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Evaluating a new concept to integrate compressed air energy storage in spar-type floating offshore wind turbine structures

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ABSTRACT

This paper presents a new concept for integrating compressed air energy storage (CAES) into spar-type floating wind turbine platforms. A preliminary investigation of the implications of integrating the proposed concept on the design and dynamic characteristics of a 5 MW floating offshore wind turbine (FOWT) system is presented. A simplified numerical model for sizing the spar to cater for a given compressed air pressure and energy storage capacity is presented. This is then used in a parametric analysis to establish the relationship between the storage capacity, the spar geometry and the additional mass of the floating configuration to support high air pressures. Numerical simulations for the dynamic response are then performed using the marine engineering software tool ANSYS Aqwa© to study the effect of the added steel mass of the spar resulting from CAES integration on the dynamic response characteristics under irregular wave conditions. The results are compared to those derived for a conventional FOWT-spar configuration without an energy storage system. It is shown that it is technically feasible to integrate short-term energy storage capacities on the order of Megawatt-hours. Although integration of CAES in the floating spar results in a significant increase in the weight of the floating structure, it is shown that this also results in a reduction in the motion experienced by the FOWT for the met ocean conditions considered in this study.

1. Introduction

Floating offshore wind turbine (FOWT) technology will unlock the vast wind resources available at more distant and deeper offshore sites (> 100 m depth) where environmental and planning issues are expected to be less problematic. A number of full-scale prototypes have been deployed. It is estimated that eventually, FOWT technology will become cost-competitive when compared to existing seabed-mounted technologies currently used in shallow waters (James and Costa Ros, 2015; Myhr et al., 2014). Many different FOWT support structure concepts are currently under development (James and Costa Ros, 2015). The majority of concepts may be classified into three different groups, depending on the governing principles used to achieve stability: spar-type buoys, which are stabilised using ballast located below the centre of buoyancy of the floater to create a positive metacentric height; semi-submersible platforms which achieve stability through a distributed buoyancy and a wide water plane area; and tension-leg platforms (TLPs) which rely on multiple tensioned moorings to keep the floater stable. The floating spar-buoy concept is apparently the most technically-proven concept for floating wind turbines considering the fact that this technology was adopted in the first ever full-scale FOWT prototype *Hywind*, that had been deployed in Norway by Statoil way back in 2009 (Skaare et al., 2015). The first commercial floating wind farm, consisting of five 6 MW FOWTs supported using similar spar technology has been commissioned by Statoil off the coast of Scotland last year.[1]

As offshore wind capacity is expected to grow significantly over the next decades, the implementation of energy storage technologies will become indispensable to solve the grid-related issues arising from the intermittency of wind power. Different storage technologies for wind farm applications have been considered (Díaz-González et al., 2012; Zhao et al., 2015). Integrating energy storage within the wind turbine structure offshore will not only facilitate energy management, but will also offer opportunities for further cost reductions associated with the long power transmission cables required to transmit the energy to shore. This paper investigates the possibility of integrating compressed air energy storage (CAES) within FOWT spar-type structures using a new concept which is patent pending (Sant and Buhagiar, 2016). In the

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[1] Statoil, https://www.statoil.com/en/news/worlds-first-floating-wind-farm-started-production.html, Accessed December 2017.

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Nomenclature

d	sea depth [m]
f_{sp}	factor of safety for spar [-]
h_1	draft of spar [m]
h_2	total height of spar [m]
h_3	height of spar above mean sea level [m]
p_1	pre-charge or minimum air pressure [N/m^2]
p_2	maximum air pressure [N/m^2]
r_p	air compression ratio [-]
t_{ca}	material thickness of spar required for CAES only [m]
t_{sp}	total wall thickness of spar [m]
t_{st}	wall thickness of spar buoy required for supporting wind turbine without CAES [m]
CoG	centre of gravity location with respect to mean sea level [m]
$C_{D,tw}$	wind turbine tower drag coefficient [-]
CM	centre of mass [m]
D	spar diameter [m]
E	energy storage capacity [Wh]
GM	metacentric height without compressed air [m]
GM_{ref}	metacentric height of reference spar [m]
GM_F	metacentric height when spar is charged to the maximum storage capacity with compressed air [m]
H_w	wave height [m]
H_{rna}	height of RNA above mean sea level [m]
H_{wt}	wind turbine tower height above mean sea level [m]
I	second moment of area of spar about waterplane area [m^4]
M_{ca}	mass of compressed air stored in spar [kg]
M_{fowt}	mass of floating wind turbine (RNA and tower) [kg]
M_{sp}	total mass of spar, excluding ballast [kg]
$M_{sp,b}$	mass of spar ballast [kg]
$M_{sp,ca}$	mass of spar for supporting CAES only [kg]
$M_{sp,tot}$	total mass of spar including ballast and compressed air [kg]
$M_{sp,wt}$	mass of spar materials for supporting FOWT only without CAES [kg]
M_{tot}	mass of the entire floating structure [kg]
R	ideal gas constant [J/kg K]
S_E	specific energy stored [W-h/kg]
T	compressed air temperature [K]
T_z	zero-wave crossing period [s]
V_d	volumetric displacement of spar [m^3]
V_A	internal volume of pressure vessel on sea-bed [m^3]
V_B	internal volume of spar [m^3]
ρ_{sw}	density of sea water [kg/m^3]
ρ_c	density of concrete ballast [kg/m^3]
ρ_{sp}	density of spar material [kg/m^3]
ρ_{sw}	density of sea water [kg/m^3]
σ_y	yield strength of spar material [N/m^2]
σ_H	hoop stress [N/m^2]
σ_L	longitudinal stress [N/m^2]
amsl	above mean sea level [m]
CAES	compressed air energy storage
CoG	centre of gravity
FOWT	floating offshore wind turbine
FoS	factor of safety [-]
MCST	Malta Council for Science & Technology
RMS	Root Mean Square
RNA	Rotor Nacelle Assembly
TLP	tension leg platform

present paper a concept for integrating CAES is presented. The same concept, but applied to FOWT TLP platforms, has already been presented by Sant et al. (2017) elsewhere. This paper presents a preliminary evaluation of the CAES concept for FOWT spar-type floating platforms. A simplified model is presented to determine the spar dimensions for given buoyancy requirements, metacentric height, energy storage capacity and other CAES parameters. A parametric study is then carried out with this numerical model for the NREL 5 MW baseline wind turbine (Jonkman et al., 2009). This is followed by a preliminary structural dynamic analysis of different spar geometries when operating under irregular wave conditions.

2. Background

2.1. A floating spar-type platform with integrated energy storage

Fig. 1 shows the proposed CAES concept integrated in a FOWT spar-type supporting platform. It consists of two pressure vessels interconnected by a pneumatic umbilical. The lower vessel is installed on the seabed while the floating spar serves as a larger second pressure vessel and keeps the FOWT stable and afloat. Once the entire system is deployed at sea, the pressure vessels are pre-charged with compressed air to a pre-set level. Excess energy from the wind turbine during periods of high wind speeds and low energy demand is used to operate a hydraulic machine in pump mode to inject deep sea water at high pressure into the lower pressure vessel. Consequently, energy is stored in the form of compressed air with a uniform pressure maintained in both upper and lower pressure vessels. During periods of high energy demand, stored energy is released by operating the hydraulic machine in motor mode to power an electrical generator. A thermodynamic analysis of the proposed energy storage concept has recently been presented by Buhagiar and Sant (2017). The study has shown that the overall thermal efficiency of the storage cycle was found to reach 95%, when excluding losses associated with the hydraulic machine.

The concept presents a number of advantages:

- Increasing the volume of air by using the floater as a pneumatically-interconnected pressure vessel reduces the pressure ratio of the air compression process required to achieve a desired energy storage capacity. In reality, this reduces the air temperature rise, hence minimising thermal loses and improving the efficiency of each energy storage cycle.
- Compressing air hydraulically through a liquid piston reduces the physical dimensions of the machinery required, given that hydraulic pumps and motors have a higher power-to-weight ratio compared to air compressors and turbines.
- Dedicating the floater support structure to also serve as a CAES

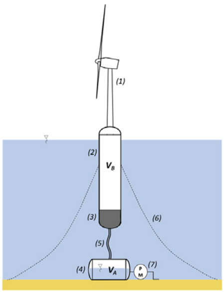

Fig. 1. CAES concept integrated in a FOWT spar-type structure showing the: wind turbine (1), spar supporting the FOWT and compressed air with internal volume V_B (2), concrete ballast (3), seabed pressure vessel with internal volume V_A (4), pneumatic umbilical (5), catenary moorings (6), and a hydraulic pump/motor coupled to an electrical motor/generator (7).