An Efficient Approach for Fault Detection and Fault Tolerant Control of Wind Turbines

Ali Abdo*, Jamal Siam*, Ahmed Abdou**, Hakam Shehadeh*, Ashraf Al-Rimawi*
*Electrical and Computer Engineering Department / Birzeit University / Birzeit / Palestine
aabdo@birzeit.edu, jsiam@birzeit.edu, hshehadeh@birzeit.edu, aalhalabi@birzeit.edu
**Electronic and Communication Engineering Department / Al-Quds University / Jerusalem / Palestine
aabdou@staff.alquds.edu

***Abstract*—This paper presents an efficient technique for monitoring and control of wind turbines. Fault tolerant control (FTC) is designed using Parity-Space approach to diagnose the sensor faults in the wind turbine. Based on the fault detection system an FTC scheme is proposed to accommodate and reconfigurable the control signals. The main contribution of this study is to develop a monitoring and control system of wind turbine, which reduces the system components as well as to increase the reliability and safety of wind turbines. The sensors which considered in this study are pitch position, generator speed and rotor speed sensors. Real data of wind measurement and real parameters of wind turbine is used to illustrate the proposed scheme.**

***Index Terms*—wind turbine, fault detection, parity-space approach; fault tolerant control**

I. Introduction

Wind is considered a significant, indispensable clean energy source. The process of energy extraction from the wind has evolved over the last decades. A wind turbine is a machine that converts wind power to electricity, which is in return connected to the electrical network. The increasing demand from the authorities trend the renewable and clean energy sources was reflected on using large numbers of megawatt size wind turbines. These machines are expensive and complex, therefore, their reliability and safety are the primary concerns in its operation. On the other hand, it should produce maximum energy.

FTC strategy consisted mainly from two steps integrated with each other. The first step is fault detection and isolation (FDI), [7], [5], [2], and the second step is the reconfiguration of the controller to accommodate the fault in the process [1]. The performance and stability of the FTC schemes depend upon the accuracy and promptness of the applied fault diagnosis technique [10]. All of these techniques react to the faulty condition by reconfiguring the controller to maintain the system performance and stability. Therefore, in case of faulty components in the process, FTC could be considered to ensure the safe operation under real time conditions, [12], [5]. FDI can be achieved using different techniques, in the last two decades, there was too many progress on model-based fault diagnosis technique, and it was the interest of research institutes. Extensive research work in industries and universities has been devoted to the model and observer based fault diagnosis technique, [3], [4] [6], [7]. Nowadays, model-based fault diagnosis is considered as a branch of control engineering and advanced control theory.

Literature reviews show that, several general FTC schemes can be applied in wind turbines [13], [14]. However, the effective combination of the FDI with FTC is still a challenge research topic with its implementation in real systems. In this paper, the wind turbine will be modeled by representing it as a group of subsystems. A new approach of using parity-space approach with the reconfigurations on control signals is proposed for wind turbines. For FD purpose, a Parity-space approach is used to generate a residual signal, after that, an evaluation method for the residual signal will be applied. Fault information will be generated based on comparing the evaluated residual signals for each sensor with a threshold value. FTC will be responsible for handle the faulty sensors information and reconfigure the control parameters to keep wind turbine in safe mode of operation. In this paper, we propose a new scheme for the FDI and FTC in wind turbines for the following objectives:

- Utilize the parity space approach in FD design for wind turbine. The main advantages of this approach are its simplicity in On-line computation and its powerful in elimination of the initial conditions effects.
- Reduce the wind turbine components. The proposed FTC approach can replace the redundant sensors signal with estimated ones.
- Increase the reliability and safety of wind turbines, through achieving a high FTC performance for wind turbines.

The organization of this paper is as follows: Section I includes an introduction and literature review related to this work. Section II presents preliminaries and the basic idea of the proposed approach. Wind model and wind turbine model are presented in Section III. FTC and controller design and given in Section IV. In Section V the proposed scheme is illustrated using the real data of wind turbine and actual wind measurements. Finally, conclusion remarks are given in Section VI.

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II. Preliminaries And Basic Idea

A. Parity-Space Approach

This approach depends mainly on the measured signals from the process to derive the parity relation. Parity vector v_s is the design parameter in this approach, which is introduced to modulate the residual dynamics.

Considering the state space presentation, the parity relation can be used to generate the residual signal. The following linear discrete-time invariant system,

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{Ax}(k)+\mathbf{Bu}(k)+\mathbf{E}_d\mathbf{d}(k)+\mathbf{E}_f\mathbf{f}(k) \quad (1)\\ \mathbf{y}(k) &= \mathbf{Cx}(k)+\mathbf{Du}(k)+\mathbf{F}_d\mathbf{d}(k)+\mathbf{E}_f\mathbf{f}(k) \quad (2)\end{aligned}$$

In the following, we assume that $\mathbf{C}$ is full row rank without loss of generality. The derivation of the residual signal is based on parity space approach. To start with the nominal system (i.e. $\mathbf{d}(k)=\mathbf{0}$ and $\mathbf{f}(k)=\mathbf{0}$). In this case system (1)-(2) can be expressed as follows:

$$\mathbf{y}(k)=\mathbf{CA}^s\mathbf{x}(k-s)+\mathbf{CA}^{s-1}\mathbf{Bu}(k-s)+\ldots+\mathbf{Du}(k) \quad (3)$$

Based on the input and output relationship with considering the past state variable $\mathbf{x}(k-s)$, then a compact form can be constructed as follows,

$$\mathbf{y}_s(k)=\mathbf{H}_{o,s}\mathbf{x}(k-s)+\mathbf{H}_{u,s}\mathbf{u}_s(k) \quad (4)$$

where,

$$\mathbf{y}_s(k)=\begin{bmatrix}\mathbf{y}(k-s)\\ \mathbf{y}(k-s+1)\\ \vdots\\ \mathbf{y}(k)\end{bmatrix},\quad \mathbf{u}_s(k)=\begin{bmatrix}\mathbf{u}(k-s)\\ \mathbf{u}(k-s+1)\\ \vdots\\ \mathbf{u}(k)\end{bmatrix},$$

$$\mathbf{H}_{o,s}=\begin{bmatrix}\mathbf{C}\\ \mathbf{CA}\\ \vdots\\ \mathbf{CA}^s\end{bmatrix}\in\mathscr{R}^{m(s+1)\times n},$$

$$\mathbf{H}_{u,s}=\begin{bmatrix}\mathbf{D} & \mathbf{0} & \ldots & \mathbf{0}\\ \mathbf{CB} & \mathbf{D} & \ddots & \vdots\\ \vdots & \ddots & \ddots & \mathbf{0}\\ \mathbf{CA}^{s-1}\mathbf{B} & \ldots & \mathbf{CB} & \mathbf{D}\end{bmatrix}\in\mathscr{R}^{m(s+1)\times p(s+1)}.$$

It is obvious that, the following rank condition holds for $s\geq n$,

$$\big(rank(\mathbf{H}_{o,s})\leq n\big)<\big(\text{row number of matrix } \mathbf{H}_{o,s}=m(s+1)\big)$$

This condition leads to, for $s\geq n$ there will be a row vector $\mathbf{v}_s$ $(\neq\mathbf{0})\in\mathscr{R}^{1\times m(s+1)}$ such that

$$\mathbf{v}_s\mathbf{H}_{o,s}=\mathbf{0} \quad (5)$$

In general, $\mathbf{v}_s\mathbf{H}_{o,s}=\mathbf{0}$ is essential to completely remove the influence of the initial state and the past input signals.

We conclude that, the set of vectors satisfying (5) is called parity space of the s-th order,

$$\mathbf{P}_s\triangleq\{\mathbf{v}_s|\mathbf{v}_s\mathbf{H}_{o,s}=\mathbf{0}\} \quad (6)$$

Based on that, a residual signal can be generated as follows:

$$\mathbf{r}(k)=\mathbf{v}_s\big(\mathbf{y}_s(k)-\mathbf{H}_{u,s}\mathbf{u}_s(k)\big) \quad (7)$$

Technical systems are affected by disturbances and faults. In order to include these effects the output equation (4) is reformulated to:

$$\mathbf{y}_s(k)=\mathbf{H}_{o,s}\mathbf{x}(k-s)+\mathbf{H}_{u,s}\mathbf{u}_s(k)+\mathbf{H}_{d,s}\mathbf{d}_s(k)+\mathbf{H}_{f,s}\mathbf{f}_s(k) \quad (8)$$

where,

$$\mathbf{d}_s(k)=\begin{bmatrix}\mathbf{d}(k-s)\\ \mathbf{d}(k-s+1)\\ \vdots\\ \mathbf{d}(k)\end{bmatrix},\quad \mathbf{f}_s(k)=\begin{bmatrix}\mathbf{f}(k-s)\\ \mathbf{f}(k-s+1)\\ \vdots\\ \mathbf{f}(k)\end{bmatrix},$$

$$\mathbf{H}_{d,s}=\begin{bmatrix}\mathbf{F}_d & \mathbf{0} & \ldots & \mathbf{0}\\ \mathbf{CE}_d & \mathbf{F}_d & \ddots & \vdots\\ \vdots & \ddots & \ddots & \mathbf{0}\\ \mathbf{CA}^{s-1}\mathbf{E}_d & \ldots & \mathbf{CE}_d & \mathbf{F}_d\end{bmatrix}\in\mathscr{R}^{m(s+1)\times k_d(s+1)},$$

$$\mathbf{H}_{f,s}=\begin{bmatrix}\mathbf{F}_f & \mathbf{0} & \ldots & \mathbf{0}\\ \mathbf{CE}_f & \mathbf{F}_f & \ddots & \vdots\\ \vdots & \ddots & \ddots & \mathbf{0}\\ \mathbf{CA}^{s-1}\mathbf{E}_f & \ldots & \mathbf{CE}_f & \mathbf{F}_f\end{bmatrix}\in\mathscr{R}^{m(s+1)\times k_f(s+1)}.$$

Thus, the residual signal in (7) becomes

$$\mathbf{r}(k)=\mathbf{v}_s\big(\mathbf{H}_{d,s}\mathbf{d}_s(k)+\mathbf{H}_{f,s}\mathbf{f}_s(k)\big) \quad (9)$$

In the following subsection, the basic idea of the proposed approach of the design FD system is explained.

B. Basic Idea

Model-based FTC system is shown in Fig. 1. The generated residual signal (7) is evaluated using$\mathscr{L}_2$-norm. The Decision logic will detect the fault based on the threshold value. After that the fault information will be sent to the control unit to accommodate the faulty case. The basic idea behind this work is to utilize redundant signal of sensors and the estimation ones to adapt the sensors faults in wind turbines.

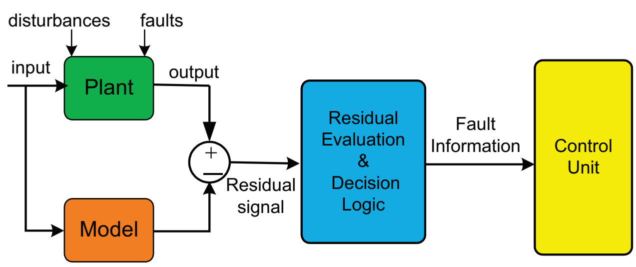

Fig. 1: Model-Based FTC System

TABLE I: Wind model parameters

Symbol	Abbreviation
v_w	combined wind speed
v_m	mean wind
v_s	wind stochastic component
v_{ws}	wind shear
v_{ts}	tower shadow
χ	angular position
α	aerodynamic parameter
H	aerodynamic parameter
R	Length of each blade
r_0	radius of the rotor shaft

III. Wind Model and Wind Turbine Model

A. Wind Model

Extracting wind-energy requires building and controlling wind-turbines taking into account the factors that affect this extraction. In general, wind turbines uses the wind as a primary energy-sources. Therefore, this wind-source must be characterized and interfaced with the wind-transducer that converts it into a usable form. This is done through building a coupled wind-source model, that takes into account the stochastic variability of the wind, the shear-coupling and the shadowing effects with the energy transducer. Dolan and Lehn [8] proposed a wind model that represents a benchmark for wind-energy turbines. This study uses Donal's model as the characteristic wind-source-model. The basic features of the model are illustrated by the set of equations (10-12) with the symbols defined in Table I.

$$
\begin{aligned}
v_w(t) &= v_m(t)+v_s(t)+v_{ws}(t)+v_{ts}(t) && (10)\\
v_{ws}(t) &= \frac{2v_m(t)}{3R^2}\left(\frac{R^3\alpha}{3H}\chi+\frac{R^4\alpha(\alpha-1)}{8H^2}\chi^2\right.\\
&+\left.\frac{R^5\alpha(\alpha-1)(\alpha-2)}{30H^3}\chi^3\right) && (11)\\
v_{ts,i}(t) &= \frac{m.\bar{\theta}_{r,i}(t)}{3.r^2}.(\psi+v) && (12)
\end{aligned}
$$

where, m, $\bar{\theta}$, v and $\bar{\theta}_{r,i}(t)$ are defined as follows:

$$
\begin{aligned}
m &= 1+\frac{\alpha(\alpha-1)}{8H^2}\\
\psi &= 2\alpha^2\left(\frac{R^2-r_0^2}{(R^2+r_0^2)sin(\bar{\theta}_{r,i}(t))^2+k^2}\right.\\
v &= 2\alpha^2k^2\left(\frac{(r_0^2-R^2)(r_0^2sin(\bar{\theta}_{r,i}(t))^2+k^2)}{(R^2sin(\bar{\theta}_{r,i}(t))^2+k^2)}\right)\\
\bar{\theta}_{r,i}(t) &= \theta_r(t)+\frac{2\pi(i-1)}{3}-2\pi.floor\left(\frac{\theta_r(t)+\frac{2\pi(i-1)}{3}}{2\pi}\right)
\end{aligned}
$$

where the function $floor(y)$ is the largest integer not greater than y, $\chi=cos\big(\theta_r(t)\big)$, and $i=1,2,3$ represent the number of the blades.
The values of wind model parameters used in Matlab simulation are as follows: $\alpha=0.1$, $H=81m$, $R=58m$ and $r_0=1.5m$.

B. Wind Turbine Model

The overall wind turbine model is divided into sub-models. The relation between the sub models: pitch and blade system, control system, generator and converter and the drive train are seen in Fig. 2.

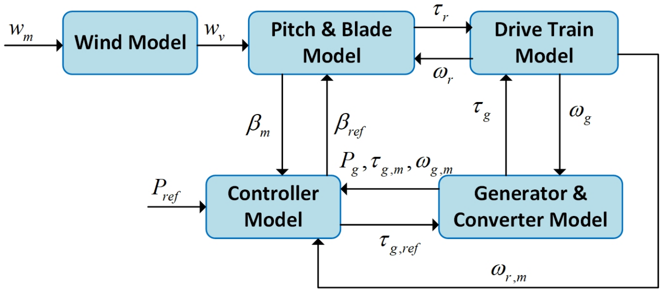

Fig. 2: Wind Turbine Model Structure

C. Pitch and blade Model

This model contains the model information of the wind model, pitch model as well as the aerodynamic of the winds. In order to guarantee sufficient power production, the blade pitching mechanism is controlled. However, modern wind turbines rotor blades are pitch-regulated in such a way so as to turn the axis and tilt them to accommodate rapid wind speed direction changes. In our design we are mainly interested in optimum operation of the wind turbine preventing any further electrical overloads and high speeds. The following second-order differential equation describe this dynamic, [11]

$$\ddot{\beta}(t)=-2\xi\omega_n\dot{\beta}(t)-\omega_n^2\beta(t)+\omega_n^2\beta_{ref}(t) \qquad (13)$$

where, β is the pitch angle, β_{ref} is the reference pitch angle, ω_n is the natural frequency of the pitch model, and ξ is the damping ratio of the pitch actuator model.

D. Aerodynamic Model

This model is based on the wind power acting as a torque on the blades. The model of the torque on the blades is described by the following equation [15], [16], [17]:

$$\tau_r(t)=\frac{\rho\pi R^3C_q\left(\lambda(t),\beta(t)\right)v_w(t)^2}{2} \qquad (14)$$

$C_q\left(\lambda(t),\beta(t)\right)$ is the mapping of the torque coefficient with the bitch angle. $\lambda(t)$ is the tip speed ratio and is given by:

$$\lambda=\frac{\omega_r.R}{v_w} \qquad (15)$$

where ω_r is the angular rotor speed and v_w is the wind speed. The values of the model parameters used in Matlab simulation are as follows: air density $\rho=122kg/m^3$, $\xi=0.6$ and $\omega_n=11.11rad/sec$.

TABLE II: Drive Train Model Parameters

Symbol	Abbreviation
B_g	Viscous friction for the high-speed shaft
J_g	Moment of inertia high-speed shaft
N_g	Drive train gear ratio
B_r	Viscous friction of the low-speed shaft
J_r	Moment of inertia of the low-speed shaft
η_g	Generator's efficiency
K_{dt}	Torsion stiffness of the drive train
$\theta\Delta(t)$	Torsion angle of the drive train
B_{dt}	Torsion damping coefficient of the drive train
$\omega_g(t)$	Generator speed
$\omega_r(t)$	Rotor speed
$\tau_r(t)$	Rotor torque of the low speed shaft
$\tau_g(t)$	Generator torque of the high speed shaft

E. Drive Train Model

In this model kinetic energy at the drive trains is converted into electrical one. The model is described as follows, [18]:

$$\begin{aligned}\dot{\omega}_r(t) &= \big(-(B_{dt}-B_r)\omega_r(t)+(B_{dt}/N_g)\omega_g(t)\\ &- (K_{dt})\,\theta\Delta(t)+\tau_r(t)\big)/(J_r) \qquad (16)\\ \dot{\omega}_g(t) &= \big((B_{dt}\eta_{dl})\omega_r(t)-((B_{dt}\eta_{dl}/N_g)-B_g)\omega_g(t)\\ &- (K_{dt}\eta_{dt})\theta\Delta(t)-\tau_g(t)N_g\big)/(J_gN_g) \qquad (17)\\ \dot{\theta}\Delta(t) &= \omega_r(t)-\omega_g(t)/N_g \qquad (18)\end{aligned}$$

The values of the model parameters used in Matlab simulation are as follows: $B_{dt} = 775Nms/rad$, $B_r = 7.1Nms/rad$, $B_g = 45.6Nms/rad$, $N_g = 95$, $K_{dt} = 2.7.10^9 Nm/rad$, $\eta_{dt} = 0.97$, $J_g = 390kg.m^2$ and $J_r = 55.10^6 kg.m^2$.

F. Generator and Converter

In this paper a first order differential equation is used to represent the converter as follow, [9]:

$$\dot{\tau}_g(t)+\alpha_g\tau_g(t) = \alpha_g\tau_{gr}(t) \qquad (19)$$

where τ_g and τ_{gr} are the generator torque and the reference generator torque respectively, α_g is model parameter.
The generated power from wind turbine is modeled as follows:

$$P_g(t) = \eta_g\omega_g(t)\tau_g(t) \qquad (20)$$

The values of the model parameters used in Matlab simulation are as follows: $\alpha_g = 50rad/s$ and $\eta_g = 0.98$.

G. Controller

The main objective in controller design is to achieve the maximum power point tracking in the partial and full load wind regions. Wind turbine controller is highly dependent on the wind speed which is a variable parameter. Therefore, to keep a simple control structure the wind is divided into four regions, and each region has it own controller as follows:
Region one: In this region, wind speed is less than $3m/sec$. Therefore, wind turbine is in an idle state waiting for higher winds.
Region two: Wind speed between $(3-12.5m/s)$, it is required to optimize of the wind power over this region. In order to obtain an optimal power the blade pitch angle is set to zero and an optimal tip speed ration λ_{opt} is obtained from a lookup table.
Region three: In this region, the wind speed is high enough $(12.5-25m/sec.)$ to produce the reference power of the wind turbine. To control the wind turbine output power (P_g) the pitch angle can be tuned to obtain the required power.
Region four**:** In this region, the wind speed is higher than $25m/sec.$ which is a high speed wind and may damage the wind turbine. For safety reasons the wind turbine will be parked.

Since the control unit is working in four different operation regions, a simple switched discrete controller is designed as follows: In region one, no action is required and the turbine is turned off waiting higher-speed wind to start working. In region four, i.e. in a very high speed wind the control unit activates the braking on the turbine blades with pitching the blade angles to 90 degrees. In region two and three, a switching technique is when the controller switches from region two to three, with the condition:

$$P_g \geq P_r \quad \vee \quad \omega_g \geq \omega_{nom} \qquad (21)$$

ω_{nom} is the nominal generator speed. On the other hand, it switches from mode region three to two with the condition:

$$\omega_g < \omega_{nom} - \Delta\omega \qquad (22)$$

$\Delta\omega$ is the tolerant value and it is added to avoid the switching of the controller between the two modes rapidly.
The control in region two (Torque Control) for the reference torque but keeping the pitch angle set to $\beta_r = 0$:

$$\begin{aligned}\tau_{g,r} &= K_{opt}\left(\frac{\omega_g}{N_g}\right)^2 \qquad (23)\\ K_{opt} &= \frac{1}{2}\rho AR^3\frac{Cp_{\max}}{\lambda^3_{opt}} \qquad (24)\end{aligned}$$

where $K_{opt} = 1.217$, A is swept area by the turbine blades, and $C_{p_{max}}$ is the maximum value of the power coefficient.

The control process in region three (Pitch Control) is done by regulating the speed of the rotor to meet that of the turbine's rated one using a discrete PI controller, to produce the maximum rated power without practically damaging the turbine. Equation (25) is used to keep $e = \omega_g - \omega_{nom}$ at minimum value.

$$\beta_r[k] = \beta_r[k-1]+K_pe[k]+(K_i.Ts-K_p)e[k-1] \qquad (25)$$

The values of the model parameters used in Matlab simulation are as follows: $K_i = 0.7$, $K_p = 3$, $\Delta\omega = 10rad/sec$ and the reference output power $P_r = 4.8.10^6$ Watt.

H. Wind Turbine Sensors

Sensors are the system elements which its responsibility to measure system characteristics and to provide the controller with these measurements. Controller will take action based on these measurements. Malfunction of sensors means that incorrect information to the control unit which may lead to lose the stability of the wind turbine. Since wind turbines are highly expensive devices, high reliability and safety in its operation should be integrated in its design. In this benchmark model, we considered the most frequent sensor faults which are:

(1) pitch position sensors $\beta_{1m,1}, \beta_{2m,1}, \beta_{3m,1}$, is used to measure the pitch angle on the three blade wind turbine. Due to the importance of this sensor in control additional sensors $(\beta_{1m,2}, \beta_{2m,2}, \beta_{3m,2})$ are added to ensure physical redundancy in these measurements. This type of sensor are expected to suffer from electrical or mechanical faults.

(2) rotor speed sensor $\omega_{r,m1}$, is used to measure the low speed of the shaft in the blade side. A redundant sensor is added also for this measurement $\omega_{r,m2}$.

(3) generator speed sensor $\omega_{g,m1}$, is used to measure the high speed of the shaft from the generator side. A redundant sensor is added also for this measurement $\omega_{g,m2}$. Both speed measurements are done using encoders, and it can give faulty measurements due to either electrical or mechanical faults.

IV. Fault Tolerant Control Strategy

In this paper, we propose an FTC scheme based on calculation and estimation of the faulty measurements as shown in Fig. 3. Blades pitch angle position should be identical on all the three blades to keep the symmetrical wind force on them. Therefore, the actual six sensors which is used is high redundancy measurements, which could be reduced to three sensors. Moreover, if a fault is detected in one of the three sensors, FTC unit can isolate the faulty sensor measurement and replace it by calculated one based on the health two sensors. Speed sensors (rotor and generator) are also doubled

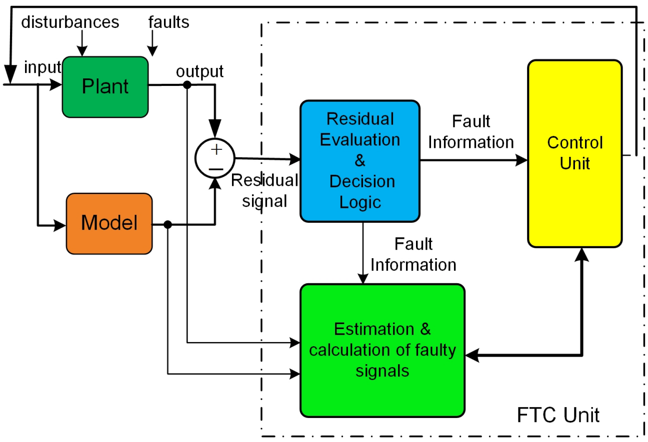

Fig. 3: proposed FTC scheme

for hardware redundancy. Since both sensors are installed on the same shaft, then it can estimate the measurements of these sensors without need for redundant sensor signal. Furthermore, these measurements could be used to identify the faulty sensors and isolate it. This strategy in FTC will lead to reduce the number of physical redundancy of sensors, which means reduce the cost. In the same time, this technique will not cause any reduction in the reliability or safety of wind turbine.

V. Implementation Results

Wind turbine model has be implemented and simulated in Matlab. The input signal is a real input wind data as shown in Fig. 4.

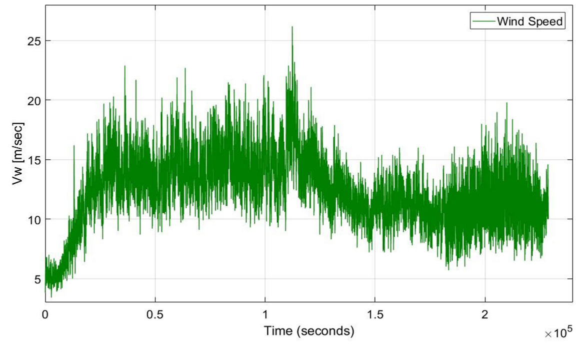

Fig. 4: Real input wind data

A. Fault Detection and FTC Results

I would like to mention here that parity space approach is a discrete base model. Therefore, all the wind-turbine models are converted to dissect one using Matlab function (c2d). Parity vectors are computed for all wind-turbine models as follows: Drive train parity vector:

$$vs_{DriveTrain} = \begin{bmatrix} -0.7071 & -0.0005 & 0.7071 & 0.0005 \end{bmatrix}$$

Parity space vector of the rotor speed:

$$vs_{Rot.Speed} = \begin{bmatrix} -0.006 & 0.241 & -0.673 & 0.662 & -0.225 \end{bmatrix}$$

Parity space vector of the generator speed:

$$vs_{Gen.Speed} = \begin{bmatrix} 0.008 & 0.212 & -0.663 & 0.678 & -0.235 \end{bmatrix}$$

Parity vector of the first pitch blade:

$$vs_{Pitch,1} = \begin{bmatrix} 0.3824 & -0.8142 & 0.4369 \end{bmatrix}$$

Parity vector of the second pitch blade:

$$vs_{Pitch,2} = \begin{bmatrix} 0.3981 & -0.8160 & 0.4192 \end{bmatrix}$$

Parity vector of the third pitch blade:

$$vs_{Pitch,3} = \begin{bmatrix} 0.3958 & -0.8162 & 0.4209 \end{bmatrix}$$

The followings are some simulation results of the sensors faults:

Pitch angle sensor fault: A sensor fault is applied on second pith sensor from sample 1700 to sample 1800 as shown in Fig. 5, whereas the value of fault is equal to 1.5. Fig. 6 shows the value of threshold setting depends on the maximum disturbance value in the system. The threshold value is equal to (0.35). A fault is detected in the interval [1700-1800] and no false alarms are present. **Rotor speed sensor fault:** The simulation of the output Rotor speed measured from sensor is shown in Fig. 7. The value of threshold is equal to (0.12) to obtain optimum fault detection of the signal. When the residual signal is above 0.12, a fault is detected at interval between [1500-2000] as shown in Fig. 8.

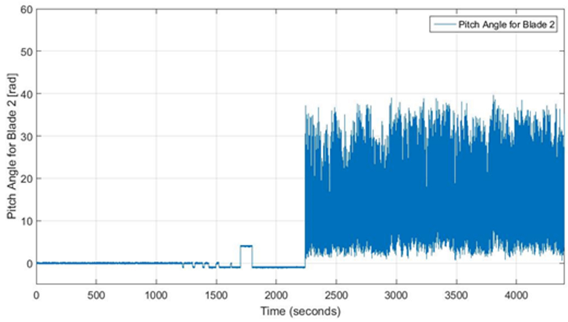

Fig. 5: Fault in the pitch angle of blade 2

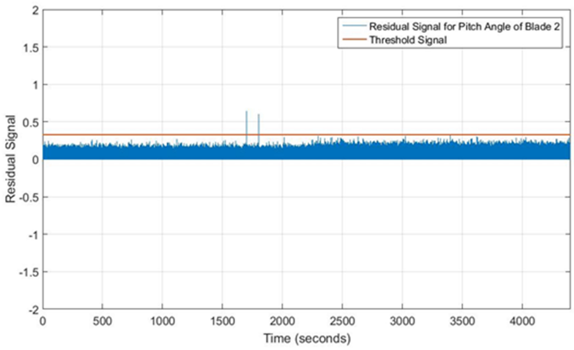

Fig. 6: Threshold value and residual signal of the second pitch

VI. Conclusion

The wind turbine system is implemented in Matlab/Simulink. After that, the parity-space approach is applied to the model to detect the faulty sensors (pitch angle positions of the blades and the speed sensors). Results show that, parity space approach was successful in detecting the faulty sensors. The fault-tolerant control proposed scheme was designed independent of the controller, i.e. the proposed scheme doesn't change the controller parameters; however, it guarantees the correct measurements to the control unit. Simulation results illustrated the proposed scheme successfully.

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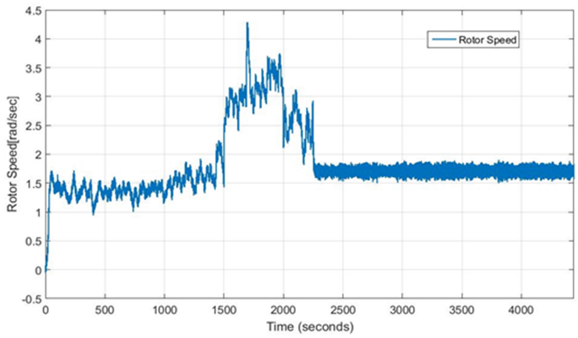

Fig. 7: Fault in the rotor speed measurement

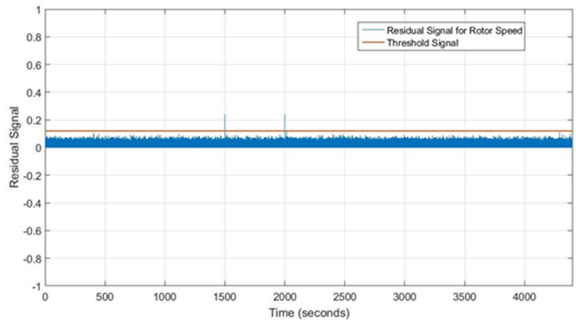

Fig. 8: Threshold value and residual signal of the rotor speed measurement

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