WP3 - Control interaction identification and mitigation

Neptune Final Event

Jef Beerten – KU Leuven & EnergyVille

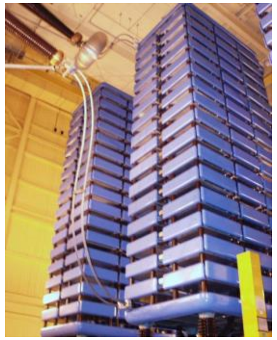
27 September 2023

A power system in change

And changing dynamics

- ‘Old’ electrical power system
  - Physical principles of rotating machines determined system problems





- Future power systems = converter-based
  - With fast converter control, we can completely steer the response
  - … but this fast control brings along new challenges

Images source: WikiCommons (public domain)

Control interactions in future AC/DC power systems

- Reliable control of the entire system is a prerequisite for a stable system operation
- Power electronic converters react much faster than traditional generators
- New control interaction patterns emerge as a result, but they do not fit the traditional classifications
- New types of interactions can bring about new problems and could ultimately give rise to a system shutdown
- New problems generally require a higher level of modelling detail and do not fit traditional power system paradigms
- Details of control implementations are often hidden because of IP considerations
- In future power systems, guaranteeing control interoperability is key

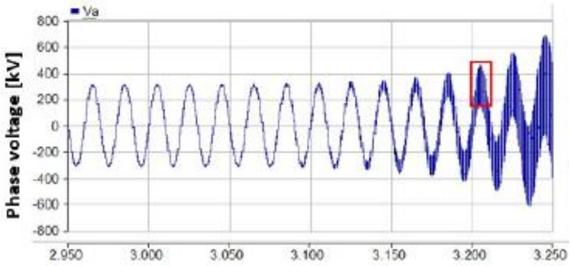


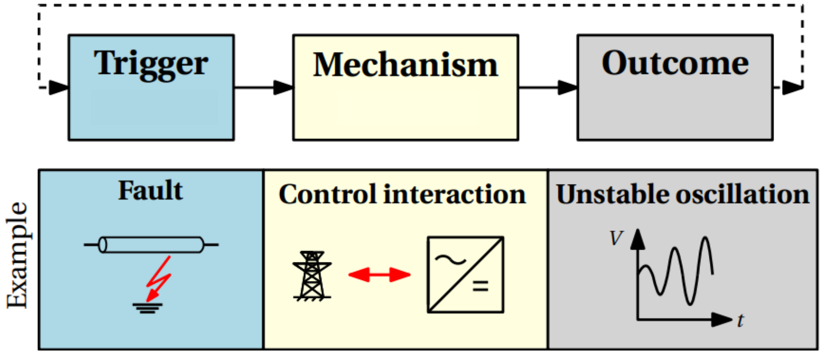
Image source (upper): Siemens – Inelfe link

Image source (lower): A. Bayo Salas, PhD thesis

Classification of converter-related problems

Some highlights

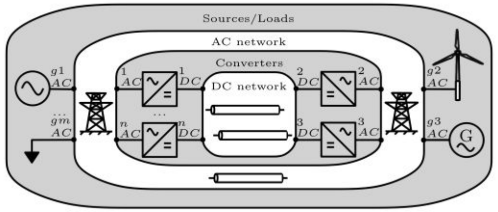
- Converter-related instabilities and interactions do not fit traditional power system stability classifications
- Detailed assessment of real-life events, in a cross-system way to investigate analogies and mechanisms that lead to instabilities and interactions



CONVERTER OR CONTROL LIMITATIONS			POWER QUALITY DEGRADATION	CONTROL INTERACTIONS
(A1) limited under/over-voltage ride-through capability	(B1) limited/inadequate voltage support	(C) limited synchronization capability	(D) nonlinear converter or control behavior	(F) electrical interactions among converter controls and/or with passive grid components
(A2) limited under/over-freq. ride-through capability				(G) electrical interactions between converter-controlled rotating machines and passive grid components
(A3) limited over-current ride-through capability	(B2) limited/inadequate frequency support		(E) amplification of converters emissions by passive grid components	(H) electromechanical interactions between converter controls and rotating machines
fundamental frequency phenomena			non-fundamental frequency phenomena	

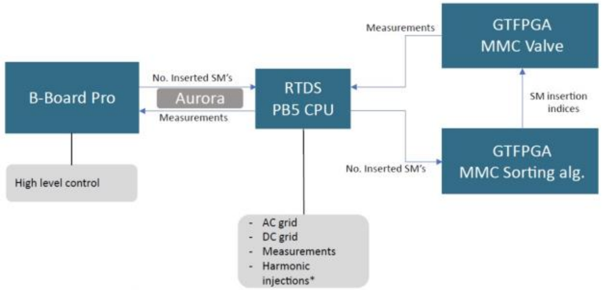
Component software model development

Some highlights



- New software package to investigate converter-related stability
  - High-bandwidth model of converters and other grid elements
  - Integrated with power-flow routines from WP1
- Demonstrator in the lab for Controller-Hardware in the Loop studies
  - Switched-level representation of converters
  - Control code running on hardware platform

- Accurate time-domain EMT model libraries for verification purposes
  - Automated impedance scanning tool in PSCAD
- New classes of high-bandwidth models for power system studies
  - Relying on dynamic phasor and harmonic-state space methods



Interaction analysis techniques

Some highlights

- Blackbox-ready analysis methods
  - Impedance-based assessment methods of hybrid AC/DC systems
  - Fitted frequency data turned into state-space models
- Identification of critical oscillation modes
  - Eigenvalue decompositions of augmented bus admittance matrix
  - Relative gain array techniques to participations of converters in critical modes
- New ways to look into the system
  - Aggregated participation factor analysis based on black-box models
  - Prediction of component behaviour by means of fitting techniques

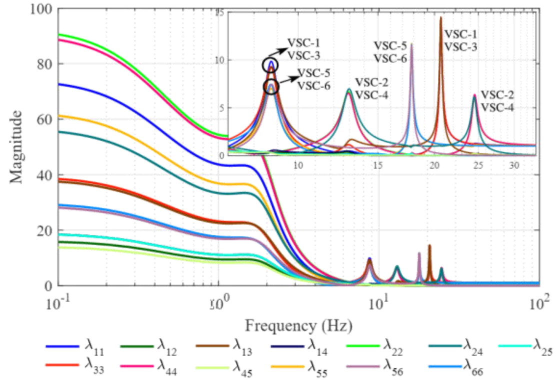
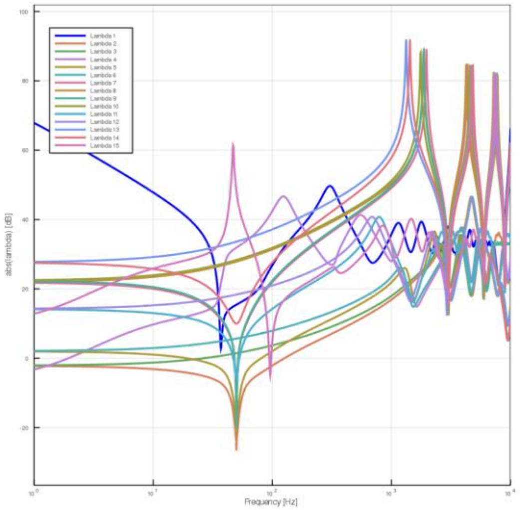


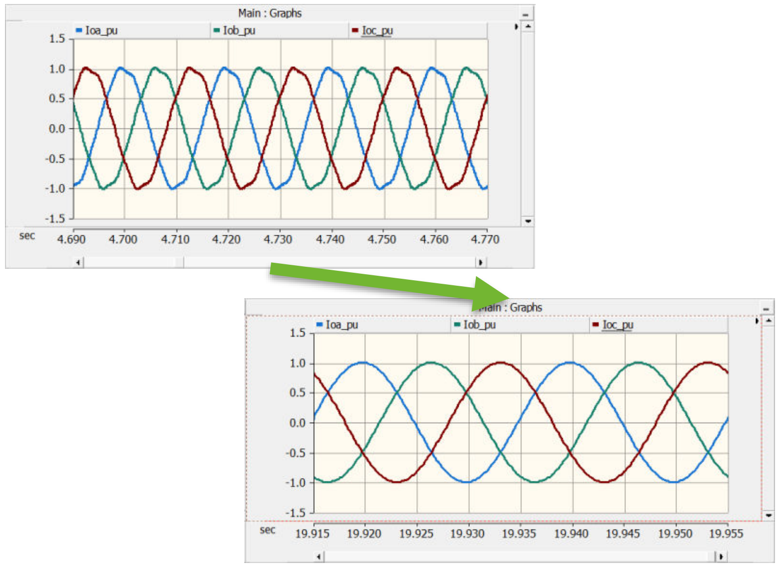
Figure 3.9: Network relative gain profile for the base case showing the interactive patterns



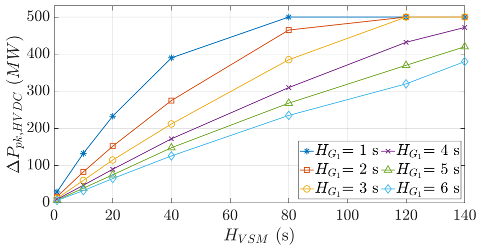
Adverse interaction mitigations

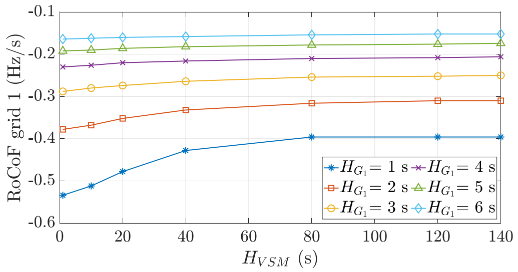
Some highlights

- Active filtering functionalities
  - Accurate control design studies only made possible due to developed highly accurate state-space models
  - Investigation of conflicting control functionalities due to internal frequency couplings



- Grid-forming control features
  - Contribution to AC system inertial support

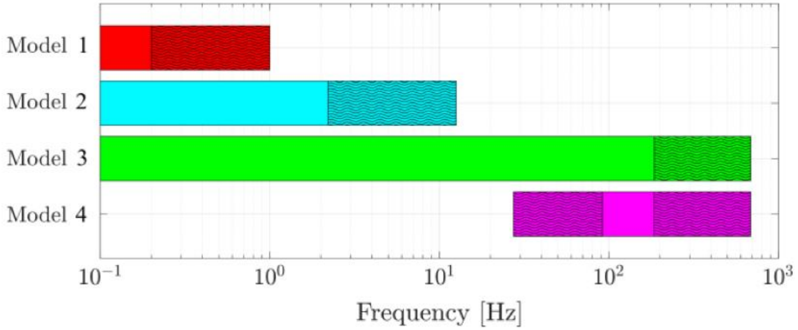




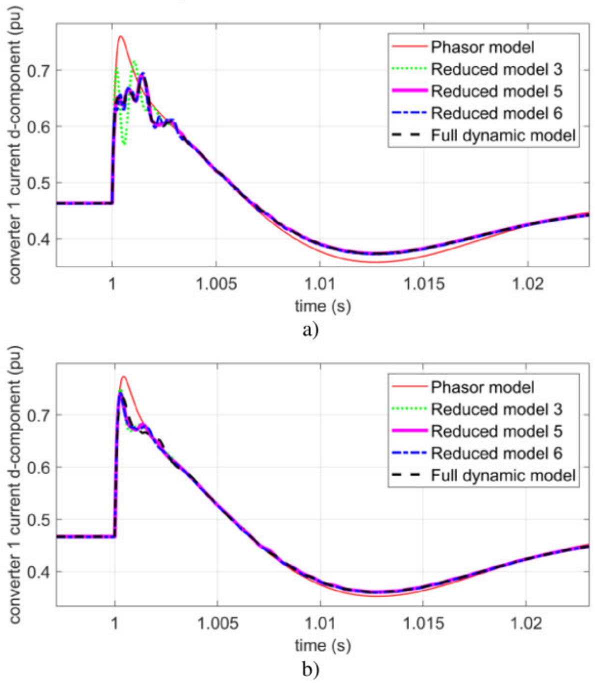
Guidelines for interaction studies

Some highlights

- VSC model order reductions
  - Based on level of details for different control loops
  - Accounting for mathematical simplifications based on modelling approach (EMT vs. RMS-based models)
  - Recommendations to choose apropriate models



- Network model order reductions
  - Which part of the network has to be studied in detail?
  - Based on eigenvalues of full-order models, and participation of different subsystems



Key recommendations

- Software models and methodologies have to be updated in order to be able to represent the behaviour of converters and the other components in the power system over an extended frequency range. In light of the real-life problems observed over the past decade, failing to do so poses risks to system security, given the observed inaccuracies of traditional power system modelling paradigms relying on phasor theory.
- In an environment where control implementations are subject to stringent IP-related limitations, models of the control implementation and the hardware should be embedded in highly accurate blackbox models, for instance using DLL's for time-domain models. Over the next years, methods need to be developed further to screen for potential problems, both in the time-domain as well as in the frequency-domain.
- In future power systems, the overall converter control design should evolve in such a way that interactions with the system can be largely limited to lower frequency ranges linked to traditional power system operation. By solving high-frequency problems and challenges mainly in the system design phase, the applicability and accuracy of more traditional phasor-based tools for large-scale system studies can be reassessed and re-evaluated, such that they can stay at the core of power system operational studies.

Neptune

Thank you for your attention!

jef.beerten@kuleuven.be

With the support of the Energy Transition Fund

economie

EnergyVille KU LEUVEN vito imec UHASSELT

Converter-Related Interactions in Power Systems

Events, Classifications, Tools and Mitigation

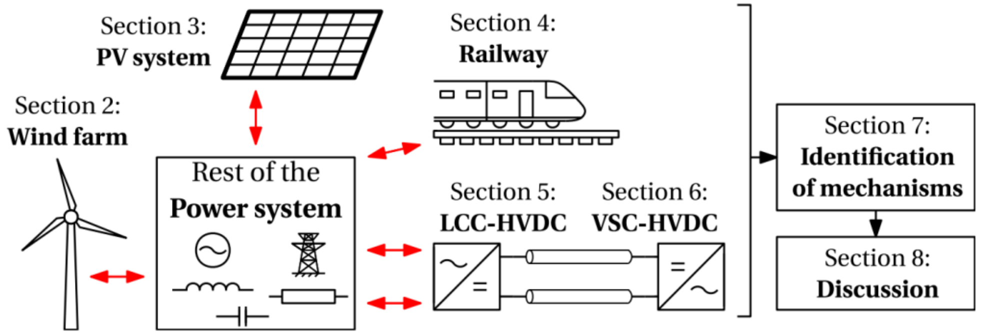
Özgür Can Sakinci

Neptune Final Event, 27 September 2023

Converter-Related Interactions in Power Systems: Events, Classifications, Tools and Mitigation

Energy Ville

Events and Classifications



State-of-the-art

- New types of instabilities linked to power electronics
  - Cascaded phenomena with multiple causes and consequences.
  - Changing the way power systems are being operated.
  - Underlying device characteristics not clearly understood.

- Phenomena commonly studied for specific type(s) of systems
  - No analogy between similar events observed in different types of systems.
  - Blocking the development of a clear and encompassing classification.

Overview of emerging subsynchronous oscillations in practical wind power systems

Jan Shair[a], Xiaorong Xie[a,*], Luping Wang[a], Wei Liu[a], Jingbo He[b], Hui Liu[c]

IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 33, NO. 6, JUNE 2018

Train–Network Interactions and Stability Evaluation in High-Speed Railways–Part I: Phenomena and Modeling

The Journal of Engineering

The 14th IET International Conference on AC and DC Power Transmission (ACDC 2018)

Review of oscillations in VSC-HVDC systems caused by control interactions

Congqi Yin[1], Xiaorong Xie[1], Shukai Xu[2], Changyue Zou[2]

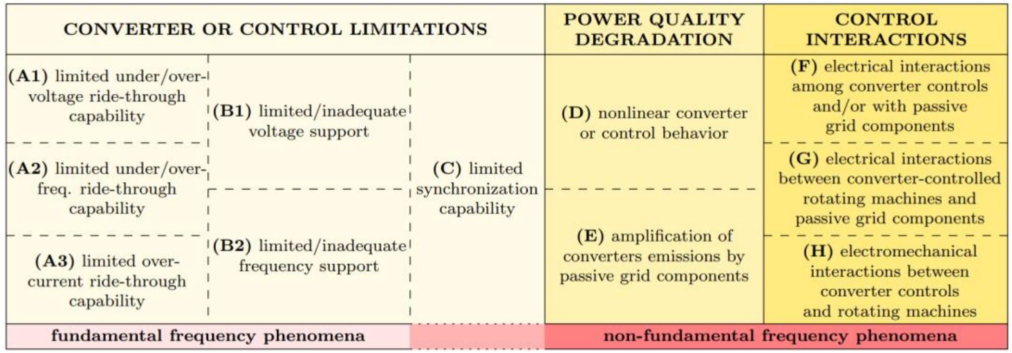
KU LEUVEN

Events and Classifications

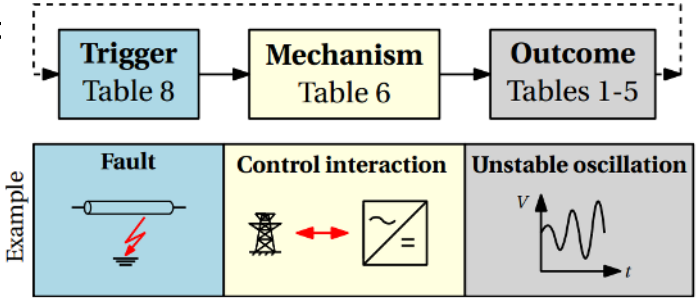
The Neptune Approach

1. Overview of real-life events
2. Identification of patterns
   - To pinpoint underlying mechanisms
   - Helping determining modeling requirements

- Three underlying mechanisms
  1. Converter control limitations
  2. Power quality degradation
  3. Control interactions

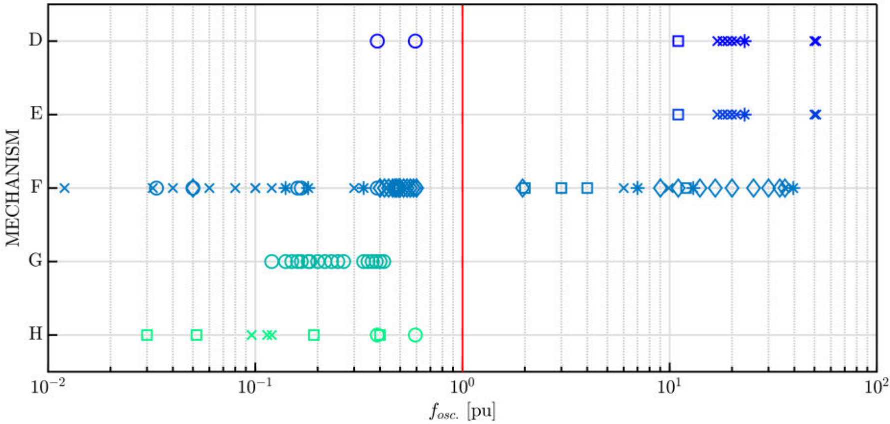


Example: 9 August 2019 UK Blackout



A fault (Trigger T1) initiated an interaction between WF controls and poorly-damped grid resonance (Mechanism F), resulting in growing voltage oscillations (Outcome).

The oscillations (Trigger T5) set off the over-current protection control (Mechanism A3), causing converters to trip (Outcome).



P. De Rua, T. Roose, Ö. C. Sakinci, N. Campos, J. Beerten, Identification of mechanisms behind converter-related issues in power systems based on an overview of real-life events, Renewable and Sustainable Energy Reviews, Volume 183, 2023, https://doi.org/10.1016/j.rser.2023.113431.

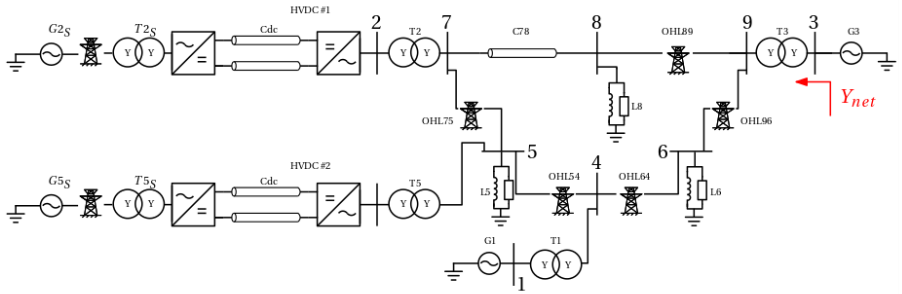
Converter-Related Interactions in Power Systems:

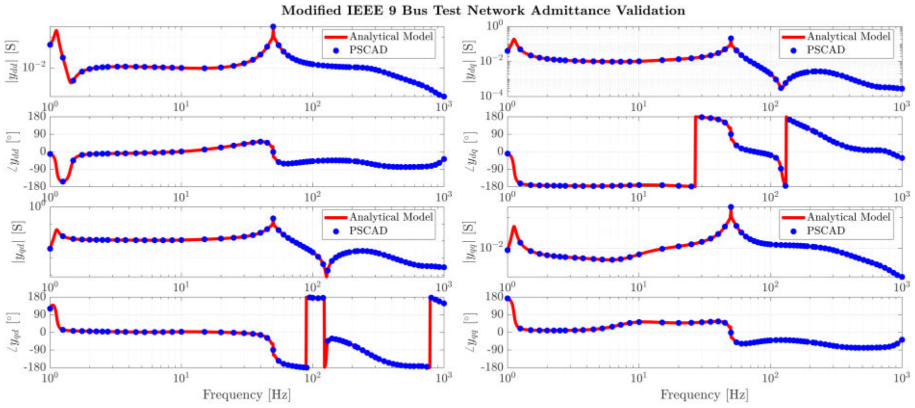
Events, Classifications, Tools and Mitigation

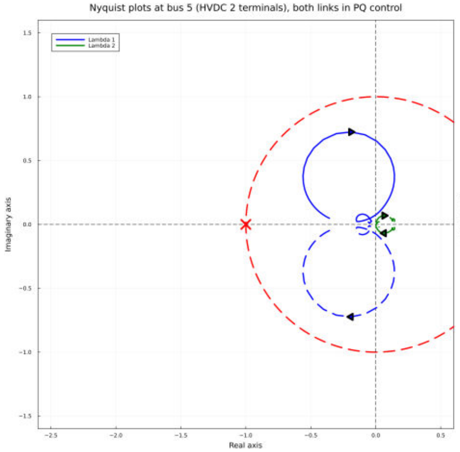
HVDCstability.jl

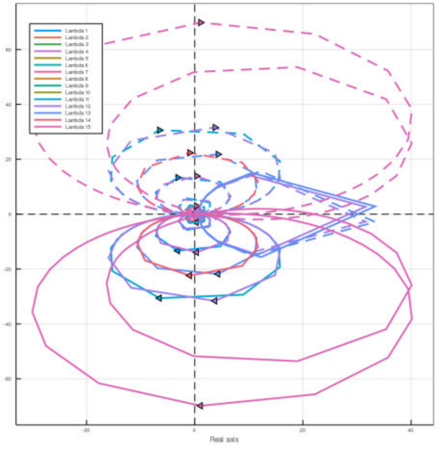
Stability Assessment Tool

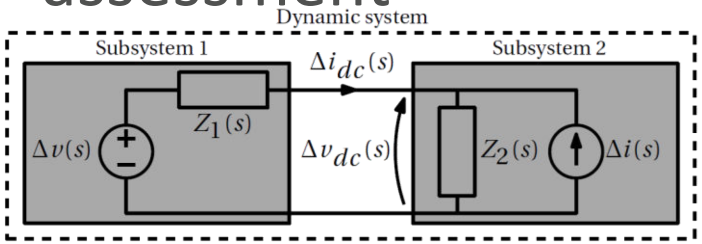
- Includes detailed models of converters, cables, overhead lines, transformers and synchronous generators
  - Frequency domain
  - Valid over an extended frequency range
- Automated single/multi-terminal stability assessment

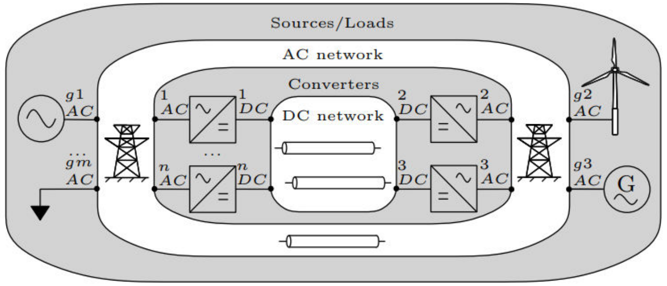












Component Model Development

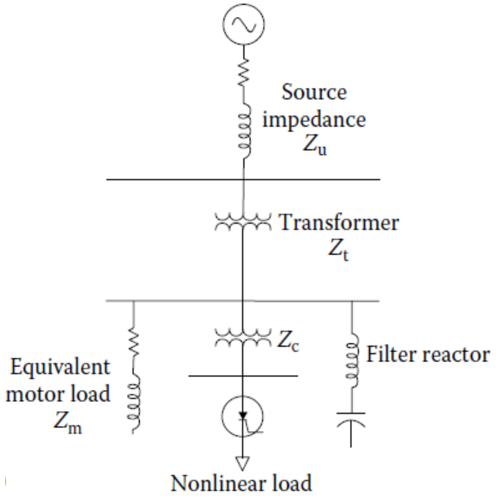
Frequency-Lifted Converter Models

- Useful tools to analyze time-varying dynamic behavior.
  - Without harmonics: Periodicity only at fundamental frequency
    - Well-developed modeling and analysis techniques exist (e.g. modal analysis).
    - Available in commercial software.
  - With harmonics: Multi-frequency periodicity
    - Advanced modeling frameworks are needed to study the impact of harmonics.
- Comparison of dynamic phasors and harmonic state-space
  - Originate from similar hypotheses, lead to models with same dynamics
  - Both enable the design of advanced controllers actively controlling harmonics.

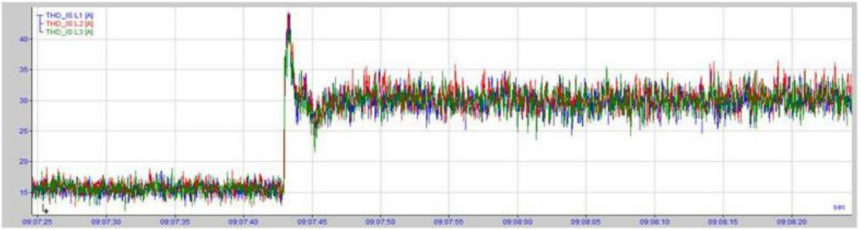
Converter-Related Interactions in Power Systems:
Events, Classifications, Tools and Mitigation

Filtering as an Interaction Mitigation Measure

- Passive filtering
    - Tuned for a specific harmonic and network topology.
    - Might result in resonances.
- Active filtering
    - Using converter control functionalities to suppress harmonics.
    - High-voltage applications of active filtering are challenging.
        - Limited switching frequency & possible control interactions.



Source: J. C. Das, Power System Analysis: Short-Circuit Load Flow and Harmonics, 1st ed. New York: CRC Press, Apr.2002.

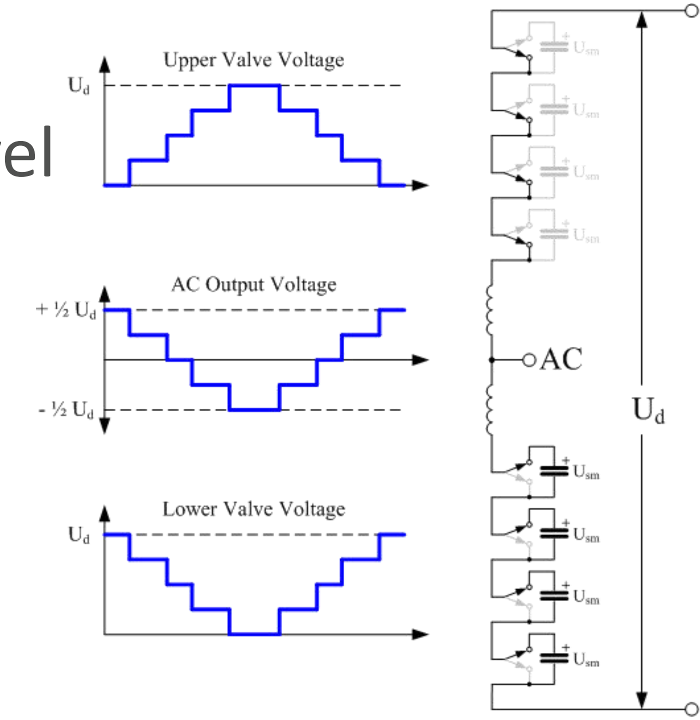


Source: Hernandez Manchola, A., Priebe, T., Hölzer, M. and Dommaschk, M. (2019), VSC HVDC active damping for the Sylwin 1 offshore wind power plants. The Journal of Engineering, 2019: 4748-4753. https://doi.org/10.1049/joe.2018.9240

Harmonic Filtering & MMC

Modular Multilevel Converters

- Standard VSC-HVDC converter topology in new installations.
- Superior harmonic performance (compared to two-level VSC) due to the modular structure.
  - Reduced power electronics switching
    - High controller bandwidth, low switching losses.
    - Making advanced controllers possible, a.o. active harmonic filtering.
- Using dynamic phasor models for controller design
  - Making traditional eigenvalue-based interaction analysis possible.

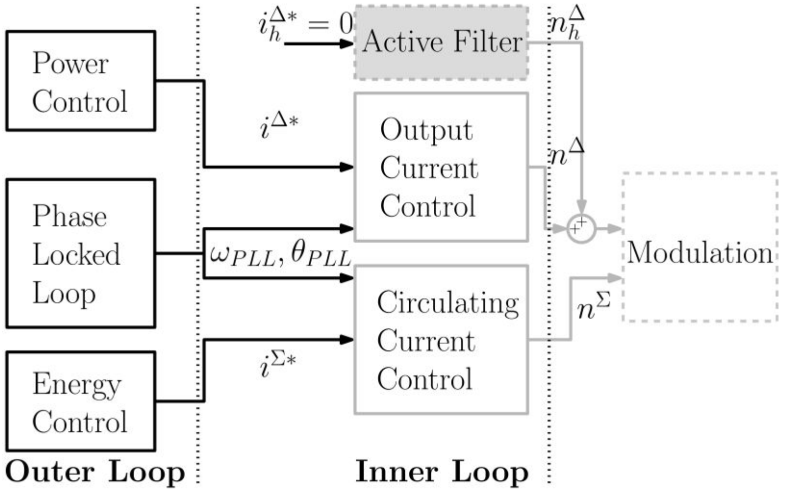


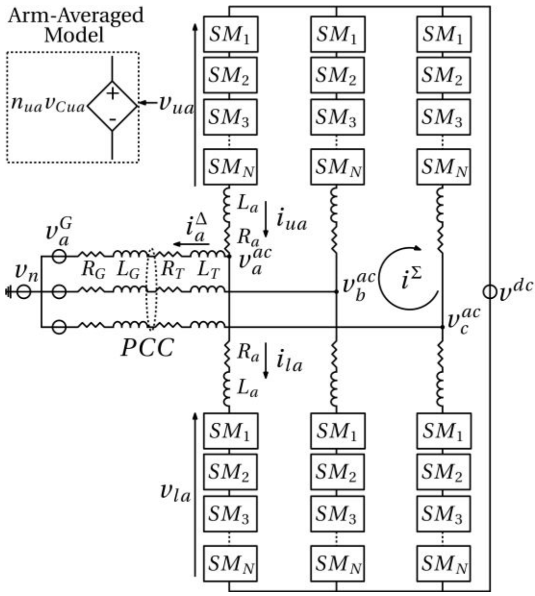
Source: Wikipedia

Active Filtering with the MMC

Control Architecture

- Active filtering is implemented as an additional controller.
  - Suppression of 5th and 7th harmonics in the converter current.
- Dynamic phasor model of a half-bridge MMC representing harmonics up to 650 Hz is used.
  - Systematic design not possible without the developed DP model.
    - Traditional models do not include these harmonics.

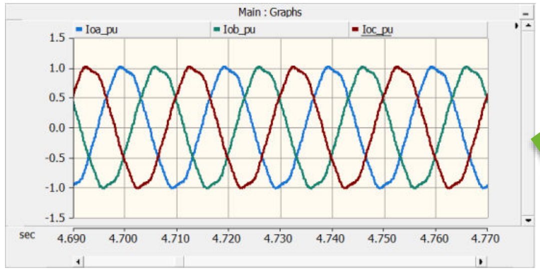


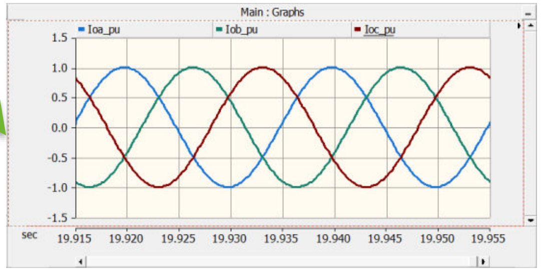


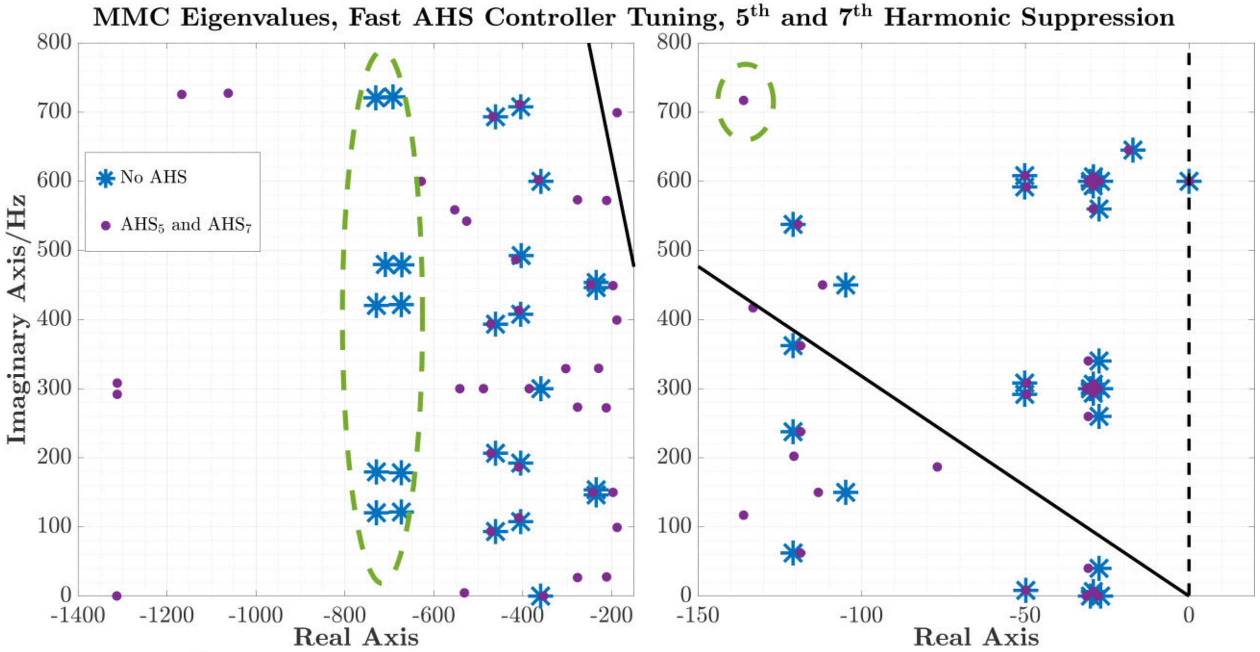
Active Filtering with the MMC

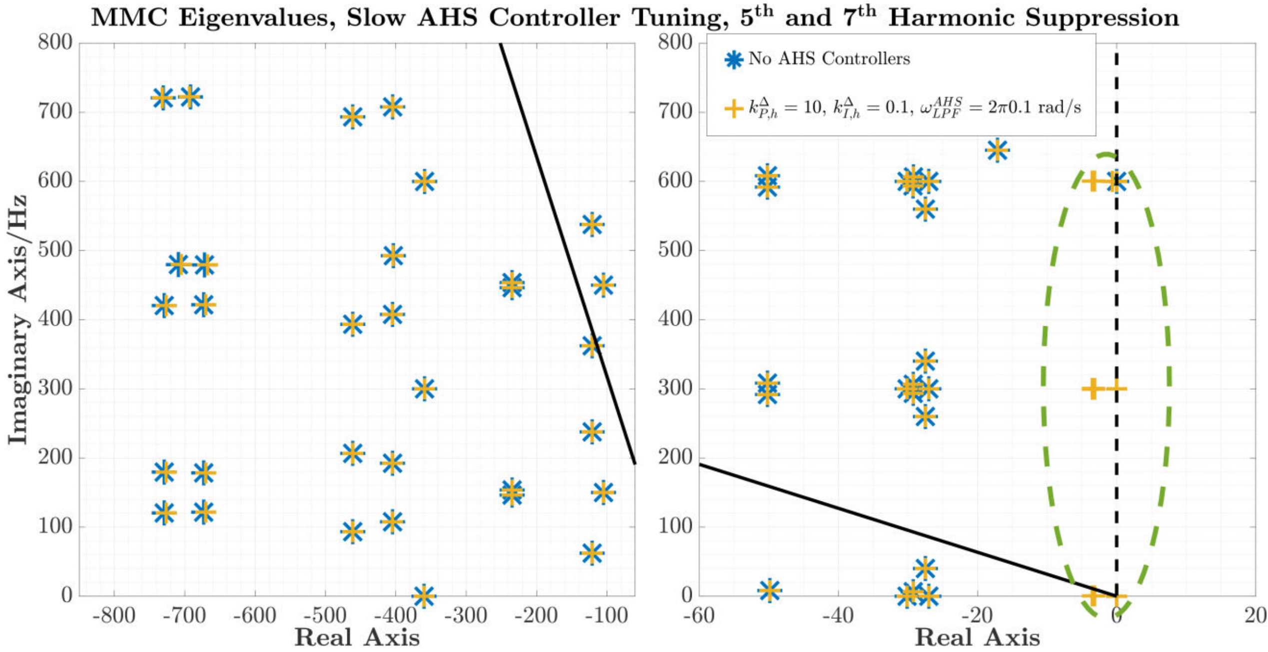
Impact on Stability

- Tuning of the active filtering action influences interactions
  - Fast active filtering of current harmonics interacts with current control



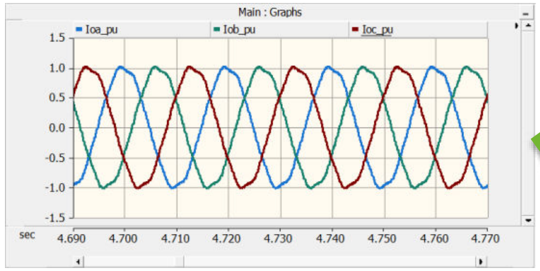


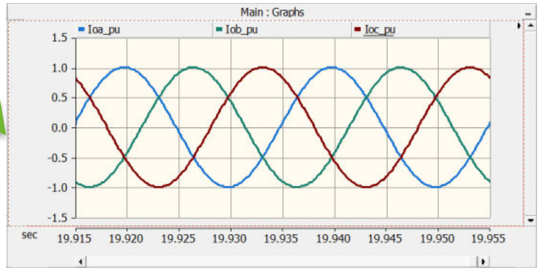




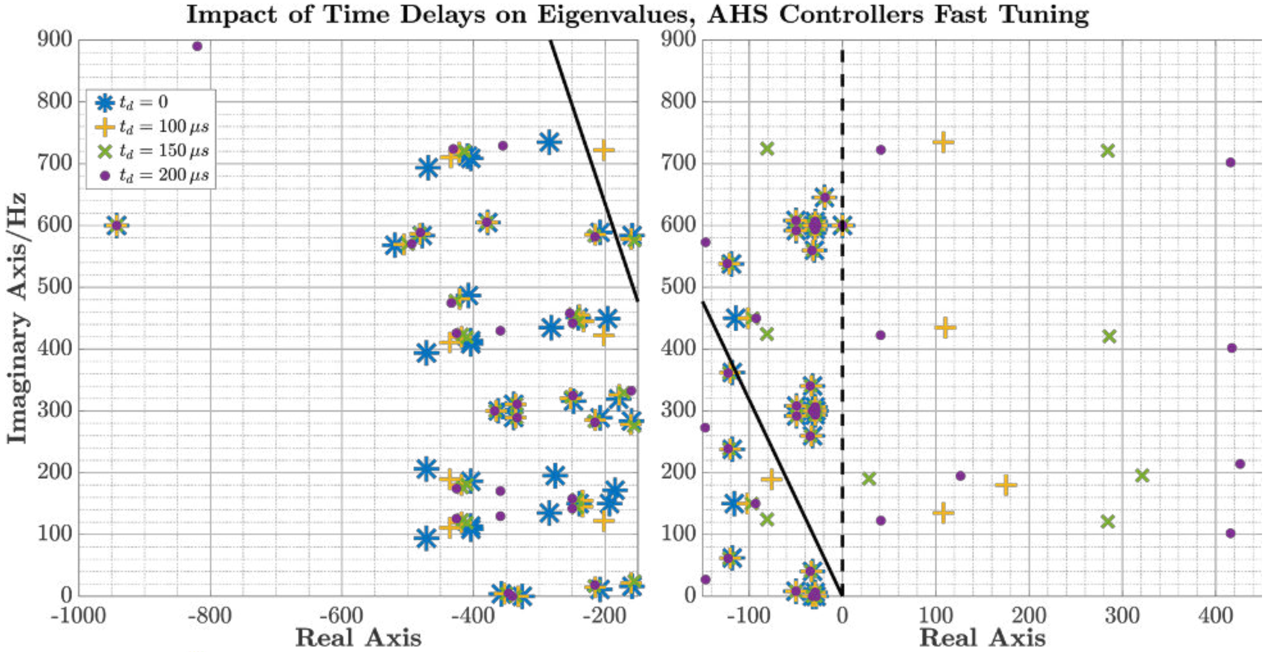
Active Filtering with the MMC

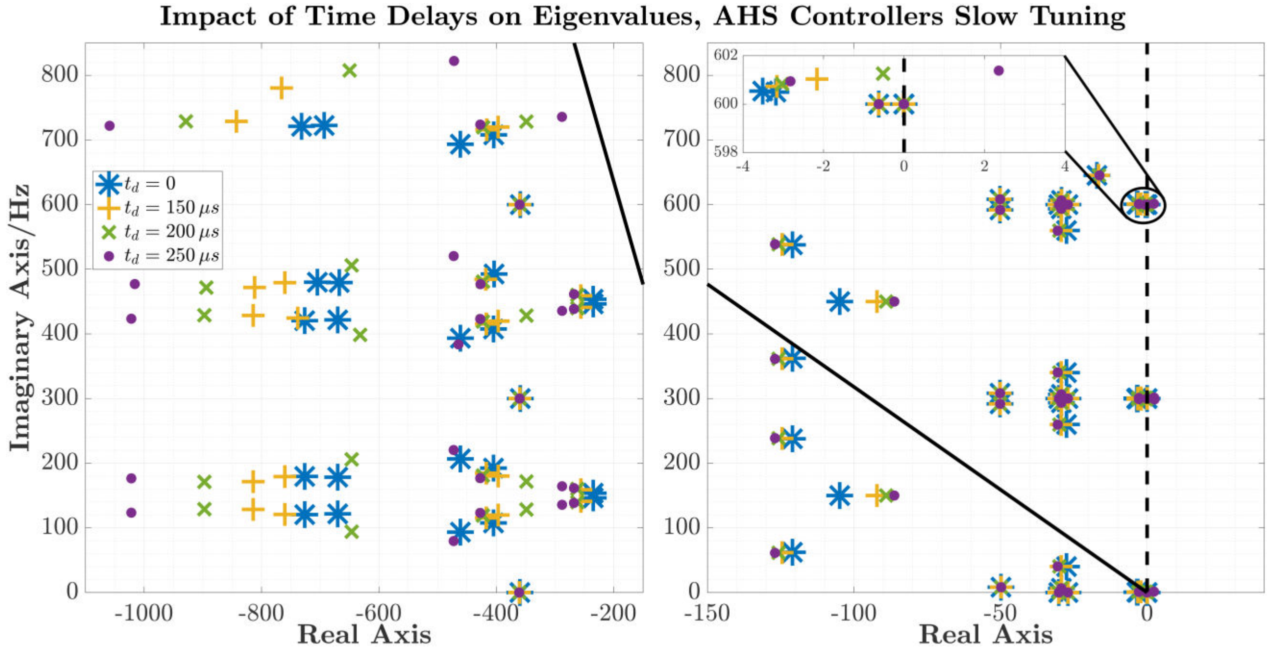
Impact on Stability





- Computational time delays strongly impact stability
  - Higher stability margins when slow tuning is used.





Conclusions

- Identified mechanisms behind converter-related interactions.
  - Converter limitation, power quality degradation and interaction
  - Both the mechanisms and their triggers impact the choice of modeling requirements.
- Developed detailed models for stability analysis.
  - System-level stability analysis tool and converter models representing harmonics.
  - Enabling the design and analysis of advanced controllers.
- Investigated the impact of active output current harmonic suppression on stability.
  - Power quality is increased, but the interaction risk is higher.
  - Interactions depend on the speed of active filtering action and time delays.

Thank you for your attention!

ozgurcan.sakinci@kuleuven.be

With the support of the Energy Transition Fund

Model order reduction of converter-based ac power systems based on interaction modes identification

Prof. Goran Grdenić, PhD
University of Zagreb

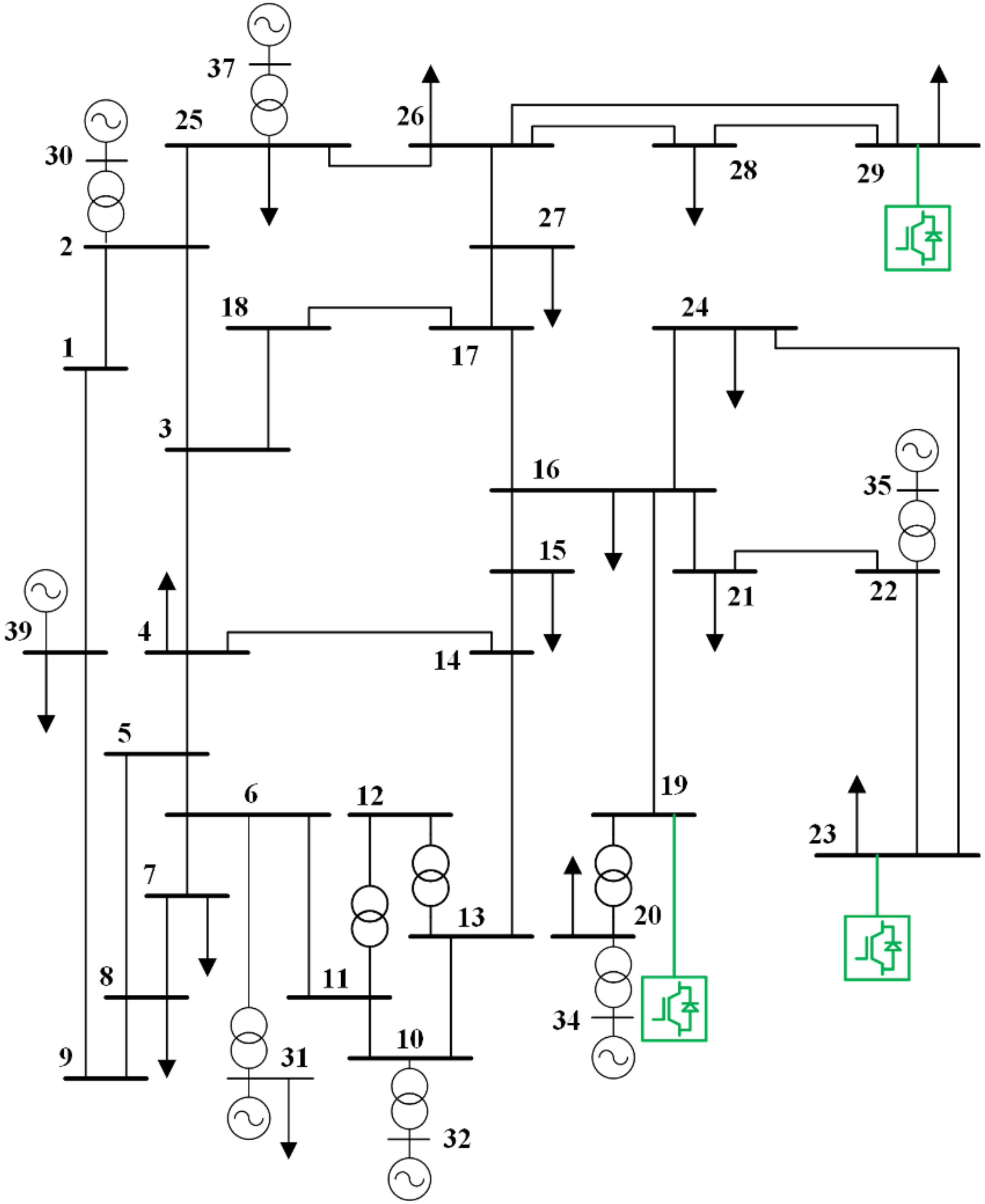
Research context

- Increasing application of power electronics devices has changed the aspects of ac grid modeling
- Possible detrimental interactions appear at much higher frequencies compared to synchronous generator-based power systems
- Ac line and converter models with extended validity in the frequency range are mandatory
- However, modeling all the lines and converters in a system in high-frequency resolution in often not necessary and requires high computational power

[1] C. Buchhagen, C. Rauscher, A. Menze and J. Jung, "BorWin1 – First Experiences with harmonic interactions in converter dominated grids," in *International ETG Congress*, Bonn, 2015.
[2] C. Rathke and M. Greeve, "Operating Experience of HVDC Links Behaviour After Switching Events in the Onshore Grid," in *Proceedings in CIGRE B4 Colloquium*, Winnipeg, 2017.

Research context

- Objective of the research: development of ac grid model order reduction (MOR) methodology in converter-based power systems



Proposed ac grid model order reduction methodology

Frequency validities of line models

MODAL ANALYSIS

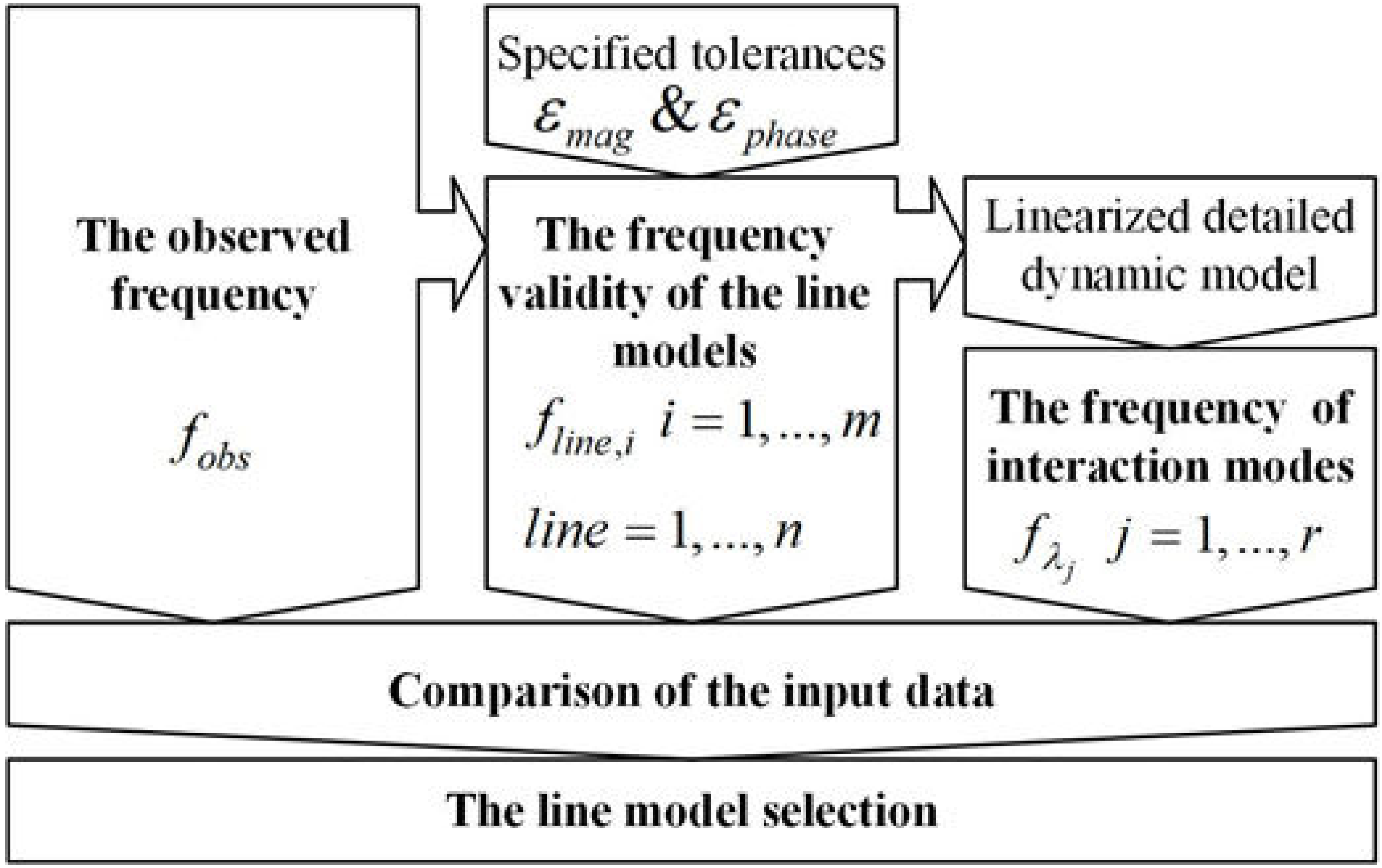
Subsystem participations

Interaction modes

Line model selection

$$I_{line,PED} = \left\{ \lambda_j \mid \sum_{x_k \in A_{line}} p_{kj} > \eta_{line} \wedge \sum_{x_k \in A_{PED}} p_{kj} > \eta_{PED} \right\}$$

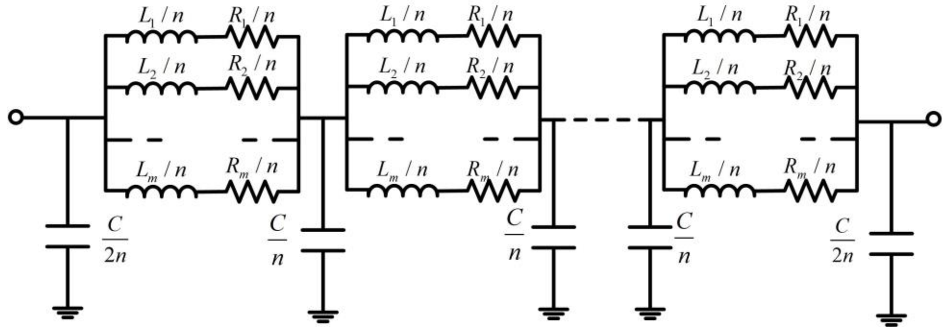
Proposed ac grid model order reduction methodology

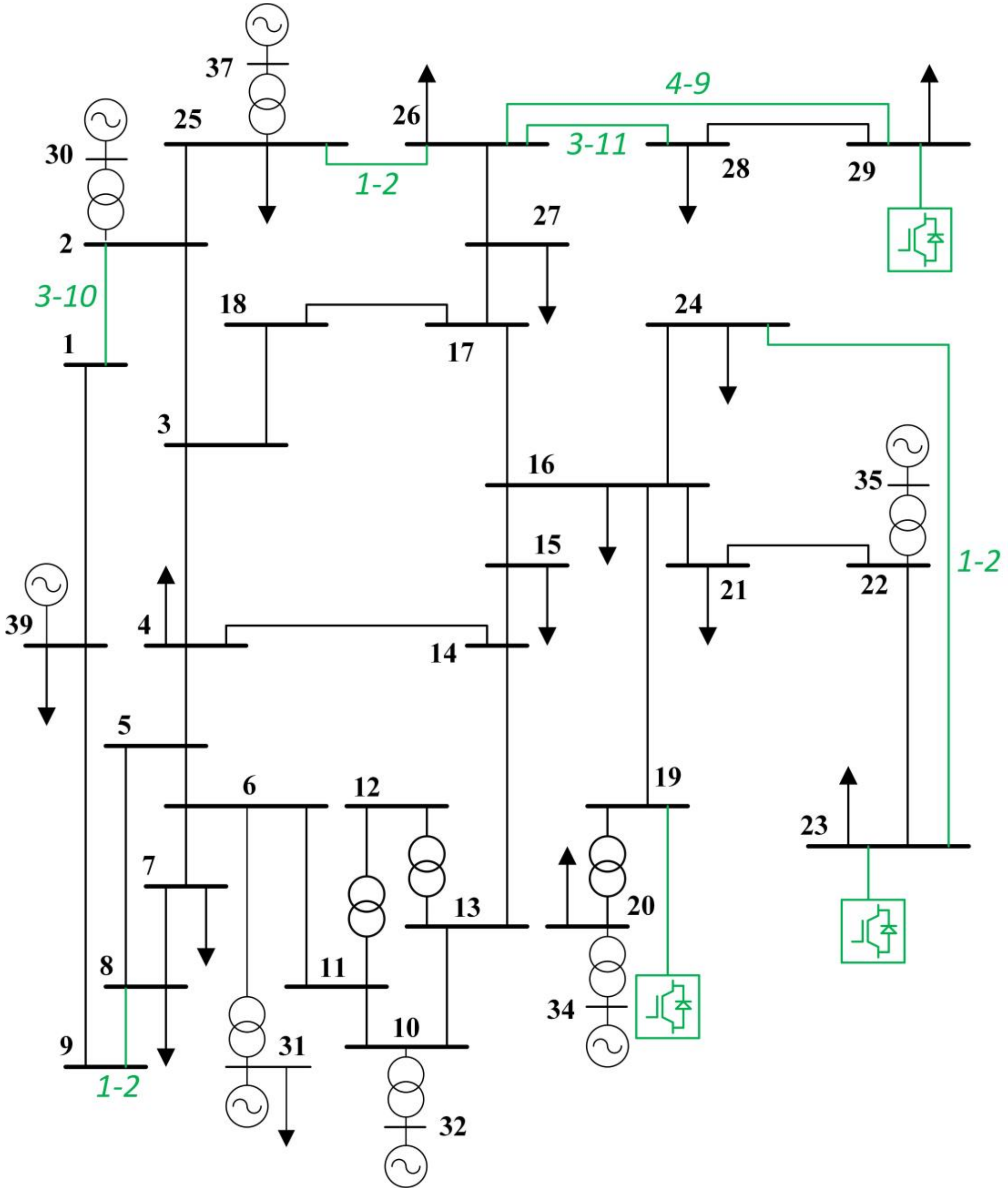


$$S_{line} = \left\{ f_{\lambda_j} \mid f_{\lambda_j} < f_{obs} \lor \lambda_j \in (I_{line,PED} \lor PED) \right\}$$

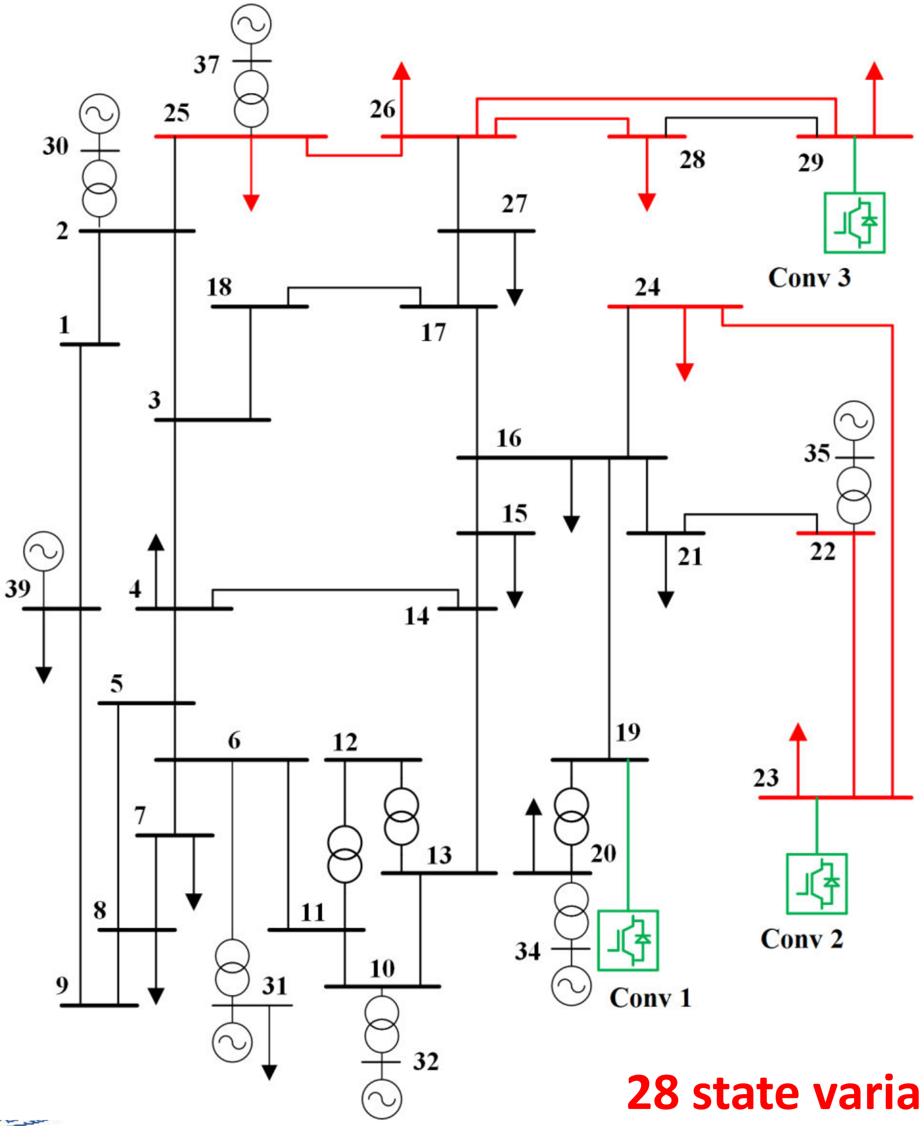
Modified IEEE 39 bus system

- The frequency limit: 1000 Hz
- Magnitude and phase tolerances for line modeling: 5 dB and 5°
- Most of the lines modeled using a single PI section
- Total number of state variables: 534
- Total number of ac grid state variables: 414



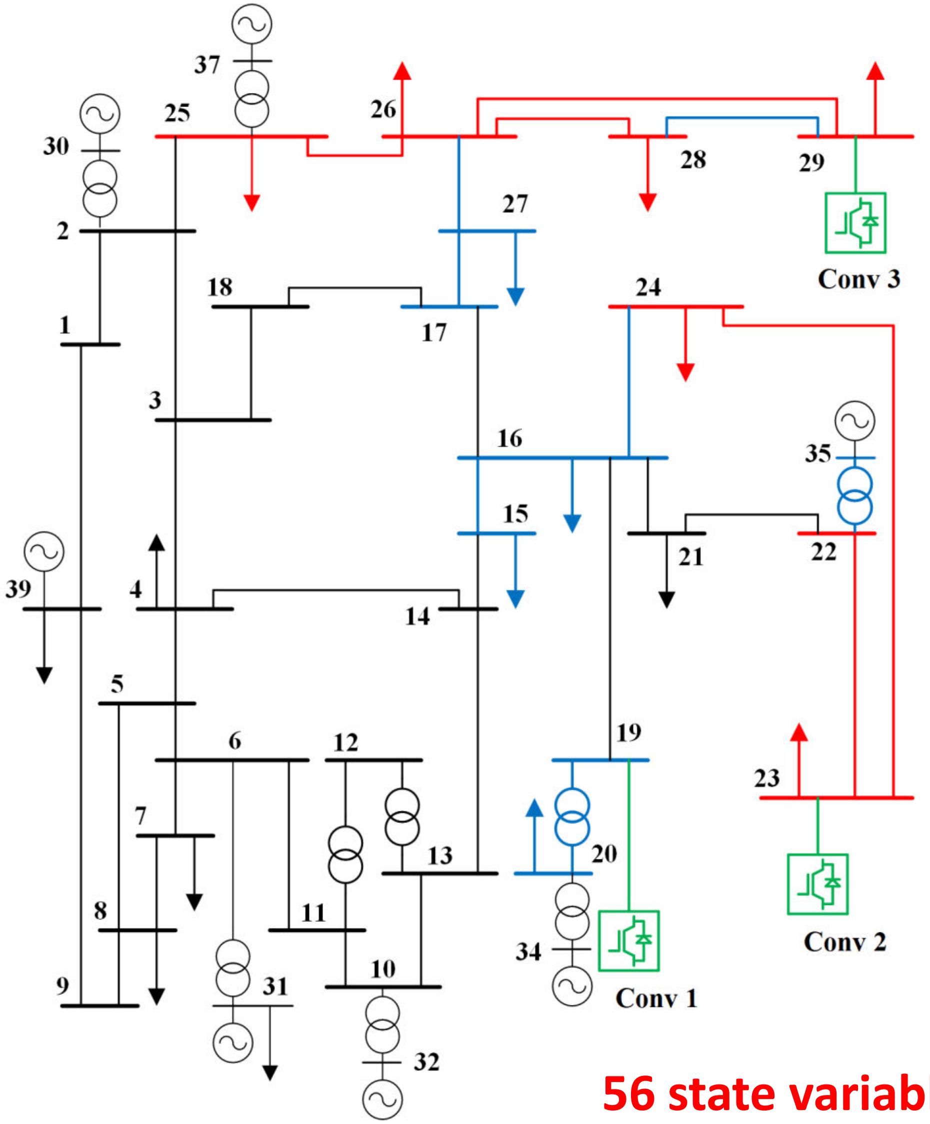


Converter threshold: 20%
Ac line threshold: 10%



28 state variables

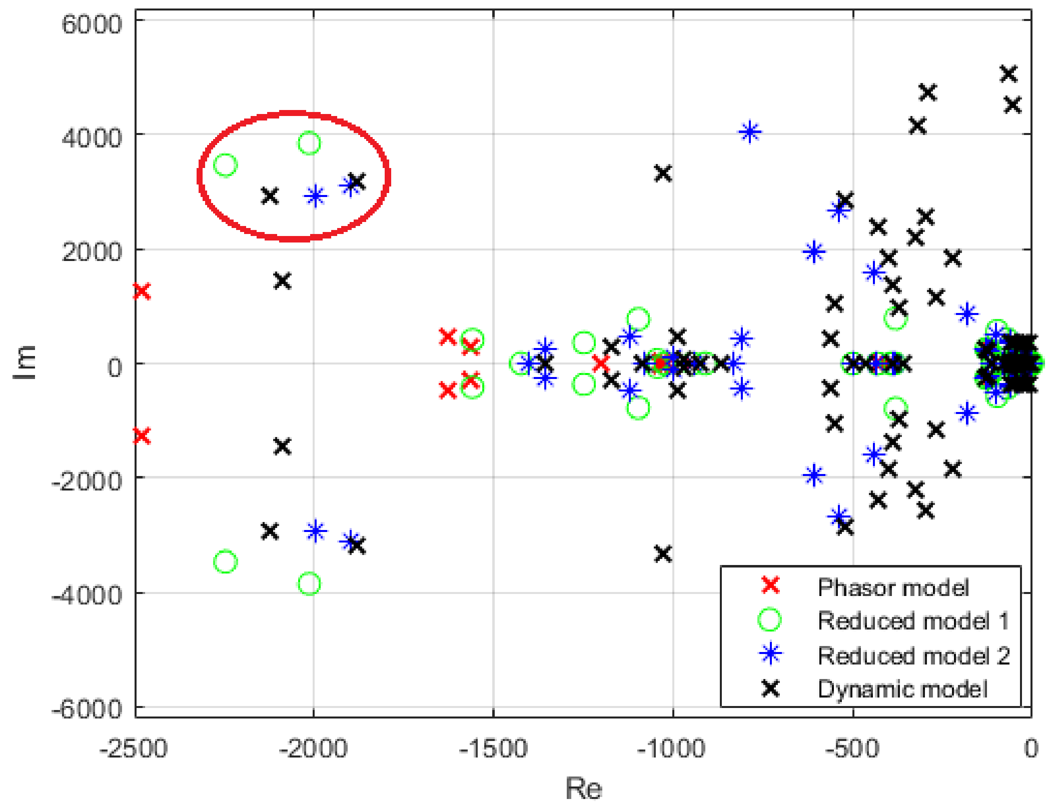
Converter threshold: 20%
Ac line threshold: 2.5%

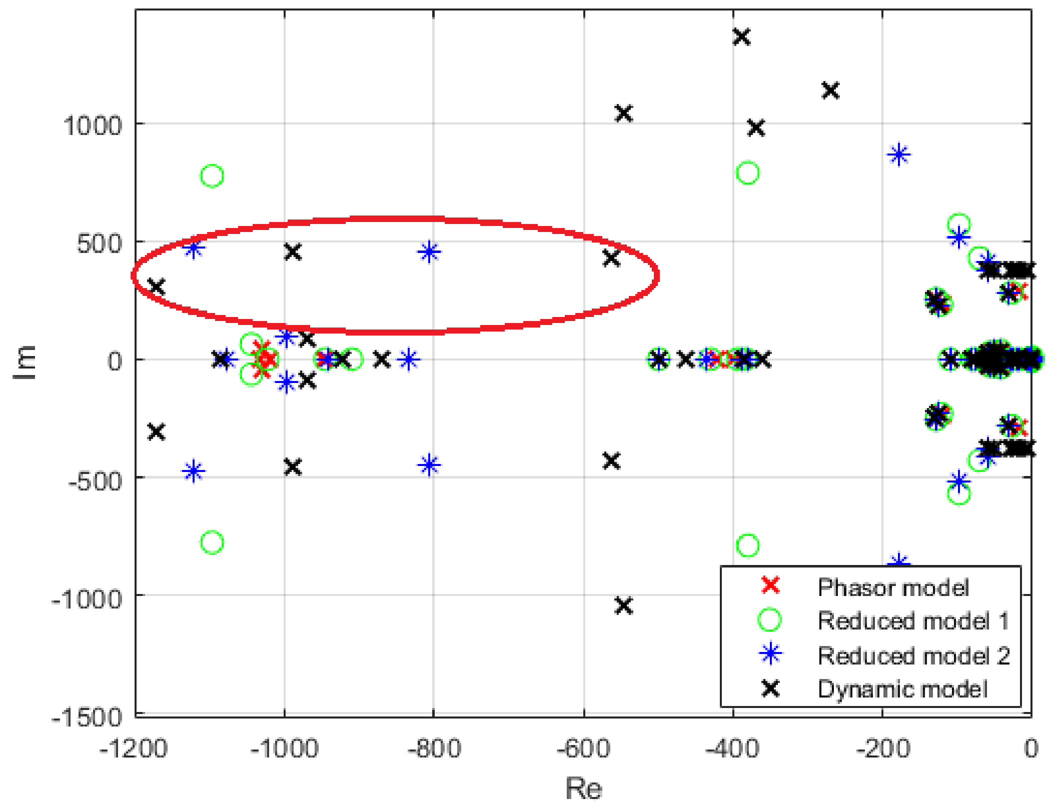


56 state variables

Analysis of interaction modes

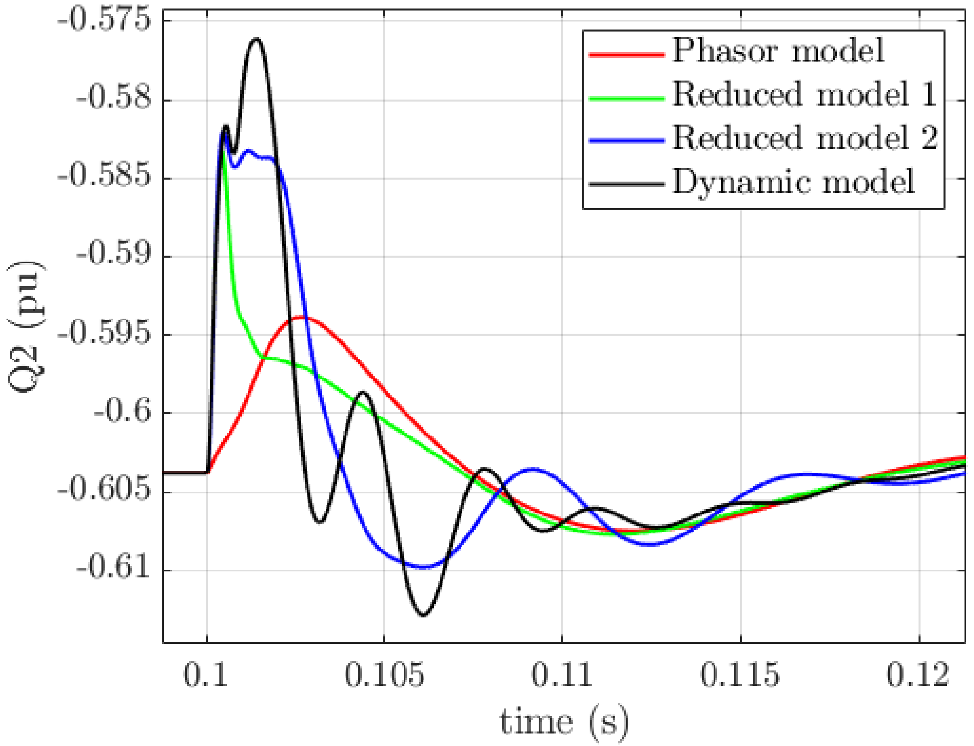
- Comparison of different ac grid models

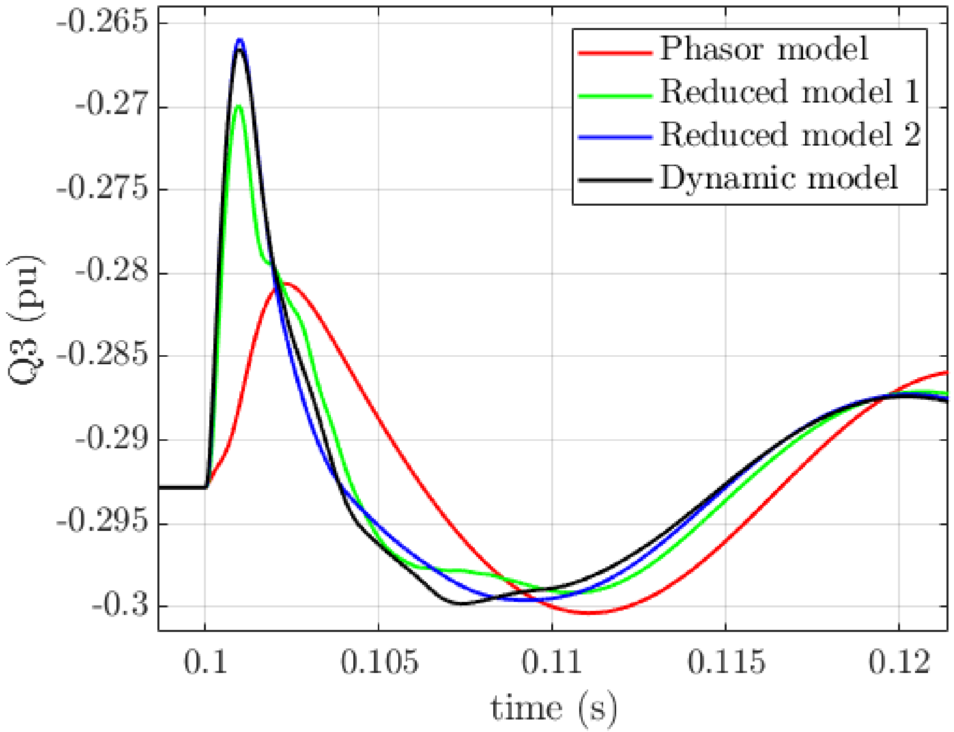




Time-domain simulations

- Detected interaction modes are mostly related to reactive power measurements



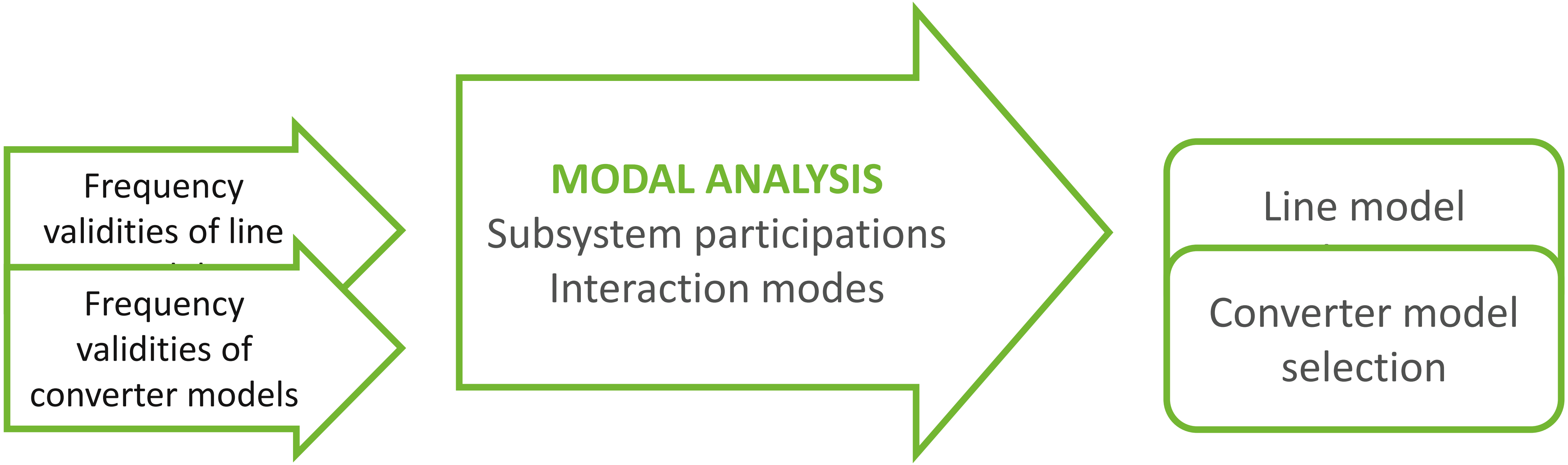


Energy Ville

Proposed ac grid model order reduction methodology

- The subsystem participation thresholds affect the size of the reduced model – the higher the thresholds, the reduced model is simpler but less accurate, and vice versa
- However, the methodology identifies more significant lines and the necessary level of their model complexity

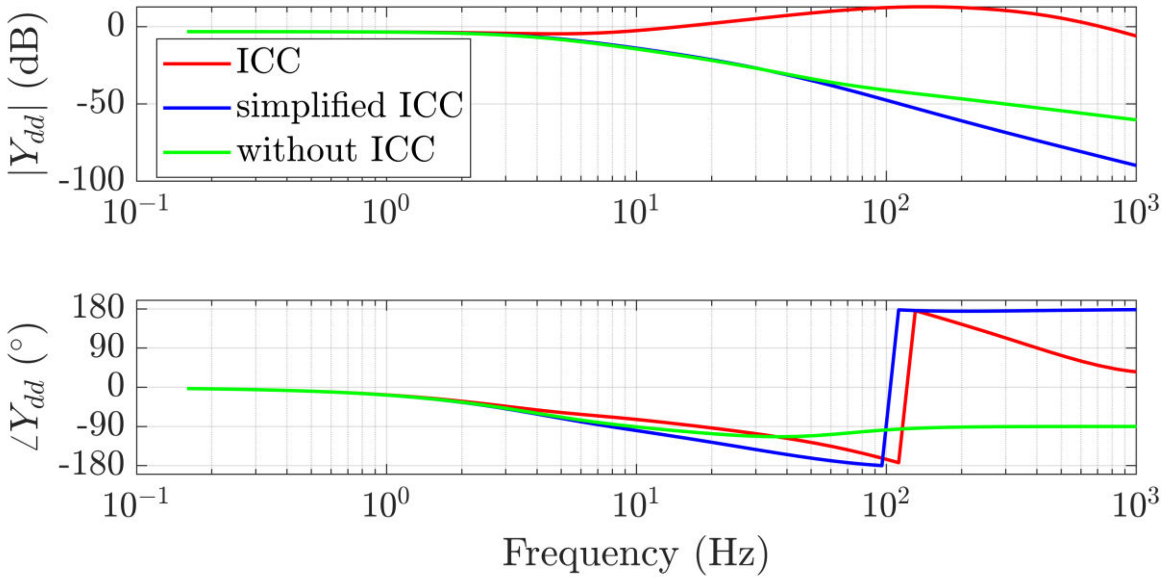
The methodology extension

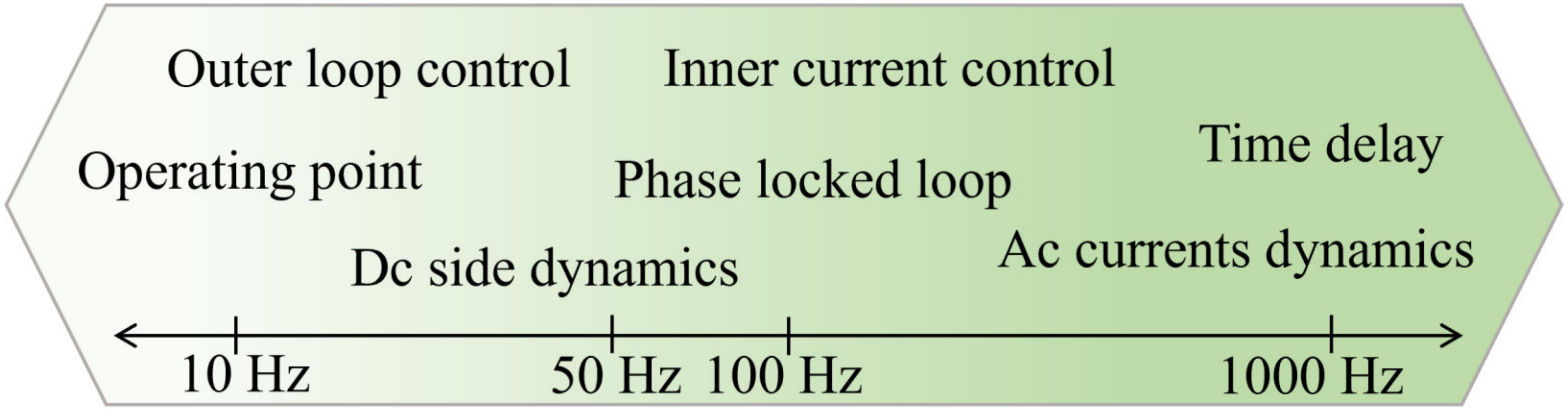


- Objective of the research: establishment of validity boundaries in the frequency domain of different VSC reduced-order models for the application in ac system stability studies

VSC model order reduction

- Time-averaged models and two-level topology
- Admittance-based assessment of various converter parameters and modeling details





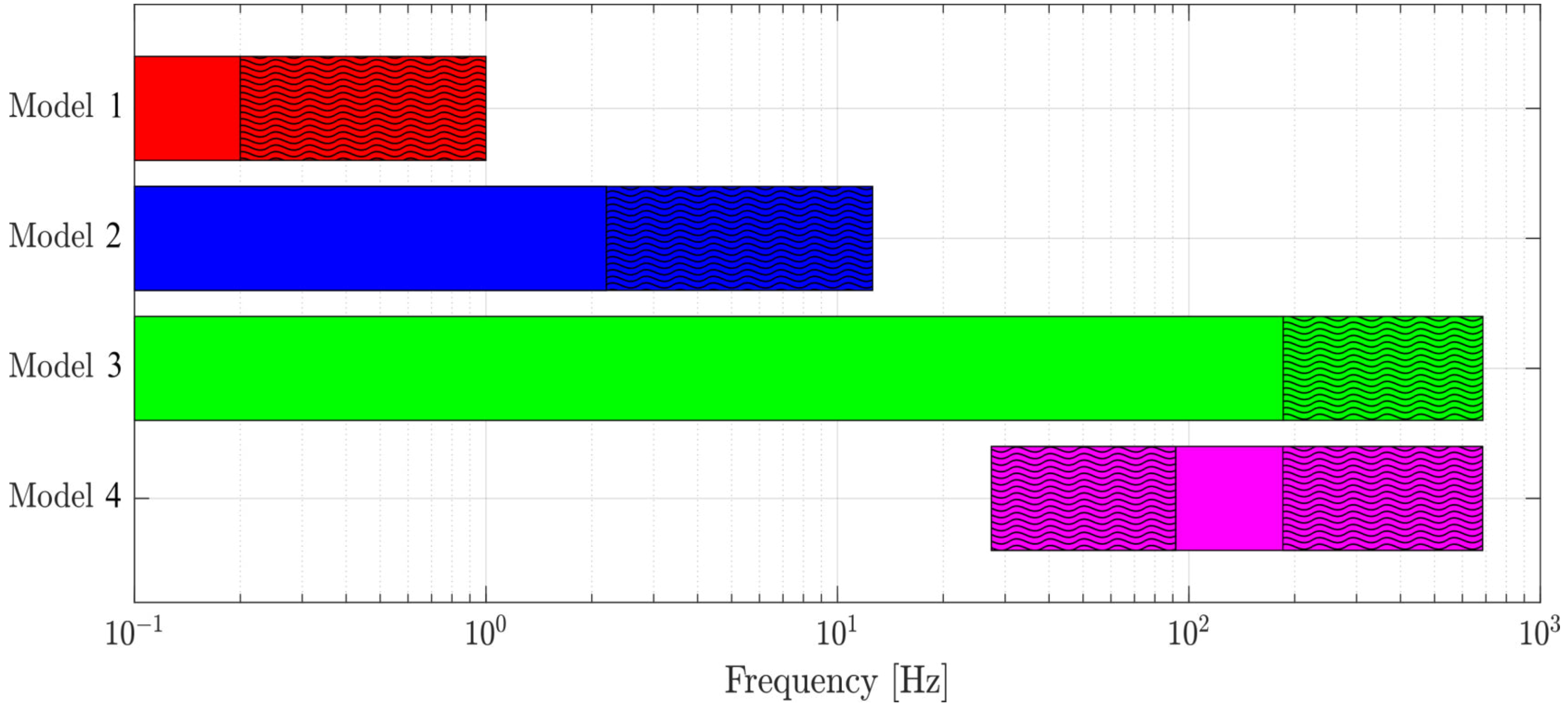
VSC model order reduction

- The set of four reduced-order VSC models is proposed and analyzed

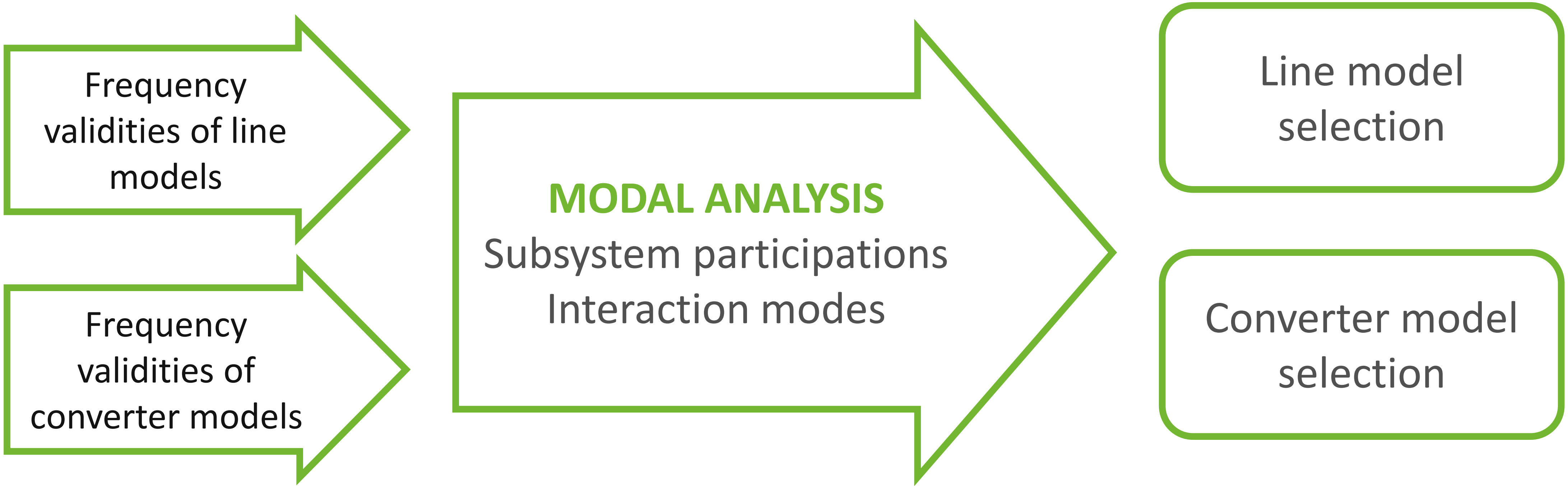
	Outer loops	P&Q filter	PLL	PLL filter	ICC	ICC voltage filter	ICC current filter	EMT currents	Dead time	Number of state variables
Model 1	+	+								4
Model 2	+	+	+	+	+	+	+			14
Model 3	+	+	+	+	+	+	+	+	+	18
Model 4			+	+	+	+	+	+	+	14

VSC model order reduction

- A parametric sensitivity analysis is conducted to determine the validity range of the proposed reduced-order models



Future research



- Establishment of reduced-order models for other VSC topologies and control strategies
- Merge of the proposed ac grid MOR methodology with VSC reduced-order models

Publications

- G. Grdenić, M. Delimar, and J. Beerten, “AC Grid Model Order Reduction Based on Interaction Modes Identification in Converter-Based Power Systems,” *IEEE Transactions on Power Systems*, vol. 38, no. 3, May 2023.
- G. Grdenić, F. J. Cifuentes Garcia, N. de Morais Dias Campos, F. Villella, and J. Beerten, “Model Order Reduction of Voltage Source Converters Based on the Ac Side Admittance Assessment: From EMT to RMS,” *IEEE Transactions on Power Delivery*, vol. 38, no. 1, Feb. 2023.
- G. Grdenić, M. Delimar, J. Beerten, “Ac Grid Modelling in Power Electronics-Based Power Systems for Eigenvalue Stability Studies,” in Power System Operation with 100% Renewable Energy Sources, Elsevier, Nov. 2023.

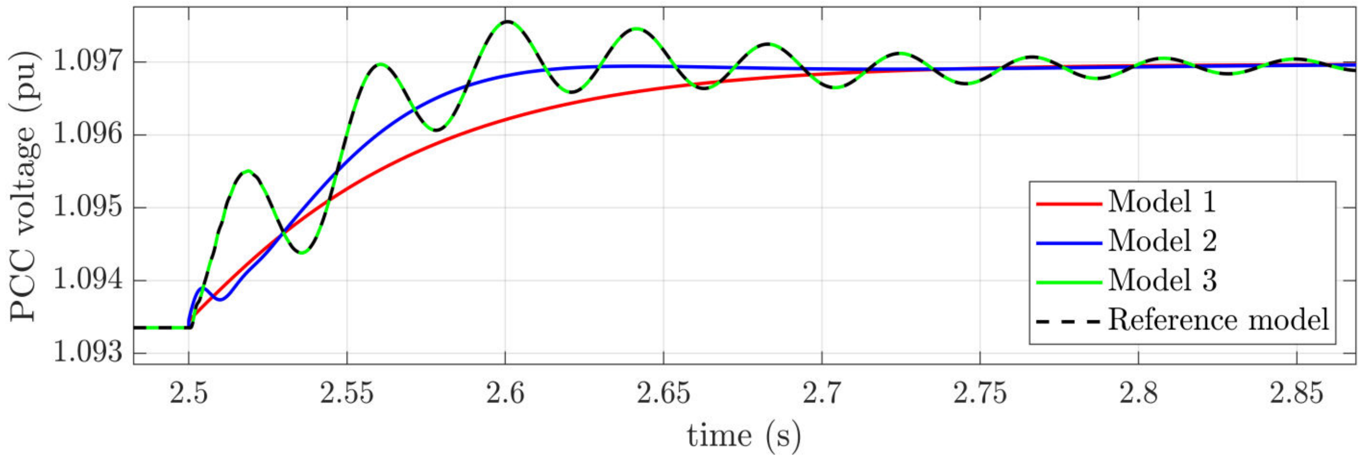
Thank you for you attention!

It was an honour to be a part of the NEPTUNE project!

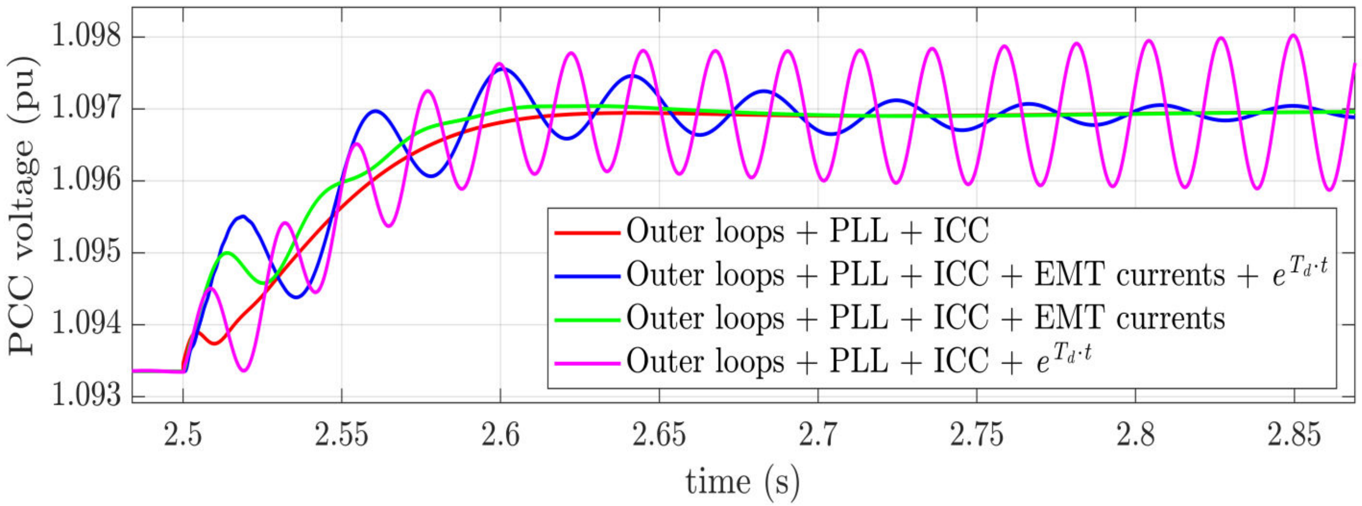
Questions?

(goran.grdenic@fer.hr)

Appendix



PCC voltage (pu)
1.097
1.096
1.095
1.094
1.093
2.5
2.55
2.6
2.65
2.7
2.75
2.8
2.85
time (s)
Model 1
Model 2
Model 3
Reference model



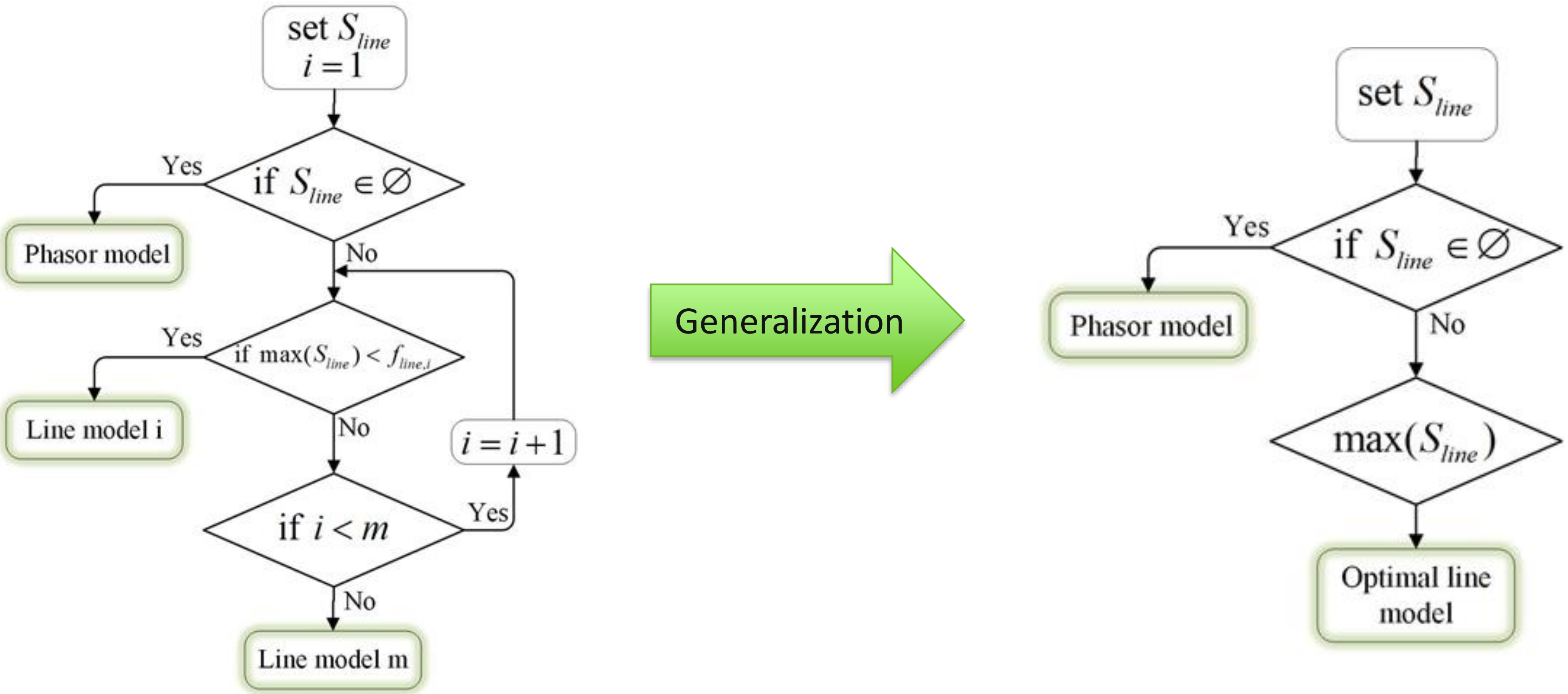
PCC voltage (pu)
1.098
1.097
1.096
1.095
1.094
1.093
2.5
2.55
2.6
2.65
2.7
2.75
2.8
2.85
time (s)
Outer loops + PLL + ICC
Outer loops + PLL + ICC + EMT currents + $e^{T_d \cdot t}$
Outer loops + PLL + ICC + EMT currents
Outer loops + PLL + ICC + $e^{T_d \cdot t}$

Appendix

$$S_{line} = \left\{ f_{\lambda_j} \mid f_{\lambda_j} < f_{obs} \;\vee\; \lambda_j \in \left(I_{line,PED} \;\vee PED\right) \right\}$$

Variant 1

Variant 2



Roadmap and valorisation

Neptune Final Event

Jef Beerten – KU Leuven & EnergyVille

27 September 2023

Renewable energy

To decarbonise our electrical systems

Energy
Ville

High Voltage Direct Current

Enabling the energy transition

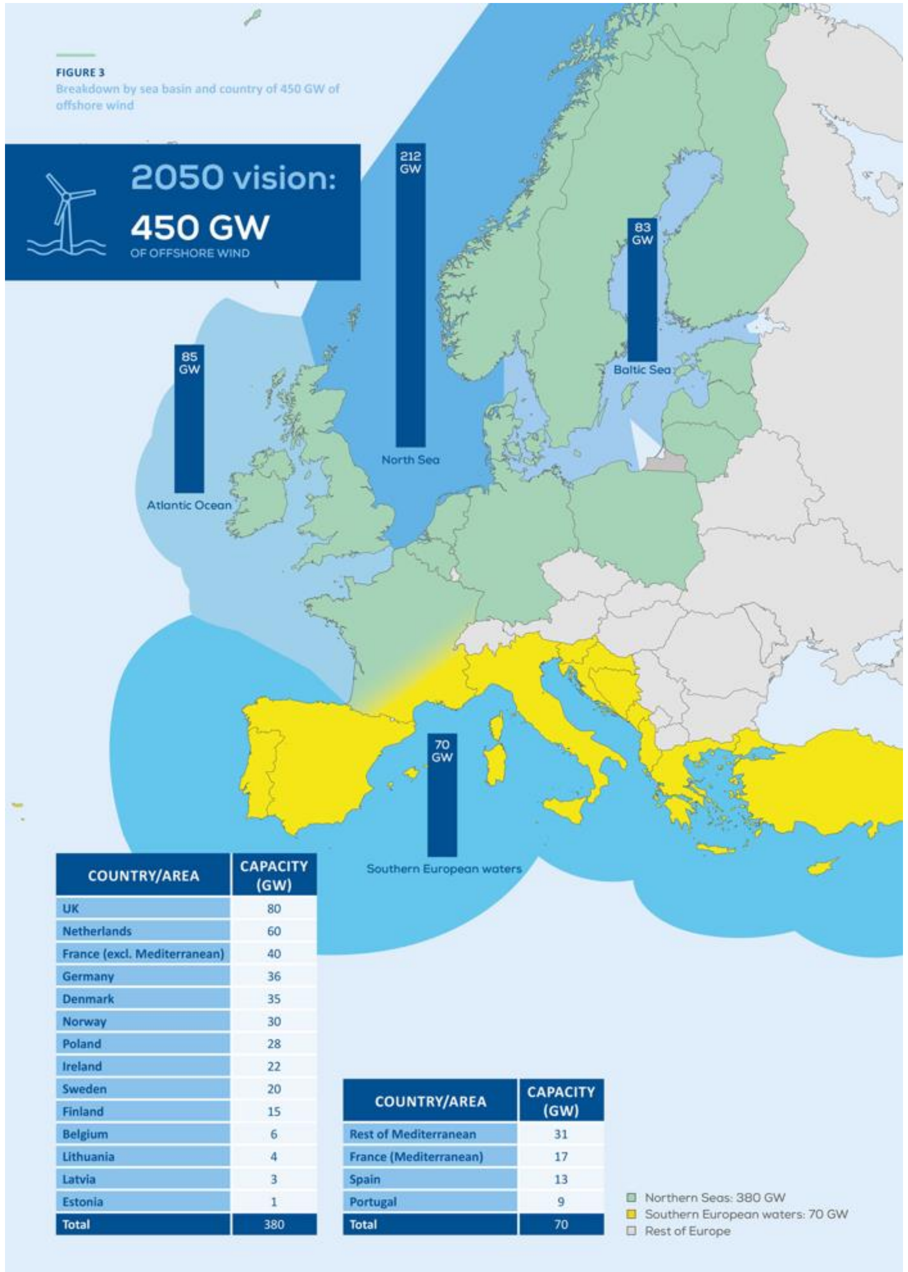
HVDC Light Converter Hall (Picture courtesy of ABB)

‘Towards HVDC Grids’ roadmap

Background

- Offshore wind energy is on the rise
  - About 25 GW of wind offshore installed to date in Europe
  - Expected increases up to 200 GW (300 GW) in the North Sea by 2050, 450 GW in total
- Connections are increasingly further from shore
  - HVDC becomes only realistic option
  - Meshing is needed
  - Needs to be integrated in the existing system (hybrid AC/DC)
- Towards a new backbone grid to integrate wind and solar
- HVDC/power electronics dominated systems behave fundamentally different compared to conventional AC systems
  - Planning, protection & controls

FIGURE 3
Breakdown by sea basin and country of 450 GW of offshore wind



COUNTRY/AREA	CAPACITY (GW)
UK	80
Netherlands	60
France (excl. Mediterranean)	40
Germany	36
Denmark	35
Norway	30
Poland	28
Ireland	22
Sweden	20
Finland	15
Belgium	6
Lithuania	4
Latvia	3
Estonia	1
Total	380

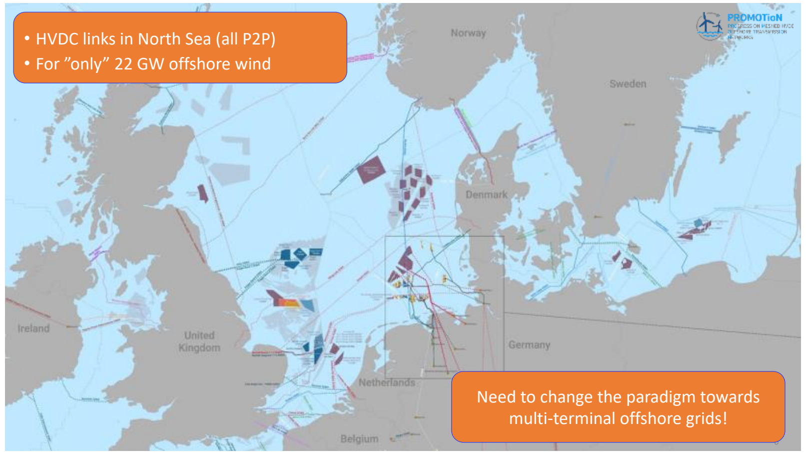
COUNTRY/AREA	CAPACITY (GW)
Rest of Mediterranean	31
France (Mediterranean)	17
Spain	13
Portugal	9
Total	70

Neptune

Energy Ville

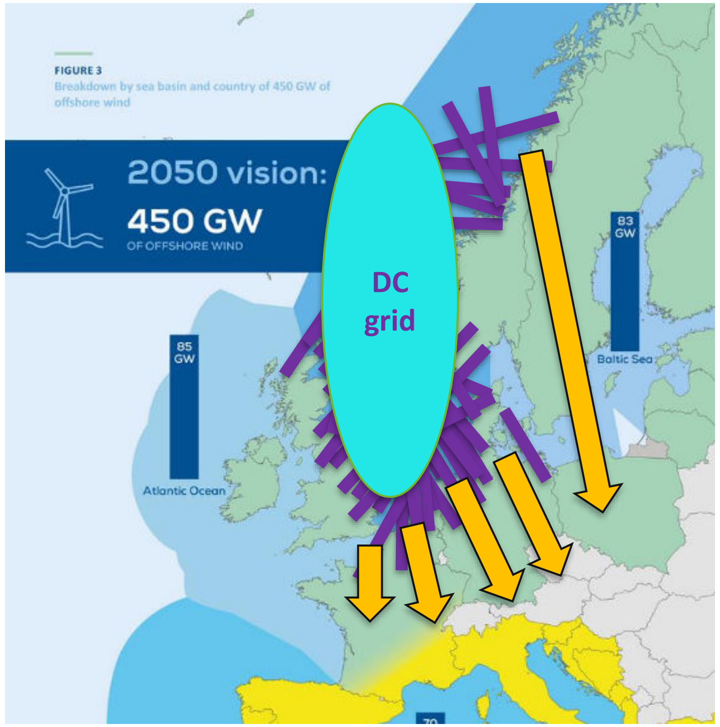
Research vision

From point-to-point connections…



HVDC is key technology for large-scale integration of renewable energy sources

towards meshed HVDC grids



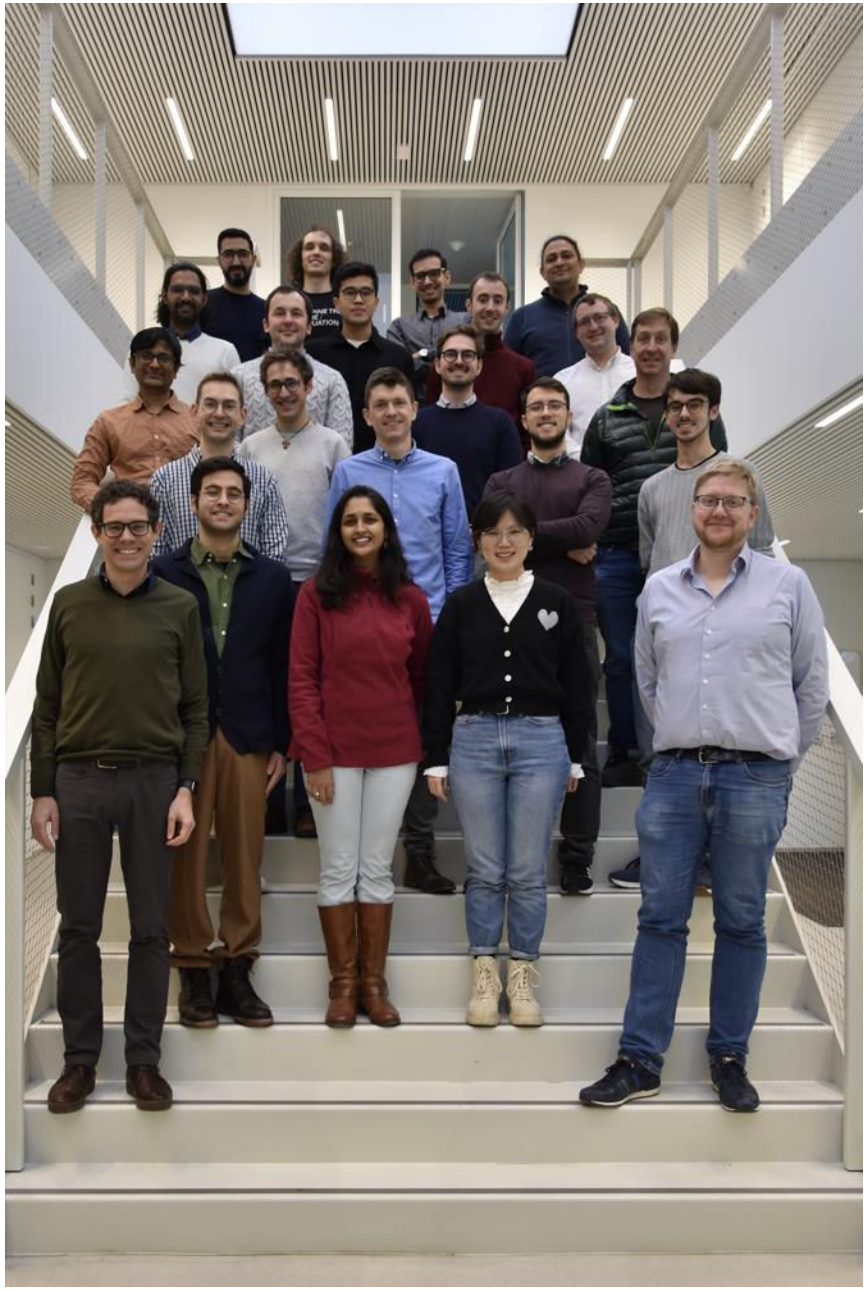
What do we see as the future?

TODAY	IN FUTURE
From point-to-point connections …	… to multi-terminal and meshed grids
Protection From conventional AC system protection …	… to fast-acting DC &AC system protection
Control From one manufacturer per link …	… to multi-vendor interoperability
Operation From HVDC as “assistance” for AC grid …	… to AC & HVDC grid as parts of same grid
Planning From HVDC as addon element…	… to HVDC (grids) directly included as potential grid element for grid expansion integrating all available “features”
Grid code From complying with AC system/TSO requirements …	… to complying with both AC and DC grid requirements in a multi-stakeholder environment

Towards HVDC Grids

3 research lines

- Models and tools for analyzing and improving control interactions with and within HVDC grids and links
- Algorithms, models and equipment for HVDC grids protection
- Models and tools for grid planning and operation including HVDC, while accounting for uncertainty, reliability and flexibility



Energy Ville

Roadmap for HVDC grid

Now-2030:

Multi-terminal hybrid connections

(no mesh)

2030-2035:

Offshore energy hubs

2035-2045:

Meshed offshore grids

First deep inland reinforcement

2045-:

EU-wide interconnection

Now-2030:

Underground cable at EHV when needed

2030-2040:

Underground cable at EHV when possible

2040-:

Only undergrounding

Offshore Innovation and Development Stages

Future challenges for planning and steady state operational models

Now-2030: Radial hybrid connections

2030-2035: Offshore energy hubs

2035-2045: Meshed offshore grids

2045-: EU-wide interconnection

Now-2030:

- Cross border ancillary service provision
- Value of / trade-offs with storage
- Extendability of hybrid connections
- Operational control models

2030-2035:

- Connection sizing considering offshore market design
- Connection sizing and reserve requirements
- Trade-offs between HVDC transmission and molecule transport
- Effect of large connections on system stability
- DC hubs vs AC hubs
- AC network reinforcements from the shores

2035-2045:

- Reliability & resilience of the offshore grid:
- Operational models for offshore RC centres
- Determination of actions in various system states and time frames
- Dynamic stability constrained operational models
- Dynamic firewalling, e.g., settings based on system state instead of pre-determined settings

2045-:

- System design for zero inertia grids
- AC network reinforcements with UGC
- Operational models for back-bone operators
- Determination of actions in various system states
- Dynamic stability constrained operational models
- How to do firewalling in a strongly interconnected system when DC grid becomes the “new AC”?

Offshore Innovation and Development Stages

Future challenges for power system control

Now-2030: Radial hybrid connections

- Grid-forming capabilities
- Mode switching compatible
- Converter passivity design
- Power system 'strength' characterisation
- Vendor control code in interaction studies (DLL)
- Next-gen computation tools for increased system size and detail
- Control of multi-terminal systems
- Improved cable models

2030-2035: Offshore energy hubs

- Control of multi-terminal DC infrastructure
- Control of parallel AC/DC infrastructure
- Multi-vendor compatibility
- Towards partially open control structures
- Functional specifications for AC and DC connection
- Systemwide converter limit characterisation
- Defining system characteristics based on network indicators

2035-2045: Meshed offshore grids

- Control of meshed DC systems
- Partially-open control philosophies
- Screening for inertial distribution in AC power system
- Impact on large-scale system stability
- Dynamic firewalling of HVDC infrastructure, e.g., settings based on system state instead of pre-determined settings
- Towards re-assessment of use of traditional power system tools

2045-: EU-wide interconnection

- System control for low-inertia grids
- Dynamic impact of network reinforcements with UGC
- Grid-of-Grids approach to power system control
- Dynamic impact of bulk power DC transmission
- How to do firewalling in a strongly interconnected system when DC grid becomes the "new AC"?

Offshore Innovation and Development Stages

Future challenges for power system protection

Now-2030: Radial hybrid connections

2030-2035: Offshore energy hubs

2035-2045: Meshed offshore grids

2045-: EU-wide interconnection

Now-2030:

- Define multivendor systems in R&D projects
- Functional requirements and specifications of DC protection systems
- Protection relay design and demonstration
- DC relay functional test set
- Functional test procedures towards standardisation
- AC and DC system co-design and towards more optimal systems

2030-2035:

- DC protection aware power system design
- Multi-vendor DC protection
- DC circuit breaker on market and installed in EU
- Strategies and industrial implementation of protection strategies
- Hybrid (OHL/cable) protection systems
- Digitisation of DC systems
- Key standardisation
- Automated testing procedures

2035-2045:

- Multi-vendor DC protection by design
- Towards expandable and reconfigurable networks
- DC protection/breakers as standard technology
- Tools for integrated AC/DC protection strategies and design
- AC and DC protection in converter dominated systems
- Interconnection between different protection strategies
- Expansion capable industrial systems

2045-:

- Freely expandable large scale multiterminal networks - towards a ‘supergrid’
- Protection and system design in zero inertia systems

NEPTUNE as corner stone

- NEPTUNE has resulted in a material increase in the fundamental research into HVDC grids
  - Focusing simultanuously on the three axes of planning and operation, protection and control

- Development of much-needed methodologies and tools
  - These tools have become building blocks for our follow-up projects

NEPTUNE as enabler

- Enabler for a generation of young researchers
  - Over 50 junior and senior reseachers have been building highly sought-after skills for offshore HVDC grids
- Enabler for fundamental research into HVDC grids
  - Build-up of key competences, set-ups and tools
- Enabler for ongoing research
  - Stepping stone for other activities within wider R&D roadmap

NEPTUNE as accelerator

- Accelerated the research in the roadmap requiring public funding
  - Acceleration of in-depth knowledge gathering
  - Acceleration of building up-to-date lab infrastructure
  - Acceleration in skill development
- The NEPTUNE project has been an accelerator for new HVDC grids research at EnergyVille
  - Fundamental insights from NEPTUNE have found their way into new projects

Towards valorisation

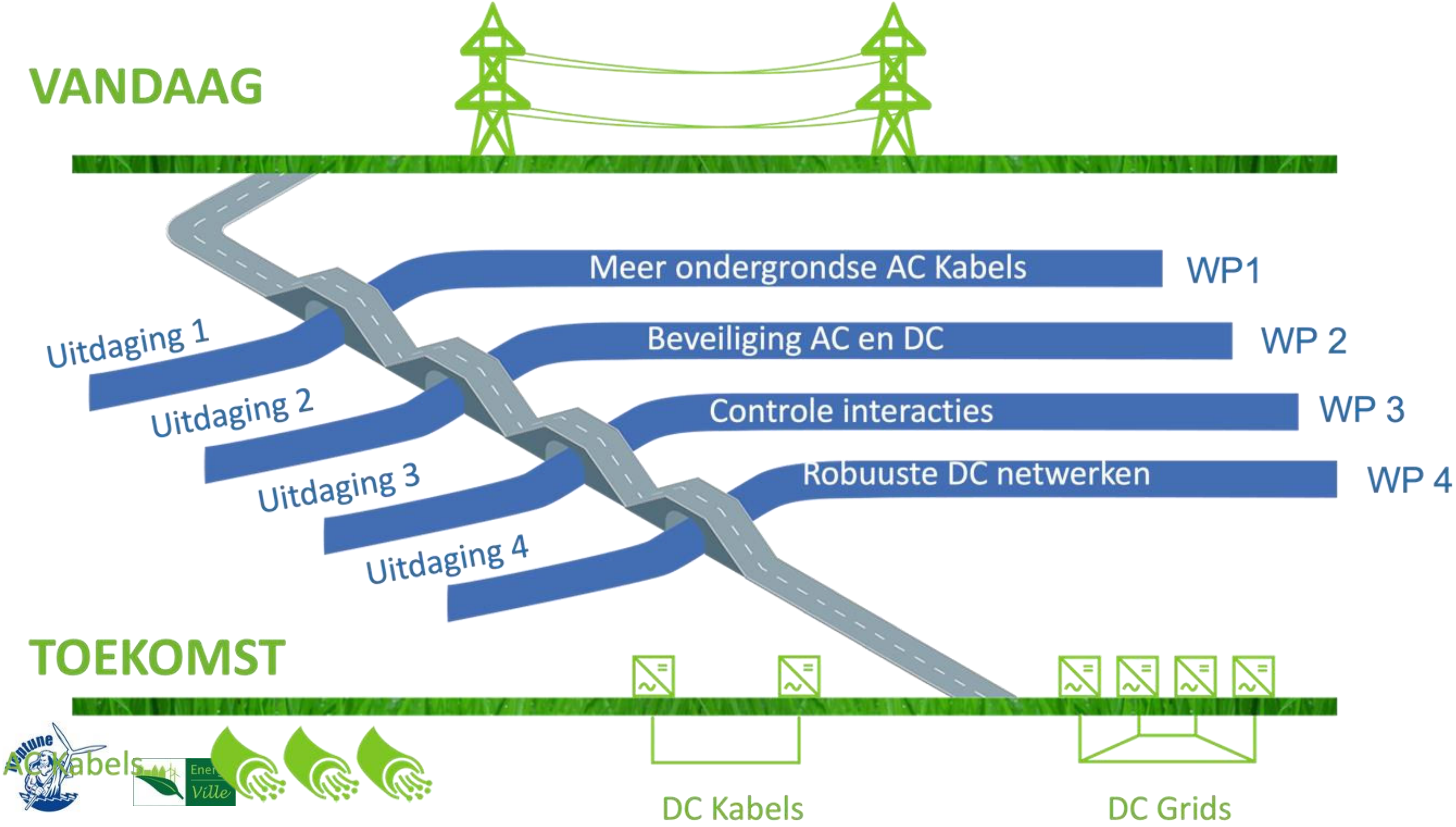
- The fundamental knowledge acquired within Neptune has been key to start new projects on HVDC
  - Over 20 follow-up projects have already resulted from Neptune
    - Long-term and short-term bilateral projects with OEMs and TSOs
    - Publicly funded follow-up projects with industry involvement

HVDC & Cable Competence Centre (HC3)

Innovative solutions for underground high-voltage grids

- Research + investment budget

- Develop international competence centre
- Centered on R&D roadmaps
- Professional operation
- Technology watch
- Workshops and training
- Link with industry


VANDAAG
Meer ondergrondse AC Kabels
WP1
Uitdaging 1
Beveiliging AC en DC
WP 2
Uitdaging 2
Controle interacties
WP 3
Uitdaging 3
Robuuste DC netwerken
WP 4
Uitdaging 4
TOEKOMST
AC Kabels
DC Kabels
DC Grids

Thank you for your attention!

jef.beerten@kuleuven.be

With the support of the Energy Transition Fund

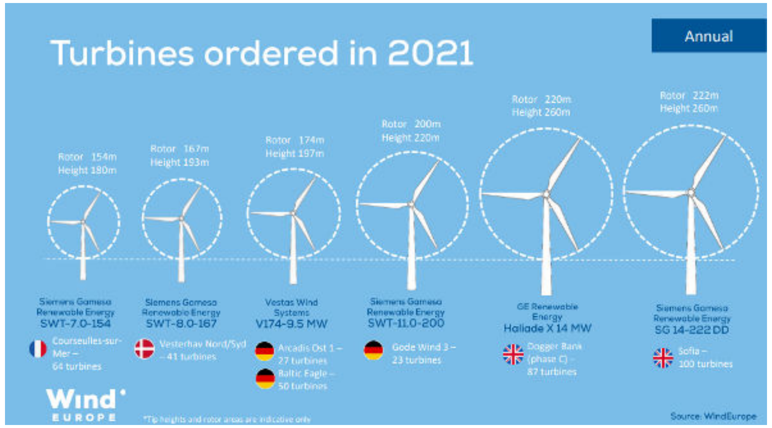
Nicolaos A. Cutululis

To HVDC or not to HVDC?

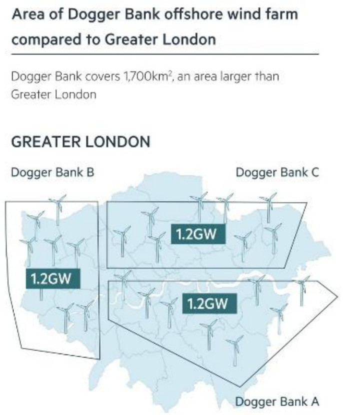
Main message….

Offshore wind

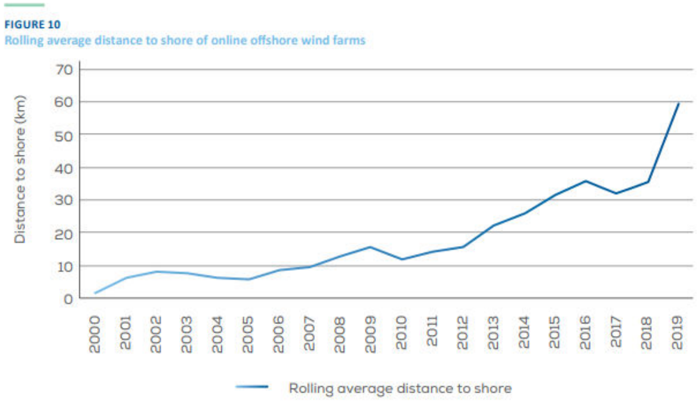
Bigger



Larger

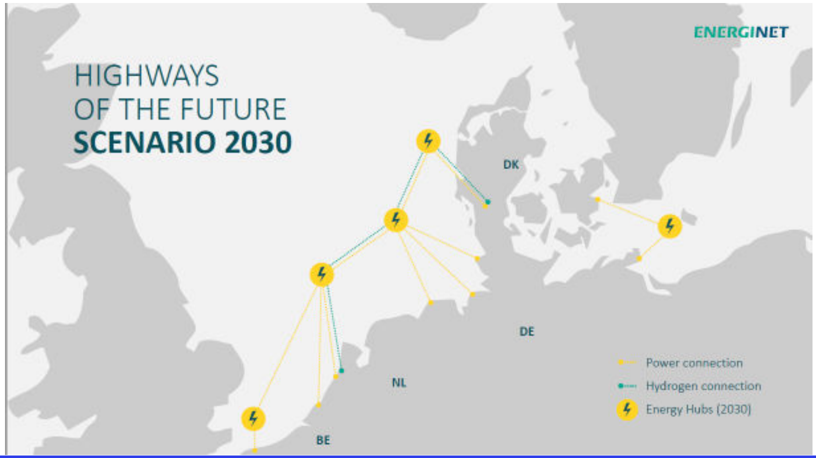


Further



Source: WindEurope

Offshore grids and hubs



Where do we need to go?

Ambitious goals

- 300-> 450 GW of offshore wind by 2050
  - +/- 35 GW of wind offshore installed to date (2/3 in Europe)
  - ±100 GW by 2030
  - North Sea: 200 GW by 2050
  - Solar will see similar developments
- Offshore requires massive investments (EC: **2/3rd of 800 Billion by 2050**)
- 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

Source: Prof. Van Hertem

We need to connect 200 GW from the north sea

➔ Assume 5 GW links

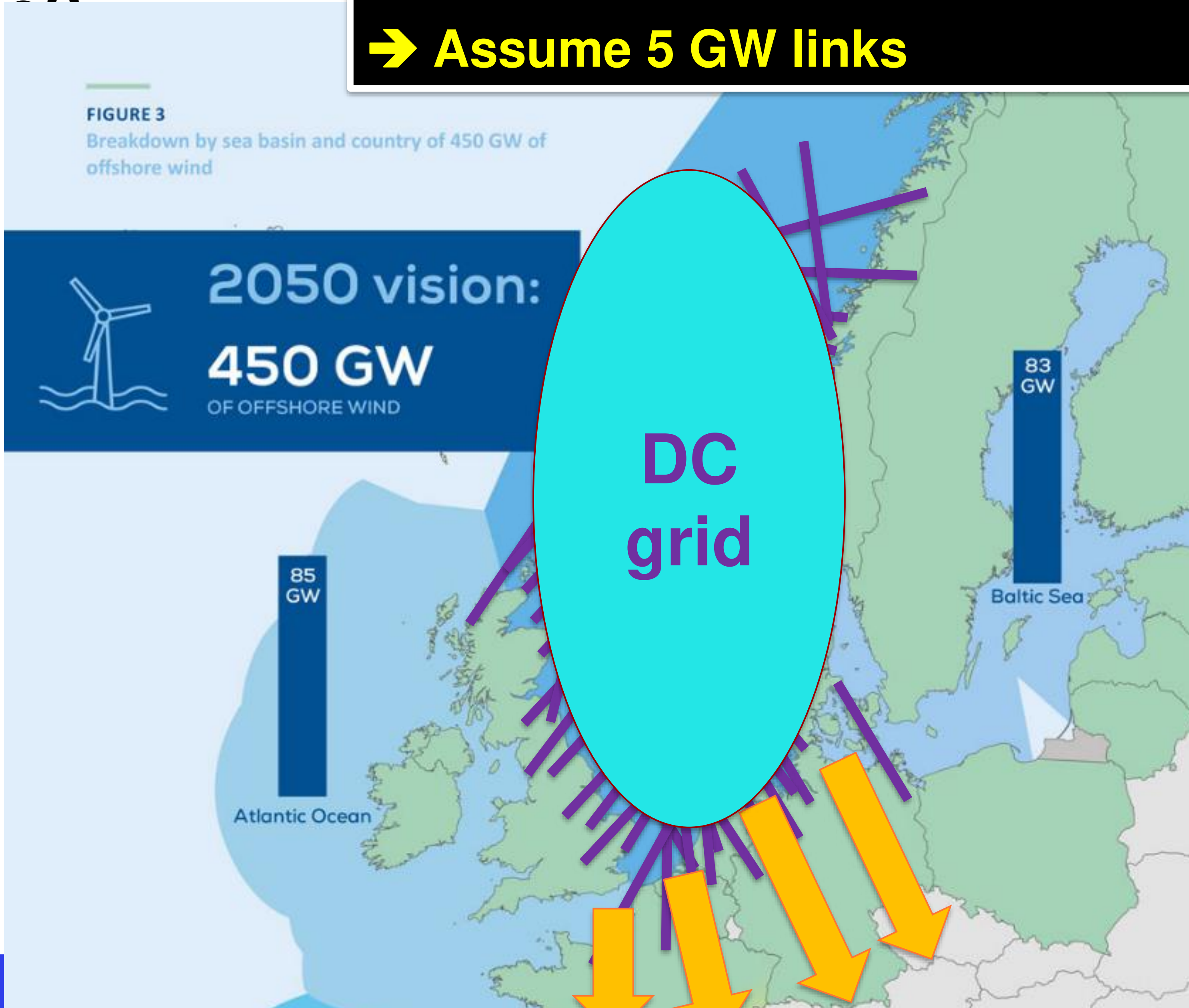


Figure: WindEurope

Offshore grids with hubs/islands

February 2020

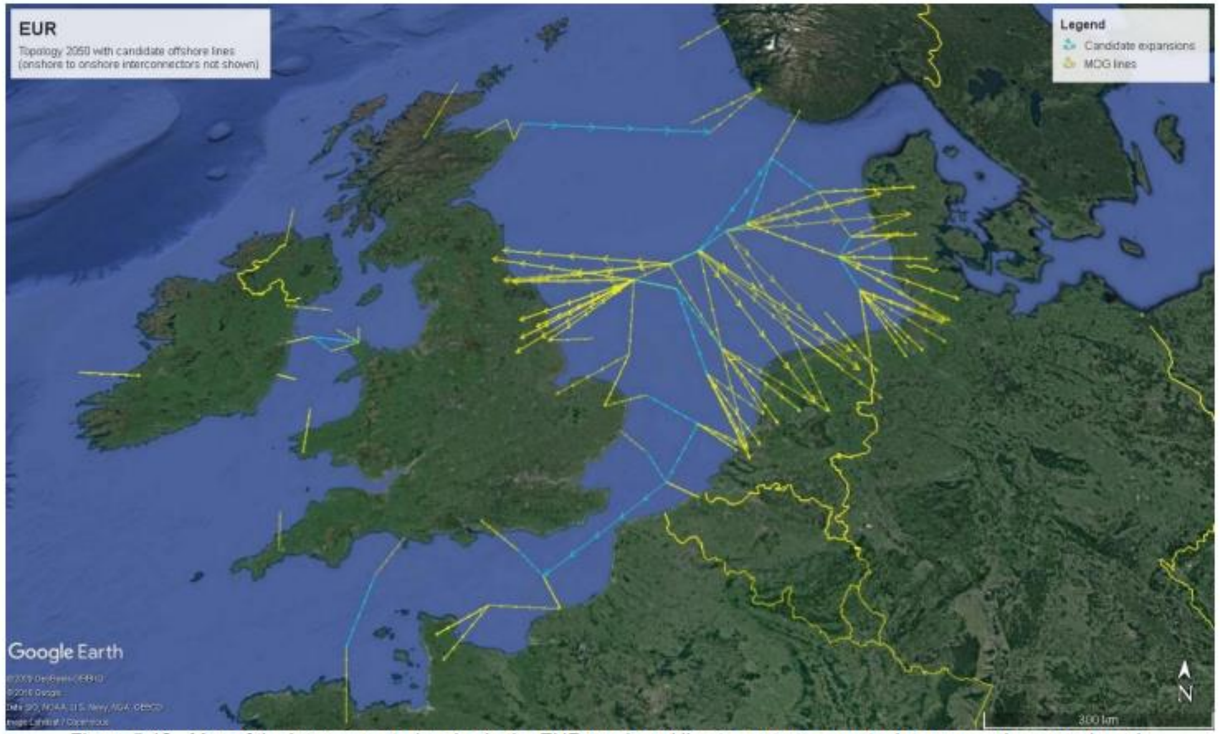
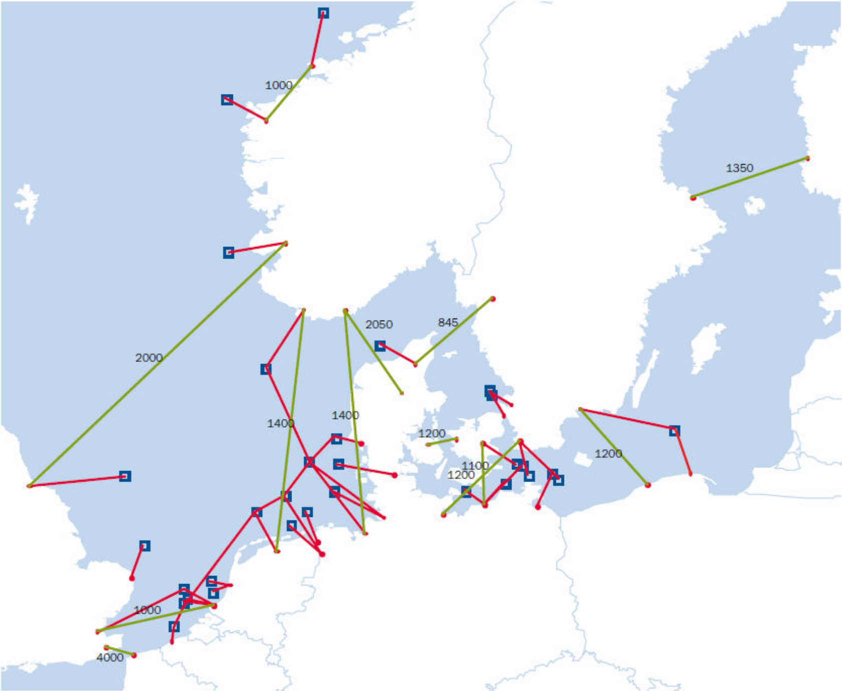


Figure 5-12 - Map of the interconnected nodes in the EUR topology (direct country-to-country interconnections not shown).

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

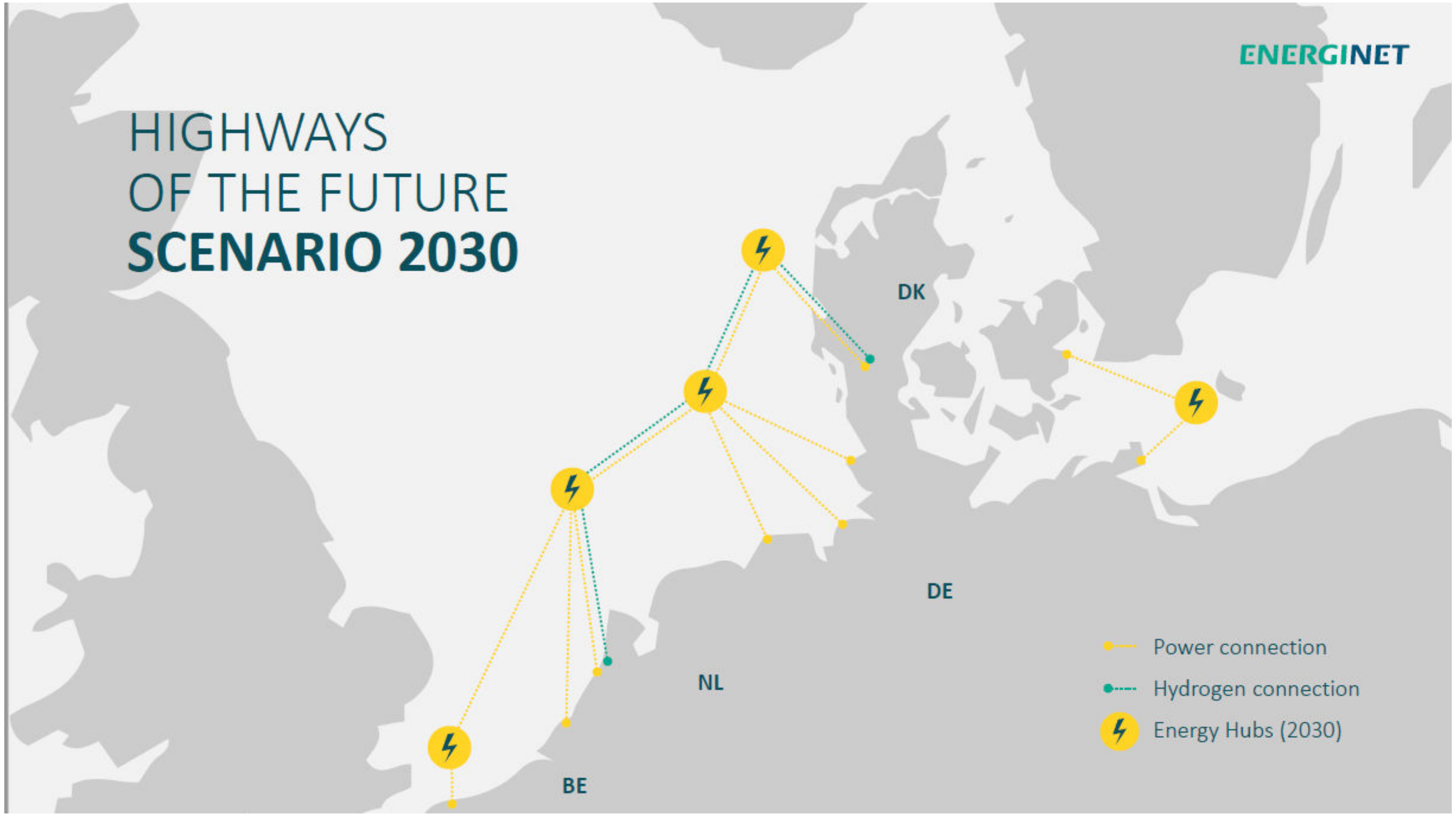
February 2009

FIGURE [22]: Possible meshed HVDC (meshed 2) connection of offshore wind farms. Dotted lines are HVDC interconnectors. NorNed2 and NorGer are replaced by a HVDC connections between Norwegian and German offshore wind farms.



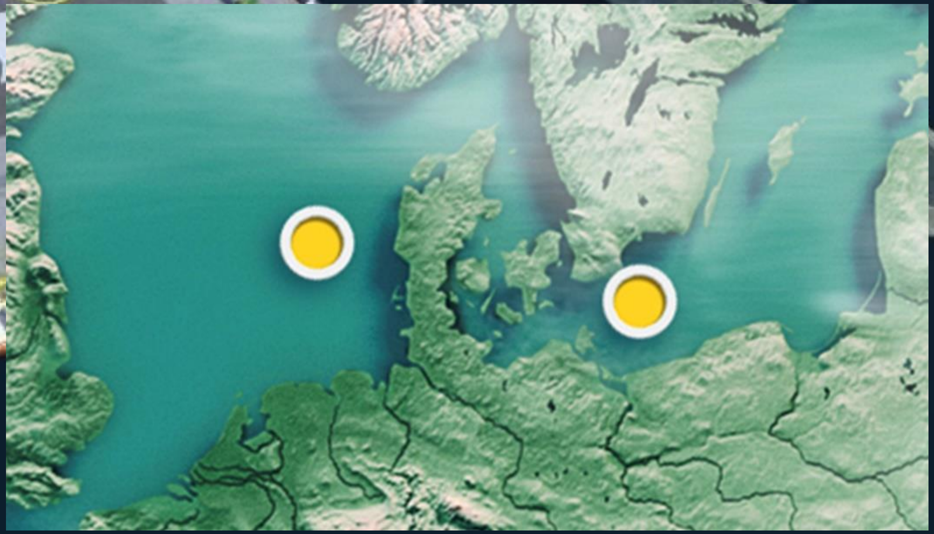
TradeWind

First steps towards an offshore HVDC grid



Source: Energinet

Wind on energy islands



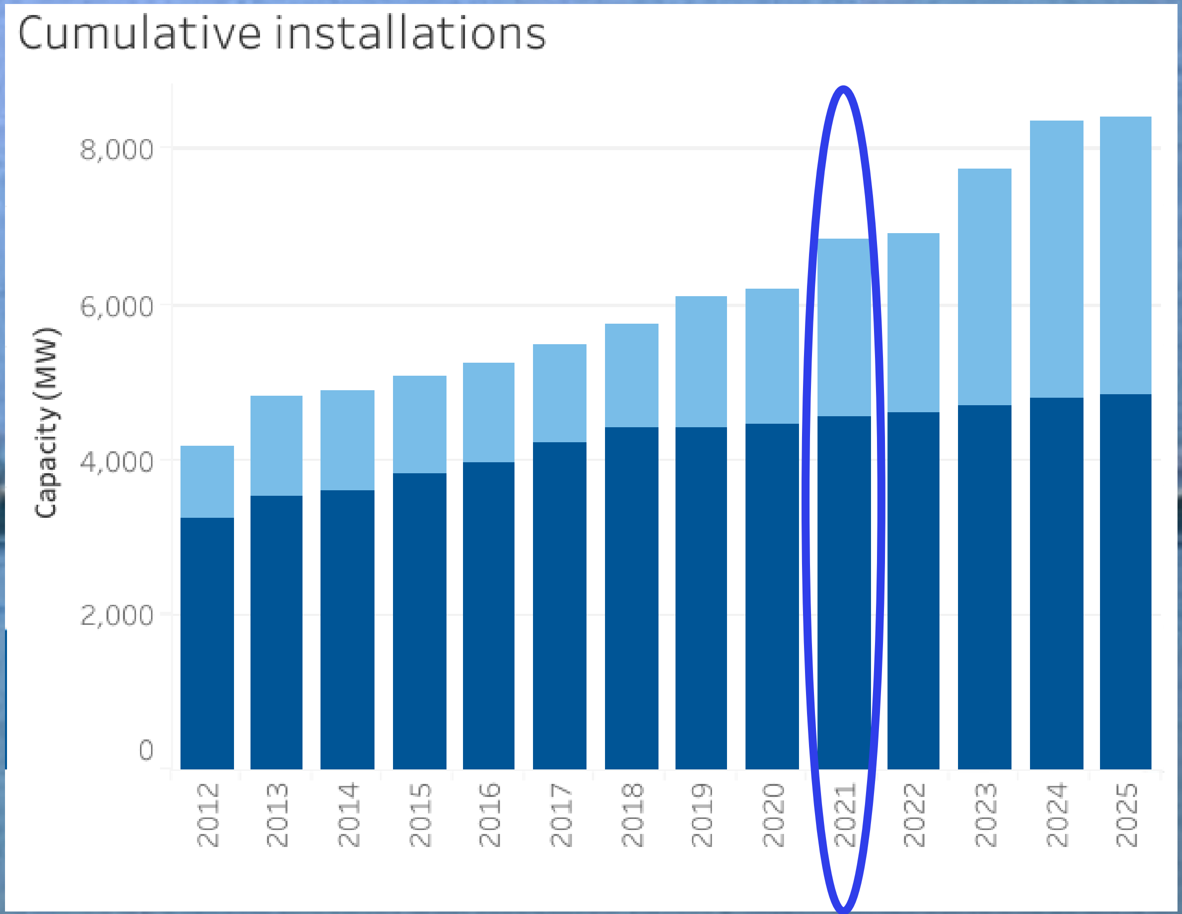
- Baltic Sea – on the existing island of Bornholm
- North Sea – app. 80 km from the west coast of Denmark

North Sea Energy Island – 10 GW

The Energy Islands – A Mars mission for the Danish Energy system?

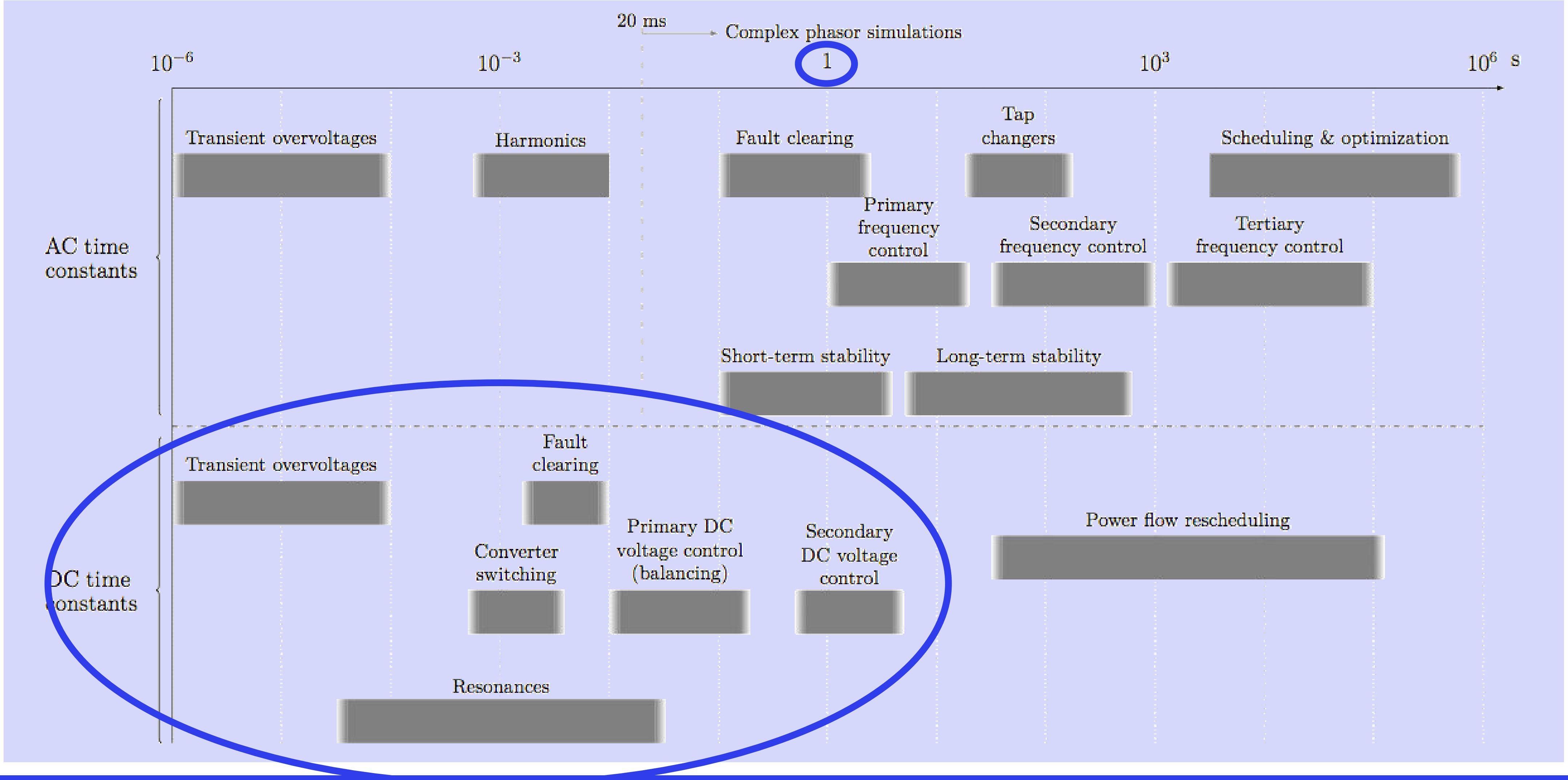
Let us look at the facts

Wind in Denmark



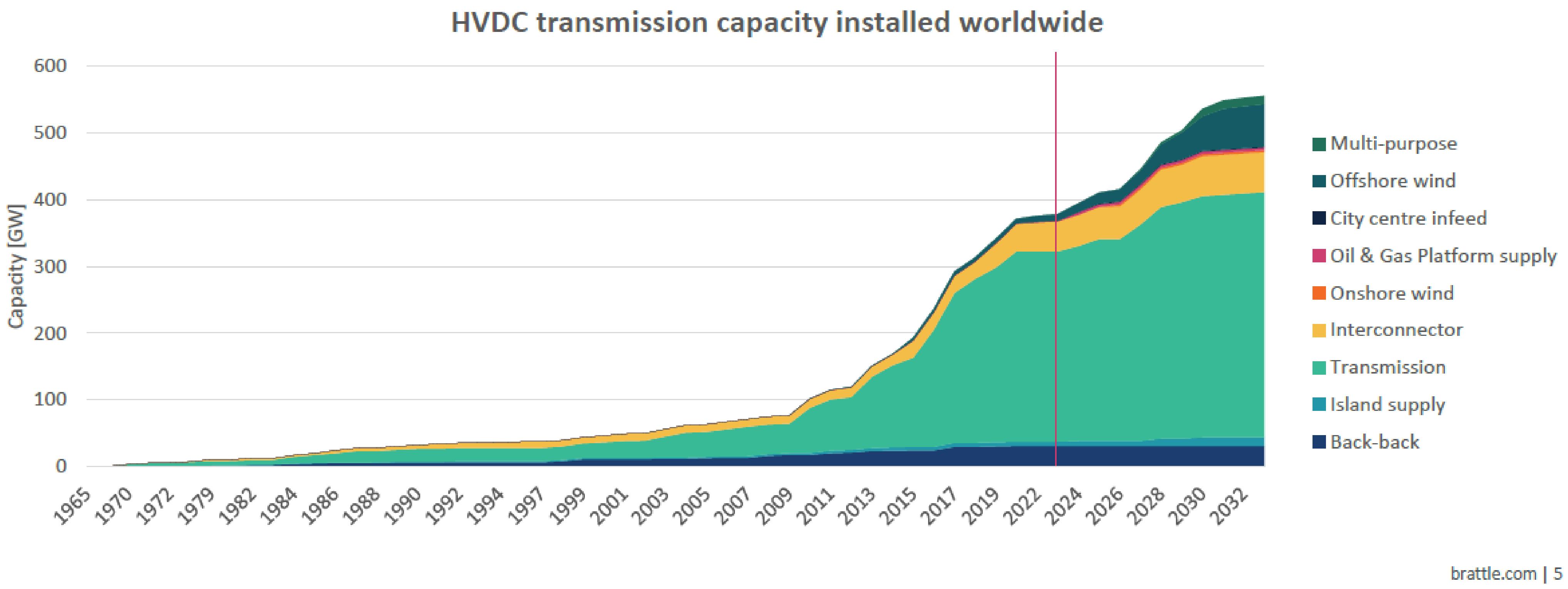
Zaporizhzhia nuclear power plant – 5.7 GW

An electron metropolis



Source: Jef Beerten, KU Leuven

…but not only offshore wind



Source: Bratte & DNV

HVDC onshore - Germany

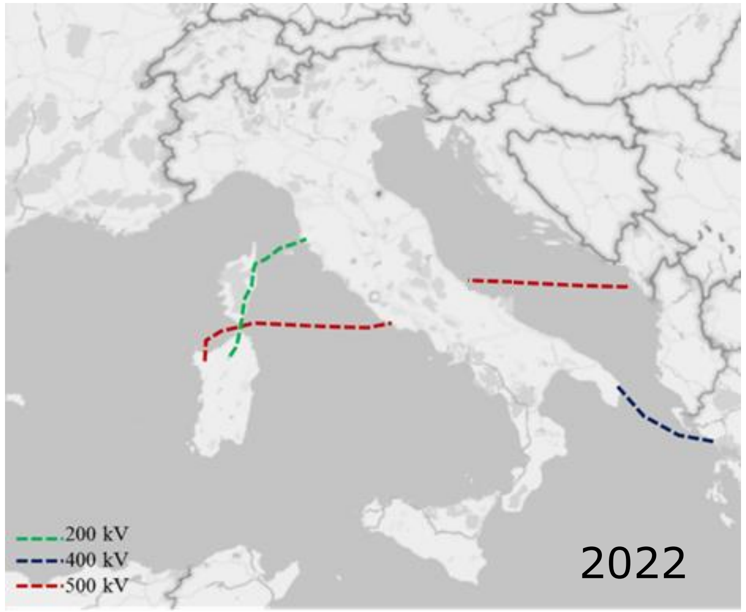
- **SuedOstLink** - 4 GW underground (2027)
- **SuedLink** - 2+2 GW underground (2028)
- **A-Nord** – 2 GW underground (2027)
- **Ultranet**: 2 GW converts AC overhead (2027)

Multi-terminal VSC HVDC

HVDC onshore - Italy

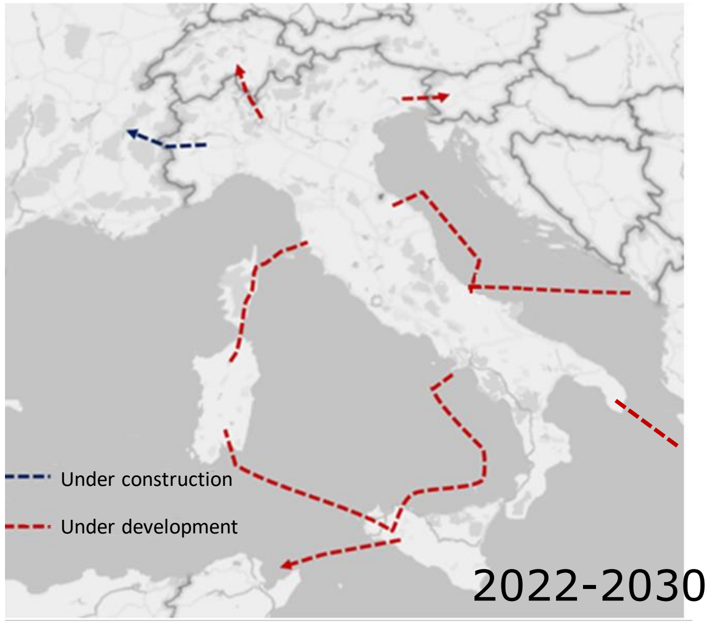
Current HVDC links in operation in Italy

(source: AEIT paper)



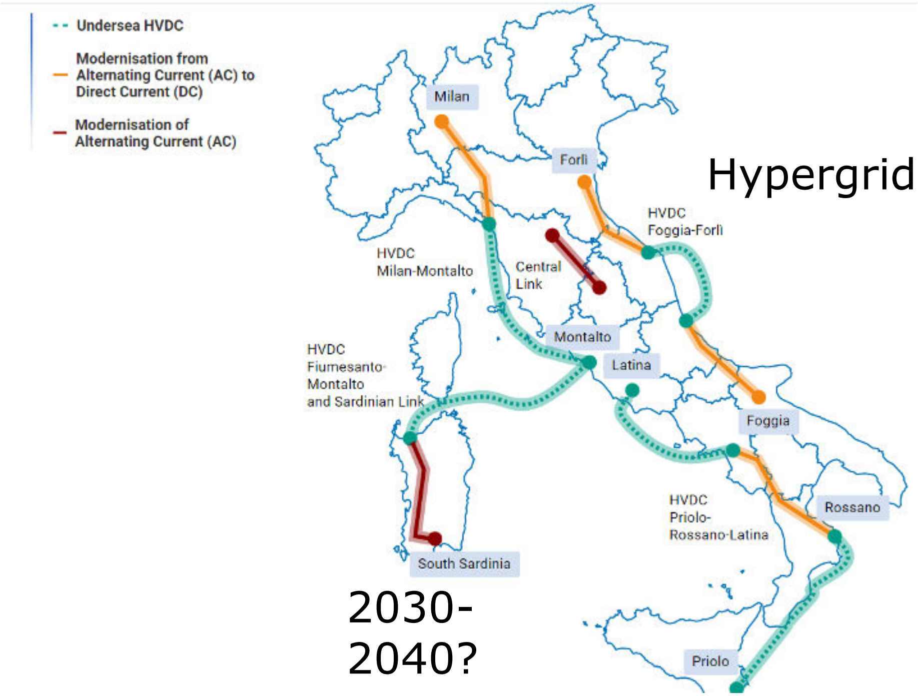
Further planned and potential HVDC links in Italy

(source: AEIT paper)



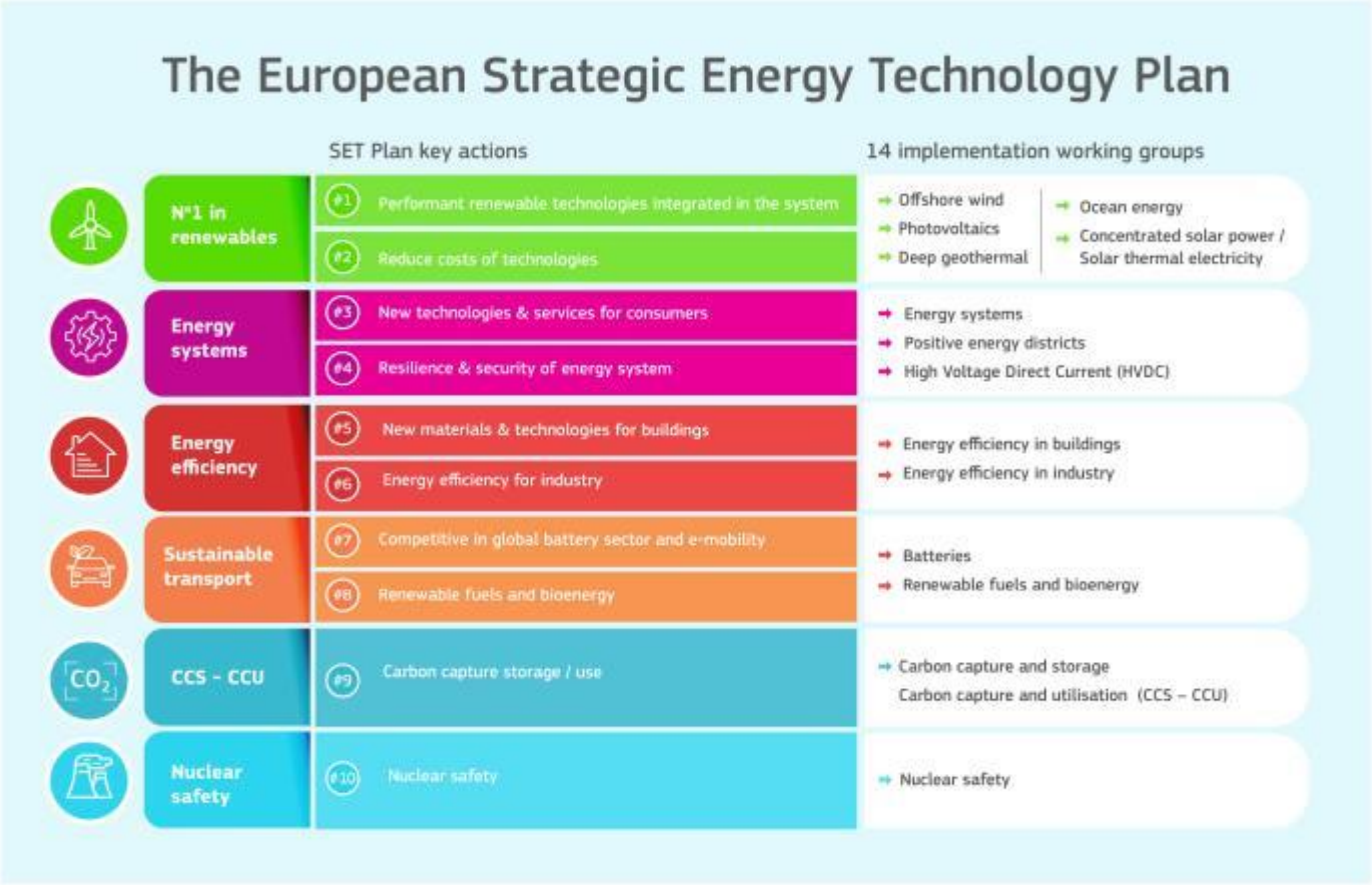
New long-term HVDC corridors in Italy

(source: Terna, PdS 2023)



SET Plan IWG HVDC and DC technologies

HVDC as Strategic Energy Technology in Europe



HVDC grid ambition levels

2027

Short term

- An operable multi-terminal, multivendor HVDC system in Europe (e.g. hybrid interconnector)
- Top-down orchestration of HVDC grid planning, enabling an efficient step-wise organic development of future HVDC grid system pieces

2030–2035

Medium term

- Multi-terminal, multivendor HVDC system is cost-effective solution for large offshore projects
- Multi-terminal multivendor HVDC system for onshore ready

2050

Long term

- Backbone grid (integrating smaller systems)
- HVDC available for deep sea applications

Research directions

- **Technology**
  - Converters, Cables, Power electronics, Other
- **Control and protection**
  - Multi-vendor interoperability, open controls, grid forming mode, AC side protection, DC side protection, firewalling…
- **Operation**
  - Control rooms, Congestion management, balancing, reliability…
- **Planning**
  - System expansion planning with HVDC
  - Cross-border investment planning for backbone application
- **Economics (Market integration)**
  - Ancillary services integration,…
- **Regulation and governance**
  - ISO – TO, offshore bidding zones,…
- **RES integration**
  - Offshore wind, Large-scale RES,…
- **Social and Enviromental**
  - Adhere to circular economy principles & be well accepted in communities

Core to the TWG activities

Supportive/ enabling of the TWG activities

Implementation plan – short term actions

Technology

- Converters (and other components such as DC breakers, GIS, etc)
- Cable systems
- Further development of Wide Band Gap (WBG) materials.
- Conversion technics and standards of HVAC overhead lines to HVDC

Control & Protection

- Multi-vendor interoperability
- Grid forming capabilities HVDC systems and DC connected wind plants
- Components and interfacing for AC & DC side protection system design
- Techno-economic benefits of HVDC converters in acting as a firewall

Operation

- Software tools for AC/DC hybrid systems (online power flow calculation, stability assessment)
- Methods for balancing & reserves sharing over MT HVDC
- Operational models and tools to accommodate different governance

Planning

- Operation principles for large HVDC grid system assets (off-shore, on-shore, off-on-shore)
- Methods and tools for combined system (HVAC and HVDC) expansion

Implementation plan – medium term actions

Technology

- Converters – cost efficient & standardized HVDC blocks
- O&M to reduce operational costs of HVDC systems
- DC-DC converters and DC power flow control technologies
- Development of subsea components for deep sea HVDC
- Development high voltage, industry grade WBG

Control & Protection

- Demonstration of grid forming control at system level & assessment of its impact on the stability of the connecting AC system.

Operation

- Implementation of methods & tools for stability management in hybrid AC-DC power system
- Recommendations to network codes for HVDC grids

Planning

- Back-to-back HVDC applications for internal continental AC grid segmentation
- Definition and agreement on HVDC-based high power corridors
- Environmental Impact assessment of HVDC life-cycles

Implementation plan – long term actions

Backbone HVDC grid covering offshore and onshore (integrating smaller systems)

Contacts

Nicolaos A. Cutululis

Technical University of Denmark

niac@dtu.dk

Dirk Van Hertem

KU Leuven

dirk.vanhertem@kuleuven.be

HVDC Implementation plan

To repeat… TO HVDC

DTU

Panel Discussion

Prof. Dirk Van Hertem

Prof. Jef Beerten Dr. Mian Wang

Dhr. Tom Pietercil Prof. Nicolaos A. Cutululis