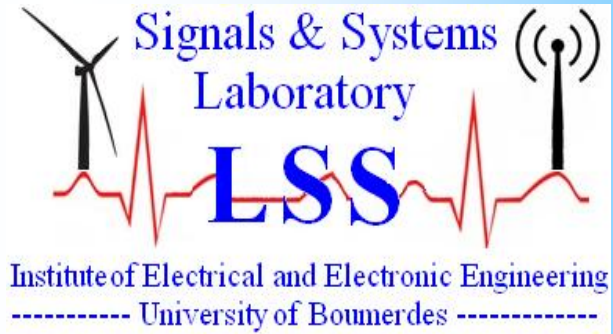


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Fault Diagnostic of Doubly-Fed Induction Generator in Stator Inter-Turn Short Circuit Based Wind Turbine

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Abstract: This paper describes a Fault Tolerant Control (FTC) of a doubly-fed induction generator (DFIG) based wind turbine model suitable for the simulation of this generator in the mode faulty mode. The dynamic model of a DFIG with stator inter-turn short circuit fault is proposed. A model (abc) is developed, which can represent both the healthy and faulty conditions. The DFIG is directly connected to the grid whereas the rotor winding is fed by back-to-back PWM converters. The Control schemes for active and reactive power regulation are designed firstly. Under different wind speed, maximum power point tracing (MPPT) control is implemented to ensure the optimum active power output. The numerical simulation developed in Matlab/Simulink studies the effects of stator inter-turn short-circuit in the DFIG. Afterward, the application of Approach technique of Adaptive Observer is used to detect this type of fault. Simulation results for this faults are shown and elucidated.

Keywords: Wind Energy, DFIG, short circuit, vector control, inter-turn short-circuit, fault diagnostic.

I. INTRODUCTION

Wind generation is one type of renewable energy resource that has been the focus of renewable energy profile in states with strong wind resources [2-3]. Practically, the doubly fed induction generators (DFIG) have become the most widely used machines in wind power generation, which have many advantages over the other generators, such as variable speed constant frequency (VSCF) operation, low mechanical stresses, and high system efficiency (Holdsworth 2003). It is reported that over 38% DFIG failures are related to stator winding faults (Amirat 2009), among which inter-turn short circuit faults are most common ones [10]. These incipient faults may produce excessive heat that will eventually lead to severe phase to phase fault or even phase to ground fault. Therefore it is significant to detect the inter-turn short circuit fault in early stage. [4-7-8]

This paper deals with the modelling and control of DFIG based wind conversion system. We use the stator flux-oriented vector control algorithm to control the speed and the reactive power, under different wind speed, maximum power point tracing (MPPT) control is implemented to ensure the optimum active power output. This study is made for the healthy and stator and rotor inter-turn short circuit fault operation of the DFIG. Afterward, the application of current signatures analysis and Park's vector Approach techniques are used to detect this type of fault.

This work organized as follows: firstly we describes modelling of the DFIG with and without stator inter-turn fault. Then the control strategy and the simulation results. Finally, we presented the detect fault by current signatures analysis

The schema of the device studied is given in the Fig.1.

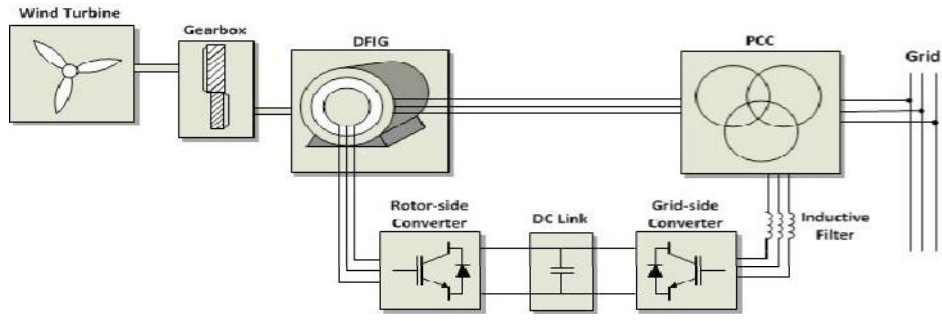
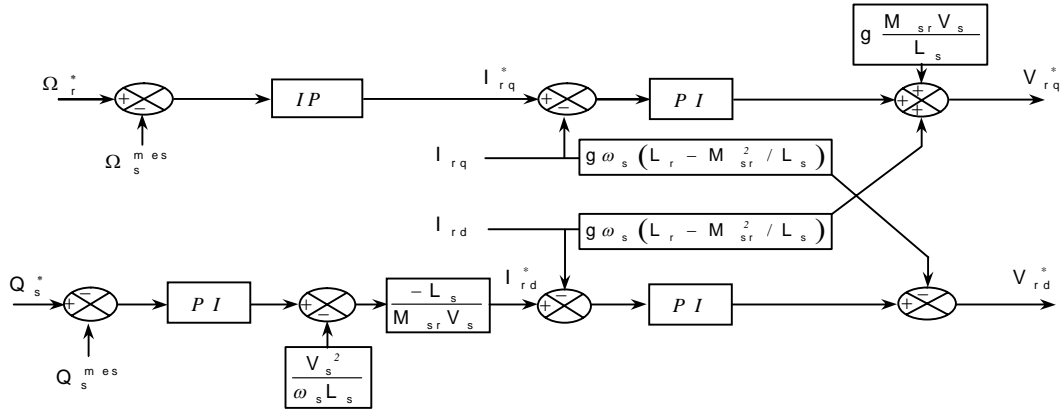


Fig. 1 Configuration of a DFIG wind turbine system.



II. DFIG MODELING

A. Model in a-b-c coordinate reference frame

The DFIG can be modelled as follows where the voltage equations of stator and rotor can be expressed using matrix notation by [10-16-17]:

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

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

Where: the vector of voltages, currents and flux of stator and rotor windings are respectively.

$$[V_s] = [V_{sa} \ V_{sb} \ V_{sc}]^t, [V_r] = [V_{ra} \ V_{rb} \ V_{rc}]^t$$

$$[I_s] = [I_{sa} \ I_{sb} \ I_{sc}]^t, [I_r] = [I_{ra} \ I_{rb} \ I_{rc}]^t$$

$$[\psi_s] = [\psi_{sa} \ \psi_{sb} \ \psi_{sc}]^t, [\psi_r] = [\psi_{ra} \ \psi_{rb} \ \psi_{rc}]^t$$

The stator and rotor resistances matrices are given by

$$[R_s] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix}, [R_r] = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}$$

Where: R_s and R_r resistance of stator and rotor windings. The instantaneous stator and rotor flux per phase are given by: [6-7]

$$[\psi_s] = [L_{ss}][I_s] + [M_{sr}][I_r] \quad (3)$$

$$[\psi_r] = [L_{rr}][I_r] + [M_{rs}][I_s] \quad (4)$$

Where:

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

The mutual inductances matrix can be written:

$$[M_{sr}] = M_s \begin{bmatrix} \cos(\theta_r) & \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) \end{bmatrix} \quad (6)$$

Where : M_{sr} : stator/rotor mutual inductances

L_r, L_s : rotor and stator winding inductances.

Replace the relations (3) and (4) respectively in equations (1) and (2); we obtain the following two expressions:

$$\begin{cases} V_s = [R_s][I_s] + [L_{ss}]\frac{d}{dt}[I_s] + \frac{d}{dt}[M_{sr}][I_r] \\ V_r = [R_r][I_r] + [L_{rr}]\frac{d}{dt}[I_r] + \frac{d}{dt}[M_{sr}]^T[I_s] \end{cases} \quad (7)$$

The electromagnetic torque is given by the following general expression [3]:

$$C_{em} = p [I_s] \frac{d[M_{sr}][I_r]}{dt} \quad (8)$$

B. Modelling of DFIG with stator inter-turn fault

The rotor winding configuration of a DFIG with an interturn short circuit fault in phase 'a' is shown in Fig. 1. A transient model for this fault scenario has been proposed in (Tallam, 2002), in which the fault level is represented by a model parameter γ . In this paper, in order to characterize the faulted phase, another model parameter f_x is introduced to describe the fault position. The DFIG model in abc is proposed.

A DFIG model in a-b-c coordinate reference frame is derived to describe the inter-turn short circuit fault at any level in any single phase of rotor. In this model, the fault position parameter f_x is defined as below for three cases that fault occurs in phase 'a', 'b' and 'c', respectively.

$$f_a = [1 \ 0 \ 0]^t, f_b = [0 \ 1 \ 0]^t, f_c = [0 \ 0 \ 1]^t$$

The fault level parameter γ denotes the fraction of the shorted winding. For modelling this defect, we assume that a number of turns « γ » from among those « a » is short-circuited. This section of turns short circuit is defined by coefficient « γ » between the number of turns short-circuited and the total number of turns of the phase « a », this coefficient is introduced in the mathematical model governing the operation of the machine. The modeling of the DFIG with fault is to introduce resistance « R_f » in parallel with the turns short circuit in phase infected (Fig.2). A voltage will be induced in mesh short-circuit, the voltage induced circulating current in the shorted turns called fault current, This latter has a proportional relationship with the fault resistance and induced voltage. [5-9].

Therefore the inductance and resistance of the faulty phase change and the mutual inductance between this phase and all other windings of the machine will be changed. The new form of the equations of stator voltages is then rewritten as follows:

$$[V_s] = [R_s][I_s] + \frac{d[\psi_s]}{dt} \quad (9)$$

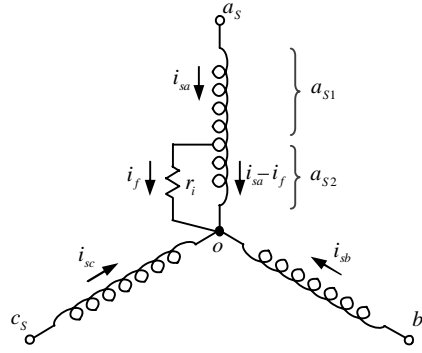


Fig. 2 Stator winding configuration with the inter-turn short circuit fault in phase 'a'.

The stator resistance matrix can be rewritten as follows:

$$[R_s] = \begin{bmatrix} (1-\gamma)R_s & 0 & 0 & \gamma \cdot R_s \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ 0 & 0 & 0 & \gamma \cdot R_s \end{bmatrix} \quad (10)$$

However, we keep the matrix of stator voltages unchanged. If we mean by « γ » fraction of the number of shorted turns of phase « a », then we have a healthy portion of a fraction $1-\gamma$ of turns and we suppose the phases "b" and "c" healthy. We will have the new inductance stator matrix following: [11]

$$[L_{ss}] = L_{fs} \text{diag} [(1-\gamma) \ 1 \ 1 \ \gamma] + M_s \begin{bmatrix} (1-\gamma)^2 & -\frac{(1-\gamma)}{2} & -\frac{(1-\gamma)}{2} & \gamma(1-\gamma) \\ -\frac{(1-\gamma)}{2} & 1 & -\frac{1}{2} & -\frac{\gamma}{2} \\ -\frac{(1-\gamma)}{2} & -\frac{1}{2} & 1 & -\frac{\gamma}{2} \\ \gamma(1-\gamma) & -\frac{\gamma}{2} & -\frac{\gamma}{2} & \gamma^2 \end{bmatrix} \quad (11)$$

Therefore, the matrix of mutual inductances is:

$$[M_{sr}] = M_s \begin{bmatrix} (1-\gamma)\cos(\theta_r) & (1-\gamma)\cos\left(\theta_r + \frac{2\pi}{3}\right) & (1-\gamma)\cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos(\theta_r) \\ \gamma\cos(\theta_r) & \gamma\cos\left(\theta_r + \frac{2\pi}{3}\right) & \gamma\cos\left(\theta_r - \frac{2\pi}{3}\right) \end{bmatrix} \quad (12)$$

Rotor inductance matrix remains equal to that of the healthy cases.

III. VECTOR CONTROL OF DFIG

In order to establish a vector control of DFIG, we recall here its modelling in the Park frame. The equations of the stator voltages and rotor of the DFIG are defined by: (1) and (2)

$$\begin{cases} V_{ds} = R_s i_{ds} + d\psi_{ds} / dt - \omega_s \psi_{qs} \\ V_{qs} = R_s i_{qs} + d\psi_{qs} / dt - \omega_s \psi_{ds} \\ V_{dr} = R_r i_{dr} + d\psi_{dr} / dt - \omega_r \psi_{qr} \\ V_{qr} = R_r i_{qr} + d\psi_{qr} / dt - \omega_r \psi_{dr} \end{cases} \quad (17)$$

The equations of stator and rotor flux are given as follows:

$$\begin{cases} \psi_{ds} = L_s i_{ds} + M_{sr} i_{dr} \\ \psi_{qs} = L_s i_{qs} + M_{sr} i_{qr} \\ \psi_{dr} = L_r i_{dr} + M_{rs} i_{ds} \\ \psi_{qr} = L_r i_{qr} + M_{rs} i_{qs} \end{cases} \quad (18)$$

The electromagnetic torque can be expressed by:

$$C_{em} = p \frac{M_{sr}}{L_r} (\psi_{ds} I_{qr} - \psi_{qs} I_{dr}) \quad (19)$$

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 [3-10].

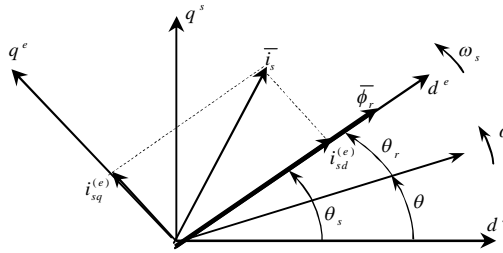


Fig. 3 Stator voltage and flux vectors in the axis

The electromagnetic torque equation becomes:

$$C_{em} = p \frac{M_{sr}}{L_s} \psi_{ds} I_{qr} \quad (20)$$

Assuming the grid is connected to the DFIG is stable, the flux ψ_{ds} becomes constant. The choice of this reference makes the electromagnetic torque and the active power produced by the machine. Dependent only of 'q' axis rotor current components [6-7-14].

In the same reference, the tensions can obtain by equations:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s \psi_{ds} = \omega_s \psi_s \end{cases} \quad (21)$$

Using the previous simplifications, the stator flux equations can be written by:

$$\begin{cases} \psi_s = L_s I_{ds} + M_{sr} I_{dr} \\ 0 = L_s I_{qs} + M_{sr} I_{qr} \end{cases} \quad (22)$$

The equations linking the stator currents to the rotor currents are deduced below:

$$\begin{cases} I_{ds} = \frac{\psi_s}{L_s} - \frac{M_{sr}}{L_s} I_{dr} \\ I_{qr} = -\frac{M_{sr}}{L_s} I_{qs} \end{cases} \quad (23)$$

In park reference, the stator active and reactive power of an induction machine are expressed as:

$$\begin{cases} P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \\ Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} \end{cases} \quad (24)$$

By replace the equation (22) and (23) in (24), the active and reactive powers can be written as a function of rotor currents as follows:

$$\begin{cases} P_s = -V_s \frac{M_{sr}}{L_s} I_{qr} \\ Q_s = \frac{V_s \psi_s}{L_s} - \frac{V_s M_{sr}}{L_s} I_{dr} \end{cases} \quad (25)$$

The rotor voltages can be written as a function of rotor currents as follows:

$$\begin{cases} V_{dr} = R_r I_{dr} + \left(L_r - \frac{M_{sr}^2}{L_s} \right) \frac{d}{dt} I_{dr} - g \omega_s \left(L_r - \frac{M_{sr}^2}{L_s} \right) I_{qr} \\ V_{qr} = R_r I_{qr} + \left(L_r - \frac{M_{sr}^2}{L_s} \right) \frac{d}{dt} I_{qr} + g \omega_s \left(L_r - \frac{M_{sr}^2}{L_s} \right) I_{dr} + g \omega_s \frac{M_{sr} V_s}{\omega_s L_s} \end{cases} \quad (26)$$

After applying the Laplace transformation to the equations (25) and (26) gives [4-9]:

$$\begin{cases} V_{dr} = \left[R_r + \left(L_r - \frac{M_{sr}^2}{L_s} \right) S \right] I_{dr} - g \omega_s \left(L_r - \frac{M_{sr}^2}{L_s} \right) I_{qr} \\ V_{qr} = \left[R_r + \left(L_r - \frac{M_{sr}^2}{L_s} \right) S \right] I_{qr} + g \omega_s \left(L_r - \frac{M_{sr}^2}{L_s} \right) I_{dr} + g \omega_s \frac{M_{sr} V_s}{\omega_s L_s} \end{cases} \quad (26)$$

The generator is connected directly to the power network side of the stator over the rotor circuit the power network from the stator side, the rotor circuit is powered by a DC source assumed constant through an inverter controlled by the PWM technique. We will adopt conventional controllers (PI) necessary to achieve control of reactive power and adjusting the speed of the DFIG. The control of rotor currents is done by regulators Proportional Integral (PI) controllers. A PI controller is also used for adjusting reactive power controller, as shown in the figure (4).

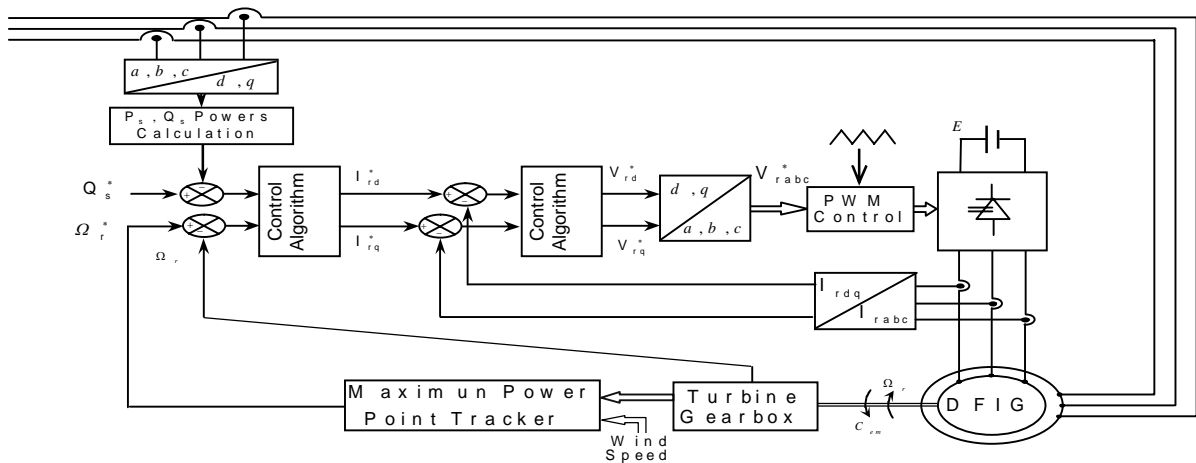


Fig.4 Block diagram of speed and reactive power controls of DFIG

IV. Simulation Results

The simulation behaviour of DFIG that we present in this part will help analyse the outputs variables with stator active and reactive power imposition to maximize the developed for both conditions with and without stator inter-turn short circuit fault applied as a wind turbine generator [9-12]. The complete drive has been simulated using MATLAB/SIMULINK. The DFIG under investigation is a 7.5KW, 230Volt.

VARIATION OF WIND SPEED

| | | | |
|------------|----|----|----|
| t (s) | 0 | 4 | 7 |
| V (m / s) | 12 | 14 | 13 |
| Q_{sref} | 0 | 0 | 0 |

A. Health operation

Several tests have been performed to check the accuracy of the proposed model in the first step, the DFIG is tested and simulated in a healthy operation with a rotor speed of 1440 rpm ,the stator and rotor currents are shown. The amplitude of the stator current (Fig.8) and rotor current (Fig.9) increase with increasing wind speed which causes the increase of the torque applied to the machine and then active power developed as shown in Figure (7)

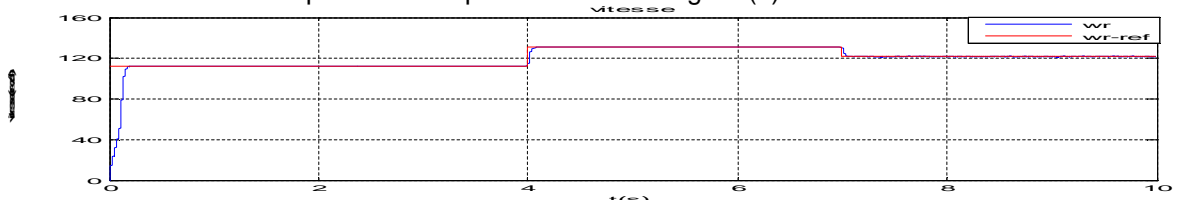


Fig. 6 Speed of healthy DFIG and its reference

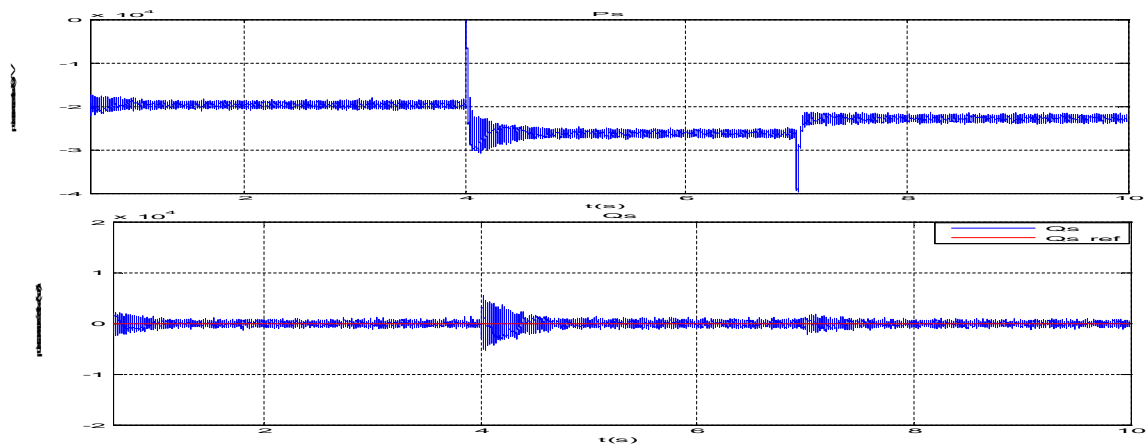
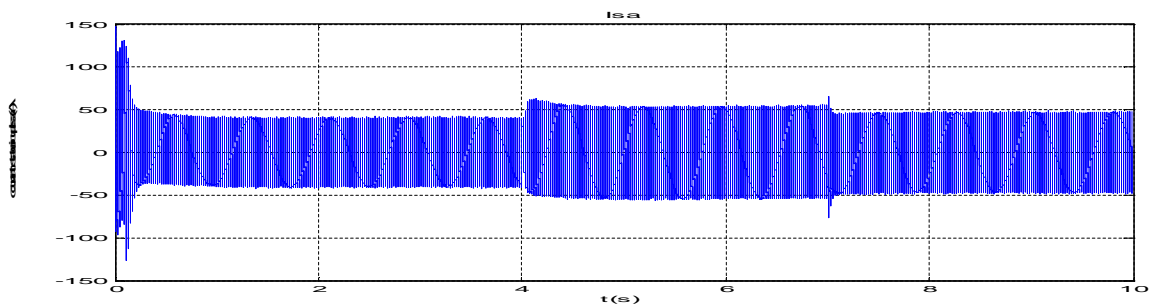


Fig. 7 Stator active and reactive powers of healthy DFIG



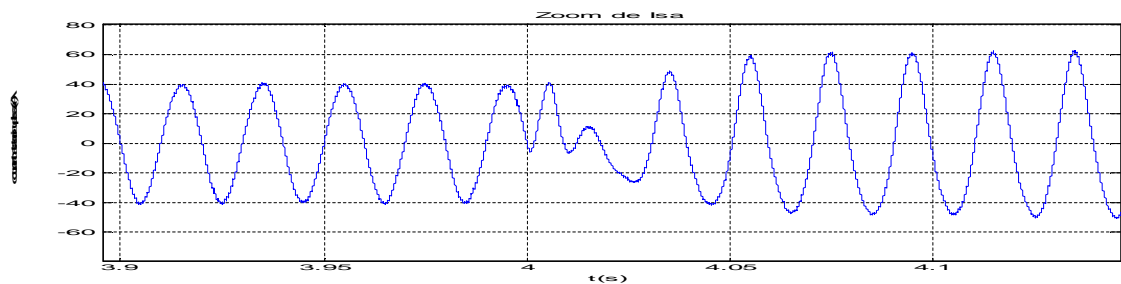


Fig. 8 Stator phase current of healthy DFIG and its zoom

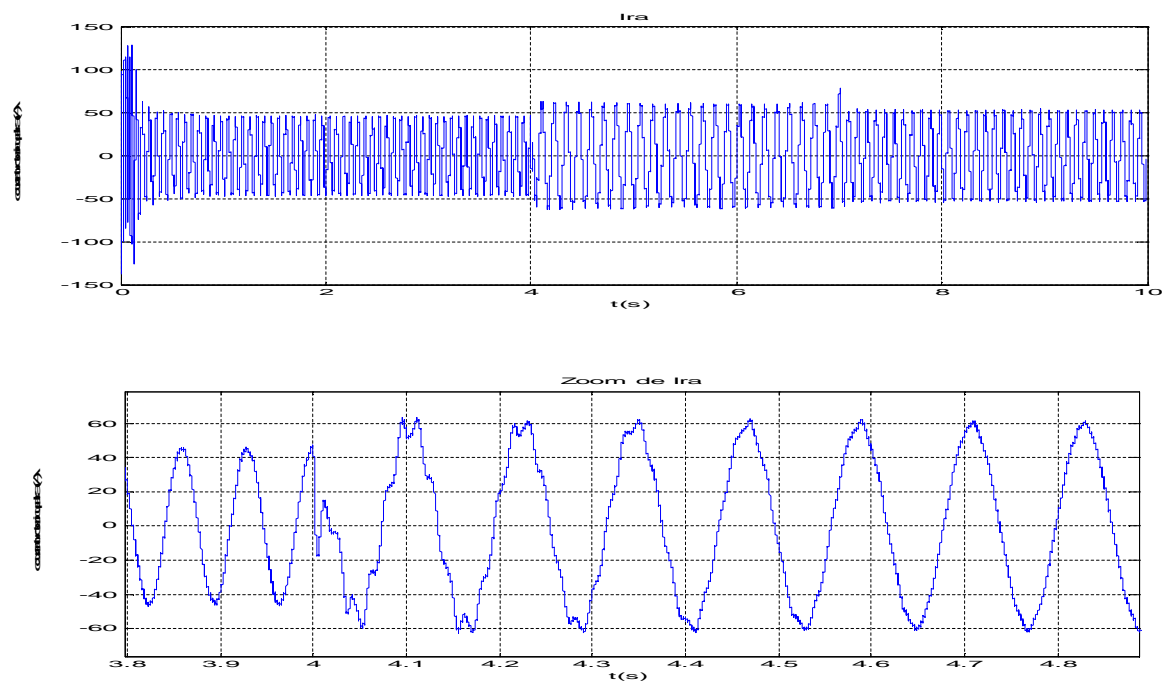


Fig.9 Rotor phase current of healthy DFIG and its zoom

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 interturn fault is introduced in winding of stator phase "a".

Table 2 THE DEGREE OF SHORT-CIRCUIT

| | | |
|--------|-----|---|
| t (s) | 0 | 2 |
| cc (%) | 0.1 | 5 |

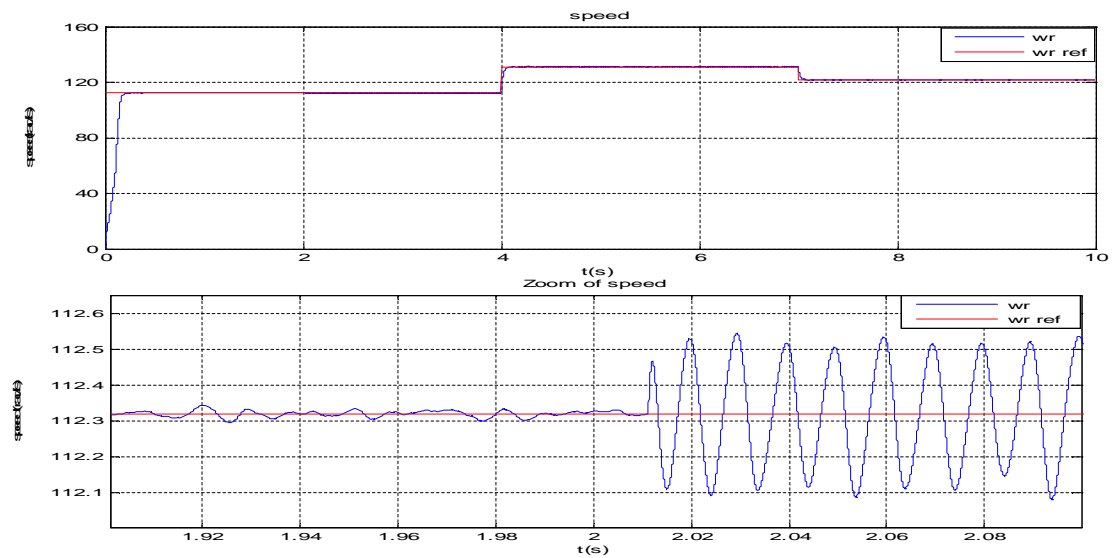


Fig. 10 Speed of faulty DFIG and its zoom with wind speed variation with Stator inter-turn short circuit

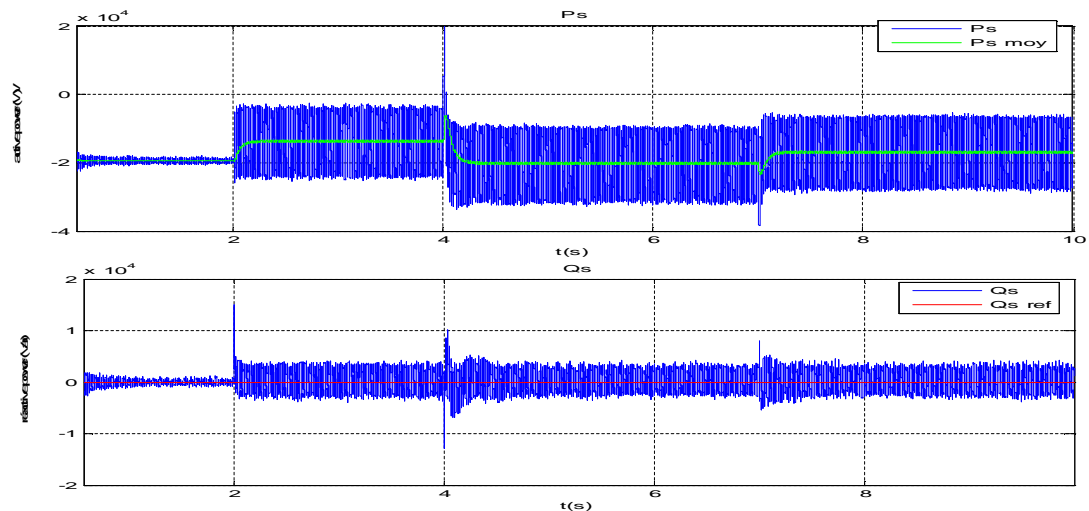


Fig. 11 Stator active and reactive powers of DFIG faulty in Stator inter-turn short circuit and its zoom

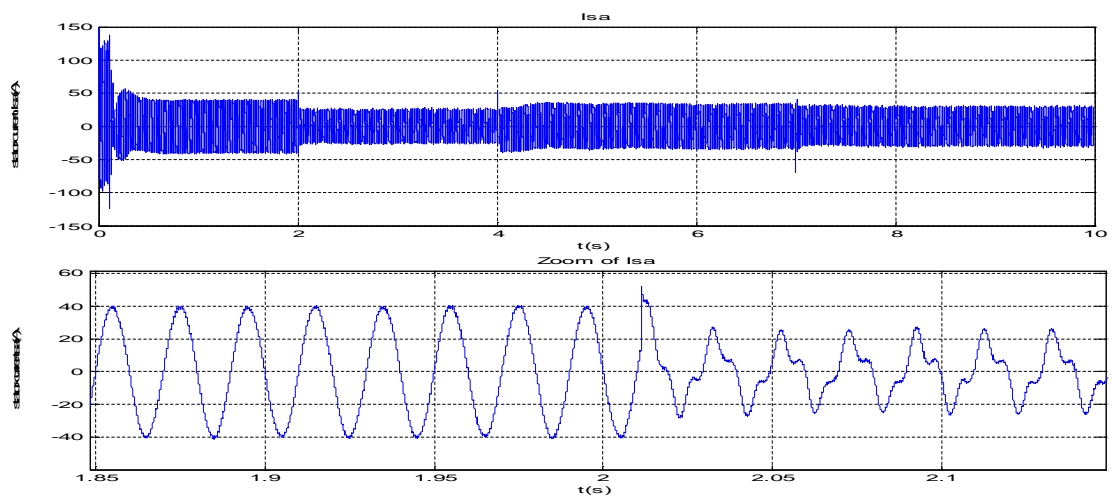


Fig. 12 Stator phase current and its zoom of faulty DFIG

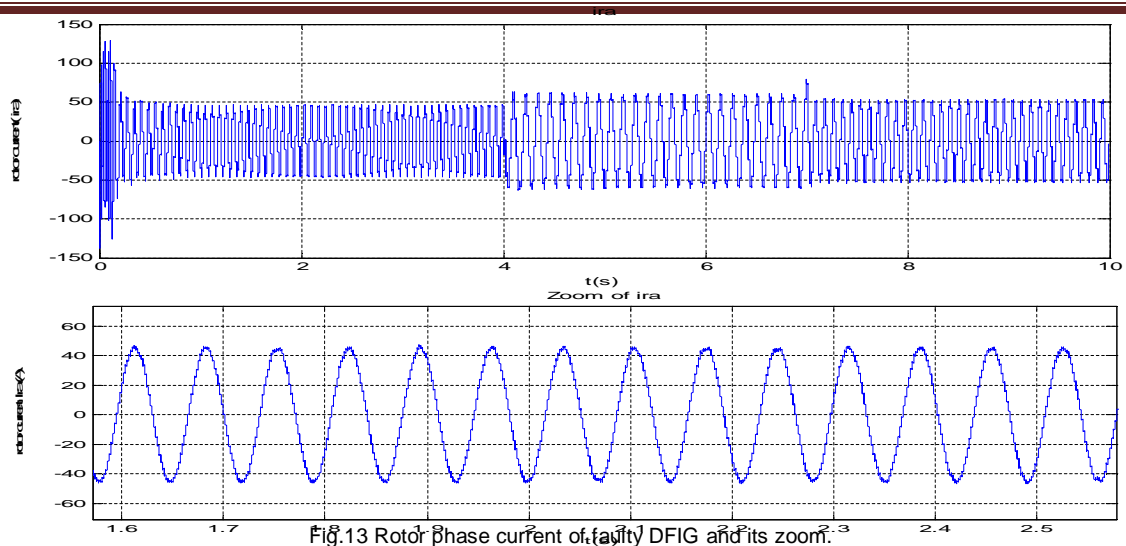


Fig.13 Rotor phase current of faulty DFIG and its zoom.

The dynamics of the speed response is fast and follows its reference in steady-state with zero static error (Fig.6). The reactive power and its reference are shown by Fig.7. We note that it presents oscillations due to harmonics injected by the inverter in the rotor circuit. Its response is insensitive to the wind speed variation and the oscillations increases except when the wind changes. The amplitude of the stator current (Fig.8) and rotor current (Fig.9) increase with increasing wind speed which causes the increase of the torque applied to the machine and then active power developed as shown in Fig.7. The speed waveform presents ripples compared to that of the healthy condition (Fig.6). We note that the mean active power supplied by the stator winding reduced (Fig.11) when the increase of the fault degree that influences on the equilibrium of the three stator phases and therefore the equilibrium of the stator currents which affects the power output . The waveform of the stator current and that of rotor current are presented by Fig.12-13 respectively. Their responses present a deformations after augmentation of stator and rotor short-circuit fault degree to 5% à time $t=2s$.

C. stator inter-turn short circuit fault detection in the DFIG

For detection of the stator short circuit fault, the technique is used: spectral analysis of the stator current and the magnitude-amplitude module of Park's current vector form analysis for the healthy and faulty condition of the DFIG. The simulation tests are carried out for an assumed constant wind speed equal to 12 m/s and for constant reactive power reference equal to 0 Var. For the faulty condition, the degree of stator inter-turn short circuit is fixed to $cc=0.1\%$. We note that the stator current spectrum contains the fundamental frequency component corresponds to stator supply frequency $f_s=50\text{Hz}$ (Fig.14.-a-). For the operation with stator short circuit fault, another frequency component are produced in the current spectrum, plus to the fundamental harmonic characteristics of the stator fault frequencies 150Hz, 250Hz, (Fig.14-b-) whose expression is given by $f_{scc}=(1+2k)f_s$.

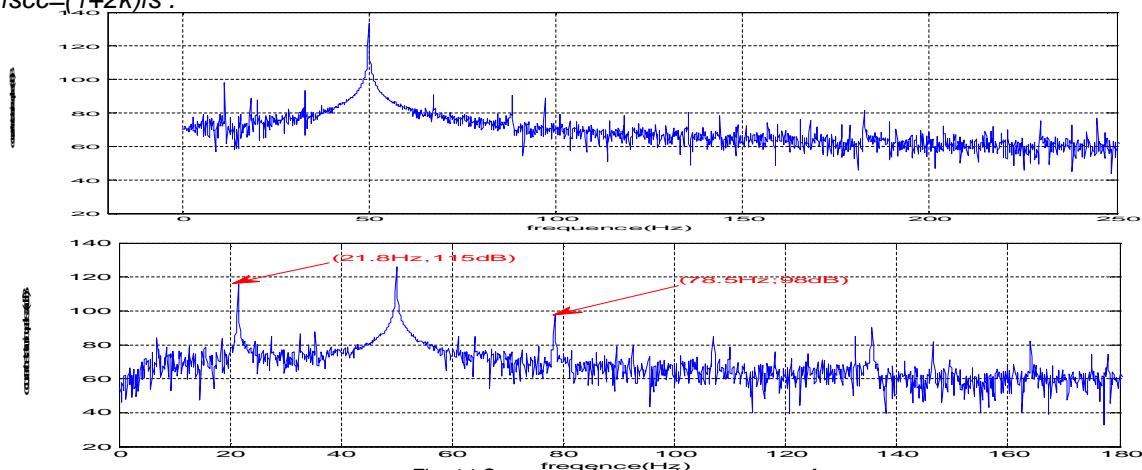


Fig. 14 Spectrum of stator phase current of :
(a)- healthy operating , (b)- faulty stator operating

V. CONCLUSION

A new approach to doubly-fed induction generator (DFIG) based wind turbine modeling has been presented with control of reactive power and adjusting the rotor speed for the healthy condition and stator inter-turn short circuit faulty condition, we observe that the short-circuit fault influences by increasing the oscillations of powers signals and deformations at the stator phase current. We found that monitoring the amplitudes of the harmonic characteristics of stator short-circuit of the stator current spectrum can detect and estimate the severity of this fault. The method of diagnostic for detection of inter-turn short circuits faults of DFIG, based on the FFT of the stator instantaneous current. We found that monitoring the amplitudes of the harmonic of the current spectrum can detect and estimate the severity of this fault. This strategy has been validated steady-state conditions by Matlab/simulink. The technique of the fault tolerant control can be a correct of the fault detection by using observers.

• Wind Turbine Parameters

Rated power: $P_s=7500W$
 Moment of the inertia: $J = 0.31125 \text{ kg.m}^2$
 Wind turbine radius: $R = 3m$
 Gear box ratio: $G = 5.4$
 Air density: $\rho = 1.25 \text{ kg/m}^3$

• DFIG Parameters

Rated power: $7500W$
 Mutual inductance: $L_m = 0.0078 \text{ H}$
 Stator leakage inductance: $L_s = 0.0083 \text{ H}$
 Rotor leakage inductance: $L_r = 0.0081 \text{ H}$
 Stator resistance: $R_s = 0.455 \Omega$
 Rotor resistance: $R_r = 0.62 \text{ m}\Omega$
 Number of pole pairs: $P = 2$
 Moment of the inertia: $J = 0.31125 \text{ kg. m}^2$
 Viscous friction: $f_v = 0.00673 \text{ kg.m}^2.\text{s}^{-1}$

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