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Ultimate loads and response analysis of a monopile supported offshore wind turbine using fully coupled simulation

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ABSTRACT

The current design of offshore wind turbines follows mainly the IEC 61400-3 standard. The list of Design Load Cases (DLCs) implied for this standard is comprehensive and the resulting number of time domain simulations is computationally prohibitive. The aim of this paper is to systematically analyse a subset of ultimate limit state load cases proposed by the IEC 61400-3, and understand the relative severity among the load cases to identify the most critical among them. For this study, attention is focused on power production and parked load cases. The analysis is based on the NREL 5 MW prototype turbine model, mounted on a monopile with a rigid foundation. The mudline overturning moment, as well as the blade-root in-plane and out-of-plane moments are taken as metrics to compare among the load cases. The simulations are carried out using the aero-hydro-servo-elastic simulator, FAST, and the key observations are thoroughly discussed. The DLC 1.6a is shown to be the most onerous load case. Although the considered load cases are limited to power production and idling regimes, the obtained results will be extremely useful for the substructure (monopile) design and for efficient reliability analysis subsequently, as is also shown partially by some previous studies.

1. Introduction

Depleting fossil fuel reserves and ever-increasing demand for energy have resulted in rapid development of renewable energy sources. Offshore wind energy presents huge potential in this regard. The combination of the hydrodynamic loading from waves and current, the aerodynamic effects of wind, structural dynamics of the support structure, and the nonlinear effects of the controller together make the design of Offshore Wind turbines a very challenging exercise. From a structural design perspective, several factors have to be considered in the design of Offshore Wind Turbine (OWT) support structures, which are absent in their onshore counterparts.

The current design of OWT support structures is performed largely following the IEC 61400-3 standard [1], which proposes a number of design situations representing the various modes of operation of the turbine, with each design situation leading to a number of Design Load Cases (DLCs). The IEC standard distinguishes two types of load cases, namely ultimate and fatigue load cases, with a further subdivision of Ultimate Limit State (ULS) cases as Normal, Abnormal and Transportation cases. The design standard recommends appropriate load factors to be associated with these load cases and also offers guidance on methods of evaluating the DLCs in order to check the structural integrity of the offshore wind turbine. The background work that forms the basis of the DLCs is proposed in Refs. [1,2] and is summarized in technical reports [3].

The DLCs listed in the IEC standard are comprehensive and require thousands of time domain simulations. There have been efforts to study various DLCs in detail. RECOFF [3] was the first project that addressed the complexity of the combination of the Oil&Gas offshore standards and the existing onshore wind energy standards, proposing a series of recommendations for the design of OWT [4], it also led to the elaboration of the IEC 61400-3 [1]. Other authors such as Tarp-Johansen applied the design standards to the design of OWT in the US and also studied the partial safety factors and characteristic values for extreme load effects [5,6]. More

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Table 1
General specifications of the 5 MW monopile OWT [19].

Rotor/Nacelle assembly	
Rated power	5 MW
Number of blades/radius	3/63 m
Cut-in, Cut-out wind speed	3 m/s, 25 m/s
Controllers	Collective pitch control and generator torque control (variable speed)
Rated rotor speed	12.1 rpm
Support structure/foundation	
Structure	Monopile with rigid foundation
Hub height	90 m above MSL
Water level	20 m above seabed

Table 2
Extreme wave heights and wind speed at the hub as a function of the return period.

T_{return} [yr]	H_S [m]	T_P [s]	$H_{\max}$ [m]	V_{hub} [m/s]
1	6.06	9.70	11.27	31.70
50	8.07	11.3	15.64	42.04

Table 3
Wind-conditioned wave height and the corresponding spectral peak period.

V_{hub} [m/s]	H_S [m]	T_P [s] (mean)
4	1,10	5,88
6	1,18	5,76
8	1,31	5,67
10	1,48	5,74
12	1,70	5,88
14	1,91	6,07
16	2,19	6,37
18	2,47	6,71
20	2,76	6,99
22	3,09	7,40
24	3,42	7,80

recently NREL did a lot of work related to floating OWTs, studying the influence of the simulation length of the DLC on the uncertainties in ultimate and fatigue loads [7] and structural response of different OWT concepts, while also comparing the results with the onshore structures. Agarwal [8,9] studied the DLC 1.2 (normal operation in turbulent wind and stochastic waves) in detail and the implications of nonlinear wave loading on the load extrapolation procedure. Moriarty et al. [10] studied the DLC 1.1/1.2 and outlined a method of statistical extrapolation procedure. Cheng [11] performed a thorough analysis on the effect of the number of wind and wave seeds and simulation length on the maximum response distribution and concluded that 50 simulations of 40mins can be considered sufficient for studying the chosen responses.

A number of relevant DLCs proposed by the IEC standard were studied in the UPWind project [12,13]. In the preliminary design phase of UpWind 4.2.5 [12] the wind loads were studied through the fatigue DLCs 1.2 and 6.4 and the extreme cases 1.3, 1.4, and 6.2a in a calm sea for a jacket substructure. For the final design phase, the considered DLCs were 2.2 and 2.3 which include system faults, and 1.6a, 6.1a and 6.2a. However, these studies were based on the assumptions such as 1-min turbulent wind and a positive small yaw misalignment. The fault cases were found not to be influencing the support structure, whereas DLC 6.1 showed the severest load condition. In addition, UpWind 4.2.8 [13] considered a reference support structure for monopile and jacket and applied a subset of DLCs on these structures. This work considered the fault load cases among other ULS load cases. The results of the ULS checks for the substructure (yield and buckling) showed that DLCs 6.1a and 6.2a appear to be governing for the monopile, whereas fault DLCs were again not influencing the loading at the seabed level. The fault cases were found to be relevant to the tower. It is to be noted that, in these studies [12,13] the DLCs were not studied in detail to understand the causes of the maximum values and the parameters affecting them, only the results at different locations of the structure were shown.

Kim et al. [14] focused on identifying the effect of the substructure type on the load characteristics of the superstructure such as the blade, hub or tower under ULS DLCs 1.6a, 6.1a and 6.2a and fault DLCs 2.1 and 2.2. The latter were not found to be design driving in any case for the monopile. It is to be noted that the focus on substructure was limited in this study, as the emphasis was more on blades and tower-top interface. Cordle et al. [15] studied the design drivers for OWTs using jacket support structures and investigated the fatigue DLCs 1.2 and 6.4, in addition to a previously considered set of extreme DLCs. It was observed that the severest extreme loading combination was given by DLC 6.1a. A clear understanding of the significance of parameters affecting the extreme values of different DLCs provides an opportunity to study the reliability of OWT substructures efficiently [16]. More recently, Galinosa et al. [17] presented a detailed load case analysis for onshore Vertical Axis Wind Turbines (VAWT) and compared with corresponding loads for Horizontal Axis Wind Turbines (HAWT). However, as the focus was on onshore turbines, it is not directly relevant for the present work.

To conclude, despite the extensive literature sampled above, to the authors' knowledge, there exists no work that systematically compares all the potentially relevant design load cases for substructure design, and ranks them in order to offer useful starting points for designers and researchers. This work aims to fulfil this gap by developing a comprehensive analysis of the most relevant Ultimate Limit State DLCs that a designer has to go through to assure that the OWT will perform satisfactorily for the entire design life. The DLCs studied are taken from the IEC 61400-3 [1] standard. The focus is on power production and parked/idling load case subset, specifically on DLCs 1.1, 1.3, 1.4, 1.5, 1.6a, 6.1a and 6.2a. The cases considered in this study were limited to those driving the design loads for the pile and being dominated by wave and wind

Table 4
List of design load cases.

DLC	Wind		Waves		Control/Events
	Model	Speed	Model	Height	
1.1	NTM	$V_{in} < V_{hub} < V_{out}$	NSS	$H_S = E[H_S\|V]$	Extrapolation of loads
1.3	ETM	$V_{in} < V_{hub} < V_{out}$	NSS	$H_S = E[H_S\|V]$	
1.4	ECD	$V_{hub} = V_r \pm 2\frac{m}{s},\ V_r$	NSS	$H_S = E[H_S\|V]$	
1.5	EWS	$V_{in} < V_{hub} < V_{out}$	NSS	$H_S = E[H_S\|V]$	
1.6a	NTM	$V_{in} < V_{hub} < V_{out}$	SSS	$H_S = H_{s,SSS}$	
6.1a	EWM	$V_{hub} = 0.95 \cdot V_{ref}$	ESS	$H_S = 1.09 \cdot H_{S,50}$	
6.2a	EWM	$V_{hub} = 0.95 \cdot V_{ref}$	ESS	$H_S = 1.09 \cdot H_{S,50}$	Loss of electrical network
6.2b	EWM	$V(z_{hub}) = V_{e50}$	RWH	$H_S = H_{red50}$	Loss of electrical network