UNKNOWN INPUT OBSERVER FOR DETECTING CURRENT SENSOR FAULTS FOR A DFIG IN WIND TURBINE

H. OUYESSAAD [(a)], H. CHAFOUK [(a)]

[(a)] IRSEEM : Technopole du Madrillet, Avenue Galilée, 76801 St Etienne du Rouvray France
[(a)] hakim.ouyessaad@esigelec.fr, [(a)] houcine.chafouk@esigelec.fr.

ABSTRACT
The objective of this paper is to detect and isolate the presence of sensor faults in dynamical systems. Unknown input observers are used which is then used to generate residuals based on the DOS observer architecture (Dedicated Observer Scheme). This diagnosis strategy is applied on the double-feed induction generator (DFIG) in wind turbines. The structure of a DOS is used for detection and isolation of multiple sensor faults. The approach is validated using signals obtained from a simulated DFIG system. The main contribution of this paper is the modelling of induction generator for wind turbines and the use unknown input observers to detect multiples and simultaneous faults in current sensors. The simulation model of DFIG is developed using MATLAB.

Keywords: wind turbine, DFIG, UIO, observer DOS, current sensor

1. INTRODUCTION

In recent years, environmental issues play an increasingly important role in our daily lives. This is particularly due to an awareness of people about the consequences of some pollution on the environment and climate conditions. This work aims to improve safety, reliability and performance of wind turbine and to predict the evolution of degraded mode, in order to improve the availability of the system (Odgaard, Thogersen and Stroustrup 2009; Blanke, Kinnaert, Lunze, Staroswiecki and Schroder 2010), The main goal of this studies-to detect, isolate faults and to determining the origin of abnormalities (i.e. failure of sensors or actuators, system malfunctions).

With the increasing size of wind turbine (Rothenhagen, Thomsen and Fuchs 2007), there is a need for improving diagnostic techniques in order to detect the favourable arguments for the occurrence of fault. Several works concern the detection of fault and their isolation in the wind system. In (Rothenhagen, Thomsen and Fuchs 2007) an observer was setup to detect sensor fault in the turbine hub. Reconfiguration has been proposed by (Rothenhagen and Fuchs 2009). An observer with unknown inputs has been proposed by (Nielsen 2009; Gálvez-Carrillo and Kinnaert 2011). In this paper, we have shown interest in the detection and isolation of currents sensors faults, for example internal faults in the DFIG are caused by the component of the generator (rotor and stator magnetic circuits, stator windings, mechanical air gap). The generator is often exposed to perturbation as the origin of the noise from the environment of the generator, the uncertainties of measurements, sensors faults or actuators. The construction of the observers is knowledge-based for the model of the generator to observe.

In this paper an unknown input observers are used as well (Chen and Patton 1999). The faults are considered as unknown inputs which should be estimated this can be done by introducing internal fault models. Other examples of this usage of the unknown input observers can be seen in (Odgaard and Mataji 2008) where the former reports similar scheme applied on fault detection of power plant coal mills and the latter estimate power coefficients for wind turbine, some examples can be found of fault detection and accommodation of wind turbine. An observer based scheme for detection of sensor faults for blade root torque sensor is presented in (Wei, Verhaegen and Van den engelen 2008). An unknown input observer based scheme was in (Rothenhagen, Thomsen and Fuchs 2007) proposed to detect such faults in a wind turbine.

In present paper, the problem of sensors fault detection and isolation the multiple and simultaneous currents sensors, in DFIG driven by a wind turbine application has been addressed. The application of DOS is possible if the system is observable.

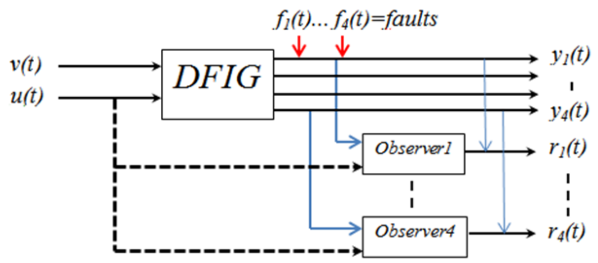

Figure 1: Structure of Observer DOS

2. SYSTEM DESCRIPTION

The DFIG is one of the most used wind generator (Khojet EL Khail 2006.), "Figure 2". Several recent papers, confirmed by industrial realizations, demonstrate the viability of this device in a wind system.

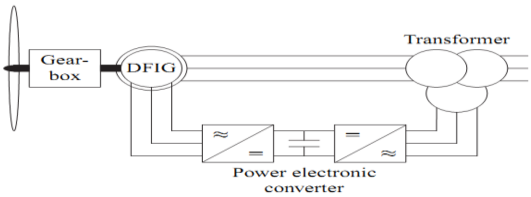

Figure 2: Wind turbine with a DFIG

The presence of a converter may result in large variations of the rotor voltages with high frequencies, rectifiers and inverters are used to solve this problem. Wind energy captured by the turbine is converted by the DFIG and is transmitted to the network by the rotor and the stator windings. The guidance system of the blades was used in order to adjust lift of the blade to the wind speed. So, it limits the power generated by the generator. With such a system, the blade is controlled by a system called "pitch control", this guidance system is not study in this paper.

3. MODEL OF THE DFIG

3.1. PARK TRANSFORMATION

The Park transformation is defined by the rotation matrix of the rotating field. It consists in the projection of the three phase coordinates (a, b, c), in frame (d, q) (El Aimani 2004). In this frame, the d-axis is chosen to coincide with stator axis at $t = 0$ and q axis is lag by 90 degree with the d axis of the direction of rotation. To investigate the DFIG the d-q model is required. The used Park transformation is given by equation (1).

$$[P(\theta)] = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta-\frac{4\pi}{3}) \\ -\sin(\theta) & -sim(\theta-\frac{2\pi}{3}) & -\sin(\theta-\frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (1)$$

The transformation is valid for both stator and rotor, equation (2) describes the global modeling of the generator, use the voltage and fluxes become respectively.

$$\left.\begin{aligned} V_{ds} &= R_s i_{ds} + \frac{d\emptyset_{ds}}{dt} - w_s\emptyset_{qs} \\ V_{qs} &= R_s i_{qs} + \frac{d\emptyset_{qs}}{dt} + w_s\emptyset_{ds} \\ V_{dr} &= R_r i_{dr} + \frac{d\emptyset_{dr}}{dt} - w_r\emptyset_{qr} \\ V_{qr} &= R_r i_{qr} + \frac{d\emptyset_{ds}}{dt} + w_r\emptyset_{dr} \end{aligned}\right\} \quad (2)$$

where V stands for voltages (V), I stands for currents (A), R stands for resistors *(Ω)*, $\emptyset$ stands for flux linkages (V·s). Indices d and q indicate direct and quadrature axis components respectively while s and r indicates stator and rotor quantities respectively. w_s and w_r is the stator and the (mechanical) rotor speed of generator.

3.2. Observer Design

It is common when modeling a system, to involve inputs that are not measurable but which nevertheless affect the state. Use the term to refer unknown inputs, and reconstruction of the state of these systems can only be done under certain condition, the observer used are called unknown input observers (Odgaard and Stoustrup 2012 a, 2009b).

Doubly fed induction machines comprise of a wound stator and a wound three phase rotor, where the rotor windings can be accessed by brushes. Usually, the stator is connected to the grid, and the rotor is fed by an inverter. In this work, an Input Observer based on an unknown input observer (UIO) with input reconstruction is used to observe the stator voltages of the DFIG. UIO observe the states of this system, where an input, the unknown input, is not used. For the reconstruction of the unknown inputs the UIO needs the measured outputs of the system and the known inputs. Using the estimated states and the known inputs, the unknown input may be reconstructed. This is thoroughly described in (Rothenhagen and Fuchs 2009). The state space model used for the DFIG is given in equations (3) to (8). The bilinear character of the DFIG is represented by the matrix A_0. The reference frame is described by matrix A_1. The input is split up into known and unknown inputs (4), with their respective input matrices B and F. It is assumed that all currents are measurable, therefore C is unity matrix.The system matrices are explicitly given in (6), and (7), where ω_r is the mechanical rotor frequency, ω_a is the rotational frequency of the reference frame.

Using this system description, it is possible to easily convert the system from stator fixed into a synchronous reference frame or any other, since the influence of the rotation is described by ω_a. Explicitly, a stator fixed system is using ω_a=0, while a system oriented uses the stator angular frequency ω_a= ω_s=2π50 s $^{-1}$. A mor detailed desctiption may be found in (Rothenhagen and Fuchs 2009).

$$\dot{x}(t) = Ax(t) + Bu(t) + Fv(t) \quad (3)$$
$$y(t) = Cx(t)$$
$$u(t) = [Vdr\ Vqr]^T,\ v(t) = [Vds\ Vqs]^T \quad (4)$$
$$A = A_0 + A_1\omega_a \quad (5)$$

$$A_0 = \begin{bmatrix} -\frac{Rs}{\sigma Ls} & \frac{p\omega_r L_h^2}{\sigma LsLr} & \frac{L_h Rr}{\sigma LsLr} & \frac{p\omega_r L_h}{\sigma Ls} \\ -\frac{p\omega_r L_h^2}{\sigma LsLr} & \frac{-Rs}{\sigma Ls} & -\frac{p\omega_r L_h}{\sigma Ls} & \frac{L_h Rr}{\sigma LsLr} \\ \frac{L_h Rs}{\sigma LrLs} & \frac{-p\omega_r L_h}{\sigma Ls} & -\frac{Rr}{\sigma Lr} & -\frac{p\omega_r}{\sigma} \\ \frac{p\omega_r L_h}{\sigma Lr} & \frac{RsL_h}{\sigma LsLr} & \frac{p\omega_r}{\sigma} & \frac{-Rr}{\sigma Lr} \end{bmatrix} \quad (6)$$

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \end{bmatrix} \quad (7)$$

$$B=\begin{bmatrix} \frac{1}{\sigma.Ls} & 0 \\ 0 & \frac{1}{\sigma.Ls} \\ -\frac{L_h}{\sigma.LsLr} & 0 \\ 0 & -\frac{L_h}{\sigma.LsLr} \end{bmatrix} F=\begin{bmatrix} -\frac{L_h}{\sigma.LsLr} & 0 \\ 0 & -\frac{L_h}{\sigma.LsLr} \\ \frac{1}{\sigma.Lr} & 0 \\ 0 & \frac{1}{\sigma.Lr} \end{bmatrix} \quad (8)$$

$(\sigma) = 1 - \frac{L_h^2}{L_r\, L_s}$: is the coefficient of Blondel

where $x(t) = [i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}]^T$ is the state system, $u(t)$ is the control vector input, $y(t)$ are measured and the output, $v(t)$ is the vector of unknown input. The matrices A, B, F and C are matrices known the parameters of matrix are defined in "Table 6", constant and consistent with the dimension signals. It is possible to reconstruct the system state observed despite the presence of unknown inputs.

The input of the system is divided in to input known and unknown (4), with their respective input matrices B and F. It is assumed that all currents are measurable output. The structure of the UIO can be defined as:

$$\dot{z}(t) = Nz(t) + Mu(t) + Ly(t) \quad (9)$$
$$\hat{x}\,(t) = z(t) + Ey(t) \quad (10)$$

wher N, M, L and E are matrices designed to achieve decoupling from the unknown input ans as well obtain an optimal observer and have to be designed in such a way $\hat{x}$ converge asymptotically to x. The matrices in the unknown input observer are found using the following equation (11)-(21), since system matrices are assumed constant.

$$P = I_n - EC \quad (11)$$

The estimation error of the stat $e(t)$, is given by:

$$e(t) = Px(t) - z(t) \quad (12)$$

It is necessary to satisfy the following conditions, if the matrices FC has full rank line, the equation (15) determine completely the matrix E of the observer. As a consequence, the observer error has to converge to zero.

$$0 = (PA - LC - NP) \quad (13)$$
$$0 = (PB - M) \quad (14)$$
$$0 = PF \quad (15)$$
$$E = F(CF)^+ + \Theta(I_m - CF(CF)^+) \quad (16)$$

The matrix N must be stable, Θ is matrix selected dy the placement of poles of N in order to reenter stability, and $(CF)^+$ is the generalized matrix of (CF):

$$(CF)^+ = ((CF)^T\, CF)^{-1}(CF)^T \quad (17)$$
$$P = I_n - F(CF)^+C + \Theta(I_m - CF(CF)^+)C \quad (18)$$
$$K = L - NE \quad (19)$$
$$N = PA - KC \quad (20)$$

At last the matrices N and K have to be designed. Therefore matrix M (14) is introduced for clarity. Solving (14) for N yields to (21). The eigenvalues of have to be in the left hand, the gain K guarantee the stability of the matrix N

$$N = (I_n - F(CF)^+C)A - [\,\Theta\ K\,]\begin{bmatrix}(I_m - CF(CF)^+)CA \\ C\end{bmatrix} \quad (21)$$

3.3. Estimation of unknown inputs

As seen earlier, the unknown input observer can estimate the state variables of the system independently unknown input $v(t)$. It is then possible to use the reconstructed state obtained also seek to estimate the unknown input. The choice of stator voltage as unknown inputs in that practice, the stator voltage are not measurable and they are not available, this is why we use the unknown input observer for the estimated

$$\dot{y}(t) = C\dot{x}(t) = CAx(t) + CBu(t) + CFv(t) \quad (22)$$
$$\hat{v}\,(t) = (CF)^+(\dot{y}(t) - CBu(t) - CA\hat{x}(t)) \quad (23)$$

The error estimation of the state tends asymptotically to zero, so $\hat{v}\,(t)$ asymptotically approaches $v(t)$. In other words, $\hat{v}\,(t)$ is the estimate of $v(t)$.

4. FAULTS DETECTION SCHEME DESIGN

The presence of faults sensors, denoted $f_c(t)=[\ f_1\ f_2\ f_3\ f_4]$ influence on the estimation error outputs. D_c is the matrix distribution of the additive faults.

$$\dot{x}(t) = Ax(t) + Bu(t) + Fv(t) \quad (24)$$
$$y(t) = CAx(t) + D_c f_c(t) \quad (25)$$

The estimation error output by unknown input observer can be seen as a dynamic system output follows:

$$\dot{\varepsilon}(t) = N\hat{x}(t) + (NE - L)D_c f_c(t) - ED_c\dot{f}c(t) \quad (26)$$
$$\hat{y}(t) = C\hat{x}(t) + D_c f_c(t) \quad (27)$$
$$\hat{x}(0) = Px_0 - z_0 \quad (28)$$

$$\dot{\varepsilon}(t) = (A - NP - LC - ECA)x(t) + (B - M - ECB)u(t) + (F - ECF)v(t) - D_c f_c(t) - ED_c\dot{f}c(t) - N\varepsilon(t) \quad (29)$$

It is therefore clear that, absent fault the signal $\hat{y}(t)$ converges asymptotically to zero, to the extent the matrix N is stable, $\varepsilon(t)$ the observer error.

4.1. Filter Bank for DFIG

The state observer for fault detection and isolation is a well-known problem. To overcome this problem, one can use a filter bank to estimate the dynamical behaviors of the system, in order to detect then and to isolate the fault. The first kind of filter bank is the Dedicated Observer Scheme (DOS) proposed by R. N. Clark in 1978 (Clark 1978; Trinh and Chafouk 2011; Ichalal, Marx, Ragot and Maquin 2006). And the second one, Generalized Observer Scheme (GOS) proposed by P. M. Frank in 1987 (Frank 1987) respectively. Each filter bank is composed by a number of observers, which are supplied with all inputs and different subsets of outputs. The observer which receives a faulty measurement provides a bad estimate of the variables, while the estimation of other observers converges to the measurements of corresponding outputs, except the output error.

5. SIMULATION RESULTS

The generation of residuals, is a fundamental step in designing a diagnosis based on models. In theory, a residual should be zero in the absence of fault and significantly different from zero in the contrary case. It is then necessary to introduce detection thresholds to avoid false alarms (Orjuela, Marx, Ragot and Maquin 2010). These thresholds can be set by the user from a statistical analysis of residues and taking. A structuring of residuals can accomplish the detecting and isolation of the faults (Gálvez-Carrillo and Kinnaert 2011; Ouyessaad, Chafouk and Lefebvre 2011). In this case, the i^{th} observer is controlled by the i^{th} output of the system and all inputs. The "Figure 1" shows the architecture of the bank of observers DOS. The faults of sensors affecting measurement $y(t)$ are denoted $f1(t)$, $f2(t)$, $f3(t)$ and $f4(t)$. Note later $r_{i,j}(t)$ the fault indicator signal (residual) calculated from the difference between the j^{th} system output and the i^{th} output estimated by the i^{th} observer DOS. If the output has a defect then there is a bad estimate of the state and residual $r_{1,i}$ may be affected.

In this section, the detection of current sensor faults by the observer Luenberger will be focused. Then, the isolation of the fault will be addressed. For this purpose, the following fault scenario will be used:

The first scenario is to introduce fault only the first step $y_1(t)$. The first fault was injected at $t = 0.3$ s and disappears $t = 0.4$ s, the fault consists of constant amplitude equal to 15% of the maximum amplitude of the output rotor current Idr, "Table 1".

Table 1: Faults Scenario I

Number	Fault number	Starting time (s)
1	$f_1(t)$	$0.3 \le t \le 0.4$

The observer 1 reconstructs the model output using only the output y_1 and all inputs of the system, in this step the measurement y_1 is affected by a fault f_1.

This output has a fault, then there is a poor estimate of the state and residuals $r_{1,1}$, $r_{1,2}$ $r_{1,3}$ and $r_{1,4}$ away from zero "Figure 4". To show the fault f_1 during its presence in y_1 (red ellipse) (Idr presence f_1) "Figure 3".

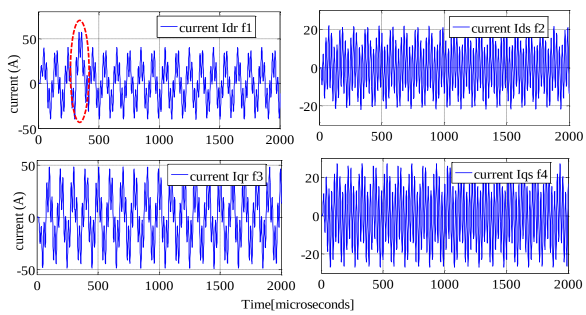

Figure 3 : Rotor and stator currents, can be seen the fault f1 in the rotor current idr

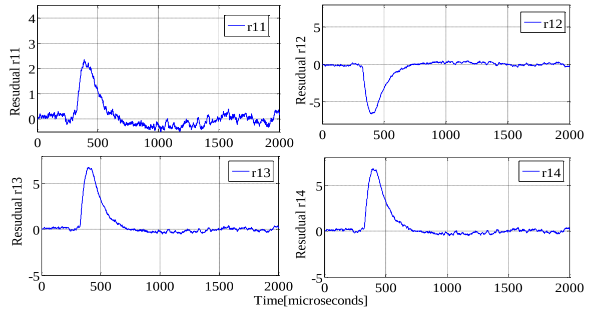

Figure 4: Fault residual for *idr*, the fault f_1 is detected during its presence in the observer 1

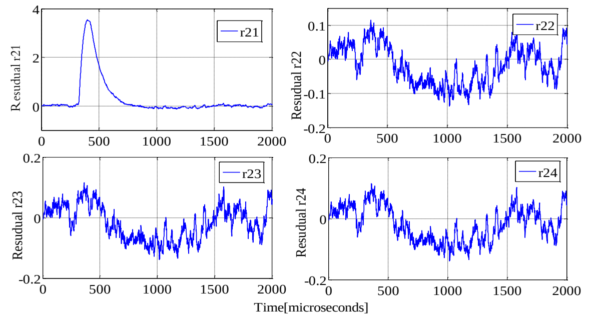

Figure 5 Fault residual for *idr*, the fault f_1 is detected during its presence in the observer 2

A sensor fault (f_1) is present in $r_{2,1}$ from time $0.3 \le (t) \le 0.4$. Using the observer 2 see "Figure 5", this sensor fault is detected without any false positive detection, other observers 3 and 4 confirmed this result, r_{31} and r_{41} with observers DOS. The signatures of the different faults are given in "Table 2".

Table 2: Signature of Faults

	Obs1				Obs2			
	$r_{1,1}$	$r_{1,2}$	$r_{1,3}$	$r_{1,4}$	$r_{2,1}$	$r_{2,2}$	$r_{2,3}$	$r_{2,4}$
$f1$	1	1	1	1	1	0	0	0
	Obs3				Obs4			
	$r_{3,1}$	$r_{3,2}$	$r_{3,3}$	$r_{3,4}$	$r_{4,1}$	$r_{4,2}$	$r_{4,3}$	$r_{4,4}$
$f1$	1	0	0	0	1	0	0	0

According to this table, the signatures $r_{1,j}$= *[1 1 1]* , $r_{2,j}$= *[1 0 0 0]*, $r_{3,j}$= *[1 0 0 0]* and $r_{4,j}$= *[1 0 0 0]* correspond the fault *f1*. Presented in "Figure 4", "Figure 6"and "Table 2". It is possible to conclude the fault f_1 appears in y_1 .

The second scenario consists to introduce multiple faults in the outputs y_1 and y_3, the following fault scenario will be used "Table.3".

Table 3: Faults Scenario II

Number	Fault number	Starting time (s)
1	$f_1(t)$	$0.9 \le t \le 1$
2	$f_3(t)$	$0.9 \le t \le 1$

It should be noted that in the simulation a measurement noise is added to the output of the DFIG (here, a random signal with zero mean and variance equal 1).

This information is confirmed by other observers. It is possible to conclude that the fault f_1 appear in the output $y1$ in interval 0.9(s) ≤ t ≤ 1(s), and that the fault f_3 appear in the output y_3 in interval 0.9(s) ≤ t ≤ 1(s). The fault consists of a window of constant amplitude equal to 15% of the maximum amplitude of the output "Figure 6", present the fault detection the four residuals $r_{3,j}$, in observer 3. The observers 2 and 4 confirmed this results, ($r_{2,1}$, $r_{2,3}$) for observer 2, and ($r_{4,1}$, $r_{4,3}$) with the observers 4 show "Figure 7".

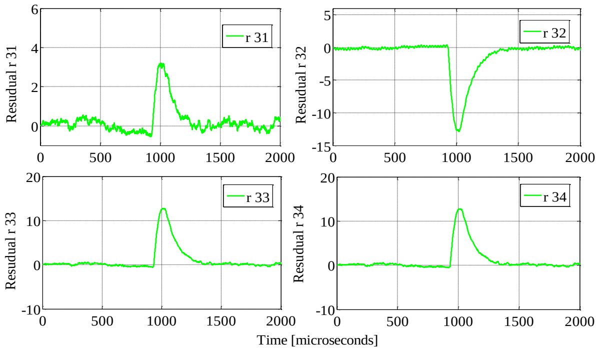

Figure 6: Fault residual in the observer 3

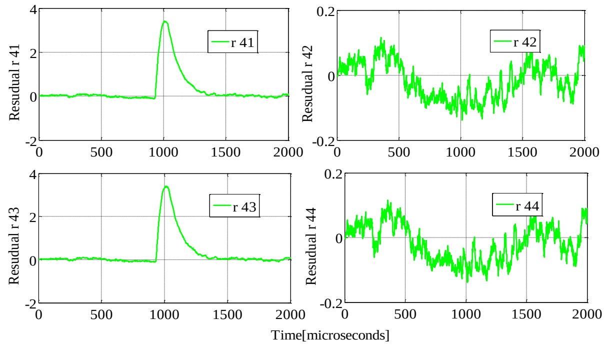

Figure 7: Fault residual in the observer 4

The third scenario consists to introduce the fault multiple and simultaneous in the outputs y_1 , y_2 and y_3, the following faults scenario will be used, see "Table.4".

Table 4: Faults scenario VI

Number	Fault number	Starting time (s)
1	$f_1(t)$	0.9 ≤ t ≤1
2	$f_3(t)$	0.9 ≤ t ≤1
3	$f_2(t)$	1.3 ≤ t ≤1.4

The fault f_1 consists of constant amplitude equal to 20% of the maximum amplitude of the output y_1, f_3 = 5% of the output y_3 and f_2 = 10% of the output y_2, show "Figure 9".

In this section introduction the multiples and simultaneous faults, with different amplitudes intended to show the sensitivity and robustness of the observers to detected the faults "Figure 9".

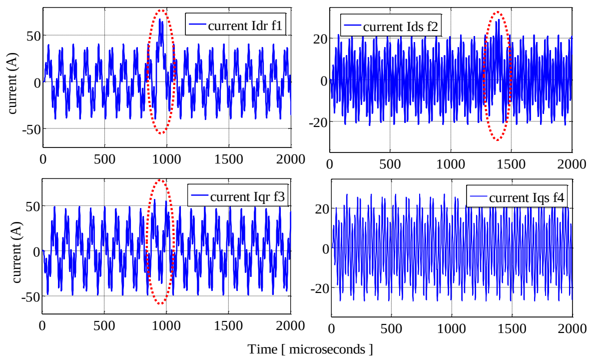

Figure 8: Rotor and stator currents, can be seen the fault f_1, f_2 and f_3 in the current sensor

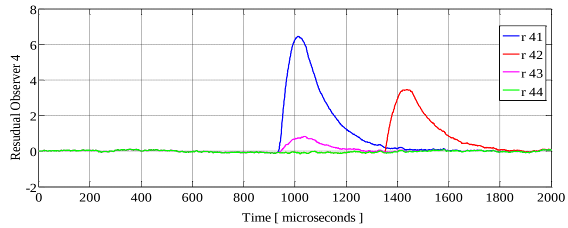

Figure 9: The four residuals signals $r_{4,j}$ in the observer four

The logical rules of the decision unit allow to detect and to locate the fault. The threshold is choose equal to 3σ (σ is the standard deviation of the signal). "Figure 10", witch present the four faults detection residuals $r_{1,4}$, $r_{4,2}$, $r_{4,3}$ and r_{44}. "Table 5" see the different event of the occurrence of multiple and simultaneous fault, detected and located by the observer DOS.

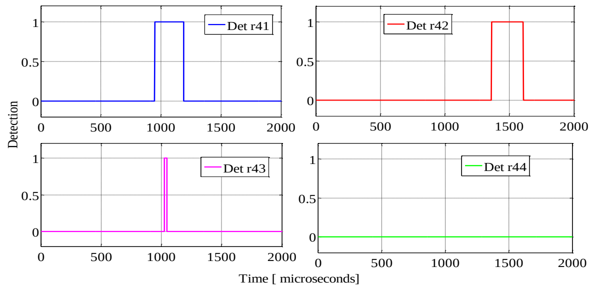

Figure 10: Single fault detection

Table 5: Generalized Table of Signature Faults

	Obs1				Obs2			
	$r_{1,1}$	$r_{1,2}$	$r_{1,3}$	$r_{1,4}$	$r_{2,1}$	$r_{2,2}$	$r_{2,3}$	$r_{2,4}$
$f1$	1	1	1	1	1	0	0	0
$f2$	0	1	0	0	1	1	1	1
$f3$	0	0	1	0	0	0	1	0
$f4$	0	0	0	1	0	0	0	1
	Obs3				Obs4			
	$r_{3,1}$	$r_{3,2}$	$r_{3,3}$	$r_{3,4}$	$r_{4,1}$	$r_{4,2}$	$r_{4,3}$	$r_{4,4}$
$f1$	1	0	0	0	1	0	0	0
$f2$	0	1	0	0	0	1	0	0
$f3$	1	1	1	1	0	0	1	0
$f4$	0	0	1	0	1	1	1	1

APPENDIX

V_{ds}; V_{qs} stator voltages in *d-q* reference frame

V_{dr}; V_{qr} rotor voltages in *d-q* reference frame

i_{ds}; i_{qs} stator currents in *d-q* reference frame

i_{dr}; i_{qr} rotor currents in *d-q* reference frame

Table 6: Parameters of the DFIG, 22kW (Rothenhagen K., Thomsen S., and Fuchs F. W., 2007)

Parameters	Values	Meaning
L_h	45.8 mH	Mutual inductance
L_s	46.8 mH	Stator inductance
L_r	46.8 mH	Rotor inductance
R_s	0.1315 Ω	Stator resistor
R_r	0.1070 Ω	Rotor resistor
P	2	Pairs of poles

6. CONCLUSION

In this paper, the problem of current sensor fault detection and isolation, for double-fed induction generator driven by a wind turbine application has been addressed. An unknown input observer scheme and a statistical detection algorithm have been used as residual generation and decision system, respectively. The approach has been validated using simulated signals of a double-fed induction generator for wind turbine. Through simulations, it has been demonstrated that multiple current sensor faults for rotor and stator have been correctly detected and isolated with a DOS observer scheme. The future extension of this work is to improve the performance of observers and insensitivity on measurement noise, in a test bank in real time. We are interesting in the FDI problem for other sensors of wind turbine (voltage, wind speed). The FDI problem for time varying rotational speed of the rotor will also be studied.

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