Fault Tolerant Control of DFIG Stator Inter-Turn fault Based Wind Turbine Using Adaptive Observer

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Abstract: In this paper we describe a fault tolerant control (FTC) based on detection of stator inter-turn short circuit (ITSC) faults in doubly-fed induction generators (DFIG) for wind power applications. The proposed technique is based on the adaptive observer (AO). We show how the proposed approach can be successfully adopted in order to offset the effect of all possible faults which can occur. To achieve this goal, we develop an algorithm that allows the passage from nominal controllers designed for healthy condition, to robust controllers designed for faulty condition. This algorithm serves as fault indicator as well.

Key words: - Wind Power, Doubly Fed Induction Generator (DFIG), Vector Control, Adaptive Observer, Inter-Turn Short-Circuit, Fault Diagnostic, Fault Tolerant Control.

I. INTRODUCTION

Wind energy generation is an economic and own alternative relatively to various exhaustible energy sources [1].

this paper deals with the problem of the wind turbine speed control. The considered generator is a doubly fed induction (DFIG). The rotor is connected to the power grid through an AC-DC-AC converter, while the stator is directly connected to the network. The fundamental advantage of this arrangement is that the power flowing through the converter is only a fraction of the total wind turbine power.

To maximize the wind energy extraction, variable wind turbine speed control (MPPT), were proposed.

This technique requires the knowledge of the wind speed, and consists in varying the turbine speed reference according to that of the wind [2-3]. In the other hand, different techniques have been used to design the MPPT control law. In [7-5-8], a simple linear controller is proposed. However, for systems such as DFIG-wind turbine, which enjoys non-linear dynamics, the performance of such regulator degrades during wide variations of wind speed. Also neural, fuzzy or hysteresis methods are used to design the wind turbine control system [9]. However, those techniques do not make use of the exact nonlinear DFIG-wind turbine model in the control design. Consequently, the obtained controllers are generally not backed by formal stability analysis and their performances cannot be expressly quantified.

The fault detection and localization unit detects the occurrence of fault and determines its nature. This can be realized by analysing the change of the rotor resistance and then take the appropriate decision: accept the default or stop the machine and execute a curative maintenance. [10-12].

To obtain this difficulty, some previous works propose adaptive observer for estimating rotor resistance [4-6].

In this paper proposes a novel adaptive estimation method developed, to design an adaptive observer

The controlled quantities are calculated using stability analysis based on Lyapunov theory. Theis method of control is implemented by Matlab/simulink and several steady results are given and confirm the validity of the approach.

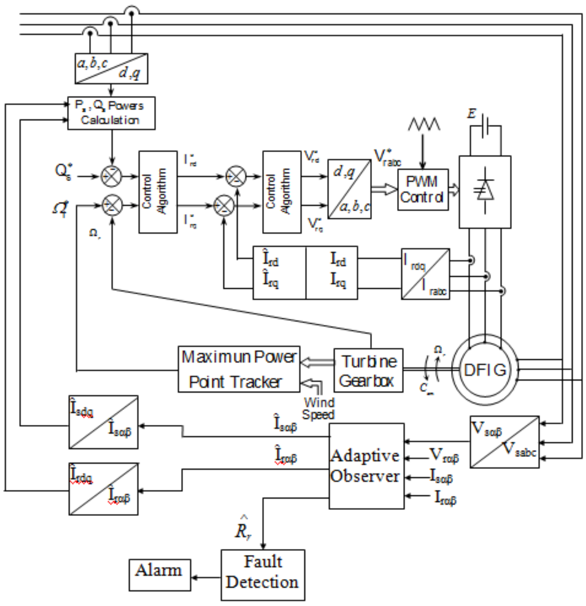

Fig.1 Block diagram of speed and reactive power controls of DFIG

The schema of the device studied is given by Fig.2.

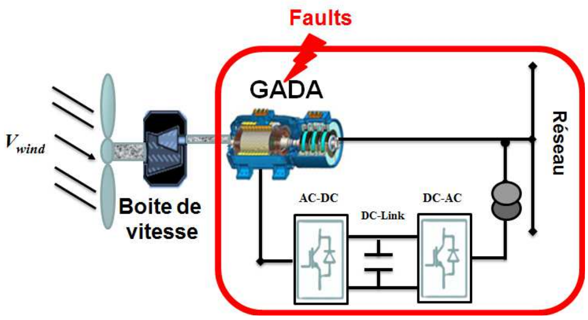

Fig. 2 Block scheme of the wind energy conversion system based a DFIG.

II. DFIG MODELING

In the stator reference frame (αs-βs), the mechanical/electrical energy conversion process is described by the equations of DFIG are defined by:

$$\begin{cases} V_{\alpha s} = R_s . i_{\alpha s} + \dfrac{d\psi_{\alpha s}}{dt} \\ V_{\beta s} = R_s . i_{\beta s} + \dfrac{d\psi_{\alpha s}}{dt} \\ V_{\alpha r} = R_r . i_{\alpha r} + \dfrac{d\psi_{\alpha r}}{dt} + \omega_r \psi_{\beta r} \\ V_{\beta r} = R_r . i_{\beta r} + \dfrac{d\psi_{\alpha r}}{dt} - \omega_r \psi_{\alpha r} \end{cases} \quad (1)$$

The equations of stator and rotor flux are given as follows: [4-20]

$$\begin{cases} \psi_{\alpha s} = L_s . i_{\alpha s} + M_{sr} . i_{\alpha r} \\ \psi_{\beta s} = L_s . i_{\beta s} + M_{sr} . i_{\beta r} \\ \psi_{\alpha r} = L_r . i_{\alpha r} + M_{rs} . i_{\alpha s} \\ \psi_{\beta r} = L_r . i_{\beta r} + M_{rs} . i_{\beta s} \end{cases} \quad (2)$$

The electromagnetic torque can be expressed by:

$$C_{em} = p \frac{M_{sr}}{L_r} \left(\psi_{ds} I_{qr} - \psi_{qs} I_{dr} \right) \quad (3)$$

The principle of vector control with stator flux oriented of the DFIG is shown in Figure (3). The stator flux vector will be aligned on the‘d’ axis and the stator voltage vector on the ‘q’ axis, this last constraint is favorable to obtain a simplified control model [23].

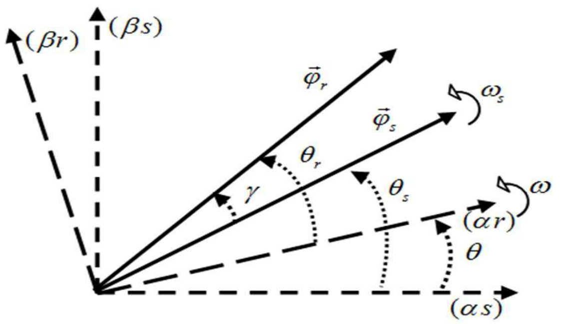

Fig. 3 Respective position of the references (αs, βs) and (αr,βr)

In a stationary reference frame (α*s*-β*s*), The DFIG electrical equations written in the state-space can be expressed as follows: [22].

$$\begin{cases} \dfrac{dX}{dt} = AX + BU \\ Y = CX \end{cases} \quad (4)$$

With

$$X = \left[i_{\alpha s} \;\; i_{\beta s} \;\; \Phi_{\alpha r} \;\; \Phi_{\beta r} \right]^t, Y = \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \end{pmatrix}$$

$$u = \left[u_{\alpha s} \;\; u_{\beta s} \;\; u_{\alpha r} \;\; u_{\beta r} \right]^t$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}$$

$$B = \begin{bmatrix} \dfrac{L_m}{\sigma L_s L_r} I_2 & -\dfrac{1}{\sigma L_s} I_2 \\ -\dfrac{1}{\sigma L_r} I_2 & \dfrac{L_m}{\sigma L_s L_r} I_2 \end{bmatrix},$$

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

With $A_{11} = \begin{bmatrix} \left(\dfrac{-1}{\sigma \tau_s} - \dfrac{L_m^2}{\tau_s \sigma L_s L_r} \right) & 0 \\ 0 & \left(\dfrac{-1}{\sigma \tau_s} - \dfrac{L_m^2}{\tau_s \sigma L_s L_r} \right) \end{bmatrix},$

$$A_{12} = \begin{bmatrix} \dfrac{L_m}{\tau_r \sigma L_s L_r} & \dfrac{w L_m}{\sigma L_s L_r} \\ \dfrac{w L_m}{\sigma L_s L_r} & \dfrac{L_m}{\tau_r \sigma L_s L_r} \end{bmatrix},$$

$$A_{21} = \begin{bmatrix} \dfrac{L_m}{\tau_r} & 0 \\ 0 & \dfrac{L_m}{\tau_r} \end{bmatrix}, A_{22} = \begin{bmatrix} \dfrac{-1}{\tau_r} & -w \\ w & \dfrac{-1}{\tau_r} \end{bmatrix},$$

$$B_{11} = \begin{bmatrix} \dfrac{1}{\sigma L_s} & 0 \\ 0 & \dfrac{1}{\sigma L_s} \end{bmatrix}, B_{12} = \begin{bmatrix} \dfrac{-L_m}{\sigma L_s L_r} & 0 \\ 0 & \dfrac{-L_m}{\sigma L_s L_r} \end{bmatrix}$$

$$B_{21} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, B_{22} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$$

And $\sigma = 1 - L_m^2 / \left(L_s \, L_r \right)$, $w = p \, \Omega_{mec}$

where R_s and R_r are the stator and rotor resistance, respectively.. L_s , L_r and L_m are the stator and rotor full inductance, the magnetization inductance, respectively.

The electromagnetic torque equation becomes:

$$C_e = \frac{3}{2} p \frac{L_m}{L_r}\left(\Phi_{\alpha r}\, i_{\beta s} - \Phi_{\beta r}\, i_{\alpha s}\right) \tag{5}$$

II. DFIG WITH STATOR INTER-TURN FAULT OF A STATOR PHASE WINDING

An inter-turn fault of a stator phase winding is a result of the deterioration of insulation between the individual coils. This is in essence a short circuit of the stator phase winding, which changes the symmetrical stator current to one that is asymmetrical. For predicting the electrical behavior from the stator supply due to an inter-turn fault, it would appear that the impedance of the short-circuited stator winding has decreased. [11]

The degree to which its impedance has decreased depends on the severity of the fault. To simulate the inter-turn fault on the DFIG, the impedance of the stator phase winding is decreased by placing a resistor in parallel with the winding, as shown in Fig. 4 [16].

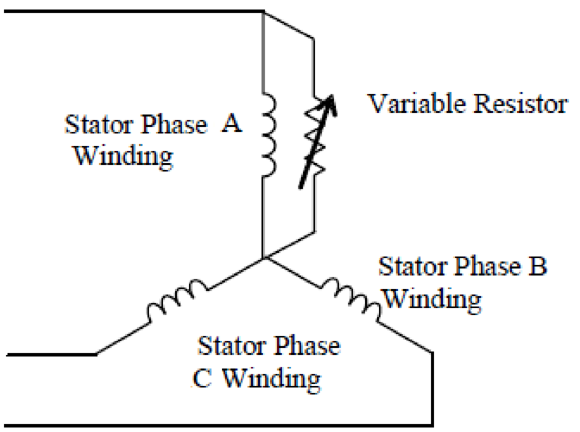

Fig. 4 Stator winding configuration with the inter-turn short circuit fault in phase 'a'.

The stator resistance matrix can be rewritten as follows:

$$[R_s] = \begin{bmatrix} (1-\mu)R_s & 0 & 0 & \gamma.R_s \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & \mu.R_s \end{bmatrix} \tag{6}$$

However, we keep the matrix of stator voltages unchanged.

If we mean by « μ » fraction of the number of shorted turns of phase « a » , then we have a healthy portion of a fraction $1-\mu$ of turns and we suppose the phases "b" and "c" healthy. We will have the new inductance stator matrix following: [15-17]

$$[L_{ss}] = L_{fs}\, diag[(1-\mu)\ 1\ 1\ \mu] + M_s \begin{bmatrix} (1-\mu)^2 & -\frac{(1-\mu)}{2} & -\frac{(1-\mu)}{2} & \mu(1-\mu) \\ -\frac{(1-\mu)}{2} & 1 & -\frac{1}{2} & -\frac{\mu}{2} \\ -\frac{(1-\mu)}{2} & -\frac{1}{2} & 1 & -\frac{\mu}{2} \\ \mu(1-\mu) & -\frac{\mu}{2} & -\frac{\mu}{2} & \mu^2 \end{bmatrix}$$

(7)

Therefore, the matrix of mutual inductances is:

$$[M_{sr}] = M_s \begin{bmatrix} (1-\mu)\cos(\theta_r) & (1-\mu)\cos\left(\theta_r + \frac{2\pi}{3}\right) & (1-\mu)\cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) \\ \mu\cos(\theta_r) & \mu\cos\left(\theta_r + \frac{2\pi}{3}\right) & \mu\cos\left(\theta_r - \frac{2\pi}{3}\right) \end{bmatrix} \tag{8}$$

Rotor inductance matrix remains equal to that of the healthy cases. [18-19-21]

III. ADAPTIVE OBSERVER

The objective is to determine the mechanism adaptation of the speed and the rotor resistance. The structure of the observer is based on the DFIG model in stator reference frame.

A linear state observer can then be derived as follows by considering the mechanical speed as a constant parameter during a sampling time since its variation is very slow.

The model of the observer is written [11-13-14]

$$\begin{cases} \dfrac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + G\left(Y - \hat{Y}\right) \\ \hat{Y} = C\hat{X} \end{cases} \tag{9}$$

With

$$X = \left[i_{\alpha s}\ \ i_{\beta s}\ \ \Phi_{\alpha r}\ \ \Phi_{\beta r}\right]^t, Y = \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \end{pmatrix}$$

$$u = \left[u_{\alpha s}\ u_{\beta s}\ \ u_{\alpha r}\ \ u_{\beta r}\right]^t$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

And $\mathrm{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}, I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

We put $a = \dfrac{1}{\sigma L_s}\left(R_s + R_r \dfrac{L_m^2}{L_r^2}\right),\ b = \sigma L_s L_r$

The machine parameters are assumed to be perfectly known, the rotor resistance is unknown. We define

$$\delta R_r = R_r - \hat{R}_r \tag{10}$$

The symbol $\wedge$ denotes estimated values and G is the observer gain matrix. We will determine the differential system describing the evolution of the error

$$e = X - \hat{X} \tag{11}$$

The state matrix of the observer can be written as

$$\hat{A} = A + \delta A \tag{12}$$

With

$$\delta A = \begin{pmatrix} +\frac{1}{\sigma L_s}\delta R_r & 0 & -\frac{L_m}{bL_r}\delta R_r & 0 \\ 0 & +\frac{1}{\sigma L_s}\delta R_r & 0 & 0 \\ -\frac{L_m}{L_r}\delta R_r & 0 & +\frac{\delta R_r}{L_r} & 0 \\ 0 & -\frac{L_m}{L_r}\delta R_r & 0 & \frac{\delta R_r}{L_r} \end{pmatrix} \tag{13}$$

Then, we can write

$$\frac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + G\left(Y - \hat{Y}\right) \tag{14}$$

$$\frac{de}{dt} = (A - GC)e - \delta A\hat{X} \tag{15}$$

We define the Lyapunov function

$$V = e^T e + \frac{(\delta R_r)^2}{\lambda_2} \tag{16}$$

λ is a positive scalar.

This function should contain terms of the difference $\delta\omega$ and δR_r to obtain mechanism adaptation. The stability of the observer is guaranteed for the condition

$$\frac{dV}{dt} < 0 \tag{17}$$

The derivative of the Lyapunov function

$$\frac{dV}{dt} = 2e^T\frac{de}{dt} + 2\frac{\delta R_r}{\lambda_2}\frac{d\delta R_r}{dt} \tag{18}$$

The first terme becomes

$$2e^T\frac{de}{dt} = 2e^T(A - GC)e - 2e^T\delta A\hat{X} \tag{19}$$

The rotor flux components can not be measured. In addition, the flux dynamic is faster than the machine parameters dynamic. Consequently, we accept that

$$\begin{cases} \hat{\Phi}_{\alpha r} = \Phi_{\alpha r} \\ \hat{\Phi}_{\beta r} = \Phi_{\beta r} \end{cases} \tag{20}$$

Thus

$$e^T\delta A\hat{X} = \frac{\delta R_r}{\sigma L_s}\delta R_r\left(\hat{i}_{\alpha s}e_{i\alpha s} + \hat{i}_{\beta s}e_{i\beta s}\right) - \frac{L_m}{bL_r}\delta R_r\left(\hat{\Phi}_{\alpha r}e_{i\alpha s} + \hat{\Phi}_{\beta r}e_{i\beta s}\right) \tag{21}$$

For the second term of (16), we can write

$$2\frac{\delta R_r}{\lambda_2}\frac{d\delta R_r}{dt} = 2\frac{\delta R_r}{\lambda_2}\frac{d}{dt}\hat{R}_r - 2\frac{\delta R_r}{\lambda_2}\frac{d}{dt}R_r \tag{22}$$

We consider the hypothesis of a slowly varying regime for the machine parameters, thus

$$\frac{dR_r}{dt} = 0 \tag{23}$$

Consequently

$$\frac{d\hat{R}_r}{dt} = -\frac{d\delta R_r}{dt} \tag{24}$$

Finlay, we obtain

$$\frac{dV}{dt} = 2e^T(A - GC)e + 2\delta R_r \begin{bmatrix} \frac{L_m}{bL_r}\left(\hat{\Phi}_{\alpha r}e_{i\alpha s} + \hat{\Phi}_{\beta r}e_{i\beta s}\right) \\ -\frac{1}{\sigma L_s}\left(\hat{i}_{\alpha s}e_{i\alpha s} + \hat{i}_{\beta s}e_{i\beta s}\right) \end{bmatrix} + 2\frac{\delta R_r}{\lambda_2}\frac{d}{dt}\hat{R}_r \tag{25}$$

If the term $\frac{dV}{dt} = 2e^T(A - GC)e$ is negative, the condition $\frac{dV}{dt} < 0$ is verified for

$$2\delta R_r \begin{bmatrix} \frac{L_m}{bL_r}\left(\hat{\Phi}_{\alpha r}e_{i\alpha s} + \hat{\Phi}_{\beta r}e_{i\beta s}\right) \\ -\frac{1}{\sigma L_s}\left(\hat{i}_{\alpha s}e_{i\alpha s} + \hat{i}_{\beta s}e_{i\beta s}\right) \end{bmatrix} + 2\frac{\delta R_r}{\lambda_2}\frac{d}{dt}\hat{R}_r = 0 \tag{26}$$

This condition can be verified if

$$2\frac{\delta R_r}{\lambda_2}\frac{d}{dt}\hat{R}_r = \frac{2L_m}{bL_r}\delta R_r\left(\hat{\Phi}_{\alpha r}\, e_{i\alpha s} + \hat{\Phi}_{\beta r}\, e_{i\beta s}\right) - \frac{2}{\sigma L_s}\delta R_r\left(\hat{i}_{\alpha s} e_{i\alpha s} + \hat{i}_{\beta s}\, e_{i\beta s}\right) \quad (27)$$

We obtain the adaptation mechanism in the form

$$\hat{R}_r = \int_0^t \lambda_2 \left[\frac{L_m}{bL_r}\left(\hat{\Phi}_{\alpha r}\; e_{i\alpha s} + \hat{\Phi}_{\beta r}\; e_{i\beta s}\right) - \frac{1}{\sigma L_s}\left(\hat{i}_{\alpha s} e_{i\alpha s} + \hat{i}_{\beta s}\; e_{i\beta s}\right) \right] dt \quad (28)$$

The matrix of gain G is selected such as the eigenvalues of the matrix A−GC are in the left plane half of the complex plan and that the real part of the eigenvalues is larger in absolute value than the real part of the eigenvalues of the state matrix A.

The estimated electromagnetic torque is expressed

$$\hat{C}_e = \frac{3}{2}\, p\, \frac{L_m}{L_r}\left(\hat{\Phi}_{\alpha r}\; \hat{i}_{\beta s} - \hat{\Phi}_{\beta r}\; \hat{i}_{\alpha s}\right) \quad (29)$$

IV. SIMULATION RESULTS

A doubly-fed induction generator model was developed in Matlab/simulink, the simulation results shown below are for a 7500W generator, The simulation test involves the wind speed variation and the reactive power reference constant equals to zero.

A Health operation

the DFIG is tested and simulated in a healthy operation with wind speed applied to the DFIG then the simulation results for active and reactive power developed as shown in Fig (6-7-8)

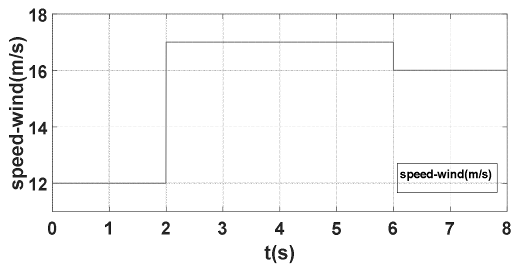

Fig. 5 Variation of wind speed

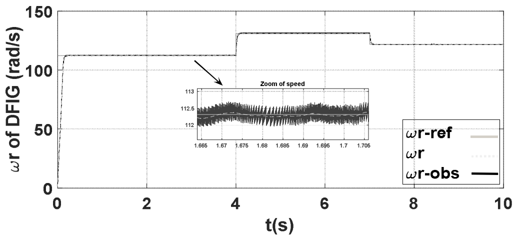

Fig. 6 Speed of healthy DFIG and its reference with variation of wind speed

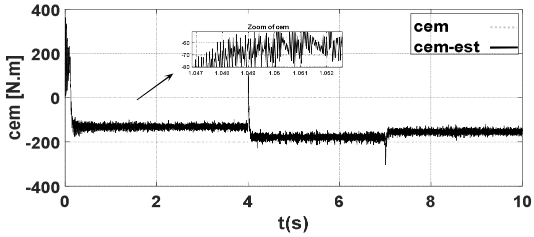

Fig. 7 Electromagnetic torque

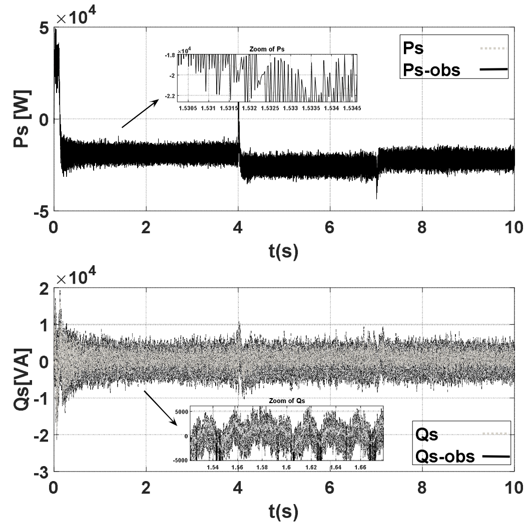

Fig.8 Stator active and reactive powers of healthy DFIG with wind speed variation

B Inter-turn stator fault operation of the DFIG

In this part, we present simulation results for the DFIG operation with stator inter-turn short circuit fault. The inter-turn fault is introduced in winding of stator phase "a".

We note that the performances of DFIG reduced when the increase of the fault dergre that influences on the equilibrium of the three stator phases and therefore the equilibrium of the stator currents which affects the power output, this increase is due to the presence of short-circuit fault. Their responses present a deformations after augmentation of stator and rotor short-circuit fault degree to 5% à time t=1s.

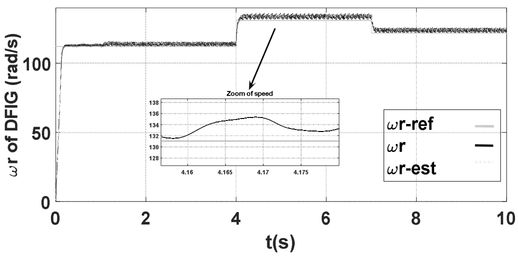

Fig. 9 Speed of faulty DFIG and its zoom with wind speed variation with Stator inter-turn short circuit

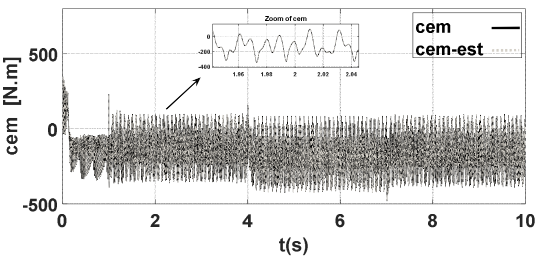

Fig. 10 Electromagnetic torque of faulty DFIG

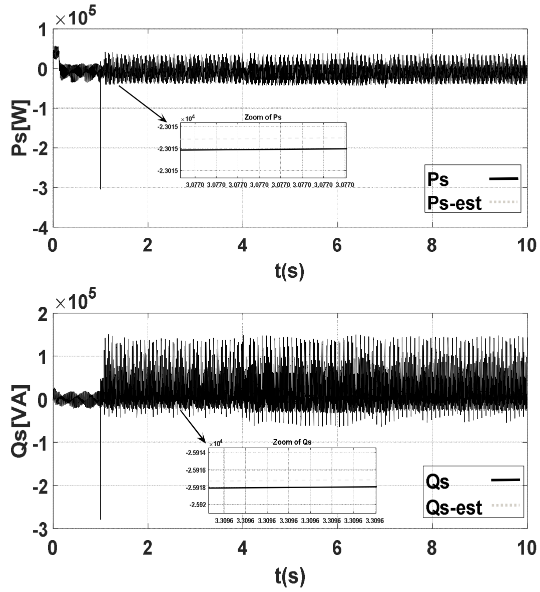

Fig. 11 Stator reactive and active powers of faulty DFIG with wind speed variation.

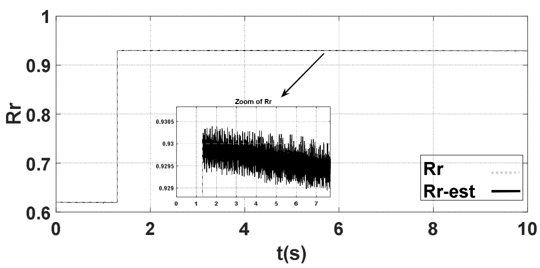

Fig.12 Observed rotor resistance of faulty DFIG.

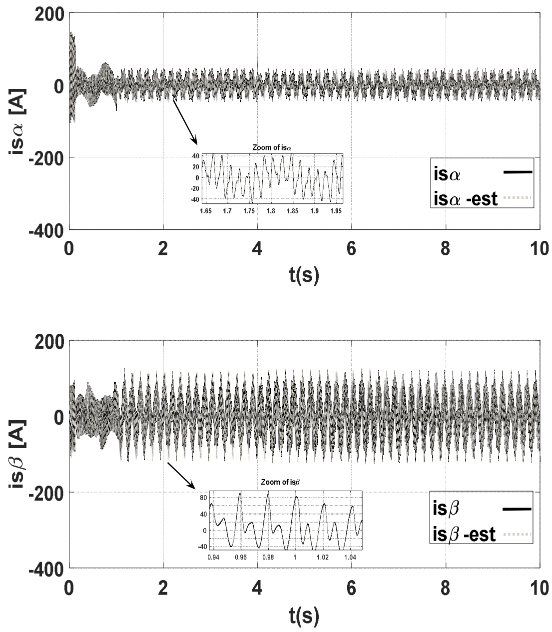

Fig. 13 Stator phase current and its zoom of faulty DFIG with speed wind variation

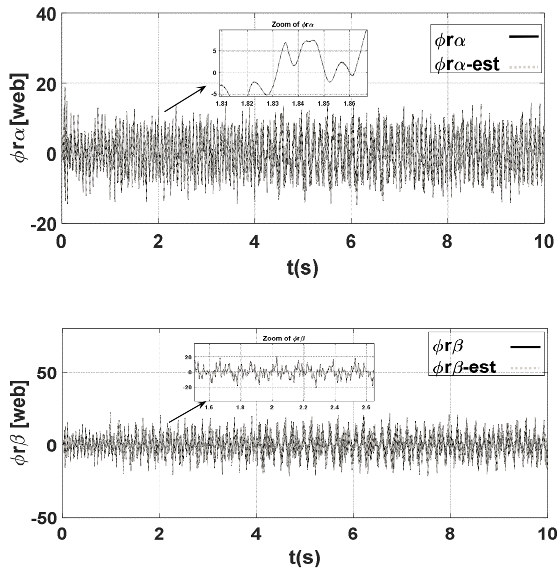

Fig. 14 Reference rotor flux of faulty DFIG.

V. CONCLUSION

In this paper, we presented a new scheme of adaptive observer of Double Fed Induction Generator, based on the estimation of the value of the rotor resistance. The estimation of the rotor resistance is based on the use of the error between real and estimated value of DFIG in faulty condition, this will have to improve the performances of the adaptive observer. The results show that the proposed adaptive observer offers better performances of robustness and stability and precision., even in presence of rotor resistance variation. The formal results are confirmed by simulations.

Future works concern real true implementation of the proposed scheme to validate these theoretical results.

Appendix I. Double Fed Induction Generator Parameters

Electrical	Index	Value
Rated power	P_s	7500W
Stator resistance	R_s	0.455 Ω
Rotor resistance	R_r	0.62 Ω
Stator leakage inductance	L_s	0.0083 H
Rotor leakage inductance	L_r	0.0081 H
Magnetizing inductance	L_m	0.0078 H
Number of pole pairs	P	2
Inertia	J	0.31125 kg. m^2
Viscous friction	f_v	0.00673 kg.m^2.s^{-1}

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