multiDC: Controlling the power flows

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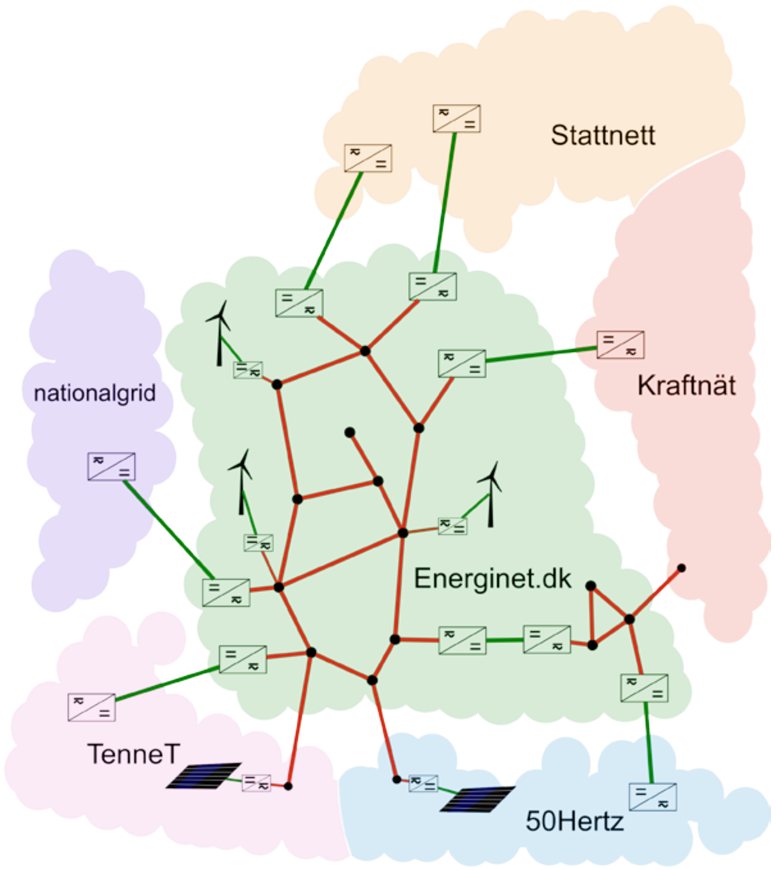
Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids

- Innovation Fund Denmark Grand Solutions
- Partners:
  - **Two neighboring TSOs**: Energinet, Svenska kraftnät
  - **Three universities**: DTU, KTH, Univ. of Liege
  - **One major manufacturer**: ABB
  - Advisory Board: RTE, Nordic RSC
- **25.7 million DKK**
- **4 years**; Start May 1, 2017



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Three main drivers

- 100% renewables
  - Varying/zero inertia systems
  - North Sea Wind Power Hub

- 100% inverter-connected devices
  - How is stability and operation affected?
  - How to model them?

- HVDC Grids

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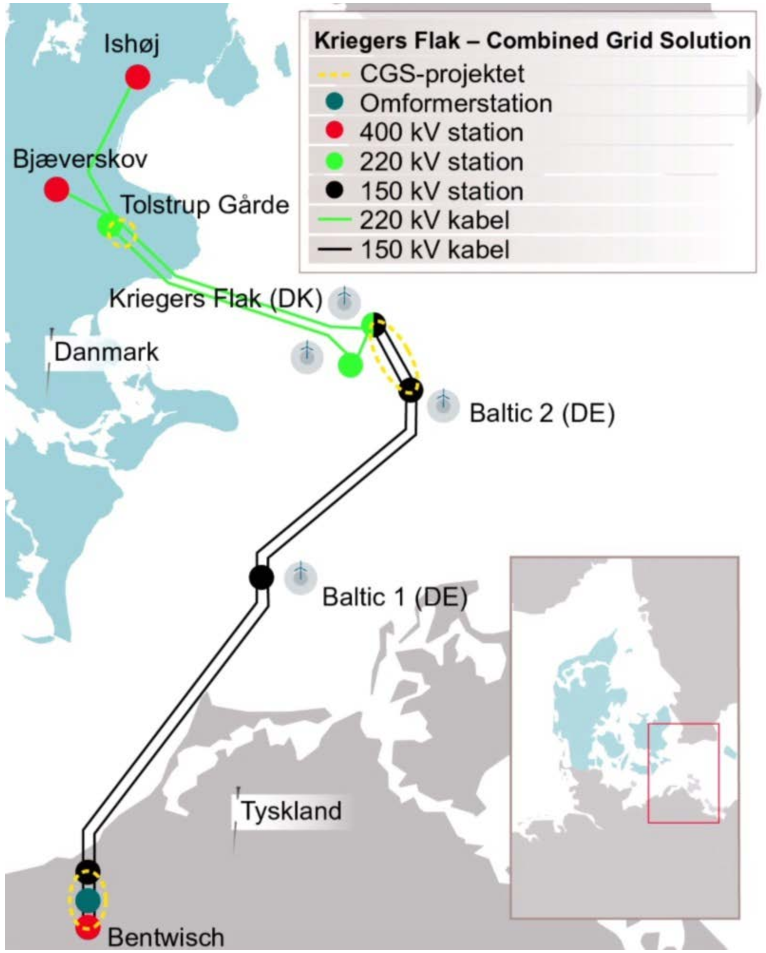
Kriegers Flak

- Denmark – Germany: AC+HVDC
- First interconnection **in the world** that integrates off-shore wind farms along its path
- 400 MW Back-to-Back HVDC
- Wind Farm Kriegers Flak (DK) : 600 MW
- Wind Farm Baltic (DE) : 336 MW
- HVDC Master Controller to:
  - Control voltage
  - Avoid overloadings
  - Ensure market outcome by mitigating wind forecast errors



North Sea Wind Power Hub

- Construction of island(s) in the middle of the North Sea
- Integration of up to 150 GW of off-shore wind farms
- HVDC interconnections to Denmark, Germany, the Netherlands, UK, Great Britain, Norway, Belgium
- Coupling the energy markets
- Agreement between Denmark, Germany, and the Netherlands already signed (2017)

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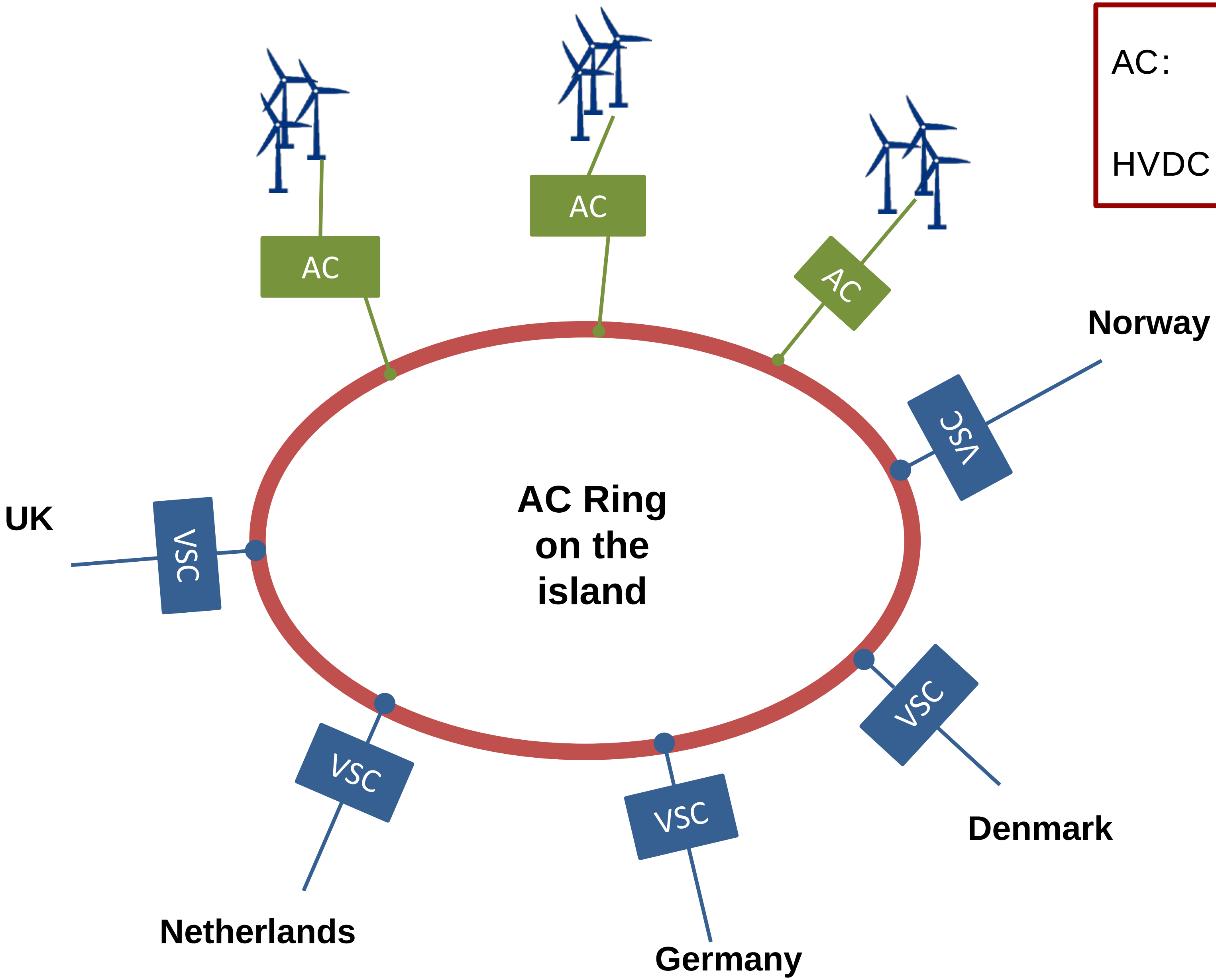
How will the wind farms be connected to the island?

How will the island be connected to the mainland?

These are still open questions

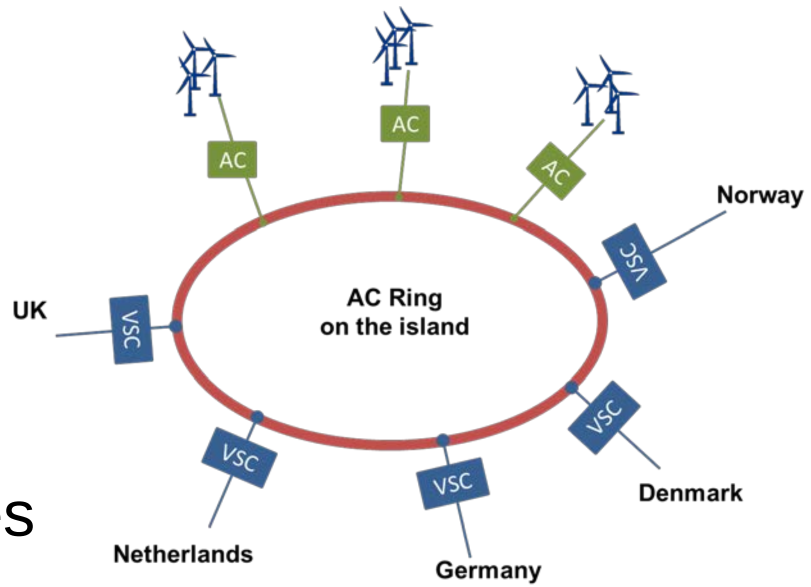
AC: Low-frequency AC

HVDC: Point-to-point HVDC



Challenges and Opportunities

- Zero-inertia AC Ring
  - Fast transients
- Coordination of the control of the VSC converters
  - Grid-forming shared among the converters?
  - Dealing with failures (N-1)
- Sharing wind power among the countries
  - Ownership of wind farms
  - Do we need to adapt the market structures?



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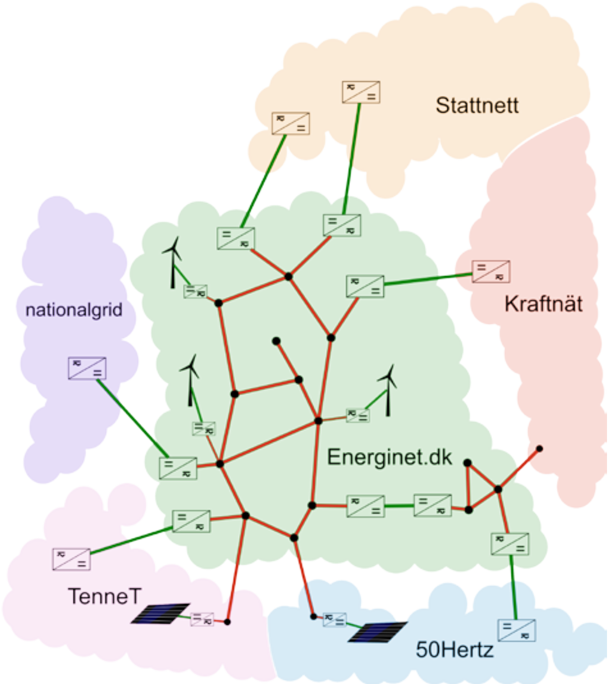
Addressing current challenges while preparing for the North Sea Wind Power Hub



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The three pillars of multiDC

Stability of zero-inertia systems

Coordinated control of multi-area AC/DC systems

Market integration of meshed HVDC connections

Implementation at PowerlabDK

PowerLabDK

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Stability of zero-inertia systems: multiDC contributions (May 2017-*current*)

- Robust frequency control for varying inertia systems
- Open-source VSC-HVDC model and analysis
  - Grid supporting VSC to weak AC grid
- Zero-inertia systems:
  - **Investigate operation at frequencies different from 50 Hz**
  - Identify gains that affect stability and propose alternatives

Misyris, Chatzivasileiadis, Weckesser, *Robust Frequency Control for Varying Inertia Power Systems,* ISGT Europe 2018, link to paper

Misyris, Guyennet, Chatzivasileiadis, Weckesser, *Grid Supporting VSCs in Power Systems with Varying Inertia and Short-Circuit Capacity*, accepted at IEEE Powertech 2019

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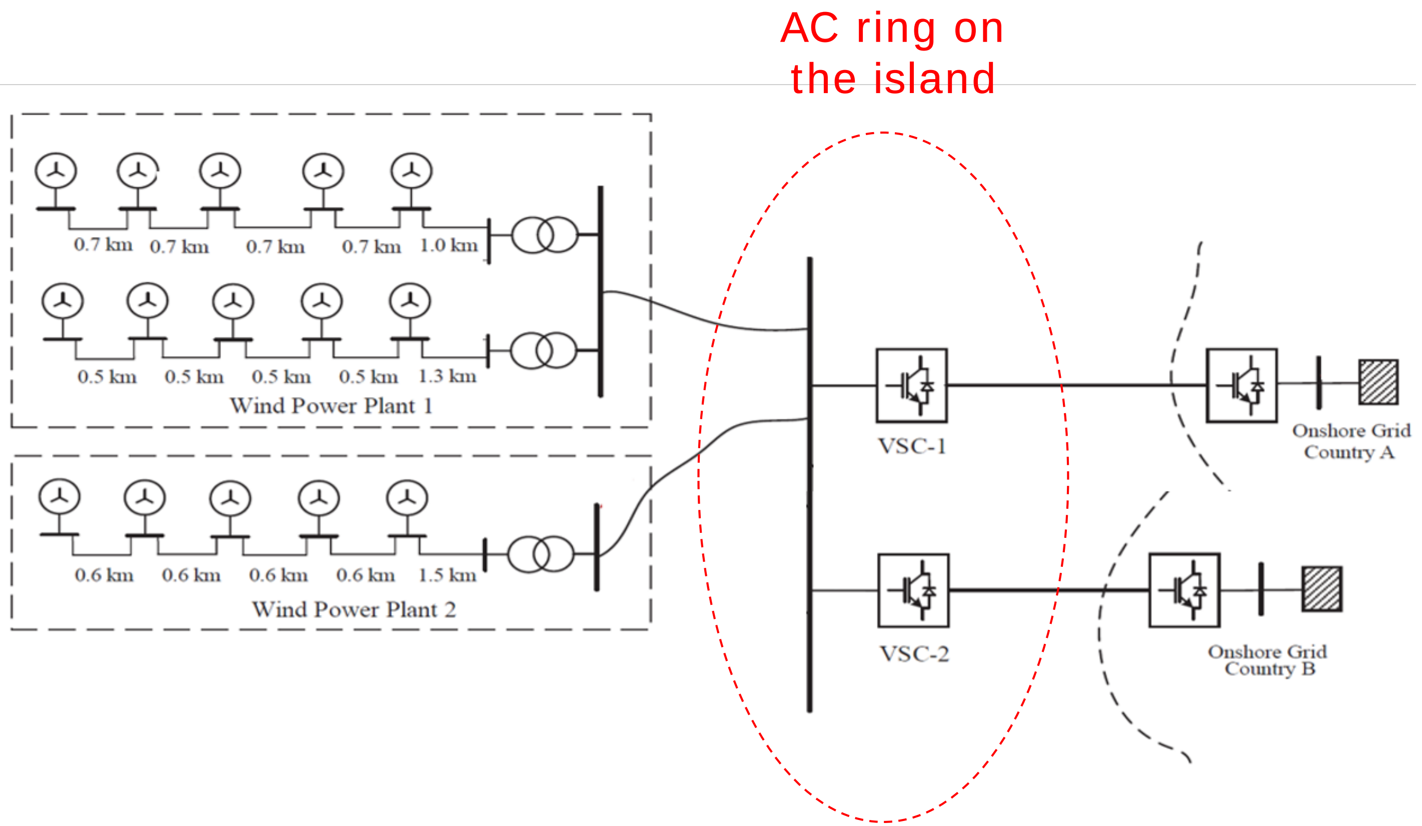
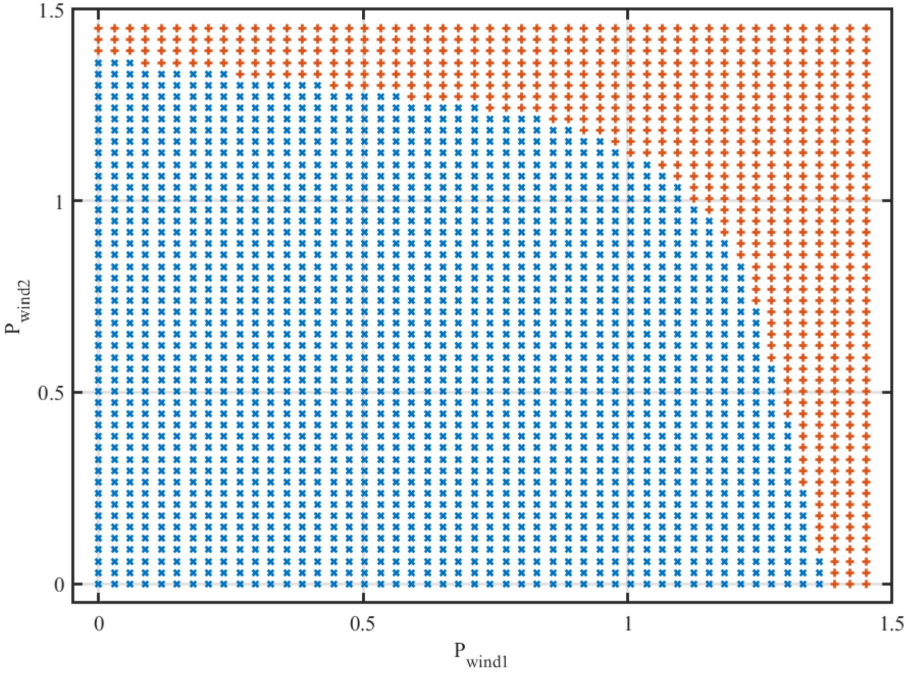
System Configuration – Zero Inertia

- Offshore AC network
  - Wind generation Voltage Source Converters
  - Offshore Voltage Source Converters
- Onshore Voltage Converters
- Steady-state and small-signal stability analysis

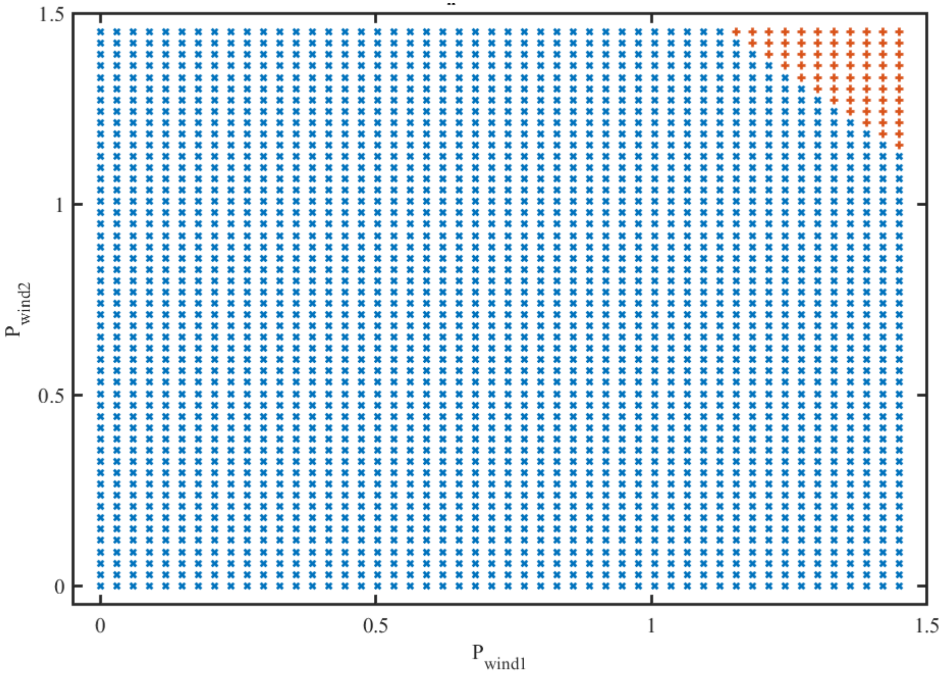


Stable and unstable operating region

50 Hz

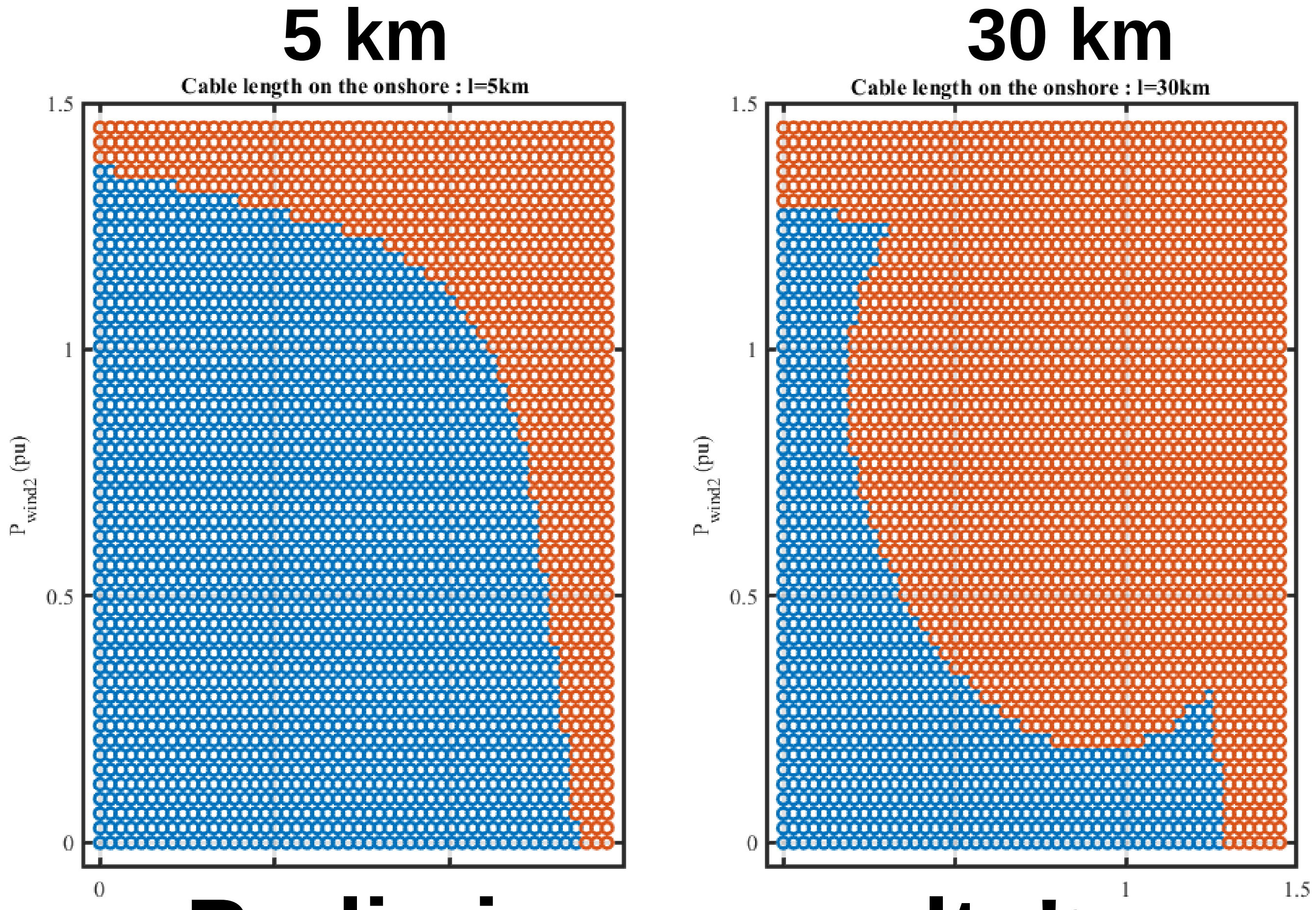


16.67 Hz



- The stable operating region increases when the offshore system operates at lower frequency

Impact of cables length on the small-signal stability limit – f_n = 50 Hz



Given the same control settings

- **Increase of cable length decrease** the small signal **stability limit** of the system

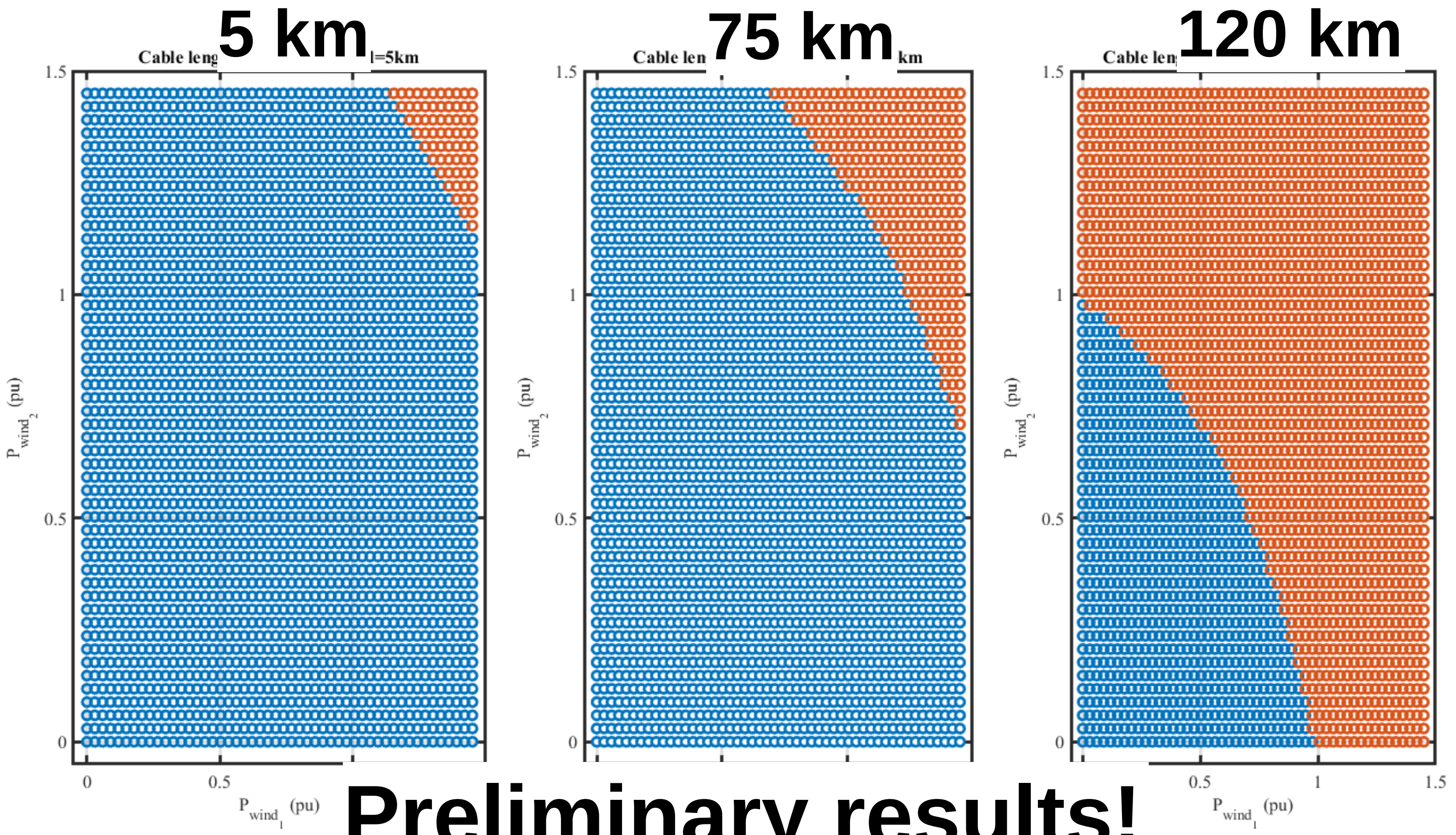
- Additional **filters** are required **to improve** the **minimum damping ratio** of the system

Preliminary results!

Impact of cables length on the small-signal stability limit – f_n = 16.67 Hz

Given the same control settings

- Increase of cable length **slightly reduces** the small signal stability limit of the system
- **Longer distances** between the wind farms **can be achieved**
- Cost reduction



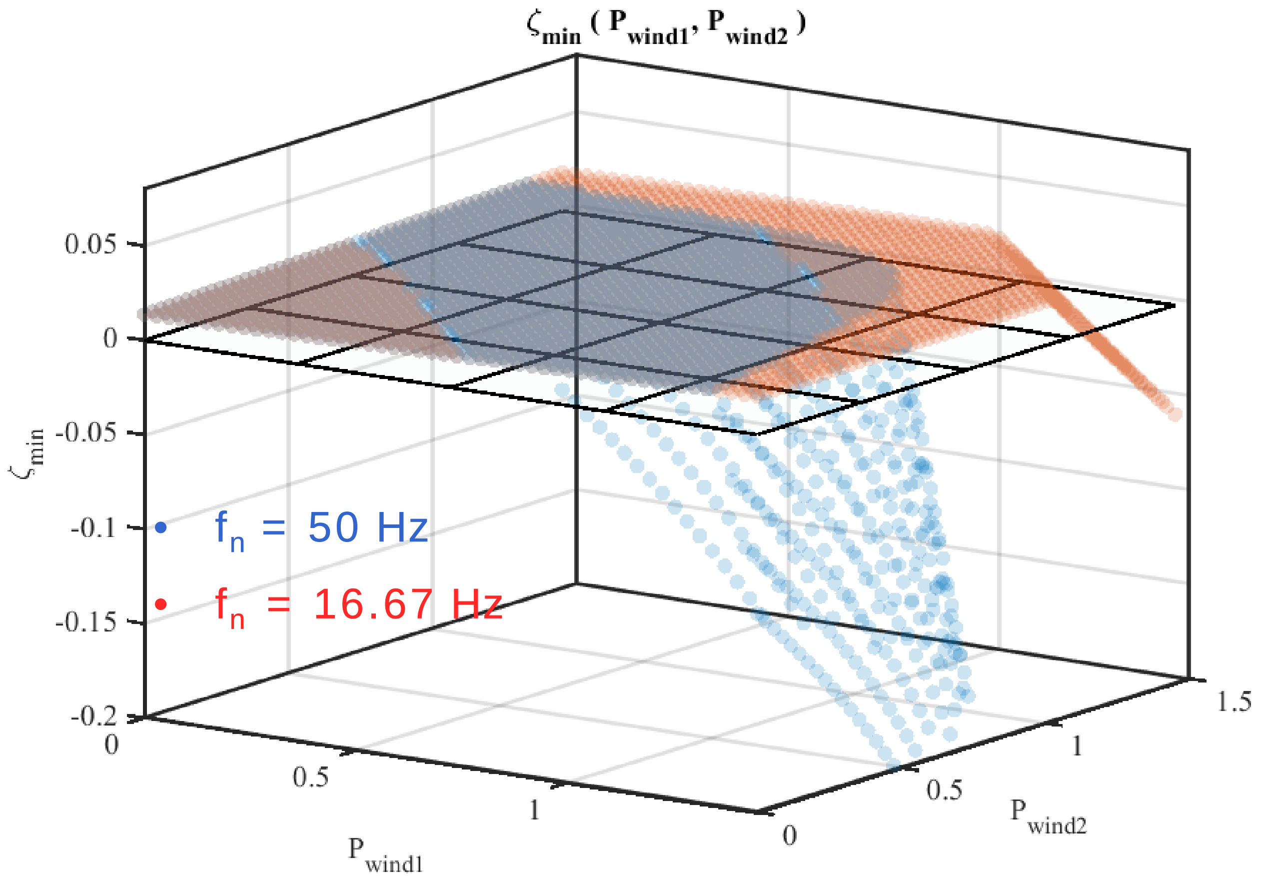
Preliminary results!

Key insights (up to this point)

- **Minimum damping ratio** almost the same over the stable operating region

- In case of **lower frequency** on the offshore island
  - **Increase of stable operating space**
  - Increased robustness against wind generation power disturbances

- Further analysis necessary



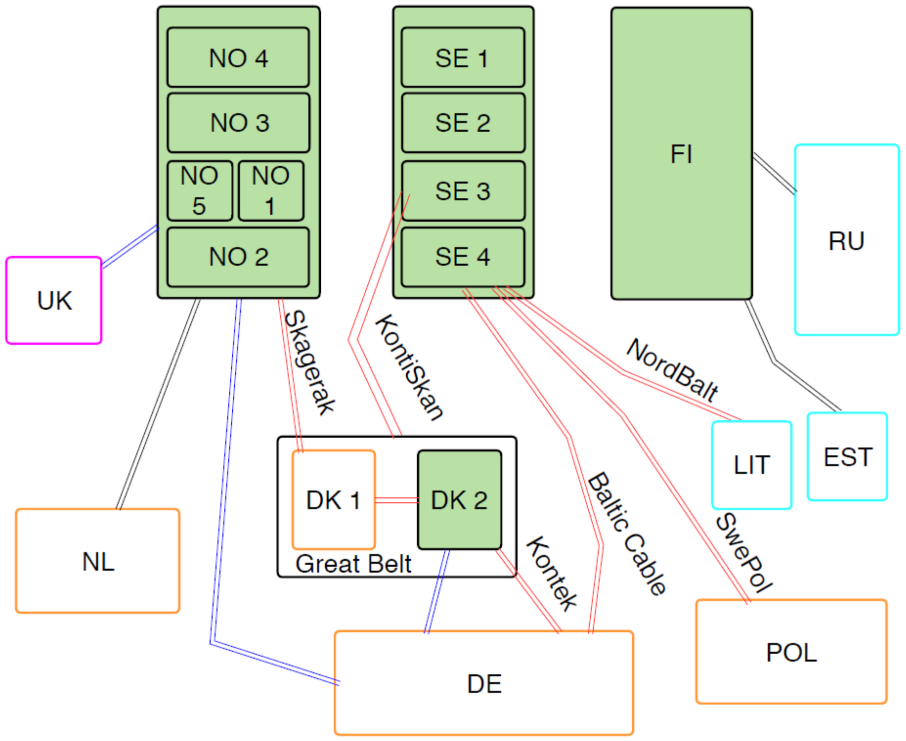
Coordinated Control of multi-area AC/DC systems

Coordinated control of multi-area AC/DC systems

- Focus on **Emergency Power Control (EPC)** mechanisms and sharing of reserves between asynchronous systems

- Currently, EPC in Nordics works as follows:
  - If **f < threshold** then **transfer = xx MW**

- **Goal**: move from stepwise-triggers to **droop-frequency** control
  - Transmitted power is continuous and linearly dependent on the frequency deviation



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EPC: Trigger (existing) vs Droop (proposed)

- Trigger: power continues to get transferred even if ROCOF becomes positive
  - This power does not help reduce the frequency nadir

- **Droop: for any inertia level, the required power is less than in the “trigger” EPC**

	No EPC	All links in EPC	Total	Unused
[GWs]	$f_{min,no}$ [Hz]	f_{min} [Hz]	[MW]	[%]
80	48,50	48,93	2378	59
100	48,68	49,05	2138	61
125	48,83	49,16	1538	48
150	48,93	49,23	1238	36
175	49,00	49,27	1238	37

- Does not cross the minimum freq. threshold

- Uses 61% less power

Obradovic, Ghandhari, Eriksson, *Assessment and Design of Frequency Containment Reserves with HVDC interconnections*, Best Paper Award at NAPS 2018, link to paper

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Cost savings from droop-frequency EPC

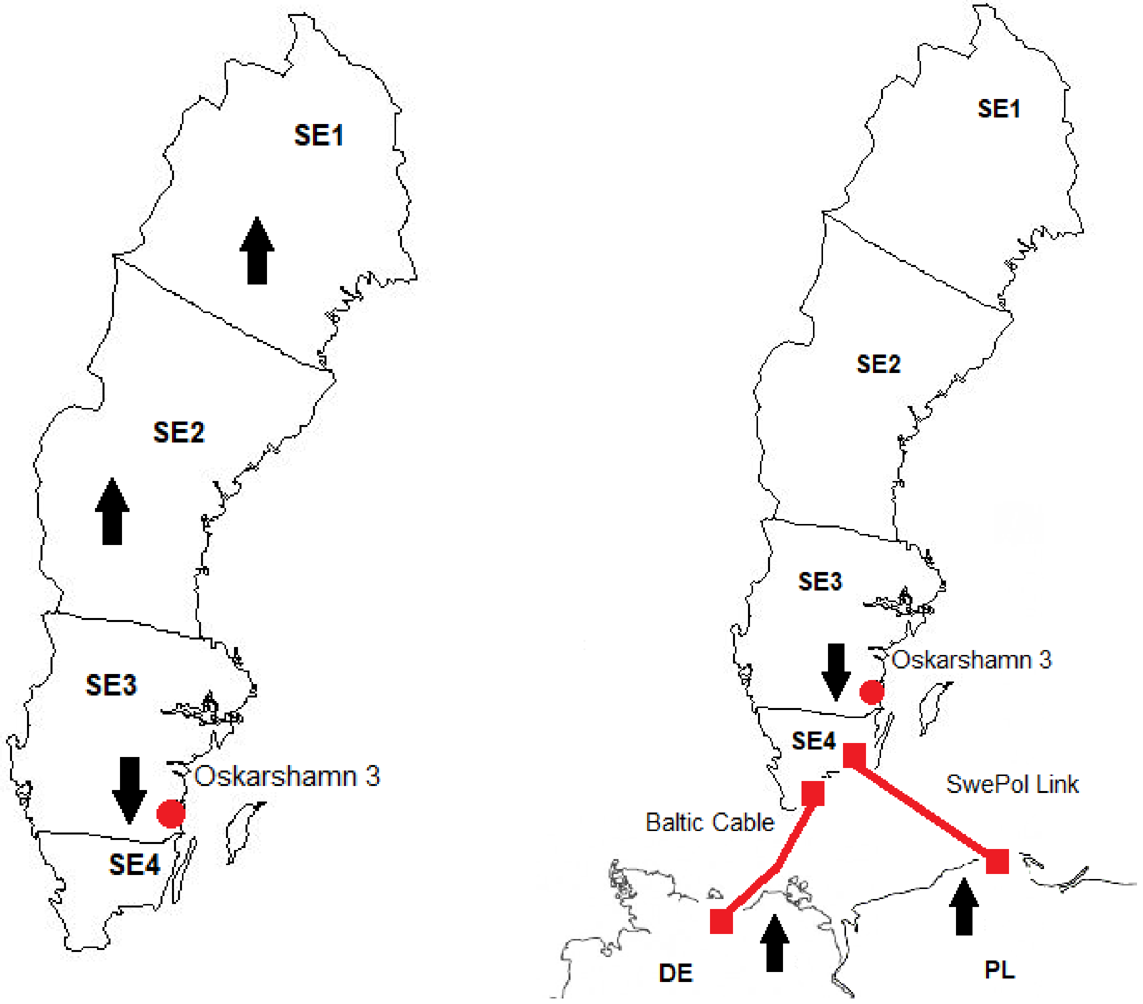


Figure: Synchronous (left) and asynchronous (right) redispatch schematic map.

- Re-dispatch using synchronous generators (Synchronous re-dispatch)
- Re-dispatch using cross-border interconnections (Asynchronous re-dispatch)
- Frequency reserves support with fast Emergency Power Control (EPC) from HVDC links

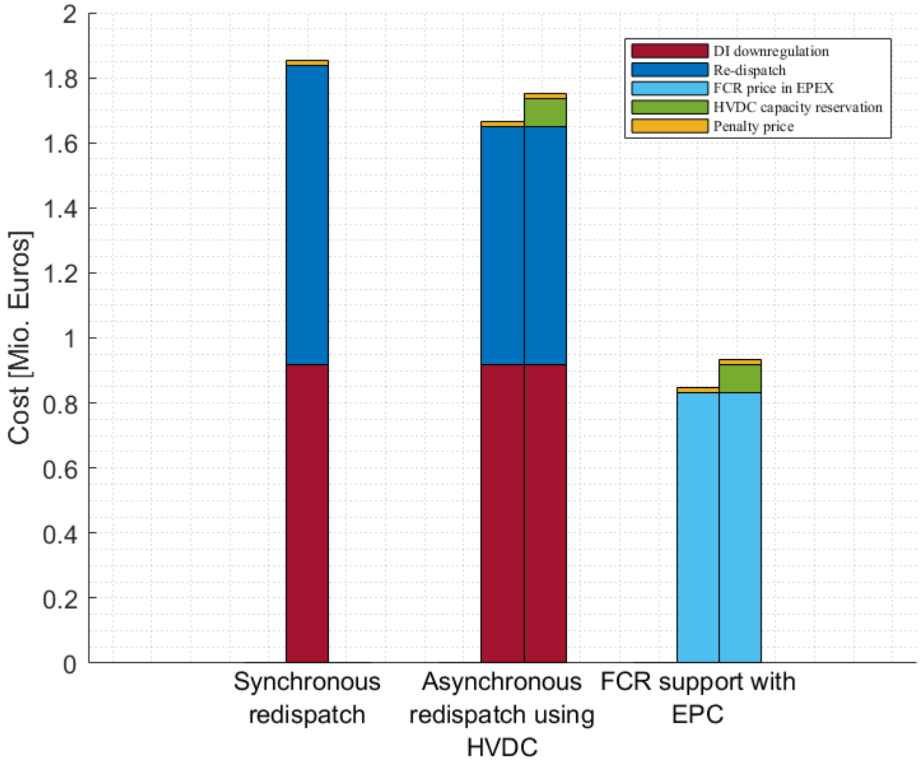
Cost Savings

- **2018:**
  - Current paradigm **(real data)**:
    Cost of **1.85 million Euros/year**
  - Asynchronous redispatch:
    Savings of 0.2 million Euros/year
  - **FCR with HVDC EPC:**
    Savings of **0.9-1.8 million Euros/year**

FCR with HVDC EPC:

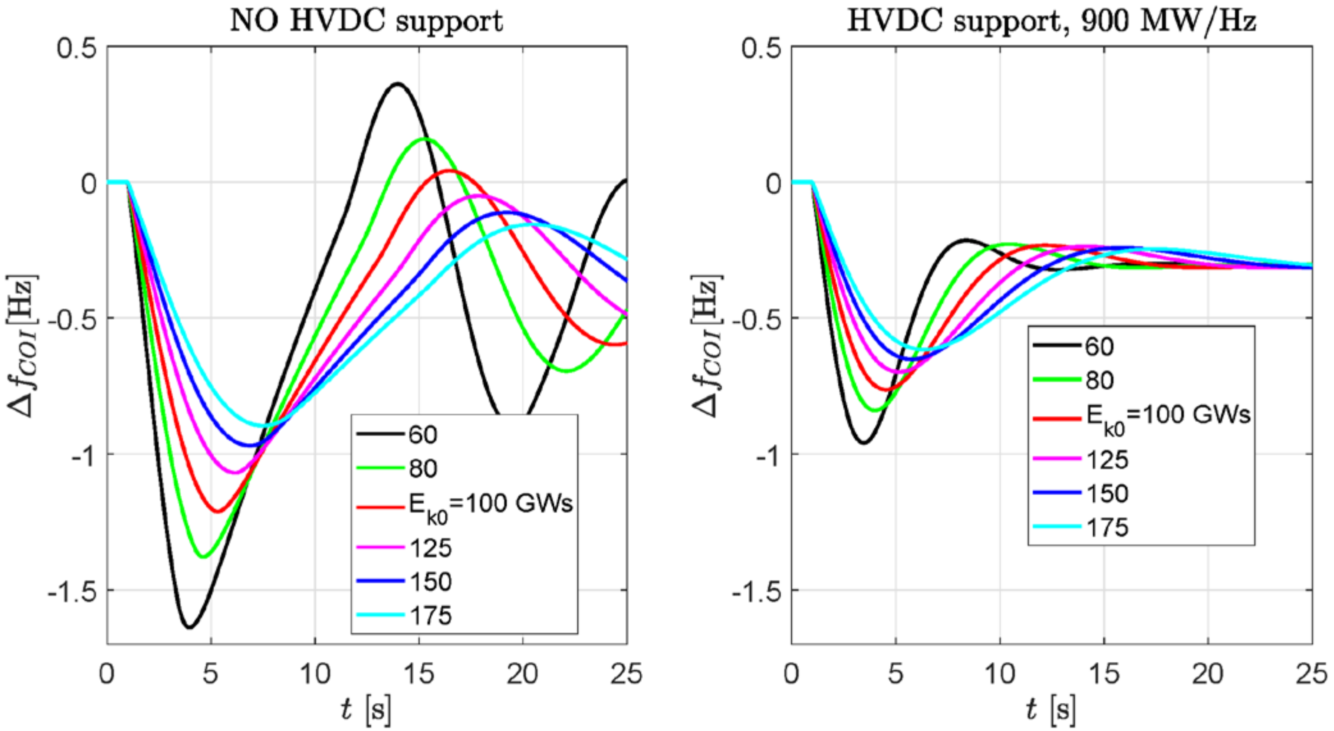
- 2020: Savings of 1.9 – 2 million Euros/year

- **2025: Savings of 3 – 14 million Euros/year (50% cost reduction)**



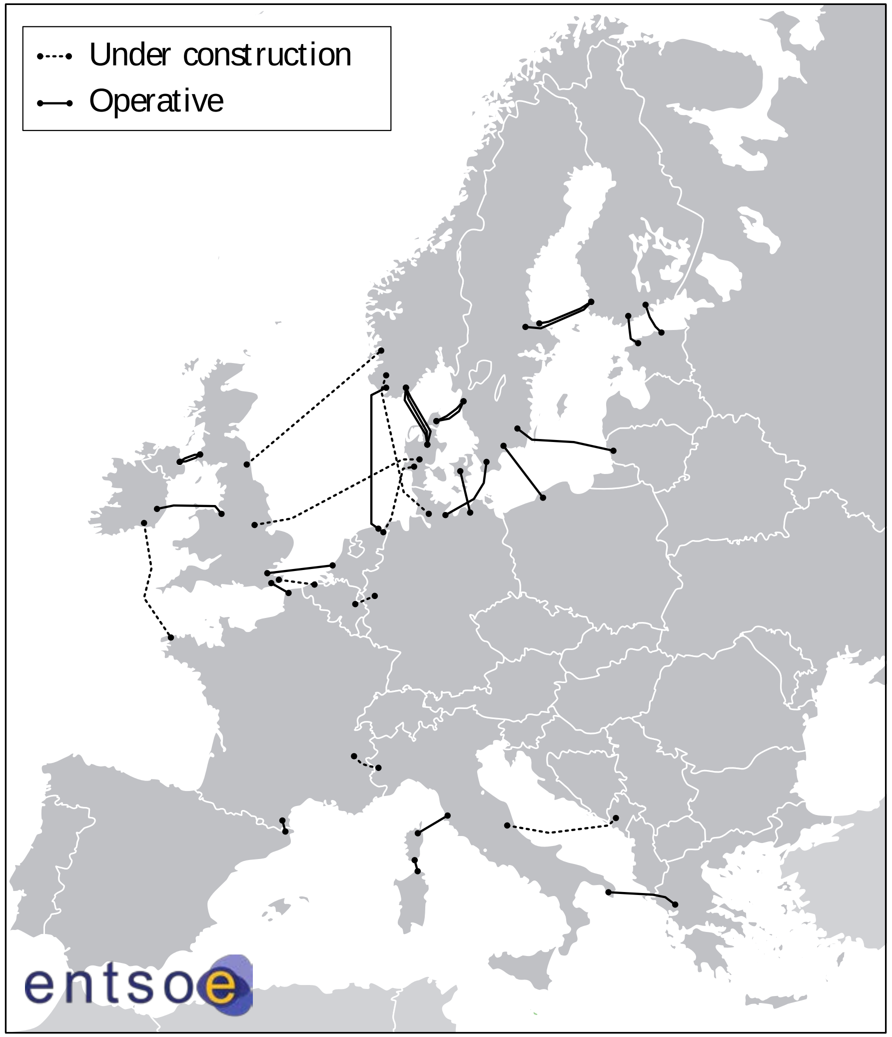
Next Steps

- **Stability assessment** of the **droop-frequency** control function of the **HVDC EPC** for the Nordic system



Market Integration of HVDC:
The cost of losses and the value of HVDC flexibility

Motivation



- **HVDC interconnectors:**
  - usually longer than **AC** interconnectors
  - often connecting areas belonging to different TSOs (at least in Europe)
- HVDC losses are not negligible
- If **price difference** between areas is **small**, TSOs cannot recover the cost of HVDC losses, i.e. cost of losses higher than potential revenue
- **Problem especially for transit countries**, such as **Denmark**

Some examples - Denmark

- In 2017 the **price difference** between **SE3** and **DK1** has been zero for more than 5300 hours (**61%**), resulting in **1.2 M€** losses.

- In 2017 the **price difference** between **DK1** and **DK2** has been zero for more than 6400 hours **(73%),** resulting in **0.8 M€** losses.

- In 2017 the **price difference** between **DK1** and **NO2** has been zero for more than 4000 hours **(47%)**, resulting in **3.2 M€** losses.

Source: https://www.nordpoolgroup.com/

Some examples - Finland

- In 2017 the **price difference** between **FI** and **EE** has been zero for more than 6600 hours (**76%**), resulting in **3 M€** losses.

- In 2017 the **price difference** between **FI** and **SE3** has been zero for more than 8600 hours (**99%**), resulting in **3.8 M€** losses.

- For these **5 HVDC interconnectors**, losses amounts to **12 M€ per year.**

- Considering the number of HVDC interconnectors and all the new projects, this number is intended to **grow significantly.**

Source: https://www.nordpoolgroup.com/

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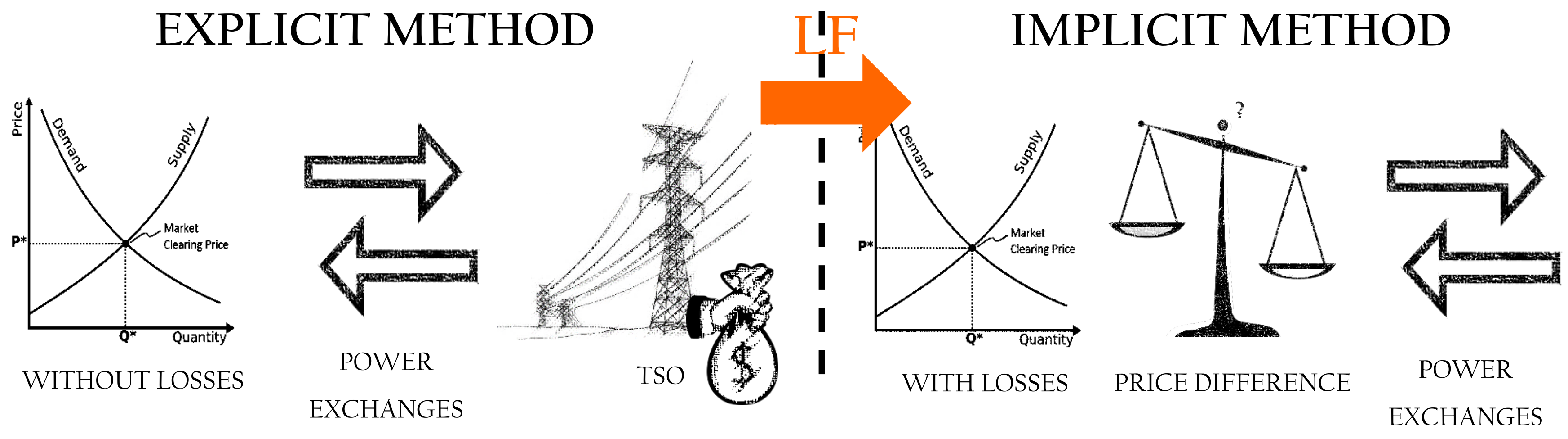
Problem statement

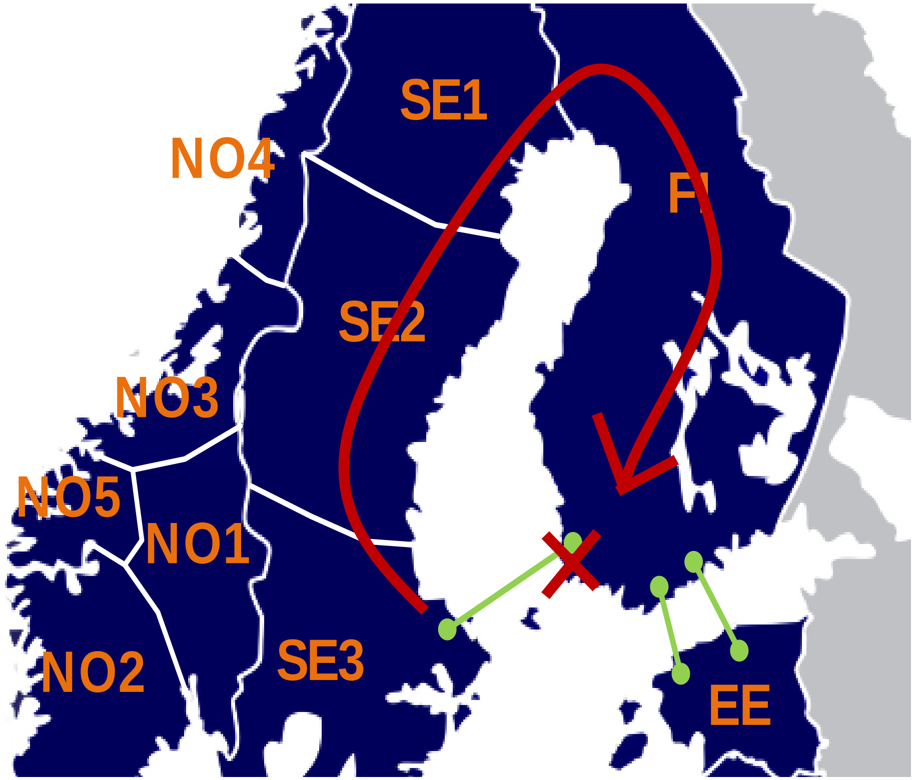
- Introduction of an HVDC loss factor in market clearing*

**Fingrid, Energinet, Statnett, Svenska kraftnät, Analyses on the effects of implementing implicit grid losses in the Nordic CCR, April 2018*



- To move from the explicit to the implicit method, a **loss factor** has to be included in the market clearing algorithm.
- **Is it a good idea to introduce a loss factor <u>only</u> for HVDC lines in meshed grids?**

Implicit grid losses - Nordic CCR

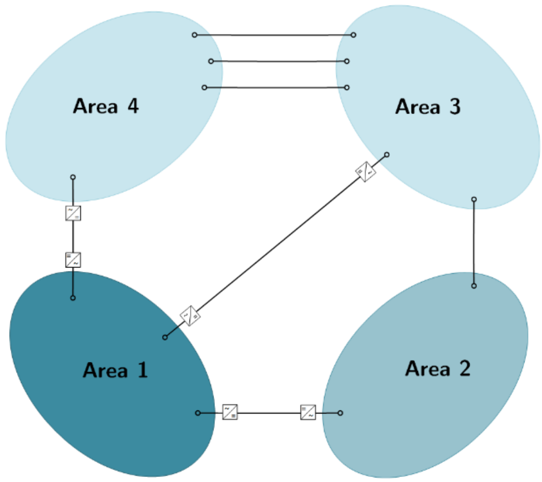


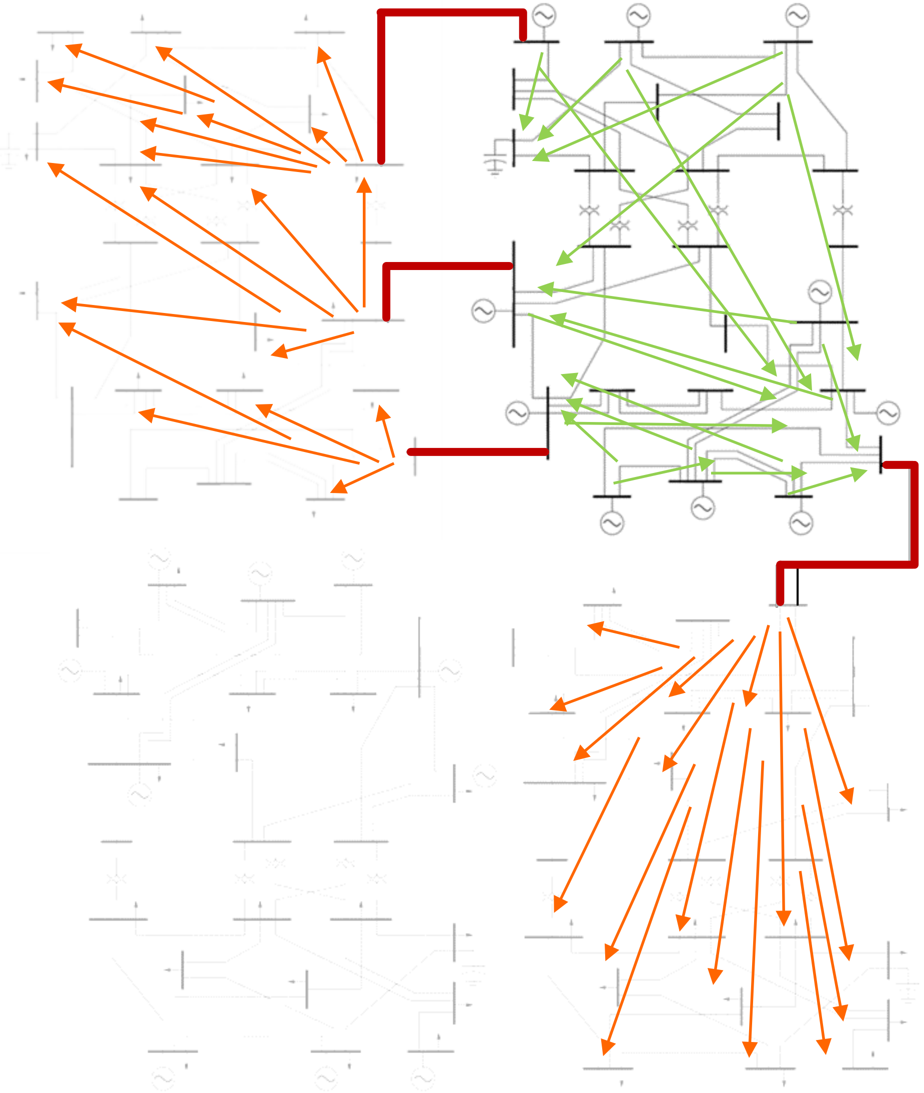
- Nordic TSOs, April 2018: *Analyses on the effects of implementing **implicit grid losses** in the **Nordic CCR***
- All simulations with implicit grid losses show an economic benefit
- One exception is FennoSkan

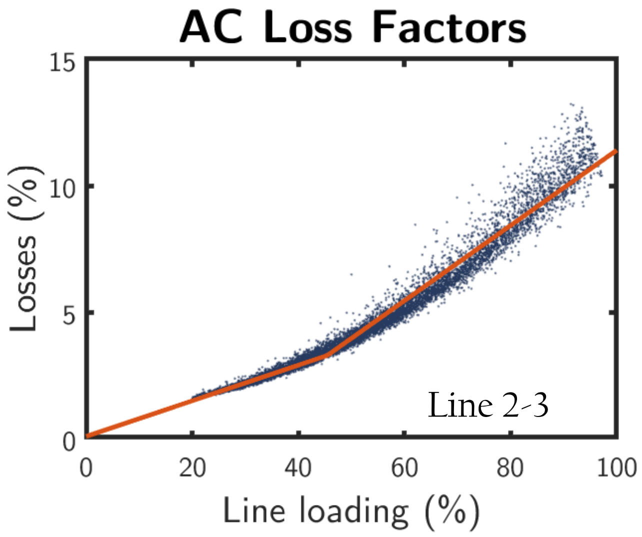
* Fingrid, Energinet, Statnett, Svenska Kraftnät, *Analyses on the effects of implementing implicit grid losses in the Nordic CCR*, April 2018

Introduced Methodology for AC loss factors

System emulating DK1, DK2, SE, NO





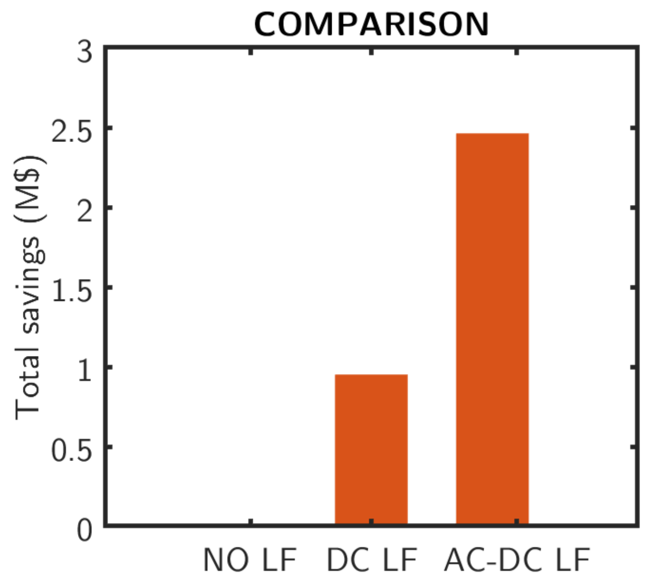


More info:

A. Tosatto, T. Weckesser, S. Chatzivasileiadis, *Market Integration of HVDC lines*, available: https://arxiv.org/abs/1812.00734

Economic evaluation

- The results show that the introduction of HVDC loss factors for this specific system is **beneficial** for most of the time.
- However, there are cases where the social welfare is **decreased** (**>14%**).
- **Theory guarantees** that this does not happen with LFs for **both AC** and **DC** systems
- The introduction of **AC-LFs double the benefit**.



More info:

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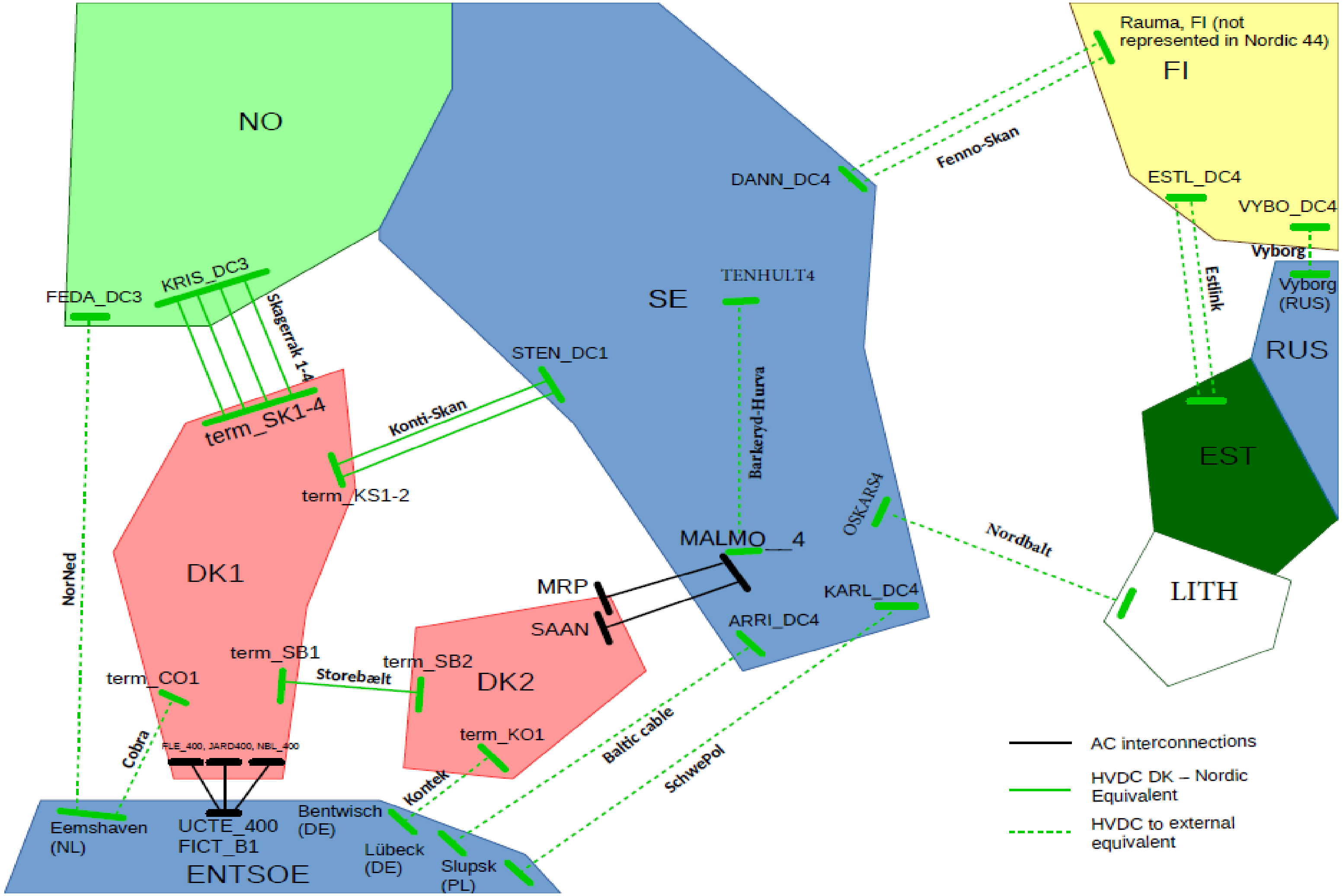
Wrap-up and next steps

- **Is it a good idea to introduce a loss factor <u>only</u> for HVDC lines in meshed grids?**
- The HVDC loss factor can act positively or negatively w.r.t. the amount of system losses depending on the **system under investigation**.
- If to be introduced in the market clearing algorithm, the recommendation is to consider the losses in **both AC** and **DC systems**.
- **Next steps: determine the value of HVDC corrective control, and price it appropriately**

Open-source models and demonstration

Development of a dynamic AC/HVDC Nordic model



- Open-source HVDC models for *both* LCC and VSC controllers
- Modeling both in RMS and EMT
- Powerfactory and RAMSES (U.Liege)

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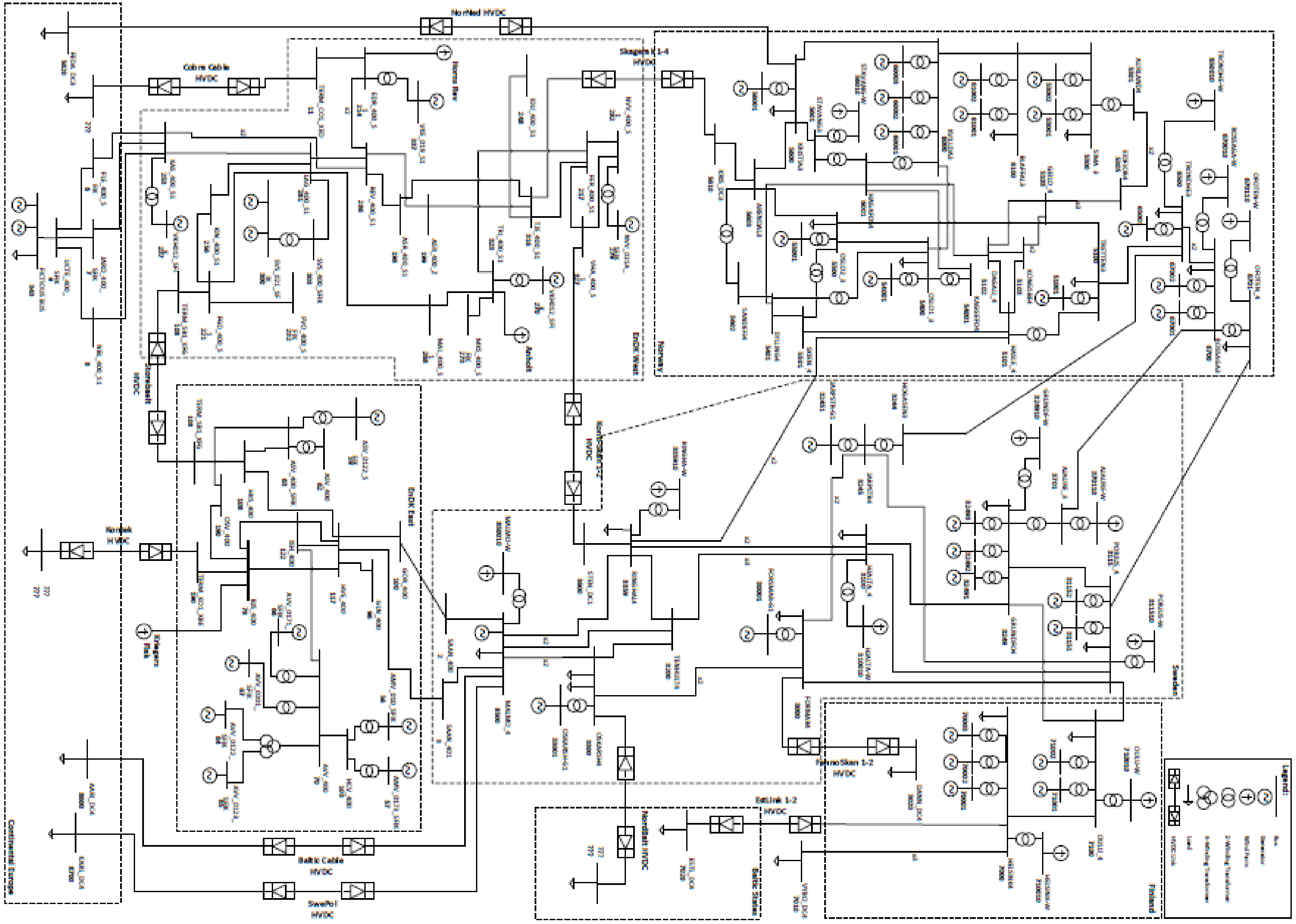

- 423 buses
- 80 synchronous machines
- 2 asynchronous areas
- *Open source* (including HVDC models)

multiDC contributions and next steps

- Develop **open source dynamic models** of both VSC-HVDC and LCC-HVDC
- Investigate stability of **zero-inertia** AC systems: robust control, operating at different AC frequencies
- Deep investigation of **droop-frequency based EPC** for HVDC
  - Stability analysis
  - Cost Savings
- **Market Integration of meshed HVDC lines**
  - Cost of losses
  - What is the value of HVDC flexibility? How to price HVDC corrective control?

Demonstration at PowerlabDK

- **Advanced functionalities** of **Kriegers Flak** Master controller
- Zero-inertia systems: Impact of **RMS vs EMTP** modelling
- **Droop-frequency-based EPC** for the Nordic system

Hopefully test the most promising functions at Energinet!

Conclusions

- **multiDC: Holistic approach** to the emerging problems of multiple **HVDC interconnections and grids**
  - Zero-inertia AC grids
  - Emergency power control coordination of multi-area AC/DC grids
  - Market Integration of HVDC
- Developing solutions applicable to the North Sea Wind Power Hub
- Real implementation at PowerlabDK

Interested to hear more?

Join us in the multiDC demonstration event at DTU in September 2019!

www.multi-dc.eu