Modeling and Power Control of Cascaded Doubly-Fed Induction Generators Using a fractional-order PI$^{\lambda}$ controller

Sihem DJEBBRI[(1)], Samir LADACI[(2)*]

[(1)] Department of Electrical Engineering, 20 Août 1955 University, Skikda, Algeria.
[(2)] Department of Automatic Control Eng., Ecole Nationale Polytechnique Algiers, Algiers, Algeria.
*Corresponding author e-mail: samir.ladaci@g.enp.edu.dz

Abstract: This paper deals with the power control of the cascaded doubly-fed induction generator (CDFIG) for wind energy applications. using a fractional order proportional integral (FOPI) controller within a field oriented control (FOC) scheme. The FOPI controller has a similar structure to the classic proportional-integral (PI) controller but FOPI controller considers non integer integration orders in determining the control action. This allows obtaining responses of the controlled system with different characteristics such as oscillations, stability and rise time. In this study FOPI strategy is simulated within a FOC scheme using a mathematical model of cascaded doubly-fed induction generator (CDFIG).

The system can be an attractive alternative to conventional double output wound rotor induction generators. Cascaded doubly-fed induction generator examined in the paper consists of two identical wound rotor induction machines having their rotors mechanically and electrically coupled.

The system employs two cascaded induction machines to eliminate the brushes and copper rings in the traditional DFIG. In this case, Cascaded induction generators require lower maintenance. In CDFIG both stators of connected machines are accessible. The control strategy for flexible power flow control is developed. The independent control of the active and reactive power flows is achieved.

Key words – Cascaded Doubly Fed Induction Generators, Variable Speed Generator, Speed Control, Fractional-order control, PI control, Active-Power and Reactive Power Adjust, Power Flow Diagrams.

1. INTRODUCTION

Today the wind parks occupy a very considerable place in the field of the production of electrical energy [1-4]. Indeed, thanks on the one hand to the sensitivity and the importance of the sector of energy production and on the other hand to the development and consequently to the various structures of the chains of production [2], the wind mills play a dominating role to satisfy the energy needs and the economic requirements.

Then, the wind mills are generally equipped with asynchronous machines with double food (DFIG) functioning at variable speed [3][4].Unfortunately, in this structure of conversion, the presence of the system ring-brushes reduces in particular the reliability of the machine [5]. However, with regard to this work, one proposes study the performances of chains wind mill where two DFIG are coupled electrically and mechanically via their rotors, in order to improve the performances of the chains of production. All two DFIG thus coupled is called cascade is in summary (CDFIG) [3] [6].

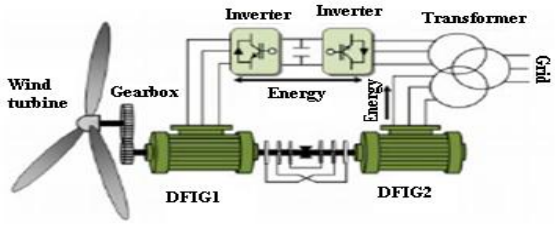


Fig. 1 CDFIG configuration for wind power generation.

Thus, the structure of the chains of production is illustrated by fig. 1. The stator of the first machine is connected directly to the electrical supply network on the other hand the stator of the second machine is connected to the same network via frequency converter that one supposes ideal.

Two configurations of connection of the rotors of the two DFIG are possible. Direct connection results from the connection of the same phases or opposite connection results by reversing two phases [7]. In what concerns us, it is considered that the two rotors are connected this last configuration illustrated in the figure below (see fig. 2).

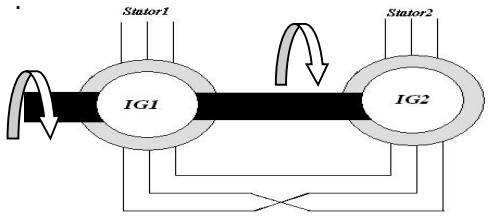


Fig. 2. Mechanical and electric connections of CDFIG

Recently, Fractional order control has found a great interest in the research and engineering communities. The main reason is their ability to better represent physical phenomena and present more interesting dynamics particularly for the aim of controlling these processes [8-10].

This work intends to introduce a fractional order PI$^{\lambda}$ controller to deal with the CDFIG system in order to enhance its performance.

2. NOMENCLATURE

P_i :	active power
Q_i :	reactive power
I_{si} $(i=1,2)$:	stator currents
$I_{dsi}(i=1,2)$:	stator currents on the axis d
$I_{qsi}(i=1,2)$:	stator currents on the axis q
I_{ar}, I_{br}, I_{cr} :	rotor currents
$I_{.dr}$:	rotor current on the axis d
I_{qr} :	rotor current on the axis q
s_1 :	slip of the 1st machine.
s_2	slip of the 2nd machine.
s :	slip of the cascade of two machines.
C_e :	electromagnetic couple
C_r :	resistive torque
J :	inertia of the revolving masses
f :	coefficient of viscous friction
K_p ;	constant proportional of the regulator
K_i ;	constant integral of the regulator
CDFIG	Cascaded Doubly-Fed Induction Generator
DFIG	Doubly-Fed Induction Generator

In the following paragraph, we present the modeling of the CDFIG in the reference of Park, and, in that which succeed it, the control of the transit of powers active and reactive between the wind generator and the electrical supply network. Then, we develop the control lines where one presents the synthesis of the regulators. Finally, by using the Matlab/simulink software, we present the results of simulations and their discussions.

3. MODELISATION OF THE CASCADE

A- *Electric equations [11-13]*

1) *First machine*

$$\begin{cases} V_{ds1} = R_{s1}.i_{ds1} + \dfrac{d}{dt}\phi_{ds1} - \omega_s \phi_{qs1} \\ V_{qs1} = R_{s1}.i_{qs1} + \dfrac{d}{dt}\phi_{qs1} + \omega_s \phi_{ds1} \\ V_{dr1} = R_{r1}.i_{dr1} + \dfrac{d}{dt}\phi_{dr1} - (\omega_s - \omega_{r1}).\phi_{qr1} \\ V_{qr1} = R_{r1}.i_{qr1} + \dfrac{d}{dt}\phi_{qr1} + (\omega_s - \omega_{r1}).\phi_{dr1} \end{cases} \quad (1)$$

2) Second machine

$$\begin{cases} V_{ds2} = R_{s2}.i_{ds2} + \dfrac{d}{dt}\phi_{ds2} - (\omega_s - \omega_{r1} - \omega_{r2}).\phi_{qs2} \\ V_{qs2} = R_{s2}.i_{qs2} + \dfrac{d}{dt}\phi_{qs2} + (\omega_s - \omega_{r1} - \omega_{r2}).\phi_{ds2} \\ V_{dr2} = R_{r2}.i_{dr2} + \dfrac{d}{dt}\phi_{dr2} - (\omega_s - \omega_{r1}).\phi_{qr2} \\ V_{qr2} = R_{r2}.i_{qr2} + \dfrac{d}{dt}\phi_{qr2} + (\omega_s - \omega_{r1}).\phi_{dr2} \end{cases} \quad (2)$$

According to, the configuration of fig. 2, we can deduce the following relations:

$$\begin{cases} V_{dr1} = V_{dr2} = V_{dr} \\ V_{qr1} = V_{qr2} = V_{qr} \end{cases} \quad et \quad \begin{cases} i_{dr} = i_{dr1} = -i_{dr2} \\ i_{qr} = i_{qr1} = -i_{qr2} \end{cases} \quad (3)$$

The preceding equations can be written in the form of state (4).

$$\dot{X} = AX + BU \quad (4)$$

Where,

$$X = [i_{ds1}\ i_{qs1}\ 0\ 0\ i_{ds2}\ i_{qs2}]^T \quad (5)$$

$$U = [\frac{di_{ds1}}{dt}\ \frac{di_{qs1}}{dt}\ \frac{di_{dr}}{dt}\ \frac{di_{qr}}{dt}\ \frac{di_{ds2}}{dt}\ \frac{di_{qs2}}{dt}]^T \quad (6)$$

$$A = \begin{bmatrix} R_{s1} & -\omega_s L_{s1} & 0 & -\omega_s L_{m1} & 0 & 0 \\ \omega_s L_{s1} & R_{s1} & \omega_s L_{m1} & 0 & 0 & 0 \\ 0 & -(\omega_s-\omega_1)L_{m1} & (R_{r1}+R_{r2}) & -(\omega_s-\omega_1)L_{r1}+L_{r2}) & 0 & (\omega_s-\omega_1)L_{m2} \\ (\omega_s-\omega_1)L_{m1} & 0 & (\omega_s-\omega_1)L_{r1}+L_{r2}) & (R_{r1}+R_{r2}) & -(\omega_s-\omega_1)L_{m2} & 0 \\ 0 & 0 & 0 & (\omega_s-\omega_1-\omega_2)L_{m2} & R_{s2} & -(\omega_s-\omega_1-\omega_2)L_{s2} \\ 0 & 0 & -(\omega_s-\omega_1-\omega_2)L_{m2} & 0 & (\omega_s-\omega_1-\omega_2)L_{s2} & R_{s2} \end{bmatrix} \quad (7)$$

$$B=\begin{bmatrix} L_{s1} & 0 & L_{m1} & 0 & 0 & 0 \\ 0 & L_{s1} & 0 & L_{m1} & 0 & 0 \\ L_{m1} & 0 & L_{r1}+L_{r2} & 0 & -L_{m2} & 0 \\ 0 & L_{m1} & 0 & L_{r1}+L_{r2} & 0 & -L_{m2} \\ 0 & 0 & -L_{m2} & 0 & L_{s2} & 0 \\ 0 & 0 & 0 & -L_{m2} & 0 & L_{s2} \end{bmatrix} \quad (8)$$

B- Magnetic equations

** First machine*

$$\begin{cases} \phi_{ds1} = L_{s1}.i_{ds1} + L_{m1}i_{dr} \\ \phi_{qs1} = L_{s1}.i_{qs1} + L_{m1}i_{qr} \\ \phi_{dr1} = L_{r1}.i_{dr} + L_{m1}i_{ds1} \\ \phi_{qr1} = L_{r1}.i_{qr} + L_{m1}i_{qs1} \end{cases} \quad (9)$$

** Second machine*

$$\begin{cases} \phi_{ds2} = L_{s2}.i_{ds2} - L_{m2}i_{dr} \\ \phi_{qs2} = L_{s2}.i_{qs2} - L_{m2}i_{qr} \\ \phi_{dr2} = -L_{r2}.i_{dr} + L_{m2}i_{ds2} \\ \phi_{qr2} = -L_{r2}.i_{qr} + L_{m2}i_{qs2} \end{cases} \quad (10)$$

C- Equations of the powers

The active and reactive powers relating to the stator of the first machine and that of the second are respectively defined by the relations (11) and (12).

$$\begin{cases} P_{s1} = V_{ds1}.i_{ds1} + V_{qs1}.i_{qs1} \\ Q_{s1} = V_{qs1}.i_{ds1} - V_{ds1}.i_{qs1} \end{cases} \quad (11)$$

$$\begin{cases} P_{s2} = V_{ds2}.i_{ds2} + V_{qs2}.i_{qs2} \\ Q_{s2} = V_{qs2}.i_{ds2} - V_{ds2}.i_{qs2} \end{cases} \quad (12)$$

From where,

$$\begin{cases} P_g = P_{s1} + P_{s2} \\ Q_g = Q_{s1} + Q_{s2} \end{cases} \quad (13)$$

D- Equations mechanics

The expression of the electromagnetic couple is:

$$C_e = P_1 L_{m1}(i_{dr}.i_{qs1} - i_{ds1}.i_{qr}) + P_2 L_{m2}(i_{dr}.i_{qs2} - i_{ds2}.i_{qr}) \quad (14)$$

And, that dynamic is:

$$J\frac{d\Omega}{dt} = C_e - C_r - f.\Omega \quad (15)$$

4. SYSTEM OF CONTROL

The CDFIG is connected to the network via its first stator while controlling the sizes of the second stator. One controls the active and reactive power which transit by stator 1, not to overload stator 1 in the case or the aerodynamic power is higher than the acceptable power of the stator1, which returns, in this case, to create a second way, via stator 2.

We use the diphasic modeling of the machine, we direct the reference (*dq*) in ordered to align the axis *d* on the stator flow ϕ_s.

$$\begin{cases} \phi_{ds1} = \phi_{s1} \\ \phi_{qs1} = 0 \end{cases} \quad (16)$$

For the machines of great power, we can neglect the resistance of the stator [7]. Under these conditions, we are:

$$\begin{cases} V_{ds1} = 0 \\ V_{qs1} = V_s = \omega_s.\phi_{s1} \end{cases} \quad (17)$$

By replacing the flow and the tension of the first stator in the whole of the equations, we will have:

$$\begin{cases} i_{dr} = C_1.i_{ds2} - C_1.\dfrac{L_{m1}.V_s}{\omega_s.L_{s1}.L_{m2}} \\ i_{qr} = C_1.i_{qs2} \end{cases} \quad (18)$$

$$\begin{cases} i_{ds1} = \dfrac{V_s}{\omega_s.L_{s1}}\left(1 + \dfrac{C_1.L_{m1}^2}{L_{s1}.L_{m2}}\right) - C_1\dfrac{L_{m1}}{L_{s1}}.i_{ds2} \\ i_{qs1} = -C_1\dfrac{L_{m1}}{L_{s1}}.i_{qs2} \end{cases} \quad (19)$$

$$\begin{cases} V_{ds2} = R_{s2}.i_{ds2} + (L_{s2} - C_1 L_{m2})\dfrac{di_{ds2}}{dt} - s\omega_s(L_{s2} - C_1 L_{m2})i_{qs2} \\ V_{qs2} = R_{s2}.i_{qs2} + (L_{s2} - C_1 L_{m2})\dfrac{di_{qs2}}{dt} + s\omega_s(L_{s2} - C_1 L_{m2})i_{ds2} + C_1 s\dfrac{L_{m1}.V_s}{L_{s1}} \end{cases} \quad (20)$$

$$\begin{cases} P_{s1} = -C_1.V_s.\dfrac{L_{m1}}{L_{s1}}.i_{qs2} \\ Q_{s1} = \dfrac{V_s^2}{\omega_s.L_{s1}}\left(1+\dfrac{C_1.L_{m1}^2}{L_{s1}.L_{m2}}\right) - C_1.V_s\dfrac{L_{m1}}{L_{s1}}.i_{ds2} \end{cases} \quad (21)$$

Where,

$$C_1 = \frac{L_{m2}}{L_{r1} + L_{r2} - \dfrac{L_{m1}^2}{L_{s1}}} \quad (22)$$

With:

$$s = s_1.s_2 = \frac{\omega_s - \omega_{r1} - \omega_{r2}}{\omega_s} = \frac{\omega_s - (P_1 + P_2).\Omega_r}{\omega_s} \quad (23)$$

$$s_1 = \frac{\omega_s - P_1.\Omega_r}{\omega_s} \quad , \quad s_2 = \frac{s_1\omega_s - P_2.\Omega_r}{s_1.\omega_s}$$

With:

A. Synthesis of the regulator

The loop of adjustment is illustrated by the diagram of fig. 3.The regulator used is of proportional integrating type (PI). This last is simple to implement and for a best fit of its coefficients ensures the desired performances [3].

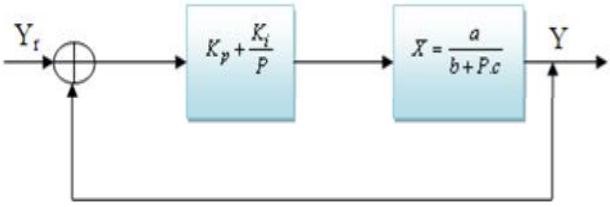


Fig. 3 CDFIG control with PI Regulator

$$X = \frac{M^2.V_s}{\left(2.L_r L_s R_s - M^2 R_s\right) + P.2.L_s\left(L_r L_s - M^2\right)}$$

$$\frac{K_i}{K_p} = \frac{R_s\left(2.L_r L_s - M^2\right)}{2.L_s\left(L_r L_s - M^2\right)} \qquad T_r = \frac{2.L_s\left(L_r L_s - M^2\right)}{K_p.V_s.M^2}$$

,

For a response time: T_r =10ms ,

We will have:

K_p =0,0001185312;

K_i =0,001842.

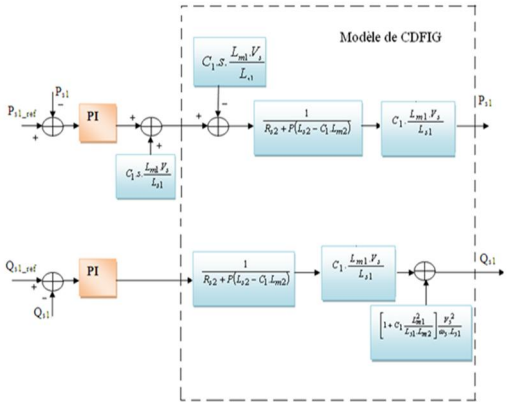


Fig. 4 Schéma bloc du contrôle de puissance

The main objective of this work is to use a fractional-order controller in order to benefit from its advantages as it is well know that it can improve the system performance like the time response and the rise time, and increase the robustness of the controlled system against disturbance and noises [14-15].

By introducing a fractional-order integrator in the PI controller we obtain the PI$^{\lambda}$ controller where λ is a real number in the interval]0 ,2[.

5. RESULTS OF SIMULATION

The test of simulation consists in imposing an active power of P_{s1} reference = -1.5 Mw and a reactive power of reference of Qs1=0 MVAR. This allows an operation with a unit power-factor. Fig. 5 shows that the active and reactive power of CDFIG follow perfectly their set points with a very small response time for λ = 0.7.

Fig. 6 illustrates the benefic action of the fractional order PI$^{\lambda}$ controller on the control signals for λ = 0.9. This is validated ith different control schemes in recent literature [16].

Fig. 7, gives a comparative response of the system using the integer order and fractional order PI controller. It demonstrates the superiority of the proposed fractional order PI$^{\lambda}$ controller.

Figures Fig. 8 and 9 present the currents signals of the stator 1 and the stator 2 which remain bounded during the experiment.

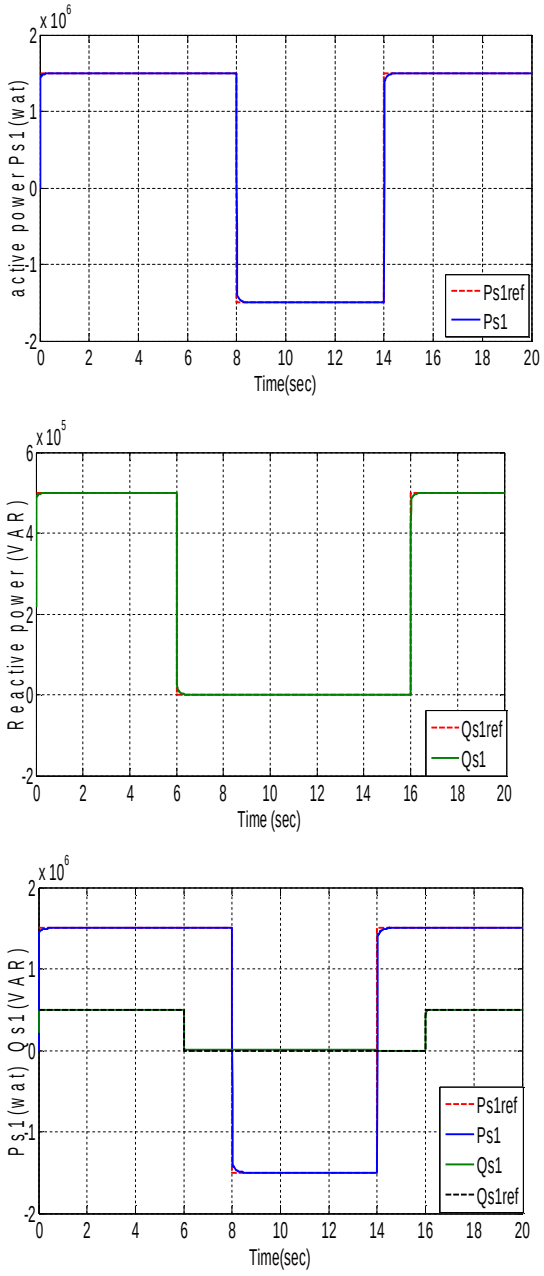


Fig. 5 Active and reactive power Control with fractional controller PI^{λ} with λ=0.7

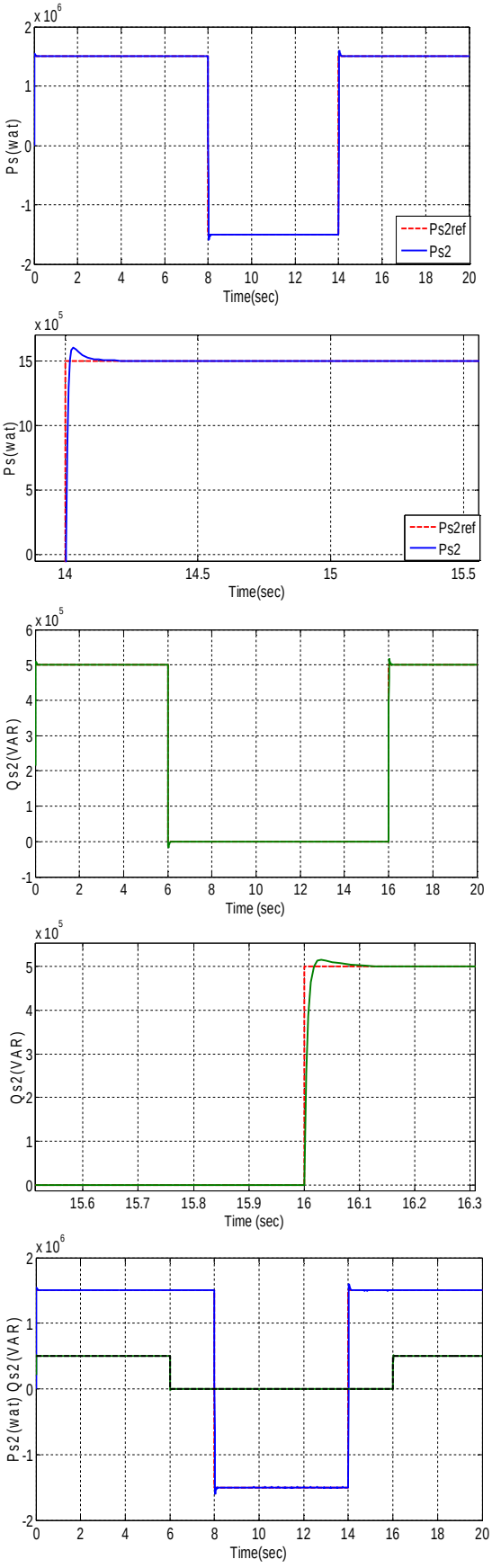


Fig. 6 Active and reactive power Control with fractional PI^{λ} controller with λ=0.9

Comparative results

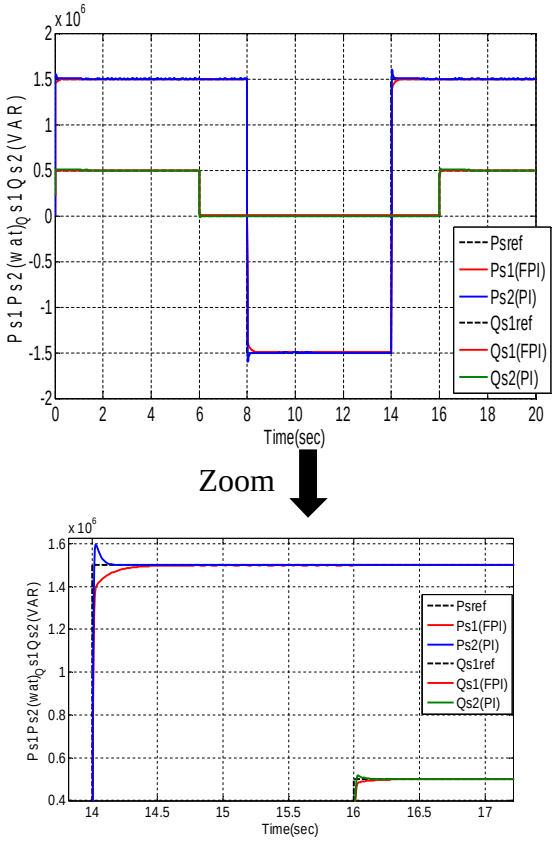


Fig.7 Comparative power control of Active and reactive power with classical PI and fractional PI$^{\lambda}$ controller

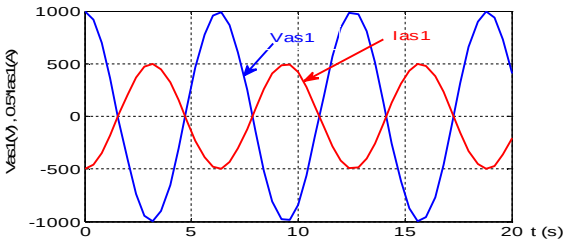


Fig. 8 Current and tension of stator 1

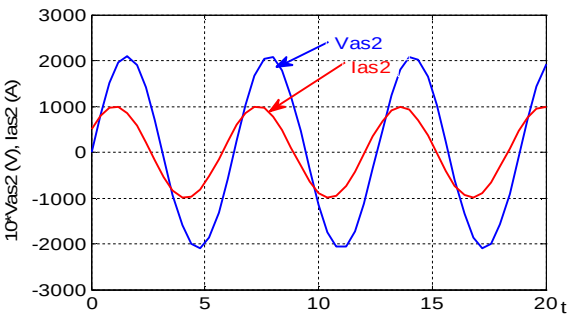


Fig. 9 Courant and tension of stator 2

6. CONCLUSION

The idea to install a cascade of two DFIG in the chains of wind conversion is promising solution for stage with the disadvantage of the system ring-brushes when only one DFIG is envisaged. The order uncoupled from the powers proved to be powerful, allowing even an operation with a unit reactivity power coefficient.

In this work, we have in beginning introduced a general description on the asynchronous cascade of two machines with double food and the objective of this system into the wind energy production. The wind generator, which is the subject of our study, is based on the cascade of two DFIG, the objective was to model the CDFIG in the reference of Park and control transit of power (active and reactivates) between the wind generator and the conventional electrical supply network.

To through the study carried out under wind operation, one manages to control stator 1 through stator 2.Stator 1 product always of energy activates while following the reference.

Stator 2 product or consumes active and reactive energy while following the speed of the wind. In hypo synchronous, it consumes energy and into hyper-synchronous it provides to the network energy , two energies are varies independently one of the other , which, it is noticed that the variation of active energy does not any influence more the pace of the reactive energy which presents a value depend magnetizing of the magnetic circuit fixes then it takes a fixed and null value in permanent mode.
Using a fractional order proportional integral (FOPI) controller give a better results than the classic proportional-integral (PI) controller in the responses of the controlled system with different characteristics such as oscillations, stability and rise time. In this study FOPI strategy is simulated within a FOC scheme using a mathematical model of cascaded doubly-fed induction generator (CDFIG).

➢ **Parameters of CDFIG**

The machines used, are identical:
P=1.5 MW ; Vg=690V
P1=P2=2; f1=f2=: 0.0071N.m.s/rad;
J1=J2=50 Kg.m^2.

Rs1= Rs2= 0.012Ω ;Rr1= Rr2= 0.021Ω ;
Ls1= Ls2= 0.0137H ;Lr1= Lr2= 0.0137 H ;
Lm1=Lm1= 0.0135H;

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