A Design Perspective: What Distinguishes Floating Wind Farms With Conventional- and Shared Mooring Systems?

EERA DeepWind 2024

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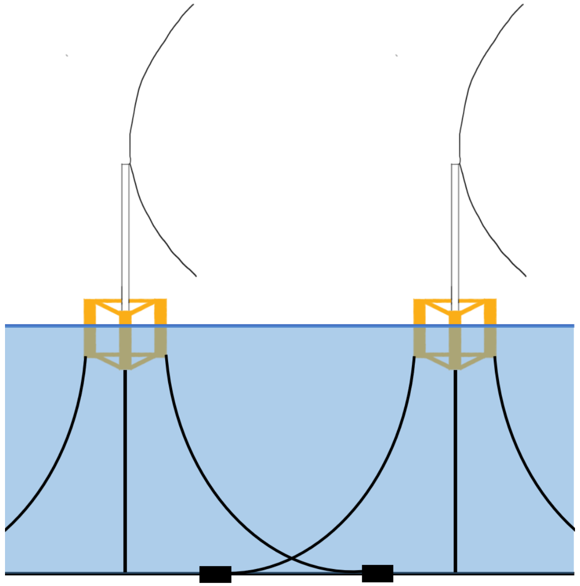
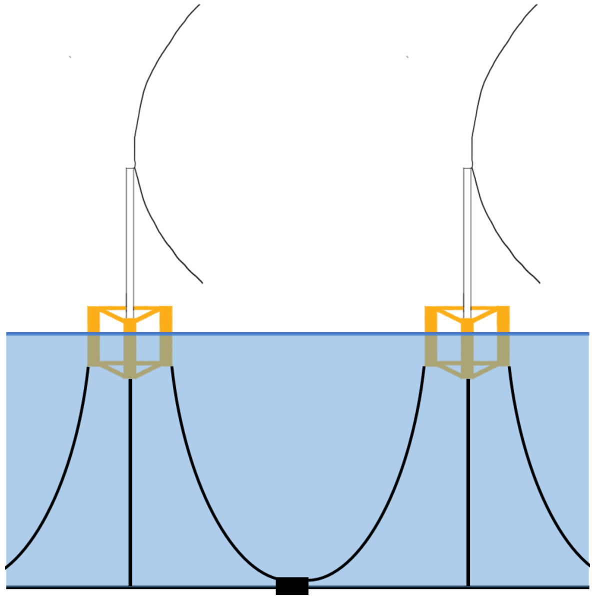
1. SINTEF Ocean
2. NTNU
3. NOV APL
4. Cefront Technology
5. DNV
6. Equinor

Conventional mooring systems

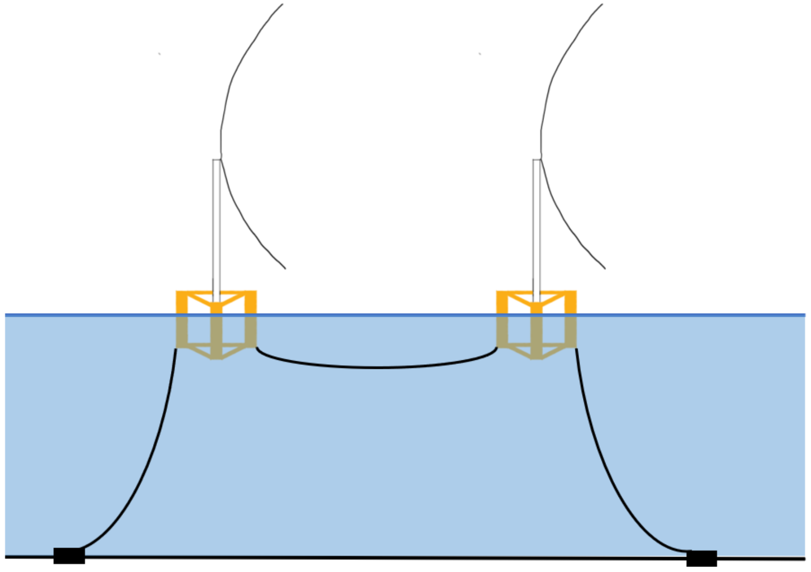
- **Conventional system:** individual mooring lines with shared- or individual anchors
  - Hywind Tampen



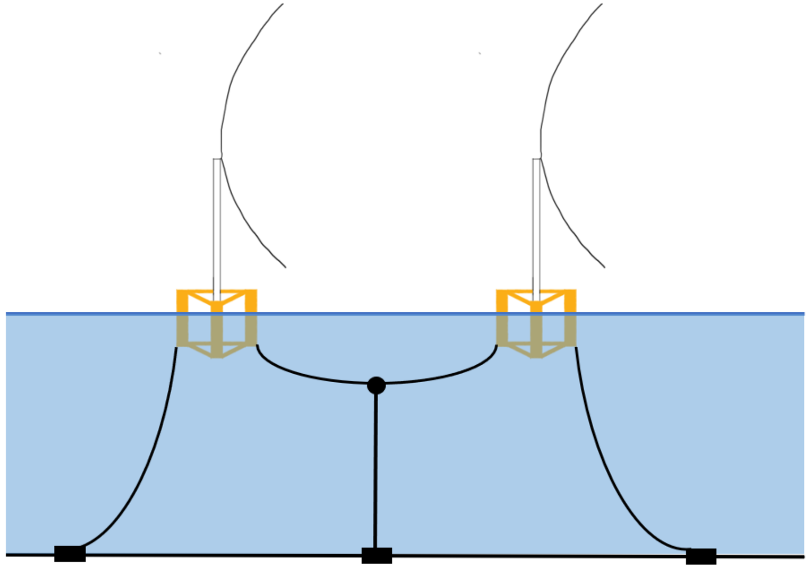


Shared mooring systems

- **Shared mooring system:** shared line(s) and possible anchor(s)



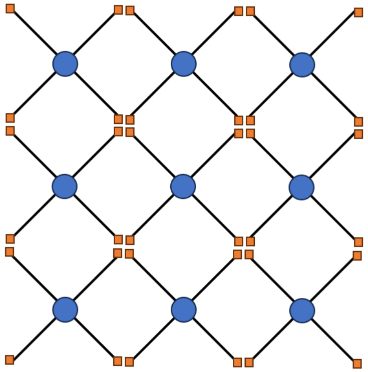
- Direct shared line floater-to-floater
- Indirect shared line floater-moored buoy-floater



Motivation

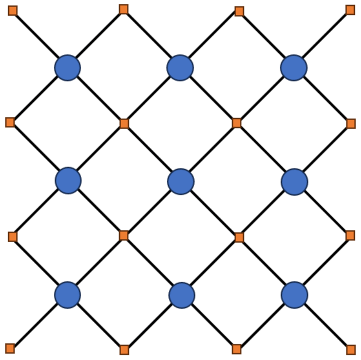
- Shared systems possible a mean to reduce:
  - Costs
  - Material usage
  - Seabed impact

Individual lines and anchors



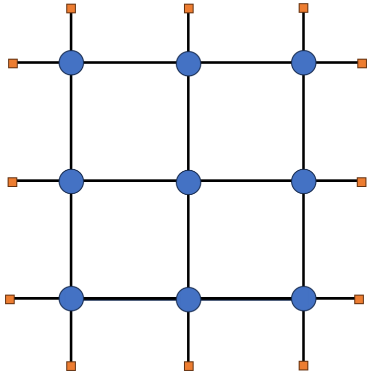
9 wind turbines
36 mooring lines
36 anchors

Individual lines, shared anchors



9 wind turbines
36 mooring lines
24 anchors

Shared lines, individual anchors



9 wind turbines
24 mooring lines
12 anchors

Shared mooring system

- **Synthetic fiber** ropes in combination with **buoys** and **clump weights**
  - General trend: avoid chain and other components
  - 3-4 lines for each turbine
- Wide range of horizontal **eigenperiods**
  - Low frequency range
  - Total system load
- **Cumulated** offset and static loading
  - Large range of static mooring line tension
  - **Slack lines**
- Line failure consequences

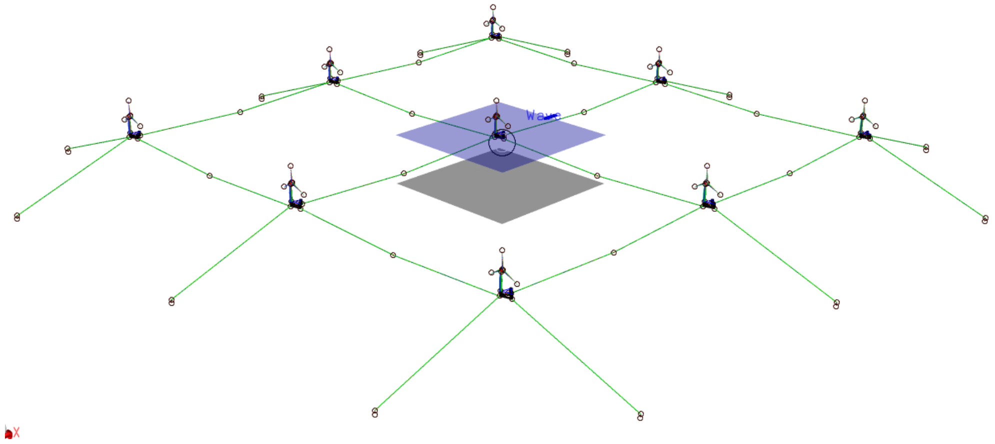


Figure taken from [1]

[1] Rajasree, V. R. N., et. al., *Modelling and dynamic analysis of wind farms using SIMAPy and SIMA*, NTNU, CYBERLAB KPN Presentation 2023.

Rules and regulations

- DNV ST-0119 will be revised
- Floating Wind Reliability Joint Industry Project

- DNV, ISO, NORSOK, API, IEC, HAVTIL

➢ Targeted towards **conventional mooring systems**

➢ Existing rules and regulations are currently not **adequate for shared systems**

Previous academic work about shared mooring

- Lozon, E. and Hall, M., ***Coupled loads analysis of a novel shared-mooring floating wind farm***, Applied Energy 332 (2023) 120513.
- Hall, M., et. al., ***Shared Mooring Systems for Deep-Water Floating Wind Farms***, NYSERDA Report, 2022, Contract 142869.
- Ahmad, I. B., et. al., ***An optimisation methodology for suspended inter-array power cable configurations between two floating offshore wind turbines***, Ocean Engineering 278 (2023) 114406.
- Xu, H., et. al., ***Shared mooring systems for offshore floating wind farms: A review***, Energy Reviews 3 (2024) 100063.
- Connolly, P. and Hall, M., ***Comparison of pilot-scale floating offshore wind farms with shared moorings***, Ocean Engineering 171 (2019) 172-180
- Hall, M., et. al., ***Design and analysis of a ten-turbine floating wind farm with shared mooring lines***, Journal of Physics: Conference Series 2362 (2022) 012016.
- Wang, Y., et. al., ***Preliminary Investigation of a Shared Mooring Arrangement for a Floating Offshore Wind Turbine Farm in Deep Water***, OMAE2022-81245
- Liang, G., et. al., ***Influence of Aerodynamic Loads on a Dual-Spar Floating Offshore Wind Farm With a Shared Line in Parked Conditions***, OMAE2022-78929.
- Sauder, T., ***Second-order wave loads on floating wind parks with shared mooring***, 2023, J. Phys.: Conf. Ser. 2626 012038.
- Kvittem, M. et. al., ***Rational Simplification of High Fidelity Wind Turbine Models Used for Mooring Analysis***, Journal of Physics: Conference Series 2626 (2023) 012049.
- Wilson, S., et. al., **Linearized modelling and optimization of shared mooring systems**, Ocean Engineering 241 (2021) 11000**.**
- Liang, G., et. al., ***Modelling of a Shared Mooring System for a Dual-Spar Configuration***, OMAE2020-18467.

Main differences between conventional and shared mooring systems

Static – and dynamic behavior

- Direct load transfer between units
- Increased range of static mooring line loads
  - Due to cumulative tension
  - Possible slack leeward line
- Coupled floater response
  - Coupled eigenmodes

Special design considerations

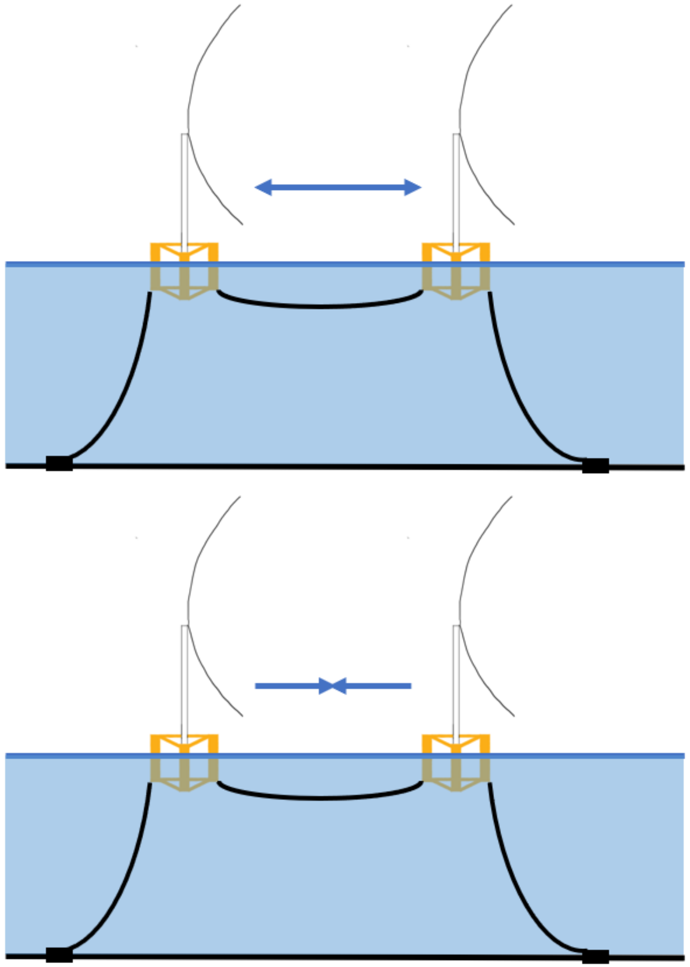
- Line failure and consequences
- Alternative cable topology layouts and design criteria
- Alternative park control and wake steering strategies
- Turbine spacing
  - Aerodynamics
  - Mooring system design
- Sailing depth requirements for shared horizontal lines
- Installation procedures
- Operation, maintenance and repair

Numerical modelling requirements

- Large numerical models
- Increased number of design load cases
  - ULS
  - ALS
  - Turbines in production and stand-still
- Varying environmental conditions
  - Dynamic wake effects
  - Inhomogeneous wave?

Design load cases – Ultimate Limit State

ULS criteria: design mooring system to avoid failure due to extreme loads. 50-year load/load effect [1]



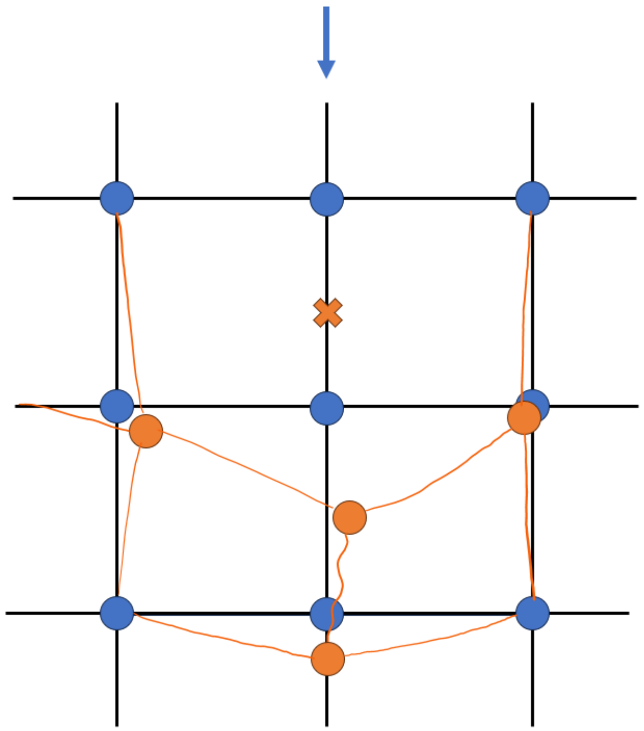
- Similar design load as for conventional systems?
- **Coupling effects** might change extreme responses
- Coupled **eigenmodes**
- Direction of environmental loads
  - DNV-ST-0119 Most unfavorable direction?
- Turbines in operation and stand-still

[1] DNV AS, DNV-ST-0119 – Floating wind turbine structures, 2021.

Line failure – Accidental Limit State

ALS assumption: post-damage behavior and remaining redundancy after **unexpected** line break. 1-year load/load effect [1]

- **Today's practice** for shared anchors
- Large number of failure modes and load cases
  - Static analysis for early-stage design
  - Transient load analysis after failure
- Shut-down requirements?
- Post damage behavior **layout- and design** dependent [2]



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[2] Lozon, E. and Hall, M., *Coupled loads analysis of a novel shared-mooring floating wind farm*, Applied Energy 332 (2023) 120513.

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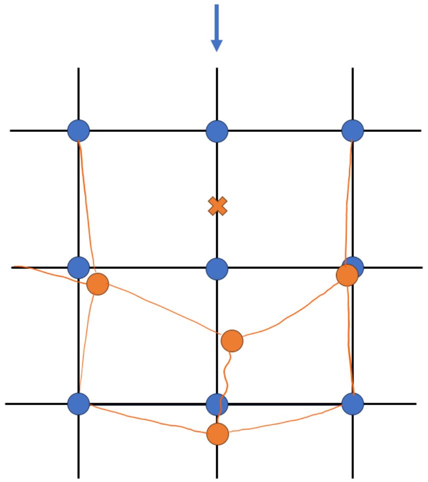
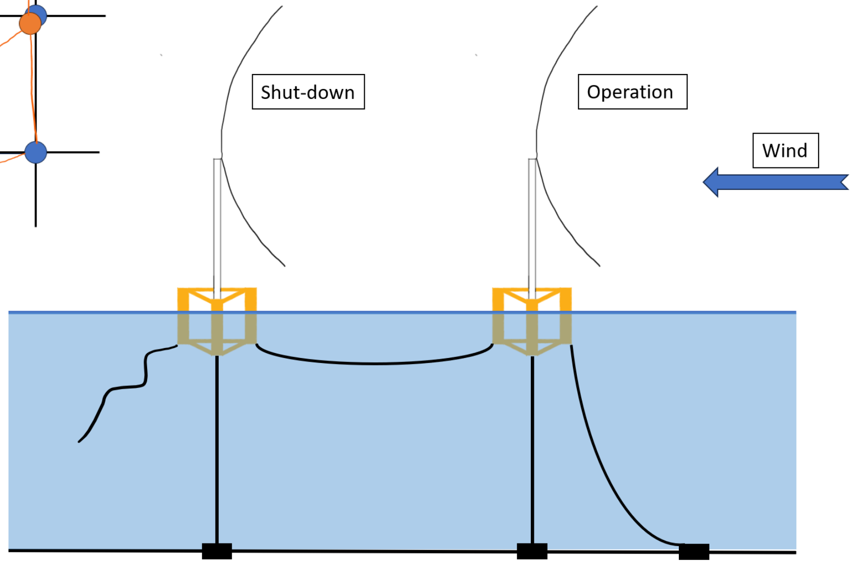
Line failure - Different turbine states

- Crucial to **avoid shut-down** on all turbines
  - Economical consequences
- Line replacement: ~2 weeks
- Control system
- Disconnection of power cable





Inter-array power cable

- Common practice:
  - 2 cables connected to each unit
  - 1 extra cable for export
- Cable layout
  - (a),(b): floater motion
  - (c): relative motion
- Weak link connection

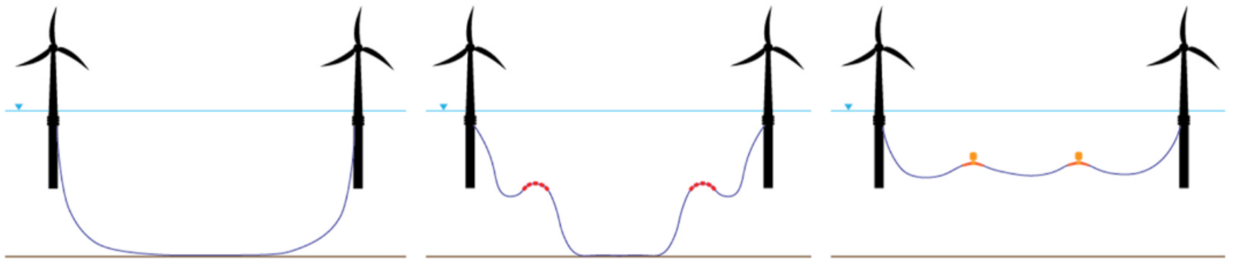


Fig. 1. Cable configurations. From left, (a) Free hanging catenary; (b) Lazy wave; (c) Fully suspended.

Figure taken from [2]

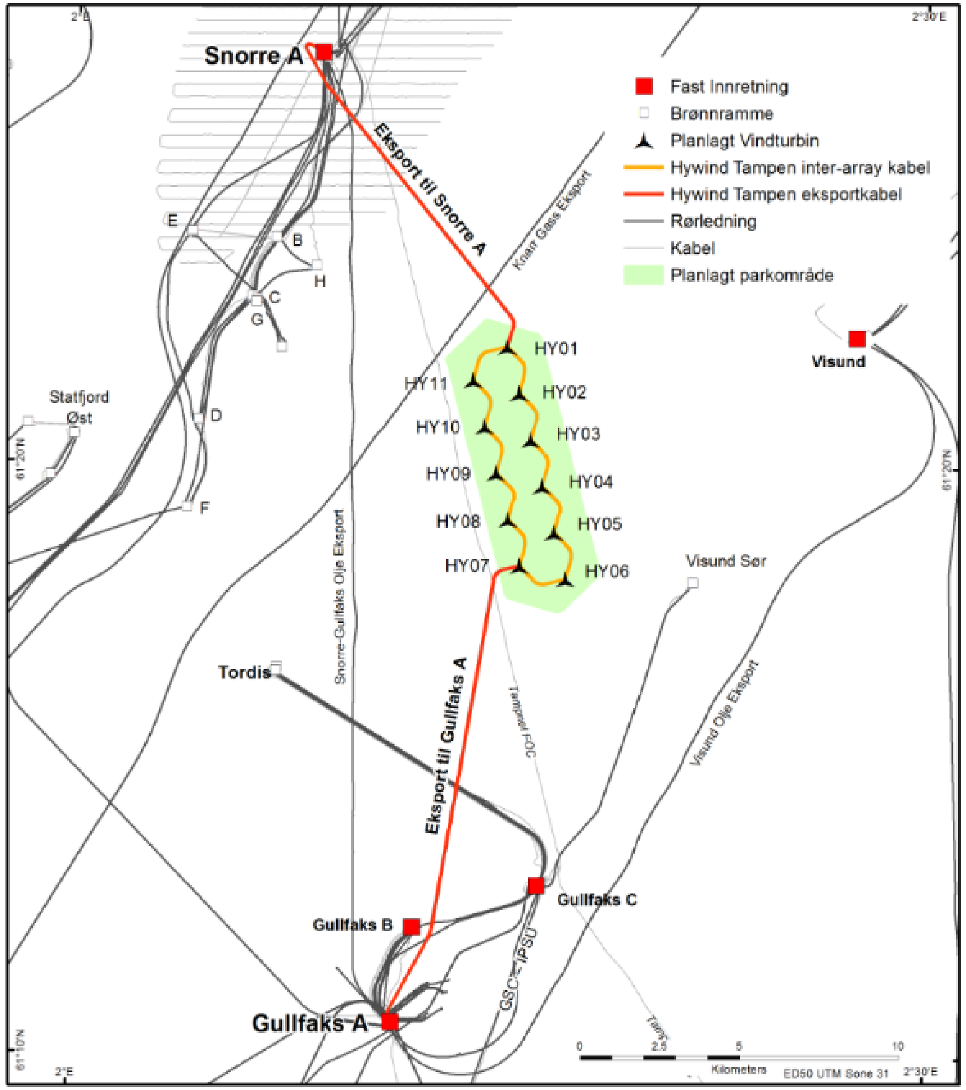


Figure taken from [1]

[1] Equinor, *Hywind Tampen – PL050 – PL057 – PL089 – PUD del II – Konsekvensutredning*, 2019

[2] Ahmad, I. B., et. al., *An optimisation methodology for suspended inter-array power cable configurations between two floating offshore wind turbines*, Ocean Engineering 278 (2023) 114406

Control system

- Maximized power production and load control
  - Similar as for conventional systems
- Alternative **park control** [1]
- **Wake steering** strategies
  - Reduced wake effects vs. increased wear
- Cumulated load mitigation
- **Line failure**
  - Control strategies to reduce loads and continue production

[1] Meyers, J., et. al., *Wind farm flow control: prospects and challenges*, Wind Energ. Sci., 7, 2271–2306, 2022

Numerical simulations of shared mooring systems

- **Time domain:** full system effects
  - Different methods available [1]
- **Frequency domain:** not used extensively for design of conventional systems
- **Industry standard:** experience combined with time domain analysis
- Increased need for efficient tools with many degrees of freedom
  - Coupling modes
  - Increased number of load cases in early-stage design
  - Increased number of iteration for layout- and mooring system design
  - Optimization
  - Full quadratic transfer functions

[1] Kvittem, M. et. al., *Rational Simplification of High Fidelity Wind Turbine Models Used for Mooring Analysis*, Journal of Physics: Conference Series 2626 (2023) 012049.

[2] Sauder, T., *Second-order wave loads on floating wind parks with shared mooring*, 2023, J. Phys.: Conf. Ser. 2626 012038.

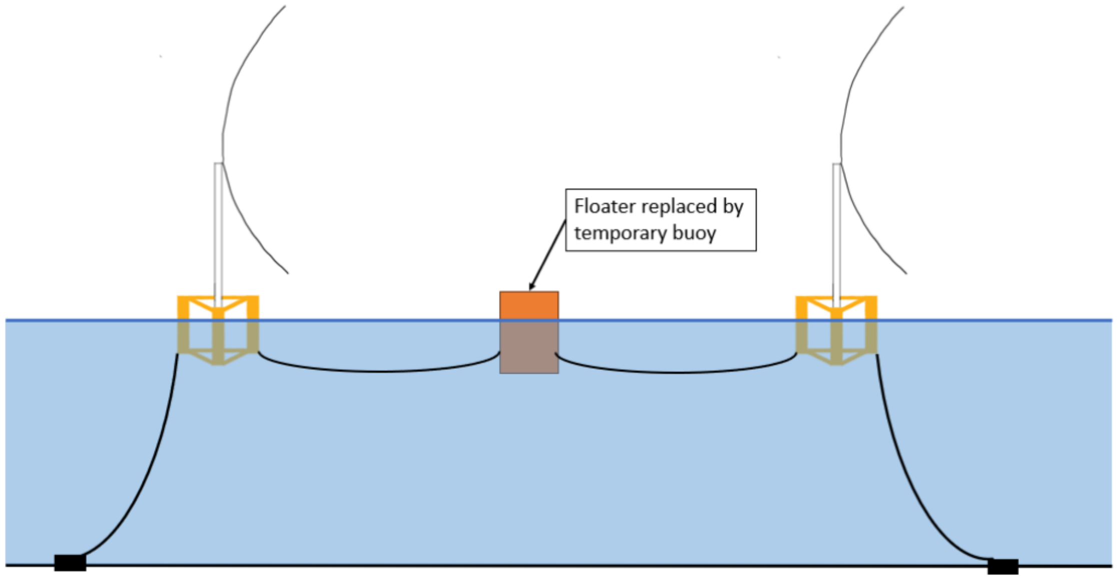
Installation

- **Today:** installation expected to be more complex
  - Taut lines
  - Station keeping during installation
- **Integrity** of mooring system in installation phase
  - Hywind Tampen [1]
- Desirable to design for no **re-tensioning** of lines

[1] Equinor, https://www.equinor.com/news/20230823-hywind-tampen-officially-opened, visited 2024-01-09

Repair

- Integrity of system during repair
  - Unit towed to shore
  - **Temporary** solution?
  - **Pre-tension** hook-off/on



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Thank you for your attention!

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