Fuzzy-Variable Gain PI Control of WECS Based on a Doubly Fed Induction Generator

Tsiory Patrick ANDRIANANTENAINA [(a)], Zazad d'Edissak TSARALAHY [(b)], Jean Nirinarison RAZAFINJAKA [(c)], Hervé MANGEL [(d)]

[(a) (c)] Automatic Laboratory, Department of Electricity, Higher Polytechnic School, University of Antsiranana, Madagascar
[(b)] Electrical machines Laboratory, Department of Electricity, Higher Polytechnic School, University of Antsiranana, Madagascar
[(d)] Research institute Dupuy de Lôme, Department of Electricity, Universities Institute of Technology, University of Brest, France
otantikroysti@gmail.com[(a)], zazad86@gmail.com[(b)], razafinjaka@yahoo.fr[(c)], Herve.Mangel@univ-brest.fr[(d)]

ABSTRACT
This paper presents a study of powers control for a Doubly Fed Induction Generator (DFIG) used in Wind Energy Conversion System (WECS). For this purpose, a new topology using hybrid controller is applied for the powers generated by the DFIG. The hybridization consists to combine a variable gain PI (VGPI) controller with a fuzzy logic one. The results of simulation show that this technique can be realized and leads to good performances as disturbance rejection and robustness with respect of operating variation and parametric variation of the machine.

Keywords—DFIG, vector control, WESC, power control, VGPI, fuzzy logic, hybridization.

1- INTRODUCTION

The development and the exploitation of renewable energies met a great growth these last years. Among these sources of energies, the windmill represents a significant potential not to replace existing energies, but to give solutions for the request, which always increases. The wind power can contribute with a significant part for the new sources of energy not emitting a gas for purpose of greenhouse (Andrianantenaina and *al* 2015). Currently, windmill system with variable speed based on the DFIG is widely used. Indeed, the DFIG presents more advantages. Several controls applied on the DFIG have been already proposed as (Andrianantenaina and *al* 2015; Razafinjaka and Andrianantenaina 2015,2016; Boualouch 2015) which give good performances.

These last years, several researches are about the intelligent controllers such us fuzzy logic and neural network which have enjoyed great success in recent years for their robustness against disturbances which may affect process. Here, a hybridization of fuzzy logic with variable gain PI is proposed. After modeling the wind turbine and DFIG, we have established a vector control to control the active and reactive power control. The aim of this work is to present the performance and robustness of these controllers.

2- WIND POWER CONVERSION SYSTEM

Figure 1 shows a general scheme of the system which is composed by a turbine, a multiplier, the DFIG and two converters.

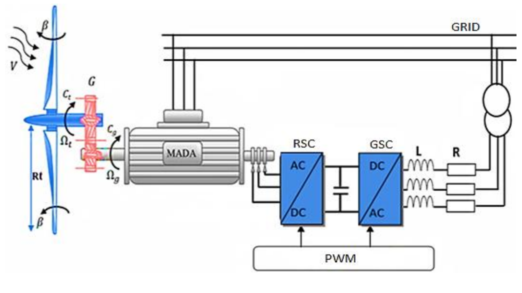

Figure 1: General scheme of wind turbine based on DFIG

The total kinetic is,

$$P = \frac{1}{2}\rho\pi R_T^2 V^3 C_p(\lambda,\beta) \quad (1)$$

With ρ the air density, V, the wind velocity, R_T, the blade length and C_P, the energy extraction coefficient (Doumi *et al 2016*).

For windmills, the energy extraction coefficient C_P, which depends of the wind velocity and the turbine is usually defined in the interval (0,35÷0,59). The coefficient C_P is function of the specific velocity λ and the angle of the blade β. Figure2 shows the characteristic of C_P according λ (Razafinjaka and Andrianantenaina 2015, 2016)

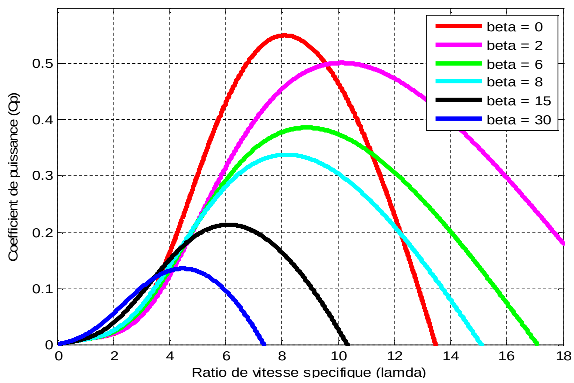

Figure 2: Turbine Power coefficient

The DFIG transforms the mechanical energy to electrical.

3- DFIG MODELING AND ITS VECTOR CONTROL

The DFIG model is described in the referential Park. The different equations below give the global modeling of the machine (Andrianantenaina and *al* 2015); Razafinjaka and Andrianantenaina 2016; Andrianantenaina and *al* 2016; Rouabhi and *al* 2015; Tarfaya and *al* 2015).

3.1. Electrical equations

$$\begin{cases} V_{sd} = R_s i_{sd} + \dfrac{d\phi_{sd}}{dt} - \omega_{coor}\phi_{sq} \\ V_{sq} = R_s i_{sq} + \dfrac{d\phi_{sq}}{dt} + \omega_{coor}\phi_{sd} \\ V_{rd} = R_r i_{rd} + \dfrac{d\phi_{rd}}{dt} - (\omega_{coor} - \omega)\phi_{rq} \\ V_{rq} = R_r i_{rq} + \dfrac{d\phi_{rq}}{dt} + (\omega_{coor} - \omega)\phi_{rd} \end{cases} \quad (2)$$

3.2. Magnetic equations

$$\begin{cases} \phi_{sd} = L_s.i_{sd} + M.i_{rd} \\ \phi_{sq} = L_s.i_{sq} + M.i_{rq} \\ \phi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \phi_{rq} = L_r.i_{rq} + Mi_{sq} \end{cases} \quad (3)$$

3.3. Torque and power expressions

The electromagnetic torque is expressed according to current and fluxes by:

$$C_{em} = -p\frac{M}{L_s}(\phi_{sq}i_{rd} - \phi_{sd}i_{rq}) \quad (4)$$

With p, the number of pair poles

Stator active and reactive powers are expressed by:

$$\begin{aligned} P_s &= V_{sd}I_{sd} + V_{sq}I_{sq} \\ Q_s &= V_{sq}I_{sd} - V_{sd}I_{sq} \end{aligned} \quad (5)$$

The rotor active and reactive powers are given by:

$$\begin{aligned} P_r &= V_{rd}I_{rd} + V_{rq}I_{rq} \\ Q_r &= V_{rq}I_{rd} - V_{rd}I_{rq} \end{aligned} \quad (6)$$

3.4. DFIG vector control

In order to control the electricity production, a method, which not depends of active and reactive powers, is proposed. It consists to establish relations between rotor voltages delivered by the converter with active and reactive powers. Referential d-q related of spinning field and a stator flux aligned is adopted. So (Razafinjaka and Andrianantenaina 2015; Boualouch 2015; Doumi *et al 2016*)

$$\begin{cases} \phi_{sd} = \phi_s \\ \phi_{sq} = 0 \end{cases} \quad (7)$$

Flux equations become:

$$\begin{cases} \phi_{sd} = \phi_s = L_s.i_{sd} + M.i_{rd} \\ 0 = L_s.i_{sq} + M.i_{rq} \\ \phi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \phi_{rq} = L_r.i_{rq} + Mi_{sq} \end{cases} \quad (8)$$

If the network is supposed stable, the stator flux is constant. Moreover, the stator resistor may be neglected; it is a realist hypothesis in the generator used in windmill. Taking into account all these considerations:

$$\begin{aligned} V_{sd} &= 0 \\ V_{sq} &= V_s = \omega_s\phi_s \end{aligned} \quad (9)$$

By the equation (8), a relation between stator and rotor currents can be established:

$$i_{sd} = \frac{\phi_s}{L_s} - \frac{M.i_{rd}}{L_s} \quad (10)$$

$$i_{sq} = -\frac{M}{L_s}i_{rq}$$

Using simplifying hypothesis, the equations of powers give:

$$\begin{cases} P_s = -V_s.\frac{M}{L_s}i_{rq} \\ Q_s = -V_s.\frac{M}{L_s}i_{rd} + \frac{V_s^2}{L_s.\omega_s} \end{cases} \quad (11)$$

In order to control the generator, expressions showing the relation between rotor voltages and rotor currents are:

$$\begin{cases} V_{rd} = R_r i_{rd} + L_r\sigma\frac{di_{rd}}{dt} - g\omega_s L_r\sigma i_{rq} \\ V_{rq} = R_r i_{rq} + L_r\sigma\frac{di_{rq}}{dt} + g\omega_s\left(L_r\sigma i_{rd} + \frac{MV_s}{\omega_s L_s}\right) \end{cases} \quad (12)$$

Where g and σ denote respectively the slip and the leakage coefficient.

Fig.3 built by relations (11), (12), (13) and (14) shows diagram where rotor voltages are the input and active and reactive powers are the output.

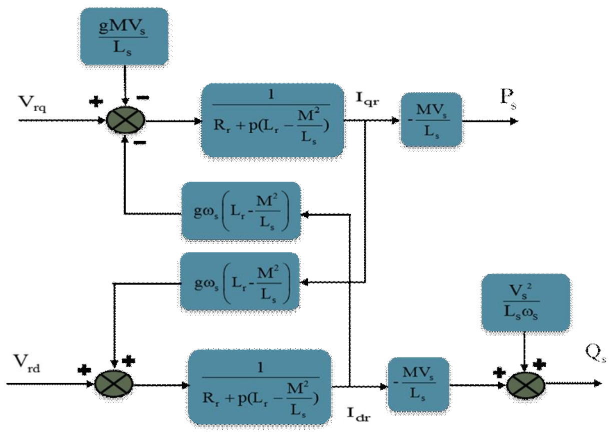

Figure 3: Block Diagram of simplified DFIG model

4- THE HYBRID CONTROLLER

This new topology of hybrid controller named Fuzzy-VGPI is built on combination of the variable gain PI controller and the fuzzy logic one. First, the general characteristics of the VGPI controller is showed and followed by the presentation of the fuzzy logic controller. Based on these two types of controllers, the technique of hybridization will be studied.

4.1- VGPI Controller Structure

The use of PI controllers to command a DFIG is often characterized by an overshoot in tracking mode and a poor load disturbance rejection. This is mainly caused by the fact that the gains of the controller cannot be set to solve the overshoot and load disturbance rejection problems simultaneously. Overshoot elimination setting will cause a poor load disturbance rejection and rapid load disturbance rejection setting will cause important overshoot or even instability for the system (Chikouche 2013; Miloudi 2007)

To overcome this problem, the use of VGPI controllers is proposed. A VGPI controller is a generalization of the classical PI controller where the proportional and integrator gains vary along a tuning curve. Each gain of the proposed controller has four tuning parameters (Chikouche 2013; Miloudi and Draou 2005; Miloudi 2007; Shreyash Vir and Sarika Kalra 2016):

- Initial gain value or start up setting which permits overshoot elimination.
- Final gain value or steady state mode setting which permits rapid load disturbance rejection.
- Gain transient mode function which is a polynomial curve that joins the gain initial value to the gain final value.
- Saturation time which is the time at which the gain reaches its final value.

The entire number n of the gain transient mode polynomial function is defined as the degree or order of the variable gain PI controller.

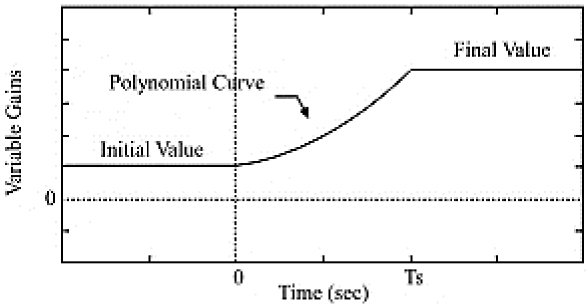

Figure 4: Variable PI Gains Tuning Curve

If e(t) is the signal input to the VGPI controller the output y(t) is given by (Chikouche 2013; Miloudi and Draou 2005; Miloudi 2007; Shreyash Vir and Sarika Kalra 2016):

$$y(t)=K_p e(t)+\int_0^t K_i e(t)dt \tag{13}$$

With

$$K_p=\begin{cases}(K_{pf}-K_{pi})(\frac{t}{t_s})^n+K_{pi} & \text{if } t<t_s\\ K_{pf} & \text{if } t\geq t_s\end{cases} \tag{14}$$

$$K_i=\begin{cases}K_{if}(\frac{t}{t_s})^n & \text{if } t<t_s\\ K_{if} & \text{if } t\geq t_s\end{cases} \tag{15}$$

Where K_{pi} and K_{pf} are the initial and final values of the proportional gain K_P and K_{if} is the final value of the integrator gain K_i. The initial value of K_i is taken to be zero. It is noted that a classic PI controller is a VGPI controller of degree zero.

The VGPI controller in vector control of DFIG is used as presented in Figure 5.

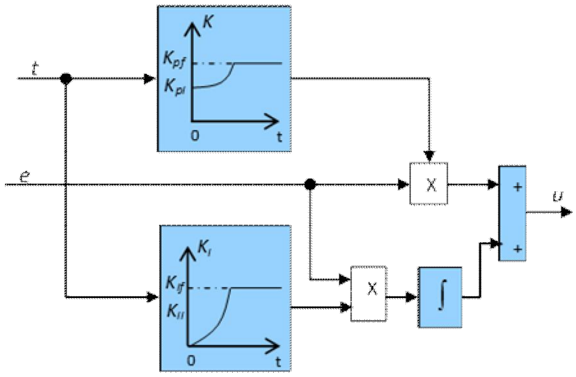

Figure 5: The Structure of VGPI Controller

For the VGPI synthesis, a generalized method using by (Andrianantenaina and *al* 2015, 2016) is chosen to determine the parameters of the classical PI controller. The gains of classical PI are taken to be the terminal values of the VGPI controller. These conditions are adopted: n =1, T_S=0.1[s]

4.2- Fuzzy logic controller

The method built around fuzzy logic avoids modeling the system but it is clear that having knowledge of its behavior is always useful. The reasoning is close to human perception. Nowadays, the fuzzy logic controller begins to take an important place in electrical applications. It can be used for optimization, and command (Andrianantenaina and *al* 2015; Razafinjaka and Andrianantenaina 2015, 2016). Figure 6 gives the common scheme for fuzzy logic controller.

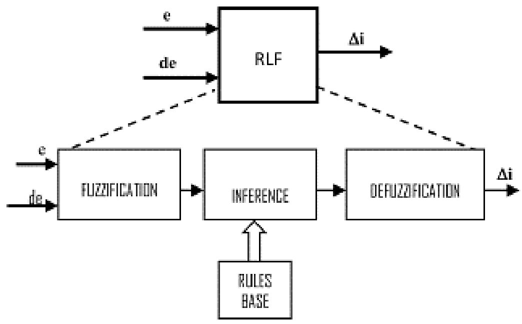

Figure 6: Structure of a fuzzy controller

With e, de and Δi denote respectively the error, the error variation and the output. The fuzzification consists in projecting a real physical variable distributed on the domains variable characterizing this variable: linguistic variable is so obtained and the fuzzification makes it possible to have a precise measurement by the membership degree of the real variable to each fuzzy subset. Generally, the inference method is a logical operation by which one admits a proposal under the terms of its relation with other proposals held for true. At this stage, rules are established by the knowledge of the desired behavior of the system.

They are often as:

(If x_1 is A) AND (x_2 is B) THEN $S_k = C_k$ (16)

Here x_1 and x_2 are the inputs and S_k the output which is also a linguistic variable. Membership functions may be defined for the output variable and there are several

inference methods, which may be applied. The results of aggregation of the inference rules give still fuzzy variables. To be used in a real control, these fuzzy variables must be translated into real or numerical variables: it is the function of the defuzzification block.
In this paper, the Sugeno's methods are chosen: a singleton is used as the membership function of the rule consequent combined by max-min method for the rule evaluation. Thus, in relation (16), C_k is a constant. The Sugeno defuzzification is then weighted average method.

$$s = \sum \frac{\mu(s_k).s_k}{\mu(s_k)} \qquad (17)$$

For the two inputs (e, de), the triangular and trapezoidal forms are used (Andrianantenaina and *al* 2015; Razafinjaka and Andrianantenaina 2015, 2016). The number of membership functions may be N=3, 5 or 7. Here N=3 is adopted. The output uses the singletons as membership function.

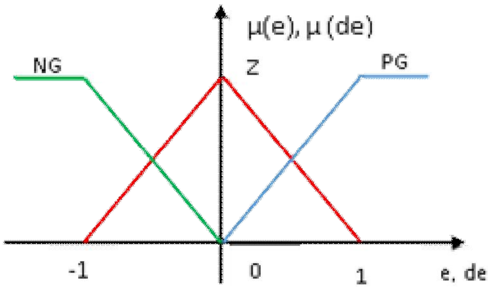

Figure 7: inputs Membership functions

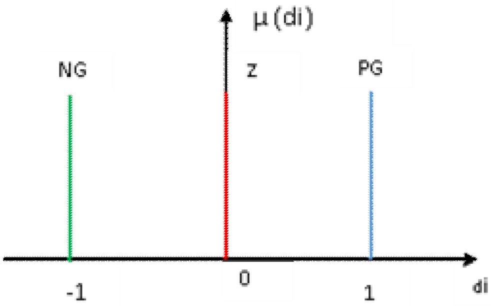

Figure 8: Output Membership functions

Table 1 gives the inference matrix.

Table 1: Rules base for N = 3

		E		
		NG	Z	PG
de	NG	NG	NG	0
	Z	NG	0	PG
	PG	0	PG	PG

The table 1 gives 9 rules. For example,
R_1: (IF e = NG) AND et (de = NG) THEN Δi = NG

4.3- Hybrid controller: FUZZY-VGPI

The hybrid controller is built on combination of these two topologies. Figure 9 shows the block diagram of the fuzzy-VGPI controller system.

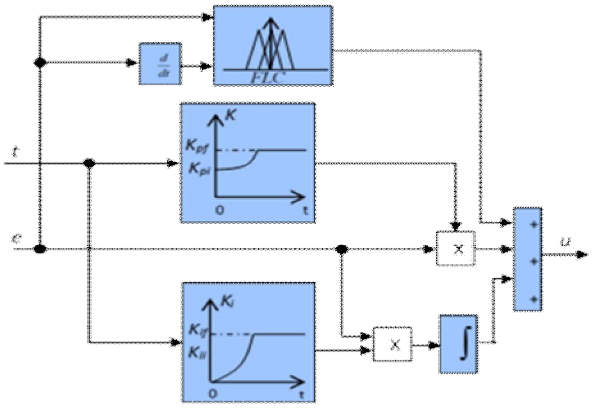

Figure 9: Basic scheme of proposed hybrid controller: FUZZY-VGPI

There are generally two used methods for controlling the independent regulation of active and reactive powers of the DFIG (Andrianantenaina and *al* 2015): the direct method, which consists to neglect the coupling terms and to put a controller on each axe to control active and reactive powers. In this case, the controllers command directly the rotor voltages of the machine. The second method takes into account the coupling terms and compensates them by using two loops that permit to control the powers and the rotor currents: it is called the indirect command and is based on the relations (11) and (12).
The block diagram with VGPI and FUZZY-VGPI is given by figure 10.

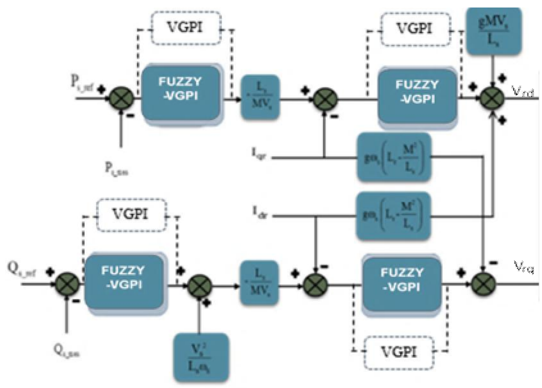

Figure 10: Block diagram of the vector control of the DFIG with VGPI and FUZZY-VGPI

5- SIMULATION AND RESULTS

The proposed method has been tested by tracking, disturbance rejection and robustness following speed and parameters variations specially the rotor resistance.
These conditions are so adopted:

- For the reference Tracking:

Variation of the active power reference P_{ref} and the reactive power reference Q_{ref}.

- For the Robustness Test:

We varied the speed,1450 rpm to 1600 rpm at t = 4,5 [s], and. the rotor resistance Rr to 2*Rr at t = 5 [s]

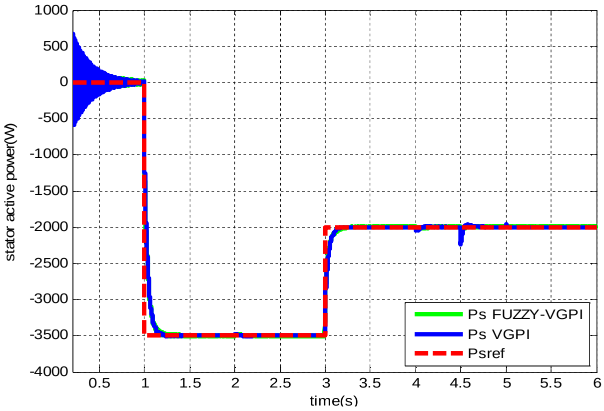

Figure 11: Active power curves

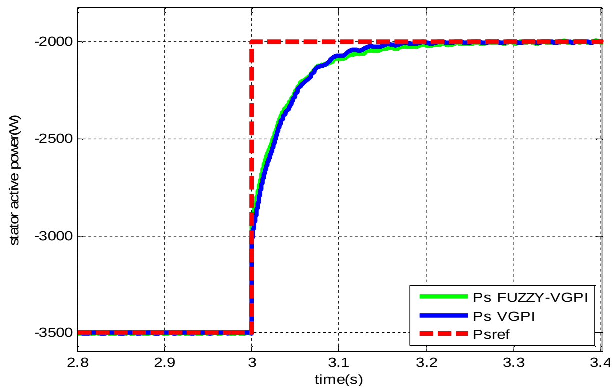

Figure 12: zoom on active power tracking

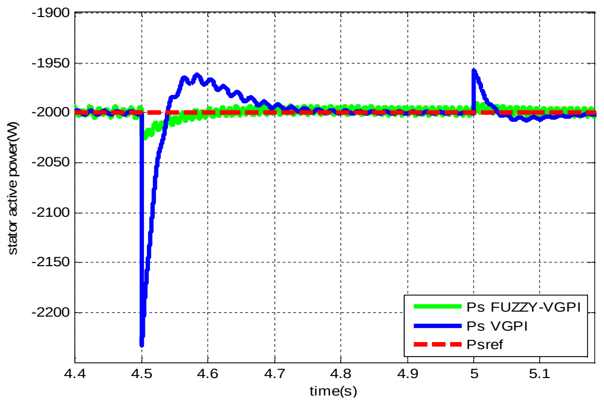

Figure 13 : Zoom on active power curve following speed and rotor resistance variations

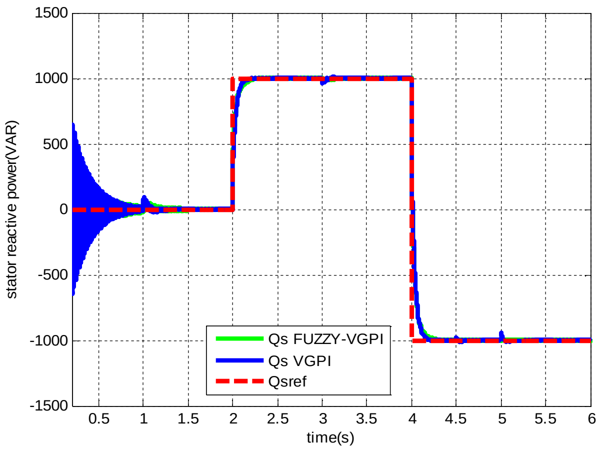

Figure 14: reactive power curves

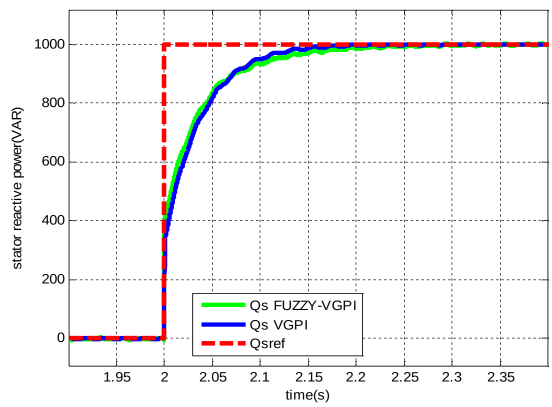

Figure 15: zoom on reactive power tracking

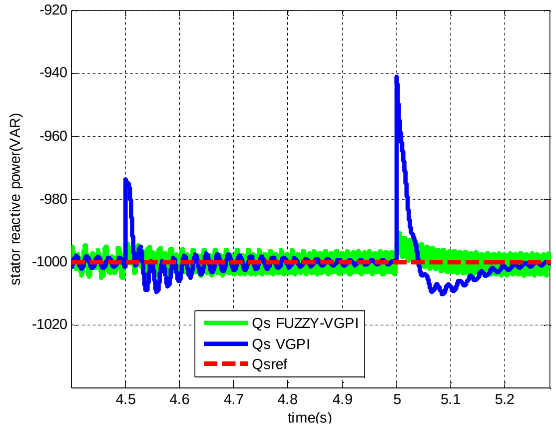

Figure 16: Zoom on reactive power curve following speed and rotor resistance variation

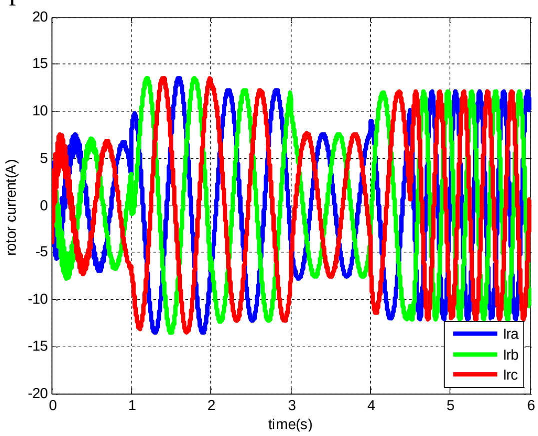

Figure 17 : Rotor currents

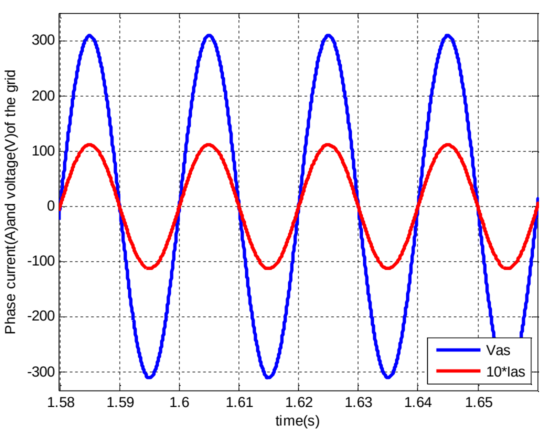

Figure 18: Stator voltage and current when Qs = 0

Table 2: Simulation results

Tests	VGPI n = 1, Ts=0,1(s)	FUZZY-VGPI n = 1, Ts=0,1(s)
Transient Behavior	D_1 = 0% t_M =0,2 [s]	D_1 = 0% t_M =0,2 [s]
t = 4,5 [s] Ω↑	ΔP = 230 [W] Δt = 0,25 [s]	ΔP = 25 [W] Δt = 0,1 [s]
t = 5 [s] R_r↑	ΔP = 42 [W] Δt = 0,2 [s]	ΔP = 10 [W] Δt = 0,05 [s]

Here t_M denotes the settling time or the duration, which the output reaches the steady state when the set point change is applied.

By Figure 11 and Figure 14, we can notice that the power references are well followed by the generator.

The negative sign of the active power shows that the generator injects the energy into the grid and the negative sign of the reactive power functions in capacitive mode, for inductive mode the power becomes automatically positive.

By Figure 12 and Figure 15, we can conclude that the both controllers give the same performance on tracking test with a quicker response and without overshoots.

For the robustness test, Figure 13 and Figure 16 show the effect of varying the parameters of the generator. Based on these results, we found that the fuzzy-VGPI is more robust and has better performance than VGPI one.

When Qs = 0, statorique voltage and statorique current are purely sinusoidal and in phase (Figure 18). It ensures a good quality of the energy injected into the grid.

6- CONCLUSION

In this paper, a new topology to obtain a hybrid controller is proposed to be applied on DFIG used in WECS. The hybridization consists to combine a variable gain PI controller and fuzzy logic controller. The comparative study is made between VGPI controller and Fuzzy-VGPI one. The simulation results highlight that Fuzzy-VGPI gives better performances on disturbance rejection and robustness in respect of the speed and parameters variation especially with rotorique resistance variation.

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