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Mooring design and selection for floating offshore wind turbines on intermediate and deep water depths

A. Campanile [a], V. Piscopo [b,*], A. Scamardella [b]

[a] The University of Naples "Federico II", Department of Industrial Engineering, Via Claudio 21, 80125 Naples, Italy
[b] The University of Naples "Parthenope", Department of Science and Technology, Centro Direzionale Isola C4, 80143 Naples, Italy

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ABSTRACT

The paper focuses on design and selection of mooring systems for Floating Offshore Wind Turbines (FOWTs) for intermediate and deep water depths, based on ultimate, accidental and fatigue limit state design conditions, with reference to power production, parked wind turbine and mooring line fault conditions. Platform static and dynamic offsets are determined by a purposely developed 6DOF programme in the frequency domain, accounting for first and second order motions. The Dutch tri-floater platform, together with the well-known 5 MW NREL wind turbine, is assumed as reference design. Besides, two sites, the one in the Southern North Sea, near Dogger Bank on water depths ranging from 50 up to 80 m, the other one in the Northern North Sea, near the Troll field area on water depths ranging from 200 up to 350 m, are assumed as candidate deployment areas, to investigate the effect of: (i) line number, (ii) platform admissible offset and line scope, (iii) offshore/onshore planned maintenance inspections and (iv) mooring technology on relevant installation and maintenance costs. A preliminary cost analysis is also performed and some recommendations are given to correctly choice the most suitable mooring configuration, as a function of water depth.

1. Introduction

During the last decade offshore wind energy was one of the fastest growing maritime sectors, with a total installed capacity expected to reach 40 GW by 2020 and 150 GW by 2030, meeting 4% and 14% of the EU total electricity consumption (EWEA, 2013). The trend leads to increase both power and number of wind turbines, moving production farms from shallow to intermediate/deep waters, requiring specialized substructures to harvest the promising offshore market potential, provided that current commercial substructures, such as monopiles, gravity-based foundations, tripods and jackets, are economically limited to 40–50 m water depths. Nevertheless, even if intermediate/deep water offshore designs are expected to be competitive, in terms of Levelised Cost of Energy (LCoE), with bottom-fixed support structures, current technology is still in a pre-commercial phase, as research activities in the field started in the mid-1990s and the first two full-scale floating offshore wind turbine (FOWT) prototypes have been deployed only recently, the former off the island of Karmøy, north of Stavanger, the latter 5 km off the Portuguese coast of Aguçadoura.

Currently, FOWTs exhibit different configurations, mainly depending on water depth. In intermediate water depths, from 50 up to 120 m, tension leg platforms and semi-submersible support structures are the most common designs, while in deep waters, beyond 120 m, spar-type configurations seem to represent the most feasible choice, even if semi-submersible structures have been in any case proposed as an alternative design. As concerns the semi-submersible configuration for intermediate water depths, one of the first comprehensive studies was carried out within the "Drijfwind" project (Bulder et al., 2002), with the main aim of developing a preliminary design for a candidate deployment site in the Southern North Sea, on 50 m water depth, off the Netherland continental shelf. The structure, with a tri-floater configuration, was provided with large heave plates at the bottom of each column and a conventional hybrid six-line mooring system. Recently, "Principle Power" (Roddier et al., 2010) and "DeepCwind" Consortium (Robertson et al., 2014) developed similarly shaped configurations, with 3-line conventional moorings, for two candidate deployment sites on intermediate and deep water depths, respectively.

In the same years, several feasibility studies have been performed, to investigate the economic viability of offshore wind power production and optimize the design of both support structures and mooring systems. In this respect, Sclavounos et al. (2008) carried out a parametric study, focusing on different mooring technologies for several candidate designs,

* Corresponding author.
E-mail addresses: antonio.campanile@unina.it (A. Campanile), vincenzo.piscopo@uniparthenope.it (V. Piscopo), antonio.scamardella@uniparthenope.it (A. Scamardella).

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namely tension leg platforms, spar-type and barge configurations, on different water depths. Fylling and Berthelsen (2011) proposed an integrated tool to optimize the design of spar-type support structures, including mooring systems and power take-off cables. Brommundt et al. (2012) developed a new tool devoted to the optimization of catenary mooring systems for semi-submersible structures deployed at two candidate sites located in the North Sea, namely Greater Ekofirsk area and Troll field, on 75 and 330 m water depths, respectively. Benassai et al. (2014a,b, 2015) optimized the catenary mooring systems of FOWTs with tri-floater support structure for three candidate sites in the Southern Mediterranean Sea at different water depths, from 50 up to 300 m, focusing on symmetric and asymmetric patterns and different mooring technologies, namely chain cables and steel wire ropes. Finally, Hall et al. (2014) developed an alternative form of support structure optimization problem, abstracting from geometry details and focusing on hydrodynamic performance coefficients, to provide a more complete and intuitive exploration of the design space.

The growing interest in exploiting offshore wind resources on intermediate and deep-water depths is also proved by the variety of rules and guidelines provided in the last years by several Classification Societies, namely American Bureau of Shipping (ABS, 2015), Bureau Veritas (BV, 2015) and Det Norske Veritas (DNV, 2014) among others. Particularly, current rules for the offshore wind energy sector furnish criteria for design, construction, installation and survey of permanently sited installations, focusing on three main topics: (i) support structures, (ii) station-keeping systems and (iii) onboard machinery and equipment, including safety and lifesaving appliances. Besides, despite of current codes for the offshore oil and gas industry, the so-called "environmental class" approach is applied, as FOWTs are expected to be mass produced units, which implies that several locations, with fairly similar metocean conditions, can be grouped together, reducing design, installation and maintenance costs. Furthermore, structural safety is ensured by the so-called "safety class" method, so as all structural elements, including mooring system, are designed to meet assigned target safety levels, defined in terms of collapse consequences and annual failure probabilities.

Due to the novelty of this research field, the paper focuses on design and selection criteria of mooring systems for FOWTs, with semi-submersible support structure, on intermediate and deep water depths. In this respect, following the main outcomes of past researches, the choice of: (i) line type, number and scope, (ii) platform admissible offset and (iii) type of planned maintenance inspections that, in turn, influence the expected mooring lifetime, represents a basic issue to minimize the mooring weight and reduce the overall installation costs. Hence, in the paper the following main subjects are fully investigated and discussed:

(i) The incidence of platform admissible offset, line number and offshore/onshore maintenance inspections on mooring scantlings is systematically investigated at different water depths, as various design strategies for mooring systems of FOWTs have been applied in the past by different researchers (Bulder et al., 2002; Sclavounos et al., 2008; Fylling and Berthelsen, 2011; Brommundt et al., 2012; Benassai et al., 2014a,b; 2015). In this respect, it must be pointed out that the choice of platform admissible offset and line number strongly differs from the common design procedure, generally applied for semisubmersible offshore structures in the oil & gas industry, due to the greater incidence of wind loads in harsh weather conditions and couplings between wave and wind components. Hence, the choice of proper design parameters reveals to be quite challenging, as mooring weight and stationkeeping redundancy, in case of failure of one mooring line, mainly depend on platform admissible offset and line number, respectively. Furthermore, offshore/onshore maintenance inspections also play a fundamental role in the assessment of mooring life, which has not been fully investigated till now, provided that FOWTs are devoted to mass production, differently from offshore structures operating into the oil & gas sector, which implies that all strategies, devoted to possible savings of maintenance activities, have to be undertaken;

(ii) Minimum weight configurations are identified and a preliminary cost analysis is performed, to investigate the incidence of water depth on mooring installation costs, as the Levelised Cost of Energy of FOWTs mainly depends on installation expenses, related to support structure, wind turbine and mooring system. In this respect, no many theoretical works have been performed on the argument and the topic needs to be further analysed, to investigate the incidence of different design strategies on mooring scantling and installation costs;

(iii) Some recommendations are provided to speed up the design and selection process of mooring systems for FOWTs and detect the minimum weight configuration, as a function of water depth. Particularly, it must be pointed out that no many research activities have been carried out in the past to provide some guidelines for mooring design of FOWTs, that generally differs from the design procedure commonly applied for semisubmersible offshore structures operating in the oil & gas industry, mainly due to different issues related to mass production and wave/wind load couplings.

The Dutch tri-floater platform (Bulder et al., 2002), coupled with the 5 MW NREL wind turbine (Jonkman et al., 2009), is assumed as reference design for two candidate deployment sites, the former located in the Southern North Sea, west of Dogger Bank, on water depths ranging from 50 up to 80 m, the latter in the Northern North Sea, near the Troll field area, on water depths ranging from 200 up to 350 m. Finally, platform motion analysis is carried out in the frequency domain by a dedicated programme developed in Matlab (MathWorks, 2014) and mainly based on de-coupling of static, wave and low frequency motions.

2. Mooring design criteria

2.1. Station-keeping requirements

In current analysis ultimate (ULS), accidental (ALS) and fatigue (FLS) limit state design criteria, provided by the Offshore Standard DNV-OS-J103 (DNV, 2013) and mainly based on the "safety class" approach, are applied for design and selection of mooring systems for FOWTs. In this respect, redundant station-keeping systems shall be designed according to normal safety class requirements, based on 10^{-4} annual failure probability, while non-redundant configurations shall comply with high safety class levels, corresponding to 10^{-5} annual failure probability, reflecting the increased risk should the support structure face to disengage from its position, in case of failure of one mooring line (DNV, 2013). Mean $T_{c,mean}$ and dynamic $T_{c,dyn}$ components of total tension T_d in each mooring line are determined based on quasi-static analysis in the frequency domain, even if a coupled analysis of platform/mooring lines in the time-domain is generally needed to correctly estimate both line tension and nonlinear effects in the dynamic response of floating offshore structures in deep water depths. Nevertheless, in the early design stage the quasi-static analysis is still practical and feasible, as stressed by Lim et al. (2016), who compared the results obtained by quasi-static and coupled analysis in frequency and time domains respectively, founding a reasonable agreement between the two analysis methods. Furthermore, by the comparative study between an uncoupled analysis in the frequency domain and a coupled aero-hydro-servo-elastic simulation in the time-domain, carried out by Huijs et al. (2014), with reference to the GustoMSC tri-floater support structure equipped with the NREL 5 MW wind turbine, it is gathered that: (i) in the wave frequency range, between 0.3 and 2.0 rad/s, motions and accelerations are rather well predicted by the frequency domain motion analysis, (ii) in the low frequency range (<0.3 rad/s) the coupled simulations show considerable response around the structure natural frequencies, respect to the frequency