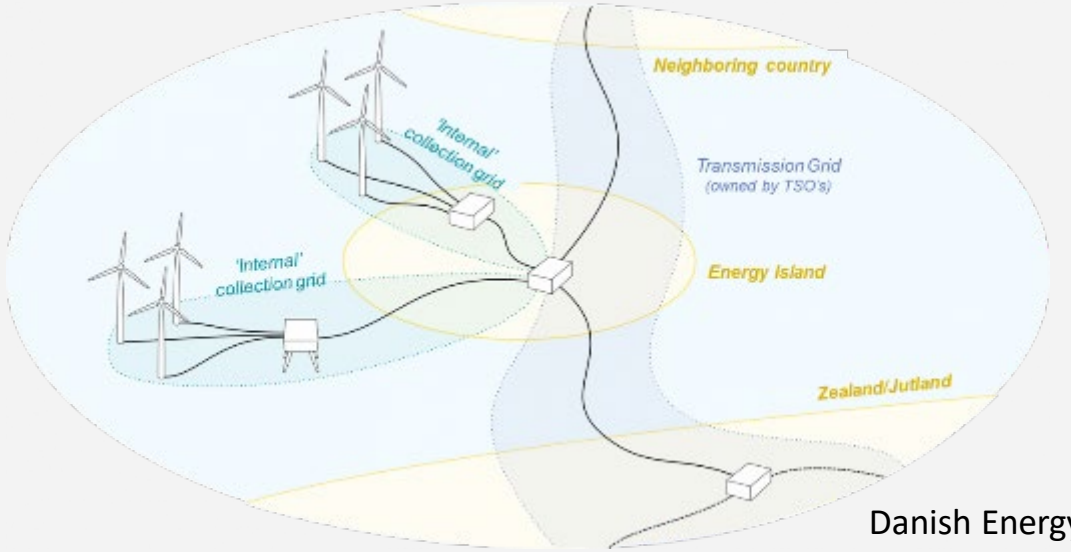
SUMMARY – DC PROTECTION TESTING

- Broad range of testing performed on HVDC protection (IEDs)
- Tests required including
  - Standalone testing (basic characteristic, dynamic performance,…)
  - System testing (design, interactions, commissioning,…)
- Various configurations used to test:
  - RTDS
  - IED test suite (non-RT)
  - …

MEETING KEY CHALLENGES OF THE ENERGY TRANSITION

Future outlook and ongoing research

- Vast European targets demand:
  - Large(r) scale multiterminal HVDC grids
    - With DC protection (CBs, …)
  - Multivendor HVDC systems
  - Energy hubs (islands)
- Key benefits in paradigm shift to true multivendor HVDC
- Standardisation: ongoing, but much work remains



Danish Energy Agency

MEETING KEY CHALLENGES OF THE ENERGY TRANSITION

Future outlook and ongoing research

- Interoperability fits within EnergyVille roadmaps (HVDC control, protection, planning)
- Key ongoing research:
  - Energy hubs / islands
  - Interoperability enabled by openness (MV MTDC)
  - HVDC and cable dominated systems
  - Digital substations and offshore system integration
  - Key collaborations with industrial partners
- Key harmonisation:
  - IEC, CIGRE, IEEE SA, IEA,…

TOWARDS STANDARDISATION IN HVDC PROTECTION

- Protection functions (relays or other)
  - Functional requirements / specification
  - Functional testing
  - **TC95 WG3**
- System structure
  - B4.85 (TB forthcoming)
  - (CENELEC -> IEC)
  - Ongoing research projects
- Interfaces between different devices
  - B4.85
  - Ongoing research projects

Please talk to me if you are interested in functional testing of DC protection (all T&D voltage levels)
-> IEC TC95 WG3

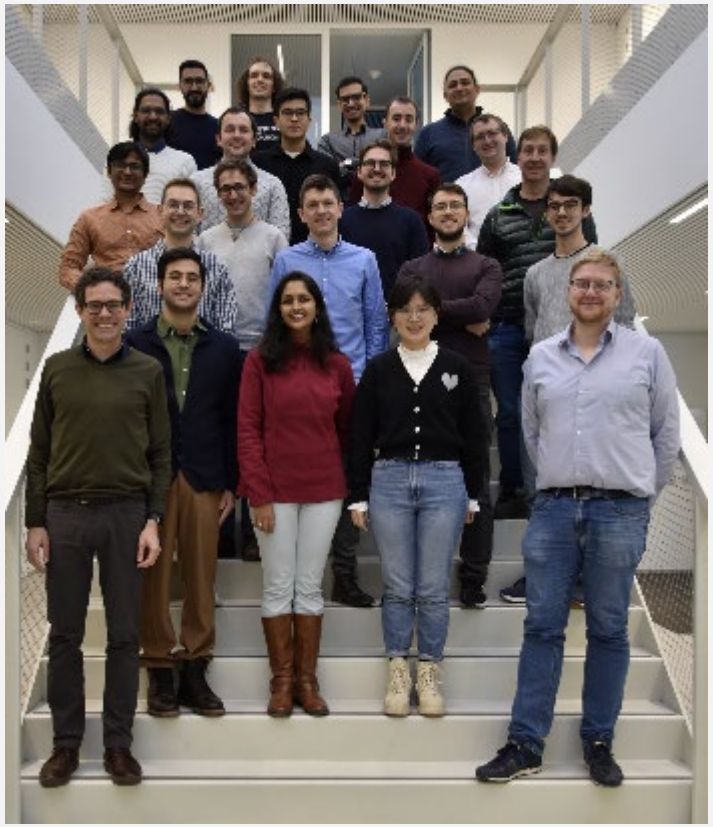
HVDC AND CABLE COMPETENCE CENTRE (HC3)

New center of expertise on underground high-voltage connections

- Significant new funding (€14M) including €9M investment in lab facilities
- Scaling up of core activities (fundamental research as well as industrial collaboration)
  - HVDC protection systems
  - HVDC control
  - HVDC planning
  - Digital substations
- Building on background of industrial collaborations to help solve the key challenges of the energy transition

JOB AND INTERNSHIP OPPORTUNITIES

- KU Leuven / EnergyVille are seeking collaborators at all levels:
  - Assistant professor (high voltage systems)
  - Innovation manager
  - Senior postdoc
  - Junior postdoc
  - PhD student
  - Simulation engineer
  - Intern / thesis students
- Please get in contact if you are interested in:
  - HVDC grids
    - Protection, control and planning
  - Real-time simulation and CHIL testing of future energy systems



geraint.chaffey@kuleuven.be

FUNCTIONAL TESTING OF HVDC PROTECTION SYSTEMS – TOWARDS MULTIVENDOR

GERAINT CHAFFEY - GERAINT.CHAFFEY@KULEUVEN.BE