Proceedings of the ASME 39th International Conference on Ocean, Offshore and Arctic Engineering
OMAE 2020
June 28-July 2, 2020, Fort Lauderdale, USA

OMAE2020-19166

VIRTUAL PROTOTYPING OF A LOW-HEIGHT LIFTING SYSTEM FOR OFFSHORE WIND TURBINE INSTALLATION

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ABSTRACT

Due to the ever higher demands from the energy market, the quantity, dimension and power capacity of newly installed offshore wind turbines are continuously increasing. In terms of logistical management, economic feasibility and engineering difficulty, the traditional installation methods, predominantly represented by using Jack-up vessel and offshore cranes, will hit their limitations soon in the future. Offshore turbines have a relatively fixed geometric profile and physical characteristics: a slender cylindrical tower with huge blades attached on the top end. In this work, we exploited these features and designed a low-height lifting system for deploying wind turbine onto a floating spar platform. The low-height lifting system lifts the wind turbine with wires attached to the bottom of the tower, and keeps the balance of the tower with extra tug lines on the mid-section. The wires and tug lines are cont rolled by an active 6DOF compensation system. The low-height lifting system removes the necessity of a huge offshore crane onboard and can scale well to even larger wind turbines. The design is virtual prototyped in the simulator of Offshore Simulator Centre using Fathom simulation software. Different design configurations are discussed in terms of the general arrangement, system dimensions and control methods.

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INTRODUCTION

The trends are showing that the global energy demand is increasing and there is huge concern regarding the environmental foot prints of these over-consumption.Due to that the energy production regime has to shift toward cleaner sources such as wind energy. Wind turbines can be used in order to convert wind energy to electricity which can be used by end consumers. A wind turbine consists of blades, hub, nacelle, tower and substructure. Higher wind speed quality at sea and limited land resources made offshore wind turbines a priority in energy supply chain.

Offshore Wind Turbines (OWT) has two variations of bottom fixed installations and floating versions. The substructure can vary based on the type of the installations, for example in case of bottom fixed installation jacket type foundations, monopiles, gravity based and tripods are possibilities and for the floating structures semi submersibles, Tension Leg Platform(TLP) and spar buoy are the options. In water depths above 150 meters floating OWTs has economical advantage compared to the bottom fixed structures while the installation costs are one of the major portion of the project expenses. In order to increase the competitive advantage of this designs innovative installation concepts has to be developed [1]. Different OWT design concepts were proposed by academia and industry such as MIT TLP, ITI Energy Barge and OC3 Hywind spar buoy(see Fig. 1). Collaboration of Massachusetts Institute of Technology (MIT) and National Renewable Energy Laboratory (NREL) has proposed a TLP design as substructure supporting the wind turbine [2]. TLP is connected to seabed using four vertical tendons. ITI Energy barge concept was developed by Department of Naval Architecture and Marine Engineering of University of Glasgow and Strathclyde within a contract with ITI energy company [2]. ITI Energy Barge is using a barge floater as substructure of the wind turbine which connected to sea floor using eight catenary moorings. Hywind is the name of spar buoy concept proposed by Equinor. In this concept wind turbine is installed on top of a spar buoy which is connected to the seabed using three anchor lines.

Among proposed design concepts the most dominant one is the Hywind concept. This concept was realized within the

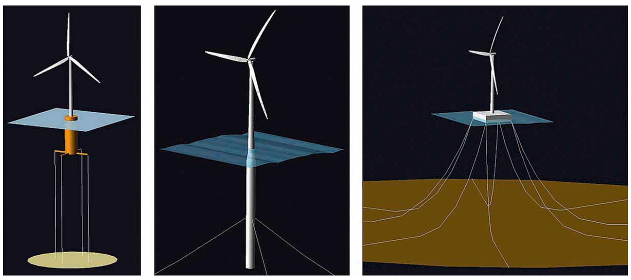

FIGURE 1. (a) MIT/NREL TLP (b) Hywind Spar Buoy (c) ITI Energy Barge

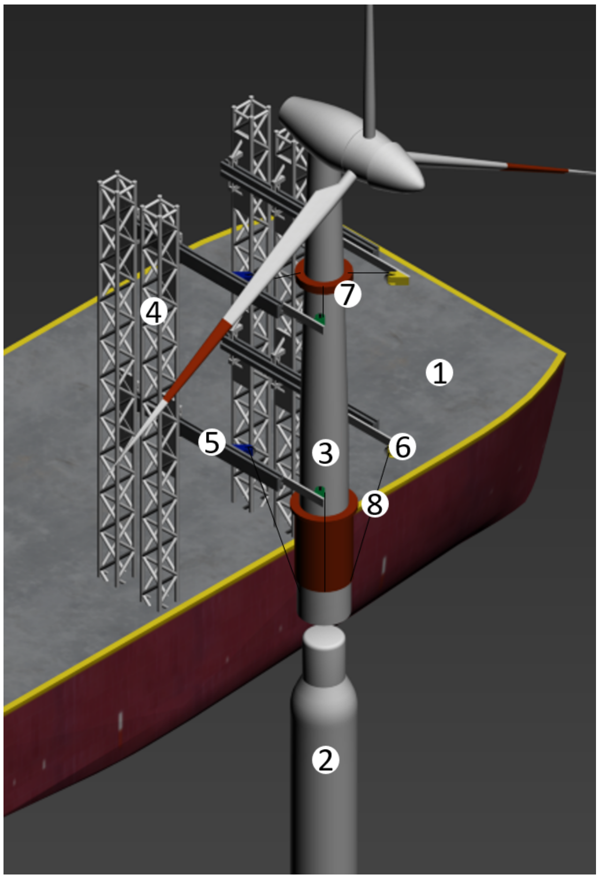

FIGURE 2. Low-height lifting system: 1.Vessel 2.Spar 3.Tower 4.Supporting truss 5.Double-sliding jib 6.Winch 7.Collar 8.Wire

Hywind demo project and commercialized through the Hywind Scotland wind farm. In Hywind Scotland project which was the first floating wind farm worldwide, the spar foundations were upended in the fjords in Norway and then the tower is lifted and installed on it. Then the spar and tower assembly were towed to the final operational site and connected to the pre-installed anchors. From experience of this project it is concluded that this type of installations are time consuming and resource demanding and there is a need for improved installation concepts. In order to overcome the difficulties of the Hywind Scotland project the floating buoy can be attached to the anchor lines and then the wind turbine can be lifted as a single object and installed on top of the floating buoy. The main challenges in this concept are complex marine environment and different dynamic behavior of involved structures such as installation vessel, wind turbine and the floating spar.

General purpose offshore crane is traditionally used for wind turbine installation for its well-accumulated technology and industry experience. However, offshore wind turbine has a low self-weight compared to its characteristic length. For example, DTU 10-MW Wind Turbine has a hub height of 119 meter and a self-weight of 1300 ton [3]. As a reference, the Liebherr BOS 45000 offshore crane has a lifting capacity of 1400 ton but only a jib length of 102 meter. By observation, the wind turbine tower can be approximated as a slender column with small horizontal footprint and radial symmetry, while the entire assembled top part of the wind turbine, including blades, hub, nacelle and tower, has a relatively high centre of gravity and requires a large spacial clearance on top.

With those unique characteristics in consideration, we propose a novel low-height lifting system concept for offshore wind turbine installation, specifically for wind turbines similar to Hywind Scotland project(see Fig.2). This new design has a left-right symmetry, each side has two supporting truss on the ship side, one double-sliding jib on the bottom and one on the top. Each jib has two winches connecting to the tower. The system lifts the entire top part of the turbine from the bottom of the tower instead of from the top, and distributes the lifting load on four oblique lifting wires. A sliding collar around the neck of the tower is connected by four tug wires on the top. The four sliding jibs allow the system to move the turbine from the centre of the deck to ship side. The top and bottom winches also serves as 6DOF control system to actively track the position and orientation of the bottom spar. With no lifting structures above the turbine, the size of the lifting system is reduced and not limited by the height of the turbine anymore. Because the height of the turbine usually increases faster than the radius of the tower, this new design also supports better scalability for larger wind turbines in the future.

We prototyped and simulated this new design in FATHOM simulation environment in real time. The supporting vessel, lifting system, top part of the wind turbine and bottom spar all have high accuracy rigid body dynamics, the vessel and the spar also have realistic hydrodynamics, lifting wires are simulated with Algoryx flexible wire dynamics, and 6DOF winch control system are designed in FATHOM.

FATHOM SIMULATION SOFTWARE

FATHOM is an in-house multi-physics simulation software developed by Offshore Simulator Centre AS. It is designed for real-time simulation of complex marine operations. The basic design structure is shown in Fig.3. The fathom core is in charge of coordinating behaviors of all functional modules, sending input and output data and defining behaviors of control systems. FATHOM uses Algoryx Dynamics as physics engine and also supports various modelling methods of hydrodynamics, e.g. mesh-based time domain method and coefficients-based frequency-to-time domain method. The user and hardware can both give simulation instructions to Fathom core and the physics

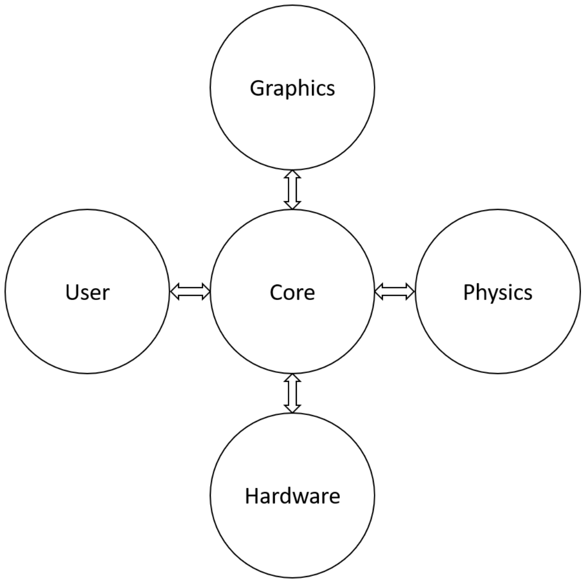

FIGURE 3. Fathom design structure

FIGURE 4. OSC simulator

module simulates the physical behavior of a scene setup, under the instruction of Fathom core, e.g. changing wire payout speed, adding external force, commanding joint force/speed, changing weather condition. Moreover, with machine-in-the-loop capability, some hardware, such as supplier provided DP system, can also participate in the simulation process. After each step of the simulation, the fathom core then collects scene information, e.g. position, orientation, speed, pressure and force of each object, and send it to graphics module for visualization. The graphics module can not only visualize 3D tangible objects, but also abstract information such as flow rate, force, velocity and power consumption. Fathom can also deploy the simulation and visualization in a distributed network, meaning some heavy simulation tasks can be dedicated to a separate computer and visualization can also be carried out remotely.

OPERATION PROCEDURE

The entire installation operation can be separated into several key steps:

1. Deploy and moor the spars on the wind farm before turbine installation.
2. Load pre-assemble turbines (including tower, nacelle, blades and hub) onto a single installation vessel(see Fig.5) from an onshore site.
3. After arrival at the wind farm, use longitudinal skid beams to move the pre-assembly along the center line of the vessel, align it to the lifting system,
4. The double-sliding jibs slide towards the center line of the vessel, ready for wire connection.
5. Connect both bottom lifting wires and top tug wires to the tower.
6. Tower lift-off, active 6DOF control OFF.
7. Use double-sliding jibs to transport the tower to the ship side, align the tower to the spar.
8. Active 6DOF control ON, lower the tower to the spar.
9. Tower to spar connection.
10. Disengage lifting system.

We propose this operation procedure in order to reduced the downtime during the operation and with active 6DOF control system working, the weather window can be expanded.

ACTIVE 6DOF COMPENSATION

By changing the length of lifting wires and tug wires, the lifting system is able to control the position and orientation of the top part of the wind turbine. With specifically designed control algorithm, the system can actively compensate the movement of the spar and the vessel, in order to keep a relative static transform between the wind turbine and the spar. The relationship between the world transforms(position and orientations) of the vessel, the tower and the spar can be shown in Eqs. 1-3

$$T_{tower} = T_{spar} \cdot T_{t2s} \tag{1}$$
$$T_{tower} = T_{vessel} \cdot T_{t2v} \tag{2}$$
$$T_{collar} = T_{vessel} \cdot T_{c2v} \tag{3}$$

T_{t2s} is the transform from tower to spar, which is also the control target of the system. In most cases, when the control system is activated, the tower is expected to track the orientation of the spar while also to keep a user-defined vertical distance to the spar top. T_{t2v}, T_{c2v} are the transform from tower to vessel and from collar to vessel. They are derived control target from T_{t2s} assuming the horizontal jibs do not move when 6DOF control is activated. When all lifting wires and tug wires are tensioned and quasi-static(the wind turbine will not go up because of axial rotation), the system becomes over-constrained, T_{t2v}, T_{c2v} become injective functions of the wire lengths [4].

$$T_{t2v} = T_{t2v}(L_{bottom}) \tag{4}$$
$$T_{c2v} = T_{c2v}(L_{top}) \tag{5}$$

L_{bottom}, L_{top} are the lengths of bottom lifting wires and top tug wires. By using reverse kinematics the control target of wire length can be retrieved

$$L_{bottom} = L(T_{t2v}) \tag{6}$$
$$L_{top} = L(T_{c2v}) \tag{7}$$
$$L(T_{a2b}) = dist(T_{a2b} \cdot P_a, P_b) \tag{8}$$

Eq. 8 is the distance function between two ends of the wire. P_a and P_b are points on reference frame a and b.

For four top wires which are connect to the collar, their lengths are defined by the transform of the collar. Naively, the collar should have the same world rotation of the wind turbine and minimize the motion between itself and the lifting tool. So the control target of the collar is

$$R_{collar} = R_{tower} \tag{9}$$
$$T_{collar} = \begin{bmatrix} R_{collar} & P_{collar} \\ 0 & 1 \end{bmatrix} \tag{10}$$

P_{collar} is the point of intersection of a line defined by wind turbine control target and a plane defined by the position of four top winches. One can argue that the collar should also be able to rotate around the tower to achieve minimal tug wire lengths, but current design is proven to sufficient enough and mechanical feasibility should be discussed more thoroughly before making the design decision. The control system can adapt to both configurations with minimal adjustment.

RESULT & ANALYSIS

A scene is setup in FATHOM, see Fig.5. The extra wind turbines both on board and on the ocean surface are added for a more realistic operation condition. The wave condition is following the JONSWAP spectrum with head sea $H_s = 0.1m$ and $T_p = 10s$. On top of that there is $H = 2m$ and $T = 15s$ swell coming from beam sea.

Fig.6 shows the relative motion between the tower and the spar with active 6DOF control system on/off. Tower to spar top view projection shows the trajectory of the center axis of the tower projected to the top surface of the spar, and tower to spar

FIGURE 5. Visualized scene in Fathom

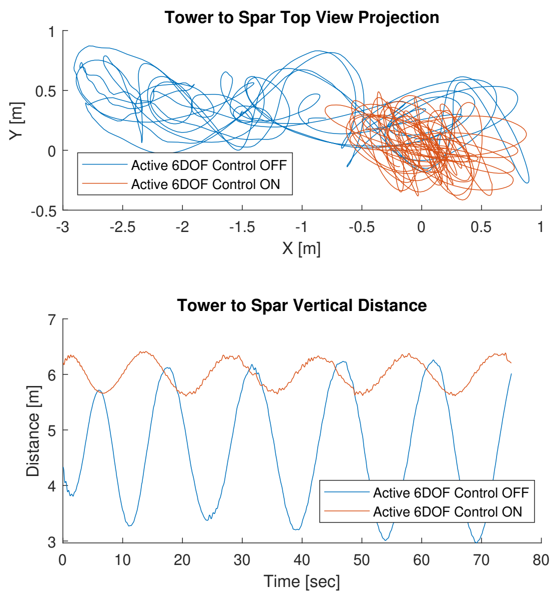

FIGURE 6. Tower to spar relative motion

vertical distance shows the distance between the bottom surface of the tower and the top surface of the spar. The control target of this distance is 6 meters. Fig.6 shows that active 6DOF control system can reduce the relative motion between the tower and the spar.

The effectiveness of the control system and the overall lifting capability of the design is dependent on the capacity of the winches, the material property and the dimension of the wires and the overall structure design of the lifting system, which needs more detailed analysis.

SUMMARY

We have designed a new low-height lifting system for offshore wind turbine installation, particularly for spar foundation wind turbine similar to Hywind Scotland project. The new design exploits the unique characteristic of wind turbine and provides reduced lifting system size and better scalability. A simple but novel active 6DOF compenstaion control algorithm is also proposed in accompany to the system. The new design is prototyped in Fathom simulation software and the result shows this concept is feasible and the control system can minimize the relative motion between the tower and the spar. As this new design is still in concept design phase, new challenges and details will emerge in later design phase.

ACKNOWLEDGMENT

This research is funded by the Research Council of Norway (RCN) project no. 237929: CRI MOVE and in cooperation with Offshore Simulator Centre AS, Norway.

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