Dynamic Performance Analysis of a 15MW Floating Offshore Wind Turbine in the Ninh Thuan Offshore Area

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ABSTRACT: Vietnam possesses significant untapped potential for offshore wind power, serving as a crucial catalyst for the nation's transition towards sustainable energy sources. In addition to fixed offshore wind turbines, the implementation of floating offshore wind turbines (FOWTs) holds immense promise in leveraging domestic supply chain resources. This research paper aims to explore the viability of FOWTs in the offshore areas of Vietnam. Specifically, a 15 MW offshore wind turbine mounted on a semi-submersible floating platform was chosen as the focus of this study, with the environmental conditions modeled based on the Ninh Thuan offshore area. The NREL OpenFAST code was employed to simulate the behavior of the FOWT systems, enabling a comprehensive analysis of their loads and overall performance.

1. INTRODUCTION

Vietnam possesses significant untapped potential for offshore wind power (Quang et al., 2020), making it a critical catalyst for the nation's transition towards sustainable energy sources. Vietnam's offshore regions, particularly the Ninh Thuan and Binh Thuan offshore areas, hold substantial potential for harnessing offshore wind energy. In Binh Thuan, the water depths are predominantly shallow, making it conducive for the deployment of fixed wind turbines. Conversely, the Ninh Thuan offshore area, characterized by water depths ranging from approximately 100 to 300 meters, presents favorable conditions for the utilization of floating wind turbines. In addition to fixed offshore wind turbines, the implementation of floating offshore wind turbines (FOWTs) holds immense promise in leveraging domestic supply chain resources. This research paper aims to explore the viability of FOWTs in the offshore areas of Vietnam, focusing on a 15 MW offshore wind turbine mounted on a semi-submersible floating platform. The environmental conditions in the Ninh Thuan offshore area were modeled to provide a realistic representation for analysis. To evaluate the performance and behavior of the FOWT systems, we employed the NREL FAST code, enabling a comprehensive analysis of loads and overall system performance.

By examining the feasibility and potential of FOWTs in the specific context of Vietnam, this study aims to contribute valuable insights for policymakers, researchers, and industry stakeholders. The findings can inform decision-making processes, foster the development of offshore wind energy projects, and facilitate the transition towards a more sustainable and renewable energy landscape in Vietnam.

The remainder of this paper is structured as follows: section 2 provides information of the 15 MW reference offshore wind turbine, the semi-submersible floater and the mooring system. Section 3 and 4 present the methodology employed in this study, including the modeling of the simulation and environmental conditions based on

Ninh Thuan offshore area. Section 5 presents the results and analysis of the FOWT system performance. Finally, Section 6 concludes the paper with a summary of the findings and recommendations for future research and implementation.

2. 15 MW SEMI-SUBMERSIBLE FLOATING OFFSHORE WIND TURBINE MODEL

This section provides a comprehensive presentation of the specific specifications of the key components utilized in this study: the 15 MW wind turbine, the semi-submersible floating platform, and the mooring system. Fig. 1 and Fig. 2 offer visual representations showcasing the overall configuration of the 15 MW wind turbine system and the detailed layout of the mooring system, respectively

2.1 Wind turbine

The wind turbine utilized in this study is the International Energy Agency (IEA)-15-240-RWT, which is a reference wind turbine with a power rating of 15 megawatts (MW) (Gaertner et al., 2020) . This turbine is an open source for research of modern floating offshore wind turbine. The IEA-15-240-RWT features an upwind configuration with three blades. It incorporates a variable-speed control system along with collective pitch control, enabling optimal power generation and improved efficiency. The rotor diameter measures 240 meters, and the hub height of the wind turbine stands at 150 meters. The detailed specifications of the wind turbine are shown in Table 1.

2.2 Platform

Table 2 presents the semi-submersible floating platform specifications which are based on the UMaine VolturnUS-S Reference Platform (Allen et al., 2020). This innovative platform design offers stability and adaptability, making it suitable for offshore wind installations. The platform has a volume displacement of 20,206 cubic meters, providing buoyancy to support the wind turbine and other components. With a freeboard of 15 meters and a draft of 20 meters, the platform strikes a balance between stability and minimizing the vertical profile above the water surface. The platform's center of buoyancy is positioned below the still water level at -13.63 meters, contributing to the platform's stability. The total mass of the platform is 17,839 tons, and the center of mass (CM) lies below the still water level at -14.94 meters. The platform's roll inertia about the CM is 1.25E+10 kgm², the pitch inertia is 1.25E+10 kgm², and the yaw inertia is 2.37E+10 kgm². These specifications ensure that the platform maintains stability and withstands environmental loads while accommodating the wind turbine's operations.

Table 1 15-MW offshore wind turbine specifications (Gaertner et al., 2020)

Description	Value
Rated power of wind turbine	15
Rotor orientation	Up wind, 3 blades
Control	Variable speed, collective pitch
Rotor diameter [m]	240
Hub height [m]	150
Cut-in, rated, cut-out wind speed [m/s]	3/10.59/25
Rated rotor speed [rpm]	7.56 (Gearless)
Rotor Nacelle Assembly (RNA) Mass [t]	991
Tower Mass [t]	1263

Table 2 Semi-submersible floating platform specifications (Allen et al., 2020)

Description	Unit	Value
Volume Displacement	m^3	20,206
Freeboard	m	15
Draft	m	20
Center of Buoyancy below still water level (SWL)	m	-13.63
Platform Mass	ton	17,839
Center of Mass (CM) of Platform below SWL	m	-14.94
Platform Roll Inertia about CM	kgm^2	1.25E+10
Platform Pitch Inertia about CM	kgm^2	1.25E+10
Platform Yaw Inertia about CM	kgm^2	2.37E+10

2.3 Mooring system

The mooring system, as shown in Table 3, includes three catenary mooring lines. Each mooring line is constructed using R3 Studless Mooring Chain with a nominal diameter of 185 millimeters. The mooring lines have an axial stiffness of 3,270 MN (Mega-Newtons) and an unstretched length of 850 meters. The fairleads, located at a depth of 14 meters below the still water level, have a radius of 58 meters. The mooring lines connect to the anchors, situated at a radius of 837.9 meters.

Table 3 Mooring system specifications (Allen et al., 2020)

Description	Unit	Value
Water depth	m	200
Number of mooring lines		3
Line type		R3 Studless Mooring Chain
Mooring chain nominal diameter	mm	185
Mooring line mass density (air)	kg/m	685
Axial stiffness (EA)	MN	3,270
Unstretched mooring line length	m	850
Depth to fairleads below SWL	m	14
Radius to fairlead	m	58
Radius to anchor	m	837.6
Minimum Breaking Load (MBL)	kN	22,286

3. NUMERICAL SIMULATION TOOL

The simulation of the 15 MW FOWT system was conducted using the open-source code OpenFAST (OpenFAST 2018), an aero-hydro-servo-elastic wind turbine simulation software developed by the National Renewable Energy Laboratory (NREL). The validation of the FAST code has been accomplished through a comparative analysis with either a model test involving a semi-submersible floating wind turbine, as detailed by Coulling et al. (2013), or within the context of the OC5 phase II project, as documented by Robertson et al. (2017). An overview of the OpenFAST code is shown in Fig. 3. In this paper, the numerical simulation model of whole the 15 MW semi-submersible system was developed and published (Garrett et. al 2022)

OpenFAST offers a robust platform that integrates wind, wave, and current simulations, as well as dynamic mooring system modeling. By inputting key parameters, such as the elastic model of the blades and tower, aerodynamic properties of the airfoil, control schedule for generator torque and blade pitch angle, and hydrodynamic data of the platform, OpenFAST simulates the entire FOWT system under complex environmental conditions.

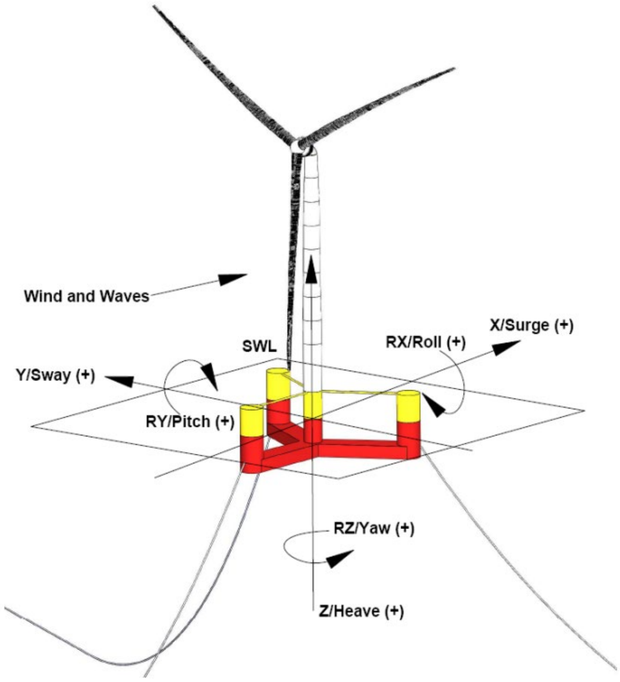

Figure 1. Overview of the 15 MW semi-submersible floating offshore wind turbine.

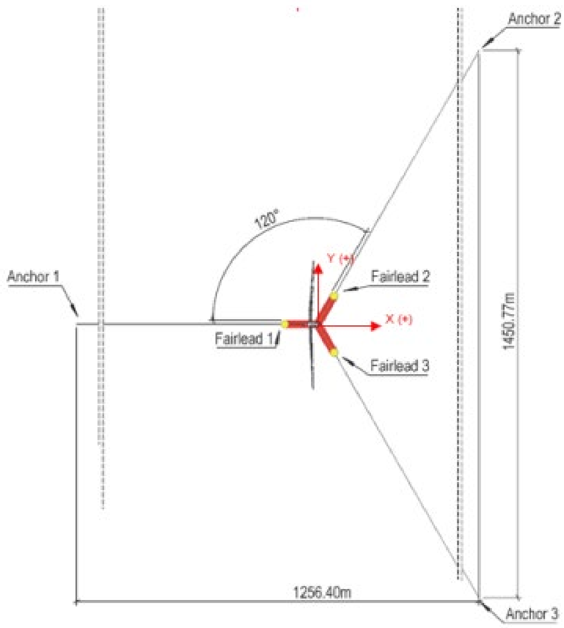

Figure 2. Configuration of the mooring system

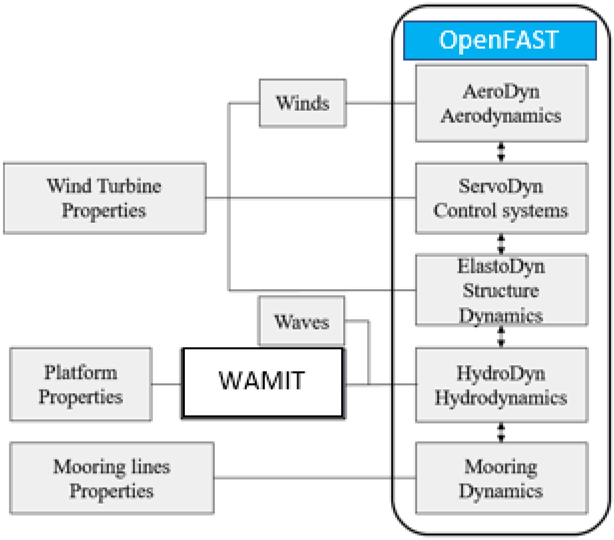

Fig. 3 OpenFAST structure

4. ENVIRONMENTAL CONDITIONS

In order to comprehensively assess the response of the FOWT system, environmental conditions of Ninh Thuan offshore were gathered and consolidated using data provided by the Vietnam Institute of Seas and Islands. Moreover, adhering to the guidelines specified in the IEC 61400-3-2 standard (IEC 2019), this study focuses on the analysis of three distinct design load cases (DLCs). Each DLC corresponds to a unique environmental scenario, playing a vital role in evaluating the system's performance under various conditions.

DLC1.1 encompasses normal turbulence winds, typical sea state waves, and wind-generated current speeds. This DLC provides a baseline for evaluating the FOWT system's behavior under regular operating conditions. It allows for the examination of how the turbine responds to standard wind and wave patterns, as well as the impact of wind-generated currents on the overall system performance.

DLC1.6a focuses on normal turbulence winds, a severe sea state wave, and normal current speeds. By introducing a severe sea state wave, DLC1.6a aims to assess the FOWT system's response under more challenging wave conditions. This DLC provides valuable insights into how the turbine copes with elevated wave heights while considering the impact of turbulence and current speeds on the overall system dynamics.

DLC6.1a represents an extreme environmental condition with a 50-year-return period. It incorporates extreme wind speeds, wave heights, and current speeds to evaluate the FOWT system's robustness and survivability under severe conditions. DLC6.1a is crucial for understanding the system's behavior during rare, high-intensity events and contributes to the assessment of long-term system reliability. In this DLC, the wind turbine is parked, and blade angle is set at 90^0.

Detailed wind, wave, and current conditions for each DLC are listed in Table 5. The sea states ranging from 1 to 11 represent normal sea states, while sea states 12 and 13 correspond to extreme sea states over a 50-year-return period. To accurately model turbulent wind conditions, the Turbsim program (Jonkman, 2014) is utilized, generating realistic wind models with statistical characteristics. Additionally, irregular waves based on the JONSWAP spectrum are generated using the OpenFAST, ensuring accurate representation of wave conditions for the FOWT system.

Table 4. Design load cases

Item	DLC1.1	DLC 1.6a	DLC 6.1a
Wind model	NTM	NTM	EWM
Sea state	NSS	SSS	ESS
Wind and wave directionality	0°, COD	0°, COD	0°, COD
Current model	NCM	NCM	ECM
Wind turbine status	Operation	Operation	Parked, RNA Yaw $0,\pm8^0$ blades: 90^0

Note: COD is co-directional, ECM is extreme current model, ESS is extreme sea state, EWM is extreme wind speed model, NTM is normal turbulence model

Table 5. Sea states based on data from Vietnam Institute of Seas and Islands

DLC	Sea State	Wind	Wave Hs	Wave Tp	Current
		m/s	m	s	m/s
DLC1.1	SS1	4	0.12	2.9	0.4
DLC1.1	SS2	6	0.47	2.9	0.4
DLC1.1	SS3	8	0.63	2.9	0.4
DLC1.1	SS4	10	1.05	3.68	0.4
DLC1.1	SS5	12	1.33	3.88	0.4

DLC1.1	SS6	14	1.81	4.51	0.4
DLC1.1	SS7	16	2.36	5.08	0.4
DLC1.1	SS8	18	3.01	5.74	0.4
DLC1.1	SS9	20	3.79	6.38	0.4
DLC1.1	SS10	22	4.71	7.18	0.4
DLC1.1	SS11	24	5.6	7.72	0.4
DLC1.6	SS12	4-24	8.8	10	0.4
DLC6.1	SS13	42.1	8.8	10	1.47

5. RESULTS

The output obtained from the OpenFAST simulation consists of time-series data encompassing various parameters such as wind turbine displacement, loads, and performance. Fig. 4 illustrates the mean values and standard deviations of surge motion, pitch angle, and wind turbine generator output power under normal operation condition of DLC1.1. The average offset position of the floating platform is approximately 20 meters, while the mean platform pitch angle remains about 4 degrees. Due to the platform's pitch angle, the rated generator power is slightly lower than 15 MW. Figs 5 to 9 present the maximum values recorded for important parameters across the three Design Load Cases (DLCs). These values are obtained from the time history output of OpenFAST and offer valuable insights into extreme events. This analysis enables the identification of critical events and enhances the comprehension of the system's behavior under various DLCs.

As illustrated in Fig. 5, the greatest out-of-plane blade deflection is observed during DLC1.6, which represents wind turbine operation under extreme wave conditions.

Fig. 6 and Fig. 7 present the maximum values of platform movements. The highest Surge motion reaches approximately 28.3 units, equivalent to 14% of the water depth (200m). This parameter plays a crucial role in ensuring the safety considerations during the design of the array power cable. The maximum sway occurs during the parked wind turbine condition of DLC6.1a. This sway is attributed to the wind turbine blades being aligned at 90 degrees to rotor plane, generating lateral thrust that causes the entire system to shift sideways. Furthermore, the maximum roll rotation is also induced by this force, as shown in Figure 7, with a value below 6 degrees. As a result of this alignment, the platform yaw also reaches its maximum, approximately 4 degrees. Lastly, the peak platform pitch angle reaches approximately 6 degrees under wind turbine operating conditions of DLC1.6a.

Relating the nacelle acceleration of floating offshore wind turbine, as displayed in Fig. 8, it is evident that the highest acceleration is observed during DLC 6.1a, with a value is 2.5 m/s^2. Additionally, the maximum acceleration experienced during operational wind turbine conditions is recorded at 2.3 m/s^2. These acceleration values conform to the recommended limits outlined by the wind turbine manufacturers for safe operation, it's about 3 m/s^2.

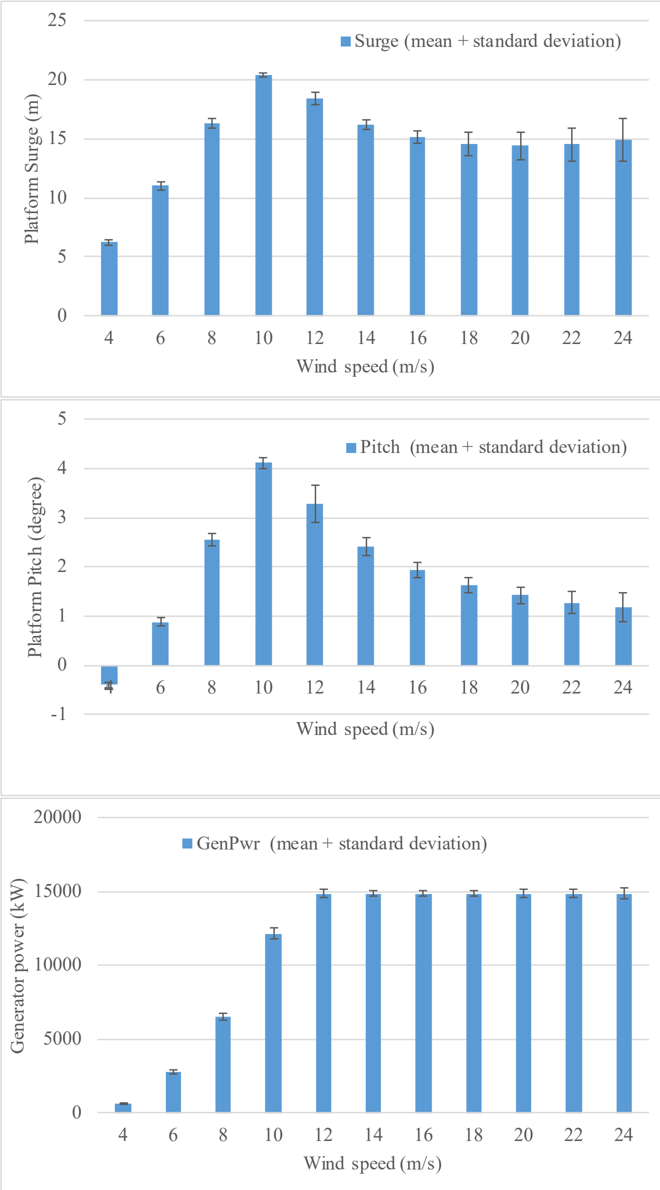

Figure 4. Mean values and standard deviations under normal operation conditions.

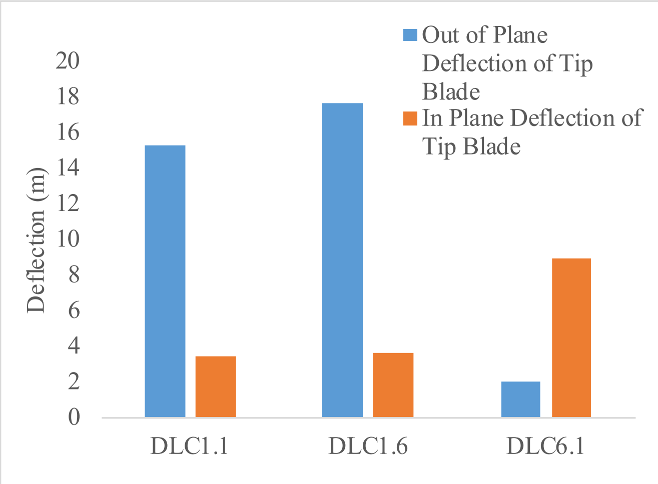

Figure 5. Extreme blade deflection for three DLCs

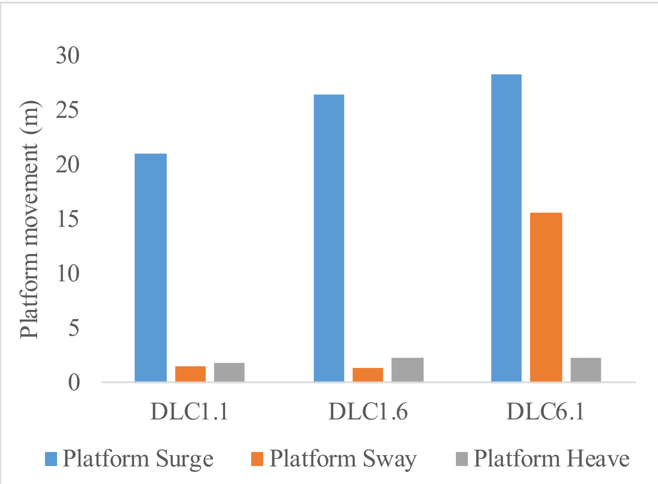

Figure 6. Extreme responses of floating platform for three DLCs

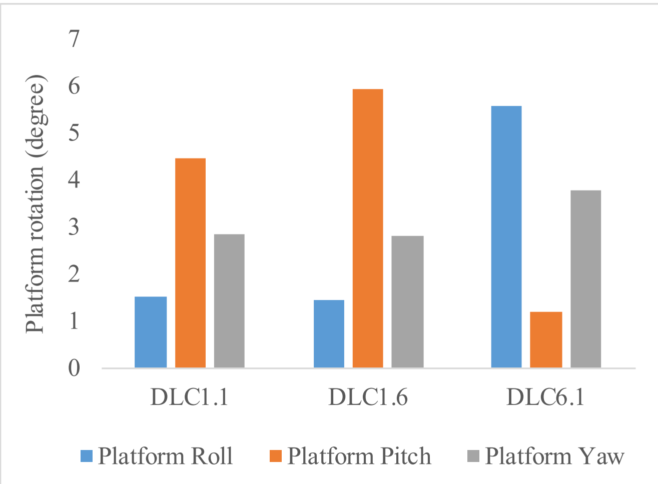

Figure 7. Extreme platform rotations for three DLCs

Fig. 9 depicts the fairlead tension within the mooring system for three DLCs. It was determined that the maximum tension occurs during the extreme environmental conditions of DLC 6.1a. The recorded maximum tension reached 5340 kN, which is approximately 24% of the chain's breaking strength. This indicates a safe design for the mooring system. It should be noted that future mooring system designs may take into account variations in water depth to optimize system performance

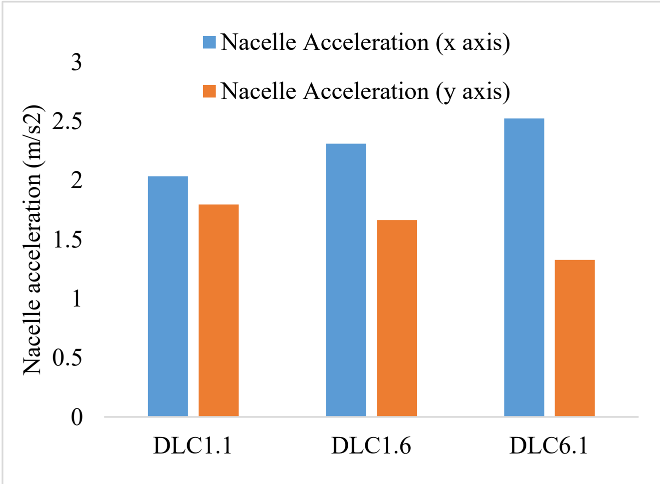

Figure 8. Extreme nacelle acceleration for three DLCs

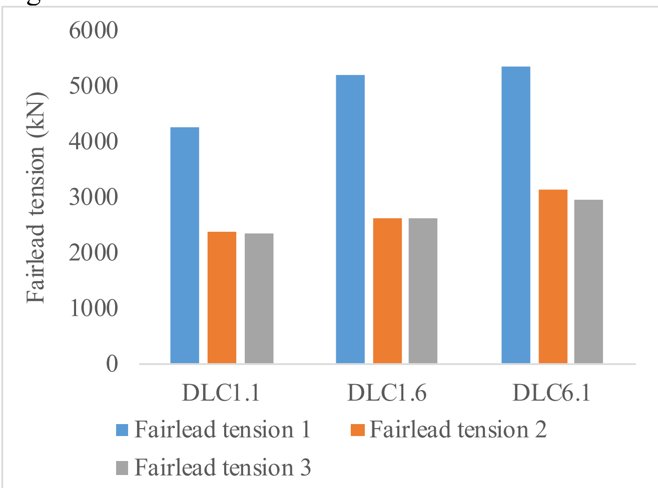

Figure 9. Extreme fairlead tensions for three DLCs

6. CONCLUSIONS

This paper has presented a comprehensive analysis of the viability of a large FOWT in the offshore areas of Ninh Thuan offshore. Through the utilization of advanced simulation tools and careful consideration of environmental conditions, valuable insights have been obtained regarding the behavior and performance of the FOWT system.

The results obtained from the OpenFAST simulation, including time-series data and statistical analyses, have shed light on various parameters such as wind turbine displacement, loads, and performance. The mean values and standard deviations of surge motion, pitch angle, and wind turbine generator output power under DLC1.1 normal operation condition have been examined.

The maximum values of important parameters across the three DLCs have been identified. These extreme values, extracted from the time history output, have provided valuable insights into critical events. Notably, during DLC1.6a representing wind turbine operation under extreme wave conditions, the largest out-of-plane blade deflection was observed. The analysis has highlighted the maximum values of platform movements. The surge motion, reaching approximately 14% of the water depth, has implications for the design of the array power cable. Extreme platform pitch, nacelle acceleration and mooring line tensions are all suitalbe for operational of wind turbine.

These findings contribute to the understanding of the FOWT system's response and performance under different environmental conditions, providing valuable insights for the design, operation, and planning of offshore wind energy projects in Ninh Thuan offshore area. The comprehensive assessment carried out in this study assists in mitigating risks, optimizing system design, and ensuring the long-term reliability and sustainability of floating offshore wind power in Ninh Thuan's offshore regions.

The research conducted in this paper facilitates the progression towards a more sustainable and renewable energy landscape in Ninh Thuan, leveraging the untapped potential of offshore wind power and paving the way for a greener future.

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