DIRECT TORQUE CONTROL OF DOUBLY FED INDUCTION GENERATOR USED FOR WIND ENERGY

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Abstract— *this paper deals with the modelling, control and simulation of a wind energy conversion system based on a Doubly Fed Induction Generator 'DFIG'. The idea is to implement a decoupled control system of DFIG to ensure a better quality of energy and make the system insensitive to disturbances. Simulations are presented, on the one hand to illustrate the performances provided by the DTC.*

Keywords- *Wind System, Variable Speed, Wind Turbine, DFIG, PWM, Vector Control, DTC.*

1. INTRODUCTION

The Direct Torque Control (DTC) technique was introduced in the second half of the 1980 as a competitive method of conventional methods, based on PWM and flow decoupling and torque by orientation of the magnetic flux.

The DTC is a control technique that ensures torque and torque decoupling and simple to implement [1].

It has already well known advantages over conventional techniques, in particular as regards the reduction of the torque response time, the improvement of its robustness with respect to variations in the rotor parameters, and the absence of Park transformations. On the other hand, this torque control law adapts itself by nature to the absence of a mechanical sensor (speed, position) [1].

2. MODELLING OF WIND SYSTEM

In the wind turbine conversion chain, the turbine and the generator are the most important elements, since the turbine ensures a transformation of the kinetic energy of the wind into mechanical energy which makes it possible to rotate the rotor of the generator and The latter is the component that ensures the conversion of mechanical energy into electrical energy.

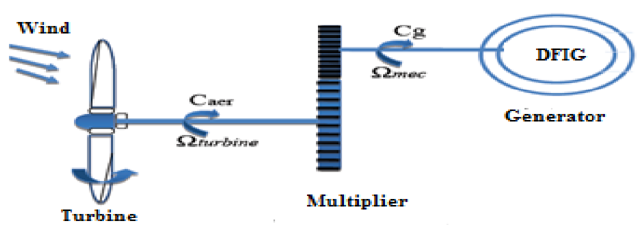


Fig.1 Wind turbine

2.1 Modelling of the Turbine:

Wind speed or wind power is defined as follows [2-12-13]:

$$P_v = \frac{1}{2}\rho S v^3 \quad (1)$$

P_v : is the total power theoretically a vailable.

ρ : is the air density (1.22 kg / m³ at atmospheric pressure at 15ºC).

S : is the circular surface swept by the turbine, the radius of the circle is determined by the length of the blade.

v : is the wind speed.

In reality, the conversion device (the wind turbine) extracts an aerodynamic power P_{aer} less than the available power P_v .

$$P_{aer} = C_p.P_v = C_p(\beta,\lambda)\frac{1}{2}\rho S v^3 \quad (2)$$

The power coefficient C_p, represents the aerodynamic efficiency of the wind turbine $(\frac{P_{aer}}{P_v})$. It depends on the characteristic of the turbine [2-15].

This coefficient varies with the orientation angle of the blades (β) and the speed ratio (λ).

The speed ratio is defined as the ratio between the linear velocity of the blades and the speed of the wind:

$$\lambda = R\frac{\Omega_{turbine}}{v} \quad (3)$$

$\Omega_{turbine}$: is the speed of the turbine.

R : Radius of the wind turbine.

Knowing the speed of the turbine, therefore the aerodynamic torque directly determined by:

$$C_{aer} = \frac{P_{aer}}{\Omega_{turbine}} = C_p\frac{1}{2}\rho S v^3\frac{1}{\Omega_{turbine}} \quad (4)$$

The expression of the power coefficient of a 1.5 MW wind turbine is approximated by the equation:

$$C_p(\beta,\lambda) = \big(0.5 - 0.0167(\beta-2)\big)\sin\left[\frac{\pi(\lambda+0.1)}{18.5-0.3(\beta+2)}\right] - 0.00184(\lambda-3)(\beta-2) \quad (5)$$

The parameters of the selected wind turbine are given in Table 1.

Table1. The wind turbine parameters.

Parameters	Units	Value
The tip speed ratio max $\lambda(C_{P\,max})$	[ ]	9
The power coefficient $C_{P\,max}$	[ ]	0.59
The radius of the wind	[m]	35.25
The gain multiplier	[ ]	90
The air density	[kg/m3]	1.225

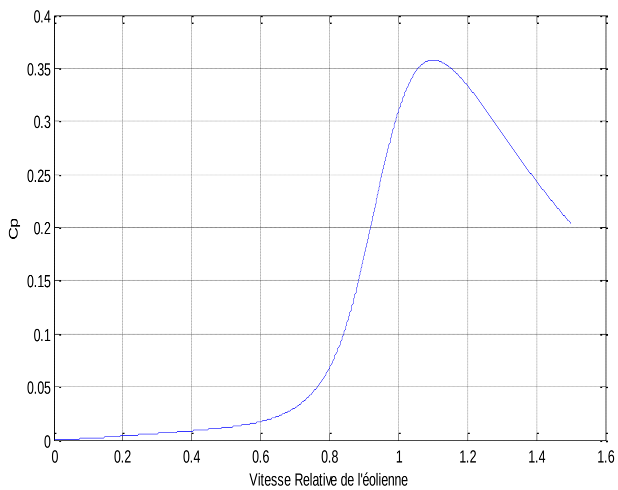


Fig.2: Power coefficient.

And it is observed that the maximum value of the curve will never exceed the theoretical limit of Betz (0.59).
The speed multiplier is the connection between the turbine and the generator. It is designed to adapt the speed of the turbine $\Omega_{turbine}$, rather slow to that required by the generator Ω_g [3].
This multiplier is modeled mathematically by the following equations [2-14-16]:

$$C_g = \frac{C_{aer}}{G}$$

$$\Omega_{turbine} = \frac{\Omega_{mec}}{G} \qquad (7)$$

With G: Gain of the speed multiplier and Ω_{mec} is the mechanical speed.

The fundamental equation of the dynamics makes it possible to determine the evolution of the mechanical speed from the total mechanical torque (C_{mec}) applied to the rotor:

$$J\frac{d\Omega_{mec}}{dt} = C_{mec} \qquad (8)$$

This mechanical torque takes into account the electromagnetic torque C_{mec} produced by the generator, the torque of the viscous friction C_{vis} , and the torque resulting from the multiplier C_s [4].
The resistance torque due to friction is modeled by a coefficient of viscous friction f: $C_{vis} = f.\Omega_{mec}$

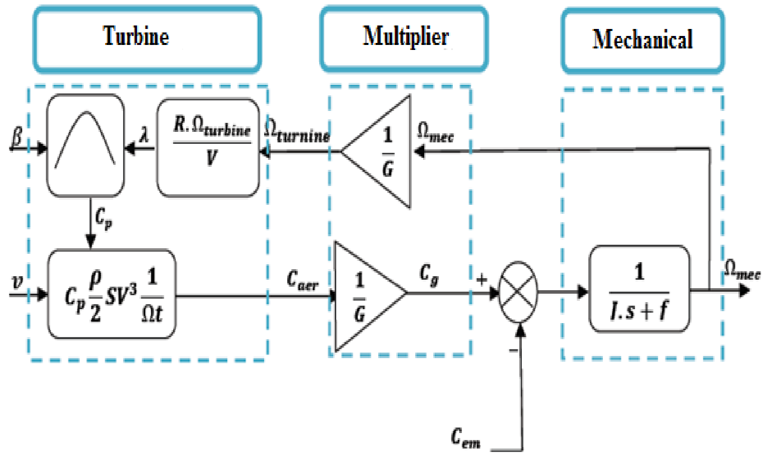


Fig.3: Block diagram of the turbine model.

2.2 Modeling of DFIG:

The general equations of the asynchronous double feeding machine in a three-phase reference frame [5-17]:

Electrical equations:

By applying the faraday law to each winding, we can write:

$$\begin{cases}[V_s] = [R_s][I_s] + \frac{d\varphi_s}{dt}\\ [V_r] = [R_r][I_r] + \frac{d\varphi_r}{dt}\end{cases} \qquad (9)$$

Magnetic equations:

The hypotheses we have presented lead to linear relations between flux and currents. They are expressed in matrix form as follows:

$$\begin{cases}[\varphi_s] = [L_{ss}][I_s] + [M_{sr}][I_r]\\ [\varphi_r] = [M_{sr}][I_s] + [L_{rr}][I_r]\end{cases} \qquad (10)$$

The four inductor matrices are:

$$[L_{ss}] = \begin{bmatrix} L_s & M_s & M_s\\ M_s & L_s & M_s\\ M_s & M_s & L_s\end{bmatrix};[L_{rr}] = \begin{bmatrix} L_r & M_r & M_r\\ M_r & L_r & M_r\\ M_r & M_r & L_r\end{bmatrix} \qquad (11)$$

$$[M_{sr}] = [M_{rs}]^T =$$

$$M\begin{bmatrix} \cos\theta & \cos(\theta - \frac{4\pi}{3}) & \cos(\theta - 2\pi/3)\\ \cos(\theta - 2\pi/3) & \cos\theta & \cos(\theta - \frac{4\pi}{3})\\ \cos(\theta - \frac{4\pi}{3}) & \cos(\theta - 2\pi/3) & \cos\theta\end{bmatrix} \qquad (12)$$

I_s : Inductance of each winding of the stator.
I_r : Self-inductance of each rotor winding.
M_s: Mutual inductance between two stator phases
M_r: Mutual inductance between two rotor phases
L_s : Inductance of each stator winding
L_r : Inductance of each rotor winding
R_s : Resistance of each stator winding
R_r : Resistance of each rotor winding

2.3 Representation of the GADA in two-phase reference frame (*dq*):

The modeling of the DFIG is described in the *d-q* Park reference frame. The following equations systems describe the total generator model [6-10-11].

Electrical equations:

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\varphi_{qs}}{dt} - \omega_s \varphi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r)\varphi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d\varphi_{qr}}{dt} - (\omega_s - \omega_r)\varphi_{dr} \end{cases} \quad (13)$$

,

Magnetic equations:

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + \mathrm{M}\, I_{dr} \\ \varphi_{qs} = L_s I_{qs} + \mathrm{M}\, I_{qr} \\ \varphi_{dr} = L_r I_{dr} + \mathrm{M}\, I_{ds} \\ \varphi_{qr} = L_r I_{qr} + \mathrm{M}\, I_{qs} \end{cases} \quad (14)$$

Expression of active and reactive power:

The active and reactive power at the stator is defined as:

$$\begin{cases} P_s = V_{ds} I_{ds} + V_{qs} I_{qs} \\ Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} \end{cases} \quad (15)$$

For active and reactive rotor powers:

$$\begin{cases} P_r = V_{dr} I_{dr} + V_{qr} I_{qr} \\ Q_r = V_{qr} I_{dr} - V_{dr} I_{qr} \end{cases} \quad (16)$$

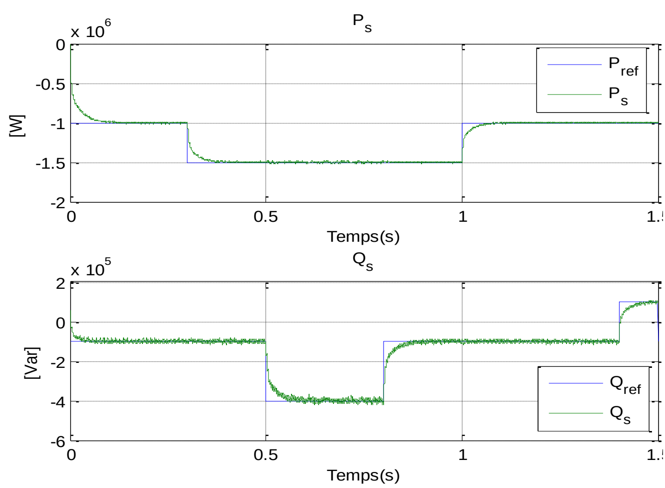
Expression of the electromagnetic torque:

$$\mathrm{C}_{em} = p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \quad (17)$$

With p : Number of pole pair.

3. Indirect control of active and reactive power:

This method consists of taking into account the coupling terms and compensating them by carrying out a system comprising two loops for controlling the powers and the rotor currents. This method is called indirect method [4].



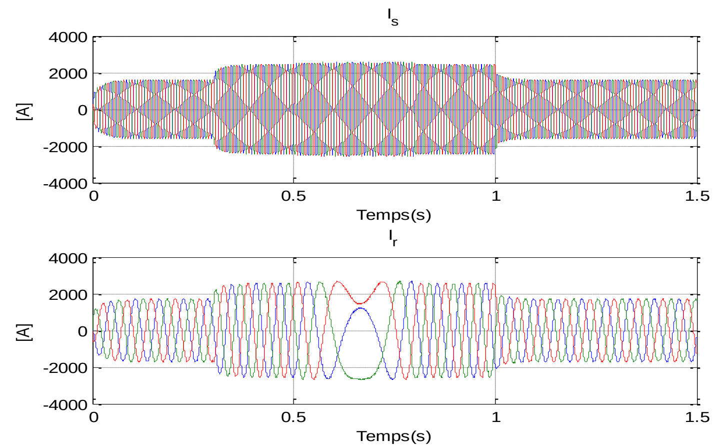


Fig.4: System response

4. Direct torque control of DFIG:

4.1 Introduction :

The DTC is a control technique that ensures torque and torque decoupling and simple to implement [1].

It has already well known advantages over conventional techniques, in particular as regards the reduction of the torque response time, the improvement of its robustness with respect to variations in the rotor parameters, and the absence of Park transformations. On the other hand, this torque control law adapts itself by nature to the absence of a mechanical sensor (speed, position) [7]. The DTC command from external references, such as torque and flux, does not seek, as in conventional commands (vector or scalar), the voltages to be applied to the machine but seeks the best switching state of the inverter for Satisfy user requirements [8-18].

4.2 Principle:

The direct control methods of the DTC torque consist of directly controlling the closing or opening of the inverter switches from the calculated values of the stator flux and the torque [19-21].

4.3 Operation and sequences of a three-phase voltage inverter:

The voltage inverter switches must be controlled in such a way as to maintain the flow and torque of the machine. The stator voltage vector V_s can be written in the form [20-22]:

$$\overline{V_s} = \sqrt{\frac{2}{3}}\, U_c \left[S_a + S_b e^{j\frac{\pi}{2}} + S_c e^{j\frac{4\pi}{3}} \right] \quad (18)$$

Or (S_a, S_b, S_c) represent the logic state of the 3 switches: Si = 1 Means that the top switch is closed and the down switch is open (V_i = +U_0/2) and Si= 0 means that the up switch is open and the down switch is closed (V_i= − U_0/2).

We will therefore try to control the flux and the torque via the choice of the voltage vector which will be done by a configuration of the switches. Since we have 3 switches, there are $2^3 = 8$ possibilities for the vector Vs. 2 vectors (V_0 and V_7) correspond to the zero vector: (S_a, S_b, S_c) = (0, 0, 0) and (S_a, S_b, S_c) = (1, 1, 1).

4.4 Control of stator flux and electromagnetic torque:

4.4.1 Principle of stator flow control:

From the model of the asynchronous machine in a reference frame linked to the stator and the expression of the stator voltage:

$$V_s = R_s I_s + \frac{d\varphi_s}{dt} \quad (19)$$

The stator flux is estimated from the following equation:

$$\varphi_s(t) = \int_0^t (V_s - R_s I_s)dt \quad (20)$$

With the assumption that R_s remains constant and that the term $(R_s I_s)$ is negligible in view of the V_s.
Over a periodic period of control [0, T_e] corresponding to a sampling period T_e the commands (S_a, S_b, S_c) are fixed, so we can write [8]:

$\varphi_s(t) \approx \varphi_{s0} + V_s T_e$. Where φ_{s0} : is the flux vector at time t = 0.
Within a time intervalT_e, The end of the vector φ_s moves on a straight line whose direction is given V_s. Figure (5) illustrates this principle, when the vector $V_s = V_3$ is selected for example.

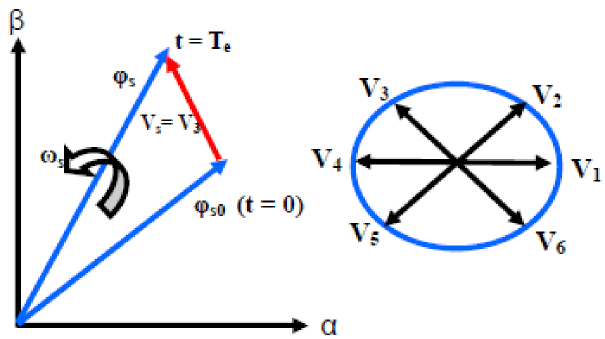


Fig.5: Evolution of the end of the vector φ_s [8].

4.4.2 Principle of electromagnetic torque control

The electromagnetic torque is proportional to the vector product between the stator and rotor flux vectors in the following expression:

$$C_e = K(\overline{\varphi_s} * \overline{\varphi_r'}) = K|\overline{\varphi_s}||\overline{\varphi_r'}| \sin\gamma \quad (21)$$

With:
$\overline{\varphi_s}$: represents the stator flux vector;
$\overline{\varphi_r'}$: represents the rotor flux vector returned to the stator;
γ : represents the angle between the stator and rotor flux vectors.
According to this expression, the torque therefore depends on the amplitude of the two vectors φ_s and φ_r' and their relative position.

4.4.3 Estimation of stator flux:

The flux estimation can be carried out on the basis of the measurements of the stator magnitudes current and voltage of the machine.

From the equation:

$$\overline{\varphi_s} = \int_0^t (\overline{V_s} - \overline{R_s I_s})dt \quad (22)$$

We obtain the components α and β of the vector $\overline{\varphi_s}$.

$$\begin{cases} \varphi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s I_{s\alpha})dt \\ \varphi_{s\beta} = \int_0^t (V_{s\beta} - R_s I_{s\beta})dt \end{cases} \quad (23)$$

These equations represent the computation steps necessary to estimate the amplitude of the stator flux.

4.4.4 Estimation of electromagnetic torque:

The electromechanical torque can be estimated from estimated fluxes and measured stator currents, which can be given the following form [9]:

$$C_{em} = p(\varphi_{s\alpha} I_{s\beta} - \varphi_{s\beta} I_{s\alpha}) \quad (24)$$

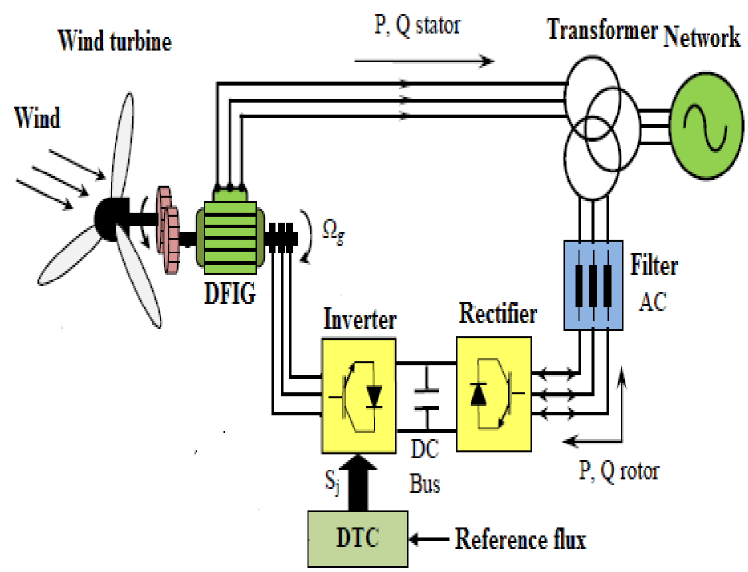


Fig.6: Structure of the direct torque control of DFIG.

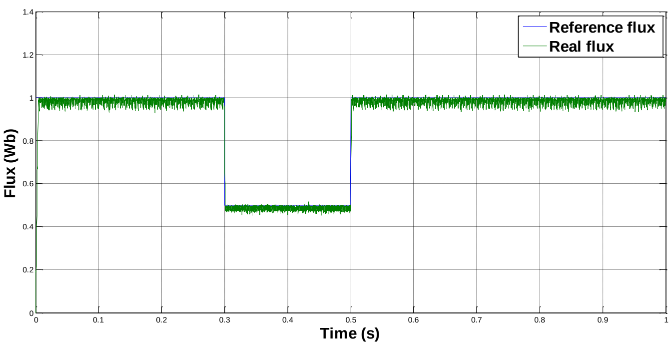
The principle is the direct control of the torque of the double-feed asynchronous machine by the application of the various voltage vectors of the inverter, which determines its state. The two controlled variables are the rotor flux and the electromagnetic torque which are controlled by hysteresis regulators.
The power converter used in the rotor side of the machine is a conventional two-level voltage inverter (Figure 6). The latter makes it possible to reach eight distinct positions in the phase plane, corresponding to the eight voltage sequences of the inverter.
The parameters of the adopted double fed indication generator are given in the following table2.

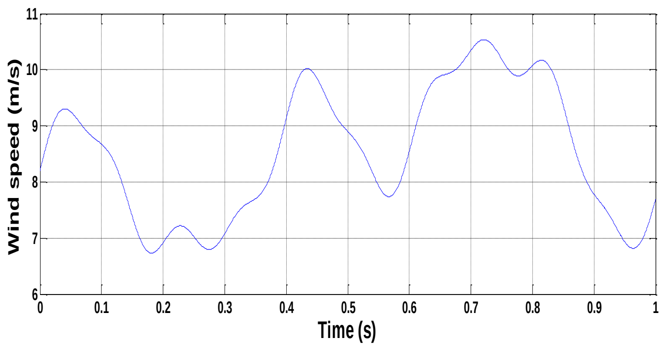
Table 2. The machine paramètres.

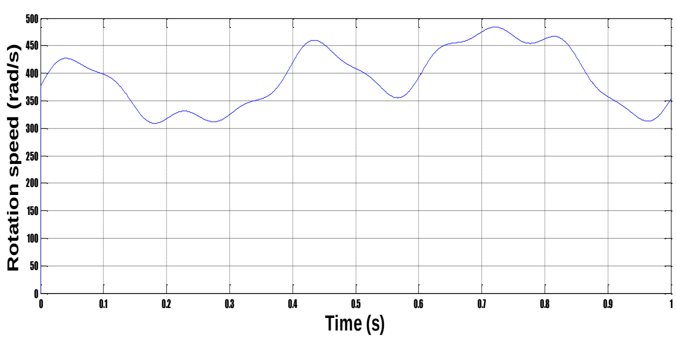
Parameters	Units	Value
The nominal power	[MW]	1.5
The stator voltage	[V]	690
The stator frequency	[Hz]	50
The number of poles pairs	[ ]	2
The stator inductance	[H]	0.0137

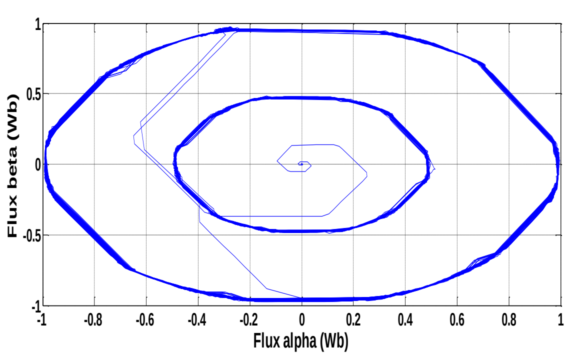
The rotor inductance	[H]	0.0136
The mutual inductance	[H]	0.0135
The rotor resistance	[Ω]	0.021
The stator resistance	[Ω]	0.012
The inertia	[Kg.m²]	1000
The friction coefficient	[N.m.s/rad]	0.0024

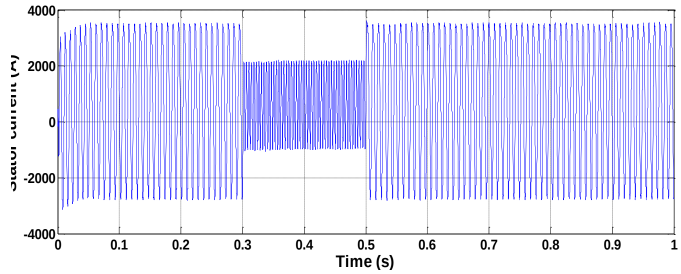
4.5 Simulation results:

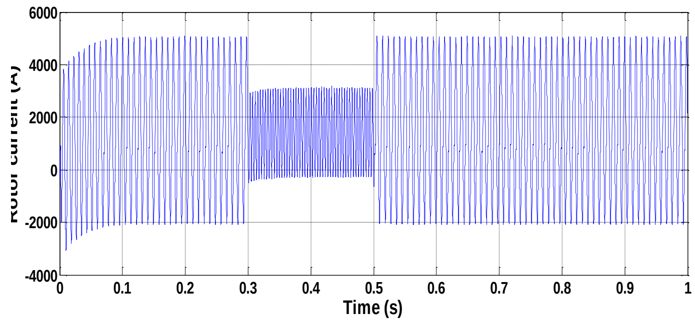


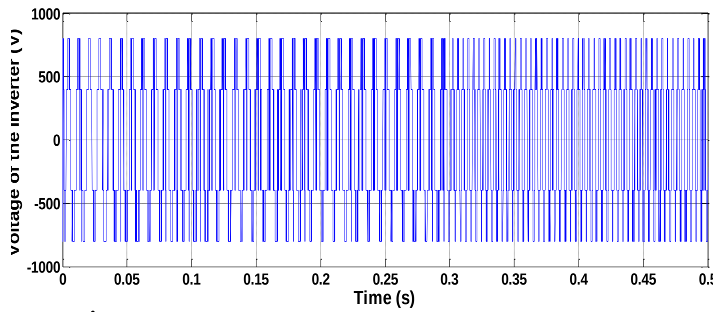


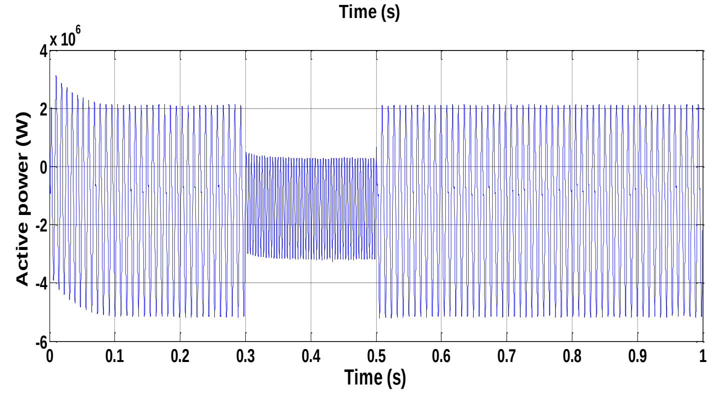












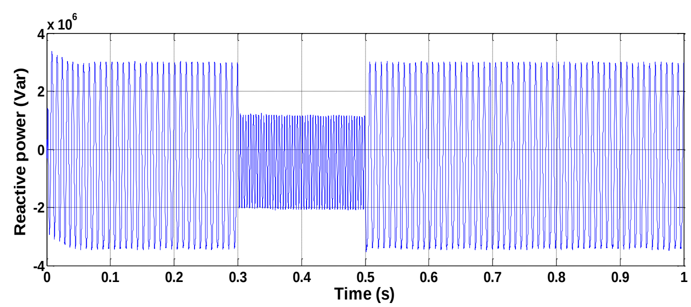


Fig.7: System response

The results obtained confirm the effectiveness of the control strategy used (DTC) for controlling the DFIG based wind

energy conversion system and attest to the desired performance.
From these results, it appears that the direct torque control (DTC) is more robust with respect to the vector control.
When a rotor flow step is applied as a reference, the rotor flux follows perfectly the set point value and remains in the hysteresis band.
Similarly, the stator and rotor currents respond well to changes imposed on the couple and their shapes are very close to the sinusoid. It is also observed that they establish themselves rapidly in the transition phase and this without significant overruns.

5. Conclusion:

Takahashi's direct torque control strategy is an easy way to implement it. The magnitudes of rotor flux and electromagnetic torque are calculated solely from the variables associated with the rotor. Moreover, this control does not require the application of a pulse width modulation (PWM) control on the inverter, which greatly improves the controlled quantities. The DTC command, characterized by the fact that there is no overshoot with respect to the set point and by weak transient oscillations and short response times. The choice of a hysteresis corrector despite its simplicity is a well-suited solution.

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