Electromechanical Interactions of Full Scale Converter Wind Turbine with Power Oscillation Damping and Inertia Control

Mohamed Edrah[a], Xiaowei Zhao[a*], William Hung[b], Pengyuan Qi[a], Benjamin Marshall[c], Shurooque Baloch[d], Aris Karcanias[e]

[a] *School of Engineering, University of Warwick, Coventry, CV4 7AL, U.K.*
[b] *WH Power Systems Consultant Ltd, Warwick, U.K.*
[c] *The National HVDC Centre, 11 Auchindoun Way, Cumbernauld, G68 0FQ, U.K.*
[d] *National Grid ESO, Faraday House, Warwick, CV34 6DA, UK.*
[e] *PA Consulting, 10 Bressenden Place, London SW1E 5DN, U.K.*

**Corresponding author: xiaowei.zhao@warwick.ac.uk*

Abstract

In this paper, the impacts of power oscillation damping (POD) and inertia controller on the structural system of wind turbine (WT) are evaluated. Synchronous generators (SGs) fitted with well-established power system stabilisers (PSS) are declining leading to reduced power system inertia and damping capability which are critical to system stability performance. The WTs will become more dominant and should therefore be capable of providing inertia response and POD to maintain system performance. However, there has been some concern amongst the industry regarding effects of inertia and POD controls on WT performance when the active power modulation is utilised by both controllers particularly during frequency event that leads to low-frequency power oscillations. A detailed grid-connected full-scale converter (FSC)-WT system which combines aerodynamic, electrical, and mechanical characteristics was developed to assess its interactions with the POD and inertia controllers and also the resulting impact on the WT structural system. The obtained results show that the implementation of the POD/inertia controllers on the FSC-WT can improve the inertia response and oscillation damping but will affect the dynamics of its drivetrain, blades, and tower. However, these effects are shown to be smaller than the effects caused by the credible electricity system faults.

Keywords: POD, inertia response, active power modulation, wind turbine, electromechanical interactions.

1. Introduction

Low-frequency electromechanical oscillations are one of the concerning issues in modern power systems as poorly-damped or unstable power oscillations can cause severe problems in power systems including large-scale blackouts. Low-frequency power oscillations are also observed in the GB network between areas of Scotland and England. The typical frequency of power oscillations observed is around 0.5 Hz at times of high level of power transfer between Scotland and England [1]. These electromechanical oscillations are monitored by several phasor measurement units (PMUs) which are installed at different sites around the transmission system between Scotland and England to provide information to the transmission system operator (TSO) [2].

In recent years, there has been a significant growth in wind energy in the GB system as wind energy has emerged as a promising alternative energy source [3]. In the final quarter of 2018, wind energy's contribution to UK electricity needs has reached 21.5%, making wind energy the UK's single biggest source of renewable power [4]. This is in line with the UK Government's target of cutting greenhouse gas emissions by at least 80% below an agreed 1990 baseline by 2050 [5]. With the continual increase of wind power, the stability of the GB electricity system will face more significant challenges in the coming years as more SGs with well-established PSS will be replaced by WTs leading to low system inertia and poor damping capability. To date, the impact of the POD on WT performance is not fully understood and hence POD capability has not been actively incorporated so far. The main objective of this project is therefore set out to address if there is any unfavourable interaction between the WTs structural system and the associated POD and inertia controllers when both are activated.

The variable speed wind turbines, including doubly-fed induction generator (DFIG) and FSC-WTs are widely used due to their excellent control features [6, 7]. At present, the FSC-WTs are more common, due to their wider speed range, the ability to withstand low voltage ride-through (LVRT), and the potential to support voltage stability of the main grid. FSC-WTs are connected to the grid via fully controlled voltage source converters (VSCs) which makes it possible to fulfil the most advanced grid codes requirements on the market today. According to [8], most of the installed offshore wind turbine (OWT) technology in the UK is FSC-WTs, which accounted for 87% of the total installed OWTs as the end of 2017.

FSC-WTs are fully decoupled from the main grid by a full-size power converter leading to poor and thus they do not directly engage in low-frequency power oscillations damping and or provide inertia response capabilities [9, 10]. Furthermore, due to the intermittent nature of WTs and their geographical location, the generated power can have an adverse effect on the overall system damping [9]. Moreover, WTs with frequency support capability could excite lightly damped power oscillations [11]. Therefore, the damping contribution from installed FSC-WTs is of significant importance, and this can be achieved by the addition of POD that manipulates the VSC controller to modulate FSC-WT's power outputs [10].

A thorough survey of the literature shows that the utilisation of FSC-WTs to participate in the damping of electromechanical oscillations has received increasing attention. Some papers evaluate the FSC-WT capability to provide POD by using active or reactive power modulations [12-15]. In [12, 14, 15] an auxiliary POD control is attached to the active power control loop within the generator side converter to damp low-frequency power oscillations. The obtained simulation results indicate that the use of active power modulation of FSC-WTs to damp power oscillations is a powerful means to introduce additional damping torque. On the other hand, reactive power modulation is used in [12, 13, 15] to damp electromechanical oscillations. The obtained results indicate that the power oscillation can be damped by controlling the terminal voltage of the FSC-WT in a similar way to the SG-PSS. However, the simulation results of [15] show that the use of reactive power modulation can deteriorate the voltage stability.

Although the active power modulation is more effective than reactive power modulation [16] by directly changing the electromagnetic torque of the generator, the use of active power modulation may have the risk of deteriorating the shaft dynamics and increase the forces on the mechanical structure of the WTs [15]. Moreover, WTs with frequency support capability weakened the damping ratio for the turbine torsional oscillations [11]. Therefore, FSC-WTs could be subjected to additional disturbances on their structural dynamics in providing damping capability which has not yet been investigated in the literature. Also, unlike conventional SGs where the POD and inertia controllers are typically installed in different control loops, the WT POD and inertia controllers are designed and integrated into the active power control loop. This is why the industry is concerned about the practical impact of the POD on WT's structure system and the interaction with the inertia controller. However, the need for WTs to have the capability of damping power system oscillations has been considered by some PSOs and future grid codes might require WTs to provide POD and inertia support [17, 18].

The previous research in this area focused primarily on the capability of FSC-WTs to provide damping capability without considering the structural dynamics of FSC-WT and the interaction with the inertia controller. Those studies were carried out using rather simple aerodynamic and structural models of WTs that lack some of the important mechanical features. Few papers have investigated the interactions between electrical and mechanical systems of the WTs. In [19], the effect of a grid fault on the modes of the DFIG-WT structure system was investigated using a detailed mechanical structural model. The obtained results show that large grid disturbance can induce vibrations in the WT blades and tower. Reference [20] also indicates that grid disturbances can cause dangerous tower vibrations under high-speed wind conditions. The voltage sag impact on tower vibration is investigated in [21, 22] and the results show that voltage sag can affect the WT mechanical performance such as tower vibrations. The effects of the POD on the DFIG-WT structural system were investigated in [23] and the results showed that the POD controller could have some effect on the turbine structural system, but these effects are less significant than those caused by grid faults.

Most of the conducted research in this area focuses on the effects of grid disturbances on the structural system of WTs. The reference [23] has investigated the effect of the POD on DFIG-WTs but did not take into account other supplementary controllers within the same control loop such as inertia controller which can interact with the POD controller and lead to higher structural loading. The active power utilization for POD and inertia support might affect the turbine's structural system as it is directly related to the electromagnetic torque. Therefore, applying POD and inertia controls could excite some of the structural vibrations of the WT such as tower, drivetrain, and blades, which can lead to failure. Therefore, as presented in the present paper, a comprehensive FSC-WT utility-scale model that combines aerodynamic, structural, and electrical systems is developed to investigate unfavourable effects that POD control could have on the structural system of a grid-connected FSC-WT with an inertial response controller. The results obtained have been compared to those arising from variable wind speeds or transient system 3-phase short-circuit faults. These provide an insight into the level of impact caused by the POD as compared to those conditions which the WTs are designed to withstand. The analysis is conducted using a combination of two different simulation packages, namely FAST and Matlab/Simulink, which are used to model in detail the aerodynamics, structural and electrical features of a gird connected WT.

The major contributions of this paper are: 1) Identify potential electromechanical interactions of FSC-WT caused by POD/inertia controllers which have not been investigated yet in the literature. Both POD and inertia controllers are integrated into the active power control loop and their interactions can lead to higher structural loading and thus the effects of POD/inertia controllers on FSC-WT has been conducted using nonlinear analysis of a utility-scale grid-connected WT system with detailed electrical, aerodynamic, and mechanical structural modelling. 2) Define the natural vibration frequencies of the WT blades, tower, and drivetrain by a nonlinear simulation and investigate the POD/ inertia controllers' effects on them including variable wind speed. This offers a broad understanding of electromechanical interactions of the FSC-WT through typical operating conditions when the WT provides POD/inertia response capability. 3) Examine the effects of LVRT on FSC-WT and compare them with those may be triggered by the action of POD/inertia controllers and compare their relative impact on the WT.

The remaining parts of this paper are organised as follows: Section 2, explains the developed grid-connected FSC-WT models with its electrical and structural systems. Section 3 shows the development of the proposed POD/inertia controllers. The impacts of POD/inertia controllers on the structural system of the WT for different wind speed conditions such as 1) steady wind speed, 2) variable wind speed and 3) when the FSC-WTs are subjected to a grid fault are analysed and discussed in Section 4, followed by conclusions and recommendations in Section 5.

2. Grid-Connected FSC-WT System

A complete model of a utility-scale grid-connected FSC-WT system, which combines aerodynamic, electrical, and mechanical characteristics, are described in this part. Two nonlinear different software environments are used to model aerodynamic, mechanical, and electrical parts of grid-connected FSC-WT in detail. FAST (Fatigue, Aerodynamics, Structures, and Turbulence) developed by the National Renewable Energy Laboratory (NREL) WT analysis tool [24] is employed to develop comprehensive aerodynamics and mechanical WT model. The detailed aerodynamics and mechanical WT model are then connected to MATLAB/Simulink simulation package [25] where the electrical aspects are simulated. The above combined FSC-WT model was then connected to a two-area electrical test system with four SGs where inter-area oscillation effects are produced. A POD and inertia controllers were developed and added to the WT model to damp a low-frequency electromechanical oscillation and provide inertia response.

2.1 Two-areas Power System

The simulation scenarios have been conducted using a two-area test system which is based on the two-area standard test system and it is presented in Fig. 1. The selected two-area system is extensively used to investigate inter-area power oscillations [26]. In order to connect the NREL-5 MW WT model, the two-area benchmark power system is scaled-down. The two-area system has four SGs each rated at 10 MVA and they are divided between the two areas equally. Each SG has an excitation system and a governor but there is no PSS. The total system demand is divided between area 1 and area 2 to create a power flow from area 1 to area 2.

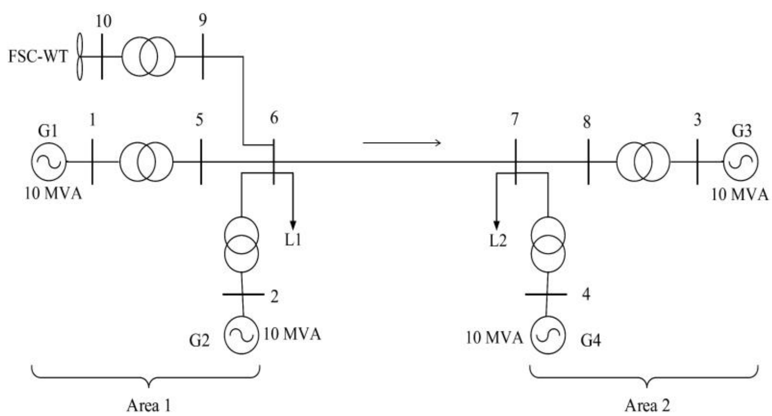

Fig. 1 The modified test system including FSC-WT.

2.2 FSC-WT Model

FSC-WTs are variable-speed WTs connected directly to the main grid via fully-rated ac/dc-dc/ac power converters as shown in Fig. 2. The WT generator can operate at a wide range of wind speeds with maximum power conversion efficiency. The generator is connected to the machine-side converter (MSC) which is used mainly to control the generator electrical torque to extract optimum power from any particular wind speed. The grid-side converter (GSC) is connected to the grid and it is usually used to regulate the voltage of the dc link. The GSC may also be used to control the reactive power flow to the grid. For FSC-WT, pure active power is transmitted through the dc-link which completely decouples both sides in terms of frequency and voltage. A complete detailed FSC-WT model includes the aerodynamic model, the mechanical model, and models of the electrical components and their associated controllers are shown in Fig. 2.

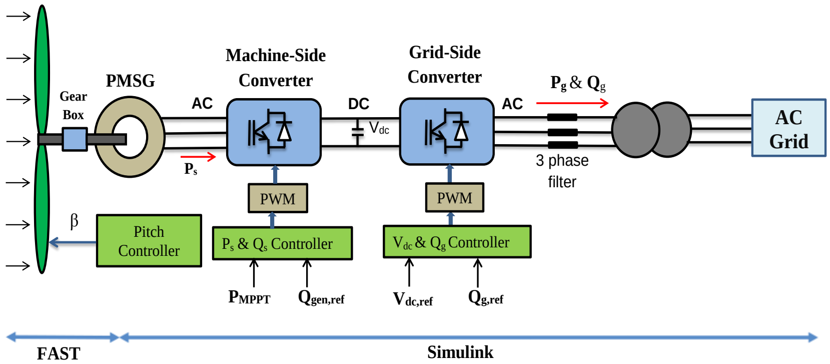

Fig. 2 Developed FSC-WT model using FAST and Simulink.

2.2.1 Mechanical and aerodynamics models

The increase of WT ratings is the most dominant trend in recent years, especially for the OWTs. WTs are also becoming more and more flexible. The flexibility of WTs structure such as blades, tower, drivetrain and other components [19] cannot be neglected when the interactions between the electrical and the mechanical aspects of WTs need to be assessed. An accurate WT model must contain many degrees of freedom (DOFs) to capture the most important dynamic effects. Therefore, in this paper, the detailed aerodynamic and structural systems of the WT are modelled using FAST software [24]. FAST is a comprehensive aeroelastic simulator capable of predicting both the extreme and fatigue loads of three-bladed, horizontal-axis WTs. In FAST, WTs can be modelled as a combination of rigid and flexible bodies. The rigid bodies are platform, nacelle, and hub and the flexible bodies include blades, tower, and drivetrain. The displacement and velocities of WT's mechanical parts can be obtained by FAST equations of motion and blocks that integrate several DOFs accelerations. With the consideration of WT flexible structure, tower bending (tower fore-aft and side-to-side), blade bending (flap-wise and edgewise blades deflections), rotor speed, and drivetrain torsion.

The structure of WT modelled in FAST is combined with a WT aerodynamic code which is created using the Blade Element Momentum (BEM) concept [27]. All scenarios within this paper have been conducted using the most recent version of FAST (FAST-V8) [28]. Both structural and aerodynamic models are based on realistic data obtained from NREL 5-MW OWT, which was developed by NREL with detailed specifications representative of a typical utility-scale WT. The NREL-WT is a conventional horizontal-axis, three-bladed, variable speed WT with blade-pitch control. The detailed specifications of the NREL 5-MW OWT are described in [29].

2.2.2 Modelling of FSC-WT controllers

The FAST simulation tool is an effective and accurate tool to study WT's aerodynamics and structure system, but the representation of the electrical system is incredibly basic and cannot correctly represent the characteristic of complicated WT electrical system. Therefore, FAST software is used in conjunction along with MATLAB/Simulink to incorporate a well-presented generator, converters, and the associated control models. By doing this, the mechanical stress and vibrations of various WT sections can be examined under various scenarios such as grid transients, proposed POD, and wind turbulence. Thus, the effects of the FSC-WT control system on the WT structural system can be examined.

FSC-WTs is connected to the ac grid via two full-rated converters which are completely controlled independently through the decoupled *d-q* vector control approach which is well enveloped for FSC-WTS. Therefore, the characteristics of the FSC-WTG during steady-state and transient periods are mainly dependant on the control strategy of the converters. The generated power is converted from three-phase ac voltage with variable frequency and magnitude into dc via MSC, which is normally controlled to capture optimal power from any particular wind speed. Then the GSC convert the dc voltage into ac with fixed frequency and magnitude for grid connection. The GSC is normally controlled in such a way to keep the dc-link voltage at a set value and may also be used to regulate the reactive power exchanged with the grid.

The converters (MSC and GSC) of FSC-WTG are both modelled in MATLAB/Simulink as current-controlled converters. Fig. 3 shows the conventional vector control scheme of the MSC in which each control loop has a cascaded structure. The typical vector control of MSC and GSC of FSC-WTG are well described in the literature [30, 31] and will not be covered here.

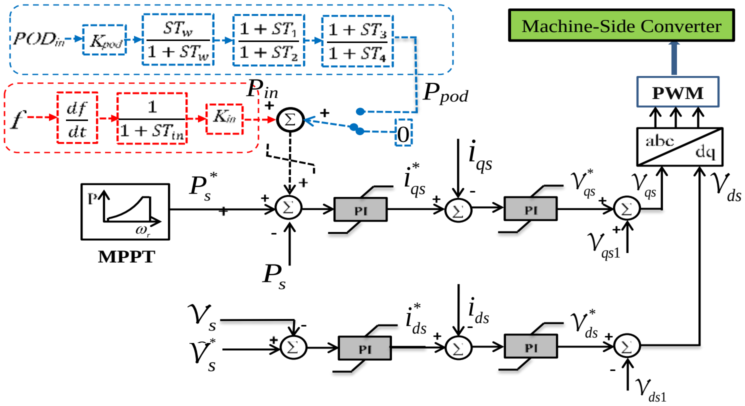

Fig. 3 MSC control scheme and the developed POD (dashed blue lines) and the inertia controller (dashed red lines).

3. POD and Inertia Controls Design

This section presents the proposed POD and inertia control approaches by utilizing the kinetic energy of FSC-WTs. First, the proposed POD controller is presented and then the WT inertia emulation controller is discussed.

3.1 POD control design

POD controller is developed in this section to damp electromechanical oscillations. The developed POD is attached to the active power controller within the MSC of FSC-WT as presented in Fig. 3 with dashed blue lines. The POD controller is similar to the well-known traditional PSS. This type of controller is very popular and is extensively employed in SGs as it is simple robust and can be easily tuned [32]. The mathematical equation of the examined POD controller is shown in (1).

$$P_{pod} = K_{pod}\left(\frac{ST_w}{1+ST_w}\right)\left(\frac{1+ST_1}{1+ST_2}\right)\left(\frac{1+ST_3}{1+ST_4}\right)POD_{in} \qquad (1)$$

The deviation of measured active power at the tie-line near area 1 has been selected as an input signal (POD_{in}). This signal is passed to the POD gain K_{pod}. The gain defines the damping value produced by the POD controller. To filter the input signal, a washout filter is implemented with a specific time constant to allow specific frequency ranges to go throw and thus the POD controller can only operate during low-frequency power oscillations. The filtered signal passed to a lead-lag compensator with a second order. This compensator is needed to create a phase for the output signal by adjusting the values of T_1-T_4 and thus producing a phase opposed to the original power oscillation.

Different techniques can be used to tune the parameters of the POD such as the gain and the compensator values to guarantee optimal POD performance. Particle swarm optimization (PSO) based algorithm is a well-known optimisation method and has been widely used to address optimisation problems and determine PSS parameters [33, 34]. Therefore, in this paper, PSO is proposed to tune the POD controller by finding the best values to obtain the optimal damping performances. The optimal performance is obtained by using PSO algorithm in conjunction with the established nonlinear FSC-WT model in MATLAB/Simulink simulation. As the PSO algorithm generally aims to minimise the objective function, the variation of active power between area 1 and area 2 is selected as an objective function of the PSO. The obtained best possible parameters of the POD are shown in (2) and they are obtained with the following operation condition: fixed wind speed of 14 m/s and area 1 is exporting around 17 MW to area 2.

$$P_{pod} = 0.12\left(\frac{10S}{1+10S}\right)\left(\frac{1+1.65S}{1+0.103S}\right)\left(\frac{1+1.273S}{1+1.082S}\right)POD_{in} \qquad (2)$$

3.2 *WT inertia emulation control*

Unlike conventional SGs which can naturally release the kinetic energy stored in their rotating mass to provide inertia response, WTs cannot release the kinetic energy stored in the rotating turbine rotor and the generator rotor without a suitable controller. For WTs providing inertia response, they need to be coupled with the system frequency through an auxiliary controller which is added to the active power control loop within the MSC as shown in Fig. 3 with dashed red lines.

During normal steady operating conditions, the WT will deliver its maximum power defined in MPPT curve without any effect from the inertia controller as the value of P_{in} is negligible. However, in the event of frequency disturbances, the inertia controller output P_{in} will vary depending on the relationship defined in (3) where the virtual inertia gain K_{in} is selected as 2H. For instance, in the event of a falling frequency, the power demand on the FSC-WT will increase emulating the release of stored kinetic energy leading to the slowdown of the WT. The additional power P_{in} can be expressed as:

$$P_{in} = K_{in} \times df \ / dt \qquad (3)$$

The grid frequency f is estimated using a phase-locked loop (PLL) synchronisation of the WT. The output of the inertia controller is added to the output of the POD controller and then passed through a limiter of 15% to make sure that the created signal (P_{pod} and P_{in}) is within the predefined FSC-WT limits.

As both POD and inertia controllers are installed on the active power control loop, they need to be managed to avoid each signal being cancelled. Therefore, the POD signal is passed through a switch to priorities the inertia response which will last only for a few seconds then the POD will be activated to damp power oscillations.

4. Simulation Results and Analysis

In this section, the effect of POD (without and with the inertia controller) on the FSC-WT structural parts such as blades, tower, and drivetrain examined by a nonlinear time-domain simulation assessed under a steady wind speed of 14 m/s at the hub height. All simulations were executed using a fixed-step solver with a 5 µs step size. The simulation results will show the behaviour of the NREL 5-MW after 60 seconds as the nonlinear simulation model need some time to reach a steady-state operation point after starting. At first, the effectiveness of the proposed POD without and with the inertia controller is evaluated, then the effects of the proposed POD on the WT's structural parts are investigated under different wind speed conditions and during a grid fault.

4.1 POD and Inertia Controllers - steady wind speed

In order to assess the effectiveness of the developed POD without and with an inertia controller, a low-frequency power oscillation is created between area 1 and area 2 as well as a frequency disturbance. Therefore, L2, shown in Fig. 1, increased by 2MW at the 60s to create a frequency disturbance which results in power oscillation between the two areas. The simulation results show a poorly damped inter-area power oscillation with a frequency of 0.67 Hz occurs on the transmission line between the two areas as indicated in Fig. 4 (a) with a dashed black line.

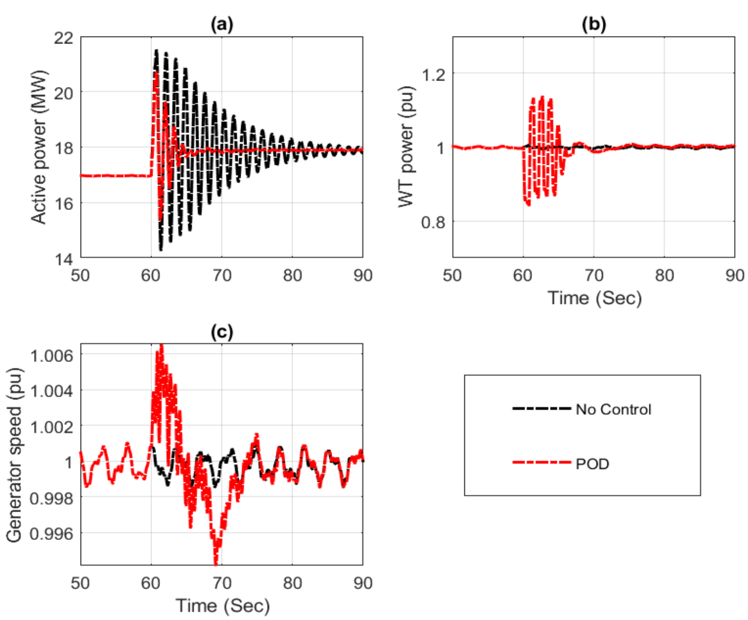

Fig. 4 WT response (a) power oscillation between area 1 and area 2, (b) generated power, (c) generator speed.

With the proposed POD, the power oscillation is damped effectively within a short time as shown in Fig. 4 (a) with a dashed red line. This indicates that the utilisation of active power output of the FSC-WT by the developed POD is very effective to suppress inter-area power oscillation. The WT power without the POD is constant at the rated power as the wind speed is above the rated value as shown in Fig. 4 (b). However, in the case with the POD, the output power starts to change when the POD controller starts to damp power oscillations at 60 s and last only for a few seconds. The generator speed of FSC-WT is also constant without POD controller and it is around the rated speed shown in Fig. 4 (c) and it starts to change also at 60 s when the POD controller is activated to damp the electromechanical oscillation. The generator speed is increased when the WT injects kinetic energy to the rotating mass to decrease its output power as a result of the POD action. In contrast, the speed decreases to allow more power which is extracted from kinetic energy stored in the turbine rotating mass.

The dynamic performance of the WT with the inertia controller only or with the POD is shown in Fig. 5. It is clear that the inertia controller affected the effectiveness of the POD controller as shown in Fig. 5 (a) with the dashed green line. The inter-area oscillation last longer when the WT is equipped with both the POD and inertia controllers. This is because both controllers are within the same control loop and thus inertia controller is prioritised over POD to provide inertia response and thus the POD is activated after the WT provided the inertia response which is about 3s. The WT power is increased at 60 s to provide inertia response and help to improve the frequency nadir which is improved from 49.45Hz to 49.6 Hz as shown in Fig. 5 (b, d). The provided power by the inertia controller results in less kinetic energy made available for the POD controller which adversely affects its performance.

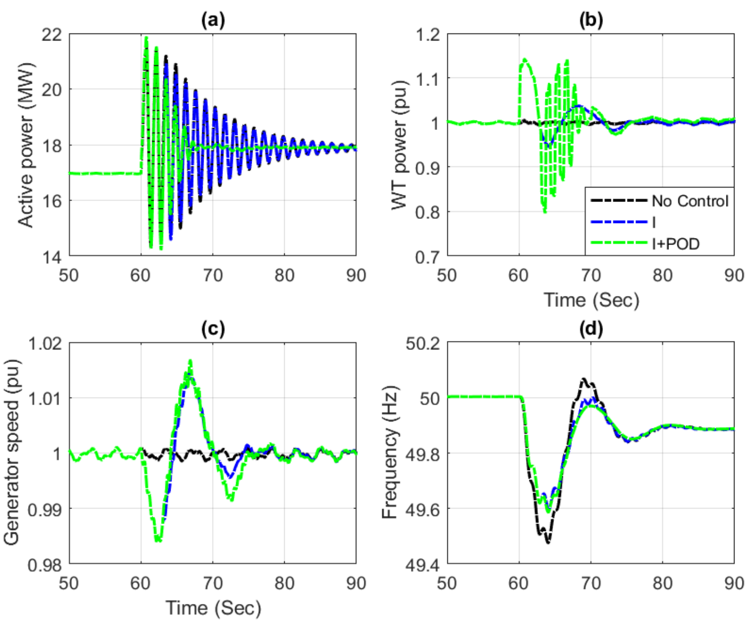

Fig. 5 WT response (a) power oscillation between area 1 and area 2, (b) generated power, (c) generator speed, (d) grid frequency.

The dynamic response of FSC-WT blades and tower are shown in Fig. 6. The deflection of WT blades tip due to flap-wise and edge-wise bending is revealed in Fig. 6 (a, b). When the WT is fitted with the POD controller, the magnitude of the flap-wise deflection is slightly reduced. This is because the WT is operated at the optimal power when POD is activated which in turn reduced the torque leading to higher generator speed. By letting more wind pass through the WT blades, the thrust force of the wind is reduced and hence less flap-wise deflections. However, the blades edge-wise tip deflection in the case of the POD remains almost the same. A large magnitude of the flap-wise deflection is observed in the case of the inertia control caused by a rapid increase in the electromagnetic torque of WT generator triggered by the inertia controller. This shows that the inertia controller can affect the WT blades more than the POD for a short time. However, both POD and inertia controller has negligible effects on the blades edgewise.

Moreover, Fig. 6 (c, d) shows the side-to-side and fore-aft movements at the top of the WT tower which is moving regularly at a frequency of 0.272 Hz. The tower side-to-side and fore-aft bends are generated by the aerodynamics of the WT and the pitch angle of the turbine blades as well as torque deviations and the total inertia of the drivetrain. Installing POD control on the WT can marginally reduce both tower side-to-side and fore-aft movements when the POD is activated. However, inertia controller without and with POD can have a noticeable effect on the magnitude of the WT tower fore-aft displacements. The tower side-to-side displacements are slightly affected where the effects of the inertia controller are also larger than the POD.

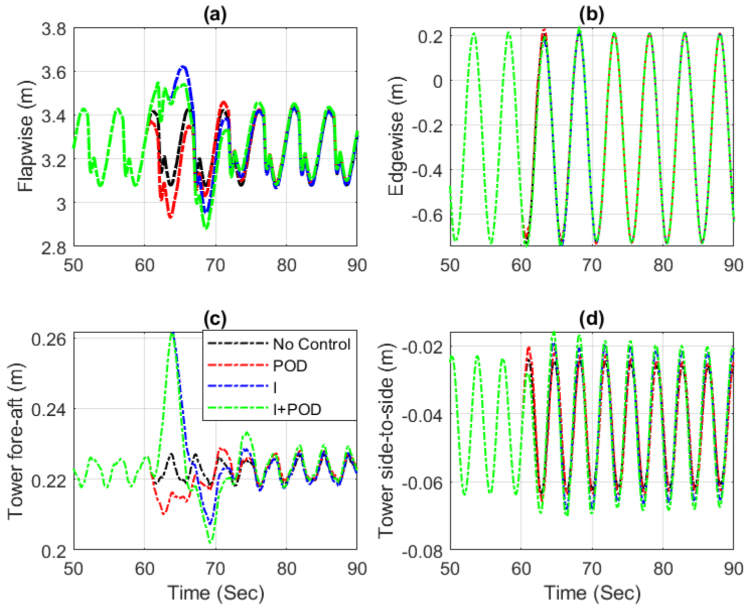

Fig. 6 WT response (a) blades flap-wise (b), blades edge-wise tip deflections, (c) tower fore-aft & (d) tower side-to-side displacements.

The obtained nonlinear simulation results are further examined by Fast Fourier Transform (FFT). The WT blades tip flap-wise and edge-wise oscillations are analysed by FFT and the results of the frequency-domain analysis are shown in Fig. 7 (a, b). Several inherent frequencies of the WT blades have been identified such as (1P, 2P, 3P, etc) frequencies. Each blade oscillating at its natural frequency of 0.2 Hz (usually known as 1P frequency). WT tower side-to-side and fore-aft oscillations are also analysed by FFT and the results of the frequency-domain analysis are shown in Fig. 7 (c, d). Both fore-aft and side-to-side tip deflections are oscillating at a similar frequency of 0.272 Hz. Other frequencies observed on tower fore-aft are associated with WT blades frequencies. The POD and inertia controllers did not introduce new frequencies for the WT blades or the tower, but they might slightly influence the magnitude of the existing natural frequencies. The POD has some impacts on the blades tip flap-wise and the inertia controller has some impacts on the WT tower side-to-side and fore-aft oscillations.

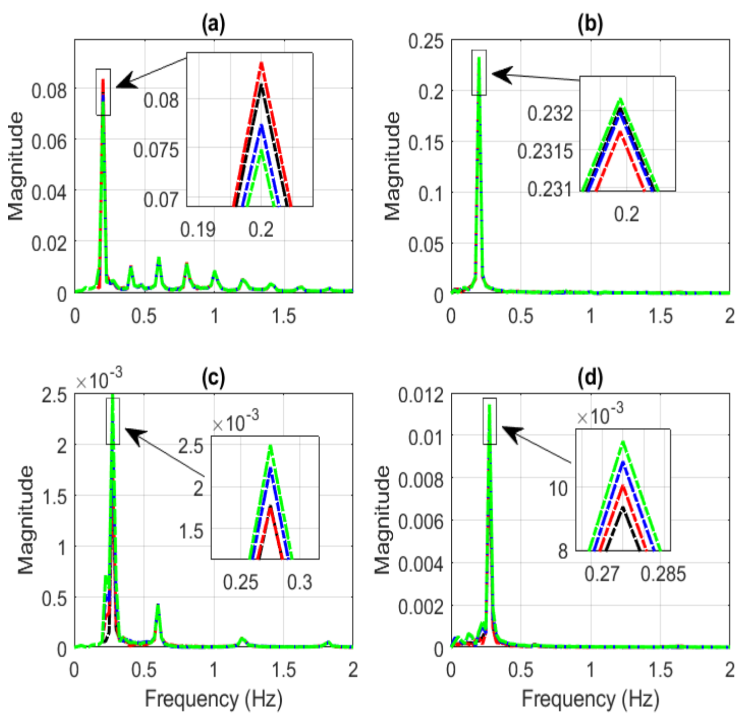

Fig. 7 Frequency domain analysis of the WT (a) flap-wise tip deflection, (b) edge-wise tip deflections, (c) tower fore-aft displacements, and (d) tower side-to-side displacements.

To investigate the effects of the POD controller on the drivetrain, the drivetrain acceleration of the grid-connected FSC-WT is shown in Fig. 8. The oscillation of the drivetrain acceleration is just around zero in case without any control. However, in the case of the POD controller, drivetrain acceleration accelerates to almost 1.2 deg/sec^2 just after the activation of the POD controller at 60 s to suppress the inter-area oscillation. The excited oscillation of the drivetrain acceleration gradually declined to its typical value (around zero) within less than 15 s. More drivetrain accelerations are observed when the WT is equipped with both POD and inertia controller. This is because more time is need by the POD controller to damp the power oscillation.

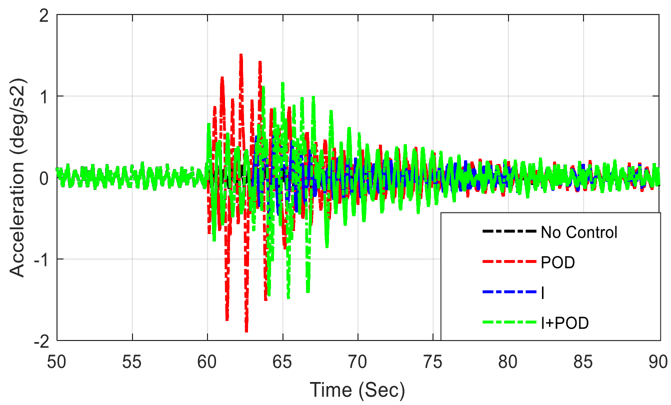

Fig. 8 WT drivetrain acceleration.

4.2 POD effects - variable wind speed.

In practice, the wind speed is variable in its nature and hence the WT output also varies. Therefore, the impacts that the POD/inertia controllers may have on the WT mechanical system are evaluated under variable wind speed conditions as presented in Fig. 9 (a). The mean value of the variable wind speed has is 15 m/s with a turbulence characteristic standard IEC-type B and it is created by a wind simulator turbsim [35].

The dynamic response of the WT blades and tower during the variable wind speed condition are shown in Fig. 9 for all cases. The effects of the POD/inertia controllers on the deflection of blades tip due to flap-wise and edge-wise bending shown in Fig. 9 (b, c) are similar to the obtained results in section A. However, the wind speed variations can cause larger blades deflections and thus the effects of the POD/inertia control action on WT blades are minimum in comparison to those created by wind speed variations.

The impacts of the POD/inertia controllers on the tower fore-aft and side-to-side displacements at the top of the tower during variable wind speed conditions are shown in Fig. 9 (d, e). Fitting the FSC-WT with the POD controller can slightly affect both tower side-to-side and fore-aft movements when the POD controller is activated in a similar way to the steady wind speed and wind speed variations can cause larger displacements. However, the activation of the inertia controller or POD following the inertia control action can cause large displacements of the tower fore-aft and they are larger than those caused by wind speed variations.

The drivetrain torsional vibrations are also examined under variable wind speed conditions and with the POD/inertia controllers as shown in Fig. 9 (f). It is clear that the vibrations of the drivetrain acceleration caused by wind speed variations are comparable to those caused by POD/inertia controllers.

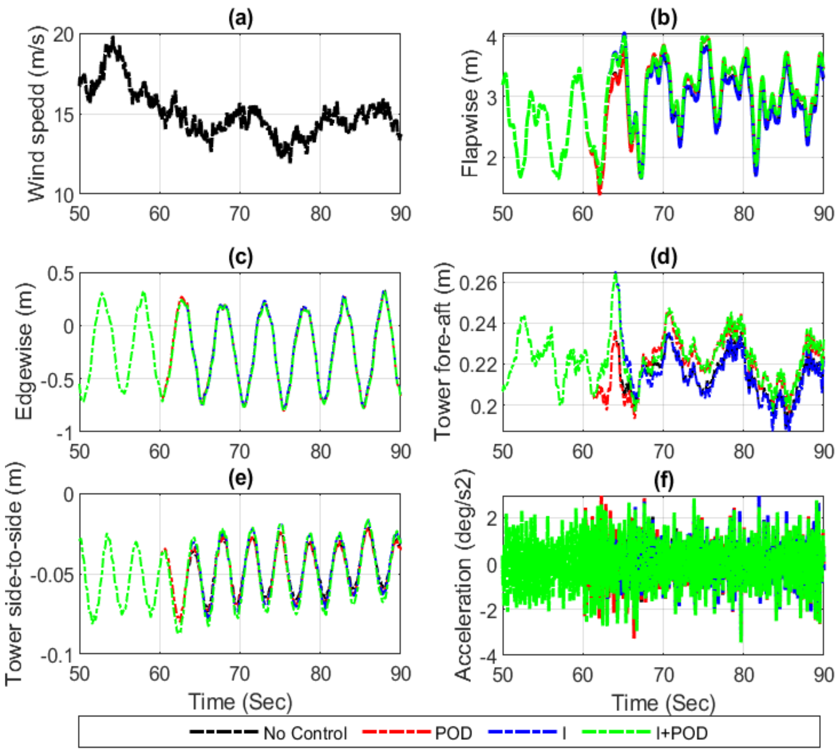

Fig. 9 WT response (a) wind speed, (b) blades flap-wise tip deflection, (c) blades edgewise tip deflections, (d) tower fore-aft displacements, (e) tower side-to-side displacements, and (f) drivetrain acceleration.

4.3 Impacts of three-phase short circuit.

WTs are required to meet GB grid code criteria for LVRT (under section CC.A.4A3.2), which means that they should not disconnect during a specified range of grid disturbances. They are designed to withstand the impacts of wide voltage ranges of disturbances. Therefore, in this section, the impacts of LVRT will be compared to those caused by the POD/inertia controllers. A self-clearing three-phase short circuit fault is applied at the terminal of the FSC-WT at t = 60 s and cleared after 140 ms. This results in voltage sag to about 0.15 pu at the terminal of the WT during the fault and then recovers to normal voltage level as shown in Fig. 10 (a). The voltage sag reduces the generator torque leading to a momentarily rise in rotational speed, while the pitch controller is trying to restore the speed to the pre-disturbance level. In comparison, the resulting changes in the generator speed shown in Fig. 10 (c) is about twice that of the POD case shown in Fig. 5 (b).

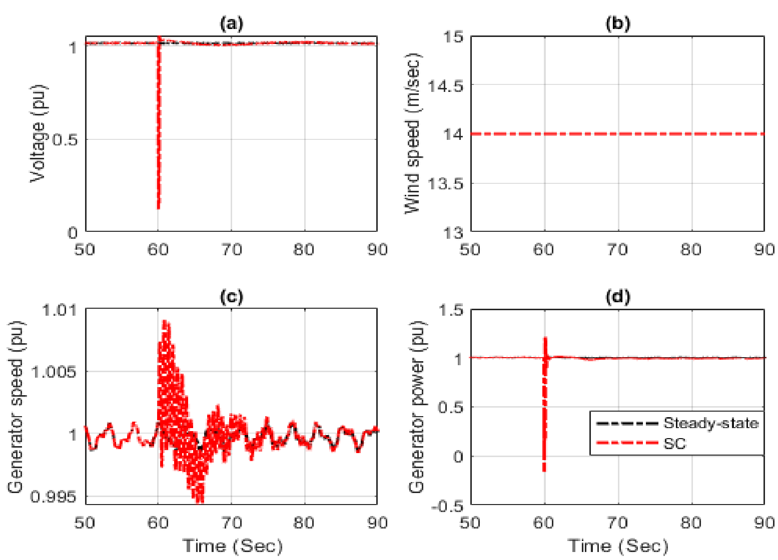

Fig. 10 WT (a) terminal voltage, (b) wind speed, (c) generator speed, and (d) generator power.

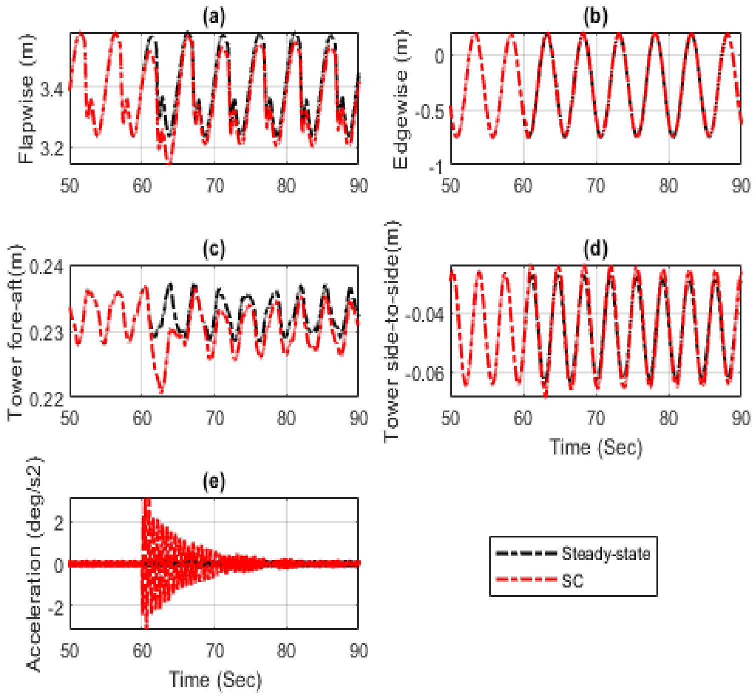

Fig. 11 WT (a) blade 1 flapwise tip deflections, (b) edgewise tip deflections, (c) tower fore-aft displacements, (d) tower side-to-side displacements, and (e) drivetrain acceleration.

The dynamic response of WT blades, tower, and drivetrain is shown in Fig. 11. The magnitude of flap-wise deflection and tower movements are much larger than that observed early with the POD but they are less than those caused by inertia controller due to the rapid change in the electromagnetic torque. The effects on the drivetrain are shown in Fig. 11 (e) and it is clear that the effects of the three-phase fault on the drivetrain acceleration are larger than those produced by the POD/inertia controllers and wind speed variations shown in Fig. 9 (f).

5. Conclusions and recommendations

In this paper, we investigated the impacts that the POD/inertia controllers may have on the FSC-WT structural system. This study was conducted using a detailed model that incorporates important features of a grid-connected utility-scale FSC-WTs, such as a mix of fixed and moving frames with defined degrees-of-freedom, coupling with the tower-blade-drivetrain vibrations, as well as aerodynamic loads. To damp electromechanical oscillations, a POD controller was developed based on the traditional well-established PSS. The results obtained clearly demonstrate the effectiveness of FSC-WT on damping the power system oscillations when equipped with POD. The inertia controller has improved the system inertia response but could marginally affect the POD performance.

The results also show that the POD may marginally excite some of the FSC-WT structural system inherent frequencies but providing inertia response with and without POD can have a considerable impact on the WT drivetrain, blades, and tower. These impacts caused by the POD and inertia controller are larger than those caused by wind speed variations but similar to or less than those caused by credible grid faults.

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