PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

How to Protect a DC Grid?

Geraint Chaffey, Dirk Van Hertem. KU Leuven, Belgium. PROMOTioN WP4, PROMOTioN WP9.

WindEurope Offshore 2019, Copenhagen

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

How to Protect a DC Grid - Overview

- Introduction to DC grid protection
- Protection systems and associated impact
- Techno-economic analysis of HVDC protection
- HVDC protection IED
- Towards demonstration of protection systems

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Introduction

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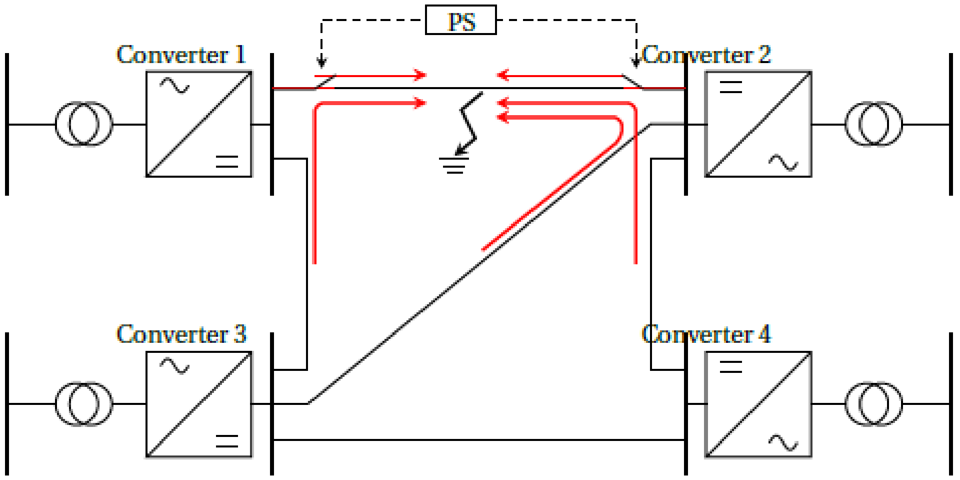
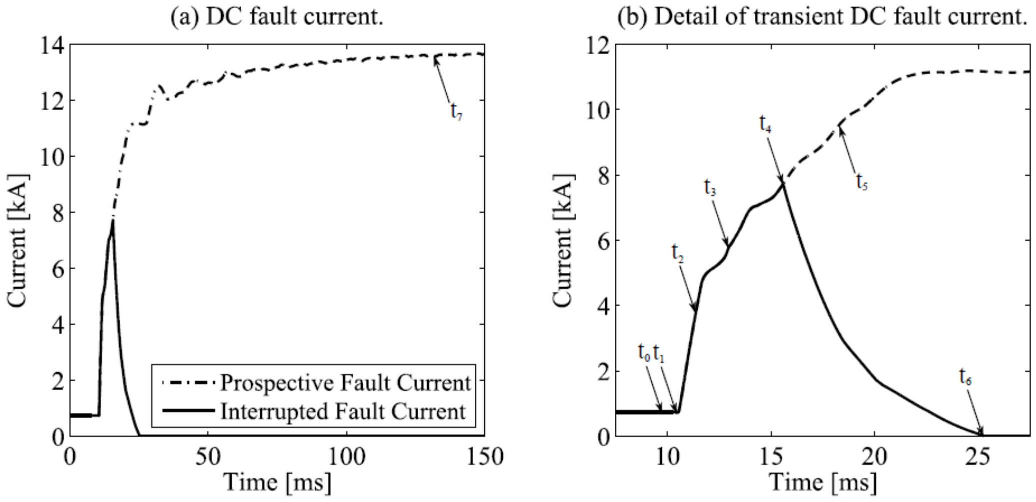
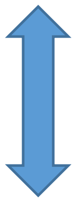
Fault Currents within a DC Grid





- Fault current characteristics
  - No zero crossings
  - High rate-of-rise
  - High steady state value



- Sensitive (& expensive) converters and fast controls

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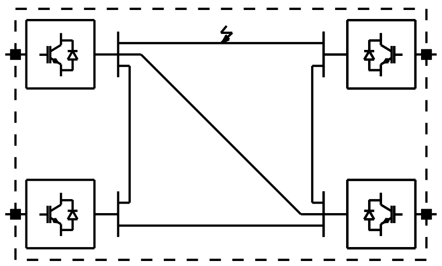
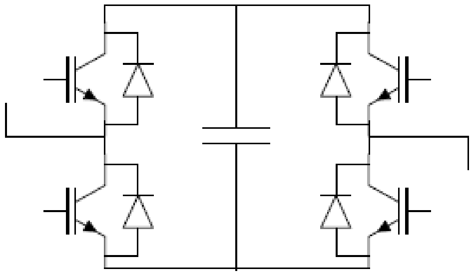
Different Technologies Exist to Interrupt a DC Fault Current



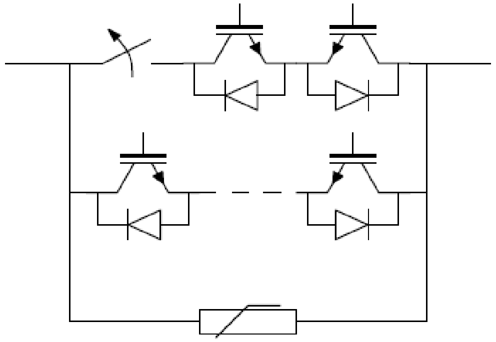
Converter AC breakers

- As used in existing projects
- Slow (40-60 ms opening time)
- Not selective



Fault-current blocking converters

- Higher losses compared to half-bridge
- Fast (responsive within a few ms)
- Not selective



DC circuit breakers

- Operating time of 2-10 ms
- Trade-off in losses vs speed
- Allows selective fault clearing

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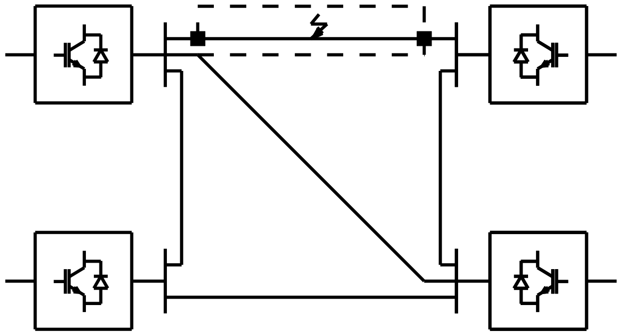
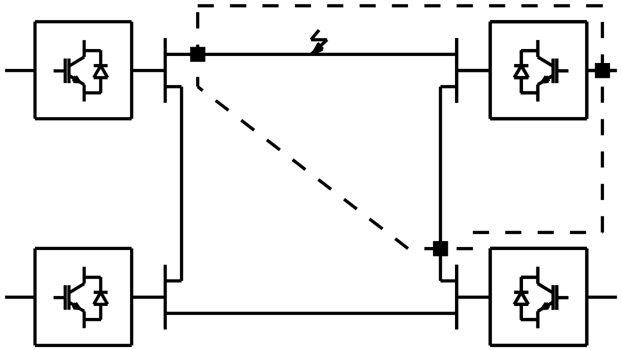
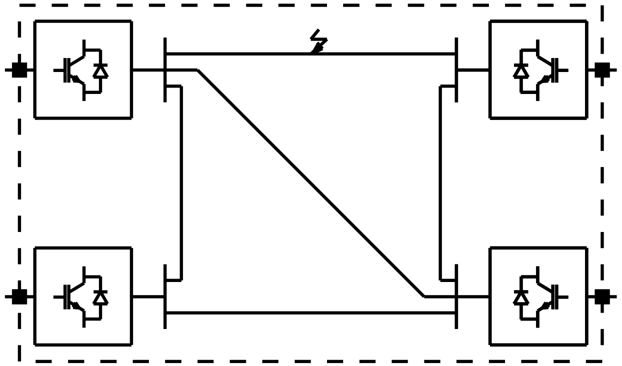
Different Configurations Lead to Different Fault Clearing Strategies



Selective:
Using DC breakers on every line end



Partially selective:
Split DC grid in sub-grids (protection zones)



Non-selective:
Temporary shut down the whole DC grid

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Trade-offs in Protection System Design

Protection system design choices influence:

- Recovery time / impact of DC fault
- Duration and extent of real/reactive power outage
  - **AC system impact!**

Key considerations:

- Cost of assets (particularly offshore)
- Cost of losses
- Reliability
- Maturity of technology

…Trade-offs under study – first technical and then technical + economic

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HVDC Protection Systems

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DC Grid Protection System Development

PROMOTioN WP4 aims:

- To develop a set of functional requirements for various DC grids: from small scale to large overlay grids and for a variety of system configurations and converter topologies
- To analyse a wide range of DC grid protection philosophies on a common set of metrics
- To develop detailed protection methodologies for selected methods
- To investigate the key influencing parameters of protection systems on the cost-benefit evaluation
- To develop configurable multi-purpose HVDC protection IEDs to enable testing of the methodologies

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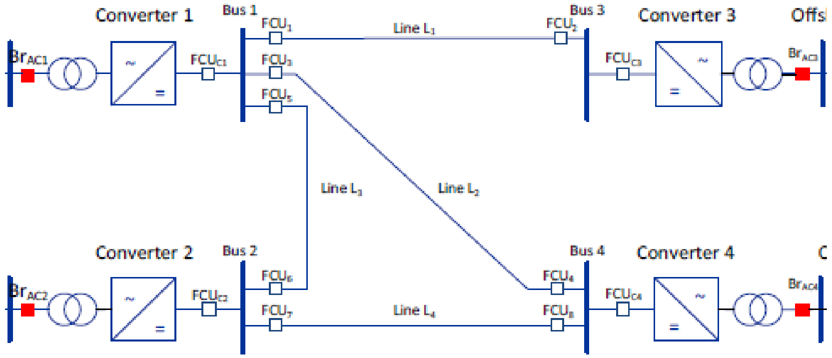
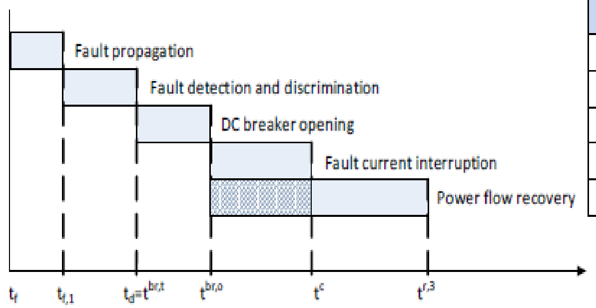
Methods to Characterize Fault Clearing Strategies





Interval	Duration
t_f-$t_{f,1}$	us to ms
$t_{f,1}$-t_d	us to ms
t_d-$t^{br,o}$	0.5-20 ms
$t^{br,o}$-t^c	few ms
$t^{br,o}$-$t^{r,3}$	tens of ms

Protection zone		C1	C2	C3	C4	Protection equipment in operation
1	$F_{L1,ptg}$	CO	CO	PS	CO	Br_1, Br_2
2	$F_{L2,ptg}$	CO	CO	CO	CO	Br_3, Br_4
3	$F_{L3,ptg}$	CO	CO	CO	CO	Br_5, Br_6
4	$F_{L4,ptg}$	CO	CO	CO	CO	Br_7, Br_8

Key components

Technical layout

Primary fault clearing sequence

Backup fault clearing sequence

Protection matrix

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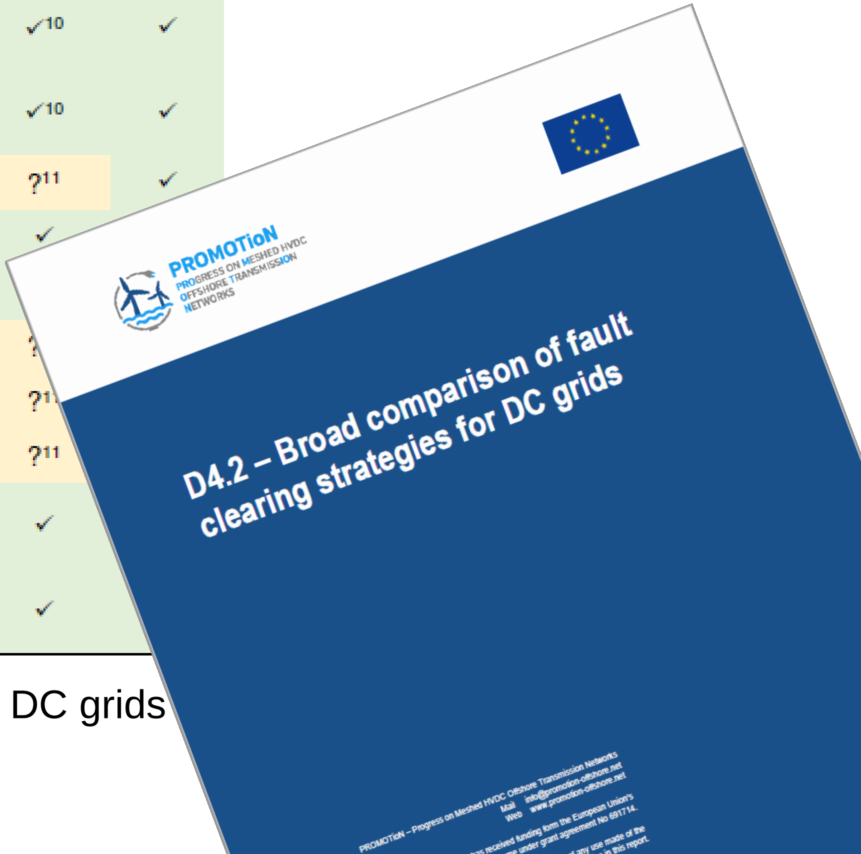
Broad Comparison of Protection Strategies

	STRATEGY ABBR.	PHILOSOPHY	MAIN COST DRIVER	FEASIBILITY				
				Low impact grid	Med. impact grid	High impact grid	Symm. Mon.	Bip.
1	FS DCCB Option 1	Fully Selective	DCCB	✓	✓	✓	✓	✓
2	FS DCCB Option 2	Fully Selective	DCCB and Converters	✓	✓	✓	✓[10]	✓
3	FS DCCB Option 3	Fully Selective	DCCB	✓	✓	✓	✓[10]	✓
4	FS SFCL	Fully Selective	SFCL	✓	✓	✓	?[11]	✓
5	NS ACCB	Non-Selective	/	✓	×	×	✓	[illegible]
6	NS FB	Non-Selective	FB	✓	✓	×	[illegible]	[illegible]
7	NS DCCB	Non-Selective	DCCB	✓	✓	×	?	[illegible]
8	NS SFCL	Non-Selective	SFCL	✓	✓	×	?[11]	[illegible]
10	Open Grid	Non-Selective	DCCB	✓	✓	×	?[11]	[illegible]
11	ParS PS	Partially Selective	DCCB/DCDC	✓	✓	✓	✓	[illegible]
12	ParS TS	Partially Selective	DCDC/DCCB/FB	✓	✓	✓	✓	[illegible]

D4.2: broad comparison of fault clearing strategies for DC grids



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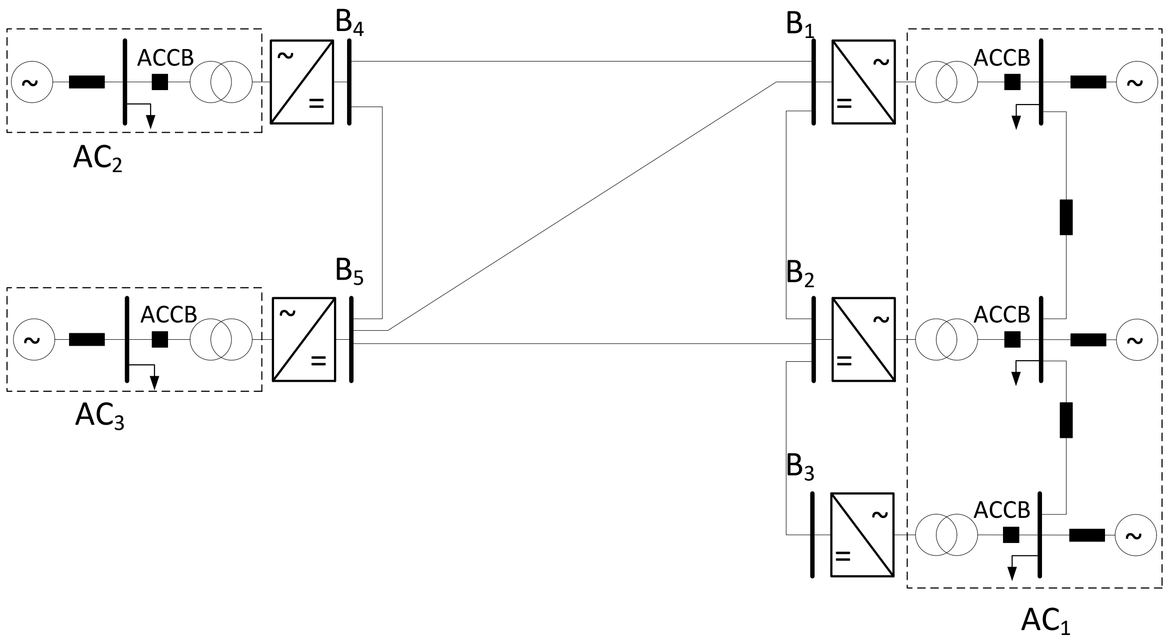
Performance of HVDC Protection Systems

- Detailed analysis performed on selected HVDC protection implementations
- Key Performance Indicators (KPIs) developed to provide means of comparison of (functional) performance:
  - Efficiency indicators
  - Failure indicators
  - Cost indicators
- Example comparison of impact presented in next slides
  - Impact on PCC



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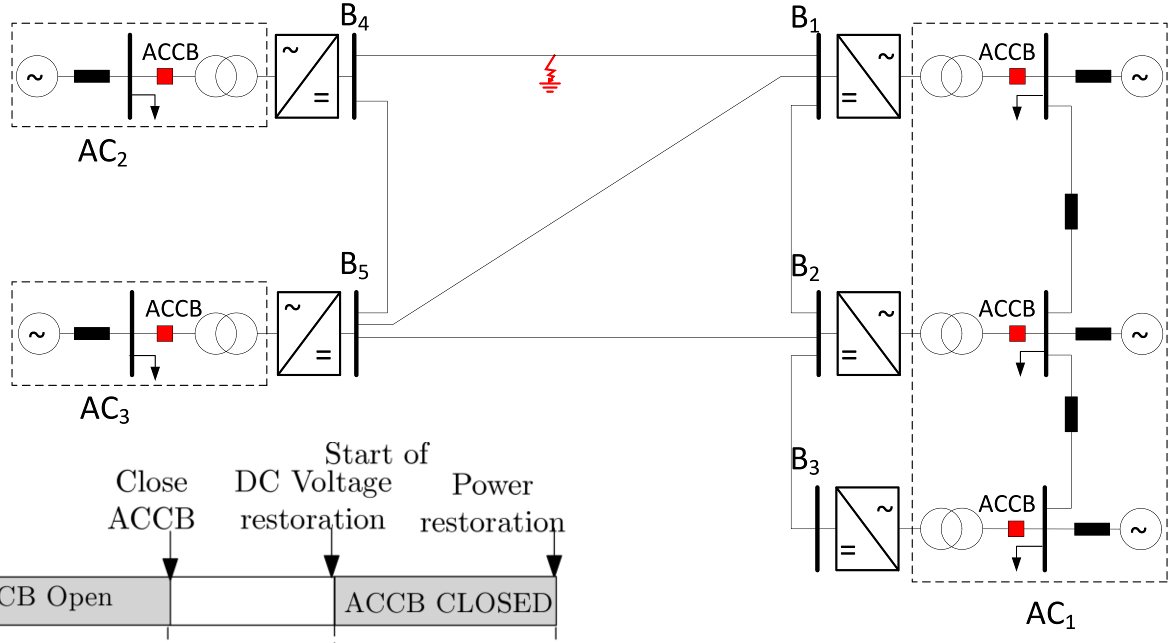
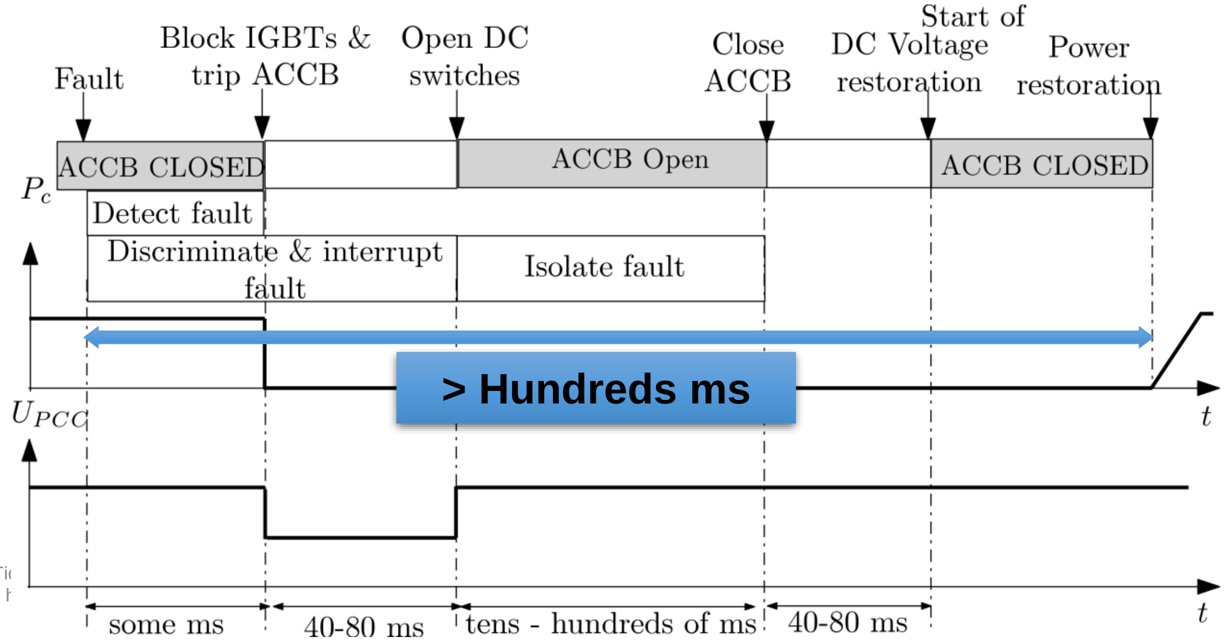
Non-selective DC Fault Clearance (AC Circuit Breakers)

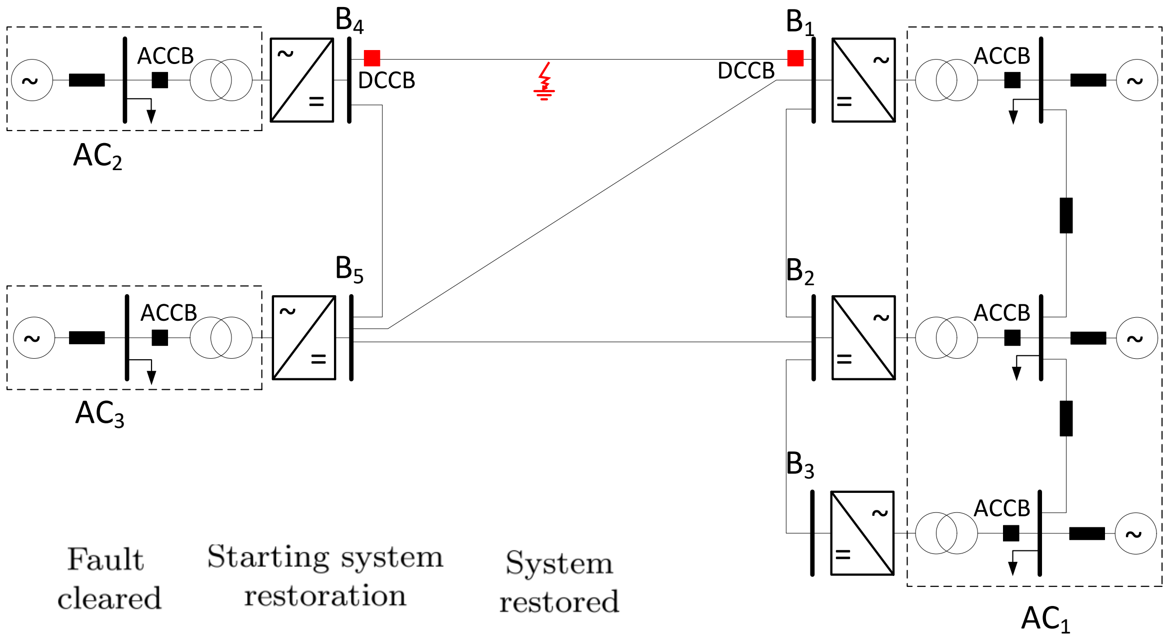
- Impact on DC grid
  - Loss of whole DC grid
- Impact on AC grids
  - Loss of generation/load
- Impact on connected offshore wind
  - Likely to require additional FRT

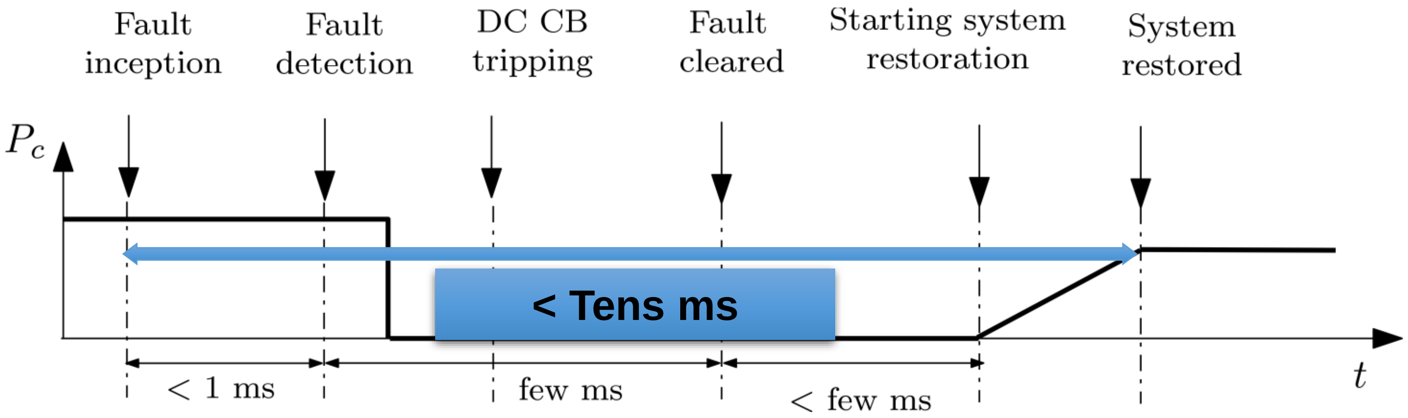




Fully Selective DC Fault Clearance (DC Circuit Breakers)

- Impact on DC grid
  - Temporary power & voltage transient
- Impact on AC grids
  - Very short transient
- Impact on connected offshore wind
  - No additional FRT required





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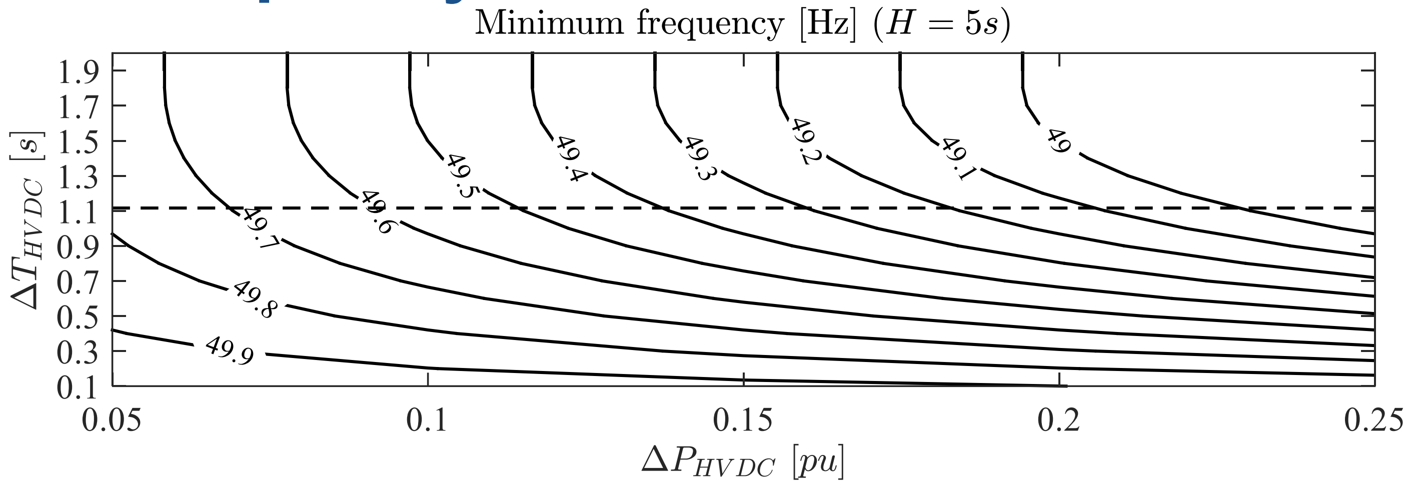
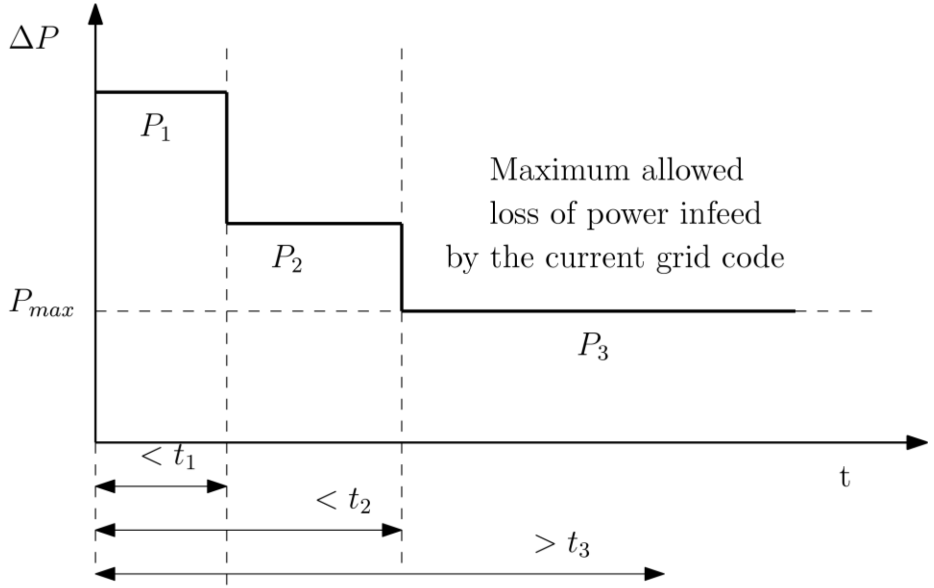
Impact on Onshore AC System Frequency

- Even relatively large losses don't cause AC system to drop outside operational limits over short periods (e.g. 500 ms)



- Could a possible grid code allow for momentary losses?
  - Transient loss P_1: restoration within t_1 (e.g. one cycle)
  - Temporary loss P_2: restoration within t_2 (e.g. hundreds ms)
  - Permanent loss P_3: equal to maximum allowed permanent loss



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Towards a Cost Benefit Analysis of DC Grid Protection

- Technical analysis of trade-offs completed
- However, decision making is strongly based on economic factors
- Techno-economic trade-offs examined in CBA:
  - Cost data
    - Cost models for DCCBs
    - Cost data from PROMOTioN database
  - Technical data
  - Grid data
  - Failure data (risk based approach)

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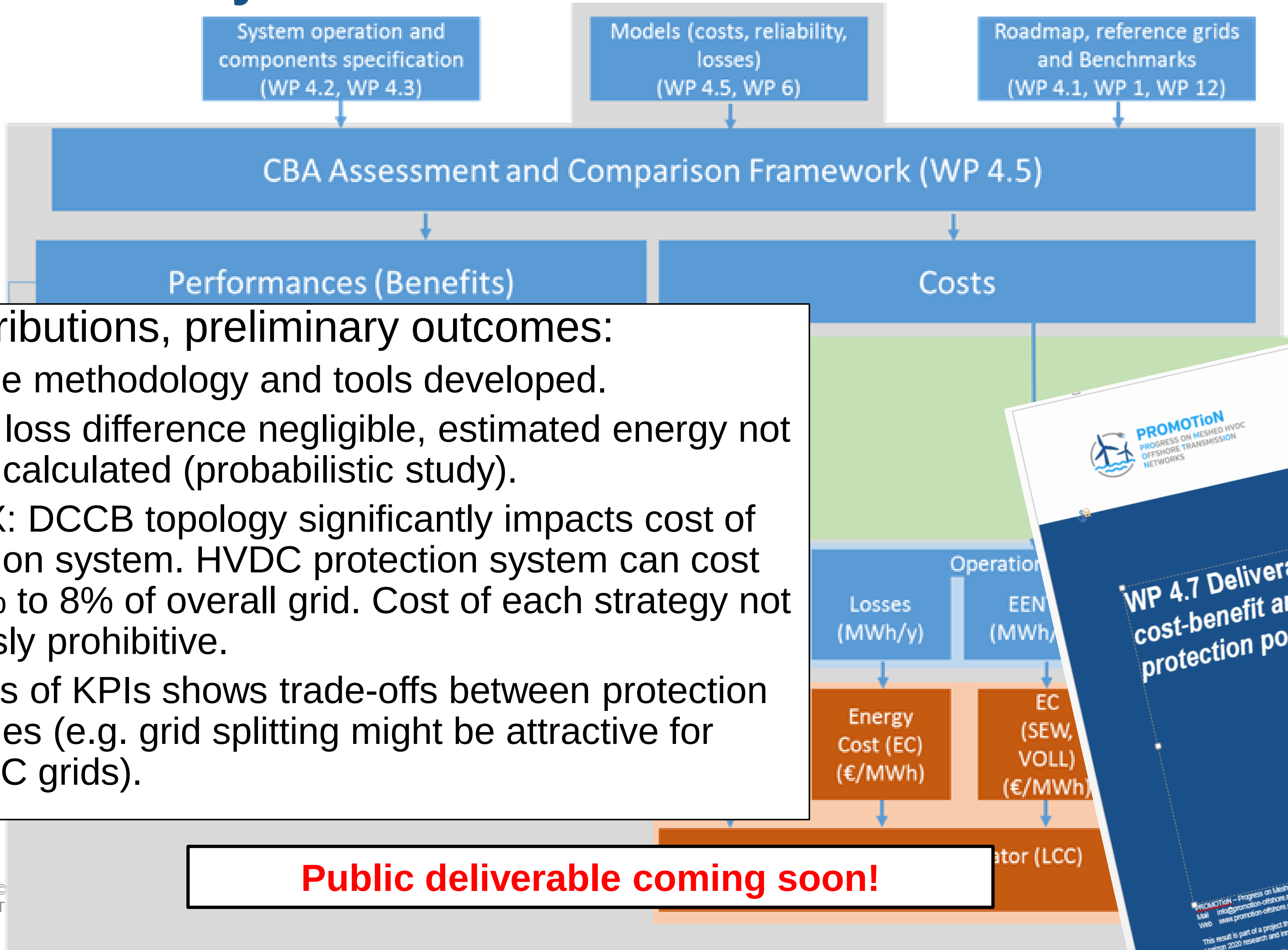
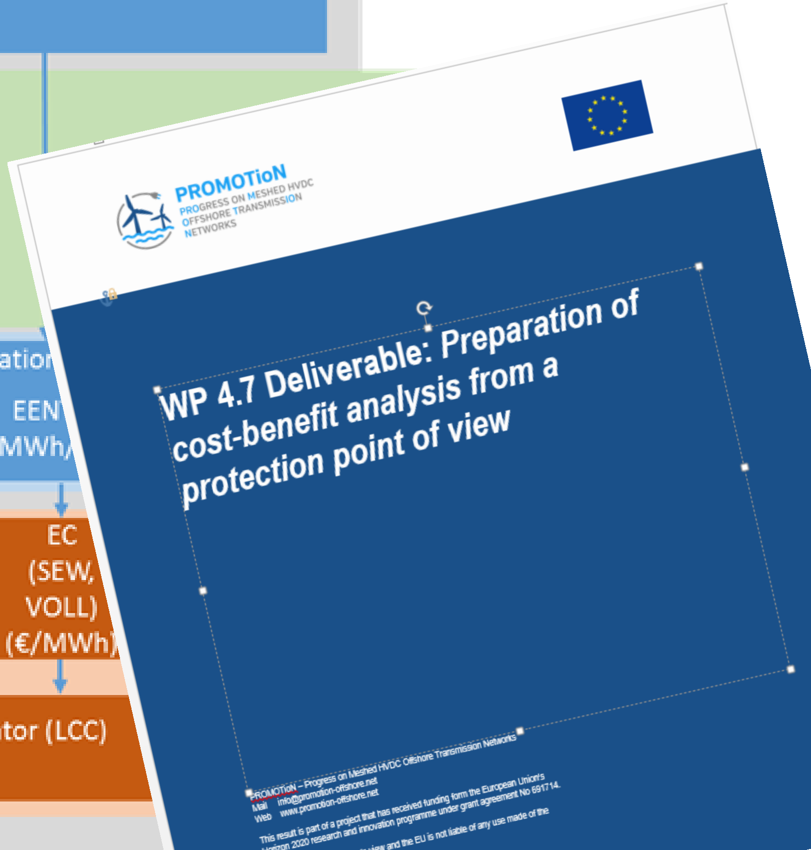
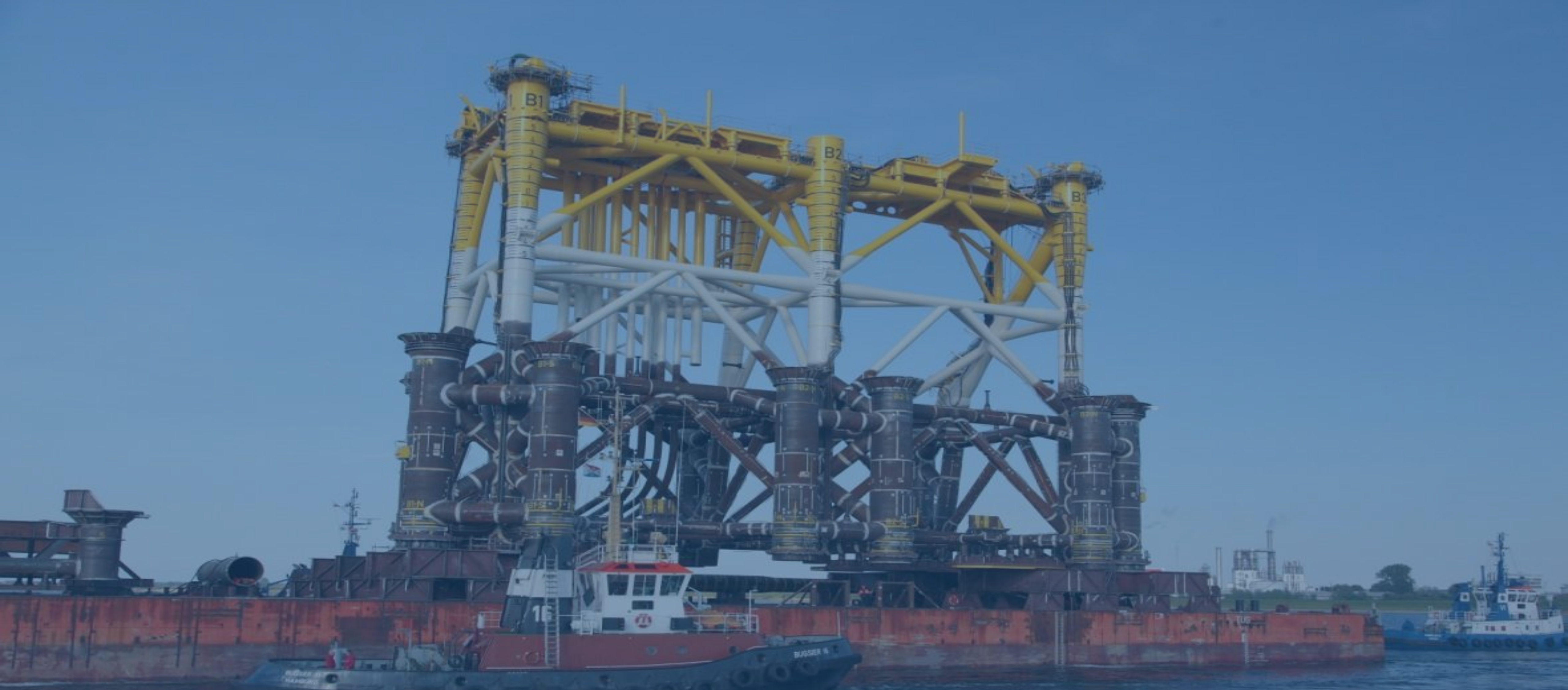
Cost Benefit Analysis



- Key contributions, preliminary outcomes:
  - Valuable methodology and tools developed.
  - OPEX: loss difference negligible, estimated energy not served calculated (probabilistic study).
  - CAPEX: DCCB topology significantly impacts cost of protection system. HVDC protection system can cost e.g. 4% to 8% of overall grid. Cost of each strategy not obviously prohibitive.
  - Analysis of KPIs shows trade-offs between protection strategies (e.g. grid splitting might be attractive for large DC grids).



Public deliverable coming soon!



HVDC Protection IEDs

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HVDC Protection IEDs – PROMOTioN IED Development

Protection IED (relay) executes fault detection/discrimination algorithms in a real system

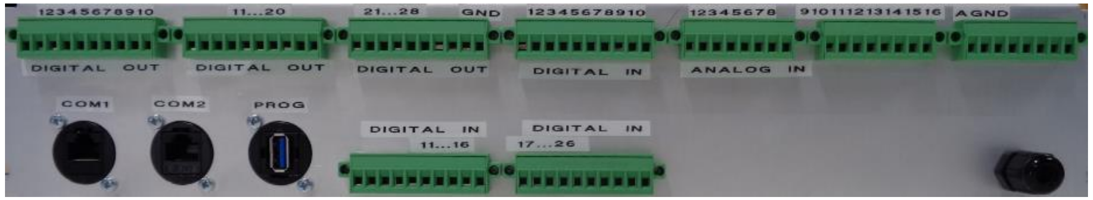
- Not commercially available / not implemented on real system

Functional specification including:

- Novel algorithms
- Order of magnitude faster than typical AC protection

PROMOTioN HVDC Protection IED for MTDC:

- Open source protection IED prototype for research and education in HVDC protection
  - GUI for settings and fault recorder
  - 6+ algorithms for HVDC grids
  - Highly reconfigurable by user
  - Digital and Analogue IO
    - e.g. for connection to RTS



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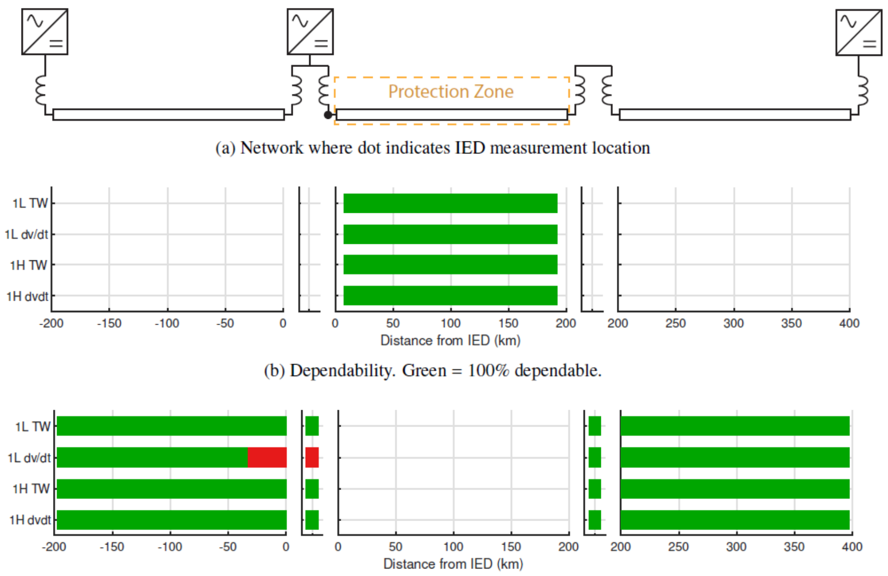
HVDC Protection IEDs – Unit Testing

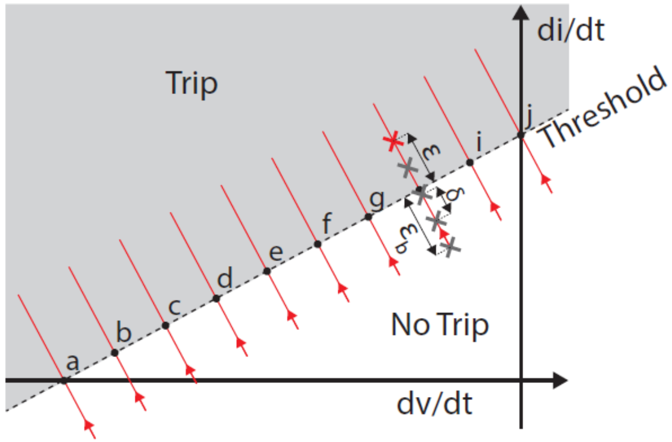
- No standardised tests for HVDC protection equipment
- Tests developed:
  - Functional type testing
  - Dynamic validation type testing

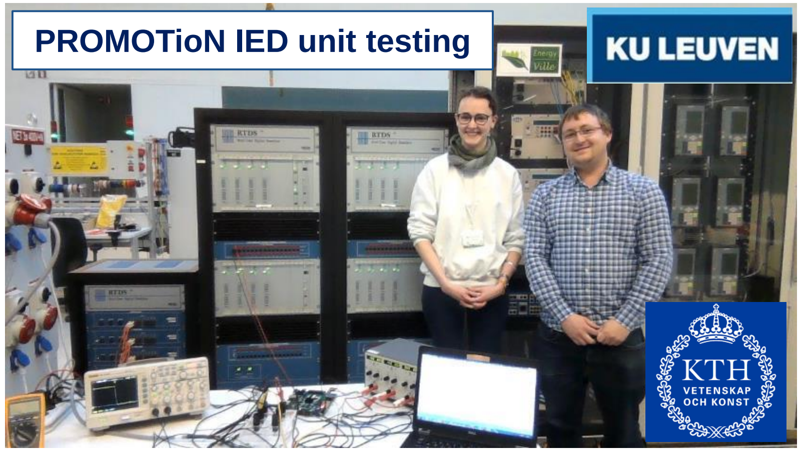


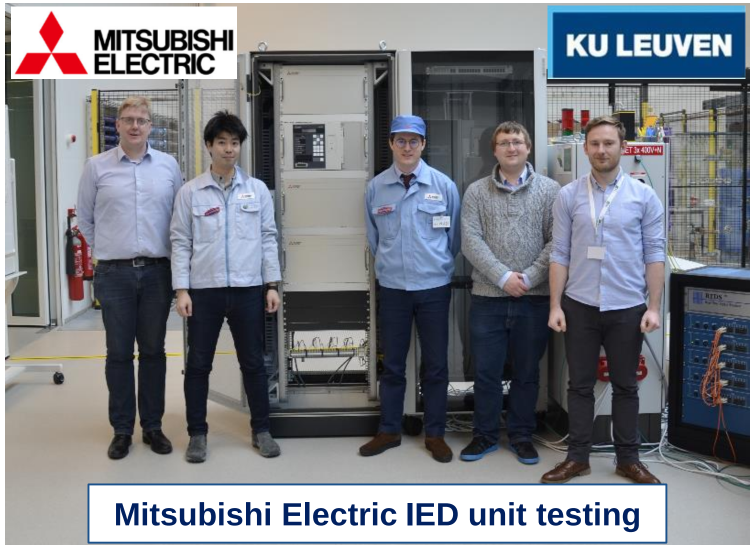
(a) Network where dot indicates IED measurement location

(b) Dependability. Green = 100% dependable.

(c) Security. Green = secure. Red = not secure.







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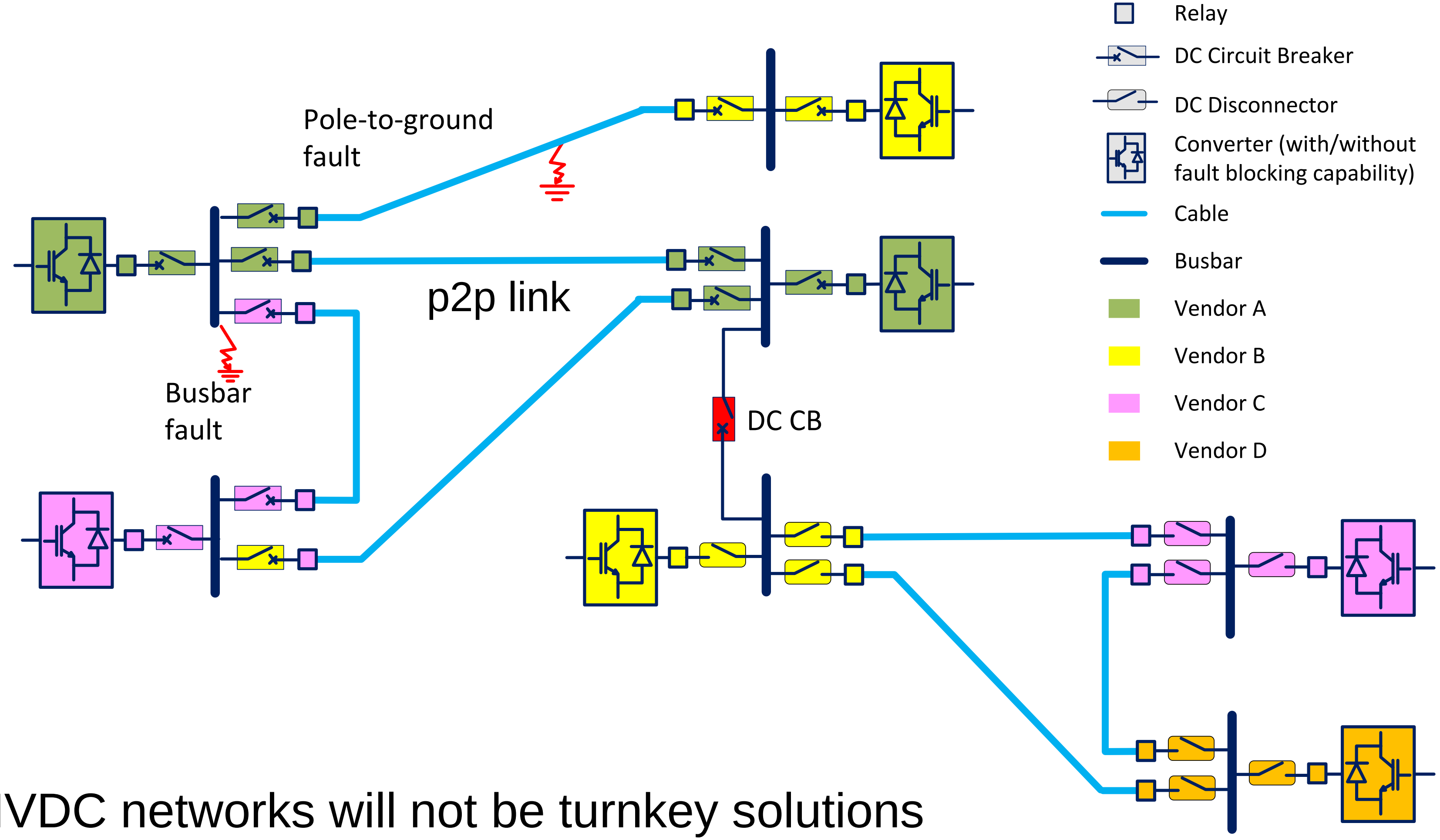
Towards large scale and multivendor systems



- Large scale HVDC networks will not be turnkey solutions
  - Will surely be required to be multi vendor systems!!

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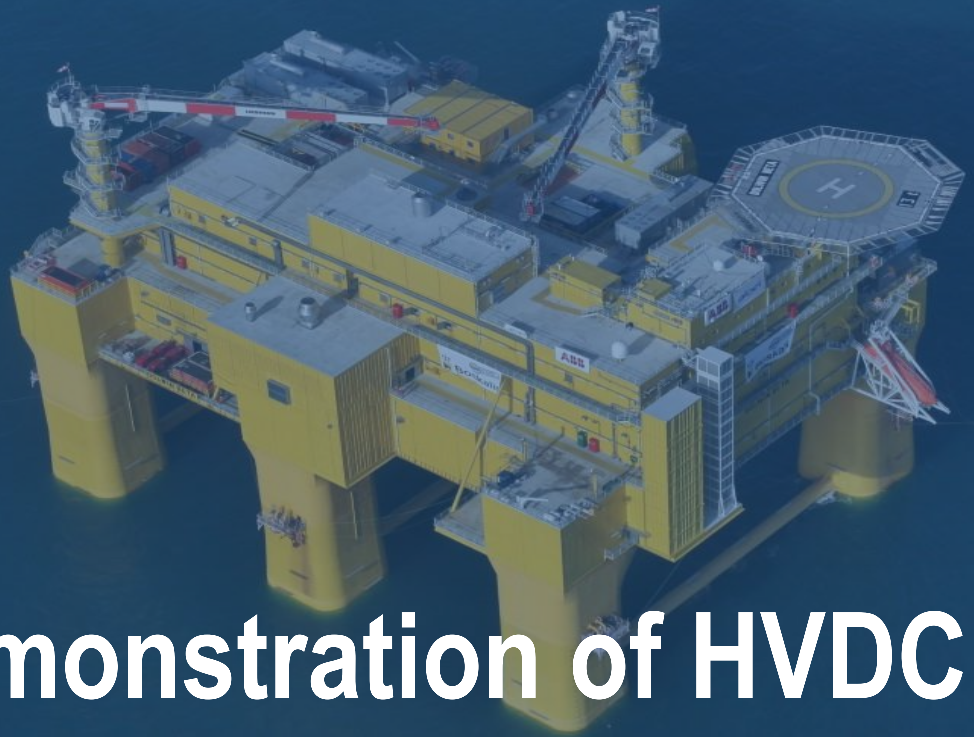

Towards Demonstration of HVDC Protection Systems

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Towards Demonstration of HVDC Protection Systems
PROMOTioN WP9

Demonstration of partially selective and fully selective protection:

- Realistic HVDC circuit breaker models (simulated)
- Industrial HVDC network case study (simulated)
- HVDC protection IEDs (hardware in the loop)

Demonstration of non-selective protection:

- Low speed / communication based strategy
- Demonstration of strategy including communication aspects

Overall aim: To demonstrate successful operation of multivendor HVDC protection in a realistic system

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Towards Demonstration – Industrial Test Case in RTS

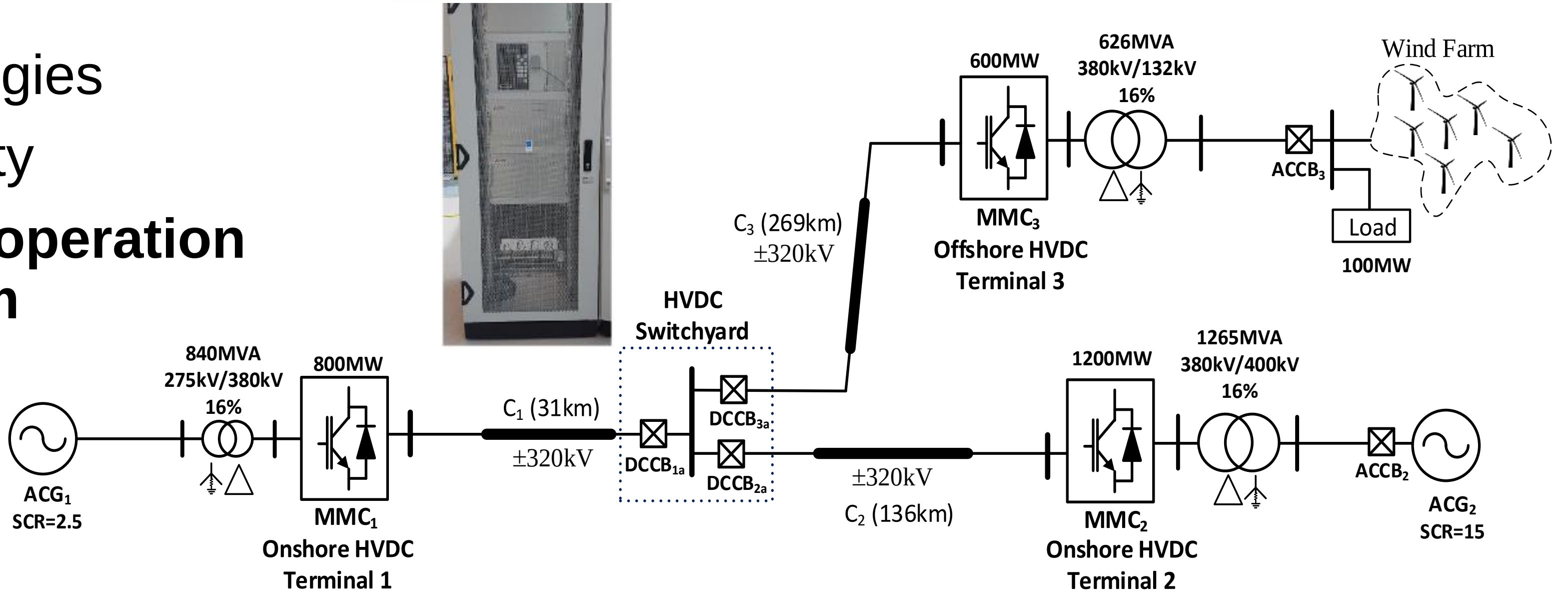
Study case with parameters based on Caithness Moray Shetland HVDC system

Verify performance of HVDC IEDs

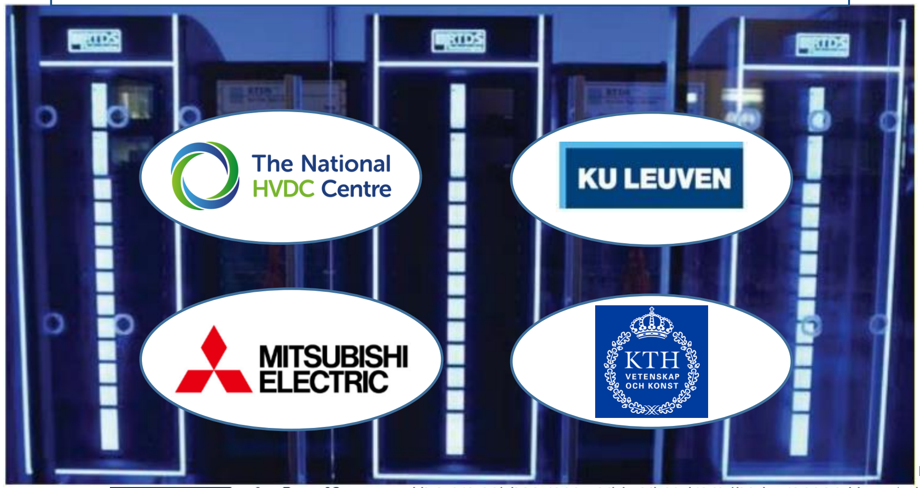
Verify operation of protection strategies

Examine multivendor interoperability

Demonstrate overall successful operation of multivendor protection system



Industrial validation of protection system



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How to Protect a DC Grid? Summary

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Summary

- Expected protection strategies and implementations examined
- Protection system design procedures set out
- Test procedures to examine functional performance defined
- Cost-benefit analysis performed for example networks and methodology will be available for use in real systems
- Algorithms and protection IEDs developed and tested in realistic systems
- Requirements for and examples of multivendor interoperability set out

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So... How to Protect an HVDC Grid?

- Answer is likely to be highly case specific:
  - AC system constraints
  - Choices by system operator
  - Location of system (onshore/offshore)
- But, there are numerous options
  - Each technically feasible but with different trade-offs (cost, system impact,…)
- We have provided the tools for analysis, example implementations and associated trade-offs, and are working towards an industrial demonstration case study

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Conclusions

- HVDC networks can be protected in many feasible configurations
- In general… protection of MTDC networks is no longer a stumbling block for development of European multiterminal HVDC networks

Check out our upcoming public output:

- Latest deliverable:
  - D4.7: Preparation of cost-benefit analysis from a protection point of view – Q1 2020
- Upcoming demonstration events (free):
  - D9.4: Demonstration of selective protection systems interoperability and primary and back-up protection – Scotland, Q2 2020.
  - D9.5: Hardware-in-the-loop test environment and guidelines for non-selective protection systems demonstration – Lyon, Q3 2020.

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How to Protect a DC Grid?

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