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a benchmark model

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Published in:
Elsevier IFAC Publications / IFAC Proceedings series

Publication date:
2009

Document Version
Early version, also known as pre-print

Preprints of the 7th IFAC Symposium on
Fault Detection, Supervision and Safety of Technical Processes
Barcelona, Spain, June 30 - July 3, 2009

Fault Tolerant Control of Wind Turbines – a benchmark model

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Abstract: The installed energy generation capacity of wind turbines is increasing dramatically on a global scale; this means that reliability of wind turbines is of higher importance. A part of this task is to improve fault detection and accommodation schemes of the wind turbine. This paper presents a benchmark model for simulation of fault detection and accommodation schemes. This benchmark model deals with the wind turbine on a system level containing sensors, actuators and systems faults in the pitch system, drive train, generator and converter system.

1. INTRODUCTION

Today wind turbines contribute to a larger and larger part of the world's power production, at the same time the size of the standard turbine increases. Wind turbines in the megawatt size, as most often installed at present, are expensive, consequently the reliability of these turbines are important. Their off time should be as little as possible. An important part of ensuring this is to introduce advanced fault detection, isolation and accommodation systems in the wind turbines. In the state-of-the-art industrial wind turbines fault detection and accommodation schemes are simple and are most often conservative. Consequently the use of advanced fault detection, isolation and accommodation methods could improve the reliability of the turbine, even though, for some faults, it might result in production with limited power. Alternatively condition monitoring is used to monitoring some mechanical components such as gear box etc, see [Hameeda et al. (2009)]

Some work has been performed on model based fault detection, isolation and accommodation on wind turbines. In [Wei et al. (2008)] an observer based scheme to detect sensor faults in the pitch system was presented. A parity equations based scheme for fault detection on wind turbines was presented in [Dobrila and Stefansen (2007)], an unknown input observer was proposed for detection of sensor faults around the wind turbine drive train in [Odgaard et al. (2009)]. Fault detection of electrical conversion systems can be found e.g. in [Poure et al. (2007)].

In order to test different detection, isolation and accommodation schemes on the wind turbine application, this paper presents a bench mark model of a wind turbine at system level, containing: sensors actuators and systems faults. This bench mark model is based on a realistic generic three blade horizontal variable speed wind turbine with a full converter coupling. This generic turbine has a rated power at 4.8 MW.

In Section 2 the functionality of wind turbines are described, the fault scenarios are presented in Section 3, in Section 4 the wind turbine model is presented, Section 5 presents the test signals, and a summary is written in Section 6.

2. WIND TURBINE DESCRIPTION

Wind turbines generate electrical energy from the wind energy. In this test bench model a specific kind of turbine is considered. It is a three blade horizontal axis turbine with a full converter; it is a variable speed turbine as well. The general functionality is that wind turns the wind turbine blades around, and the energy conversion from wind energy to mechanical energy in terms of a rotating shaft can be control by changing the aerodynamics of the turbine by pitching the blades or by controlling the rotational speed of the turbine relative to the wind speed. The mechanical energy is converted to electrical energy by a generator fully coupled to a converter. Between the rotor and the generator a drive train is used to increase the rotational speed from the rotor to the generator. The converter can be used to set the generator torque, which consequently can be used to control the rotational speed of the generator as well as the rotor. A more detailed description of the general function of the wind turbine can be seen in [Sharpe et al. (2001)]. The objective of the control system is to follow the power reference; or if not possible minimize the reference error. This control of power should be done such that mechanical vibrations are kept minimal.

A system overview can be seen in Fig. 1, this figure shows the relations between: Blade & Pitch System, Drive Train, Generator & Converter, and Controller. Since it is a three blade turbine all three pitch positions are measured, in the simple control the same reference is provided to all actuators.

In addition each pitch position is measured with two sensors in order to ensure physical redundancy.

The generator and rotor speeds are also measured with two sensors each for the same reason. These variables are defined as: β_{r1}, β_{r2}, β_{r3} for the pitch reference to blade 1, 2 and 3; $\beta_{1,m1}$, $\beta_{1,m2}$, $\beta_{2,m1}$, $\beta_{2,m2}$, $\beta_{3,m1}$, $\beta_{3,m2}$ are the all pitch positions measurements starting the two measurements for the blade 1 followed by the two measurements for blade 2 and blade 3 in the end; the two rotor speed measurements are defined as $\omega_{r,m1}$, $\omega_{r,m2}$; the two generator speed measurements are defined as $\omega_{g,m1}$, $\omega_{g,m2}$.

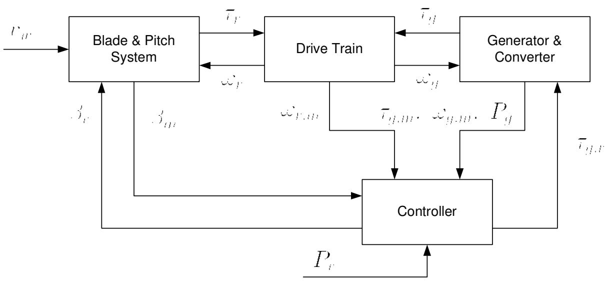

Fig. 1 System overview of case wind turbine

2.1 *Control Systems Concept*

The controller operates in principle in four zones. Zone 1 is start up of the turbine, Zone 2 is power optimization, Zone 3 is constant power production, Zone 4 is high wind speed. The focus of this bench mark model is on the normal operation consequently only Zone 2 & 3 are considered, see e.g. [Johnson et al. (2006)]. It should be noticed that these control zones often are divided into more zones for implemental reasons, in order to handle the transitions between the control modes as smoothly as possible.

In Fig. 2 the power curve for the wind turbine is plotted. From this figure it can be seen that, for wind speeds between 0 and 12.5 m/s, the turbine is controlled to obtain optimal power production. The optimal power is obtained if the blade pitch angle is equal 0 degrees, and if the tip speed ratio is constant at its optimal value. The tip speed ratio, λ, is defined as in (1), where R is the radius of the blades, v_w is the wind speed, and ω_r is the angular rotor speed.

$$\lambda = \frac{\omega_r \cdot R}{v_w}, \tag{1}$$

The optimal value of λ, which is denoted λ_{opt}, is found as the optimum point in the power coefficient mapping of the wind turbine. This optimal value is achieve by setting the reference torque to the converter, $\tau_{g,r}$.

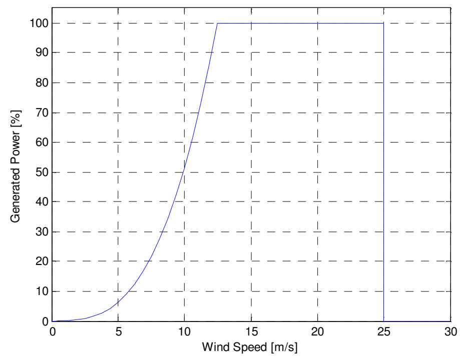

Fig. 2 Illustration of the reference power curve for the wind turbine depending on the wind speed.

The torque in this power optimization zone is found as:

$$\tau_{g,r} = K_{opt} \cdot \omega_r^2. \tag{2}$$

$$K_{opt} = \frac{1}{2}\rho A R^3 \frac{C_{p_{max}}}{\lambda_{opt}^3}, \tag{3}$$

where: ρ is the air density, A is the area swept by the turbine blades, $C_{P_{max}}$ is the maximal value of C_p (the power coefficient table), relating the to λ_{opt}.

Then the power reference is achieved and controller is switched to control Zone 3. In this zone the control objective is to follow the power reference, P_r, this is obtained by controlling β_r, such that the C_p is decreased. In an industrial control scheme a PI controller is used to keep ω_r at the rated value by changing β_r.

3. FAULT SCENARIOS

In this bench mark model a number of faults are considered, these are covering different kinds of possible faults in the wind turbine. In the following these different kinds of faults are listed. These faults have different degrees of severity. Some are very serious and should result in a fast safe close down of the wind turbine and others are less severe in the way that the controller can be accommodated to handle these faults.

3.1 Sensor Faults

A number of possible sensor faults are considered in this bench mark model. The first is the pitch position measurements, these faults are denoted, $\Delta\beta_{1,m1}$, $\Delta\beta_{1,m2}$, $\Delta\beta_{2,m1}$, $\Delta\beta_{2,m2}$, $\Delta\beta_{3,m1}$, $\Delta\beta_{3,m2}$, these faults are either electrical or mechanical faults in the position sensors, and can result in either a fixed value or a gain factor on the measurements.

Secondly the rotor speed measurement can be faulty, denote these faults as $\Delta\omega_{r,m1}$, $\Delta\omega_{r,m2}$, these are measured quite similar to the generator speed measurements of which the faults are denoted as $\Delta\omega_{g,m1}$, $\Delta\omega_{g,m2}$. These are measured using encoders, and faults can be due to both electrical and mechanical faults, which results in either a fixed value or a gain factor on the measurements.

3.2 Actuator Faults

Both the converter and pitch systems can fail. Converter faults are denoted as $\Delta\tau_g$ and can result in an offset. The cause of this fault is an offset in the internal converter control loops.

The pitch systems, which in this case are hydraulic, have a possibility of faults on all three blades, these faults are denoted as $\Delta\beta_1, \Delta\beta_2, \Delta\beta_3$. The considered faults in the hydraulic system can result in changed dynamics either due to dropped main line pressure or high air content in the oil.

3.3 System Faults

The considered system fault is found in the drive train, where the friction changes with time. This change will result in two correlated fault signals:$\Delta\omega_r, \Delta\omega_g$.

3.4 Severity of Faults

All these faults are summarized and listed in Table 1.

Fault No.	Fault	Sym	Type
1a)	Sensor Faults	$\Delta\beta_{1,m1}, \Delta\beta_{1,m2}, \Delta\beta_{2,m1}$ $\Delta\beta_{2,m2}, \Delta\beta_{3,m1}, \Delta\beta_{3,m2}$	Fixed Value
1b)	Sensor Faults	$\Delta\beta_{1,m1}, \Delta\beta_{1,m2}, \Delta\beta_{2,m1}$ $\Delta\beta_{2,m2}, \Delta\beta_{3,m1}, \Delta\beta_{3,m2}$	Gain Factor
2a)	Sensor Faults	$\Delta\omega_{r,m1}, \Delta\omega_{r,m2}$	Fixed Value
2b)	Sensor Fault	$\Delta\omega_{r,m1}, \Delta\omega_{r,m2}$	Gain Factor
3a)	Sensor Fault	$\Delta\omega_{g,m1}, \Delta\omega_{g,m2}$	Fixed Value
3b)	Sensor Fault	$\Delta\omega_{g,m1}, \Delta\omega_{g,m2}$	Gain Factor
4a)	Actuator Fault	$\Delta\tau_g$	Offset
5a)	Actuator Fault	$\Delta\beta_1, \Delta\beta_2, \Delta\beta_3$ (hydraulics)	Changed Dynamics
5b)	Actuator Fault	$\Delta\beta_1, \Delta\beta_2, \Delta\beta_3$ (air in oil)	Changed Dynamics
6)	System Fault	$\Delta\omega_r, \Delta\omega_g$	Changed Dynamics

Table 1 Faults considered in the bench mark model.

In order to deal with these faults in prioritized order the severity and consequences of these considered faults as well as the time of development of the faults are listed in Table 2.

It should be noticed that the severity level of all the sensor faults are set low due to the physical redundancy of the sensors, no sensor fault should be a problem if it is detected fast and if the sensor system is reconfigured. It should also be noticed that the changed dynamics of the drive train due to increased friction is not that severe, but it is an indication of the wear of the drive train, which in the end results in a total break down of this drive train, meaning a highly severe fault.

Fault No	Consequence	Severity	Dev. Time
1a)	False measurement, reconfigure system	Low	Medium
1b)	False measurement, reconfigure system	Low	Medium
2a)	False measurement, reconfigure system	Low	Medium
2b)	False measurement, reconfigure system	Low	Medium
3a)	False measurement, reconfigure system	Low	Medium
3b)	False measurement, reconfigure system	Low	Medium
4a)	Slow torque control, indicates serious problems	High	Fast
5a)	Problems with pump or leakage, slow control actions	High	Medium
5b)	Air in oil, slow control actions	Medium	Slow
6)	Increased level of drive train vibrations	Medium	Very Slow

Table 2 Severity and time of development of the considered faults.

3.5 FDI Requirements

The FDI requirements are listed in this subsection, the detection time, T_D, for the respective faults are defined in relation to the sampling time for the control system, T_s, and in this case equals 0.01 s. Time of detection: T_D for all the sensor faults should meet $T_D < 10 \cdot T_s$; for the converter faults it should fulfill $T_D < 5 \cdot T_s$; for the pitch system fault due to dropped pump pressure (5a), $T_D < 8 \cdot T_s$ should be achieved, and for air in the oil (5b) , $T_D < 600 \cdot T_s$ should hold; detection of increased drive train friction should just be achieved. Monte Carlo studies should be applied in order to test that the proposed scheme can detect the respective faults with these requirements. Each simulation run should correspond to a specific realisation of the measurement noise independent from the previous ones), and the simulation should be repeated 100 times.

False detections: The number of false detection should be kept low, the mean time between false detection should be larger than 100000 samples, in case of a false positive detection, and the detection should be off after three samples.

Missed detections: All faults should be detected.

Problems with the system: A major problem in the wind turbine control system in general is that the wind turbine is driven by a disturbance, the wind. It is, however, measured to some degree but only with a poor measurement resulting in a high noise level on this measurement, as well as a large risk of an offset of the wind measurement, it can be calibrated but, it should be considered in the FDI system. One should also be aware of the non-linearities in the aerodynamics of the turbine, as well as the switching control structure. The FDI system should as well be robust towards uncertainties in this aerodynamic model, partly because it is difficult to exactly measure the mappings on the specific turbines, they might as well change with time due to debris build up, for more information on this specific problem consult [Johnson et al. (2006), Odgaard et al. (2008)].

3.6 Accommodation Requirements

This bench mark model contains both fault for which the system should be reconfigured to continue power generation, as well as very severe faults which should result in a safe and fast close down of the wind turbine. The last group contains the severe faults in the two actuators with fault numbers 4b) and 5a), for all other faults the fault should be accommodated in some way and the turbine should continue its operation. In all cases detection of faults should be reported to the system operator, as well as automatic action taken. In case of only one sensor fault system performance should not decrease, in other cases some decreases in the system performance could be expected. Large transients when accommodating the fault should be avoided.

4. WIND TURBINE MODEL

In this section the different model parts are presented. The parts are presented in the following order: Wind model, Blade and Pitch model, Drive train model, Generator/Converter model, Controller and parameters of the models. The model will be presented in terms of equations since they collected from other publications; application related variables are defined; however generic parameters are not defined in the following due to a paper length consideration.

4.1 Wind Model

In order to generate comparable test result of detection and accommodation schemes, a predefined wind sequence is proposed used. $v_w(t)$ is provided as a vector containing a defined test sequence of the wind.

4.2 Blade & Pitch Model

This model is a combination of the Aerodynamic and pitch model.

Aerodynamic Model

The aerodynamics of the wind turbine is modeled as torque acting on the blades. This aerodynamic torque, τ_r, can be represented by, see [Johnson et al. (2006)]:

$$\tau_r(t) = \frac{\rho\pi R^3 C_q(\lambda(t), \beta(t)) v_w(t)^2}{2}, \tag{4}$$

where C_q is the torque coefficient table, β, is the pitch angles. In order to model that the three blades can have different β values, a simple way to model can be obtained by:

$$\tau_w(t) = \Sigma_{1\leq i\leq 3} \frac{\rho\pi R^3 C_q(\lambda(t), \beta_i(t)) v_w(t)^2}{6}. \tag{5}$$

This model is valid for small difference between β values, as the sizes used in this model, in comparison simulations it has been seen that this simple model has similar behavior as a more detailed model.

Pitch System Model

The hydraulic pitch system is modeled as a closed loop transfer function of the hydraulic pitch system. In principle these are piston servo system which can be modeled quite well by a second order transfer function, consult [Merritt (1967)] on the hydraulic modeling.

$$\frac{\beta(s)}{\beta_r(s)} = \frac{\omega_n^2}{s^2 + 2\cdot\zeta\omega_n\cdot s + \omega_n^2}, \tag{6}$$

Notice here that the hydraulic pressure drop is assumed being abrupt; while the air content increase changes slowly. The parameters for the pressure drop case are denoted ω_{n2}, ζ_2 and the parameters for the increased air content model are denoted ω_{n3}, ζ_3.

4.3 Drive Train Model

The drive train is modeled by a two mass model.

$$\dot{\begin{bmatrix} \omega_r(t) \\ \omega_g(t) \\ \theta_\Delta(t) \end{bmatrix}} = \mathbf{A}_{dt} \begin{bmatrix} \omega_r(t) \\ \omega_g(t) \\ \theta_\Delta(t) \end{bmatrix} + \mathbf{B}_{dt} \begin{bmatrix} \tau_r(t) \\ \tau_g(t) \end{bmatrix}, \tag{7}$$

$$\mathbf{A}_{dt} = \begin{bmatrix} -\frac{\mathbf{B}_{dt}-\mathbf{B}_r}{J_r} & \frac{\mathbf{B}_{dt}}{N_g J_r} & \frac{-K_{dt}}{J_r} \\ \frac{\eta_{dt} B_{dt}}{N_g J_g} & \frac{-\frac{\eta_{dt} B_{dt}}{N_g^2} - B_g}{J_g} & \frac{\eta_{dt} K_{dt}}{N_g J_g} \\ 1 & \frac{-1}{N_g} & 0 \end{bmatrix},$$

$$\mathbf{B}_{dt} = \begin{bmatrix} \frac{1}{J_r} & 0 \\ 0 & \frac{-1}{J_g} \end{bmatrix}, \tag{8}$$

where: J_r is the moment of inertia of the low speed shaft, K_{dt} is the torsion stiffness of the drive train, B_{dt} is the torsion damping coefficient of the drive train, B_g is the viscous friction of the high speed shaft, N_g is the gear ratio,

J_g is the moment of inertia of the high speed shaft, η_{dt} is the efficiency of the drive train, and $\theta_\Delta(t)$ is the torsion angle of the drive train. The fault in terms of lower drive train efficiency is model by another parameter η_{dt2}

4.4 Generator and Converter Model

The converter dynamics can be modeled by a first order transfer function.

$$\frac{\tau_g(s)}{\tau_{g,r}(s)} = \frac{\alpha_{gc}}{s+\alpha_{gc}}, \tag{9}$$

The power produced by the generator is given by

$$P_g(t) = \eta_g \omega_g(t) \tau_g(t). \tag{10}$$

4.5 Controller

The wind turbine controller in this simulation model works in two regions as presented in Section 2.1. Region 1 is denoted power optimization and Region 2 is denoted power reference following. The controller is implemented with a sample frequency at 100 hz. The controller starts in mode 1.

The control mode should switch from 1 to 2 if:

$P_g[n] \geq P_r[n] \ \wedge \omega_g[n] \geq \omega_{nom}$,

The control mode should switch from 2 to 1 if:

$\omega_g[n] < \omega_{nom} - \omega_\Delta$,

Control Mode 1:

The converter reference signal in this control mode is defined in (2)-(3), and $\beta_{\mathrm{ref}} = 0$

Control Mode 2:

$$\beta_r[n] = \beta_r[n-1] + k_p e[n] + (k_i \cdot T_s - k_p) e[n-1], \tag{11}$$

$e[n] = \omega_r[n] - \omega_{nom}$.

In this case the converter reference is used to suppress fast disturbances by

$$\tau_{g,r}[n] = \frac{P_r[n]}{\omega_g[n]}, \tag{12}$$

4.6 Sensors

The sensors are modeled by the actual variable valued added with stochastic noise.

4.7 Model Parameters

In the test bench model the following model and controller parameters are used.

Blade and pitch model:
$R = 57.5$, $\rho = 1.225$, $\zeta = 0.6$, $\omega_n = 11.11$, $\zeta_2 = 0.45$, $\omega_{n2} = 5.73$ $\zeta_3 = 0.9$, $\omega_{n3} = 3.42$.

Drive train model:
$B_{dt} = 9.45$, $B_r = 0$, $B_g = 0$, $N_g = 95$, $K_{dt} = 2.7e9$, $\eta_{dt} = 0.97$, $\eta_{dt2} = 0.92$, $J_g = 390$, $J_r = 55e6$
Generator and converter model: $\alpha_{gc} = 50$, $\eta_{gc} = 0.98$

Controller:
$K_{opt} = 1.2171$, $K_i = 1$, $K_p = 4$, $\omega_{nom} = 162$, $\omega_\delta = 5$, $P_r = 4.8 \cdot 10^6$
Sensors:
$m_w = 1.5$, $\sigma_w = 0.5$, $m_{\omega_r} = 0$, $\sigma_{\omega_r} = 0.025$, $m_{\omega_g} = 0$, $\sigma_{\omega_g} = 0.05$, $m_{\tau_g} = 0$, $\sigma_{\tau_g} = 90$, $m_{P_g} = 0$, $\sigma_{P_g} = 1e3$, $m_\beta = 0$, $\sigma_\beta = 0.2$

5. TEST DEFINITION

In this test bench model setup a predefined wind speed sequence is used. It consists of real measured wind data from a wind park. This wind speed sequence can be seen in Fig. 3. In the listing of the possible faults, which in it self is a limited list of all possible faults in the wind turbine. The test includes 5 sensors faults, 3 actuator faults and 1 system fault. The faults are presented in the following in the same order as the in Table 1.

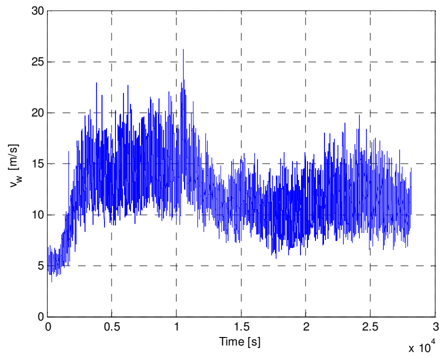

Fig. 3 An illustration of the wind speed sequence used in this test bench example.

Fault 1: fault type 1a) $\beta_{1,m1} = 5°$ in the time period 2000s-2100s. ***Fault 2:*** fault type 1b)$\beta_{2,m2} = 1.2 \cdot \beta_{2,m2}$ in the time period 2300s-2400s. ***Fault 3:*** fault type 1a) $\beta_{3,m1} = 10°$ in the time period 2600s-2700s. ***Fault 4:*** fault type 2a) $\omega_{r,m1} = 1.4\mathrm{rad/s}$ in the time period 1500s-1600s. ***Fault 5:*** fault type 2b) and 3b) $\omega_{r,m2} = 1.1 \cdot \omega_{r,m2}$ and $\omega_{g,m1} = 0.9 \cdot \omega_{g,m1}$ in the time period 1000s-1100s. ***Fault 6:*** fault type 5a) parameters in pitch actuator 2 is abruptly changed from ω_n, ζ to ω_{n2}, ζ_2 in the time period from 2900 s to 3000 s. ***Fault 7:*** fault type 5b) parameters in pitch actuator 3 from ω_n, ζ to ω_{n3}, ζ_3 it is slowly introduced over 30 s, with a linear function, then active in 40 s, where after it is slowly decreasing again other 30 s. The fault begins at 3500 s and ends at 3600 s. ***Fault 8:*** fault type 4a) $\tau_g = \tau_g + 2000\mathrm{Nm}$ from 3800s to 3900s.

These faults should be detected and handled according to the requirements in Section 3.5 and Section 3.6 respectively. In order to validate the detection schemes false positive detection rate, a set of data simulated on an advanced model of the wind turbine is provided for a fault free run, on the same wind speed sequence.

Plots of some of the relevant states and measurements during this sequence of wind input and defined faults are presented in Fig. **4** and Fig. 5. Power, rotor speed and rotor speed measurements, generator speed measurement and pitch angle measurements can be seen.

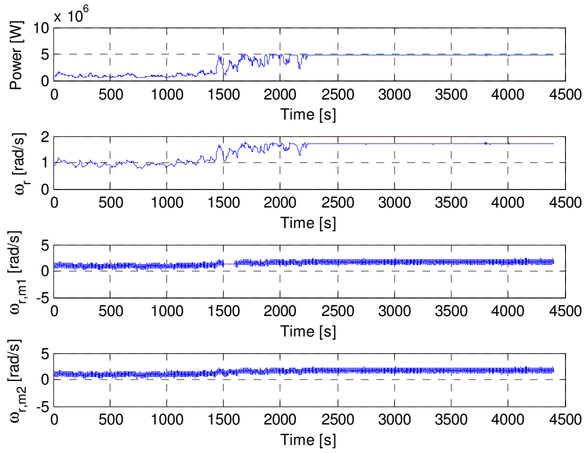

Fig. 4 Power, rotor speed and rotor speed measurements during the test sequence.

The bench mark model package contains a wind speed sequence, measurements for a fault free simulation on an advanced model, and a Simulink model with a parameter file. This package can be obtained by contacting the first author of the paper. In addition if a proposed solution implemented in Matlab/Simulink is provided to the first author in 2009, simulation result of the proposed solution on the advanced wind turbine model will be provided to the proposer of the detection and accommodation scheme, contact the first author for further details.

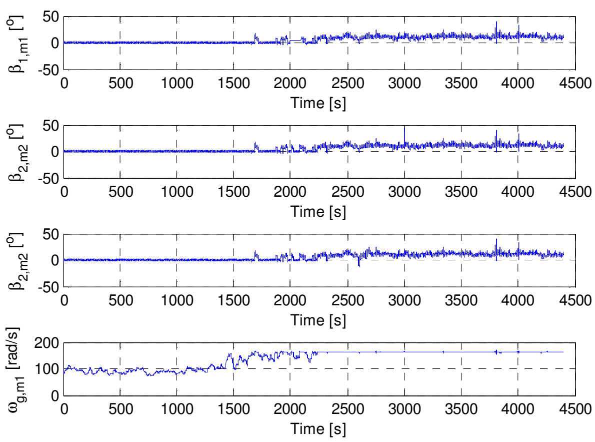

Fig. 5 Pitch measurements and generator speed measurement.

6. SUMMARY

In this paper a bench mark model for simulation fault detection and fault accommodation in wind turbines is presented. The model simulates actuator, sensor and system faults in pitch actuators, drive train and converter system. Different kinds of faults are included in this test bench model. This model gives a possibility to test different kinds of fault detection and accommodation schemes on a realistic wind turbine model. The author provides as well a possibility of test of the proposed algorithms on a more advanced and detailed simulation model.

7. REFERENCES

[Dobrila and Stefansen (2007)] C. Dobrila and R. Stefansen. Fault tolerant wind turbine control. Master's thesis, Technical University of Denmark, Kgl. Lyngby, Denmark, 2007.

[Hameeda et al. (2009)] Z. Hameeda, Y. Honga, Y. Choa, S. Ahnb, and C. Song. Condition monitoring and fault detection of wind turbines and related algorithms: A review. *Renewable and Sustainable Energy Reviews*, 13 (1): 1–39, January 2009. doi: doi:10.1016/j.rser.2007.05.008.

[Johnson et al. (2006)] K. Johnson, M. Pao, L.Y.and Balas, and L. Fingeresh. Control of variable-speed wind turbines - standard and adaptive techniques for maximizing energy capture. *IEEE Control Systems Magazine*, pages 71–81, June 2006. doi: 10.1109/MCS.2006.1636311.

[Merritt (1967)] H. E. Merritt. *Hydraulic control systems*. John Wiley & Sons, Inc., - edition, 1967.

[Odgaard et al. (2008)] P. Odgaard, C. Damgaard, and R. Nielsen. On-line estimation of wind turbine power coefficients using unknown input observers. In *Proceedings of the 17th World Congress The International Federation of Automatic Control*, pages 10646–10651, Seoul, Korea, July 2008. IFAC, IFAC.

[Odgaard et al. (2009)] P. F. Odgaard, J. Stoustrup, R. Nielsen, and C. Damgaard. Observer based detection of sensor faults in wind turbines. In *Proceedings of European Wind Energy Conference 2009*, Marseille, France, March 2009. EWEA, EWEA.

[Poure et al. (2007)] P. Poure, P. Weber, D. Theilliol, and S. Saadate. Fault-tolerant power electronic converters: Reliability analysis of active power filter. In P. Weber, editor, *Proc. IEEE International Symposium on Industrial Electronics ISIE 2007*, pages 3174–3179, 2007. doi: 10.1109/ISIE.2007.4375123.

[Sharpe et al. (2001)] D. Sharpe, N. Jenkins, and E. Bossanyi. *Wind Energy Handbook*. Wiley, 2001.

[Wei et al. (2008)] X. Wei, M. Verhaegen, and T. van den Engelen. Sensor fault diagnosis of wind turbines for fault tolerant. In *Proceedings of the 17th World Congress The International Federation of Automatic Control*, pages 3222–3227, Seoul, South Korea, July 2008. IFAC.