PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

Functional Requirements from AC and DC grids to DC grid protection

Dirk Van Hertem

KU Leuven and EnergyVille

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KU LEUVEN

Energy Ville

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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- First suggestions for functional requirements

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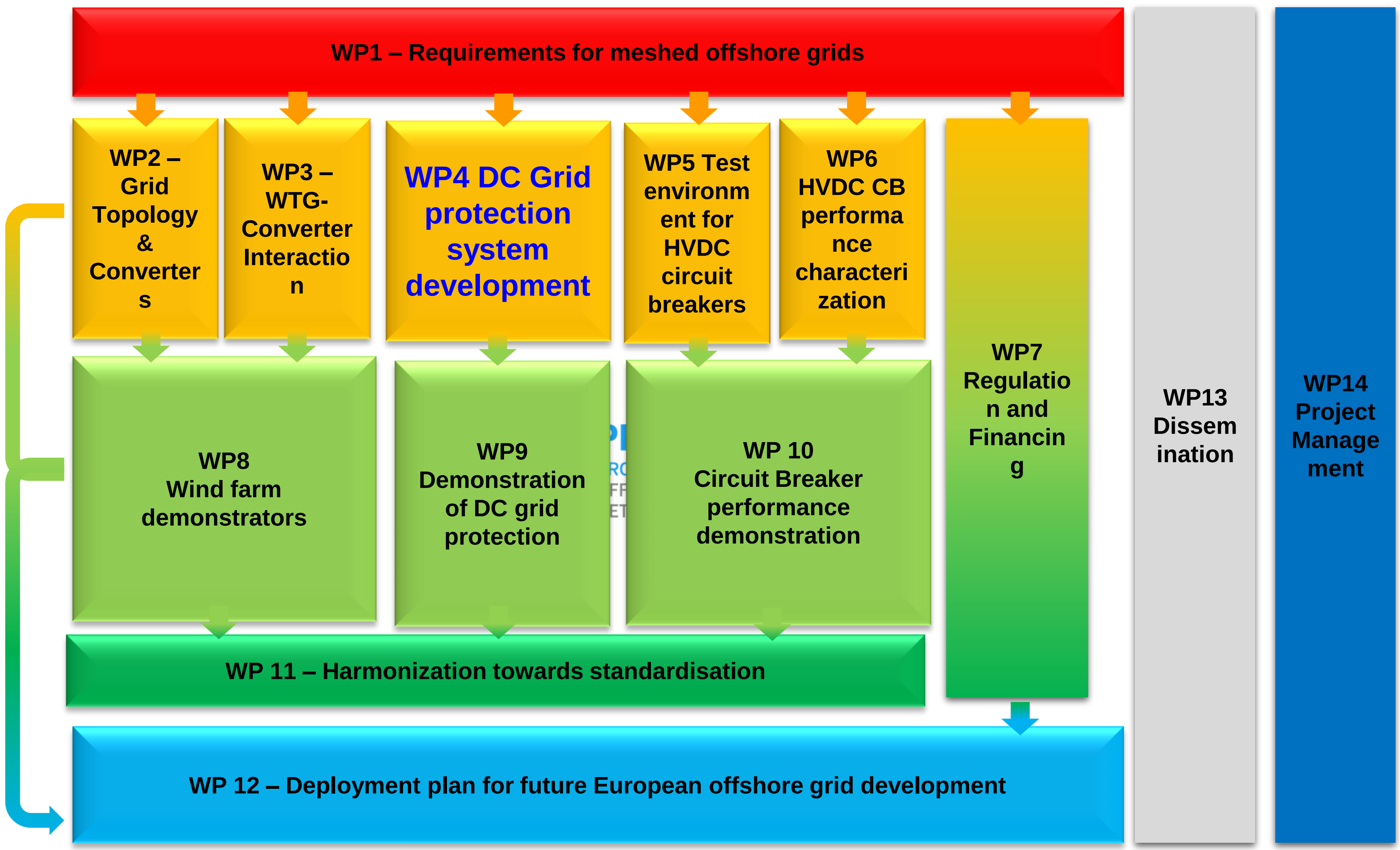
Promotion Horizon 2020 project (2016-2019)



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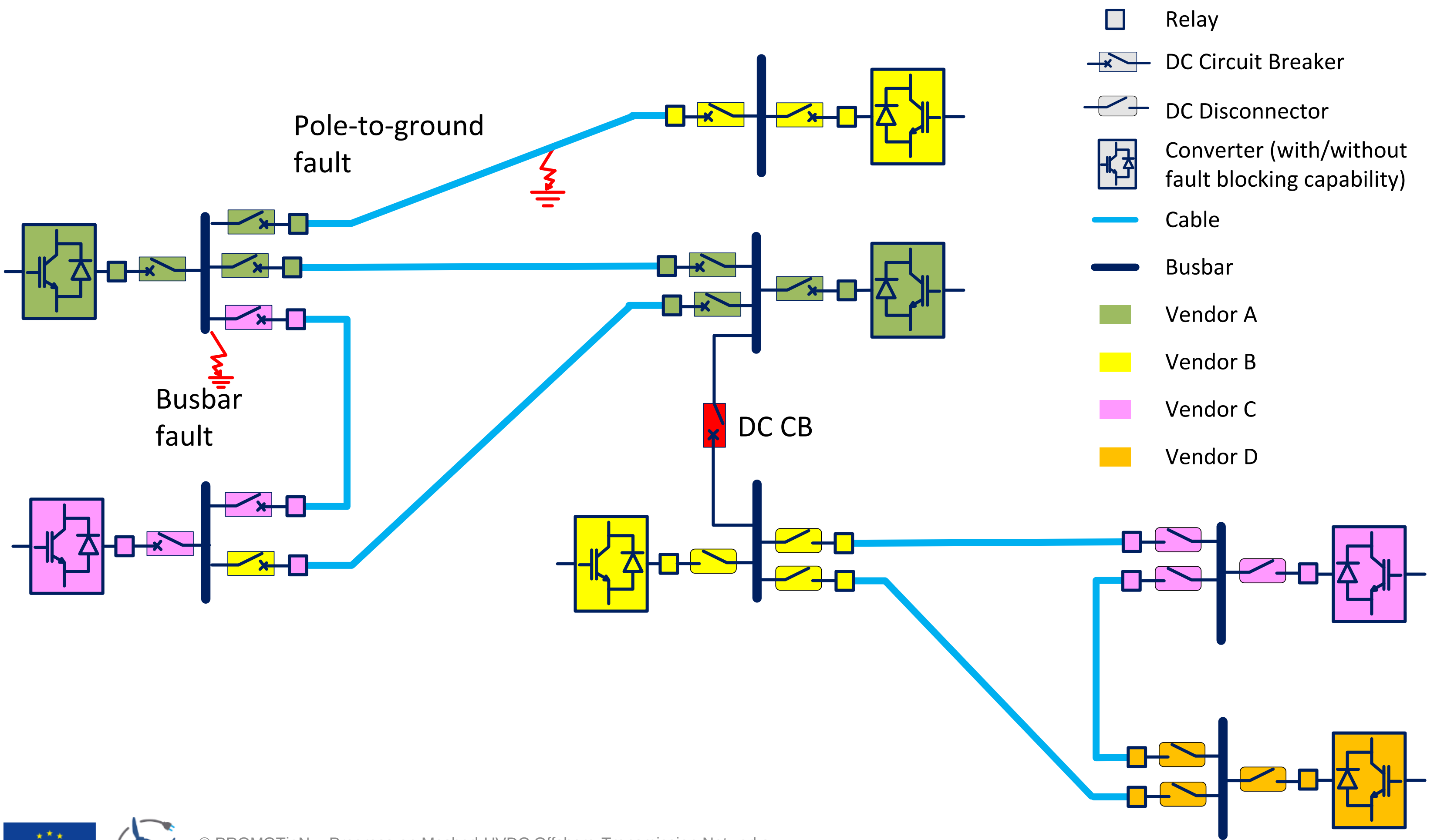
Towards an HVDC grids with the most appropriate, cost effective, multi-vendor protection system



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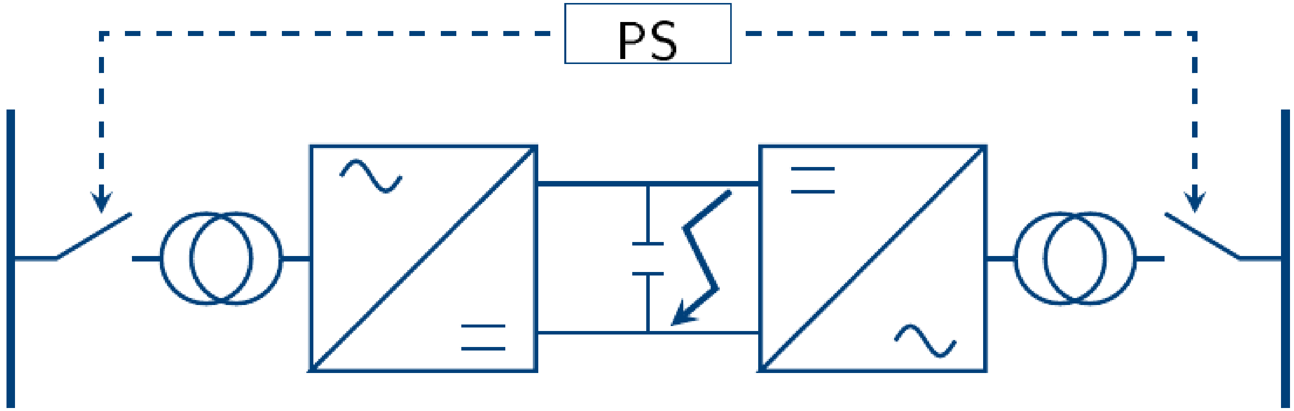
DC grids and DC grid protection

- VSC HVDC is receiving massive attention from industry, especially for offshore connections and interconnectors
- DC grids are seen as a logical evolution
  - Offering redundancy
  - Possible cost savings
- DC grids require protection
- Current VSC HVDC protection: at the AC side
  - ➔ not a good solution for the future pan-European grid



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WP4: develop multi-vendor protection systems

- ↗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 identify the best performing methods for the systems under study
- ↗to develop detailed protection methodologies for the selected methods
- ↗to develop configurable multi-purpose HVDC protection IEDs to enable testing of the methodologies
- ↗to investigate the key influencing parameters of protection systems on the cost-benefit evaluation

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What are our expectations of DC grid protection?

- Protection system: What to protect?
  - Humans
  - System
  - Components
- For the AC system:
  - After single fault, selective protection system clears fault
  - Backup protection if that fails
  - Protection operates in 60 – 200 ms
  - Operated N-1: no single credible fault/contingency causes large sustained outage
    - Expected behavior at a single line fault
    - Expected behavior at busbar fault
    - Expected behavior at fault at lower levels (e.g. distribution)
    - Fault ride through behavior of wind farm
  - 3 GW / 1.8 GW / … maximum loss of infeed

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What are our expectations of DC grid protection?

- What about the DC grid?
  - Same as AC?
  - Which reliability?
  - Are the limits (delays, power loss,…) the same?
  - What are relevant faults at the DC side
    - Pole to pole?
    - Pole to ground?
    - Busbar?
  - What is the accepted behavior at the DC side
  - AND the connecting AC systems
    - Continental Europe, Ireland, offshore wind, offshore load
  - Do we expect the same for all systems?
    - Small --> medium --> large

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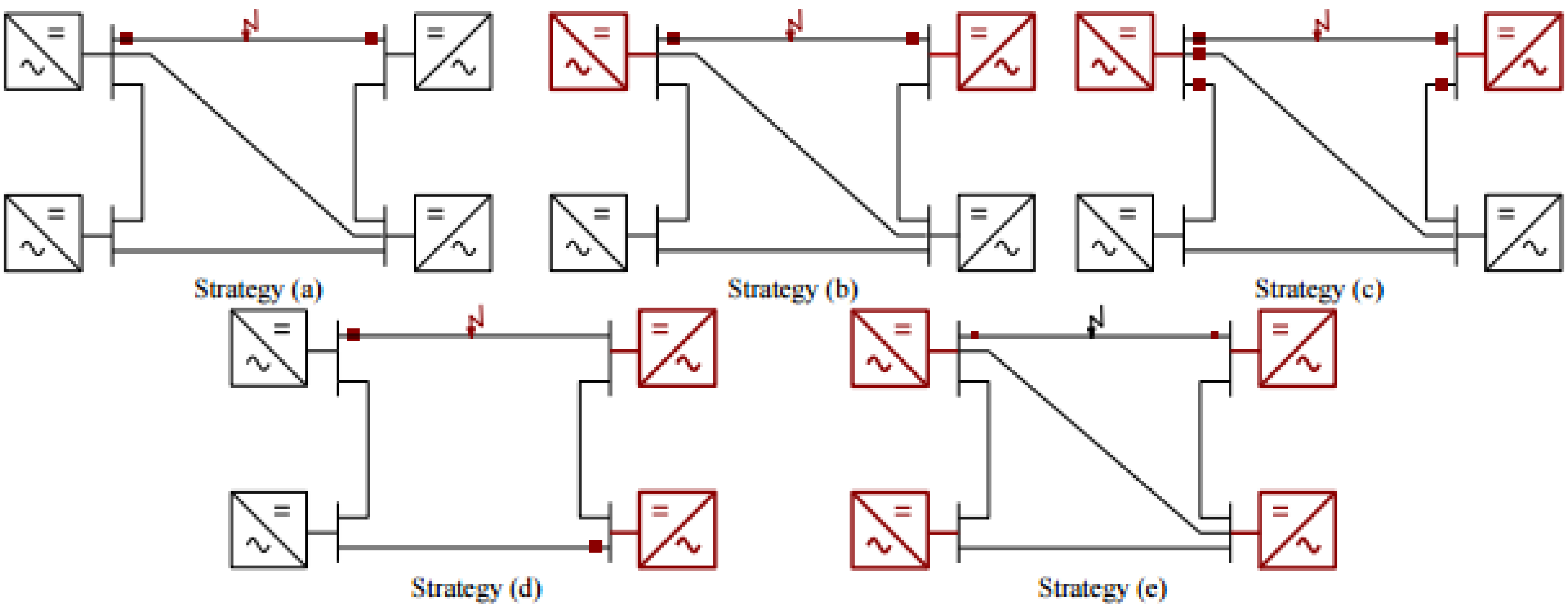
Overview: Fault clearing strategies (zones-impact)

- ↗Type (a) line protection : impact only on the faulty line
- ↗Type (b) line+ protection : impact on the faulty line and on the closest MMC converter
- ↗Type (c) open grid protection : impact of all the breakers at a bus
- ↗Type (d) grid splitting protection : impact only on the faulty zone
- ↗Type (e) low-speed HVDC grid protection : impact on the entire grid



Functional requirements?

System and components constraints

Expected performance for DC grids (small, medium and large)
- Various DC faults

→ Functional requirements for DC grids

- Current technology
- What is the limit now?
- What is the limit in 2050?

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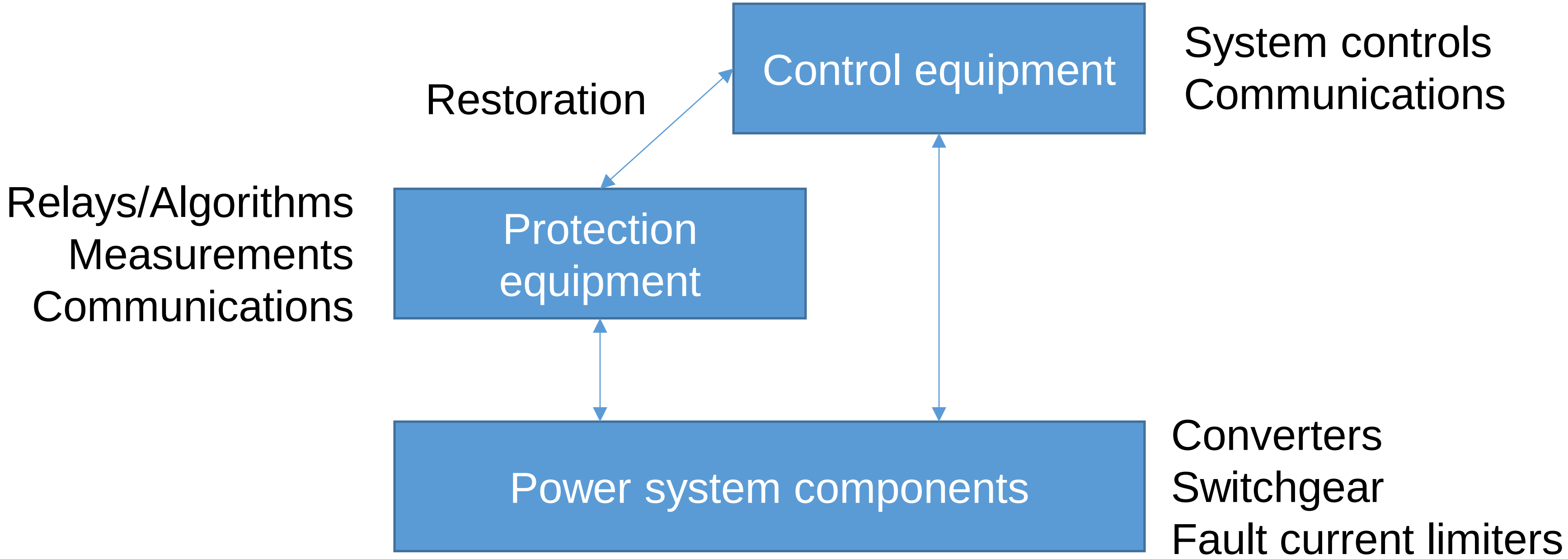
Components of DC grid protection: influencing eachother



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System functional requirements lead to requirements for protection

- Selectivity & speed
  - E.g., maximum portion of the grid which can be disconnected
  - Maximum time for which grid can be disconnected
- Backup protection
  - Lower probability, but higher impact
- Robustness towards system changes
- Suitable protection philosophies
  - Selective
  - Partly selective
  - Non-selective
- Suitable fault clearing strategies

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Protection requirements lead to requirements for protection components

- Protection algorithms
  - Speed
  - Selectivity
  - Sensitivity
  - Reliability
- Breakers
  - Speed
  - Interruption capability
  - Energy absorption capability
- Fault current limiters
  - Di/dt …
- Suitable candidates
  - Protection algorithms
    - Non-unit
    - Unit/Pilot
  - Breakers: Mechanical, Hybrid
  - Inductors/SFCL/…

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Why relevant? Faults occur and they influence the total system

- Potential Faults/events:
  - AC faults (single-phase-to-ground, three-phase-to-ground)
  - Outage of a converter
  - DC line faults (pole-to-ground, pole-to-pole)
  - DC busbar faults
- Potential effects on the AC & DC systems:
  - DC system: overvoltage, under voltage, overcurrent, DC grid instability, DC overload
  - AC system: overvoltage, under voltage, overcurrent, AC grid instability (transient stability, small signal stability, frequency stability), AC overload
  - ➔ what is acceptable?

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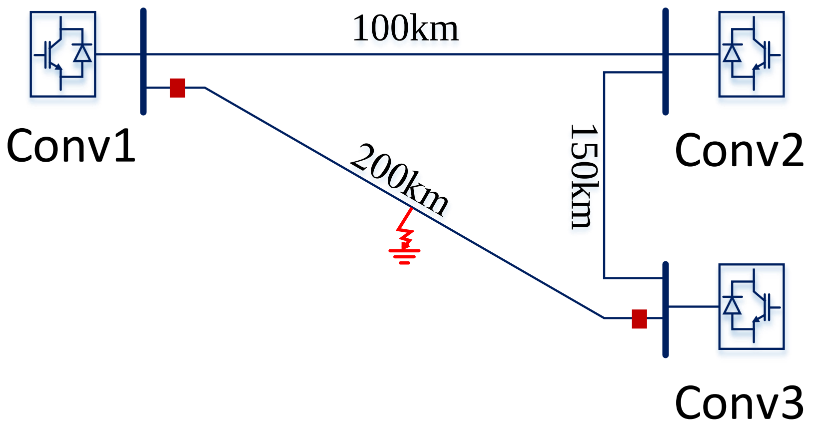
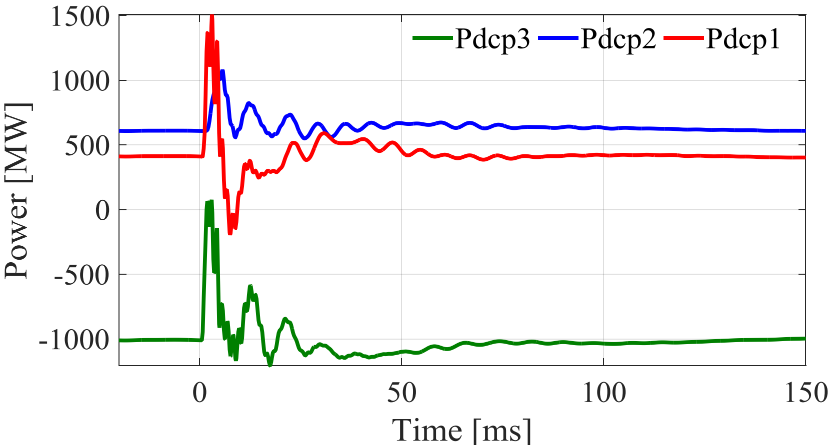
DC Line (pole-to-ground) fault: example 1

Utilizing fast selective DC protection (fault clearing ~5ms):

- DC system:
  - Possible overload post fault clearing
- AC system:
  - Very short transients



Test system: 3-terminal bipolar with metallic return



DC Power during and after pole-to-ground fault

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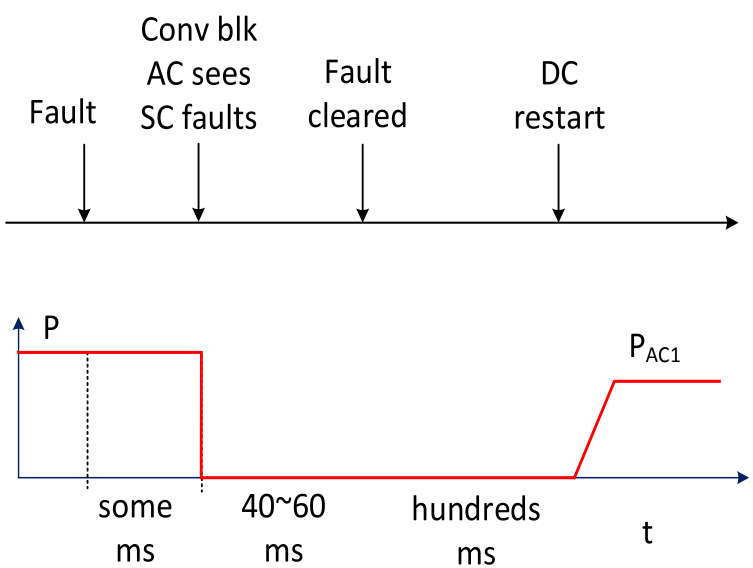
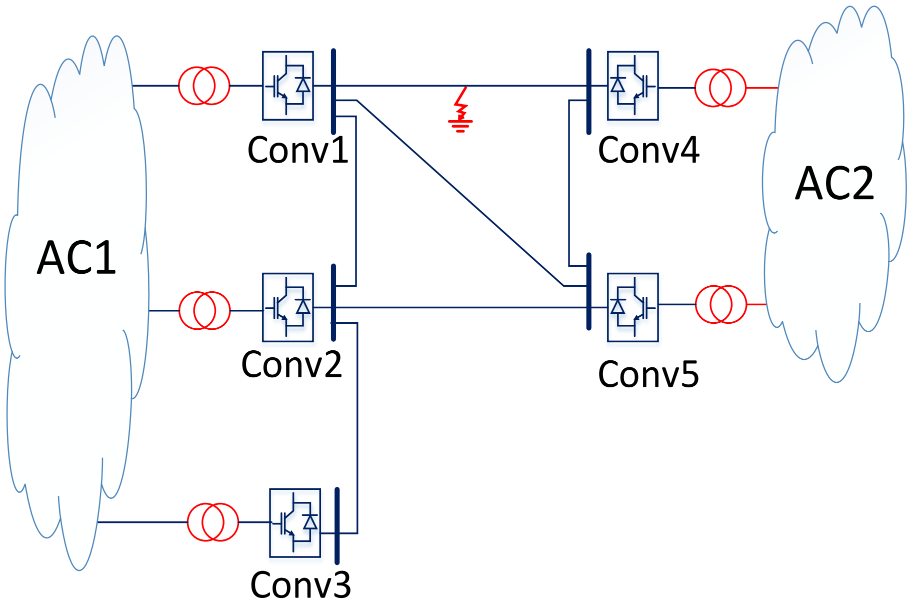
DC Line (pole-to-ground) fault: example 2

Utilizing AC circuit breaker for fault clearing (fault clearing 2~3 cycles):

- DC system:
  - Outage of the whole DC system
  - Possible large fault currents depending on grounding configuration
- AC system:
  - See multiple short-circuit faults once converters are blocked
  - Possible instability





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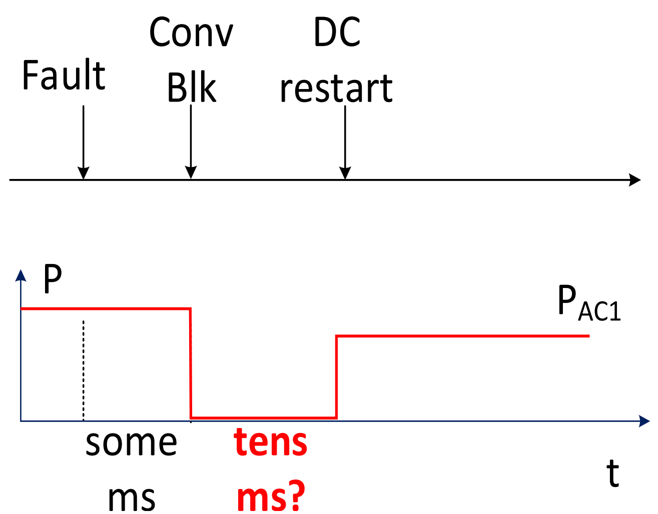
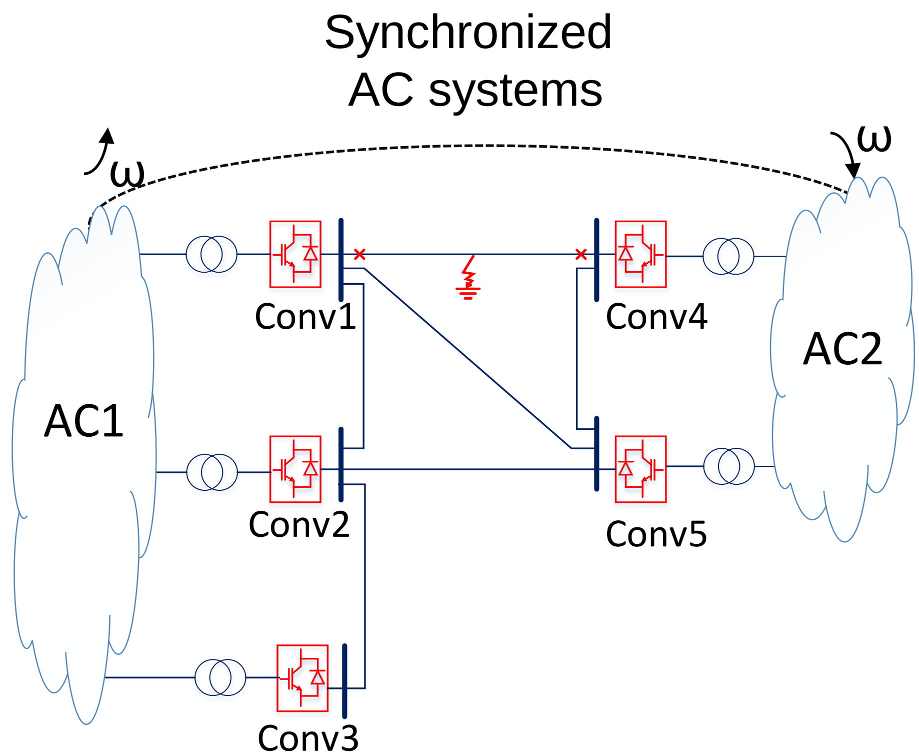
DC Line (pole-to-ground) fault: example 3

Utilizing converters with fault blocking capability:

- DC system:
  - Outage of the whole DC system
- AC system:
  - Short interruption
  - Possible instability
    - Asynchronous AC systems
    - Synchronous AC systems





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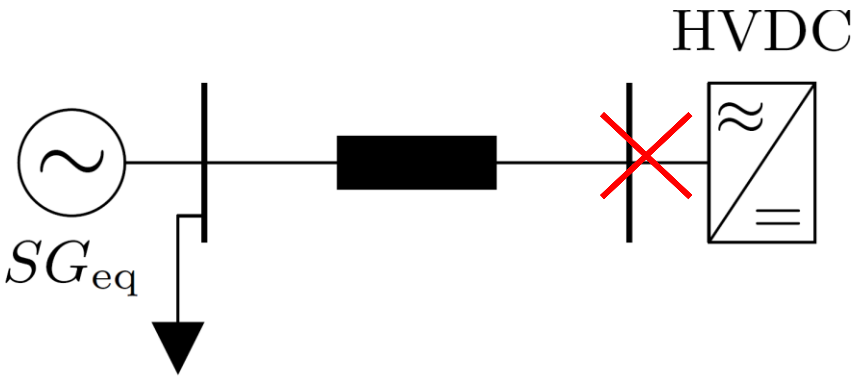
HVDC converter outage: influence on ac frequency and generator rotor angles

Simplified representation of ac system:

- Equivalent synchronous generator (SG_{eq}) with inertia constant H
- Droop control action is neglected within the considered time frame (0-0.2s)
- HVDC converter outage = Load step on synchronous generator



$$2 \cdot H \frac{d\omega}{dt} = \Delta P = P_{HVDC}$$

$$\frac{d\delta}{dt} = \omega_{base} \cdot (\omega - 1)$$

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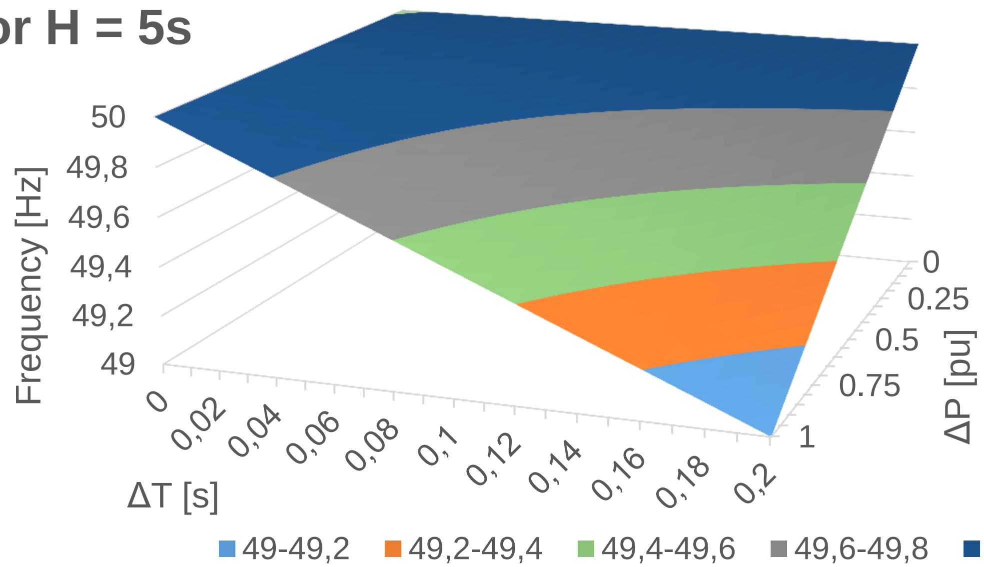
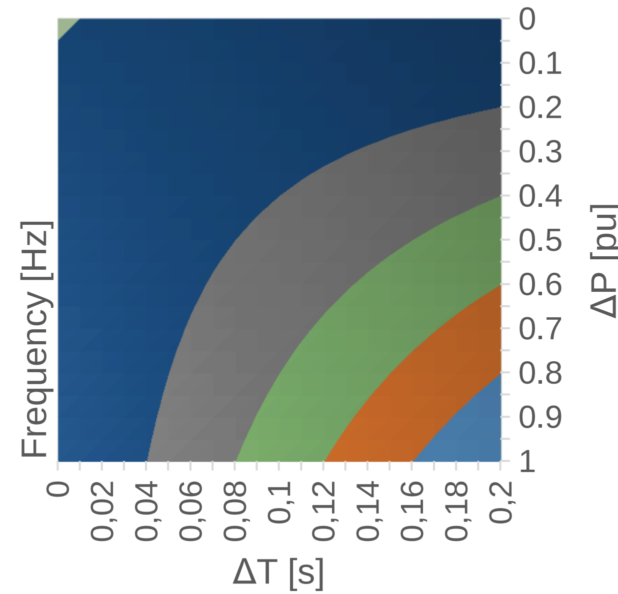
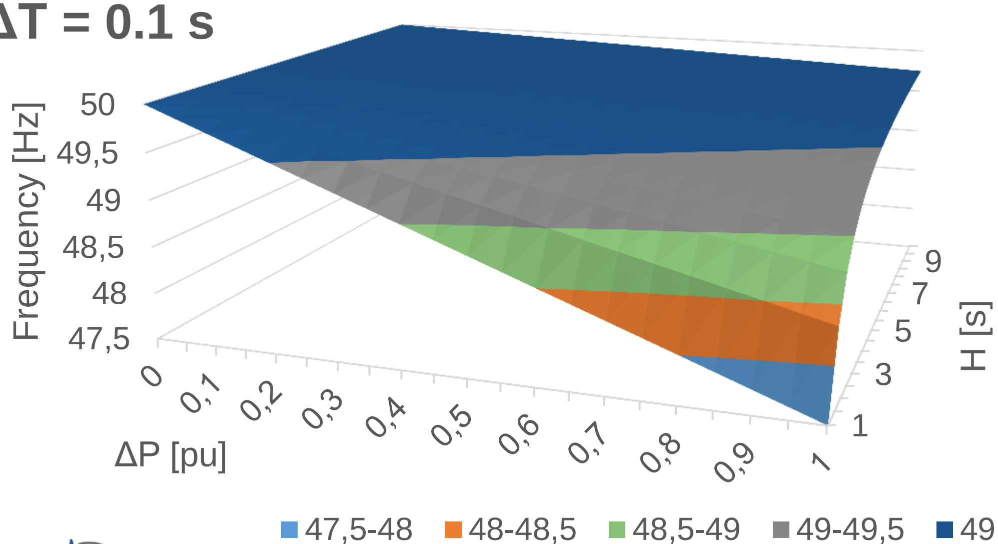
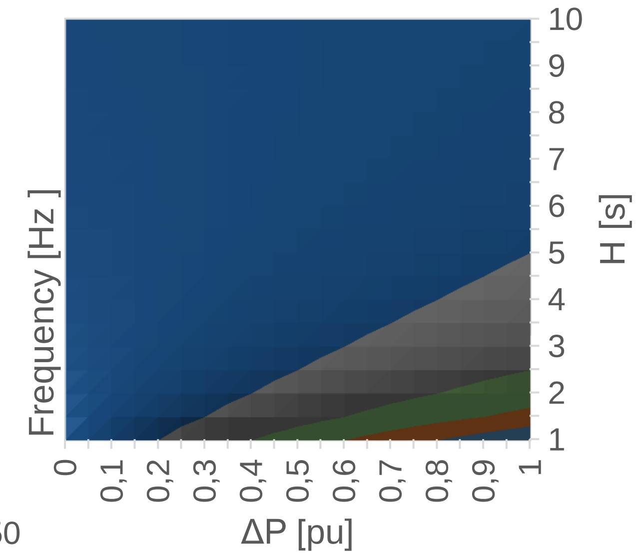
For H = 5s





For ΔT = 0.1 s





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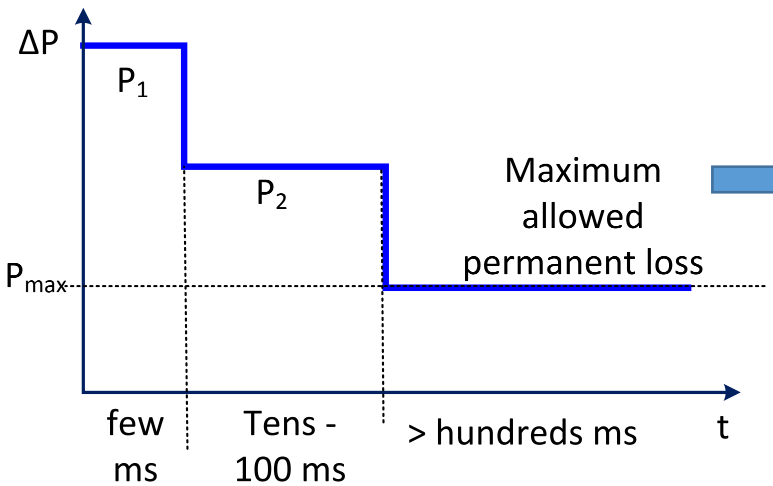
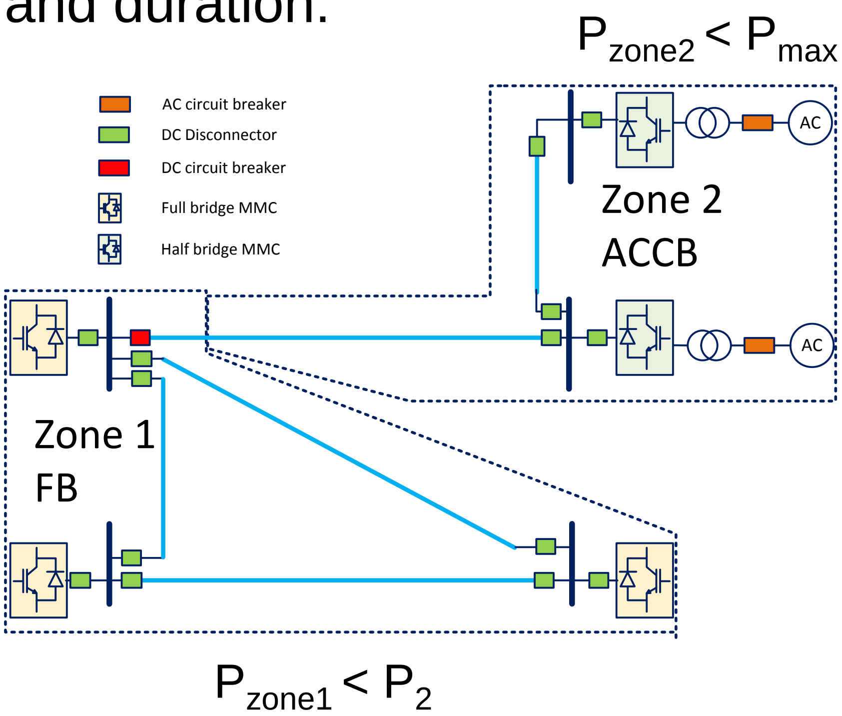
Constraints from synchronous AC Systems

↗Maximum loss of power infeed and duration:





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Constraints from asynchronous AC Systems

- Maximum temporary power loss and duration
  - at **a node**
  - to **a synchronous zone**
  - to **a control area**

- Voltage support requirement

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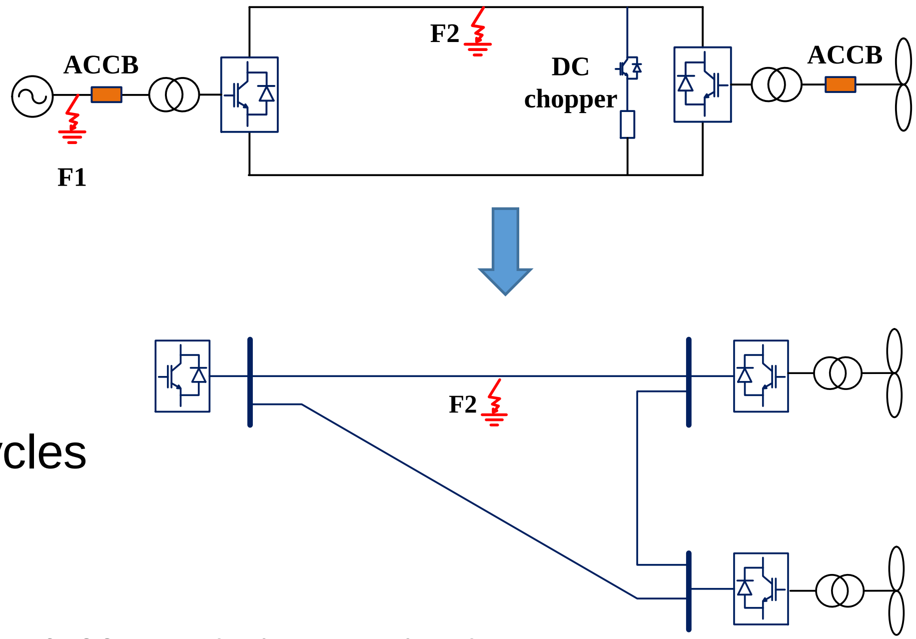
Constraints from wind farms

↗Point-to-point HVDC offshore links

- ↗AC fault ride-through: <u>hundreds ms </u>(e.g. 384 ms for 30% $V_{remaining}$ GB [1])
- ↗DC faults are protected using AC circuit breakers: <u>2~3 cycles</u>



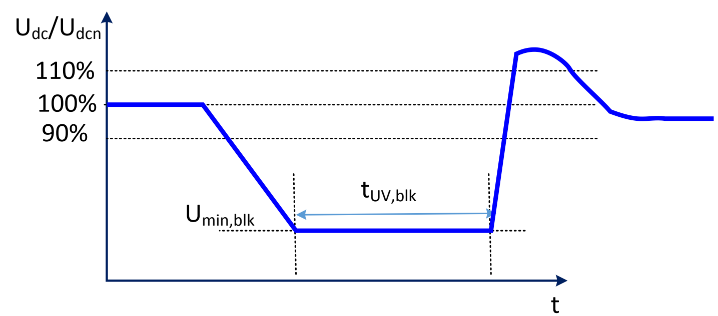
↗Constraints to DC grids:

- ↗Fault interruption: within 2 ~3 cycles
- ↗Converter DC LVRT capability?

[1] A. J. Beddard and U. Oj, "Factors Affecting the Reliability of VSC-HVDC for the Connection of Offshore Windfarms," PhD thesis, 2014.

Constraints from DC grid components

- Converter (for all types of converters):
  - U_{dc} at the converter terminal
    - Normal operation: 90% - 110%
    - Minimum voltage and duration for a converter has to stay unblocked: 0.8pu hundreds ms?
  - I_{arm} of the converter
    - IGBT (maximum instantaneous current limit):
      - 2 [pu] on maximum dc value allowed by IGBT
      - Future technology: SiC, GaN?
    - Diode/thyristors
      - Surge withstand capability [kA2t]



DC fault ride through capability

When a converter is allowed to be blocked and tripped

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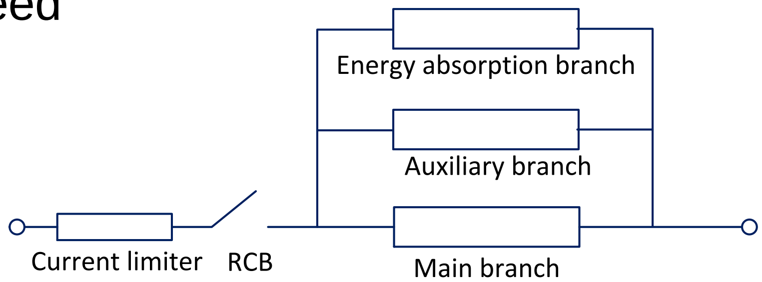
Constraints from DC grid components

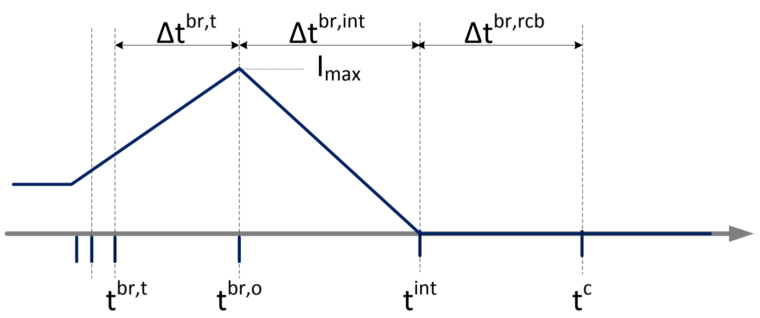
➔ Currently collecting inputs for different components

↗DC Circuit Breakers: constraints to relay speed

Parameter	Unit	Typical value	Foreseeable values(2030-2050)
Breaker tripping delay	[ms]	Hybrid: 2-3 ms, Mechanical: 5-10 ms	
Fault current interruption capability	[kA]	Hybrid: 5-10 kA, Mechanical: 10-16 kA	
Energy absorption capability	[MJ]	~ 10 MJ	
Bypass delay	[ms]	?	
Residual current interruption capability	[kA]	0.1 kA	
Maximum current rate of rise	[kA/s]	3-5 kA/s	
Maximum breaker surge arrestor voltage	[pu]	1.5	
Rated voltage	[kV]	320	500?



Structure of a DC circuit breaker



Fault interruption process

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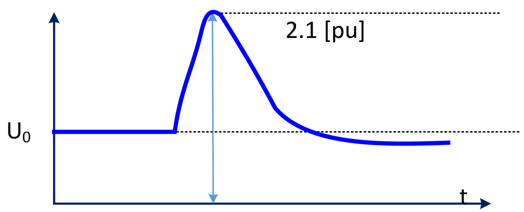
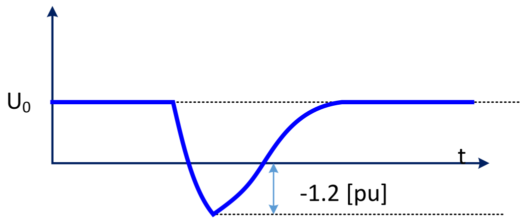
Constraints from DC grid components

↗Cable constraints [3]:

Parameter	Unit	Typical value	Foreseeable values(2030-2050)	Remarks
Lightning impulse withstand level	[pu]	2,1 (same polarity)		Lightning impulse withstand level
Switching impulse withstand level	[pu]	1,2 (opposite polarity)		Switching impulse withstand level
Maximum continuous dc voltage (applied during type and routine test)	[pu]	1,85		Maximum continuous dc voltage (applied during type and routine test for 15minutes)
Thermal overload limit	[pu]	?		

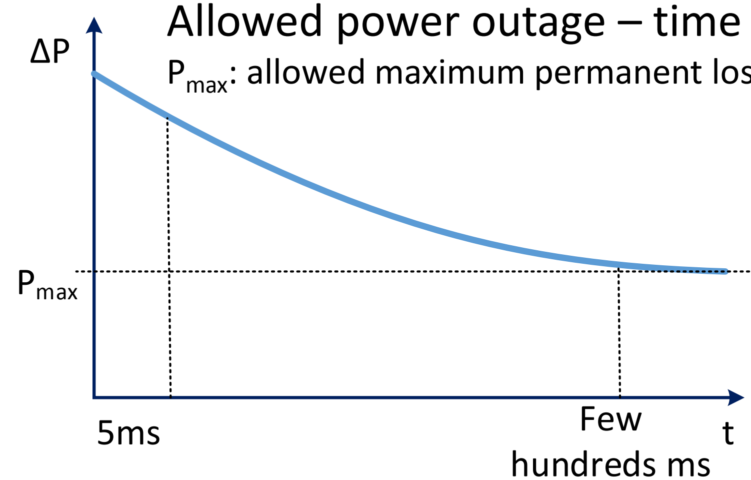


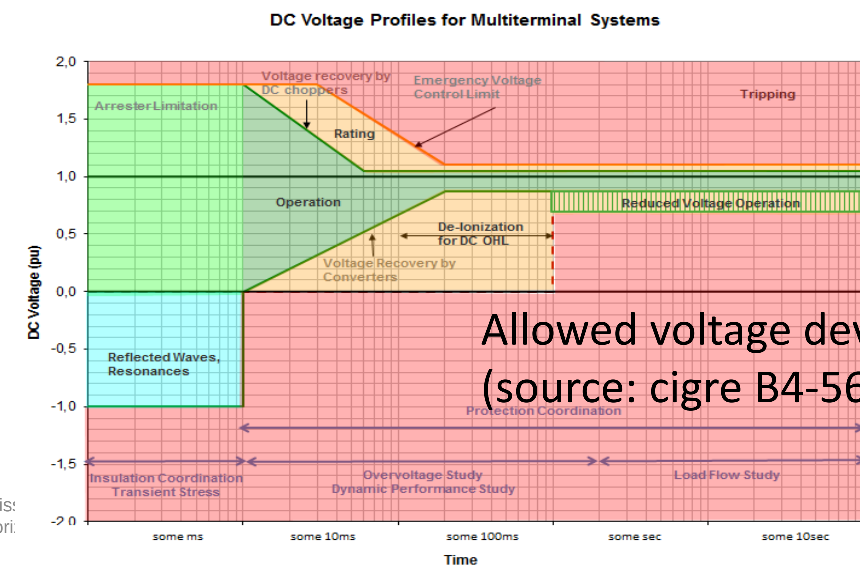


[3] Cigre WG B1.32 - Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 500 kV

Towards Functional Requirements of DC Grids

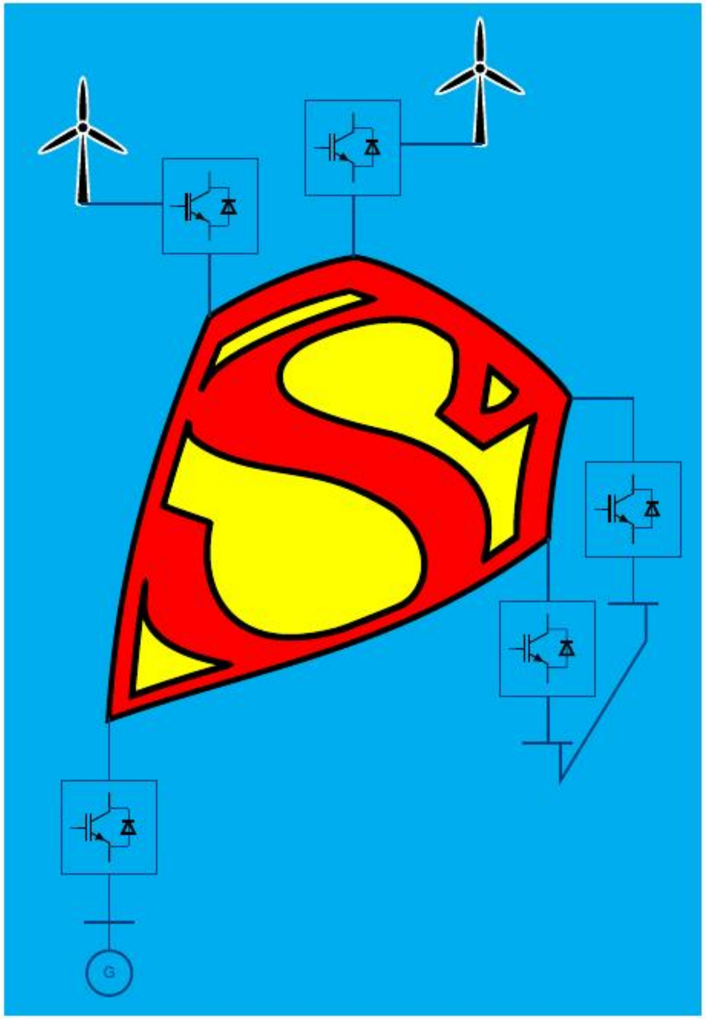
- Stress on AC and DC system
- AC side system fault ride through capability
- DC side voltage capability
- Chicken and egg problem: DC grid design depends on what we expect from its operations and operational expectations depend on the system in place
- What do we want as behavior? What is acceptable?

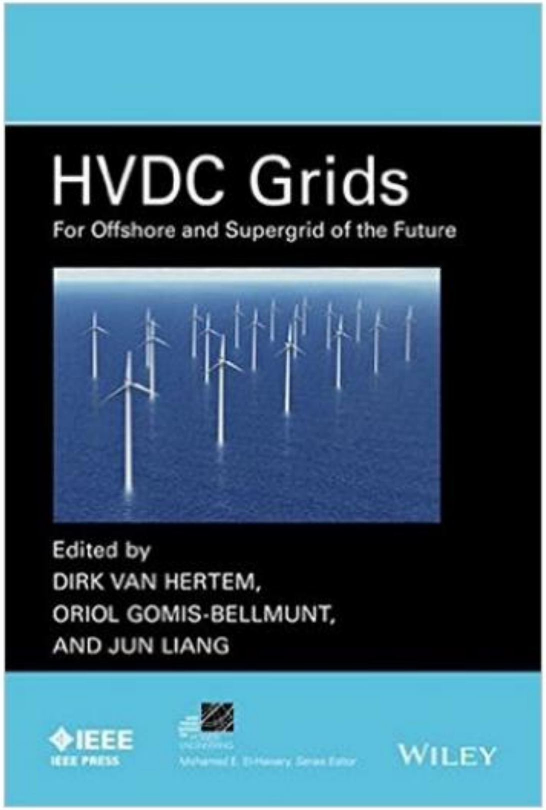




Allowed voltage deviations (source: cigre B4-56)

Questions?





Dirk Van Hertem
Dirk.VanHertem@esat.kuleuven.be

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APPENDIX

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PROJECT COORDINATOR

DNV GL, Kema Nederland BV
Utrechtseweg 310, 6812 AR Arnhem, The Netherlands
Tel +31 26 3 56 9111
Web www.dnvgl.com/energy

CONTACT

PARTNERS

Kema Nederland BV, ABB AB, KU Leuven, KTH Royal Institute of Technology, EirGrid plc, SuperGrid Institute, Deutsche WindGuard GmbH, Mitsubishi Electric Europe B.V., Affärsverket Svenska kraftnät, Alstom Grid UK Ltd (Trading as GE Grid Solutions), University of Aberdeen, Réseau de Transport d'Électricité, Technische Universiteit Delft, Statoil ASA, TenneT TSO B.V., German OFFSHORE WIND ENERGY Foundation, Siemens AG, Danmarks Tekniske Universitet, Rheinisch-Westfälische Technische Hochschule Aachen, Universitat Politècnica de València, Forschungsgemeinschaft für. Elektrische Anlagen und Stromwirtschaft e.V., Dong Energy Wind Power A/S, The Carbon Trust, Tractebel Engineering S.A., European University Institute, Iberdrola Renovables Energía, S.A., European Association of the Electricity Transmission & Distribution Equipment and Services Industry, University of Strathclyde, ADWEN Offshore, S.L., Prysmian, Rijksuniversiteit Groningen, MHI Vestas Offshore Wind AS, Energinet.dk, Scottish Hydro Electric Transmission plc