ORIGINAL ARTICLE

Fault condition effects on the dynamic response of V-shaped offshore wind turbine

Madjid Karimirad[1] · **Constantine Michailides**[2]

Abstract

Offshore wind is an extensive renewable energy resource appropriate for fulfilling the increasing energy needs and increasing the security of energy supply. The issues related to the design of the support structure, installation, grid connection, operation, and maintenance in normal and fault conditions significantly influence the levelized cost of the produced energy. The feasibility of different concepts should be numerically calculated and assessed for all aforementioned issues. In this paper, the dynamic response of the V-shaped semisubmersible under different possible fault conditions is examined. Different response quantities of the floating wind turbine are compared for the case that the system operates under operational and fault conditions. The response quantities include motions of the platform in all six rigid-body degrees of freedom, mooring line tension, tower base-bending moment, and functionality of the wind turbine. A numerical model accounting for fully coupled dynamic analysis of the offshore wind turbine under different fault conditions has been developed. It is found that for the V-shaped semisubmersible, the mooring line tension is significantly affected by different fault conditions compared to the rest examined response quantities; the maximum value of the tension of the mooring lines is increased by a factor of 1.6 due to fault conditions. Among the different fault conditions, shutdown case seems to have the largest influence on the functionality and responses of the V-shaped floating wind turbine. For emergency shutdown fault conditions, backlash occurs that results in large variation of tower-bending moment.

Keywords Floating wind turbine · V-shaped semisubmersible offshore wind turbine · Fault conditions · Mooring lines

1 Introduction

Offshore wind turbines are subjected to a variety of loads. Detailed analysis of different conditions (operational, fault, and extreme) is necessary in order we to understand the performance of different floating wind turbines and to recognize critical circumstances caused by the operation of the turbine in normal, survival, or fault conditions. The latter is the focus of this paper; the present paper is a further study based on

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the former analysis under normal conditions for the braceless V-shaped semisubmersible floating wind turbine [1].

The international standards such as Germanischer Lloyd, Det Norske Veritas, and International Electrotechnical Commission [2–4] require different design load cases to be considered. Normally, the design of a floating wind turbine is dominated by the harshest loads. However, the transient load cases are also important compared to the basic load cases addressing the operational and parked states of offshore wind turbines [5]. Several conditions may result in transient loads such as abnormal wind, shutdown of the turbine, loss of grid connection, faults in the control, and/or protection system. Hence, a need to study the responses of offshore wind turbines during fault conditions exists [6–9]. Yaw instability was reported for a floating wind turbine supported by a barge platform when the turbine was idling with a faulted blade. In addition, an increase in yaw and roll responses of a parked spar-type wind turbine with one-seized blade is reported by Jiang et al. [10]. Jiang et al. [10] used the aeroelastic code HAWC2 [11] to analyse floating wind turbines

and presented that fault cases have a significant effect on the mooring responses of a spar-type wind turbine. Bachynski et al. [7] developed a non-linear computational tool (Simo–Riflex–AeroDyn) to study floating wind turbines during pitch actuator fault, grid loss, and shutdown, and reported that large stochastic variations and uncertainties related to the maximum loads are induced by fault events. The previous studies [12] have shown that fault conditions may cause extreme transient responses that could affect the ultimate strength of the structure. Moreover, for some fault conditions (e.g., seized blade, where the pitch mechanism is stopped working and the blade cannot feather), the effect of the fault on fatigue damage is more noticeable. This is due to the fact that the seized blade influences the aerodynamics of rotor and the global dynamics are affected by harmonic excitation. Hence, documenting the performance and structural integrity of offshore wind turbines under fault conditions is important.

Fault conditions influence the design and lifetime of offshore wind turbines due to their transient effects. Especially, for recent proposed concepts, the study of the effects of fault conditions on their dynamic response is of critical importance. The proposed concept in this paper is similar to the braceless V-shaped semisubmersible that has been introduced in Fukushima floating offshore wind farm demonstration project [13], see Fig. 1. Karimirad and Michailides [1] studied the V-shaped semisubmersible concept and proposed an optimum design of it in terms of hydrostatic/hydrodynamic stability, used material, required dimensions, and power performance in operational conditions.

In the present paper, the dynamic response of the braceless V-shaped semisubmersible [14] under different fault conditions is presented. This paper is the first dealing with the operation and maintenance of the V-shaped floating wind turbine concept. The fault conditions that are examined are the pitch actuator fault, grid loss, and shutdown.

A numerical model for performing fully coupled dynamic analysis of the V-shaped semisubmersible under the different types of fault conditions has been used. The response quantities of different components of the V-shaped semisubmersible are compared for the case that the offshore wind turbine operates under operational and fault conditions. Response quantities include motions of the platform in all six rigid-body degrees of freedom, mooring line tension, tower base-bending moment, and functionality of the wind turbine. The effects of fault conditions for ultimate and accidental limit states during the design stage are presented. It is found that the mooring line tension is affected by different fault conditions compared to the other examined response quantities. Fault conditions result in a 1.6 times increase in the maximum tension of the mooring lines; this factor should be considered for addressing the structural integrity of the mooring system of the V-shaped semisubmersible. Among different fault conditions, shutdown condition (in which, the turbine is not producing any electrical power) has the largest effect on the functionality and response of the offshore wind turbine. For shutdown fault conditions, backlash occurs resulting in a large variation on the bending moment at the base of the tower. In general, the results show that the presented V-shaped semisubmersible wind turbine is a promising concept which can enhance the offshore wind industry even if fault conditions appear.

2 Geometry data and numerical modelling of the V-shaped semisubmersible floating offshore wind turbine

The V-shaped semisubmersible offshore wind turbine considered in the present paper consists of: (A) a semisubmersible floating platform with three columns and two pontoons
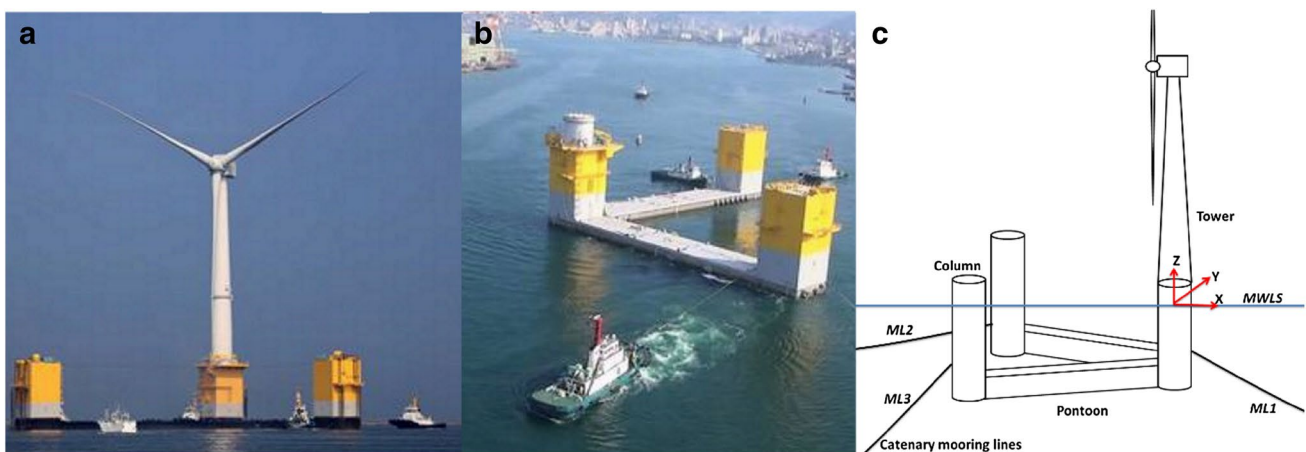

Fig. 1 **a, b** V-shaped semisubmersible offshore wind turbine as proposed in [13]; **c** schematic layout of the present floating offshore wind concept studied in this paper [1, 14]

connecting the side columns to the central column; (B) a 5 MW wind turbine placed top of the central column of the semisubmersible platform; and (C) three catenary mooring lines positioned at the three columns of the semisubmersible. The wind turbine is at the top of the central column, see Fig. 1. With regard to the mooring system that is used, three sets of single mooring lines are used with one clump mass for each. The reference NREL 5-MW wind turbine with modified tower for floating wind turbine applications is used [15, 16]. In the previous studies performed by the authors, the dimensions of the semisubmersible platform have been selected according to appropriate analysis and design criteria. Three mooring lines are used with one clump mass for each. The distributed weight of the mooring lines is 117 kg/m, the equivalent diameter is 0.138 m, and the axial stiffness is 3.0E+6 kN. As far as the clump mass, the volume is 4.4 m³ and weight is 37,000 kg. The main properties of the V-shaped semisubmersible wind turbine are listed in Table 1. More information about the design, dimensions, and characteristics of the V-shaped semisubmersible wind turbine can be found in Karimirad and Michailides [14].

Time-domain dynamic analysis is applied to investigate the responses of the V-shaped floating wind turbine under the action of wind and wave loads for the examined fault conditions. The SINTEF ocean numerical code SIMA has been used for the aero–hydro–servo-elastic dynamic analysis of the V-shaped semisubmersible offshore wind turbine, see Fig. 2.

SIMA (advanced analyses of marine operations and floating systems) is a state-of-the-art numerical tool for offshore engineering applications. The code has the ability to account for both hydrodynamic and aerodynamic loads applied and solve the equation of motions for moored platforms using coupled/integrated time-domain algorithms. For mooring system, finite-element formulation is applied, while hydrodynamics is based on potential flow, and for aerodynamic, blade-element momentum (BEM) theories are implemented. SIMA further extends the capabilities of the standalone tools SIMO [17] and RIFLEX [18]. SIMA has been extended to include aerodynamic loads on elastic structural members using blade-element momentum theory (BEM) [19]. For the present paper, the turbulent wind field is generated with the use of HAWC2 [11] and is used as input to SIMA (as an

Table 1 Properties of the V-shaped semisubmersible wind turbine

Description of quantity	Value
Total overall mass of system	10,264,350 kg
Pontoon dimensions, width × height	9 m × 5 m
Distance between columns	60 m
Diameter of columns	9 m
Draft	28 m
Elevation to tower base (above mean water level)	10 m
Yaw bearing height (above mean water level)	87.6 m
Overall tower mass	250,000 kg
Nacelle mass	240,000 kg
Rotor mass	110,000 kg
Fairlead for line 1 (x, y, z)	$(4.5, 0, -18)$ m
Fairlead for line 2 (x, y, z)	$(-55.8, 32.3, -18)$ m
Fairlead for line 3 (x, y, z)	$(-55.8, -32.3, -18)$ m
Anchor point for line 1 (x, y, z)	$(450, 0, -100)$ m
Anchor point for line 2 (x, y, z)	$(-441.7, 255, -100)$ m
Anchor point for line 3 (x, y, z)	$(-441.7, -255, -100)$ m
Length of each mooring line	453 m
Water depth	200 m

Fig. 2 Tools that are used for the aero–hydro–servo-elastic numerical modelling in SIMA
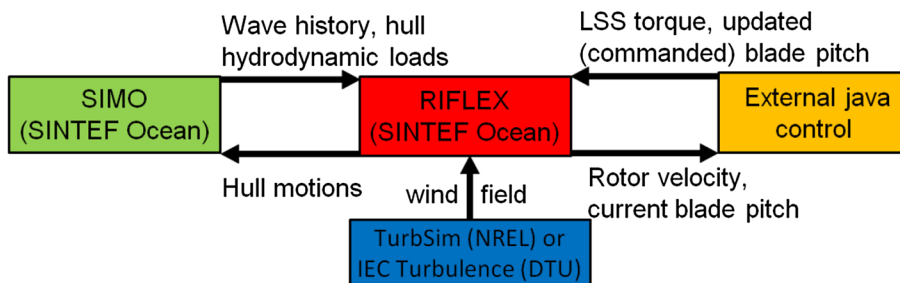
external file, pre-generated using HAWC2). The fault conditions are implemented through an external controller; SIMA can use both internal and external controllers. This makes it possible to execute coupled/integrated aero–hydro–servo-elastic simulations for the moored V-shaped semisubmersible floating wind turbine. RIFLEX is a non-linear time-domain tool using a finite-element formulation that can handle large displacements and rotations. It uses Morison equation to evaluate hydrodynamic loads on slender members of offshore structures [20]. With the appropriate use of RIFLEX, coupled analysis can be performed, where one or more rigid-body floating structures are integrated with a dynamic model of mooring system and arbitrary-coupling forces in the time domain.

The estimation of the hydrodynamic coefficients of large volume structures (e.g., semisubmersible platform) is performed with SIMO (SINTEF ocean) which can be coupled with RIFLEX to solve complicated integrated dynamic analysis of offshore structures in the time domain. The mooring lines, tower, shaft, and blades of the floating wind turbine are simulated in RIFLEX with the use of flexible beam elements. In Fig. 2, the communication between different tools of the developed numerical model in SIMA is presented. The applicability and accuracy of the numerical modelling method have been verified against experimental data [21]. To develop the numerical model of the floating wind turbine with SIMA, the panel model of the wet surface of the semisubmersible platform is created. After an appropriate convergence study with regard to the size and the number of the panels of the wet surface of the platform, hydrodynamic analysis in WAMIT [22] is performed for the calculation of hydrodynamic coefficients in the frequency domain. These coefficients are the added mass, radiation damping, hydrostatic stiffness, and excitation wave loads. SIMO is then used to model the time-domain hydrodynamic loads on the platform including the first-order and second-order wave loads based on Newman's approximation [23]. The convolution integral is used to account the memory effects (retardation functions) in the time-domain analysis. The viscous effects are also included using Morison elements; just the drag coefficients are set for Morison elements as the inertia loads are taken into account by the potential theory. It is noted that validation of the numerical methods and tools can be found in Michailides et al. [24, 25].

The mean drift forces were obtained through conservation of momentum. Using the Newman's approximation, the slowly varying drift forces have been calculated. Hence, just the first-order potential problem has been solved and the second-order problem (full quadratic transfer functions or the difference-frequency problem) is not considered. Regarding the aerodynamic loads, RIFLEX reads as input a turbulent wind field and then calculates the aerodynamic loads on the floating wind turbine. These loads are modelled

as distributed moments, lift, and drag forces that act on the blades and calculated based on the blade-element momentum method. For the aerodynamic calculations, pseudo-two-dimensional properties of the local aerofoil aerodynamics are used. The aerofoil aerodynamics have been calculated with the use of a dynamic stall model in which the static aerofoil coefficients are modified as a function of the angle of attack and the rate of change of the attack angle. The dynamic stall model used to account for unsteady aerofoil aerodynamics is based on the work of Leishman and Beddoes.

The bladed style dynamic link library controller is used to implement a variable-speed generator torque and proportional–integral (PI) collective blade-pitch controllers for the reference NREL 5-MW wind turbine. The variable-speed generator torque and PI collective blade-pitch controllers with a constant-torque target for the rated and over-rated wind speed cases use the feedback of the generator speed. The controller at below-rated wind speeds controls the generator torque (there is no feathering of the blades in the below-rated region). At over-rated wind speeds, the control is active by feathering the blades to maintain the rated power (the shaft-rotational speed is controlled as well). For a floating wind turbine at rated wind speed, depending upon the relative wind velocity, the controller behaves in a manner similar to that in the below-rated or over-rated wind speed cases. The external java controller developed by Bachynski et al. [7] is used in the present analysis and integrated into SIMA in which the fault conditions are implemented. The fault conditions that are examined in the present paper are summarised in Table 2, grid loss, blade seize without shutdown and blade seize with the shutdown. During grid loss, the generator torque is lost, and the turbine is shut down by pitching all three blades. Blade seize indicates that one of the blades loses the ability to pitch and stays fixed at its instantaneous orientation. Blade seize may be followed by a shutdown, where the two remaining blades are pitched. The time of occurrence for all fault conditions is considered at 1000 s; a sensitivity study on this selection is presented at the end of the present paper. The performance of the V-shaped semisubmersible wind turbine in different fault conditions for a sea state that corresponds to rated wind speed is examined. For the rated wind

Table 2 Examined fault conditions

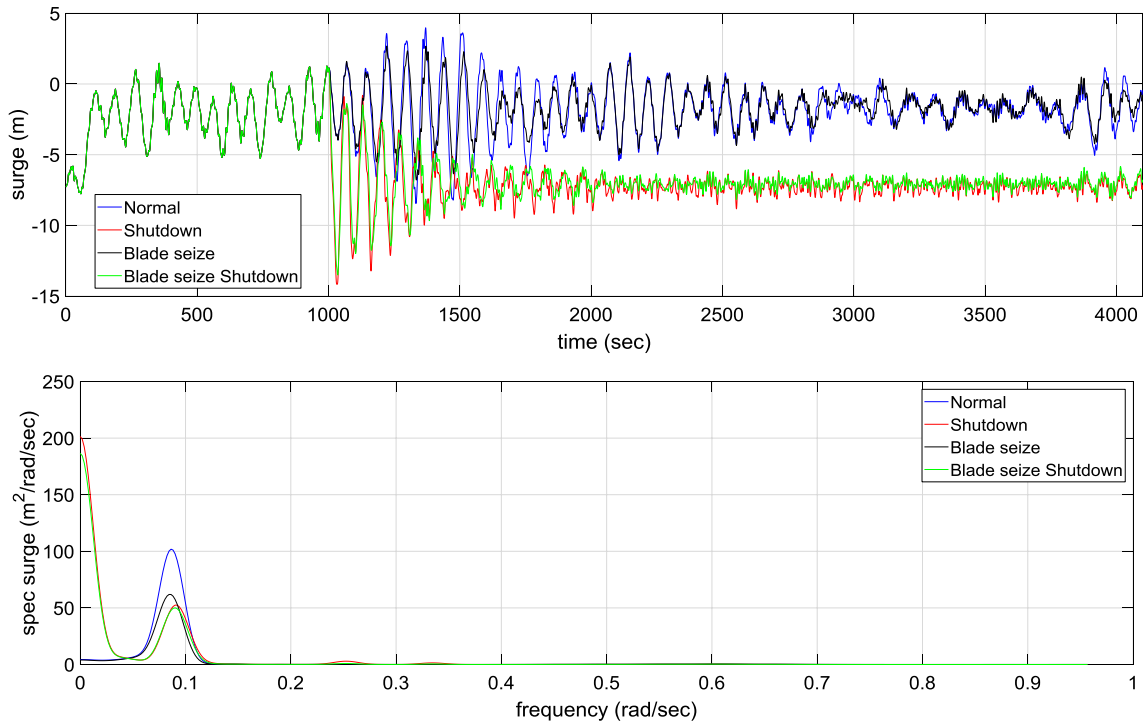| Fault case	Time of occurrence (s)	Time delay before shutdown (s)
Grid loss (with shutdown)	1000	0.1
Blade seize (without shutdown)	1000	–
Blade seize (with shutdown)	1000	0.1

Fig. 3 Time series and spectra of surge motion response for different fault and normal operational conditions

speed condition, the mean wind speed equals to 11.4 m/s, the significant wave height is 3.0 m, and the peak period is 10.0 s. These conditions correspond to a specific site, off the Norwegian coasts [26]. It is noted that for the rated wind speed conditions, the turbulence intensity is considered to have a value equal to 0.15.
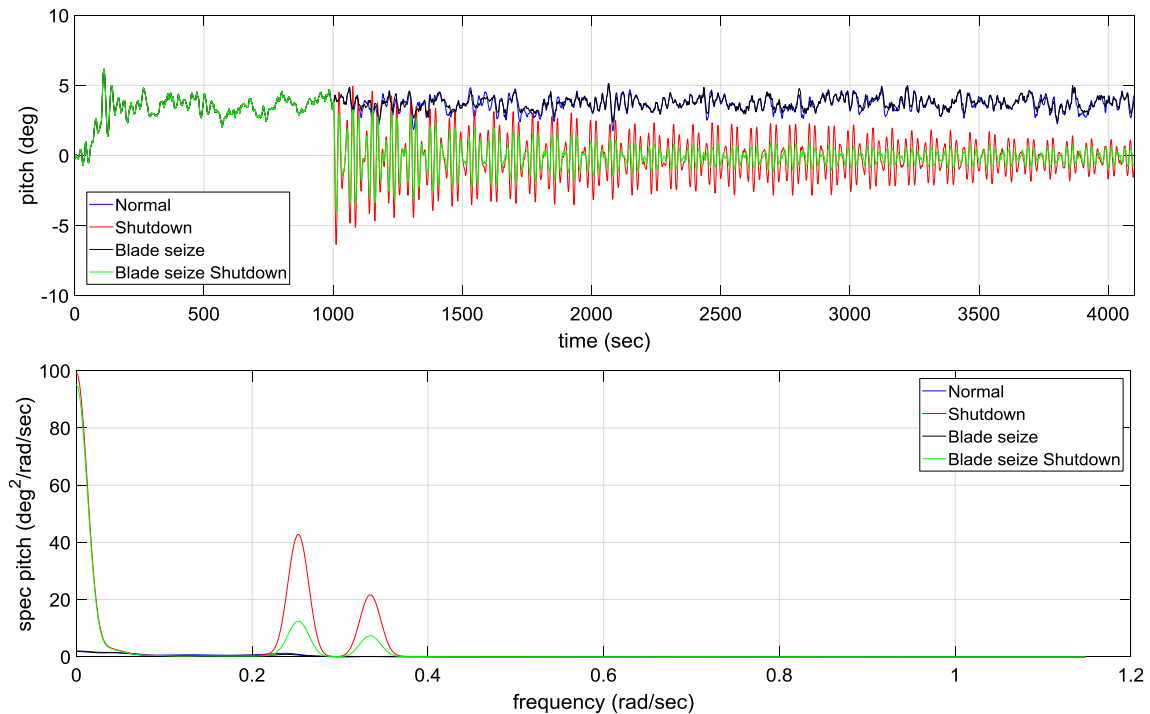

Fig. 4 Time series and spectra of pitch motion response for different fault and normal operational conditions

3 Effect of fault conditions on structural responses and functionality of wind turbine

To study the effect of fault conditions, the responses of different quantities of the floating wind turbine for different fault conditions are compared against the relevant quantities for normal operational condition. In Figs. 3 and 4, the time series and spectra of the surge and pitch motion of the platform are presented, respectively. Based on the results, for the case of shutdown (grid loss) and blade-seize shutdown conditions, a kind of a transient "impact load" appears,

which results in low-frequency resonant response for both motions. The blade-seize condition has an insignificant effect on the surge and pitch responses of the platform and the motion responses (both time series and spectra) have the same pattern compared to those occurring in a normal condition without any fault.

In Fig. 5, the statistical characteristics of the time series, the mean value (mean), standard deviation (STD), minimum (min), and maximum (max) of the six rigid-body motions of the platform are presented. As discussed previously, the surge motion response for the normal operational and blade-seize fault conditions is similar, while for the shutdown
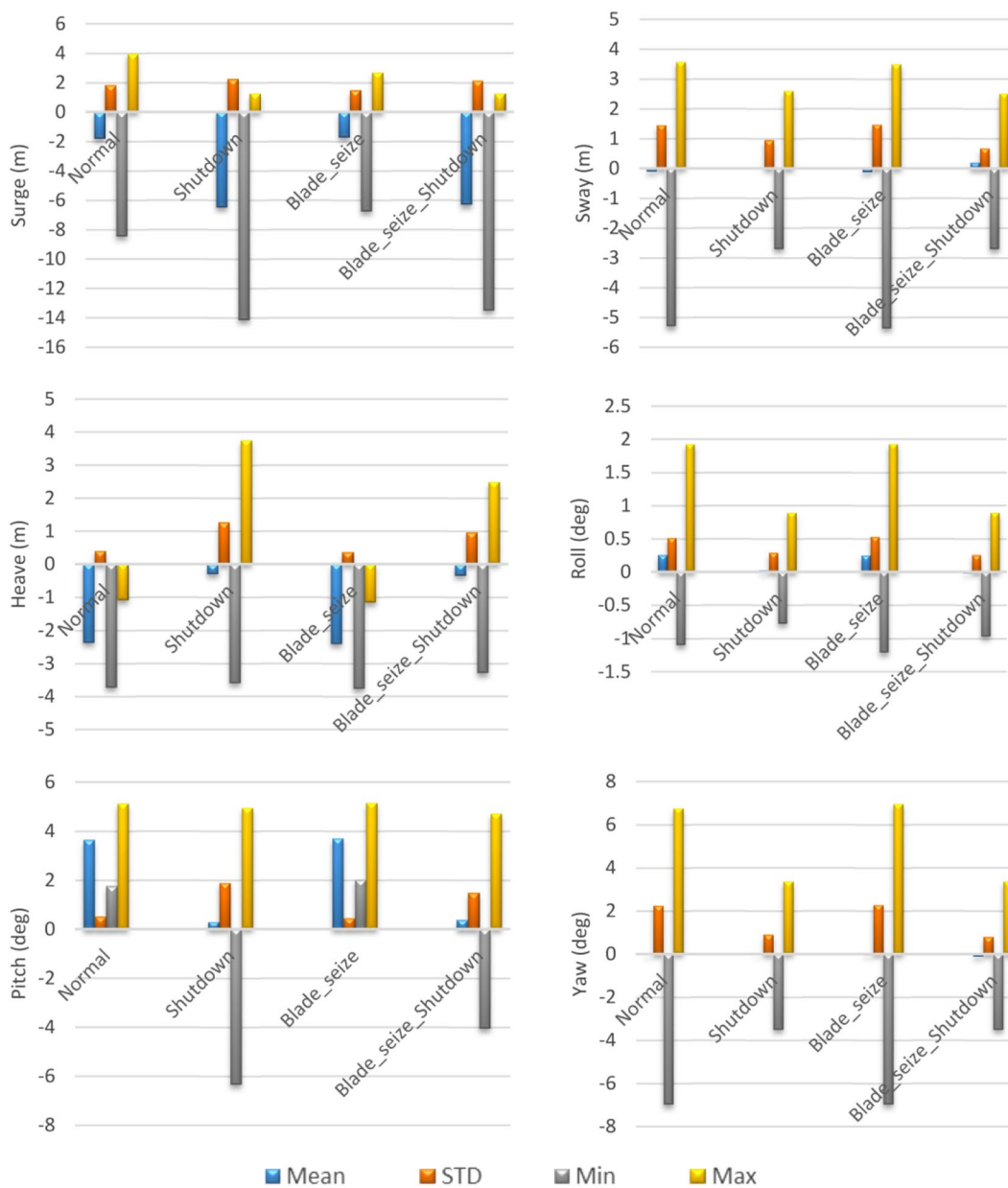

Fig. 5 Statistical characteristics of time series of motion responses for examined normal and fault conditions

conditions (grid loss and blade seize), larger maxima (minimum or maximum) are presented.

The shutdown (grid loss) condition results in 70% increase of the maxima of the surge response (in this case, the minimum value). For the sway motion response, the shutdown conditions result in smaller responses attributed to the reduction of the aerodynamic loads immediately after the shutdown condition. It is noted that the transient impact loading due to the shutdown condition has the same direction as the surge direction, and hence, the sway motion is not affected by the aforementioned fault condition. The maxima

Table 3 Ratio of maxima of platform's responses under fault and operational conditions

Response	Ratio of maxima	Description	Fault
Surge	1.7	Min	Shutdown
Sway	1.0	Min	Blade seize
Heave	3.4	Max	Shutdown
Roll	1.1	Min	Blade seize
Pitch	3.6	Min	Shutdown
Yaw	1.0	Max	Blade seize
Tension	1.6	Max	Shutdown
Bending moment[a]	0.8	Min	Shutdown

[a]The bending moment experiences a very large variation; it changes the value from $+1.1E+5$ kNm to $-0.9E+5$ kNm

of the sway response are the same for normal operation and blade-seize fault conditions. The heave response is highly affected by the shutdown (grid loss) fault condition and the relevant maxima are 3.4 times compared to the normal operating condition. However, the heave motion of V-shaped semisubmersible is small in normal operational condition. The effects of the fault conditions on the roll motion are similar to the effects for sway motion. For the pitch motion, the effects of fault conditions are similar to the effects of heave and surge motions (surge, heave, and pitch motions are in the longitudinal plane). In Table 3, the ratios between the maxima for each response are presented and compared with the relevant values for normal operational conditions.

In Figs. 6 and 7, the time series of the tension of the mooring lines and towers base-bending moment are presented, respectively. It is clear that for the shutdown (grid loss) and blade-seize shutdown conditions, an impact load is presented that results in a large tension response. For the case of the towers base moment and during the shutdown conditions, a backlash occurs, and hence, negative bending moment appears attributed to the removal of the thrust load. For these conditions, the variation of the bending moment is very large; however, the absolute value of the negative bending moment is smaller than the corresponding value of the positive bending moment.

Figure 8 shows the statistical characteristics of the time series (Mean, STD, Min, and Max) of the mooring line
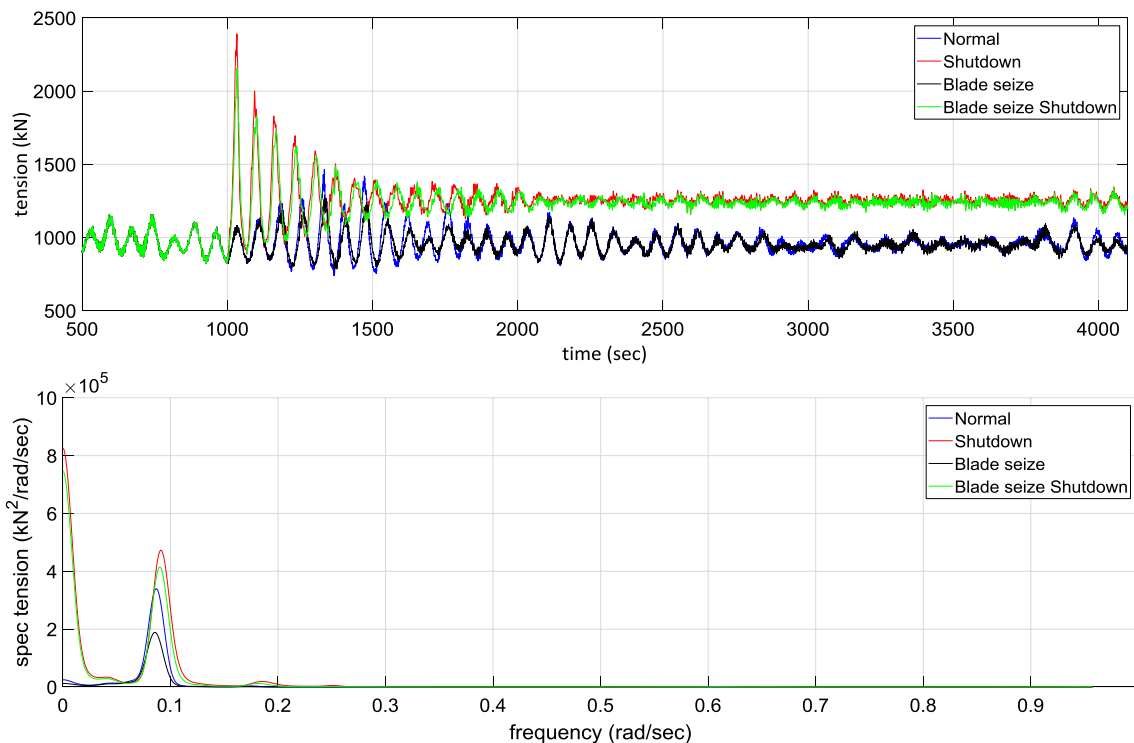

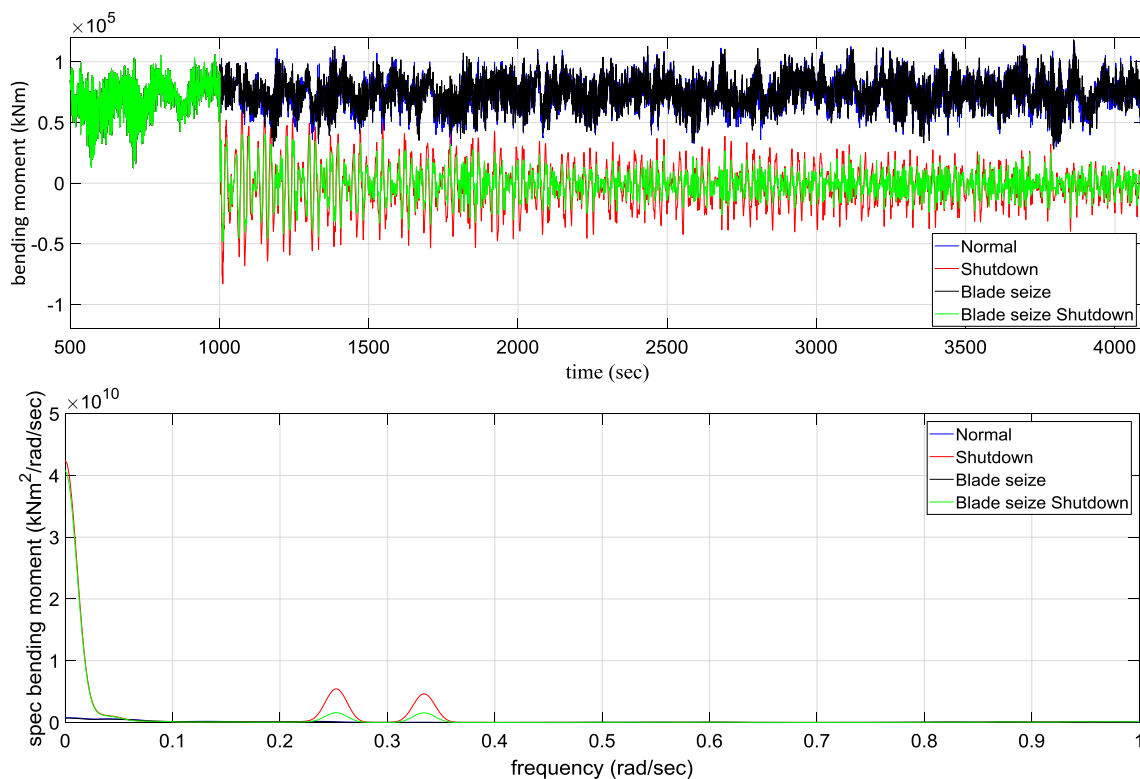**Fig. 6** Time series and spectra of tension response for different examined operational and fault conditions

Fig. 7 Time series and spectra of bending moment response for different examined operational and fault conditions
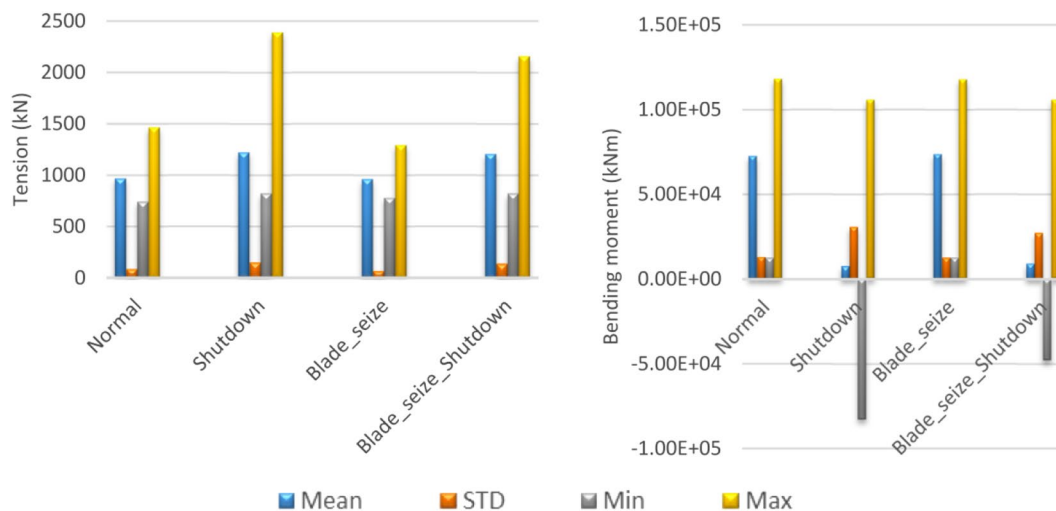

Fig. 8 Statistical characteristics of mooring line tension and tower' base-bending moment for operational and fault conditions

tension and towers base-bending moment. The shutdown (grid loss) condition results in a 160% increase of the maxima of the mooring line tension response. The shutdown condition results in a smaller response of towers base-bending moment. However, as the bending moment changes its sign (the thrust load removed at shutdown event), the bending moment variation is large (sign change).

In Fig. 9, the time series of the generated power and blade deflection are shown. The blade deflection corresponds to the flapwise out of plane elastic deformation of the blades with respect to the blade root. For shutdown (grid loss) and blade-seize shutdown conditions, the produced power is zero as expected. For the case of the blade deflection, during the shutdown condition, a backlash is presented, and
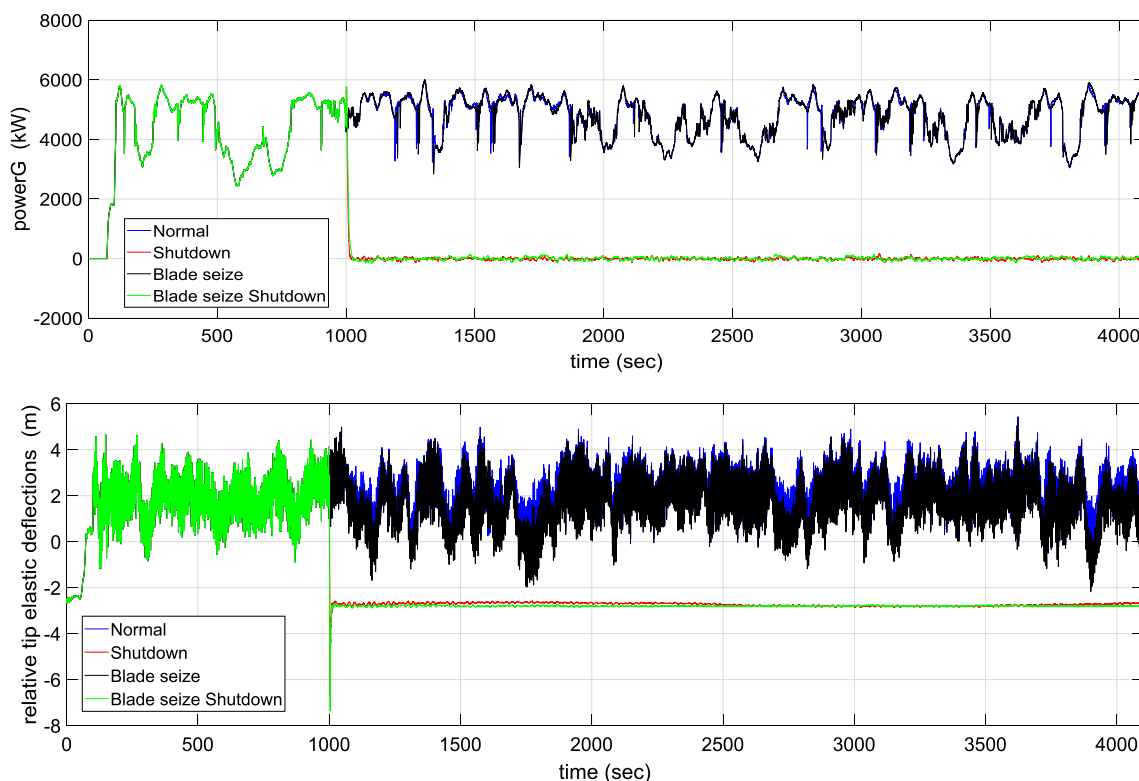
Fig. 9 Time series of generated power and blade deflection for different examined fault and operational conditions

hence, negative deflection is observed. The variation in blade deflection is very large; however, after a short time, the vibration is damped. The generated power and blade deflection are insignificantly affected when one blade is seized and the turbine may continue its function. In Fig. 10, the statistical characteristics of the time series of the wind turbine responses are presented. The rotational speed of the rotor is zero after shutdown (both blade seize and grid loss cases) as expected. For the case of blade seize without shutdown, the statistical characteristics are similar to the characteristics that correspond to operating condition. The pitch angle of the blade for the conditions associated with the shutdown is set equal to 90°. The generated power is not significantly affected by blade seize, but this does not mean that the operation of the turbine is normal. The aerodynamic loads are disturbed by the blade seized; this, in turn, will result in extra excitation of the structural members and fatigue damage due to harmonic excitation and should be strictly avoided. The blade deflections (flapwise and edgewise) are affected during the shutdown and the sign of the deflection changes; this should be well studied by having a detailed local-type finite-element model of the blade.

The parameter set in Table 2 for performing the dynamic analysis of the fault conditions are briefly studied. As the tension of the mooring lines has been found to be the most affected response by the fault conditions, the tension of

mooring lines is further examined and discussed. A sensitivity study has been performed for the tension of mooring lines with regard to the time of fault occurrence. In Fig. 11, the ratio of the mooring line tension for different times of occurrence of the fault condition relative to the base case, as presented in Table 2, is shown. As it is clear, the tension response is sensitive to the time of fault occurrence and it is roughly 25% larger (fault occurrence at 1300 s) or 30% smaller (fault occurrence at 1750 s) compared to the base case (fault occurrence at 1000 s). This is highly related to (a) the joint wave and wind excitation, (b) the response of the structure to the environmental load, and (c) the memory effects. Moreover, the sensitivity of the responses to the time delay of the controller action for shutting down the turbine is examined. As it is clear, the mooring line tension is not changed due to the delay of the controller action. It is found that the response is affected by the impact caused by shutting down the turbine rather than small delay in the controller action in commanding for feathering the blades.

4 Conclusions

The role of floating wind turbines in offshore wind technology has been increased and new floating concepts can potentially reduce the cost of electricity. Fault conditions
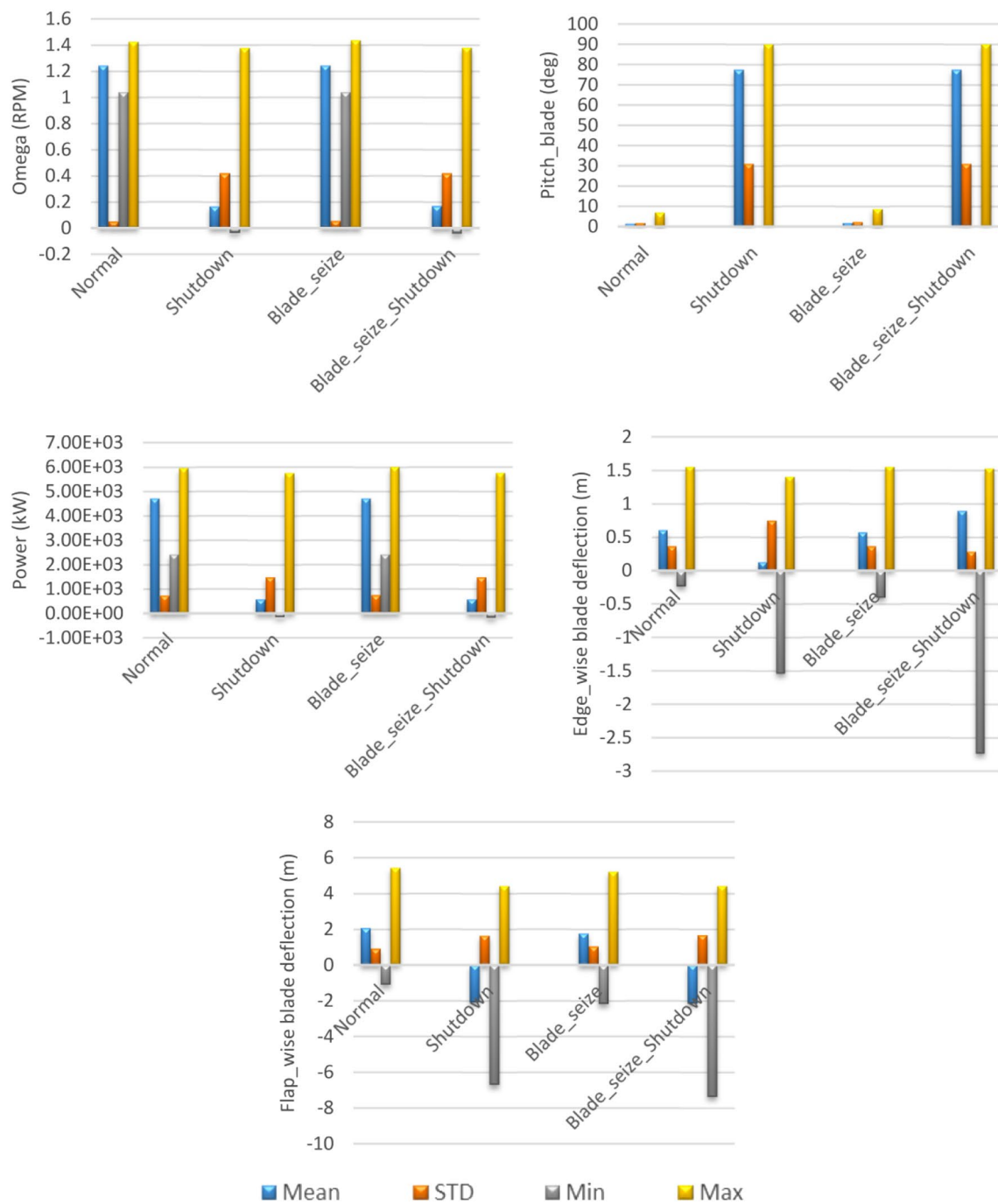
Fig. 10 Statistical characteristics of wind turbine responses for operational and fault conditions

may result in significant effects on the structural responses of such structures due to induced transient loads. In this paper, the transient effects caused by fault conditions for the V-shaped semisubmersible offshore wind turbine are examined. The presented results can be used by related industries and research groups for the design of floating wind turbines of this type. In this paper, a coupled analysis was performed for the V-shaped semisubmersible wind turbine

for highlighting the influence of the most probable fault conditions on its dynamic response. The industry has developed similar offshore wind turbines and this paper could help improving their design considerations.

The results show that the mooring line tension response is affected by fault conditions compared to motion responses and towers base-bending moment. Among different fault conditions, the shutdown fault seems to have the largest

Fig. 11 Sensitivity study of the mooring line tension due to the time of fault occurrence and time delay until control action
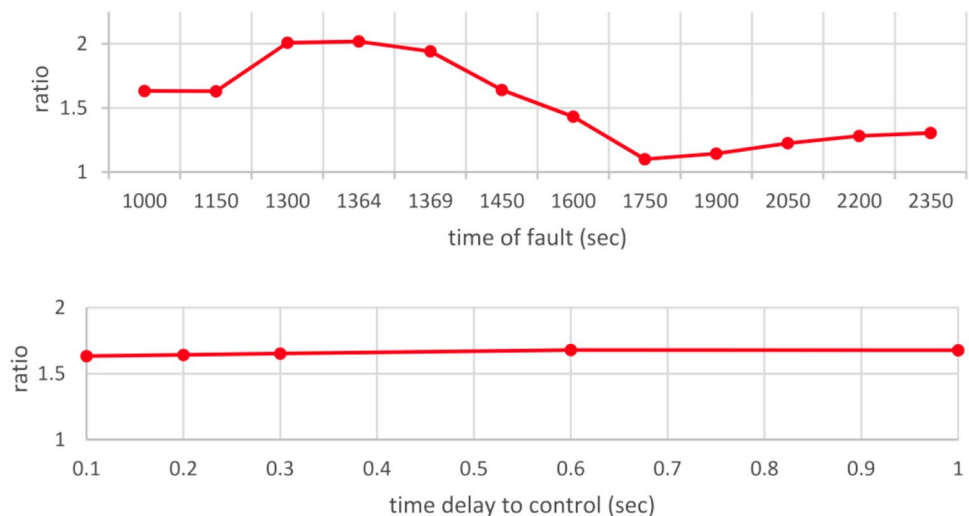
influence on the performance and response of the V-shaped semisubmersible wind turbine. After grid loss, the controller shutdowns the turbine immediately; the action of the controller results to the feather of the blades suddenly and produces an impact load on the floating wind turbine. This has a distinct effect on the mooring line tension response; compared to the maximum value of the tension of the mooring line for normal conditions, the maximum value is increased with a factor of 1.6 for fault conditions. The motion responses of the surge, heave and pitch are affected (attributed to the variation of the aerodynamic loads) compared to sway, roll, and yaw motions.

In general, for shutdown fault conditions (both grid loss and blade seize), the wind turbine is affected. For these cases, the bending moment of the tower experiences an intense variation and backlash occurs attributed to the change of the direction of the aerodynamic loads as the blades are feathered. The sudden reduction of the thrust loads on the wind turbine appears as an impact load and the wind turbine tower starts to vibrate at its natural eigenfrequencies. Although the variation of the bending moment is very large, the absolute value of the negative bending moment is smaller compared to the positive bending moment (the maximum value in normal condition). The same phenomena are observed for the blade deflection; during the shutdown condition and due to the removal of the thrust load, backlash and hence negative deflection are observed. The variation in bending moment is large; however, after a short time, the blade deflection oscillation is damped. The generated power and blade deflection are slightly affected when the blade is seized and the wind turbine may continue its function; however, there are more oscillations at the first rotor harmonics that result in fatigue damage if the wind turbine continues to operate in such conditions.

The sensitivity study of the responses to the time of fault occurrence showed that the mooring line tension ratio can

be roughly 25% larger or 30% smaller compared to the base case. The sensitivity study of the responses with regard to the time delay until the controller acts for shutting down the wind turbine showed that the tension of the mooring lines is not changed for small delay of the control action.

The authors prioritizing as future work the experimental study of the V-shaped semisubmersible that will be the basis for the increase of the accuracy of the numerical predictions and for the further improvement of this floating wind turbine concept.

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