Report

Deep Sea Offshore Wind R&D Conference
24 – 25 January 2013

Royal Garden Hotel, Trondheim

Author:
John Olav Tande (editor)
Deep Sea Offshore Wind R&D Conference
24 – 25 January 2013
Royal Garden Hotel, Trondheim

ABSTRACT
This report includes the presentations from the 10th Deep Sea Offshore Wind R&D Conference, DeepWind'2013, 24 – 25 January 2013 in Trondheim, Norway. This anniversary of the conference attracted a good selection of high quality presentations and posters. Presentations include plenary sessions with broad appeal and parallel sessions on specific technical themes:

a) New turbine technology
b) Power system integration and Grid connection
c) Met-ocean conditions
d) Operations & maintenance
e) Installation & sub-structures
f) Wind farm modelling

Plenary presentations include frontiers of science and technologies and strategic outlook. The presentations and further conference details are also available at the conference web page http://www.sintef.no/Projectweb/Deepwind_2013/

Full papers of selected presentations will be published online in Energy Procedia (Elsevier).
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<td>7. A Markov Weather Model for O&amp;M Simulation of Offshore Wind Parks, Brede Hagen, stud, NTNU</td>
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<td>8. Turbulence Analysis of LIDAR Wind Measurements at a Wind Park in Lower Austria, Valerie-Marie Kumer, UiB</td>
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<td>9. Investigation of droplet erosion for offshore wind turbine blade, Magnus Tyrhaug, SINTEF</td>
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<td>10. A Fuzzy FMEA Risk Assessment Approach for Offshore Wind Turbines, Fateme Dinmohammadi, Islamic Azad University</td>
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# DeepWind 2013 - 10th Deep Sea Offshore Wind R&D Seminar

**24-25 January 2013, Royal Garden Hotel, Kjøpmannsgata 73, Trondheim, NORWAY**

## Friday 25 January

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<td>Øyslebø, Eirik</td>
<td>Norges vassdrags- og energidirektorat</td>
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3 Scientific Committee and Conference Chairs

An international Scientific Committee was established with participants from leading research institutes and universities for reviewing submissions and preparing the conference programme. The members of the Scientific Committee of DeepWind'2013 are listed below.

Anaya-Lara, Olimpo, Strathclyde University
Berge, Erik, Kjeller Vindteknikk
Buhl, Thomas, DTU
Busmann, Hans-Gerd, Fraunhofer IWES
Bussel, Gerard J.W. van, TU Delft
Faulstich, Stefan, Fraunhofer IWES
Krokstad, Jørgen, Statkraft
Kvamsdal, Trond, NTNU
Langen, Ivar, UiS
Leithead, William, Strathclyde University
Madsen, Peter Hauge, DTU
Moan, Torgeir, NTNU
Molinas, Marta, NTNU
Muskulus, Michael, NTNU
Nielsen, Finn Gunnar, Statoil
Nygaard, Tor Anders, IFE
Reuder, Jochen, UiB
Sirnivas, Senu, NREL
Tande, John Olav, SINTEF
Uhlen, Kjetil, NTNU
Undeland, Tore, NTNU

The conference chairs were

- John Olav Gjæver Tande, Director NOWITECH, senior scientist SINTEF Energy Research
- Trond Kvamsdal, Chair NOWITECH Scientific Committee, Associate Professor NTNU
- Michael Muskulus, Vice Chair NOWITECH Scientific Committee, Professor NTNU
Opening session - Frontiers of Science and technology

Innovations in offshore wind technology,  
John Olav Tande, SINTEF/NOWITECH

Key research topics in offshore wind energy,  
Kristin Gulbrandsen Frøysa, CMR/NORCOWE

Research at Alpha Ventus deep offshore wind farm,  
Stafan Faulstich, FH IWES

WindFloat deep offshore wind operational experience,  
Pedro Valverde, EdP

HyWind deep offshore wind operational experience,  
Finn Gunnar Nielsen, Statoil
Innovations in Offshore Wind Technology through R&D

www.nowitech.no
John Olav Gjæver Tande
Director NOWITECH
Senior Scientist
SINTEF Energy Research
John.tande@sintef.no

NOWITECH in brief
► a joint pre-competitive research effort
► focus on deep offshore wind technology (+30 m)
► budget (2009-2017) EUR 40 millions
► co-financed by the Research Council of Norway, industry and research partners
► 25 PhD/post doc grants

Vision:
• large scale deployment
• internationally leading

A large growing global market
► Firm European commitment to develop offshore wind
► EU offshore wind forecast 2020:
  • Total installed capacity 40 GW
  • Total investments EUR 60.9 billions
► EU offshore wind forecast 2030:
  • Total installed capacity 150 GW
  • Total investments EUR 142.2 billions
► Significant developments also in China, Japan, Korea and USA
► The near-term large commercial market is mainly for bottom-fixed wind farms at shallow to intermediate water depths (50 m)
► Significant interest in developing floating concepts expecting large volume after 2020
► Threat: International financial crisis / economic recession

Main drivers
► Battle climate change
► Security of supply
► Industry value creation

Stern Review (2006):...strong, early action on climate change far outweigh the costs of not acting.

NOWITECH Research partners:
► SINTEF (lead)
► NTNU
► Fraunhofer IWES
► DTU Wind Energy
► RWE Innogy SE
► EDF R&D
► NCEI
► ERE
► SmartMotor AS
► NTE Holding AS
► Rystad SF
► Statkraft

NOWITECH Industry partners:
► Det Norske Veritas
► ABB
► Chiyoda
► Norsk Hydro
► Statoil

A possible Norwegian market, but uncertain
► NVE has identified 15 areas for development of offshore wind farms (total ~10 GW); five are suggested prioritized (public inquiry due 4/4-13)
► Applying the petroleum taxation regime to offshore wind farms for supply to oil and gas installations may create a immediate Norwegian market (total ~100-1000 MW)
► A significant Norwegian market for onshore turbines are expected through green certificates, e.g. 6 TWh by 2020 (total market for green certificates in Norway and Sweden is 26 TWh).
Exciting floating concepts

BlueHi (2007, 80 kW)
HiPRwind (2009, 2.3 MW)
NREL/MIT (2011, 2.3 MW)

New generator concept allows for direct HVDC connection to shore and avoiding costly offshore sub-station
New support structure avoid costly transition piece between tubular tower and jacket

NOWITECH 10 MW reference turbine

The NOWITECH 10 MW reference turbine introduces a new generator and support structure concept

Superconducting generators reduce weight

- 100 times the current density compared to copper
- More than doubles the achievable magnetic field
- Eliminates rotor losses
- Operating at 20-50 K
- New materials give new electromagnetic designs
- Possible step-changing technology
- Activity in new FP7 project: InnWind

Optimization of the offshore grid

- Inside and between wind farms
- New market solutions are required
- New technology (HVDC VSC, multi-terminal, hybrid HVDC/HVAC, ...)
- Protection, Fault handling, Operation, Control, Cost, Security of Supply

Innovative DC grid solutions for offshore wind farms avoiding need for large sub-station

Conventional system

Innovative DC grid solutions

Remote presence reduce O&M costs

- It is costly and sometimes impossible to have maintenance staff visiting offshore turbines
- Remote presence:
  - Remote inspection through a small robot on a track in the nacelle equipped with camera / heat sensitive, various probes, microphone etc.
  - Remote maintenance through robotized maintenance actions
Integrating structural dynamics, control and electric model

Best poster at EOW 2011

Reducing uncertainties by better models

- Integrated models simulate the behavior of the complete turbine with substructure in the marine environment: SIMO-RIFLEX (MARINTEK) and 3DFloat (IFE)
- Model capability includes bottom fixed and floating concepts
- Code to code comparison in IEA Wind OC3 and OC4
- Model to measurements comparison in progress

SEAWATCH Wind Lidar Buoy

- Cost efficient and flexible compared to offshore met mast
- Measure wind profiles (300 m), wave height and direction, ocean current profiles, met-ocean parameters
- Result of NOWITECH "spin-off" joint Industry project by Fugro OCEANOR with Norwegian universities, research institutes and StatOil.

Strong research infrastructure in development

- Users:
  - Research & Industry
  - Main Objectives:
    - Industrial value creation, and more cost-effective offshore wind farms
    - Build competence and gain new knowledge
  - Develop and validate numerical tools and technical solutions

From Idea to Commercial Deployment

NOWITECH achievements

- NOWITECH is about education, competence building and innovations reducing cost of energy from offshore wind
- Strong consortium with leading research and industry parties
- Excellent master and PhD programme: 25 PhD & post doc grants
- Strong scientific results: ~100 peer-reviewed publications
- R&D results give value creation and cost reductions
- Innovation process is enhanced through TRL
- Two new business developments (Remote Presence + SiC coatings)
- Strong infrastructure in development: NOWERI
- A high number of spin-off projects: total volume EUR 125 millions (EU (11), KPN etc. (10), IPN (7) and research infrastructure (3))
- Vision: large scale deployment & internationally leading

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- Vision: large scale deployment & internationally leading
### Rounding up

- Remarkable results are already achieved by industry and R&D institutes on deep offshore wind technology.
- Technology still in an early phase – Big potential provided technical development and bringing cost down.
- Research plays a significant role in providing new knowledge as basis for industrial development and cost-effective offshore wind farms at deep sea.
- Cooperation between research and industry is essential for ensuring relevance, quality and value creation.
- Test and demonstration, also in large scale, is vital to bring research results into the market place.
- Offshore wind is a multidisciplinary challenge – international collaboration is the answer!
- Outlook is demanding, but prosperous with a growing global market.

**NOWITECH**

#### NOWITECH is a joint 40M€ research effort on offshore wind technology.

- Integrated numerical design tools
- New materials for blades and generators
- Novel substructures (bottom-fixed and floaters)
- Grid connection and system integration
- Operation and maintenance
- Assessment of novel concepts

[link to NOWITECH](http://www.NOWITECH.no)

**We make it possible**

**Questions?**
Key research topics in offshore wind energy
DeepWind 2013
Kristin Guldbrandsen Frøysa
Director NORCOWE
kristin@cmr.no

Outline
- Motion compensation
- Measurements and database
- Wind farm layout
- Wind farm power control and prediction

Description of wind shear
- Empirical power law description of the vertical wind shear:
  \[ \overline{u(z)} = u_{\text{ref}} \left( \frac{z}{z_{\text{ref}}} \right)^n \]
- The logarithmic wind profile
  \[ \overline{u(z)} = \frac{u_z}{k} \ln \frac{z}{z_0} \]

Wind profiles and stability
- Measurements at high towers show, that these wind profiles based on surface-layer theory and Monin-Obukhov scaling are only valid up to ca. 50-80 m

Only few offshore measurements
- Measurements up to 100 m
  Shallow waters (~ 20 m)
- Deep water measurements possible
  Measurements only up to ~ 20 m
Satellite data (SAR, QuickScat)
Ocean wind speed map from ERS SAR from Horns Rev in the North Sea, Denmark observed 6 October 2004. The Horns Rev offshore wind farm is located in the trapezoid.

**Shortcomings:**
- limited temporal resolution
- uncertainty in determination of relevant wind speed over the rotor disk

Source: http://galathea3.emu.dk/satelliteeye/projekter/satellite_elk.html

---

**Lidar going offshore**

**Why?**
- Poor information on the offshore wind field in the relevant height interval (30..200 m)
- Corresponding mast structures are expansive and rather inflexible

**Challenges**
- Motion avoidance or motion correction
- Adaptation to harsh marine environment
- Energy for long term deployments

---

**Lidar going offshore**

- SeaZephIR (Natural Power)
- Fidar (3E)
- WindSentinel (Axys)
- Wavescan ZephIR (Fugro Oceanor)
- ZephIR lidar on spare or tension leg buoy
- Windcube on industrial buoy; mechanical stabilization
- Vindicator on a boat structure
- ZephIR on Wavescan buoy

---

**Lidar movement testing**

- Application of 55 different motion patterns on a 6-DOF motion platform, 3 hours each

---

**Offshore comparison**

**Field Test - Wind speed at 53m**

**Date [06/mm/2012]**

---

**Experimental Work**

- Motion laboratory at University of Agder (UiA)
- Calibration of simulation model
- Use of Stewart platforms to perform an offshore payload transfer experiment.

Source: Stappo & Optibard, Ltd.
HMF 2200-K4 Loader Crane

- 2012:
  - Foundation
  - Instrumentation
  - Modeling & Simulation
  - (Real Time Simulation)

- Future work (2013):
  - Control System
  - Experimentation

Real Time Simulation

- Human Operator
- Real Time PC
- Simulation Model
- Control System

Strengths of model reduction techniques

- **Physical**
  - The method solves the non-linear flow equations in a reduced space.
- **Fast**
  - The method provides CFD quality results within seconds of computational time (single CPU).
- **Power production**
  - Individual turbine production calculated.
- **Turbulence**
  - 3D flow fields for both velocity and turbulent kinetic energy are computed.
- **Transfer**
  - The model reduction technique can take advantage of improvements in the CFD tool, such as improved turbine and turbulence models.

Illustration of interface

- Wind farm Interactive Layout Design
- Interactive layout design
- Fast energy yield prediction

Regular grid

- Regular layout: what is the sensitivity of the estimated power production on changing turbine distance (± .5 D)?
Irregular grid

- Non-regular layout: investigate selected non-regular layouts. What is the energy yield compared to a regular layout setup?

Power production sensitivity

- Regular / non-regular layout: What is the sensitivity of the power production on variations of the wind rose?

- This could highlight how changes in the inflow conditions due to nearby wind farms potentially would affect the power production of the downstream wind farm.

Where we are today

- A prototype model reduction tool has been developed in NORCOWE
  - The technique has been verified by comparison to CFD results for simple cases of a few turbine rows.
  - Flow cases with more than 20 turbines have been computed within seconds on a single CPU.

Wind farm power control and prediction

Can a dynamic controlled power set point control of all turbines improve total production further?

Can "total" fatigue be reduced with control of power set points on farm level?

- Fatigue for farm turbines are highly dependent on wakes and increased turbulence from neighbor turbines.
Thank you for your attention!

www.norcowe.no
Content
Alpha ventus,…
- milestones
- layout
...RAVE…
- Objectives
- Measurements
- Exemplary results
...and beyond
- Continuation of RAVE
- Technology monitoring

The Fraunhofer Institute for Wind Energy and Energy System Technology IWES
Applications-oriented research in wind energy & energy systems technology for renewable energies
- One of 80 Fraunhofer Institutes
- Budget ~ 22 million €
- Staff ~ 300
- Funding by Federal Ministries, Länder and the EU; Industry

The Fraunhofer IWES – experimental facilities
Exemplary Highlights
Competence Center
Rotor Blade
Climate chamber
200 meter measuring mast

www.fraunhofer.iwes.de

Alpha ventus: milestones
- 2001 Approval
- 2003 FINO 1 operating
- 2008 Substation install Export cable install
- 2009 All WT installed Infield cable installed All WT operational
- 2010 Official inauguration
Alpha ventus: project details

- North Sea
- 45 km north of Borkum
- Water depth: 30 m
- 12 turbines
- 5 MW class
- AREVA Wind M5000
- Repower 5M

Alpha ventus / results 2011

- Production (2011): 267 GWh
- 4,450 full load hours

RAVE – Research at alpha ventus

- Funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
- Accompanying research at the alpha ventus test site
- 33 R&D projects
- 51 mill. €
- 50+ project partners ~200 Scientists

RAVE – Steering Committee:

Main objectives of RAVE

Demonstration Development Investigation of OWP issues

Expand research, experience & expertise

RAVE – R&D contents

- foundations & support structures
- turbine technology & monitoring
- environment & social acceptance
- grid integration

RAVE – measurements

Environmental investigations Turbine-specific measurements
RAVE – measurements

- Detailed load and turbine data from four wind turbines
- LiDAR (upwind and downwind)
- SCADA data of all turbines
- Geotechnical, oceanographic and environmental data
- Electrical data from substations
- Meteorological data from FINO1

In total about 1300 Sensors!

RAVE 2012: exemplary research results

- Development and test of non-invasive methods to monitor imperfections
- Development of a monitoring device/tool for grouted joints
- Wave load models: real/measured loads from breaking waves will be included in future design

RAVE 2012: exemplary research results

- Lidar based control can improve the energetic output of a turbine by 1-2 %
- Progress in turbulence and wake simulation and in understanding turbulence interaction between offshore wind farms
- An operation and failure statistics data base is of high relevance – progress is underway

RAVE 2012: exemplary research results

- Bubble curtains reduce pile driving noise emission effectively
- Operational sound is of lower ecological relevance
- Social acceptance increased 2011 compared to 2009;

Offshore-specific wind power forecasts and power fluctuation forecasts

Control of offshore wind farm clusters
RAVE

RAVE has achieved its goals:
• Proven the offshore-capability of the 5 MW turbine class
• Facilitated further development of offshore wind technology in many areas
• Improved the knowledge about offshore wind utilisation
• Produced an invaluable and unique data set of measurements

RAVE will continue, but the focus will move:
• from design and erection to operation and maintenance
• from demonstration to research

What is RAVE today?

• A research lab in the middle of the North Sea
• A huge unique set of measurement data
• A research community dedicated to OWP
• An interdisciplinary knowledge base for OWP topics

Technology Monitoring

Scientific Measurement and Evaluation Program ("250 MW Wind" (1989-2006))
193,000 monthly operation reports
and 84,000 incident reports from 1,500 wind turbines

Reliability
Technology development
Learning curves

To answer fundamental questions on development of wind power offshore
⇒ General monitoring

To optimize operation and maintenance
⇒ Systematic collection and evaluation of operational experiences

Thank you for your attention!

WWW.RAVE-OFFSHORE.DE
⇒ with info about the individual research projects
WWW.RAVE2012.DE
⇒ presentation slides of the International Conference RAVE 2012
RAVE SCIENCE DOCUMENTARY
"Challenge Offshore"
⇒ www.youtube.com/user/RAVEoffshore/videos

All pictures in this presentation are subject to copyright.
Why Floating Offshore Wind?

Why Offshore Wind?
- Higher wind resource and less turbulence
- Large ocean areas available
- Best onshore wind locations are becoming scarce
- Offshore wind, including deep offshore, has the capacity to deliver large amounts of energy

Why Floating Offshore Wind?
- Limited locations with shallow waters (mostly in the North Sea)
- Most of the offshore wind resource is in deep waters
- Unlimited installation sites available
- Less restrictions for offshore deployments and reduced visual impacts
- Enormous potential around the world: PT, Spain, UK, France, Norway, Italy, the Americas, Asia...

The WindFloat Technology

The WindFloat Technology leads to high stability even in rough seas

Turbine Agnostic
- Conventional turbine (3-blade, upwind)
- Changes required in control system of the turbine

High Stability Performance
- Static Stability - Water Ballast
- Dynamic Stability - Howe Plates and active ballast system
  - Move platform natural response above the wave excitation
  - Viscous damping reduces platform motions
- Efficiency – Closed-loop Active Ballast System

Depth Flexibility (>40m)
- Assembly & Installation
  - Port assembly – Reduced risk and cost
  - No specialized vessels required, conventional tugs
  - Industry standard mooring equipment

The WindFloat Technology

The WindFloat project involves knowledge, intellectual property for WindFloat and other, Multi-MW WindFloat and related equipment

Aguçadoura, Portugal, June 2006

Capacity: 200kW

WindFloat technology development – Derived from D&G concept and is now being tested full scale at sea

Phase 1 – Demonstration
- Capacity: 200kW
- WindFloat test prototype
- Location: Aguçadoura, grid connected
- ~6 km of coast, 40-50 m water depth
- Turbine: 200kW offshore wind turbine
- Test period: 24+ months

Phase 2 – Pre-commercial
- Capacity: 27MW (~5 WindFloat units)
- Location: Portuguese Pilot Zone
- Turbine: Various models and other, Multi-MW

Phase 3 – Commercial
- Capacity: 150MW, gradual build-out
- Location: TBD
- Turbine: TBD

The WindFloat Project

The WindFloat project is structured to follow a phased / risk mitigation approach

Reduced Risk and Cost

- requires NO PILLING
- is structurally decoupled from seabed
- is independent from depth
- is assembled and commissioned quayside
- does NOT require high lift capacity vessels

The WindFloat Technology

Due to the features of the WindFloat, the risk and cost of offshore works is significantly reduced
The WindFloat Project

The WindFloat project was structured as a Joint Venture, WindPlus. The Project is promoted by…

WindFloat...in a joint venture...

WindPlus...and counts with the support of...

The WindFloat Project

The development of the WindFloat project carried enormous challenges due to the lack of know-how in Portugal. The WindFloat Project followed the typical approach...the project being done for the first time...Lack of offshore know-how in Portugal...different cultures involved (US, Denmark, Portugal, France)...collaboration between two different industries that have never worked together (Oil & Gas and Wind Industry)...Standards & Rules for design exist but need to be adapted.

The WindFloat Project

Effective Risk Management must be embedded into the project since the very early beginning. Risk Management methodologies implemented throughout the project were key for the success of the project. HAZOP – Hazard Identification Study...HAZOP – Hazard and Operability Study...HRA – Hazard identification and Risk Assessment...HAZOP Action forms...HAZOP Analysis...Fabrication...Operational...Installation...Testing...HAZA...Risk Mitigation Activities

The WindFloat Project

The project was completed in less than 2.5 years. Fabrication completed in less than 9 months.

The WindFloat Project

[Diagram showing project planning stages and risk mitigation activities]
Pre-assembly of the columns outside the Dry-dock in Setúbal

Columns moved to Dry-dock

Dry-dock assembly

Mooring Pre-Lay in parallel with the fabrication

Turbine installation in the Dry Dock using the shipyard’s gantry crane

Tow from Setúbal to Aguçadoura (~400 km) using the same vessel that was used for the mooring installation
The WindFloat Project

Hook-up at final location

In Operation since December 2011!

Preliminary performance analysis
The Windfloat is monitored 24 hours a day remotely

The WindFloat is monitored 24 hours a day remotely

Survivability and performance proved in normal and extreme conditions

- The fabrication and installation were successfully complete despite all the challenges faced
- The technical results of the first 6 months of operation of the WindFloat are very promising
- The testing and monitoring of the WindFloat will continue during the next years
- WindPlus will start to prepare the Pre-Commercial phase
- One step towards the development of deep offshore wind

In Operation since December 2011!

Preliminary performance analysis

Thank you!
The starting point -2001

- Inspired by floating sailing marks.
- "Seawind" matured during 2002.

The Hywind concept

Key features
- Combines known technologies
- Designed for harsh environment
- "Standard" offshore turbine
- Water depth >100 m
- Assembled in sheltered waters, towed to field

Relies upon experience from:
- Floating platforms
- Electrical power production
- Onshore wind turbines

From idea to commercial concept

What does it take?

- Creativity
- Competence & experience
- Endurance
- Business understanding
- Professional project execution
- Management commitment
- Timing
- Funding

MODEL SCALE EXPERIMENTS 2005

- Demonstration of system behaviour
- Validation of numerical tools
- Model scale 1:47
- Irregular waves, turbulent wind, and various control strategies
Assembly and installation of Hywind Demo Summer 2009

Operation in harsh environment
- Max wind velocity: 40 m/sec
- Max sign wave height: 10.5 m

Full scale measurements
- A total of more than 200 sensors:
  - Waves and current (magnitude and direction)
  - Motion (6 DOF) and position of floater
  - Mooring line tension
  - Strain gauges at tower and hull (4 levels – bending moments and axial forces)
  - Rotor speed, blade pitch and generator power
  - Flap- and edgewise rotor bending moments
  - Motion (tower pitch) / blade pitch controllers

Hywind Operation and monitoring

Integrated Operations – implementing O&G experience
- Integration of people process and technology
- Use of data, collaborative technology and multidisciplinary work

A base for testing vessels and access systems
- Fob Trim, Shi Merkur (MSDC12), Buddy, Fob Swath1, Bayard 3
- Undertun prototype access system, MaXcoss access system
Hywind performance in 2012

- 2 stops in Q1 due to external grid faults, total 57 days. Production loss of ~1.5 GWh
- Production 2012 is 7.4 GWh (8.9 GWh without grid error)
- 11% lower than normal wind speed
- Capacity factor 2012: 37% (would be 44% without grid error)
- September production 1.1 GWh, Capacity factor 54%.
- Focus on improvements, lower O&M cost

Production during a storm condition

- 24 hour period during storm “Dagmar”, Dec 2011
- Avg. wind speed 16 m/sec
- Max wind speed 24 m/sec
- Max significant wave height 7.1m
- Power production 96.7% of rated

Metocean data. Measured versus design basis

- Wind statistics
- Wind distribution from turbine. Orientation is indicated on coastline
- Overhead view of turbine

Data interpretation and validation

- Spectrogram of mooring line force
- 1 month of data shown
- Used for:
  - Error detection
  - Identification of natural frequencies.

Full scale versus computations

- Wind speed 17.5 m/sec, Significant wave height 4.0m, Current 0.4 m/sec
- Estimated wave time history.
- Computed motion response
- Wind forces included from measured wind spectrum
- Visualization

Bending moment in tower.

- Mean wind: 13.2 m/s Hs: 3.2 m Tp: 9.0 s
- East – West and North – South axis
Importance of motion controller

Hywind evolution
Use of experience - Improved design

- Bigger turbine
- Smaller hull
- Lower costs
- Site specific

Floating wind will compete with conventional bottom fixed solutions in a mature market

The next step

Thank You
A1 New turbine technology

Design Optimization of a 5 MW Floating Offshore Vertical Axis Wind Turbine, Uwe Schmidt Paulsen, Technical Univ. of Denmark, DTU

Operational Control of a Floating Vertical Axis Wind Turbine, Harald Svendsen, SINTEF Energi AS

Control for Avoiding Negative Damping on Floating Offshore Wind Turbine, Prof Yuta Tamagawa, Uni. of Tokyo

Towards the fully-coupled numerical modelling of floating wind turbines, Axelle Viré, Imperial College, London

Geometric scaling effects of bend-twist coupling in rotor blades, Kevin Cox, PhD stud, NTNU
Design Optimization of a 5MW Floating Vertical-Axis Wind Turbine

DeepWind 2013-10th Deep Sea Offshore Wind R&D Conference
24-25 January 2013 Trondheim, No

Uwe Schmidt-Paulsen
uwep@dtu.dk

Helge Aagård Madsen, Per Hørlyck Nielsen
Jesper Henri Hattel, Ismet Baran

DTU Department of Wind Energy, Frederiksborgvej 399 Dk-4000 Roskilde Denmark
DTU Department of Mechanical Engineering, Produktionstorvet Building 425 Dk-2800 Lyngby Denmark

Contents
• DeepWind Concept
• 1st Baseline 5 MW design outline
• Optimization process
• Results
• Conclusion

The Concept
• No pitch, no yaw system
• Light weight rotor with pultruded blades
• Floating and rotating tube as a spar buoy
• Long slender and rotating underwater tube with little friction
• Torque absorption system
• C.O.G. very low – counter weight at bottom of tube
DeepWind
The Concept

- No pitch, no yaw system
- Floating and rotating tube as a spar buoy
- C.O.G. very low - counter weight at bottom of tube
- Safety system

- Light weight rotor with pultruded blades
- Long slender and rotating underwater tube with little friction
- Torque absorption system
- Mooring system

DeepWind
The Concept - Blades technology

- The blade geometry is constant along the blade length
- The blades can be produced in GRP
- Pultrusion technology:
  - Outlook: 11 m chord, several 100 m long blade length

- Pultrusion technology could be performed on a ship at site
DeepWind
The Concept- Blades technology
- The blade geometry is constant along the blade length
- The blades can be produced in GRP
- Pultrusion technology:
  - Pultrusion technology could be performed on a ship at site
  - Blades can be produced in modules

outlook: 11 m chord, several 100 m long blade length

DeepWind
Concept- Generator configurations
- The Generator is at the bottom end of the tube; several configuration are possible to convert the energy

Three selected to be investigated first:
1. Generator fixed on the torque arms, shaft rotating with the tower
2. Generator inside the structure and rotating with the tower. Shaft fixed to the torque arms
3. Generator fixed on the sea bed and tower. The tower is fixed on the bottom (not floating).
DeepWind
Concept- Installation, Operation and Maintenance

• INSTALLATION
  - Using a two bladed rotor, the turbine and the rotor can be towed to the site by a ship. The structure, without counterweight, can float horizontally in the water. Ballast can be gradually added to tilt up the turbine.

• O&M
  - Moving the counterweight in the bottom of the foundation is possible to tilt up the submerged part for service.
  - It is possible to place a lift inside the tubular structure.

DeepWind 1st BaseLine 5 MW Design Blades
- blade weight 154 Ton
- blade length 187 m
- Blade chord 7.45 m constant over length
- All GRP
- NACA 0018 profile

DeepWind 1st BaseLine 5 MW Design Performance

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power [kW]</td>
<td>5000</td>
</tr>
<tr>
<td>Rated rotational speed [rpm]</td>
<td>5.26</td>
</tr>
<tr>
<td>Rated wind speed [m/s]</td>
<td>14</td>
</tr>
<tr>
<td>Cut in wind speed [m/s]</td>
<td>5</td>
</tr>
<tr>
<td>Cut out wind speed [m/s]</td>
<td>25</td>
</tr>
</tbody>
</table>

Geometry
- Depth of the slender part (H1) [m] 5
- Radius of the slender part (R1) [m] 3.15
- Thickness of the slender part [m] 0.02
- Length of the tapered part (H2) [m] 10
- Length of the bottom part (H3) [m] 93
- Maximum radius of the platform (RP) [m] 4.15
- Thickness of the bottom part [m] 0.05

DeepWind 1st BaseLine 5 MW Design Floater

DeepWind Optimization process
- Sensitivity analysis: rotor mass does not affect floater design significantly
- Determine the Rotor Power and Thrust curve, then compute with the rotor shape during standstill and operation
DeepWind
2nd iteration 5 MW Design Rotor

Geometry
- Rotor radius ($R_0$) [m] 58.5
- H/(2$R_0$) [-] 1.222
- Solidity ($\alpha = \alpha Nc/R_0$) [-] 0.15
- Swept Area ($S_{ref}$) [m$^2$] 12318

DeepWind
2nd iteration 5 MW Design Rotor

Geometry
- Rotor radius ($R_0$) [m] 58.5 (-8%)
- H/(2$R_0$) [-] 1.222
- Solidity ($\alpha = \alpha Nc/R_0$) [-] 0.15 (-33%)
- Swept Area ($S_{ref}$) [m$^2$] 12318 (+15%)

- uniform blade profiles NACA00xx, constant chord
- piecewise uniform profiles NACA00xx, constant chord, Case-1, Case-2

DeepWind
Contents
- DeepWind Concept
- 1st Baseline 5 MW design outline
- Optimization process
- Results
- Conclusion
Results uniform profiles Case-1

- Highest stiffness in NACA0025 profile leading to the smallest displacement field and linear elastic strain level.
- NACA0015 has the highest weight.
- The tips of the rotor are fully constrained in all directions. Therefore, the maximum elastic strain occurs close to the tips.
- Apart from in the area of the tips, smaller strains, i.e., smaller than 5000 N/m, are obtained.

Results-Constant blade chord with different profile thickness Case-2

- Similar strain distribution for Case-2 as compared to the one obtained for the uniform rotor having the NACA0025 profile except at the middle section, are obtained.
- It should be noted that the total weight of the sectionized rotor in Case-2 is lower than the uniform rotor having the NACA0025 profile which has the highest stiffness.
- Using a thicker blade profile at the top (Case-2) decreases the strain values as compared to Case-1 in which a thicker profile is used at the middle.

Results case-2

- Similar strain distribution for Case-2 as compared to the one obtained for the uniform rotor having the NACA0025 profile except at the middle section.
- It should be noted that the total weight of the sectionized rotor in Case-2 is lower than the uniform rotor having the NACA0025 profile which has the highest stiffness.
- Using a thicker blade profile at the top (Case-2) decreases the strain values as compared to Case-1 in which a thicker profile is used at the middle.

Contents

- DeepWind Concept
- 1st Baseline 5 MW design outline
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- Conclusion
DeepWind

Conclusion

- Demonstration of an optimized rotor design
  - Stall controlled wind turbine
  - Pultruded sectionized GRP blades
  - 2 Blades with 2/3 less weight than 1st baseline 5MW design
  - Less bending moments and tension during operation
  - Potential for less costly pultruded blades

- Use of moderate thick airfoils of laminar flow family with smaller CDₐ and good CP
- Exploration of potential for joints
- Investigation for edgewise vibrations due to deep stall behavior

Thank You

Questions?
Operational Control of a Floating Vertical Axis Wind Turbine – start-up and shut-down
Harald G. Svendsen
Karl O. Merz

The DeepWind concept
- Floating VAWT
- Rotating spar buoy
- Stall-regulated
- No pitch, no yaw, no gearbox
- Simple blade geometry, simple installation

EU FP7 project led by DTU (“DeepWind”) – www.deepwind.eu

Control system
- Objectives
  - Maximise energy capture
  - 2p variations
  - Limit over-speed and over-torque
  - Start and stop
- How?
  - Via generator torque

Simulation model
- Aerodynamics: Fourier approximation that includes 2p and 4p variations
  \[ T_{\text{aero}}(\psi, V, \Omega) = T_0 + T_2 \cos(2\psi + \psi_2) + T_4 \cos(4\psi + \psi_4) \]
  - \( \psi \) = turbine azimuth angle relative to the wind speed
  - \( T_0, T_2, T_4, \psi_2, \psi_4 \) given by look-up tables for wind + 4 and rotor speed + \Omega, computed by BEM model and includes dynamic stall effects (Merz)
- Hydrodynamics and mooring system: Bottom end assumed fixed except in yaw
  - Magnus lift force
  - Torque absorption (one degree of freedom) spring-damper mooring system
- Structural mechanics: Spring-damper representations of tower twisting and tilting
- Electrical system: Generator torque = controller set-point
Turbine start-up and shut-down

- Achieved by adjusting the speed reference value
  - Start: 0 → target value
  - Stop: present value → 0
- Avoid conflict between normal/start/stop/parked operation by defining operational states

Normal operation

- Torque-speed map
  - Limited speed
  - Optimal speed
  - Rated torque

- High wind: Reduced reference speed (storm control)
  - Based on wind measurements
  - Limit torque
  - Capture more energy

Start-up: Example (high wind)

- Smooth start
- Critical: Transition from ramp-up to steady speed
- Increased integral gain for faster response during start

Operational states

- Speed ramp-up profile with end-point determined from slow-filtered wind measurement
- Cross-fade to speed reference given by torque-speed map (normal speed control)

Start-up

- Target speed – torque map
- Target speed – wind map

Shut-down

- Speed ramp-down to zero
- Extra torque needed to initiate shut-down
- Parked state: Reference speed = 0, integral path in PI control disabled
Shut-down: Example (high wind)
- Critical: Wind gust at the same time as braking is initiated → large torque

Conclusions
- Baseline control system for the Deepwind floating VAWT turbine has been completed
- Damps 2p variations
- Minimises stress on mooring system
- Maximises energy capture
- Safe start-up and shut-down procedures

Basic parameters – initial 5 MW design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under-water length</td>
<td>108 m</td>
</tr>
<tr>
<td>Darrieus rotor height</td>
<td>130 m</td>
</tr>
<tr>
<td>Darrieus rotor radius</td>
<td>64 m</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>14 m/s</td>
</tr>
<tr>
<td>Rated rotational speed</td>
<td>0.52 rad/s (5 rpm)</td>
</tr>
<tr>
<td>Rated torque</td>
<td>9 × 10^6 Nm</td>
</tr>
</tbody>
</table>

Control architecture

```
\[
\begin{align*}
    \text{Look-up table: } T &= f(v) \\
    \text{If } v > v_c & \rightarrow \text{shut-down} \\
    \text{Otherwise } & \rightarrow \text{load controller}
\end{align*}
```
Control for Avoiding Negative Damping on Floating Offshore Wind Turbine

2013/1/24
Yuta Tamagawa, Tokyo univ.
Makoto Iida, Tokyo univ.
Chuichi Arakawa, Tokyo univ.
Toshiki Chujo, NMRI

Introduction

- Demand for renewable energy is increasing
  - Securing laying area for wind farm
  - Wind is consistent and strong over the sea
  - Establish offshore wind turbine technology
    - Floating Wind Turbine
      - Able to use on Deep Water
      - Unstable foundation

Verification test cases
- Hywind (statoil, Norway)
- Small test turbine (Nagasaki Japan)

Purpose of research
- Applying conventional pitch control
  - Motion of float is negative damped
  - Reducing rated power (Power decrease)
  - Increasing fatigue load
- We need to develop new pitch control corresponding to floating wind turbine

We propose a new control method for floating turbine to suppress the negative damping with power kept to rate.

Experiment and Simulation

- Set floating wind turbine model on test tank with fan.
  (Cooperated with NMRI : National Maritime Research Institute)
- Software for numerical simulation : FAST
  - Developed by NREL (National Renewable Energy Laboratory)
  - Able to compute floating wind turbine
    (NREL 5MW)
Turbine and condition

- Blade Length: 600mm
- Number 3
- Rotor diameter: 1300mm
- Nacelle Weight: 1150g
- Tower Hub height: 900mm
- Float Diameter: 160mm
- Draft: 1270mm
- Displaced volume of water: 23kg

Validation of simulation

- Aero dynamic force of blade and float response to the wave are generally consistent.

Negative damping on experiment

- (Wind speed: 3.9m/s, Wave period: 2.5s, Wave height: 6cm)
- Tower pitch amplitude: increase ➔ rotor speed vibration: decrease
- Negative damping has occurred on experiment

Negative damping on simulation

- (Wind speed: 3.9m/s, Wave period: 2.5s, Wave height: 6cm)
- Tower motion and rotor speed vibration are smaller than experiment.
- Trends of parameter are matched with experiment.

Mixed control on simulation

- (Wind speed: 3.9m/s, Wave period: 2.5s, Wave height: 6cm)
- $K_p$: Control parameter of motion controller on mixed control.
- Basis of rate on right side is parameter on conventional control.
  (when $K_p=0$)
- As $K_p=0.01$, Tower motion is much suppressed though rotor speed is not so much changed.
- Mixed control can suppress the negative damping with little affect to the rotor speed.

Conclusion

- On simulation aero dynamic force of blade and float response to the wave are generally match to experiment.
- We confirmed that tower motion is amplified by onshore pitch control on experiment and simulation.
- We proposed the new control, mixed control, and shows that mixed control can reduce the tower motion with maintaining rotor speed.

Further study

- Improving simulation model, we will apply this control to practical turbine, verification test turbine or full scale turbine and investigate the applicability and effectiveness of this control in actual seas.
Towards the fully-coupled numerical modelling of floating wind turbines

Axelle Viré, J Xiang, M Piggott, C Cotter, J Latham, C Pain
avire@imperial.ac.uk
Applied Modelling and Computation Group (AMCG)
Department of Earth Science and Engineering


Motivation
Scope of a 2-year Marie Curie Intra-European Fellowship
▶ Couple two finite-element models for modelling fluid-structure interactions
▶ Apply them to the various components of a floating wind turbine

Outline
1. Modelling fluid-solid interactions for floating solids
2. Parameterisation of wind turbines
   - Actuator-disk modelling
   - Results for a fixed turbine
3. Tracking of an interface between two fluids
   - Conservative advection method
   - Results for a floating pile
4. Future work
1. Modelling fluid-solid interactions

**Fluidity-ICOM**

- Time step: \((x, u, \alpha)^n\)
- Compute \(F^s = \beta \alpha u^2\)
- Galerkin projection
  - Solid mesh: \(F^s\)
  - Fluid mesh: \(F^s\)
- Solve for \(u\)

**Y3D - Femdem**

- Time step: \((x, u, \alpha)^n\)
- Compute \(F^s = \beta \alpha u^2\)
- Galerkin projection
  - Solid mesh: \(F^s\)
  - Fluid mesh: \(F^s\)
- Solve for \(u\)

**Remarks**

- The fluid mesh is adapted dynamically in time

Dr Axelle Viré, Ocean Dynamics, Vol. 62 (2012)

---

2. Parameterisation of wind turbines

The turbine is parameterised through an actuator-disk model (Conway, J Fluid Mech, 1995)

- The disk is meshed separately from the fluid domain
- The thrust force is spread uniformly across a thin disk
  \[ T = \frac{1}{2 \pi} \alpha \omega u^2 D \]
- The reference velocity \( \frac{\alpha}{\omega} \) is computed from \( \omega \) and \( u_{ref} \)
  \[ \alpha = 1 - \frac{\omega}{\omega_{ref}} = \left( 1 - \sqrt{1 - \left( \frac{\omega}{\omega_{ref}} \right)^2} \right) \]
- The fluid mesh is adapted dynamically in time
2. Parameterisation of wind turbines

Uniform flow past a 3D turbine of constant thrust coefficient and $Re_D = 1000$

- The size of the fluid domain is $25D \times 10D \times 10D$
- The disk thickness is 2% of the disk diameter $D$
- The fluid mesh adapts to the curvatures of the velocity and pressure fields
- Reference: Potential flow past an actuator disk with constant loading

3. Tracking of an interface between two fluids

Air-water flow with a half-submerged 3D pile

- The fluid phases are immiscible
- The fluid concentration field is $\alpha_f$
- An advection-diffusion equation for $\alpha_f$
- $\alpha_f$ is constant over the elements

4. Next steps

- Detailed analysis of the results on the floating pile
- Assemble the turbine and the floating monopile
- Modelling of the mooring lines

Acknowledgements

European Commission: FP7 Intra-European Marie-Curie Fellowship
Applied Modelling and Computation Group: Prof Chris Pain, Dr Matt Piggott, Dr Jianguo Xiang, Dr Patrick Farrell, Dr Colin Cotter, Dr Stephan Kramer, Dr Cian Wilson, Dr John Paul Latham, Mr Frank Milthaler
Geometric scaling effects of bend-twist coupling in rotor blades

Deep Sea Offshore Wind R&D Seminar
Royal Garden Hotel, Trondheim, Norway
24 January, 2013

Kevin Cox, PhD Candidate
Andreas Echtermeyer, Professor
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Dept. of Engineering Design and Materials
NTNU, Norwegian University of Science and Technology

Outline
1. Motivation
2. Bend-twist coupling
3. Up-scaling relations
4. Design of baseline blades
5. Bend-twist (adaptive) blades
6. Load reduction
7. Control system
8. Mass reduction
9. Conclusions
10. Future work

Motivation
► Mass and loads grow faster than power output
\[ F = \text{scaled length/nominal length} \]
\[ m = \text{mass} \quad M = \text{bending moment} \quad P = \text{Power} \]
► How can the loads and mass be reduced?
  - Materials \rightarrow \text{Mass}
  - Control system \rightarrow \text{Loads}
  - Adaptive blades \rightarrow \text{Mass and Loads}

Up-scaling relations
► Does bend-twist coupling depend on blade geometry?
  - Nonlinear FE analysis
  - Linear scaling equations
  - Flap load
    \[ F_0 = \frac{1}{2} \rho AC_1 V^2 \]
  - Bending stiffness
    \[ K_1 = E l \]
  - Torsional stiffness
    \[ K_2 = G l \]
  - Control system
    \[ \phi_{\text{up}} = \frac{a l^2 F}{2(1 - a^2) E I G} \]

Design of baseline blades
► 4 blades selected: 30-90m (1.6 – 13 MW)
► Carbon fiber used in spar flanges
► Biaxial glass fiber used in all regions
► 30, 50, 90m blades use only the NACA 64(3)-618 airfoil
► 70m blade is the 10MW NOWITECH blade
► Load applied: 70 m/s gust with 15° yaw error

Bend-twist coupling
► Adaptive blade through passive technique
► Coupling from unbalanced composite layup
► Material design affects mass and loads

\[ \phi_{\text{up}} = \frac{a l^2 F}{2(1 - a^2) E I G} \]
\[ L = \text{beam length} \]
\[ F = \text{applied bending load} \]
\[ E I = \text{beam bending stiffness} \]
\[ G J = \text{beam torsional stiffness} \]
\[ a = \text{coupling coefficient} \]
### Results of baseline blades

<table>
<thead>
<tr>
<th>Blade length</th>
<th>Carbon in flange (% mass)</th>
<th>Tip deflection (m)</th>
<th>1st flapwise freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30m NACA</td>
<td>19.51</td>
<td>4.08</td>
<td>1.443</td>
</tr>
<tr>
<td>50m NACA</td>
<td>19.31</td>
<td>7.06</td>
<td>0.803</td>
</tr>
<tr>
<td>90m NACA</td>
<td>19.27</td>
<td>13.22</td>
<td>0.489</td>
</tr>
<tr>
<td>70m NOWITECH</td>
<td>15.57</td>
<td>4.70</td>
<td>0.658</td>
</tr>
</tbody>
</table>

The equation for the relationship between blade length and carbon mass in the flange is:

\[ y = 0.0001x^2 + 0.073x \]

- **y**: Carbon mass in flange (% mass)
- **x**: Blade length (m)

### Bend-twist (adaptive) blades

- Carbon fibers rotated to 23° off axis in NACA blades
- Carbon fibers rotated to 20° off axis in NOWITECH blade
- Mass, geometry, composite layups, loads held constant

### Bend-twist coupling on load reduction

<table>
<thead>
<tr>
<th>Blade</th>
<th>% Reduction in Flap Load</th>
<th>% Reduction in Bending Moment</th>
</tr>
</thead>
<tbody>
<tr>
<td>30m NACA</td>
<td>10.84</td>
<td>9.23</td>
</tr>
<tr>
<td>50m NACA</td>
<td>10.98</td>
<td>9.25</td>
</tr>
<tr>
<td>90m NACA</td>
<td>9.95</td>
<td>8.68</td>
</tr>
<tr>
<td>70m NOWITECH</td>
<td>10.42</td>
<td>10.46</td>
</tr>
</tbody>
</table>

### Bend-twist coupling on control system

- Further studies performed on 70m blade
  - Induced twist vs. wind speed (with and without control system)
  - Control system pitch angle vs. wind speed
  - Load reduction \( \Rightarrow \) \( C_p \) reduction
  - \( C_p \) requires pitch back to stall \( \Rightarrow \) nullifies load reduction

### Bend-twist coupling on blade mass

- Load reduction only effective for non-operating conditions
- Maximum load condition: 70 m/s gust
- 70m NOWITECH blade: 10-11% reduction in flap load \( \Rightarrow \) 2.2% mass reduction

### Conclusions

- 4 blades between 30 and 90m were designed
- Linear beam method: induced twist is independent of up-scaling
- Nonlinear FEA: agrees with linear beam
- However, velocity not actually constant
  - Increases with blade length (hub height) \( \Rightarrow \) higher loads
  - Higher loads \( \Rightarrow \) more induced twist on larger blades?
- Bend-twist coupling on flap load alleviation
  - Independent of blade size
  - 10-11% reduction with 6-7° tip twist (during 70 m/s gust)
Conclusions

► Bend-twist coupling on flap bending moment reduction
  • Independent of blade size (possibly more effective for smaller blades)
  • 9-10% reduction with 6-7° tip twist (during 70 m/s gust)

► Bend-twist coupling on control system
  • Induced pitch towards feather requires CS pitch towards stall
  • Nullifies load alleviation during operation
  • Load alleviation only effective during non-operational gusts

► Bend-twist coupling on blade mass
  • Reduction in maximum load allowed for lighter blade

Future studies

► All studies were performed as quasi-static analyses
  • How do the blades behave dynamically
    • Natural frequencies
    • Control system
    • Power collection

► Shear failure and damage evolution in the composite layup was not considered

► Additional blade designs to be studied to confirm results

► Consider other off-axis carbon angles: 10° and 15°

► Change % of carbon fibers in spar flanges

Thank you for your attention!

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A2 New turbine technology

High Power Generator for Wind Power Industry: A Review, Zhaoqiang Zhang, PhD stud, NTNU

Superconducting Generator Technology for Large Offshore Wind Turbines, Niklas Magnusson, SINTEF Energi AS

Laboratory Verification of the Modular Converter for a 100 kV DC Transformer-less Offshore Wind Turbine Solution, Sverre Gjerde, PhD stud, NTNU

Multi-objective Optimization of a Modular Power Converter Based on Medium Frequency AC-Link for Offshore DC Wind Park, Rene A. Barrera, NTNU
High-power generators for offshore wind turbines

Presented by: Zhaoqiang Zhang (NTNU)
Authors: Zhaoqiang Zhang, Robert Nilsen, Arne Nysveen (NTNU)
Anyuan Chen, Alexey Matveev (SmartMotor)

DeepWind 2013, 24-25 January, Trondheim, Norway

Outline

- Introduction of this research
- Review of the generators in operational offshore wind farms
  - Average rating of turbine; Drive trains; Generators
- Generator mass
  - Problems description; Modeling approach; Optimization results
- Review of the solutions for high power generators
  - Direct-driven DFIG; Conventional radial-flux PM generators; Ironless PMSG; Super conducting generator; HVDC generator
- Conclusion

Introduction

- Objective:
  - Investigate the technological challenges related to the high-power generators for offshore wind turbines
  - High-power: >6MW

Generators in operational offshore wind farms (I)

- By the end of 2012, 1886 wind turbines installed in 57 offshore wind farms; total operational capacity of 5.45 GW.

Figure 1:
(a) Development of average rating per turbine.
(b) Market share of drive trains.
DT: Direct drive Train; MGT: Multi-stage Geared drive Train; SGT: Single-stage Geared drive Train

Figure 2:
(a) Market share of different machine types
DFIG: Doubly-Fed Induction Generator; SCIG: Squirrel-Cage Induction Generator; PMSG: Permanent Magnet Synchronous Generator
(b) Average power vs. machine types for 2008-2012

Generator mass

- It is not clear how the structural mass evolves as the power grows.
- Estimation with scaling law gives much error.
- Structural design demands extensive knowledge on mechanical and structural analysis.
- In this paper
  - The total mass: estimated by statistically investigation of the commercial design and curve fitting;
  - Active mass: finite element analysis and optimization;
  - Supporting mass: Total mass-active mass
Modeling (I)

Start with given generator specification
Generating population
GA initializing
Back-EMF calculation
Initialize
Inductance (2D transient FEA)
converged?
Calculating weight, cost, and efficiency.
Stopping criteria met?
Save optimization results and stop.
Next generation
Update
Modeling (II)

<table>
<thead>
<tr>
<th>Table 1: Generator specification.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>Power (MW), ( P )</td>
</tr>
<tr>
<td>Speed (rpm), ( N )</td>
</tr>
<tr>
<td>Phase number, ( \phi )</td>
</tr>
<tr>
<td>Air gap (mm), ( a )</td>
</tr>
<tr>
<td>Stator voltage (kV), ( V )</td>
</tr>
<tr>
<td>Slot per pole per phase, ( q )</td>
</tr>
<tr>
<td>PM relative permeability, ( \mu_r )</td>
</tr>
<tr>
<td>Slot wedge thickness (mm), ( t )</td>
</tr>
<tr>
<td>Min. area of 1 turn coil (mm²), ( A_{min} )</td>
</tr>
<tr>
<td>PM specific cost (€/kg), ( c_{PM} )</td>
</tr>
<tr>
<td>Copper specific cost (€/kg), ( c_{Cu} )</td>
</tr>
<tr>
<td>Steel specific cost (€/kg), ( c_{St} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2: Free variables.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>Frequency (Hz), ( f )</td>
</tr>
<tr>
<td>Outer diameter (m), ( D )</td>
</tr>
<tr>
<td>PM thickness (mm), ( d )</td>
</tr>
<tr>
<td>Thickness of rotor back iron (mm), ( t_{rot} )</td>
</tr>
<tr>
<td>Thickness of stator back iron (mm), ( t_{stat} )</td>
</tr>
<tr>
<td>Ratio of tooth height over tooth width, ( k_1 )</td>
</tr>
<tr>
<td>Ratio of PM width over pole pitch, ( k_2 )</td>
</tr>
<tr>
<td>Ratio of tooth width over slot pitch, ( k_3 )</td>
</tr>
<tr>
<td>Current density (A/mm²), ( j )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3: Constrains.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
</tr>
<tr>
<td>Slot pitch (mm), ( s )</td>
</tr>
<tr>
<td>Flux density in yoke of stator and rotor (T)</td>
</tr>
<tr>
<td>Electric load (kA/m), ( I_e )</td>
</tr>
</tbody>
</table>

Modeling (III)

Total mass
Optimization objective
- Cost function: cost of the active material
- Constrain in efficiency: \( >95\% \)

Optimization results (I)

Solutions for high-power generators
- Industry and academic designs
- More system components, less generator mass and higher efficiency are the concerns of these solutions.
  - Direct-driven DFIG
  - Conventional radial-flux PM generator
  - Ironless PM generator
  - Super conducting generator
  - HVDC generator
**Direct-driven DFIG**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10 MW</td>
</tr>
<tr>
<td>Speed</td>
<td>10 rpm</td>
</tr>
<tr>
<td>Stator voltage</td>
<td>23.5 kV</td>
</tr>
<tr>
<td>Rotor voltage</td>
<td>0.7 kV</td>
</tr>
<tr>
<td>Slip</td>
<td>0.2</td>
</tr>
<tr>
<td>Stator internal diameter</td>
<td>6 m</td>
</tr>
<tr>
<td>Pole number</td>
<td>600</td>
</tr>
<tr>
<td>Current density</td>
<td>2.5 A/mm²</td>
</tr>
<tr>
<td>Magnetic load</td>
<td>0.6 T</td>
</tr>
<tr>
<td>Slot per pole per phase (stator)</td>
<td>1.5 (laminated and 2 non-laminated)</td>
</tr>
<tr>
<td>Air gap</td>
<td>1 mm</td>
</tr>
<tr>
<td>Efficiency</td>
<td>94%</td>
</tr>
<tr>
<td>Construction weight</td>
<td>282 ton</td>
</tr>
</tbody>
</table>

**Conventional radial-flux machine (I)**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>10 MW</td>
</tr>
<tr>
<td>Speed</td>
<td>10 rpm</td>
</tr>
<tr>
<td>Stator diameter</td>
<td>10 m</td>
</tr>
<tr>
<td>Pole number</td>
<td>320</td>
</tr>
<tr>
<td>Slot per pole per phase</td>
<td>1</td>
</tr>
<tr>
<td>Air gap</td>
<td>10 mm</td>
</tr>
<tr>
<td>Pole number</td>
<td>600</td>
</tr>
<tr>
<td>Copper weight</td>
<td>12 ton</td>
</tr>
<tr>
<td>PM weight</td>
<td>6 ton</td>
</tr>
<tr>
<td>Laminations weight</td>
<td>47 ton</td>
</tr>
<tr>
<td>Construction weight</td>
<td>111 ton</td>
</tr>
</tbody>
</table>

**Conventional radial-flux machine (II)**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>8 MW</td>
</tr>
<tr>
<td>Speed</td>
<td>11 rpm</td>
</tr>
<tr>
<td>Stator voltage</td>
<td>3.3 kV</td>
</tr>
<tr>
<td>Stator segments</td>
<td>12</td>
</tr>
<tr>
<td>Pole number</td>
<td>120</td>
</tr>
<tr>
<td>Slot number</td>
<td>144</td>
</tr>
<tr>
<td>Air gap diameter</td>
<td>6.93 m</td>
</tr>
<tr>
<td>Air gap</td>
<td>8.66 mm</td>
</tr>
<tr>
<td>Electric load</td>
<td>150 kA/m</td>
</tr>
<tr>
<td>Efficiency</td>
<td>92%</td>
</tr>
<tr>
<td>Copper weight</td>
<td>9.2 ton</td>
</tr>
<tr>
<td>Magnet weight</td>
<td>3.6 ton</td>
</tr>
<tr>
<td>Laminations weight</td>
<td>31 ton</td>
</tr>
<tr>
<td>Construction weight</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Ironless PM generator**

**Super conducting generator**

**HVDC generator**

Compare with Vestas V90-3MW
Conclusions (I)

This presentation presents a thorough investigation of the global operational offshore wind farms from the perspective of generators, and gives the quantitative analysis.

It is found that the dominant solution for offshore energy conversion system is the multi-stage geared drive train with the induction generators.

Conclusions (II)

With the help of numerical method and genetic algorithm, it is found that most of the cost and mass for high-power generators go to the supporting structure.

It is therefore not economic to simply upscale the conventional technology of iron-cored PM generator.

Furthermore, developing lightweight technology or other cost-effective solutions becomes necessary.

Conclusions (III)

It reviews the generator solutions for high-power offshore wind turbines.

References

Superconducting Generator Technology for Large Offshore Wind Turbines

Niklas Magnusson1, Bogi Bech Jensen2, Asger Bech Abrahamsen2, Arne Nysveen3
1SINTEF Energy Research, Norway
2Technical University of Denmark, Denmark
3Norwegian University of Science and Technology, Norway


Motivation

- Weight and volume reductions
- Practically rare earth metal independent

In the end, it is all about costs

Superconductors

- Materials that carry large DC current densities lossfree at low temperatures
- Exhibit losses under AC operation
- Widely used in MRI diagnostics equipment at hospitals
- Under evaluation for several large scale power applications

The concept

- Rotor field generated by superconducting coils at cryogenic temperatures
- Stator (armature) windings composed of copper conductors at room temperature

Volume and weight is magnetic field dependent

- \( P = \omega \tau \)
  - \( \omega \) is the angular frequency (given by maximum tip speed)
  - \( \tau \) is the torque
- \( \tau \propto B / V \)
  - \( B \) is the air gap magnetic field
  - \( I \) is the stator current (given by stator constraints)
  - \( V \) is the generator volume

The only variables to play with are the magnetic field strength and the volume

Volume and weight: Superconductor versus permanent magnets

- Permanent magnet air gap flux density \( \approx 1 \) T
- Superconductor air gap flux density \( \approx 2.5 \) T
- Superconductor generator volume 40% less than corresponding permanent magnet generator

Additionally, the superconductor field windings are light weighted.
Rare earth metal dependency:
Superconductor versus permanent magnets

10 MW generator:
• Permanent magnet based: 6 ton RE PM
• Superconductor based: 10 kg RE in HTS

A permanent magnet based off-shore generator technology would double the world market for such magnets

The superconductor possibility –
Current trends in research

Choosing superconductor
• Choice of operating temperature, magnetic field strength, cost and availability
• Superconducting wires are under development – increasing performance, reducing costs

Several actors – several concepts

Conductors

<table>
<thead>
<tr>
<th>Material type</th>
<th>Operating temperature</th>
<th>Magnetic field</th>
<th>Current density</th>
<th>Cost 2012</th>
<th>Cost 2020 (at large scale deployment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>4.2 K</td>
<td>5 T</td>
<td>1000 A/mm²</td>
<td>1 €/kAm</td>
<td>1 €/kAm</td>
</tr>
<tr>
<td>NbCco</td>
<td>40 K</td>
<td>3 T</td>
<td>200 A/mm²</td>
<td>30 €/kAm</td>
<td>30 €/kAm</td>
</tr>
<tr>
<td>MgB2</td>
<td>20 K</td>
<td>2 T</td>
<td>200 A/mm²</td>
<td>3 €/kAm</td>
<td>1 €/kAm</td>
</tr>
<tr>
<td>Cu</td>
<td>50°C</td>
<td>1 T</td>
<td>4 A/mm²</td>
<td>50 €/kAm</td>
<td>50 €/kAm</td>
</tr>
</tbody>
</table>

Generator activities

<table>
<thead>
<tr>
<th>Material type</th>
<th>Transmission</th>
<th>Power rating</th>
<th>Industrial interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>Direct drive</td>
<td>10 MW</td>
<td>General Electric</td>
</tr>
<tr>
<td>YBCO</td>
<td>Direct drive</td>
<td>10-15 MW</td>
<td>AMSC</td>
</tr>
<tr>
<td>MgB2</td>
<td>Direct drive</td>
<td>10 MW</td>
<td>Advanced Magnet Lab, European consortia – Suprapower, InnWind.EU</td>
</tr>
</tbody>
</table>

American Superconductor (AMSC)
SeaTitan 10MW
• HTS – Superconducting field winding
• Copper armature winding
• Generator diameter: 4.5-5 meters
• Weight: 150-180 tonnes (55-644m²/kg)
• Efficiency at rated load: 96%

Challenge
• HTS price and availability

Advantage
• Relatively simple cooling system with off-the-shelf solutions
• Cooling power

American Superconductor (AMSC)
SeaTitan 10MW
• HTS – Superconducting field winding
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Challenge
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Advantage
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• Cooling power

Advanced Magnet Lab (AML)
10MW fully superconducting
• MgB2 – Fully superconducting generator
• Superconducting field winding
• Superconducting armature winding

Challenge
• Complicated cooling system and higher cooling power
• Improvement in MgB2 wire is needed
• AC losses

Advantage
• Cheap superconductor
• Fully superconducting
• More torque dense

\[ P = \frac{1}{2} \rho \cdot \dot{V} \times A \times B \times V \]
Aiming at integrated wind turbine concepts with:

- Light weight rotor
- Low-weight, direct drive generator
- Standard mass-produced tower and substructure
- Design of 10-20 MW concepts
- Hardware demonstrators of critical components

A joint European effort with more than 25 partners

**INNWIND.EU**

**MgB₂ superconducting rotor coils**

- MgB₂ superconductors from multiple producers
- Scaled race-track coils

Evaluating key components


Taking advantage of existing magnet technology

Summary

- Superconducting generators may reduce volume and weight
- Material development intensive
- Basic design concept under evaluation
- Reliability to be proven
- Cost is both the prime concern and the prime driver
Outline

- Why transformerless turbine?
- Proposed concept with control system
- Laboratory verification
- Conclusion

Why transformerless turbine? I

- 10 MW offshore wind turbine
- Weight of generator
- Low voltage—heavy cables
- Transformer in nacelle

Why transformerless turbine? II

- Transformerless system:
  - Reduce nacelle weight
  - Modularity
  - DC-distribution directly from converter
- Challenges:
  - Insulation of generator
  - Modular converter system
  - Design, Operation, Control
- Unproven technologies

Proposed concept

- Modular stator
  - Ironless
- Standard AC/DC-converter modules
- Seriesconnected DC-bus
- 100 kV DC output
  - Light weight

Converter control

- Modular control
- Standard 3-phase control system
- Independent/asynchronous
- Voltage- and torque reference from master
Laboratory set-up I
- 45 kW prototype
  - Modular, ironless
  - SmartMotor
- 3 stator segments and converters
- DC-grid:
  - Resistor load
  - Fixed DC-voltage

Laboratory set-up II
- Generator modelling
- Operation of series connected converters
- Modular control
- Fault tolerance

Experimental results I
- Magnetic decoupling of stator segments
- Converter 3 disconnected
- Step change load resistor
- No coupling effect

Experimental results II
- Current control mode
  - Constant torque
  - Speed ramp
  - Stable, unbalanced operation

Experimental results III
- Comparison with simulation

Conclusions on converter control
- Series connected, modular converter for transformerless wind turbine
- Laboratory set-up presented
- Experimental verification
  - Generator behaviour
  - Series connected converter
  - DC-bus voltage control
- Further work: Fault analysis, generator insulation verification
Thank you

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sverre.gjerde@ntnu.no

**Experimental results I**
Comparison of 3-phase and segmented stator winding

- 3-phase voltages
- Three 3-phase voltages

**Proposed system III**
- Medium voltage level
- Inherent redundancy possibility

**Proposed system II**
- Axial Flux PMSG
  - IronLess Stator
- Modular design
  - SmartMotor
- Innovative insulation solution

**Converter control I**
- Main control:
  - Power
  - Speed control
  - Pitch
  - DC-voltage reference
- DC-voltage
  - Set-point
  - Droop regulated
  - Priority: Balanced bus-voltages
Multi-objective Optimization of a Modular Power Converter Based on Medium Frequency AC-Link for Offshore DC Wind Park

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Marta Molinas
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Department of Electric Power Engineering
10th Deep Sea Offshore Wind R&D Conference, DeepWind'2013, Trondheim, Norway

Outline:
1. Introduction
2. Power converter topologies
3. Models and Constraints
4. Results
5. Conclusions

Offshore Wind turbine challenges

Optimal design targeting three objectives
Maximize efficiency ($\eta$): Reduce power losses. Less conversion stages.
Maximize power density (p) and
Maximize Ratio power to mass (M) of conversion system: Minimize weight/Size for a given power. Increase the Frequency.

Assumption: DC Grid is more convenient for offshore wind farms [MEYER]

New WECS architectures for offshore applications. Design taken into account all stages of the system.

Study of operative frequency in Power converter

Different stages - Optimum Take into account all stages in the Power converter

WECS Studied*

• Modularity → Reliability.
• Transformer: Insulation, Ratio. Flexibility for series or parallel connection.
• Constrains parameters:
  • Circuit breaker Technology
  • Generator Voltage and Power rating

WECS Studied: Modular Power Converter

Case of Study

AC-LINK Converter Module

Module based on Back-to-Back Converter topology (B2B)

Module based on Back-to-Back Converter with three phase squared wave output (B2B3p-Sq)

Module based on Back-to-Back single-phase Converter topology (B2B-1p)

Module based on Indirect Matrix Converter topology (IMC)

Module based on Back-to-Back Converter topology (B2B)

AC-Link frequency. Operating transformer frequency.

Switching Freq. generator side. It can be lower than sw. freq. of transformer side. It is optimized in this study. Minimum value of 500Hz (10*50Hz).

Switching Freq. transformer side. It is equal to transformer freq.

Selection of the AC-Link frequency and the Power per module in order to obtain the best relation of the three objectives.

Outline:
1. Introduction
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AC-LINK Converter Topology (AC/AC)

- 3-phase sinusoidal waveform
- B2B: Back-to-Back
- IMC: Indirect Matrix Converter
- DMC: Direct Matrix Converter

B2B-3pSq: B2B with 3-phase output

B2B-1p: B2B with 1-phase output

IMC [Holtsmark]

DMC [Garces]

Module based on Back-to-Back Converter topology (B2B)

fsw1: Switching Freq. generator side. It can be lower than sw. freq. of transformer side. It is optimized in this study. Minimum value of 500Hz (10*50Hz).

fsw2: Switching Freq. transformer side. It is equal to transformer freq.

ftr: AC-Link frequency. Operating transformer frequency.

flc: Cut-off frequency of LC filter. Setting it to be 3 times lower than the switching frequency and limiting it to 20 times the supply frequency (20*50=1KHz).

*In this study the Clamp Circuit is not taken into account.
Module based on Direct Matrix Converter topology (DMC)

- \( f_{sw} \): AC-Link frequency. Operating transformer frequency.
- \( f_{tr} \): Cut-off frequency of LC filter. Setting it to be 3 times lower than the switching frequency and limiting it to 20 times the supply frequency (20*50=1KHz).
- \( f_{tr} \): Switching Freq. It should be higher than transformer freq. It is equal to 6*ftr in this study.
- In this study the Clamp Circuit is not taken into account.

Module based on Reduced Matrix Converter topology (RMC)

- \( f_{sw} \): AC-Link frequency. Operating transformer frequency.
- \( f_{tr} \): Switching Freq. It is equal to transformer freq. The minimum value is 800[Hz], this limit is considered controllability and harmonics distortion in generator side.
- In this study the Clamp Circuit is not taken into account.

Outline:
1. Introduction
2. Power converter topologies
3. Models and Constraints
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Objectives Evaluation

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Power Density</th>
<th>Ratio Power to mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta = \frac{P_{in} - P_{losses}}{P_{in}} )</td>
<td>( \rho = \frac{P_{in}}{vol} )</td>
<td>( \sigma = \frac{P_{in} - P_{losses}}{mass} )</td>
</tr>
</tbody>
</table>

Semiconductor Losses

- Evaluate at moment of each switching action. Switch On, Switch Off and Reverse Recovery.
- Number of switching actions are dependent of modulation scheme.

Converter volume

- \( V_{vol} = \eta_{eff} \cdot (vol_{device} + vol_{ps}) \)
- Heat sink volume depends on thermal resistance based on worst case assumption in thermal design.
**DC link Capacitor**

Proportional model in order to estimate the capacitor volume from the reference capacitor.*

\[
V_{O1,\text{cap}} = \frac{C}{C_{\text{ref}}} \left( \frac{V_{\text{DC}}}{V_{\text{ref}}} \right)^2 \cdot V_{O1,\text{ref}}^2
\]

- The capacitance is designed in order to limit the DC voltage ripple*.


---

**Filters**

The Inductance is designed in order to limit the current ripple*, **.

\[
L_{B1B2} \propto \frac{V_{\text{DC}}}{I_{\text{rms}} f_{\text{sw}}}
\]

Proportional model in order to estimate the Inductor volume* and losses from the reference Inductor.

\[
V_{O1,\text{cap}} = K_{\text{Ind}} \cdot (V_{\text{filter}} - V_{\text{ref}})^{3/2}
\]

\[
P_{\text{core,1}} = \left( P_{\text{core,ref}} + P_{\text{core,ref}} \cdot \left( \frac{I_{\text{ref}}}{I_{\text{ref}}} \right)^{3/2} \right) \cdot \left( \frac{V_{O1,\text{cap}}}{V_{O1,\text{ref}}} \right)
\]

** Magnetic components losses**

- **Core Losses** → based on Steinmetz equation
  \[
P_{\text{core}} = K_{\text{core}} \cdot V_{O1,\text{cap}} \cdot f_{\text{tc}} \cdot B_{\text{fc}}
\]

  highly dependent of magnetic material, volume and waveform voltage

- **Copper Losses** → losses of all windings
  \[
P_{\text{Cu}} = \sum_{i=1}^{\text{nw}} \frac{\rho_{\text{Cu}} N_{i}(\theta) M_{L}(\theta) I_{i}^2 (1 + THD^2)}{A_{w}(\theta)}
\]

  \(K_{\text{cu}}\) as a function of frequency, winding design (layers, conductor)

---

**Transformer volume and losses**

Design process aims to minimize the volume of the transformer taking into account some assumptions.

- **Type transformer structure**
  - dry shell-type transformers
  - optimal set of relative dimensions***

- **Temperature rise**
  - \( \alpha \) Power losses
  - \( \alpha \) / (surface area)

- **Power rating**
  - each winding carry the same current density

**NTNU – Trondheim**

Norwegian University of Science and Technology

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**Transformer volume and losses**

Example: Transformer volume calculation

\[
P = 625 \ [\text{kW}]
\]

\[
V_{\text{output}} = 33 \ [\text{kV}]
\]


Parameters and Design Constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power</td>
<td>10 [MW]</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>690[V]</td>
</tr>
<tr>
<td>Output DC Voltage</td>
<td>33 [kV]</td>
</tr>
<tr>
<td>Generator Frequency</td>
<td>50[Hz]</td>
</tr>
<tr>
<td>DC-Link Voltage-ripple</td>
<td>1%</td>
</tr>
<tr>
<td>Current Input ripple</td>
<td>20%</td>
</tr>
<tr>
<td>Current Output ripple</td>
<td>20%</td>
</tr>
<tr>
<td>Generator Power factor</td>
<td>0.9</td>
</tr>
<tr>
<td>Magnetic material</td>
<td>Metalloy alloy 2805SA1</td>
</tr>
<tr>
<td>Max. OT Transformer</td>
<td>70 K</td>
</tr>
<tr>
<td>AC-Link Freq. [kHz]</td>
<td>[0.5, 10]</td>
</tr>
<tr>
<td>Power x module [MW]</td>
<td>[0.2, 10]</td>
</tr>
</tbody>
</table>

Device Reference:
- Inductor (filters): Siemens 4EU and 4ET
- DC-link Capacitor: EPCOS MKP DC B256
- AC-Capacitor: EPCOS MKP AC B2536
- IGBT Module: Infineon IGBT4 FZXXR17HP4
- Diode Module: Infineon IGBT3 DDXXS33HE3
- Heat Sink: Bonded fin – DC/AC series BF
- Axial FAN – Heat sink: Semikron SKF 3-230 series

Back-to-Back Topologies: Generator Side VSI and input filter

Optimal selection of switching frequency.

AC Link Frequency

Conclusions

• Six different modular power converters solution based on medium frequency link have been compared and their convenience for offshore WECS is evaluated.

• It has been found that WECS based on RMC and square wave AC-Link will lead the best tradeoff between efficiency and power density in range of AC-Link frequencies from 500[Hz] to 10[KHz].
Thanks for your attention

Multi-objective Optimization of a Modular Power Converter Based on Medium Frequency AC-Link for Offshore DC Wind Park

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B1 Power system integration

Wind Turbine Electrical Design for an Offshore HVDC Connection, Olimpo Anaya-Lara, Strathclyde Univ.

Frequency Quality in the Nordic system: Offshore Wind variability, Hydro Power Pump Storage and usage of HVDC Links, Atsede Endegnanew, SINTEF Energi AS

Coordinated control for wind turbine and VSC-HVDC transmission to enhance FRT capability, Antonio Luque, University of Strathclyde

North Sea Offshore Modeling Schemes with VSC-HVDC Technology: Control and Dynamic Performance Assessment, K. Nieradzinska, University of Strathclyde

Upon the improvement of the winding design of wind turbine transformers for safer performance within resonance overvoltages, Amir H Soloot, PhD, NTNU
Wind Turbine Electrical Design for an Offshore HVDC Connection,

Olimpo Anaya-Lars
Max Parker
Kerri Hart
Alasdair McDonald

Content

1. Offshore wind generation: sub-systems
2. Offshore transmission alternatives
3. Conventional wind turbine generator technology
4. Alternative WT generator topologies
5. Grid code compliance and fault management
6. More key questions to answer

Offshore wind generation: sub-systems

Complex mix of sub-systems and technology (and very possibly vendors)
Different control objectives

Offshore transmission alternatives

- Simple point-to-point:

- Complex connections:

Source: Carl Barker, Alstom

Offshore transmission alternatives

- DC Grid Configurations:

Courtesy of IBERDROLA
Conventional wind turbine generator technology (on- and off-shore)

- Variable-speed wind turbines have more control flexibility and improve system efficiency and power quality.
- Exploit features provided by WT power electronics

Wind turbine generator technology

- Technical characteristics of wind turbine technologies are significantly different from conventional power plants.
- And electrical networks were designed around conventional plant based on synchronous generators.
- Should wind generators emulate synchronous machines and provide similar dynamic characteristics in terms of voltage/frequency control, system damping, etc.?

Full Converter wind turbine

- IGBT-based Voltage Source Converter
- Thyristor-based Phase-controlled rectifier
- Diode-based rectifier

Generator-side converter configurations

Overview of connection methods

- Star
- Cluster

AC String

- Link to adjacent string
- Isolator – normally open
- Isolator – normally closed
- Circuit breaker
- Transmission Platform
- 400kV AC

DC String

- Link to adjacent string
- Isolator – normally open
- Isolator – normally closed
- Circuit breaker
- Transmission Platform
- 330kV DC
Example Wind Farm Layout

- 1GW transmission platform rating.
- ±300kV HVDC link.
- Turbines: 10MW, Swept diameter 170m.
- Spacing: 7 diameters, 1190m.
- 10x10 square.
Windfarm Layout, Star Connection

Breakdown of losses

Breakdown of costs

Grid Code Compliance:

Converter-connected generation and inertia
Issues

Grid Code Compliance – fault management

TSO and point of Grid Code compliance

Enhanced control strategies to facilitate Fault Ride-Through
Investigate the requirements for control of offshore wind farms to contribute to onshore network performance
More key questions to answer

- What is the optimum wind turbine design for a HVDC-connected wind farm?
- What are the most appropriate grid connection and power quality requirements for a DC transmission system?
- What is the overall reduction in cost of the optimised wind turbine?
- What is the potential increase/decrease in O&M costs and overall benefit to the economics of a wind farm?

Source: Kerri Hart, Strathclyde (PhD research project with SSE renewables)
Frequency Quality in the Nordic system: Offshore Wind variability, Hydro Power Pump Storage and usage of HVDC Links

by
Atsede G. Endegnanew
Hossein Farahmand
Daniel Huertas-Hernando
SINTEF Energy Research

Introduction

- Large development of offshore wind power in the North Sea (in 2020: > 35 GW and 2030: 96 GW)
- Large potential for hydro power generation in Norway with pumped storage (11 GW)
- Price difference between system price and water value
- Pumped storage used during high wind production
- Investigate the effect of wind power variability (on North sea) and pumped storage on Nordic power system frequency

Model description

- Nordic synchronous power system
  - Norway, Sweden, Eastern Denmark, and Finland
- Continental European synchronous system
  - West Denmark and rest of UCTE
- Primary control: 6% droop and ±0.2 Hz
- Secondary control: LFC on generators and HVDC links
- Wind farms and NorGer power flow are modeled as a negative load
- Initial power flow data are taken from NordPool data from 11 November 2010
- NorGer flow and pumping data taken from market analysis

Wind variation

- Modeled as linear power production change of ΔP within time span of ΔT
- Average wind speeds above 25 m/s
- NorGer HVDC link flow changes were also modeled linearly

HVDC Controller

- Same basic control topology as the original structure
- Constant current control mode
- The central controller has an additional input: ΔP
  - compensates for a given power imbalance
  - ΔP signal comes from Ramp Following Controller (RFC)

Pumping Vs. Offshore wind production

Tonstad & NorGer HVDC cable & German offshore wind
Ramp Following Controller (RFC)

- Two inputs: frequency deviation and power flow deviation
- Gets signal from ACE between two interconnected areas, change in load, change in production or flow on HVDC
- HVDC cable track changes in wind power production

Load Frequency Controller (LFC)

- Area control error (ACE) shared among several generators
- Each generator contributes according to its rating

LFC controllers

- LFC in Danmark:
  - ± 90 MW capacity
  - Three largest thermal generators
  - Monitor the German-Danish border flows
  - Monitors the German-Danish border flows
- HVDC cable track changes in wind power production

Simulation

- Loss of 2000 MW offshore wind power generation in western Denmark
- Power flow variation from Germany to Norway: 930 MW to 530 MW
- Initial pumping load at Tønstad: 160 MW
- Two cases:
  - Case 1: Reduction and stop of pumping (slow)
  - Case 2: Stop of pumping (fast) and change to generation

Studied result

- Nordic frequency

Results

- Western Danish power system loses 2000 MW
- RFC on HVDC links between Nordic and western Danish systems follow the change
- Frequency deviation in Nordic power system due to LFC in Norway
- 443 MW variation in power flowing from Germany to Norway
- Different rate of change in pumping

Conclusions

- Large offshore wind production variations in North Sea will correlate with variable power flows between Continental Europe and Nordic region
- RFC control together with LFC in the Nordic region and West Denmark can contribute to power system balance restoration (in the event of large variations in offshore wind generation). RFC will have an impact on the Nordic frequency quality
- In addition, the rate of change of pumped storage in hydropower stations will introduce an additional load, which also will affect the Nordic frequency. The relative rate of change in pumping stations with respect to the variations of wind power and flows between the Nordic and Continental Europe system / North Sea will also affect the frequency
- Frequency deviations found in this study, assuming realistic wind power and power flows variations and pumping rates, although significant are still within the allowed limits in all the cases studied
- Offshore wind variability, pumped storage loads and power flow on the HVDC links connected to the Nordic power system are likely to have significant influence on the Nordic frequency quality in the future
Simulation Results (2)

**Case B = ΔP=2000 MW**
- Excess power observed in the Western Danish power system
- Reversing the power flow on SK3 reduces the steady state imbalance at the German-Danish border
- Nordic frequency deviation remains within allowed limits

**Graphical Representation:**
- hvdc control + lfc in Denmark + lfc in Norway
- hvdc control, sk3 reversed + lfc in Denmark + lfc in Norway
Outlines

Variable-speed Wind Turbines
- DFIG
- FRC

HVDC Systems
- Voltage Source Converter "VSC"

Case Studies - Control Strategies
- Case Study
- VSC Control Strategies

Simulation Results
- Wind Farms Output (V-I)
- Cluster Platform (V-I)
- HVDC Link

Variable Speed Wind Turbines
DFIG and FRC Wind Turbine
- Higher control flexibility and improve system efficiency and power quality: Independent control of the $P_{ref}$ and $Q_{ref}$
- Partial control of the WT: DFIG
- Full control of the wind turbine: FRC
- Fast control of the WT: Power electronic system
- Voltage-reactive support for large transients: without altering the wind turbine dynamics

Case Study – Control Strategies

Case Study
Electrical Array for large Offshore Wind Farm

HVDC Systems
- Technical advantage of HVDC
  1. HVDC link can work between two ac system with different frequency
  2. Capability to recover from power failures utilizing adjacent grids: "black start"
  3. DC High transmission capacity: "No inductance or capacitance effects", "no skin effect"
  4. Accurate and fast control of the active and reactive power

- Economic Considerations
  1. For distance higher than ≈ 50 km HVAC higher investment
  2. Long distance: less power losses
Control Strategies – Case Study

Basic VSC Control
Active and reactive power control

\[ P = \frac{E_{dc}}{X_p} \sin \theta_p \]
\[ Q = \frac{E_{dc}^2}{X_p} - \frac{E_{dc}V_p \cos \theta_p}{X_p} \]

Fig. 4: Back to Back Converters

Control Strategies – Case Study

Coordination of VSC Control: P/f – Vdc/f and Q Control

- P/f power controller:
  \[ P_t = P_1 + P_2 + P_3 \]
  1. The dynamic response of the P/f power controller has improved the implemented system
  2. Faster response to load changes or transients, adaptive to damping support

- Reactive Power Controller:
  \[ Q_t = Q_1 + Q_2 + Q_3 \]
  1. Control of reactive power

Fig. 5: Simple VSC scheme with P/f Controller

Control strategies:
- DC voltage Controller:
  1. Combined with Frequency controller improve network dynamic performance
  2. Control of the medium voltage of the inverter capacitors
- Third Harmonic Injection:
  1. Prevent over-modulation and improving 15% voltage output

Simulation Results

V-I First Transient

Fig. 8: Wind Farm Performances
Fig. 10: Cluster Collection Platform

V-I Second Transient

Fig. 10: Wind Farm Performances
Fig. 12: Cluster Collection Platform

Transmission Platform and Grid

Fig. 13: First Transient
Fig. 14: Second Transient
The results further demonstrate flexibility of the proposed control system to integrate different offshore wind farms during large transients. It has been shown also high improvements in the fault ride-through capability of both systems. Thus, mentioned controllers have improved the recovery time from large transients in the ac and dc scheme. By using mentioned controllers, the results has shown great controllability and flexibility of the power transferred from both schemes. It is possible to conclude that an integration of both layouts into one scheme where DFIG and FRC wind farms are connected together, the mentioned control system should coordinate and transfer the active and reactive without causing major hazards to the control system.
North Sea Offshore Modeling Schemes with VSC-HVDC Technology: Control and Dynamic Performance Assessment

University of Strathclyde

Outline of Presentation

• North Sea Connection
• VSC-HVDC
• Control strategy
• Tested systems configuration
• Results
• Conclusions

North Sea Connections

What is VSC

• VSC = Voltage Source(d) Converter
• Capacitor is normally used as energy storage
• VSC uses a self-commutated device such as GTO (Gate Turn Off Thyristor) or IGBT (Insulated Gate Bipolar Transistor)

Why VSC-HVDC…

• Power transfer over long distances
• Lower power losses compared to AC transmission
• Independent control over active and reactive power
• Voltage support
• Wind farm is decoupled from the onshore grid,
• Connected to the weak network
• Black start capability
**Point-to-point Connection**

Different control strategies employed for offshore wind farm and onshore grid.

**Vector Control**

- Three-phase rotating voltage and current are transformed to the dq reference frame.
- Comparative loops and PI controllers are used to generate the desired values of M and T and feed their values to the VSC.
- Phase-locked-loop (PLL) is used to synchronize the modulation index.

*Vector Control Diagram*

**Control Strategies – Inner Controller**

\[ v_{cd} = -u_d + \omega L_i - v_{cd} \]

\[ v_{cq} = -u_q - \omega L_i - v_{cq} \]

**Inner Controller**

Responsible for controlling the current in order to protect the converter from overloading during system disturbances.

\[ u_d = k_p (i_d^* - i_d) + k_i (i_d^* - i_d) dt \]

\[ u_q = k_p (i_q^* - i_q) + k_i (i_q^* - i_q) dt \]

**Control Strategies – Outer Controller**

**Controllers Schematics**

*Wind farm side VSC*

Active power and AC voltages control

*Onshore grid side VSC*

DC and AC voltages control

**Controllers Schematics Diagram**

*Controllers Schematics Diagram*
In this model, the VSC-HVDC system controls are as follows:

VSC1,2 converter controls active power flow and AC voltage control.
VSC3,4 converter controls DC and AC Voltages.

Test System Configuration – AC regional grids

Test System Configuration - slack bus

Results – active & reactive power, AC voltages

Results – active & reactive power,

Results – DC Voltages
Conclusions

- The controllers can respond to any power demand
- There are significant advantages in terms of power flow controllability
- This can prove to be very advantageous for connection of variable wind generation and assist in the power balancing of interconnected networks.
Contents

1. Challenges for wind farms
2. Transient phenomena in Offshore wind farm
3. Resonance Overvoltages
4. Prototype wind turbine transformer for the investigation of resonance overvoltages
5. Measurement results
6. Conclusion
7. Future plan

Challenges for wind farms

- Different challenges
  - Financial
  - Political
  - Environmental
  - Technological challenges: can be better understood by observing the failures in wind farm which has occurred up to now.

Breakdown of component failures for an offshore wind farm (Nitschke et al., 2006)

Table: Component damages

<table>
<thead>
<tr>
<th>Component</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>18%</td>
</tr>
<tr>
<td>Blades</td>
<td>17%</td>
</tr>
<tr>
<td>Generator</td>
<td>10%</td>
</tr>
<tr>
<td>Transformer</td>
<td>13%</td>
</tr>
<tr>
<td>Nacelle</td>
<td>10%</td>
</tr>
<tr>
<td>Control eq.</td>
<td>8%</td>
</tr>
<tr>
<td>Others</td>
<td>13%</td>
</tr>
</tbody>
</table>

SINTEF report: "HSE challenges related to offshore renewable energy", 15-02-12

Transients phenomena in Offshore wind farm

1. Switching transients → Energization and Deenergization
2. Lightning transients
3. Earth fault

Prototype wind turbine transformer

500kVA 11/0.230 kV

Resonance Overvoltages

1. It may occur during earth fault or energization transients if:
   a. The quarter-wave frequency of cable is close to one of resonance frequencies of transformer, especially the dominant resonance frequency.
   b. The surge impedance of cable is much lower than transformer input impedance and much higher than source impedance.
2. It leads to the highest overvoltage amplitudes with high dv/dt compared to normal energization overvoltages.
The winding designs

- Layer winding
- Disc winding
- Pancake winding

Measurement on 500 kVA transformer

The Diagnosis of resonance frequencies in 500 kVA transformer to select the less critical winding design for fixed-length cable energization in wind farms

Measurement Results for voltage drop

Measurement Results for voltage to ground

The frequency response of the three windings for voltage drop near to HV terminal can be observed and compared in these figures.

Measured voltage-to-ground distribution in layer winding

The dominant resonance frequency in the layer winding is approximately 1 MHz, which means the energization of the transformer with about 50 meter cable is not recommended (see the equation). The voltage ratio can be maximum mainly in the taps near to HV terminal. But, there is also one voltage ratio peak near to ground. Higher cable length is less critical.
The dominant resonance frequency in the disc winding is approximately 70 kHz and there are many resonance peaks between 100 and 500 kHz, which means the energization of the transformer with cables more than 100 meter is not recommended. The reason is that the voltage ratio peaks appeared in all the taps (see the right figure).

The frequency response of the pancake winding is combination of layer and disc winding, i.e. resonance peaks in both 10kHz < f < 1MHz and f> 1MHz. According to the frequency response, the energization can be performed with 100-500 meter cables considering the installation of the protective devices in the taps near to the HV terminal.

• Resonance overvoltages at LV terminal for 500 kVA:
  The dominant resonance frequency for layer winding is 1.6 MHz which the amplitude of transferred voltage is around 80 p.u.. The dominant resonance frequency for disc and pancake is 800 kHz which the amplitude is 6 and 38 p.u., respectively.

• Resonance overvoltages inside windings for 500 kVA:
  1. The voltage drops for taps near to HV terminal of the three windings, have high amplitudes (25 p.u.) at dominant resonance frequencies.
  2. The layer and pancake windings have lower values further down in the middle of winding and near to ground. But, the disc winding keeps the high value of voltage drops at resonance frequencies which means more potential of internal stresses.
  3. The Voltage to the ground in near to HV terminal has low values at resonance frequencies (about 10 p.u.) for disc and layer winding.

Future plan
• Developing analytical model of the 500 kVA transformer: 1-verification with the measurements, 2-study the effect of various design parameters on the frequency response.
• Modifying the analytical model with transformer kVA scaling equations in order to observe resonance frequency shifts in 8 MVA transformer compared to 500 kVA one.

Thanks for your attention
Any question?
B2 Grid connection

Planning Tool for Clustering and Optimised Grid Connection of Offshore Wind Farms, Harald G. Svendsen, SINTEF

The role of the North Sea power transmission in realising the 2020 renewable energy targets - Planning and permitting challenges, Jens Jacob Kielland Haug, SINTEF Energi AS

Technology Qualification of Offshore HVDC Technologies, Tore Langeland, DNV KEMA

Evaluating North Sea grid alternatives under EU’s RES-E targets for 2020, Ove Wolfgang, SINTEF Energi AS
Planning Tool for Clustering and Optimised Grid Connection of Offshore Wind Farms

**Background**
- NOWITECH – Norwegian Research Centre for Offshore Wind Technology
  - Has supported development of Net-Op Applied on North Sea offshore grid analyses
  - www.nowitech.no
- EERA-DTOC – EU FP7 project
  - Aims to establish and integrated Design Tool for Offshore wind farm Clusters, including electrical grid design
  - www.eera-dtoc.eu

**Net-Op**
- Offshore grid expansion optimisation (planning tool)
  - **Input:** allowable connections + cost parameters + time series for wind power, demand and power prices
  - **Output:** Optimal design (number + capacity of cables)
  - Ref: Trötscher & Korpås, dx.doi.org/10.1002/we.461

**Net-Op approach**
- **Optimisation**
  - Mixed integer linear programming (MILP) problem formulation
  - Cost function = cost of investment + operational costs (net present value)
  - Cost = fixed cost + cost per MW × rating
  - ‘Fixed cost’ may be distance dependent
  - Sampling of operational states to account for variable wind, demand and prices
  - Need to limit number of allowable connections
  - MATLAB implementation

**Applicable to wind farm cluster level?**
Technology for a better society

Net-Op DTOC – an upgraded version

- Modifications
- Multiple cable types (AC, DC)
- Pre-optimisation processing
- Clustering algorithm
- Automatic generation of allowable connections
- Interface to external MILP solvers
- Result export to PSSE, Google Earth plot (KML)
- Command-line tool

Pre-processing: Generate allowable set of connections

1: Clustering
2: Add cluster branches
3: Replace AC by DC
4: Add DC mesh

Case study: Kriegers Flak

- Wind farms:
  - Kriegers Flak (DK+DE+SE), Baltic 1 (DE)
- Cost parameters
  - Based on Windspeed project (D2.2 – Garrahd Hassan)
- Time series
  - 2010 hourly values for:
    - wind production (from DTU’s CorWind model – N. Cutululis)
    - demand (daily and seasonal profile as used in TradeWind & OffshoreGrid projects)
    - area prices (from Nordpool & EEX)

Input data

Wind farms

- Duration curves
- Weekly average

Power prices

2010

Power demand

Extract showing two weeks

Wind power

Power prices

Power demand

DK

SE

DE

DK

SE

DE
**Conclusion**

- Net-Op DTOC is a tool for clustering and grid connection optimisation of offshore wind farms
- High-level automated offshore grid planning, taking into account
  - Investment costs
  - Variability of wind/demand/power prices
- Benefit of power trade between countries/price areas
- The tool will be integrated in the DTOC framework (www.eera-dtoc.eu)
The role of the North Sea power transmission in realising the 2020 renewable energy targets -

Planning and permitting challenges

Background

- October 19th 2011 – EC Energy Infrastructure Package
  - Measures that can affect planning and permitting practices for power transmission projects in the North Sea
- Background: Enormous investments needed in energy infrastructure to reach European energy and climate goals
- Challenges:
  - Not all investments are commercially viable
  - Building permits take too long to obtain

What are the planning and permitting barriers for power transmission projects in the North Sea?

- Review of secondary literature

Challenges (1): Wind farm connections

- In most countries a permit to connect to the grid is required
- Some countries - Sweden, Germany, Belgium and the Netherlands, also require a permit to lay cables on the seabed
- Examples of permitting of wind power installations and cables being done by different authorities (Germany)
  - Can lead to more complex procedures and increased time use
- Few countries have provided information on the permitting process and the extent of coordination between authorities
- A more integrated approach between infrastructure permitting and grid connection permitting should be promoted
- Complex process - even more so for cross-border projects (hub-to-hub connections, tee-ing in of a wind farm)
- Permitting procedures for cross-border projects should be reviewed and simplified

Challenges (2): Interconnectors

Administrative challenges

- Different number of permits required in different countries
- Conflicts with environmental authorities represent a critical barrier
- Lack of coordination and standardisation of environmental impact assessments
  - Examples of projects being subject to an EIA in only one of the affected countries
  - Difficult for the TSOs to predict the decision made by environmental authorities
- Important not to see the one-stop shop model as the major solution
  - TSOs preferred interacting directly with the different authorities
  - One/Few procedures, rather than one/Two authorities
- However, DK experiences show that the one-stop-shop model can be improved
  - Conflicts were reduced as the Danish TSO engaged in direct dialogue with different authorities and private stakeholders

Challenges (3): Sea use

Shipping

- Maritime authorities routing demands with regard to shipping lanes causes major barriers
- Installation and maintenance of cables hinders shipping
- Emergency anchorages can damage cables - major economic impacts and temporary obstruction of shipping lanes during repair work

Fishing interests

- During cable installation fishing interests are denied access to areas used for fishing - recurring demands of compensation
- Fishing appliances can damage cables (trawl equipment) - cable burying reduces the risk
- Military interests, sand extraction, wind farms and other cables and pipelines can also represent barriers

Challenges (4): Onshore infrastructure

- Landfall points-overhead electricity lines and converter stations receives major public criticism
  - Demand for underground cables
- A strong onshore grid is a prerequisite for transmission of offshore power - in many European countries reinforcements are often delayed due to low public acceptance
- In addition to being an economically sound solution, moving towards a meshed grid could;
  - Reduce the need for onshore transmission reinforcements
  - Reduce onshore connection-points
  - Minimised space use as a result of more integrated infrastructure (possibly less maritime spatial conflict) – Cobra cable bundling with wind park connectors increases acceptance

(Source: Seaenergy 2020 and OffshoreGrid)
The EC’s energy infrastructure package


- The North Sea is one of 12 prioritised trans-European energy infrastructure corridors – projects of common interest (PCI) will be
  - Eligible for EU funding through Connecting Europe Facility (CEF) - 9.1 billion from 2014-2020
  - Benefit from a special permit granting procedure

(cont.)

- Time limit - three years
- One Stop Shop
- Member States must take measures to streamline the EIA procedures
- Citizens will be involved before the project developer submits the formal application for a permit - in contrast to current practices in many member states
- Impact assessments will be taken into account at an earlier stage in the process and will be more closely connected to public and stakeholder involvement
- The Commission also acknowledges the benefits of effective upfront maritime spatial planning – impact assessment

Can maritime spatial planning facilitate power transmission permitting?

- Several studies point to the potential importance of MSP in facilitating effective permitting processes
  - Cobra cable (the Netherlands and Denmark transit country: Germany)
- Recently enacted maritime spatial plan in German EEZ
  - positive effect as it facilitated for early identification of conflicts by early stakeholder dialogue (water and shipping authorities and nature protection authorities)
- However, the maritime plan did not reserve areas for interconnector corridors or for cable connections (OWF) – stakeholders carrying zoning rights posed some difficulties

In conclusion

- No insurmountable planning and permitting barriers to power transmission in the North Sea today, but more research is needed
- Maritime spatial planning could be important for conflict management and effective permitting procedures as different sea uses are expected to increase considerably in the North Sea
- In addition to being an economically sound solution, moving towards a meshed grid could have several benefits related to current and future planning and permitting challenges that are crucial to realise a North Sea offshore grid
- Thank you!
Presentation outline
- Introduction to Det Norske Veritas (DNV)
- Building a position in power system transmission and distribution
- Research and innovation in DNV
- Risk based approach for development of offshore HVDC transmission technologies

Build and share knowledge
- We invest 6% of our revenue in research and development
- We take a lead role in joint industry research and development projects
- Through our standards, rules, recommended practices and software solutions we share knowledge with the industry

Risk based approach for development of offshore HVDC transmission technologies
**Motivation**

**Background**
- 40 GW offshore wind in Northern Europe by 2020
- 150 GW offshore wind in Europe by 2030
- Grid connection of offshore oil & gas installations
- The vision of an offshore Super Grid

**The challenge**
- To date there exists no operational experience with high capacity offshore HVDC transmission technologies.
- Installations far from shore and in harsh marine environments will require high focus on Reliability, Availability and Maintainability.
- Interoperability challenges arise with technology from multiple vendors.

---

**Lack of relevant standards for offshore transmission**

- Offshore IEC Standards and DNV Standards only up to 1.5 kV DC (36 kV AC)
- Lack of standards for HVDC gas insulated switchgear (HVDC GIS)
- No standards for interconnection of Voltage Source Converters (VSC's)
- No standards for HVDC circuit breakers
- No standard addressing performance of offshore grids

---

**Technology Qualification Process**

**DNV's Definition of Qualification:**

Qualification is the process of providing the evidence that the technology will function within specific limits with an acceptable level of confidence.
Technology Qualification Process

**DNV RP-A203**

- First edition published in 2001
- Qualification of new technologies where failure poses risk to life, property, the environment or high financial risk.
- Qualification of technologies that are not new
  - Proven components assembled in a new way
  - Not covered by existing requirements and standards
  - Proven technology in a new environment
- Developed for the offshore oil & gas industry to increase stakeholder confidence in applying new technologies.

---

Why do we need technology qualification?

- Testing is conducted according to old schemes that do not take into account new failure modes
- Equipment placed in a new environment
  - Harsh climate
  - Difficult access
- New approach to maintenance and repair strategy
- Auxiliary systems
  - Control of ocean environment
- Higher voltage, current and power ratings
  - Converter and cables
- New applications
  - Multi-terminal DC (MTDC)
  - Meshed MTDC grid
- New design of major components
  - DC converter stations and valves
  - Cables
  - DC switchgear
- System behaviour
  - Control, protection and communication

- Increases the **RISK** exposure

---

Added value of technology qualification for offshore HVDC

- Demonstration of technology capabilities
- Address stakeholder uncertainties
  - Maturity and uncertainty of technologies
  - Feasibility of offshore HVDC transmission
- Address the risk exposure
  - Identification and categorization of technologies w.r.t. industry experience and maturity
  - Identification and understanding of failure modes and the risk picture
  - Development of methods and activities to address the risks
  - Overall reliability and availability of technologies and systems

---

Qualification Basis

- Technology specification
- Standards and industry practice
- Maintenance and Operation strategy
- Boundary conditions

Requirements specification

- Reliability, Availability, Maintainability
- Functional requirements
Technology Assessment

Technology breakdown
- Component
- Purpose/description
- Grid level
- Main challenges

Technology categorization
1. No new technical uncertainties
2. New technical uncertainties
3. New technical challenges
4. Demanding new technical challenges

Technology Assessment

Technology categorization
1. No new technical uncertainties
2. New technical uncertainties
3. New technical challenges
4. Demanding new technical challenges

Application Area
- Known
- Limited Knowledge
- New

Degree of novelty
- Proven
- Limited field history
- New or unproven

Technology Assessment

Based on STRI experience from Testing, Simulation & Studies

- Accredited high voltage testing for testing of major equipment according to relevant standards and customer requirements, e.g. CIGRE recommendations for MI DC cables and extruded DC cables. IEC 60840 and IEC 62067 for extruded AC cables.
- Simulation of HVDC and HVAC systems using most suitable program; SIMPOW, PSS-E, PSCAD-EMTDC, DigSilent etc.
- Feasibility and application studies involving users and manufacturers

Technology Assessment

Level 2-4 categorized offshore HVDC technologies

- Fast and selective detection, location and clearing of faults in a DC grid
- DC circuit breaker
- Control system for MTDC
- Polymer cable system (rating)
- Dynamic cable system
- DC Switchgear (AIS*/GIS*)
- DC/DC converter

Technology Assessment

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Level 2-4 categorized offshore HVDC technologies

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- Dynamic cable system
- DC Switchgear (AIS*/GIS*)
- DC/DC converter

Technology Assessment
Other relevant initiatives

Relevant initiatives

- Cigré
  - SC B4 - HVDC and Power Electronics
    - B4-52, B4-55, B4-56, B4-57, B4-58, B4-59, B4-60
  - SC B1 - Insulated Cables
- EC DG Energy
  - Working group for offshore/onshore grid development
- NSCOGI
  - WG 1 Offshore Transmission Technology
- ENTSO-E
  - Regional Group North Sea (RG NS)
- IEC/CENLEC
  - TC 115 High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV
    - CLC/SC 115 High Voltage Direct Current (HVDC) Transmission for DC voltages above 100 kV (Provisional)

German commission for electrical, electronic & information technologies
- Technical guidelines for first HVDC grids - A European study group

Future work

Joint Industry Project

Why:
- Need for a faster, more efficient and more reliable deployment of offshore HVDC transmission systems.

How:
- Integrating ongoing activities and experiences of different technologies in new environments with a proven method for risk management - the DNV RP-A203.

Why DNV KEMA and STRI?

DNV KEMA
- Independent foundation with the purpose of safeguarding life, property and the environment
- More than 40 years of experience in managing risk for the offshore oil and gas sector
- Established as a world leader in providing risk management and independent assurance services
- International operations with access to high voltage testing facilities
- The world's largest test facility conducting testing for wind energy projects with 30 years of wind energy experience
- Leading certification agency for offshore wind projects
- Continuously running 30-40 Joint Industry Projects

STRI
- Independent power systems consulting company with an assembled high voltage test facility
- Several large skid laboratory test facility for control tests on products with system voltages up to 1500V
- Test facility for testing of isolation, corona, ice, wind, fog and other factors
- Experience in system studies for wind power integration and HVDC applications, including multi-terminal VSC technology

Joint Industry Project

Scope of work
- Activity 1 – Develop a Technology Qualification procedure for offshore HVDC transmission technologies
- Activity 2 – Qualification examples
- Activity 3 – Hearing process and publication

Participants
- Manufacturers
- Developers
- Operators

Timeline
- Kick off in October 2012
- Industry wide hearing by Q1 2014
- Final publication in Q2 2014
Thank you for your attention!

Safeguarding life, property and the environment

www.dnv.com
Evaluating North Sea grid alternatives under EU's RES-E targets for 2020

Ove Wolfgang, Hans Ivar Skjelbred and Magnus Korpås, SINTEF Energy Research

About study

- Are RES-E targets important for North Sea Grid?
  - Offshore wind-power must be connected
  - Norwegian hydropower can balance RES-E variability
  - Surplus in the Nordic area

- Role of North Sea power transmission in realizing the 2020 renewable energy targets (2010-13)

- For North Sea grid configurations:
  - Quantify energy system effects
  - Evaluate costs and benefits

Content

1) Benefit calculation (grid cases)
2) Costs calculation (technology options)
3) Cost/benefit assessment
4) Conclusions

Tool for calculation of benefits

- EMPS model
  - No: Samkjøringsmodellen
  - Hydropower scheduling
  - Energy system planning
  - Forecasting
  - SDP

- Minimizes operational cost for a given system

- Benefit of a cable: reduced system costs

North Sea nodes

Norway: ~ 2 TWh/year

EMPS inputs

North Sea node
Wind-farm capacity (MW)
Electrification (MW)

Main inputs for stage 2020

<table>
<thead>
<tr>
<th>Input</th>
<th>Major reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>RES-E</td>
<td>National action plans</td>
</tr>
<tr>
<td>Thermal power capacity</td>
<td>ENSO-E, 2020 forecast</td>
</tr>
<tr>
<td>Consumption</td>
<td>National action plans</td>
</tr>
<tr>
<td>Transmission capacity</td>
<td>ENTSO-E, Dena II, SINTEF</td>
</tr>
<tr>
<td>Prices (fuel, CO2, ...)</td>
<td>EC Roadmap, 2020-forecast</td>
</tr>
</tbody>
</table>
Power prices (average)

EMPS outputs

<table>
<thead>
<tr>
<th>Country</th>
<th>Average Price (€/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB</td>
<td>4.2</td>
</tr>
<tr>
<td>France</td>
<td>4.2</td>
</tr>
<tr>
<td>Belgium</td>
<td>4.1</td>
</tr>
<tr>
<td>Netherlands</td>
<td>4.0</td>
</tr>
<tr>
<td>Germany</td>
<td>2.9</td>
</tr>
<tr>
<td>Norway</td>
<td>2.6</td>
</tr>
<tr>
<td>Sweden</td>
<td>3.3</td>
</tr>
<tr>
<td>Finland</td>
<td>3.2</td>
</tr>
<tr>
<td>Estonia</td>
<td>2.1</td>
</tr>
<tr>
<td>Ireland</td>
<td>2.0</td>
</tr>
</tbody>
</table>

EMPS outputs

Average annual net flow > 10 TWh/year

Importers and exporters
Annual average in TWh.

A1. One direct cable to GB
A2. Two direct cables to GB
B1. Alternative Northern landing in Norway
B2. Alternative landing in Norway and GB
B3. Alternative southern landing in Norway
C1. Northern integration
C2. Southern integration
C3. Doggerbank integration
D1. Flexible southern transmission – Norwegian side
D2. Flexible southern transmission

Investment costs

Table: Costs for 600 MW modules (PV)

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost</th>
<th>Unet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench laying cost</td>
<td>0.76</td>
<td>M/km</td>
</tr>
<tr>
<td>Cable cost, fixed charge</td>
<td>5.0</td>
<td>M</td>
</tr>
<tr>
<td>AC/DC converter stations and platforms offshore</td>
<td>167.2</td>
<td>M</td>
</tr>
<tr>
<td>DC breaker and switching gear onshore, per cable</td>
<td>45.3</td>
<td>M</td>
</tr>
<tr>
<td>DC breaker and switching gear offshore, per cable</td>
<td>55.7</td>
<td>M</td>
</tr>
</tbody>
</table>

Source: Wind speed project: http://www.windspeed.eu

Costs: inputs

Cost-benefit for 2nd 1400 MW direct connection

- Benefits: 60 M € / year
- Costs: 123 M € / year

A1. One direct cable to GB
A2. Two direct cables to GB
Cost-benefit for alternative landing of 2nd cable (relative to A2)

Benefits / Costs / Total (in M€ per year)

B1. Alternative landing in Norway for 2nd cable
B2. Alternative landing in Norway and GB for 2nd cable
B3. Alternative southern landing in Norway

+20/+14/+6
+24/-11/+35
+6/-8/+14

Offshore integration technologies

- Integration
  - North Sea nodes
  - 1400 MW NO-GB cable
- Investment costs
  - Saved cable meters
  - Extra offshore equipment

1) T-junction
   - Optimized for 2020 wind power
   - Non-flexible
   - Least expensive

2) Flexible setup
   - Preparation for future
   - 1400 MW infrastructure
   - DC breakers: Flexible
   - High cost

3) "DC case"
   - 1400 MW
   - Fewer DC breakers
   - Intermediate costs

Higher prices in NOR-VESTSYD

GB-North prices are lower but volatile

Evaluation

Table: Relative to direct Northern connection (M€ per year)

<table>
<thead>
<tr>
<th>Case</th>
<th>250 MW wind</th>
<th>1000 MW wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>He</td>
<td>DC</td>
</tr>
<tr>
<td>Costs</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>-30</td>
<td>-26</td>
</tr>
</tbody>
</table>

Northern: Direct vs. integrated connection

All simulated cases 2004

Evaluation

Harald Stenersen, SINTEF Energi AS

SINTEF Energi AS
Offshore integration gives reduces transmission
Example: Wind 200 MW, electrification 100 MW

<table>
<thead>
<tr>
<th>System costs</th>
<th>Offshore wind farm</th>
<th>Wind power Northern wind farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 MW</td>
<td></td>
<td>1100 MW</td>
</tr>
<tr>
<td>1300 MW</td>
<td></td>
<td>1400 MW</td>
</tr>
</tbody>
</table>

Evaluation

C2. Southern integration
Table: Relative to direct Southern connection (M € per year)

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 MW wind</td>
<td>-19</td>
<td>-20</td>
</tr>
<tr>
<td>1000 MW wind</td>
<td>-9</td>
<td>-27</td>
</tr>
<tr>
<td>Total</td>
<td>-29</td>
<td>-11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flex / DC</th>
<th>Benefits</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC T-junction</td>
<td>-16</td>
<td>-21</td>
<td>-37</td>
</tr>
<tr>
<td>Integrated</td>
<td>-22</td>
<td>-27</td>
<td>-49</td>
</tr>
</tbody>
</table>

D1. Flexible southern transmission – Norwegian side
Table: Relative to Southern Integration (M € per year)

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Costs</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>72</td>
<td>-50</td>
</tr>
</tbody>
</table>

Evaluation

Additional cases
- No nuclear power in Germany
- No exchange with exogenous countries

Major findings
1) Cables between GB and NO: mostly used for export to GB
2) 2nd direct connection GB – NO in 2020
   a) Not profitable
   b) Northern route gives highest benefits and lowest costs
3) Offshore integration relative to direct connections
   a) Benefits: Lower because of reduced flexibility
   b) Costs: Lower for T-junction, higher for full flex
   c) Cost/benefit: 250 MW / 3 TWh wind: direct connections
   1000 MW / 4 TWh wind: integrated solutions
4) Leg to Germany: Extra costs > Extra benefits

Evaluation

Conclusions

Limitations & uncertainties
- Many
  - Mathematical model vs. real world (limitations)
- Uncertainties
  - RES-E implementation
  - Economic development
  - EU policies (RES-E, GHG)
  - Nuclear power
  - Technology developments
- Limitations
  - Beyond 2020 developments
  - Balancing markets
  - Competition
  - Failures
  - Price variation
  - Not-considered uncertainties
- ... and many others

Evaluation

Conclusions

Limitations
- Beyond 2020 developments
- Balancing markets
- Competition
- Failures
- Price variation
- Not-considered uncertainties
- ... and many others
Exact geographical locations of nodes

Renewable electricity generation
Based on EU directive and national plans for 2020

Sun-power: Within-day profile area 34

Wind-power: Within-day profile area 52
(A) The 34 within-week sequential time-steps in model
(B) Relative load-profile for area 34

Thermal power capacity change 2008 - 2020
(ENTSO-E forecast)
- Existing units database (2008)
- Increased capacity: new efficient units
- Reduced capacity: retirement of oldest

North Sea transmission cables in basecase

ENTSO-E forecast for thermal power capacity

<table>
<thead>
<tr>
<th>Country</th>
<th>Denmark</th>
<th>Sweden</th>
<th>Finland</th>
<th>Belgium</th>
<th>Netherlands</th>
<th>Germany</th>
<th>UK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard coal</td>
<td>200</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>750</td>
<td>200</td>
<td>1750</td>
</tr>
<tr>
<td>Lignite</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Bio</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Gas</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Nuclear</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Oil</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>Total</td>
<td>8800</td>
<td>8800</td>
<td>8800</td>
<td>8800</td>
<td>8800</td>
<td>8800</td>
<td>8800</td>
</tr>
</tbody>
</table>

Unit aggregation
(for handling of problem-size with start-up costs)

Fossil-fuel price forecast
- Reference: A Roadmap for moving to a competitive low carbon economy in 2050
- Primes model simulation
- Reference scenario
  (Includes 20/20/20 policy)
Coal-power cheaper than gas-power

\[
\text{Coal price} = \frac{9.9 (\text{€/MWh}) + 16.5 (\text{€/ton}) - 0.37 (\text{ton/MWh})}{0.4 (\text{MWh/ton})} = 60.0
\]

\[
\text{Gas price} = \frac{23.7 (\text{€/MWh}) + 16.5 (\text{€/ton}) - 0.2 (\text{ton/MWh})}{0.6 (\text{MWh/ton})} = 45.0
\]

Consumption
Mostly based on ENTSO-E forecast

Transmission capacity matrix

Duration curves German 2004-prices
A2, G: No exogenous trade. A2, GA: G + no nuclear in Germany
C1 Met-ocean conditions

Wave-induce characteristics of atmospheric turbulence flux measurements, Mostafa Bakhoday Paskyabi, UiB

Experimental characterization of the marine atmospheric boundary layer in the Havsul area, Norway, Constantinos Christakos, UiB

Buoy based turbulence measurements for offshore wind energy applications, Martin Flügge, Univ of Bergen

Effect of wave motion on wind lidar measurements - Comparison testing with controlled motion applied, Joachim Reuder, Univ of Bergen

Turbulence analysis of LIDAR wind measurements at a wind park in Lower Austria, Valerie-Marie Kumer, Univ of Bergen
Wave–induced characteristics of atmospheric turbulence flux measurements

Mostafa Bakhoday Paskyabi
Geophysical Institute, University of Bergen, Norway
Mostafa.Bakhoday@gfi.uib.no
and
M. Flugge, J. B. Edson, J. Reuder

Wind and Wave energy distribution in period

Outline

- In Situ wind data sources and uncertainties.
- Particular problems on buoys and ships measurements.
- The air-sea fluxes: Definitions, parameterizations, and measurements.
- Sea Surface.
- Field work.
- Wave–dependent hydrodynamic properties.
- Results.

In Situ wind data sources and uncertainties

Upper: R/V Roger Revelle and WHOI flux buoy.
Lower left: R/P FLIP. Lower right: direct flux sensors.

Why accurate air-sea fluxes are important

- Sensitive indicators of changes in the climate system, integrating changes in:
  - Wind Speed
  - Air/Sea temperature difference
  - Vertical moisture differences
- Reducing large uncertainties on currently air-sea fluxes
  (Validation against measurements is rare and of limitation in space. Cross checks of different products (NOAA/NESDIS/NCEP and NODC/COADS, European ECMWF, British SOC, etc.) reveal large differences, but cannot tell which one is better)
- Consistency of air-sea fluxes with the ocean dynamics and energetics.

The air-sea fluxes

- Turbulent fluxes
- Radiative fluxes
- Freshwater flux
- Net surface fluxes
Turbulent fluxes

- Momentum flux is expressed as
  \[ \tau = -\rho \left( \frac{\partial U}{\partial z} \right)^2 \]

- Estimated via:
  - direct method (Eddy Correlation),
  - Bulk parameterizations,
  - indirect technique (Inertial Dissipation)

Eddy correlation

- Statistical meaning:
  - \( \left\langle u' v' \right\rangle \) can be considered as the second mixed moments, i.e. co-variances of variables

- Requirements:
  - Time resolution should be high (10-20 Hz).
  - Time of record should be relatively long (more than 20 min).
  - Stable platform.

- Instrumentations:
  - Sonic anemometer.
  - Fast-response thermometer.
  - Fast-response infrared hydrometer.

Eddy correlation for moving platforms: Particular Problems

- Wind flow distortion
- Sea spray and salt contamination
- Ship and buoy motion
- Other contaminations

Bulk parameterizations

Conventional, Eq.

\[ \tau = -\rho \left( \frac{\partial U}{\partial z} \right)^2 \]

is parameterized by the following bulk formula

\[ \tau = \rho C_L U \mathbf{U}' \]

where \( U \) is the horizontal mean wind speed at height \( z \) meters above the ocean surface.

The vertical velocity profile is given based on Monin-Obukhov similarity theory by

\[ U(z) = \frac{\tau}{\rho} \left( \ln \frac{z}{z_0} - \theta_w \right) \]

Field Work

- During 13 April to 29 June 2010.
- Air-Sea Interaction Tower (ASIT).
- A moored buoy about 600 meters away from ASIT.
Wind forcing and wave condition

Wind speed: correction scheme

• 6DOF motion correction for wind speed vector using accelerometer, gyroscope, and compass:

Wind speed: wave-dependent surface hydrodynamic properties

Total wind stress can be written as

\[ T = T_v + T_p + T_w. \]

Following Jansse 1994, the wave–dependent total wind velocity is given by

\[ U_{w,\phi}(z) = \frac{\alpha}{z} \left( \frac{z + z_i}{(z + z_i) + z} \right)^n, \]

where \( z_i \) is the wave stress contribution in the effective roughness \( \zeta_e = \delta + z_i \).
Wind speed: wave-dependent surface hydrodynamic properties

The wave speed is expressed as

\[ u_w = \sqrt{\frac{1}{\rho_0} \int_0^\infty \int V_x(x,t) \, dx \, dt} \]

where \( u_w \) is the wind speed, \( \rho_0 \) is the air density, \( x \) is the horizontal distance, \( t \) is the time, and \( \varepsilon \) is the wind energy input rate. The wind energy input rate is given by

\[ \varepsilon = \frac{1}{2} \rho_0 C_{D_{\text{sw}}} \frac{u_w^3}{\varepsilon} \]

The drag coefficient is then extracted by assuming a bulk relation for wave-induced momentum.

wave-dependent surface hydrodynamic properties for days 130-140

wave-dependent surface hydrodynamic properties for days 160-170

wave-dependent surface hydrodynamic properties for days 160-170
Conclusions

We presented briefly:
- Hydrodynamic properties of water surface.
- Motion correction.
- Wave-induced momentum stress.
- Comparisons made between fixed and moving platforms.

Thank you
Experimental characterization of marine atmospheric boundary layer in the Havsl area, Norway

Konstantinos Christakos, Joachim Reuder, Birgitte R. Furevik-
*Geophysical Institute, University of Bergen, Norway
*Norwegian Meteorological Institute, Norway

10th Deep Sea Offshore Wind R&D Conference, 24/25.01.2013, Trondheim

Outline

- Introduction
- Data overview
- Results
- Outlook

Marine Atmospheric Boundary Layer (MABL)

- Average wind profiles
- Wind shear over the rotor disk
- Turbulence
- Atmospheric stability
- Wind-waves interactions

the main problem:
- the lack of observational data in the relevant altitude range (sea surface to 200m)

Remote sensing instruments (i.e. LIDAR)

LIDAR (Light Detection And Ranging)

Advantages:
- Simultaneous measurements in several heights (up to 200 m)
- 3D wind velocity vector (u, v, w)

Disadvantage:
- absence of temperature measurements (vertical gradient).

Atmospheric stability?
Stability and turbulence affect wind energy production [1], [2]

How can atmospheric stability be estimated?

Wharton and Lundquist (2012) suggested different turbulence parameters for classifying wind profiles by stability [2],[3], based on onshore data (in western North America)
Turbulence parameters

- The horizontal turbulent intensity is a dimensionless parameter which is defined as the standard deviation of horizontal velocity fluctuation divided by the mean horizontal wind speed:

\[ I_u = \frac{\sigma_u}{U} \]

- The TKE is defined as the sum of the velocities variances in latitudinal (u), longitudinal (v) and vertical (w) direction divided by 2:

\[ \text{TKE} = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \]

Data overview

- 4 years (2008-2012) wind profile data were collected at the small island of Storholmen which is located 8 km northwest of the island of Vigra on the west coast of Norway.

Fig. 1: Location of Storholmen island (black square) in Ålesund, Norway. Source: Google Maps

Data overview

- The wind speed was measured by WindCube v.1 LiDAR at 8 height levels between 60 m and 200 m a.s.l. (above sea level).
- For higher levels the data availability was reduced due to low aerosol concentration in the air which leads to a low SNR.

Only complete 10 min. average wind profiles (75249) between 60 m and 150 m a.s.l. have been used for the presented analysis.

Investigation of Turbulence Intensity and Wind Speed

- Log-normal distribution is applied to describe the turbulence intensity distribution for different classes of wind speed at 100 m a.s.l.

Results:
- For increasing wind speed:
  1. The center of distribution moves towards lower turbulence intensities
  2. The probability density for the peak value increases

Turbulence Intensity and Wind Profiles

- Average wind profiles for different classes of horizontal turbulence intensity (at 100 m a.s.l.).
- The number of profiles for each class is given in parenthesis

Results:
- Clear dependency between turbulence intensity and wind profiles
- For turbulence intensities greater than 6%, increase of U is related to decrease of turbulence intensity.
- For turbulence intensities below 9%, the average profiles are closely grouped between 10 m/s and 12 m/s

Turbulence Intensity and Wind Shear

- The wind profiles have been normalized to 1 at 100 m a.s.l.

Result:
- A general increase in wind shear for decreasing turbulence intensities.
TKE and Wind Profiles
- Average wind profiles for different classes of TKE (at 100 m a.s.l.).
- The number of profiles for each class is given in parenthesis.

Results:
- Clear dependency of TKE on wind profiles.
- The higher the TKE, the higher the wind speed.
- TKE is mainly generated by wind shear in MABL.

TKE and Wind Shear
- The wind profiles have been normalized to 1 at 100m a.s.l.

Result:
- For lower levels: for increasing TKE, the wind shear decreasing.
- For higher levels: very little variation between TKE and wind shear.

Summary and outlook
- Measurements of offshore wind conditions are essential for the accurate characterization of MABL.
- Remote sensing instruments can provide a rich of source data for a better understanding of turbulence of the wind field.
- Turbulence parameters such as turbulence intensity and TKE are strongly related to the wind profiles.
- For offshore conditions turbulence intensity seems more promising for the classification of stability.
- Need for simultaneous measurements of temperature gradient and turbulence parameters for the classification of stability.

References

Acknowledgements
The authors express appreciation to Vestwind Offshore AS for sharing the wind data. The lead author expresses his gratitude to NORCOVE and Statoil ASA for received travel grant.

Thanks for your attention!
Application of the NORCOWE DCF System for Ship based measurements

Martin Flügge¹, Joachim Reuder¹
¹Geophysical Institute, University of Bergen, Norway

January 30th, 2013

Background

- Offshore wind farms located close to shore line and/or in shallow water → jacket or monopile foundations
- Increased demand for sustainable energy → development of floating turbines that can be moored in deep water

Results from Sullivan et al. (2008) suggest that surface waves influence the lower part of the MABL in horizontal and vertical directions
- Increase of loads and fatigue on turbine rotor blades!

Main challenge

- Turbulent air-sea exchange processes are not fully understood
- Most research sites are located close to shore and on small islets close to shore
- For real offshore conditions, only a few measurement sites are available in shallow waters → FINO platforms, ASIT, FLIP

Continuous measurements in deep water are needed for the highly required characterization of the MABL

Measurements from floating platforms

Platform motion and flow distortion will contaminate measurements from floating platforms

Solution: Measurements taken by means of the Direct Covariance Flux Method → removal of platform motion in postprocessing of the data

\[ \mathbf{U}_{\text{true}} = \mathbf{T}(\mathbf{U}_{\text{obs}} + \omega_{\text{obs}} \times \mathbf{R}) + \mathbf{V}_{\text{mot}} \]

- \( \mathbf{U}_{\text{true}} \): desired wind vector in the reference coordinate system
- \( \mathbf{T} \): coordinate transformation matrix for rotation from platform to the reference coordinate
- \( \mathbf{U}_{\text{obs}} \): measured wind velocity in the platform frame
- \( \omega_{\text{obs}} \): angular velocity vector of the platform coordinate system
- \( \mathbf{R} \): position vector of the wind sensor with respect to the motion package
- \( \mathbf{V}_{\text{mot}} \): translational velocity vector
The NORCOWE DCF-system

Gill R3A sonic anemometer:
- sampling rate up to 100 Hz
- provides 3D wind speed components (U, V, W) and sonic temperature \(T_s\) -- direct computation of turbulent heat and momentum fluxes
- Measurements have to be rotated from anemometer reference frame to earth frame

Crossbow NAV440:
- integrated GPS and Attitude & Heading reference system (AHRS)
- Measurement of 3-axis angular rates and accelerations up to 100 Hz internally integrated to velocity and position
- Internal coordinate transformation provides attitude and velocity information in earth frame

\[
U_{\text{true}} = T(U_{\text{obs}}) + \Omega \times \mathbf{r} + V_{\text{IMU}}
\]

\[
V_{\text{IMU}} = V_{\text{GPS}} + V_{\text{ACC}}
\]

The NORCOWE DCF-system

MOXA UC-7420:
- Data logging and control unit
- RISC-based ready-to-run industrial LINUX computer
- 8 RS-232 / 422 / 482 serial ports and PCMCIA interface for WLAN
- 1 CF slot and 2 USB2 ports for external memory storage

The system is powered by 230 V AC or 12 V DC and can easily be attached to a mast or any kind of frame

System performance

Cruise to Marstein Fyr November 28th to 30th 2012

- Data presented for November 29th 16:00h – 17:00h
- Moderate winds from southwest - southeast

Figure: Attitude angles in Earth frame computed from integrated angular rate sensor output. The IMU was mounted below the sonic anemometer on the front bow of R/V Håkon Mosby.
Effect of wave motion on wind lidar measurements - Comparison testing with controlled motion applied

24–25 January 2013, Trondheim, NORWAY

Prepared by: Jon O. Hellevang (CMR)
Presented by: Joachim Reuder (UiB)

Outline of presentation

- We will presented the key results from a comparison test between a pulsed and continuous wave (CW) lidar systems subject to controlled wave motion
- Background/aim
- Test site/setup
- Results
- Summary

Note: Results from offshore field test will be given by Jan-Petter Mathisen, Fugro OCEANOR at 16:15 "Measurement of wind profile with a buoy mounted lidar."

Project aim/organisation

- Aim: Demonstrate autonomous measurement system using floating buoy
- Part of the project: "Autonomous measurement of wind profile, current profile and waves for mapping of offshore wind potential, design and operation of offshore wind turbines."
- Comparison test presented here is part of WP2: Concept for wind profiling (with CMR as work package coordinator)
- Financed by the Research council of Norway (NRC) and Statoil (in addition to in-kind from Fugro OCEANOR, CMR and UiB)
- Fugro OCEANOR as project owner

Background

- Mapping of offshore wind potential is of high economic importance for the power companies with respect to bankability and profitability of the investments
- Building, installing and operating offshore wind mast is very expensive
- Using autonomous measurement system on floating buoy could be a very cost efficient solutions if found sufficient accurate and reliable

Test Site / Setup

- University in Agder, Grimstad campus
- Reasonable flat within a radius of 1km
- Sea to the south and east, while there are hills further to the west
- Motion platform placed 10 meter west of a 9 meters tall building
- Motion platform: Bosch Rexroth Boxel 6-DOF E-motion 1500 Motion System
- Lidor compared during test:
  - Wind Cube V.1 (pulsed)
  - ZephIR 300 (CW)
- Two similar lidars fixed on the ground used as reference measurement

Motions applied

- 55 motions tested:
  - 9 roll; A=3, 5, 10 and 15° | f=0.1 and 0.2Hz (tilt east-west)
  - 6 pitch; A=3, 5, 10, 15 and 20° | f=0.1 and 0.2Hz (tilt north-south)
  - 6 «random» pitch (based on Pierson-Moskowitz spectrum)
  - 5 yaw; A=39° | f=0.025, 0.005, 0.1, 0.15 and 0.2Hz
  - 3 surge; A=40cm | f=0.1 and 0.2Hz
  - 5 heave; A=20 and 40cm | f=0.1, 0.15, 0.2 and 0.4Hz
  - 11 vertical circle; r=30cm | A=3, 5, 10 and 12.5°, 3 and 5° offset
- Approximately 3 hours for each motion (total of 10 days)
- Pure sine-wave, except ‘random’ motions
- Results presented are horizontal wind speed at 85 meter based on 10 minute average data (NB: No motion compensation applied)
Results - Horizontal wind speed
- Slight bias observed during baseline measurements
- Average of all tests with motion show very small deviation between reference and moving units
- Only yaw motion with Wind Cube shows significant deviation
- Note the higher reading with circle motion with offset pitch angle compared to the one without any offset in pitch angle
- The average wind speed is about 5 m/s
- Next slides show more details

Results - Std. dev and regression
- Gradients (A) and coefficient of deterministic ($R^2$) are quite good for all tests
- High increase in standard deviation for Wind Cube during circle w/offset and pitch might be related to lower average wind speed (3.6 m/s) compared to the other tests (4.4 m/s)
- Note: The regression is forced through origin ($Y=Ax$), reference lidar on x-axis and moving lidar on y-axis. Based on 10 minute data obtained during each test

Results – Yaw motion
- Increasingly underestimation of the wind speed with yaw frequency for Wind Cube (A=39° for all tests)
- We believe that the Wind Cube wind speed calculation algorithm is somehow failing when subjected to such fast yaw motion, as the lidar only measure four points in about four seconds (ZephIR measure 50 points in one second)
- $R^2$ is very good throughout all tests
- Note: Such fast yaw motion might not be realistic during operation

Results – Roll motion
- The results indicate a decrease in horizontal wind speed and increase in standard deviation with increasing roll angle

Results – Pitch motion
- We observe increase in standard deviation with increasing roll angle
- Average wind speed and gradient indicate different trend for the two lidar systems

Results – Vertical Circle
- It seems as the test with offset angle has higher reading compared to the other tests, especially for the Zeph IR lidar (we expect an opposite trend)
- Possible explanations might be:
  - Measurement with an offset angle has in general lower wind speed (3.3 m/s) compared to the tests without any offset (4.8 m/s)
  - Higher standard deviation and poorer $R^2$ during testing with offset angle
  - Somewhat different wind direction during the two types of motion (130-180° vs. 206-328°)
  - Different wind profile
Results – Wind direction

- Very small impact of motion on wind direction measured
- Bias can be explained by offset during setup
- We observe that the ZephIR lidars shows a 180° deviation compared to Wind Cube during many of the tests
- ZephIR has a 180° wind direction unambiguity, which is solved using a local met station on the lidar
- Structural disturbance at the ground level where ZephIR has the local met station can explain the errors with ZephIR
- This might also be a problem in open areas if the buoy is rotating

Summary

- Relatively small deviation between moving and reference lidars
- Most measurements are with the measurement uncertainty
- Increasingly underestimation of the wind speed with yaw frequency for Wind Cube
- The standard deviation is increasing with tilt angle
- In general the deviation seems to increase somewhat with tilt angle (as expected by theory)
- ZephIR measure 180° wrong wind direction during many of the tests (probably due to nearby structures and setup)

Note: Results from offshore field test with ZephIR lidar will be given by Jan-Petter Mathiesen, Fugro OCEANOR at 16:15 “Measurement of wind profile with a buoy mounted lidar”

Acknowledgment

- University of Agder, campus Grimstad, especially Eivind Arne Johansen and Geir Hovland, for helping out with the practicalities of setting up this test
- Martin Flügge (UiB) and Stian H. Stavland (CMR) for assisting with running the test
- Joakim Reuder (UiB) and Ivar Øyvind Sand (CMR) for valuable input to the test
- NORCOWE and NOWITECH for renting us the Wind Cube lidars and NORCOWE for renting us the motion platform used
- The project owner Fugro OCEANOR for allowing the results to be published
- The Research Council of Norway and Statkraft as external funder of the project
- For more information: jono@cmr.no
System performance

Figure: IMU output of corrected velocity components in earth frame. The IMU was mounted below the sonic anemometer at the front bow of R/V Håkon Mosby.

System performance

Figure: Uncorrected wind components from the sonic anemometer mounted at the front bow of R/V Håkon Mosby.

Summary

• The Norwegian Center for Offshore Wind Energy has two state-of-the-art DCF-systems
• The first offshore deployment took place in November 2012
• Preliminary results show that the system is able to provide all necessary attitude and velocity information needed to correct for platform motion
• The system is easy to transport and can be mounted on any kind of platform, i.e. ships, buoys, masts, etc.
• The system can easily be extended with additional instrumentation

Thank you for your attention!

References

• Lien J.R. and G. Løvhøiden, 2001: Generell fysikk for universiteter og høyskoler, Universitetsforlaget
Overview

- Data
  - Measurement campaign
- Methods
  - TKE calculations
- Results
  - Case study
- Outlook
  - WindCube 100S
DATA – measurement campaign

- Summer 2010
- WindCube v1 (Leosphere)

DATA – WINDCUBE™ v1

- 4 positions 0/90/180/270
- 9 altitudes 40/65/70/85/100/135/160/185/200m

DATA – WINDCUBE™ v1

- 10m streamlines (VERA)
- 950 hPA wind field (GFS analysis)

DATA – WINDCUBE™ v1

METHODS
METHODS – TKE calculation

- Turbulence Intensity $T I$
  \[ TI = \frac{\sigma(v)}{v} \]
- Turbulent kinetic energy $TKE$
  \[ TKE = \frac{1}{2} (u'^2 + v'^2 + w'^2) \]
  - TKE generation due to wind shear
    \[ \frac{\partial TKE}{\partial z} = \frac{\partial u'}{\partial z} \cdot \nu \frac{\partial v'}{\partial z} = \frac{\partial u'}{\partial z} \frac{\partial v'}{\partial z} \]
  - TKE redistribution due to vertical advection

METHODS – TKE calculations

- Orientation of CS in main wind direction
- Interpolate data on regular time grid of 4s

RESULTS – wind rose

- Two wake signals at 90° and 330°, with visible wake expansion at 330°

RESULTS – TI/TKE distribution

- Contour plots of wind direction, horiz. wind speed and TKE

RESULTS – case study

- September 25th 2010
RESULTS – case study

- September 25th 2010
- Contour plots of the wind components u, v and w

RESULTATE – Vergleiche

- TKE Profile
  - NW: TKE = 6 m²/s²
  - SO: TKE = 3.5 m²/s²
  - O: TKE = 3 m²/s²

- TKE Anteil an gesamter kinetischer Energie
  - O: 21%
  - SO: 7%
  - NW: 5%

CONCLUSION

- Windcube v1 captures nicely wind regimes of region
- Windcube v1 can resolve wake effects of wind turbine
- Generated turbulence is unisotrope
  - Irregular loads to following wind turbines
- Gained information could help layout design and optimize efficiency of already existing parks
OUTLOOK

- Work will be continued with the scanning WindCube 100s
- Test deployment February 2013 at Sola Airport
- Develop and improve scanning patterns and measurement strategies for turbine and park related wake deployments

OUTLOOK – WindCube100s

- 16.8.2012 15:00
- South-westerly winds

OUTLOOK – WindCube100s

- Increase in wind speed
- Drop in temperature

Thanks for your attention 😊
C2 Met-ocean conditions

Wave driven wind simulations with CFD, Siri Kalvig, University of Stavanger / StormGeo

New two-way coupled atmosphere-wave model system for improved wind speed and wave height forecasts, Olav Krogøæter, StormGeo / University of Bergen

Measurement of wind profile with a buoy mounted lidar (presentation and paper) Jan-Petter Mathisen, Fugro OCEANOR

Numerical Simulation of Stationary Microburst Phenomena with Impinging Jet Model, Tze Siang Sim, Nanyang Technological University
Wave driven wind simulations with CFD

DeepWind'2013, 24-25 January, Trondheim, Norway
Siri Kalvig¹, Richard Kvemeland² and Eirik Manger³
¹StormGeo, Norway
²University of Stavanger, Norway
³Acona Flow technology, Norway

Introduction

- Motivation
- Wave-wind interactions
- Method
- Results
- Conclusions & comments

Motivation

A typical offshore wind picture.... How does a "non-flat" sea affect the wind fields?

Wind wave interaction

Wind sea and swell influences the atmosphere different!

Wind sea - waves generated by local wind
Swell - long period waves generated by distant storms

Most common is a mixture of wind sea and swell, and this makes the picture even more complicated.

- Field experiments and numerical simulations show that during swell conditions the wind profile will no longer exhibit a logarithmic shape and the surface drag relies on the sea state (i.e. Smedman et al. 2003 & 2009, Semedo et al. 2009).

- There is a gap between “best knowledge” (science) and “best practice” (codes, standards) and there is a need for improved guidance on the impact atmospheric stability and wave-wind interaction in the MABL can have on the offshore wind industry (Kalvig et al 2013, Wiley Wind Energy, in press).

- Swell can result in both higher and smaller effective surface drag and it is likely that swell can create different wind shear and turbulence characteristics so that a wind turbine site will be exposed to other external environmental condition than it was designed for.
**Wind wave interaction**

- Sullivan et al. (2008) developed a large-eddy simulation (LES) with a two-dimensional sinusoidal wave and identified flow responses for three cases: wind opposing swell, wind following swell and wind over a swell surface with no movement.
- The flow responses in the different cases where very different and 'fingerprints' of the surface wave extended high up in the MBL.

Aim at develop a wave-wind simulation set up with open source CFD and with more computational effective methods.

**Method**

- The open source CFD toolbox OpenFOAM is used for both mesh generation and CFD computations.
- Wave speeds (c), wave amplitude (a), wave length (L) are input parameters to the model.
- To start with a relatively small domain with length of 250 m and a height of 50 m was established. Various sensitivity analyses were performed where different wind velocities and sea states where studied in detail (Kverneland, master theses Uis 2012).
- Temperature and the Coriolis effect are not taking into account and only uniform wind is studied. The calculations use a Reynolds averaging Navier-Stokes (RANS) approaches and since the wave moves it is necessary with a transient (time varying) simulation. The turbulence closure model used is the standard k-epsilon model.

**Method**

- NORCOWE & NOWITECH organized a wind turbine blind test in 2011-2012, BT1 & BT2.
- BT1: Eight independent modelling groups submitted 11 sets of simulations. No obvious "winner" and large spread of results (Krogstad et.al. 2011).

Currently working with the Actuator disk and actuator line method.
Aiming at coupling the wave set up with a turbine wake model.

**Method**

- Need to simulate wave movements!
Need a new boundary condition that take into account the sinusoidal movement of the "ground".

**Results**

- In general:
The wind speed profile and the turbulent kinetic energy pattern far above the waves will be different depending on the wave state and wave direction.
Results

Wind aligned with waves: Vertical profile (at x=210 m) of mean values of the horizontal and vertical component of the wind flow for six cases with different inlet velocity (openFOAM FieldAverage is used for mean values).

Wind opposing waves: Vertical profile (at x=210 m) of mean values of the horizontal and vertical component of the wind flow for six cases with different inlet velocity.

Mean turbulent kinetic energy for wind aligned with the waves and wind opposing the wave.

Various wave states opposed with wave propagation. Vertical profile of horizontal wind speed and mean horizontal wind speed.

Uniform wind of 5 m/s at the inlet.

Wave with:
c=8 m/s, a=3 m, L=40 m

"Instant" velocity profiles over the wave surface. Lines for every 5 m in the interval of 145-200 m (over one whole wave length). Wind aligned and wind opposed the wave propagation result in very different response in the wind field.

"Instant" turbulence profiles over the wave surface. Lines for every 5 m in the interval of 145-200 m (over one whole wave length). Wind aligned and wind opposed the wave propagation result in very different response in the wind field.
The SWAN wave model

- Simulating Waves Nearshore
- Simulates the wave spectrum
- Includes effects such as
  - Shoaling
  - Refraction
  - Whitecapping
  - Bottom friction
- Has been modified at StormGeo to read 2D-spectra from Grib files
- Run operationally for N. Europe

WRF Model

Non-hydrostatic mesoscale weather prediction system
- Weather Research and Forecasting model
- Large and growing set of parameterization options
  - Surface layer schemes
  - Boundary layer schemes
  - Microphysics schemes
  - Cumulus schemes
  - Radiation schemes
- Nesting capability
- Nudging capability
- Assimilation capability
- Open Source project

Outline

- WRF, SWAN, and the coupled system
- Results
  - Three cases:
    - Stormy weather.
    - Cold air outbreak.
    - Inversion.
  - Yearly statistics.
- Summary

Coupled model

- The most difficult part was how the SWAN model should influence the WRF model.
- Parameterizing the effect that the ocean surface has on the atmosphere is still an active field of research.
- The key parameter the SWAN model modifies is the roughness length, $z_0$, seen by the WRF model. This is communicated through the Charnock parameter, $z_c$:
  
  $$z_c = z_0 \left( \frac{u_*}{g} \right)^2$$

  where $u_*$ is the friction velocity and $g$ the gravitational constant.
Coupled model

- Technical work is done
  - WRF and SWAN are set up to run within Earth System Modelling Framework, ESMF
- Information exchanged every hour
  - SWAN receives 10 m winds from WRF
  - WRF receives a new roughness parameter, $z_0$, from SWAN
- One year run with both the MYNN2 and MYJ Planetary Boundary Layer (PBL) scheme in WRF, coupled with SWAN and the HEXOS parameterization is finished.

WRF and SWAN: coupled run

+1 hour

WRF

SWAN

+1 hour

WRF

$z_0$

SWAN

+2 hours

WRF

WRF

SWAN

SWAN
WRF and SWAN: coupled run

Result: Stormy case in November 2010

Wind Speed uncoupled, 40m
Friction velocity, $u^*$ uncoupled
Difference, $u^*$, coupled-uncoupled

Friction velocity, $u^*$

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A new two-way coupled atmosphere-wave research and forecasting system is implemented: WRF-SWAN.

- Two different PBL-schemes: MYJ and MYNN2.
- HEXOS parameterization for computing the new roughness parameter from SWAN that goes into WRF. Function of wind age.
- Janson parameterization – ongoing work. Function of wave growth.

---

- Reduces the well-known positive bias in WRF with both PBL-schemes.
- Reduces the MAE in the MYNN2-SWAN setup.
- Increases slightly the MAE in the MYJ-SWAN setup.
- Strong winds greater than 15 m/s are reduced too much in the coupled runs.

---

From previous research on many different PBL-schemes by e.g. O. Krogsgaeter (2013) and A. Hahmann (2012):

* MYJ scheme perform best in offshore conditions with WRF stand alone.
* MYNN2 scheme perform slightly better in this new coupled system.
Results

Comparison with Sullivan et al. 2008:
An openFOAM URANS set-up with a wave with $a=1.6$ m, $L=100$ m and $c=12.5$ m/s on a domain of $1200 \times 100$ m is being compared with Sullivan et al’s LES simulations. Preliminary results are promising and it looks like we are able to capture the same dynamics as Sullivan et al. But current simulations is too coarse and more refined simulations are needed.

Summary

- Wave wind simulations with openFOAM is on going PhD work at University of Stavanger/StormGeo/Norcowe.
- A cost efficient CFD method for flow over wave simulations, based on RANS turbulence closure is developed.
- The response in the boundary layer over the wave are very different for cases where the wind is aligned with the wave propagation and wind opposing the wave.
- Case of $U=5$ m/s and $c=10$ m/s wave: A low level speed up is created in the lowest meters for wind aligned with a fast moving wave. The profiles over the wave do not exhibit a logarithmic profile (or power law profile). Turbulent kinetic energy is slightly higher for wind opposing the wave than wind aligned with the wave.
- Preliminary result shows pattern that compares well to Sullivan et al. (2008). More detailed studies need to be performed.
- Next step: Test the significance and the implications of wave-wind interaction on the offshore wind turbine loads and wakes. Wave movement code and turbine modelling code need to be coupled.

References


Acknowledgements:
- Eirik Manger, Acona Flow Technology
- OpenCFD, academic support agreement

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Measurement of wind profile with a buoy mounted lidar

Jan-Petter Mathisen
Date: 24 January 2013

Contents Menu
- History
- Project description
- Lidar technology
- Onshore motion test
- Description of field test
- Results and discussion
- Conclusions

History
First Automatic Wind Turbine
1887 Mayark Scotland
First Norwegian Wind Mill at Fram

Participating organizations:
- Fugro OCEANOR
- University of Bergen
- Christian Michelsen Research
- Statoil
- MarinTek

Project tasks
- Formulation of requirement and specification of the system
- Concept study
- Development of a prototype including hydrodynamic simulations
- Development of a compensation algorithm for the buoy motion
- Building of a prototype buoy
- Field test of the buoy

Present technology
- FINO1 German Bight
- Price NOK 50 mil
Measurement system

Wavescan buoy

ZephIR 300 lidar

ZephIR 300 lidar from Natural Power

Principles of operation:
- Laser radiation scatters from atmospheric aerosols
- A laser is focussed at a point incident with the aerosols
- Aerosol movement follows the wind
- Scattered radiation is ‘Doppler’ shifted by the wind speed
- The ‘in-line’ component of wind speed is measured

Benefits of the SEAWATCH Wind Lidar Buoy

- Wind profile, meteorological parameters, waves, current profile and other parameters can be measured from one single buoy
- The ZephIR can measure wind at 10m which is according to the WMO standard
- No recalibration is required for the ZephIR
- The Wavescan buoy is lightweight and small and is therefore easy to deploy and recover from vessels
- A standard single point mooring system is used

Test location Titran

Testing of Lidar buoy off the wind test centre

Preliminary results without compensation
Wind speed and direction

Wind speed for different heights

Scatter plot

Frequency distribution

Further work

Fuel cell from EFOY
Measurement of wind profile with a buoy mounted lidar

Jan-Petter Mathisen
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Abstract

Traditionally wind profile measurements for offshore wind farms have been obtained by using cup anemometers mounted on wind masts. This is a very expensive method to acquire wind profile data, and the wind data will also be influenced by distortion from the mast and the sensors. A much cheaper way of obtaining offshore wind data is using a buoy mounted lidar. In addition a buoy can also measure waves, current profile and other parameters.

To be able to measure the wind profile from a buoy, a ZephIR 300 lidar from Natural Power was mounted on a Fugro OCEANOR Wavescan buoy. The Wavescan buoy is specially designed for severe environmental conditions, and has been in operation world-wide since 1985.

The buoy system was tested off Titran off the island Frøya on the coast of central Norway. This is an ideal test site as it is in a very tough environment and near to a test centre for wind measurements with 3 instrumented met masts. The wind test centre is a part of the NOWITECH infrastructure programme. A reference lidar supplied by Natural Power was also located at the wind test centre. The distance between the reference lidar and the buoy was approximately 3.5 km. The Wavescan buoy was deployed for a period of one month during March-April 2012. The buoy lidar recorded 10 minutes average wind profile at 10 heights from 11.5 to 218m every third hour, while the reference lidar measured the wind at 53 m height continuously. During the measurement period the significant wave height varied between and 0.5 and 3.6m.

The wind speed from the buoy lidar has been compared with the reference lidar showing that there is practically no bias, while there is some scatter with a correlation coefficient ($R^2$) of 0.93. For higher wind speeds, which are mainly towards the coast, $R^2$ is 0.95 with a slighter larger bias. The scatter can be explained simply by the distance between the lidars, and that the reference lidar is located on land. We are therefore planning to compare the buoy mounted lidar measurements with closer offshore wind mast data.

Keywords: Wind profile measurement; lidar; buoy
1. Introduction

The interest for offshore wind farms is increasing due to increased demand of energy world wide and that climate change has increased the interest for renewable energy.

Reliable data of the wind profile for the relevant height of recent and future wind generators (30-300m) are important both for design, estimation of wind energy potential and during operations. As the power production of wind turbines increases with the 3rd power of the wind speed, accurate measurements of the wind profile is important both with respect to financing and profitability of the investments. Up to now such measurements have been carried out on bottom mounted met mast which is expensive and stationary. By measuring the measurements from a portable buoy the cost will be decreased by a factor 10 or more.

A research project was therefore initiated for development and demonstration of an autonomous system for measuring wind profile, waves and current profile from an anchored floating buoy.

The system should be able to measure wind profile in the region from 10-300 meters above sea level, relevant for actual and future offshore wind farms. Applications for such a measurement system include:

- Mapping of wind potential
- Optimisation of wind farm during operation
- Determination of structural loads and expected fatigue
- Validation of numerical simulations of the atmospheric and oceanic boundary layer
- Measurement of wake effect

The project included the following tasks:

1. Formulation of requirement and specification of the system
2. Concept study
3. Development of a prototype including hydrodynamic simulations
4. Development of a compensation algorithm for the buoy motion
5. Building of a prototype buoy
6. Field test of the buoy

The following institutions participated in the project: Fugro OCEANOR, Statoil, University of Bergen/Uni Computing, Christian Michelsen Research (CMR) and Marintek. The project has been funded by the Norwegian Research Council, Statoil and the participants as in kind contribution except for the work carried out by Marintek which was fully financed.

2. Lidar motion test

To examining the influence of wave motion on the lidar wind profile measurements, a motion test was carried out at the University of Agder, Grimstad autumn 2011. A motion platform was rented free of charge from the University in Agder, campus Grimstad, as this infrastructure was funded by NORCOWE. A motion sensor and sonic anemometer was also rented free of charge from NORCOWE. The motion platform used had 6 degrees of freedom, with the possibility of controlling frequency and amplitude individually. The motions along the following principal axis; roll, pitch, yaw, heave and surge, in addition to the combined motions; heave, surge and pitch were applied. The objective of the setup was to simulate actual wave motion.

ZephIR 300 from Natural Power and Wind Cube from Leosphere were included in the test, being continuous wave (CW) and pulsed lidars respectively. One of each type was mounted on the motion platform, while the other two were located at the ground as reference instruments. A picture of the test setup is shown in Figure 1.

Details regarding the test are given in [1].
3. Compensation algorithm

The compensation algorithm for motion corrections has been developed by Uni Computing, University of Bergen. The algorithm can use all the 6 degree of freedom data measured by the wave sensor in the buoy, to compensate the lidar wind measurements for the buoy motion. The algorithm uses the 1 sec data from the Wave sensor to compensate the 1 sec wind measurements at each height.

4. Description of the measurement system

The Wavescan Lidar buoy includes a ZephIR 300 lidar attached to the Wavescan buoy. Below is given a description of the different elements and the arrangement of the system.

4.1. The Wavescan buoy

The Wavescan buoy is Fugro OCEANOR’s largest buoy well suitable for rough sea condition. The horizontal diameter is 2.8 m and the weight (without mooring) is approx. 925 kg. It has large buoyancy, 2800 kg, meaning that it is well able to withstand mooring load in deep waters.

The Wavescan buoy has a discus shaped hull that can be split in two to ease transportation. A keel with counterweight is mounted under the hull to prevent capsizing of the buoy.

A cylinder in the middle of the buoy hull contains all electronic modules, the power package and the wave sensor (integrated with the data logger). The instrument container has diameter 0.7 m and height 1.46 m, giving a volume of 0.56 m³. The different electronic modules are mounted into special splash proof compartment boxes to secure safe handling of the sensitive electronics. The buoy is equipped with a mast to support the meteorological sensors and the antennae. The meteorological parameters are measured 3.5m above sea level. This version of the buoy has a modified design with larger solar panels with a capacity of 40W each.

The buoy hull includes wells for mounting different sensors.
4.2. The ZephIR lidar

ZephIR is a Continuous Wave (CW) lidar. The principle by which ZephIR measures the wind velocity is simple: a beam of coherent radiation illuminates the target (natural aerosols), and a small fraction of the light is backscattered into a receiver. Motion of the target along the beam direction leads to a change in the light’s frequency via the Doppler shift. This frequency shift is accurately measured by mixing the return signal with a portion of the original beam, and sensing the resulting beats at the difference frequency on a photo detector. The essential features are readily seen in the simplified generic CLR depicted below.

CW systems are the simplest form of Lidar and possess the advantage of reduced complexity and high reliability for long periods of autonomous and remote operation. A CW system is physically focused to the required range and it is essentially the tightness of that focus that determines the probe length: the shorter the range, the smaller this length. The latest version of ZephIR has an effective probe length of ±1m, ±6m and ±15m at 40m, 100m and 150m ranges respectively. ZephIR can measure to a minimum range of 10m or shorter if required. Wind profiling is achieved by focusing at a number of chosen ranges in turn.

As a result of physically focusing the laser at each height of interest ZephIR achieves comparable sensitivity at each height: a critical design parameter for deployments in clean air with low concentrations of natural aerosols. CW lidar is highly sensitive and, as a consequence, it can achieve an acceptable signal-to-noise ratio in a much shorter timescale than other lidar methods.

ZephIR scans its beam in a 30 degree cone and continuously gathers 50 independent line-of-sight wind speed measurements per second, from which the wind vector is derived. The rapid data rate opens up possibilities for examination of detailed flow and turbulence across the measured disk. In addition, the velocity resolution of ZephIR is very high and its accuracy is measured to be 0.003m/s against a calibrated moving belt target.
5. The SEAWATCH wind lidar buoy

SEAWATCH Wind Lidar buoy consists of a standard Wavescan buoy with the ZephIR 300 mounted on the lifting ring on the central cylinder as shown in Figure 4. For measuring the current profile an Aquadop Profiler from Nortek mounted in one of the wells can be included. The laser head is located 2.5m above the sea level, so the lowest measurement height for the lidar is 12.5m. In addition a wind sensor is included on the lidar 2.5m above the sea level and a standard wind sensor mounted on the top of the met mast 3.5m above the sea level.
6. Field test

The field test was carried out off Titran at the island Frøya, see Figure 5. This is an ideal test site since it is an exposed location and near a wind test centre with 3 instrumented met masts. The wind test centre is a part of the NOWITECH infrastructure programme. A reference lidar supplied by Natural Power was located at the wind test centre. The reference lidar is shown in Figure 6.

The Wavescan buoy with the ZephIR lidar was deployed 24 March 2012 and was recovered 19 April 2012. A picture of the buoy is shown in Figure 7. The distance between the reference lidar and the buoy was approx. 3.5km. The buoy lidar recorded 10 minutes average wind profile at 10 heights from 12.5m to 218m every third hour, while the reference lidar measured the wind at 53 m height continuously. In addition the buoy measured waves and wind and humidity at the buoy met mast every 30 minute.

![Figure 5. The location of the field test](image)

![Figure 6. The ZephIR reference lidar](image)
Time series of wave height is presented in Figure 8. The significant wave height was largest during the first part of the test and reached a maximum of 3.5m on the 28th March. The wave height was below 1m after 9th April.

Time series of wind speed at 53m both for the buoy mounted and reference lidar are presented in Figure 9. As for waves the wind speed is strongest before 5th April with a maximum wind speed of 20m/s. After 5th April the wind speed is mostly below 10m/s i.e. fresh breeze (B5). The wind direction measured by the Gill ultrasonic wind sensor located on the buoy met mast 3.5m above sea level is given in Figure 10. The wind direction was mainly between south-west and north until 8th April, and after then the wind direction was mainly between north and east i.e. offshore wind.

The wind speed at 3 heights measured by the ZephIR on the buoy is presented in Figure 11. There are some gradients at strong winds at the beginning of the measurement period, while there are small gradients after 1st April. During the first period the wind direction was from south-west with maritime polar air masses, while polar arctic air masses are present during northerly winds. These two air masses have different stability which will affect the wind profile. With northerly winds the air masses are transported over land over a distance of more than 3 km which has higher friction than air masses over sea, which may also affect the stability.
Figure 9. Time series from the onshore reference lidar and the buoy mounted lidar for the test period.

Figure 10. Wind direction measured by the buoy wind sensor 3.5m above sea level.
Scatter plot of the buoy lidar vs. the reference lidar is shown in Figure 12, which shows that there is practically no bias, while there is some scatter as indicated by a squared correlation coefficient of 0.93. Since the scatter is largest for small wind speeds, we have prepared a scatter plot for the period before 5th April. The scatter is then lower with a squared correlation of 0.95, while the bias is slightly larger. During the period after 5th April there is mainly offshore wind as discussed before, which may give larger gradients between the reference and buoy lidars.

Figure 11. Wind speed at 10, 53 and 218m measured by the ZephIR at the buoy.

Figure 12. Scatter plot of the buoy mounted lidar vs. reference lidar for the whole period (left) and for the period before 5th April (right)

7. Conclusions

To be able to measure the wind profile from a buoy, a ZephIR 300 lidar from Natural Power was mounted on a Fugro OCEANOR Wavescan buoy. The Wavescan buoy is specially designed for severe environmental conditions, and has been in operation world-wide since 1985.

The buoy system was tested off Titran off the island Frøya on the coast of central Norway. This is an ideal test site as it is in a very tough environment and near to a test centre for wind measurements with 3 instrumented met masts. The wind test centre is a part of the NOWITECH infrastructure programme. A reference lidar supplied by Natural Power was also located at the wind test centre. The distance between the reference lidar and the buoy was approximately 3.5 km. The Wavescan buoy was deployed for a period of one month during March-April 2012. The buoy lidar recorded 10 minutes average wind profile at 10 heights from 11.5 to 218m every third hour, while the reference lidar...
measured the wind at 53 m height continuously. During the measurement period the significant wave height varied between and 0.5 and 3.6m.

The wind speed from the buoy lidar has been compared with the reference lidar showing that there is practically no bias, while there is some scatter with a correlation coefficient ($R^2$) of 0.93. For higher wind speeds, which are mainly towards the coast, $R^2$ is 0.95 with a slighter larger bias. The scatter can be explained simply by the distance between the lidars, and that the reference lidar is located on land. We are therefore planning to compare the buoy mounted lidar measurements with closer offshore wind mast data.

Acknowledgements
Thanks to natural Power for supplying the reference lidar and to NOWITECH for getting access to the infra structure at the wind test centre at Titran.

References
Numerical Simulation of Stationary Downburst Phenomena with Impinging Jet Model

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Ph.D student
Nanyang Technological University, Singapore
24 January 2013

Content
1. Background
2. Objectives
3. Methodology
4. Results and discussion
5. Conclusion
6. Future work

Background

• What is downburst?
The famous atmospheric scientist, Fujita (1985), in his report “The Downburst-Microburst and Macroburst”, defined downburst:
as an intense, transient downdraft of air that induces an outburst of damaging wind on or near the earth’s surface.

Background

• Where can downburst be found?

United States
- Account for about 1/3 of extreme wind. (2002)

Australia
- About ½ of downbursts in thunderstorms contribute to extreme wind gust. (2002)

Asia
- Thunderstorm type downbursts occur in cyclonic and non-cyclonic areas. (2004)

Background

The “thunderstorm” type downburst occurs in cyclonic and non-cyclonic areas. (2004)

Downburst wind starts off by travelling vertically downward.
Upon impinging on the ground, it spreads out radially along the earth's surface as outflow.
Severe cases:
The strength can be equivalent to a tornado.
Implications:
Wind hazard to ground structures.

Background

The high speed outflow at earth’s surface is important to the ultimate load limit of structures.
This might be a concern for large structures.
Examples are:
- Offshore wind turbines (2011), transmission towers

Background

• Downburst wind starts off by travelling vertically downward.
• Upon impinging on the ground, it spreads out radially along the earth’s surface as outflow.
• Severe cases:
The strength can be equivalent to a tornado.
• Implications:
Wind hazard to ground structures.
Objectives
• Understand downburst outflow near the earth surface and investigate on the interaction with large structures.

Methodology
• Literature from the past 10 years from present indicates few main methods of investigating/understanding the outflow near earth surface.
  – 1. Laboratory “Impinging jet model” method (2007)

Methodology
• To help us gain a rough understanding of the flow characteristics.
• Employ the simplest laboratory “Impinging jet model”.
• First proven to match closely with the downburst by Hjelmfelt

Methodology
• In the research:
  – Numerically simulate downburst, with impinging jet Model in 2D axi-symmetric domain.
  – Computational Fluid Dynamics (CFD) technique. Perform steady-state Reynolds Averaged Navier Stokes (RANS) and transient RANS.
  – Characterise the flow of a stationary impinging jet and understanding the flow features.

Axi-symmetric CFD
Computational domain

Boundary conditions

Assumptions
Incompressibility
Temperature and buoyancy effect neglected.

Legend
Re: Reynolds number based on diameter of B
U: Inlet velocity at B
D: Diameter of B (independent variable)
H: height of A
\nu: kinematic viscosity of air
z/D: normalised radial distance from D

Results and discussion
• Grid and domain independence test
Results and discussion
• Validated with Kim and Hangan (2007) experimental data of the impinging jet at different locations along the wall (other locations are not shown.)


Results and discussion
Velocity magnitude (m/s) plot contour.

High speed flow region (close to 7.57 m/s) encountered at the “inlet” and at the “wall” region.

Results and discussion
Reynolds number dependency
Re = 20,000 ; Re=2,000,000

Results and discussion
At very high Reynolds number.

Results and discussion
Changing the diameter D of the “inlet”.

Results and discussion
Effects of changing the height H of the inlet from the wall surface (only location r/D=1.0 and r/D=2.5 shown).
Results and discussion
Effects of gravity (in the negative axial direction)

Conclusion
1) Maximum peak velocity magnitude in the whole computing domain occurs at r=1D.
2) As Reynolds number is increased, the height at which the maximum velocity is decreased.
3) As Reynolds number gets extremely large, the flow is approximately inviscid, and the flow becomes more periodic and vortices are more organised and periodic.
4) Decreasing the height H of the inlet results in increase of the peak speed of that location.
5) There is no significant effect on the flow due to gravity and changes in the diameter.

Future works
- Study effects of buoyancy and density stratification
- Performing a 3-dimensional simulation using Large eddy simulation (LES) method to study the vortices.
- Study the interaction effect of the flow with obstacles blocking the flow.
- Study the effects due to ocean waves, where the waves are modelled as roughness elements.
Posters

Magnetically Induced Vibration Forces in a Low-Speed Permanent Magnet Wind Generator with Concentrated Windings, Mostafa Valavi, PhD stud, NTNU

Stability in offshore wind farm with HVDC connection to mainland grid, Jorun I Marvik, SINTEF Energi AS

A Markov Weather Model for O&M Simulation of Offshore Wind Parks, Brede Hagen, stud, NTNU

Turbulence Analysis of LIDAR Wind Measurements at a Wind Park in Lower Austria, Valerie-Marie Kumer, UiB

Investigation of droplet erosion for offshore wind turbine blade, Magnus Tyrhaug, SINTEF

NOWIcob – A tool for reducing the maintenance costs of offshore wind farms, Iver Bakken Sperstad, SINTEF Energi AS

Long-term analysis of gear loads in fixed offshore wind turbines considering ultimate operational loadings, Amir Rasekhi Nejad, PhD, NTNU

Methodology to design an economic and strategic offshore wind energy Roadmap in Portugal, Laura Castro-Santos, Laboratório Nacional de Energia (LNEG) (poster and paper)

Methodology to study the life cycle cost of floating offshore wind farms, Laura Castros Santos, Laboratório Nacional de Energia (LNEG) (poster and paper)

Two-dimensional fluid-structure interaction of airfoil, Knut Nordanger, PhD stud, NTNU

Experimental Investigation of Wind Turbine Wakes in the Wind Tunnel, Heiner Schümann, NTNU

Numerical Study on the Motions of the VertiWind Floating Offshore Wind Turbine, Raffaello Antonutti, EDF R&D

Coatings for protection of boat landings against corrosion and wear, Astrid Bjørgum, SINTEF Materials and Chemistry

Numerical model for Real-Time Hybrid Testing of a Floating Wind Turbine, Valentin CHABAUD, PhD stud, NTNU

Advanced representation of tubular joints in jacket models for offshore wind turbine simulation, Jan Dubois, ForWind – Leibniz University Hannover

Comparison of coupled and uncoupled load simulations on the fatigue loads of a jacket support structure, Philipp Haselbach, DTU Wind Energy

Design Standard for Floating Wind Turbine Structures, Anne Lene H. Haukanes, DNV

Nonlinear irregular wave forcing on offshore wind turbines. Effects of soil damping and wave radiation damping in misaligned wind and waves, Signe Schløer, DTU
Magnetically Induced Vibration Forces in a Low-Speed PM Wind Generator with Concentrated Windings

Mostafa Valavi, PhD Candidate
Department of Electrical Power Engineering, NTNU
Supervisor: Professor Arne Nysveen

INTRODUCTION

Permanent Magnet (PM) machines with concentrated windings have been gaining importance in the last few years due to several significant advantages over machines with distributed windings. One attractive application is direct-driven wind generators where the gearbox is eliminated, and this is a very effective way to increase the reliability and reduce the maintenance works. It could be a distinct advantage particularly in offshore wind farms, where the maintenance operations are difficult and expensive. The most important drawback of using concentrated windings is that the vibration level of these machines can be significantly higher than conventional machines. It is mainly due to the presence of low order harmonics in the radial magnetic forces.

GENERATOR SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Rated power</td>
<td>50 kW</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>90 Hz</td>
</tr>
<tr>
<td>Rated speed</td>
<td>517 rpm</td>
</tr>
<tr>
<td>Rated current</td>
<td>100 A rms</td>
</tr>
<tr>
<td>Number of poles</td>
<td>116</td>
</tr>
<tr>
<td>Number of stator slots</td>
<td>120</td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>1777 mm</td>
</tr>
<tr>
<td>Stator inside diameter</td>
<td>3650-3524</td>
</tr>
<tr>
<td>Permanent magnets</td>
<td>NdFeB N45</td>
</tr>
</tbody>
</table>

THEORY

- Maxwell's stress tensor
  \[ f_{ij} = \frac{1}{2\mu_0} (\varepsilon_{ij} - \varepsilon_{kk} \delta_{ij}) \]
- Radial magnetic force waves
  \[ f_r(\theta,r) = f_{r\max} \cos(m\delta - k\theta) \]
- Mode shapes

- Radial forces are the main cause of magnetic vibration.
- Dominant vibration mode is the lowest mode.
- In PM machines with concentrated windings, low modes of vibration can be excited.

CONCLUSION

Radial magnetic forces in a low-speed 120-slot/116-pole wind generator are calculated using finite element method and Maxwell's stress tensor. These forces are the main cause of the magnetic vibration. Flux density distribution due to PM and MMF magnetic fields is analyzed. It is shown that slotting harmonics play an important role in the field characteristics. Radial forces are investigated in no-load and load conditions. It is found that amplitude of the lowest spatial harmonic order (4th) is considerable even in no-load, however it increases while the machine is loaded. It is shown how slotting and MMF harmonics contribute to produce this lowest vibration mode.
Analysis of grid faults in offshore wind farm with HVDC connection

Jorun I. Marvik, Harald G. Svendsen
SINTEF Energy Research, Trondheim, Norway

Introduction

Future offshore wind farms are expected to be built farther away from shore and have larger capacities than today. This leads to new challenges related to grid connection. At distances longer than roughly 100 km, HVDC transmission is preferred over AC transmission due to large charging currents in AC-cables. Conventional LCC HVDC is not suited for connection to weak grids like offshore wind farms, and the less mature VSC HVDC technology is preferred instead.

A future large offshore wind farm with full power converter turbines and three-terminal VSC HVDC grid connection has been modelled in PSCAD. With three terminals the HVDC link can be used for direct transmission between the onshore terminals in addition to transmission of wind power. This work focuses on responses to faults in the collection- and transmission system. Due to the power electronics interfaces, the system has low short circuit capacity and missing inertia. Also, DC-cables are discharged very fast during faults. This leads to different fault responses than in conventional grids.

Offshore wind farm with HVDC transmission

Faults in wind farm AC collection grid

2-phase short circuit in collection grid
A) Active power on collection grid- and turbine side of one wind turbine converter
B) Wind turbine DC-link voltage and AC terminal voltage

3-phase short circuit in collection grid
A) Active power on collection grid- and turbine side of one wind turbine converter:
B) Wind turbine DC-link voltage and AC terminal voltage

Impedance seen by relay at offshore HVDC terminal:

Conclusions – AC collection grid faults

- Fault detection with conventional impedance protection is difficult in the offshore AC-grid, as Impedance protection is based on Impedance changing from a large value during normal operation to a small value during fault.
- The surplus energy in the DC-link during the AC-voltage dip is consumed by a DC-chopper when the DC-voltage goes above 1.2 pu. The wind turbine can therefore operate undisturbed through the short-circuits.

Faults in HVDC transmission-grid

Earth-fault halfway between converters C1 and Cwf

Conclusions - HVDC transmission grid faults:

- In this case, the HVDC cable between terminals C1 and Cwf has to be disconnected within 15 ms to assure stable operation (i.e. very fast).
- Fast detection is possible e.g. based on rate-of-change of current together with DC-voltage level, but fast DC breaker is required for disconnection.
- When HVDC terminal C1 is disconnected, the active power delivered to HVDC terminal C2 is increased accordingly, due to the DC-voltage droop on the active power controller in the converter in C2.
A multivariate Markov chain model is presented for generating sea state time series based on observed time series. Two ways of capturing the seasonal variation in the sea state parameters resulted in two distinct models which quality was assessed by comparing their statistical properties to what was obtained from observed time series. Two different sea state data sets were considered in the validation, and it was found that both models compared favorably to those empirical data. It was concluded that Model 1 worked best for the longest data set considered, but was challenged by the shorter time series, where Model 2 worked best.

Main objective: Create a stochastic weather model for the sea state conditions based on observed time series which can be used in an O&M simulation tool.

A Markov chain model has recently been created by Scheu et. al. [1], and used in an operating tool for an Offshore wind farm. This model generated time series for significant wave height and wind speed and was concluded to be suitable. However, other sea state parameters such as wave period, and wind- and wave direction may also be important in an O&M simulation tool.

For this purpose a more flexible model is needed.

Two multivariate Markov chain models were implemented:

Model 1 is a generalization of the weather model mentioned. This model estimates transition probabilities separately for each month. The generalization lies in the discretization procedure, where multivariate weather states were constructed. The weather state is represented by an integer which reflects the values for all sea state parameters with uncertainties corresponding to the resolutions.

In Model 2 an other approach of dealing with the seasonal variation for the sea state parameters was used:

The seasonal variation in the mean value and standard deviation for wave height, wind speed and wave period was assumed to be deterministic functions with a period of one year. This seasonal variation were removed from the observed times series with a transformation. The transformed time series were assumed to be stationary by estimating only one transition matrix.

Both models were assed by comparing statistical properties such as first and second order moments, correlations, marginal distributions, persistence of good weather windows and waiting time between these weather windows. Weather windows were characterized by small waves with a large period combined with calm wind. Statistical parameters were calculated for whole time series and on a monthly scale and both visual comparison and calculation of test statistics were performed.

The figures below shows how some of the statistical parameters considered were reproduced by Model 1 for the longest data set.

Both models reproduce the statistical parameters well, especially the results for persistence and waiting time for weather windows were promising. Both models were therefore concluded to be suitable for O&M simulation of Offshore Wind parks. Due to a high number of weather states both models need long datasets sets to ensure that the simulated time series is different from the observed one. It has also been demonstrated that Model 1 is most restrictive to short datasets.

TURBULENCE ANALYSIS OF LIDAR WIND MEASUREMENTS AT A WINDPARK IN LOWER AUSTRIA

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\textbf{LIDAR}

An increase in nacelle height and rotor diameter of wind turbines in recent years has made measurements of wind profiles via meteorological masts difficult. In response, LIDAR remote sensing has become increasingly important. With this technique, wind information at different heights is easily accessible and enables an analysis of boundary layer processes.

\textbf{Measurement Campaign}

In this study, we analyzed Doppler LIDAR measurements conducted in a field campaign at a wind park operated by VERSURENE Renewable Power GmbH, near Bruck-an-der-Laßnitz (Lower Austria). A WINDCUBE\textsuperscript{TM} V1 (WLS7) Doppler LIDAR collected data over a three-month period in summer 2010.

\begin{itemize}
  \item **Measurement (analyzed) period**: 7.7 (25.8) - 6.10.2010
  \item **Scanning technique**: VAD
  \item **Data availability**: 70%
\end{itemize}

The device was located 2.5 rotor diameters (165 m) west of the wind turbine WEA4 (Wind Energy Anlagen) and around 10 rotor diameters (> 650 m) southeast of the wind turbine WEA5 (figure 2a). As the wind rose in figure 2b shows, the device is capable of capturing the ambient flow, which is influenced by the large and small scale topography.

\textbf{Methods}

Due to a high sampling rate of 0.25 Hz, so that calculations of variances and covariances of wind parameters are possible. This allows an analysis of turbulence through derived parameters such as turbulent kinetic energy (TKE) or turbulence intensity (TI), calculated as the following:

\[ \text{TKE} = \frac{1}{2} (u'^{2} + v'^{2} + w'^{2}) \]
\[ \text{TI} = \frac{\sigma_{u}(v^{2} + w^{2})}{\bar{u}^{2}} \]

where \( u, v \) and \( w \) are the wind components, \( u \) is the horizontal wind speed and \( \sigma_{u}(v^{2} + w^{2}) \) its standard deviation. The spectral energy gap \( S_{u}(v^{2} + w^{2}) \) and \( w \) times series is used for the correct estimation of the turbulence scale (figure 3). On the basis of the momentum equation it is possible to calculate the tendency \( T_{KE} \) of [4]

\[ T = -AD + B + S + TT \]

These terms are representing advection \( AD \), buoyancy \( B \), shear \( S \), turbulent transport \( TT \), pressure correlations \( P \) and dispersion \( D \) as the sources and sinks of TKE.

\textbf{Results}

- The turbulence distribution shows two peaks for easterly and northwesterly winds (figure 4). These are consistent with the location of the WINDCUBE\textsuperscript{TM} (figure 2a). The peaks at 10° vanish at measurement altitudes above blade tip height (100 m) in contrast to the ones at 330°. This indicates the wake expansion of WEA5.

- As TKE reproduces the same information as TI, it enables due to its tendency equation a more detailed analysis of turbulence.

\textbf{Conclusion & Outlook}

A detailed turbulence analysis is possible with LIDAR wind data from a WINDCUBE\textsuperscript{TM} V1, leading to a quantitative description of the wake region. Aerodynamic turbulence distribution indicates a dominating shear generation. The maximum shear induced turbulence is located around blade tip height and leads to irregular loads on the rotor blades. Considering this knowledge in the operation of wind parks is crucial for the operators, as it leads to more efficient lifetime emission production of wind farms. Moreover, the gathered information can be used for optimizing layouts of new wind farms as well as for intelligent operation of already existing ones. This work will be continued at the University of Bergen, using a scanning Doppler LIDAR for further investigations.

\textbf{References}

Investigation of droplet erosion for offshore wind turbine blades

Etienne Cheynet (ENSMA) and Magnus Tyrhaug (NTNU)

Supervisors: Sergio Armada (SINTEF), Mario Polanco-Loria (SINTEF) and Astrid Bjørgum (SINTEF)

Introduction

Droplet erosion as one type of leading edge erosion on wind turbine blades, has been studied, in order to obtain a better understanding of the mechanisms and a resistance surface treatment. The target is to develop tools helping the industry to achieve a 20 year lifetime of blades.

Different coatings were investigated by erosion tests, material characterization and numerical modeling.

Methods and materials

Droplet erosion test facility
- Sample velocity 180 m/s
- Changeable nozzles

Characterization
- Nanindentation
- Scratch test
- IFM
- SEM

Modelling of droplet impact
- Evaluation of a numerical model to simulate rain erosion
- Rain is modelled using the Smoothed Particle Hydrodynamics (SPH) formulation
- Coating is modelled with Finite Element Method (FEM)

Materials investigated
- Dummy samples for erosion test facility
- HDPE
- PVC
- Protective surface coatings
- 3M™ Wind Protection Tape
- Polyurethane composite coatings
  - 100% PUR
  - PUR with SiC additives (15um and 20mm)
  - PUR with FunzioNano® additives

Experimental Results

Characterization of TS Polyurethane Nanindentation, IFM of scratch test and cross sections.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Modulus (MPa)</th>
<th>Hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% PUR</td>
<td>273.5</td>
<td>20.8</td>
</tr>
<tr>
<td>2.5% FunzioNano</td>
<td>108.8</td>
<td>9.8</td>
</tr>
<tr>
<td>2.5% nanoSiC(20mm)</td>
<td>122.3</td>
<td>10.9</td>
</tr>
<tr>
<td>5.0% coarseSiC(15mm)</td>
<td>115.0</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Erosion test
Erosion pattern obtained at 180 m/s with rain droplets for HDPE.

Erosion rate
The erosion resistance of the sample is evaluated through the erosion rate (loss of mass per time).

Numerical results

The discretisation of the rain field into particles moving independently is limited by the SPH formulation. The particle field is still considered as a continuum medium despite minimized interaction between particles.

Conclusions

Experimental
- Test facility provides suitable conditions to perform droplet erosion.
- Thermal sprayed Polyurethane composite coatings shows promising mechanical properties as a protective coating.
- Further characterization of materials are required.

Modelling
- Discrete Element Method (DEM) must be considered as an alternative formulation to simulate the droplets flow.
- A study of single droplet impacts, comparing the stress and pressure distribution with theoretical data to rank the coatings susceptibility to wear can be an alternative study.

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We would like to thank the people of SINTEF Dept. of Applied Mechanics and Corrosion for great help and advices during our work.

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NOWITech Norwegian Research Centre for Offshore Wind Technology
NOWIcob – A tool for reducing the maintenance costs of offshore wind farms
Matthias Hofmann (matthias.hofmann@sintef.no), Iver Bakken Sperstad,
SINTEF Energy Research

Abstract
One of the goals for the NOWITECH research project is to develop a scientific foundation for implementation of cost-effective operation and maintenance (O&M) concepts and strategies for deep-sea offshore wind farms. One task towards fulfilling this goal is the development of a framework and model for optimizing the maintenance and logistics activities. This model aims to help decision makers choosing the right maintenance strategies and logistic support.

Objectives
Main objective: reduce the cost of energy of far-offshore wind farms by implementation of cost-effective O&M concepts and strategies.

Cost-benefit model for offshore wind farms (Norwegian offshore wind power life cycle cost and benefit model – NOWIcob)

Method
The scientific approach for the model is based on a time-sequential event-based Monte Carlo technique. As illustrated in the figure below, the model takes into account both controllable options, as the logistics and maintenance choices made for the wind farm, and a number of external factors. The availability, life cycle profit, and other performance parameters are the output of the model.

Results
The NOWIcob model is tested on some first cases. The following figure shows the availability, calculated as the ratio of produced electricity to the theoretical production without downtime, for the case of a far-offshore wind farm where a mother/daughter vessel concept is compared with the possibility of an offshore accommodation platform. The results are given as estimated probability distributions based on 100 simulation runs.

Conclusions
The NOWIcob model aims to help reducing the cost of energy for offshore wind farms. Consequences of different decisions related to the maintenance and logistic strategy can be analysed and the most effective solution can be chosen taking uncertainties into account. The model can also be used to minimize and understand the uncertainty of a wind farm project by evaluating different risk mitigation measures.

For future work, it is planned to extend the weather model to several weather parameters as for example wave period. For future work, it is planned to extend the weather model to several weather parameters as for example wave period. A main focus is on the representation of weather and the access criteria. Weather is represented by values of the significant wave height and the wind speed. Based on historic data, a Markov transition matrix is generated and used for generating random weather with hourly resolution. These modelled time series have the same statistical properties as the historic data, such as correlation between wind and wave, persistence, and seasonal variations.

Another focus is on the vessels and the possibility to include future vessel concepts in the model. Examples of such are mother/daughter vessel concepts, offshore accommodation platforms, and crew transfer vessels that are offshore several shifts. In addition, the weather limitations for the various capabilities and operations of the vessels are considered.

References
Methodology to design an economic and strategic offshore wind energy Roadmap in Portugal

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Abstract: The main objective of this paper is to establish a roadmap for offshore wind energy in Portugal. It will determine the best sea areas to install fixed and floating offshore wind farms in this region, using spatial analysis of four economic indexes: Internal Rate of Return (IRR), Net Present Value (NPV), Discounted Pay-Back Period (DPBP) and Levelized Cost Of Energy (LCOE). Several economic parameters will be considered (Portuguese offshore tariff, investment and O&M costs, credit values, etc.). Three different discounted rates were used into the sensitivity analysis. Several types of physical restrictions will be taken into account: submarine electrical lines, bathymetry, seabed geology, environmental conditions, protected areas in terms of heritage, navigation areas, fault lines, etc. Moreover, location settings as proximity to shipyards or ports will be considered to complement the strategy. All of them will define the result area to install offshore wind farms along Portuguese coast. Spatial operations, considering economical, physical and strategic issues, have been carried out using Model Builder of GIS (Geographic Information Systems) software. Results indicate the Portuguese areas economically suitable for installing offshore wind farms.

**ECONOMIC DEVELOPMENT**

- Levelized Cost of Energy (LCOE): the approach of the International Energy Agency defines the costs as a summation of the total cost of the initial investment and annual operating and maintenance costs.
- Net Present Value (NPV): it is the net value of all revenues (cash inflows – sale of electricity) and expenses (cash outflow – financial costs and O&M costs) of the project, discounted to the beginning of the investment.
- Discounted Payback Period (DPBP): it uses the cash flow of each year with the respective discount rate and adds it to all previous cash flows with respective discount rate. The year when this sum is greater or equal than the initial investment is the year of the payback.

**METHODOLOGY**

**INPUT DATA**

- Economic parameters:
  - Spatial distribution for the number of hours at full capacity production (NEPs) in each point of the Portuguese coast.
  - Total power of the farm: 50 MW.
  - Costs of installed system: 3155 €/kW per fixed turbine and 16575 €/kW per floating turbine.
  - O&M costs: 2143 €/kW/year for 7 MW wind turbine.
  - Lifecycle: 20 years.
  - Tax: 30%.
  - Inflation: 2.35% /year.
  - Discount rate: 5%, 7.5% and 10% (different scenarios).
  - Fixed tariff: 168 €/MWh, as in WindFloat.
  - Market tariff: 50.66 €/MWh.
  - Credit: 70% investment, 15 years, 5.4% interest.

- GIS parameters:
  - Bathymetry: up to 40 m (fixed offshore wind) and 40 – 200 m (floating offshore wind).
  - NEPs: 3000 h/year.
  - Wind speed: 7 m/s.
  - Ports: 10 m of draft.
  - Shipyards: 15120 m\(^2\) of area.
  - Docks: 120 m of length.

**GIS DEVELOPMENT**

**SELECT ECONOMIC MAP**

- IRR
- NPV
- DPBP
- LCOE

**RESULTS**

- IRR
- NPV
- DPBP
- LCOE

**CONCLUSIONS**

- This methodology could be used to analyse other offshore renewable energies, as wave energy, in future works.
- Ports selected: Leixões, Aveiro, Lisbon, Setúbal, Sines.
- Shipyards selected: Arsenal Afife, ENVC (Estaleiros Navais de Viana do Castelo) and Lisnave.
- The economic roadmap of offshore wind energy in Portugal gives feasible results for investors in some areas: Peniche, Viana do Castelo.
- It could improve the regional development of other parallel industries as naval construction, research clusters, maintenance industries and wind turbine developers.

**REFERENCES**

- Work funded by FCT/MCTES (PIDDAC) and FEDER through project PTDC/SEN-ENR/105403/2008.
DeepWind'2013, 24-25 January, Trondheim, Norway

Methodology to design an economic and strategic offshore wind energy Roadmap in Portugal

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Abstract

The main objective of this paper is to establish a roadmap for offshore wind energy in Portugal. It will determine the best sea areas to install fixed and floating offshore wind farms in this region, using spatial analysis of four economic indexes: Internal Rate of Return (IRR), Net Present Value (NPV), Discounted Pay-Back Period (DPBP) and Levelized Cost Of Energy (LCOE). Several economic parameters will be considered (Portuguese offshore tariff, investment and O&M costs, credit values, etc.). Three different discount rates were used into the sensitivity analysis. Several types of physical restrictions will be taken into account: submarine electrical cables, bathymetry, seabed geology, environmental conditions, protected areas in terms of heritage, navigation areas, seismic fault lines, etc. Moreover, location settings as proximity to shipyards or ports will be considered to complement the strategy. All of them will define the resulting area to install offshore wind farms along Portuguese coast. Spatial operations, considering economic, physical and strategic issues, have been carried out using Model Builder of GIS (Geographic Information Systems) software. Results indicate the Portuguese areas economically suitable for installing offshore wind farms.

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Keywords: offshore wind energy, roadmap, renewable energy, economic areas, GIS

1. Introduction

A successful roadmap contains a clear statement of the desired outcome followed by a specific pathway for reaching it. This pathway should include the following components: goals, milestones, gaps and barriers, action items, priorities and timelines [1].

The development of the process ensures that a roadmap identifies mutual goals and determines specific...
and achievable actions towards realizing a common vision. The process includes two types of activities (Expert judgement and consensus and Data and analysis) and four phases (Planning and preparation, Visioning, Roadmap Development and Roadmap Implementation and revision) [1].

The main objective of this paper is to define the conditions applicable to the specific Portuguese context to design an offshore wind energy roadmap, in terms of fixed and floating wind devices.

This study determines the Portuguese coast areas which have more economic feasibility to install offshore wind structures. Several physical restrictions will be taking into account: submarine electrical cables, bathymetry, seabed geology, environmental conditions, protected areas in terms of heritage, navigation areas, seismic fault lines, etc. Furthermore, location settings as proximity to shipyards or ports will be considered to complement the strategy. All of them will define the resulting area to install offshore wind farms along Portuguese coast. Spatial operations, considering economic, physical and strategic issues, have been carried out using a GIS (Geographic Information System) tool developed in the Model Builder™ software.

On the other hand, economic indexes, such Internal Rate of Return (IRR), Net Present Value (NPV), Pay – Back Period (PBP) or Levelized Cost of Energy (LCOE), will be used to determine if it is economically feasible to install offshore wind turbines in Portugal. They will be carried out considering several economic parameters such as Portuguese offshore tariff, investment and O&M costs, credit values, etc. Finally, three different discount rates have been considered into the analysis.

2. Development of the model

2.1. Economic development

The Levelized Cost of Energy (LCOE) evaluates the economic cost of power generation system throughout its life cycle [2]. There are several approaches to the LCOE definition [2–4], for the current work the process described in IEA (International Energy Agency) has been considered. It defines the costs as a summation of the total cost of the initial investment, annual operating and maintenance costs, annual fuel and carbon costs and the cost of decommissioning. This model does not take into account extremely volatile values, like interest rates and tax rates that differ from country to country and region to region. It is very useful to compare normalized costs of energy production from different sources, regardless of the floating parameters. Since a clean renewable energy source is being analysed, the parameters “fuel costs” and “cost of carbon” were considered to be zero. The “decommissioning cost” was also considered to be zero since the site is usually reused for a new project, taking advantage of the groundwork and construction already carried out.

The Net Present Value (NPV) is the net value of all revenues (cash inflows) and expenses (cash outflow) of the project, discounted to the beginning of the investment. Essentially, revenues include cash inflows from the sale of electricity and costs include cash outflows due to the financial costs and the operation and maintenance of the offshore wind farm. For energy projects, the NPV is considered the present value of benefits subtracted from the present value of the costs. The investment decision on the project occurs when the NPV is greater than zero. If it is equal to zero, it will be indifferent for investors implement monetary resource in the project. If the NPV is negative, then the investor must discard the project, because it will bring him losses. If the investor has to choose various types of project, it will tend to choose the project with the highest NPV, since this option will provide greater return on investment.

The Internal Rate of Return (IRR) is a measure of a project’s magnitude in the financial markets evaluation scale. When the IRR is above the discount rate, the project generates a rate of return higher than the discount rate of capital, thus, in principle, the project will be economically viable. When the IRR obtained is below the discount rate, the return required by investors will not be achieved [4]. The IRR calculus is a polynomial equation of N degree, where there are N different roots or solutions to the equation. However, when the investment pattern is normal (i.e., the initial investment or outflows are
followed by a stream of inflows), all the solutions are negative or imaginary, except for one positive solution. Otherwise, if the cash flow is such that the outflows occur during or near the end of project’s life, then the possibility to obtain multiple positive solutions is increased. Situations where there is only one an approximate value are easy to analyze. However, when the results do not contain an approximate value rather multiple positive solutions, it is a doubtful situation and the IRR analysis should be dismissed and other economic indicators should be used [2].

Finally, the Discounted Payback Period (DPBP) uses the cash flow of each year with the respective discount rate and adds it to all previous cash flows with the respective discount rate. The year when this sum is greater or equal than the initial investment will be the year of the payback.

2.2. Calculating with GIS

Model Builder™ of GIS software has been used to determine the best Portuguese areas for offshore wind power development [5].

Two different tools have been designed using GIS techniques: GIS tool 1 and GIS tool 2. GIS tool 1 calculates the area allowed and introduces the economic maps for one particular case with a number of wind turbines established. On the other hand, GIS tool 2 introduces restrictions of ports, shipyards and docks taking into consideration output of GIS tool 1.

Taking into account several spatial operations, GIS tool 1 allows establishing a map which considers the physical restrictions selected by the user. This tool will give a first approximation of the areas where offshore wind farms could be installed in Portugal, without considering economic aspects, which could be added after, as Figure 1 shows:

![GIS tool 1 diagram](image)

**Figure 1:** GIS tool 1.

Firstly, the map of all the physical restrictions will be obtained. Moreover, each of these restrictions should be reclassified. For this purpose, allowed areas will be defined as 1 and not allowed areas will be defined as 0. Therefore, all these physical restrictions reclassified should be sum up, obtaining the map of
all the physical restrictions.

Secondly, the bathymetry restriction should be added, which will be different depending on the type of offshore wind substructure (fixed or floating).

Furthermore, two physical parameters: NEPs and wind speed, will be used as part of the classification process. Their consideration is useful in terms of giving a no economic preview of the best areas in terms of offshore wind.

Finally, all the restrictions will be joined and multiplied by the economic map selected (IRR, NPV, DPBP or LCOE), obtaining the economic parameters restricted.

On the other hand, GIS tool 2 introduces restrictions of ports, shipyards and docks taking into consideration output of GIS tool 1. In this sense, the parameters which will be reclassified and the maximum distance from ports, shipyards and docks, should be defined by the user.

3. Input data

3.1. Objectives

There are three different types of input data:

- **Physical restrictions**, which limit the strategic area using bathymetry, seabed geology, heritage protected areas and environmental conditions data.
- **Location settings**: they are related to technical infrastructure of ports, docks and shipyards.
- **Economic parameters**: they are used to map the economic results along the Portuguese coast, giving information about the feasibility of the area analysed.

3.2. Physical restrictions

Physical restrictions are defined as those that limit the strategic area taking into account geotechnical or legislative issues. Therefore, in these terms, the following physical restrictions will be defined [6] [7]: bathymetry, buoys for tanker vessels, submarine electric cables, supply lines, navigation areas, anchorage
areas, seismic fault lines, pilot area, submerged electrical lines protection area, environmental protected areas, heritage and protected areas, seabed geology (rock areas).

Otherwise, bathymetry restriction will be taken into consideration separately to the other physical restrictions because it can change when different wind substructures were considered: fixed or floating. In this sense, depths up to 40 m will involve fixed structures (monopiles, jackets, tripods and gravity foundation) [8] and depths from 40 to 200 m will be considered for floating platforms (TLP, semisubmersible, spar and barge).

Finally, two restrictions take into consideration wind resource: spatial distribution for the number of hours at full capacity production (NEPs) [9] [10] in each point of the Portuguese coast and wind speed (m/s).

3.3. Location settings

There are some factors that will not be included in GIS spatial operations, but which will also be taking into account:

- Proximity to shipyards with enough capacity to construct the platforms and with the appropriate docks.
- Proximity to ports which have surface to wind turbine storage and future maintenance.

All these factors can help us to establish a best strategy for the roadmap. In this sense, the main ports and shipyards in Portugal which can support offshore wind technology should be defined.

Firstly, shipyards location is one of the keys in designing a good strategy for the roadmap. They will be responsible for constructing floating or fixed substructures, so they should be placed close to the future offshore wind farms location. However, shipyards should have enough capacity to support these type of constructions.

On the other hand, ports also have importance for determining best area where establish offshore wind farms. Regarding installation, they should have surface enough to storage blades, gearboxes, nacelles and towers of the wind turbines. Furthermore, they should support offshore supply vessels for installation and maintenance (preventive and corrective).

3.4. Economic parameters

The economic parameters will be used as inputs to obtain economic maps with the mathematical program Matlab™. The most important ones are:

- Spatial distribution for the number of hours at full capacity production (NEPs) [9] [10] in each point of the Portuguese coast.
- Total power of the farm: 50 MW.
- Costs of installed system: 3315 €/kW per fixed turbine [11] and 16575 €/kW per floating turbine.[b]
- O&M costs: 150 k€ per turbine per year or 21.43 €/kW/year for 7 MW wind turbine [11]
- Lifecycle: 20 years.
- Tax: 30%.
- Inflation: 2.35%/year.
- Discount rate: 5%, 7.5% and 10% (different scenarios)
- Fixed tariff: 168 €/MWh, as in WindFloat [12]
- Market tariff: 50.66 €/MWh
- Credit: 70% investment, 15 years, 5.4 % interest [13]

Taking into account all these previous parameters and the correspondent formulas [2] four economic maps have been developed along Portuguese coast: Internal Rate of Return (IRR), Net Present Value (NPV), Discounted Pay – Back Period (DPBP) and Levelized Cost of Energy (LCOE). Moreover, they

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[b] The cost of the installed system for floating offshore wind has been considered as five times the cost of fixed offshore turbines.
will be developed for three different discount rates: 5% (scenario 1), 7.5% (scenario 2) and 10% (scenario 3).

4. Application and results

4.1. Allowed areas

GIS tool 2 will be required to define the allowed areas in terms of ports, shipyards and docks. Firstly, their main characteristic field should be defined. In this sense, the following parameters have been considered: 10 m of draft for ports, 15120 m$^2$ of area for shipyards and 120 m of length for docks.

Draft has been the parameter considered to ports, considering the draft of the installation vessel, which could be between 3 – 8.9 m [14] [15] [16] depending on the type of ship (cargo barge, sheeleg crane, etc.). This value could be higher if a tug boat from port to wind farm was used to transport the floating platform, whose draft is, at least, 12.5 m [17]. However, the first approximation will be 10 m because in fixed offshore wind technology could not be transported using a tug boat.

Secondly, the buffers of each field are made considering 80 km of distance from ports and shipyards. Characteristics of docks and shipyards are useful for floating platforms, which will be constructed on them. In this sense, the limits are established in relation to the dimensions of these platforms, which can vary from 12.5 m to 120 m, depending on the type of structure [18], so the maximum length considered will be 120 m and the maximum area for each platform 18x120 m$^2$. Moreover, the number of wind turbines considered (7) should be taken into account.

Therefore, shipyards which are suitable taking into account their area and length of dock are: Arsenal Alfeite, ENVC (Estaleiros Navais de Viana do Castelo) and Lisnave.

4.2. Economic results with restrictions for fixed offshore wind energy

If Internal Rate of Return (IRR) and the Discount Pay – Back Period (DPBP) for scenarios 1 and 2 with all the explained restrictions are analysed, the atlas of Figure 3 will be as follows:

![Figure 3: IRR (a) and DPBP with restrictions for discount rate of 5% (b) and 7.5% (c).](image)

IRR does not depend on the discount rate considered. Therefore, there only is one scenario. Figure 3 shows one area called as IRR A, which is characterized by Internal Rate of Return from 5.72% to 8.54%. It implies that depending on the discount rate considered, the project will or will not be viable. In fact, in terms of IRR, the project will only be economic viable for the 5% and 7.5% of discount rate scenarios.

Furthermore, Figure 3 shows the DPBP for two scenarios: 1 and 2. Scenario 3 does not appear because
the unique areas where DPBP is different from the life cycle of the project are restricted areas (more than 40 m). Moreover, in scenario 1 there are two areas, one is next to Viana do Castelo (North), and identified as DPBP A, and the other one is close to Peniche (West), whose values go from 12.56 years to 17.43 years.

As far as LCOE maps with restrictions is concerning, a comparison between the three scenarios could be developed, as it is shown in Figure 4:

![Figure 4: LCOE with restrictions for 5% (a), 7.5 % (b) and 10% (c) of discount rate respectively.](image)

LCOE results are very different depending on the discount rate considered. However, one area in each map called LCOE A could be distinguished. It has values from 78.8 to 92.9 €/MWh, in the scenario 1, from 92.54 to 109.1 €/MWh in scenario 2 and from 106.95 to 126.09 €/MWh in the scenario 3.

Finally, Figure 5 shows the results for Net Present Value (NPV) with restrictions:

![Figure 5: Net Present Value (NPV) with restrictions for 5% (a), 7.5 % (b) and 10% (c) of discount rate respectively.](image)
Most of the NPV results, for all the scenarios considered, are negative, excepting region A for scenario 1, whose values go from 13 M€ to 36 M€.

4.3. Economic results with restrictions for floating offshore wind energy

In floating offshore wind farms LCOE will be the only economic parameter which will be evaluated. As in the fixed offshore case, a comparison between the three scenarios could be taken into account, as Figure 6 shows:

![Figure 6: LCOE with restrictions for 5% (a), 7.5% (b) and 10% (c) of discount rate respectively.](image)

**Figure 6: LCOE with restrictions for 5% (a), 7.5% (b) and 10% (c) of discount rate respectively.**

Two areas can be distinguished: A and B. Area A has values from 300 to 435.86 €/MWh in scenario 1 (a), from 340 to 518.58 €/MWh in scenario 2 (b) and from 380 to 605.25 €/MWh in scenario 3 (c).

5. Conclusion

Values for Internal Rate of Return (IRR), Net Present Value (NPV), Discounted Pay – Back Period (DPBP) and Levelized Cost Of Energy (LCOE) have been analysed for each point of the Portuguese coast. Then, several types of physical restrictions, as bathymetry or protected areas, have been applied. This fact will reduce the region of study. In this context, one area has been obtained. It is called as A and it is located in the Centre - North of Portugal, where economic results have been much better than in other regions.

Moreover, three different discount rates (5%, 7.5% and 10%) have been taken into account, constructing a map for each of these scenarios. Regarding results, scenario 1 and scenario 2 will be the best ones. Moreover, economic indexes depend on two factors: the offshore wind device considered (fixed or floating) and the scenario analysed.

On the other hand, ports and shipyards which were well located in relation with the installation selected area have been considered.

Finally, after analysing each point of the Portuguese coast, a conclusion could be established: there are some areas in the Centre - North where offshore wind farms could be installed. It could be the beginning of a new technology market and a new economic feasible business to carry out in Portugal. The economic roadmap of offshore wind energy in Portugal gives feasible results for investors. In this sense, it could improve the regional development of other parallel industries as naval construction, research clusters, maintenance industries and wind turbine developers.
Acknowledgements

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References


Methodology to study the life cycle cost of floating offshore wind farms

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Abstract. The main objective of this paper is to determine a theoretical methodology process to study the life cycle cost of floating offshore wind farms. The principal purpose is adapting the LCC (Life-Cycle Cost Calculation) from several authors to the offshore wind energy world. In this sense, several general steps will be defined: life cycle definition, process breakdown structures, viability study and sensitivity study. Moreover, technical and economic issues and their relations will be considered. On the other hand, six life cycle phases needed to install a floating offshore wind farm will be defined: design and development, manufacturing, installation, exploitation and dismantling. They will be useful to define the majority of the steps in the process. This methodology could be considered in future works to calculate the real cost of constructing floating offshore wind farms.

**ECONOMIC MAPS TOOL**

Conception & Design

MODELS SELECTION (MS)

ECONOMIC STUDY (ES)

ES1: Life-cycle process definition

ES2: Process breakdown str.

ES3: Cost model selection

ES4: Initial cost breakdown str.

ES5: Cost calculation

ES6: Variables dependence

ES7: Final cost breakdown str.

ES8: Category of cost selection

ES9: Results breakdown structure

**TECHNICAL STUDY (TS)**

P1: Conception & definition

P2: Design & development

P3: Manufacturing

P4: Installation

P5: Exploitation

P6: Dismantling

**RESULTS**

\begin{tabular}{|c|c|c|c|c|c|}
\hline
P1.1 & P1.2 & P3.1 & P4.1 & P5.1 & P6.1 \\
\hline
Market study & Engineering project & Offshore wind turbines manufacturing & Offshore wind turbines installation & Taxes & Offshore wind turbines dismantling \\
\hline
Law factors & Design of the farm & Floating platforms manufacturing & Floating platforms installation & Assurance & Floating platforms dismantling \\
\hline
\end{tabular}

\begin{tabular}{|c|c|c|c|c|c|}
\hline
C1 & C2 & C3 & C4 & C5 & C6 \\
\hline
6.79 M€ & 0.24 M€ & 215.38 M€ - 405.62 M€ & 18.73 M€ - 392.09 M€ & 107.93 M€ - 113.53 M€ & 0.0058 M€ - 30.87 M€ \\
\hline
\end{tabular}

**LCS\textsubscript{FOWF} = C1 + C2 + C3 + C4 + C5 + C6**

**CONCLUSIONS**

- Methodology LCS\textsubscript{FOWF} has been established.
- Development of the Economical Study
- Phases Economical Study
- Definition of the life-cycle phases
- Most important costs: manufacturing and installation
- Calculation of the costs for an specific location

Main dependences

- Wind Turbines: number, power, cost per MW, mass, diameter.
- Floating platforms: number, cost in shipyard (steel, direct labor, direct materials, no direct activities (management, amortization of the machines, etc.).
- Climate: height and period of waves, wind speed at anemometer height, wind parameters (shape and scale).
- Location: depth, distances (to shore, to port, to shipyard).
- Anchoring and mooring: weight, cost per kilogram, number of mooring lines.
- Electrical systems: cost per section of electrical cable, number of electrical cables, grid and cable voltages.
- Installation: number, speed and fleet of vessels used in installation phase.
- O&M: failure probability.

References:

Methodology to study the life cycle cost of floating offshore wind farms

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Abstract

The main objective of this paper is to determine a theoretical methodology process to study the life cycle cost of floating offshore wind farms. The principal purpose is adapting the LCC (Life-Cycle Cost Calculation) from several authors to the offshore wind energy world, providing a new method which will be called LCS\textsubscript{FOWF}. In this sense, several general steps will be defined: life cycle definition, process breakdown structure, viability study and sensitivity study. Moreover, technical and economic issues and their relations will be considered. On the other hand, six life cycle phases needed to install a floating offshore wind farm will be defined: conception and definition, design and development, manufacturing, installation, exploitation and dismantling. They will be useful to define the majority of the steps in the process. This methodology could be considered to calculate the real cost of constructing floating offshore wind farms.

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Keywords: Life Cycle; Wind Turbine; Economical Evaluation

1. Introduction

Due to fossil fuels have a limited life span \cite{1} \cite{2}, the use of renewable energies, whose use is unlimited, will be of utter importance. Furthermore, the European goals for promoting the renewable energy sector have been established in 2009. In fact the 20\% of final energy consumption should be from this type of energies in 2020 \cite{3}.

In this context, ocean energy could help to achieve this objective. In particular, floating offshore wind energy could be developed taking into account some traditional industries, as naval or industrial sectors.

However, this development will not be carried out without a preliminary study of the main costs which...
this type of farms involves.

The main objective of this paper is defining a methodology to study the Life-Cycle Cost System of Floating Offshore Wind Farm (LCS_{FOWF}). However, life cycle cost will not be understood as the cost of environmental issues [4] and emissions [5], as in other publications [6]. LCS_{FOWF} will be considered as the cost necessary to deal with each of the phases of the life cycle.

Firstly, a general methodology with several steps will be put forward. However, only the Economic Study will be considered in this paper. Several of the most important phases of which it is composed are: the life-cycle definition, the process breakdown structure, the cost model selection, the initial cost breakdown structure and the cost calculation.

This methodology will be applied to the particular case of Galicia (North-West of Spain), where wind resource has good values in deep waters.

### Nomenclature

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Cost of conception and definition</td>
</tr>
<tr>
<td>C2</td>
<td>Cost of design and development</td>
</tr>
<tr>
<td>C3</td>
<td>Cost of manufacturing</td>
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<td>C4</td>
<td>Cost of installation</td>
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<tr>
<td>C5</td>
<td>Cost of exploitation</td>
</tr>
<tr>
<td>C6</td>
<td>Cost of dismantling</td>
</tr>
</tbody>
</table>

### 2. Methodology

#### 2.1. General structure

Methodology put forward for calculating the costs of a floating offshore wind farm is based on two different methods of life-cycle cost calculation [7] [8]. This new methodology will be named as Life-Cycle Cost System of a Floating Offshore Wind Farm, LCS_{FOWF}, and it will be developed in several steps:

- Economic Study (ES).
- Models Selection (MS).
- Technical Study (TS).
- Economic Maps Tool (EMT).
- Restrictions Maps Tool (RMT).
- Results (R).

MS will define each of the models which will be taken into consideration in the study according to offshore wind turbines, floating offshore wind platforms, mooring lines, anchors, electric system, installation, accommodation, maintenance, seabed and dismantling. These aspects will be explained in future works.

TS consists in all the engineering calculation related to electrical cables, mooring and anchoring dimensions and feasibility of mooring lines.

EMT will implement the ES using numeric calculation, which will originate the maps of the economic indexes and the maps of the different types of models taking into account the main characteristics of the location.

Results obtained from EMT will be processed with the RMT, which has been developed using a GIS (Geographic Information System) software whose results are the allowed areas considering the geographical restrictions of the site.

Consequently, not only EMT results but also RMT results will be used to determine the R for a particular geographic case.
A detailed description of the model has been presented in [9]. A general scheme could be seen in Figure 1:

![Diagram of LCSFOWF Methodology](image-url)

**Figure 1**: General methodology.

However, this preliminary study will only take into consideration the first four parts of the ES. Thus, maps with restrictions and sensitivity analysis will not be developed.

### 2.2. Economic Study

The ES is of utter importance in the methodology because it helps to define each of the costs involved in the development of floating offshore wind farms. In this sense, ES bears in mind the following phases:

- Phase ES1: life-cycle process definition.
- Phase ES2: process breakdown structure.
- Phase ES3: cost model selection.
- Phase ES4: initial cost breakdown structure.
- Phase ES5: cost calculation.
- Phase ES6: variables dependence.
- Phase ES7: final cost breakdown structure.
- Phase ES8: category of cost selection.
- Phase ES9: results breakdown structure.

However, this paper will be explained the first four phases because the others will be explained more in detail in the future.
2.3. Life-cycle process definition

Life-cycle process has been defined modifying the recommendations of IEC 60300-3-3:2004 [7] because this normative is focused more in a product than in a process. Therefore, the main phases of the life-cycle of a floating offshore wind farm are:

- Phase 1: Conception and definition.
- Phase 2: Design and development.
- Phase 3: Manufacturing.
- Phase 4: Installation.
- Phase 5: Exploitation.
- Phase 6: Dismantling.

All of them could be represented as Figure 2 shows:

![Figure 2: Life-cycle of a floating offshore wind farm.](image)

2.4. Process breakdown structure

Process breakdown structure determines which are the main stages and sub-stages of the process. A floating offshore wind farm will be composed by several main components: offshore wind turbines, floating offshore platforms, moorings, anchorages and electrical elements. Thus, each of the phases of the life-cycle process definition will be developed for each of these elements, as Figure 3 shows:

![Figure 3: Breakdown structure of a floating offshore wind farm.](image)

2.5. Cost model selection

IEC 60300-3-3:2004 [7] proposes several models to calculate the life-cycle cost. However, the present study will only take into account the model based on the life-cycle phases.

2.6. Initial cost breakdown structure and cost calculation

Initial Cost Breakdown Structure (CBS) of a floating offshore wind farm is based on the disaggregation of the main costs of life-cycle. In this sense, the costs will be: C1 is the cost of conception and definition, C2 is the cost of design and development, C3 is the cost of manufacturing, C4 is the cost of installation, C5 is the cost of exploitation and C6 is the cost of dismantling.

Thus, the \( LCS_{FOWF} \) could be formulated as:

\[
LCS_{FOWF} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6
\]
However, in order to obtain their main dependences, each of these costs should be subdivided in sub-costs dependent that should be analyzed separately. This subdivision is too complex to be analyzed in the present study so it will be explained in a future paper, where phases from E55 to E59 will be described. Nevertheless, in order to give a notion of the main dependences in costs, the following parameters could be considered:

- Number of wind turbines.
- Power of wind turbines.
- Cost (in €) per MW of wind turbine.
- Mass of the floating platform.
- Mass of the wind turbine.
- Cost of steel necessary to build the floating platforms at shipyard.
- Cost of direct labor at shipyard.
- Cost of direct materials at shipyard.
- Cost of no direct activities (management, office materials, amortization of the machines, etc.) at shipyard.
- Height and period of waves.
- Wind speed at anemometer height.
- Wind shape and wind scale parameters.
- Depth.
- Weight of anchoring and mooring.
- Anchoring and mooring cost per kilogram.
- Number of mooring lines.
- Cost per section of electrical cables.
- Number of electrical cables.
- Wind turbine diameter.
- Distance to shore.
- Grid and cable voltages.
- Distance to port.
- Distance to shipyard.
- Number, speed and fleet of vessels used in installation phase.
- Failure probability.

3. Case of study

The models considered for developing this paper have been:

- Floating offshore semisubmersible platform.
- No cohesive soil.
- There is no accommodation platform.
- Synthetic fiber is the mooring material.
- Plate anchor.
- HVDC Electrical chain configuration.
- Wind turbine tower will be assembled onshore.
- Dismantling considered will be “tree falls”.
- Preventive maintenance will be carried out with a helicopter.
- Mooring and anchoring installation are developed with an Anchor Handling Vehicle (AHV).
- Substation installation is developed with a cargo barge and a heavy lift vessel.
- Floating platform will be installed taking into account a tug boat, because draft of semisubmersible platform considered is less than shipyard draft.
- Floating offshore substation.

Moreover, a port and a shipyard (Navantia) located in Ferrol, A Coruña (North West of Spain), closest to
a very good area of wind resource in deep waters, have been considered.

4. Results

Firstly, C1 and C2 will be constant and independent on the location considered. Thus, their atlas cannot be defined. Their values are 6.79 M€ and 0.24 M€ respectively.

However, C3, C4, C5 and C6 will basically be dependent on the distance to shore and the depth of the location. Therefore, they can be calculated for each point of the geography considered (coast of Galicia), giving the correspondent map for each cost.

C3 values range from 215.38 M€ for the closest areas to the Galician shore to 405.62 M€ for the most remote areas. Furthermore, C4 values range from 18.73 M€ to 392.09 M€. As it is shown in Figure 4, the cost of installation grows in a different way of manufacturing, whose increases depth by depth are lower.

![Figure 4: Values for C3 and C4.](image)

Secondly, C5 values from 107.93 M€ to 113.53 M€ and C6 values from 0.0058 M€ to 30.87 M€, as Figure 5 shows. The value of exploitation basically is composed by the cost of operation and maintenance and it does not change a lot with the number of trips of the maintenance vessels, as it was expected. In fact, it oscillates between 105 M€ and 115 M€ depending on the location of the farm: nearshore or farshore respectively.

![Figure 5: Values for C5 and C6.](image)
Finally, the total cost value from 365.50 M€ and 945.62 M€, as Figure 6 shows:

**Figure 6:** Values for the total cost.

5. Conclusions

The methodology of Life-Cycle Cost System of a Floating Offshore Wind Farm (LCS\textsubscript{FOWF}), which is based on the study of the costs of each of the phases of the life-cycle, has been proposed. It is composed by five steps: Economic Study, Models Selection, Technical Study, Economic Maps Tool, Restrictions Maps Tool and Results. However, only the Economic Study has been developed in the present paper.

EE is composed by nine phases which will help to carry out the cost of each phase of the life-cycle of a floating offshore wind farm. The life-cycle phases considered are: conception and definition, design and development, manufacturing, installation, exploitation and dismantling.

Results show how one of the main dependences on costs are the distance to shore and the depth of where the farm will be installed. Furthermore, manufacturing cost and installation cost absorb the maximum percentage of the total costs, directly followed by maintenance.

Finally, they give an approximation to the real costs in this type of constructions. This first step could be used to calculate the economic viability of a floating offshore wind farm in the future.

References


Two-dimensional fluid-structure interaction simulation of NACA0012 airfoil

Knut Nordanger, PhD Candidate, Dept. of Mathematical Sciences, NTNU
Trond Kvamsdal, NTNU and Runar Holdahl, SINTEF ICT

Aims
- demonstrate the capability of the SINTEF ICT-developed isogeometric solver IFEM to simulate flow past an oscillating object
- simulate realistic airfoil shapes
- combine mesh movement and turbulence model

Isogeometric analysis
- the same set of basis functions (B-splines or NURBS) is used for both the geometry representation and the analysis

- intended to bridge the gap between design and analysis
- exactly the same geometry is used in the analysis as in the design (no approximations)
- yield higher accuracy per degree of freedom than traditional finite elements
- based on technologies from computational geometry
- allows for smooth curves and surfaces

Problem description
Flow past an oscillating NACA0012 airfoil is simulated using the incompressible Navier-Stokes equations in ALE (Arbitrary Lagrangian-Eulerian) formulation. Structural movements are calculated using a traditional Newmark scheme.

The main quantities of interest in this study are the drag and lift coefficients.

Geometry definition
IFEM offers
- multi-patch/block-structured meshes
- parallelization on patch level

Fluid flow
Incompressible Navier-Stokes equations
\[ \frac{\partial u}{\partial t} + (u \cdot \nabla) u - \nabla \cdot \sigma(u, p) = f \quad \text{in} \; \Omega(t) \]
\[ \nabla \cdot u = 0 \quad \text{in} \; \Omega(t) \]
Interface condition \[ n = u^n \] on \( \Gamma_i \)

Mesh movement
Arbitrary Langrangian-Eulerian formulation
\[ \rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla) u - \nabla \cdot \sigma(u, p) = f \quad \text{in} \; \Omega(t) \]
\[ \nabla \cdot u = 0 \quad \text{in} \; \Omega(t) \]

Mesh update based on nonlinear finite deformation analysis

Mesh update based on nonlinear finite deformation analysis

Further work
- study oscillating airfoil shapes (e.g., NACA0012 and NWC/TE101 reference turbine)
- structural analysis of airfoil on flow
- coupling procedures
- 3D simulations
- aerodynamic forces

References

NOWITECH
Norwegian Research Centre for Offshore Wind Technology
**Introduction**

Wind turbines operating in the wake of an upstream turbine are exposed to conditions which are significantly different from a free standing turbine. The incoming flow field is characterized by a non-uniform velocity profile and turbulence intensities significantly higher than in the free stream. This leads to reduced power production and increased fatigue of the downstream turbine.

Detailed wake measurements under controlled conditions are indispensable for a better understanding of wake aerodynamics, in particular wind farms, and as benchmark and development basis for the further improvement of CFD models.

**Objectives**

- Provide and compare highly detailed wake measurements for the two cases:
  - a) unobstructed wind turbine, T1
  - b) wind turbine operating in the wake of an upstream turbine, T2
- Investigate wake asymmetries observed in previous measurements and evaluate the influence of the tower

**Experimental Setup**

- Closed loop wind tunnel with closed test section (1.9 m x 2.7 m x 11 m)
- Five-hole probe measurements (3-dim. Velocity profile)
- Hot-wire anemometry (turbulence intensity)
- Large, fully operational model turbines (D=0.9 m)

**Operational conditions**

- $U_L = 10.5 \text{ m/s}$
- Reynolds number based on the tip speed and the chord length, $\text{Re} = 1.2 \times 10^6$
- $\text{TSR}_{\text{first/turbine}} = 6$, $\text{TSR}_{\text{second turbine}} = 4$

**Results**

**Velocity measurements**

- **Single turbine wake, T1**
- **Tandem wake, T2**

**Turbulence measurements**

**Wake expansion and recovery**

**Conclusion**

- Overall wake structure, expansion and recovery as predicted by wake theory.
- Clearly observable tower wake characterized by the highest velocity deficit and turbulence intensity.
- Tower wake deflected in the direction of the wake rotation (opposite to the rotation of the rotor).
- Faster wake recovery due to the enhanced turbulence intensity by the deflected tower wake in the left part of the wake.
- Persistent asymmetries in the far-wake.
Numerical Study on the Motions of the VertiWind Floating Offshore Wind Turbine

Raffaello Antonutti – IDCORE research engineer @ EDF R&D *

Christophe Peyrard – EDF R&D #

EDF R&D LNHE – Chatou (France)

**Project VertiWind**
A floating offshore wind demonstrator project. One 2 MW rated unit is to be installed off Côte d’Azur, in France.

Technology developers
- Néosphare: Vertical Axis Wind Turbine design.
- Technip: Floater, mooring, and installation design.

Project partners
- EDF EN, Seal Engineering, Bureau Veritas, Oceanide, IFP EN, Arts & Métiers, USTV.

Governmental funding

**Pseudo-quadratic viscous damping**
Express the viscous damping coefficient as a linear function of motion amplitude. Iterative implementation.

A nonlinearity is introduced in the linear Equations of Motion. Dynamic response is hence linearised about each solution.

**Dynamic response analysis with wind-induced trim**
- Static equilibrium trim angle under 50-yr return, 1-minute averaged wind speed = 12°.
- Calculate hydrodynamic loads and coefficients for new hull (linear potential BEM: AQUA+).
- Solve Equations of Motion in the frequency domain:
  - Increased hydrodynamic coupling, esp. heave & pitch;
  - Increased heave and pitch excitation at low periods.

**Horizontal offset and nonlinear mooring stiffness**
- Mooring restoring forces are nonlinear. Thus global K matrix is a function of wind/wave/current induced offset.
- Solve Equations of Motion in the freq. domain:
  - Increased surge response at large T: resonance;
  - Left-shift in pitch natural period.

**Future steps**
- Moorings – FEM dynamic model using Code_Aster
- Wind turbine aerodynamic BEM model
- Viscous excitation forces based on Morison approach
- Fully coupled time domain simulation

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Coatings for protection of boat landings against corrosion and wear

Astrid Bjørgum, Ole Øystein Knudsen and Sébastien Equey, SINTEF Materials and Chemistry and Arya P. Bastiko, NTNU

Introduction

In addition to corrosion protection boat landings need protection against impact and scour due to impact from the service boat. Coating maintenance offshore is expensive. Boat landings located in tidal and splash zones are particularly difficult to maintain due to constant wetting by seawater. Offshore oil & gas industry has reported lifetimes above 20 years for certain coating systems also in the splash zone. Offshore wind farm owners, however, have seen that protective coating systems on boat landings are damaged after few years in service.

To ensure secure access to the wind turbines for the O&M people, high friction coating systems are preferred for the boat landing.

The objective of this study has been to study abrasion and mechanical properties of different corrosion protective coating systems for boat landings.

Experimental work

Coating systems used to protect boat landings and/or known to have long lifetimes in the splash zone of offshore oil & gas installations were applied on steel samples by the coating suppliers:

<table>
<thead>
<tr>
<th>Coating system</th>
<th>Coat 1</th>
<th>Coat 2</th>
<th>Coat 3</th>
<th>DFT [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU</td>
<td>Zinc rich epoxy</td>
<td>Epoxy</td>
<td>Polyurethane topcoat</td>
<td>310</td>
</tr>
<tr>
<td>PSO1</td>
<td>Zinc rich epoxy</td>
<td>Modified epoxy</td>
<td>Polyisocyanate topcoat</td>
<td>350</td>
</tr>
<tr>
<td>PSO2</td>
<td>Zinc rich epoxy</td>
<td>Surface tolerant epoxy mastic</td>
<td>The same topcoat, 450</td>
<td></td>
</tr>
<tr>
<td>Epoxy1a</td>
<td>Epoxy Alu Primer</td>
<td>Surface tolerant epoxy mastic</td>
<td>Curing times 3 years (Epoxy1a) and 450</td>
<td></td>
</tr>
<tr>
<td>Epoxy1b</td>
<td>Epoxy mastic</td>
<td>Surface tolerant epoxy mastic</td>
<td>3 months (Epoxy1b) and 500</td>
<td></td>
</tr>
<tr>
<td>Epoxy2</td>
<td>Glasper reinforced epoxy</td>
<td>Glasper reinforced epoxy</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>HDG</td>
<td>Hot dip galvanized Powder coating</td>
<td>Hot dip galvanized Powder coating</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>HDG_powder</td>
<td>Glasper reinforced polyester</td>
<td>Glasper reinforced polyester</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Reinforced</td>
<td>Glasper reinforced polyester</td>
<td>Glasper reinforced polyester</td>
<td>1500</td>
<td></td>
</tr>
</tbody>
</table>

Vulcanised neoprene rubber applied on steel samples in approximately 4.5 mm thickness were used to simulate the fenders on service boats.

Abrasion testing was done to determine the ability of the boat landing coatings to resist wear due to contact with the rubber fender on the boats. Testing was performed by sliding the rubber sample against the coated surface, applying a 200 N weight load at a frequency of 0.1 Hz for 700 s in air and 1800 s in artificial seawater. The load used was estimated from Herz’ equations assuming that the service boat acts with a propulsion force of 10,000 N against the boat landing.

Results

**Abrasion testing** of the coating systems showed generally:

- Decreasing friction coefficients with increasing testing time
- Faster degradation of Rubber than the other coating systems
- Weight loss despite some rubber settled on the coating surfaces
- Educed surface roughness

**Impact testing** of the coating systems showed:

- Cracking of the PU, PSO and HDG-powder coatings
- No cracking of Epoxy1a, Epoxy1b, Epoxy2 and Reinforced coatings

Conclusions

- Increased roughness and low weight loss in the abrasion test indicate that the well cured Epoxy1a is suitable for boat landings
- High friction coefficients but high weight loss may question use of the Reinforced coating on boat landings
- High surface roughness and low weight loss indicate that HDG may be a compromise to organic coating systems for boat landings

Mechanical properties were investigated by:

- Vickers hardness according to ISO 14705
- Impact resistance according to ISO 6272
- Adhesion according to ASTM D1002-10
Real-time Hybrid Testing of a Spar-type Wind Turbine
PhD-student Valentin Chabaud, Dept. of Marine Technology, NTNU

Real-time Hybrid Testing
Up to now scale model testing of floating wind turbines has mainly been used as a necessary step towards large scale prototype testing, but intrinsic issues prevented it from generating trustworthy data to validate numerical models upon:

- Generating good wave and wind conditions demands specific facilities
- Scaling effects arising from Froude/Reynolds scaling impairs accuracy

Real-time hybrid testing (RTHT) overcomes those shortcomings by performing scale model testing only on a subpart of the whole structure, the remainder being simulated numerically. The loads acting on the virtual substructure are calculated from online-measured motions of the physical substructure and actuated back on the latter in real-time. RTHT brings also the ability to focus the experimental study on a substructure and consequently to limit the sources of uncertainties.

Reduction numerical computational time
Numerical method for aerodynamics
Advanced actuation strategies require the modeling of both substructures (numerical, but also physical for observing purposes). Aerodynamics (numerical substructure) must be modeled in a fast and accurate enough way. 3 methods are compared:

<table>
<thead>
<tr>
<th>Name</th>
<th>Call-in-the-loop (CIL)</th>
<th>Look-up tables (LUT)</th>
<th>Analytic Actuator Disc (AAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>AeroDyn (NREL)</td>
<td>LUT for thrust and torque, calculated from CIL</td>
<td>Analytic model, empirical coefficients</td>
</tr>
<tr>
<td>Wake modeling</td>
<td>Dynamic</td>
<td>Quasi-static</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>Discretized 2D field</td>
<td>Punctual + Shear</td>
<td>Punctual + Shear</td>
</tr>
<tr>
<td>Main advantage</td>
<td>Conventional</td>
<td>Simplistic</td>
<td>Fast and simple</td>
</tr>
<tr>
<td>Main disadvantage</td>
<td>Slow</td>
<td>Inaccurate, limited</td>
<td>Punctual turbulence model</td>
</tr>
</tbody>
</table>

Actuator disc turbulence model
- Turbsim (NREL) is used to generated full-field wind files
- Wind speed / direction is averaged over the rotor area
- The root-mean-squared wind speed is filtered in time
- The wind profile is modeled through a linear shear

Results
- Quasi-static wake modeling (LUT) is insufficiently accurate
- AAD and CIL methods correlate well
- Carefully reducing a 2D wind field to a punctual representation is reasonable regarding rigid body motions
- AAD allows larger (~ 2 times) time-steps than CIL
- CPU time for one iteration (ms): CIL 0.3, AAD 0.001, LUT 0.002

The AAD method appears as the most appropriate choice to model rigid body motions of floating wind turbines.

Further work
- Coarsen discretization in time and space to improve performance
- Include yaw dynamics modeling
- Move on to the next task: Observer and actuation strategy design

Objectives
The main objective is to make all the items of the RTHT loop fit into one time step by:

- Reducing numerical computational time
- Reducing force control delay (actuator dynamics compensation)
- Inhibiting filtering delay (observer design)
- Lengthening the time step (actuation strategy design)

While keeping an acceptable level of accuracy.

We focus at first on the wave tank case (physical hydrodynamics, mooring and inertia; numerical aerodynamics, generator and control), with 2 degrees of freedom (pitch and surge).

NOWITECH Norwegian Research Centre for Offshore Wind Technology
Advanced representation of tubular joints in jacket models for offshore wind turbine simulation

Motivation
Offshore wind farms are increasingly realized in water depths beyond 30m, where lattice support structures are an interesting option to withstand the severe environmental actions. One of the main tasks for the future is the optimization of support structure designs, making the exploitation of offshore wind resources more competitive. Jacket substructures show strong potentials in a broad spectrum of water depth from 25 up to 70m and this work addresses the optimization of jackets, using an advanced simulation approach specifically optimized for jackets. The ultimate goal are lighter jacket structures or improved fatigue performance. Both aspects, less material consumption as well as additional fatigue life time lead to lower cost support structures for offshore wind turbines in deeper waters.

Simple beam models
- enhanced beam models
  - consideration of chord-brace overlap (relevant for wave loads) and local joint flexibilities (using springs)
- sophisticated beam models with joint regions as superelements

Improved Superelement Application for Jackets
- rigid link increases stiffness of detailed FEM joints (cf. Figure 3, left)
- ovalization of chord walls due to local brace loading obstructed
- a minimum ratio \( \alpha \) of chord stub length and chord diameter is thus necessary to avoid this “artificial” stiffening due to rigid links

Enhanced fatigue performance of joints in OC4 jacket
- typical jacket geometry allows for relatively small superelements
- small cut-out regions enable a quasi-static extrapolation of member forces into local joint region (cf. Figure 5)

Conclusions
- predicted fatigue damage of essential joints significantly reduced by ~20% (see Figure 6)
- study shows that predicted jacket fatigue life time is increased by up to 15% - enabled by optimized superelement approach!
A comparison of the moments and forces at the joints of a jacket structure is made between fully coupled aero-hydro-elastic simulations in HAWC2 and decoupled load predictions in the finite elements software Abaqus. The four legged jacket sub structure is modeled in moderate deep water of 50 m and designed for the 5 MW NREL baseline wind turbine. External conditions are based on wind and wave joint distribution in the North Sea. In both simulation cases, the integrated loads acting on the jacket legs are computed as time series. The analyses of the fully coupled and decoupled simulations show that differences depending on the structural stiffness and the applied wave loads occur. Variation in the amplitudes of the moments and forces on the jacket legs up to 25 % was observed.

The design of offshore wind turbine structures is based on computer simulations of various load cases that the turbine is expected to experience in its life time as stipulated in the IEC 61400-3 standard [3]. The computation of the loads on the sub structure based on these design load cases requires fully coupled aero-hydro-elastic simulations. However on many occasions, the turbine design is made by a manufacturer and the sub structure (such as a jacket) design is made at another company and it is often not possible to have a fully integrated model in a simulation platform. It is then imperative to understand the difference in sub structure internal forces and moments from those obtained in fully coupled load simulations against those determined using uncoupled load simulations where the tower top loads from the rotor are captured using an aerelastic software and then used in a different software in which the tower, transition piece and sub structure are represented.

The tower, transition piece and jacket structure of the UpWind 5MW turbine [4] are modeled in the Abaqus [5] platform. The hydrodynamic loads are input to Abaqus using a Matlab based code that uses the Morison equation [6] based on wave kinematics obtained using a second order non linear irregular wave model. The tower top fore-aft and side to side forces and bending moments are input to the Abaqus model based on normal turbulent wind simulations conducted in the HAWC2 aeroelastic software [7] between 8 m/s and 25 m/s mean wind speeds. Wind and waves are aligned in all load simulations performed. The DLC 1.1 [3] load case simulations results are obtained in HAWC2, from which the tower top moments are transferred to the Abaqus model.

The comparison between the fully coupled simulation performed with HAWC2 and the uncoupled simulation shows that the extreme and fatigue loads on the jacket leg joints differed significantly between the two cases. The decoupled simulation method predicts higher extreme forces and moments in the Y- and K-connection joints of the jacket support structure. The comparison shows clearly that aeroelastic and hydroelastic coupling can account for at least 25 % of difference in loading on the jacket structure when compared to uncoupled simulations. The effects of fully coupled simulations can depict a bigger influence on larger and more flexible offshore wind turbines.

The work presented in this paper is a part of the Danish Advanced Technology Foundation (ATF) project titled, Cost-effective deep water foundations for large offshore wind turbines, contract le no.010-2010-2. The financial support is greatly appreciated.
Introduction

Offshore wind power is expected to play an increasingly important role in the future energy supply and floating wind turbine solutions have received considerably more attention during the last few years. A large number of concepts are being developed, full-scale prototypes have already been installed and several are under operation in testing phases. Floating wind turbine structures have several advantages compared to their bottom-fixed peers. Much of the world’s shallow waters have already been developed and/or are subject to other interests than energy production. Other areas, closer to shore, are just not suitable for bottom fixed installations due to physical reasons.

The abundant wind resources available in deep waters, advancing technologies, the potential for a global market and the ideal water depths and currents have made floating wind turbines increasingly attractive. In such cases the structure needs to be up-ended, stabilized and the turbine is then installed using a crane barge. A spar is generally moored using caissons or large mooring buoys.

A semi-submersible is a free-surface stabilized structure with relatively shallow draft. It is a very flexible structure thanks to its relatively low draft and high flexibility related to soil conditions. It is a heavy loaded structure with a considerable amount of steel and a relatively high manufacturing complexity due to the many welded connections. A semi-submersible structure is kept in position by a tension leg system, which physically is actors and/or cables. In 2011 the first large scale semi-sub prototype, Principle Power’s WindFloat platform, was installed outside Portugal. The 2.0 MW turbine is on a semi-submersible plug is the first offshore wind turbine to be installed without the use of heavy lift vessels or pile driving equipment. All final assembly, installation and pre-commissioning of the turbine and substructure took place on land in a controlled environment and the complete system was then towed to the final position. In such cases the structure needs to be up-ended, stabilized and the turbine is then installed using a crane barge. A spar is generally moored using caissons or large mooring buoys.

The Tension Leg Platforms (TLP) are tension restrained structures with relatively shallow draft. The tension leg philosophy enables low structural weight of the substructure, and thus lower material costs. TLPs have high buoyancy and are held back by tendon arms connected to the anchors. This adds additional requirements with regard to soil conditions at site.

No TLP has yet been deployed as a large scale prototype, but the PelaStar concept is being developed by Glasoint Associates is probably the concept furthest in development. The Pelastar concept is currently being considered for a demonstration site in 60-100 m water depth outside the UK.

A Global Market

The development of deep water offshore floating systems has so far been mainly led by Northern European countries, but today a considerable amount of R&D concepts and leading of floating systems are performed also in the US, Japan and elsewhere in the EU, creating the potential environment and global market. Recent developments are described below:

- In late December 2012, the European Commission decided to provide project funding for a 27MW floating offshore wind farm, utilizing the WindFloat semi-submersible structures and the next generation multi-megawatt offshore wind turbines.
- In the UK, EDF plans to invest £25m in a 5 to 7 MW demonstrator project in 60 to 100 m water depth. Considerable parts of UK Round 3 zones are in deep waters, suitable for floating wind turbine installations.
- The Japanese government are currently involved in several large national development projects with floating wind turbine platforms, e.g. the Fukushima Floating Pilot Wind Farm and the Katsushima demonstration turbine, a 1:2 spar solution with a 100 kW turbine installed in 2012. A full scale 2 MW turbine is under construction from a spar, the unit being deployed in 2013 as part of the Gunpachi demonstration project. In addition, in mid-2013 Japan released a plan to build the world’s largest offshore wind farm with 434 turbines mounted on floating platforms outside the coast of Fukushima.
- In late December 2012, the US Department of Energy (DOE) decided to partly fund the development of seven offshore wind projects, including three floating projects, utilizing their vast deep-water wind resources.

Development of design standard for floating wind turbine structures

Background

Floating wind turbines is a field currently undergoing major development. Several companies and research institutes are investing resources into different technologies, pilot projects and even planning of commercial floating wind farms. Developing standards for design of floating wind turbine structures is crucial and necessary for the industry to continue to grow. A technical standard embodies the collective experience of an industry and contains normative requirements that shall be satisfied in design. Development of a standard for floating wind turbine structures will lead to:

- Expert consensus on reliable approaches to achieve a tolerable level of safety
- Industry consensus on practicable approaches to achieve tolerable level of safety
- Experience from the industry reflected in the contents of an industry-wide standard regarding safe design, construction and in-service inspection
- A tool to be used related to innovative designs and solutions within given acceptance criteria
- A full-fledged reference code supplementing existing offshore wind turbine structure codes that do not cover floating units

As a first step towards developing a standard for design of floating wind turbine structures, a DNV Guideline for Offshore Wind Turbine Structures was established in 2009 as a supplement to DNV-OS-101 Design of offshore wind turbine structures. The development of this guideline was based on identification of current floating wind turbine concepts in conjunction with experience from other floating applications. The guideline, which is less formal than an official standard document, addresses float-specific issues such as stability and station keeping.

The standard DNV-OS-101 “Design of Offshore Wind Turbine Structures” provides principles, technical requirements and guidance for design, construction, in-service inspection and decommissioning of offshore wind turbine structures. However, DNV-OS-101 does not cover float-specific design issues. This is also the case for other existing standards for offshore wind structures e.g. IEC61400-3 Wind Turbines - Part 3: Design requirements for offshore wind turbines and GL (IV Part 3) Guideline for the certification of offshore windfarms.

Joint Industry Project

As the consequence of failure is primarily a loss of economic value, this is evaluated through a cost-benefit analysis. The analysis is to be used as an input part of the basis for selecting target safety level. This target safety level originally developed for small, individual turbines on land has been extrapolated to be used also for:

- Safety-philosophy and design principles
- Site conditions, loads and response
- Materials and corrosion protection
- Structural design
- Design of anchor foundations
- Stability
- Station keeping
- Control and protection system
- Mechanical system and electrical system
- Transport and installation
- In-service inspection, maintenance and monitoring
- Cable design
- Extreme load analysis

The project secures quality assurance through a technical reference group where all participants have a representative. The standard will also go through an internal DNV and external industry hearing process. The standard is expected to be released during Q2 2013.

Assessment of acceptable safety level

An important task in the JIP is to determine which safety level that is necessary or acceptable in design of floating wind turbine structures. The target safety level of the existing standards is taken as equal to the safety level for wind turbines on land as given in IEC61400-1 Wind turbines - Part 1: Design requirements, i.e. normal safety class.

As the consequence of failure is primarily a loss of economic value, this is evaluated through a cost-benefit analysis. The analysis is to be used as an input part of the basis for selecting target safety level. This target safety level originally developed for small, individual turbines on land has been extrapolated to be used also for:

1. Larger MW size turbines on land
2. Offshore floating wind turbine concepts
3. Support structures for offshore turbines
4. Many large turbines in large offshore wind farms
5. Structures and mooring systems

It is foreseen that the future floating wind farms will consist of a large number of different size wind turbines. Different target safety levels may be required for offshore turbines in a large farm. The selected target safety level is likely to depend on the number of turbines in the wind farm.

Structural design

Another important issue is structural design. Reliability-based calibration of partial safety factors requirements for design of structural components is assessed for e.g. tendons and mooring lines. Existing design standards from other industries are capitalized on, e.g. DNV-OS-C105 Design of offshore Steel Structures, General (LRFD Methods) and DNV-OS-C105 Structural Design of TLPs (LRFD Method) for tendons and DNV-OS-EX301 Position Mooring for mooring lines. The JIP has access to full scale data from Hywind (Statoil) and analysis data from Pelastar (Glosten Associates) and WindFloat (Principle Power). These data will be used as part of the basis for calculating the safety factors.
Nonlinear irregular wave forcing on offshore wind turbines. Effects of damping in misaligned wind and waves.

S. Schløer, H. Bredmose, R. Klinkvort

AGENDA
An offshore wind turbine with a monopile foundation is considered and the importance of the damping from the soil, waves and structure is investigated in a situation with misaligned wind and waves.

Schløer et al. (2012) investigated the effect from fully nonlinear irregular wave forcing on the fatigue life of the monopile and the tower and found that under normal conditions, where the wind and waves are aligned and the wind turbine is in operation, the aerodynamic damping is so strong that the effects from the nonlinearity of the waves become insignificant. However, in cases where the aerodynamic damping is absent, the effects from the wave nonlinearity on the fatigue life is of magnitude 30 %. It was further found that excitation of the first structural eigenmode due to the waves mainly occurred in the tower, while the corresponding mode in the monopile was more static.

Model setup
The dynamic behavior of the wind turbine and foundation is calculated in the aeroelastic code Flex5, Øye (1996). The wave kinematics are calculated using a fully nonlinear potential flow wave model, Engsig-Karup et al. (2009), and afterwards included into Flex5 to form the hydrodynamic loads.

Table 1 Five representative sea states combined with a corresponding wind velocity and turbulence intensity are considered. Each sea- and wind state are given a probability of occurrence and a wind-wave-misalignment-distribution, stated in Table 1.

Two situations are considered: In the first case no damping is applied to the structure. In the second damping is applied to the monopile and tower so that the first structural eigenmode has a damping equal to a log. decrement of 8%. The 8 % represents all the damping which exist beside the aerodynamic damping such as soil-, radiation- and structural damping.

EQUIVALENT LOAD RANGE
Figure 1 shows the equivalent loads, \( L_{eq} \), of the force in the bottom of the tower and monopile perpendicular \((y)\) and aligned with the wind direction \((\phi)\). \( L_{eq} \) is calculated for each sea state including the wind-wave-misalignment distribution stated in Table 1 with 0% and 8% of log. damping.

In the tower the equivalent loads perpendicular to the wind direction decrease significantly when the 8% of damping is included both for the linear and nonlinear waves. It is further seen that \( L_{eq} \) in the tower perpendicular to the wind direction due to the nonlinear waves are up to 50 % larger than \( L_{eq} \) due to the linear waves. In the monopile and in the tower aligned with the wind direction the effects from both the 8% damping and the nonlinearity of the waves are small.

ACCUMULATED FATIGUE DAMAGE
The fatigue analysis is based on the relative probability of occurrence, \( P_r \), and the probability of the wind wave misalignment distribution.

The ratio between the fatigue damage with and without damping for the nonlinear waves is shown in Figure 3. The fatigue damage in the tower is reduced with 50 % in the direction perpendicular to the wind direction \((\phi)\) when the 8% of damping is included. Aligned with the wind and in the monopile the effects from the damping is less significant however the fatigue damage is still reduced with 5 %.

DISCUSSION
The analysis indicates that the nonlinearity of the waves and the damping can change the fatigue damage particularly in the tower and in the direction perpendicular to the wind. The reason that the effects are strongest in the tower is because the first structural eigenmode is excited in the tower. The monopile can more be seen as a force “transmitter”. The aerodynamic damping is the strongest damping effect but the additional damping effects can also lead to a reduction in the fatigue damage. It is therefore important to know the magnitude of the damping which can be expected at an offshore wind farm site in order not to overestimate the fatigue damage. Next to aerodynamic damping, soil damping gives the largest contribution to the overall damping.

Soil friction is currently included in Flex5 through adaption of the recent model of Hededal and Klinkvort (2010) which takes the effects of pre-consolidation and creation of gaps into account.

Soil damping is introduced into the model by hysteresis. Figure 4 shows an example of such a spring element. The new soil model will allow dynamic computations with more physical soil damping. The next step is to investigate the impact on the structural dynamics.

Acknowledgements
This research was carried out as part of the Statkraft Ocean Energy Research Programme, sponsored by Statkraft (www.statkraft.no). This support is gratefully acknowledged.
D Operation & maintenance

Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind, Iain Dinwoodie, PhD Stud, Univ Strathclyde

Vessel fleet size and mix analysis for maintenance operations at offshore wind farms, Elin E. Halvorsen-Weare, SINTEF ICT/MARINTEK

NOWIcob – A tool for reducing the maintenance costs of offshore wind farms, Iver Bakken Sperstad, SINTEF

WINDSENSE – a joint development project for add-on instrumentation of Wind Turbines, Oddbjørn Malmo, Kongsberg Maritime AS

Long-term analysis of gear loads in fixed offshore wind turbines considering ultimate operational loadings, Amir Rasekhi Nejad, PhD stud, NTNU
Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind

I Dinwoodie, Y Dalig, I Lazakis, D McMillan, M Revie
iain.dinwoodie@strath.ac.uk

Overview

Motivation and Objectives

Methodology – Knowledge, Operational Model and Decision Support Tools

Demonstration Case study

Conclusions and Future Work

Motivation & Objective

Existing models typically engineering approaches
Lack of models that help high level decision making
“To develop a methodology to allow O&M models to effectively inform developer and operators decisions”

Requirements

Knowledge of offshore wind turbine and vessel market

Accurate, robust and efficient operational model

Relevant and practical decision making models

Background Expertise

Offshore costs driven by failures and accessibility

<table>
<thead>
<tr>
<th>Vessel Type</th>
<th>Transfer</th>
<th>Field Support</th>
<th>Jack-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time/day rate</td>
<td>£1750</td>
<td>£3150</td>
<td>£4100–£2000</td>
</tr>
<tr>
<td>Failures/yr</td>
<td>1.8</td>
<td>8.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Operation time</td>
<td>&lt;1/2 day</td>
<td>1.5 day</td>
<td>2 days</td>
</tr>
<tr>
<td>Direct cost impact</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

All important, jack-up strategy currently highest impact but may change in future

Strategy Specification

Fix on fail (spot market)
Batch fix on fail (x fails before commission)
Short term (1-6) month yearly charter
Purchase
Modelling Approach

Climate Model – Correlated Auto-Regressive model

Failure Model – Markov Chain Monte Carlo simulation

Decision Models – BBN informed decision tree analysis and emulator models

Climate Model

Correlated Auto-Correlated wind and wave model

\[ X_i = \mu + \varepsilon_i + \sum_{j=1}^{n} \phi_j (X_{i-j} - \mu) \]

De-trend time series and use correlation matrix in AR simulation process

Maintains key site characteristics and computationally simple

Failure model

Markov Chain Monte Carlo failure simulation

\[ \lambda(t) = \rho \beta t^{\beta-1} \]

\[ R < \lambda(t) \times \frac{\Delta t}{8760} \]

Decision Support Models

Bayesian Belief Networks – informed decision tree

Output risk profile

Decision Making Models

Case Study

Simple demonstration wind farm – 60 x 5 MW

Failures based on onshore observations

Identified strategies can be chosen for early life and remaining duration

Uncertainty represented by failure rate and electricity market price
Case Study - Results

Optimal strategy identified at two operation decision point using decision tree

Project costs estimated including likelihood of different results

Key financial risks from uncertainties and decision consequences can be identified

Future Work

Further integrate operational and decision support models

Perform full scale analysis on existing and future wind farms

Use of emulators to perform wide ranging high level analysis based on operational model

Thanks for listening

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http://www.strath.ac.uk/windenergy
Motivation

1. Motivation
2. Problem description
3. Mathematical model formulation
4. Some numerical results
5. Conclusions and further research

Problem description

- One or more wind farms has a number of wind turbines that require maintenance operations during a planning horizon
- Vessel resources and maintenance infrastructure can be shared between the wind farms
- Maintenance infrastructure/bases can be onshore ports, offshore installations, mother vessel concepts...
- Vessel resources can be purchased or chartered and can be CTVs, supply vessels, crane vessels, helicopters...

Motivation

- EU’s 2020-20-20 target – to be meet by 2020
- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels
- 20% of EU energy consumption to come from renewable resources
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency
- 25-30% of the cost from producing energy from offshore wind farm comes from the operation and maintenance (O&M) activities
- Vessels to support O&M activities – one of the most costly resources in the supply chain

Problem description

- Maintenance bases can have investment costs and have a maximum vessel capacity
- Vessel resources are associated with a given maintenance base
- Each vessel resource has:
  - investment cost or time charter cost
  - variable cost
  - service speed
  - deck load
  - deck size
  - crew capacity
  - operational and safety weather requirements
**Problem description**

- Vessel fleet and maintenance infrastructure need to support the wind farm(s)
- Preventive maintenance operations are executed to extend the life of a wind turbine and keep the number of failures down
- Corrective maintenance operations are executed due to unforeseen failures to the system
- Each maintenance operation is divided into up to three maintenance activities

**Mathematical model formulation – constraints**

Restricting the number of vessels that can be based at a maintenance base
Budget constraint restricting the investment in vessels and bases
Maintenance activities are either executed within their hard time windows or postponed until next planning horizon
Only one vessel can be used to execute a maintenance activity at the same time
Determining the number of vessels that need to be purchased or chartered
Operational constraints - weather
Safety constraints - weather
Balancing constraints and flow conservation constraints
Binary, integer and non-negative requirements

**Objective:**

Determine the minimum cost fleet and maintenance infrastructure that can execute all, or most, of the maintenance activities during the planning horizon

**Mathematical model formulation – objective function**

Minimize

Cost of maintenance bases +
Fixed cost of vessels +
Variable cost of using vessels to execute maintenance activities +
Penalty cost for maintenance activities executed outside their soft time window +
Penalty cost for not executed maintenance activities +
Travel cost for vessels
**Numerical results**

- Mathematical model formulation implemented in Xpress-IVE
- 15 problem instances
- Planning horizon of one year (360 days)
- 2 maintenance bases – one port and one offshore installation
- 9 vessel types: 3 CTVs, 2 supply vessels, 2 helicopters, one multipurpose vessel, one jack-up rig
- 1-3 wind farms
- 20-200 wind turbines per farm

**Conclusions and further research**

- A deterministic optimization model has been developed for the fleet composition problem for maintenance operations at offshore wind farms
- The model is implemented in commercially available software
- Numerical results show that the model can be used to provide decision support on optimal or near-optimal vessel fleet within acceptable computational time
- Future research should focus on modifying the model to capture other relevant aspects to the problem not yet discovered
- The problems underlying uncertain nature can make it relevant to investigate ways of incorporating uncertainty into the model

**Vessel fleet analysis for operation and maintenance activities at offshore wind farms**

DeepWind 2013
Trondheim 25 January 2013
Elin E. Halvorsen-Weare1,2, Christian Gundegjerde3, Ine B. Halvorsen3, Lars Magnus Hvattum1, Lars Magne Nørås1
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3Department of Industrial Economics and Technology Management, NTNU, Norway

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2Department of Maritime Transport Systems, MARINTEK, Norway
3Department of Industrial Economics and Technology Management, NTNU, Norway
NOWIcob – A tool for reducing the maintenance costs of offshore wind farms

Iver Bakken Sperstad, Matthias Hofmann
SINTEF Energy Research
Trondheim, 25 January 2013

Outline
1. Describe prototype of life-cycle profit model (NOWIcob)
2. Illustrate use by test cases
3. Possible applications

Model overview: Input and output

Controllable options
- Choice of vessel mix
- Number of maintenance personnel
- Time-/condition-based maintenance

Uncontrollable external factors
- Weather
- Failures
- Price for vessel
- ... 

NOWIcob: Norwegian offshore wind power life cycle cost and benefit model

Life-cycle profit model
Event-based simulation of operational phase of an offshore wind farm
Focus on maintenance activities
- Weather limits
- Weather model
- New maintenance concepts
Monte Carlo to take into account uncertainties
Long-term, system-wide perspective

Model overview: Flow scheme

Nowitech Norwegian Research Centre for Offshore Wind Technology

Results
Availability, O&M costs, life-cycle profit, ...

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NOWIcob: Norwegian offshore wind power life cycle cost and benefit model

Life-cycle profit model
Event-based simulation of operational phase of an offshore wind farm
Focus on maintenance activities
- Weather limits
- Weather model
- New maintenance concepts
Monte Carlo to take into account uncertainties
Long-term, system-wide perspective

Model overview: Flow scheme

Input data
Weather simulation
Maintenance & logistics
Results
**Input data**
- Locations
  - Weather data
- Turbines
  - Power curves
  - Subcomponents
- Maintenance tasks
  - Failure/inspection rates
  - Maintenance type
  - Operation steps
  - Working duration
  - Cost of spare parts etc.
- Weather data
- Power curves
- Subcomponents

**Weather simulation**
- Markov chain weather model
  - Transition matrix from historic weather data
  - Generates simulated time series
- Markov chain weather model
  - Transition matrix from historic weather data
  - Generates simulated time series

**Weather simulation: Markov chain model**
- From state
  - To state

**Weather simulation**
- Simulated time series
  - Same statistical properties
  - Wind speed and wave height
  - Hourly resolution
  - Captures seasonal variations

**Maintenance & logistics**
- Entire life time of the wind farm
- Scheduling for each shift
- Restrictions:
  - Weather
  - Personnel
  - Vessels
- Taking into account:
  - Waiting time
  - Travel time
  - Access time
  - Working time
Results

- Electricity produced
- Electricity-based availability ($E/E_{ideal}$)
- Net present value of
  - Income
  - O&M costs
  - Profit

Multiple simulation runs

- New weather and new failures
- Histogram of results
  - Estimating probability distribution
  - Uncertainties / risks

Examples of results

- Test case: Far-offshore wind farm (150 km)
  - Conventional logistics solution
  - New concepts:
    - Mother ship
    - Offshore platform

Examples of results: conventional

- Histogram of results

Examples of results: concepts

- Histogram of results
  - Mother ship
  - Platform
  - Conventional
Examples of results: availability vs personnel

![Graph showing availability vs personnel]

Examples of results: profit vs personnel

![Graph showing profit vs personnel]

Possible applications

- Optimizing the maintenance strategy (design phase)
- Sensitivities – important parameters for offshore wind
- Estimating life-cycle O&M costs and profit
- Evaluating introduction of new technical concepts

Summary

- NOWicob: Norwegian offshore wind power life cycle cost and benefit model
- Simulating O&M of offshore wind farm
- Focus on weather, access criteria, and novel concepts
- Output: Availability, O&M costs, profit, ...
"Windsense – a joint development project for add-on instrumentation of Wind Turbines"

By Oddbjørn Malmo, Kongsberg Maritime AS

Indicative cost breakdown (with 3 MW WTG’s)

CoE = Annualized CAPEX + Annualized OPEX
Annual Energy Production

Key assumptions
- “All-inclusive” engineer-procure-construct (EPC) cost
- The cost structure for actual offshore wind projects is highly dependent on site specific conditions
- Park size constrained by grid capacity

Main challenge:
CoE of wind power must be reduced by at least 30%
Offshore even more

Operation & Maintenance Costs (O&M)

- Offshore O&M costs are 2-7 times higher than onshore costs
- O&M cost per produced kWh
  - Onshore: 0.05 NOK/kWh
  - Offshore: 0.1 to 0.2 NOK/kWh
- Value of lost production
  - 1% loss in a 50 MW plant at 30% capacity amounts to 1.6 MNOEk/year @ 0.5 NOK/kWh

Planned vs. unplanned service trips

Figures for a 240 MW wind park
- 80 turbines @ 6 MW
- 40 preventive maintenance trips
- 120 corrective maintenance trips
- 1.5 failures per year per turbine

The absolute minimum (in red), and what you also should have (in blue)

(2) Source: DOWEC offshore reference wind farm case study
(3) Source: VESTAS
Requirements according to IEC 61400-1 ed.3

8 Control and protection system

8.1 General

Wind turbine operation and safety shall be governed by a control and protection system that meets the requirements of this clause. Manual or automatic intervention shall not compromise the protection functions. Any device allowing manual intervention must be clearly visible and identifiable, by appropriate marking where necessary. Settings of the control and protection system shall be protected against unauthorized interference.

8.2 Control functions

The control functions may govern or otherwise limit functions or parameters such as:

- power;
- rotor speed;
- connection of the electrical load;
- start-up and shutdown procedures;
- cable twist;
- alignment to the wind.

8.3 Protection functions

The protection functions shall be activated in such cases as:

- overspeed;
- generator overload or fault;
- excessive vibration;
- abnormal cable twist (due to nacelle rotation by yawing).

Windsense is aimed to develop

- A cost-efficient add-on instrumentation system for monitoring of technical condition and lifetime related parameters for critical components in a wind turbine
- Analyse these data primarily for prediction of component degradation and estimation of remaining lifetime.
- Develop sensors and system components that allow on-line acquisition and analysis of data which are currently only obtained by operator handheld equipment.

Windsense Work packages and responsibilities

<table>
<thead>
<tr>
<th>Status</th>
<th>Work package</th>
<th>Responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>✔️</td>
<td>WPA1</td>
<td>SKRISTI</td>
</tr>
<tr>
<td>✔️</td>
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<tr>
<td>✔️</td>
<td>WPA9</td>
<td>TRONET</td>
</tr>
</tbody>
</table>

Windsense Illustration of data acquisition and analysis

Condition monitoring (CM)

Key: Early warning and less manual inspections

- CM sensors added for real-time condition assessment of all critical Wind Turbine Components i.e.
  - Gearbox
  - Rotor blades
  - Main bearings
  - Drive shafts
  - Oil system
  - Power electronics etc.

Typically observed parameters:

- Temperature
- Oil quality
- Vibration
- Manual wear inspections

Better instrumentation required for online monitoring of Rotor Blades:

- Loads
- Local strain
- Cracks
- Delamination
- Surface defects

Additional parameters for offshore and floating wind turbines

- Structural loads
- Moorings
- Scouring
- Corrosion

Additional parameters for offshore and floating wind turbines

- Structural loads
- Moorings
- Scouring
- Corrosion
Methods and systems employed especially in the process and offshore industry provides

- An indication of degraded performance or technical condition in a plant
- Efficient drill down capability
- Triggers further investigation with analysis and diagnostics either through CM system or by manual inspection
- Includes decision support for intervention planning

A substantial reduction in maintenance cost and increased energy production for offshore wind turbines by

- A significant reduction in number of unplanned service trips
- A reduced number of stops and less downtime
- Controlled operation at reduced load when this is safe rather than full shut down until maintenance can be performed

### Application of methods

A: The method is commonly used in wind turbines today and normally included in SCADA

B: The method is commonly used in wind turbines today as a manual inspection

C: The method is more advanced and is used on some turbines today, or used in special cases. It typically requires special competence from the operator.

D: The method is rarely used, either because it is time-consuming, expensive or that the benefit is not well proven.

E: Experimental methods or prototypes.

F: Future ideas

### Elimination of insan"
• Replace manual inspections with remote on-line measurements and analysis
• Implement automated diagnostics tools

Downtime

- Reduce consequential damages
- Enable delay of maintenance until proper weather window occur
- Reduce downtime by more efficient fault identification and diagnostics
- Improve maintenance planning by better diagnostics and estimation of remaining lifetime
Long-Term Analysis of Gear Loads in Fixed Offshore Wind Turbines Considering Ultimate Operational Loadings

Introduction

- The annual failure rate of the wind turbine gearbox assembly, reported by the EU funded ReliaWind project, is about 5% per wind turbine.

Objectives

- The ultimate objective of this research is to establish a reliability-based design method for gears in wind turbines.

Outline

- Introduction
- Objectives
- Methodology
- Results: 5 MW case study
- Conclusions

Introduction

- Gears have been around for at least 5,000 years!
- Aristotle (330 BC) writes of gears as if they were commonplace so the beginnings must go back much farther.
- With such a long history, why still problem?

Introduction

- An overall review of the published researches indicates that the Design process may have the biggest contribution to this premature failure.

Scope of this paper

Flowchart of structural reliability analysis steps
Methodology

A) Methods for Gear Load Calculation:
   - A-1) Multi Body System (MBS) method
   - A-2) Rigid Body, Rigid Contact (RBRC) method

B) Methods for long-term extreme load analysis
   - B-1) Long-term extreme value analysis
   - B-2) Design state or contour line method

Verification of RBRC method

The RBRC method is verified by comparison with a detailed MBS model of NREL 750 kW wind turbine, developed at CeSOS.

<table>
<thead>
<tr>
<th>Stage</th>
<th>MBS (mean, kN)</th>
<th>RBRC (mean, kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st stage</td>
<td>169.4</td>
<td>171.0</td>
</tr>
<tr>
<td>2nd stage</td>
<td>156.1</td>
<td>157.4</td>
</tr>
<tr>
<td>3rd stage</td>
<td>67.7</td>
<td>68.1</td>
</tr>
</tbody>
</table>

In MBS method, each component is modelled as a rigid or flexible body connected with appropriate joints or stiffness to the others.

The motion equation of entire drivetrain is expressed as:

\[ M \ddot{x} + C \dot{x} + Kx = F \]
Methods for long-term extreme load analysis

B) Long-term extreme value analysis:
- All peak values:
  \[ F_{peak}^{-1}(x) = \frac{1}{m} \int_{x_m}^{x} f(x) \, dx \]
- All short-term extremes:
  \[ F_{short}^{-1}(x) = \frac{1}{m} \int_{x_m}^{x} f(x) \, dx \]
- Up-crossing rate:
  \[ F_{up}^{-1}(x) = \exp \left( - \int_{x_m}^{x} \frac{f(x)}{m} \, dx \right) \]

Results: 5 MW

A floating sun concept gearbox is designed at CeSOS/Nowitech in accordance with wind turbine gearbox design codes e.g. IEC 61400-4 and based on the wind turbine data from NREL 5 MW reference turbine.

Results: 5 MW

The aerodynamic simulation of 5 MW case study wind turbine is carried by the Hawc2 version 11.3.
Results: 5 MW

Concluding remarks

- The 20-year expected extreme value of the 5 MW gearbox input torque is 1.89 times the rated value.
- The cut-out wind speed has the biggest contribution in the long-term gearbox extreme loads.
- 3 long-term extreme value analysis methods are described. It is found that the difference between the methods is about 5-6% of the mean value.
- The difference between Rigid Body, Rigid Contact (RBRC) method and MBS for gear load calculation is about 1% of mean value in LS stage.
E Installation & sub-structures

Structures of offshore converter platforms - Concepts and innovative developments, Joscha Brörmann, Technologiekontor Bremerhaven GmbH

Dynamic analysis of floating wind turbines during pitch actuator fault, grid loss, and shutdown, Erin E. Bachynski, PhD stud, NTNU

Use of a wave energy converter as a motion suppression device for floating wind turbines, Michael Borg, Cranfield University

Loads and response from steep and breaking waves. An overview of the ‘Wave loads’ project, Henrik Bredmose, Associate Professor, DTU Wind Energy

Effect of second-order hydrodynamics on floating offshore wind turbines, Line Roald, ETH Zürich
Innovative design for offshore converter platforms

DeepWind'2013

Recent Designs

1. Recent designs
   a. Design & Construction
   b. Installation & Maintainability
2. Optimizations to topside designs
3. Approaches to effective designs

Meerwind OSS (288MW)
- Jacket founded
- Crane Lifted
- Water depth 24.7m MSL
- Approx. 46m x 30.5 x 12m
- Approx. 16,836m³
- 3 Decks + Cable- and Roofdeck
- Partly enclosed
- Air cooled
- External cable deck
- Centralised Design

Baltic II OSS (288MW)
- Jacket founded
- Self erecting
- Water depth 32.5m MSL
- Approx. 40m x 38m x 15.4m
- Approx. 23,408m³
- 3 Decks + Rooftopdeck
- Fully enclosed
- Seawater cooled
- Internal cable deck
- Decentralised Design

Content

1. Recent designs
   a. Design & Construction
   b. Installation & Maintainability
2. Optimizations to topside designs
3. Approaches to effective designs

RECENT DESIGNS

- Cable deck underneath the platform
- 1st and 2nd deck hosting main equipment and oil separator as well as shelter facilities
- 3rd deck hosts auxiliaries, control systems and auxiliary generators
- 4th deck host table heat exchanger, crane and helideck
Recent Designs

- Thematic segregation into 3 preassembled sections (HV, MV, HVAC)
- Continuous separation into 3 decks
- Further segregation into 28 smaller “container” along main axis 28

Installation & Maintainability

- Allocation of equipment is done with emphasis to keep the CDG as low as possible
- Minimization of the extent of the cable deck is utilized by smart allocation of switchgears, transformers and shunt reactors

Recent Designs

- Equipment < 6t mounted on „equipment-tables”
- Applies to equipment located on 1st and 2nd deck having no access via hatches
- Footprint aligned with topside steel structure (multiples of deck stiffener)
- Adjacent tables share same girder
- Orientation either parallel or 90° according to deck stiffener orientation

Recent Designs

- Low floor vehicle
- Load capacity of module table and component
- Maneuverable on floor and corridors without additional need for stiffening
- Rotatable around 5 vertical axis
- Storable on platform
- Capable to handle 6 module variants:
  - 2,400mm x 600mm
  - 2,800mm x 1,800mm
**Recent Designs**

**Installation & Maintainability**

- Lifting cart
- Lifting capacity of module and component
- Storable on platform
- Capable to handle 2 module variants:
  - 600mm x 600mm
  - 1,200mm x 600mm

**Optimization of topside designs**

- Integration of equipment foundations into topside structure
- Using provided “Holland Profiles” within deck structure
- Reduces interfering contours in lower decks

**Recent Designs**

**Installation & Maintainability**

- Wall penetration modules
- Enables quick installation of equipment
- According to maximum required clear width of module tables
- Bolted onto the wall

**Optimization of topside structures**

- Superimposed crane column
- Using provided “Holland Profiles” and walls to convey the forces into the topside structure
Dynamic analysis of floating wind turbines during pitch actuator fault, grid loss, and shutdown

Erin E. Bachynski, Mahmoud Etemaddar, Marit I. Kvittem, Chenyu Luan, Torgeir Moan
Center for Ships and Ocean Structures, NTNU
NOWITECH
10th Deep Sea Offshore Wind R&D Conference
Trondheim, January 25th, 2013

What are the consequences of control system faults?
How do the loads due to faults compare to loads due to extreme conditions?

Outline
• Floating wind turbine models
• Analysis tool: Simo-Riflex-AeroDyn
• Blade pitch and grid faults
• Floating turbine responses
• Summary

Fault Condition Implementation in Simo-Riflex-AeroDyn
• Nonlinear time domain coupled code
• Single structural solver
• Control code (java) modified to allow
  – Blade pitch error at a given time
  – Grid error at a given time
  – Emergency shutdown (aerodynamic braking, grid disconnect)
• Fault conditions for different platforms, including advanced hydrodynamics
• Good agreement with HAWC2 (land-based and spar, including fault)

Semi-Sub 1: Active Ballast
• Small hydrostatic restoring stiffness ($C_{st}/C_{tau}$)
• Ballast system: PID loop, 20 minutes (Roddier, 2011)

<table>
<thead>
<tr>
<th>Floating Wind Turbine Models</th>
<th>Spar TLP Semi-Sub 1 Semi-Sub 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (m)</td>
<td>320 150 320 200</td>
</tr>
<tr>
<td>Displacement (tonnes)</td>
<td>8 227 5 796 4 640 13 473</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>120 22 17 20</td>
</tr>
<tr>
<td>Surge period (s)</td>
<td>129.5 41.9 99.9 115.9</td>
</tr>
<tr>
<td>Sway period (s)</td>
<td>129.5 41.9 159.8 115.9</td>
</tr>
<tr>
<td>Heave period (s)</td>
<td>31.7 0.6 20.0 17.1</td>
</tr>
<tr>
<td>Roll/Pitch period (s)</td>
<td>29.7 2.8 42.1 26.0</td>
</tr>
<tr>
<td>Yaw period (s)</td>
<td>8.2 18.0 66.7 80.2</td>
</tr>
</tbody>
</table>

Semi-Sub 1: Active Ballast
Normal operation
Sudden shutdown during normal operation
Consequent Static Angle

<table>
<thead>
<tr>
<th>WS (m/s)</th>
<th>Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7.0</td>
</tr>
<tr>
<td>11.4</td>
<td>13.1</td>
</tr>
<tr>
<td>14</td>
<td>8.4</td>
</tr>
<tr>
<td>17</td>
<td>6.8</td>
</tr>
<tr>
<td>20</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Outline
• Floating wind turbine models
• Analysis tool: Simo-Riflex-AeroDyn
• Blade pitch and grid faults
• Floating turbine responses
• Summary
Fault and Shutdown

- Blade seizure (B/C): one blade stops pitching
- Grid loss (D): generator torque drops to zero
- Shutdown (C/D): generator torque drops to zero, all unfaulted blades pitch to feather (90 deg)
- Shutdown begins 0.1 s after fault occurs

Environmental/Fault Conditions

<table>
<thead>
<tr>
<th>Fault Definition</th>
<th>EC U (m/s)</th>
<th>Hs (m)</th>
<th>Tp (s)</th>
<th>Turb. model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: No fault</td>
<td>1</td>
<td>8.0</td>
<td>2.5</td>
<td>9.8</td>
</tr>
<tr>
<td>B: Blade seizure</td>
<td>2</td>
<td>11.4</td>
<td>3.1</td>
<td>10.1</td>
</tr>
<tr>
<td>C: Blade seize + shutdown</td>
<td>3</td>
<td>14.0</td>
<td>3.6</td>
<td>10.3</td>
</tr>
<tr>
<td>D: Grid loss + shutdown</td>
<td>4</td>
<td>17.0</td>
<td>4.2</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Maximum loads

- Largely unaffected by fault
- Exceptions:
  - Semi-sub 1: pitch motion after shutdown
  - Spar & TLP: yaw after blade seize + shutdown

Motions and Mooring Loads

- Platform-Pitch Motion
- Platform-Yaw Motion
- Tower Base FA Moment
- Tower Top FA Moment
- Tower Base SS Moment
- Tower Top SS Moment
- Tower Top FA Moment
- Platform-top FA Moment
**Tower Top Bending Moments**

- Blade seize increases both fore-aft and side-side loads
- Side-side loads are reduced by shutdown

---

**Maximum loads**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Land-based</th>
<th>TLP</th>
<th>Semi-sub 1</th>
<th>Semi-sub 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform Pitch Motion</td>
<td>6A/6A</td>
<td>6A/6A</td>
<td>2D/2D</td>
<td>6A/6A</td>
</tr>
<tr>
<td>PlatformYaw Motion</td>
<td>6A/6A</td>
<td>5A/4C</td>
<td>10C/10C</td>
<td>6A/6A</td>
</tr>
<tr>
<td>Tower Base FA Moment</td>
<td>2C/2D</td>
<td>6A/6A</td>
<td>6A/6A</td>
<td>2D/2D</td>
</tr>
<tr>
<td>Tower Base SS Moment</td>
<td>8C/8C</td>
<td>6A/6A</td>
<td>6A/6A</td>
<td>6A/6A</td>
</tr>
<tr>
<td>Tower Top FA Moment</td>
<td>5B/5B</td>
<td>4B/5B</td>
<td>6A/6A</td>
<td>6A/6A</td>
</tr>
<tr>
<td>Tower Top SS Moment</td>
<td>4B/7A</td>
<td>3B/7A</td>
<td>2B/7A</td>
<td>3B/7A</td>
</tr>
</tbody>
</table>

**Blade Bending Moments**

- Relatively small change in load magnitude
- Unfaulted blades are also affected by blade seize (flapwise)
- Edgewise loads can be large during shutdown

---

**Summary**

- Fault has relatively little effect on global motions/mooring loads
  - Exception: semi-sub 1 (pitch due to shutdown)
  - Exception: spar & TLP (yaw due to blade seize)
- Fault has relatively little effect on tower base loads for floating platforms (compared to wave-induced loads)
- Blade seize faults greatly increase tower top loads
  - Shutdown works for mitigation in high winds, less effect for lower winds
  - Shutdown less effective for spar, semi-sub
- Blade seize faults increase flapwise blade loads
- Shutdown can cause large edgewise blade loads

---

**Future Work**

- Azimuthal dependence
- Misaligned wind and wave conditions – with and without fault
- Fatigue due to undetected/unmitigated faults
- Sensor faults
- Different control strategies in response to blade seize
- Detailed analysis of gearbox loads due to fault

---

**Thank you!**
Approaches to Effective Designs

- Introduction of a design hierarchy with
- Breakdown the design problem into sub-problems
- Problem formulation down to single equipment level

- Introduction of Generic Algorithms to solve allocation problem automatically
- Development of relevant:
  - design constraints
  - safety requirements
  - equipment requirements
  - cost functions
- Introduction of interface variants as an additional degree of freedom during design
  - Development of an equipment database including variables:
    - oilvolume
    - accessiblesides
    - solascategory
    - massinstallation
    - massoperation

QUESTIONS?

THANK YOU FOR YOUR ATTENTION
Use of a wave energy converter as a motion suppression device for floating wind turbines

25th January, 2013
Michael Borg, Cranfield University

Outline

• Introduction
• System Description
• Methodology
• WEC Parameters
• Numerical Model
• Results
• Conclusions

Introduction

• Floating platforms subject to large-amplitude motion
  → Increased fatigue loads
  → Reduced aerodynamic performance

Increased cost of electricity

Methodology

• Hypothetical WEC is considered.
  • No characteristic constraints
  • No geometry considered → No hydrodynamic forces
  • Assumed to move only in heave
  • Connected to FOWT with spring-damper system
  • Identify spring-damper characteristics for two cases:
    1. Maximum Motion Reduction
    2. Maximum Energy Extraction

System Description

• 5MW Vertical Axis Wind Turbine mounted on Trifoater
  • Dogger Bank site, North Sea
    → JONSWAP spectrum
    → $H_s = 4.9 \text{ m}$ ; $T_z = 10\text{s}$
  • Hypothetical WEC: additional degree of freedom in heave
    → Connected through PTO spring-damper coupling

Introduction

• Use of passive damping devices to reduce motion
  • Increased system energy yield
  • Shared infrastructure and reduced costs

Introduction

• Wind Energy
• Wave Energy

FOWT SYSTEM

Electricity from wind AND wave

Wave-induced energy dissipated

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  • Hypothetical WEC: additional degree of freedom in heave
    → Connected through PTO spring-damper coupling
WEC Parameters

- Mass → 3 cases: 2.5%, 5% and 10% of FOWT mass
  → based on Refs. [1], [2]

- Damping → Damping ratio (\( \zeta \)) varied from 0.17 to 7.7 → 5 cases

- Stiffness → 3 cases: WEC nat. freq. (\( \omega_n \)) = FOWT \( \omega_n \)
  1 case: Varied 25% to 200% FOWT \( \omega_n \)
  → constant damping
  \[ m \ddot{x} + 2 \zeta \omega_n \dot{x} + \omega_n^2 x = F_{\text{exc}} \]

Numerical Model

- Cummins Eqn. used with radiation-force approximation
- Aerodynamics modelled with Double Multiple Streamtube model with modifications [4]
- Gyroscopic forces also included [5]

Results

Maximum Energy Extraction

- Found to occur with largest mass and lowest PTO damping
- Shifting WEC \( \omega_n \) reduces power absorbed

Effects of WEC Damping

- Increase in PTO damping led to smaller motion reduction
  - Damping ratio > 1 → RAO deteriorates

Maximum Motion Reduction

- Occurs when WEC \( \omega_n \) is lower than FOWT \( \omega_n \)
  - 15% reduction in heave mean amplitude
  - 29% reduction in RAO peak response

Conclusions

- Proposed concept of using a WEC to reducing FOWT motion and increase cost-effectiveness.
- Maximum energy extraction from the WEC is achieved by matching the WEC \( \omega_n \) to the FOWT \( \omega_n \) and using low damping ratios.
- Maximum motion reduction of the FOWT is achieved by shifting the WEC to a lower frequency than the FOWT \( \omega_n \).
- Importance of maximising energy yield per unit area of ocean utilised.
References

Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation

\[ F = \frac{1}{2} \rho C_D |U|U + \rho C_M A \frac{dU}{dt} \]

Better: Fully nonlinear wave kinematics and Morison equation

\[ F = \frac{1}{2} \rho C_D |U|U + \rho C_M A \frac{dU}{dt} \]
Hydrodynamic loads

Simples: Linear wave kinematics and Morison equation

Better: Fully nonlinear wave kinematics and Morison equation

Advanced: CFD and coupled CFD

Forces from a fully nonlinear potential flow solver

Allan Engsig-Karup, Harry Bingham and Ole Lindberg

Apply within Flex5 aero-elastic model

Flex5, developed by Stig Øye at DTU
Widely used in industry
Modal approach → runs at 8 x real time

Apply a sea state at offshore boundary

Response in bottom of tower

Fully nonlinear waves versus linear waves

$H_b = 9.4 \text{ m}, \quad T_p = 14.2 \text{ s}, \quad W = 5 \text{ m/s}$

Schlaer et al (OMAE 2012)

The OC4 jacket

Jacket and reference turbine modelled in HAWC2
Fully nonlinear wave loads.

Response in bottom of tower

Fully nonlinear waves versus linear waves

$H_b = 9.4 \text{ m}, \quad T_p = 14.2 \text{ s}, \quad W = 5 \text{ m/s}$

Structural excitation. Ringing and/or impulsive loads.
Aero-dynamic damping helps, though, when wind and waves are aligned.
Fatigue study and misalignment study.

Schlaer et al (OMAE 2012)

Storm sea state. Turbine standstill.
Severe ringing/impulsive excitation.

Torben Juul Larsen
Taesong Kim
Larsen et al Europ. Offsh. Wind 2011
Wave loads on offshore wind turbines
ForskEL, DTU Wind, DHI, DTU MEK. 2010-2013.

Task D: Physical validation test
Task A: Boundary conditions for phase resolving wave models
Task C: Aero-elastic response to fully nonlinear waves
Task B: CFD computation of monopile loads

The OpenFOAM® CFD solver
Open source CFD toolbox
Vast attention during last 3 years
This study: interFoam solver
3D incompressible Navier-Stokes
two phases (water and air)
VOF treatment of free surface

Waves2Foam wave generation toolbox has been developed and validated
(Niels Gjel Jacobsen
PhD thesis 2011; Paper in Coastal Engineering)

Second-order focused wave group
First-order wave field
(Sharma & Dean 1981)

\[
\mathbf{F}^\text{first-order} = \frac{1}{2} \int \left( \mathbf{u} \cdot \nabla \mathbf{u} + \nabla \mathbf{u} : \nabla \mathbf{u} \right) \, dx,
\]

Second-order wave field

\[
\mathbf{F}^\text{second-order} = \frac{1}{2} \int \left( \mathbf{u} \cdot \nabla \mathbf{u} + \nabla \mathbf{u} : \nabla \mathbf{u} \right) \, dx + \frac{1}{2} \int \left( \mathbf{u} \cdot \nabla \mathbf{u} + \nabla \mathbf{u} : \nabla \mathbf{u} \right) \, dx.
\]

2D wave calibration
Free surface elevation

Platform height of 8.96

Platform height of 8.96m

\[
t = 58.8 \text{s}
\]
Detailed calculation of forces from steep regular waves

Third-harmonic force compared to FNV theory

Coupling of OpenFOAM and OceanWave3D

- 3 hours times series of 2D irregular waves computed in hours with OceanWave3D
- Selected event analysed with OpenFOAM (~1 day)

- Small "warmup" period for the CFD-computations: No initialization of pressure and pseudo air velocities
- Morison forces and CFD-computations agrees for small wave heights
- Discrepancies after passage of main event is attributed to diffraction effects

Coupling of OpenFOAM and OceanWave3D

- Irregular waves: JONSWAP \( T_p = 12 \text{s}, H_s = 8 \text{m} \)
- Large domain \( \rightarrow \) Impossible to resolve with CFD alone!
- Rather trivial test case as it serves as validation

Wave loads on offshore wind turbines
ForskEL, DTU Wind, DHI, DTU MEK 2010-2013

Task A:
- Boundary conditions for phase resolving wave models

Task B:
- CFD computation of monopile loads

Task C:
- Aero-elastic response to fully nonlinear waves

Task D:
- Physical validation test

Terp Paulsen et al (2012)

Bo Terp Paulsen

Terp Paulsen et al Eur. Offsh Wind 2011

Terp Paulsen et al (2012)
Wave loads Task D
Physical validation test

New tests at DHI with a rigid and a flexible structure

DHI:
Flemming Schlütter
Anders Wedel Nielsen
Jacob Tomfeldt Sørensen

Results and brief analysis for flexible pile

Irregular JONSWAP waves, unidirectional
h=20m
Tp=14s
Hs=11m

Free surface elevation 0.15m from pile
Measured inline force on pile
Acceleration of top point
Displacement of top point

Experimental setup

PVC pipe
Scale 1:80
Two masses
→ right natural frequencies (1,2)

Results and brief analysis

'continuous' forcing of 1st natural mode
Impulsive load from breaking wave
from wave-nonlinearity
Wave loads on offshore wind turbines
ForskEL, DTU Wind, DHI, DTU MEK. 2010-2013.

Task D: Physical validation test

Task C: Aero-elastic response to fully nonlinear waves

Task B: CFD computation of monopile loads

Correlation of ringing to eta, t

Which waves give the largest forces?

Sahlberg-Nielsen and Slabiak (2013)
Effect of Second-Order Hydrodynamics on Floating Offshore Wind Turbines

L. Roald, J. Jonkman, A. Robertson, N. Chokani

25.01.2013, Deepwind, Trondheim

Outline

- Introduction
- Analysis approach
- Analyzed Systems
- Results
  - Comparison to first-order hydrodynamic forces
  - Comparison to aerodynamic forces
- Conclusions

Second-order hydrodynamics

- Radiation/diffraction approach:
  - Assume potential flow
  - Assume small wave amplitude $a$
  - Perturbation series with respect to $a$

  First-order excitation force:

  \[ F_{\text{ex}}^{(1)} = \text{Re} \left( \sum_{j=1}^{N} a_j X_j \text{e}^{i\omega_j t^*} \right) \]

  Second-order excitation force:

  \[ F_{\text{ex}}^{(2)} = \text{Re} \left( \sum_{i=1}^{N} \sum_{j=1}^{N} a_i a_j X_i X_j \text{e}^{i(\omega_i t^* + \omega_j t^*)} + a_i a_j X_i X_j \text{e}^{i(\omega_i - \omega_j) t^*} \right) \]

  sum-frequency difference-frequency

Second-order hydrodynamics

Pitch motion of spar configuration from the DeepCWind wave tank tests:

### Second-order hydrodynamics

Pitch motion of spar configuration from the DeepCWind wave tank tests:

![Graph showing hydrodynamic forces](image)


1. Are second-order hydrodynamics important for floating offshore wind turbines?

2. What are the differences to second-order analysis of traditional offshore structures?

### Analysis Methodology

- **WAMIT:** First- and second-order hydrodynamics in the frequency domain
- **FAST:** Aerodynamics, structural dynamics, control system properties and first-order hydrodynamics in the time domain

Calculation of first-order hydrodynamic properties in WAMIT

System linearization in FAST

Calculation of first- and second-order forces and motion response in WAMIT

Post-processing

### Analyzed systems

**OC3 Hywind spar:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [rad/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.051</td>
</tr>
<tr>
<td>Heave</td>
<td>0.204</td>
</tr>
<tr>
<td>Roll</td>
<td>0.215</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.215</td>
</tr>
<tr>
<td>Yaw</td>
<td>0.761</td>
</tr>
</tbody>
</table>

**DeepCWind TLP:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [rad/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.156</td>
</tr>
<tr>
<td>Heave</td>
<td>0.156</td>
</tr>
<tr>
<td>Roll</td>
<td>3.375</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.386</td>
</tr>
<tr>
<td>Yaw</td>
<td>3.374</td>
</tr>
</tbody>
</table>

### First- and second-order results: OC3 Hywind

- Considered sea state: $H_s = 3.66$ m, $T_p = 9.7$ s

![Graph showing comparison of first and second order results](image)
First- and second-order results: UMaine TLP

- Considered sea state: $H_s = 3.66 \, \text{m}$, $T_p = 9.7 \, \text{s}$

Comparison of Mean Drift Force and Mean Thrust

- Test case: OC3 Hywind
- Operating turbine: Mean drift force less than 1% of mean rotor thrust
- Idling turbine: Mean drift force less than 15% of mean rotor thrust

Comparison of aerodynamic and second-order response

- Test case: OC3 Hywind
- Environmental condition:
  - $H_s = 3.66 \, \text{m}$, $T_p = 9.7 \, \text{s}$
  - Wind speed = 17.6 m/s
- Simulation in FAST including aerodynamics and first-order hydrodynamics
- Simulation in WAMIT including first- and second-order hydrodynamics

Current limitations

- Influence of turbine tower flexibility
  - Shift of the eigenfrequencies
  - Inaccurate first- and second-order response

<table>
<thead>
<tr>
<th>Eigenfrequencies of UMaine TLP</th>
<th>Hydodynamic forces of the Umaine TLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>0.156</td>
</tr>
<tr>
<td>Sway</td>
<td>0.156</td>
</tr>
<tr>
<td>Heave</td>
<td>5.975</td>
</tr>
<tr>
<td>Roll</td>
<td>3.388</td>
</tr>
<tr>
<td>Pitch</td>
<td>3.392</td>
</tr>
<tr>
<td>Yaw</td>
<td>0.374</td>
</tr>
</tbody>
</table>
**F Wind farm modelling**

Wind farm optimization, Prof Gunner Larsen, DTU Wind Energy

Blind test 2 - Wind and Wake Modelling, Prof Lars Sætran, NTNU

A practical approach in the CFD simulations of off-shore wind farms through the actuator disc technique, Giorgio Crasto, WindSim AS

3D hot-wire measurements of a wind turbine wake, Pål Egil Eriksen, PhD stud, NTNU

Near and far wake validation study for two turbines in line, Marwan Khalil, GexCon AS
TOPFARM – A TOOL FOR WIND FARM OPTIMIZATION

G. C. Larsen, P. E. Réthoré

Outline

- Introduction – vision and philosophy
- Importance of wind farm (WF) flow field modeling
- Wind farm optimization
  - Optimal power production
  - Optimal economic performance
- The TOPFARM platform in brief
- Demonstration example 1
- Demonstration example 2
- Conclusion
- Future activities
- References

Introduction – vision and philosophy

- Vision: A "complete" wind farm topology optimization, as seen from an investors perspective, taking into account:
  - Loading- and production aspects in a realistic and coherent framework
  - Financial costs (foundation, grid infrastructure, ...) and and subjected to various constraints (area, spacing, ...)
- Philosophy: The optimal wind farm layout reflects the optimal economical performance as seen over the lifetime of the wind farm

Importance of WF flow field modeling (1)

- Wind Farm (WF) wind climate deviates significantly from ambient wind climate:
  - Wind resource (decreased)
  - Turbulence
    - Turbulence intensity increased
    - Turbulence structure modified (... incl. intermittency)
- ... and the WF turbines interact dynamically through wakes

Importance of WF flow field modeling (2)

- WF wind climate characteristics important for:
  - Design of wind turbine (WT) control strategies
  - Wind farm optimization. Potential approaches:
    - Optimizing the power output ... and ensuring that that the loading of the individual turbines is beneath their design limit
    - Optimizing wind farm topology from a "holistic" economical point of view ... throughout the life time of the WF

Optimal power production – input (1)

- Ambient/undisturbed flow conditions on the intended WF site assumed given! – measured or modelled (with meso-scale models or others...)
  - Mean wind distribution ... conditioned on wind direction (deterministic)
  - Roughness/shear ... conditioned on wind direction (deterministic)
  - Turbulence parameter distributions ... conditioned on wind direction (stochastic)
  - Wind direction distribution
Optimal power production – input (2)

- Wind Turbines (WT) strongly simplified and basically represented by characteristics as:
  - Thrust curve ("flow resistance")
  - Power curve (production)

Optimal power production – WF flow field

- Typically modelled using stationary approaches, such as e.g.
  - The N.O. Jensen model (simple top hat model based on momentum balance)
  - Parabolised CFD models with an eddy viscosity closure (UPM model (ECN WindPRO), Ainsley model (GH Windfarmer), ...)
  - Linearized RANS model (FUGA) based on a first order perturbation approach. Numerical diffusion omitted! (mixed spectral formulation)

Optimal economical performance – input

- In a "true" rational economical optimization of the wind farm layout, the goal is to determine the optimal balance between capital costs, operation and maintenance (O&M) costs, fatigue lifetime consumption and power production output ... possibly under certain specified constraints
- Same input as used for optimizing power production ... supplemented by
  - Wind turbine information sufficiently detailed for setting up aeroelastic model(s) of the turbines in question

Optimal economical performance – modeling

- Stationary flow fields and rudimentary WT models may suffice for optimizing wind power production ... but is clearly not sufficient for achieving the overall economical WF optimum
  - Non-stationary characteristics of the WF flow field have to be considered to enable prediction of reliable WT dynamic loading ... which is essential for fatigue load estimation, cost of O&M, ...
  - Detailed WT modeling (i.e. aeroelastic modeling) is needed to obtain main component structural response in sufficient detail and of sufficient accuracy
  - Cost models are needed to aggregate different types of quantities into an objective function

Optimal economical performance – objective function

- Relatively simple ... because all elements have the same unit
- No cost models are consequently required!
- Objective function ... to be optimized:

\[
P_{\text{tot}} = \sum_{i=1}^{n} \sum_{j=1}^{m} a(x_i, y_j)
\]

Optimal economical performance – summary

- The main parameters governing/dictating WF economics include the following:
  - Investment costs - including auxiliary costs for foundation, grid connection, civil engineering infrastructure, ...
  - Operation and maintenance costs (O&M)
  - Electricity production/wind resources
  - Turbine loading/lifetime
  - Discounting rate
The TOPFARM platform in brief

- Multi-fidelity optimization approach requires a hierarchy of models
  1. Stationary wake (analytical model) + Power curve
  2. "Poor man's LES": i.e., DWM (Database - generic production/load cases + interpolation)
  3. DWM (Simulation)

- HAWC2:
  - Non-linear FE model based on a multi-body formulation
  - Aerodynamics based on Blade Element Momentum and profile look-up tables ... that in turn "delivers" the boundary conditions for the quasi-steady wake deficit simulation
  - WT generator model included
  - WT control algorithms included
  - Output is power and forces/moments in arbitrary selected cross sections

The TOPFARM platform in brief – module 1

- Basic simplifying approach:
  - Only costs that depend on wind farm topology and control - variable costs - are of relevance in a topology optimization context
  - Fixed costs may be included in the objective function (Module 5). However, as seeking the stationary points for this functional involves gradient behaviour only, the fixed costs will not influence the global optimum of the objective function

The TOPFARM platform in brief – module 4 (1)

- Examples of required cost models ... to transform the physical quantity in question into an economical value:
  - Financial costs
    - Foundation costs
    - Grid infrastructure costs
    - Civil engineering costs
  - Operational costs
    - Turbine degradation (fatigue loading/lifetime)
    - Operation and maintenance costs (O&M)
  - Electricity production/wind resources

The TOPFARM platform in brief – module 4 (2)

- Objective function (OF):
  - The value of the wind farm power production over the wind farm lifetime, $WP$, refers to year Zero
  - All operating costs (in this example $CD$ and $CM$) refer to year Zero ... with the implicit assumption that the development of these expenses over time follows the inflation rate ... and that the inflation rate is the natural choice for the discounting factor transforming these running costs to net present value
  - $FB = WP_n - C \left( \frac{F_n - F_1}{N_1} \right)^{\frac{1}{N_1}}, \quad WP_n = WP - CD - CM$,
  - $C$ denotes the financial expenses (e.g., including grid costs ($CG$) and foundation costs ($CF$))
Demonstration example 1 (1)

- Generic offshore wind farm:
  - 6 × 5 MW offshore wind turbines
  - Water depths between 4 m and 20 m

Demonstration example 1 (2)

- Result of a gradient based optimization (SLP):

Demonstration example 1 (3)

- Result of a genetic algorithm + gradient based optimization (Simplex)

Demonstration example 2 (1)

- Middelgrunden

Demonstration example 2 (2)

- Middelgrunden

Demonstration example 2 (3)

- Middelgrunden - ambient wind climate
DTU Wind Energy, Technical University of Denmark

### Demonstration example 2 (4)
- Middelgrunden iterations: 1000 SGA + 20 SLP

### Demonstration example 2 (5)

- **Optimum wind farm layout (left) and financial balance cost distribution relative to baseline design (right).**

### Demonstration example 2 (6)
- **Evaluation:**
  - The baseline layout was largely based on visual considerations
  - The optimized solution is fundamentally different from the baseline layout ... the resulting layout makes use of the entire feasible domain, and the turbines are not placed in a regular pattern
  - The foundation costs have not been increased, because the turbines have been placed at shallow water
  - The major changes involve energy production and electrical grid costs ... both were increased
  - A total improvement of the financial balance of 2.1 M€ was achieved compared to the baseline layout ... over the WF lifetime

### Conclusion (1)
- A new approach has been developed that allow for wind farm topology optimization in the sense that the optimal economical performance, as seen over the lifetime of the wind farm, is achieved
- This is done by:
  - Taking into account both loading (i.e. WT degradation, O&M) and production of the individual turbines in the wind farm in a realistic and coherent framework .... and by
  - Including financial costs (foundation, grid infrastructure, etc.) in the optimization problem
- The model has been implemented in a wind farm optimization platform called TOPFARM

### Conclusion (2)
- Proof of concept has, among others, included various sanity checks ... and optimization of a generic offshore WF, an existing offshore WF and an existing onshore WF
- The results are over all satisfying and give interesting insights on the pros and cons of the design choices. They show in particular, that inclusion of the fatigue load degradation costs gives some additional details in comparison with pure power based optimization
- The multi-fidelity approach is found necessary and attractive to limit the computational costs of the optimization

### Future activities
- More detailed and realistic cost functions
- Improvement of the code (e.g. parallelization)
- Inclusion of WF control in the optimization problem
- Inclusion of atmospheric stability effects in the WF field simulation ... basically by developing a spectral tensor including buoyancy effects
- Cheapest rather than shortest cabling between turbines
- Inclusion of extreme load aspects
- Simplified aeroelastic computations in the frequency domain ... to improved computational speed
- Development of a dedicated “self-generated” wake turbulence spectral tensor
- Development of a more DWM-consistent eddy viscosity
References (1)

- Larsen et al. (2011). **TOPFARM - NEXT GENERATION DESIGN TOOL FOR OPTIMISATION OF WIND FARM TOPOLOGY AND OPERATION.** Publishable final activity report. Risø-R-1805 (EN)

References (2)

BT2 is a follow-up of BT1:

LR Saetran, F Pierella and P-A Krogstad; "Blind test" calculations of the performance and wake development for two model wind turbines in tandem. To be submitted for publication

Contributors:
- Meventus (Agder Energy); V Bhutoria and JA Lund (OpenFOAM, ALM / LES (CFD))
- Alcona Flow Technology; E Manger (ANSYS FLUENT Version 14.0, CFD – Full Rotor)
- CMR Instrumentation; A Hallager and IØ Sand (Music, BEM + CFD)
- DTU Mech. Eng. And Limme Flow Center/KTH Mechanics; R Mikkelsen and S Sarmast (EllipSys3D/FLEX5, CFD, Actuator line)
- GexCon; L Saelen and M Kahlil (CMR-Wind, CFD (BEM))
- NTNU, Dept Marine Tsechn; J de Vaal L. (Fluent ASAD, Axi-sym Actuator Disc)
- METU Center for Wind Energy; O Uzol and NS Uzol (Aerosim, Free-wake)
- Puerto Rico, Leonardi
Global performance
(Power and thrust coefficients)

Compulsory results:
Turbine #1: Power coeff $C_p$ at best condition $TSR=6$

Compulsory results:
Turbine #1: Thrust coeff $C_t$ at best condition $TSR=6$

Turbine #2:
- Power coeff $C_p$ for $TSR=2.5, 4$ and $7$
- Thrust coeff $C_t$ at $TSR=2.5, 4$ and $7$

Now a close look at some wake data!
Wake data comparison:
Simplest case; Design condition

Wake 2\textsuperscript{nd} turbine, TSR=4, X/D=1. Mean velocity $U$ on a horizontal diagonal and on a vertical diagonal.

Wake 2\textsuperscript{nd} turbine, TSR=4, X/D=1. Reynolds normal stress on a horizontal diagonal and on a vertical diagonal.

Wake 2\textsuperscript{nd} turbine, TSR=4, X/D=1. Mean velocity $U$ on a horizontal diagonal.

Wake profiles at X/D=1, 2.5 and 4.

Wake 2\textsuperscript{nd} turbine, TSR=4. Reynolds normal stress on a vertical diagonal.

Wake profiles at X/D=1, 2.5 and 4.

And what happens at low wind speeds?

TSR = 7
Wake 2nd turbine, TSR = 7. Mean velocity U on a horizontal diagonal
Wake profiles at X/D = 1, 2.5 and 4

Wake 2nd turbine, TSR = 7. Reynolds normal stress on a vertical diagonal
Wake profiles at X/D = 1, 2.5 and 4

And now on to a tougher case:
Low tip speed ratio;
TSR = 2.5

The wake is a complicated 3D periodic and turbulent flow

Vorticity, Mikkelsen & Sarmast

The wake is a complicated 3D periodic and turbulent flow

Vorticity, Mikkelsen & Sarmast

Transverse velocity after a "drag disk", Pierella
What is TURBULENCE in this case: “Are we comparing apples and bananas…?”

Tentative conclusions….

- Predictions for Cp and Ct at design condition for 1st turbine show more scatter than expected.
- Large scatter for Cp and Ct for 2nd turbine, both on and off “best” condition.
- Wake mean velocity field qualitatively OK?
- Wake turbulence intensity field not necessary with logarithmic ordinate axis… (ref BT1)
- The following conclusions were for BT1 – are they still valid?
  - Uncertainty much higher for Cp at high TSR and these do not appear to be systematic trends with respect to methods or models used.
  - BEM as good as CFD for Cp and Gp.
  - Data not extraordinary but good and performed as the expected, i.e. shift these results and making models in a bottom line section. Predicted steady results quite close to experimental.
  - Wake computed with Spalart-Allmaras, not at in CFD turbulence models as well as with LES. LES more accurate. No obvious answer among other models.
  - Many used openFoam, but results appear to be dependent on setup, boundary conditions and turbulence models rather than CFD code.
  - Scaling of kinetic energy dissipation models. Too large differences to be due to turbulence models. Do the methods predict turbulence in the wakes behind wind turbine correctly?

Turbulent diffusion appears to be underestimated in most models. Much longer fetch is needed to see in the far wake when profiles are predicted.

The experimental data for BT2 will be published by Fabio Pierella (2013).

A package with detailed description of the experiment and the experimental data is available. Email: lars.satran@ntnu.no
**A practical approach in the CFD simulation of off-shore wind farms through the actuator disc technique**

F. Castellani, A. Gravdahl, G. Crasto, E. Piccioni, A. Vignaroli

Presenter: Dr. Giorgio Crasto, WindSim AS

Contact author: Prof. Francesco Castellani, University of Perugia

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**THE WindSim MODEL**

**Key features**

- WindSim (WS) is commercial software package for wind flow simulations based on Computational Fluid Dynamics (CFD)
- WS provides a user-friendly interface for the CFD core PHOENICS (by CHAM)
- The code solves automatically the Reynolds Average Navier Stokes (RANS) equations (steady solution) on different direction sectors

- Very easy to setup a simulation on a real terrain case
- Easy grid control
- Quite fast solution
- Strictly Cartesian orthogonal grid
- Solution with RANS and quite standard turbulence models

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**TURBULENCE MODELS**

The RANS equations are closed with different versions of the k-ε model or the k-ω model:

- k-ε Standard
- k-ε Modified
- RNG k-ε
- k-ε with YAP correction
- k-ω

There is a fundamental lack of physics when using RANS and the k-ε/k-ω model with relevant adverse pressure gradients (Réthoré et al., 2010).

Applying some small changes on a open part of the code (Q1 file) it’s possible to test even more solutions for turbulence models.

**WAKES MODELLING**

WindSim provides two different ways to consider wakes in the numerical solution:

1. Using analytical models in the post-processing of the CFD/RANS calculations
   a. Jensen model (momentum deficit theory)
   b. Larsen model (turbulent boundary layer equations)
   c. Model with a turbulent depending rate of wake expansion

2. Use the actuator disc (AD) model within the CFD/RANS calculations
   a. Only axial forces are applied on the disc
   b. All rotational effects are disregarded
   c. The thrust is applied according to the thrust coefficient curve of the wind turbine using the actual speed calculated on the rotor (correction with axial induction).

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**USE OF THE TESTBATTERIES**

- The test battery is a numerical tool designed to be used during the development of each new version of the code.
- With the test battery it is possible to run the model in a batch/silent mode, changing the calculation parameters automatically and check all monitored outputs.
- The test battery can be very useful also for research purpose.

A good part of the development of the test battery was carried-out at the WindSim headquarter in Norway by Emanuele Piccioni, a PhD student from the University of Perugia during his four-months stage within the Erasmus Placement project.

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**The Grid**

Using an orthogonal Cartesian grid WS is designed to operate on rectangular domains. This introduce different boundary layers conditions between orthogonal and skewed direction sectors.

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TESTING A NEW SOLVER WITH THE TESTBATTERIES

Adjusting the convergence criteria for the new GCV, a SIMPLE-C solver acting on a collocated, BFC grid.

RESUL TS FROM THE SINGLE-WAKE CASE

Using the testbattery to reach the upstream wind speed conditions:

RESULTS FROM THE SINGLE-WAKE CASE

Assessing the performance on complex-terrain

RESUL TS FOR THE DOUBLE WAKE CASE

Due to the flow symmetry it is possible to move the sensor rather than changing the wind direction.

DEALING WITH SKEWED FLOWS

Due to the flow symmetry it is possible to move the sensor rather than changing the wind direction.
DEALING WITH SKEWED FLOWS

In this case it is necessary to rotate the layout (and the sensor positions). If the terrain is not flat also the rotation of the DTM is needed. This is the only possibility to have the rotors exactly facing the wind.

CALCULATING THE REYNOLDS STRESS TENSOR COMPONENTS

The eddy viscosity was estimated according to the chosen turbulence model (RNG k-ε) in order to solve the equations:

\[-\rho u'_i u'_j = \mu_T \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad \mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \]

\[C_\mu = 0.0845 \quad k = \frac{1}{2} (u'^2 + v'^2 + w'^2)\]

The turbulence is modeled as isotropic; the partial derivative of the wind speed components were evaluated using a discrete approach.

ESTIMATION THE POWER OUTPUT

\[\text{power} = \int \bar{\mathbf{u}} \cdot \Delta p \cdot dA\]

\(A_s\) is the swept area

\(\bar{\mathbf{u}}\) is the bulk velocity over the swept area

\(\Delta p\) is the max pressure drop over the swept area

The Sexbierum test-case (1/4)

- The Sexbierum case is a well-investigated wind farm with a very detailed database of measurements; such case represents a reference case for benchmarking wakes numerical models.
- Sexbierum is located in the Northern part of the Netherlands (Cleijne 1992, 1993), around 4 km from the seashore.

Cleijne J.W., "Results of Sexbierum Wind Farm", Report MT-TNO 92-388, 1992

The Sexbierum test-case (2/4)

18 turbines HOLEC three-bladed machines, hub height 35 m, power of 310 kW, for a total power of 5.4 MW.

The wind farm layout is a semi-rectangular grid of 3×6 turbines.

Seven fixed met-masts M1-M7 and a mobile met-mast used to measure the wake along the main wind direction T18-T27.

The Sexbierum test-case (3/4)

(a) Speed ratio U/Uref
(b) Turbulent kinetic energy ratio Tke/TkeRef

Figure 5: speed (a) and turbulent kinetic energy (b) ratio profiles at different level observed 2.5 diameters downstream - position b, 75 m downstream of T18.
**The Sexbierum test-case (4/4)**

(a) Speed ratio $U/U_{ref}$

(b) Turbulent kinetic energy ratio $TKE/TKE_{ref}$

Figure 6: speed (a) and turbulent kinetic energy (b) ratio profiles at hub height observed 2.5, 5.5 and 8 diameters downstream.

**Validation, Horns Rev (first 3 rows)**

Computational characteristics:
- Resolution: $D/10$ (8 meter)
- # cells: 5.0 M

Production for all eight turbines in each three first columns for case with income wind from $270^\circ$ and wind speed of 10 m/s at hub height. Variability due to sector division.

**Validation, Lillgrund**

Lillgrund is an offshore wind farm located in Øresund consisting of 48 wind turbines (Siemens SWT-2.3-93)

The presence of shallow waters caused the layout of the wind farm to have regular array with missing turbines (recovery holes).

- Very close inter-row spacing
- Onshore effects
- Interesting wind farm for wake simulations

**Validation, onshore wind farm**

For the turbines placed in north-west of the domain (quite far from the met-mast) there is no difference in yawing even larger than $20^\circ$

This misalignment is not fully captured by the actuator disc implemented. Orographic but also meteorological effects.

**Conclusions**

1. WindSim with the Actuator disc model can be a useful tool for simulation of wakes on real cases (offshore and onshore);
2. Using RANS and the k-ε turbulence model can introduce some critical issue for the model not realizable (near wake);
3. Another critical part of the model can be connected with the lack of swirl in the wake (near wake);
4. Comparison with SCADA data is possible but a large uncertainty can be introduced by rotors yaw misalignments (this issue is more critical in onshore wind farms).

**FUTURE WORK**

1. **ON THE MODEL SIDE**
   a. Complete the simulations with different wind speed conditions using the testbattery
   b. Improving turbulence modeling (realizable models?)
   c. Define the best force distribution on the rotor
   d. Introduce thermal stratification
   e. Introduce swirl of wake

2. **ON THE EXPERIMENTAL SIDE**
   a. Understand misalignments (for onshore application)
   b. Introduce much more information on the actual wind direction
   c. Analyze seasonal behaviors
THANK YOU FOR YOUR ATTENTION

If you want to know more about this tool...

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Prof. Francesco Castellani, University of Perugia (IT)
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3D hot-wire measurements of a wind turbine wake

Pål Egil Eriksen
PhD candidate, NTNU/NOWITECH

Per-Åge Krogstad
NTNU

Outline of the presentation

- Experimental setup
- Measurement technique
- Time averaged results
- Phase-locked-averaged (PLA) results
- Possibilities for further analysis of the data
- Conclusions

Experimental setup (1/2)

- Exact same setup which was used in Blind Test 1
- Turbine positioned 4D from the entrance of the test section
- Test section: 11.2m x 1.8 m x 2.7 m
- Allows for measurements 5D downstream of the turbine
- Data collected at 1D, 3D & 5D for 720 x 16 along a horizontal line.
- Equipped with a balance and a traverse system
- Turbulence level: 0.3 %

Experimental setup (2/2)

- Wind turbine model
  - Diameter: 0.9 m
  - Hub height: 0.8 m
  - Re tip: ~100,000 at λt=6.
  - Peak efficiency ~45% at λt=6.
  - Operated at a constant rpm using a frequency converter.
  - Instrumentation: Torque sensor, rpm measurement using photo cell & slip rings.
  - Photo cell and constant rotational speed makes phase locked averaging possible.

Measurement technique (1/2)

- CTA hot wire anemometry
  - 2.5 μm wire -> capable of high frequency response

- Blind test 1
  - Used a single crosswire probe
    - Consists of two wires
    - Resolves two velocity components simultaneously
    - Neglects cooling velocities normal to the plane of interest
    - Can not resolve all shear stresses and third order moments

Measurement technique (2/2)

- Current experiment
  - Probe (hereafter called 2xw-probe) consisting of two cross wire probes measuring in orthogonal planes.
  - Resolves all three components of the velocity vector
  - Solved using an iterational procedure where binormal cooling is taken into account
  - Probe crossection ~ 2mm
  - Resolves all turbulent stresses
**Time averaged results (1/2)**

- Velocity defect
  - Quite good match
  - Deviation in the freestream of the order of 2-3%
  - Probe rotation has a minor effect

**Time averaged results (2/2)**

- Turbulent kinetic energy
  - Quite good match
  - Some deviation near the peak. Could be due to:
    - Difference in pitch angle
    - Difference in probe response to flowfield
    - Bump at z/R = -1.16. Why?
      - Phase-locked average of the data can give us the answer.

**Phase locked average (1/4)**

- Averaging with respect to rotor position
  - Position is determined using the rotational speed and the photo cell
- PLA of turbulent kinetic energy
  - Reveals position of tip vortices.
  - Shows that the tip vortex of one blade is located at a different radial coordinate.
  - May explain the bump in Figure 8.

**Phase locked average (2/4)**

- Can investigate how the presence of the vortices affects the mean velocity field

**Phase locked average (3/4)**

- The turbulence level in the tip vortex region is dominating in the wake (as shown in figure 9)
- PLA can also be used to reveal more of the internal structure of the wake.
  - By plotting the axial normal stress on a logarithmic scale the turbulence produced by the boundary layer on the blade can also be visualized.
  - Can also see a peak in the centre with increased turbulence intensity.

**Phase locked average (4/4)**

- A close up of the radial velocity reveals a 3p variation in the centre region
  - Could also be seen in Figure 9
Other possibilities

- The dissipation rate $\varepsilon$ can be estimated, e.g. from the dissipation spectrum.
  - Relevant information for numerical modelers.
- Investigation of isotropy
- Triple correlations can yield information which can be useful for estimating terms in the transport equations for turbulent kinetic energy.

Conclusions

- The new results match quite well with the old blind test results.
- Phase locked average can reveal a lot of information about the structure of the wake, which it is not possible to find from time averaged measurements.
- There are many possibilities for further analysis on the dataset.
Near and far wake validation study for two turbines in line

Marwan Khalil / Lene Sælen
GexCon AS

Trondheim, 25th of Jan. 2013

CMR-Wind
• FLACS
  – FLACS is a commercial CFD software used for explosion safety and mitigation studies
• CMR-Wind
  – Research version of FLACS developed within NORCOWE for the simulation of wind farms
• Solver
  – Reynolds-Averaged Navier-Stokes equations (RANS), transient and in 3D.
  – Incompressible, turbulence models, terrain, turbines
• Preprocessors
  – Scenario menu, terrain reader, visualization of turbines

Experimental setup

The CMR-Wind engine
• Staggered grid
• Cartesian grid
• Incompressible
• 2nd order accurate
• k-ε turbulence model with wall functions
• Terrain and sea roughness.
• Atmospheric stability.

Energy capture
• Wind turbines are modelled by source terms in the momentum and turbulence equations in cells within the rotor area

Wind turbine models
• Actuator Disc model
  – Model rotor area by a porous disk
  – Momentum sink uniformly distributed
  – Requires power and thrust curve as input
• Actuator disk + BEM
  – Model rotor area by a porous disk
  – Use BEM to calculate radial distribution of forces
  – Requires blade geometry (airfoil shape, cord length, twist angle) and drag and lift coefficients for the airfoil as inputs.
Simulation setup

- Tunnel walls included, constant cross section area
- Uniform inlet velocity: 10 m/s
- Turbulence intensity at inlet: 0.3%

<table>
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<th>Grid resolution</th>
<th>Δx</th>
<th>Δy</th>
<th>Δz</th>
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<td>0.1 a</td>
</tr>
<tr>
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**Summary**

- Modeling of the wind tunnel wall is important.
- The model performs reasonably well but underestimates the wake effect.
- Measurements of the drag and lift coefficients of NREL S826 airfoil is needed.

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**Acknowledgements**

- NORCOWE and NOWITECH funding.
- Krogstad PA, Strøen L, Pierrilla F, and Eriksen PE from NTNU for providing the experimental data and for fruitful discussions about the measurements.
- Lund JA from Meventus for providing the modeled drag and lift coefficients of NREL S826 airfoil.

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**Questions**
Closing session

Deep offshore and new foundation concepts, Arapogianni Athanasia, European Wind Energy Association

Optimal offshore grid development in the North Sea towards 2030, Daniel Huertas Hernando, SINTEF Energi AS

New turbine technology, Svein Kjetil Haugset, Blaaster (no presentation available)
Outline

1. Offshore wind industry – End of 2012
2. Market outlook – future trends
3. Deep offshore concepts
   a) State of the art
   b) Challenges
   c) Recommendations
4. Conclusions

Offshore wind power

2012: Expected annual installations

ABOVE 1 GW

Total installed capacity close to 5GW in Europe

Share of installed capacity in Europe in 2012

Sea Basins’ share of cumulative installed capacity
Deep offshore concepts – OWIG Task Force

The Task Force ‘Deep Offshore & new foundation concepts’ included representatives from:

- Acciona,
- Alstom,
- Blue H,
- Catalonian Institute for Energy Research,
- CENER,
- DNV,
- EDF,
- EDP,
- HEXICON,
- IEC,.
- NASS & Wind,
- National Technical University of Athens,
- Principle Power,
- Risø DTU,
- Statkraft,
- The Glosten Associates

Deep offshore task force

1. Definitions
2. State of the art
3. Identifying Challenges
4. Recommendations

Deep offshore - definitions

Deep offshore environment starts at water depths greater than 50 m.

Concept maturity:
- R&D stage: research and development on various designs using modelling tools.
- Demonstration stage: numerical demonstration of concept feasibility including dedicated experiments of the concept.
- Pilot stage: testing a down-scaled model in a controlled environment to provide realistic indicators for feasibility and cost-effectiveness.
- Prototype stage: testing a full scale model to assess its concept maturity before commercialisation.
- Pre-production: deploying a limited number of full scale devices in one location to validate overall system principles, fabrication and installation methodologies.
- Serial (commercial) production stage: commercial deployment following pre-commercial deployment, within a wind farm layout.

Substructure types

- Monopile 74%
- Gravity Based Foundation 16%
- Jacket 5%
- tripod 2%
- Floating 3%

Market outlook

There are 4 foundations:
- Poseidon 33kW
- Sway 150kW
- Hywind 2.3 MW
- Windfloat 2MW

Site characteristics

- Online
- Under construction
- Consented

Deep offshore concepts – OWIG Task Force

1. Definitions
2. State of the art
3. Identifying Challenges
4. Recommendations

Deep offshore task force

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2. State of the art
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### Deep offshore wind concepts

<table>
<thead>
<tr>
<th>Nr</th>
<th>Project name</th>
<th>Company</th>
<th>Type of floater</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Advanced Floating Turbine</td>
<td>MHI Marine Power</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>2</td>
<td>Concept 1 TLP</td>
<td>Tnet Marine</td>
<td>Semi-submersible</td>
</tr>
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<td>3</td>
<td>Spar buoy</td>
<td>Statoil</td>
<td>Semi-submersible</td>
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<td>4</td>
<td>WindFloat</td>
<td>Principle Power</td>
<td>Semi-submersible</td>
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<tr>
<td>5</td>
<td>Spar buoy</td>
<td>Nautica Windpower</td>
<td>Buoyant tower and downwind turbine</td>
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<tr>
<td>6</td>
<td>Aero-generator</td>
<td>X Wind Power Ltd</td>
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<td>7</td>
<td>Transom Buoy</td>
<td>Gamesa</td>
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</tr>
<tr>
<td>8</td>
<td>Blue H</td>
<td>Blue H</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>9</td>
<td>DeepCWind</td>
<td>Consortium: University of Maine, AEWC, Seawall, Maine Maritime Academy, Technip, NREL, MARIN, etc.</td>
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<td>11</td>
<td>Vertiwind</td>
<td>IDEOL</td>
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<tr>
<td>12</td>
<td>Hexicon platform</td>
<td>Hexicon</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>13</td>
<td>HiPRwind</td>
<td>EU project</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>14</td>
<td>Karmoy Sway</td>
<td>Gusto</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>15</td>
<td>Ocean Breeze</td>
<td>Xanthus Energy</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>16</td>
<td>Pelastar</td>
<td>Glosten Associates</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>17</td>
<td>Poseidon Floating Power</td>
<td>Floating Power</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>18</td>
<td>Sea Turf</td>
<td>Sea Turf</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>19</td>
<td>Sea Twirl</td>
<td>Sea Twirl</td>
<td>Semi-submersible</td>
</tr>
<tr>
<td>20</td>
<td>Trifloater Semisub</td>
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<td>Semi-submersible</td>
</tr>
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<td>21</td>
<td>Vertiwind</td>
<td>Technip/Nenuphar</td>
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<td>22</td>
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<td>24</td>
<td>Pelagic Power</td>
<td>Pelagic Power</td>
<td>Semi-submersible</td>
</tr>
</tbody>
</table>

### Key challenges and recommendations

#### Technical
- Modelling and numerical tools
- Optimised wind turbines
- Control of the whole system
- Connection to the grid – cabling
- Installation
- Economics

#### Non-technical
- Stable and clear legislative framework
- Spatial planning
- Risk perception
- Standardisation - cooperation

### Conclusion
- Vast potential still to be tapped
- The deep offshore concepts provide a solution
- The deployment has already started
- The industry is getting ready to develop numerous concepts
- Attention to be paid on the challenges and their assessment for a successful deployment

### Thank you
Optimal offshore grid developments in the North Sea towards 2030

Daniel Huertas Hernando

Deep Wind 2013 – Strategic Outlook Session
25th January 2013

Motivation: Strategic Outlook – 2030

Hydro power
(Flexibility, Storage, Balancing)

Grid

Offshore wind
(Penetration, Variability)

What is the Strategy to reach this Vision?

How to define a robust development path to deploy our Strategy?

Strategy:
- Can be highly beneficial from an economic perspective
- Contributes to reaching the European 20-20-20 targets and beyond
- Will increase the security of supply
- Is a step towards an integrated electricity market
- Helps to smooth fluctuations and integrate RES
- Connects northern storage capacities to the power system

(Conclusions of IEE-EU project OffshoreGrid)

IEE OffshoreGrid

- Techno-economic study
- Cost-benefit analysis of different design options
- First in-depth analysis of how to build a cost-efficient grid in the North and Baltic Seas
- Coordinator: 3E, 8 partners, consultancy & applied research
- SINTEF: Harald Svendsen, Leif Warland, Magnus Korpås, DHH

www.OffshoreGrid.eu
Sensitivity Analysis & Robustness

Main Aspects considered

- Potential for large scale offshore wind deployment.
- Potential for flexible generation – increased hydro power potential in Norway.
- Analysis of onshore grid reinforcement strategies for offshore grid topologies.
- SINTEF: Hossein Farahmand, Stefan Jaehnert, DHH

European Interconnected Network (2030)

Tool: Power System Simulation Tool (PSST) - DC Power Flow

- Detail model of Norway
- Offshore Grid
- Detail model of the UK
- Detail model of ENTSO-E

Wind Power Scenarios in Northern EU

- Detail model of ENTSO-E

<table>
<thead>
<tr>
<th>Country</th>
<th>2020 Total installed Capacity (GW)</th>
<th>2030 Total installed Capacity (GW)</th>
<th>Offshore Wind Power (GW)</th>
<th>Offshore Wind Power (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>4.26</td>
<td>4.66</td>
<td>2.16</td>
<td>2.16</td>
</tr>
<tr>
<td>Germany</td>
<td>49.8</td>
<td>55</td>
<td>8.81</td>
<td>13</td>
</tr>
<tr>
<td>Denmark</td>
<td>6.51</td>
<td>7.21</td>
<td>2.81</td>
<td>3.21</td>
</tr>
<tr>
<td>Estonia</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Finland</td>
<td>2.35</td>
<td>2.95</td>
<td>0.85</td>
<td>1.45</td>
</tr>
<tr>
<td>France</td>
<td>22.93</td>
<td>23.94</td>
<td>3.94</td>
<td>3.94</td>
</tr>
<tr>
<td>UK</td>
<td>30.06</td>
<td>37.68</td>
<td>16.3</td>
<td>22.7</td>
</tr>
<tr>
<td>Ireland</td>
<td>6.37</td>
<td>7.48</td>
<td>2.12</td>
<td>2.38</td>
</tr>
<tr>
<td>Lithuania</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Latvia</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>Netherlands</td>
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<td>Sweden</td>
<td>9.08</td>
<td>11.13</td>
<td>3.08</td>
<td>3.13</td>
</tr>
</tbody>
</table>

Wind Power Scenarios in Northern EU

- Offshore wind farms in 2020 (red) and 2030 (red-black)

Scenario Analysis of Hydro Power Potential

(D16.2 & CEDREN SINTEF Report http://www.cedren.no)

<table>
<thead>
<tr>
<th>Plant</th>
<th>2020 MW</th>
<th>2030 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Storage Plant Tonstad</td>
<td>1420</td>
<td>1420</td>
</tr>
<tr>
<td>Pump Storage Plant Holen</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Pump Storage Plant Auliard</td>
<td>1430</td>
<td>2420</td>
</tr>
<tr>
<td>Pump Storage Plant Tysso</td>
<td>1300</td>
<td>2300</td>
</tr>
<tr>
<td>Power Plant Auliard</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Power Plant Sveinsaker</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Power Plant Aulkka</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Power Plant Sveinsaker</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Power Plant Auliard</td>
<td>700</td>
<td>1300</td>
</tr>
<tr>
<td>Power Plant Tysso</td>
<td>700</td>
<td>1300</td>
</tr>
</tbody>
</table>

Amount of new power capacity: 11200 18200


Grid Implications of Hydro Power Flexibility in Norway

- Grid reinforcement in Norway according to Statnett grid development plans
- Special attention is paid to the corridor where the hydro production capacity expansion is proposed (highlighted in yellow)

Offshore Grid Alternatives

- Case A
- Case B
- Case C
Internal Constraints

Detail model of UCTE: Present level of internal Constrains in DE and NL

Detail model of the UK

Reinforced Grid in Norway – allows use of Hydro flexibility potential

www.twenties-project.eu

Internal Constraints + Expansion

Detail model of the UK+ TYNDP 2012

Reinforced Grid in Norway – allows use of Hydro flexibility potential

www.twenties-project.eu

No-Internal Constraints

www.twenties-project.eu

Detail model of UCTE: No significant internal constrains. NTC between market areas + DC power flows & Loop-Flows

Reinforced Grid in Norway – allows use of Hydro flexibility potential

www.twenties-project.eu

Operating costs

<table>
<thead>
<tr>
<th>Case</th>
<th>Onshore Grid Constraints in the ENTSO-E and the UK</th>
<th>Offshore grid Constraints</th>
<th>Cost (Milliard EUR/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>No constraint</td>
<td></td>
<td>92.7498</td>
</tr>
<tr>
<td>Case B</td>
<td>Internal Constraint</td>
<td></td>
<td>92.7665</td>
</tr>
<tr>
<td>Case C</td>
<td>Internal Constraint with Expansion</td>
<td></td>
<td>92.8462</td>
</tr>
</tbody>
</table>

The Impact of Internal Onshore Constraint

Onshore grid constraints inland strongly influence the optimal use of wind and hydro resources. Limitations to transfer the power inland hence increase the operating cost significantly.

This work has performed a detailed techno-economic study to quantify this effect.
Pumping Strategies
Specific Case (Tonstad & NorGer HVDC cable)

Tonstad Reservoir in Norway

- The reservoir is drained very fast during winter time until hour 3000
- From hour 3000 to 6000 there is a filling season with high natural inflow to reservoir
- During the above period, small fluctuations have been observed
- The small fluctuations are assumed to be the effect of wind production variability

Tonstad pumping pattern

www.twenties-project.eu

Main conclusions

- Onshore grid constraints strongly influence the lines across a meshed offshore grid, therefore affecting the optimal use of wind and hydro
- Long term strategies for the development of offshore grids and onshore grid expansion must be done in a coordinated way to ensure optimal developments
- The analysis demonstrates the correlation between the pumping strategies in the Norwegian system and the onshore and offshore wind variations around the North Sea

Summary

- Work done in IEE-JU OffshoreGrid, FP7- TWENTIES, FME NOWITECH have performed detailed techno-economic studies of:
  - In-depth analysis of how to build a cost-efficient grid in the North and Baltic Seas
  - Identification of required transmission capacity between the Nordic region and Northern Continental Europe for optimal use of hydro power and wind power generation
  - Sensitivity analysis on effect of onshore grid constraints

Thank You !!
Motivation: Strategic Outlook – 2030

How to define a robust development path to reach this Vision?

Research can contribute to this task by:

- Considering different Scenarios including different configurations of offshore grids in the North Sea.
- Performing sensitivity analysis of the considered configuration(s) on different important key parameter & assumptions

The main focus of such analysis is to gain knowledge about the key relationships and driving forces so better decisions can be made (today) about the best strategy to reach our Vision.

Grid Implication Studies: Northern Europe

Tool
Power System Simulation Tool (PSST) – DC Power Flow

Generation portfolio and demand:
The scenarios and data are consistent with Market Model

Grid Model
- ENTSO-E UCTE Study Model (winter 2008)
- British (National Grid-Seven Year Statement)
- Nordic and Eastern Europe data (SINTEF-NVE & TradeWind)

Modelling Development
- 5651 buses, 2410 generators, 9611 branches
- 2020, 2030 Scenarios

Hydro modelling

Since there is a limited amount of water storage in hydro reservoirs, its long-term utilisation is essential to be optimised

The water values reflect the expected future value of the other types of production that the hydro generators substitute

The water values are imported from the market model (EMPS) and used as exogenous input to the next model (PSST)

Inflow Scenarios in the Norwegian Power System

European Interconnected Network (2030)

PSST + Offshore Meshed Grid (IEE-EU OffshoreGrid Project)

Main Results in a Nutshell – Total costs

- Hub connection saves €14 bn.
- Additional interconnections costs €5-8bn and bring benefits €16-21
- The financial numbers speak clearly for an offshore grid.
The simulated reservoir (black curve) follows the seasonal variation.

Comparing Tønsstad Simulated Reservoir Trajectory

- IC: Present Internal constraint
- ICE: Expanded transmission according to TYNDP2012+ German Grid Plan
- NC: No internal constraints – NTC limited

增加的WPP至63 GW

Wind energy is stored in the Norwegian reservoir helping the Norwegian power system to cover the load in depletion season and fill up the reservoir in the filling season.

Exchange Variation (high and baseline wind-dry year)
Material shown IEE-EU OffshoreGrid project (Leif and Harald)
TWENTIES (Hossein Farahmand, Stefan Jaehnert)

**Cross-border capacities**

- Significant expansion of cross-border transmission capacities

<table>
<thead>
<tr>
<th>Year</th>
<th>Nordic</th>
<th>NorBalt</th>
<th>Cobra</th>
<th>Britned</th>
<th>Skagerrak</th>
<th>Storbelt</th>
<th>Kusten-Skan</th>
<th>Kusten</th>
<th>Baltic</th>
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<tbody>
<tr>
<td>2010</td>
<td>700</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>900</td>
<td>500</td>
<td>720</td>
<td>550</td>
<td>525</td>
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<tr>
<td>2030</td>
<td>1400</td>
<td>700</td>
<td>700</td>
<td>1000</td>
<td>1600</td>
<td>500</td>
<td>720</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

**High marginal transmission profit on corridors crossing the North and Baltic Sea in 2030 (due to price differences) => arbitrage / investment potential**

- 2010: 2030:
  - Marginal profit
    - 80 EUR/kW
    - 40 EUR/kW
    - 0 EUR/kW
    - 200 EUR/kW
    - 100 EUR/kW
    - 0 EUR/kW

**Transmission expansion**

- Although marginal profits Main expansion only occurs around the North Sea
- Increasing the capability of transmitting energy from renewable energy sources (Sweden, Scotland) to load centres (Southern Germany, Southern UK)
- No expansion within the North Sea due to high investment

**Electrical prices – before and after transmission expansion**

<table>
<thead>
<tr>
<th>Year</th>
<th>Nordic</th>
<th>DK-DE</th>
<th>DE-BE</th>
<th>NL-BE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>450</td>
<td>-</td>
<td>-</td>
<td>1400</td>
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<tr>
<td>2030</td>
<td>1100</td>
<td>1400</td>
<td>2400</td>
<td>2400</td>
</tr>
</tbody>
</table>

**Marginal profit**

High marginal transmission profit on corridors crossing the North and Baltic Sea in 2030 (due to price differences) => arbitrage / investment potential
ENTSO-e (2010) scenario calibrated to generation mix reported by ENTSO-e

- Significant shift of generation sources up to 2030
- Increase of WPP up to 191 GW
- Decommissioning of nuclear / lignite power plants

Generation portfolio / Mix

2010 scenario calibrated to generation mix reported by ENTSO-e

Increased production variability due to balancing of WPP

Increased production variability due to balancing of WPP

The Grid Expansion in the German Power System

DE and NL + TYNDP 2012 + German Grid Plan

www.twenties-project.eu

The Grid Expansion in the British Power System

The UK+ TYNDD 2012

www.twenties-project.eu

Some “hints” of the North Sea Power Wheel

Without Expansion

With Expansion