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Sensorless Speed and Reactive Power Control of a Double-Feed Induction Generator using Adaptive Observer in Wind Turbine Power Plant

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Abstract: This work presents a new method for the synthesis of a sensorless speed and reactive power control applied to a wind turbine system based to a Doubly Fed Induction Generator (DFIG). The proposed method based on adaptive observers: The rotor speed is adapted using adaptation mechanisms. Stability analysis based on Lyapunov theory is used to guarantee the stability of the observer. To verify the consistency of the proposed approach. We will be interested in the study of vector control based on the synthesis of classical controllers.
Simulation results provided with the MATLAB/SIMULINK environment show the consistency of the proposed approaches.

Keywords: Sensorless, Vector Control, Wind Turbine, Doubly Fed Induction Generator, Adaptive Observer,

1. INTRODUCTION

Wind turbines are generally located in mountainous areas with harsh environmental conditions. The electrical energy producing from wind turbine is an economic and own alternative relatively to various exhaustible energy sources [1]. In this context, this paper deals with the problem of the wind turbine speed control. The considered generator is a doubly fed induction (DFIG). To improve the reliability of these systems, it is necessary to detect and characterize the defects early in order to anticipate the final shutdown of the system. Several studies have shown the value of using stator currents to monitor asynchronous generators and associated wind turbines. In variable speed or transient turbines, conventional Fourier transform tools do not allow local non-stationary behaviors to be demonstrated. There exist various publications describing advancement in the theory and practice of state observers and its applications in various fields of electrical engineering.
The validation by simulation of proposed methods based on observers states spaces such as adaptive observer with the application of the spectral analysis technique of the stator current and the module of the park's vector for the DFIG. [14].
In the proposed method of rotor speed estimation through adjusting the error between the reference and adjustable models by algorithm of control, the estimated rotor speed can be obtained. For controlled DFIG, the parametric variation modifies the performances of the control system when we use a control law with fixed parameters [8, 3]. This can be realized by analyzing the performances that will be degraded to high speed of wind turbine. To offer control robustness, This problem can be remedied by replacing the switching function by a smooth continuous function [23]. The sensorless control method is implemented by MATLAB/SIMULINK and several steady and dynamic experimental results are given. We conclude this work with a conclusion about the work carried out and a presentation of the research perspectives.

2. DESCRIPTION MODEL OF WIND TURBINE DFIG

1.1 Model in a-b-c coordinate reference frame

The DFIG can be modeled as following where the voltage equations of stator and rotor can be expressed using matrix notation by [1, 20, 21]:

$$[V_s] = [R_s][I_s] + \frac{d[\psi_s]}{dt} \tag{1}$$

$$[V_r] = [R_r][I_r] + \frac{d[\psi_r]}{dt} \tag{2}$$

$$[\phi_s] = [L_{ss}][I_s] + [M_{sr}][I_r] \tag{3}$$

$$[\phi_r] = [L_{rr}][I_r] + [M_{rs}][I_s] \tag{4}$$

With
$$[L_{ss}] = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \quad [L_{rr}] = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \tag{5}$$

From equations (1) and (2), the dynamic model developed of the DFIG under the stationary (α,β) reference is obtained as follows: [9, 10, 22]

$$\begin{cases} \dfrac{di_{\alpha s}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + R_r\dfrac{L_m^2}{L_r^2}\right)i_{\alpha s} + \dfrac{1}{\sigma L_s}R_r\dfrac{L_m}{L_r^2}\phi_{\alpha r} + \dfrac{1}{\sigma L_s}\omega\dfrac{L_m}{L_r}\phi_{\beta r} + \dfrac{1}{\sigma L_s}v_{\alpha s} + \dfrac{L_m}{\sigma L_s L_r}v_{\alpha r} \\ \dfrac{di_{\beta s}}{dt} = -\dfrac{1}{\sigma L_s}\left(R_s + R_r\dfrac{L_m^2}{L_r^2}\right)i_{\beta s} - \dfrac{1}{\sigma L_s}\omega\dfrac{L_m}{L_r}\phi_{\alpha r} + \dfrac{1}{\sigma L_s}R_r\dfrac{L_m}{L_r^2}\phi_{\beta r} + \dfrac{1}{\sigma L_s}v_{\beta s} + \dfrac{L_m}{\sigma L_s L_r}v_{\beta r} \\ \dfrac{d\phi_{\alpha r}}{dt} = \dfrac{R_r L_m}{L_r}i_{\alpha s} - \dfrac{R_r}{L_r}\phi_{\alpha r} - \omega\phi_{\beta r} + v_{\alpha r} \\ \dfrac{d\phi_{\beta r}}{dt} = \dfrac{R_r L_m}{L_r}i_{\beta s} - \dfrac{R_r}{L_r}\phi_{\beta r} + \omega\phi_{\alpha r} + v_{\beta r} \end{cases} \tag{6}$$

The electromagnetic torque equation becomes:

$$C_{em} = p\frac{M_{sr}}{L_s}\psi_{ds}I_{qr} \tag{7}$$

3. ADAPTIVE OBSERVER

This observer is defined by the following dynamic model: [13, 15, 17]

$$\begin{cases} \dfrac{d\hat{X}}{dt} = \hat{A}\hat{X} + BU + G\left(Y - \hat{Y}\right) \\ \hat{Y} = C\hat{X} \end{cases} \tag{8}$$

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

$$A=\begin{bmatrix} -\left(\frac{R_s}{\sigma L_s}+\left(\frac{R_r L_m^2}{\sigma L_s L_r^2}\right)\right)I & \frac{L_m}{\sigma L_s L_r}\left(\frac{R_r}{L_r}I-\omega J\right) \\ \left(\frac{L_m R_r}{L_r}\right)I & -\left(\frac{R_r}{L_r}I-\omega J\right) \end{bmatrix},\ \hat{A}=\begin{bmatrix} -\left(\frac{R_s}{\sigma L_s}+\left(\frac{R_r L_m^2}{\sigma L_s L_r^2}\right)\right)I & \frac{L_m}{\sigma L_s L_r}\left(\frac{R_r}{L_r}I-\hat{\omega}J\right) \\ \left(\frac{L_m R_r}{L_r}\right)I & -\left(\frac{R_r}{L_r}I-\hat{\omega}J\right) \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{\sigma L_s}I & \frac{L_m}{\sigma L_s L_r}I \\ 0_{2x2} & I \end{bmatrix},\ C=\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix},\ J=\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},\ I=\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

And $G \in R^{nxp}$, Observer gain matrix.

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

All the electromechanical parameters of the machine are assumed to be constant and known. Both the drive speed is to be estimated the parameters.

We define the differences: $\delta\omega=\omega-\hat{\omega}$ (9)

The symbol $\wedge$ denotes the estimated value and G the observer gain matrix.

The observation error is: [4, 11, 18] $e=X-\hat{X}$ (10)

The state matrix of the observer can be written: $\hat{A}=A+\delta A$ (11)

With:
$$\delta A=\begin{pmatrix} 0 & 0 & 0 & +\frac{L_m}{b}\delta\omega \\ 0 & 0 & -\frac{L_m}{b}\delta\omega & 0 \\ 0 & 0 & 0 & -\delta\omega \\ 0 & 0 & +\delta\omega & 0 \end{pmatrix} \tag{12}$$

And
$$\frac{de}{dt}=(A-GC)e-\delta A\hat{X}$$
(13)

We define the function of Lyapunov: [2 , 7, 12, 16]

$$V=e^T e+\frac{(\delta\omega)^2}{\lambda} \tag{14}$$

λ is positive reality.

The function V must contain the differences and in order to establish the mechanisms of adaptation. The stability of the observer is guaranteed for the condition:

$$\frac{dV}{dt}<0 \tag{15}$$

The derivative of the Lyapunov function V is:

$$\frac{dV}{dt}=2e^T\frac{de}{dt}+2\frac{\delta\omega}{\lambda}\frac{d\delta\omega}{dt} \tag{16}$$

The first term of (16) becomes:

$$2e^T \frac{de}{dt} = 2e^T (A - GC)e - 2e^T \delta A \hat{X} \tag{17}$$

The components of the rotor flux are not measurable. The dynamics of these flows is very fast compared to that of the speed.

Thus, to simplify equation (17), we assume that:

$$\begin{cases} \hat{\Phi}_{\alpha r} = \Phi_{\alpha r} \\ \hat{\Phi}_{\beta r} = \Phi_{\beta r} \end{cases} \tag{18}$$

We can verify that:

$$e^T \delta A \hat{X} = \frac{L_m}{b} \delta\omega \left(\hat{\Phi}_{\beta s}\, e_{i\alpha s} - \hat{\Phi}_{\alpha r}\, e_{i\beta s} \right) \tag{19}$$

For the second and third terms of (16) we can write:

$$2\frac{\delta\omega}{\lambda_1}\frac{d\delta\omega}{dt} = 2\frac{\delta\omega}{\lambda_1}\frac{d}{dt}\hat{\omega} - 2\frac{\delta\omega}{\lambda_1}\frac{d}{dt}\omega \tag{20}$$

The drive speed vary slowly with respect to the electrical variables.

Therefore, we can write:

$$\frac{d\omega}{dt} \approx 0 \tag{21}$$

Which give:

$$\frac{d\hat{\omega}}{dt} = -\frac{d\delta\omega}{dt} \tag{22}$$

Finally, we obtain:

$$\frac{dV}{dt} = 2e^T (A - GC)e - \frac{2L_m}{b} \delta\omega \left(\hat{\Phi}_{\beta s}\, e_{i\alpha s} - \hat{\Phi}_{\alpha r}\, e_{i\beta s} \right) + 2\frac{\delta\omega}{\lambda_1}\frac{d}{dt}\hat{\omega} \tag{23}$$

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

$$-\frac{2L_m}{b} \delta\omega \left(\hat{\Phi}_{\beta s}\, e_{i\alpha s} - \hat{\Phi}_{\alpha r}\, e_{i\beta s} \right) + 2\frac{\delta\omega}{\lambda_1}\frac{d}{dt}\hat{\omega} = 0 \tag{24}$$

This condition is verified if:

$$2\frac{\delta\omega}{\lambda_1}\frac{d}{dt}\hat{\omega} = +\frac{2L_m}{b} \delta\omega \left(\hat{\Phi}_{\beta s}\, e_{i\alpha s} - \hat{\Phi}_{\alpha r}\, e_{i\beta s} \right) \tag{25}$$

We obtain the mechanisms of adaptation allowing reconstructing the mechanical pulsation and the rotor resistance. [6, 19]

$$\hat{\omega} = \int_0^t \lambda_1 \left[\frac{L_m}{b} \left(\hat{\Phi}_{\beta s}\, e_{i\alpha s} - \hat{\Phi}_{\alpha r}\, e_{i\beta s} \right) \right] dt \tag{26}$$

The observed electromagnetic torque is expressed by:

$$\hat{C}_e = \frac{3}{2} p \frac{L_m}{L_r} \left(\hat{\Phi}_{\alpha r}\, \hat{i}_{\beta s} - \hat{\Phi}_{\beta r}\, \hat{i}_{\alpha s} \right) \tag{27}$$

3.1. The healthy operation

To illustrate the performance of the proposed control, we will study several modes of operation. The first mode corresponds to the healthy operation. Then, we will study the impact of the following perturbations: High speed and variation of the rotor resistance.

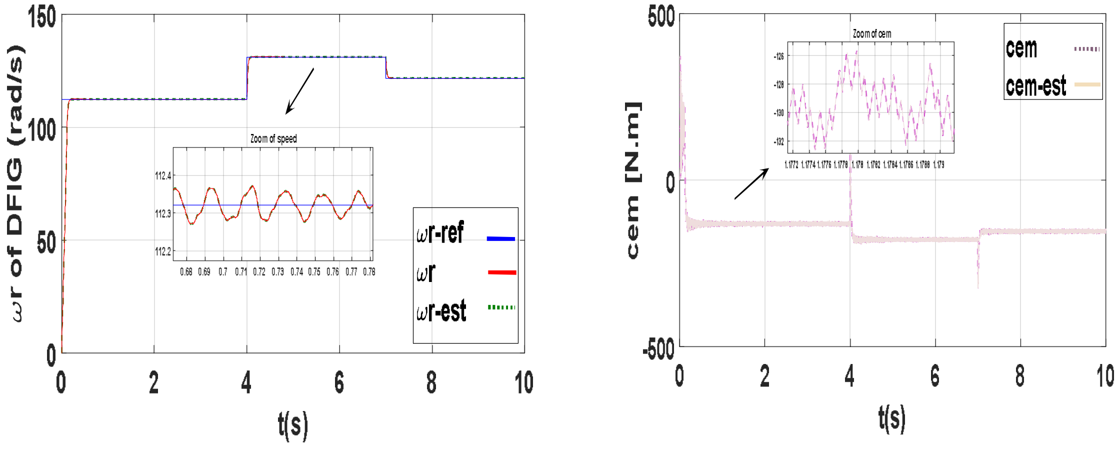

Fig 1. Rotation speed and electromagnetic torque of the DFIG

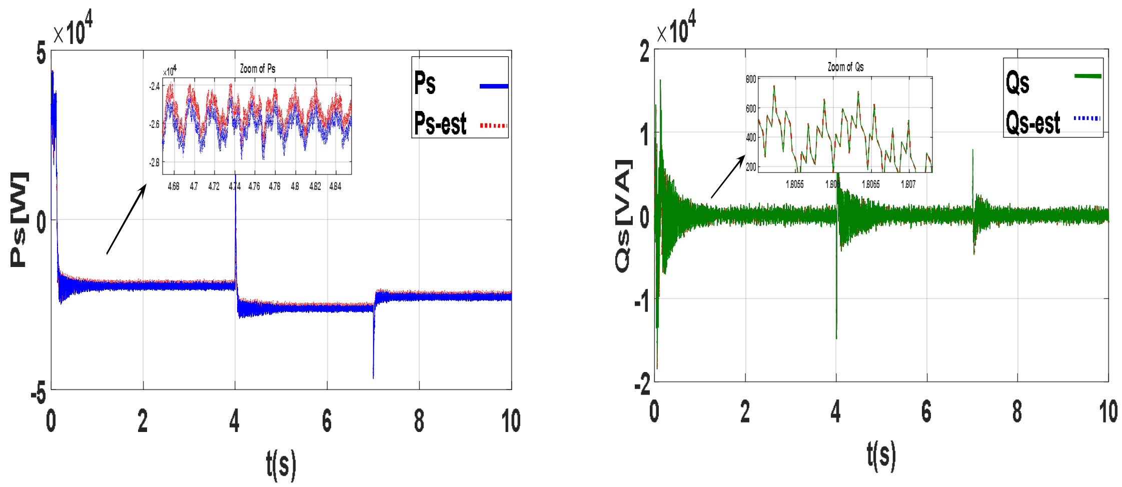

Fig 2. Stator active power and reactive power with variation of wind speed

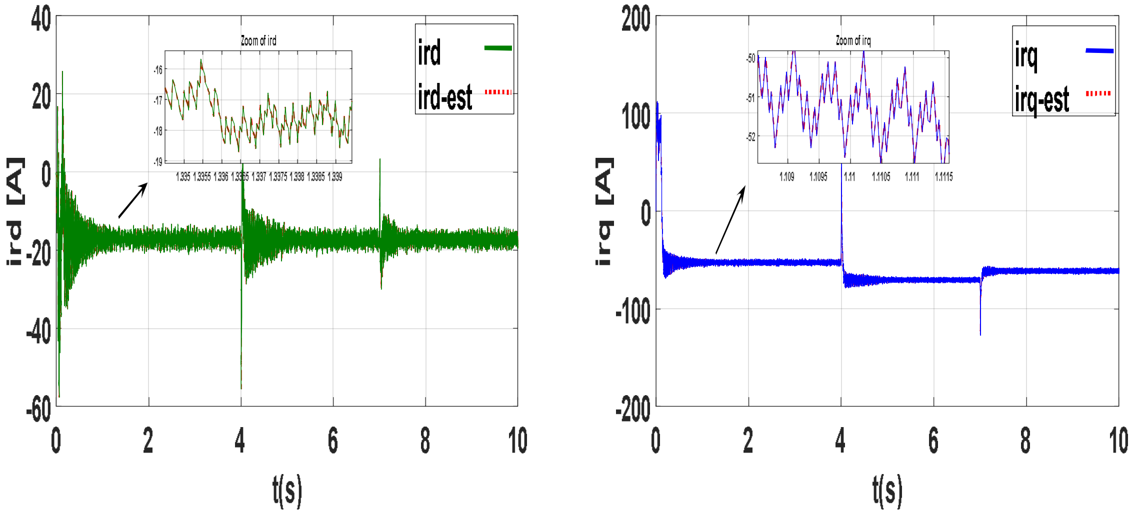

Fig 3. Park's rotor currents, with variation of wind speed (i_{rd} , i_{rq})

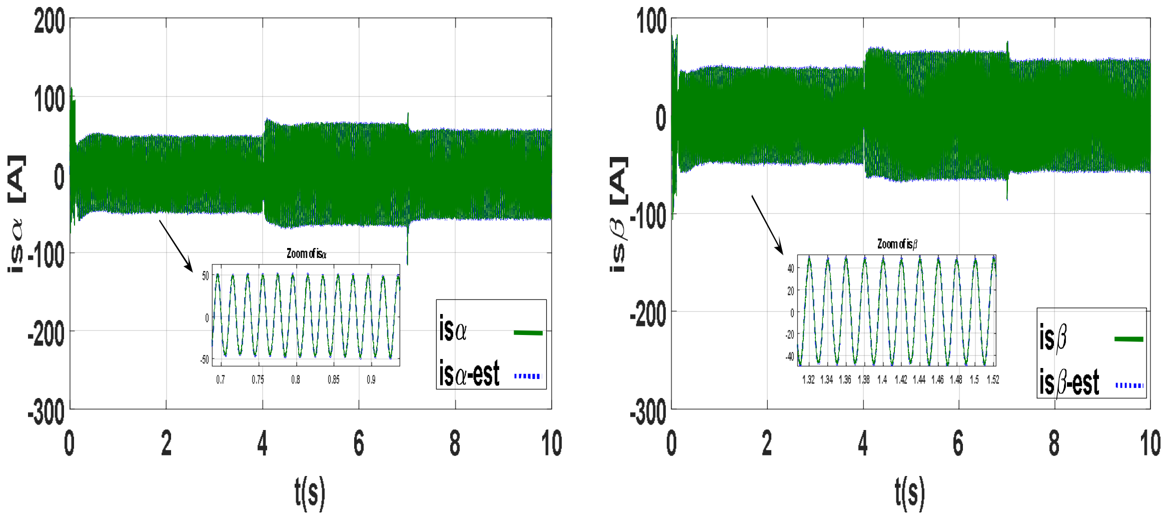

Fig 4. Stator currents, with variation of wind speed ($I_{s\alpha}$, $I_{s\beta}$)

3.2. Operation with high speed

We shall now present the simulation results for a DFIG operation with high speed using a model in the three-phase system. Knowing the variation of the wind speed with the time of its applications, presented by following tables: [5].

Table 1. Variation of wind speed

t (s)	0	2	6
V(m/s)	12	17	16
Q_{sref} (var)	0	0	0

The curves of the rotational speed of the DFIG, the stator active and reactive power, the current of the stator phase "a", the current of the rotor phase of the variation of short circuit are shown in the figures (5 to 8) with stator high speed.

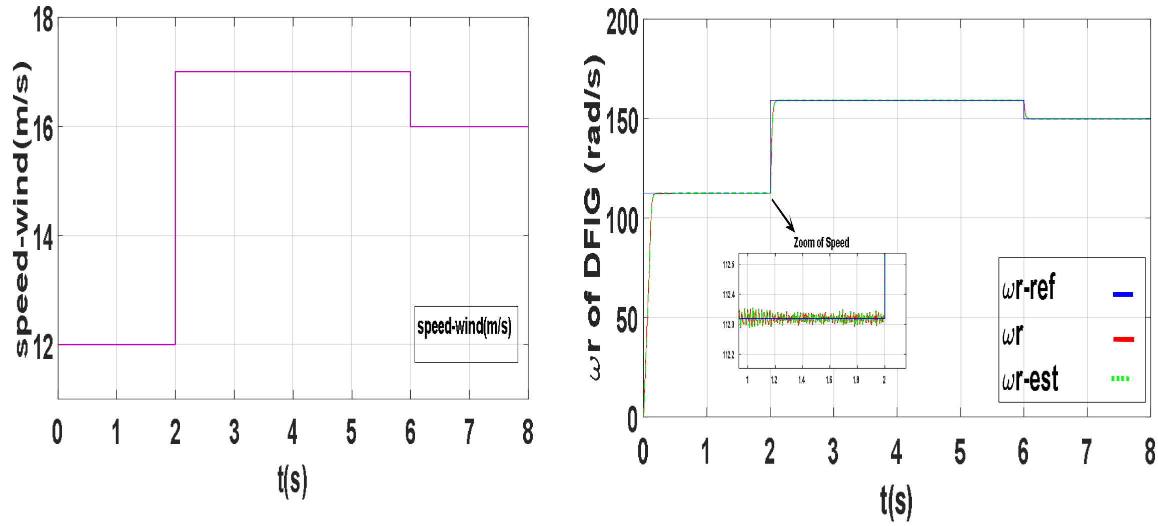

Fig 5. Variation of wind speed and rotation speed of the DFIG

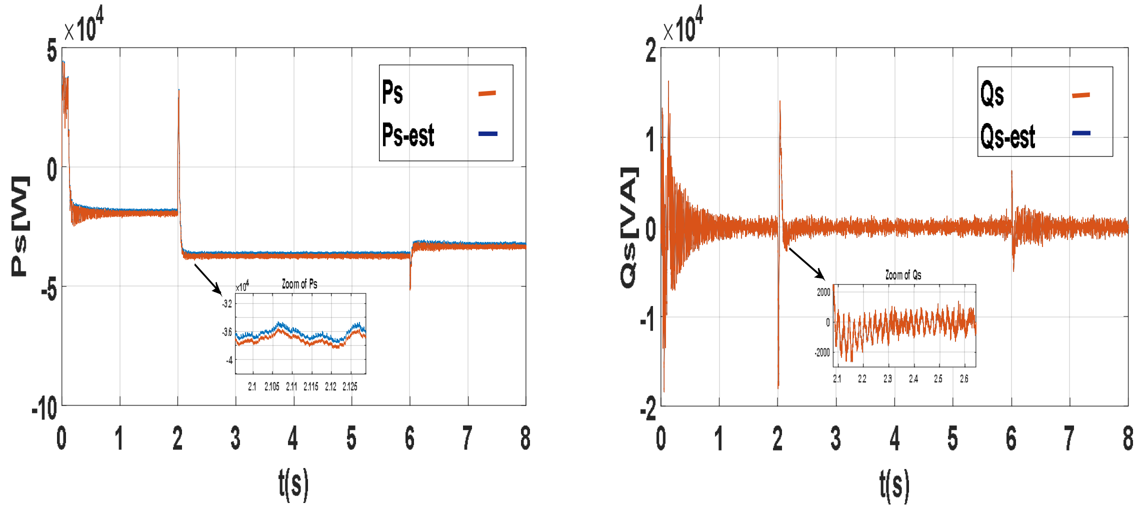

Fig 6. Active and reactive stator power

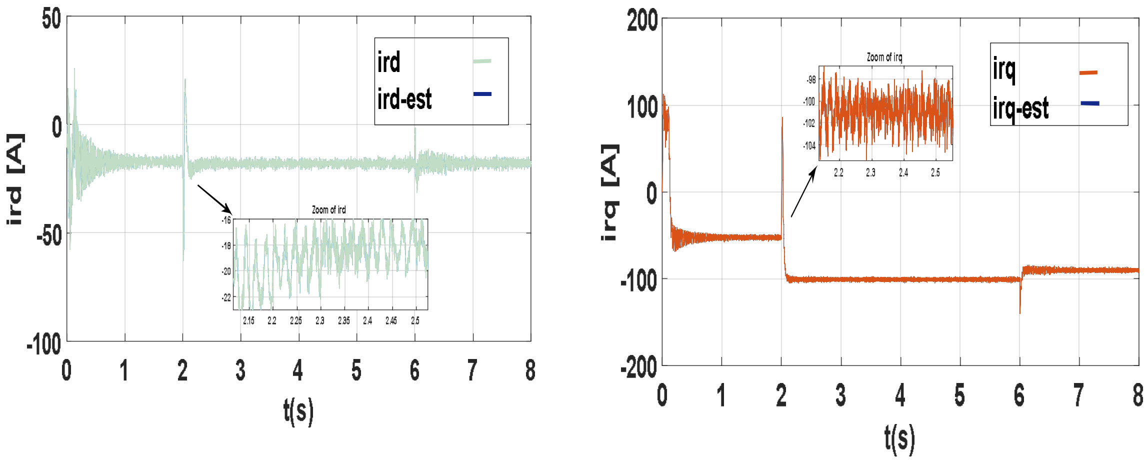

Fig 7. Park's rotor currents (i_{rd} , i_{rq})

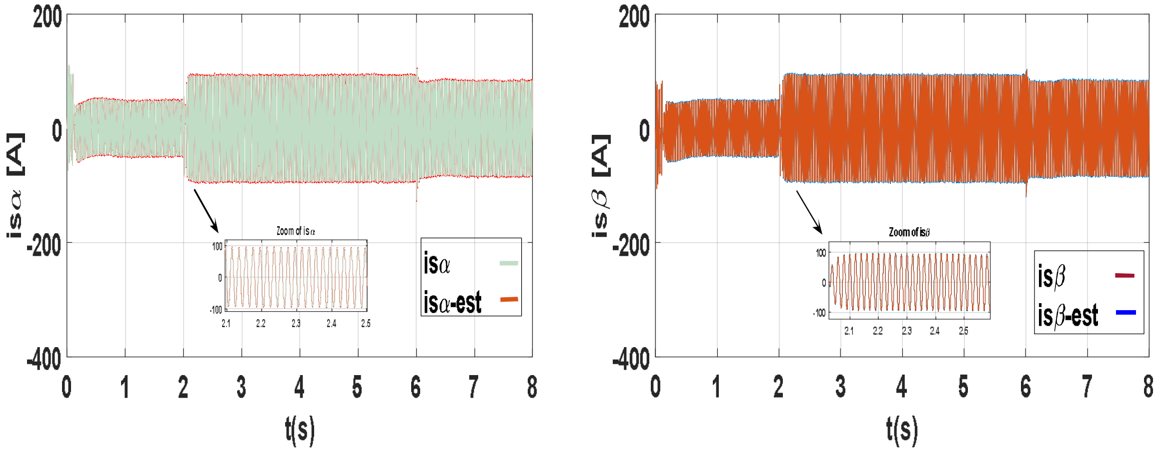

Fig 8. Stator Current ($I_{s\alpha}$, $I_{s\beta}$)

The schema of the device studied is given in the Fig.9. The generator is directly connected to the grid on the stator side, and the rotor circuit is supplied by a supposedly constant DC voltage source through an inverter controlled by the MLI technique.

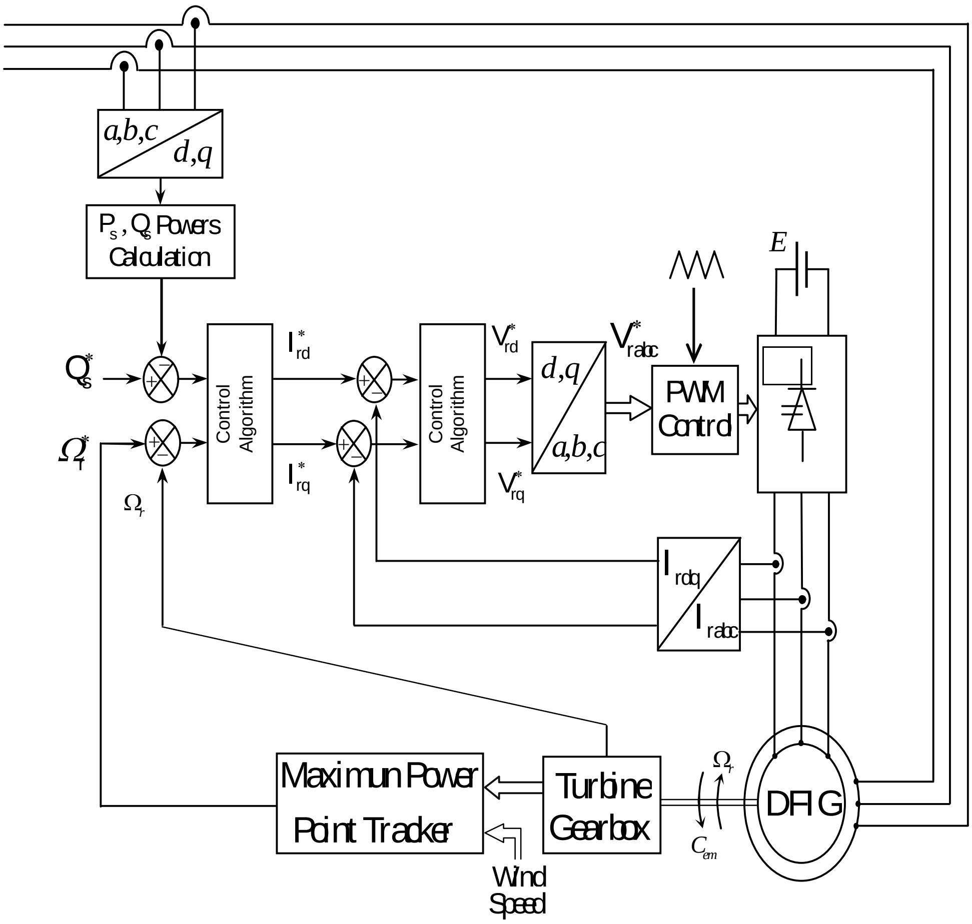

Fig.9 Block diagram of speed and reactive power controls of DFIG

The block diagram of Adaptive Observer is shown in figure (10).

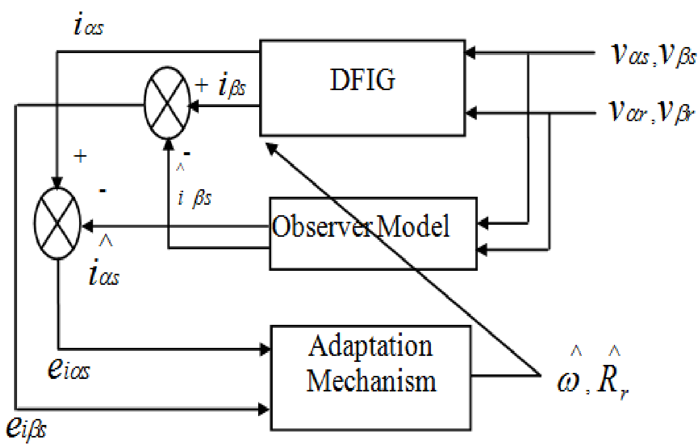

Fig. 10. Global Adaptive Observer

3.3 Interpretation of results

The present rotational speed of the ripple relative to the healthy operation is noted. The active and reactive stator power and the direct and quadrature rotor currents and the stator phase current have oscillations of higher amplitudes than those corresponding to the healthy operation. Consequently, the results with adaptive observer are good performances of robustness and precision of operation in degradation against high speed.

4. Spectral analysis in the DFIG

we present the technique of three-phase stator current spectral analysis, of the Park vector module for detection of the DFIG. The simulations are made for a supposedly constant wind speed equal to 12 m/s and the reference reactive power 0var. the calculation is performed under the MATLAB/Simulink environment with a calculation step of 0.03ms.

4.1 Spectral analysis of the current of the stator phase "a"

(Fig.11), We notice that the spectrum of the three-phase stator current appear harmonics (close to the fundamental) which corresponds to the supply frequency *fs = 50Hz*.

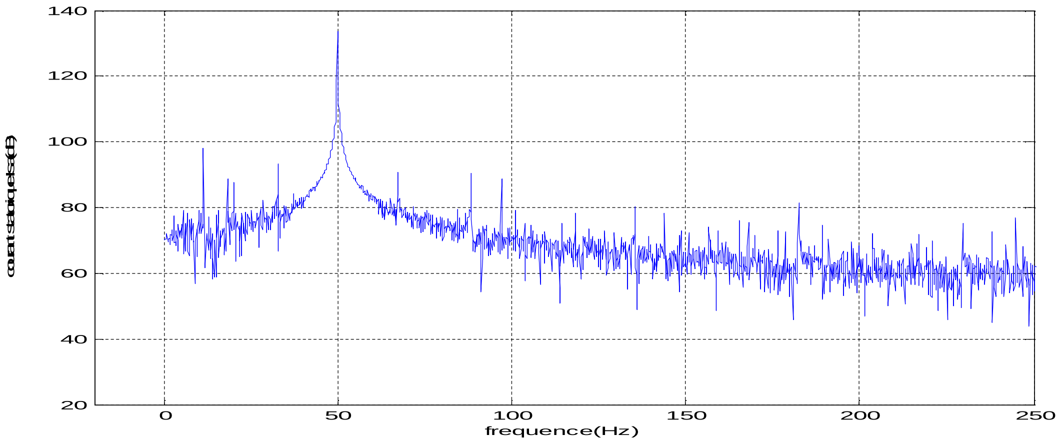

Fig 11. Three - phase stator current spectrum

4.2 Spectrum of the park's current vector module

The spectrum of the amplitude magnitude module of the park's current vector for the healthy state of the DFIG illustrated in Fig (12), which additionally contains the DC component of the additional harmonics generated by the rotor feed. [5]

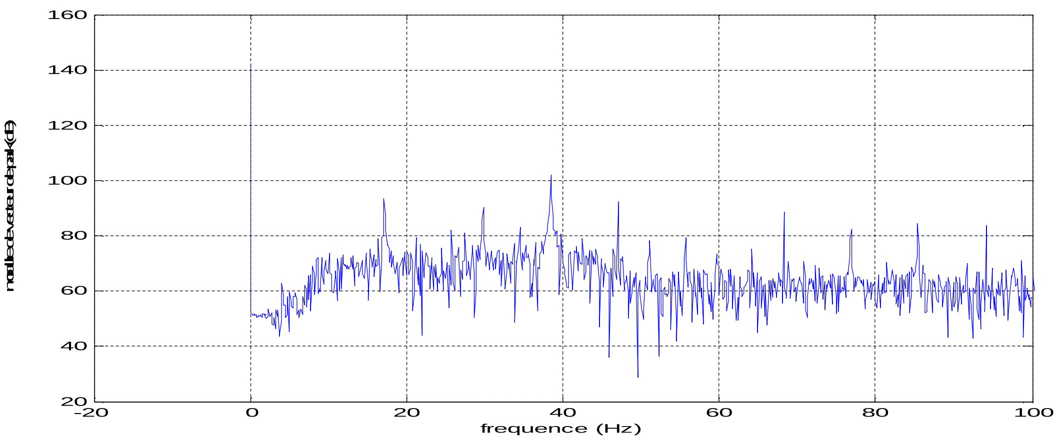

Fig. 12. Spectrum of the park's current vector module

5. Conclusion

We presents a sensorless MPPT control for wind turbine equipped with a DFIG. We developed novels Algorithms of Adaptive Observers for speed estimation in a sensorless controlled doubly fed induction generator (DFIG) based Wind Turbine with a high speed applied as a wind turbine generator, the DFIG is tested and simulated with a rotor speed of 1440 rpm and a high speed of 1600 rpm applied as a wind turbine generator, the stator and rotor currents are shown. The DFIG in variables speed can be estimated in different working modes. It appears that the high speed applied as a wind turbine generator doesn't allocate the performances of the proposed control. The power active and reactive tracks the reference value. It's the same for the speed response. Consequently, the global control scheme introduces high performances of robustness, stability and precision, particularly, under reference speed variation. The technique presented in the previous sections The obtained algorithms of the speed have the advantage to be easily implantable in a calculator. The formal results are confirmed by simulations in the MATLAB /simulink.. However, this work, which is not exhaustive of course, could give rise to further studies in the following:

- Experimental validation of the proposed control.
- Fault tolerant control of the Wind Turbine.

Appendix A. DFIG and Wind Turbine Parameters

Wind Turbine Parameters
Rated power: Ps=7500W
Moment of the inertia: J = 0.31125 kg.m^2
Wind turbine radius: R = 3m
Gear box ratio: G = 5.4
Air density: ρ= 1.25 kg/m^3
DFIG Parameters
Rated power: 7500W
Mutual inductance: Lm = 0.0078 H
Stator leakage inductance: Ls = 0.0083 H
Rotor leakage inductance: Lr= 0.0081 H
Stator resistance: Rs = 0.455 Ω
Rotor resistance: Rr = 0.62 Ω
Number of pole pairs: P = 2
Moment of the inertia: J = 0.31125 kg. m^2
Viscous friction: f_v $\tilde{}$.00673 kg.m^2.s^{-1}

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