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Offshore Wind Turbines – Research and Development

Abstract

The purpose of the present study is to review the state-of-the-art in research and development of offshore wind turbines in order to address the latest findings and trends in structural design and response analysis. This could enhance a development of sophisticated offshore wind turbines. To complete such a task, a detailed review of offshore wind renewable energy potential, wind, wave and sea current loading as well as structural analysis and design procedures and experimental work are presented.

Keywords: renewable energy sources, offshore wind turbines, waves, wind, sea current, loads, structural response

1. Introduction

Continuous growth of global energy requirements, reduction of fossil fuels, environmental impact awareness and an initiative to harvest huge and relatively unused offshore renewable energy capacities led towards development of different technologies capable of transforming offshore wind, sea current, wave, thermal and salinity gradient energy into usable form of electricity, [1]. Different technologies are applied in diverse sea environments involving complex interaction between structures and environment to exploit and transform naturally originated kinetic energy into electrical one.

Along with environmental aspects, i.e. gas, particles and waste emission reduction, encouraging and incentive economic and societal impacts of renewable energy technology need to be addressed. It is well known that offshore renewable energy technology strongly relies on extensive research and development activities resulting with acquisition of specialized skills with appreciable competitive diligence at demanding international market. Moreover, construction, maintenance and decommission of offshore renewable energy objects is strongly relied on the ship production industry and offshore operations that can act as a leaver for economic development in broader, state level sense, [2].

Main societal impacts can be summarized into four main benefits, i.e. development and implementation within the existing energy system inevitably results in energy sources diversification leading toward energy system independence, more powerful geostrategic position and export oriented production, [3].

Such context results with inevitable need for rational and sophisticated approach to research, development, design, production and operative issues in order to maintain a desired design life of renewable energy structures. Otherwise, large investments could be easily jeopardized, [4]. This issue turns out to be particularly important in case of offshore wind turbines, as such structures are usually very large and exposed to complex simultaneous interactions between three loading sources, i.e. wind, waves and sea current.

It is therefore the purpose of this study to review the state-of-the-art in research and development of offshore wind turbines to address the latest findings and trends in structural design and response analysis standards. This will contribute to enhanced development of sophisticated offshore wind-turbine analysis and design methodology. A detailed review of offshore wind renewable energy potential, wind, wave and sea current loading as well as structural analysis and design procedures and experimental work are reported.

2. Offshore wind renewable energy potential

Two basic types of resource potential can be identified, i.e. theoretical and technical one, depending on the physical and technical properties. The former, although accurately quantified, does not have practical relevance since it takes into account only natural and climatic parameters, while the latter considers practical constraints and energy losses and estimates the energy output created using the implemented technology.

The global theoretical wind potential is estimated to be about 6000 EJ/yr (1666666 TWh/yr), while the technical potential of onshore wind potential estimates differ from 70 EJ/yr (19400 TWh/yr) up to 450 EJ/yr (125000 TWh/yr) depending on the considered data and assumptions, as well as on a technical development. Offshore technical potential estimates range from 15EJ/yr (4000 TWh/yr) to 130 EJ/yr (37000 TWh/yr). For the comparison, global electricity production in 2008 was about 73 EJ (20200 TWh). More detailed data, with references estimation methods, as well as the considered natural, practical and technological issues taken into account can be found in [4].

In the available literature, Croatian wind potential, both in theoretical and technical case, has never been estimated. However, data related to mean wind speed at different altitudes is available in [5], Figure 1. Although such data is representative for offshore wind turbine initial design stage, further research on incident wind loadings is inevitable as such loading conditions are often related to wind turbine limit design states, [3].

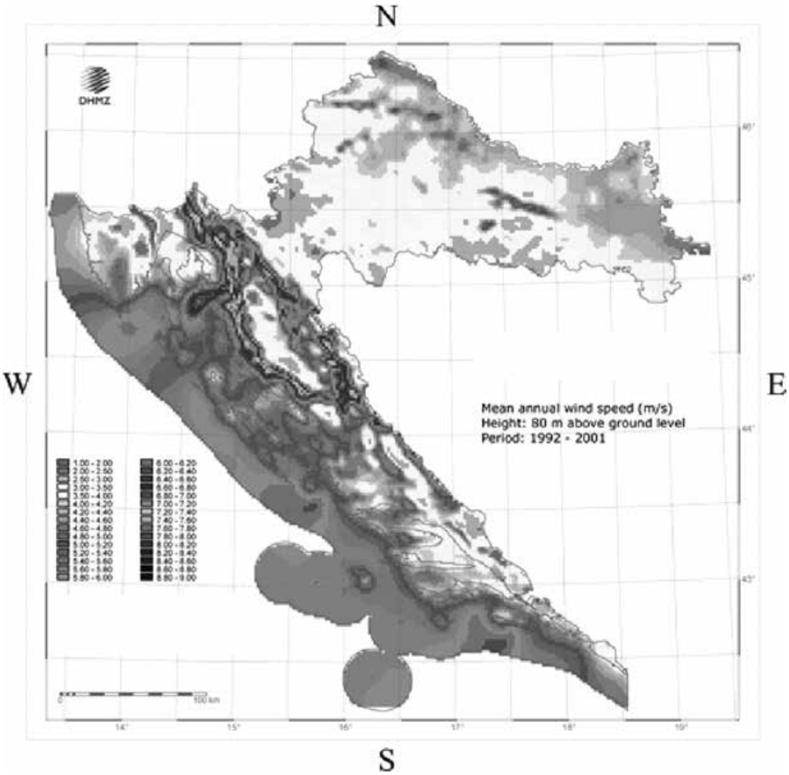

Figure 1. Mean annual wind speed at 80 m altitude in Croatia, [5]

3. Offshore wind turbines

The first offshore renewable energy power plant was built in 1991 in Denmark with almost 5 MW of the total installed power produced by eleven wind turbines, [4]. Since that time, the energy production demands increased considerably that led to a continuous growth of offshore turbine installations accompanied with an increase in the unit rated power reaching 9.5 MW, [6]. Usually, offshore wind turbines are defined as aerokinetic devices driven by the atmospheric winds. In that way, a rotational motion is induced and air kinetic energy is transformed into the electrical energy. One of the most prominent offshore aerokinetic energy extraction devices is horizontal axis wind turbine with fixed support structure (mainly monopile or gravity-base) as used in many countries, e.g. Belgium, China, Germany, Norway, Sweden, United Kingdom.

A common installed power is between 2 MW and 5 MW for water depths up to 25 m with a clear trend of increasing turbine size. For the sea depths between 30 m and 40 m, the jacket supporting structure is commonly applied. Main effort of current research activities is focused on reducing production costs and developing new technologies that would make possible to install wind power plants in deep sea by using different types of floating support structures such as spar, tension leg and semisubmersible support, [7], as shown in Figure 2.

Due to a nearly flat sea surface, offshore wind turbines have some favorable properties. In particular, nearly constant average wind velocity at the hub height along with weaker atmospheric turbulence, as compared to the wind developing over land, results with higher operating efficiency and lower structural fatigue of wind turbines. In addition, for offshore wind turbines it is possible to use longer wind turbine rotor blades for the same height of the wind turbine in comparison to the onshore wind turbines that yields more energy offshore than onshore.

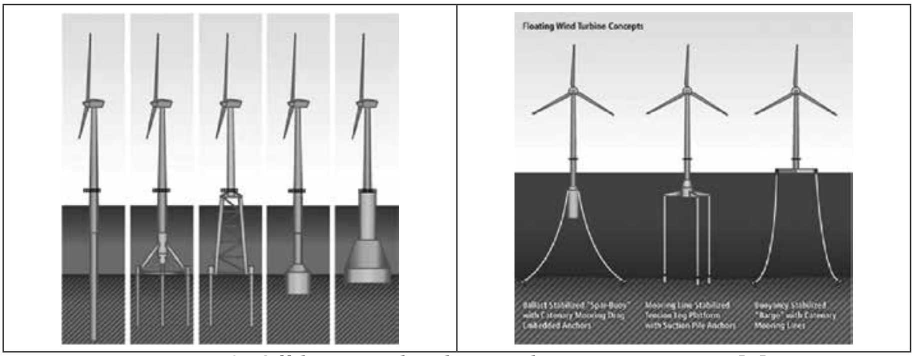

Figure 2. Offshore wind turbine underwater structure, [4]

On the other hand, drawbacks are mainly related to a demanding maintenance of offshore wind turbines, especially at high sea, which requires development of special-purpose ship types. Hence, in order to design, manufacture, install and maintain such a complex offshore engineering structure operating in an aggressive meteorological and corrosive environment, highly specialized engineering knowledge and skills are required. More detailed overview of the present status, challenges and different technical and operational aspects related to offshore wind power plants can be found in [8, 9].

4. Loading and response analysis

Wind turbine substructure is in close relation to the sea depth, while floating concept remains more complex in loading and response analysis with respect to fixed offshore wind turbine. Therefore, the methodology of loading and response analysis will be illustrated in case of a floating substructure that is also applicable in case of a fixed substructure. Three load types can be identified, i.e. wind, hydrodynamic, and mooring system loads. A complete offshore wind turbine dynamic response and analysis model needs to take them all into account together with various aspects of fluid-structure interaction, particularly in case of an aeroelastic behavior of turbine blades. The main purpose of turbine dynamic response analysis is development of satisfactory design solutions, [10].

4.1 Aerodynamic loads

The simplest and straight forward aerodynamic analysis of wind turbines steady-state wind loads is usually performed using the Blade Element Momentum (BEM) theory, while more complex cases are usually studied using Computational Fluid Dynamics (CFD).

The BEM theory was developed based on the assumption of the energy extracting stream tube and actuator disc mainly for the purposes of aerodynamic analysis of the rotating lifting profiles. It is very similar to a well-known strip theory commonly used in seakeeping analysis of ships, since it divides the rotor blades into elements to calculate the trust and torque induced by each one of them and then integrates the elemental values along the blade, Figure 3.

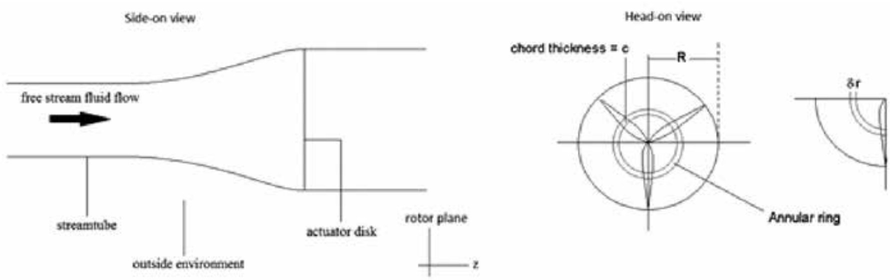

Figure 3. Basic principles of the Blade Element Momentum theory

Due to its simplicity, the BEM theory assumptions and limitations need to be clearly identified and pointed out. Primary assumption is that the flow field around lifting profile is always in equilibrium and that changes in the vorticity in the wake are adjusted instantaneously, i.e. the calculations need to be considered as static. In addition, the momentum balance is assumed to be achieved in the plane parallel to the rotor. Such assumption is not accomplished when the blades experience large deflection. BEM theory is not applicable in case of heavily loaded rotors with large pressure gradients, since the forces acting on the blade elements are supposed to be two-dimensional and spanwise flow is neglected.

One of the major limitations of the BEM theory is that the influence of shed vortices on the wake velocity is not taken into account. This limitation is often compensated by the application of the tip-loss correction function, usually Prandtl tip-loss function, which sharply decreases as the radial position approaches the blade tip. This results in the induction factor increment and a decrease in relative velocity and flow incidence angle. Consequently, lift and drag forces decrease near the blade tip. Other corrections implemented into the BEM theory also exist, like the hub-loss correction, as well as the Glauert and skewed wake correction, corresponding to turbulent and skewed wake operating conditions, respectively. A detailed review of the BEM theory principles is outlined in [11].

Nevertheless, in reality, wind turbines operate in complex flow conditions including turbulence, wind shear, tower shadowing, turbine response to wave loading and upstream wakes, which all creates complex and unsteady flow around turbine blades. Therefore, from an aerodynamic aspect, floating wind turbines represent quite an interesting modeling challenge that requires joint interdisciplinary effort. Therefore, CFD simulations are usually combined with experimental data leading toward development of simpler, faster and more powerful tools like FAST, ADAMS, AeroDyn, etc., [10].

4.2 Hydrodynamic loads

Three floating types of structures are usually used for floating offshore wind turbine: spar, semi-submersible and TLP, [7]. These types of structures are well known in the offshore industry with respect to their motion characteristics and critical components. However, many new design issues may arise due to downsizing and the smaller payload, [12]. This applies to the structure, mooring, power take-off cables and umbilical.

Floating wind turbines differ from bottom-fixed turbines by their larger rigid-body motions, where coupling effects between wind and wave loads and induced responses need to be taken into account. In general, there are two types of analysis of the dynamics of wind turbines: frequency domain and time domain. Frequency domain analysis has been used in the oil and gas industry and it is simple to use. However, it cannot take into account nonlinear dynamic characteristics (like mooring, viscous drag and control systems). For this purpose, the time domain analysis is widely used for design and analysis.

Different types of floaters have different dynamic characteristics. A comprehensive dynamic–response analysis of three offshore floating wind turbine concepts (spar, TLP and barge) were presented in [13]. The concepts were compared based on the nonlinear time-domain model. Hydrodynamics part incorporates linear hydrostatic restoring forces, nonlinear viscous drag, sea currents and platform motion. The added-mass and damping contributions are derived from linear wave radiation, including free-surface memory effects and the incident wave excitation from linear diffraction in regular or irregular seas.

Dynamic analysis of spar type wind turbine is presented in [14]. Hydrodynamic added mass, damping and resulting force were obtained in the frequency domain using the linear potential theory. The hydrodynamic study of the floater is combined with the FAST code to obtain a coupled aero-servo-hydro-elastic model. Spar type was also considered, [15]. The second-order mean drift forces were also calculated to account for the slowly-varying drift forces and motions through the Newman approximation method. The viscous drag force of the hull was calculated using the Morison equation, [12].

Design requirements for TLP structure were discussed in [16]. The potential flow model included only the first-order wave forces and the mean drift forces based on the first-order solution. Additionally, the Morison-type viscous forces were applied to the main column and spokes, using quadratic drag for the tangential and axial flow. Effects of the second-order wave forces on TLP (and spar) were studied in [17] by using the methodology developed for the oil and gas industry. It was found that for the TLP, the second-order forces are quite large that leads to a larger motion response where the sum-frequency effects dominate the overall motion response.

Development of the numerical model for a semi-submersible floater was presented in [18]. The model-test results, including static loading and decay tests, were used for calibration of a developed model. Comparison between simulation results and model test results for two sea states without wind was presented. Similar comparison of a semi-submersible floater is reported in [19].

4.3 Mooring system

Offshore wind turbines in deeper waters are exposed to stronger and steadier winds, which are used to improve an overall efficiency of the wind farm. Moreover, wind farms in areas more distant from the shore line are less sensitive to space availability. Fulfillment of regulations like restriction of noise and visual pollution is easier to achieve far from the coast. However, in water depths larger than 50 m to 60 m, fixed support structures are not the most cost-effective solution. For such wind farms, the existing mooring technology and computational models from the offshore oil and gas industry may be applied.

There are currently two main lines of research on mooring issues with respect to offshore renewable energy.

The first line is focused on developing and validation of the coupled model for the floating wind-turbine response. This started with an implementation of quasi-static models by taking into account non-linear restoring forces of the mooring system only, [20]. More sophisticated models capable of describing dynamics of mooring lines are further developed based on experience from the oil and gas industry. These models incorporate inertial and damping forces due to surrounding sea water, as well as loads caused by waves acting directly on mooring lines, [21] and [22].

The second line of research deals with structural optimization to reduce the cost of a mooring system. The frequency-domain techniques are commonly used to calculate the wave frequency and the low-frequency motions of a supporting structure. The procedures are focused on mooring lines, as the properties of wind turbines are used as input data, [23]. More complete approaches to the optimization can be found in studies where the supporting structure of wind turbines is a part of the optimization procedure, [24].

4.4 Dynamic response analysis

Based on the outlined environmental loads, a procedure for the analysis can be outlined in the following steps, [25]:

1. Turbine floater properties selection in alignment with the tower and rotor properties;
2. Model development within a comprehensive simulation tool enabling coupled dynamic response analysis;
3. Loading analysis based on predetermined design loading conditions with particular focus on ultimate and fatigue loading analysis;
4. Dynamic response analysis and evaluation of the turbine response in the frequency and time domains.

The software package capable of capturing the above outlined procedure and applicable within the first structural design step is the servo-elastic tool FAST developed by NREL (National Renewable Energy Laboratory). FAST is usually coupled with the AeroDyn rotor aerodynamics software and HydroDyn platform that focus on hydrodynamic aspects, [25]. The latter package relies on the data (frequency domain hydrodynamic coefficients) determined using the WAMIT software. An example of the floating offshore wind-turbine dynamic response in time domain is presented in Figure 4.

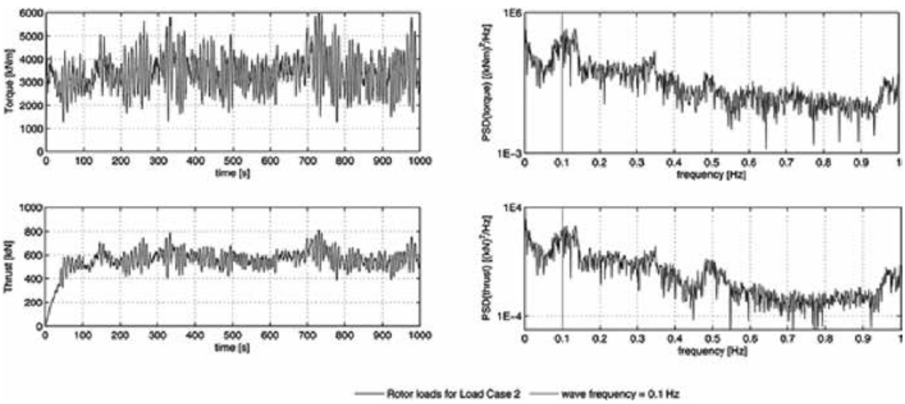

Figure 4. An example of an offshore wind-turbine dynamic response, [26]

The long-term analysis of offshore wind-turbine loads is usually relied on the International Electrotechnical Commission (IEC) guidelines that recommend statistical extrapolations to determine extreme wind-turbine loads. Two common extrapolation methods, usually applied in this case, are the direct integration and the linearized inverse FORM procedure. The former method estimates the wind-turbine nominal load for the design period, while the latter approach determines load exceedance based on the anticipated probability, [27].

5. Experimental work

State-of-the art approach to wind turbine modeling and dynamic response analysis needs to be verified using experimental data acquired using the combined wind-tunnel and water-tank experiments, as well as *in situ* measurements. As indicated in [28], the current dynamic-response prediction methodologies suffer of significant inaccuracy. It is important to emphasize that even a prediction of typical steady-state operating conditions results with surprisingly dispersive data as compared to the experimental values, e.g. turbine power prediction ranged between 25% and 175% as compared to the measurement. In case of bending moments, the difference between predicted and measured data is even larger, especially in case of larger wind speeds. It is therefore inevitable to perform a thorough research on modeling procedures and to verify them using the experimental results.

6. Conclusions

The focus of current efforts with respect to offshore wind turbines is on research and development of computational and experimental tools to analyze complex and interacting wind, wave and sea current loads. Another important topics are structural response analysis and wind-turbine design. In that sense, some suggestions and comments were addressed in the present study. Significant discrepancies between experimental and computational data indicate a necessity to further combine and improve those methodologies. The final goal is a suitable and cost-effective wind-turbine design, particularly in the floating offshore context.

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Istraživanje i razvoj pučinskih vjetroturbina

Sažetak

U radu je prikazano trenutno stanje istraživanja i razvoja pučinskih vjetroturbina što je osobito važno u kontekstu formulacije suvremene metodologije za analizu odziva i projektiranje konstrukcije tih pučinskih objekata. Stoga su detaljno prikazani energetski potencijali vjetra kao i opterećenja uslijed djelovanja vjetra, valova i morskih struja. Također, su iznesene temeljne smjernice za provedbu analize odziva i projektiranja kao i eksperimentalni rad.

Ključne riječi: obnovljivi izvori energije, pučinske vjetroturbine, valovi, vjetar, morska struja, opterećenja, odziv konstrukcije