

REVIEW OF DESIGN CONCEPTS, METHODS AND CONSIDERATIONS OF OFFSHORE WIND TURBINES

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Abstract:

The aim of this paper is to do a literature review of the design process of offshore wind turbines (OWTs). The paper uses an approach in which the design process of an OWT is divided into three steps. Firstly, different requirements which should be satisfied by an OWT are classified. Secondly, different design solutions are reviewed and some design choices such as number of blades and tip speed ratio is explained. Finally the analysis tools to evaluate the solutions are studied and the up-scaling rule which is a way to get some general insight in an OWT characteristic is explained.

Keywords: design requirements, design solutions, analysis tools.

1 Introduction

The condition in which an OWT works is challenging. It should be installed in water and has difficulties in accessibility, corrosion from salt water, additional loads from waves and in some cases floating ice. Considering these issues an OWT consists of several different parts that are designed to fulfill some requirements.

The objective of this paper is to do a literature review of the design process in which an OWT is developed. A systematic approach is used to do the literature study in which the design of an OWT is divided into several steps consisting of: defining the requirements, selecting ideas as solutions and using tools and technical knowledge to verify the solutions.

Therefore, at first a brief overview of the requirements that an OWT should fulfill will be presented. Then different solutions that are currently available to satisfy the needs will be reviewed. In this phase some design variants such as number of blades and tip speed ratio, will be discussed.

The next step is to review the tools that are used to verify the proposed solution. In this part a review of available design codes to fulfill this task will be given. Especially up-scaling rules, which are tools to redesign a verified product and use it in a different size as it was initially designed for will be discussed. The result of this work is to highlight the guidelines which were found in the literature for overall design of OWTs.

This is part of a PhD project which is running at Delft University of Technology and the final result should be the conceptual and preliminary design of a large scale OWT (up to 20 MW) in which the current status of OWTs should be investigated carefully. Based on this investigation the modifications to current concepts, knowledge and tools should be done to pave the road to achieving large scale OWTs.

2 Design Process of a product

A design process is a guide to help make choices when designing a product. Design as a process can take many forms depending on the object being designed and the individual or individuals participating. Therefore, there are countless philosophies for guiding the design process of a product.

A design process may include a series of steps followed by designers. Depending on the product or service some of these stages may be irrelevant or ignored in real-world situations in order to save time, reduce costs or because they may be redundant in the situation.

A simple guideline which is valid in many engineering design processes is an approach in which the design process is divided into three steps. In this iterative approach, the first step is to define different needs and requirements such as: ease of use, an acceptable life time and resistance against external conditions.

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The second step is to generate and develop solutions and concepts that can satisfy the requirements and needs. There are some tools and methods that can help to generate ideas such as: brainstorming, 6-3-5 method [1], TRIZ [2], and using patents. In this step, all design solutions have the same weight.

The third step is to evaluate design solutions. This is the most important phase in the design process, because the previous non weighted design solutions get a weight and finally one of them is selected as an optimum choice.

2 Defining the requirements for an OWT

The design of OWTs has many similarities to those of land based turbines, but there are a number of differences as well as additional considerations such as:

- An additional requirement in the design of OWTs is the combined effect of the wind and the waves on the load spectrum. It is likely to be the case that the high winds are accompanied by large waves, but not necessarily that extreme winds are accompanied by extreme waves at precisely the same time. These complex loadings have to be taken into account for designing an OWT especially from a structural point of view [3].
- Except some specific application of OWTs, almost all of them are operating as wind farms and are grid connected systems and will be part of a national and possibly international grid network. That is, the generated power should be fed smoothly into the grid so that the required power quality which contributes to grid stability can be achieved [4].
- For an offshore location, the poor access and extreme weather condition can postpone the maintenance. Therefore, there is a higher demand for Reliability, Availability, Maintainability and Serviceability (RAMS) in order to decrease the overall cost of generated electricity and make OWTs competitive [5].
- Because of a limited time for working offshore due to bad weather conditions and expensive and time consuming logistic and

installation activities, there is a higher demand for OWTs to be installed quickly.

- The environment in which an OWT works is corrosive. Both the salty water and the corrosive air can cause serious failures. The exterior corrosion protection of the various steel components features a paint system satisfying the standards required for offshore platforms. Interior corrosion protection requires improved painting systems and maintaining a dry environment inside the machine.
- To make OWT cost competitive, there is a tendency to harvest more power by manufacturing them larger. This issue presents additional design requirements as the size increases such as transportation and installation problems.

These issues present new challenges to an industry that has to date little direct experience of operating offshore and requires new solutions and concepts.

3 Design solutions for OWTs

An optimum OWT design solution is determined by many factors such as turbine size, soil conditions, water depth and distance from shore. This paper will not explain how to find an optimum design solution for an OWT, but it explains possible design solutions that exist. Particularly rotor, drive train, and support structure concepts will be explained in detail.

3.1 Rotor Concepts

There are two types of rotor concepts for horizontal axis wind turbines, upwind and downwind. A downwind configuration allows the rotor to have free yawing and it is simpler to implement than active yawing which requires a mechanism to orient the nacelle with the wind direction in an upwind configuration. Therefore, in an offshore environment where RAMS is a design requirement, a downwind configuration can be matched better with this requirement and gives a higher robustness [6].

Another advantage of the downwind configuration is the reduction of blade root flap bending moment. This can be achieved by pre-coning the blades in the downwind direction so centrifugal moments counteract the moments due to thrust forces [7].

The main disadvantage of the downwind configuration is the tower shadow that can

cause periodic loads. This periodic load may result in fatigue damage to the blades and may impose a ripple on the generated electrical power; however there is some smoothing effect in the power fluctuations if we consider OWTs as a wind farm [8, 9]. These effects can be decreased by a teetering hub and an individual pitching mechanism while on the contrary these increase the complexity and the associated maintenance.

Both upwind and downwind configuration can have one, two, three or even more blades and selection of the number of blades is a trade off among three different points of view that are discussed below:

- **Operation point of view**

Despite higher moment of inertia of three bladed rotors, the main advantage of them is that the polar moment of inertia with respect to yawing is constant while for a two bladed rotor it varies with azimuthal position with the highest amount when the blades are horizontal and the lowest when they are vertical [7].

This phenomenon contributes to a smooth yawing of three bladed rotors and an imbalance for two bladed rotors. To overcome this problem a teetering hub can be used for two bladed rotors that can lessen this effect when the nacelle yaws [10].

- **Performance point of view**

In general the optimum tip speed depends on the number of blades and profile type used [11].

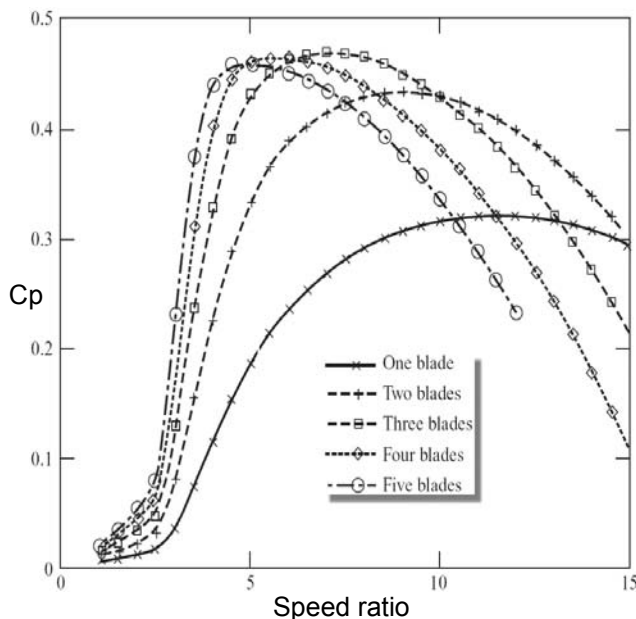


Figure 1: Effect of number of blades on power performance [7]

The fewer the number of blades, the faster the rotor needs to turn to extract maximum power from the wind. Three bladed rotors have a higher achievable performance coefficient which does not necessarily mean that they are optimum. Two bladed rotors might be a suitable alternative because although the maximum C_p is a little lower, the width of the peak is higher and that might result in a larger energy capture. To achieve this goal a variable speed rotor can be used [7].

- **Structural design point of view**

There is a coupling between tip speed ratio, number of blades and rotor solidity. To be optimum, a high speed ratio rotor should have less blade area than the rotor of a slower turbine. For a given number of blades the chord and thickness decreases as the tip speed ratio increases and this results in an increase in blade stresses [12].

There are some preferences for using a higher tip speed ratio and hence less number of blades in an OWT. Reducing the number of blades reduces the weight of the rotor and subsequently the weight of the support structure. In addition, it shortens the time required for transportation and installation which directly decreases the cost of energy.

Using a higher tip speed ratio also increases the rotational speed and thus reduces the torque on power train and this result in a lighter drive train while the penalty for a higher noise level emission of a high TSR rotor is negligible for an OWT. However a pitch mechanism could be used as an alternative solution or in combination with the variable speed rotor.

3.2 Control Strategies

One of the goals of a wind turbine control strategy is to optimize the power production. Below rated wind speed, the goal is to maximize energy production and above rated wind speed the goal is to limit the power production. This goal can be achieved by the combination of different methods such as variable/constant rotor speed and pitch/stall regulation.

Constant speed stall regulated turbines do not have an active option to control the input power. Therefore sometimes they are called passive stall. Constant speed pitch regulated turbines usually use the pitch mechanism to only limit the power production in the above rated regime. Variable speed pitch regulated turbines maximize the power production below rated

speed and limit the power production above rated speed [7].

However there are some other studies such as ICORASS which has a special design. The basic design philosophy for this project is a reduction of maintenance cost mainly by selecting a high robust reliable concept which has a lower failure rate [6].

To fulfill these requirements a variable speed stall regulated concept is used. With increasing wind speed above the rated the aerodynamic power coefficient decreases by decreasing the rotor speed so that the tip speed ratio is below its optimum and the aerodynamic efficiency is decreased.

3.3 Drive Train

The rotor hub transfers the momentum in the wind to the drive train as a load vector with six components. Only the torque component is needed in the generator to generate electricity.

The other loads are transferred by means of bearings to the tower. The torque component is transferred to the generator either by means of a geared drive train or a direct drive as discussed below:

- **Geared Drive Trains**

The geared drive train uses a gear box to step up the rotor speed to a level that is suitable for a generator. It consists of a low speed shaft that is connected to the rotor, a gearbox and a high speed shaft to transfer the torque to the generator for generating electricity.

It was shown that the gearbox is a troublesome component within geared drive train concepts. For a typical turbine, 20% of the downtime is due to gearbox failures, and an average gearbox failure takes about 256 h to repair [13].

However it is useful to note that blades have the highest failure rates in a wind turbine [14]. Due to the problems that can arise with a low RAMS in an OWT and the high rate of failures caused by gearboxes, investigations continue to generate new concepts and use the alternative concept which is the direct drive.

- **Direct Drive**

In a direct drive concept, the gearbox is eliminated and the generator is directly driven by the rotor hub. The two types of direct-drive generators are the wound rotor synchronous generator and permanent magnet rotor

synchronous generator. However, wound rotor concepts for growing megawatt scale OWT are more expensive and are around 10 meters in diameter or more and it makes the transportation and installation of them difficult [15].

For the continuous increasing size of OWT and decreasing their rotational speed, the wound rotor is not a suitable candidate. Therefore, it has been offered to use a single stage gearbox (with a gear ratio in the order of 6 or higher) and a permanent magnet generator, the so-called Multibrid system, illustrated in Fig. 2 [16].

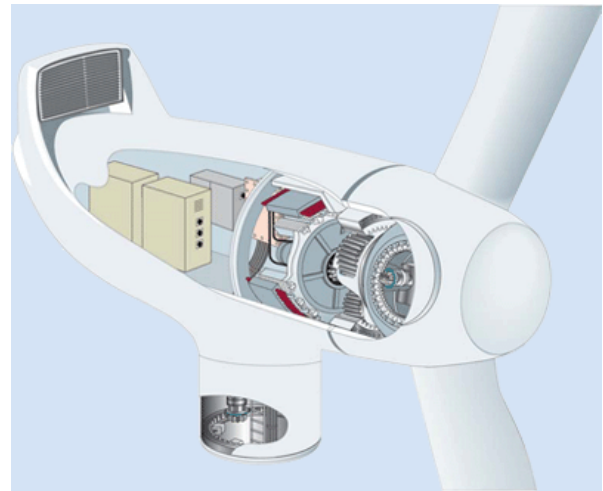


Figure 2: Multibrid generator drive train configuration [16]

The multibrid concept combines some of the disadvantages of both the geared and direct drive systems. The system has a gearbox and it has a special and therefore expensive generator and a fully rated converter. But, compared to direct drive systems, a significant decrease in the generator cost and an increase in the generator efficiency can be obtained.

3.4 Support Structure

The concept “support structure” is used to indicate the entire structure below the nacelle which means the support structure consists of a tower and a foundation [17].

The tower elevates the rotor into the air and transfers all the loads to the foundation. The foundation supports the tower, the rotor and the nacelle and resists against loading from wind and waves. Ferguson classifies offshore bottom mounted support structures according to three basic properties that are: installation principle, structural configuration and foundation type [18].

For simplicity, classification of support structures in this paper is based on water depth that each concept can be used economically, and gravity base, monopile, tripod and floating support structures are reviewed.

Support structure Concept	Water depth (m)
Gravity Base	0-10
Monopile	0-30
Tripod	>20
Floating	>50

Table 1: Concepts for support structures

- **Gravity base structures (GBS)**

From structural point of view, a GBS is a monotower that is fixed at the top of a gravity base foundation, Fig. 3.

The foundation consists of a large flat base to resist overturning loads imposed by the wind and wave, and a conical part at the water surface level to break the ice and reduce the ice load by causing the ice sheets to bend downwards and break-up as they contact the conical section [17].

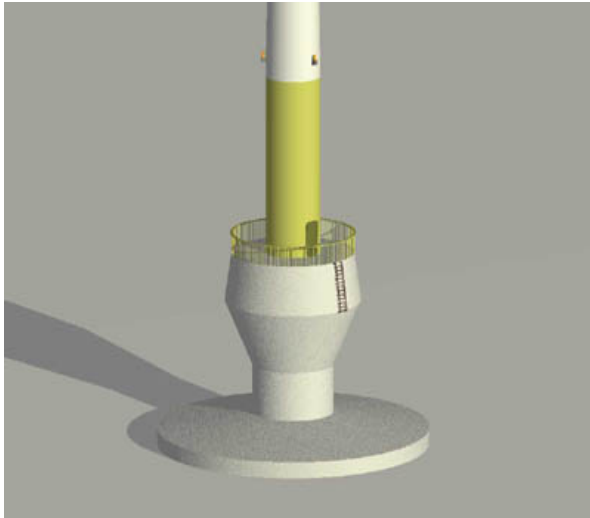


Figure 3: A typical Gravity Base Support Structure [19]

In order to keep the attachment between the GBS and the sea bed, ballasts are laid on the flat base. In this way, the foundation always remains in compression under all environmental conditions and can not be detached from the seabed.

- **Monopile**

The monopile support structure consists of a steel pipe as a foundation which is driven or drilled (sometimes the combination) into the soil.

The monopile is equipped with a transition piece to absorb tolerances on the inclination of the monopile and to reduce the assembling time required at sea and the tower which is mounted offshore on the top of the transition piece.

The steel pipe transfers all the loads by means of vertical and lateral earth pressure to the ground.

Therefore, both uncertainties in the ground properties and scour holes can lead to a structure with a quite different structural frequency than designed for. Because of these reasons, designing a monopile support structure is a challenging task.

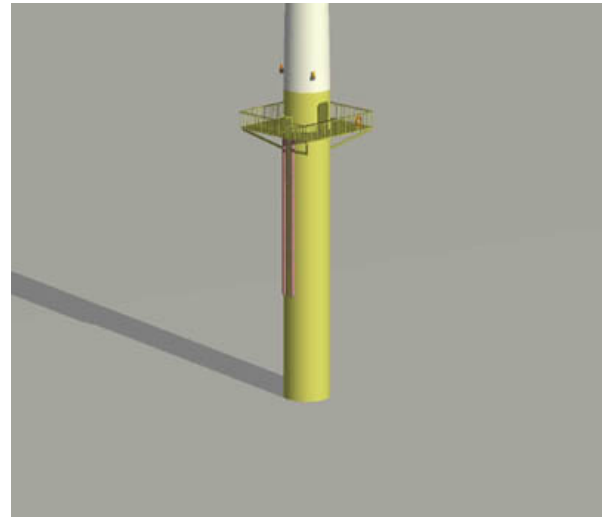


Figure 4: A typical Monopile Support Structure [19]

- **Tripod**

The tripod consists of a central steel shaft and three cylindrical steel tubes with driven steel piles. The central part distributes the loads to the cylindrical tubes and acts as a transition piece for the tower.

The cylindrical tubes give additional stiffness and strength and increase the capacity of the structure to support additional overturning moments [17].

The foundation has the advantage that it requires less protection against scour than the monopile, which generally has to be protected against scour in sandy sea beds.

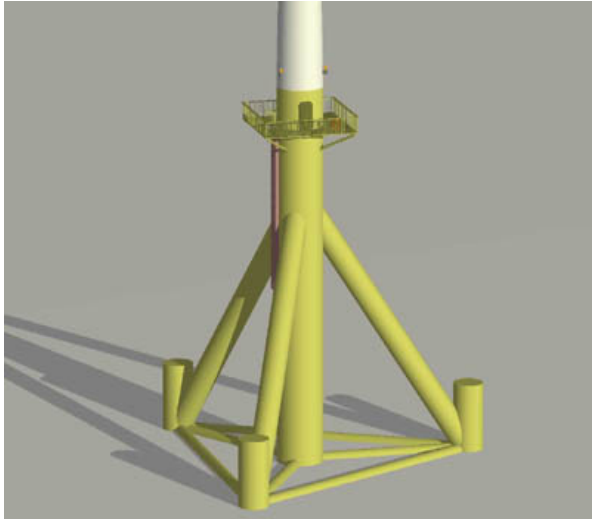


Figure 5: A typical Tripod Support Structure [19]

- **Floating**

Current fixed-bottom technology has seen limited deployment to water depths of around 30-m thus far. A floating support structure increases the flexibility in locating the turbine in water depths of up to 200 meters and is well known from oil and gas industry.

The floating support structure consists of a floating platform and a platform anchoring system. The platform has a transition piece to install the tower on top of that.

The platform can have several topologies such as single and multiple turbine floaters. The anchoring system fixes the platform and can be gravity base, drag embedded, driven pile, suction anchor type [20].

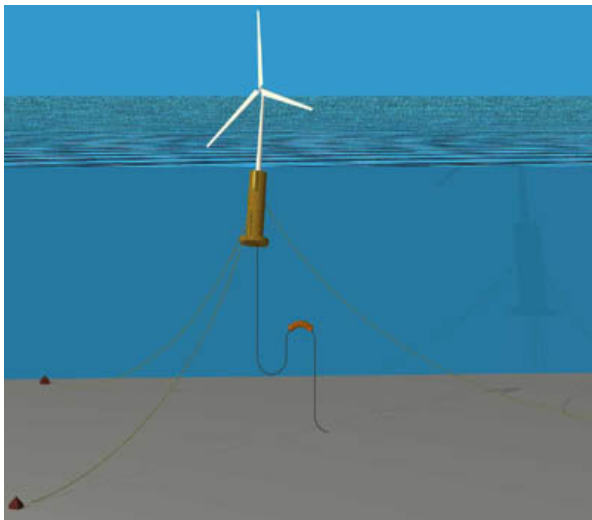


Figure 6: Candidate Floating Support Structure - Based on Spar Buoy Concept [19]

4 Current Offshore Technology

So far a brief overview of available concepts was given and to continue it is worthwhile to mention the current status of the most used concepts for OWTs.

The dominant rotor configuration is the variable speed three bladed upwind with a collective pitch and the yaw system. However there are some offshore projects with two bladed such as Lely in the Netherlands.

Nowadays, the most used concept for the drive train is the geared drive train, with three stages gearbox and a doubly fed induction generator.

This concept has a power electronic converter feeding the rotor winding with a power rating of approximately 30% of the rated power of the turbine to adapt the frequency of the generated electricity to the frequency of the grid.

It has the lightest, low cost solution with most used standard components, and a low energy yield due to the high losses in the gearbox. Major improvements in performance or cost reductions can not be expected for this concept [16].

Therefore, it is not clear yet whether this concept can be applicable for larger scale OWTs with a higher demand for decreasing the cost and increasing the performance, or that an alternative concept should be used.

Direct drive does not have a weight or cost advantage over conventional geared drive trains but especially in the permanent magnet generator type of design, it comprises a simpler drive train than the geared drive trains and may fulfill better the RAMS requirements in an offshore environment.

Besides economical point of view, the design drivers for selecting a support structure are mainly governed by water depths and soil conditions (and most probably the size for larger scales).

Therefore, for the Baltic and North sea waters with sandy bedplates and water depths below 30, the monopile is the most common used support structure, except in the shallowest water depths (up to max. 10 m) where the GBS is preferred.

5 Verification of design solutions

The behavior of an OWT is made up of complex interactions of subsystems and analyzing this behavior requires the skill of a multidisciplinary team in areas such as meteorology, rotor aerodynamic, control and electrical engineering, structural and civil engineering.

To be able to analyze such a complex system, it is necessary to use computational design codes capable of performing complete simulations of the behavior of wind turbines over a wide range of different operational conditions.

This section continues with reviewing some common design codes and the up scaling laws respectively.

5.1 Design Codes

In the wind energy community, the following wind turbine design codes are commonly used. A short description of the design codes is presented below.

- **BLADED**

The software is developed by Garrad Hassan and Partners, Ltd. BLADED is an integrated simulation package for wind turbine design and analysis. The Garrad Hassan approach to the calculation of wind turbine performance and loading has been developed over the last fifteen years and has been validated against monitored data from a wide range of turbines of many different sizes and configurations. The program includes a model for wave loading [21].

- **OWECOP (Integral analysis of the cost and potential of offshore wind energy)**

The Energy research Centre of the Netherlands (ECN) has developed a computer program for the analysis of wind energy exploitation at sea. Unique about the program is that it couples a geographic information system (GIS) to a spreadsheet model that calculates the costs of wind farming [22].

- **EeFarm (Grid integration of large offshore wind farms)**

For the design of the electrical infrastructure of offshore wind farms ECN has developed a computer program called EeFarm. EeFarm calculates the steady state voltages and currents in the farm and in the connection to shore. It can handle a number of different designs with AC and DC connections [23].

- **FAST (Fatigue, Aerodynamics, Structures, and Turbulence)**

The FAST code is being developed through a subcontract between National Renewable Energy Laboratory (NREL) and Oregon State University. NREL has modified FAST to use the AeroDyn subroutine package developed at the University of Utah to generate aerodynamic forces along the blade. This version is called FASTAD. There is a possibility to link a user defined code for modeling the wave loads in case of an OWT application [24].

- **AeroDyn**

AeroDyn is an aerodynamics code for use by designers of horizontal-axis wind turbines to predict the aerodynamics loads on the blade. It is written to be interfaced with structural-dynamics codes like MSC.ADAMS®, FAST, YawDyn, and SymDyn [25].

- **YawDyn**

YawDyn is developed at the Mechanical Engineering Department, University of Utah, US with support of the National Renewable Energy Laboratory (NREL), National Wind Technology Center. YawDyn simulates e.g. the yaw motions or loads of a horizontal axis wind turbine, with a rigid or teetering hub. There is a possibility to link a user defined code for modeling the wave loads in case of an OWT application [26].

- **WAsP**

WAsP is developed at RISO and it is a program for the analysis of wind data as well as wind atlas generation, wind resource assessment, wind resource mapping, and the siting of wind turbines and wind farms [27].

- **CONTOFAX**

The CONTOFAX program is developed at Delft University of Technology. The program determines the necessary and possible operations in an offshore wind farm for a given maintenance strategy. Different maintenance strategies can be evaluated and the total O&M costs, the achieved availability and the produced energy of the wind farm can be determined. Furthermore spare part logistics can be assessed with the program [28].

- **FLEX4**

The code is developed at the Fluid Mechanics Department at the Technical University of Denmark. The program simulates turbines with one to three blades; fixed or variable speed generators pitch or stall power regulation. The turbine is modeled with relatively few degrees of

freedom combined with a fully nonlinear calculation of response and loads [29].

- **GAST (General Aerodynamic and Structural Prediction Tool for Wind Turbines)**

GAST is developed at the fluid section, of the National Technical University of Athens. The program includes a simulator of turbulent wind fields, time-domain aeroelastic analysis of the full wind turbine configuration and post-processing of loads for fatigue analysis [30].

- **S4WT (SAMCEF for Wind Turbines)**

SAMTECH s.a. is a European specialist in computer aided engineering software for finite element analysis and multi-disciplinary optimization. SAMCEF for wind turbines provides access to detailed linear or non-linear analyses of all relevant wind turbine components such as gearbox, blade and generator [31].

- **PHATAS (Program for Horizontal Axis Wind Turbine Analysis Simulation)**

The PHATAS programs are developed at ECN Wind Energy of the Netherlands. The program is developed for the design and analysis of onshore and offshore horizontal axis wind turbines. The program includes a model for wave loading [32].

- **GAROS (General Analysis of Rotating Structures)**

The program is developed by Aerodyn Energiesysteme, GmbH and it is a general purpose design code for the dynamic analysis of coupled elastic rotating and non rotating structures with special attention to horizontal-axis wind turbines [33].

- **Maintenance Manager (Operation and maintenance of a wind turbine)**

ECN has developed this program as an easy-to-use maintenance information system. The program is structured such that a wind turbine manufacturer, its maintenance departments and their technicians can be provided with the relevant turbine data like: design information, information on spare parts and procedures [34].

- **FOCUS (Fatigue Optimization Code Using Simulations)**

FOCUS is an integrated wind turbine design tool, developed by Knowledge Centre Wind turbine Materials and Constructions (WMC), and includes modules developed by ECN. FOCUS consists of four main modules, SWING (stochastic wind generation), FLEXLAST

(calculation load time cycles), FAROB (structural blade modeling) and Graph (output handling) [35].

- **WAKEFARM**

The WAKEFARM program is developed by ECN. The program gives, in conjunction with an aero-elastic code, the possibility to perform design calculation on wind turbines which have to be placed in wind farms. Multiple wake effects and wind farms which consist of different turbine types can be modeled in a straightforward way. Parts of the WAKEFARM program have been incorporated in the FYNDFARM program. In FYNDFARM, wind farms can be analyzed in an integrated and user friendly way [36].

- **FYNDFARM**

The FYNDFARM program is developed by ECN. With this tool the user can control the energy yield, the technical life time of wind turbines and the noise emission. The user can create multiple designs for a specific location. For each design the user can determine whether or not a design limitation, for noise, fatigue or minimum energy yield is exceeded [37].

- **HAWC (Horizontal Axis Wind Turbine Code)**

HAWC is developed at Riso in Denmark. The model is based on the FE method using the substructure approach. The code predicts the response of horizontal axis two- or three bladed machines in time domain [38].

- **DHAT (Dynamic analysis of Horizontal Axis Turbines)**

DHAT originates from Germanischer Lloyd (GL) WindEnergie GmbH, which is a certifying body for wind turbines. DHAT is used as an in-house tool. The structural model description in this code is based on a modal formulation. A good comparison was done by Buhl and Manjock for load simulations in ADAMS /WT and FAST-AD with simulations in GL's DHAT [39].

5.2 Up-scaling Rules

In addition to stated design codes, a simple way to get some general insight in an OWT is to find the relation between a number of important parameters that govern the turbine characteristic.

As the rotor diameter changes some other important parameters such as power, rotor speed, torque and stresses also change and by studying these changes the behavior of the turbine can be analyzed with a low accuracy.

The fundamental relationships between rotor diameter and parameters mentioned above can be formulated by using up-scaling laws [40]. These scaling relations start with three distinct assumptions:

- The number of blades, airfoils, turbine materials, drive train and support structure concept are the same
- The tip speed ratio remains constant
- All other geometrical parameters vary linearly with rotor diameter

Based on these assumptions the relation between rotor diameter and other important parameters is given in table 2.

Parameter	Proportionality
Rotor diameter	D
Average wind speed at hub height	D^{α^*}
Rated Power	$D^{3\alpha+2}$
Rotor axial force	$D^{2\alpha+2}$
Rotor speed	$D^{\alpha-1}$
Rotor torque	$D^{2\alpha+3}$
Blade thickness	D
Blade chord	D
Blade sectional area	D^2
Blade flapwise stress	D^0
Blade lead-lag stress	D^1
Blade natural frequencies	D^0
Blade flapwise stress	D^0
Blade lead-lag stress	D^1
Blade natural frequencies	$D^{-\alpha}$
Blade weight	D^3
Drive train torque	$D^{2\alpha+3}$
Drive train weight	$D^{2\alpha+3}$
Tower sectional area	D^2
Tower mass	D^3

* α = power law exponent

Table 2: Scaling relations

It should be emphasized that scaling relations can only be used when the design concepts and components do not change. If this condition is met then the effect of size on the general behavior of the turbine can be predicted with a low accuracy.

6 Summary

In the design process of OWTs a number of challenges that are different from onshore wind turbines are encountered. The most important

difference is the additional design requirements that an OWT faces. In this paper the additional design requirements that an OWT should fulfill were explained.

These design requirements act as design constraints for which a concept should be designed. Therefore, after explaining the design requirements, the next step was assigned to reviewing the current concepts and configurations. A strive was made to compare alternative concepts in terms of advantages and disadvantages. However, the optimum concept depends on several parameters and finding an optimum concept and design solution is beyond the scope of this paper.

In the design process loop, an important step is the verification of design solutions. Because of the complex behavior of OWTs, design codes should be used to analyze the design solutions. Reviewing the design codes that are used to verify the design solutions was the next step. Therefore, a brief overview of origination and application of several design codes which are known in the wind energy community was given.

The up-scaling rule that describes the effect of one turbine parameter on a limited number of design parameters was explained. Normally rotor diameter is the independent parameter while others like power, forces and stresses are dependent parameters. Scaling rules can help redesign any wind turbine for other scales, as long as the concepts remain the same.

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