PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

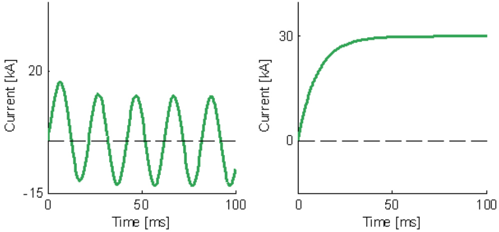
Protection of DC grids

Presentation Offshore Wind Energy 2017

Dirk Van Hertem, KU Leuven
June 7, 2017

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

Difference between AC and DC with respect to fault clearing



- No zero crossings in DC current ⇒ interruption of the arc?
- No fundamental frequency ⇒ relaying algorithms to detect the fault?
- Fast increase of DC current ⇒ speed?

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Why do we need to investigate DC grid protection?

- AC protection is well known: AC Breaker at each line end, good redundancy
- AC protection is moderate expense in total system cost
- DC system protection (VSC): currently at the AC side
- For DC grids: We do not know?
- Several option exist:
  - Opening AC breakers (disconnecting the entire DC grid)
  - Having DC breakers as in AC systems
  - New concepts:
    - Using fault current limiting converters
    - Fault current limiters in the grid (potentially superconducting)
    - ...
  - What is the optimal solution?
    - Technically
    - Economically
- DC grids give the opportunity/challenge to start from a clean sheet

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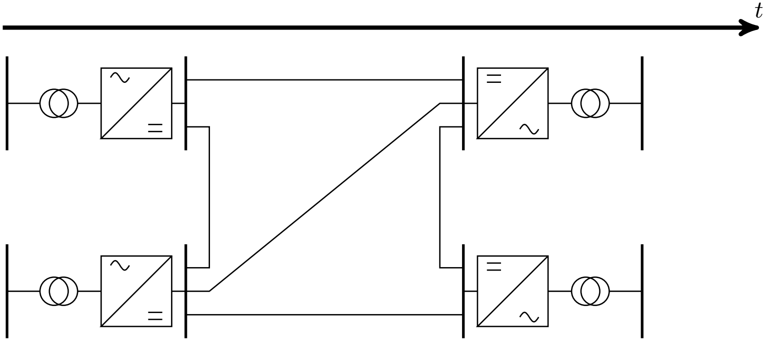
Line opening in a DC grid

Example: 4 terminal MT HVDC system



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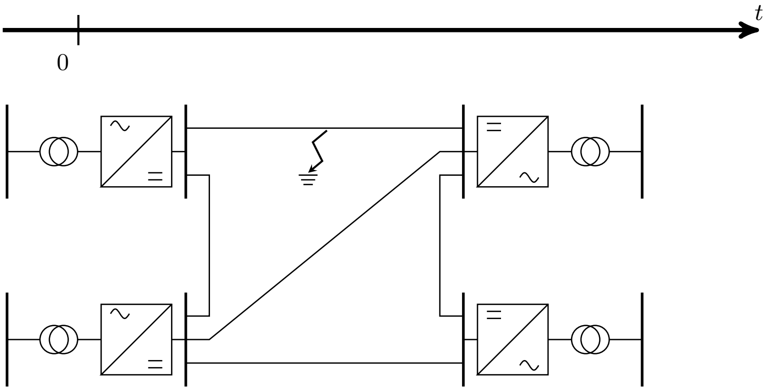
Line opening in a DC grid

Fault occurs in the DC circuit ($t = 0$)



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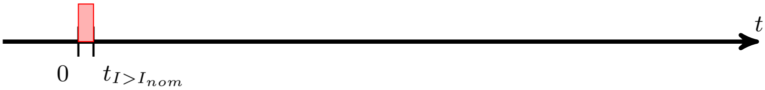
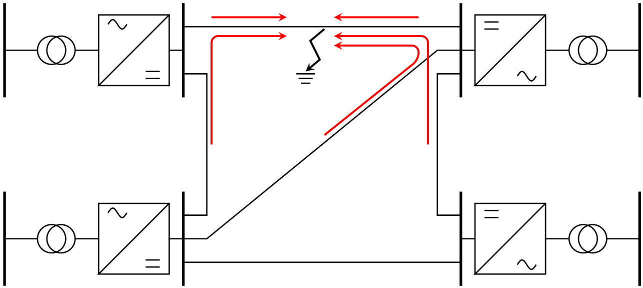
Line opening in a DC grid

high di/dt throughout the system: cable discharge





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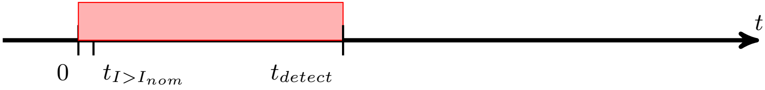
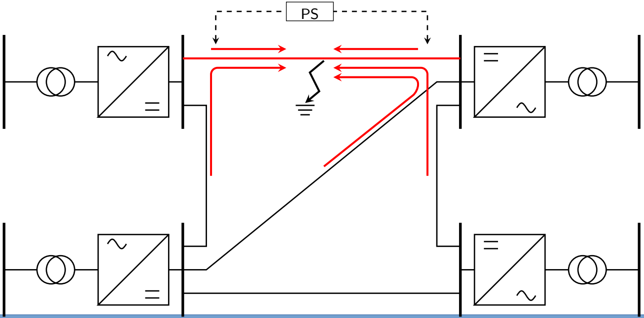
Line opening in a DC grid

Protection system must indicate the faulted line





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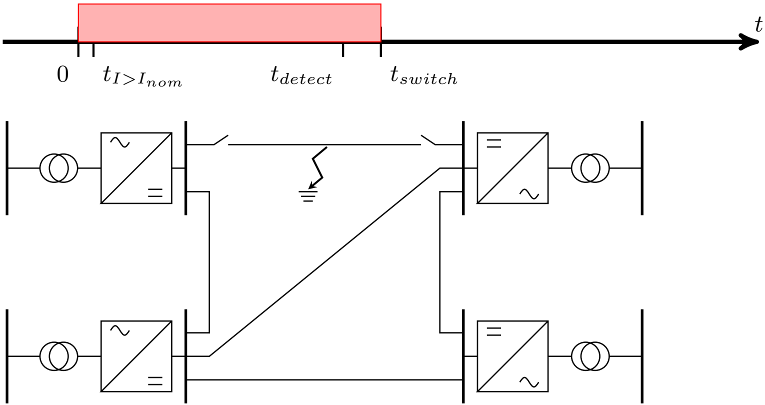
Line opening in a DC grid

Opening of the faulted line ($t < xms$)



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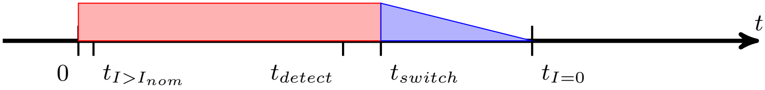
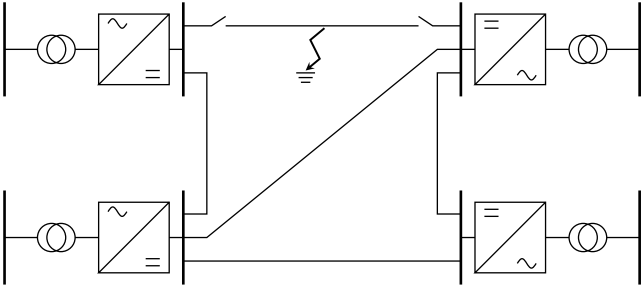
Line opening in a DC grid

While the breaker opening process is also in the ms time range





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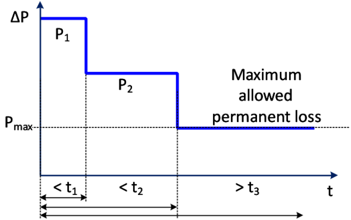
First step: determine requirements

- Defined fuctional requirements: what do we expect from the protection system?
  - for components
  - for subsystems
- DC side limitations need to be defined
- Loss of infeed to an AC node/zone/system: variable over time, dependent on the system
- Defined small, medium and large impact systems + benchmark systems with potential faults
- Identified faults in DC systems in these zones and made preliminary assessment



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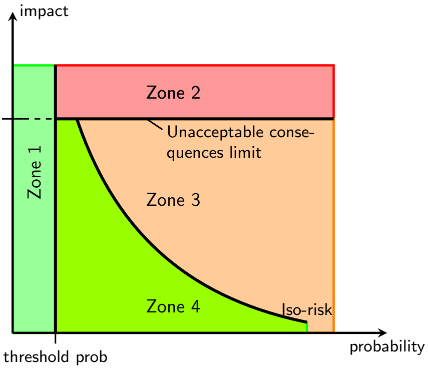
Ideal solution: Risk based protection system design

- Zone 1: out of norm
  - Highly unlikely
  - No particular protection design to address them
- Zone 2: unacceptable consequences
  - High impact, high probability
  - Reduce probability or impact (e.g., by adapting system design or protections)
- Zone 3: unacceptable risk
  - Medium impact, med-high probability
  - Adaptation protections needed
- Zone 4: acceptable risk
  - Low impact, med-high probability
  - No actions necessary
- Example:
  - Probability of a pole-to-pole fault in a cable vs overhead line



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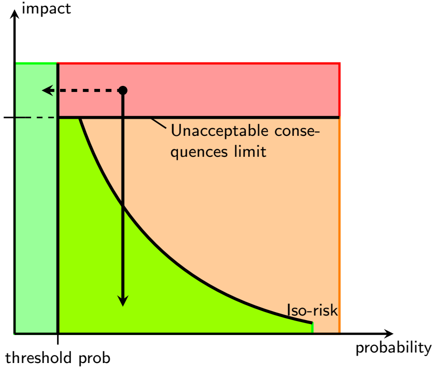

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Benchmarking different fault clearing strategies

- Step 1: a literature study of fault identification methodologies and protection philosophies
- Step 2: qualitative assessment of fault clearing strategies. Linking protection with specific systems (protection matrix concept)
- Step 3: quantitative (high level) assessment of fault clearing strategies using selected simulation tests
- Develop a benchmarking tool/approach for different protection methods
- Comparative study and analysis of different approaches, with different breaker technologies using protection matrices
- Robustness of schemes
- Backup approach
- Effect of inductors, OHL/Cable, grounding,...

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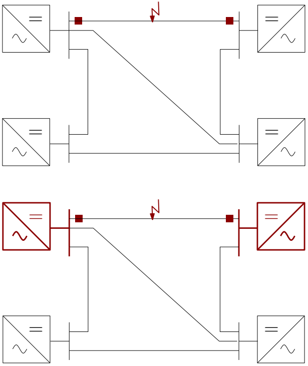
Fault clearing strategies under investigation

- Selective fault clearing strategies
  - Selective with breakers (different opening times, unidirectional - directional)
  - Different backup options (e.g. breaker between busbar and converter)
  - Superconductive fault current limiters
- Non-selective fault clearing strategies
  - Non-selective with AC breakers
  - Open Grid
  - Non-selective with full bridge MMC
  - Non-selective with DCCB at converter terminals
- Partially selective fault clearing strategies
  - Grid splitting using DCCB
  - Grid splitting using fault current limiters
  - Grid splitting using DCDC converter

Example primary fault clearing strategies

Selective:



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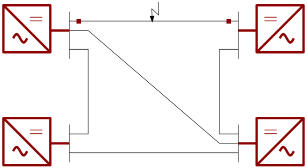
Example primary fault clearing strategies

Non Selective:



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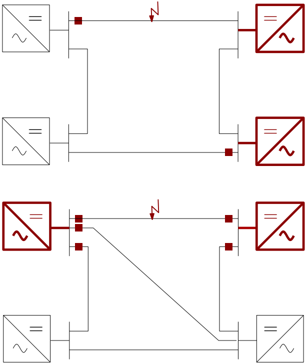
Example primary fault clearing strategies

Partially Selective:



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Performed studies

- Feasibility of fault clearing strategy considering AC network constraints (yes/no)
- Component requirements (investment cost)
- Achieved reliability (risk analysis)
- Extensibility (investment cost/feasibility)
- Multivendor/Multi-TSO (discussion)
- Robustness assessment

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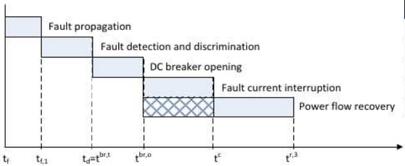
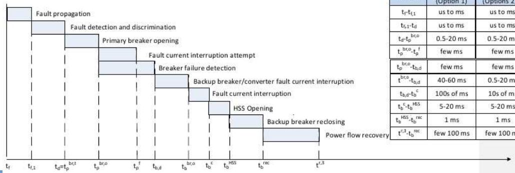
Detailed understanding of protection processes: timing diagrams for each strategy

- Setting up timing diagrams for primary protection
- ... and backup protection(s)



Interval	Duration
t_f-$t_{f,1}$	us to ms
$t_{f,1}$-t_d	us to ms
t_d-$t^{br,o}$	2-10 ms
$t^{br,o}$-t^c	few ms
$t^{br,o}$-$t^{r,3}$	tens of ms



Interval	Duration (Option 1)	Duration (Options 2,3)
t_f-$t_{f,1}$	us to ms	us to ms
$t_{f,1}$-t_d	us to ms	us to ms
t_d-$t_p^{br,o}$	0.5-20 ms	0.5-20 ms
$t_p^{br,o}$-t_p^f	few ms	few ms
$t_p^{br,o}$-$t_{b,d}$	few ms	few ms
$t^{br,o}$-$t_{b,d}$	40-60 ms	0.5-20 ms
$t_{b,d}$-t_b^c	100s of ms	10s of ms
t_b^c-t_b^{HSS}	5-20 ms	5-20 ms
t_b^{HSS}-t_b^{rec}	1 ms	1 ms
$t^{r,3}$-t_b^{rec}	few 100 ms	few 100 ms

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Protection matrix approach

- Matrix setup to evaluate how different faults in the system will affect the system
- Different faults in the system
  - Those the primary protection should cover
  - Other faults
- Influence on the connecting system
- Each combination is investigated to see whether there will be:
  - Continuous operation
  - Temporary stop
  - Permanent stop

Table 4-1 Protection matrix structure for the small benchmark network

Zone \ AC system		AC_1 C_1	AC_2 C_2	WF_1 C_3	WF_2 C_4	Protection equipment in operation
1	$F_{L1,ptg}$					
2	$F_{L2,ptg}$					
3	$F_{L3,ptg}$					
4	$F_{L4,ptg}$					
	$F_{L1,ptp}$					
	$F_{L2,ptp}$					
	$F_{L3,ptp}$					
	$F_{L4,ptp}$					
	$F_{B1,ptg}$					
	$F_{B2,ptg}$					
	$F_{B4,ptg}$					
	$F_{B1,ptp}$					

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Table 5-2 Selective fault clearing with DC circuit breakers with pole-to-ground interruption capability – Primary protec

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
	$F_{L1,ptp}$	PS	PS	PS	PS	
	$F_{L2,ptp}$	PS	PS	PS	PS	Br_{AC1}, Br_{AC2},Br_{AC3},Br_{AC4}
	$F_{L3,ptp}$	PS	PS	PS	PS	
	$F_{L4,ptp}$	PS	PS	PS	PS	
	$F_{B1,ptg}$	PS	CO	PS	CO	Br_1, Br_3, Br_5, (Br_{AC1}/Br_{c1}/C1)
	$F_{B2,ptg}$	CO	PS	CO	CO	Br_6, Br_7, (Br_{AC2}/Br_{c2}/C2)
	$F_{B4,ptg}$	CO	CO	CO	PS	Br_4, Br_8, (Br_{AC4}/Br_{c4}/C4)
	$F_{B1,ptp}$	PS	PS	PS	PS	
	$F_{B2,ptp}$	PS	PS	PS	PS	Br_{AC1}, Br_{AC2},Br_{AC3},Br_{AC4}
	$F_{B4,ptp}$	PS	PS	PS	PS	

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Detailed analysis on parameters

- A number of parameters/configurations is investigated with each strategy to assure robustness of solutions

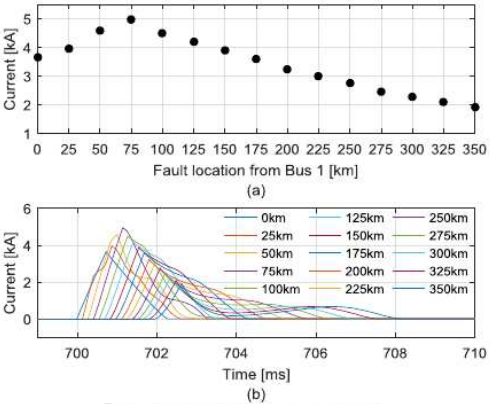

Figure 5-6 Case 1 - Maximum current in breaker Br_5

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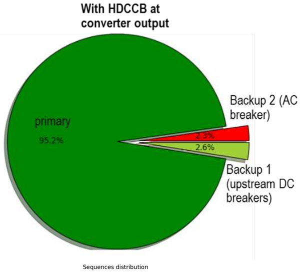
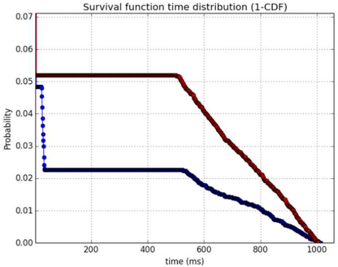
Risk assessment

- Based on a Monte Carlo Petri Net methodology (MCPN). Petri Net representation allows a quite easy modelling of the protection system dynamics (succession of events) on the basis of both flowchart and time chart descriptions
- Also allows to describe the protection system architecture including physical links between the different components (relays, DC CBB, High speed switch,. . .)





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Benchmark table

	MAIN COST DRIVER	RISK CATEGORY		EXTENSIBILITY		FEASIBILITY		
		Primary	Backup	PS->TS	TS->CO	Small impact	Medium impact	Large impact
FS DCCB Option 1	DCCB			✓	✓	✓	✓	✓
FS DCCB Option 2	DCCB and Converters			✓	✓	✓	✓	✓
FS DCCB Option 3	DCCB			✓	✓	✓	✓	✓
FS SFCL	SFCL			✓	✓	✓	✓	✓
NS ACCB	/			✘	✘	✓	✘	✘
NS FB	FB			✓	✘	✓	✓	✘
NS DCCB	DCCB			✓	✘	✓	✓	✘
NS SFCL	SFCL			✓	✘	✓	✓	✘
ParS ACCB/DCCB	DCCB			✘	✘	✓	✓	✓
ParS FB/DCCB	DCCB/FB			✓	✘	✓	✓	✓
ParS DCCB/DCCB	DCCB			✓	✘	✓	✓	✓
Pars ACCB/DCDC	DCDC Conv			✘	✘	✓	✓	✓

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Preliminary conclusions D4.2:

Report on the broad comparison of protection philosophies for the identified grid topologies

- Considering the DC grid as a single entity, depending on AC breakers is the cheapest, but offers least protection
- Alternative grid protection exist, also without using DC breakers
- More elaborate protection systems offer higher protection, with lower probability of ending in a backup state
- On smaller impact systems: all approaches are valid
- Medium impact systems: advanced options are necessary
- Larger impact systems: a selective approach with DC breakers likely
- Extensibility:
  - Limits to non-selective methods extensibility
  - Selective methods: same approach can be extended, yet might still not be plug and play
- Actual evaluation depends on many (currently unknown) parameters:
  - Grid configuration
  - Actual system and system expectations
  - Component costs
  - Component reliability

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Next steps

- Further detailing selected strategies (from concepts to engineering solutions)
- Develop programmable IED (protection relay) which can test several approaches
- Demonstrate that the fault clearing strategies work as expected under realistic conditions
- Testing performed in the new HVDC Centre using newest hardware in the loop environment

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Questions?

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

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APPENDIX

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PROJECT COORDINATOR

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

CONTACT

Dirk Van Hertem

KU Leuven/EnergyVille

dirk.vanhertem@esat.kuleuven.be

PARTNERS

Kema Nederland BV, ABB AB, Katholieke Universiteit 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), The University Court of the 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

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