Neptune
Closing event

Dirk Van Hertem – September, 27th 2023

Where do we need to go?

Ambitious goals

- 300-> 450 GW of offshore wind by 2050
- Offshore requires massive investments (EC: 2/3rd of 800 Billion by 2050)
- Solar and onshore wind need grids
- Meshed HVDC grids are the only realistic option:
    - Connections are increasingly further from shore
    - Needs to be integrated in the existing system (hybrid AC/DC)
    - Towards new backbone grid

We need to connect 200+ GW from the north sea
➔ Assume 5 GW links

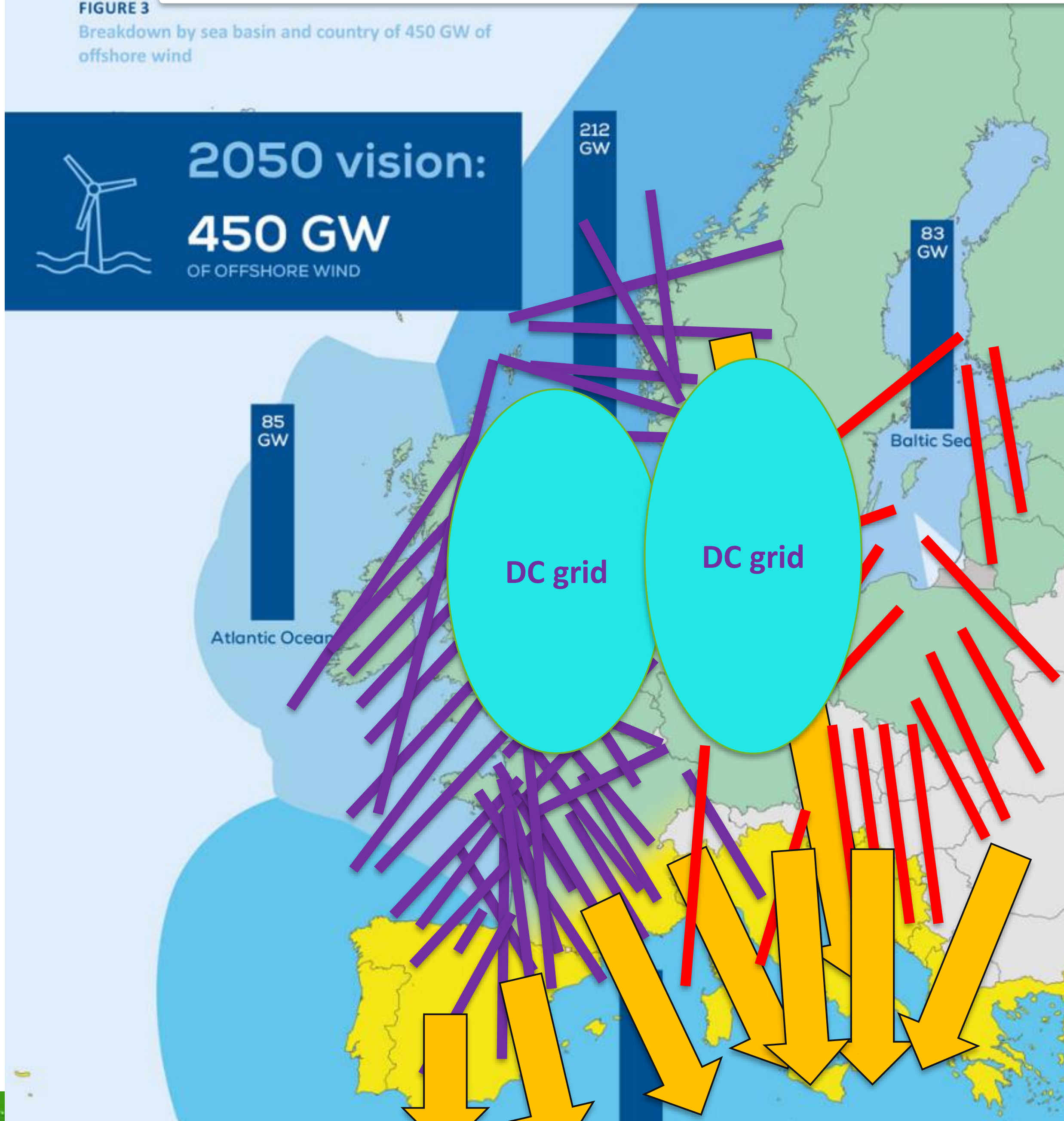
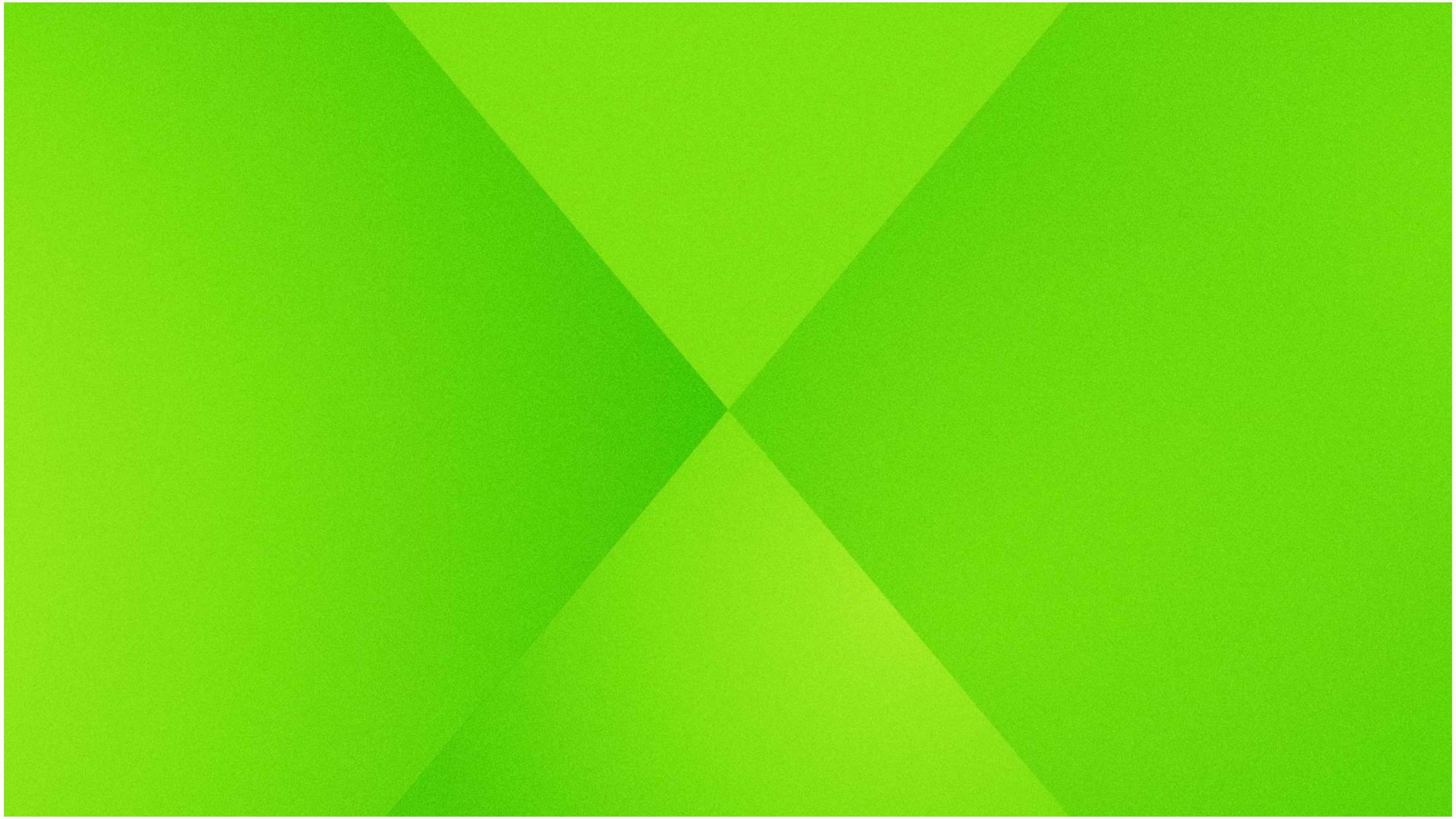


Figure: WindEurope

Neptune objectives

1. *To develop new methods and tools for more reliable and cost-effective **offshore grid expansion planning**, using HVDC systems. (WP1)*
2. *To ensure more reliable HVDC grid operation using innovative and conventional **protection** devices and algorithms **validated using laboratory hardware tests**. (WP2)*
3. *To ensure **interoperability** in order to avoid unexpected outages in offshore systems. (WP3)*
4. *To provide **recommendations for future grid codes** related to system protection and converter control. (WP2&3)*
5. *To develop competences and knowledge base, essential **for the Belgian offshore industry**, technology vendors and transmission system operator. (WP1-3)*
6. *To **accelerate the offshore grid development** in Belgium as an integrated part of the interconnected European power system, towards a supergrid. (all WPs)*

Neptune, the movie



Plan

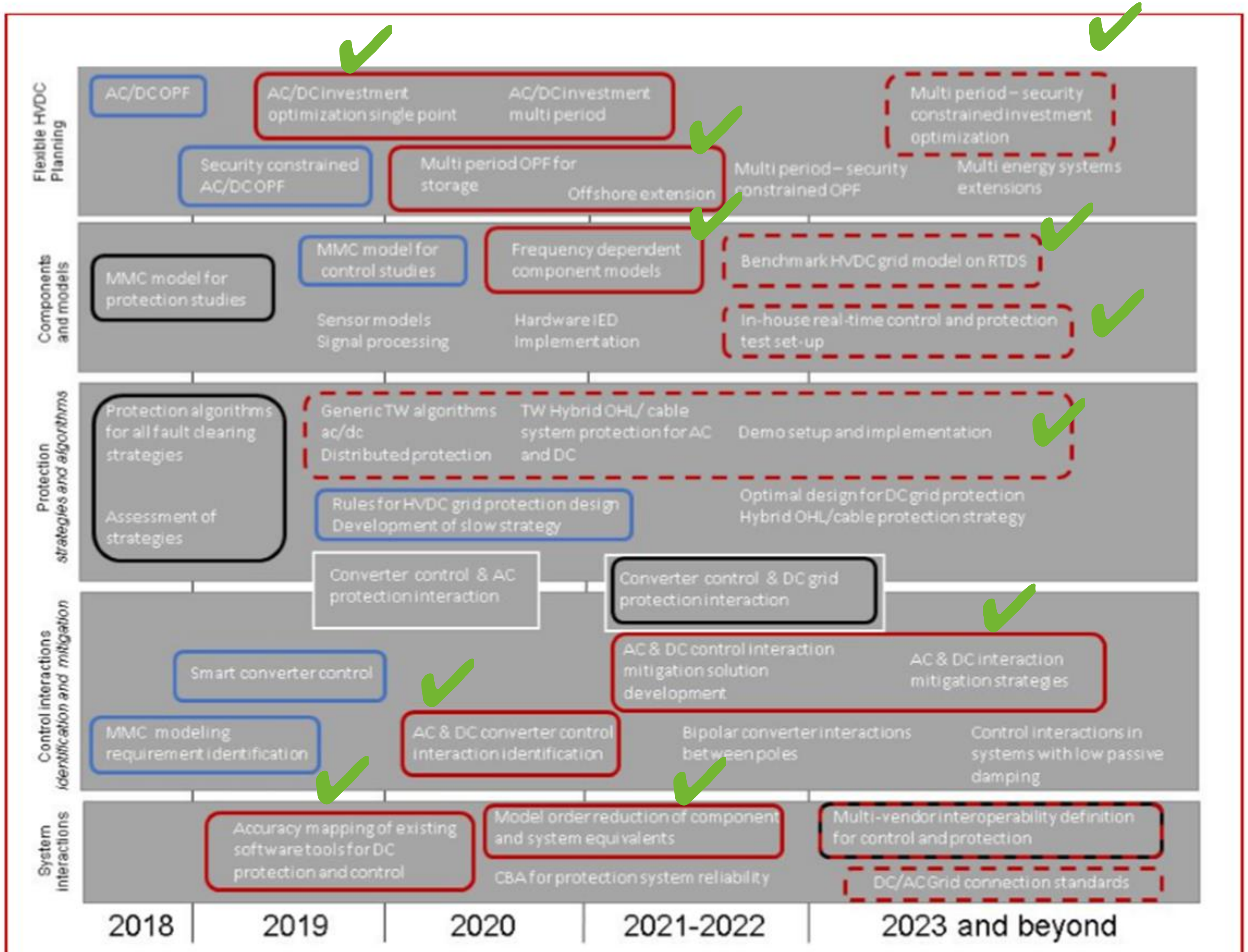


Fig. 2: R&D roadmap indicated expected research outcomes related to (offshore) HVDC grids: Red: NEPTUNE project; Blue: Industry contract; Black: public funded R&D --- Full line: full contributions, - - - dashed line: partial contribution

Advisory board

15 members

4 meetings (2 online COVID)

- FOD econ
- Elia
- Engie Fabricom → Equans
- Ampacimon
- RTE
- ABB → Hitachi Energy
- Siemens → Siemens Energy
- Nemo Link
- (CG Power Systems)
- Borealis
- TenneT
- Blauwe Cluster

- UPC
- DTU
- University of Manchester

Results

>30

number of publications

>15

number of keynote presentations and invited talks

>22

number of deliverables

>50

number of involved researchers

>6

number of PhD's from Neptune

>20

number of follow up projects

Results: workforce

>50

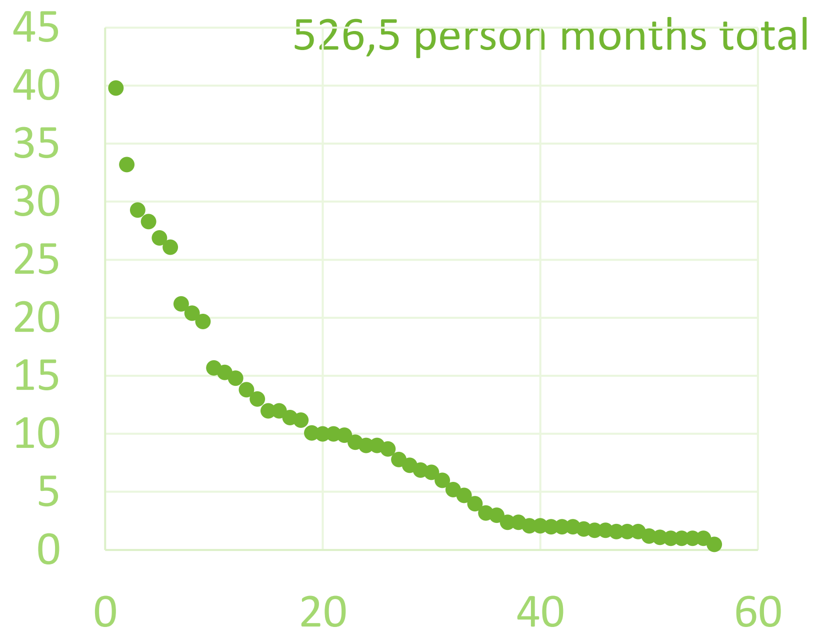
number of involved researchers

- Academia 70 % (ongoing)
- Industry 14 %
- TSO 12 %
- Consultant 5 %

- KUL 49 %
- Non-KUL 21 %

5 professors*

- 65 % Belgium
- 30 % Europe
- 5 % World



Results: Accelerator for research

>20

number of follow up projects

C3 DC relay protection
C3 Brisksim
Joint PhD Edinburgh

Cordoba

HC^3

economie

FOD Economie, K.M.O., Middenstand en Energie

Trilate
Directions
Sterna2050

DC4EU
Adored
Inter-Open

FlexPlan

elia

European Commission

WindGrid
Elia Group

TRANSNET BW

Rte

ENGIE Laborelec

ENOWA

CREG

SUPERNODE

Neptune

Energy Ville

Agenda before noon

- 10.00h: Welcome & introduction, **Prof. Dirk van Hertem (EnergyVille / KU Leuven)**
- 10.15h: Vision on Offshore wind energy, Minister of Energy **Tinne Van der Straeten**
- 10.30h: Keynote: Modern power systems dominated by power electronics and HVDC, **Prof. Oriol Gomis Bellmunt, (UPC)**
  11.00h: Offshore and Onshore Grid Planning, **Hakan Ergun, Ph.D (EnergyVille / KU Leuven)**
  - Dr. Jay Dave, (Consultant Siemens AG)
  - PhD. Kristof Philips, (EnergyVille / KU Leuven)
- 12.00h: Protection strategies and algorithms, **Willem Leterme, Ph.D (EnergyVille / KU Leuven)**
  - Prof Dirk Van Hertem (EnergyVille / KU Leuven)
  - Ing. Rick Loenders (EnergyVille / KU Leuven)
- 13.00h: Lunch & posters

Agenda afternoon

- 14.30h: Control interaction identification and mitigation, **Prof. Jef Beerten (EnergyVille / KU Leuven)**
  - Dr. Ozgur Can Sakinci, (EnergyVille / KU Leuven)
  - Prof. Goran Grdenic, (Department of Energy and Power Systems, University of Zagreb)
- 15.30h: Valorization & roadmap, **Prof. Jef Beerten (EnergyVille / KU Leuven)**
- 15.45h: Keynote: To HVDC or not to HVDC, **Prof. Nicolaos A. Cutululis (Department of Wind and Energy Systems, DTU)**
- 16.15h: Panel discussion, **Prof. Dirk Van Hertem**
  - Prof. Jef Beerten, Electrical Energy Systems and Applications, EnergyVille / KU Leuven
  - Dr. Mian Wang, Senior Consultant Network Studies, Siemens Energy
  - Ir. Tom Pietercil, Head of Department Engineering Standards & Expertise, Elia
  - Prof. Nicolaos A. Cutululius, Department of Wind and Energy Systems, DTU
- 17.00h: Closing, **Prof. Dirk van Hertem,** followed by reception

Neptune
Closing event

Dirk.vanhertem@kuleuven.be

Met de steun van het Energietransitiefonds

economie

Energy Ville KU LEUVEN vito imec UHASSELT

Neptune
Closing event

Tinne Van der Straeten – Minister of Energy

Modern power systems dominated by power electronics and HVDC

Oriol Gomis-Bellmunt, CITCEA-UPC & eRoots Analytics
oriol.gomis@upc.edu

with support from Edu Prieto, Marc Cheah, Jie Song, Carlos Collados, Vinicius Lacerda, Saman Dadjo, Josep Fanals, Josep Arévalo and all colleagues from the AC/DC grids group in CITCEA-UPC and eRoots

Energy Ville, Neptune project event

September 2023

Agenda

Low-inertia power systems

Converter Technology for hybrid AC/DC systems

Control of hybrid AC/DC systems

Grid services / Renewable power plants and loads

Conclusions

Low-inertia power systems

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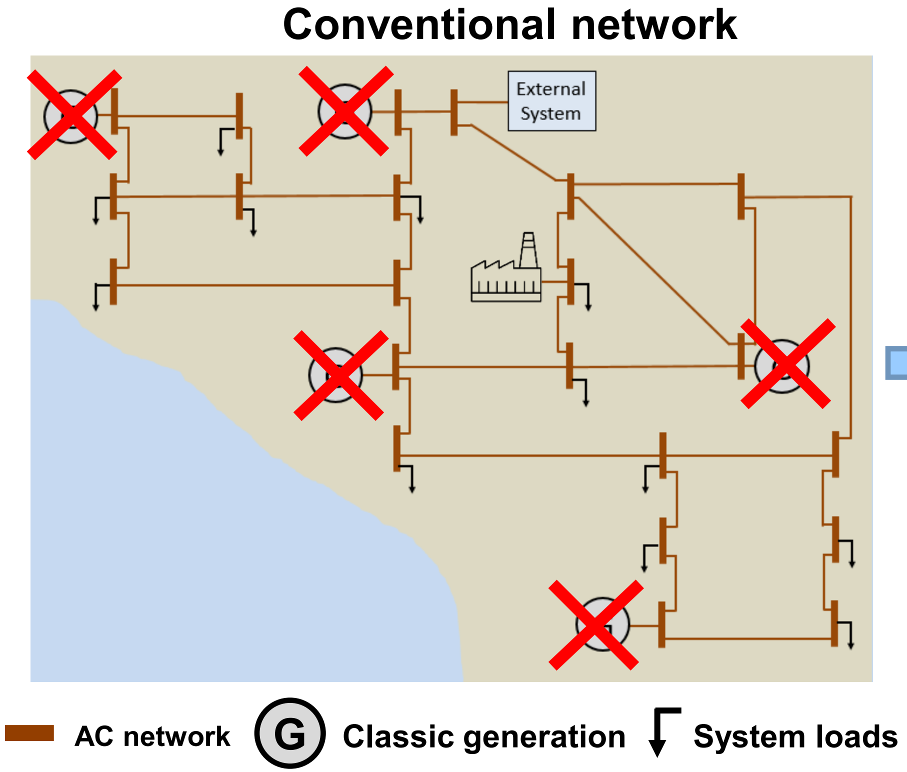
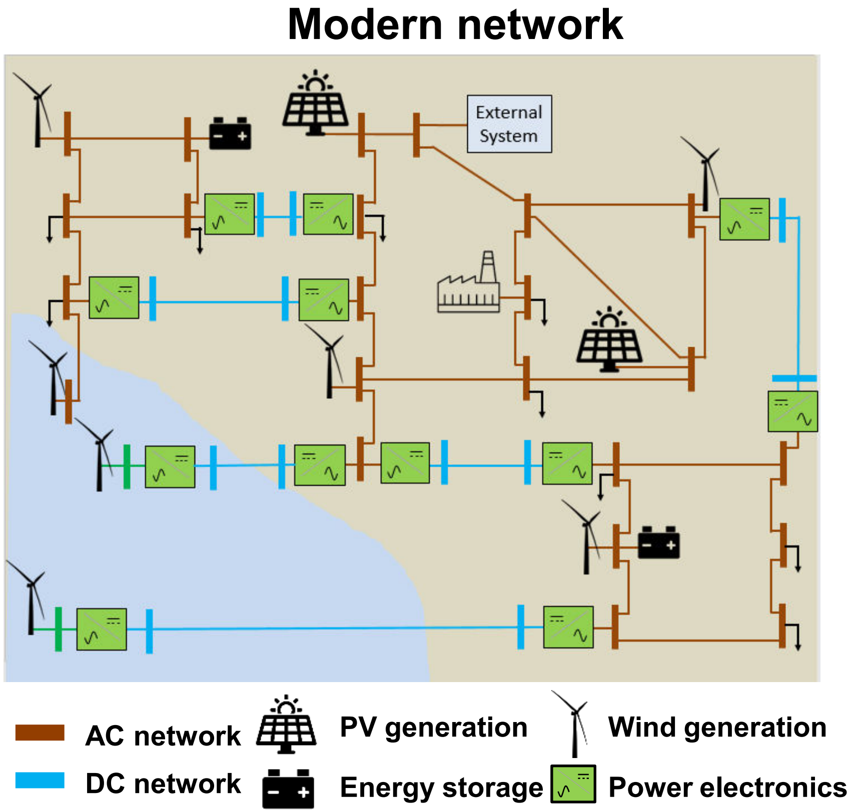
The network transition





Power electronics in power systems

Increasingly present in…

- Renewables (Wind, PV, Ocean, some hydro, …)
- FACTS / Energy storage / HVDC
- Electric vehicle / Industrial loads

Main features

- Full controllability / Fast dynamics possible
- Very limited overload capability
- Very limited inertia

Challenges due to the nature of power electronics

- Control interactions & stability? Inertia? Grid forming / following converters? Converter synchronization?
- Protections?
- Level of possible integration?

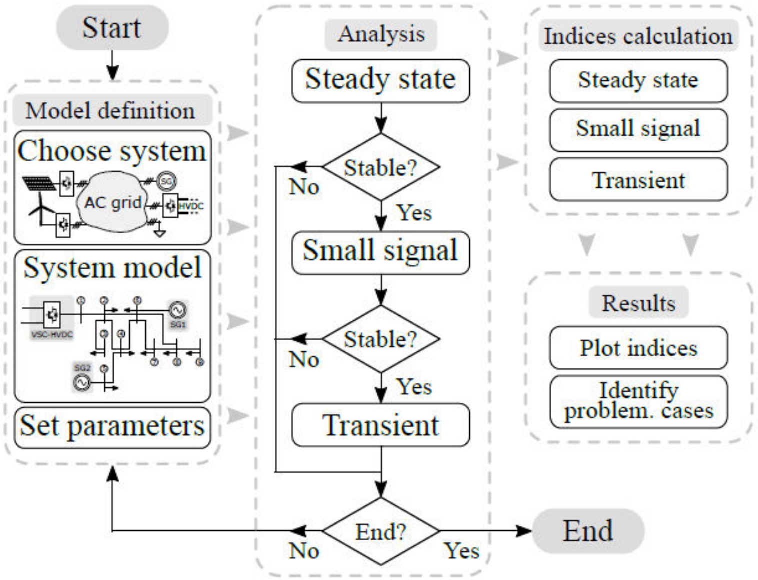
Research challenges – Systems dominated by converters

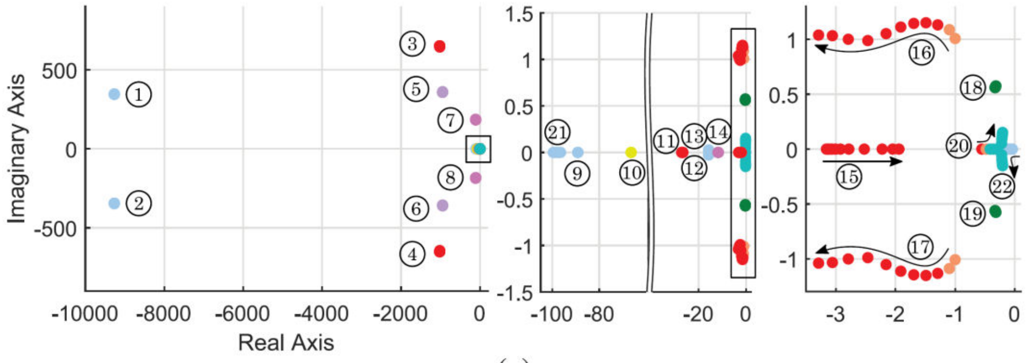
Some open questions:

- The system has low inertia, is there a problem? Can we control the frequency in low-inertia systems with fast converter control? The fast ones take the hard work → Coordination needed.
- Grid forming or grid following converters:
  - Should we move to 100 % grid forming (voltage source behaviour)?
  - Can we combine inside wind or solar power plants? What proportion?
  - Where do we need to locate grid forming?
  - Where is the limit?
- We need grid-forming converter to provide synchronization and form the grid, but do grid-forming converters need to provide inertia? In other words, should there be a requirement of “synthetic inertia”?
- What is the meaning of frequency? How it will change? Do we want to change it?

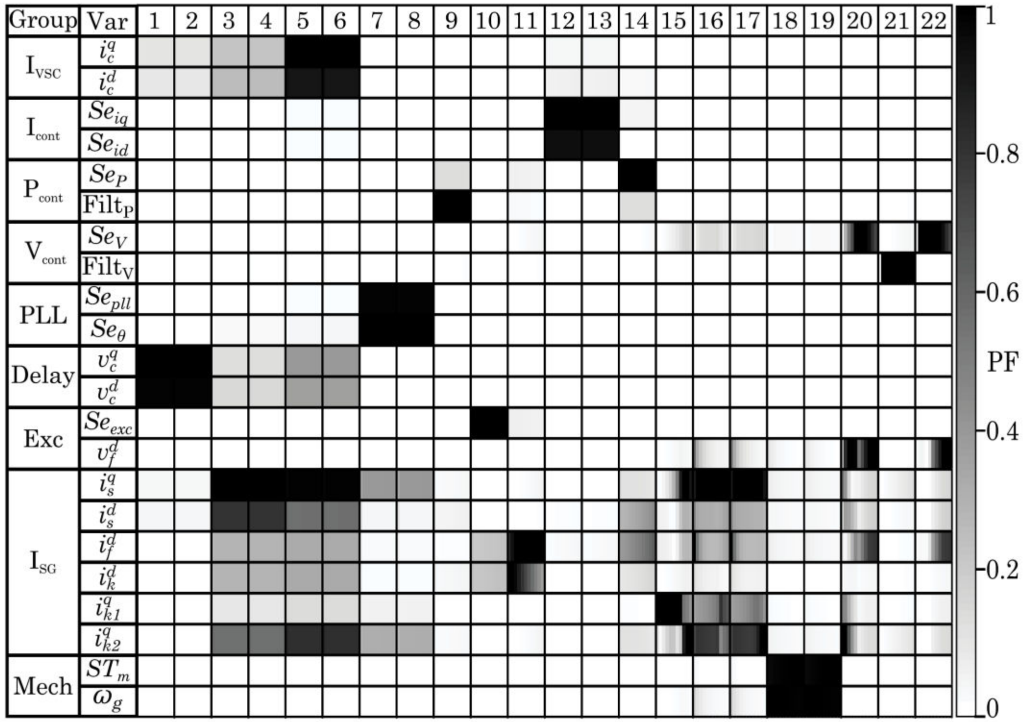
Examples studies

- Root-causes of instability?
- Consideration of different control schemes and settings
- Index-based methodology
- Consideration of different power flows
- Steady-state, small signal and transient analysis



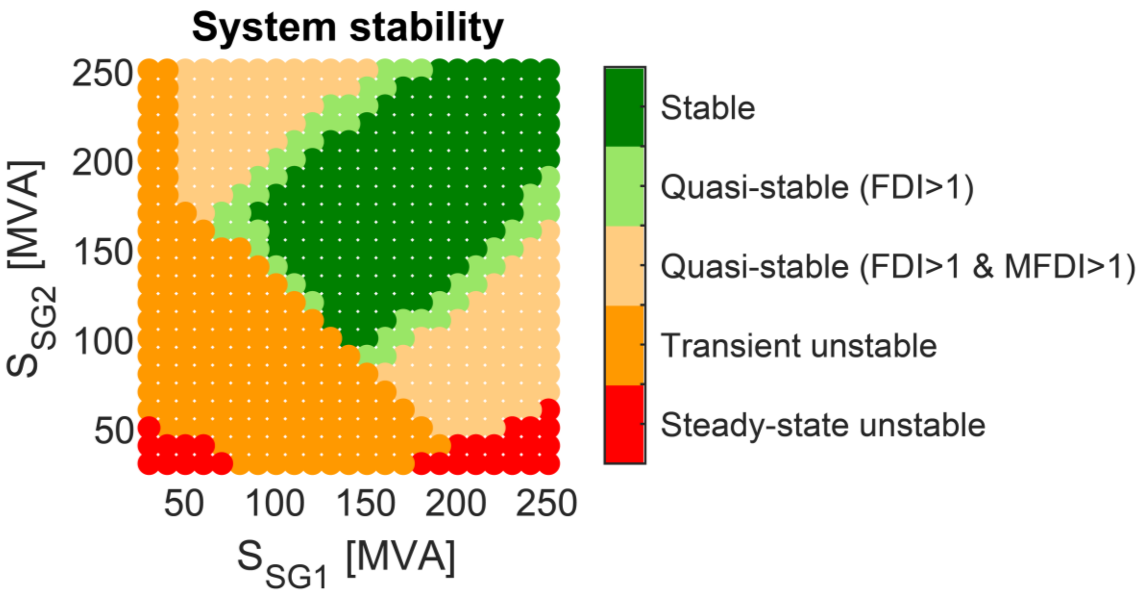


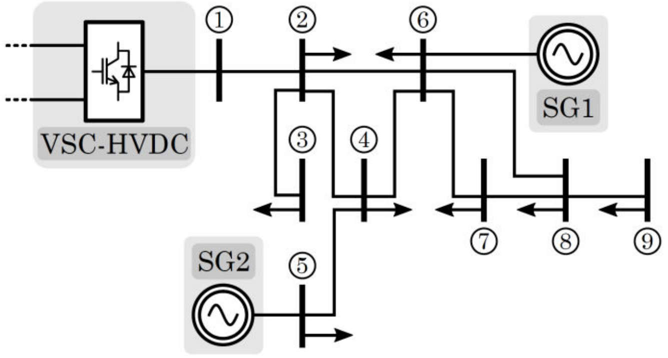
(a)

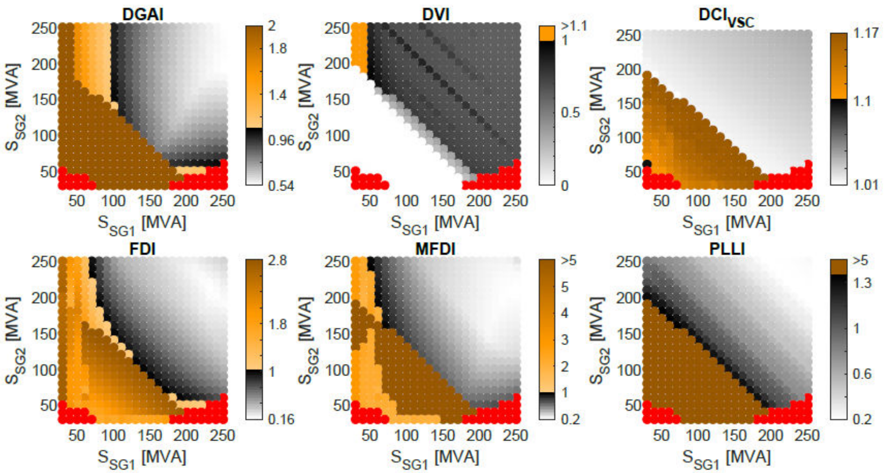


(b)

Stability Analysis of Systems With High VSC Penetration: Where Is the Limit?, IEEE Trans PWRD 2020







Dynamic Generator Angle Index (DGAI)
Dynamic Voltage Index (DVI)
Dynamic Current Index (DCI)
Frequency Derivative Index (FDI)
Maximum Frequency Deviation Index (MFDI)
PLL Index (PLLI)

Stability and operation limits of power systems with high penetration of power electronics, IJEPES 2022

Research challenges – converter saturation

Specific converter characteristics:

- Overload limitation (Current saturation, voltage → current source behavior)
- High controllability (Great adaptability, but potential interactions)

Understanding short-circuits (complex with interacting converter controllers during the fault). New methods required combining:

- Converter saturations / current source behavior
- Grid support schemes in the converters

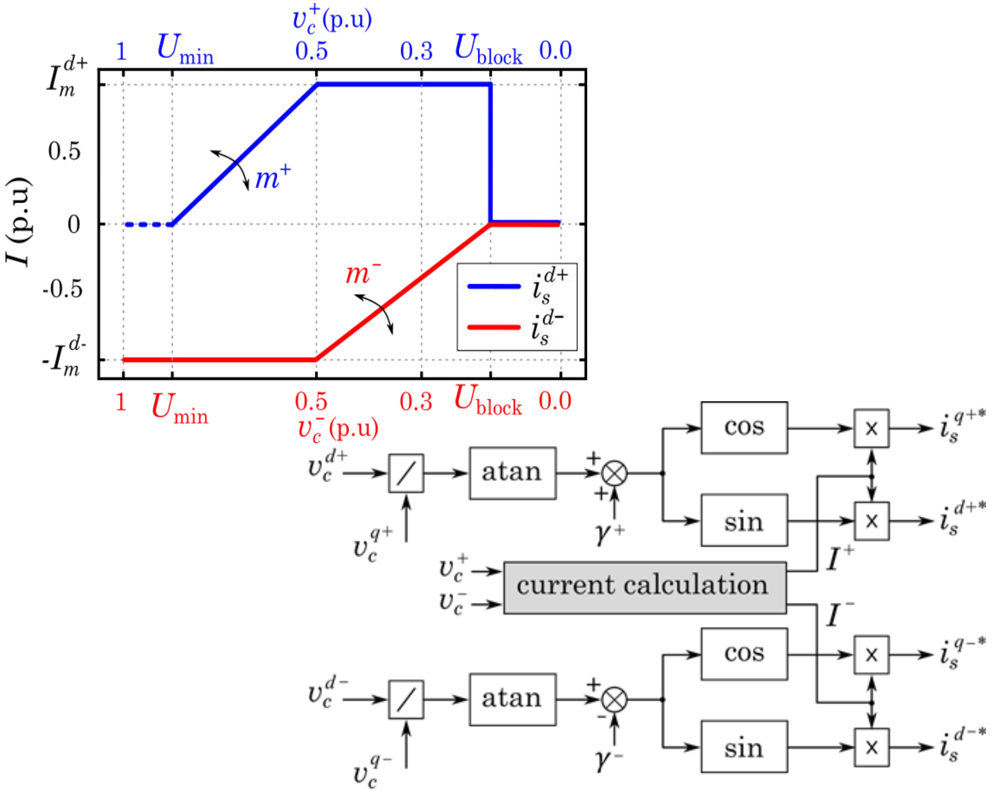
Short-circuit calculations

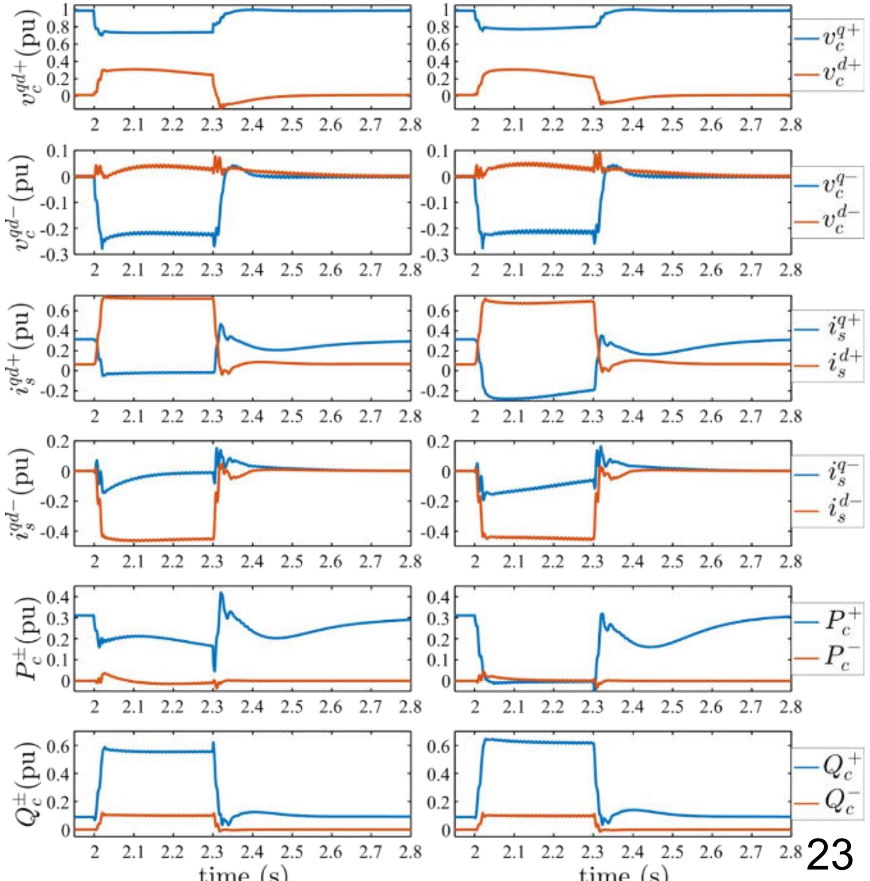
- What grid equivalents can we use? New approaches needed!
- What is the meaning of short-circuit power and short-circuit ratio in power electronics dominated power systems?

Research challenges: **Fault ride-through**

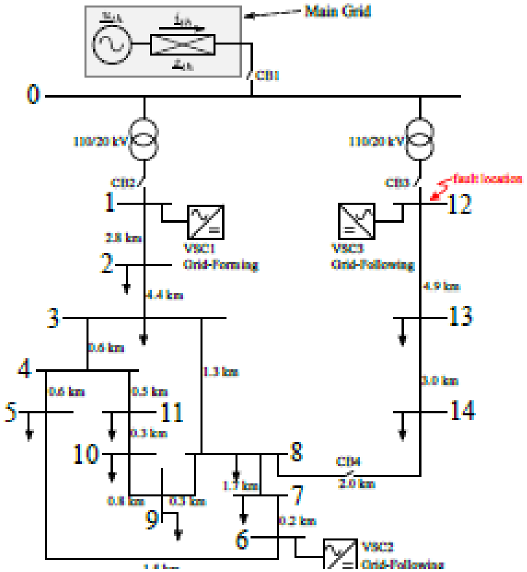
Understanding short-circuits (complex with interacting converter controllers during the fault). New methods required combining:

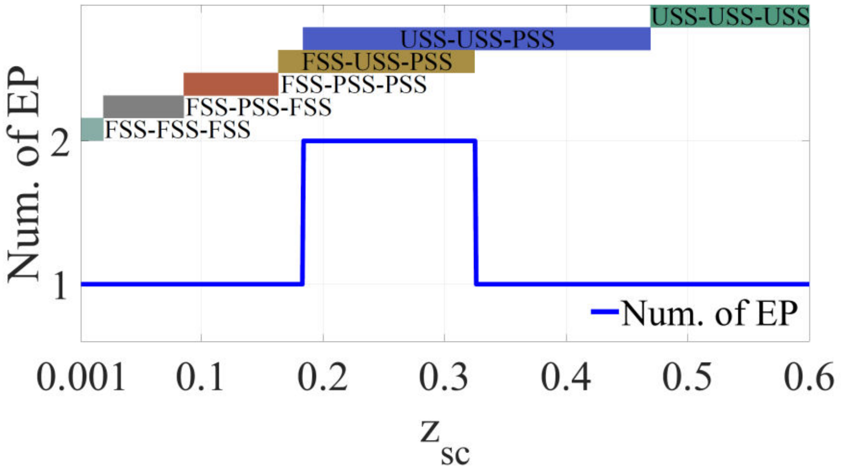
- Converter saturations / current source behavior
- Grid support schemes in the converters + Fault ride-through
- Balanced / unbalanced faults

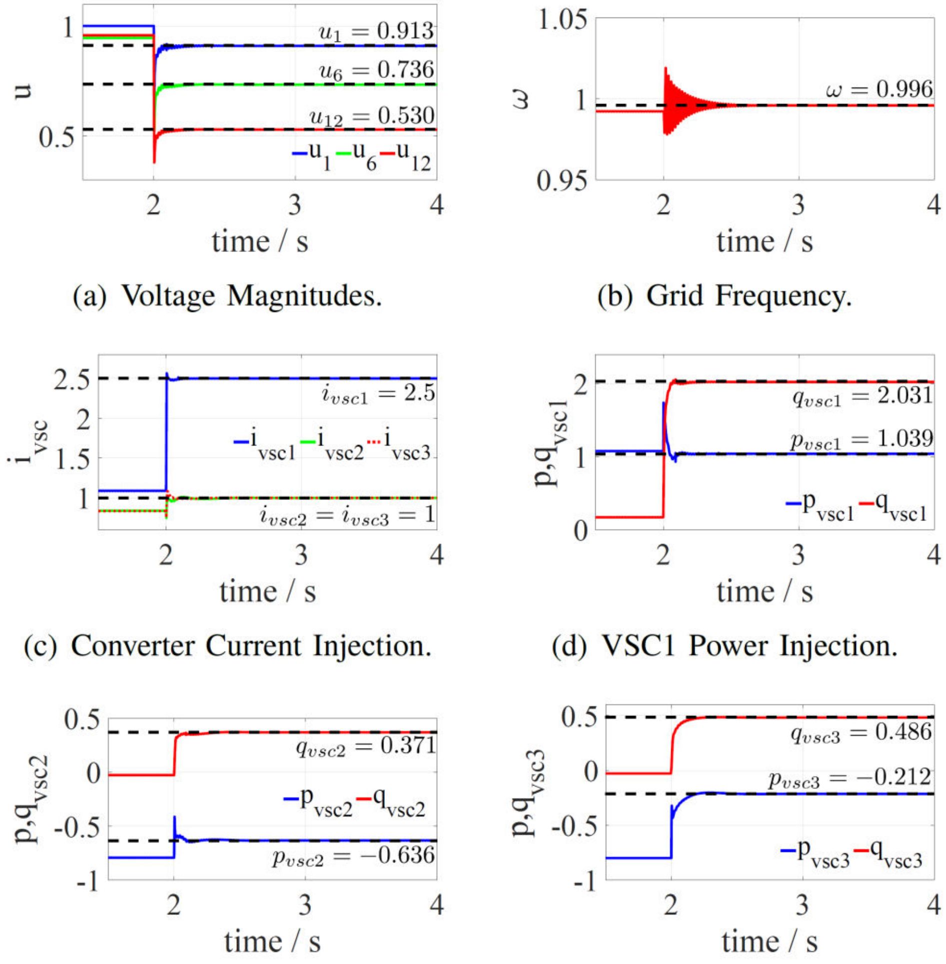




Research challenges: **Shortcircuit calculation**







(a) Voltage Magnitudes. (b) Grid Frequency.

(c) Converter Current Injection. (d) VSC1 Power Injection.

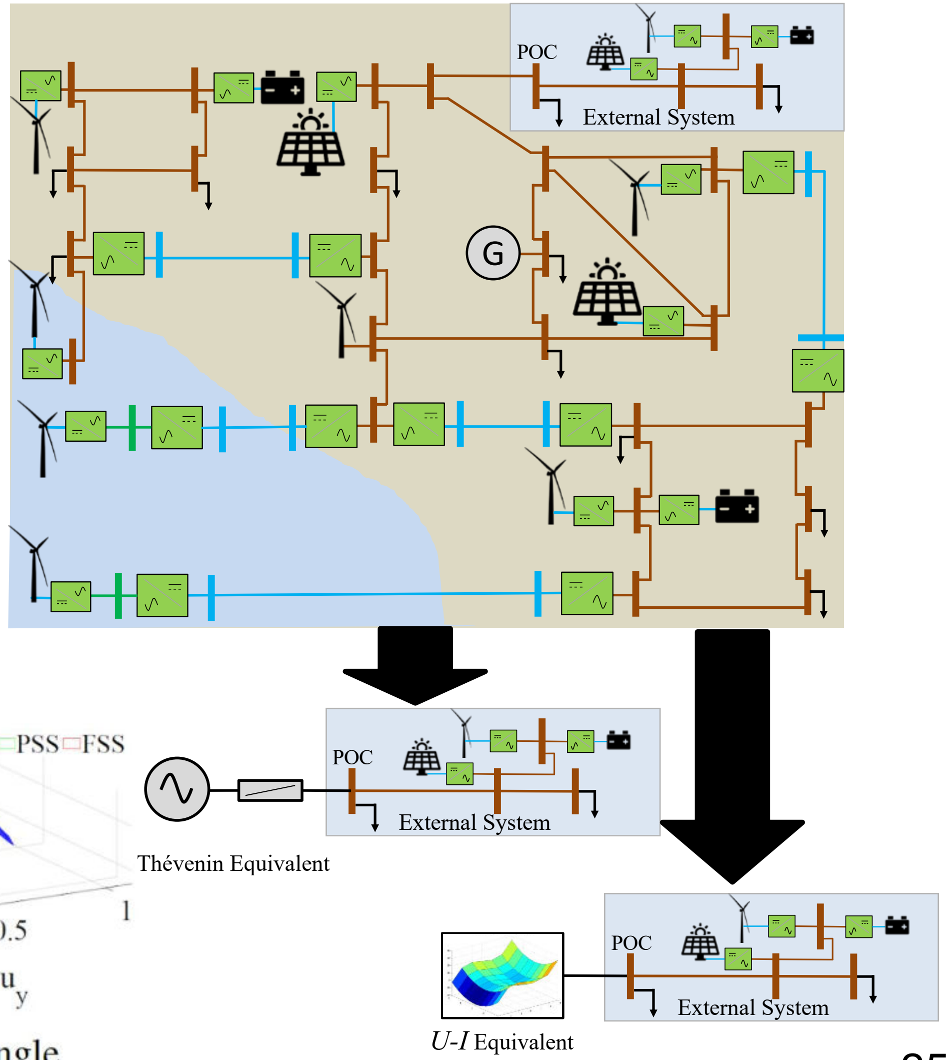
(e) VSC2 Power Injection. (f) VSC3 Power Injection.

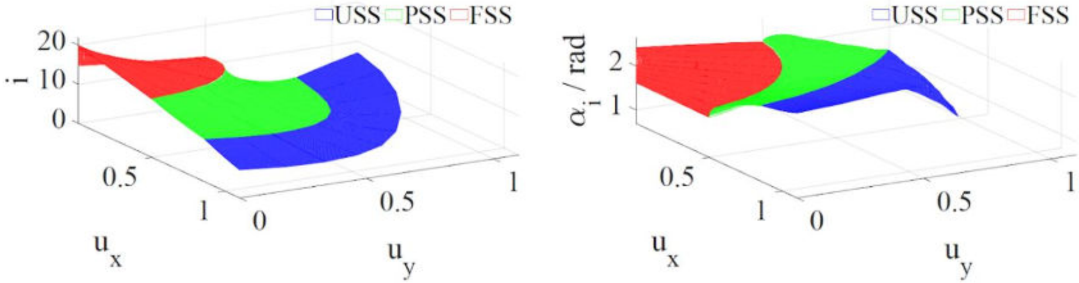
Short-Circuit Analysis of AC Distribution Systems Dominated by Voltage Source Converters Considering Converter Limitations IEEE Trans Smart Grid 2021

Research challenges: **Grid equivalents**

Grid equivalents for power systems dominated by power electronics

- What is the meaning of short-circuit power in modern power systems?
- Thevenin equivalent needs to be redefined, as it does not capture the saturation of converters.
- Voltage to current maps?





(a) Output current magnitude (b) Output current angle

Low-inertia power systems

Converter Technology for hybrid AC/DC systems

Control of hybrid AC/DC systems

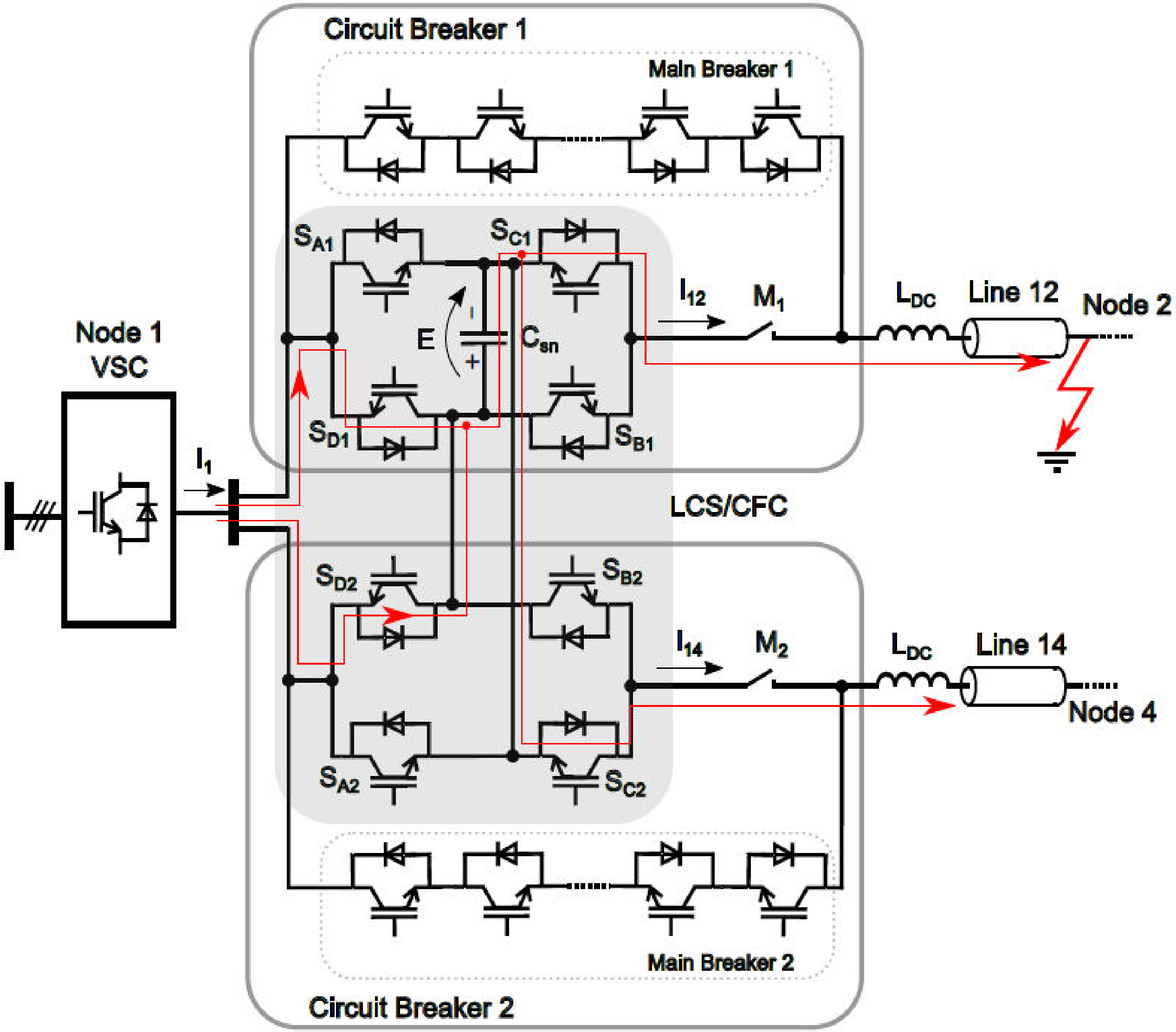
Grid services / Renewable power plants and loads

Conclusions

Converter technology for HVDC grids

- Higher voltage and higher power
- SiC, GaN and new materials
- Novel converter concepts and modulation technique to increase efficiency
- Half bridge, full bridge cells or alternative cell concepts
- Converter **reliability** and constrained operation
- Modular and **interoperable** converters
- Integration of energy storage (at cell level)
- DC-DC converters for HVDC (heterogenous connections, different voltage levels)
- Power converters to **integrate** more ports (HVAC, MVAC, HVDC, MVDC)
- FACTS for HVDC grids - Flexible DC converters (meshed DC grids)
- **Integration** of functionalities: converter, circuit-breaker, fault-current limiter, current controller.

Integration with circuit breakers



Integrated HVDC Circuit Breakers With Current Flow Control Capability, IEEE Trans PWRD 2018

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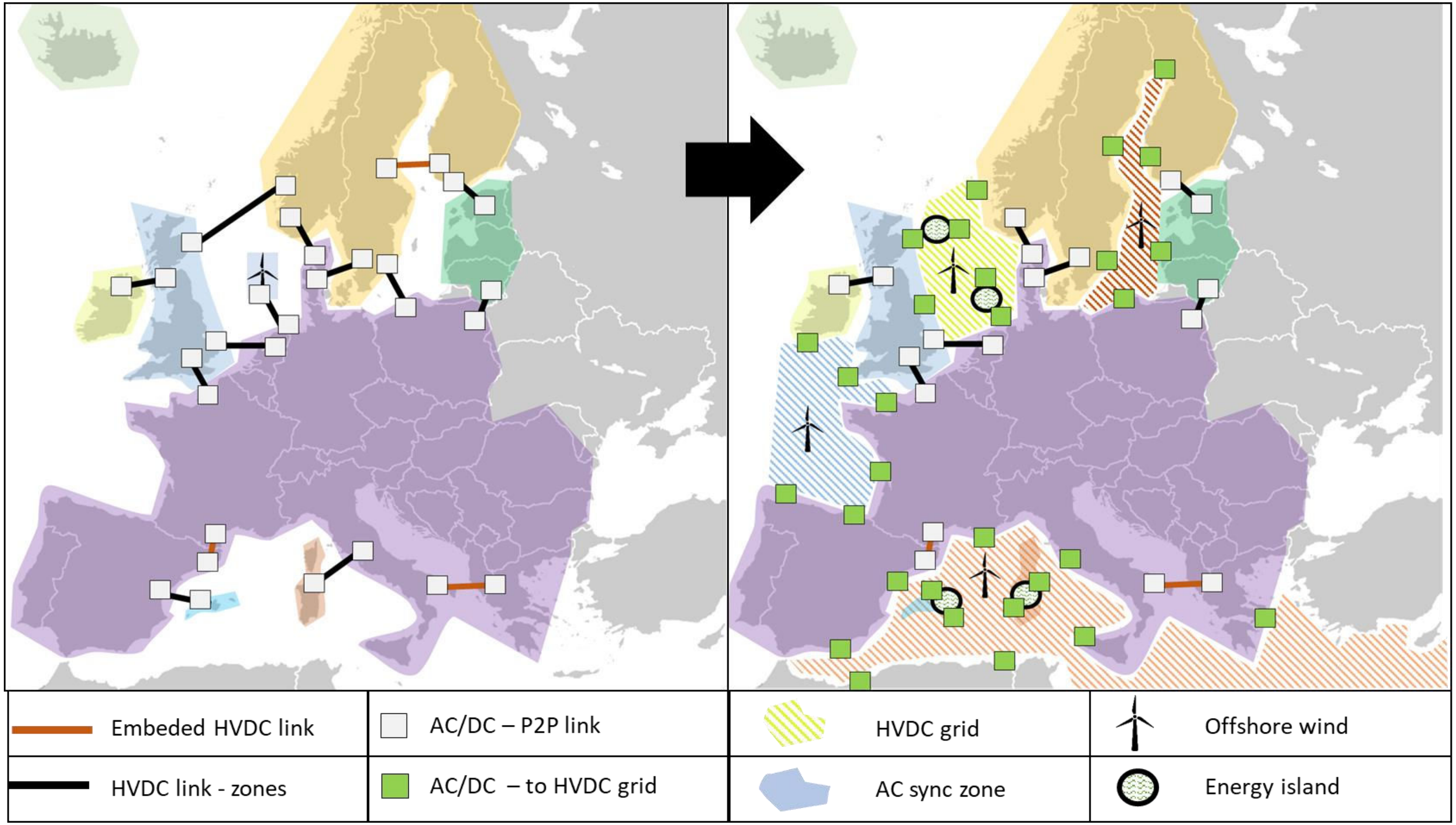
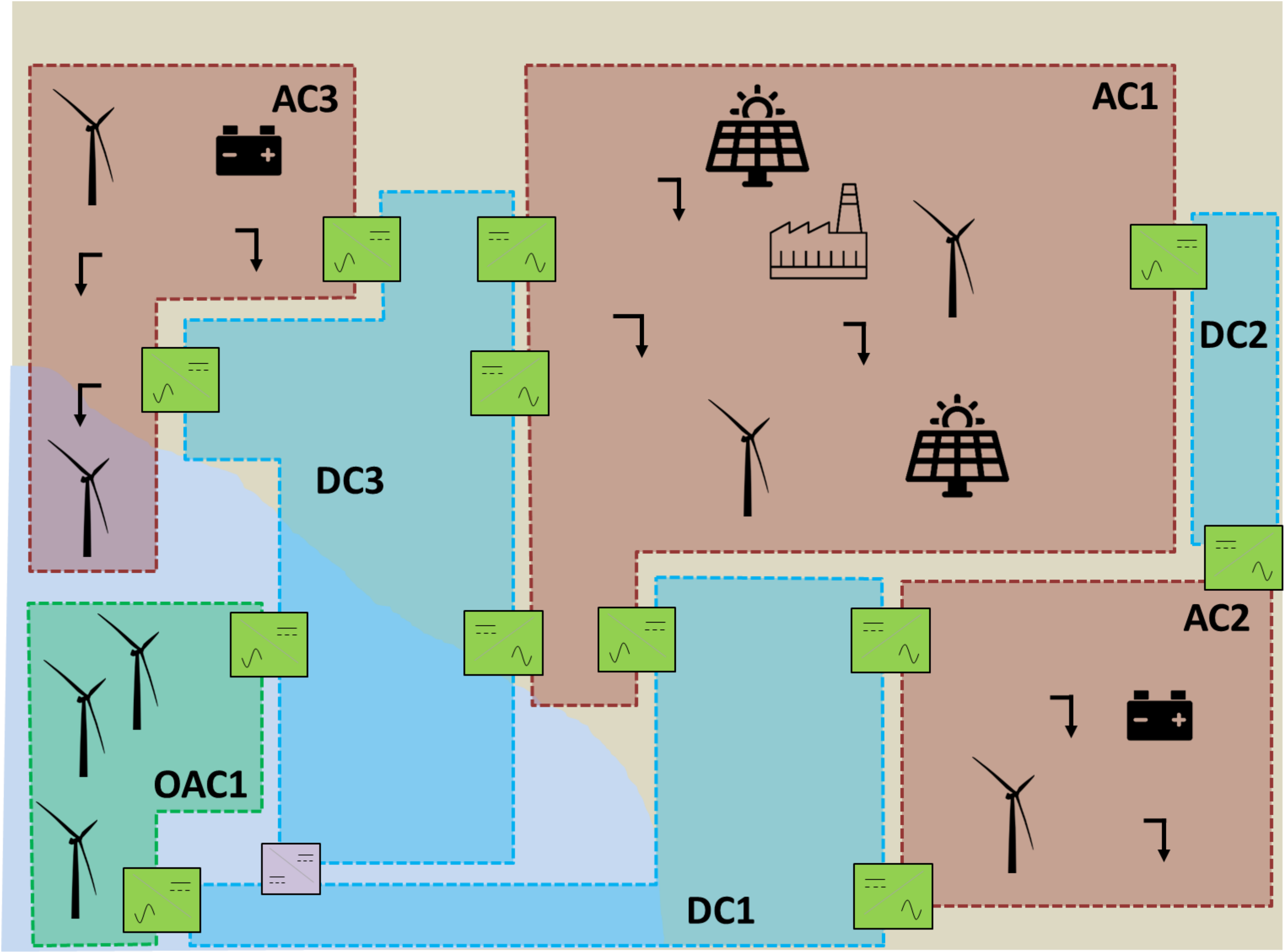
From links to grids → A grid of grids



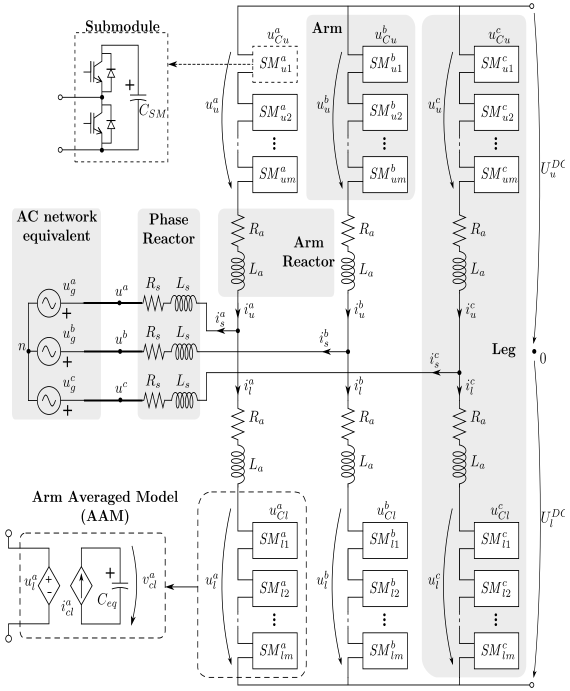
Grid of Grids – hybrid AC/DC systems considered



Principles of operation of grids of DC and AC subgrids interconnected by power converters, IEEE Transactions on Power Delivery 2021

Hybrid AC-DC systems (like our European system)

- Grid support to AC and DC subgrids (provision of ancillary services)
- Role assignment of interconnecting converters – grid forming in AC or DC side
- Fault ride-through – firewalling fault spread while supporting faulted grid
- Firewalling – shaping dynamics of interconnecting Modular Multilevel Converters (MMC) to “filter” the power transfer
  - A simple example: AC Unbalanced faults cause DC voltage oscillation at double frequency (100 Hz) in 2 or 3 level converters. In MMC it is a choice of the control design whether the oscillation is transferred to the DC side or stays internally in the MMC cells.
- Routing the power with converter control
- Resilient systems – islanded operation, black-start, system restoration



The Role of the Internal Energy in MMCs Operating in Grid-Forming Mode, IEEE Journal of Emerging and Selected Topics in Power Electronics 2020

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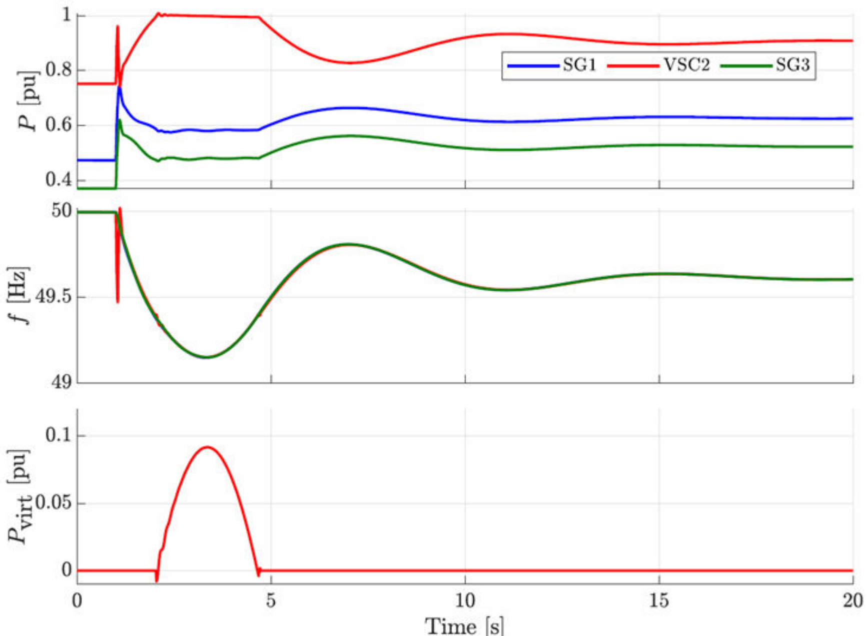
Grid forming converters

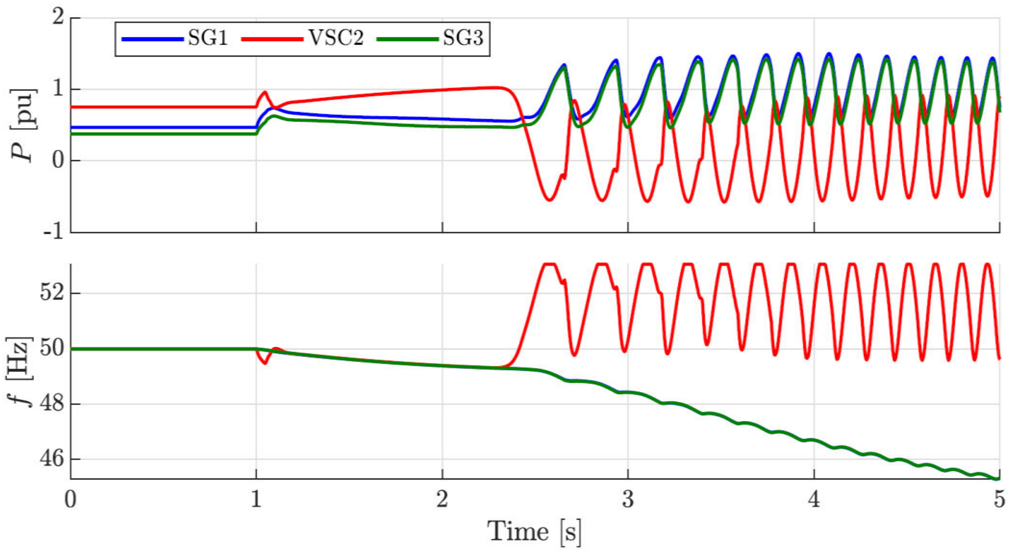
Grid forming converters increasingly needed

Challenges on how to handle limits! (current, voltage, power)

Grid forming fault ride-through

Converters may be operating at maximum operating point or very close to it. What to do when the grid-forming demands more power than the available? Some solutions exist, but are they “true” grid forming?





Renewable power plants

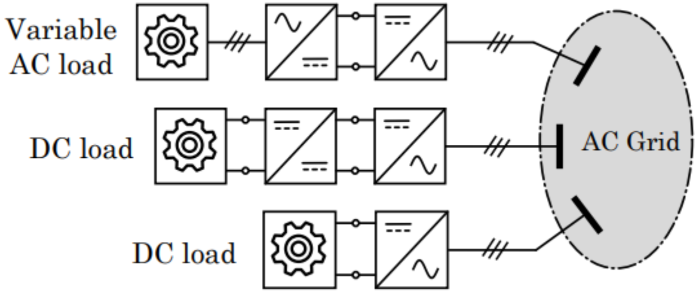
- Provide multiple services, including grid-forming and black-start
- Grid-forming control with resource limitation – what to do when we exceed the resource available and the GF demands more power?
- System resiliency provision by allowing islanded operation and resynchronization
- (Fast) frequency control and inertia provision (if needed)
- Voltage control
- Power oscillation damping
- Dynamic Virtual Power Plants
- Integration with energy storage systems and loads (H_2 electrolyzers, EV chargers, …)
- Alternative collection concepts (DC collection + large converters connecting to the AC or DC system)

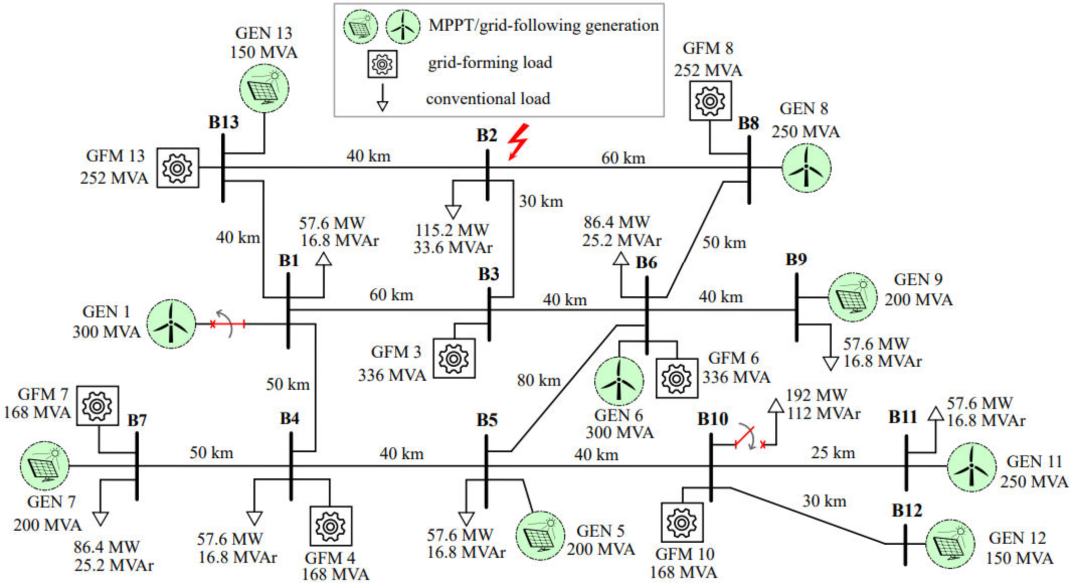
Grid forming loads

Should we implement grid-forming loads and grid-following generators?

Potential change of paradigm in future power systems:

- Current operators operate mainly generation with some demand management
- Future operators might operate mainly loads with some generation management





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Conclusions

- Low-inertia power systems are raising several challenges that need to be address to shape future power systems.
- European grid is already a hybrid AC/DC power system which will increase its complexity.
- The converters interconnecting grids can play a key role on providing support while blocking the spread of protections (firewalling and routing power)
- Renewable power plants need to provide additional services including grid-forming operation.
- More active loads can contribute in several services.
- Many challenges and opportunities for research!

Modern power systems dominated by power electronics and HVDC

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with support from Edu Prieto, Marc Cheah, Jie Song, Carlos Collados, Vinicius Lacerda, Saman Dadjo, Josep Fanals, Josep Arévalo and all colleagues from the AC/DC grids group in CITCEA-UPC and eRoots

Energy Ville, Neptune project event

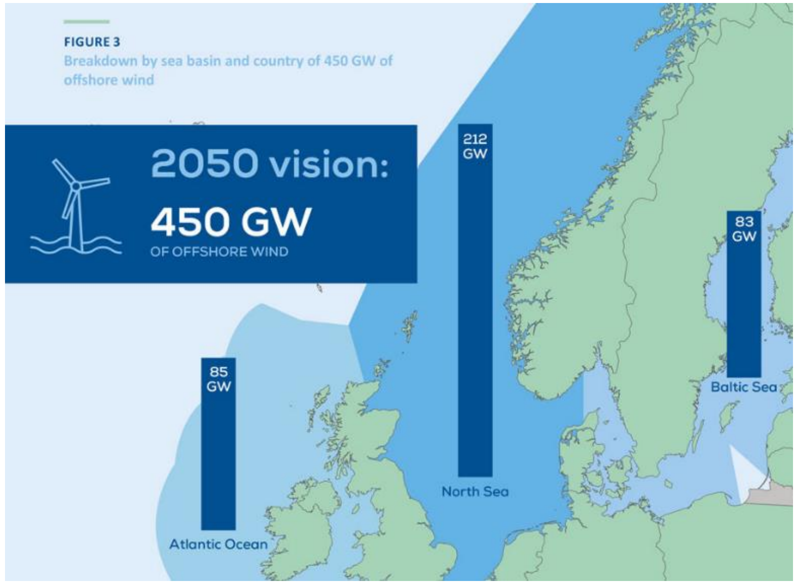
September 2023

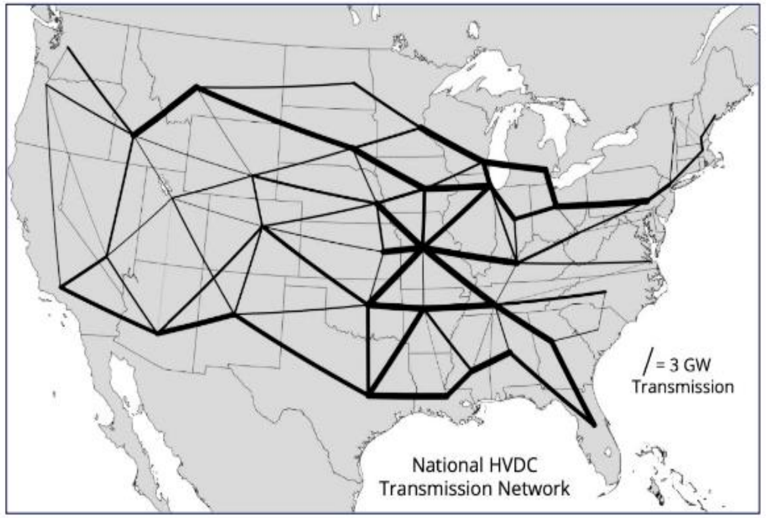
WP1: Offshore and Onshore Grid Planning

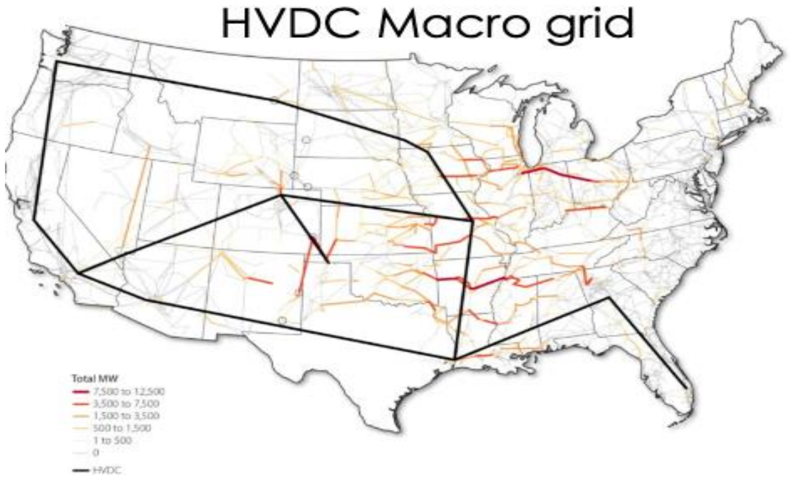
Neptune Final Event

Hakan Ergun– September, 27th 2023

The value of interconnection and HVDC grids







Investing **1.3 bn€/year** between 2025 and 2030 translates into a decrease of generation costs of **4 bn€/year**, while investing **3.4 bn€/year** between 2025 and 2040 decreases generation costs by **10 bn€/year**. (source: ENTSO-E TYNDP 2020)

Transmission expansion costs **$350B** for 100% clean energy and **$1T** more to get to 100% without macro grid

[1] F.Acevedo, et al, Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US, IEEE Transactions on Power Systems, Vol 36, no 4, 2021

Cost benefit ratio of HVDC grid 2.5 – 2.9

[2] Lew, et al, Transmission Planning for 100% Clean Electricity, IEEE PES Magazine, Nov/Dec 2021

Energy Ville

AC/DC hybrid grid, a vision?

- 58 HVDC connections in Europe to date (including back-to-back links)
- According to TYNDP 2022, 51 out of 141 transmission projects are using HVDC
- Solar developments are equally fast:
  - South to North flows
- Offshore grid development plan*
  - "… ENTSO-E, with the involvement of the relevant TSOs, the national regulatory authorities, the Member States and the Commission, must develop the first sea-basin (SB) related offshore network development plans (SB-ONDPs) by 24/01/2024, based on the goals developed by the Member States' governments…"
  - The second ENTSO-E deliverable is expected by 24/06/2025; namely "the results of the application of the cost-benefit and cost-sharing to the priority offshore grid corridors"

Subset of HVDC connections in TYNDP 2020 of ENTSO-E

*https://eepublicdownloads.blob.core.windows.net/public-cdn-container/tyndp-documents/ONDP2024/220906_ENTSO-E_Guidance_ENER_ENTSO-E_clean.pdf

Main question: how to adequately plan an AC/DC hybrid grid?

Are the existing methodologies, models and tools adequate to capture all risks and benefits when planning hybrid AC/DC grid?

- How can we better identify the need for grid expansion?
- Do the typically used cost-benefits analysis methods adequately capture all costs, risks and benefits of HVDC technology?
- Which power system phenomena should be considered in the early planning process?
- Which optimisation, simulation and data models are needed to represent these phenomena?
- What are the improvements needed for future tools used in the planning process?

Challenges tackled within NEPTUNE WP1

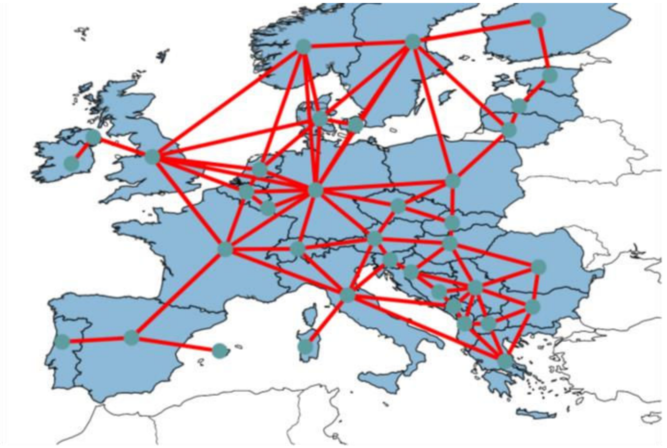
- Bridge the gap between generation and transmission expansion planning tools for holistic grid design
  - Improve uncertainty modelling in transmission / generation planning tools
  - Consider spatial and temporal correlations, find appropriate model resolutions

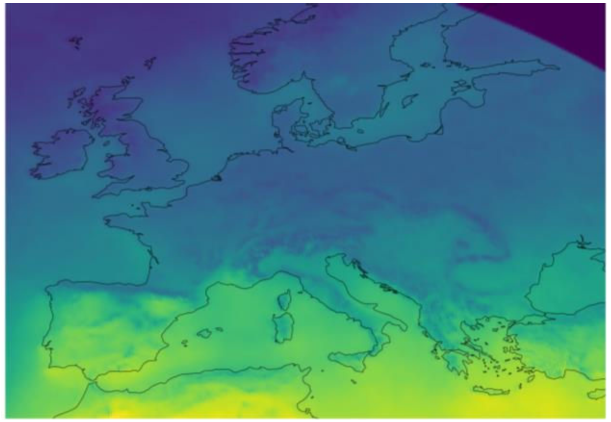
- Bridge the gap between HVDC planning and operational models
  - Investigate the effect of the grid topology and protection system design on the reserve requirements and frequency stability
  - Investigate unbalanced operation of HVDC grids in normal operation and under contingencies

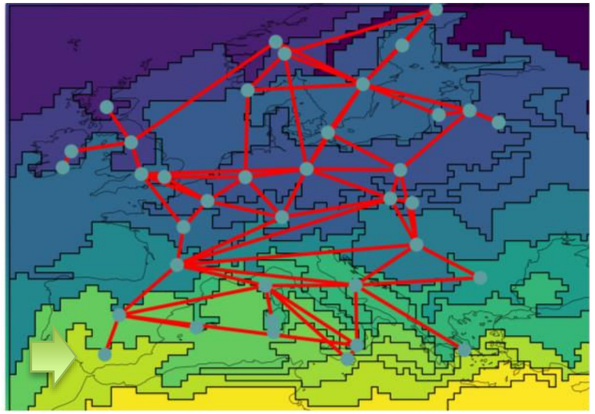
Effects of spatial representation on the identification of grid expansion needs

- The result of generation expansion planning models and thus the expected transmission bottlenecks depends on the spatial resolution that is used in the model

- ***How can we approach models with high spatial resolution while using only few model regions?***



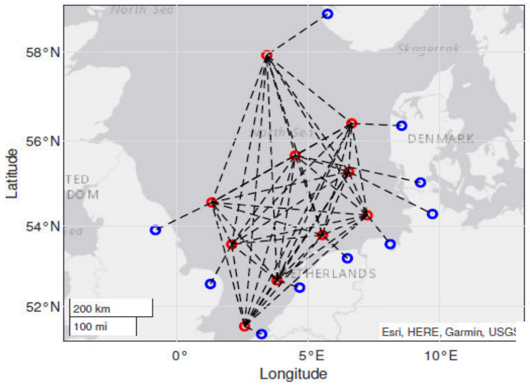




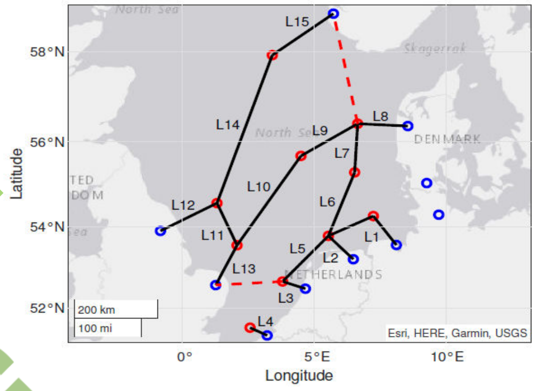
Planning of offshore HVDC grids considering protection strategies and stability

- What are the effects of the DC grid topology and the protection system design on the necessary reserves?
  - With faster DC protection, we can obtain higher reliability, and lower reserve requirements
- How can we find the optimal system design including protection, reserves and loss of load expectation?
  - Incorporating frequency deviation constraints and reserve response in the planning process
- What is our dimensioning incident?
  - DC grid failure vs pole failure
  - 5 GW DC grid: where to connect?
  - For DC grids with fast protection, a permanent loss based dimensioning incident is too conservative!

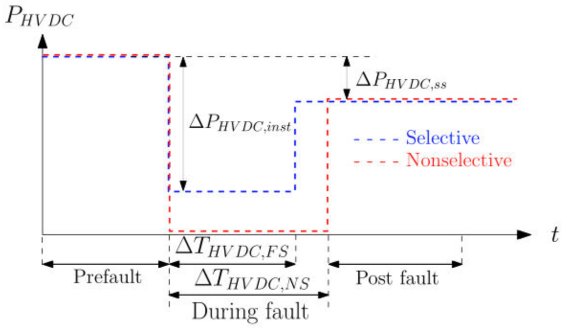
Input candidates

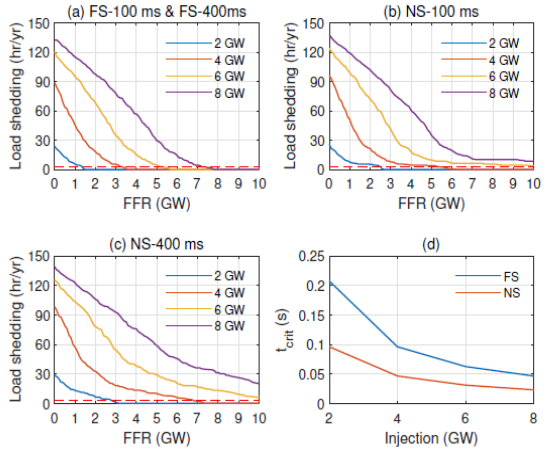


Expansion plan



Stability assessment and reserve dimensioning





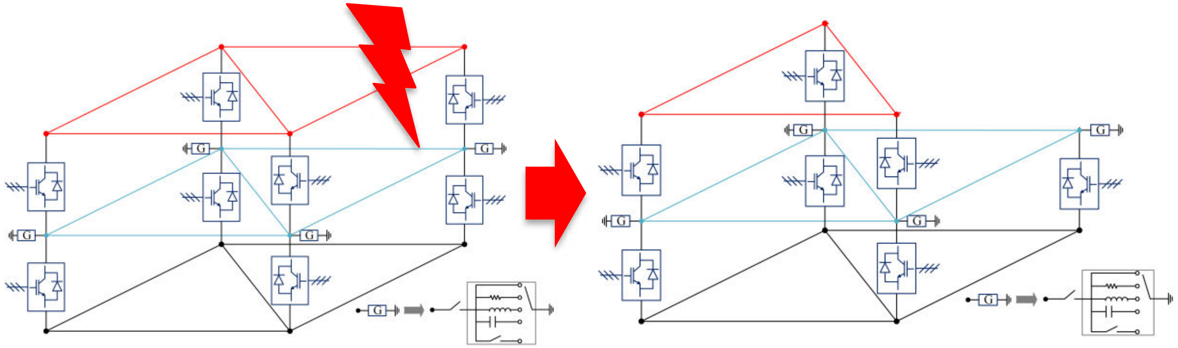
[1] Dave, J., Van Hertem, D. (sup.), Ergun, H. (cosup.) (2022). *DC Grid Protection Aware Planning of Offshore HVDC Grids.*

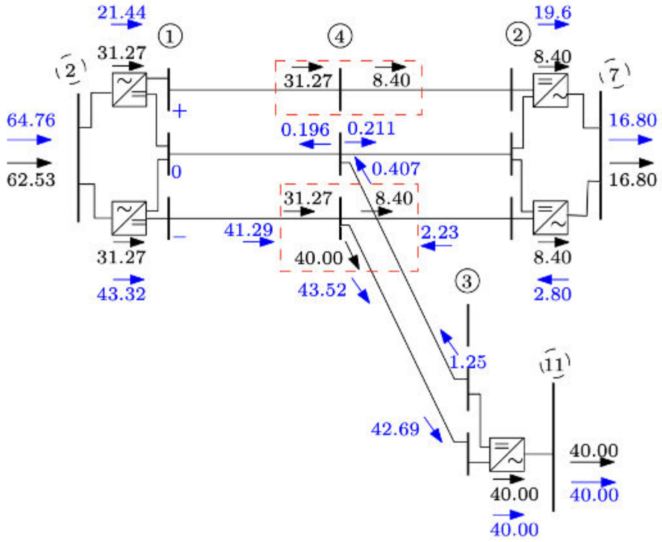
[2] Dave, J., Ergun, H., Van Hertem, D. (2020). Incorporating dc grid protection, frequency stability and reliability into offshore dc grid planning. *IEEE Transactions On Power Delivery*, *35* (6), 2772-2781. doi: 10.1109/TPWRD.2020.3011897 Open Access

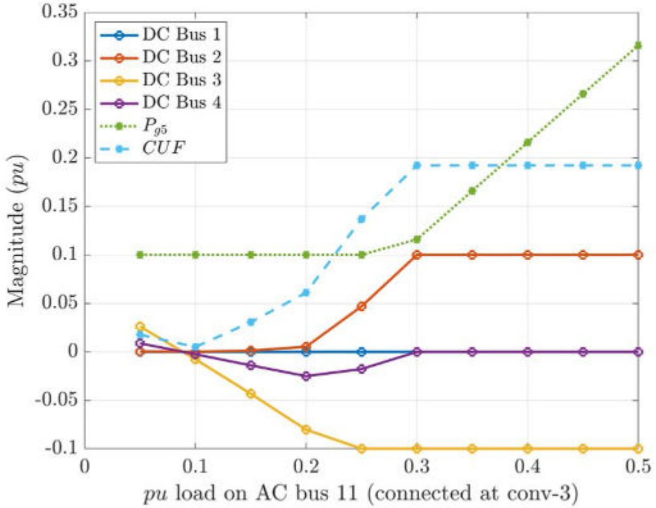
[3] Dave, J., Ergun, H., Van Hertem, D. (2021). Relaxations and approximations of HVdc grid TNEP problem. *Electric Power Systems Research*, *192*, Art.No. 106683. doi: 10.1016/j.epsr.2020.106683 Open Access

Unbalanced operation of DC grids

- Single pole outages in meshed bipolar DC grids will lead to system unbalance
- For large networks, isolating the faulty pole in the entire network will require a large redispatch need and reserve volumes
- As such, a new set of tools are required to analyse the system operation costs under unbalanced conditions to better schedule HVDC converters
- In unbalanced conditions, converter “loop flows” with higher losses might lead to better overall economic performance







Neptune as facilitator for further collaborations

- CORDOBA – Coordinated planning of hybrid offshore assets
  - Analysis of network design under different offshore market designs
  - Probabilistic analysis of cross-border ancillary service provision using hybrid interconnectors

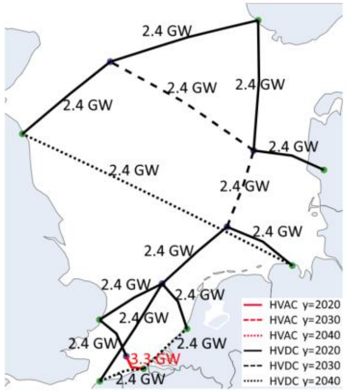


Figure 4: nOBZ $\mathcal{G}$ topology.

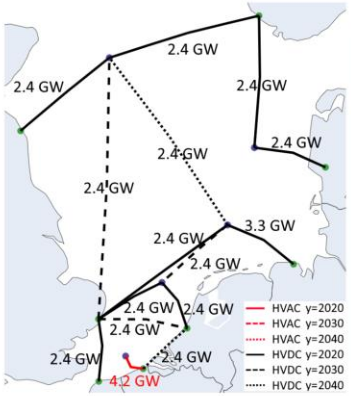


Figure 5: HMD $\mathcal{G}$ topology.

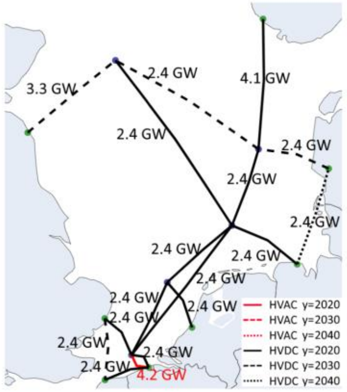
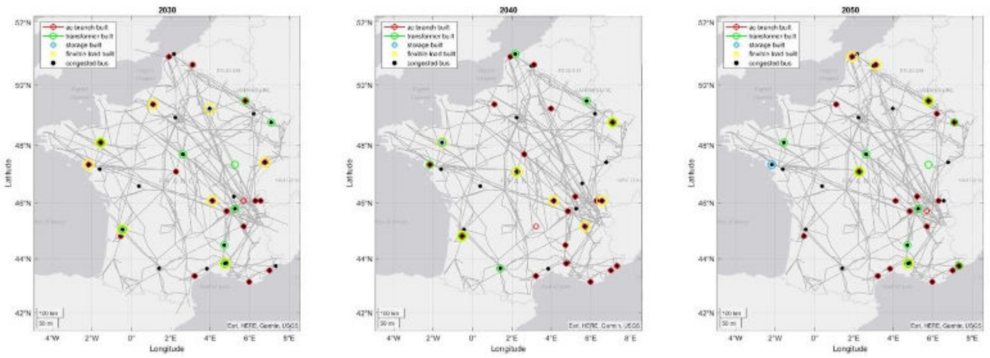
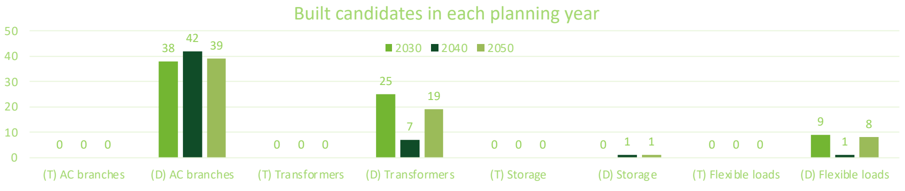


Figure 6: zOBZ $\mathcal{G}$ topology.

- FLEXPLAN
  - Horizon 2020 project to analyse trade-offs between flexibility and transmission capacity needs
  - Coordinated planning of transmission and distribution grids





Outlook – Findings from the NEPTUNE project

- We need to improve our planning tools to provide better decision support to grid planners
- Optimisation based approaches can be extended to better represent different market designs, system stability, grid protection and flexibility
- Harmonized system models are needed in the context of cost benefit analysis methods for reliable and transparent results on grid development studies

Posters

Incorporating HVDC grid protection, frequency stability and reliability into offshore dc grid planning

C.K. Jat, J. Dave, H. Ergun, D. Van Hertem

Financial Viability of a Full-Scale Meshed HVDC Grid and Hybrid Offshore Assets in the North Sea

C.K. Jat, J. Dave, S. Hardy, Hakan Ergun, Dirk Van Hertem

Spatial Representation of Renewable Technologies In Generation Expansion Planning Models

K. Phillips, J. Moncada, H. Ergun, E. Delarue

Power Flow and Optimal Power Flow Models for Asymmetric HVDC Grids: A Julia-Based Open-Source Implementation

C. K. Jat, J. Dave, H. Ergun, D. Van Hertem

A Planning Methodology for HVDC Interconnectors and Grids Considering Security Related Costs

Hakan Ergun, Jay Dave, Dirk Van Hertem

Renewable-based regions in power system planning models

K. Phillips, J. Moncada, H. Ergun, E. Delarue

Open-source toolboxes for community driven research

PowerModelsACDC.jl

- Optimal power flow model for AC/DC grids
- A number of different formulations (linear, second-order cone, nonlinear, …)
- Different problem types (OPF, TNEP, multi-period OPF, ….)

PowerModelsMCDC.jl

- Optimal power flow model for unbalanced operation of monopolar, bipolar HVDC grids

OptimalTransmissionRouting.jl

- Determining optimal transmission routes using shortest path algorithm
- Allows to assess landscape impact of transmission assets

FlexPlan.jl

- An open-source Julia tool for transmission and distribution expansion planning considering storage and demand flexibility

CBAOPF.jl

- An open-source model for conducting cost-benefit analysis for HVDC interconnectors, considering inertia constraints

WP1: Offshore and onshore grid planning

hakan.ergun@kuleuven.be

Met de steun van het Energietransitiefonds

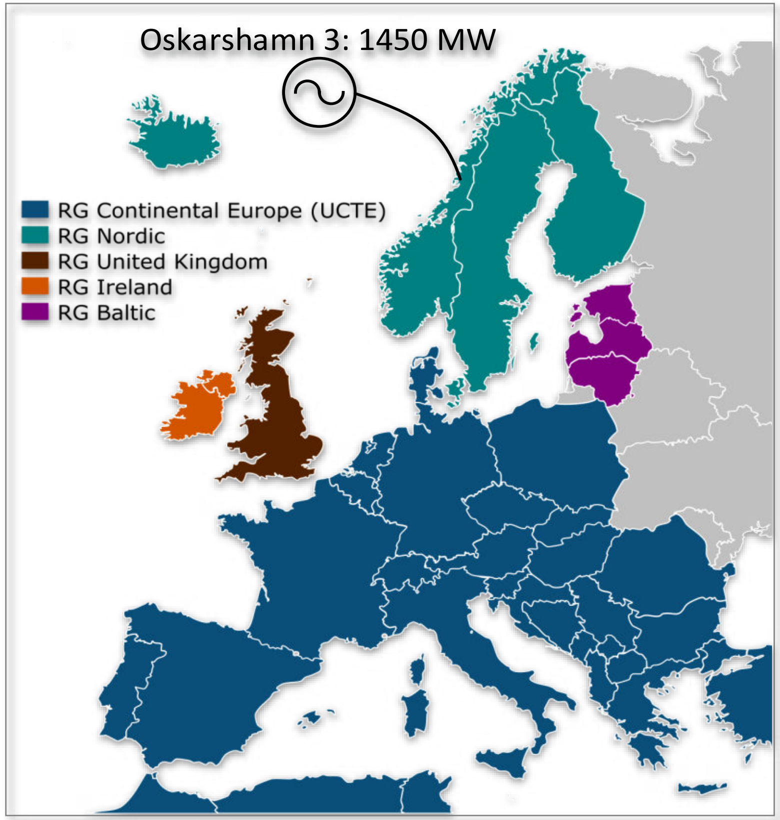
Frequency stability under offshore DC grid development

Jay Dave, Hakan Ergun, Dirk Van Hertem

Energy Ville · KU LEUVEN · vito · imec · UHASSELT

Frequency stability in present day power systems

- Frequency stability is ensured based on a defined `dimensioning incident (DI)'
  - It is the highest possible imbalance in the synchronous area
  - i.e. Oskarshamn 3 nuclear plant in the Nordic power system
- Equivalent amount of frequency containment reserves are procured to maintain the stability.
- DI is based on inland power imbalances in present systems



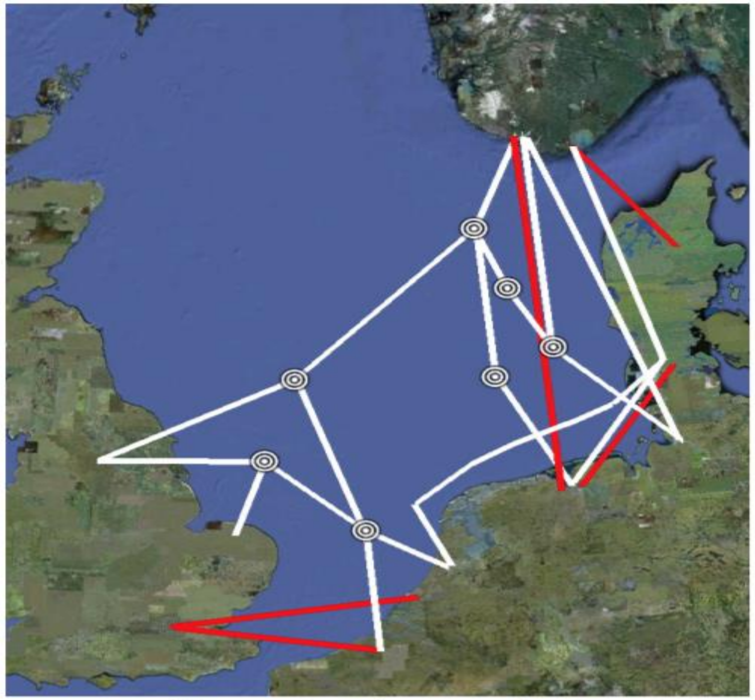
Source: Wikipedia

Frequency stability under offshore DC grid development

- Substantial offshore capacity is expected in the North Sea by 2050 (~212 GW)
  - Offshore grid is a potential solution

- Offshore connections are already near to DI for Great Britain and Nordic areas.
- DI limits the maximum amount of power that can be injected from offshore DC grid
  - 3 GW for Continental Europe
  - 1.45 GW for Nordic Power System
  - 1.32 GW for Great Britain

- DI becomes a constraint in offshore grid planning.

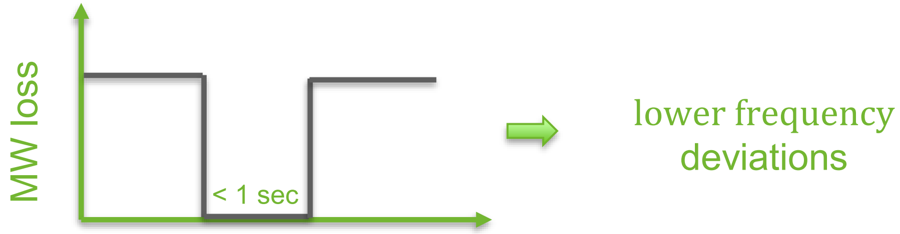


Source: WINDSPEED

Leveraging DC grid protection to ease the constraint

- If DC grid connects more than one point per area
  - Current practice defines reserves based on ***permanent loss*** of connections
  - DC grid protection leads to only a ***temporary loss*** of connections → helps reducing the required reserves

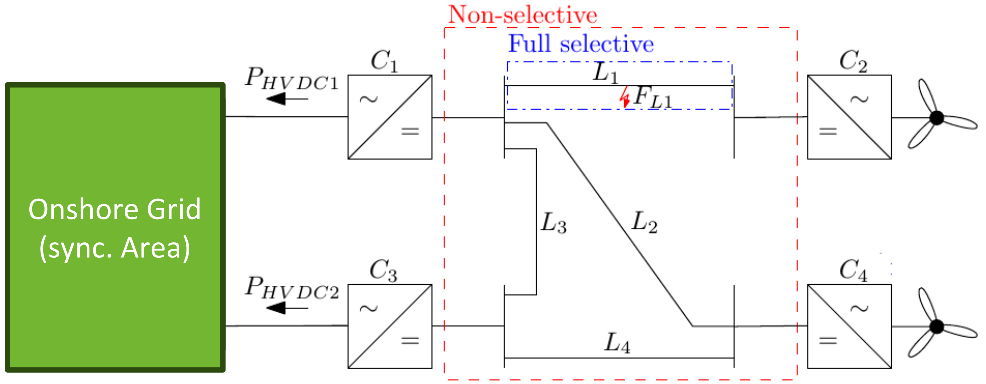
Permanent loss

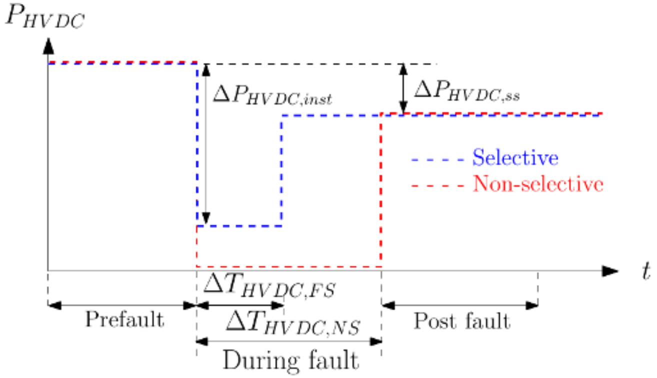


Temporary loss

Leveraging DC grid protection to ease the constraint

- Two groups of protection strategies:
  - Fully Selective (FS) : expensive, faster
  - Non-Selective (NS) : cheaper, slower

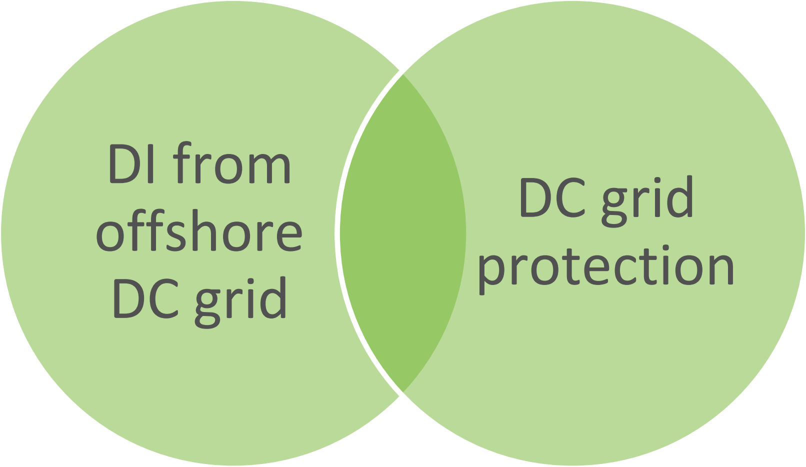




- FS quickly disconnects the faulted line using DC circuit breakers so the remaining grid only sees a small transient.
- NS disconnects the whole grid momentarily and reconnects the healthy part back.

What are we aiming for?

- Combine two concepts to add flexibility in DC grid planning and analyze
  1. Impact on reserve MW requirement
  2. Benefits in operational and planning cost



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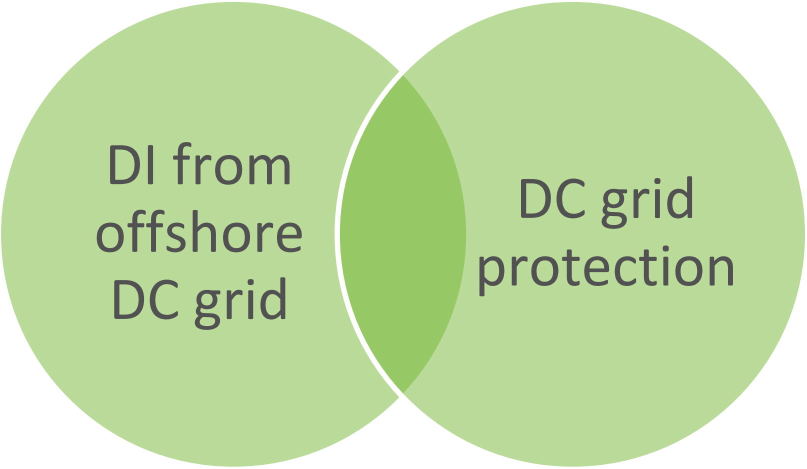
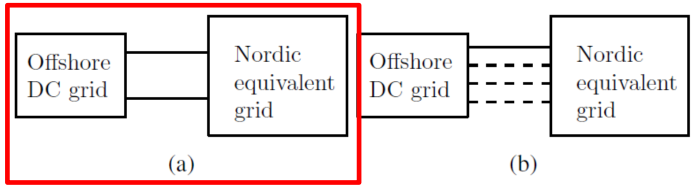


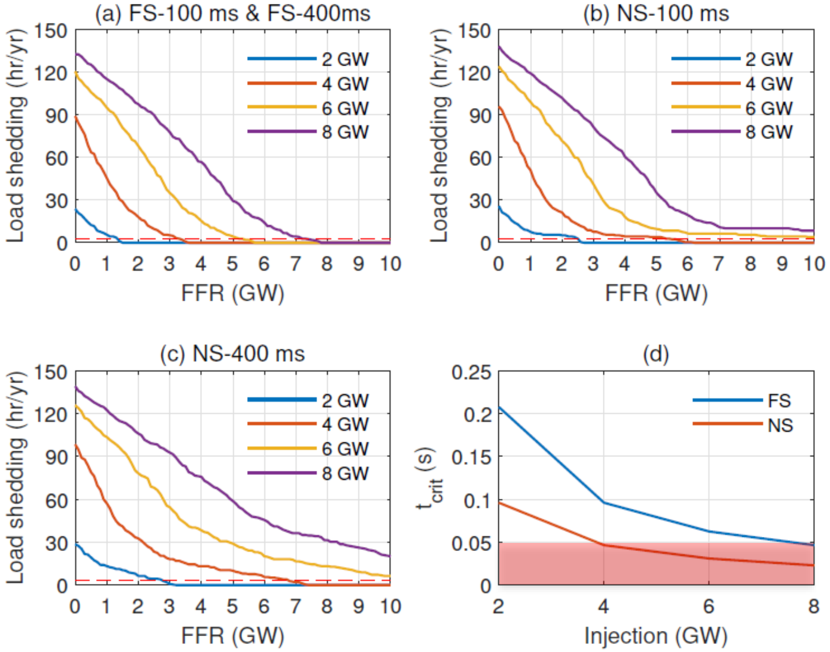
Impact on reserve requirement

- Comparing two groups of protection strategies: FS and NS with 100 ms and 400 ms of power restoration time
- When injection and no. of connections are varied between onshore and offshore systems.



(a) varying injection (b) varying #connections

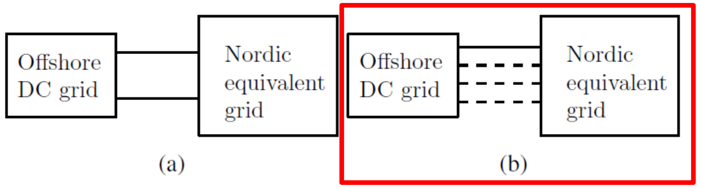
Prot. strategies		FS	NS	NS
ΔT_{HVdc}		100 ms/400 ms	100 ms	400 ms
Injection	2 GW	1400 MW	2500 MW	2800 MW
	4 GW	3300 MW	5300 MW	6800 MW
	6 GW	5200 MW		
	8 GW	7200 MW		
Connections	1	1100 MW	1100 MW	1100 MW
	2	1700 MW	2600 MW	2800 MW
	3	1700 MW	2800 MW	4900 MW
	4	1800 MW	5800 MW	7200 MW



- NS protection strategy requires a higher capacity and faster response time of reserves than FS.

Frequency stability under offshore DC grid development

- A methodology is proposed to determine the capacity of Fast Frequency Reserves (FFR) under different protection strategies.



(a) varying injection (b) varying #connections

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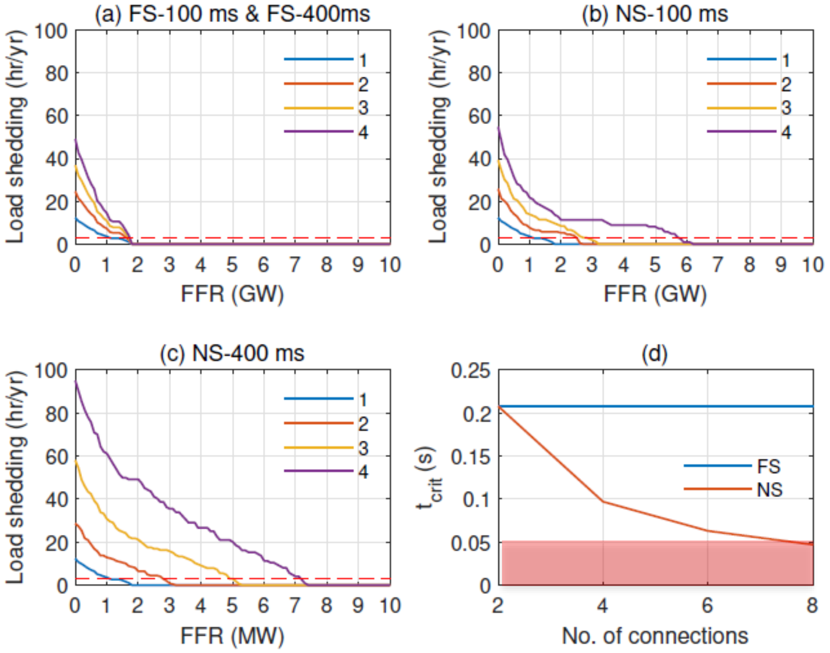
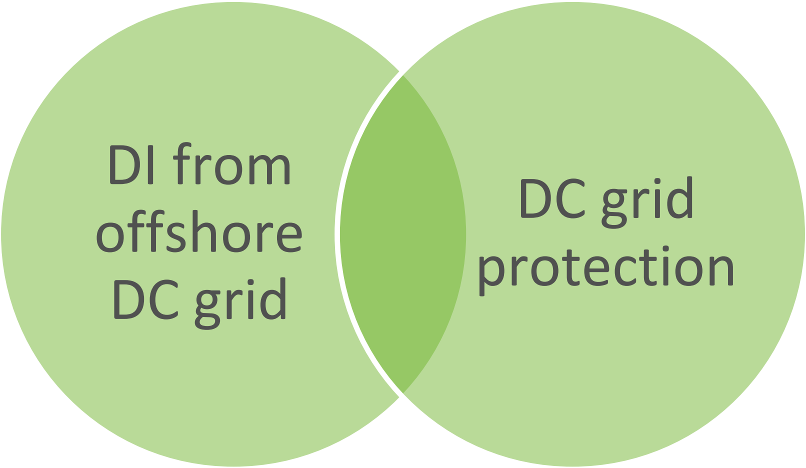


(b) Effect of varying #connections

- NS protection strategy requires a higher capacity and faster response time of reserves than FS.
- Compared to permanent loss, the protection based reserves' procurement is beneficial.

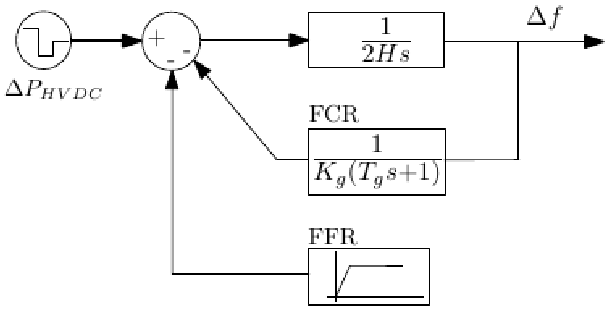
What are we aiming for?

- Combine two concepts to add flexibility in DC grid planning to analyze
  1. Impact on reserve MW requirement
  2. Benefits in operational and planning cost

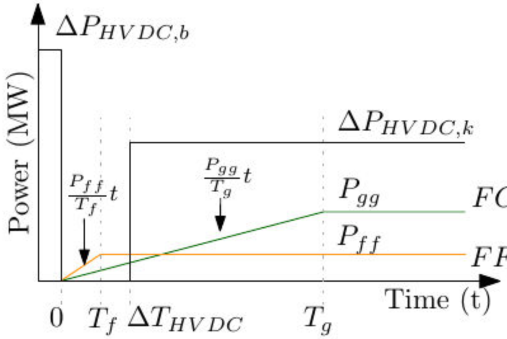


Integrating frequency stability in the offshore DC grid operation and planning

- Impact of protection is translated in mathematical equation and integrated in optimization problems.
- Two models are built: frequency constrained optimal power flow and frequency constrained optimal planning



Frequency response model



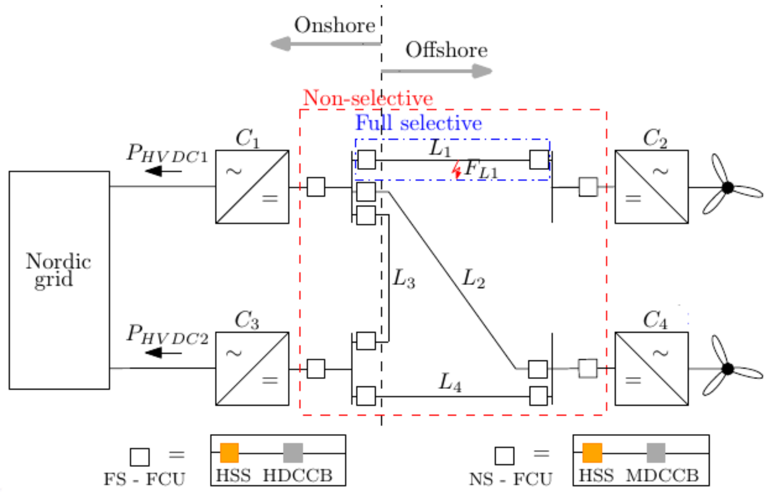
Response of different elements

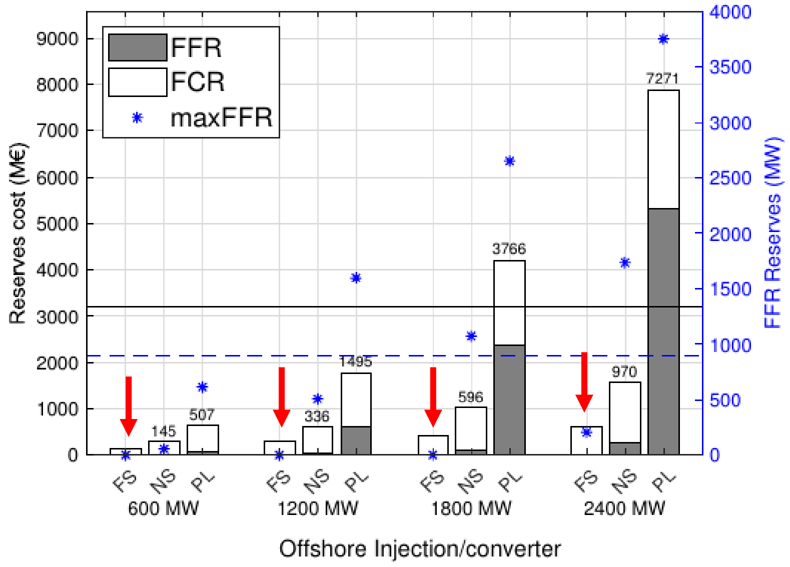
$$\frac{H}{f_0}\left(\frac{P_{gg,k}}{T_g}+\frac{P_{ff,k}}{T_f}\right) \geq \frac{(\Delta P_{HVDC,b})^2}{4|\Delta f_{max,n}|}$$

Second order cone constraint

Operational cost

- Full selective protection strategy results in
  - Lower operational cost
  - Lower reserve capacity installation
- Operational benefits far outweigh the investment for FS protections strategy because it reduces the MW requirement at each hour
  - Operational benefit ~ 970 M€
  - Additional investment cost ~ 88 M€

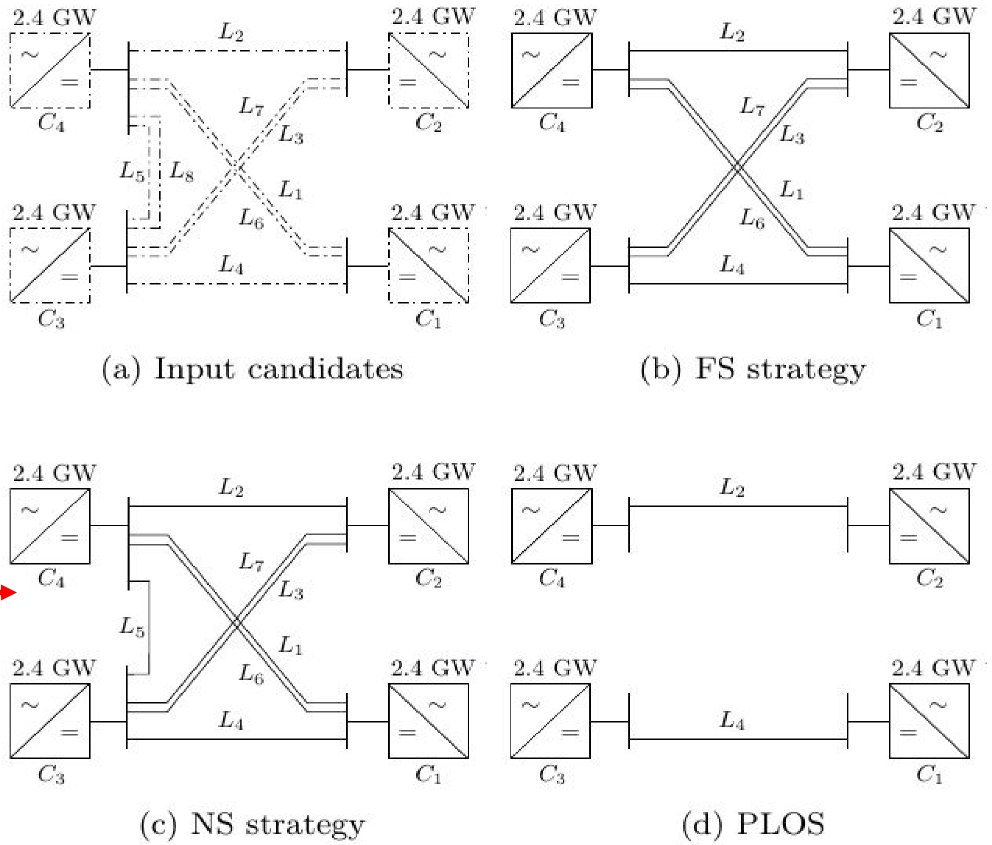




FS = Fully Selective, NS = Non-selective, PL = Permanent loss

Planning outcome

- Permanent loss of supply (PLOS) based reserve procurement results in point-to-point expansion
  - Because reserves would be too expensive for the loss of entire grid.
- Temporary loss of supply based reserve procurement allows meshed grid expansion.



Meshed grid expansion

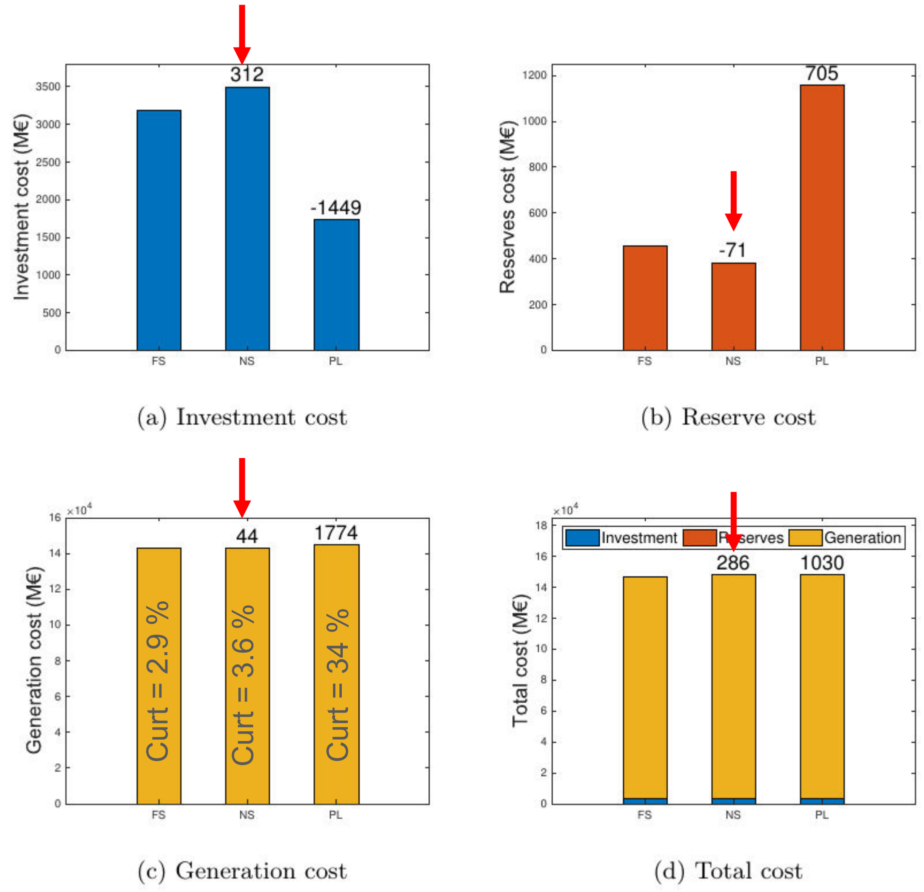
Meshed grid expansion

Point-to-point expansion

Planning cost

- Planning model finds a trade-off between different cost components – investment, curtailment and reserves cost.
- NS protection strategy requires less reserves but needs higher investment and generation costs.
- FS protection strategy is cheaper by
  - 286 M€ than NS protection strategy
  - 1030 M€ than permanent loss

- Frequency stability should be a part of the planning problem
  - Determines whether to build less, pay for reserves or resort to RES curtailment.



(a) Investment cost

(b) Reserve cost

(c) Generation cost

(d) Total cost

Conclusion

- A holistic planning methodology considering HVDC grid topology, protection strategy and frequency reserve requirements is required as developed here.

- It is clearly shown that the current way of defining dimensioning incidents is too restrictive for meshed offshore HVDC grids.

- Fully selective HVDC grid protection shows clear economic benefits as the saving in reserve procurement (or other counter-measures) by far outweighs the investment cost.

Thank you

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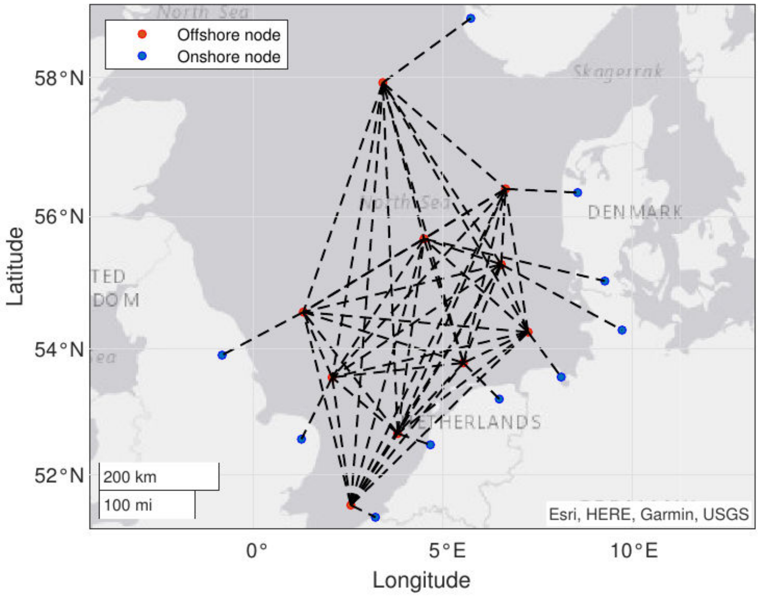
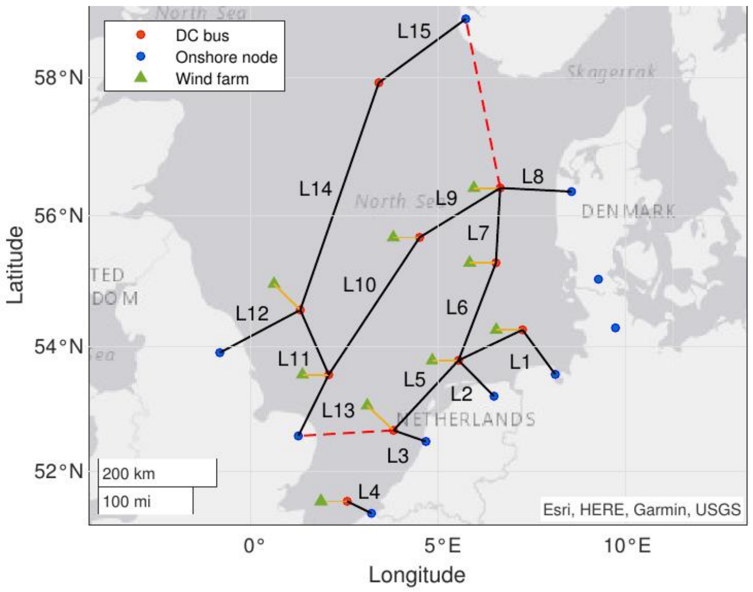
Met de steun van het Energietransitiefonds

Selecting a protection strategy for a large offshore DC grid

- An example DC grid system is studied so far.
- This part aims at recommending a strategy for a realistic test network.
- A North Sea based DC grid topology is derived through a planning exercise.

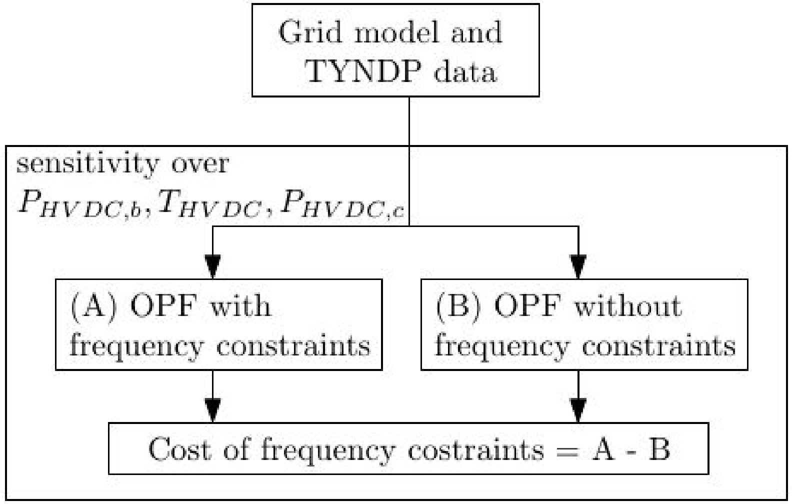


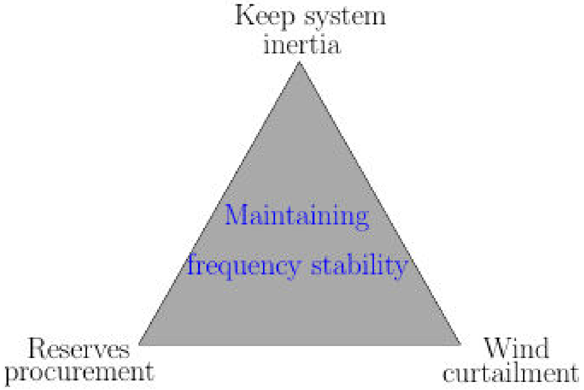


- Cost-benefit analysis is performed to determine the protection strategy.

Selecting a protection strategy for a large offshore DC grid

- A methodology is proposed to determine the cost of frequency stability.
- It finds trade-offs between basic counter-measures
  - Keeping system inertia, reserve procurement and wind curtailment.

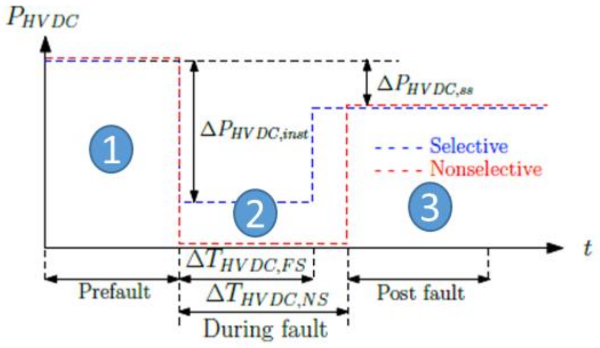


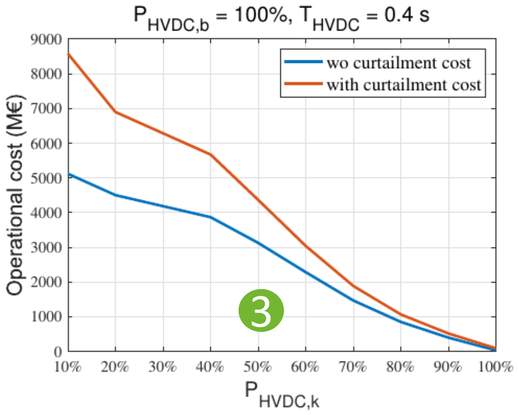


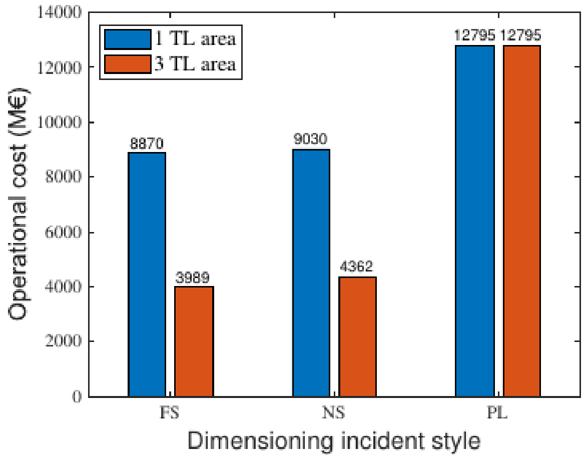
OPF = Optimal Power Flow, TYNDP = Ten Year Network Development Plan

Selecting a protection strategy for a large offshore DC grid

- Power restoration curve needs to be derived through extensive transient simulations and depends to a wide range of factors.
- A sensitivity analysis over power restoration curve's parameters is performed and a protection strategy is recommended accordingly.







- Out of three parameters, the post-restoration power flow has the most influence on the operational cost → meshed DC grid is favored.
- Full selective protection strategy is the most economical.


Neptune Final Event
Kristof Phillips

NEPTUNE: North-sea Energy Plan for Transition to Sustainable Wind Energy

https://www.energyville.be/en/research/neptune-north-sea-energy-plan-transition-sustainable-wind-energy

Generation Expansion Planning (GEP)

What is the optimal mix of generation capacity to provide electricity to all consumers at the lowest possible cost?

Current trends in energy system development

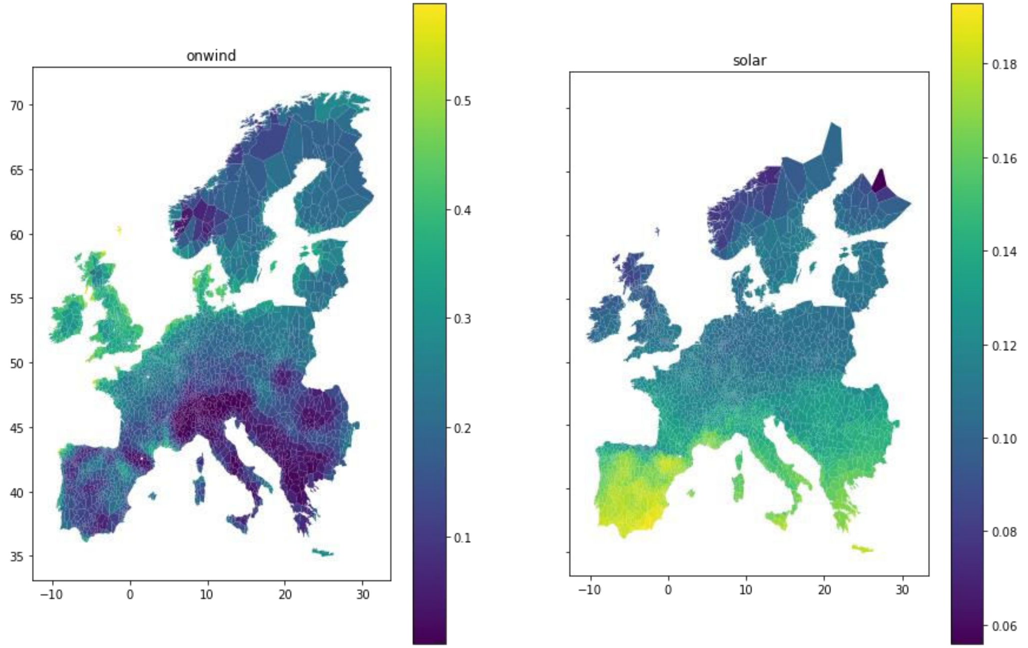
Trends

88GW of CB transmission capacity increases 2025→2040 (80 GW existing 2020) - TYNDP 2022

- High levels of renewable integration
- Rising relative value of network costs (DC links, need for strong interconnection)

Planning consequence

→ Increased need for spatial detail in generation planning
→ Planning over large areas is desired
→ Integration of transmission network in generation planning models



The ideal planning model

- Is highly spatially resolved (fine resolution)
- Covers a large geographical area
- Combines transmission and generation expansion
- Covers short- and long-term uncertainty

→ Is computationally not feasible

Our goal

- Generate insight in the importance of spatio-temporal modeling assumptions

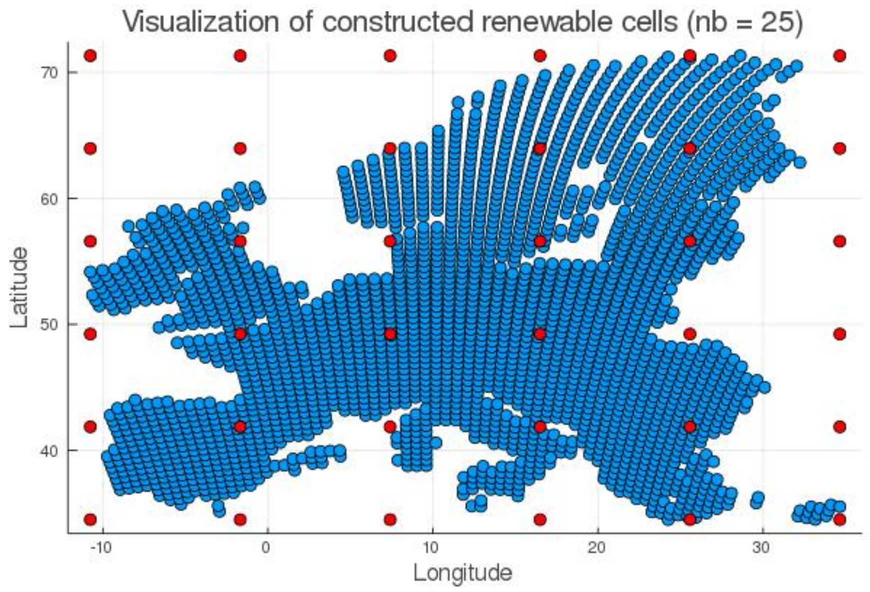
→ How does the spatial representation of renewable technologies impact planning model results?

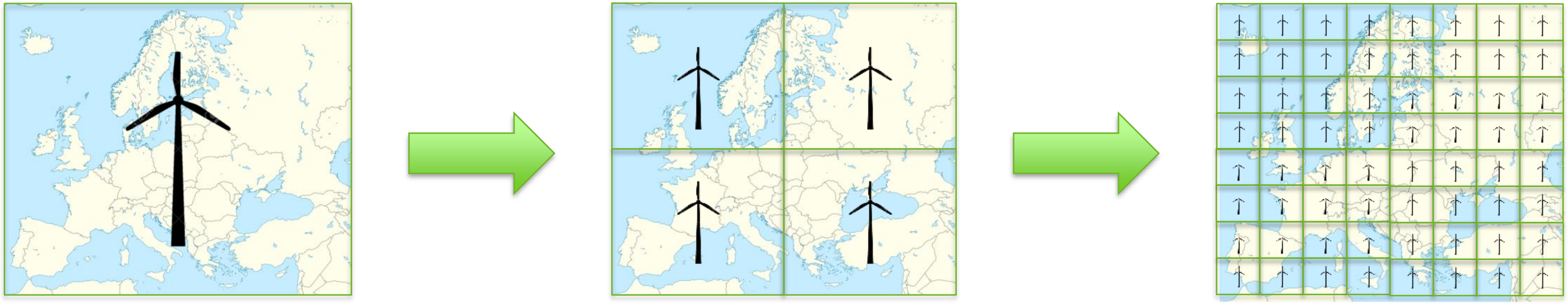
- Develop tools for tractable integrated planning

→ Can we approximate the results of highly spatially resolved models by using a low number of renewable-based regions?

Effect of renewable representation

- Flexible, representative GEP model (no transmission network)
- Case study for European region
- Spatial disaggregation of renewable technologies in multiple resolutions
- Comparison of model results in high vs low resolution (1 → 900 cells)



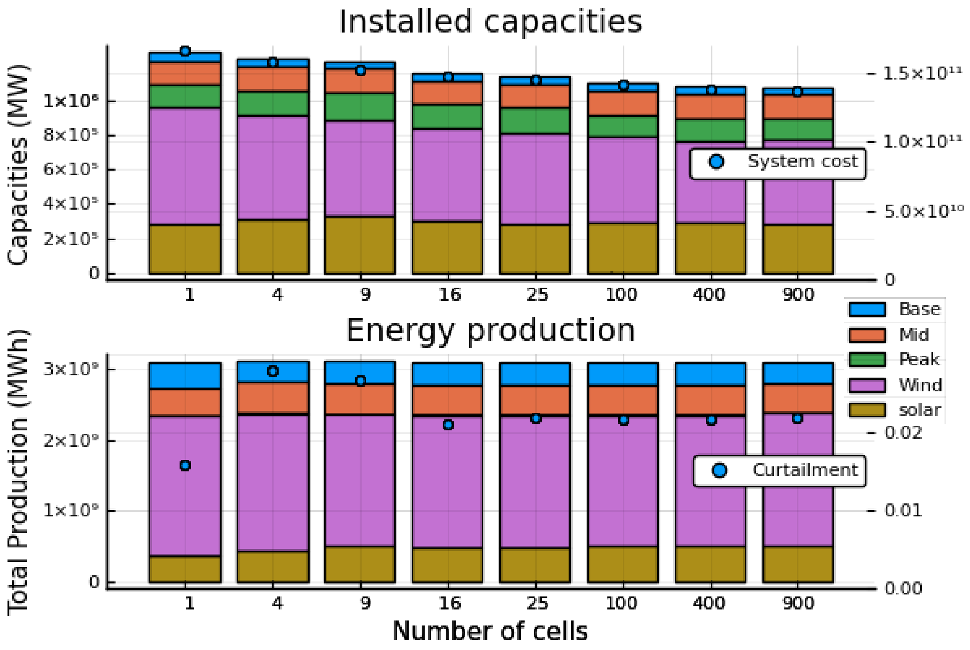


Effect of spatial representation of renewable technologies

Spatial Resolution

- In high resolution, more interesting renewable generation sites can be identified → Strong decrease ($\sim 18\%$) in total system cost
  - Majority of cost reduction ($\sim 70\%$) achieved with 25 cells
- Resolution-effect is dependent on the homogeneity of input data

→ Homogeneity of renewable technologies within model regions is desired



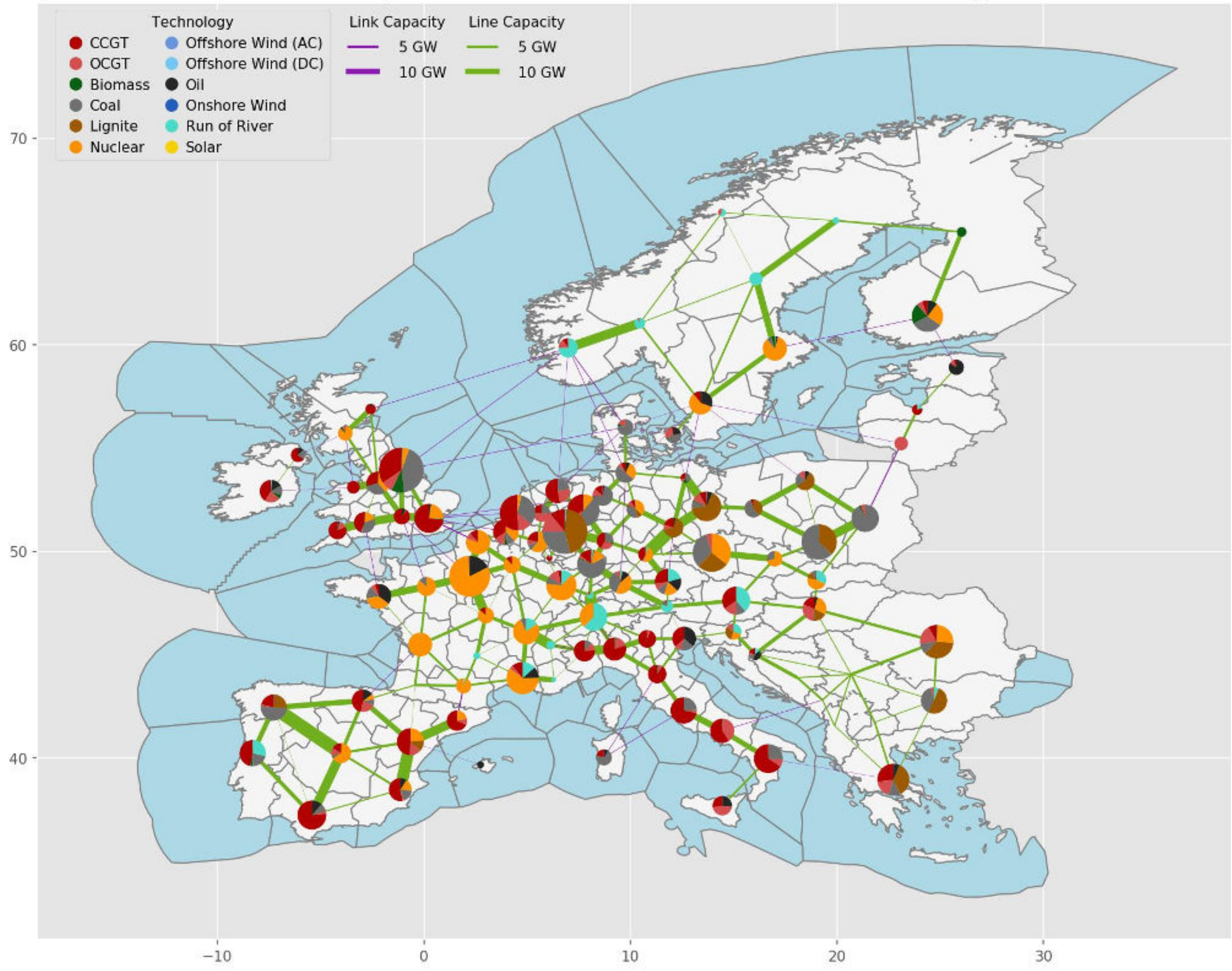
Methods to approach high-resolution solution with low-resolution model

- Resolution dependency is driven by 2 opposing factors
  1. Spatial dependence of renewable sites
  2. Identification of transmission bottlenecks
- Tackle 1 by generating model regions based on renewable time-series attributes

Methods and tools

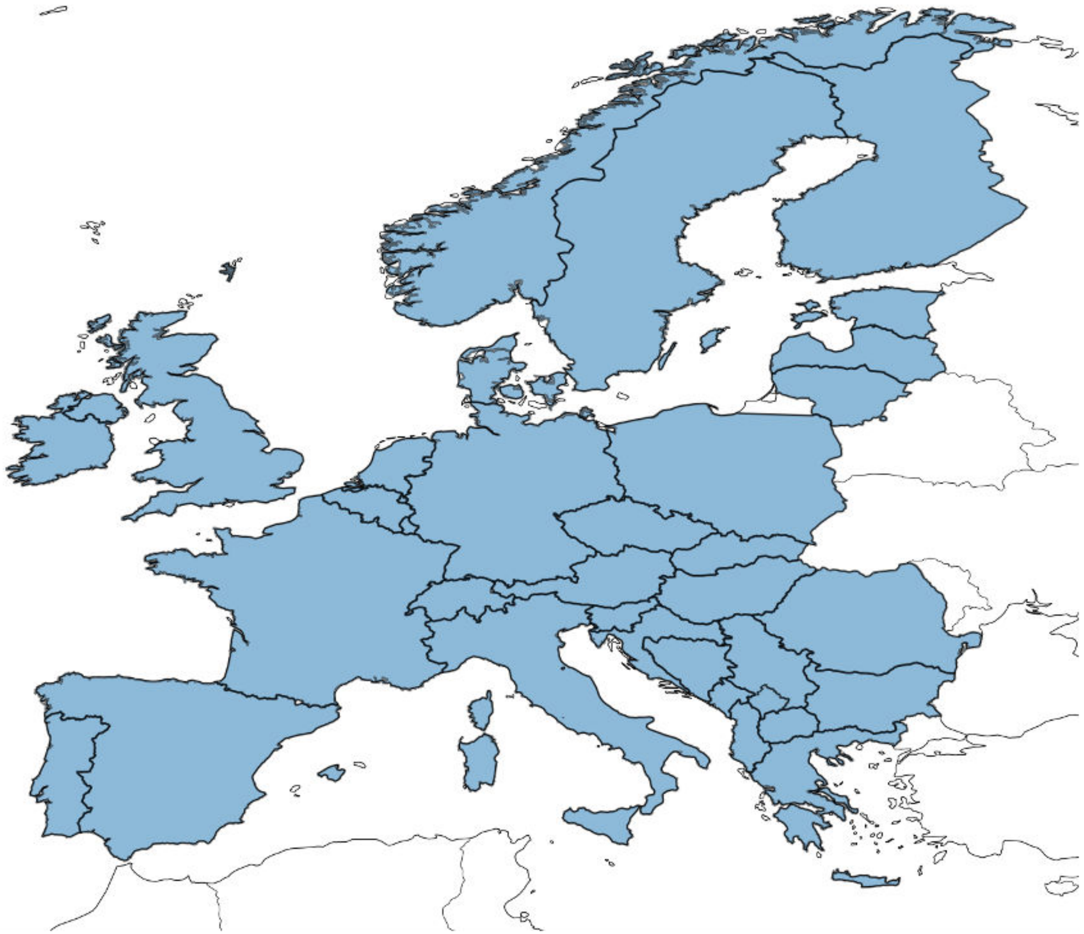
- Existing open-source planning tool
- Compare high resolution solution with low resolution outcomes of qualitatively different regions

Clustered electricity network of 100 nodes without variable renewable energy sources



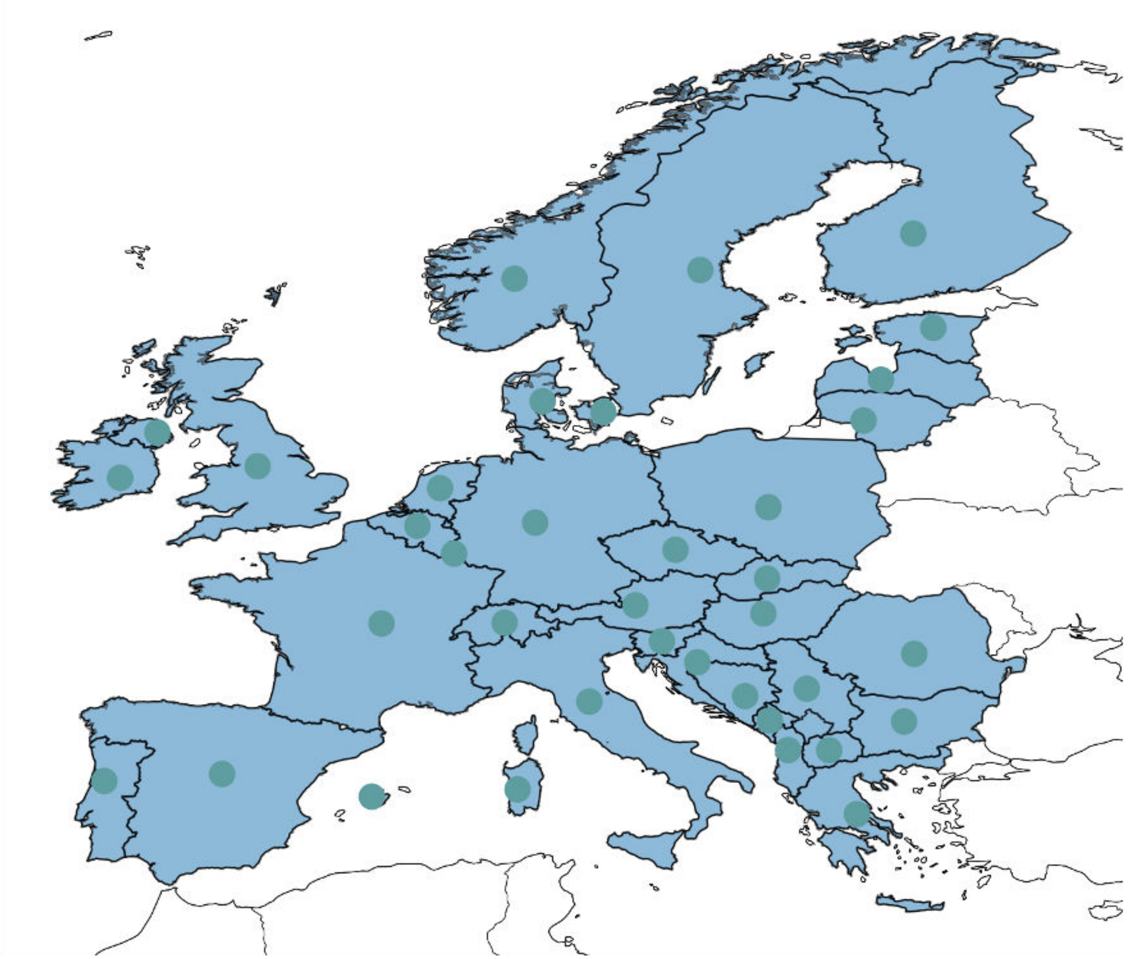
Modelling regions: convention

- Start from countries



Modelling regions: convention

- Start from countries
- Calculate properties for one or more nodes in each country



Modelling regions: convention

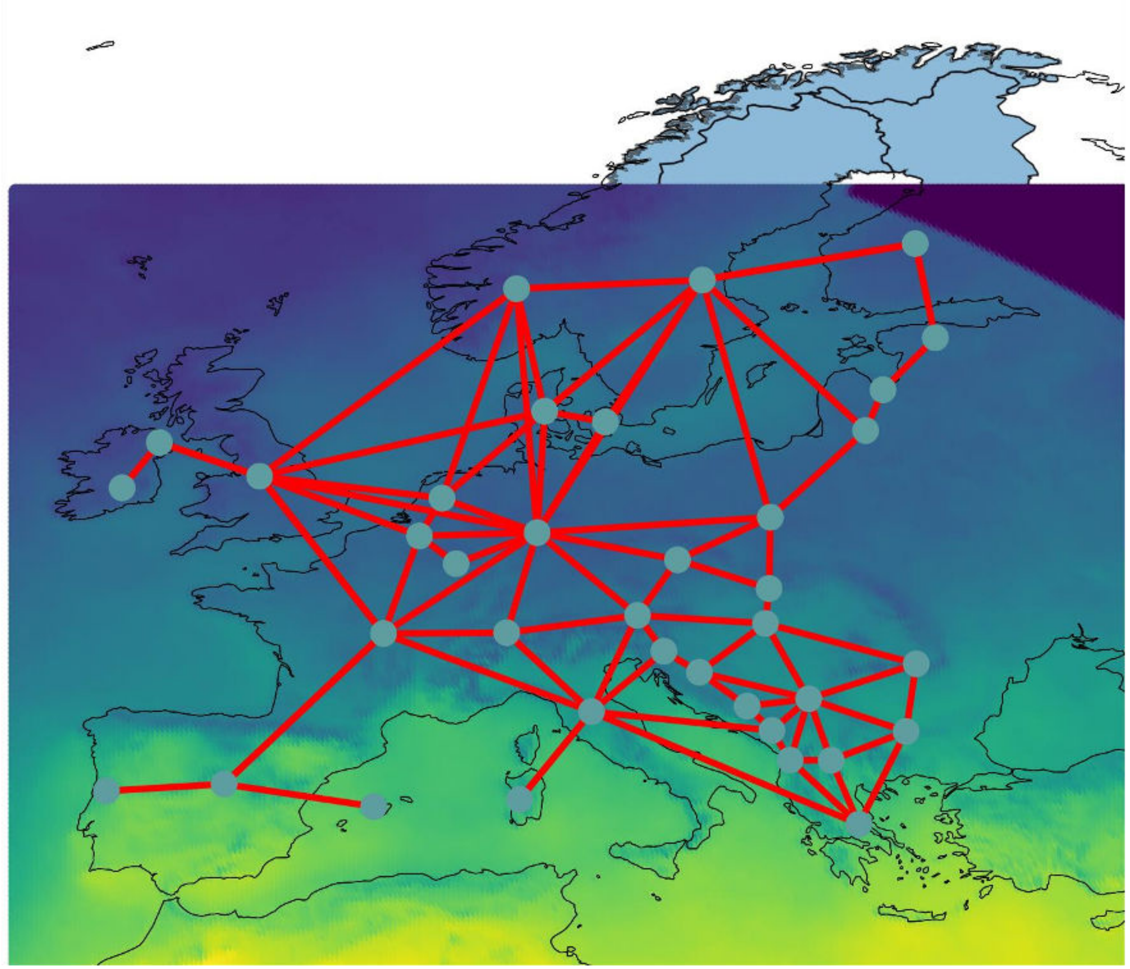
- Start from countries

- Calculate properties for one or more nodes in each country
- Add connections

Modelling regions: convention

- Start from countries
- Calculate properties for one or more nodes in each country
- Add connections

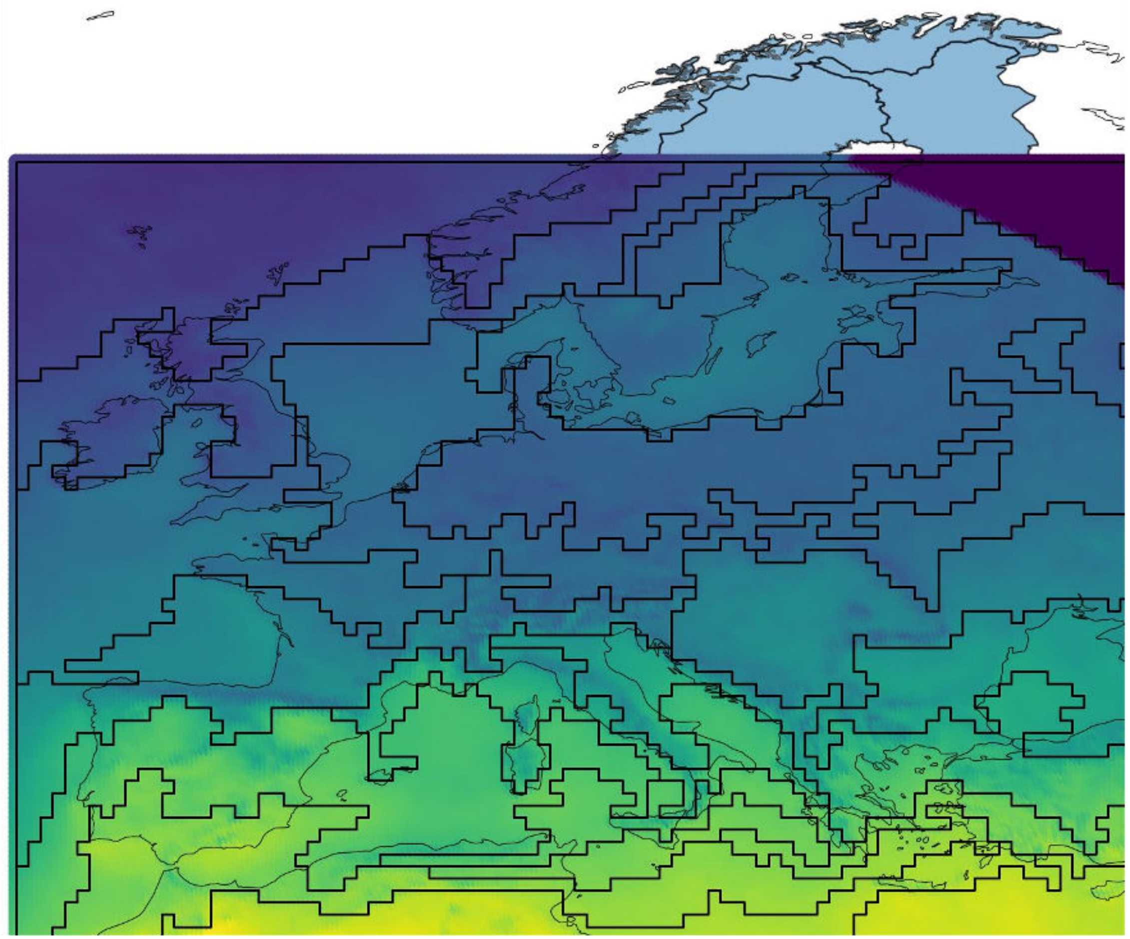
Does this make sense?



Modelling regions: alternative

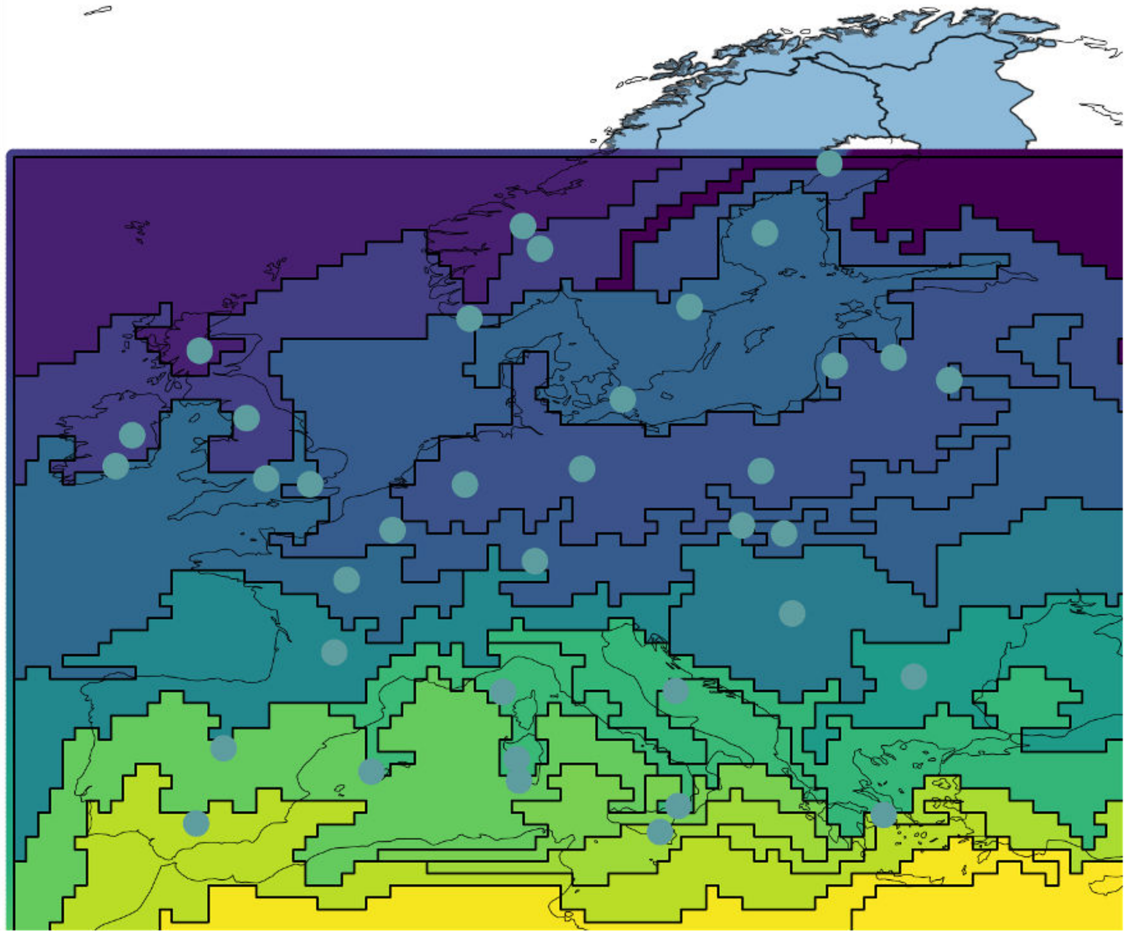
- Start from renewable potential

- Generate regions with similarity based clustering



Modelling regions: alternative

- Start from renewable potential
- Generate regions with similarity based clustering
- Calculate properties for one or more nodes in each renewable zone



Modelling regions: alternative

- Start from renewable potential
- Generate regions with similarity based clustering
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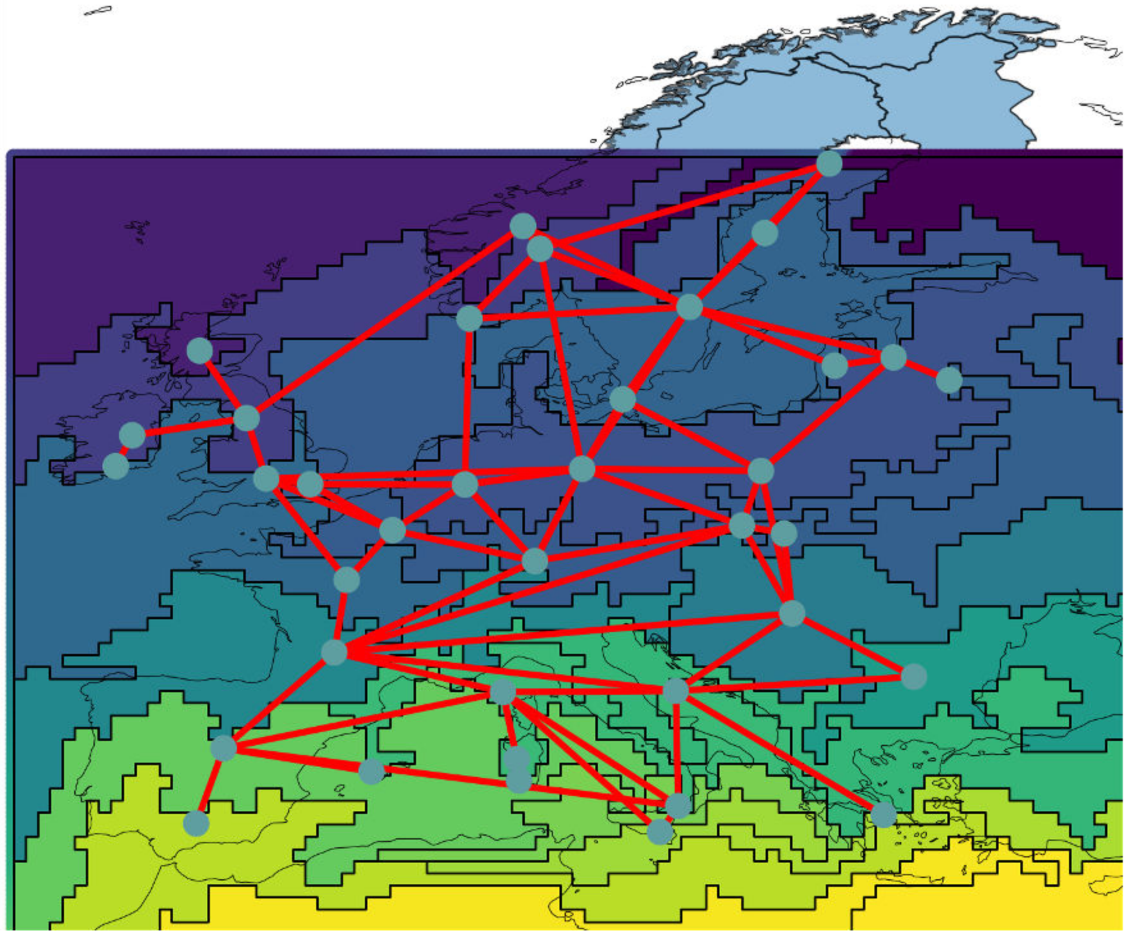


Renewable-based model regions

Results

- Convergence at high network resolution
- Focus on differences in low-resolution

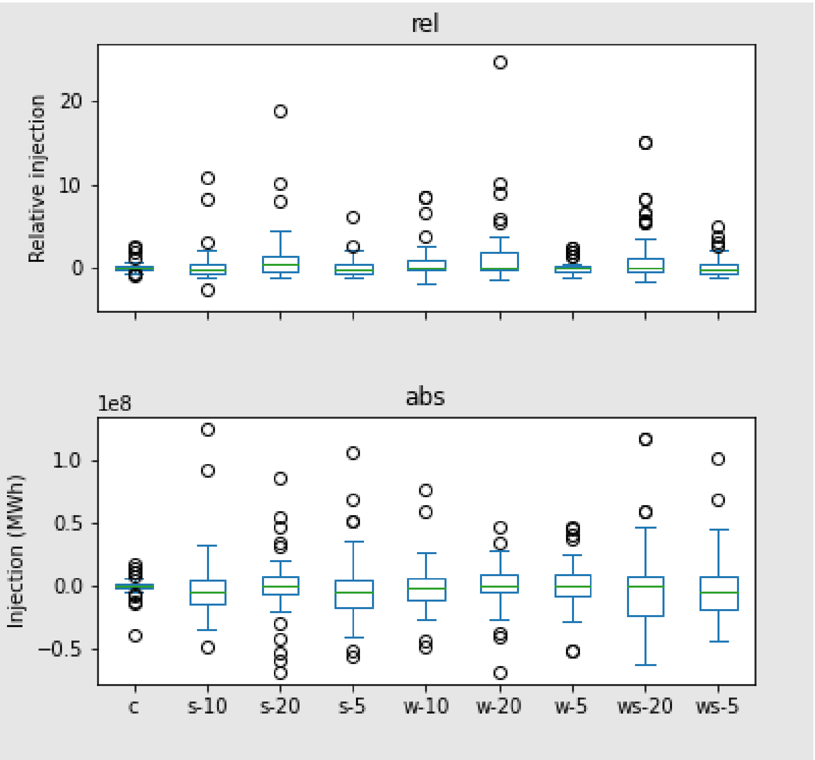
Pre-optimization

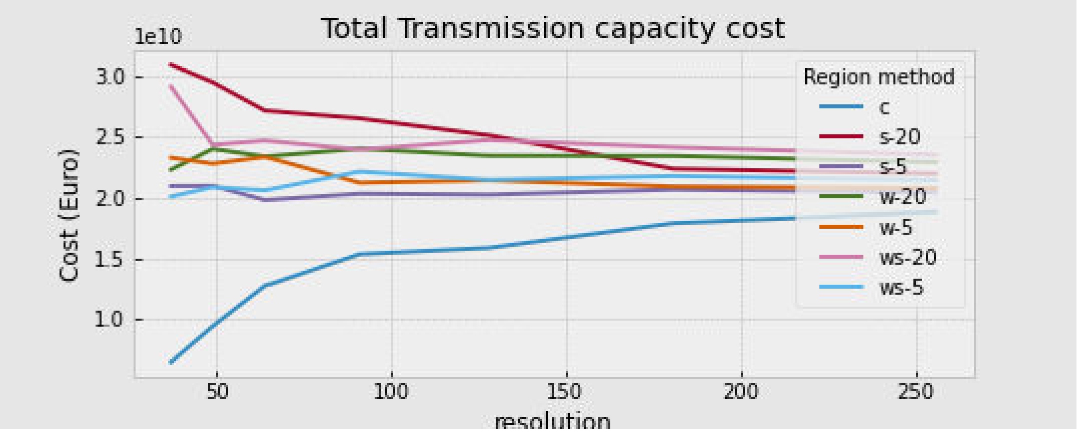
- More transmission volume is represented in all renewable-based aggregations than in the country-based case
- Few renewable regions lead to more balanced size of nodal regions

Optimized system

- A clear distinction emerges between generating and consuming regions ↔ balanced, self-providing countries
- Identification of transmission needs that are not visible in the country-based model
- Similar total cost but shift from generation to transmission investment

Nodal balances 37 nodes





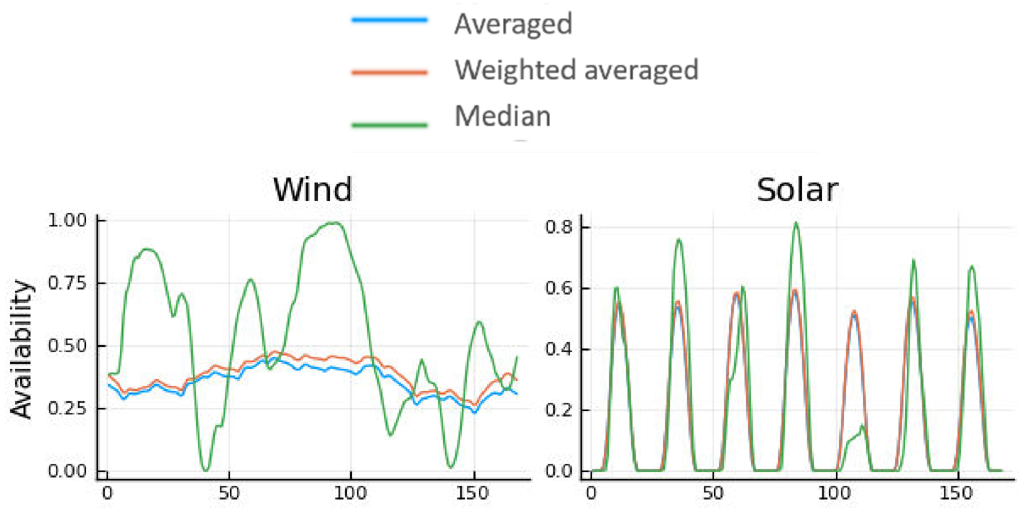
Questions?

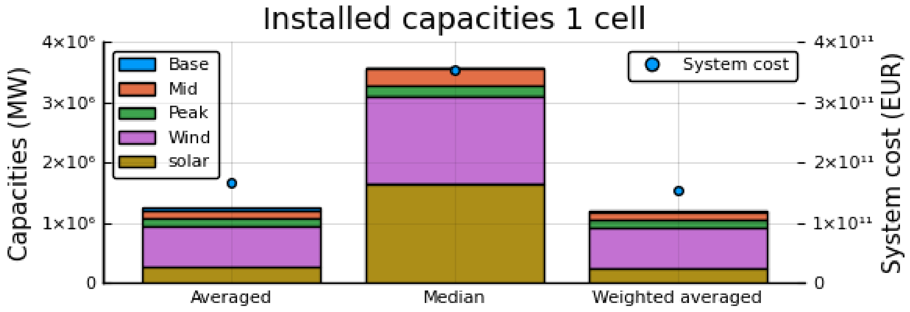
With the support of the Energy Transition Fund

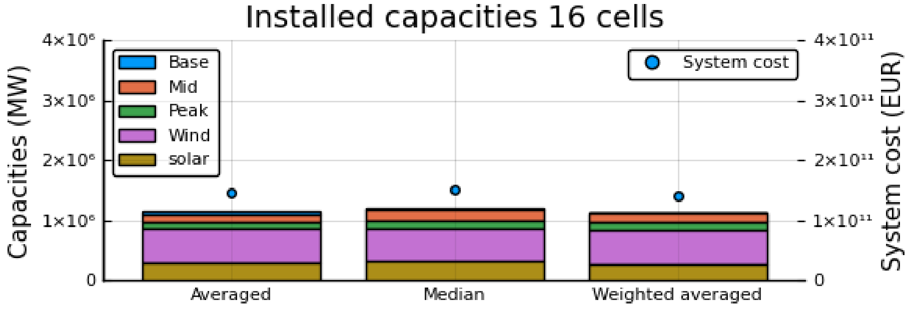
Effect of spatial representation of renewable technologies

Spatial Aggregation

- Aggregation = combining high-resolution raw input data to obtain time-series in model resolution
- Model input strongly depends on aggregation technique
- When optimizing a single model region: model output depends strongly on aggregation technique
    - Total cost, Installed capacities, curtailment
- Effect quickly diminishes with increasing number of model regions







WP2: Protection strategies and algorithms

Neptune Final Event

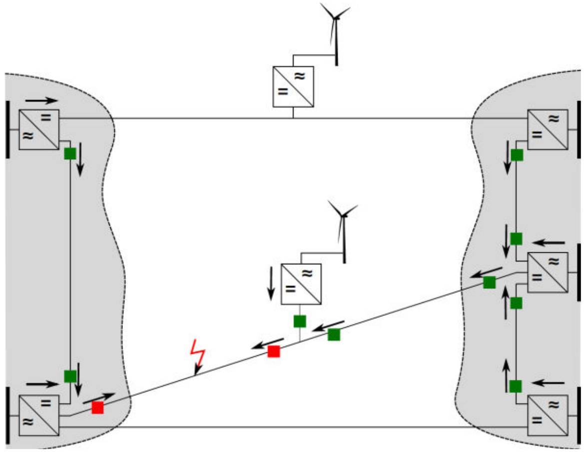
Willem Leterme – September, 27th 2023

Reliable protection essential for secure operation and efficient use of transmission system

- Protection acts whenever a fault occurs within the power system

- Protection fulfills three objectives:
  - Ensuring human safety
  - Guaranteeing continuity of power supply
  - Avoiding damage to components

- Protection encompasses
  - Detecting and identifying the fault
  - Switching off the faulted component



Offshore wind integration and HVDC systems introduce challenges for both AC and DC grid protection

- **In ac systems**, existing protection algorithms must deal with changed fault current characteristics, given differences between HVDC converters and conventional power plants

- **For dc systems**, fundamentally new protection algorithms and strategies are needed, due to differences in fault phenomena and technology for protection

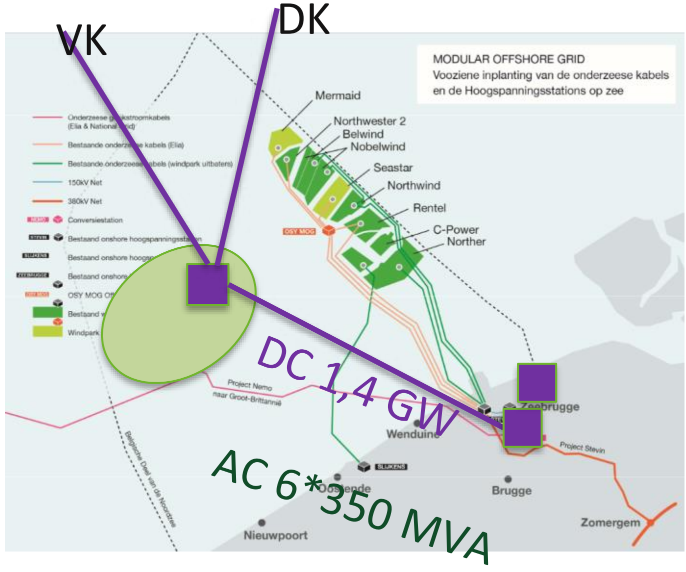
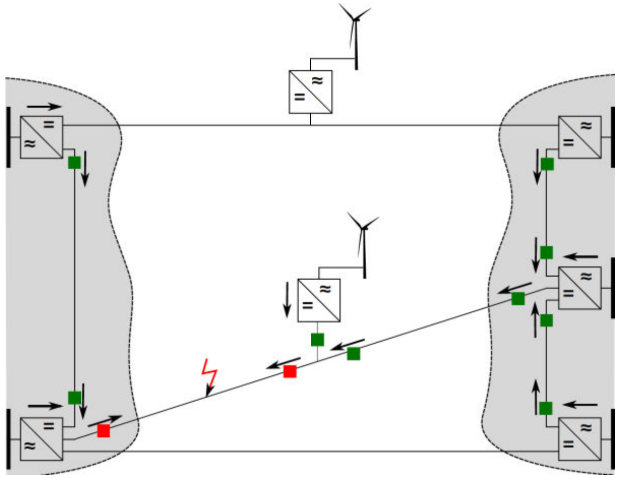
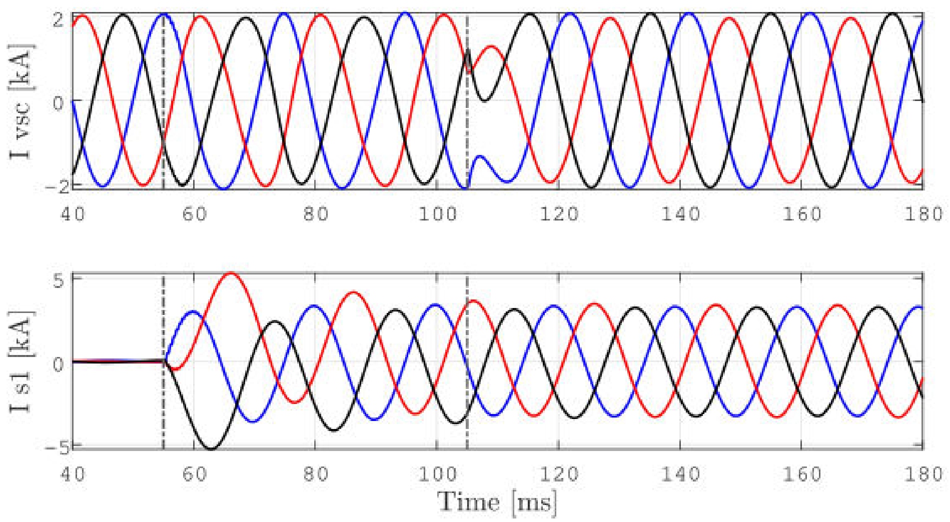


Figure: Elia



In AC grids, fault currents are changing due to replacement of synchronous machines by converters

- Fault currents are 6-8 times lower as power-electronics cannot sustain overcurrents
- Fault currents are controllable by the power-electronic converters
- Fault currents can become more variable due to changing grid infeed



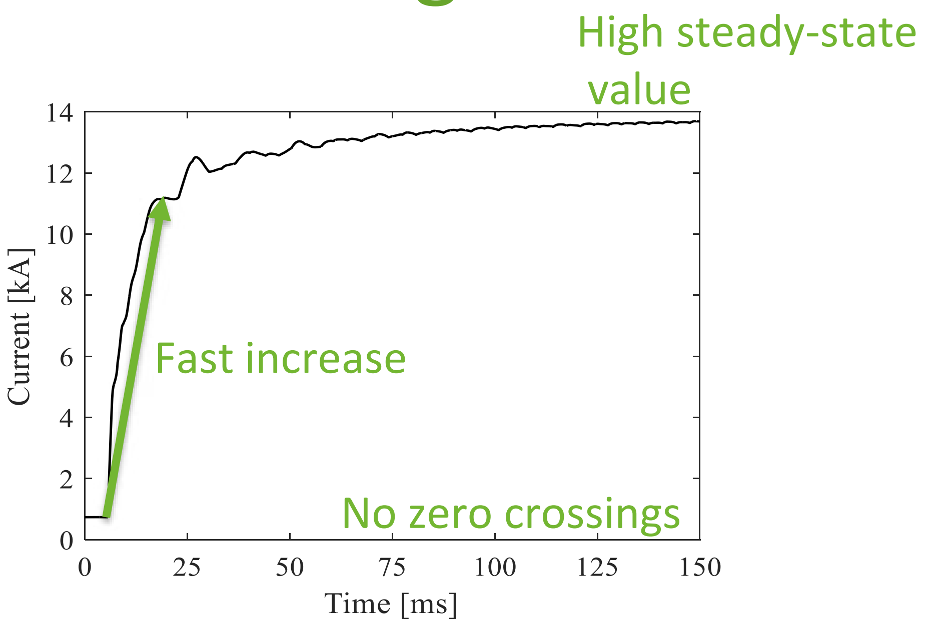
- => Lower and less predictable fault currents lead to more difficult fault detection and identification

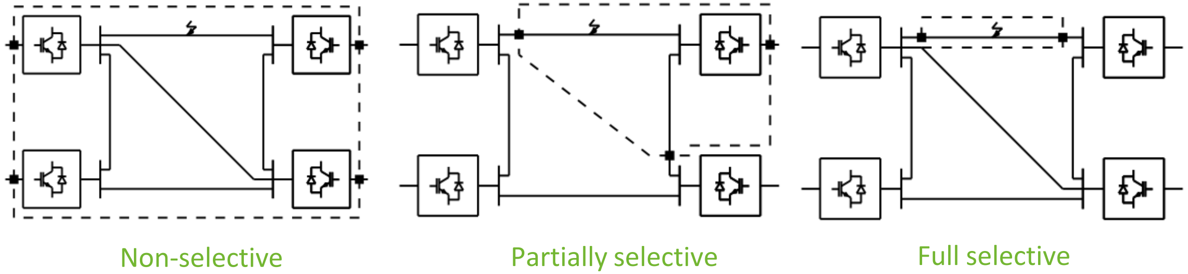
DC grids require much faster protection against faults…

- High rate of rise of current, and high steady-state currents
- Fast collapse of the voltage

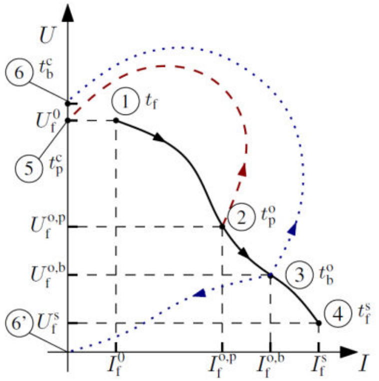
- In case of no action leading to:
  - Loss of DC voltage control
  - Damage to components

- Protection needs to react in the order of milliseconds, 10-100 times faster than in AC systems

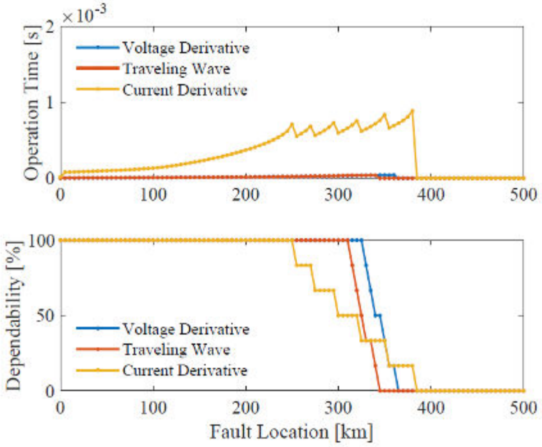




Past work: 10 years of protection research at Electa



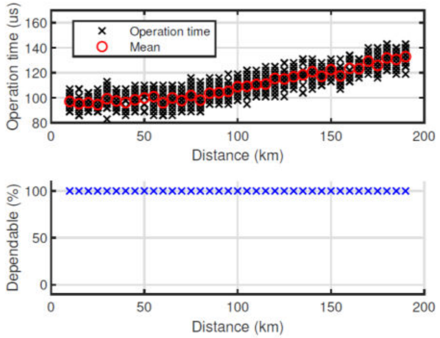
Algorithm development



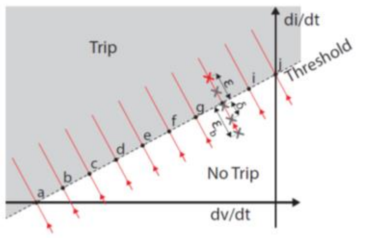
Algorithm evaluation

Academic testing

Industrial development



(b) Dependability for faults in protection zone (Cable L1)



(a) Algorithm characteristic and perpendicular test ramps

Standalone functional testing

System level testing

Standardisation

Neptune

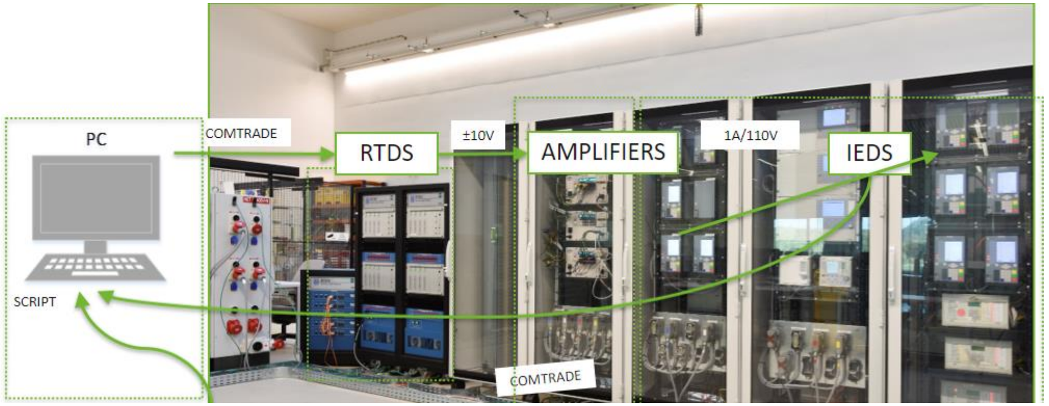
Energy Ville

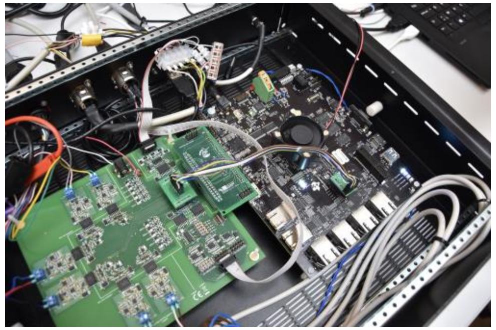
Challenges tackled within NEPTUNE WP2

- Can existing or novel protection algorithms for AC side protection deal with changed fault currents?
- Can we increase the speed of state-of-the-art HVDC grid protection IEDs with a factor 10-100?
- How to design novel DC protection algorithms for very long cables?
- What is the system impact of HVDC grid protection alternatives, and how to compare it? (with WP1)
- What should change to the grid codes when HVDC grids are being integrated?

NEPTUNE has identified challenges for future AC and DC protection algorithms and developed state-of-the-art labs

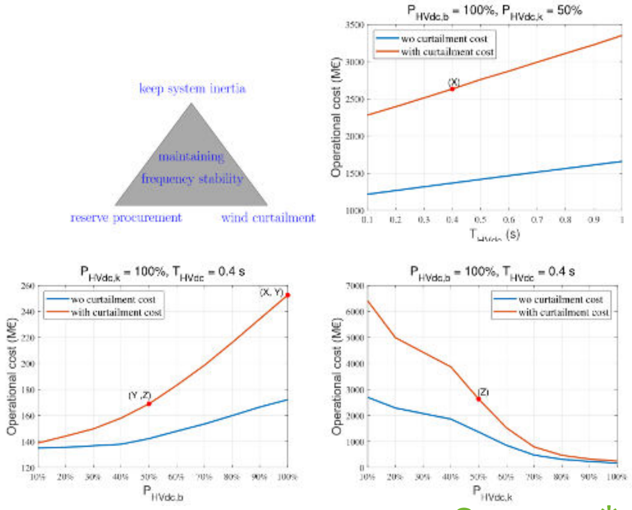
- **Existing AC protections** may fail in systems where the power-electronics dominate the fault response, and also novel concepts show less robust behavior in such systems.
- **Practical DC protection algorithm** design does not directly benefit from speed gains due to higher sampling rates, and requires trading-off hardware constraints and noise filtering
- NEPTUNE has delivered
    - An AC protection test setup (screening tool and automated real-time HIL setup for detailed analysis)
    - protection algorithms on hardware that enables MHz sampling (10-100 faster than prior art),
    - a test setup for DC protection algorithm testing



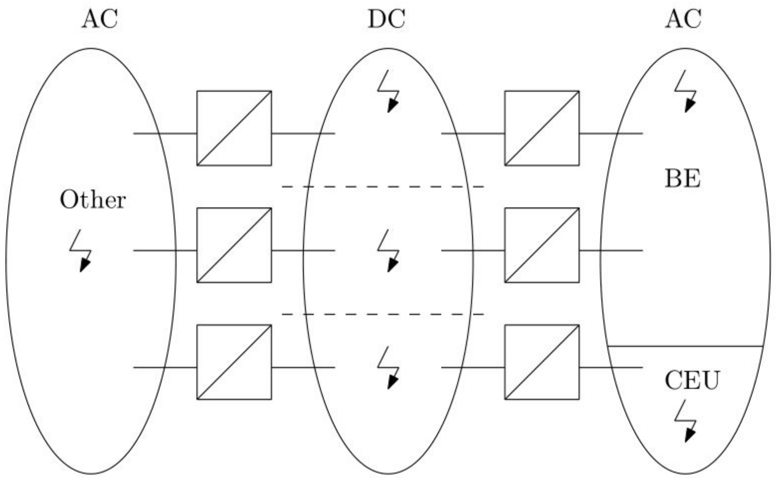


As HVDC grids scale up, HVDC protection strategies and grid codes must consider the entire AC/DC grid impact

- Present grid codes focus on AC and DC sides separately
- HVDC grid protection strategy design directly effects
  - AC system impact of DC-side faults
  - Availability of HVDC converters to deliver services to the AC system
- Future HVDC grid protection design and grid code specifications must consider AC and DC impacts
- NEPTUNE has
  - Performed a cost-benefit analysis of protection strategies, including AC system impact
  - Performed an analysis of existing grid codes and provided recommendations for integrating HVDC grids



Source *



*J. Dave, H. Ergun and D. Van Hertem, "Reducing the cost of maintaining the frequency stability using dc grid protection," *2021 International Conference on Smart Energy Systems and Technologies (SEST)*, Vaasa, Finland, 2021, pp. 1-6, doi: 10.1109/SEST50973.2021.9543118.

Main findings of WP2 within the NEPTUNE project

- Can existing or novel protection algorithms for AC side protection deal with changed fault currents?
  - If the power-electronic converters dominate the fault response, they start showing malfunctions
- Can we increase the speed of state-of-the-art HVDC grid protection IEDs with a factor 10-100?
  - The speed of protection is a trade-off between hardware constraints and possibilities, and the required filtering of noise
- How to design novel DC protection algorithms for very long cables?
  - Fast and accurate protection for very long cables currently still presents a challenge
- What is the system impact of HVDC grid protection alternatives, and how to compare it? (with WP1)
  - A cost-benefit-analysis shows that even with a large up-front cost, selective protection is the most cost-effective solution for large-scale grids on the long term
- What should change to the grid codes when HVDC grids are being integrated?
  - Grid codes should consider the AC/DC grid rather than looking at both sides separately

Outlook – Findings from the NEPTUNE project

- There is a need for an automated test setup for AC and DC protection testing, with ever increasing modeling detail to account for increasingly complex fault currents

- There is a need for integrated HVDC grid protection design methodologies, where protection design cannot be decoupled from system impacts

- As HVDC grids grow in size, a separate treatment of AC and DC sides is no longer sufficient, and grid codes must be specified for the future hybrid AC/DC grids

Come visit our posters and demos!

- Posters

Frequency-Domain Component Models for HVDC Protection Studies

Mudar Abedrabbo, Willem Leterme and Dirk Van Hertem
mudar.abedrabbo@kuleuven.be

Empowered by KU Leuven, VITO, imec & UHasselt

Novel sensor types for AC and DC grid protection

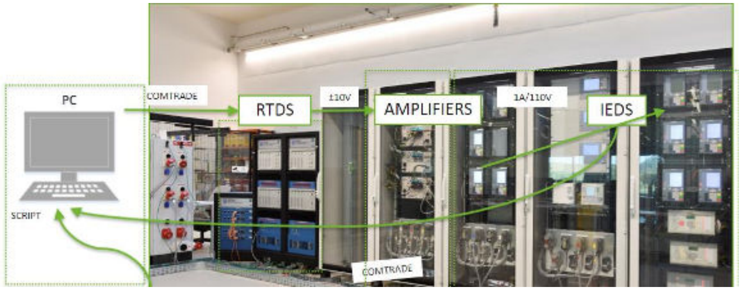
Mohammad Heidari, Dr. Willem Leterme, Prof. Dirk Van Hertem
Dept. Electrical Engineering, KU Leuven/EnergyVille, Leuven/Genk, Belgium

Analysing the Performance of Incremental Quantity based Directional Time-Domain Protection near HVAC Cables and VSC HVDC Converters

Joachim Vermunicht, Willem Leterme, Dirk Van Hertem
Dept. Electrical Engineering, KU Leuven/EnergyVille, Leuven/Genk, Belgium

Empowered by KU Leuven, VITO, imec & UHasselt

Demos



WP2: Protection algorithms and strategies

willem.leterme@kuleuven.be

Met de steun van het Energietransitiefonds

HVDC Grid Code

The Code of Future Multi-terminal HVDC Grids

Neptune Final Event

Dirk Van Hertem / Mudar Abedrabbo – September, 27th 2023

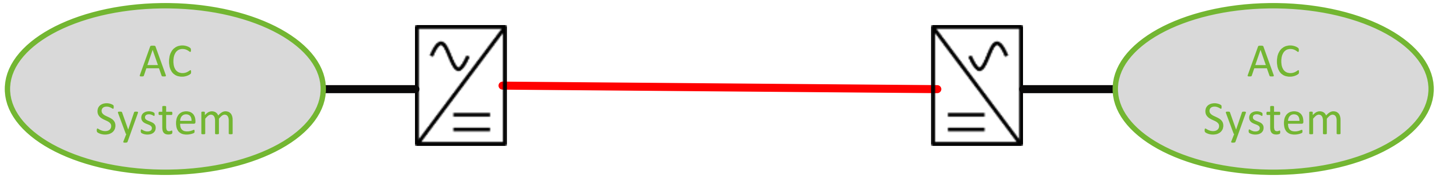
Outline

- Introduction
- What is Grid Code?
- HVDC Grid Code
- Summary

Introduction

HVDC is the solution for future power systems

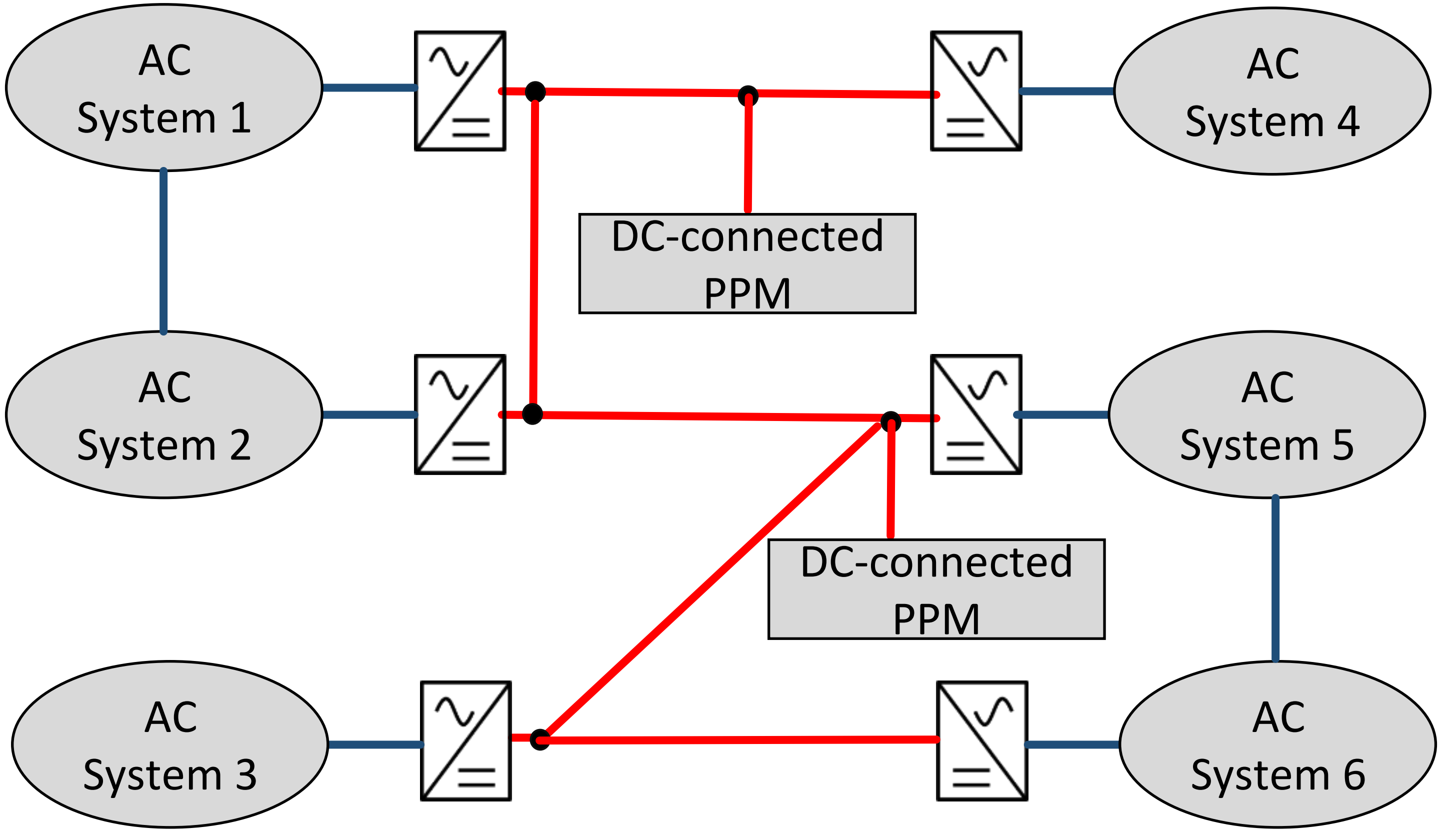
- HVDC: High Voltage Direct Current.
- More convenient for future transmission system with high penetration of renewable energy and long distance transmission.
- At present HVDC technology is mainly used in point-to-point links besides some small multi-terminal schemes in China.

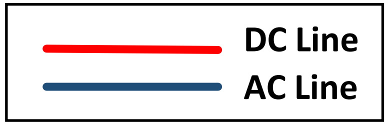


Most of HVDC links are point-to-point connections

Introduction

Evolving of HVDC Grids: Point-to-Point → Multiterminal





Power Park Module (PPM): modules generating electricity connected through power electronics.

Interconnecting point-to-point links to create a multiterminal HVDC grids

Introduction

Evolving of HVDC Grids: Point-to-Point → Multiterminal

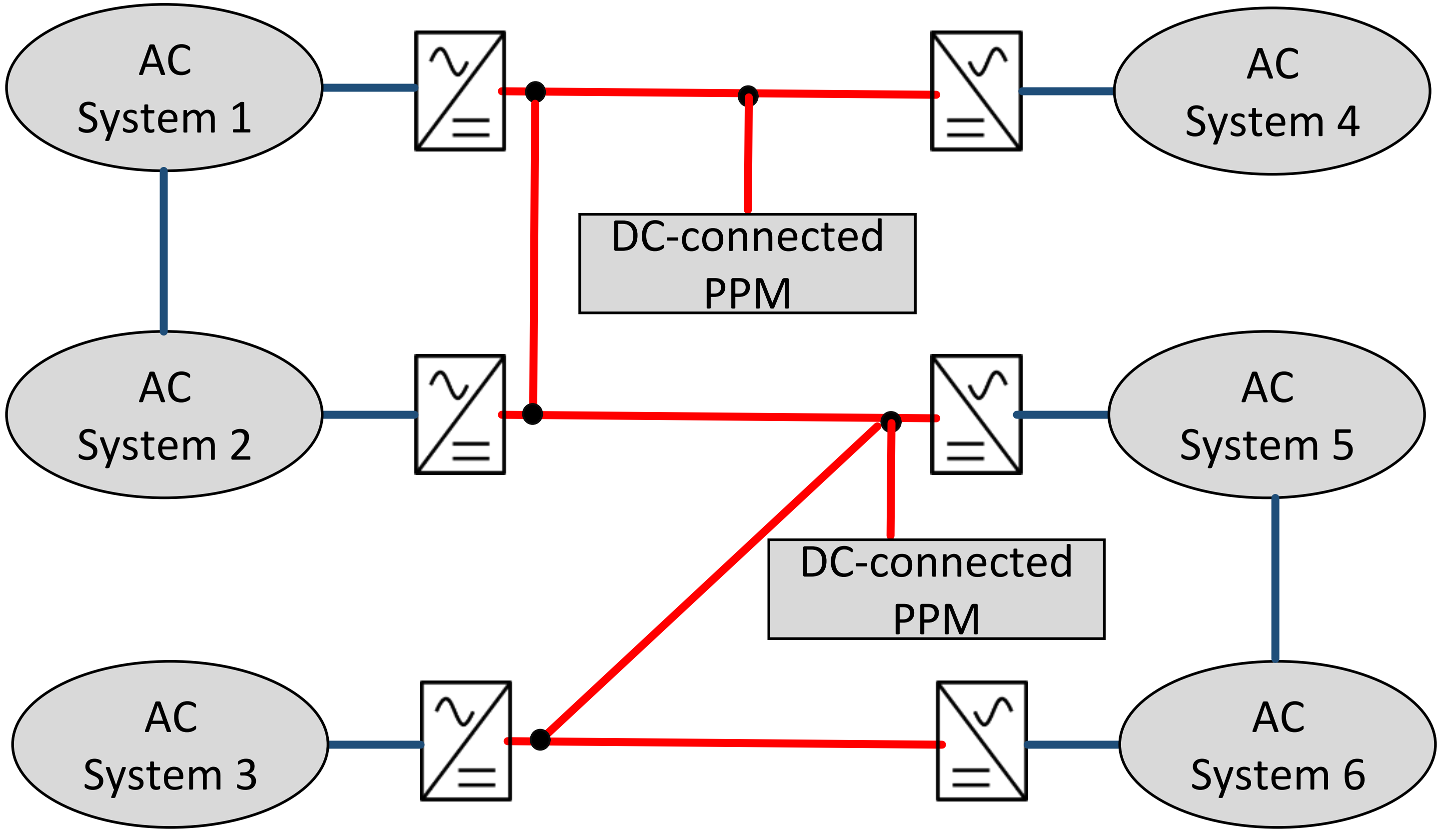
Voltage Source Converter (VSC)-based multiterminal HVDC grids provide:

- Flexibility
- Redundancy

➔ For massive integration of RES

However, this leads to:

- Multiple stakeholders
- Multiple vendors



Clear requirements on how to connect to and operate HVDC grids

➔ **HVDC Grid Code is necessary**

What is a grid code?

- The Grid Code is a set of technical requirements, standards and guidelines governing the relationship between the Grid Operator and different Stakeholders

Main categories in European Grid Codes [1]

	Operation Code	Connection Code	Planning Code	Market Code
Functionlaity	System operation requirements Emergency & restoration	Generators requirements Loads requirements	Grid feasibility Grid characteristics Grid investment	Energy balancing Congestion management
Involved Stakeholders	TSO Energy suppliers	TSO & DSO Energy suppliers System developers Consumers Technology developers	TSO & DSO Energy suppliers System developers Technology providors	TSO Market operators

"An imperfect grid code is, in many cases, better than no grid code at all" [1]

[1] IRENA report, "Grid Codes for Renewable Powered Systems", 2022.

HVDC Grid Code

Objectives

- Ensuring a minimum desired reliability and system security
- Ensuring mutual interdependence and cooperation between stakeholders at both the AC and DC interfaces
- Ensuring a safe and acceptable interaction at all device interfaces.
- Enabling future expandability
- Enabling system interoperability

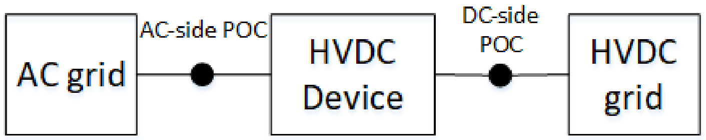
HVDC Grid Code

	Operation Code	Connection Code	Planning Code	Market Code
Functionlaity	System operation requirements Emergency & restoration	Generators requirements Loads requirements	Grid feasibility Grid characteristics Grid investment	Energy balancing Congestion management
Involved Stakeholders	TSO Energy suppliers	TSO & DSO Energy suppliers System developers Consumers Technology developers	TSO & DSO Energy suppliers System developers Technology providors	TSO Market operators

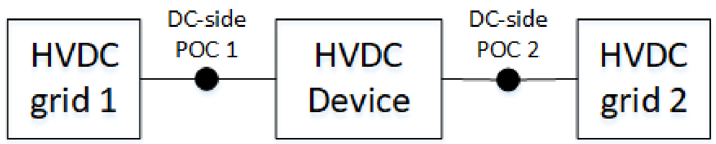
HVDC Grid Code

Connection Requirements

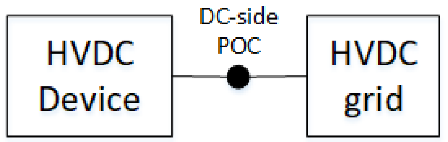
- Any HVDC device (e.g. HVDC converter, DC-connected PPM) has either one or two connection points:



HVDC Device with AC and DC interfaces



HVDC Device with two DC interfaces



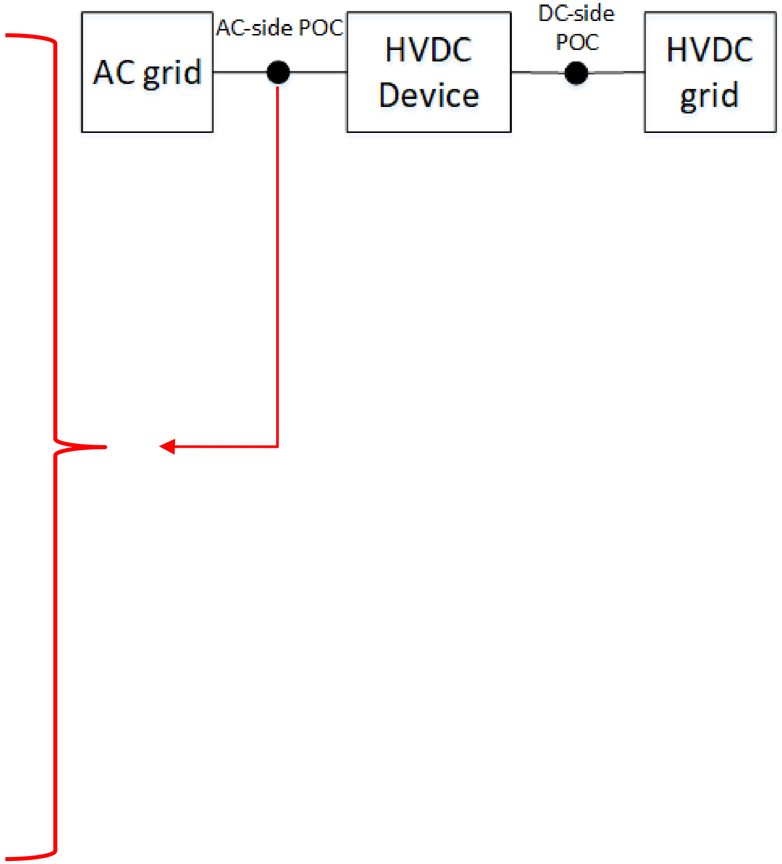
HVDC Device with 1 DC interface

HVDC connection code should define the connection requirements at both AC- and DC-side point of connection (POC)

HVDC Grid Code

Connection Requirements

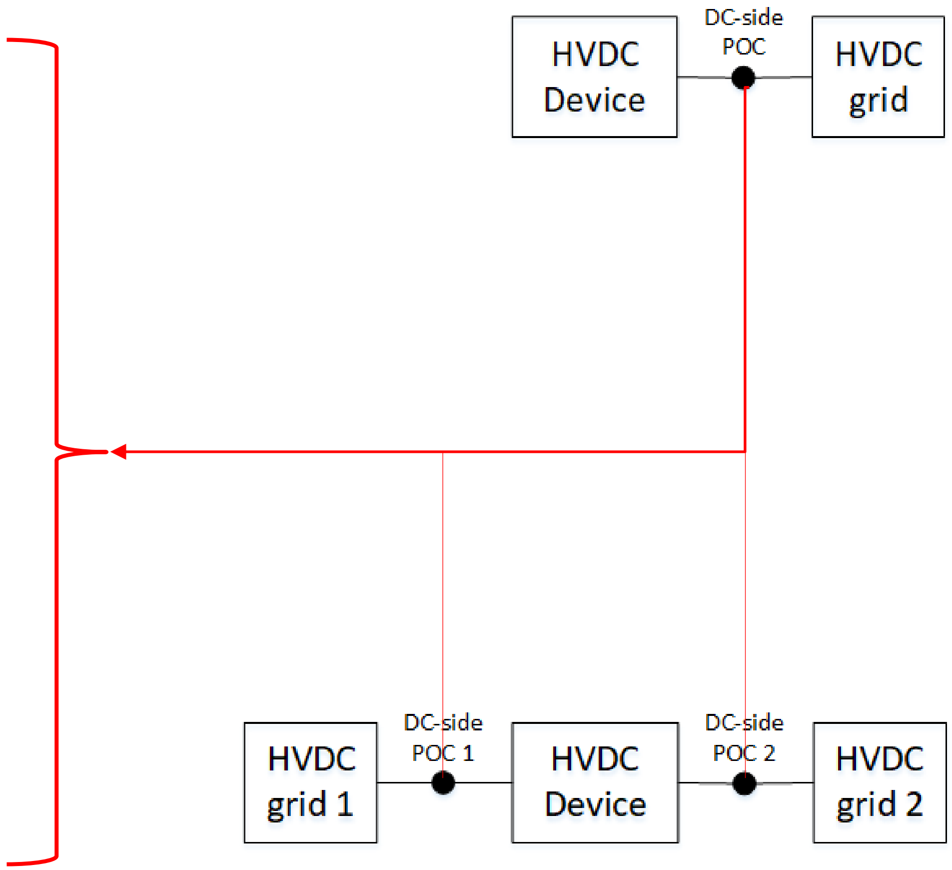
- Exist in several GCs worldwide
  - Similar connections to AC-connected PPMs
    - Frequency and active power response requirements, e.g.:
      - ✓ Frequency ranges
      - ✓ RoCoF capability
      - ✓ FFR
    - AC-side voltage and reactive power requirements
      - ✓ AC voltage ranges
      - ✓ Reactive power management (e.g. U-P/Q capability curves)
    - AC-side Fault-Ride-Through requirements
      - ✓ For symmetrical and non-symmetrical faults
      - ✓ Fast reactive current injection
    - Control schemes:
      - ✓ Grid forming/Grid following
      - ✓ Power flow control
      - ✓ Active filers/oscillation damping
      - ✓ …



HVDC Grid Code

Connection Requirements

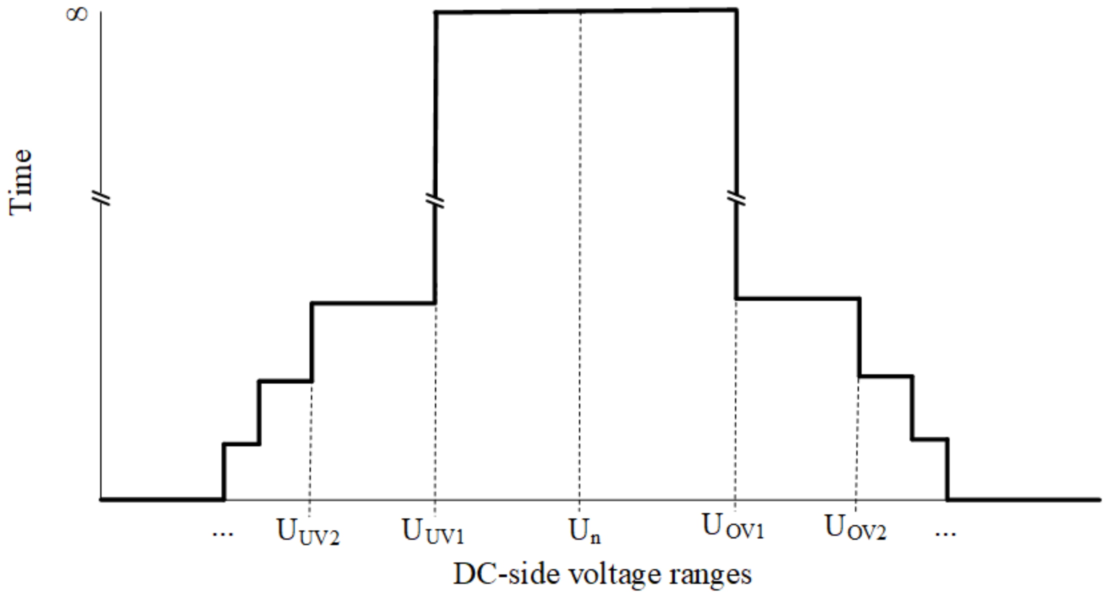
- Not yes exist in any Grid Code
  - DC-side voltage requirements
  - DC-side Fault-Ride-Through requirements
  - Control modes:
    - DC-side voltage control
    - Active power control
    - Active power-DC voltage droop control
    - Emergency power control (run-up/run/back)
    - DC-side oscillation damping
    - ...



HVDC Grid Code

Connection Requirements

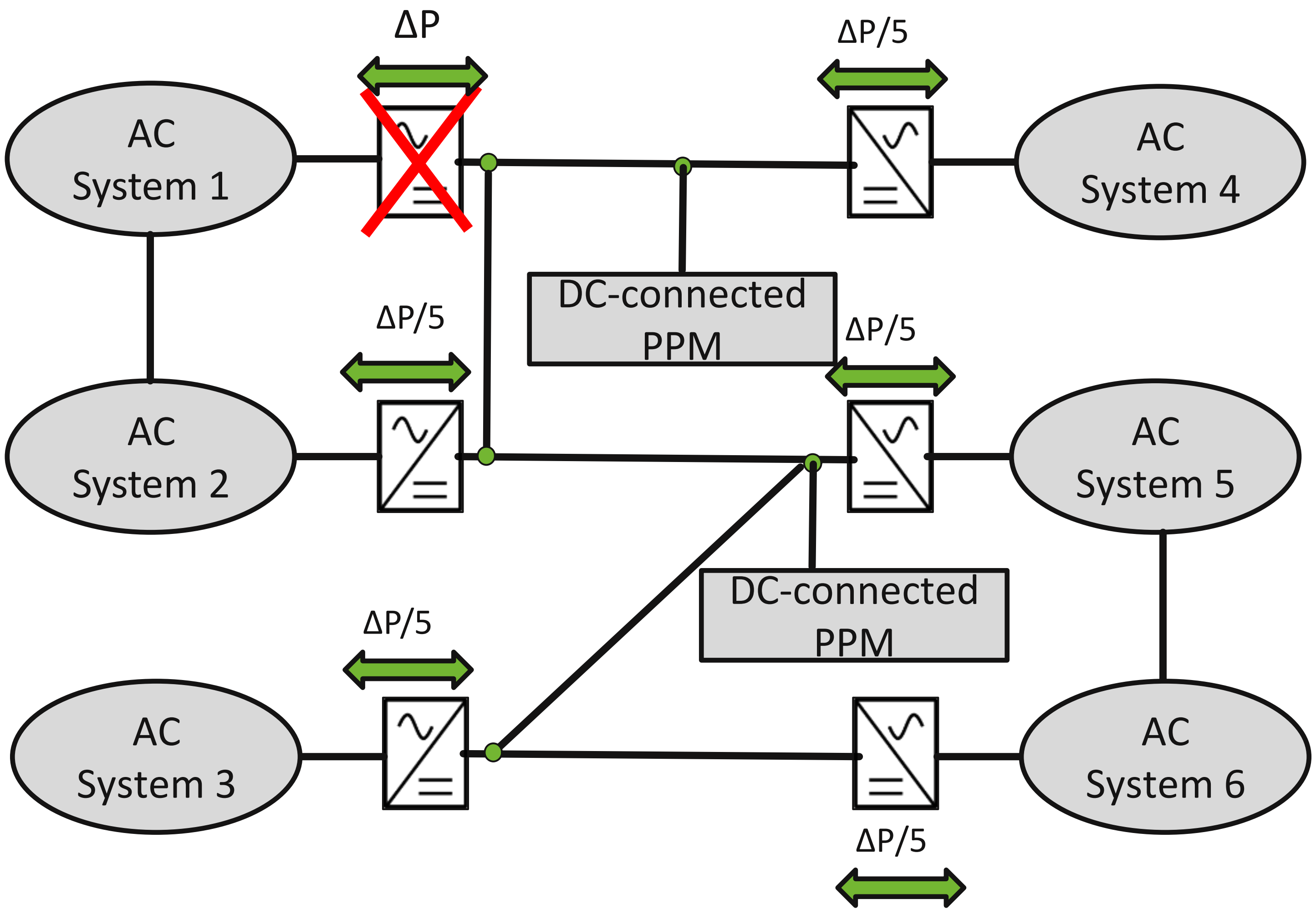
- DC-side voltage requirement:
  - Normal operation range
  - Over/undervoltage operation



HVDC Grid Code

HVDC System Requirements – Operation Code

- Primary control
  - ✓ Aiming to achieve Energy balance in HVDC grid at each node.
  - ✓ Droop control shall be active on at least one device/node to ensure energy-balance during disturbances.
  - ✓ One or more nodes shall act as an energy balancer → pre-defined DC voltage.
- Secondary control
  - ✓ Aiming to restore pre-disturbance operating point after the activation of the primary control.
  - ✓ DC grid controller is responsible to communicate new set points to HVDC devices.

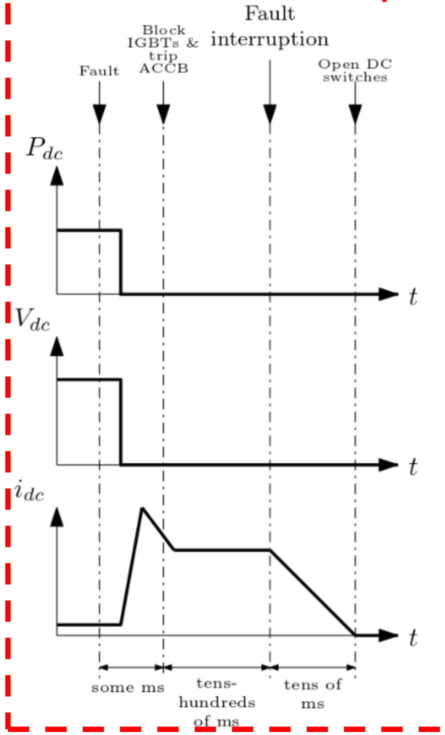


HVDC Grid Code

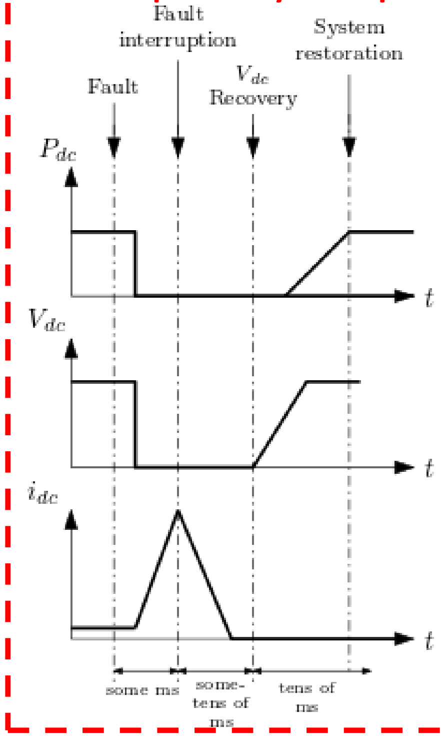
Connection Requirements

- DC-side Fault-Ride-Through requirements
  - Three HVDC protection strategies: Non-selective, partially selective and fully selective ➔ affecting the device performance during faults

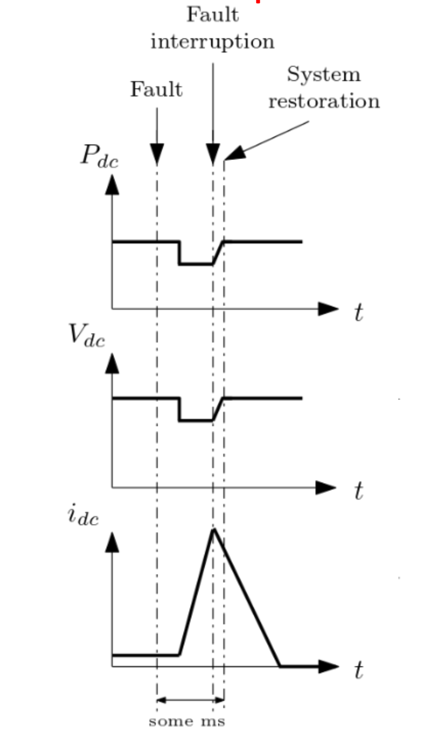
Permanent Stop



Temporary Stop



Continued Operation

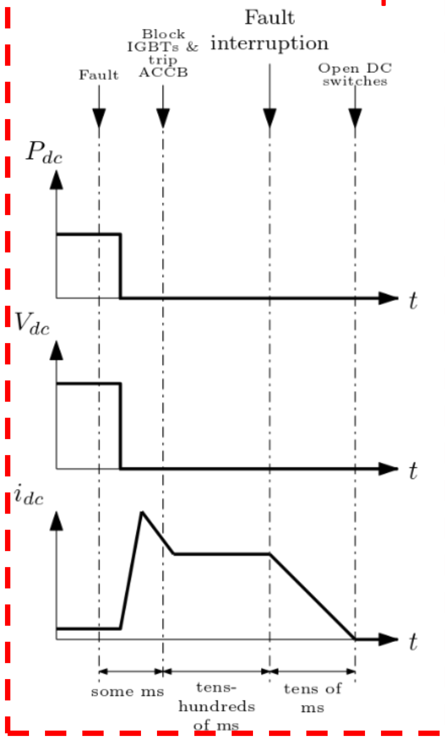


[1] European Committee for Standards - Electrical, HVDC GRID SYSTEMS AND CONNECTED CONVERTER STATIONS - GUIDELINE AND PARAMETER LISTS FOR FUNCTIONAL SPECIFICATIONS - PART 1: GUIDELINES, CLC/TS 50654-1 : 2018, 2018.

HVDC Grid Code

Connection Requirements depend on protection

Permanent Stop

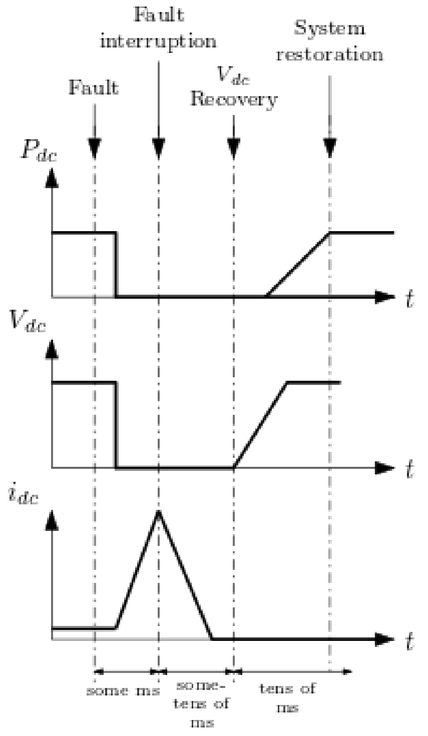


- No DC-side fault ride through requirements
- The HVDC device can be disconnected from the AC- and/or DC-sides
- Interruption of power exchange for prolonged time (e.g. seconds-tens of seconds)

HVDC Grid Code

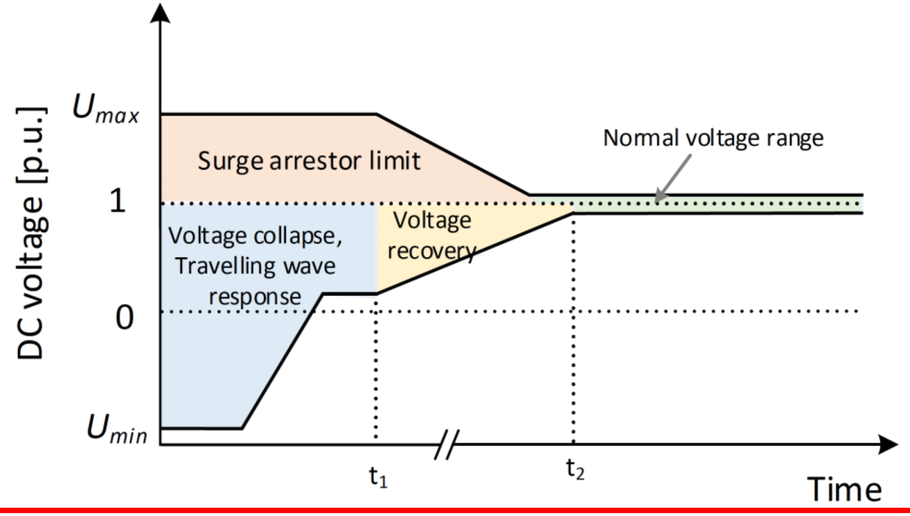
Connection Requirements depend on protection

Temporary Stop

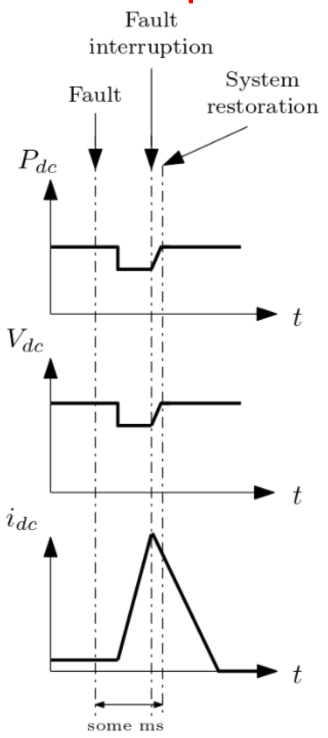


Temporary stop of an HVDC device, leading to temporary interruption of power exchange

- The HVDC device shall remain connected to the AC- and DC-sides as long as the DC-side voltage remains



Continued Operation

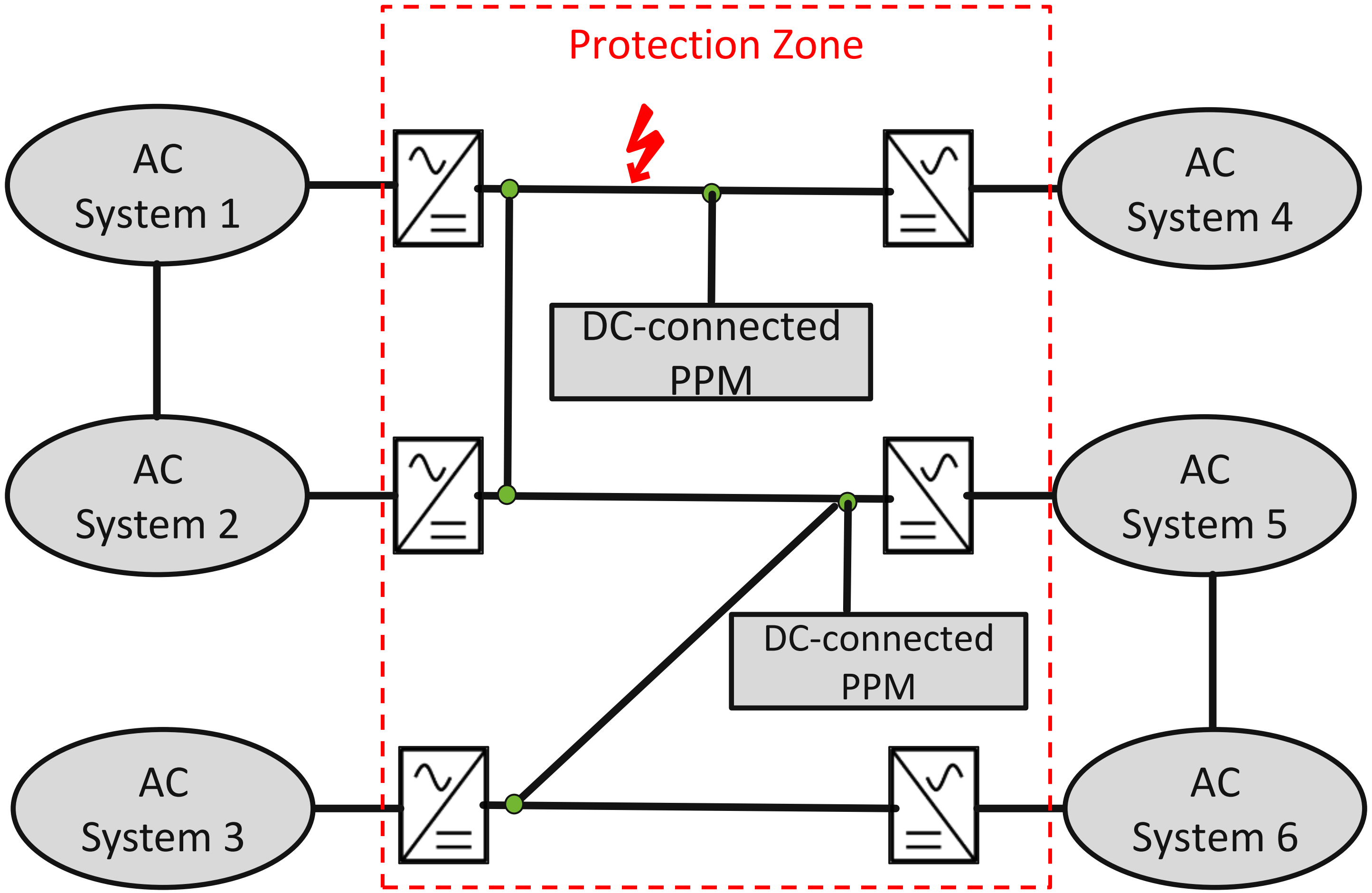


HVDC device shall keep controlling power exchange during and in post fault conditions

HVDC Grid Code

HVDC System Requirements – Operation Code

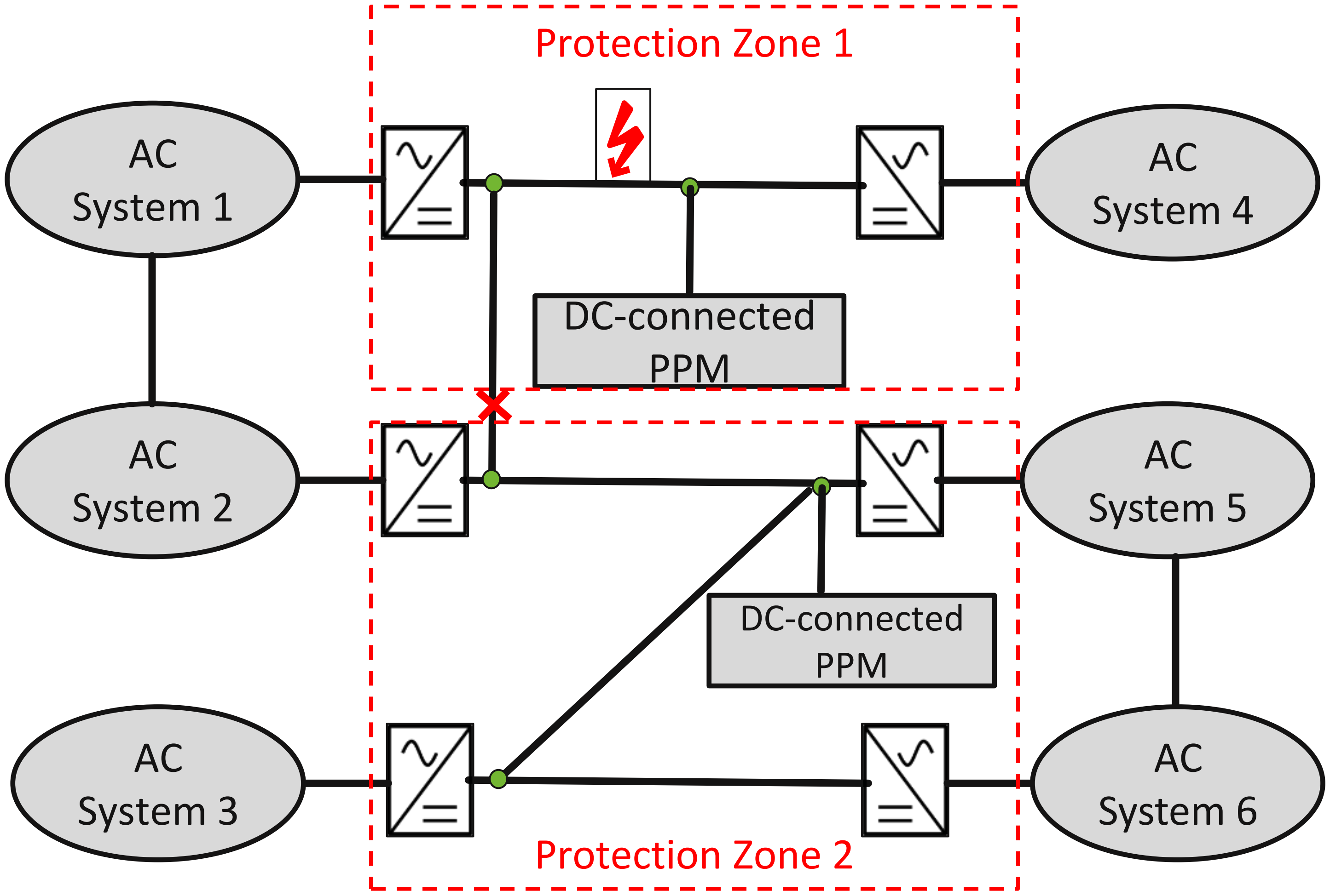
- HVDC protection philosophies
  - Non-selective
    - ✓ One protection zone
    - ✓ DC-side fault current is cleared by ACCBs, converters with fault blocking capabilities, DCCBs at the terminals of HVDC devices.
    - ✓ Interruption of power exchange for prolonged time.
    - ✓ No DC-side FRT requirements for HVDC devices.



HVDC Grid Code

HVDC System Requirements – Operation Code

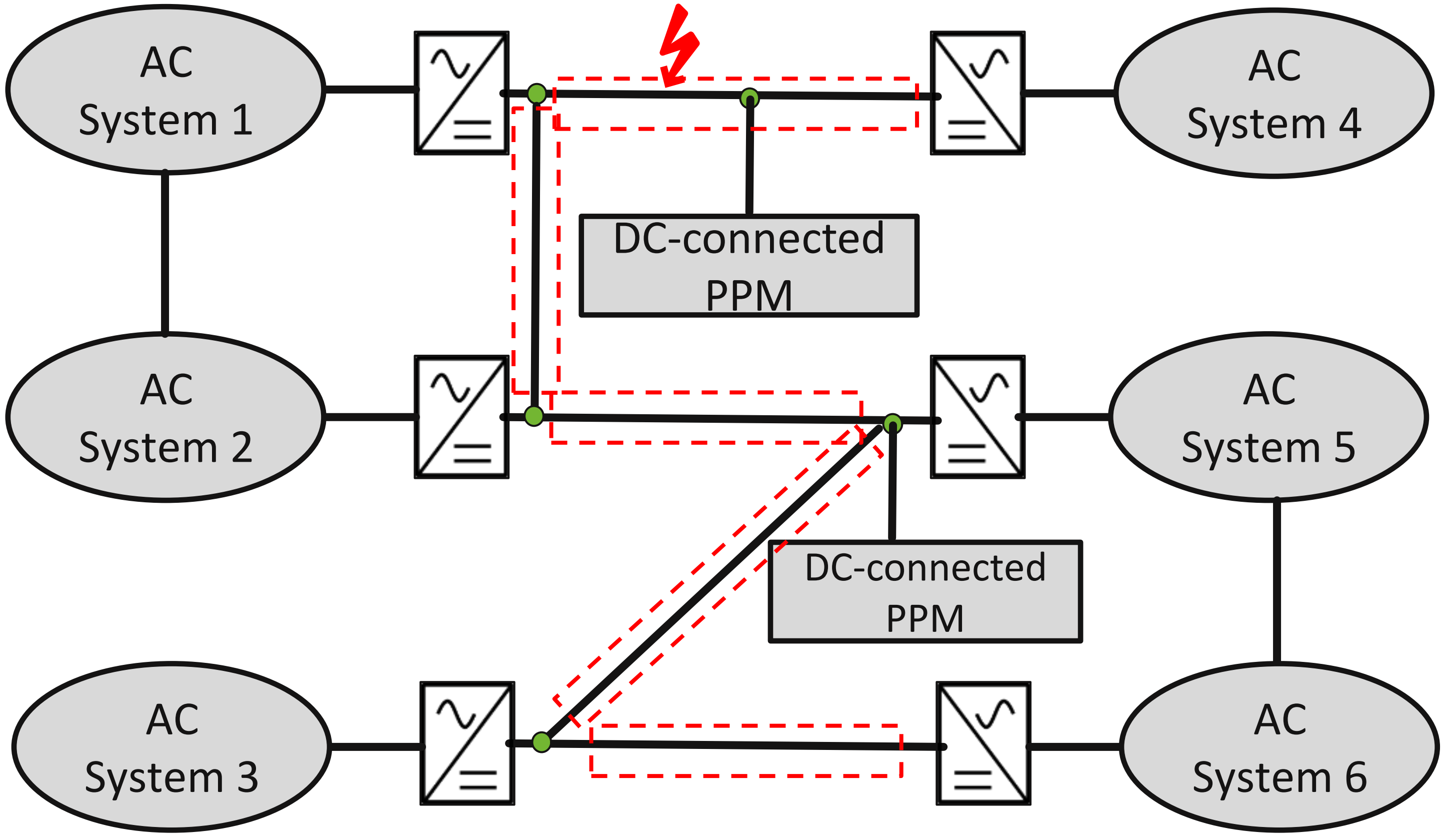
- HVDC protection philosophies
  - Partially-selective
    - ✓ Multiple protection zone separated by DCCBs or DC/DC converters.
    - ✓ DC-side fault current in a faulty zone is cleared by ACCBs, converters with fault blocking capabilities, DCCBs at the terminals of HVDC devices.
    - ✓ Interruption of power exchange in faulty zone for prolonged time.
    - ✓ No DC-side FRT requirements for HVDC devices in faulty zones, while HVDC devices outside the faulty zone should ride through the fault.



HVDC Grid Code

HVDC System Requirements – Operation Code

- HVDC protection philosophies
  - Fully-selective
    - Each line is protected individually with HVDC circuit breakers.
    - Continued operation or temporary stop are applicable for HVDC devices
    - HVDC devices shall ride through DC-side faults.
    - Short or no power exchange interruption.



HVDC Grid Code

HVDC System Requirements – Operation Code

- System operation requirements
  - HVDC system control philosophy and requirements
    - ✓ Primary control
    - ✓ Secondary control
    - ✓ Energization and de-energization
    - ✓ Supplementary control
  - HVDC Protection philosophies
    - ✓ Non-selective
    - ✓ Partially selective
    - ✓ Fully selective
  - DC Grid operating states
    - ✓ Normal operation mode
    - ✓ Alert operation mode
    - ✓ Emergency operation mode

Defining operating states in a similarly way as described in AC grid operating codes → there might be a need for a common operating code

Summary

- HVDC grids are anticipated to play a major role in future power systems with high penetration of renewable energy systems.
- Various stakeholders will need access to future HVDC grids with multi-vendor environment
  - HVDC grid code is indispensable to regulate the use of the system.
- HVDC grid code might consist of:
  - Connection requirements at both AC and DC sides → Connection code
  - HVDC operation requirements → Operation code
  - Planning code
  - Market code

Thank you for your attention

Questions?

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Met de steun van het Energietransitiefonds

economie

For further reading:

CIGRE TB657: *Guidelines for the preparation of "connection agreements" or "grid codes" for multi-terminal DC schemes and DC grids*

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Testing the waters of offshore grid protection

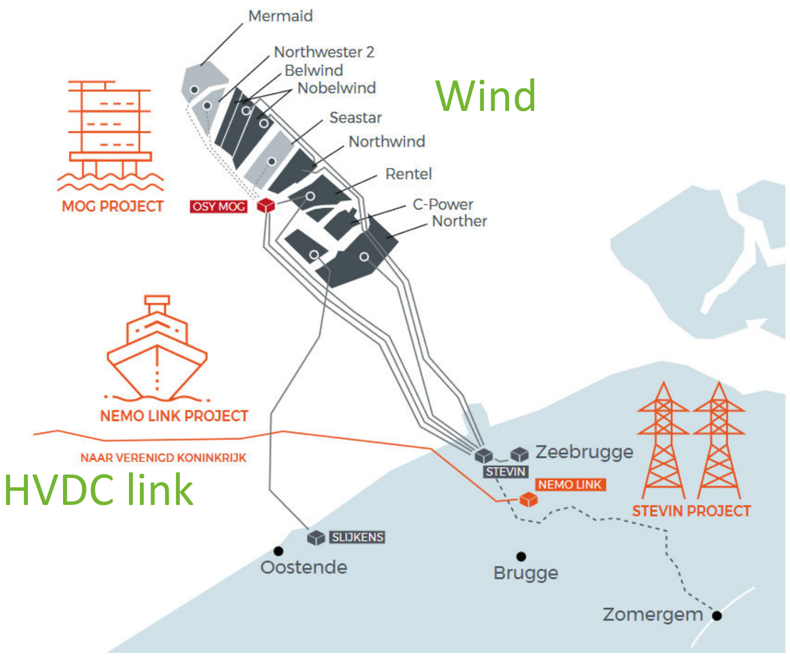
Neptune Closing event September 27th

Rick Loenders

Energy Ville KU LEUVEN vito imec UHASSELT

Challenges for current installed protection

- Converter interfaced grid elements replace conventional sources
  - e.g. in Belgium the increasing number of wind farms, new HVDC links, …
- Change in the system's response to faults
  - A lower system inertia
  - Limited fault current
  - Controlled current angles
  - Distorted waveforms
- Interconnection not only overhead lines, but more and more underground cables



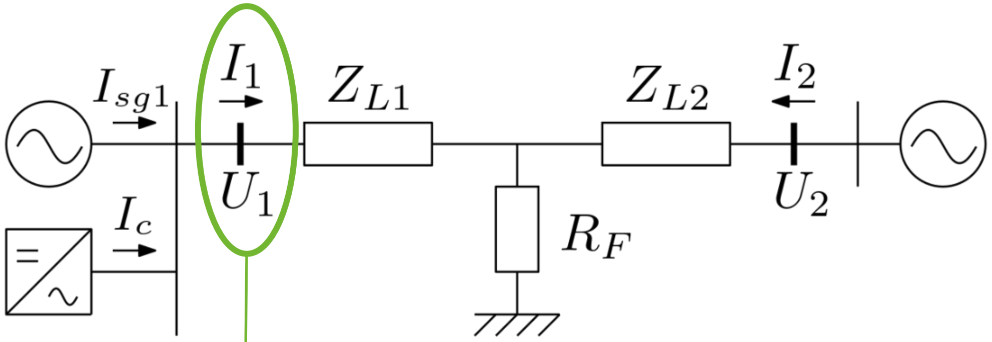
Source: Elia

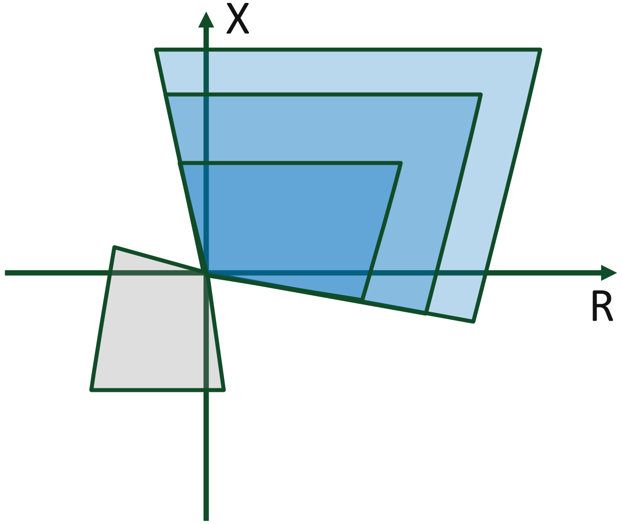
How to protect the future power system?

- Lines commonly protected using distance protection and line differential
- New protections based on incremental quantities and travelling wave
- Also developments in communication schemes, adaptive algorithms, better sensors…

Distance protection near converters

Impedance measurement of controlled current angles





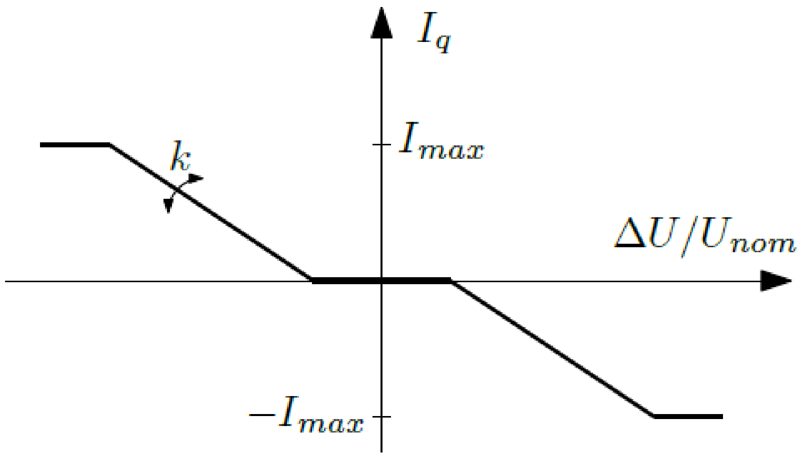
$$\underline{Z} = x\underline{Z}_l + R_f + \frac{\underline{I}_2}{\underline{I}_1} R_f$$

$$\frac{\underline{I}_2}{\underline{I}_1} R_f = \frac{|\underline{I}_2|}{|\underline{I}_1|} e^{j(\phi_2 - \phi_1)} R_f$$

Distance protection near converters

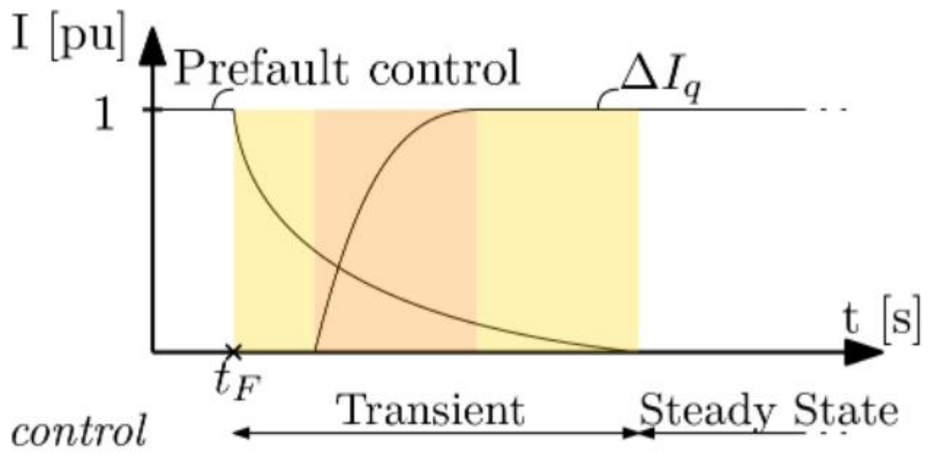
Impedance measurement of controlled current angles

- The angle depends on the injection strategy.



(a) ΔI_q-injection

- Potential malfunctions due to converter control, both during **transient** and **steady-state**



- Pre-fault control transient decays to zero (5-20ms), meanwhile activating ΔIq modulation

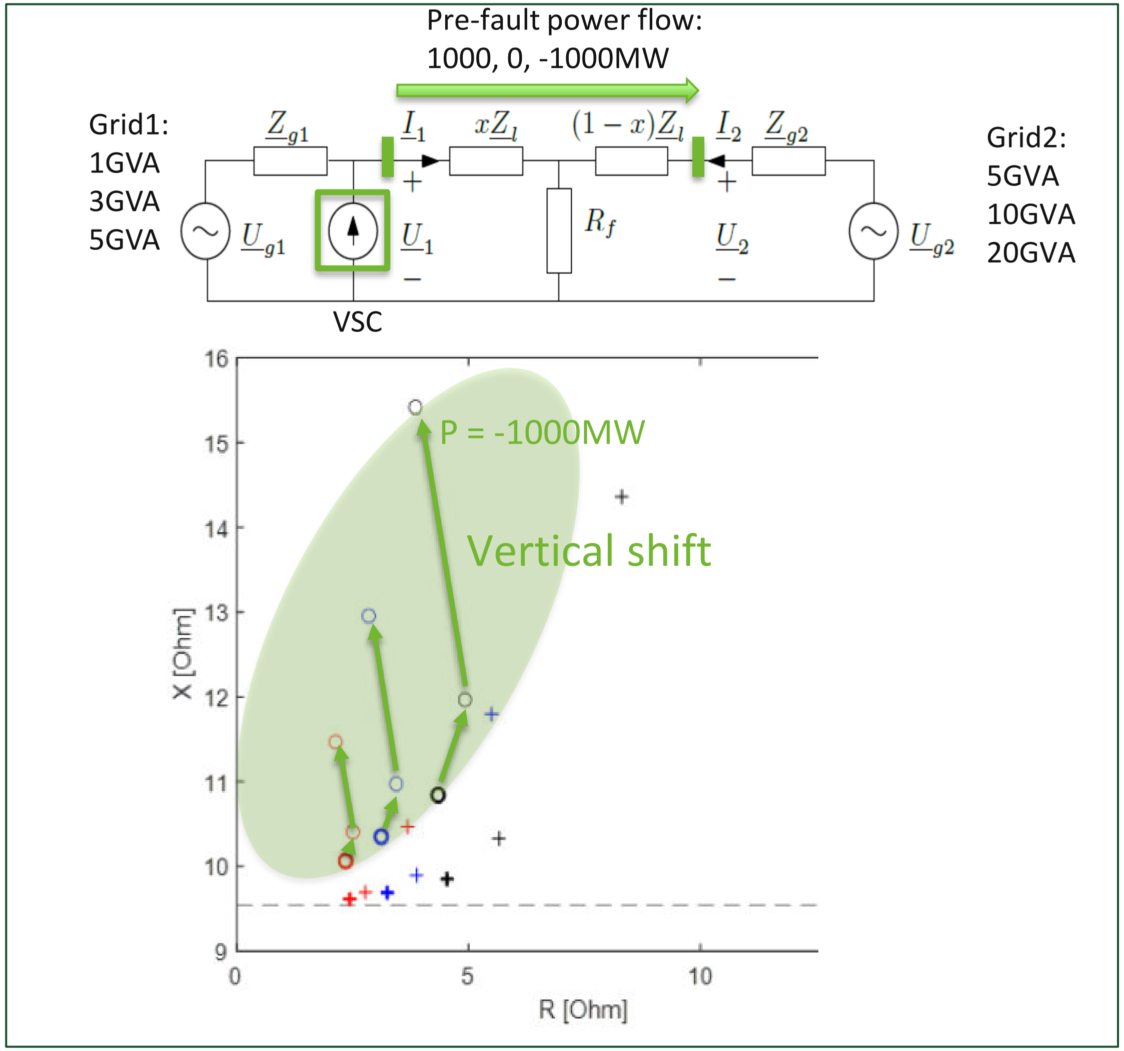
Distance protection near converters

Steady-state assessment of apparent impedance

Effect of VSC on apparent impedance by variation of relative grid strength ($SCP_{grid\ 1}$ ↘)

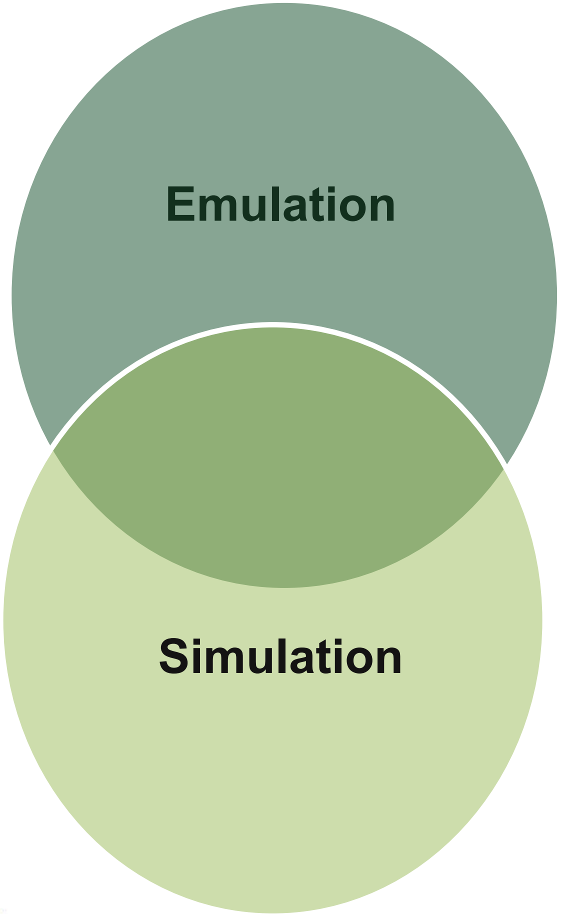
- Smaller effect on magnitude
- Significant change in angle difference

How to test transient behaviour in real-time?



Testing real-time transient response on protection application

What is real-time?



Simulation: Virtual copy of a physical process

+

Emulation: Full or partial recreation of a physical process

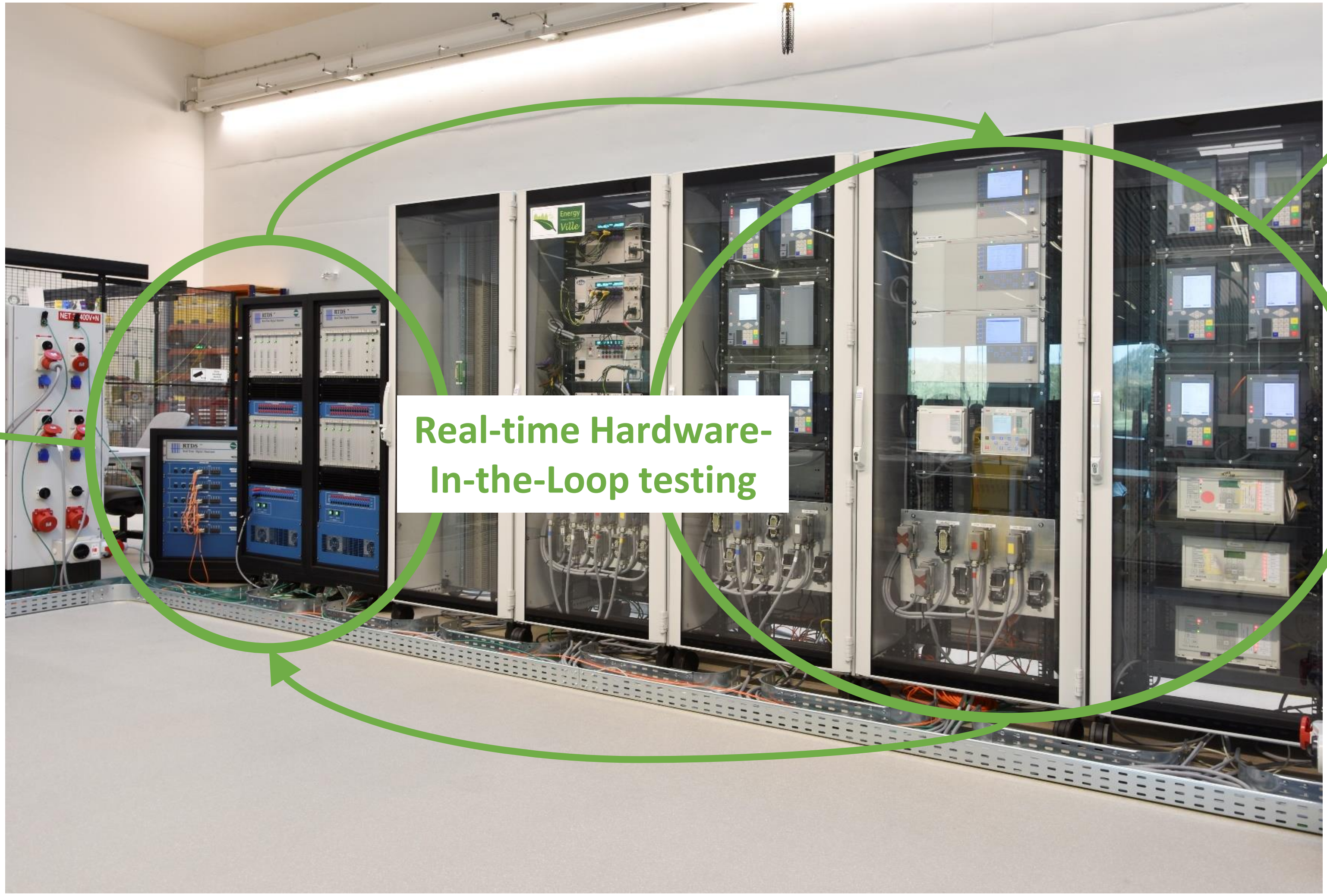
- Combination of hardware and simulated components

Hardware-in-the-Loop (HiL)

Substation protection cubicles

Real-Time Digital Simulator (RTDS)

Real-time Hardware-In-the-Loop testing

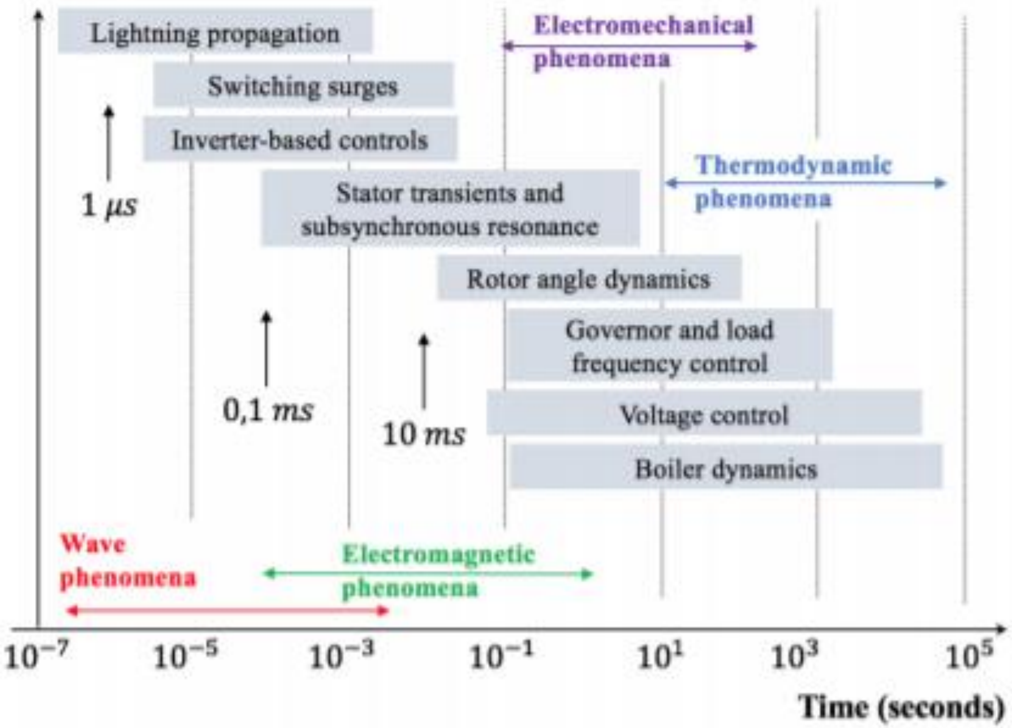


Testing real-time transient response on protection application

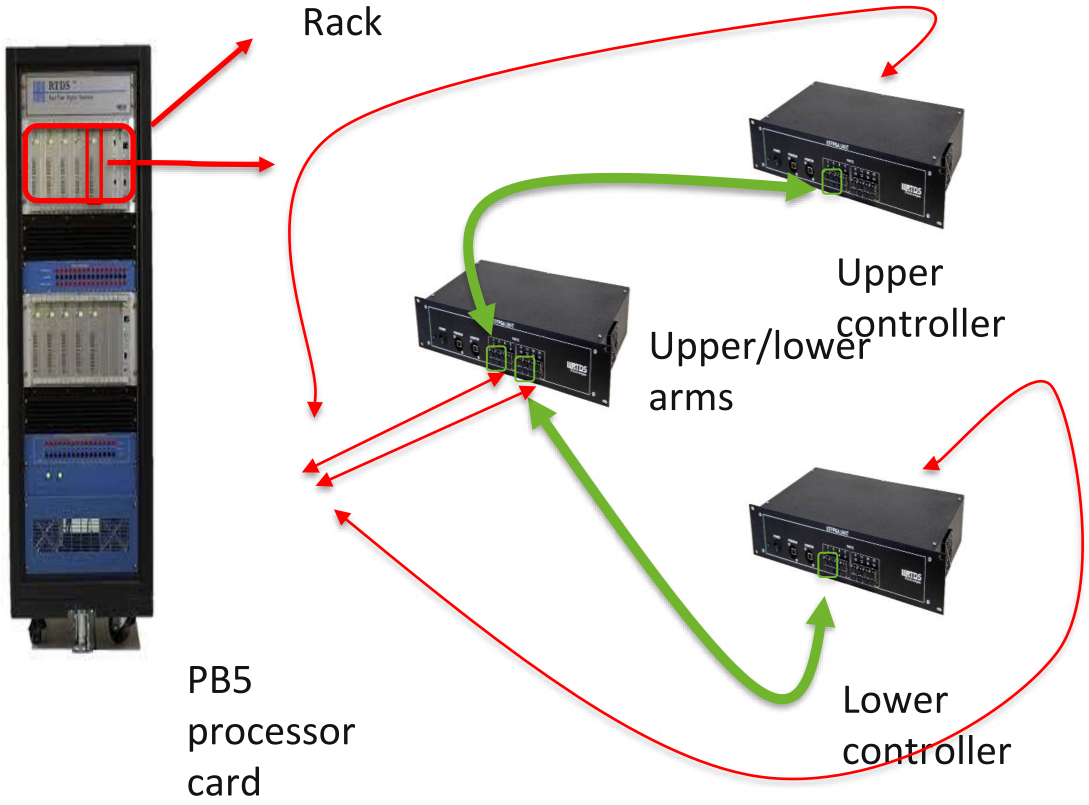
What is real-time?

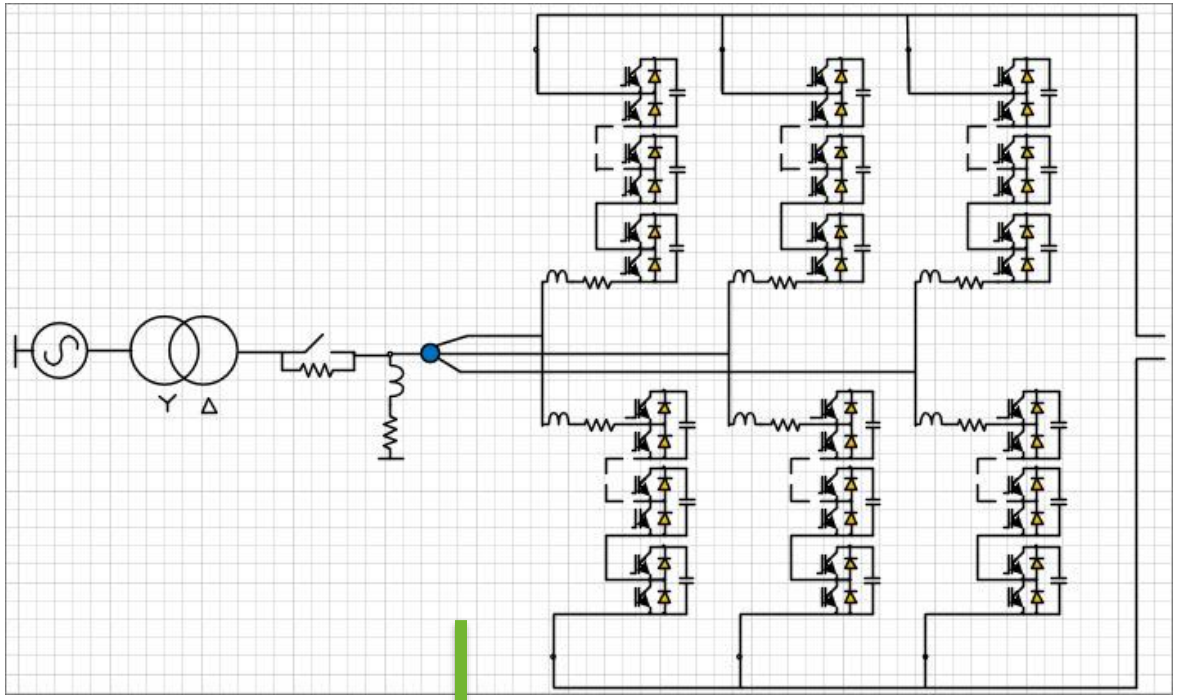
- Reproducing the behaviour of a physical system
- Running a computer-based model at the same rate than the perceived wall clock time of the system
- The time step size depends on the expected maximum frequency of the phenomena under test

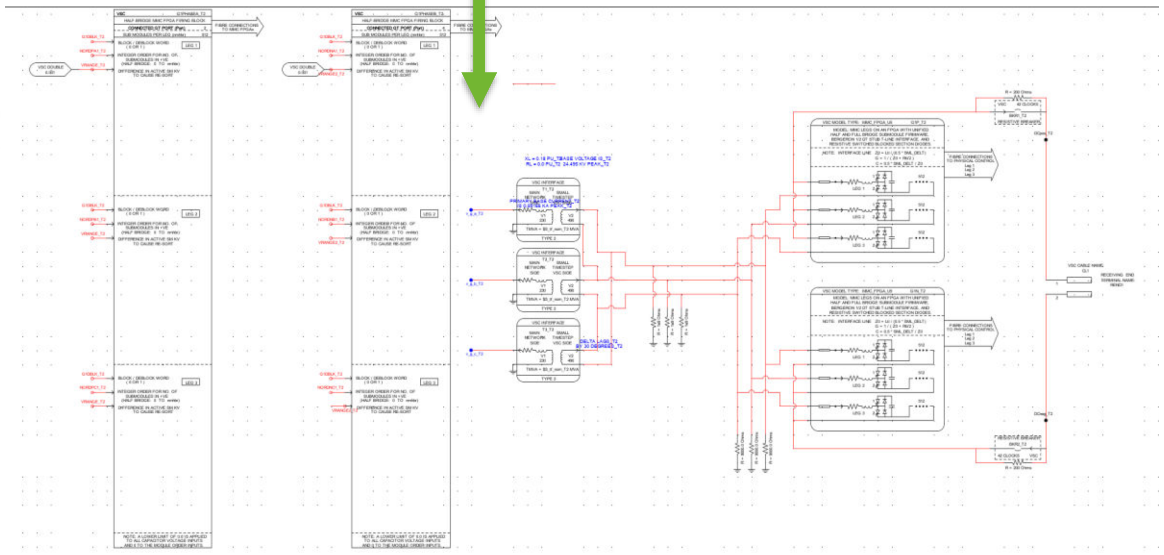
Example:



MMC modelling





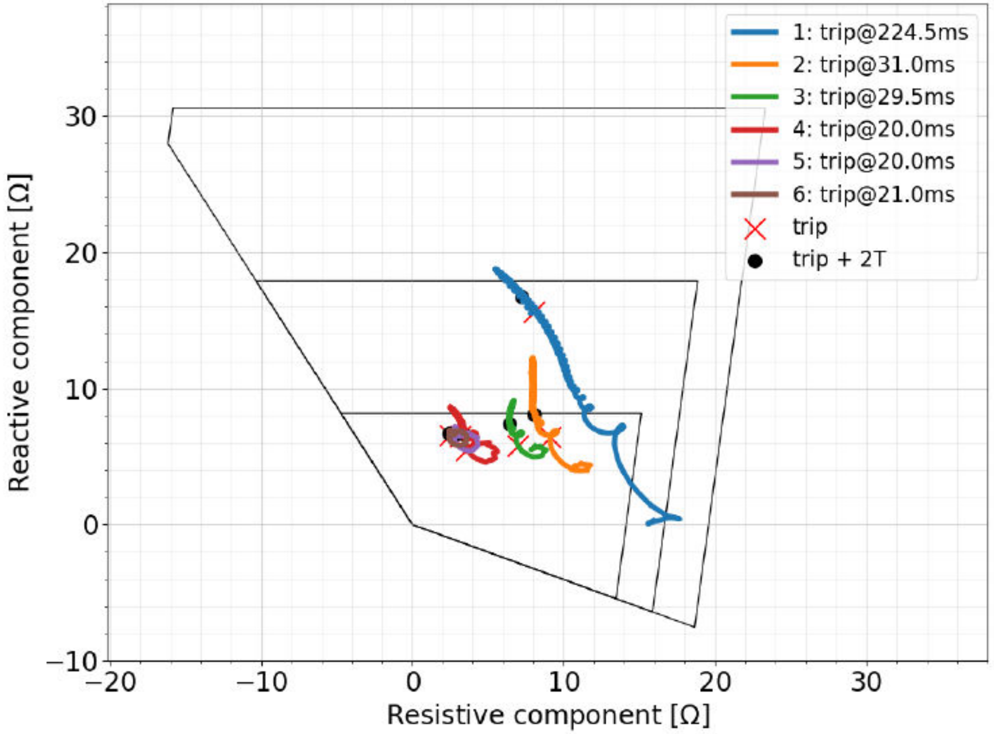


Distance protection near converters

- Neptune provided initial insights and tools for observing transient response of distance protection
  - Incorrect zone decision
  - Extended settling times

What about black-box models from manufactures?

Note! figure and results are taken from outside the NEPTUNE project

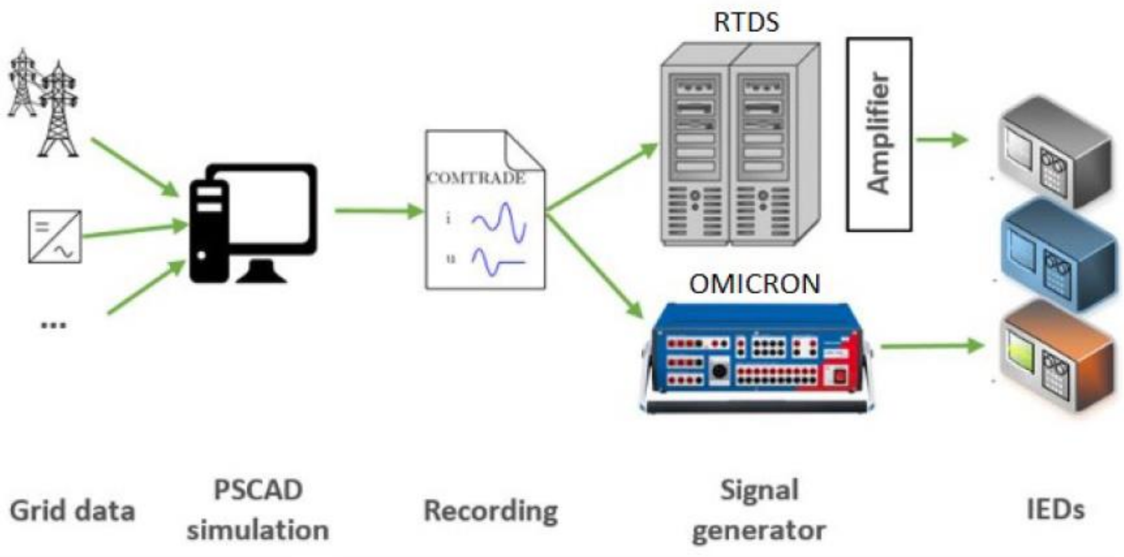


J. Vermunicht, et al. , “Distance protection in the vicinity of VSC: present Belgian situation and outlook”, CIGRE CSE, 2024 (accepted)

Alternative testing methods

Replaying of field recording

- Replay EMT simulation recordings on physical protection relays
- To verify the measured impedance with steady-state simulations

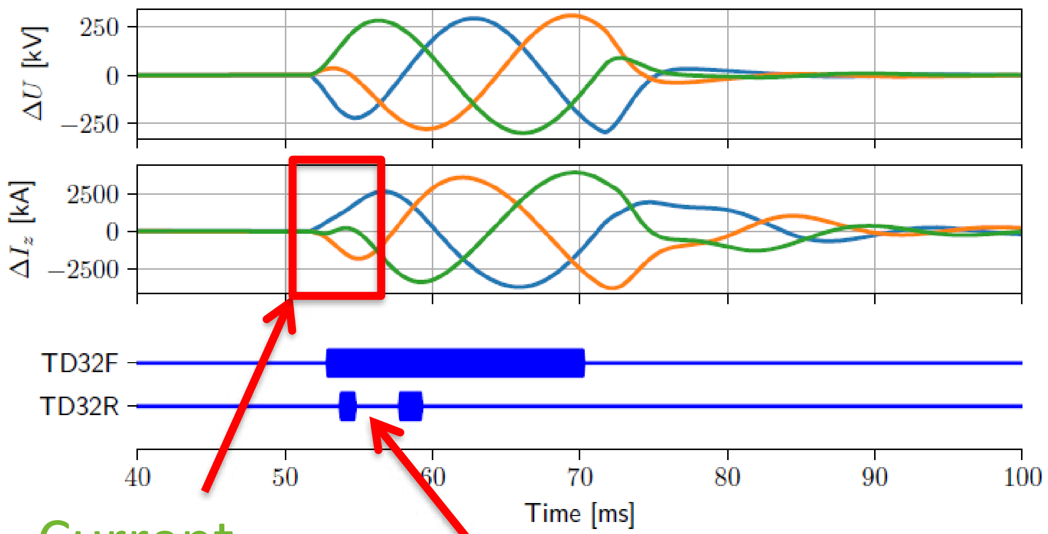


Real-time testing of new protection algorithms

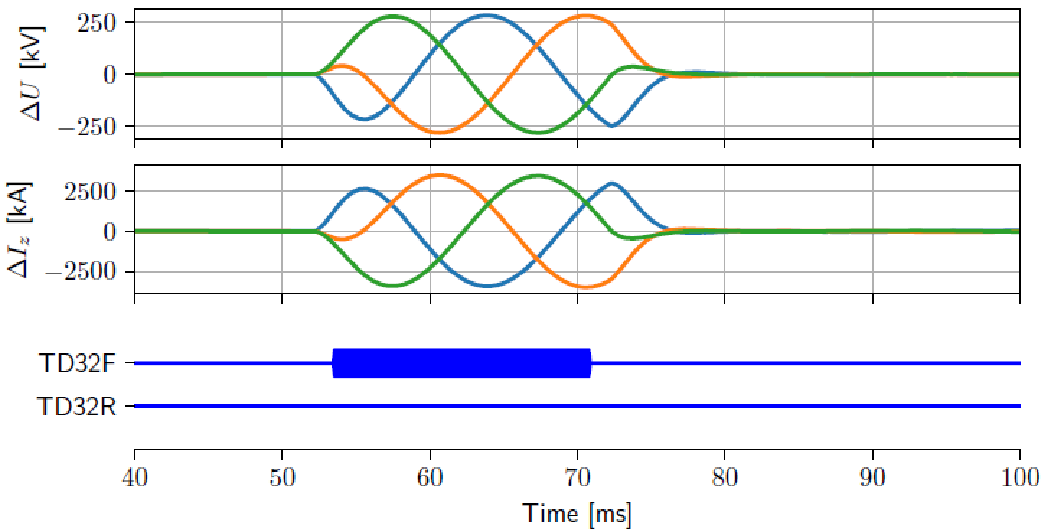
Incremental quantities near converters

- Phase shift in incremental current by VSC controls

VSC



Benchmark



Current phase shift

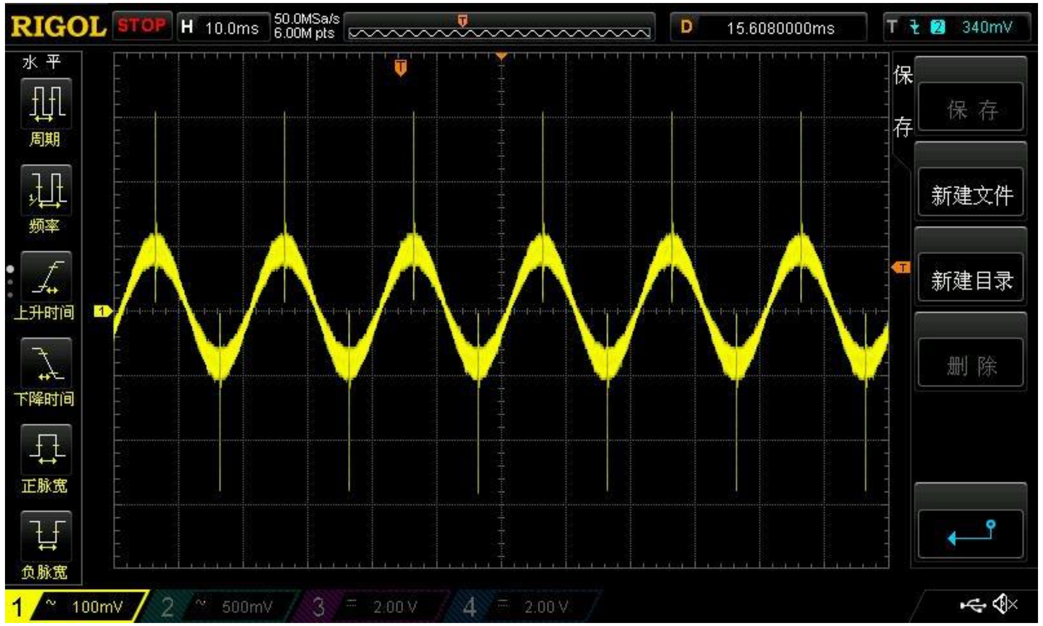
Forward & Reverse assertion

J. Vermunicht, et al. “Analysing the Performance of Incremental Quantity based Directional Time-Domain Protection near HVAC Cables and VSC HVDC Converters”, IPST, 2023

Real-time testing of new protection algorithms

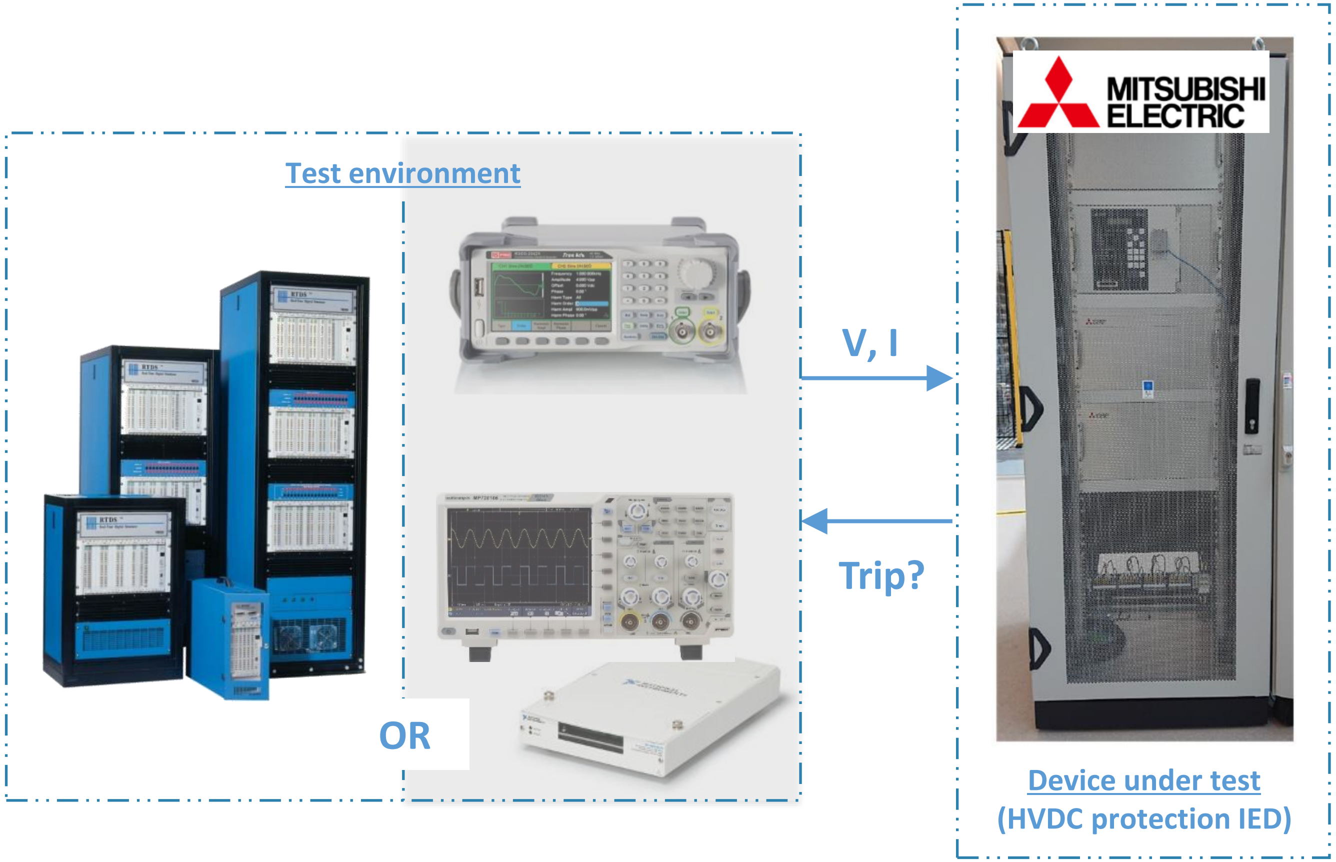
Travelling wave near converters

- Real-time platform adequate for high sampling rates?
  - Incremental quantities in kHz range, and travelling wave in MHz range
- Analogue output cards introduced spikes
  - Travelling wave protection can be sensitive to such spikes



Dynamic Validation Testing – standalone tests

- Aim of tests:
    - Determine performance of device under realistic stimuli
- Test signal (stimuli) requirement:
    - Quantities representative of real system
        - Real-time simulation
        - Or playback of simulation
- Feedback used for:
    - Trip status
    - Trip time measurement
    - Circuit breaker operation
    - Testing breaker failure



Conclusions

- Most problems arise in a situation where a converter is dominating the local short-circuit current and there is a large remote short-circuit current
- EMT-type simulations computationally heavy; difficult to use in a screening exercises
- Testing requires flexibility between modelling environments (real-time vs non-real-time)

W. Leterme, G. Chaffey, R. Loenders, J. Vermunicht, S. M. Shoushtari and D. V. Hertem, "Systematic study of impedance locus of distance protection in the vicinity of VSC HVDC converters," *16th International Conference on Developments in Power System Protection (DPSP 2022)*, Hybrid Conference, Newcastle, UK, 2022, pp. 19-24, doi: 10.1049/icp.2022.0905.

Vermunicht, Joachim, Willem Leterme, and Dirk Van Hertem. "Analysing the performance of incremental quantity based directional time-domain protection near HVAC cables and VSC HVDC converters." *Electric Power Systems Research* 223 (2023): 109599.

WP2: Protection strategies and algorithms

Testing the waters of offshore grid protection

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