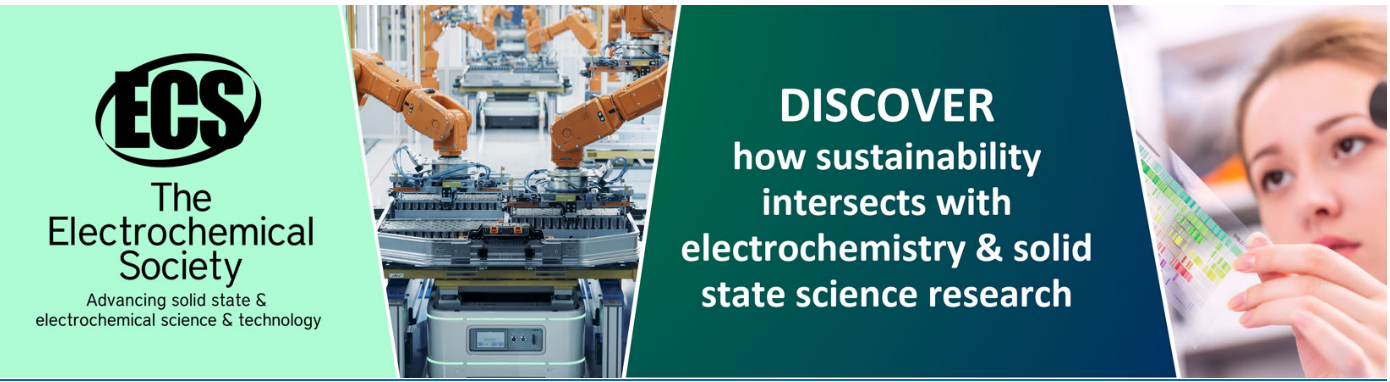
Structural Load Analysis of a Wind Turbine under Pitch Actuator and Controller Faults



Structural Load Analysis of a Wind Turbine under Pitch Actuator and Controller Faults

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In this paper, we investigate the characteristics of a wind turbine under blade pitch angle and shaft speed sensor faults as well as pitch actuator faults. A land-based NREL 5MW variable speed pitch reg- ulated wind turbine is considered as a reference. The conventional collective blade pitch angle controller strategy with independent pitch actuators control is used for load reduction. The wind turbine class is IEC-BII. The main purpose is to investigate the severity of end effects on structural loads and responses and consequently identify the high-risk components according to the type and amplitude of fault using a servo-aero-elastic simulation code, HAWC2. Both transient and steady state effects of faults are studied. Such information is useful for wind turbine fault detection and identification as well as system reliability analysis. Results show the effects of faults on wind turbine power output and responses. Pitch sensor faults mainly affects the vibration of shaft main bearing, while generator power and aerodynamic thrust are not changed significantly, due to independent pitch actuator control of three blades. Shaft speed sensor faults can seriously affect the generator power and aerodynamic thrust. Pitch actuator faults can result in fully pitching of the blade, and consequently rotor stops due to negative aerodynamic torque.

1 Introduction

To increase the wind turbine reliability and therefore to reduce the energy production costs, it is important to study the effects of malfunctions in wind turbine subsystems on power output and structural loads and responses. Wind turbine controller fault is one such malfunction. Fault in one small component, such as shaft speed sensor, results in rotor overload and consequent wind turbine shut-down by safety guard system when the shaft speed exceeds the safety threshold. Faults in pitch speed sensor result in imbalance loads on the rotor, which increases fatigue loads on bearings and gearbox and reduce the lifetime of the structure. However some fault cases might not have any effect on power output or even very small effect on shaft speed but make a considerable change in loads and responses of some structural components. To get the certification of wind turbines from the classification societies, manufacturers and owners need to document the wind turbine load analysis under fault conditions as stated by IEC-61400-1 [1]. Experiences in Germany and Denmark [2, 3] show the electrical control and mechanical pitch control system as two sub assemblies with relatively high failure rates of [0.1 to 0.2] per wind turbine per year, for modern wind turbines.

Faults in pitch angle, generator shaft speed sensor and converter sensor are simulated in a benchmark model for fault detection and isolation purpose by Odgaard et al. [4]. A single body model of wind turbine drive train is used by the same authors [5] for observer-based detection of shaft speed sensor faults. The work shows the advantages of observer-based detection without wind speed measurements. An advanced aero-elastic model is used in [6] to simulate the effects of grid fault on structural loads and controller performance of a 2MW active stall wind turbine through the coupling between DIgSILENT and HAWC2. Simulation shows the effect of grid fault on shaft loads and tower root bending moments as well as small effects on pitch angle of the blade.

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A literature study shows that a limited documented knowledge and publication is available on the effects of pitch sensor and shaft speed sensor faults on load and responses of wind turbine while practical experiences indicate the needs for such information.

There are two main objectives for this paper. 1) To compare the effect of different fault cases including fixed value (FV), additive gain (AF) and multiplicative gain (MF) on pitch sensor and shaft speed sensor to identify the individual signature of each fault case on wind turbine performance and 2) to conduct load and response analysis of wind turbine under fault conditions.

The paper is organized in the following. Section (2) presents a brief overview on the wind turbine aero-elastic model in HAWC2 [7] with a focus on the variable-speed and individual pitch-regulated wind turbine controller. Section (3) presents the simulation set-up and fault case description. In Section (4) the simulation results for each fault case are presented through the comparison of the response sensitivity due to faults.

2 Wind Turbine Model

2.1 Aero-elastic Model

To study the effect of faults on wind turbine loads and responses, an accurate aero-servo-elastic model is needed. This must include all the dynamic effects such as spatially turbulent wind field, wind shear profile and the interaction between the wind turbine structure and wind speed, such as tower shadow effect and dynamic wake model. The problem becomes more challenging when the state of the system is changed by the controller to optimize the output power and alleviate loads on the structure at different wind speeds. The HAWC2 simulation code [7] , developed by Risø, has almost all the requirements for such a study. This code has been benchmarked in the IEA OC3 and OC4 studies [10]. The aero-elastic simulation tool HAWC2 is a code designed for calculating wind turbine responses in time domain. The structural part of the code is based on the multi-body formulation. The structure is divided into primary structural members. Each structural member is modeled by Timoshenko beam elements. The structural model includes large rotation and translation of body motions. Each body connects to its neighbour with a constraint which is formulated by algebraic equation. The deformed state of the structure is accounted in aerodynamic load calculation which is important for torsion and blade twist. The extended blade element momentum method including dynamic inflow, dynamic stall, skew inflow, shear effect on induction and effects from large deflection is used to compute the aerodynamic loads. The required wind field for simulation is generated as a superposition of mean wind velocity (deterministic part) and turbulent wind velocity (stochastic part). The cartesian coordinate Mann turbulence [8] is used to generate the spatially turbulent wind field. Other primary aerodynamic effects such as tower shadow, nacelle and tower drag and exponential wind speed profile are also included in the simulations.

2.2 Controller

The controller in HAWC2 model is implemented as external DLL's. This gives the opportunity to modify the controller or make a new controller without any change in the aero-elastic part of the code. The case study in this work is based on the NREL 5MW [9] variable-speed pitch-regulated wind turbine. The wind turbine operation region is limited by cut-in and cut-out wind speeds as the lower and upper limits respectively. The region in between is divided to two main subregions. The first region is power optimization region which is from the cut-in to rated wind speed. The next region is from the rated wind speed to cut-out wind speed which is the full power region. In the power optimization region, the blade pitch angle is constant $\beta = \beta_{opt}$ and the shaft speed is controlled by the generator torque controller to follow the optimal operation point $(\beta_{opt}, \lambda_{opt})$ in order to capture the maximum power. $\lambda = \frac{R.\omega}{V}$ is the tip speed ratio which is the ratio between the rotational speed of the blade tip $(R.\omega)$ and wind velocity (V). The generator torque (τ_g) is a function of shaft speed square $\tau_g = k_1 * \omega^2$ in this region. In the full power region the output power is limited to rated power with both generator torque controller and blade pitch angle controller. The constant electrical torque is applied on the high speed shaft in this region which is $(\tau_g = \frac{P_{rat}}{\omega_{rat}})$ where P_{rat} is the rated power and ω_{rat} is the rated shaft speed. To make a smooth transition from start-up to power optimization region and from this subregion to the full power subregion two small transition regions are defined at the beginning of each subregion. More details about the controller can be found in [9]. The shaft speed in power optimization region is controlled by generator torque as a tabulated function of shaft speed. In above rated wind speed, the generator torque is constant and shaft speed is kept constant with blade pitch angle controller. The output power is limited to the rated power in above rated wind speed. The gain scheduling PI controller is used to calculate the pitch angle reference ($\theta_{ref} = KP(\theta)\omega_e + KI(\theta)\int(\omega_e)dt$) according to the differences between the rated shaft speed (ω_{rat}) and measured shaft speed (ω_m) which is shaft speed error ($\omega_e = \omega_m - \omega_{rat}$). $KP(\theta)$ and $KI(\theta)$ are proportional and integral gains respectively. In the original controller the reference pitch angle is calculated according to the pitch angle measurement of one of the three blades and unique pitch reference is calculated by the controller for all blades. To model the collective pitch angle controller with independent pitch actuators control, three identical PI pitch controller are used for three blades and pitch angle reference for each blade is calculated based on the pitch angle measurements of the same blade. In the power optimization region only shaft speed is used as an input to the controller while in full power region both shaft speed and pitch angle of the blade are measured and used as inputs to the controller. It means that the shaft speed and blade pitch angle have mutual effect on each other through the controller and fault in one of them can affect the other one.

3 Fault Simulation Setup

In this section fault simulation is explained. Both wind turbine blade pitch angle and rotor shaft speed are measured with rotary encoders. A rotary encoder, also called a shaft speed encoder, is a electro-mechanical device that converts the angular position or motion of a shaft to an analog or digital code. There are two main types: absolute and incremental (relative) encoders. The output of incremental encoders provides information about the motion of the shaft, which is typically further processed elsewhere into the information such as speed, distance and position. The output from absolute encoders indicates the current position directly. Both absolute and incremental encoders come into two basic types: optical and mechanical. For pitch position measurements both optical and mechanical encoders are used as a low-speed application but for rotor speed measurements optical-incremental encoders are the best option [11].

The fault in the encoders can arise simply by miss-adjustment of the encoder on the blade pitch bearing, or due to some dust and dirt on the opaque encoder disc, or even some problem in wire contacts. Apart from the cause of the fault, the effects of fault on the output signal from the encoder can be categorised into three main groups: fixed value fault (FV), additive gain fault (AF) and multiplicative gain fault (MF).

Four fault amplitudes which are indicated by $FA_i, i = 1, 2, 3, 4$ are used for each fault case in order to study the effect of fault amplitudes. Because these faults are mainly due to human errors or malfunctions in the encoders, no correlation between faults and environmental conditions is considered in this study. To compare the effect of fault with fault free operation conditions a set of load cases for 11 mean wind speeds from cut-in to cut-out is defined. Table 1 summarizes the applied Load Cases (LC) for each fault case and the relevant Reference Load Case (RLC). A combination of 11 mean wind speeds from 4 m/s to 23 m/s and 4 fault amplitudes for each fault case results in 44 LCs. The amplitudes of all fault case are indicated in Table 2. The fault cases are indicated by four-letter abbreviations where first two letters are used to indicate the location of faults, with (PS) for Pitch Sensor, (SS) for Shaft speed Sensor and (PA) for Pitch Actuator and the next two letters are used for fault types which are (AF) for Additive gain Fault, (MF) for Multiplicative gain Fault and (ST) for Stuck. The original simulation time length for all LCs are 900 sec and fault is initiated at $TFF = 200$ sec which is marked by a vertical dashed line in red colour on each figure. The transient effect at the beginning of each simulation is removed by neglecting the first 100sec of each simulation. For pitch sensor and pitch actuator faults, blades no.1 and no.2 are subjected to fault respectively. In the following figures only 800 sec of simulation times from 100 to 900sec are plotted.

Table 1: Definition of Design Load Cases

$V[m/s]$	FA1	FA2	FA3	FA4	R
4	LC1	LC2	LC3	LC4	RLC1
6	LC5	LC6	LC7	LC8	RLC2
8	LC9	LC10	LC11	LC12	RLC3
10	LC13	LC14	LC15	LC16	RLC4
11	LC17	LC18	LC19	LC20	RLC5
13	LC21	LC22	LC23	LC24	RLC6
15	LC25	LC26	LC27	LC28	RLC7
17	LC29	LC30	LC31	LC32	RLC8
19	LC33	LC34	LC35	LC36	RLC9
21	LC37	LC38	LC39	LC40	RLC10
23	LC41	LC42	LC43	LC44	RLC11

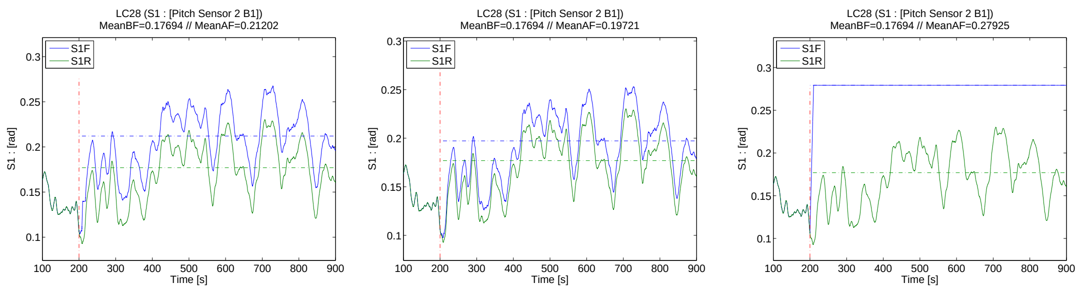
Table 2: Fault amplitudes for each fault case

Fault Case	FA1	FA2	FA3	FA4
PSAF $[deg]$	1	2	4	8
PSMF $[-]$	0.6	0.9	1.1	1.3
PSFV $[deg]$	4	8	12	16
SSAF $[rad/s]$	0.05	0.1	0.2	0.4
SSMF $[-]$	0.5	0.75	1.25	1.5
SSFV $[rad/s]$	0.2	0.4	0.8	1.2
PABE $[deg]$	0.5	1	2	4
PAST $[deg]$	4	8	12	16

4 Results and Discussion

4.1 Pitch Sensor Faults

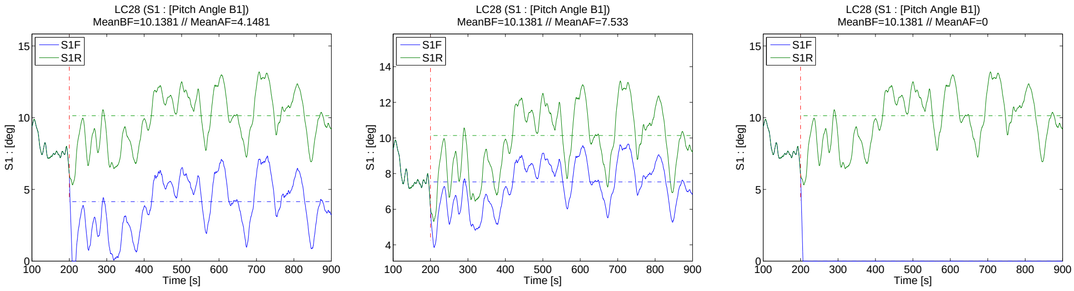
As mentioned before the collective blade pitch controller with individual pitch actuators control has been implemented in this study. It means each blade has its own controller, and fault in one blade cannot propagate directly to the other blades. In the below-rated wind speed the pitch controller is idle. When the rotor slows down from the full power region to the power optimization region, if the logical functions of the controller are not implemented properly then the pitch sensor faults can affect the response in the power optimization region as well. Figure 1 shows three pitch sensor fault cases on blade no.1 through the comparison between LC28 and the relevant reference load case RLC7. Mean values of both fault-free and faulty signals which are calculated from TFF up to the end of the simulation are indicated at the top of the figures. To visualize the magnitude of change in mean values two horizontal dashed-lines are plotted as representative of mean value of fault-free (green) and faulty signals (blue) $[TFF, 900]$ on the figures.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 1: Comparison of pitch sensor measurements with/without fault

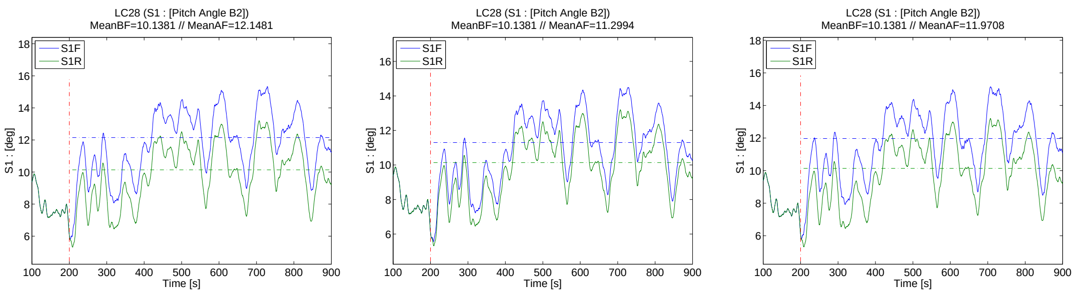
The pitch angle reference for each blade is calculated by the controller according to the shaft speed and blade pitch angle measurements. Fault in pitch sensor measurements directly affects the controller output. By comparing the pitch angle of the blade no.1 after fault, in Figure 2, with the pitch sensor measurements, in Figure 2, one can identify this effect. Figure 1 shows, how the pitch angle of the blade no.1 is affected by pitch sensor fault. Fixed value fault can be more dangerous than two other fault cases because the blade may stop completely under this fault case.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 2: Pitch angle reference of blade(1) with/without the effect of pitch sensor fault in blade(1)

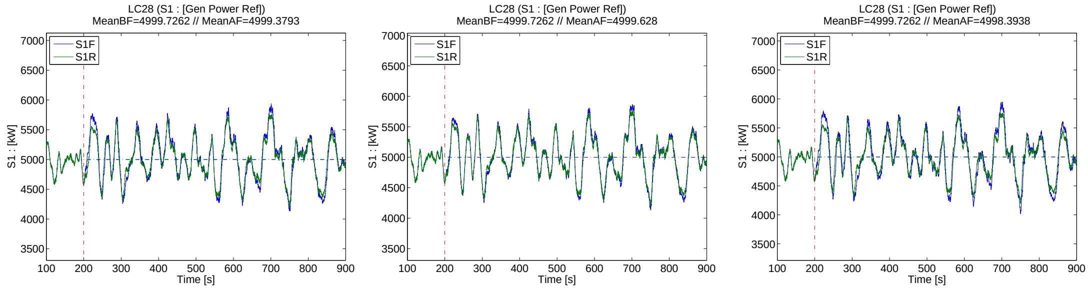
Although independent blade pitch actuators control is applied, one may expect that the fault in one blade can not affect the pitch angle reference of other blades, but the blade pitch angel of two other blades are affected by fault in the blade no.1. Figure 3 compares the pitch angle of blade no.2 for LC28 and RLC7. Due to pitch sensor fault, pitch angle of the blade no.1 increases (reduces) which reduces (increases) the aerodynamic torque on the rotor. Change in the aerodynamic torque affects the shaft speed which is one of the inputs to the blade pitch controller. The pitch angle of the two other blades will be changed to keep the power output equal to the rated power. Therefore, the sign of the change in two other blades is opposite to the sign of change in the blade no.1. Due to non-linearity between torque and blade pitch angle, the sum of change in blade no.2 and 3 is not equal to the magnitude of change in blade no.1. The magnitude of changes in blade no.2 and no.3 are equal. These relations can be used for fault isolation.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 3: Pitch angle reference of blade(2) with/without the effect of pitch sensor fault in blade(1)

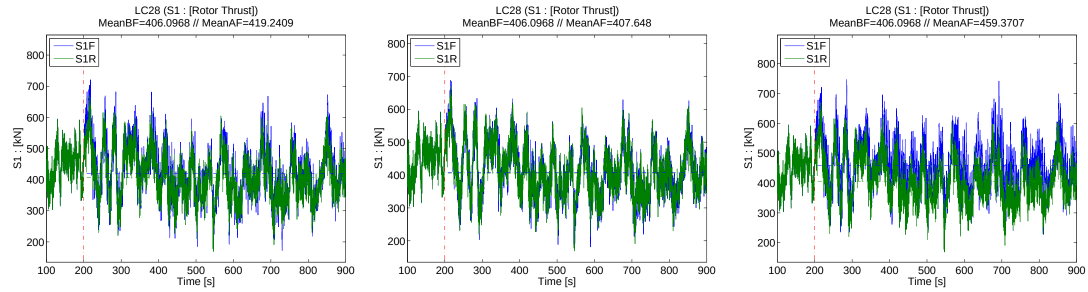
Evaluation of generator power output indicates negligible effects from pitch sensor fault on mean value of generator output power but the power quality including standard deviation and maximum are changed. Standard deviation of generator power increases by 15%, 11% and 21% for AF, MF and FV respectively.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 4: Generator power reference with/without the pitch sensor fault

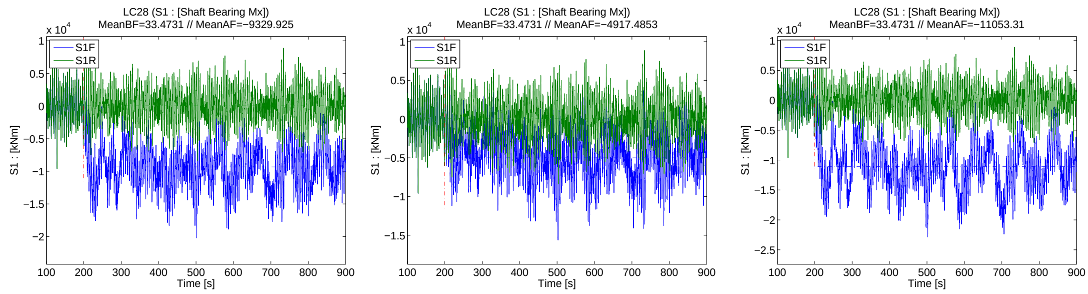
Aerodynamic thrust on the rotor is the integration of loads on three blades therefore it can be used only as a representation of the total rotor load. Figure 5 shows the effect of these three fault cases on the aerodynamic thrust. Change in mean value and standard deviation of aerodynamic thrust in AF and MF is negligible compare to FV. For FV, the mean value of aerodynamic thrust increases from 406 KN to 459 KN. Standard deviation increases by 11%.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 5: Aerodynamic thrust with/without the pitch sensor fault

By evaluating the loads and responses of all structural members it is clear that the most sensitive load component to pitch sensor fault is the shaft main bearing bending moment around X axis (M_X), which is perpendicular to the shaft axis. Figure 6 shows the time series of this load for LC28 and RLC7 for all three fault cases. The mean value of this load is almost zero before fault and increases to 9329 kNm , 4917 kNm and 11053 kNm for AF, MF and FV respectively. The maximum change in the standard deviation is for FV which is 51%.

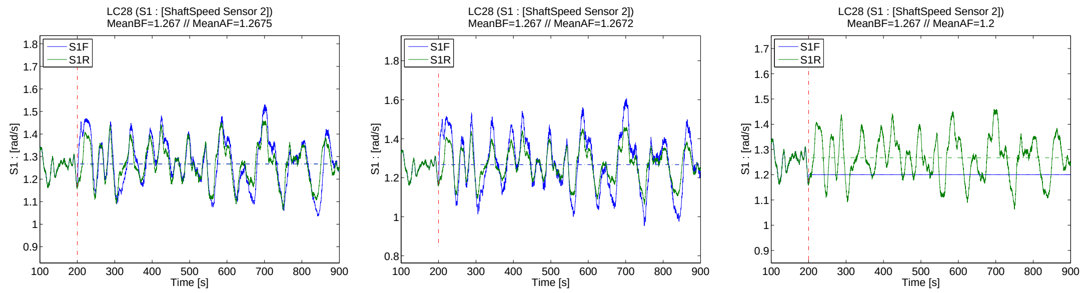


(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 6: Shaft bending moment M_X with/without the pitch sensor fault

4.2 Shaft Speed Sensor Faults

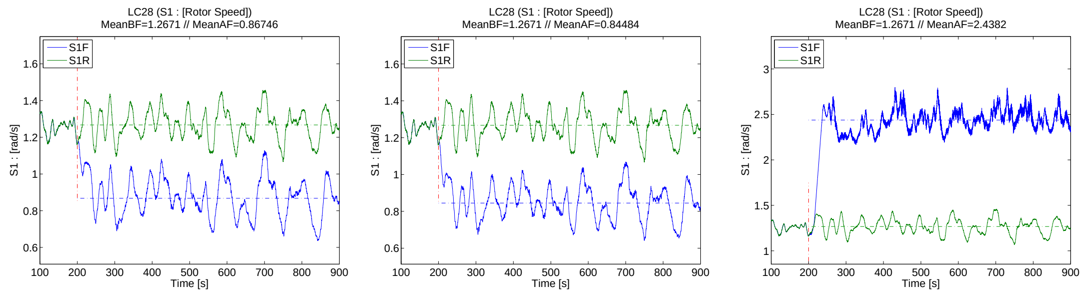
As mentioned before, shaft speed is measured with rotary encoders similar to the blade pitch angle. Therefore similar fault cases are simulated for the shaft speed sensor. Figure 7 shows the three fault cases for shaft speed measurement.



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

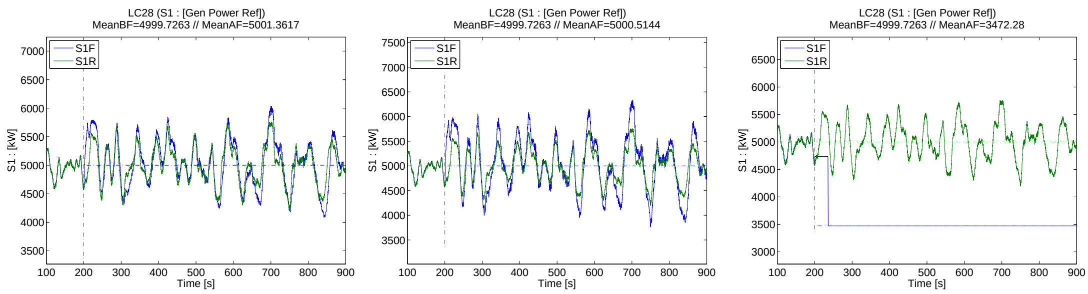
Figure 7: Three fault cases on shaft speed sensor

The effect of shaft speed sensor faults on rotor speed is illustrated in Figure 8. In above-rated wind speed, the generator constant torque strategy is used. This means that only the pitch angle of the blade is used to limit the power and loads on the rotor. Because the shaft speed is used to switch between different operation regions of the wind turbine, fault in shaft speed measurement can seriously affect the output power and total rotor load. Figure 9 and 10 show the effect of shaft speed fault on wind turbine output power and aerodynamic thrust.



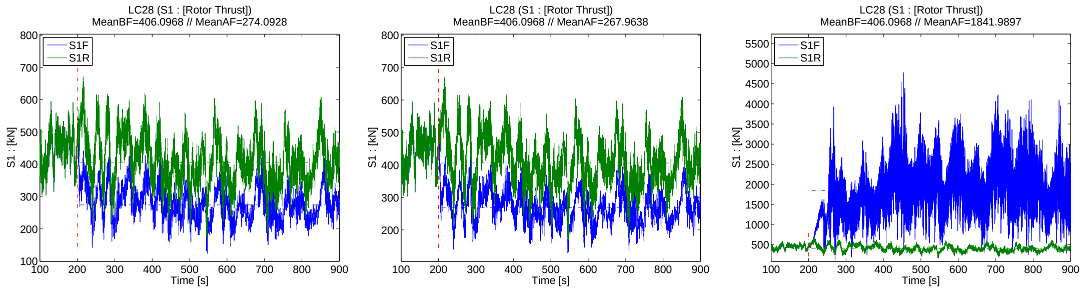
(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 8: Comparison of shaft speed sensor with and without fault



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

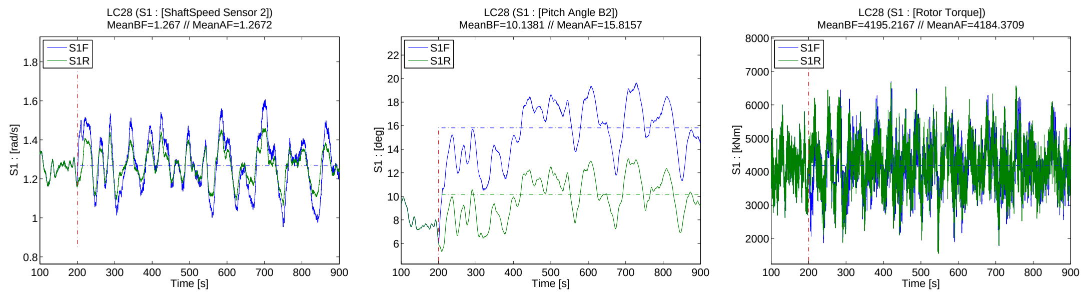
Figure 9: Effect of shaft speed sensor faults on generator power reference



(a) Additive Fault (AF) (b) Multiplicative Fault (MF) (c) Fixed Value fault (FV)

Figure 10: Effect of shaft speed sensor faults on aerodynamic thrust

The surprising result is the very small change in generator power reference for AF and MF fault cases. The mean value of shaft speed reduces from 1.26 $\frac{rad}{sec}$ to 0.84 $\frac{rad}{sec}$ after fault. This amount of change is exactly equal to the shaft speed sensor fault magnitude with opposite sign. Therefore the shaft speed sensor still shows the rated shaft speed as shown in Figure 11a. This value is used to specify the wind turbine operational states and generator reference torque and power. Therefore there is no change in the generator power reference. The transient effect can be seen few samples after fault occurrence. As soon as the shaft speed measurement starts increasing due to sensor fault, the blade pitch angle is increased by the pitch controller (Figure 11b) to reduce the torque on the rotor. Consequently, there is a reduction in shaft speed and resulting rotor aerodynamic torque is equal to the generator torque times the gear ratio (Figure 11c). A new equilibrium point is found by the controller after the fault occurrence, which hides the effect of fault in some of measurements such as generator power reference. The shaft speed sensor FV fault has a much bigger effect on wind turbine power and total rotor load. Because in the case of shaft speed sensor faults all blades are adjusted simultaneously, there is no unbalance load on the rotor.

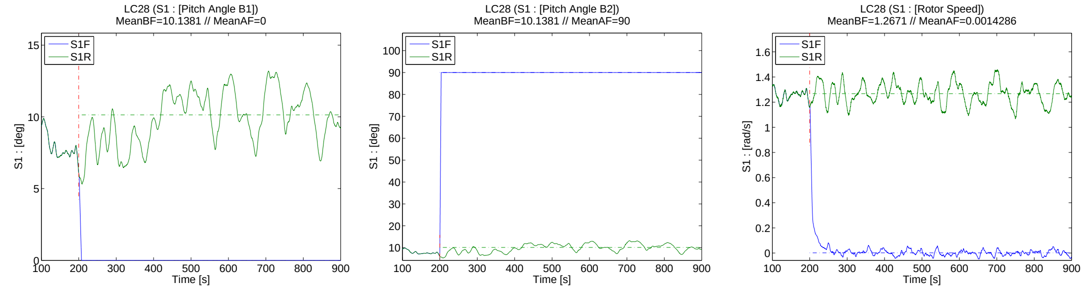


(a) Shaft speed sensor (b) Blade pitch angle (c) Aerodynamic torque

Figure 11: Effect of shaft speed sensor MF on wind turbine performance

4.3 Pitch Actuator Faults

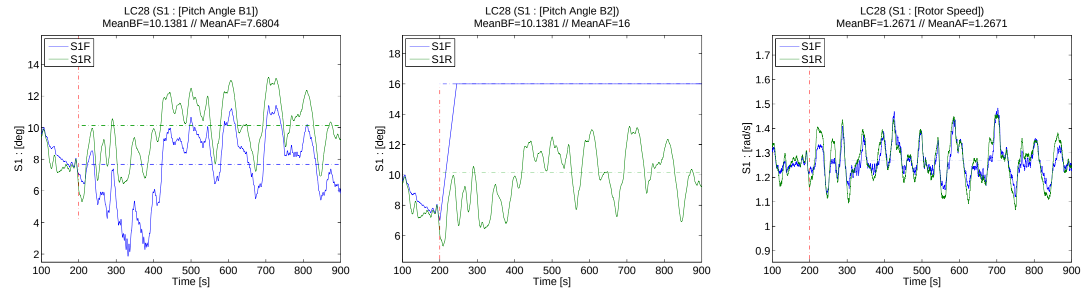
Pitch actuator bias error (PABE) and pitch actuator stuck (PAST) are also simulated in this study. Pitch actuator stuck is mainly due to valve blockage in hydraulic pitch actuator system. This fault can initiated in above rated wind speed and goes to the below rated wind speed when the rotor slows down. Pitch bias error can occur due to oil leakage in hydraulic piston or in the four-way valves in hydraulic pitch servo mechanism. For these two fault cases, blade no.2 is subjected to fault. Pitch bias error results in full pitch of the blade as shown in Figure 12b. When one blade is pitched to the full feather (90 deg) due to fault, this blade generates negative aerodynamic torque on the rotor. This negative aerodynamic torque is much bigger than the aerodynamic torque generated by two other blades, resulting in rotor deceleration. Therefore two other blades are pitched to zero pitch angle by the controller and finally the rotor will stop or work with very low shaft speed.



(a) Pitch angle of blade no.1 (b) Pitch angle of blade no.2 (c) Shaft Speed

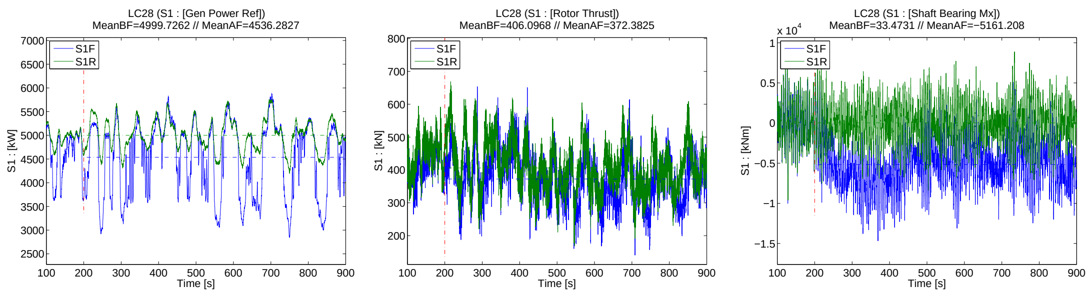
Figure 12: Effect of pitch actuator bias error (PABE) on wind turbine performance

The last fault case which is studied in this work is pitch actuator stuck. When one blade is stuck, it cannot respond to the change in the wind speed. If the independent pitch actuators control is used, two other blades can compensate for the negative effect from the faulty blade on output power up to some level: for example, if the blade sticks to the value near the mean pitch angle of the blade for the given mean wind speed. If the stuck pitch angle is far from the mean value of the pitch angle, such as the case shown in Figure 13b, the generator output power will be reduced and consequently the power quality and total load on the rotor are significantly affected. The mean value of shaft speed is still unchanged but some high-frequency changes appear after the fault. This high-frequency variation in shaft speed reduces the power quality. Similar to the pitch sensor fault, the imbalance load on the rotor results in large bending moments on the shaft and the main bearings as shown in Figure 14c.



(a) Pitch angle of blade no.1 (b) Pitch angle of blade no.2 (c) Shaft Speed

Figure 13: Effect of a stuck pitch actuator (PAST) on wind turbine performance



(a) Generator power reference (b) Aerodynamic thrust (c) Shaft bending moment M_X

Figure 14: Effect of a stuck pitch actuator (PAST) on wind turbine performance

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5 Conclusions

Three different fault cases in pitch sensor and shaft speed sensor, as well as two fault cases in pitch actuator, are simulated on the NREL 5-MW land-based variable-speed pitch-regulated wind turbine to study the effect of fault on loads and responses. The application of independent pitch actuators control reduces the penalty term of pitch sensor and pitch actuator faults on output power and thrust load. The main effect of pitch sensor fault is on the shaft main bearing bending loads. In the case of pitch sensor fault, fault isolation is possible by comparing the mean value of pitch angle on three blades. A fixed value fault can have much bigger effect than the other two faults i.e. additive gain and multiplicative gain. For a shaft speed sensor fault in the above-rated wind speed and with constant torque strategy, the power reference can be unchanged for AF and MF cases and the main effect of the fault is on thrust load. However the pitch angles of blades are affected by shaft speed sensor fault, but no imbalance load on the rotor occurs because all three blades fell the same effect. The differences between the fault-free and faulty shaft speed measurement can be a representative of fault amplitude in shaft speed sensor because in above-rated wind speed, the shaft speed is constant. Such a relation cannot be found easily for pitch sensor fault because of non-linearity between torque and blade pitch angle. FV fault case in shaft speed sensor can result in shut down of the rotor by safety system if the shaft speed exceeds the safety margin. Pitch actuator bias error can result in full pitch of the blade which slows down the rotor due to negative aerodynamic torque. Pitch actuator stuck has similar effect as pitch sensor faults on shaft main bearing bending moment. Effects on mean value of power reference and aerodynamic thrust are compensated by two other blades but the power quality is greatly reduced.

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