# Coordination of HVDC interconnections

Spyros Chatzivasileiadis

multiDC Project

www.multi-dc.eu

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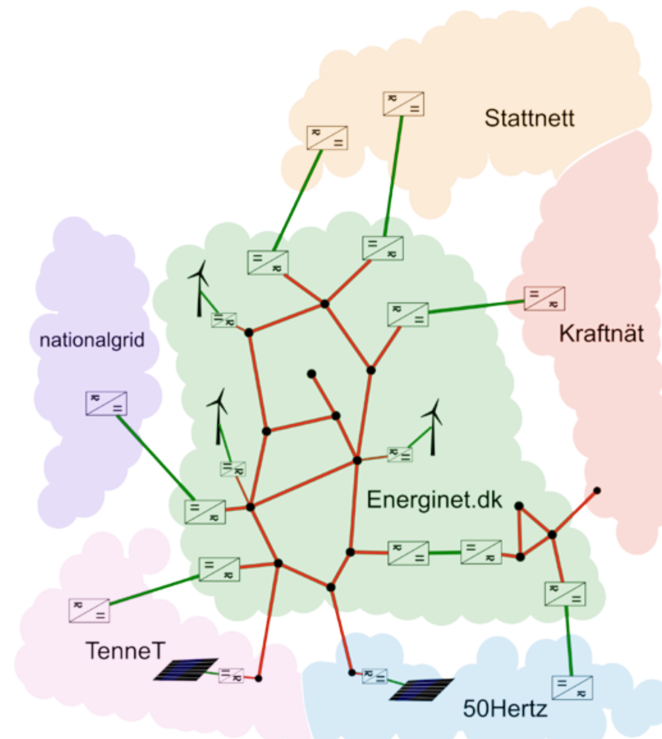
**Innovative Methods for Optimal Operation of Multiple HVDC Connections and Grids**

- 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 RSCI
- **4.2 million USD**
- **4 years**; Start May 1, 2017

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# Three main drivers

- 100% renewables
  - Varying inertia systems
  - Uncertainty
- 100% inverter-connected devices
  - How is stability and operation affected?
  - How to model them?
- HVDC Grids


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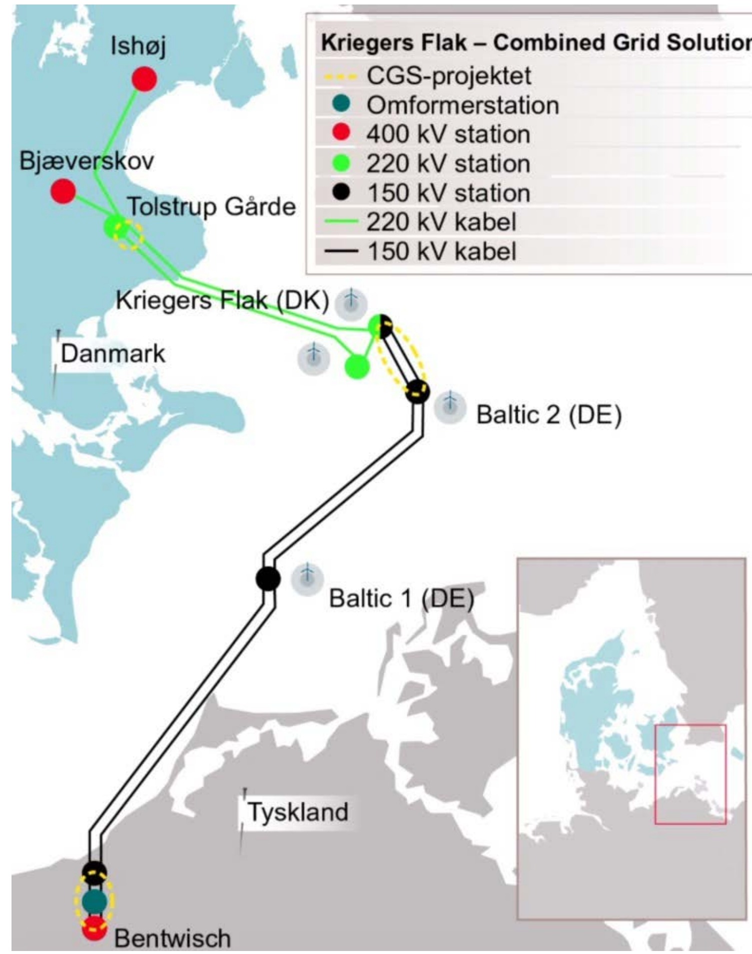
# Kriegers Flak

- 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



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# 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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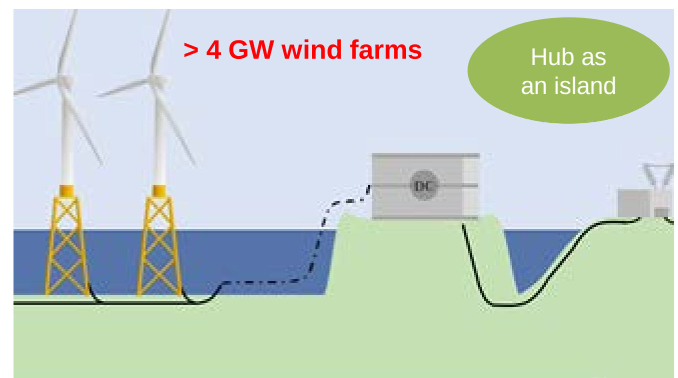
# Grid Connection Options for Offshore Wind

*Close to shore*


*Far from shore*


*Large scale far from shore*




*Information from Peter Larsen and Fitim Kryezi, Energinet
and from www.northseawindpowerhub.eu*

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- Far-shore becomes near-shore
- Distribution point for different countries
- 2030 and beyond

- Modular approach
- Each island: up to 30 GW
  Vision: 150 GW in North Sea
- First step: 12 GW

*Information from Peter Larsen and Fitim Kryezi, Energinet*
*and from www.northseawindpowerhub.eu*

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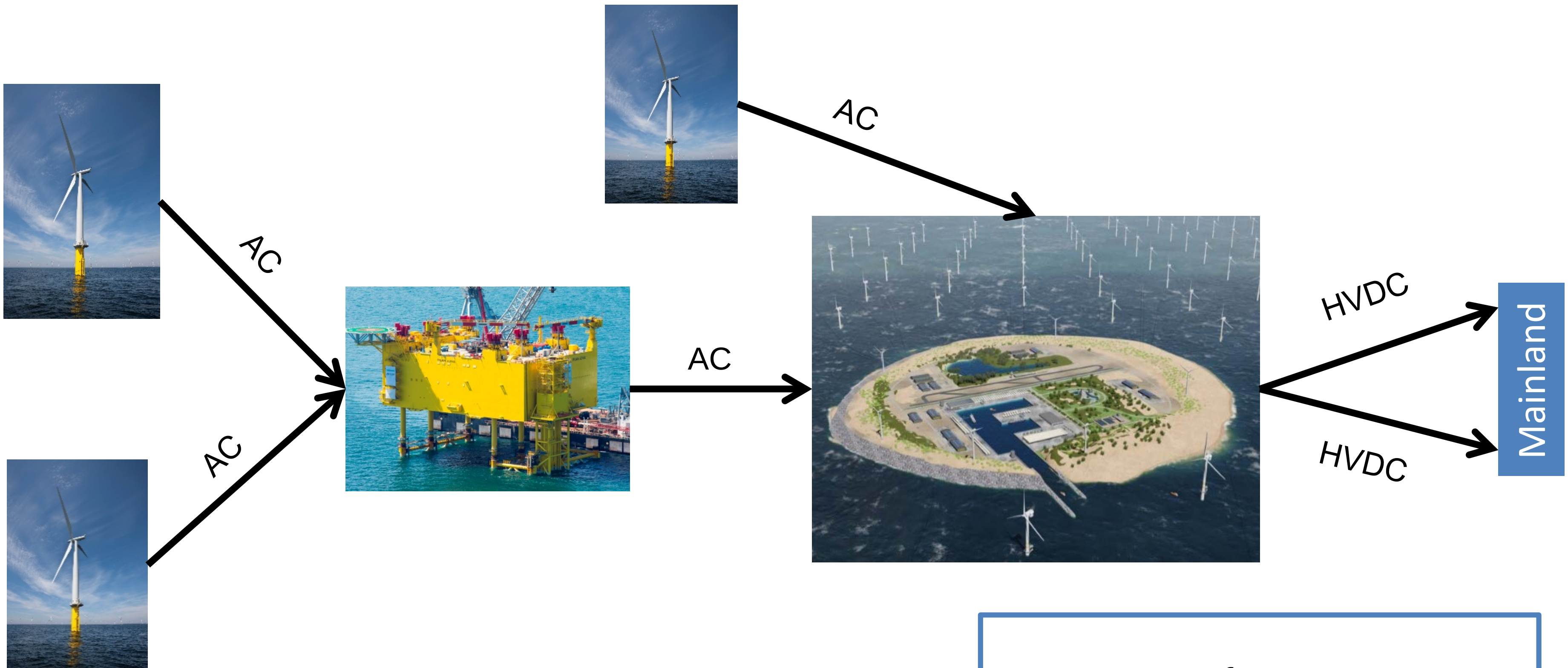
How will the wind farms be connected to the island?

How will the island be connected to the mainland?

*These are still open questions*

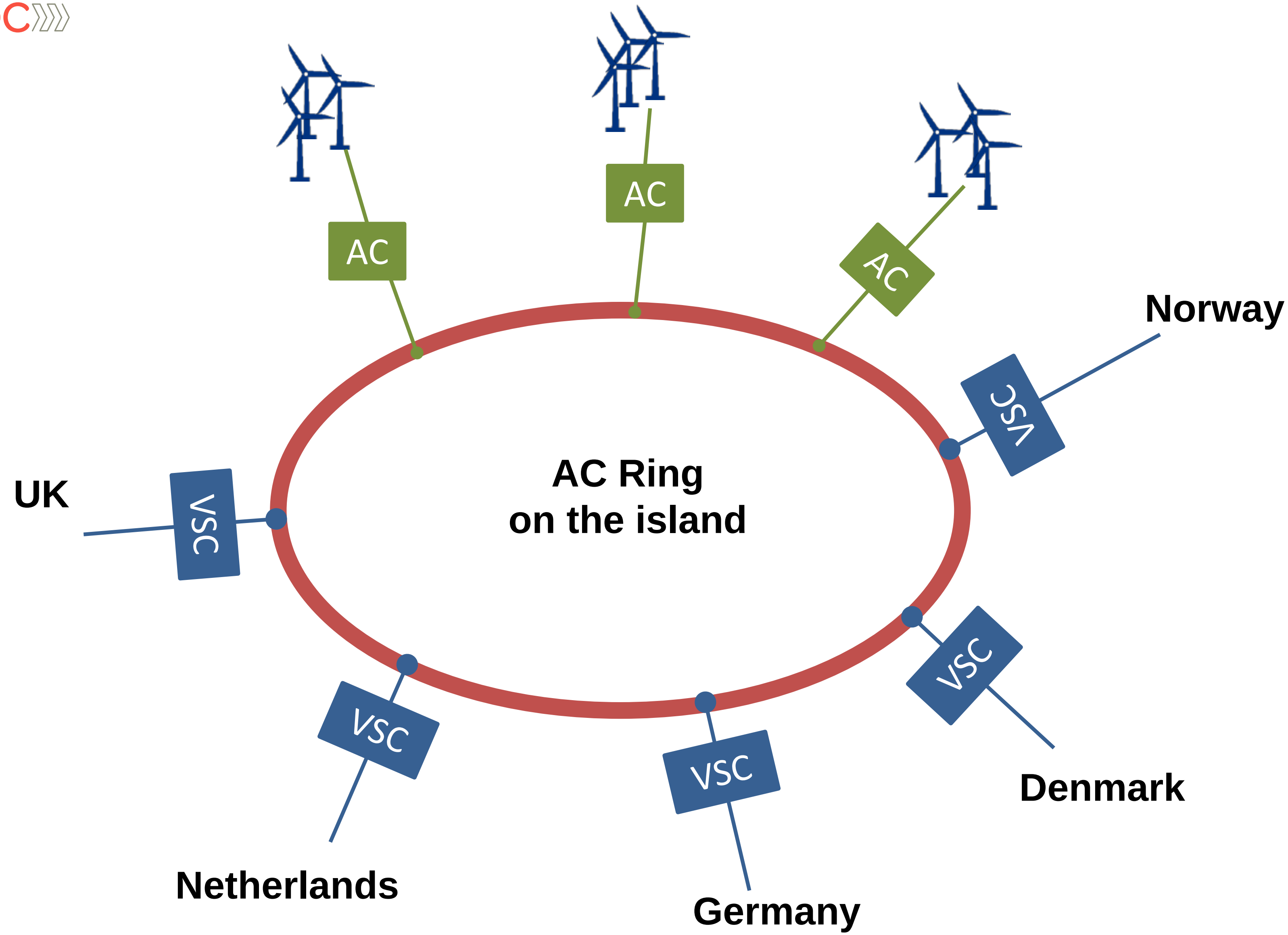
# A connection possibility




AC: Low-frequency AC

HVDC: Point-to-point HVDC

*Information from Peter Larsen and Fitim Kryezi, Energinet*
*and from www.northseawindpowerhub.eu*
Figures courtesy of Ørsted A/S, Siemens, and Northseawindpowerhub


AC
AC
AC
Norway
VSC
UK
VSC
AC Ring
on the island
VSC
VSC
VSC
VSC
Denmark
Netherlands
Germany

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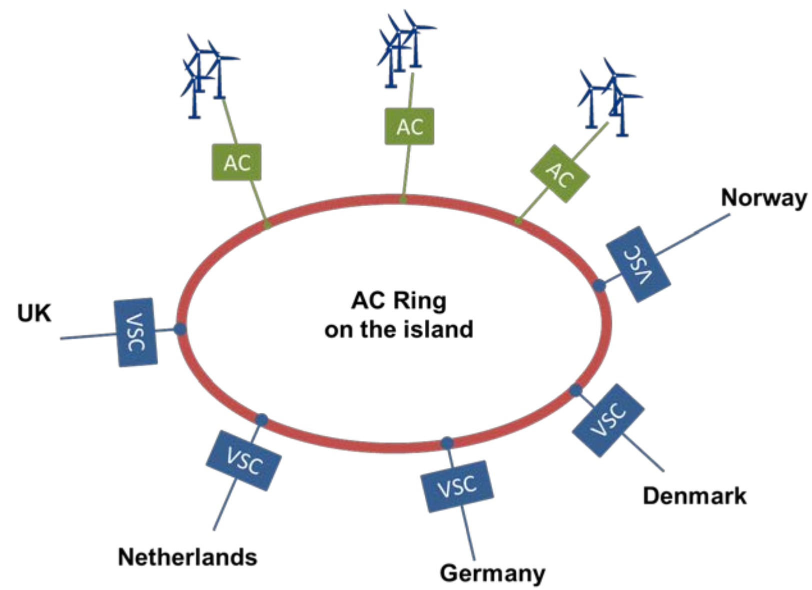
# Challenges and Opportunities

- 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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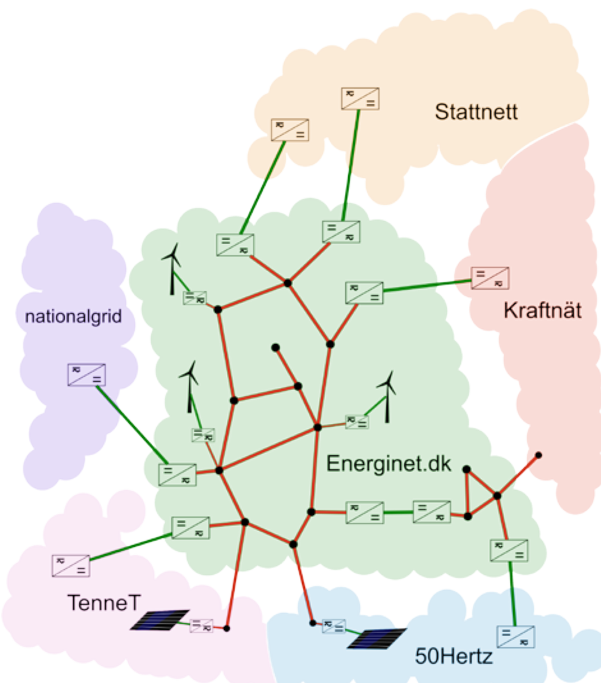
# multiDC:
# **Addressing current challenges** while preparing for the North Sea Wind Power Hub

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# The three pillars of multiDC

- Robust frequency control of varying inertia systems
- Coordinated control of AC/DC systems
- Market integration of meshed HVDC connections

**Implementation at PowerlabDK**

PowerLabDK

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# From Current Challenges to the North Sea Wind Power Hub (NSWPH)

Current Work → By the end of the project

| Current Work | By the end of the project |
| --- | --- |
| Robust frequency control of varying inertia systems | Zero-inertia AC grids |
| Coordinated control of AC/DC systems | Coordinated control of grid-forming HVDC converters |
| Market integration of meshed HVDC connections | Integration of the NSWPH to the European Market |

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# Robust Frequency Control for Varying Inertia Systems

- ***$m_i$*** and ***$d_i$*** **vary** depending on the RES infeed
  - more RES infeed → less conventional generation → lower inertia
  - less RES infeed → more conventional generation → higher inertia

$$m_i \dot{\omega}_i = -d_i \omega_i + p_{mech,i} - p_{el,i}$$

- Decreasing inertia should improve the damping ratio
  - **$d_i/m_i$** describes **how fast** a frequency deviation is **brought back to equilibrium**
- Decreasing inertia should increase ROCOF
  - Disturbances are scaled by $1/m_i$
  - With low inertia the rotor speed becomes more vulnerable to shocks

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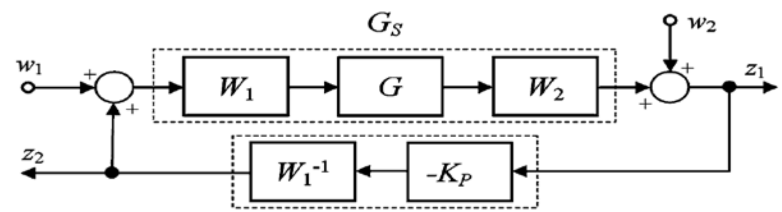
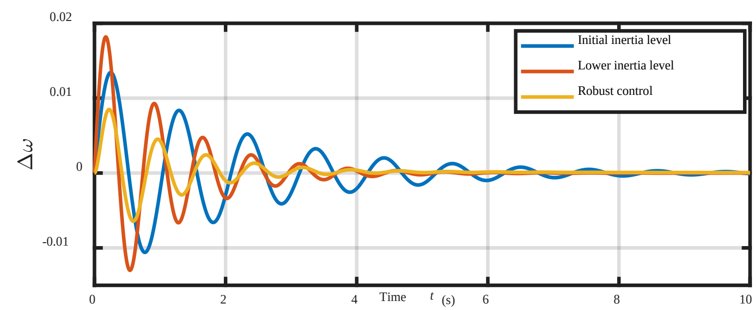
# Robust Frequency Control for Varying Inertia Systems

- $H_\infty$ optimal control
  - Minimizes the maximum singular value of the closed-loop system
- Robust frequency control
  - Attenuate the gain at higher frequencies, resulting to lower ROCOF and lower maximum frequency deviation
  - Adds some slight damping to electromechanical oscillations




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

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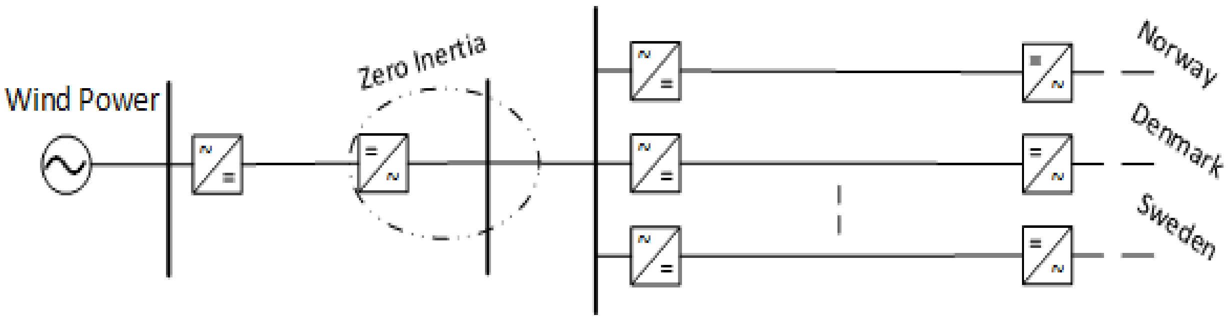
# Robust Frequency Control for Varying Inertia Systems – Future Steps

North Sea Wind Power Hub as a test case




- From low-inertia to zero-inertia
  - Zero inertia → Coupling between active and reactive control in the absence of a stiff frequency and voltage

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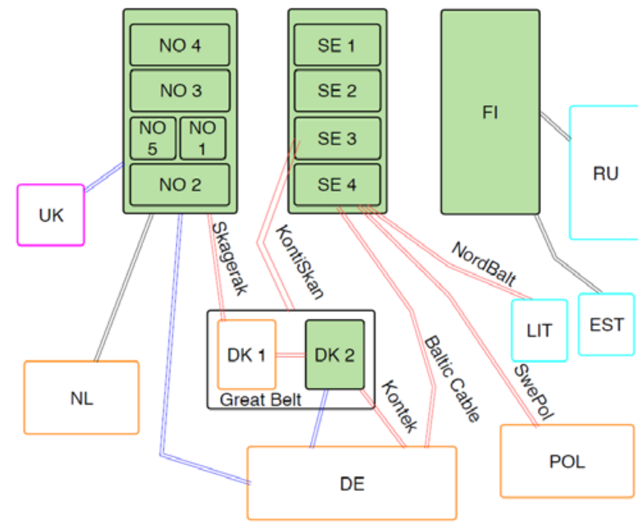
# Coordinated control of Multi-Area AC/DC systems

- 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




| HVDC link | Step | Freq. trigger [Hz] | Capacity [MW] | Ramp rate [MW/s] | Time delay [s] |
|---|---|---|---|---|---|
| KontiSkan 1+2 | 1 | 49,8 | 150 | 20 | 0,3 |
| | 2 | 49,6 | 150 | 50 | 0,1 |
| | 3 | 49,5 | 150 | 200 | 0,05 |
| Baltic Cable | 1 | 49,55 | 150 | 100 | 0,5 |
| | 2 | 49,2 | 300 | 100 | 0,5 |
| SwePol | 1 | 49,4 | 150 | 100 | 0,5 |
| | 2 | 49,1 | 300 | 100 | 0,5 |

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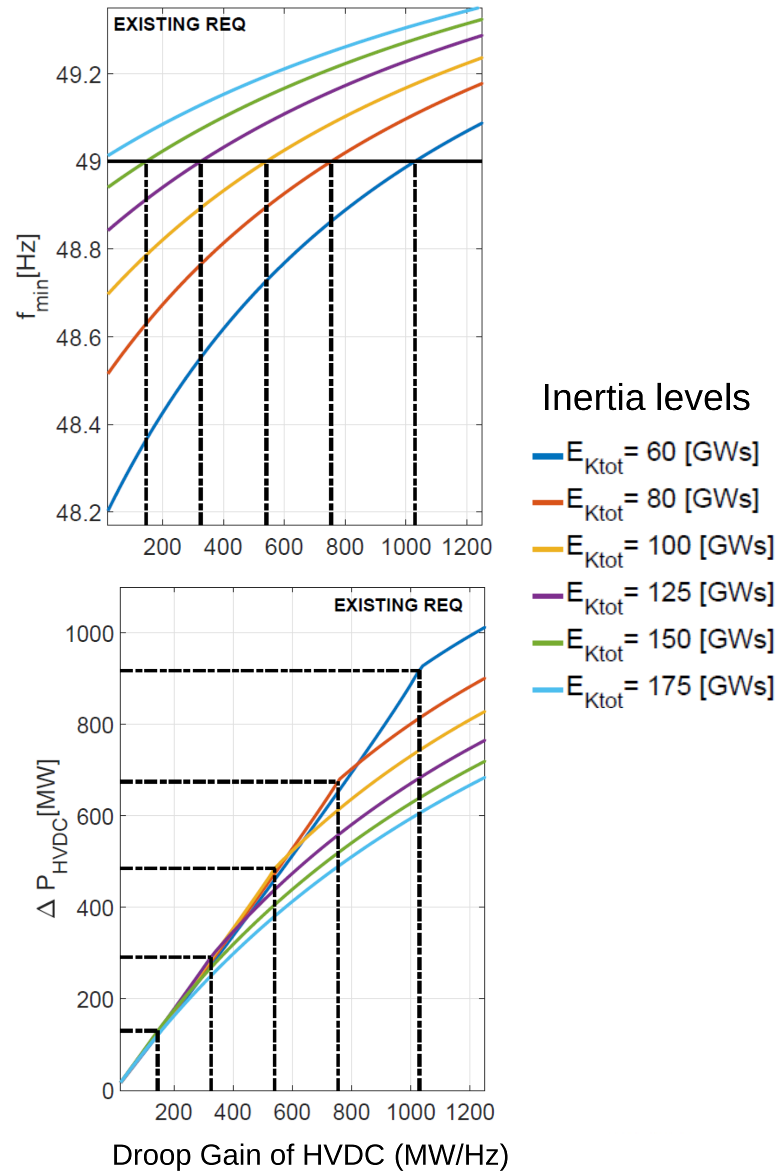
# EPC: Trigger (existing) vs Droop (proposed)

- 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 |

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



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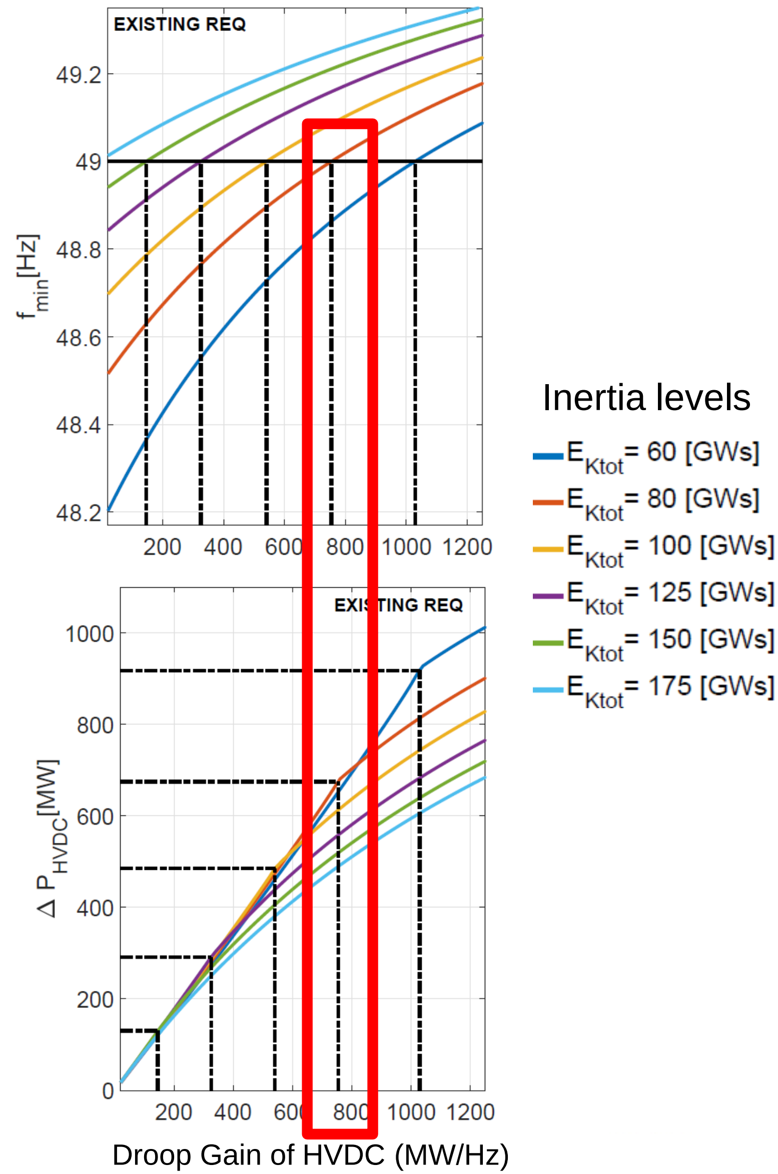


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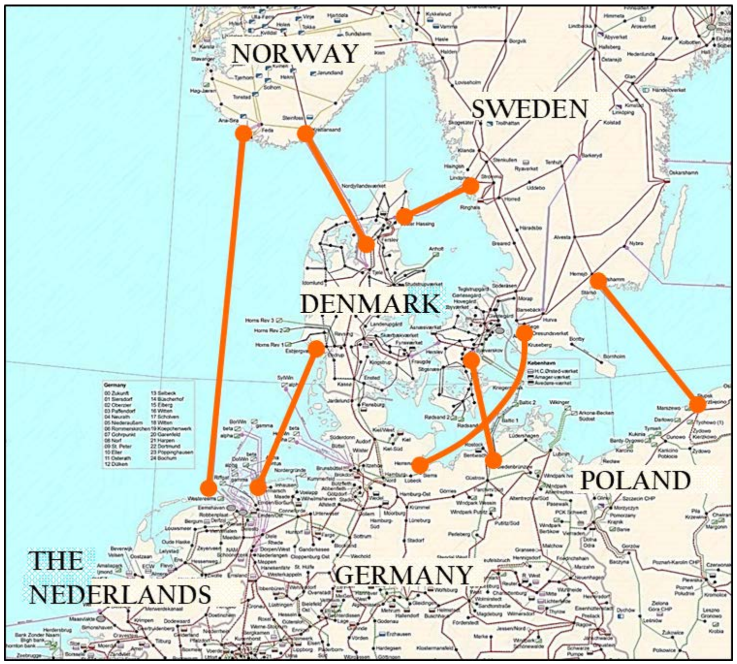
# Market Integration of HVDC




- HVDC interconnectors are usually longer than AC interconnections
- HVDC losses are not negligible
- If price difference between areas is small, TSOs cannot recover the cost of HVDC losses
  - Cost of the losses higher than potential revenue
- 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

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# An example: Kontiskan

NORD POOL — EL SPOT

| 05-07-2018 | MWh/h SE3 > DK1 | MWh/h DK1 > SE3 | EUR/MWh SE3 | EUR/MWh DK1 |
|---|---|---|---|---|
| 00 - 01 | 0,0 | 4,1 | 50,34 | 49,13 |
| 01 - 02 | 23,1 | 0,0 | 48,55 | 45,48 |
| 02 - 03 | 103,9 | 0,0 | 47,54 | 44,31 |
| 03 - 04 | 0,0 | 49,0 | 47,14 | 47,14 |
| 04 - 05 | 71,9 | 0,0 | 47,34 | 47,34 |
| 05 - 06 | 41,3 | 0,0 | 49,35 | 47,57 |
| 06 - 07 | 80,7 | 0,0 | 53,17 | 51,89 |
| 07 - 08 | 60,5 | 0,0 | 56,43 | 57,71 |
| 08 - 09 | 109,0 | 0,0 | 61,21 | 61,21 |
| 09 - 10 | 137,1 | 0,0 | 60,94 | 60,94 |
| 10 - 11 | 364,0 | 0,0 | 62,41 | 62,41 |
| 11 - 12 | 190,6 | 0,0 | 64,07 | 64,07 |
| 12 - 13 | 0,0 | 19,4 | 63,88 | 63,88 |
| 13 - 14 | 0,0 | 0,0 | 63,57 | 52,25 |
| 14 - 15 | 0,0 | 0,0 | 59,04 | 52,06 |
| 15 - 16 | 34,7 | 0,0 | 57,56 | 51,84 |
| 16 - 17 | 90,8 | 0,0 | 53,97 | 52,02 |
| 17 - 18 | 139,8 | 0,0 | 52,97 | 52,97 |
| 18 - 19 | 161,2 | 0,0 | 54,83 | 54,83 |
| 19 - 20 | 237,0 | 0,0 | 55,41 | 55,41 |
| 20 - 21 | 154,6 | 0,0 | 55,10 | 55,10 |
| 21 - 22 | 21,7 | 0,0 | 53,79 | 53,79 |
| 22 - 23 | 3,5 | 0,0 | 52,05 | 52,05 |
| 23 - 00 | 0,0 | 34,7 | 50,21 | 50,21 |

HVDC LINK BETWEEN DENMARK AND SWEDEN


- 2018: price difference Sweden-Denmark has been zero for >2400 hours (54%)
- 2017: more than 5300 hours (61%)
- Total cost of losses during those 5300 hours was approx. 0.9 M€ **for a single HVDC line**

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- Mixed complementarity problem for the market clearing

**MARKET CLEARING**

**Generator 1**
max *profit*
s.t. *production constraints*

**Generator 2**
max *profit*
s.t. *production constraints*

⋮

**Generator N**
max *profit*
s.t. *production constraints*

**TSO**
max *profit*
s.t. *transmission constraints,* ***HVDC loss factor***

**Consumer 1**
max *utility*
s.t. *consumption constraints*

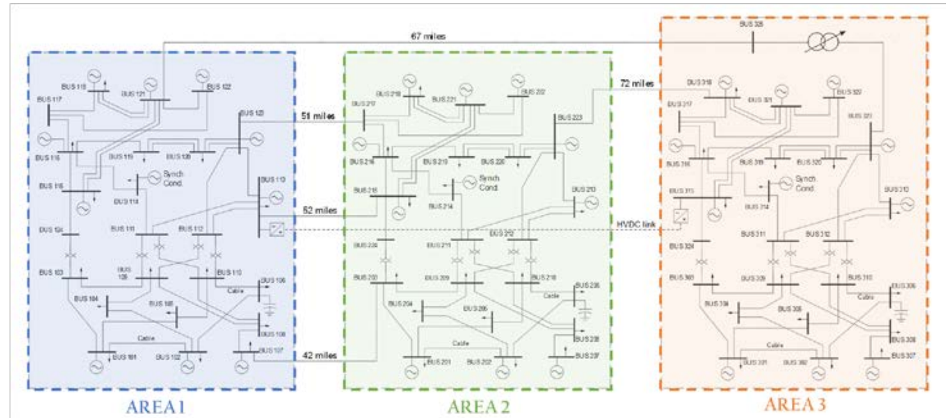
**Consumer 2**
max *utility*
s.t. *consumption constraints*

⋮

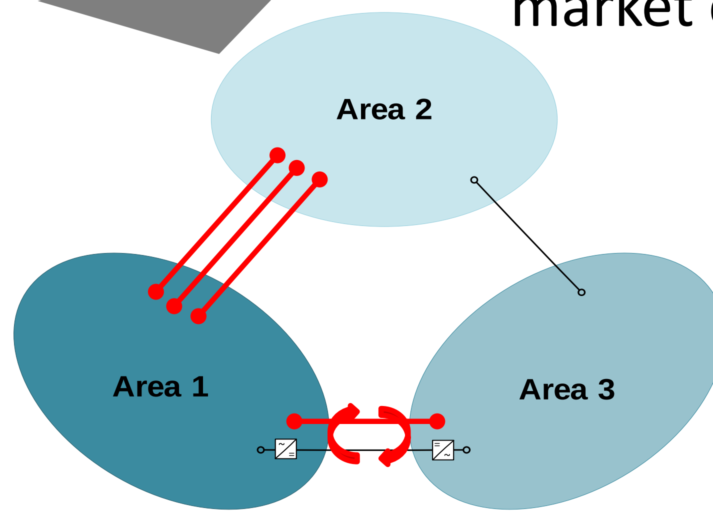
**Consumer M**
max *utility*
s.t. *consumption constraints*

**Balancing constraints**

*3-area IEEE RTS 72-bus SYSTEM*




Flow-based market coupling



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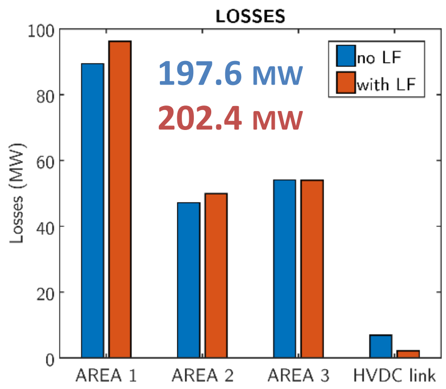
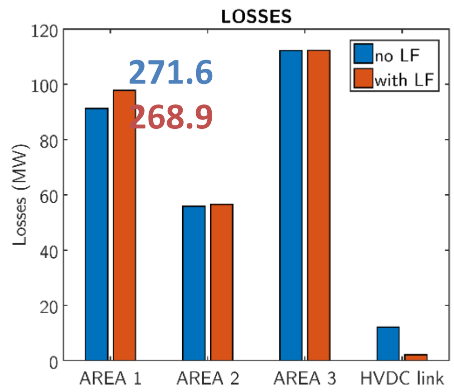
## NORMAL OPERATION




The penalization of the HVDC line results in an increase of losses in the AC system

**ECONOMIC LOSS**
**206.9 $/h**

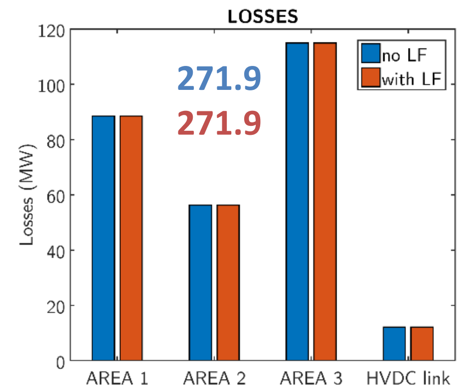
## LOOP FLOWS




With the introduction of the LF loop flows are avoided

**ECONOMIC BENEFIT**
**114.1 $/h**

## CONGESTION




Losses are covered by the price difference due to congestion

**ECONOMIC BENEFIT**
**0 $/h**

- Introducing an **HVDC loss factor** in the market clearing algorithm can have a **positive or negative effect depending on the system** under investigation
- Future work: Investigating different solutions to account for losses in non-radial HVDC systems

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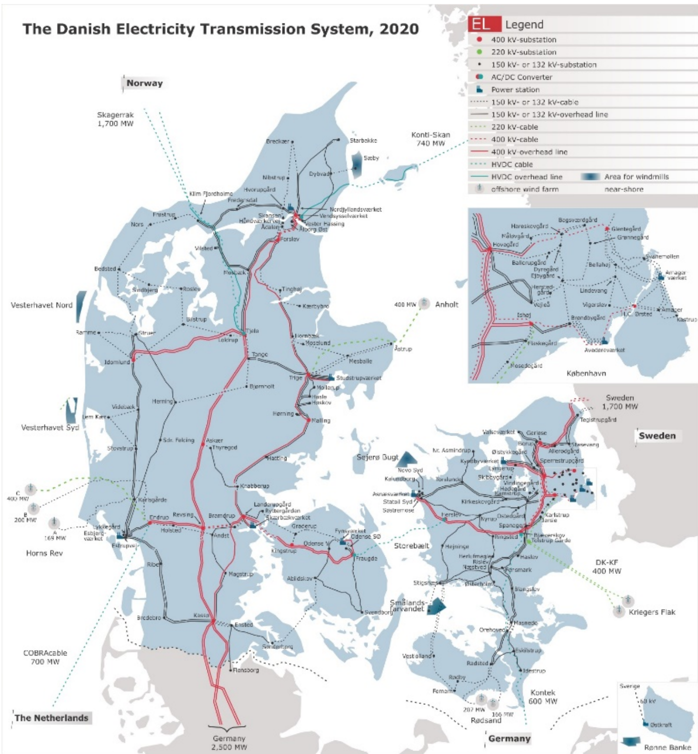
# PowerlabDK at DTU

- Power Hardware in the Loop Simulations:
  - Robust control for varying inertia
  - Control of grid-forming HVDC in a zero-inertia AC grid
  - Coordinated control of HVDC for sharing reserves in the Nordic region
- Implementation starting in September 2018

PowerLabDK

# Development of a dynamic AC/HVDC Nordic model

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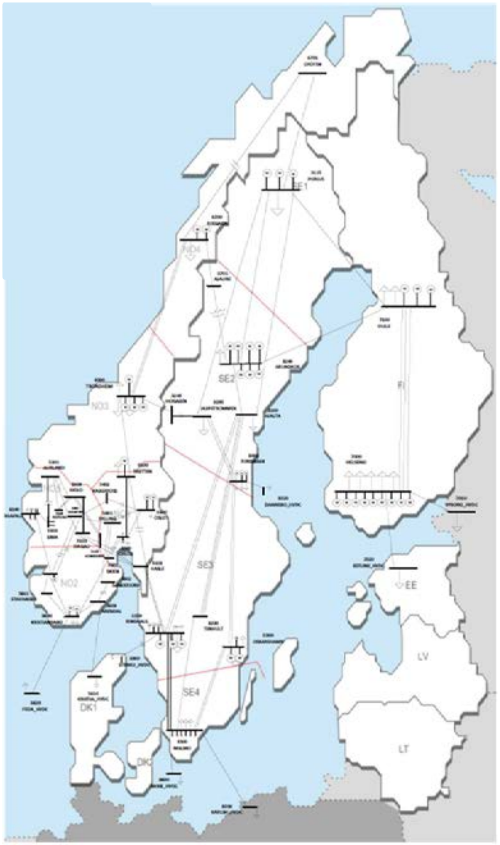
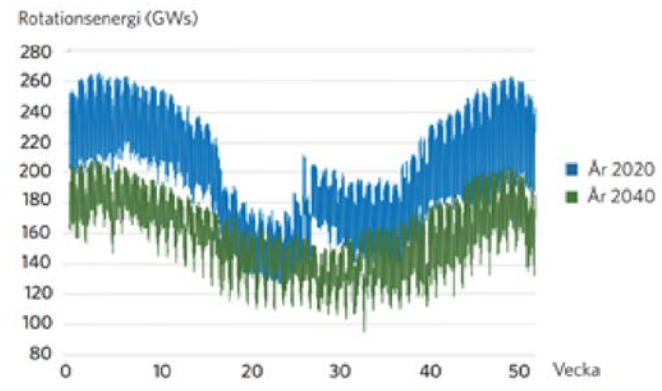


# Development of a dynamic AC/HVDC Nordic model

- Danish system: already implemented in RTDS
- Nordic-44 system (Swedish equivalent, including Norway & Finland)
  - Adjusted system kinetic energy
  - Adjusted reactive power
  - Integration of wind power (20 GW of wind by 2030)
- Working on an open-source VSC-HVDC converter model




*Estimated kinetic energy in Nordic countries in 2020 and 2040*

**Prior work on the Nordic Test System Development in**
Thierry van Cutsem, Advancements in Power System Analysis Test Cases: Voltage Stability *(18PESGM2383)*
*Tue, Aug 7, 1:00pm-3:00pm, Room OC-D133+D134*

# Conclusions

- **multiDC: Holistic approach** to the emerging problems of multiple **HVDC interconnections and grids**
  - Robust control for varying inertia and zero-inertia systems
  - 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

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# Thank you!

spchatz@elektro.dtu.dk

www.chatziva.com

www.multi-dc.eu

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