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1st DeepWind 5 MW baseline design

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Abstract

The first 5MW baseline design of the DeepWind concept is presented for a Darrieus type floating wind turbine system for water depths of more than 150 m. This design will be used as design reference to test the next technological improvements of sub-component level, being based as much as possible on existing technology.
The iterative design process involves all sub-components and the potential constraints, and the most important dependencies are highlighted and the selected design presented. The blades are designed with constraints to minimize the gravitational loads and to be produced in a controlled pultrusion process. The floating platform is a slender cylindrical structure (i.e. spar buoy) rotating along with the rotor. The stability of the platform is achieved by adding counter weight at the bottom of the structure. During operations, the rotor is tilted and acts as a gyro, describing an elliptical trajectory on the water plane. The generator is placed at the bottom of the platform and uses 5MW direct drive technology.

The conceptual design is evaluated with numerical simulations in the time domain using the aero-elastic code HAWC2. In order to investigate the concept, a double-disc blade element momentum (BEM) code for VAWTs has been included in the numerical solver through a dll.

The analysis of the design is carried out in two different steps:[1)] to estimate natural frequencies of the platform in order to avoid major resonance problems, [2)]to evaluate the baseline concept for certain load cases. A site has been chosen for the floating turbine off Norway as representative for external conditions. The structure is verified according to an ultimate strength analysis, including loads from wind, waves and currents. The stability of the platform is investigated, considering the displacements of the spar buoy and the maximum inclination angle, which is kept lower than 15 degrees.

Keywords: vertical axis; structural design; pultrusion; floating offshore wind turbine;submerged generator;direct drive wind generator

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1. Introduction

The DeepWind project aims to investigate a new offshore floating vertical axis wind turbine (VAWT) concept, able to exploit wind resources at deep offshore sites. DeepWind was started in the autumn of 2010 under the European FP7 programme area Energy2010, Future Emerging Technologies, with a co-operation between universities, research institutions and industry. Risø DTU co-ordinates the DeepWind project with participation from 12 international partners.

The DeepWind concept is an innovative floating offshore concept, based on a Darrieus type of rotor. The present design is with 2 blades, pultruded from NACA0018 airfoil profiles into a troposkein like shape. The concept features a long rotating spar buoy as support structure, direct drive subsea generator, torque absorption and mooring cables which are anchored into the sea bed. The loads on the submerged long rotating tube, the blade pultrusion- and the subsea generator technology impose technical challenges to the concept [1, 2] and require in the project R&D efforts in (i) model testing of transverse forces on the floating spar rotating in combined waves and currents [3], in (ii) exploration on the pultrusion process of manufacturing blades, and in (iii) exploring direct transmission drives of high torque converting into electrical energy.

This paper describes the result of the first 5 MW baseline design iteration process and the scientific progress achieved in deriving such a reference for the rotor and blades, the floating platform and the generator. The baseline design is intended to be used in the project on a comparative basis for optimization of sub-components and finally to be compared with a 5 MW reference offshore horizontal-axis wind turbine [4].

1.1. Design constraints

The HAWC2 simulation code describes the physics of aero-elasticity of VAWTs, and hydrodynamic forces [1, 2]. Using the engineering code in a design process towards a cost effective optimization, the following constraints as shown in Figure 1 have been identified within this iterative process [3]. The constraints are divided into 3 groups: [1)]structural constraints limiting the loads on the structure [2)]stability constraints and [3)]cost constraints. From the figure it is evident that a change of a variable can result into a benefit by reduction or increase of the design variable.

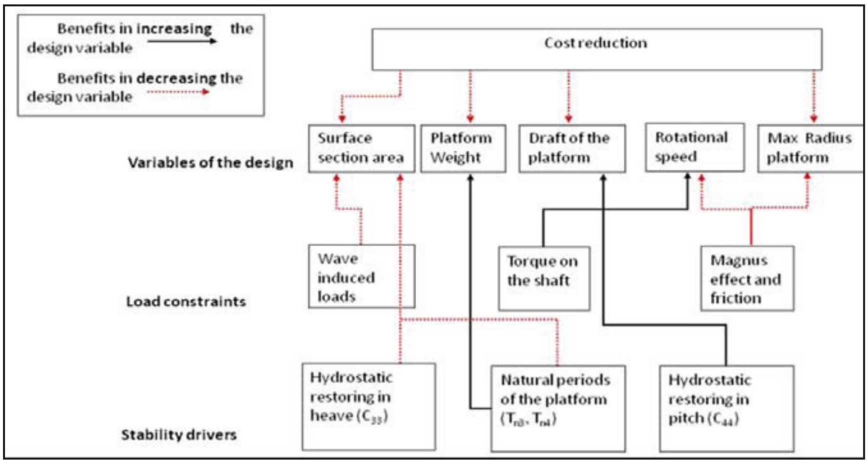


Figure 1: Constraints in developing baseline design [3]

1.2. Environmental loads

The HAWC2 simulations take into account the important aero-elastic loads on the wind turbine and the hydrodynamic loads due to the rotation of the platform in the water, i.e. Magnus effect, in-line forces and friction torque. The estimation of these loads is based on results from literature [2, 5, 6, 7]. CFD calculations and physical model test with a rotating cylinder in combined waves and current are on-going at DHI to verify the hydrodynamic loads and support their implementation in the HAWC2 model. Both the numerical simulations and laboratory tests forecast a low friction loss, and a major Magnus force in combined waves and currents associated with the rotation.

1.3. 1st Design assumptions

The post-stall as well as the effects by the wind turbulence are known to increase rotor loads in the dynamic stall region. The concept is described in 6-DOF: {(Pitch, Roll, Yaw), (Surge, Sway, Heave)}[1, 2]. The following assumptions are made in the first iteration design:

- Atmospheric turbulence effects are not considered
- Dynamic stall is not included
- Evaluation of loads are conducted on a configuration with a limited DOF, i.e. Pitch, Roll, Yaw

2. Rotor and blades design

2.1. Site conditions

The DeepWind design is site dependent [2, 3]. The HyWind test site has been selected as the representative site for the evaluation of DeepWind. The position is shown in Figure 2. For this site the environmental conditions are described by the NORSOK standard [8] as: Maximum 100 year tidal surface current in the order of 0.2 m/s; wind induced (surface) current velocity of up to 0.5 m/s; signify-

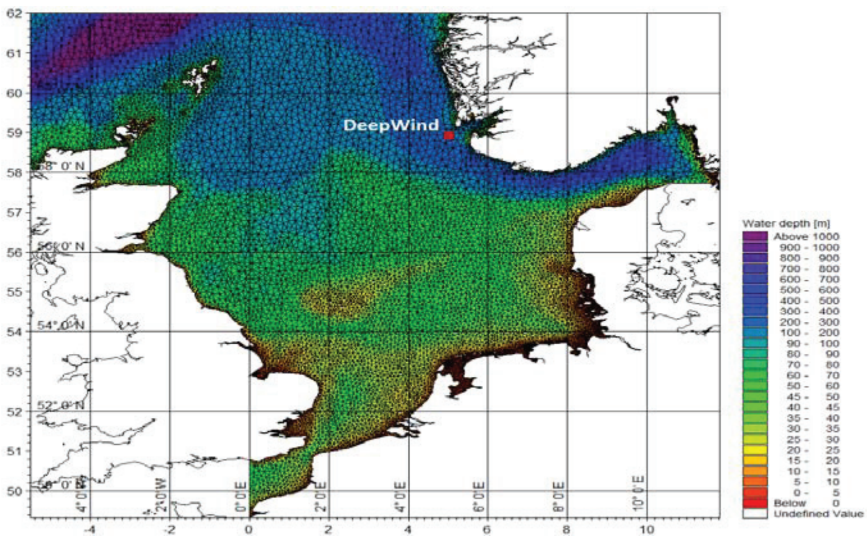


Figure 2 Approximate position of the DeepWind turbine evaluation site -here indicated with a red mark, from a map of the domain for DHI's North Sea wave hindcast model.

cant wave height H_s = 14m and related maximum peak period T_P = 16 s with annual probability of exceedance of 10^{-2} for sea-states of 3 hours duration. The extreme conditions selected and used in the evaluation of the DeepWind concept are summarized in Table 1.

Table 1: Extreme environmental conditions at the site with annual probability of exceedance of 10^{-2} for a sea-state of 3 h duration.

Velocity of the water currents at the surface	[m/s]	0.7
Maximum significant wave height H_s	[m]	14
Maximum peak wave period T_P	[s]	16
Wind speed (limit wind speed of the design)	[m/s]	<25

2.1. Rotor design

The rotor design in this first design iteration was matched to the rated power of the 5 MW NREL HAWT. Values for solidity and aspect ratio H/2R have been selected as a compromise of maximum rotor efficiency, cost reduction and considerations on the design of the floater platform. The selected values are: σ=0.23 and H/2R=1.02. Table 2 provides an overview of the rotor characteristics in terms of geometry and performance, and Figure 3 shows the power curve and the rotor efficiency. The stall regulated rotor is designed for rated power rather than to define the conditions by maximum rotor efficiency C_P. Because the efficiency decreases towards higher wind speed, as shown in Figure 3, overproduction by lower C_P is avoided.

Table 2: 5 MW rotor design

Geometry			Performance		
Rotor radius (R)	[m]	63.74	Rated power	[kW]	$5\ 10^3$
Rotor height (H)	[m]	129.56	Rated rotational speed	[rpm]	5.26
Chord (c)	[m]	7.45	Rated wind speed	[m/s]	14
Solidity (σ =Nc/R)	[-]	0.23	Cut in wind speed	[m/s]	5
Swept Area	[m^2]	10743	Cut out wind speed	[m/s]	25

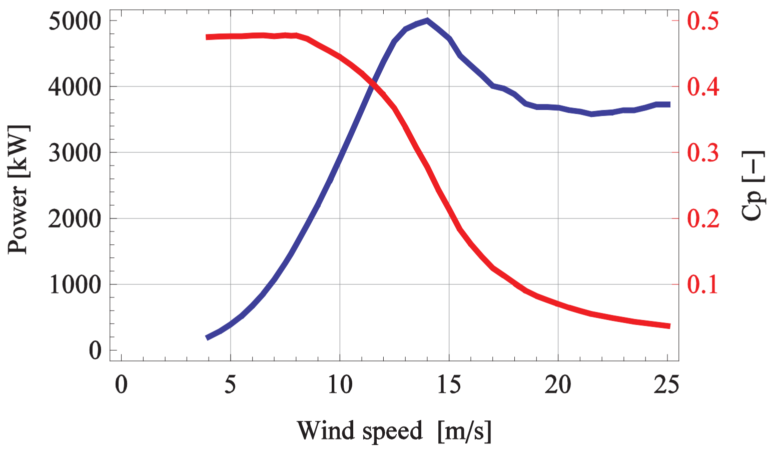


Figure 3: 5 MW DeepWind baseline design power curve(blue) and C_P (red)

The thrust increases monotonically with wind speed and has a local maximum as Figure 3 indicates.

A number of changes are planned for the next iteration loop: a) a lower value of σ improves the rotor stall characteristic and moves the rated conditions towards higher values of rotational speed and lower wind speed which results in a less costly generator, b)a thinner airfoil could improve the rotor stall characteristic. A VAWT reaches the power peak at a higher wind speed as compared to a HAWT and in order to provide a more reasonable comparison of the wind turbine concepts it is decided with DeepWind to obtain the same AEP of the 5 MW reference HAWT wind turbine, i.e. c)a rotor design with higher rated power is necessary. As in Figure 1 these changes affect the subcomponent level as well.

2.2. Blade design

The use of pultrusion technology for VAWT blade manufacture is limited to constant chord over length; it provides a surplus in terms of low manufacturing cost but at the expense of increased material consumption to compensate for structural strength of relatively thin profiles. This has shown the necessity to design blades with structured ‘stiffeners’ which can avoid heavy blade design. The present blade design is not shape optimized to account for best rigidity at lowest blade weight in the first iteration of the process. Gravity and centrifugal load combinations are limiting design parameters and have impacts on the rotor shape. A suitable alternative is to change the operating condition by changing the tip speed or rpm slightly-which changes the shape of the blade, and the loads as shown in Figure 4. The suggested design changes of the overall rotor will result in a lighter blade design. In particular it is structurally convenient to use thicker airfoils at positions which are nearer to the tower.

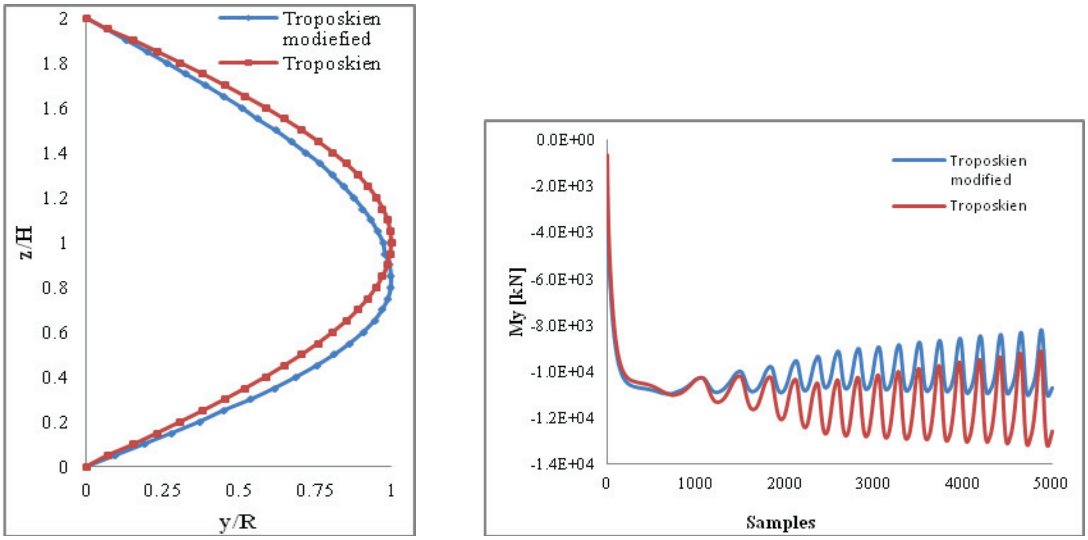


Figure 4: Left: Two different blade shapes according to two different operational conditions. Right: Loads corresponding to the two different rotor shapes [3].

The current blade span measures 189 m and weighs 154 metric tons, which at this stage is too heavy with negative impacts on the systems design. Alternative blade designs such as using piecewise constant profiles, and thick profiles are explored at the moment. A compromise in the design includes a possible increase in the rated rotational speed, or a variation of the blade properties along the blade with lighter blade material density.

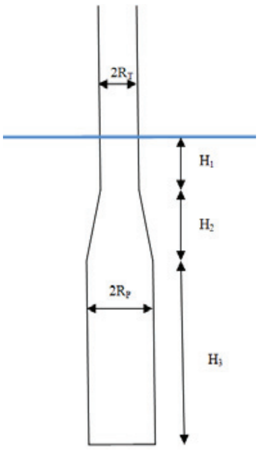
3. Floating platform

The floating platform for the DeepWind concept is based on the spar technology. The spar concept has shown to be a promising solution for floating offshore wind turbines due to its favorable motion [9]. The spar is a deep draught vertical cylinder with buoyancy chambers at the upper part and a heavier section at the lower end for stabilization. The upper part of the spar buoy is narrowed with a tapered section such that a small diameter is obtained in the wave zone, in order to limit wave loads and to connect the platform to the rotor tower. Vertical wave forces are minimized due to the deep draught of the spar buoy such that vertical motions are rather small. The low center of gravity provides large righting moment ensuring that the floater stays upright with low roll and pitch motion. The selection of the spar hull shape and size depends on functional requirements, and the following basic design requirements are considered:

- Natural periods in heave and pitch/roll should be larger than the dominating wave periods (i.e. 5s-25 s) to avoid resonant motion response
- Sufficient buoyancy to carry specified payload and weight of the mooring system
- Sufficient vertical stiffness for variable vertical load
- Sufficient stiffness in roll and pitch to avoid excessive heeling of the platform due to environmental loads
- Acceleration should be limited to avoid damage to machinery components

The baseline design is summarized in Table 3.

Table 3: Platform dimensions



Geometry of the platform

Total length (H_P=H_1+H_2+H_3)	[m]	108
Depth of the slender part (H_1)	[m]	5
Radius of the slender part (R_T)	[m]	3.15
Thickness of the slender part	[m]	0.02
Length of the tapered part (H_2)	[m]	10
Length of the bottom part (H_3)	[m]	93
Maximum radius of the platform (R_P)	[m]	4.15
Thickness of the bottom part	[m]	0.05

The most relevant stiffness parameters of the platform were calculated in [3] to verify the design for fulfillment of the design requirements. Reduction of the top weight due to a re-design of the blades will alter the shape and size of the spar hull. A preliminary study indicates that reducing the blade mass and lowering the blades' mass centre allows for reducing the diameter and draught of the spar buoy. Further optimization of the spar design is therefore considered. In this context, optimization is the same as minimizing the material cost while satisfying the design requirements. The design iterations will also include finding a feasible mooring system that can withstand the large torque from the rotating wind turbine.

4. Subsea generator technology

4.1. Generator State of the Art and Design Issues

A state of the art investigation was conducted to determine possible solutions for the generator. Types of direct drive generators on the market were found and a comparison was made between the types of generator used in and proposed for wind power applications. Types of direct drive generators on the market are presented in Table 4:

Table 4: Large Direct Drive Wind Turbines [10, 11]

Generator Type	Power/Speed	Manufacturer
EESG	4.5 MW/ 13 rpm	Enercon
PMSG	3.5 MW/ 19 rpm	Scanwind
PMSG	2.5 MW/ 14.5(16) rpm	Vensys
PMSG	2 MW/ 24 rpm	Mitsubishi
PMSG	2 MW/ 18.5 rpm	STX Windpower
PMSG	2 MW/ 15.8 rpm	EWT (Energya Wind Technologies)
PMSG	2 MW/ 19 rpm	JSW (Japan Steel Works)
EESG	1.65 MW/ 20 rpm	MT Torres
PMSG	1.5 MW/ 23 rpm	Leitwind
PMSG	1.5MW/ 19 rpm	Goldwind
PMSG	1.5(2) MW/ 18(23) rpm	Zephyros
PMSG	0.75 MW/ 25 rpm	Jeumont(not available)

Siemens Wind Energy launched a 6MW direct drive SWT-6.0 prototype in November 2010. The turbine is designed for the harsh offshore conditions. The first prototype was installed in May 2011 in Denmark. Offshore sites targeted for 2012-2013 include Denmark, UK, the Netherlands and Germany. Tests are still being carried out on the installed prototypes [12]. Because of the special sub-sea ambient conditions, it is important to identify the best candidates for the DeepWind direct drive generator. This requires an assessment of the suitable candidates for the proposed application. During the project the following generator types were considered:

1. SCIG - Squirrel Cage Induction Generator (Radial Flux RF)
2. DFIG – Doubly Fed Induction Generator(Radial Flux RF)
3. EESG - Electrically Excited Synchronous Generator (Radial Flux RF)
4. PMSG - PM Synchronous Generator(Radial Flux RF)
5. TFPM - Transverse Flux PM Generator
6. AFPM – Axial Flux PM Generator

A SWOT analysis was performed to narrow down the list of candidates. The main selection criteria were related to the efficiency, torque/weight ratio, mass of active and inactive material, fault ride through capability, ease of manufacturing, existing turbines on the market. From this assessment and analysis it can be concluded, that the candidates worth considering for the DeepWind direct drive applications are:

- ❑ Synchronous PM (**PMSG**)
- ❑ Synchronous Electrically Excited (**EESG**)
- ❑ Transverse Flux PM (**TFPMG**)

A design tool for each machine type tailored to direct drive specifications will be used to determine the suitability of each generator type. The decision for proceeding with these machine types is related to the cost of permanent magnets and the particular optimization potential for each generator.

4.2. DeepWind Generator Design approach

The analytic design algorithm for the machines was implemented in code language. Usual design rules used for power station generators were applied. It is anticipated that these will be adjusted to suit the subsea ambient conditions. The output of the analytic design will include the geometrical dimensions of the machine, mass of active and inactive materials and evaluation of losses. The geometrical dimensions obtained will be used as input for a finite element model to analyze and optimize the magnetic field distribution in the machine. For a given output, the diameter of the generator may be expected to be inversely proportional to the speed. As the direct drive turbine implies an extremely slow speed (see Table 4), the number of poles of the generator will increase. This means not only that the diameter of the machine will increase, but that the leakage field will also increase. This is not desired as it will reduce the efficiency of the generator. By observing the magnetic field in a particular machine design, suitable optimization measures can be taken in order to maximize the useful magnetic field and minimize the unwanted field effects. A thermal model of each candidate generator type will be constructed replicating the subsea ambient conditions and enabling the establishment of corresponding new appropriate design rules. This is because of the relatively unknown cooling conditions for the generator caused by the sub-sea environment and affected by the constructional details and enclosure. An optimization tool will be designed to improve the performance of the generator. By careful selection of the active materials and varying the geometry of the proposed design a new optimized machine design will be obtained. The output of the generator will be fed to a power electronic converter for conversion to voltage levels suitable for transmission to the local electricity utility grid. This will be a multi kilovolt connection, so a three level converter is anticipated. Control of the power flow will be by control of the shaft speed of the DeepWind turbine.

4.3. First Iteration Dimensions of the 5 MW Direct Drive Generator

The first iteration of the 5 MW shaft input generator, based on the estimated rated speed of 5.26 rpm and the rated torque of 9.1 MNm was for a 400 pole 17.53 Hz design with a pole pitch of around 7.85cm. This corresponds to an air-gap diameter of around 10 m outer diameter of around 10.5 m, with a core length of around 1.4 m. This will give a total mass of Copper, Iron and permanent magnet materials of around 90 metric tons. The dimensions fit very well with the estimated outer diameter of the platform which is 8.3 m, see Table 3, and will enable a reasonable construction.

5. Design evaluation

The design was evaluated with the aero-elastic code HAWC2, in the configuration with 3 DOF for the platform under conditions of the sea states[3]. The direction of the waves and the currents, with respect to the wind, was changed in order to evaluate the different loads from different combinations of wind, wave and current direction. Regarding the platform stability, the large inertia of the rotor affects the pitch and roll mode towards a large natural period. The simulations show a rotor inclination at the tower bottom less than 12º when in combinations of wind and current relative to wind direction (waves -90° and current co-parallel with wind directions, waves co-parallel and current -45º relative to wind directions) and an inclination less than 6º in still water. The tower section at sea water level displaces for the most critical sea state with around 12 m along the wind direction and 12.5m to each side, compared to still water condition with 10.5m and 0.75m, respectively.

The maximum loads were recorded at the point on the tower at the water level, and they occur at the most critical sea states (larger values of the wave height), while the mean values are strongly dependent on the currents direction [3]. For the ultimate strength of the tower, a safety factor of 2 is used for maximum loads and 4 on mean loads.

6. Conclusions

A 1st iteration conceptual 5 MW DeepWind baseline design for a Darrieus type floating wind turbine system with direct drive generator technology, for water depths of more than 150 m was carried out with a design evaluation of the concept. This design will be used as design reference to test the next technological improvements of sub-component level, being based as much as possible on existing technology. The results from the evaluation have shown that different issues in the design space are still not optimal and have to be iterated accordingly.

Acknowledgements

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