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CONCEPTUAL DESIGN OF A HYBRID FLOATING OFFSHORE WIND TURBINE INTEGRATED WITH HYDROGEN PRODUCTION AND STORAGE SYSTEM

Thanh Dam Pham
University College Cork
Cork, Ireland

Luan Cong Trinh
Technological University of the Shannon: Midlands Midwest
Limerick, Ireland

Van Nguyen Dinh
OWC, ABL Group
Cork, Ireland

Paul Leahy
University College Cork
Cork, Ireland

ABSTRACT

The shift towards renewable energy requires sustainable energy carriers, with hydrogen emerging as a crucial player in creating a lasting and stable decarbonized energy sector. Floating offshore wind turbines are expected to become a major contributor to renewable electricity because they can harness wind energy over a vast area of the ocean, areas which fixed-bottom wind turbines cannot reach. Combining floating offshore wind turbines with hydrogen production and storage potentially creates a powerful solution to address the variability of wind energy and allows the production of zero-carbon "green" hydrogen from wholly renewable sources. Additionally, integrating hydrogen systems with large floating offshore wind turbines allows for decentralized and easily-scalable energy production and storage. This approach not only boosts energy security in coastal and island states but also reduces dependence on existing energy networks.

This paper introduces a conceptual design of a hybrid system. It integrates a 15 MW semi-submersible floating offshore wind turbine with a hydrogen production and storage unit, both mounted on the same semi-submersible floating platform. The system mass properties are modeled in Catia, and its dynamic behaviors are analyzed using the OpenFAST software. Essential tests performed include free decay tests and response amplitude operator analysis to observe the platform's movements. The primary goal is to verify the system stability during different operational events and varying environmental factors. The analysis emphasizes the advantages and potential of combining offshore wind turbine technology with hydrogen storage and production systems.

Keywords: Floating offshore wind turbine, hydrogen production, hydrogen storage, response amplitude operator.

NOMENCLATURE

AC	alternating current
CoG	center of gravity
CoG_z	center of gravity in vertical direction
DC	direct current
DoF	degree of freedom
FOWT	floating offshore wind turbine
FWHS	floating wind + hydrogen production + storage
LC	load case
MEA	membrane electrode assemblies
NREL	national renewable energy laboratory
NTM	normal turbulent model
PEM	proton exchange membrane
RAO	response amplitude operator
RNA	rotor nacelle assembly
SWL	still water level

1. INTRODUCTION

The global energy landscape is undergoing a paradigm shift towards renewable energy sources, driven by growing concerns about climate change and the need for sustainable energy production [1], [2]. Among the various renewable energy options, offshore wind power has emerged as one of the most promising solutions, harnessing the vast wind resources over the ocean [3]. However, the deployment of offshore wind turbines in deeper waters poses significant challenges [4]–[6]. To overcome these challenges, FOWTs have been developed, offering greater flexibility in site selection and increased access to wind resources.

In conjunction with FOWTs, hydrogen production and storage systems can be integrated to create a decentralized and sustainable energy system. Hydrogen, a clean and versatile energy carrier, can be produced from renewable electricity through electrolysis, a process that splits water molecules into hydrogen and oxygen. Storing the produced hydrogen in high-pressure tanks allows for the decoupling of energy production and consumption, providing flexibility in energy management.

This paper presents a conceptual design for a hybrid floating offshore wind turbine system integrated with hydrogen production and storage. The system consists of a 15 MW semi-submersible FOWT [7], a PEM electrolyzer for hydrogen production, and high-pressure storage tanks for storing the produced hydrogen. PEM is chosen as the electrolyzer technology due to its good load-following capabilities which allow it to integrate smoothly with variable electricity sources. The system is modeled using Catia and NREL OpenFAST (formerly known as FAST) [8] for dynamic analysis. Free decay tests and RAO analysis are conducted to evaluate the stability and dynamic performance of the system under different operational events and environmental conditions. The results demonstrate the feasibility and potential of the hybrid system to provide a decentralized, renewable, and sustainable energy solution.

2. MODEL DESCRIPTION

2.1 Principal diagram

The decentralized floating offshore hydrogen production system represents an innovative integration of renewable energy generation and hydrogen fuel production [9]. The generated electricity is initially subjected to voltage regulation through a transformer, subsequently being rectified into direct current. This direct current is then utilized to power PEM electrolyzers. FIGURE 1 presents the schematic if the components of the FOWT and hydrogen production and storage system.

The PEM electrolyzer operates using a specialized water source. It draws from a system engineered to produce freshwater directly from seawater, with the resultant freshwater stored in a feed water tank. The electrolysis process, facilitated by the electrolyzer, results in the production of hydrogen (H_2) and oxygen (O_2) gases. While the oxygen is released into the atmosphere in a controlled manner in order to ensure environmental safety, the hydrogen undergoes a drying process before being temporarily stored in a buffer tank.

Subsequent to the storage in the buffer tank, air compressors are employed to pressurize the hydrogen gas. This compression achieves high pressures, potentially ranging from 35 MPa to 70 MPa. The compressed hydrogen is then stored in specially designed storage tanks that are strategically located within the offshore platform.

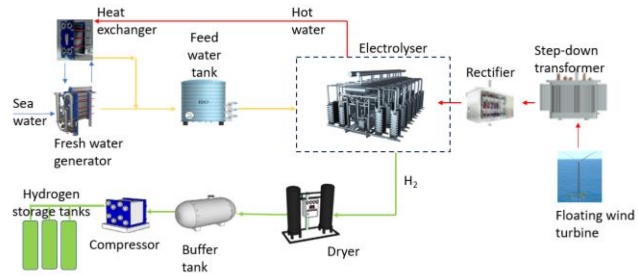

FIGURE 1: SCHEMATIC REPRESENTATION OF THE COMPONENTS OF THE FOWT AND HYDROGEN PRODUCTION AND STORAGE SYSTEM

2.2 Floating offshore wind turbine and hydrogen sub-system.

The integration of a hydrogen production and storage system with the 15 MW semi-submersible FOWT [7] marks a significant advancement in sustainable energy solutions. This system, which includes modifications to the upper structure of the platform to accommodate an additional steel deck and adjustments to the fluid ballast system, ensures that the total mass and design draft of the original FOWT system is maintained. The primary specifications of this innovative FOWT are detailed in TABLE 1, while its original configuration is depicted in FIGURE 2.

Central to the hydrogen production process are several key components, each contributing significantly to the efficiency and effectiveness of hydrogen generation. TABLE 2 presents the mass distribution of the equipment within the hydrogen sub-system and the storage tanks. The essential components include:

Step-down Transformers: Critical for modulating the voltage levels from the wind turbine generator to meet the requirements of the electrolyzer and its associated sub-systems.

Rectifiers: Convert alternating current (AC) to direct current (DC), a required step for the functionality of subsequent components such as the electrolyzer system.

Silyzer 300 PEM Modules: The heart of the hydrogen production process, these modules facilitate electrolysis as shown in FIGURE 3. The Energy Silyzer 300 from Siemens, operating on the PEM electrolysis principle, is key to the hydrogen production in this study. It features advanced PEM modules comprised of multiple electrolysis cells that enable the efficient production of hydrogen and oxygen. Siemens Energy's specially designed MEA enhances the electrolyzer's performance and efficiency. This system's adaptability, especially in response to rapid load changes and its ability to operate effectively across a power range of 10 to 100% of its nominal output, is particularly advantageous when paired with renewable energy sources. The study employs four Energy Silyzer 300 arrays, providing a total capacity of approximately 12 MW specifically for hydrogen production. This represents about 80% of the power output from a 15 MW rated turbine.

Important to note that the remaining 3 MW of power is strategically allocated for storage in a battery system. This stored energy is essential for powering auxiliary systems, such as dryers, compressors, and other necessary operational components.

Dryers: Remove moisture from the hydrogen gas, ensuring its purity.

Compressors: Increase the pressure of the hydrogen gas to the desired levels for storage or transportation.

Fresh water generators and heat exchanger: Produce the necessary fresh water for hydrogen production and recover heat loss from the electrolyzer.

Frame, pipe, and outfitting: Provide structural support and connectivity for the entire hydrogen production system.

Control Room: A center for monitoring and managing the hydrogen production process, also housing spare parts, battery and essential equipment.

The Storage Tanks for storing hydrogen at high pressure are constructed from advanced composite materials. Their detailed specifications are provided in FIGURE 4 and TABLE 3, demonstrating their integral role in the system.

The arrangement of these components on the additional deck is carefully carried out to maintain the CoG at the platform's center along the x and y axes. FIGURE 5 illustrates this layout and the integration of the entire system on the platform. With a total system mass of 1,314 tons and an average CoG_z of 2.51 m, the FWHS platform exhibits altered properties compared to the original design, as shown in TABLE 4. Despite these changes, the total mass of the system is maintained by adjusting the fluid ballast, resulting in a higher CoG for the FWHS platform.

TABLE 1 FLOATING OFFSHORE WIND TURBINE BASIC PROPERTIES [7], [10]

Parameter	Units	Value
Turbine Rating	MW	15
Hub Height	m	150
Platform Type		semi-submersible
Freeboard	m	15
Draft	m	20
Hull Displacement	m^3	20,206
Platform Mass	ton	17,754
Tower Mass	ton	1,263
RNA Mass	ton	991
Water Depth	m	200
Mooring System		Three-line chain catenary

TABLE 2 MASS DISTRIBUTION OF EQUIPMENT OF HYDROGEN PRODUCTION AND STORAGE SYSTEM

Equipment	Mass (ton)	CoG_z from SWL (m)
Step-down Transformers	27	14.80
Rectifiers	21	14.80
Silyzer 300 PEM Modules	70	15.95
Dryers	8	16.15
Buffer Tank	10	15.80
Compressors	6	15.85
Feed Water Tank	15	15.93
Fresh Water Generators	2	15.80
Frame + Pipe + Outfitting	100	15.85
Control Room	50	15.80
Deck	330	14.10
Storage Tanks	675	-9.20
Sub-total System	1,314	2.51

TABLE 3 STORAGE TANK SPECIFICATION

Tank Shell	Carbon fiber
Tank Liner	Polyethylene
Diameter of Hydrogen Storage Tank	3.1 m
Total Height of the Tank	6.0 m
Wall Thickness of the Tank	0.25 m
Volume of one Tank	27.254 m^3
Mass of one Tank	24,931 kg
Density of Hydrogen at 70 Mpa	39 kg/m^3
Total Number of Tanks Installed on the Platform	27
Mass of Hydrogen in one Tank	1,063 kg
Total Hydrogen Mass	28,700 kg

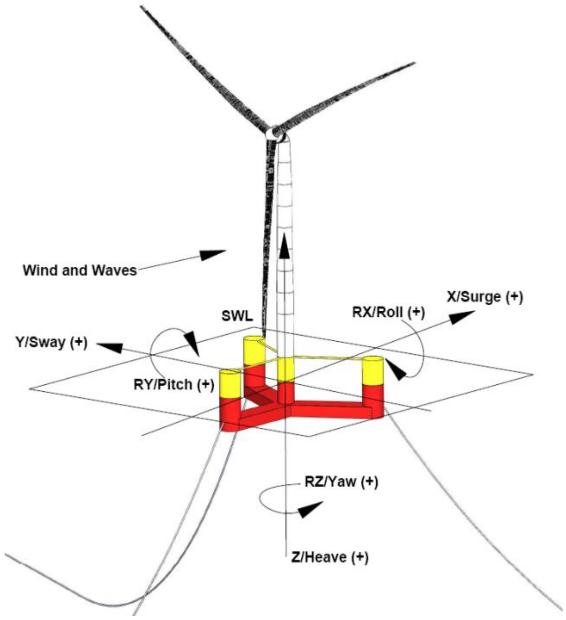

FIGURE 2: UMAINE SEMI-SUBMERSIBLE FLOATING OFFSHORE WIND TURBINE [7]

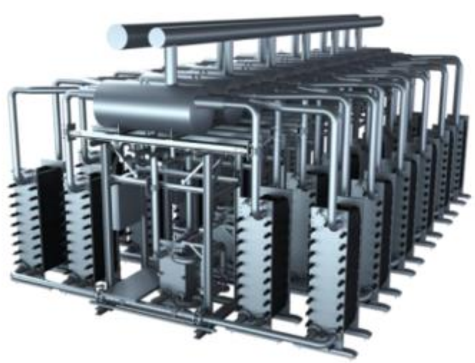

FIGURE 3: SILYZER 300 HYDROGEN PRODUCTION ARRAYS [11]

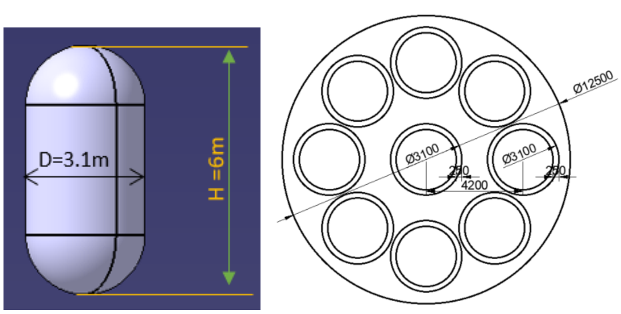

FIGURE 4: HYDROGEN STORAGE TANK AND ARRANGEMENT OF TANKS IN EACH SIDE COLUMN

TABLE 4 COMPARISON BETWEEN ORIGINAL PLATFORM (UMAINE) AND MODIFIED PLATFORM (FWHS)

Platform Properties	Unit	UMaine	FWHS	Diff.
Hull Displacement	m^3	20,206	20,206	0%
Vertical COG from SWL	m	-14.94	-14.01	-6%
Platform Mass	ton	17,754	17,754	0%
Ixx	kgm^2	1.25E+10	1.31E+10	4%
Iyy	kgm^2	1.25E+10	1.31E+10	5%
Izz	kgm^2	2.37E+10	2.37E+10	0%
Platform Steel Mass	ton	3,914	4,240	8%
Fix Ballast Mass	ton	2,540	2,540	0%
Fluid Ballast Mass	ton	10,509	9,990	-5%

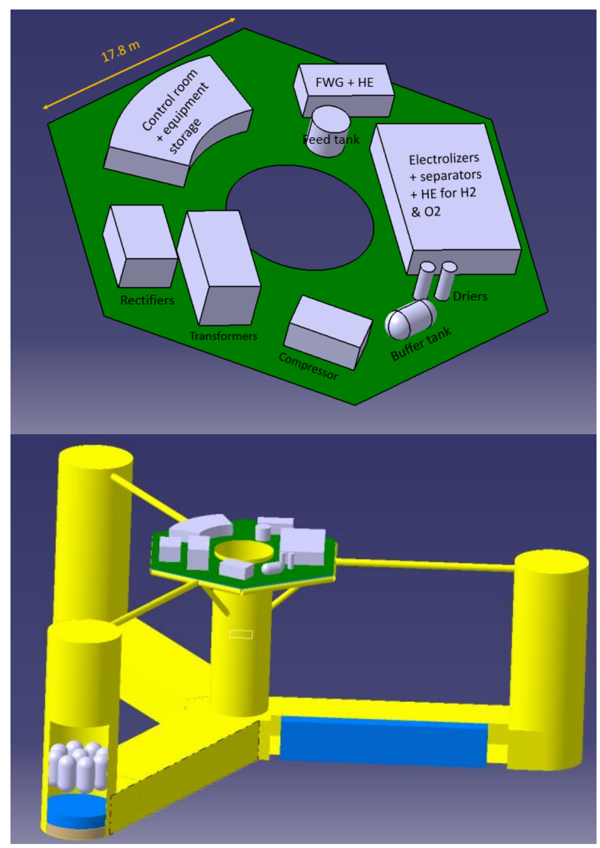

FIGURE 5: MODIFIED SEMI-SUBMERSIBLE FLOATING PLATFORM AND HYDROGEN PRODUCTION AND STORAGE SYSTEM ARRANGEMENT

3. NUMERICAL SIMULATION

The 15 MW FOWT system was simulated using the open-source code OpenFAST, which is a wind turbine simulation program produced by the National Renewable Energy Laboratory of the USA (NREL). The simulation involved the aero-hydro-servo-elastic aspects of the system. OpenFAST offers a robust framework that integrates wind, wave, and current models, along with dynamic mooring system modeling. OpenFAST employs key features such as an elastic model of the blades and tower, aerodynamic properties of the airfoil, a control schedule for generator torque and blade pitch angle, and hydrodynamic data of the platform to accurately simulate the entire FOWT system in different weather conditions. The validation of the FAST code has been achieved by carrying out a comparison study using either a model test of a semi-submersible floating wind turbine [12]–[15]. FIGURE 3 provides the structure of the OpenFAST code. The OpenFAST model of the entire 15 MW semi-submersible system has been published as open source material [16].

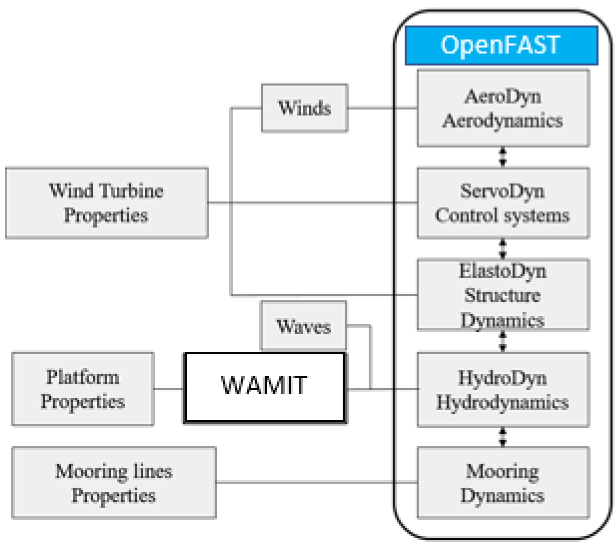

FIGURE 6: OPENFAST STRUCTURE

In this study, five load cases (LCs) are employed to examine the dynamic behavior of the FOWT system. LC0 is designated for the assessment of six-degree of freedom (DOF) platform free-decay tests, conducted in the absence of wind and wave influences. This involves a series of six separate free-decay evaluations, each corresponding to a specific DOF of the platform. The simulation of the LC involves an analytical examination and subsequent statistical analysis of the output parameters. LC1 is dedicated to evaluating the impact of NTM wind speeds on the FOWT system. Wave influences are absent from the LC1. Subsequent load cases, LC2 through LC4, involve simulations of the wind turbine system under regular wave conditions, featuring periods ranging from 2.5 to 30 seconds. These simulations are instrumental in measuring system responses for the computation of the RAO. LC1 represents scenarios where regular waves are present without any aerodynamic effects. LC2 encompasses conditions under which the wind turbines operate in steady winds at sub-rated speeds. In contrast, LC3 and LC4 involve scenarios with wind turbines operating in steady winds exceeding rated conditions. Wind and wave directions are aligned (co-directional) with a heading angle of zero degrees to ensure the platform maximizes the system's exposure to the strongest effects of wind and wave forces. Detailed descriptions and parameters of these load cases are systematically enumerated in TABLE 5.

TABLE 5 LOAD CASES FOR TEST MATRIX

Load cases	Test type	Wind	Wave
LC0	Free Decay Test	No wind	Still water
LC1	Statistics Analysis	NTM 4-24m/s	Still water
LC2	RAO	No wind	Regular wave, H= 1m,T = 2,5-30 s
LC3	RAO	Steady wind 8m/s	Regular wave, H= 1m,T = 2,5-30 s
LC4	RAO	Steady wind 16m/s	Regular wave H= 1m, T = 2,5-30 s

4. RESULTS AND DISCUSSION

In the free-decay test LC0, OpenFAST is utilized to generate time series data outputs. This data facilitates the determination of the system's natural frequencies, specifically related to the platform modes. The process involves computing the average oscillation period across various decay incidents. These derived natural frequencies are presented in TABLE 6, and their respective decay profiles are further illustrated in subsequent figures for an in-depth analysis.

Additionally, a comparative study of these frequencies is conducted between the Floating Wind and Hydrogen Storage (FWHS) system and the original Floating Offshore Wind Turbine (FOWT) system. Notably, while the FWHS model maintains the same mass and alters the Center of Gravity (CoG), the natural frequencies for Surge, Sway, and Heave modes remain unchanged. In contrast, there are minor deviations in the natural frequencies for the roll and pitch modes. The Yaw mode exhibits similar characteristics between the original FOWT and the FWHS model.

TABLE 6 NATURAL FREQUENCIES OF PLATFORM

Platform motions	Units	Value	
		Original	FWHS
Surge	Hz	0.007	0.007
Sway	Hz	0.007	0.007
Heave	Hz	0.049	0.049

Roll	Hz	0.036	0.035
Pitch	Hz	0.036	0.035
Yaw	Hz	0.011	0.011

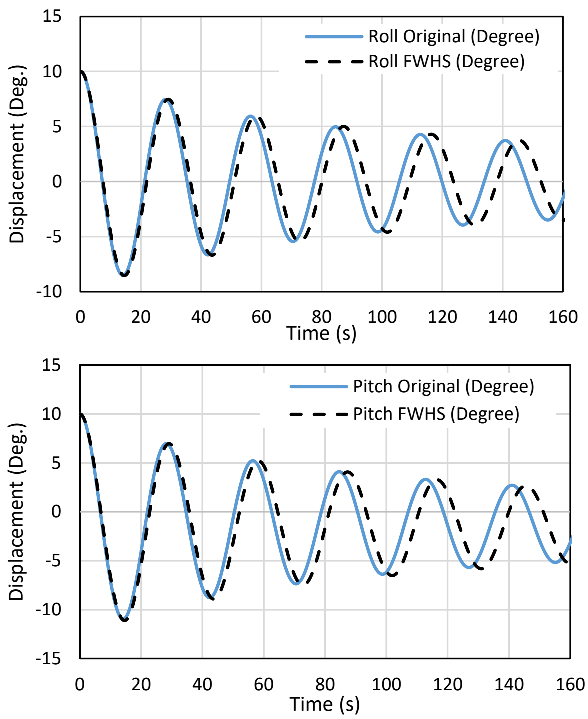

FIGURE 7: FREE DECAY TEST RESULTS FOR THE ORIGINAL (UNMODIFIED) PLATFORM AND THE PROPOSED PLATFORM

FIGURE 7 provides a statistical analysis of FOWT operating under LC1, where the wind direction is zero degree, and the semi-submersible platform is symmetrical. Consequently, the analysis focuses on the primary motion characteristics of the platform, including surge, heave, pitch, and generator power output. The time series data from OpenFAST, covering wind speeds ranging from 4 to 24 m/s, is used to calculate the minimum, mean, maximum, and standard deviation values for these parameters as can be seen in FIGURE 8.

In the operation of floating offshore wind turbines, the torque applied by the wind turbine control system remains constant, whereas the power output varies. The semi-submersible floating system exhibits high stability, as evidenced by the low standard deviation in surge and pitch measurements. This stability leads to minimal fluctuations in generator power. Such minor variations in electricity production are beneficial for the efficiency of the hydrogen system integrated with the FOWT.

The RAO is a crucial metric in naval architecture and ocean engineering, used to quantify how a floating structure, such as an offshore platform, responds to wave forces. It is a ratio of the response amplitude (like motion or force) of the body to the amplitude of wave excitation, and it varies with wave frequency as in Eq. 1. RAO provides insights into a structure's dynamic behavior, indicating potential resonance conditions and sensitivities to wave action, and is essential in both the design and operational analysis of floating structures.

$$RAO = \frac{\text{Amplitude of response}}{\text{Amplitude of excitation wave}} \tag{1}$$

For load cases LC2 to LC4, the wave heading is set at zero degrees and aligning the wind and wave directions in LC3 and LC4. In these scenarios, the RAO analysis is concentrated on the surge, heave, and pitch movements of the structure, along with the generator power output as presented in FIGURE 9. The analysis covers a frequency range from 0.033 Hz to 0.4 Hz, corresponding to wave periods between 30 seconds and 2.5 seconds. This focused examination is crucial for comprehending the distinct dynamic behaviors of floating offshore wind turbines when subjected to these specific environmental conditions.

In load cases LC2 to LC4, featuring varied operational conditions of the wind turbine, it is observed that the heave RAO remains largely unaffected. However, the pitch RAO is significantly influenced, particularly in the region of resonant oscillation frequency. The introduction of aerodynamic forces in LC3 and LC4 results in a reduction of pitch motion, which in turn slightly alters the Surge RAO, notably around the pitch natural frequency.

Regarding the generator power RAO, there is no discernible difference between LC3 and LC4. This reflects the variation of power output in response to different regular wave frequencies. Notably, the generator power RAO reaches its peak value around the pitch natural frequency. This is attributed to substantial pitch movements, which consequently increase the movement speed of the RNA at the 150m level of hub height, causing significant variations in the relative speed between the wind and the rotor blades.

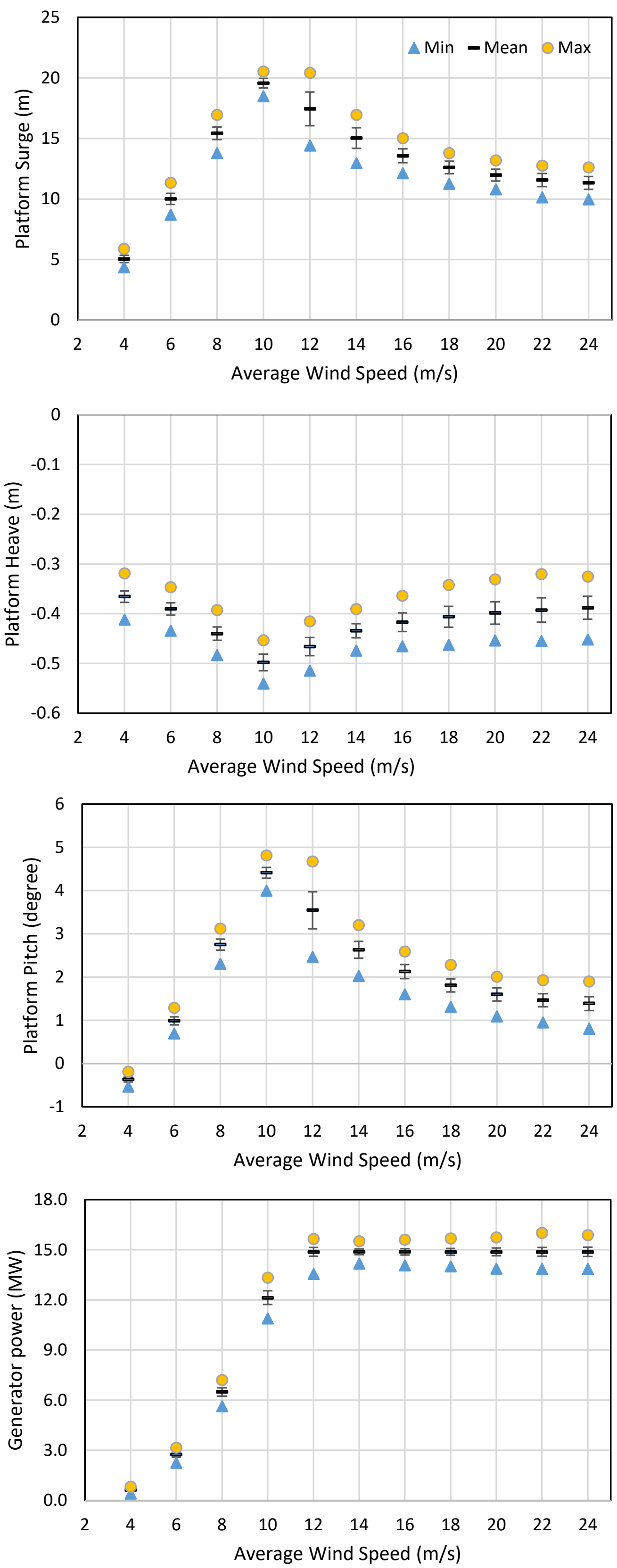

FIGURE 8: STATISTICS ANALYSIS LC1

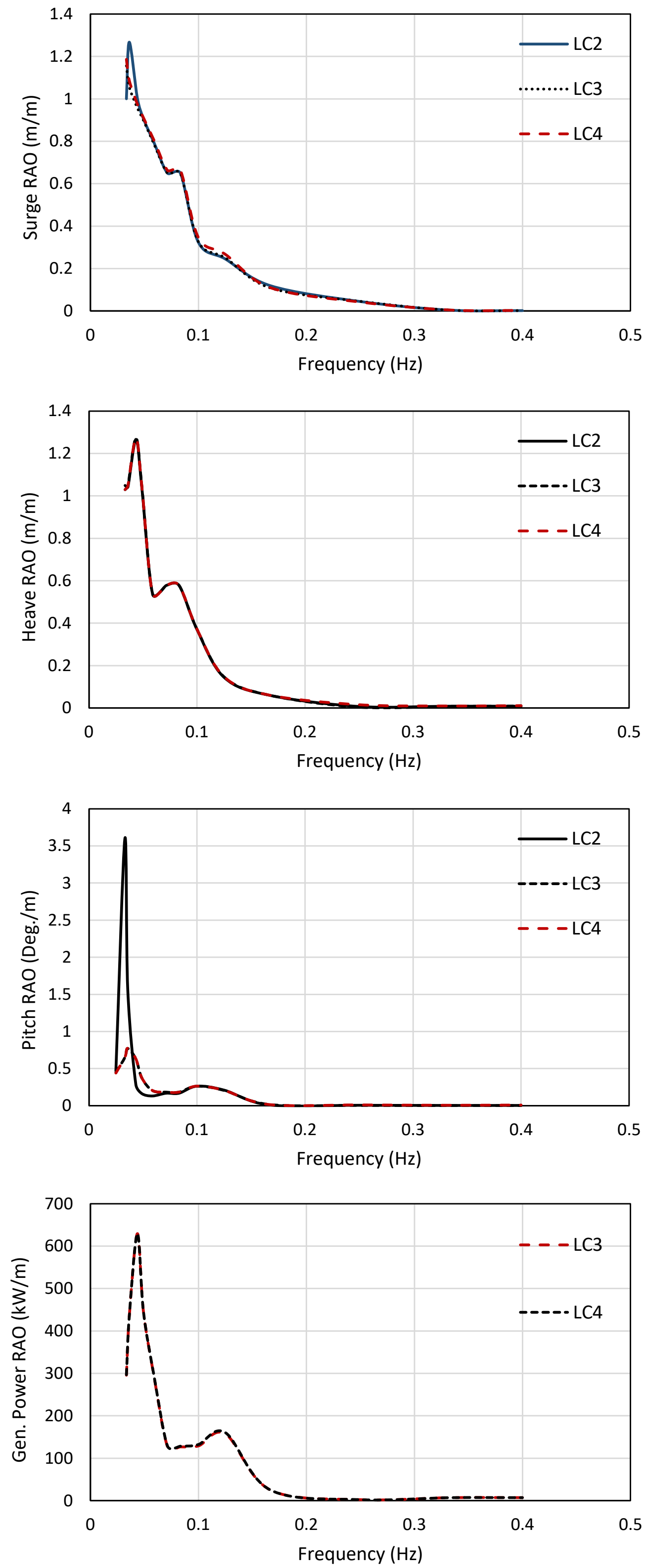

FIGURE 9: RAOS OF THE FWHS SYSTEM UNDER LC2, LC3 AND LC4

5. CONCLUSION

This research has presented a detailed examination of a novel integration of offshore green hydrogen production and storage systems with a floating offshore wind turbine. Central to this study is the innovative concept of a decentralized floating hydrogen system powered by a 15-MW floating offshore wind turbine. The system architecture encompasses critical modules for hydrogen production and storage, with tailored adaptations to the floating support structure for equipment accommodation. The strategic layout of the hydrogen production system and storage tanks, scrutinized through dynamic simulation analysis, highlights the system potential in operational efficiency and space optimization. This aspect is vital for ensuring the practical feasibility and scalability of the system.

In investigating the dynamic responses of the floating offshore wind turbine under various operational conditions (LC2-LC4), the study reveals key findings: the heave RAO remains largely consistent, while the pitch RAO significantly impacts the system dynamics, particularly in the frequency range of resonant oscillation. The aerodynamic forces present in LC3 and LC4 due to wave conditions contribute to a notable reduction in pitch motion, subtly influencing the Surge RAO around the pitch natural frequency.

Additionally, the analysis indicates minimal variation in the generator power RAO between LC3 and LC4, demonstrating the system capability to maintain stable power output under different wave frequencies. The observed peak in generator power RAO around the pitch natural frequency is attributed to the interaction of increased pitch movements with wind speed and rotor blade dynamics, a factor crucial for optimizing the hydrogen production's energy efficiency.

In essence, this research not only introduces a novel decentralized floating hydrogen system but also provides comprehensive insights into its dynamic behavior under a range of environmental conditions. These findings are instrumental in advancing the field of renewable energy technologies, particularly in the domain of offshore green hydrogen production. The practical implications of this study are significant, offering a foundation for future implementations and enhancements of such sustainable energy systems.

ACKNOWLEDGEMENTS

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