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Fault Tolerant Control of Wind Turbines using Unknown Input Observers

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Abstract: This paper presents a scheme for accommodating faults in the rotor and generator speed sensors in a wind turbine. These measured values are important both for the wind turbine controller as well as the supervisory control of the wind turbine. The scheme is based on unknown input observers, which are also used to detect and isolate these faults. The scheme is tested on a known benchmark for FDI and FTC of wind turbines. Tests on this benchmark model show a clear potential of the proposed scheme.

Keywords: Wind Turbines, Fault Accommodation, Unknown Input Observer.

1. INTRODUCTION

In the process of minimizing the cost of energy generated by wind turbines, it is of high importance to increase the reliability of these wind turbines. In this perspective fault tolerant control and fault diagnosis of wind turbines are of high interest. These methods can be applied with relevance to a number of different subsystems of a wind turbine. In this paper faults in the generator and rotor speed measurements are accommodated. These measurements correspond to the angular velocities of the shaft in a wind turbine on the rotor side and generator side of the gear box in a wind turbine. The generator speed is typically used as a feedback signal in the control schemes controlling and optimizing the energy production in a wind turbine. In addition these velocities may also not exceed given maximal values due to mechanical stresses and loads in the wind turbine. Consequently, in a typical state-of-the-art wind turbine redundant measurements are available for detection of sensors faults, however, these schemes are based on the physical redundancy resulting in a required shut down of the wind turbine in case of a fault in one of these sensors. However, analytical redundancy can be obtained in the case of a sensor fault by using the remaining sensors together with a model of the wind turbine, see Odgaard and Stoustrup [2010].

In Odgaard et al. [2009] a benchmark model for fault detection and isolation as well as fault tolerant control of wind turbines was proposed. Faults in the rotor and generator speed sensors are included in this benchmark model. In Odgaard and Stoustrup [2010] an unknown input observer based scheme was proposed for fault detection and isolation of the rotor and generator speed sensor faults in the mentioned benchmark model. Solutions to fault detection and isolation in this benchmark model is also proposed in: Chen et al. [2011], Laouti et al. [2011], Ozdemir et al. [2011], Svard and Nyberg [2011], Zhang et al. [2011], Pisu and Ayalew [2011], Blesa et al. [2011], Dong and Verhaegen [2011], Kiasi et al. [2011], Simani et al. [2011a], Simani et al. [2011b] and Stoican et al. [2011].

In this paper an FTC scheme is designed based on estimates of the generator speed based on a bank of unknown input observers. The proposed is denoted a Fault Tolerant Observer (FTO) scheme in this paper. One observer designed for each of the sets of non faulty rotor and generator speed sensors. An unknown input observer based scheme is chosen since it enables the possibility to include robustness towards the uncertainty of the wind speed, which is difficult to measure. Due to the structure of the unknown input observer these observers can share the observer state vector, meaning that at each sample the "correct" observer write its state vector into a common state vector, which each of the observers initialize their state vectors from at the next sample. The accommodation scheme also introduces an offset on the generator speed estimate, which should ensure that the generator speed is below the maximal value even though that the different observers might introduce a higher level of uncertainty due to the available healthy sensors. This FTO scheme is based on the fault detection and isolation scheme also based on the unknown input observer presented in Odgaard and Stoustrup [2010].

In this paper the proposed scheme is tested on above mentioned benchmark model only considering the faults in the rotor and generator speed sensors, extended with two other combinations of sensor faults.

In Section 2 the benchmark model of a wind turbine used in this work is presented, followed by the proposed unknown input observer based scheme in Section 3. The proposed scheme is tested in Section 4. A conclusion is drawn in Section 5.

2. SYSTEM DESCRIPTION

This paper considers a generic wind turbine of 4.8 MW described in Odgaard et al. [2009] is considered. Notice

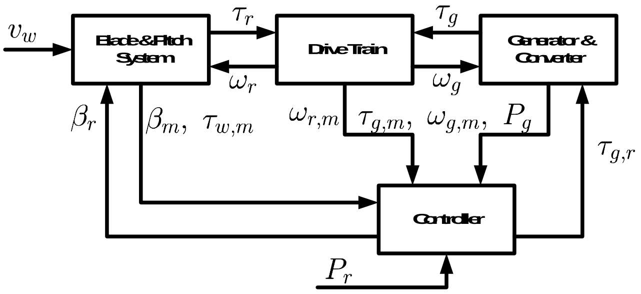

Fig. 1. This figure shows the overall model structure. v_w denotes the wind speed, τ_r denotes the rotor torque, ω_r denotes the rotor speed, τ_g denotes the generator torque, ω_g denotes the generator speed, β_r denotes the pitch angle control reference, β_m denotes the measured pitch angles, $\tau_{w,m}$ denotes the estimated rotor torque, $\omega_{r,m}$ denotes the measured rotor speed, $\tau_{g,m}$ denotes the measured generator torque, $\omega_{g,m}$ denotes the measured generator speed, P_g denotes the measured generated electrical power, $\tau_{g,r}$ denotes the generator torque reference, and P_r denotes the power reference.

that the model in that paper contains a number of fault scenarios which are disabled in the work presented in this paper. This turbine is a variable speed three blade pitch controlled turbine, with a front horizontal axis rotor.

2.1 Wind Turbine Model

The used wind turbine model are from Odgaard et al. [2009], and is not described in details in this paper, the details can be found in the mentioned paper. An overview of the model can be seen in Fig. 1, in which v_w denotes the wind speed, τ_r denotes the rotor torque, ω_r denotes the rotor speed, τ_g denotes the generator torque, ω_g denotes the generator speed, β_r denotes the pitch angle control reference, β_m denotes the measured pitch angles, $\tau_{w,m}$ denotes the estimated rotor torque, $\omega_{r,m}$ denotes the measured rotor speed, $\tau_{g,m}$ denotes the measured generator torque, $\omega_{g,m}$ denotes the measured generator speed, P_g denotes the measured generated electrical power, $\tau_{g,r}$ denotes the generator torque reference, and P_r denotes the power reference.

Each element of the model is shortly described in the following.

Wind Model The wind speed is given by a wind model including mean wind trends, turbulence, wind shear and tower shadow.

Aerodynamic and Pitch Actuator Model Aerodynamics and pitch actuators are modeled in Blade and Pitch System model, the pitch actuator is modeled as a second order transfer function with constraints. The aerodynamics are modeled by a static mapping from the pitch angle, rotor and wind speeds to the torque acting on the wind turbine rotor.

Drive Train Model The drive train, which is used to increase the speed from rotor to generator, is modeled with a flexible two-mass system. The drive train model includes the inertia of the rotor (which includes blades and the main shaft) and generator.

Converter Model The converter which controls the generator torque is modeled by a first order system with constraints. This model covers both the electrical behavior of the generator and converter.

Sensor Models This model is not shown on the figure, since models of each sensors in the figure are included in the relevant part models. The model contains a number of sensors, generator and rotor speed, pitch angles, wind speed, converter torque, electrical power. All the sensors are modeled as the measured variable added with random noise.

Controller The wind turbine operates in principle in 4 regions: Region 1 in which wind speeds are too low for the wind turbine to operate, Region 2 in which the turbine operates up to a nominal wind speed (partial load), Region 3 between nominal and rated wind speed, where the nominal power can be produced, Region 4 above rated wind speed, where the wind turbine is closed down in order to limit extreme loads on the wind turbine.

The controller is active in Region 2 & 3. In Region 2, the optimal rotor speed is obtained by using the converter torque as control signal. In Region 3 the rotor speed is kept at a given reference value by pitching the blades, (the converter keeps the power at the reference taking care of fast variations in the speed). In this paper only the second region control is considered. The basic controller in the different regions is described in Johnson et al. [2006].

3. UNKNOWN INPUT OBSERVER BASED FT OBSERVER

The proposed Unknown Input Observer based Fault Tolerant Control scheme consists of a bank of observers, each designed for the different fault scenarios: No Faults (Observer 1), a fault in one rotor speed sensor (Observer 2), a fault in one generator speed sensor (Observer 3), faults in both rotor speed sensors (Observer 4), faults in both generator speed sensors (Observer 5) and a fault in one generator speed sensor and one rotor speed sensor (Observer 6). These unknown input observers are designed using the scheme presented in Chen and Patton [1999]. These 6 designs cover all the possible combinations of faults since for the observer does not matter which of the two respective sensors of one speed is faulty, since these sensors are only modeled by stochastic noise added to the actual speed value.

It is assumed that the model of the wind turbine can be represented by a discrete time state space model of the form.

$$\mathbf{x}[n+1] = \mathbf{A}_{\mathrm{d}}\mathbf{x}[n] + \mathbf{B}_{\mathrm{d}}\mathbf{u}[n] + \mathbf{E}_{\mathrm{d}}\mathbf{d}[n] + \xi[n], \tag{1}$$

$$\mathbf{y}_j[n] = \mathbf{C}_{\mathrm{d},j}\mathbf{x}[n] + \eta[n], \tag{2}$$

where $\mathbf{x}[n]$ is the state vector, and

$$\mathbf{u}[n] = \begin{bmatrix} \tau_{\mathrm{gen,r}}[n] \\ \tau_{\mathrm{aero}} \end{bmatrix}, \tag{3}$$

$\mathbf{y}_j[n]$ defines a vector of sensor signals, corresponding to the jth observer. They are given below and for those coefficient without a number it indicates that only one of these sensors are healthy.

$$\mathbf{y}_1 = \begin{bmatrix} \omega_{\mathrm{r,m1}}[n] \\ \omega_{\mathrm{r,m2}}[n] \\ \omega_{\mathrm{g,m1}}[n] \\ \omega_{\mathrm{g,m2}}[n] \end{bmatrix}, \quad (4)$$

$$\mathbf{y}_2 = \begin{bmatrix} \omega_{\mathrm{r,m}}[n] \\ \omega_{\mathrm{g,m1}}[n] \\ \omega_{\mathrm{g,m2}}[n] \end{bmatrix}, \quad (5)$$

$$\mathbf{y}_3 = \begin{bmatrix} \omega_{\mathrm{r,m1}}[n] \\ \omega_{\mathrm{r,m2}}[n] \\ \omega_{\mathrm{g,m}}[n] \end{bmatrix}, \quad (6)$$

$$\mathbf{y}_4 = \begin{bmatrix} \omega_{\mathrm{g,m1}}[n] \\ \omega_{\mathrm{g,m2}}[n] \end{bmatrix}, \quad (7)$$

$$\mathbf{y}_5 = \begin{bmatrix} \omega_{\mathrm{r,m1}}[n] \\ \omega_{\mathrm{r,m2}}[n] \end{bmatrix}, \quad (8)$$

$$\mathbf{y}_6 = \begin{bmatrix} \omega_{\mathrm{r,m}}[n] \\ \omega_{\mathrm{g,m}}[n] \end{bmatrix}. \quad (9)$$

$\mathbf{d}[n]$ is a vector of unknown inputs, $\xi[n]$ defines the process noise, $\eta[n]$ defines the measurement noise. The discrete time model matrices are given as $\mathbf{A}_{\mathrm{d}}$, $\mathbf{B}_{\mathrm{d}}$, $\mathbf{E}_{\mathrm{d}}$, and $\mathbf{C}_{\mathrm{d},j}$ which denotes the $\mathbf{C}_{\mathrm{d}}$ matrix for the jth observer.

The unknown input observer in the discrete time form is given by (10-11). In this formulation of the observer the subscript index j refers to the observer number.

$$\mathbf{z}[n] = \mathbf{F}_j\mathbf{z}[n-1] + \mathbf{T}_j\mathbf{B}_{\mathrm{d}}\mathbf{u}[n-1] + \mathbf{K}_j\mathbf{y}_j[n-1], \quad (10)$$
$$\hat{\mathbf{x}}[n] = \mathbf{z}[n] + \mathbf{H}_j\mathbf{y}_j[n], \quad (11)$$

where $\mathbf{z}[n]$ is the observer state vector,

The following matrices are computed once.

$$\mathbf{H}_j = \mathbf{E}_{\mathrm{d}}\left(\mathbf{C}_{\mathrm{d},j}\mathbf{E}_{\mathrm{d}}\right)^{-1}, \quad (12)$$
$$\mathbf{A}_j^1 = \mathbf{A}_{\mathrm{d}}\mathbf{H}_j\mathbf{C}_{\mathrm{d},j}\mathbf{A}_{\mathrm{d}}, \quad (13)$$
$$\mathbf{T}_j = \mathbf{I}_{3\times 3} - \mathbf{H}_j\mathbf{C}_{\mathrm{d}}. \quad (14)$$

The matrice $\mathbf{P}_j[0]$ is initialized to zero matrix.

For $n > 0$ the observer matrices are computed by

$$\mathbf{K}_j^1[n] = \mathbf{A}_j^1\mathbf{P}_j[n-1]\mathbf{C}_{\mathrm{d},j}^T\left(\mathbf{C}_{\mathrm{d},j}\mathbf{P}_j[n-1]\mathbf{C}_{\mathrm{d},j}^T + \mathbf{R}_j\right), \quad (15)$$
$$\mathbf{F}_j[n] = \mathbf{A}_{\mathrm{d}} - \mathbf{H}_j\mathbf{C}_{\mathrm{d},j}\mathbf{A}_{\mathrm{d}} - \mathbf{K}_j^1[n]\mathbf{C}_{\mathrm{d},j}, \quad (16)$$
$$\mathbf{P}_j^P[n] = \mathbf{P}_j[n-1] - \mathbf{K}_j^1[n]\mathbf{C}_{\mathrm{d},j}\mathbf{P}_j[n-1](\mathbf{A}_j^1)^T, \quad (17)$$
$$\mathbf{P}_j[n] = \mathbf{A}_j^1\mathbf{P}_j^p[n](\mathbf{A}_j^1)^T + \mathbf{T}_j\mathbf{Q}(\mathbf{T}_j)^T + \mathbf{H}_j\mathbf{R}_j(\mathbf{H}_j)^T, \quad (18)$$
$$\mathbf{K}_j[n] = \mathbf{F}_j[n]\mathbf{H}_j + \mathbf{K}_j^1[n], \quad (19)$$

All observers are computed at each sample but the vectors $\mathbf{x}[n]$ and $\mathbf{z}[n]$ are given as $\mathbf{x}_i[n]$ and $\mathbf{z}_i[n]$ where i corresponds to the observer number accommodating the detected and isolated faults at sample n.

Using the FDI scheme based on unknown input observers described in Odgaard and Stoustrup [2010] beginning and end of the faults are detected with a delay below 0.03[s], which is within the requirements given in the benchmark model, see Odgaard et al. [2009].

3.1 Increased estimation noise accommodation

The correctness of $\hat{\omega}_g[n]$ depends on which measurements are fault free. The measurement noise on the rotor speed is dramatically higher than the measurement noises on the generator speed measurements. Consequently e.g. the fault case with faults on both generator speed sensors will result in higher noise level on $\hat{\omega}_g[n]$.

This is problematic since this will lead to higher amplitudes on the oscillations of $\omega_g[n]$. The controller controlling this variable are designed to keep it below the maximal value, assuming certain noise levels on the estimate/measurement of $\omega_g[n]$.

In this scheme this problem is accommodated by adding an offset to estimate, which corresponds to a decrease in $\omega_{\mathrm{g,r}}[n]$. This offset should be so large that $\max(\omega_{\mathrm{g}}[n]) < \omega_{\mathrm{g,max}}$. This offset is in the following denoted $\omega_{\mathrm{g,O}\kappa}$ where κ refers to the observer number.

3.2 Implementation of the scheme

The design is based on a discretized model of the wind turbine in the benchmark model. These matrices are $\mathbf{A}_{\mathrm{d}}$, $\mathbf{B}_{\mathrm{d}}$ and $\mathbf{C}_{\mathrm{d}}$. In addition three matrices are used in the specific design of the Unknown Input Observer, which are used to tune the observer, these are $\mathbf{E}_{\mathrm{d}}$, $\mathbf{Q}$ and $\mathbf{R}$. In this work they are found by iterations and tests.

The values of these matrices are listed below.

$$\mathbf{A}_{\mathrm{d}} = \begin{bmatrix} 0.8794 & 0.0013 & -0.5605 \\ 173.3713 & -0.8256 & 800.1107 \\ 0.0114 & -0.0001 & -0.9456 \end{bmatrix}, \quad (20)$$

$$\mathbf{B}_{\mathrm{d}} = \begin{bmatrix} 1.7184 \cdot 10^{-9} & -1.4797 \cdot 10^{-7} \\ 1.4353 \cdot 10^{-7} & -4.3079 \cdot 10^{-5} \\ 4.4674 \cdot 10^{-11} & 6.6198 \cdot 10^{-8} \end{bmatrix}, \quad (21)$$

$$\mathbf{C}_{\mathrm{d}} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix}, \quad (22)$$

$$\mathbf{E}_{\mathrm{d}} = \begin{bmatrix} 0.0093 & -1.2056 \cdot 10^{-4} \\ 0.9628 & 0.1734 \\ 2.5710 \cdot 10^{-4} & 1.1391 \cdot 10^{-5} \end{bmatrix}, \quad (23)$$

$$\mathbf{Q} = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.05 & 0 \\ 0 & 0 & 0.05) \end{bmatrix}, \quad (24)$$

$$\mathbf{R} = \begin{bmatrix} 6.32 \cdot 10^{-4} & 0 & 0 & 0 \\ 0 & 6.32 \cdot 10^{-4} & 0 & 0 \\ 0 & 0 & 5.63 \cdot 10^{-5} & 0 \\ 0 & 0 & 0 & 5.63 \cdot 10^{-5} \end{bmatrix}. \quad (25)$$

Notice that $\mathbf{C}_{\mathrm{d}}$ is on a redundant form since the two rotor and two generator speed sensors respectively represent the same state added with measurement noise.

In addition offset values are found by experiments to be $\omega_{\mathrm{g,f1}} = 0$,$\omega_{\mathrm{g,f2}} = 0.1$, $\omega_{\mathrm{g,f3}} = 0.4$, $\omega_{\mathrm{g,f4}} = 0.1$, $\omega_{\mathrm{g,f5}} = 0.4$, $\omega_{\mathrm{g,f5}} = 0.8$

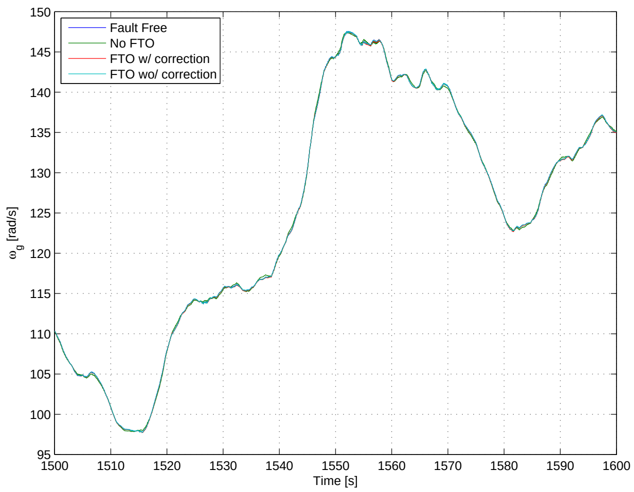

Fig. 2. ω_g in the time period in which a fault in $\omega_{\mathrm{r,m1}}$ is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

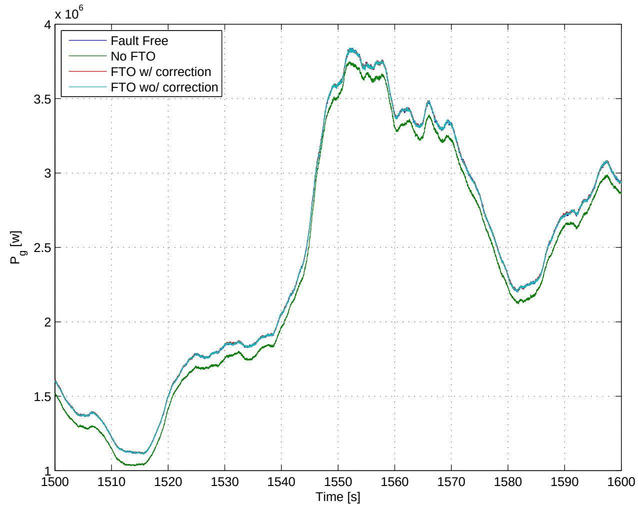

Fig. 3. P_g in the time period in which a fault in $\omega_{\mathrm{r,m1}}$ is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

4. TEST AND SIMULATIONS

The proposed scheme is in this section tested on the earlier mentioned benchmark model. In the benchmark model two fault scenarios with faults in the sensors dealt with in this paper are included. The first is a fault in one of the rotor speed sensors and the second is faults in one of the rotor speed sensors and in of the generator speed sensors. In order to test the proposed scheme in more details two additional faults are added to the benchmark model. It is one fault in one of the generator speed sensor and faults in both generator speed sensors. The last scenarios with faults in both rotor speed sensors are left out since they do not decrease the quality of the generator speed estimate much.

In the following these tests are presented by plots of $P_g[n]$ and $\omega_{\mathrm{g}}[n]$ during the specific faults in the case without a fault, control not based on the FTO scheme and with a Fault Tolerant Observer based controller with and without the offset correction.

The fault scenarios in this test is: $\omega_{\mathrm{r,m1}}[n]$ is constant with the value of 1.4rad/s in the time interval 1500s-1600s, a gain fault on $\omega_{\mathrm{g,m2}}$ with the value of 0.9 in the time interval 1900s-2000s, gain faults on $\omega_{\mathrm{r,m2}}$ with the value of 1.1 and $\omega_{\mathrm{g,m2}}$ with the value of 0.9 in the time interval 1000s-1100s, and the last fault gain faults on $\omega_{\mathrm{g,m1}}$ and $\omega_{\mathrm{g,m2}}$ with the gain value on 0.9 in the time interval 2500s-2600s.

4.1 Fault in $\omega_{r,m1}$

Fig. 2 plots $\omega_{\mathrm{g}}[n]$ during this fault, and Fig. 3 plots $P_{\mathrm{g}}[n]$ during the same fault. From these plots it can be seen that the FTO solutions keep both ω_{g} and P_g at the same trajectories as in the fault free case, while the non accommodated controller results in a decrease in the generated power.

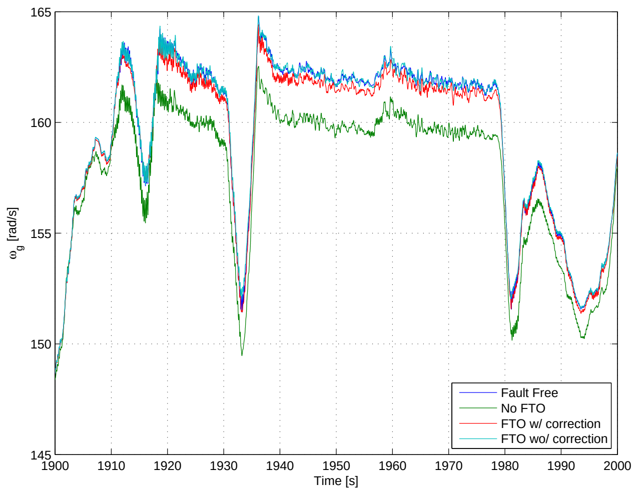

Fig. 4. ω_g in the time period in which a fault in $\omega_{\mathrm{g,m2}}$ is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

4.2 Fault in $\omega_{g,m2}$

Fig. 4 plots $\omega_{\mathrm{g}}[n]$ during this fault, and Fig. 5 plots $P_{\mathrm{g}}[n]$ during the same fault. The FTO solutions result in performance of both ω_{g} and P_g similar to the fault free case, while the non accommodated controller results in a decrease in the generated power. Also notice that the correct fault tolerant observer results in ω_{g} a bit low than the non corrected version.

4.3 Fault in $\omega_{r,m2}$ and $\omega_{g,m1}$

Fig. 6 plots $\omega_{\mathrm{g}}[n]$ during this fault, and Fig. 7 plots $P_{\mathrm{g}}[n]$ during the same fault. Again the FTO solution results in

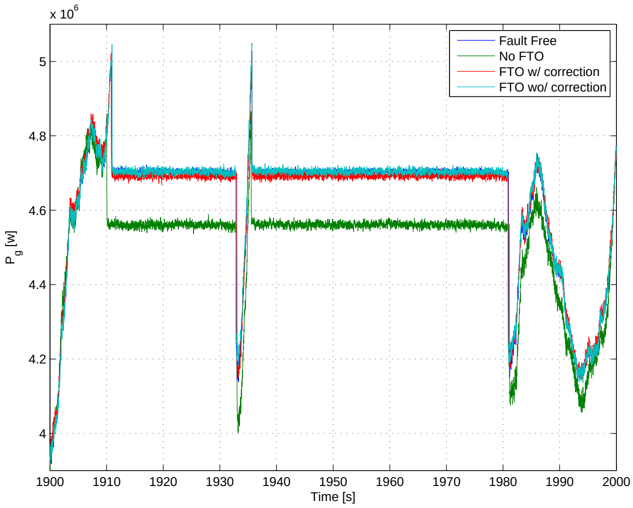

Fig. 5. P_g in the time period in which a fault in $\omega_{\mathrm{g,m2}}$ is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

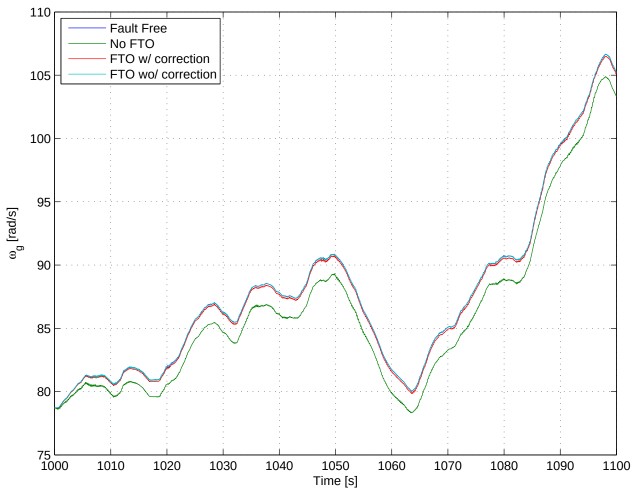

Fig. 6. ω_g in the time period in which Fault # 3 is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

a removal of the consequences of the fault, while the non accommodated controller have a decrease in the generated power.

4.4 Fault in $\omega_{g,r1}$ and $\omega_{g,m2}$

Fig. 8 plots $\omega_{\mathrm{g}}[n]$ during this fault, and Fig. 9 plots $P_{\mathrm{g}}[n]$ during the same fault. From these plots it can be seen that the non accommodated controller results in a decrease in the generated power, while the FTO solutions keep both ω_{g} and P_g at the same trajectories as in the fault free case.

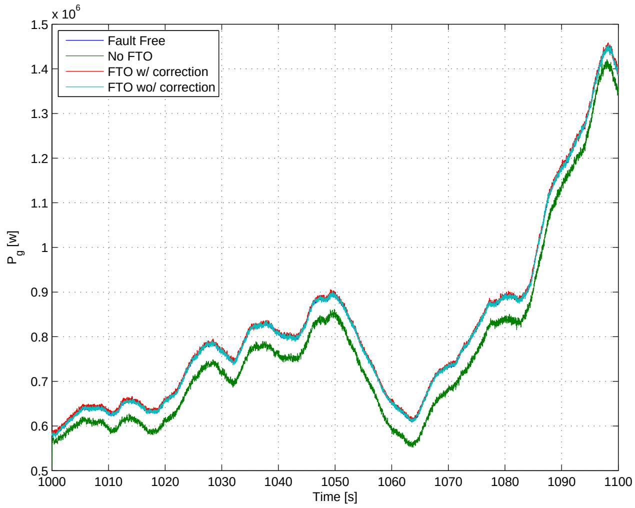

Fig. 7. P_g in the time period in which Fault # 3 is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

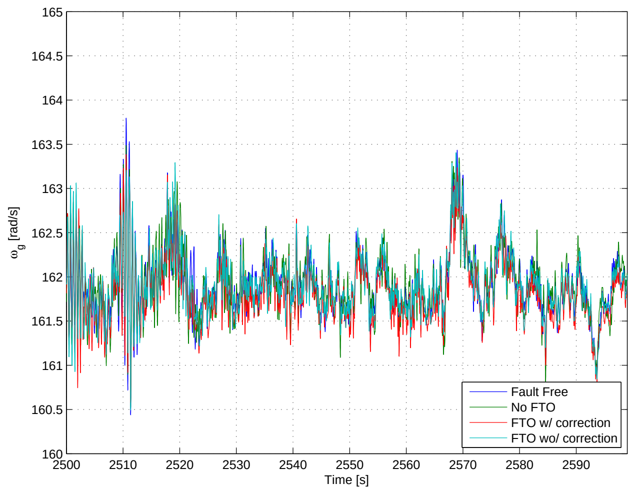

Fig. 8. ω_g in the time period in which Fault # 4 is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

4.5 Test Summary

In all four fault scenarios it can be seen that the proposed scheme accommodates the faults such that a system performance similar to the fault free one is obtained.

5. CONCLUSION

In this paper a fault tolerant unknown input observer based scheme is proposed to estimate the generator speed in a wind turbine control system, which provides a valid estimation of the generator speed during different types of faults in the rotor and generator speed measurements in the wind turbine. An offset is added to the estimate in order to keep the generator speed below the maximal value in case that the estimate has an increased noise level,

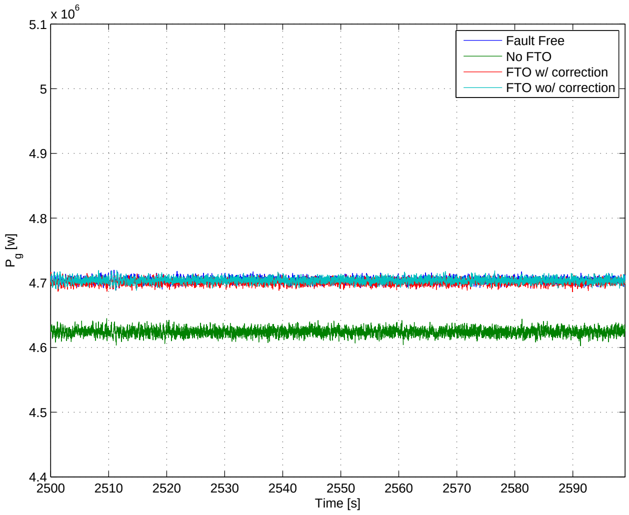

Fig. 9. P_g in the time period in which Fault # 4 is present. The controller is based on the estimated ω_g. The plot shows the fault free case, as well as three cases with faults: one without any fault accommodation, the FT observer with and without the correction component.

which results in larger variations on the actual generator speed. The scheme is tested on a known benchmark for FDI and FTC of Wind turbines. Tests on this benchmark model show a clear potential of the proposed scheme.

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