Renewable Energy 101 (2017) 364–375

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Performance changes of a floating offshore wind turbine with broken mooring line

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ARTICLE INFO

Article history:
Received 30 December 2015
Received in revised form
9 August 2016
Accepted 21 August 2016

Keywords:
Wind energy
FOWT (floating offshore wind turbine)
Broken mooring line
Transient effect
Aero-hydro-servo-elastic-mooring dynamic coupling
Drifting distance

ABSTRACT

In the present study, a series of numerical simulations of the performance changes of a Floating Offshore Wind Turbine (FOWT) with broken mooring line was carried out. For this simulation, an aero-hydro-servo-elastic-mooring coupled dynamic analysis were carried out in the time domain. The OC4 DeepCwind semisubmersible with NREL's 5-MW baseline turbine was selected as a reference platform. One of the three mooring lines was intentionally disconnected from the floating platform at a certain time. The resulting transient/unsteady responses and steady-state responses after that, mooring line tensions, and turbine performance were checked. The accidental disconnection of one of the mooring lines changes the watch circle of the floating platform and the tensions of the remaining mooring lines. In addition, the changes in the platform orientation also cause nacelle yaw error, which is directly related to the power production and structural fatigue life. When horizontal offset becomes large, power-line is likely to be disconnected and its influence was also investigated. To ensure the sustainability of a series of FOWTs associated with farm development, the influence of mooring line failure and resulting changes to the turbine performance should be checked in advance. Otherwise, successive failure of neighboring FOWTs could take place.

1. Introduction

Wind energy is the fastest growing clean and renewable energy resource. Recently, research regarding Floating Offshore Wind Turbines (FOWTs) has become very active across the world and significant progress has been made in the area of FOWT technology. Moreover, several countries have started to install prototype FOWTs at sea, and performance checks and commissioning are ongoing. Hywind is the world's first full-scale SPAR-type FOWT and was installed in 2009 in Norway [17]. Subsequently, a semi-submersible type FOWT called WindFloat with a 2-MW class turbine was constructed and installed in 2011 [19]. After the nuclear disaster in Japan in 2011, the Japanese government started to construct FOWTs near the Fukushima area in 2013. The total 7-MW FOWTs were successfully installed [4].

The FOWT research is multidisciplinary including floating body hydrodynamics, structural dynamics, control engineering, aerodynamics, and mooring dynamics. Consequently, the numerical simulation of FOWT dynamics need to be done through integrated aero-hydro-servo-elastic-mooring coupled computer-aided-engineering (CAE) tools. In this regard, a fully coupled dynamic analysis computer program was developed by combining several CAE tools. Initially, for the dynamic analysis and control of a wind turbine system, the design code for wind turbines called FAST developed by the National Renewable Energy Laboratory (NREL) was employed [7–10]. The aero-hydro-servo-elastic simulation tool FAST was then combined with the floater-mooring coupled dynamic analysis program CHARM3D [14,20,21]. The coupling between FAST and CHARM3D has been implemented by Refs. [1–3] and the developed program has been used for the coupled dynamic analyses of several FOWTs. In this paper, the unsteady response of a floating platform and the changes in the turbine performance with an accidentally disconnected mooring line will be simulated and investigated. Turbine orientation is one of the critical design considerations for FOWTs, since optimal turbine orientation aligned to the wind direction ensures the desired power output. If the platform orientation changes for some reason, the nacelle yaw angle will be changed as a result. Then, the turbine performance, such as blade pitch angle, tower base shear force and

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http://dx.doi.org/10.1016/j.renene.2016.08.044
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moment, blade root shear force and moment, will be also changed. In normal operational conditions, mooring lines maintain the position and orientation of the platform which can partially influence the orientation of the turbine. However, the mooring lines may break in response to the harsh environment or repetitive fatigue loads, and this may result in significant changes to the platform location and orientation. The drift of the platform after mooring line break may result in a collision with a neighboring platform and progressive failure can also be expected in the worst case scenario. In the offshore oil and gas industry, the effects of sudden mooring line disconnection during harsh wind-wave-current environments have been studied. Ref. [14] underscored the importance of coupled hull-mooring-riser dynamic analysis in the time domain. The transient effects on the global performance of tension-leg platform (TLP) with one tendon disconnection were investigated by Ref. [20]. Ref. [6] examined the transient behavior of mooring systems and floating production storage and offloading (FPSO) platforms in line-broken condition for some operational conditions. Ref. [18,22] selected a semi-submersible mobile offshore drilling unit (MODU) that suffered a mooring failure during hurricane Ivan and successfully simulated the platform responses and progressive mooring line failure in the time domain.

The numerical simulation in this study is conducted using the OC4 DeepCwind semisubmersible platform with an NREL offshore 5-MW baseline wind turbine [11]. The OC4 DeepCwind semisubmersible platform is moored with three catenary lines spread symmetrically. To clearly see the platform drift and turbine performance changes, incident wind and wave directions are set to be different. With this non-collinear environment, the effect of mooring line loss can be demonstrated dramatically.

2. Numerical analysis of OC4 DeepCwind semisubmersible platform in the time domain

The time domain analysis tool for an aero-hydro-servo-elastic-mooring fully coupled dynamic system is utilized in this study for the responses of the FOWT system. In order to couple the wind-turbine motion and mooring/floater dynamics, two different analysis modules, CHARM3D and FAST are combined to solve their coupling effects simultaneously. The combined inertial matrix consists of six degrees of freedom (DOF) of platform motion and 18 DOF of tower, rotor, and blade responses. The mooring line dynamics are solved independently at each time step from the feedback of platform motion. So, two analysis programs are explicitly coupled to simulate the dynamics of the FOWT including finite element mooring system. The hydrodynamic coefficients, including added mass, radiation damping, wave forces, and mean drift forces, of the floater are obtained by using a 3D diffraction/radiation pre-processor WAMIT in the frequency domain [15]. WAMIT calculates the linearized potential-flow hydrodynamic radiation and diffraction problems in the frequency domain using three-dimensional panel method. The obtained hydrodynamic and wave loading data from WAMIT are then transformed to time-domain forms by CHARM3D and fed into FAST as a platform loading input. For instance, the radiation damping part is converted into the convolution integral term in CHARM3D and transferred to the FAST at every coupled time step. The mooring dynamics coupled with hull motions are solved at each time step by a generalized-coordinate-based FEM program using high-order elements [14].

The equation of motion of the floating platform in the time domain can be expressed as follows:

$$[M + M^a(\infty)]\ddot{\xi} + K\xi = F_I(t) + F_c\left(t,\dot{\xi}\right) + F_n\left(t,\dot{\xi}\right) + F_m(t,\xi) \qquad (1)$$

where $M^a(\infty)$ denotes added mass at infinite frequency, $F_I(t)$ is the wave exciting force, K is the hydrostatic coefficient, $F_n(t,\dot{\xi})$ is the nonlinear drag force from Morison's equation, $F_m(t,\xi)$ is the mooring force, and $F_c(t,\dot{\xi})$ is the radiation damping force as follows:

$$F_c\left(t,\dot{\xi}\right) = -\int_{-\infty}^{t} R(t-\tau)\dot{\xi}(\tau)\mathrm{d}\tau \qquad (2)$$

ξ, $\dot{\xi}$, and $\ddot{\xi}$ represent the vectors of six degrees of freedom of displacements, velocities, and accelerations, respectively, of the floating body. The retardation function $R(t)$ is given by:

$$R(t) = \frac{2}{\pi}\int_{0}^{\infty} b(\omega)\cos(\omega t)\mathrm{d}\omega \qquad (3)$$

in which b is the linear radiation damping matrix. The complete nonlinear aero elastic equation of motion for the wind turbine model is:

$$M\left(\underline{q},\underline{u},t\right)\ddot{\underline{q}} + f\left(\underline{q},\dot{\underline{q}},\underline{u},\underline{u}_d,t\right) = \underline{0} \qquad (4)$$

where M is the mass matrix, f is the forcing function, $\underline{u}$ and $\underline{u}_d$ are the set of wind turbine control inputs and wind inputs, respectively, $\underline{q}$, $\dot{\underline{q}}$, and $\ddot{\underline{q}}$ are the vectors of wind turbine motions, velocities, and accelerations, respectively, and t is time.

The wind turbine dynamics including the six DOF platform dynamics, are computed by FAST, which was developed by NREL. CHARM3D calculates all the external forces acting on the platform. At each time step, CHARM3D feeds the external loadings to FAST, then FAST fills out the forcing function in Eq. (4) using forces from CHARM3D. The external forces that are derived by CHARM3D include first-order wave force, wave radiation damping force, nonlinear viscous drag force from Morison members, and mooring-induced restoring force. The second-order wave force can be also included in the time-domain analysis. In this study, the second-order difference-frequency wave force is included by using Newman's approximation method, the validity of which was well justified in Ref. [13] through comparison with DeepCwind experiments. In addition, the first- and second-order wave forces are computed based on the instantaneous position of the platform because its mean offset with one broken mooring line can be quite large.

The mooring restoring force can be estimated from the tension of the mooring line at the top (fairlead) position and its directional cosine. Then, FAST solves the equations of motion for all the degrees of freedom. Those updated platform kinematic data, which include displacement and velocity, are then used in CHARM3D in order to update external forces, which will be fed again to FAST for the next time step. For the present simulation, the time step of CHARM3D is 0.01 s and the internal time step for FAST is 0.005 s, which means that for every CHARM3D time interval, FAST internally calculates two steps and returns the resultant data to CHARM3D.

The basic concept of rotor-floater coupling is schematically shown in Fig. 1.

The control system for the 5-MW wind turbine consists of

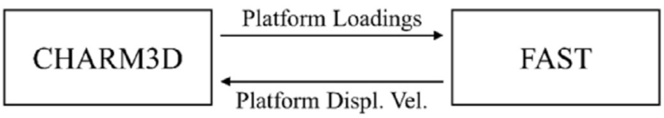

Fig. 1. Basic concept of FAST–CHARM3D coupling model.