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Vector Control of a Doubly-Fed Induction Generator by Using a Classical PI and a fuzzy PI Controllers

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***Abstract*—This work deals with the conversion of wind systems in order to improve the quality of the provided energy. To this end, we are interested in the modeling and the simulation of a Doubly-Fed Induction Generator (DFIG) with a wound rotor used in the electromechanical conversion of wind systems. In this paper, we carried out the modeling and the direct and indirect vector control of the (DFIG) by using a classical PI controller and then a fuzzy logic PI controller.**

The aim of these control systems is to minimize the interaction between active and reactive power and to ensure an efficient decoupling by the use of two algorithms: fuzzy logic control and classical control. The algorithms are developed and tested under Matlab/Simulink.

***Keywords*—Wind systems, DFIG, Modeling, Direct vector, Indirect vector, Classical PI controller, Fuzzy PI controller, Matlab-Simulink.**

I. INTRODUCTION

The vector control (also named Field Oriented Control - FOC) provides the possibility to control the DFIG as a DC machine with a natural decoupling between the flow (the inductor current) and the torque (the armature current)[1].

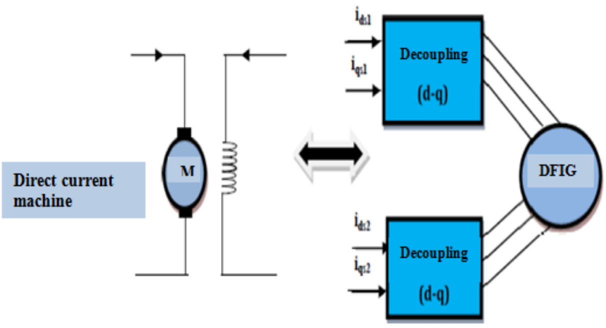

Fig. 1 Vector control

II. MODELING AND SIMULATION OF THE DOUBLY-FED INDUCTION GENERATOR

The doubly-fed induction generator (DFIG) is modeled in Park reference using the following equations [2]–[3]:

$V_{ds} = R_s i_{ds} + \frac{d}{dt}\emptyset_{ds} - \omega_s \emptyset_{qs}$ (1)

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$V_{qs} = R_s i_{qs} + \frac{d}{dt}\emptyset_{qs} + \omega_s \emptyset_{ds}$ (2)$V_{dr} = R_r i_{dr} + \frac{d}{dt}\emptyset_{dr} - \omega_r \emptyset_{qr}$ (3)

$V_{qs} = R_r i_{qr} + \frac{d}{dt}\emptyset_{qr} - \omega_r \emptyset_{dr}$ (4)

With:

$$\begin{cases} \phi_{ds} = L_S i_{ds} + M i_{dr} \\ \phi_{qs} = L_S i_{qs} + M i_{qr} \\ \phi_{dr} = L_r i_{dr} + M i_{ds} \\ \phi_{qr} = L_r i_{qr} + M i_{qs} \end{cases} (5), (6), (7), (8)$$

Also, we finally get the following mechanical equation:

$$C_{em} = C_r + j\frac{d\Omega}{dt} + f\Omega (9)$$

III. DFIG VECTOR CONTROL

To facilitate the control of the electrical production of the wind turbine, we are going to realize an independent control of active and reactive stator powers Ps and Qs. The reference mark (dq) is oriented so that:

$$\phi_{ds} = \phi_S et \phi_{qs} = 0 (10)$$

Assuming that the stator flux φs is constant (constant electrical network) and neglecting the stator resistance, we obtain for Ps and Qs:

$$P_S = -V_S \frac{M}{L_S} I_{qr} \ (11)$$

$$Q_S = -V_S \frac{M}{L_S} I_{dr} + \frac{V_S{}^2}{L_S \omega_S} (12)$$

The currents I_{qr} and I_{dr} are such that:

$V_{dr} = R_r I_{dr} + \left(L_r - \frac{M^2}{L_S}\right)\frac{dI_{qr}}{dt} + g\omega_S \left(L_r \frac{M^2}{L_S}\right) I_{qr}$ (13)
$V_{qr} = R_r I_{qr} + \left(L_r - \frac{M^2}{L_S}\right)\frac{dI_{qr}}{dt} + g\omega_S \left(L_r - \frac{M^2}{L_S}\right) I_{dr}\, g \frac{MV_S}{L_S}$ (14)

From the equations (11), (12), (13), (14), we can establish the relations between the voltages applied to the rotor of the machine and the stator powers that this generates, which allows us to describe the Block of The doubly fed induction generator (DFIG):

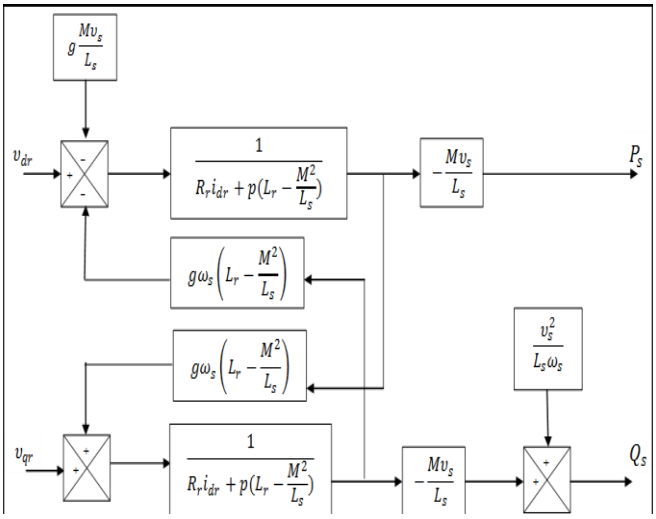

Fig.2Bloc diagram of the DFIG

We note that with a low value of slip g, we can establish the vector control because the influences of the couplings will remain low and the axes d and q can be separately controlled with their own controllers.

To make the vector control of this machine, there are two methods:

- The first method consists to neglecting the coupling terms and in setting up two regulators, one for each axis to directly control the rotor voltages of the machine. This method will be called the direct method.
- The second method consists in taking into account the coupling terms and to compensate them by setting up four regulators to control the powers and the rotor currents. This method is called the indirect method.

IV. DIRECT AND INDIRECT VECTOR CONTROL THROUGH THE USE OF A CLASSICAL PI CONTROLLER

The direct control consists to neglecting the terms of coupling between both axes because of the low value of the slip. We obtain then a vector control with a single regulator per axis as shown in fig. 3[4]–[5]–[6]–[7].

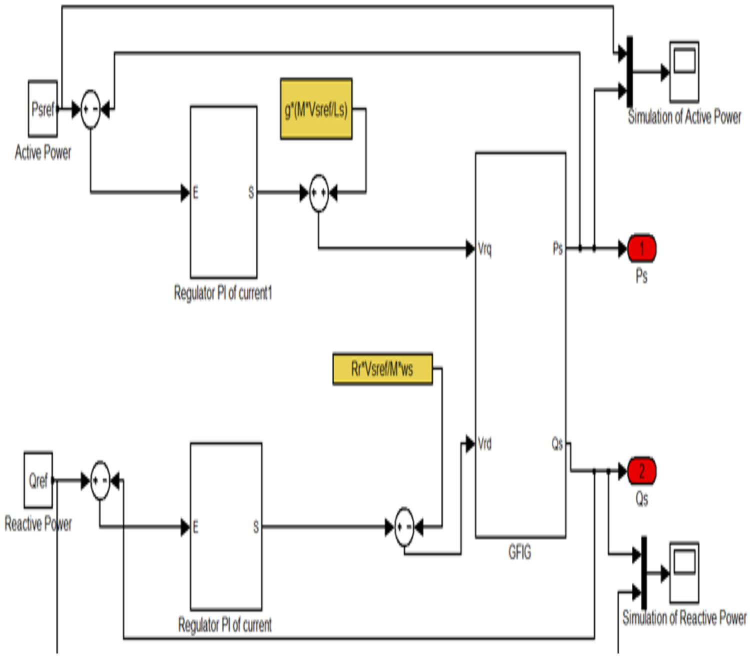

Fig.3Direct vector control with a classical PI controllers

The indirect control takes into account the coupling between (d,q) axes. We obtain then a vector control with two regulators per axis as shown in fig.4.

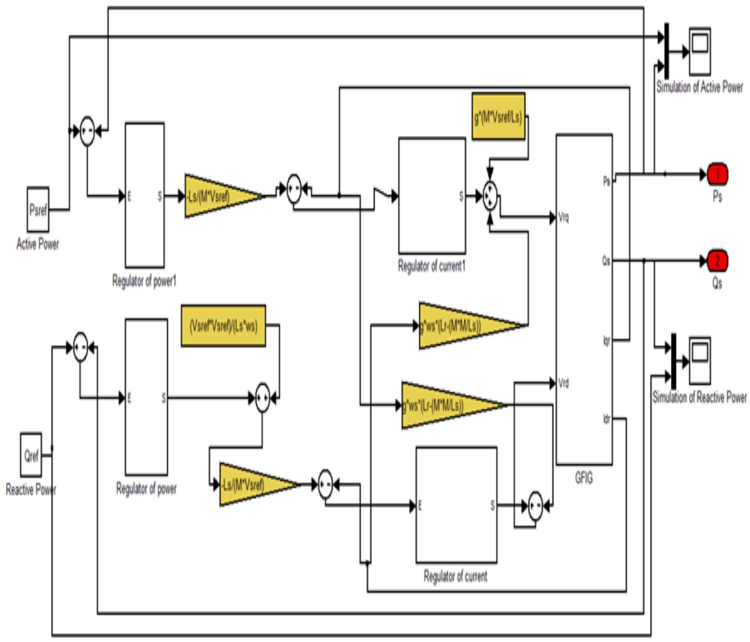

Fig.4Indirect vector control with a classical PI controllers

V. DIRECT AND INDIRECT VECTOR CONTROL THROUGH THE USE OF FUZZY PI CONTROLLERS

Fuzzy logic is a new method that has been introduced on a large scale in JAPAN, more recently it is more and more applied in Europe [8].

The structure of a control based on fuzzy logic is illustrated on the following fig.5:

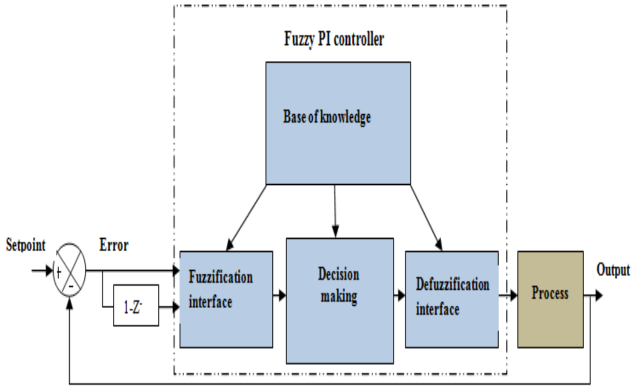

Fig. 5Basic structure of a fuzzy logic control

Our control system receives only determinist (not fuzzy) values, a fuzzy logic controller must convert determinist values to its input in fuzzy values, process them with the fuzzy rules, and convert the control signal to determinist values to apply them to the process [9].

VI. MODELING AND IDENTIFICATION OF THE FUZZY SYSTEM

The linear model of our fuzzy system is schematized in fig. 6 and 7.

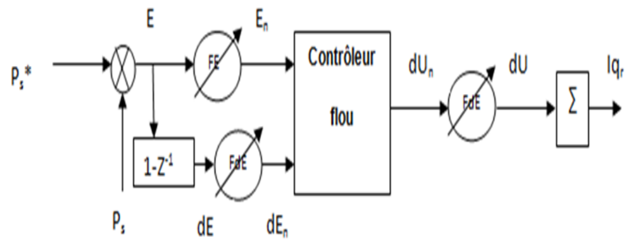

Fig. 6Diagram of the fuzzy controller of the active stator power

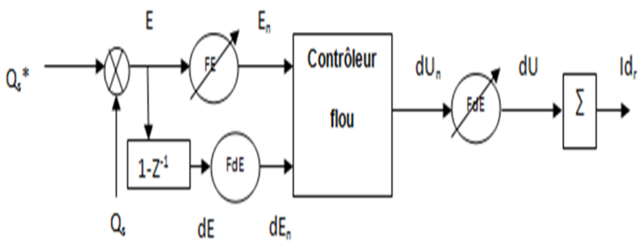

Fig. 7Diagram of the fuzzy controller of the reactive stator power

In the diagrams above, we note:

E: Error, defined by :

$E(k) = Qs*(k) - Qs(k)$ or $E(k) = Ps*(k) - Ps(k)$ (15)

dE:The derivative of the error, it is approximated by:

$\frac{E(k)-E(k-1)}{Te}$(16)

Te:Sampling period

The output of the controller is given by:

$Idr(k) = Idr(k-1) + dU(k-1)$ (17) *or*

$Iqr(k) = Iqr(k-1) + dU(k-1)$(18)

The Direct control of our system using fuzzy logic is shown in fig. 8:

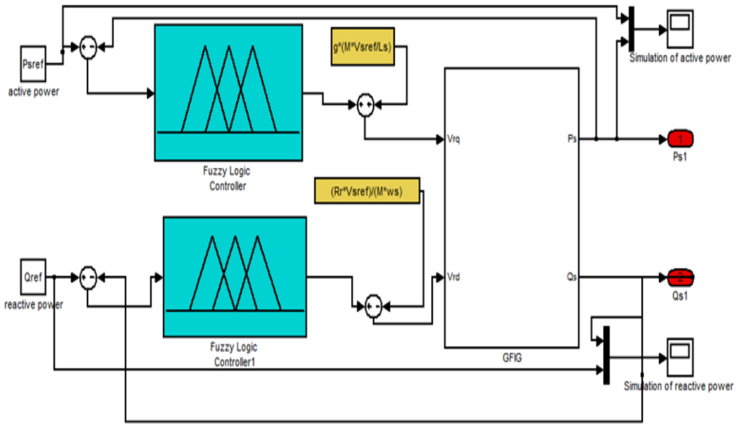

Fig.8Direct Vector Control with Fuzzy PI Controllers

After several simulation tests, we have chosen for the fuzzy controller a partition of speech universe with five fuzzy and privileged subsets the triangular and trapezoidal forms for the membership functions for the input variables (fig. 9,10). They allow easy implantation and stage of fuzzification.

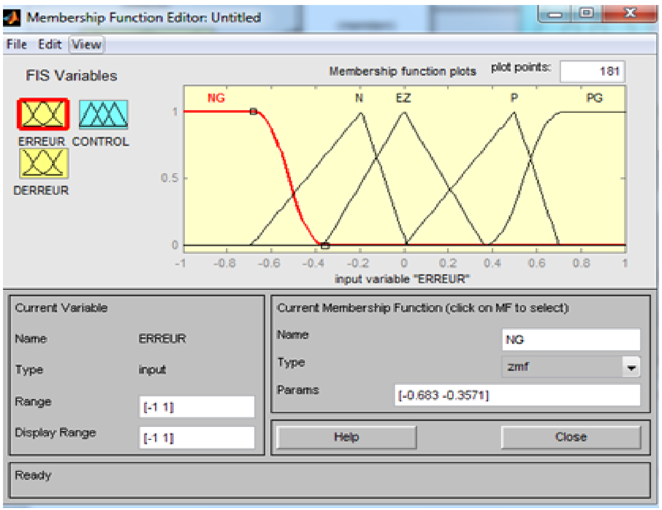

Fig. 9Fuzzification of the error

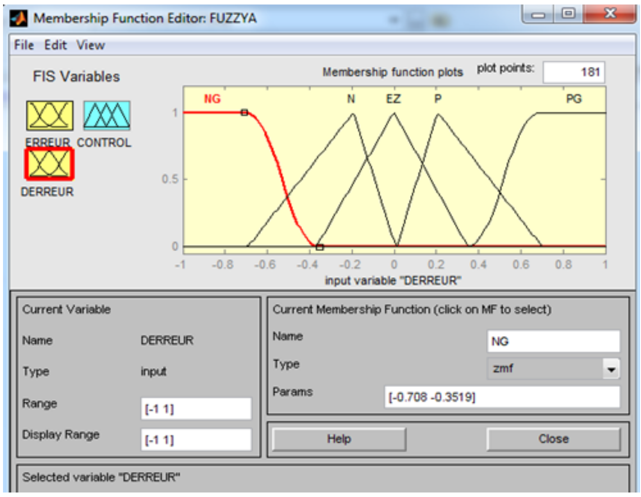

Fig. 10Fuzzification of variation of error

The establishment of the inference rules makes it possible to determine the output variable of regulators according to the input variables like shown in the following table:

		E (Error)				
		NG	N	EZ	P	PG
dE (Derivative of the error)	NG	NG	NG	N	N	EZ
	N	NG	N	N	EZ	P
	EZ	NG	N	EZ	P	PG
	P	NG	EZ	P	P	PG
	PG	EZ	P	P	PG	PG

Table IInference Matrix

After the establishment of the inference rules, we calculated, by using the center of gravity method and from the degrees of belonging to all the fuzzy sets of the output variable, the abscissa corresponding to the Value of this output. It is the method of defuzzification.

Our fuzzy controllers with two-input are represented by their characteristic surfaces (Fig.11). The controllers express the variations of the real value of the output of the regulators as a function of the inputs when the input goes through the universe of speech.

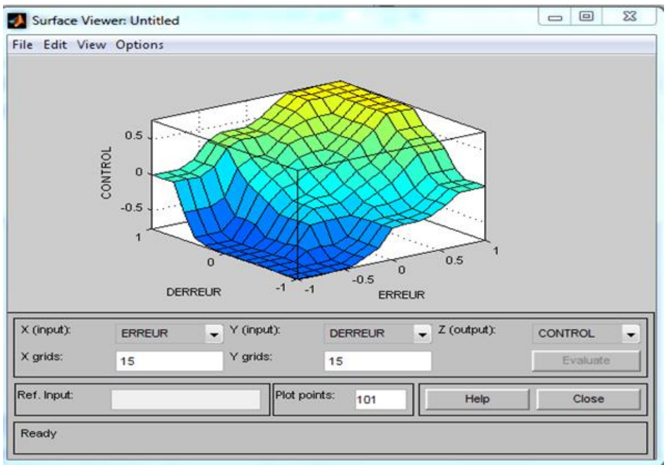

Fig. 5Stator voltage V_{sq} (V), V_{sd} (V) according to time (s).

VII. SIMULATION RESULTS

Modeling of the machine and the direct and indirect commands with a classical and a fuzzy PI has been implemented in the MATLAB environment in order to make regulatory tests.

In this part, we are going to illustrate the results of simulation of the power control by a classical PI and a fuzzy PI of a Doubly-Fed Induction Generator with oriented stator flux.

We have subjected this system to any value of active and reactive power in order to observe the behavior of its regulation.

The Doubly-Fed Induction Generator studied is characterized by the parameters given in table II:

Rotor resistance	0.21Ω	Number of pairs of poles	1
Rotor inductance	0.0136 H	Stator resistance	0.012 Ω
Mutual inductance	0.0135 H	Stator inductance	0.0137 H
Resistant couple	0.01 N.m	Single voltage of the network	230 V

Table IIGenerator settings

The earnings of the classical correctors (Kp and Ki) are calculated by the method of poles compensation and identification with a first order system and they have been refined after simulation.

A. *The direct method with a classical PI controller*

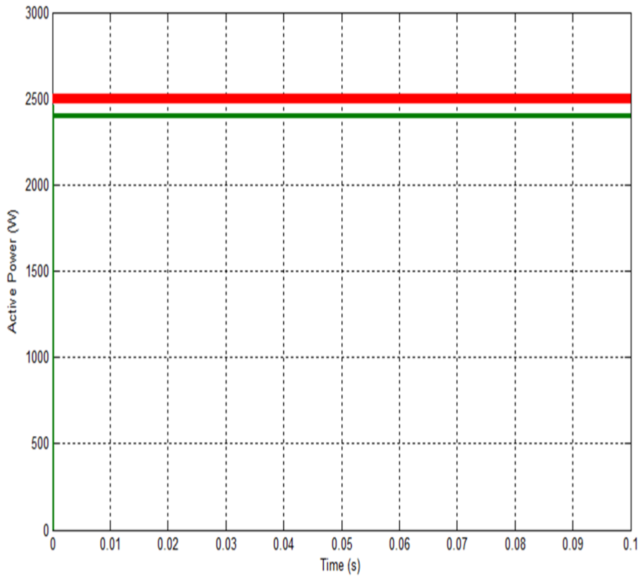

Fig. 6Active stator power with referenceP_s=2,5 kw

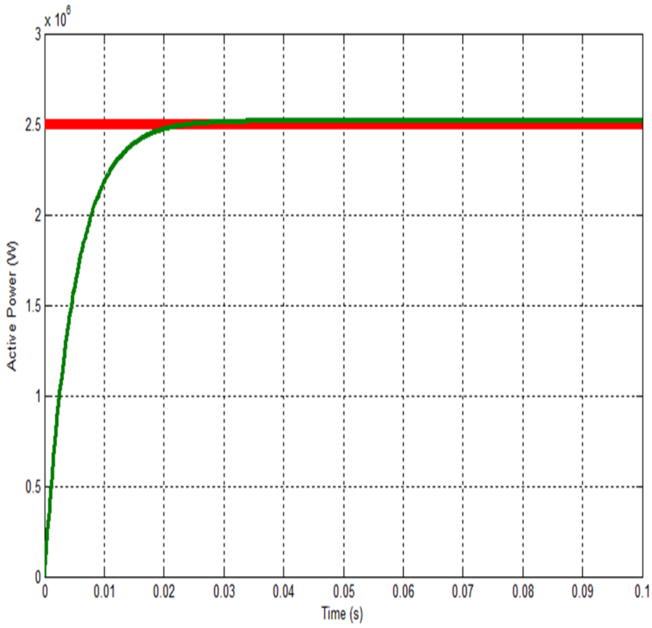

Fig. 7Active stator power with reference P_s=2500kw

B. The indirect method with a classical PI controller

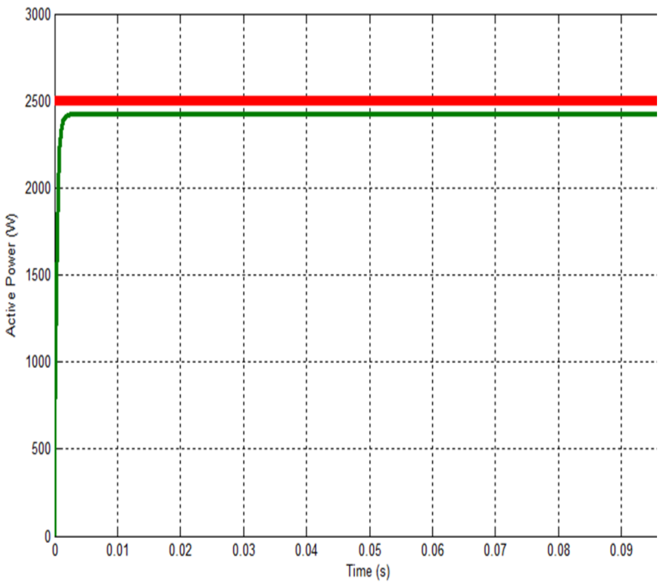

Fig. 14Active stator power with reference P_s=2,5 kw

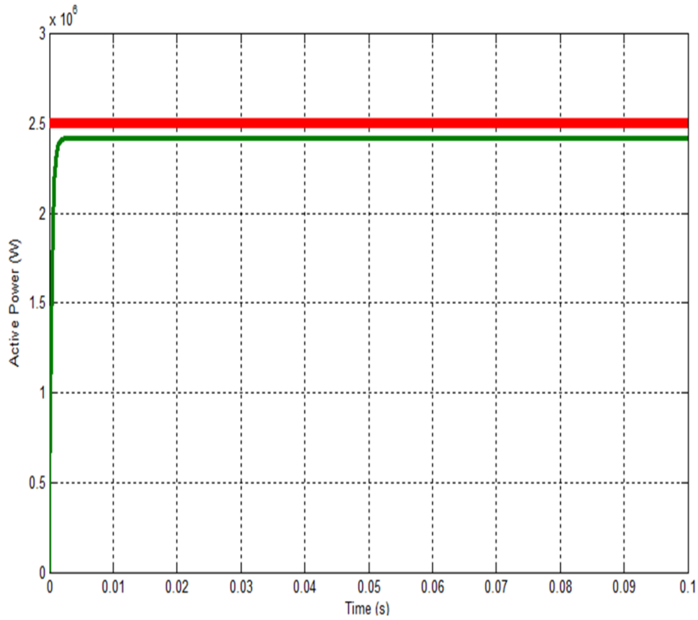

Fig. 15Active stator power with reference P_s=2500kw

C. The direct method with a fuzzy PI controller

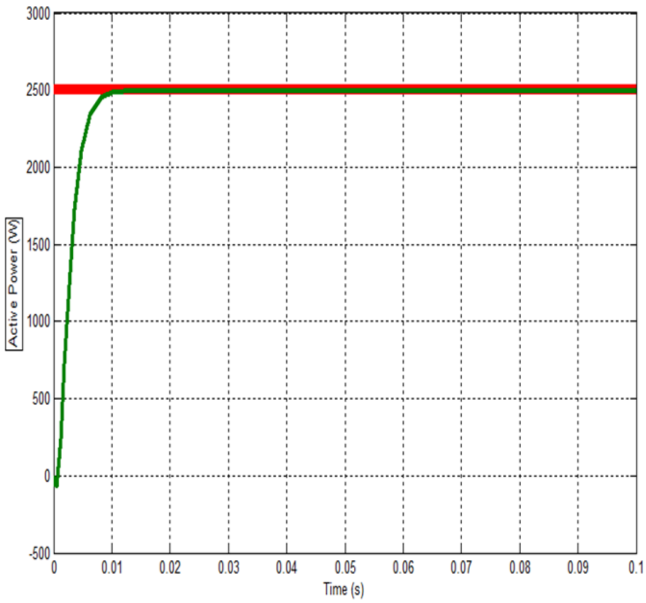

Fig. 16Active stator power with reference P_s=2,5 kw

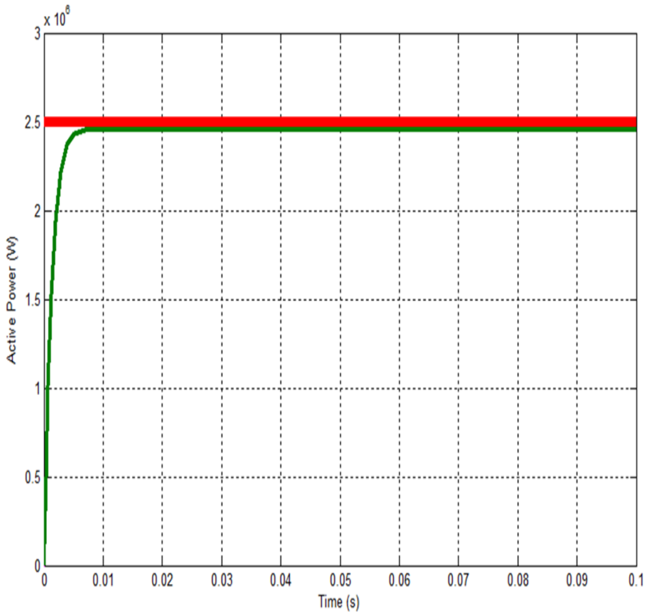

Fig. 17Active stator power with reference P_s=2500kw

In order to measure the performances of the synthesized fuzzy controller and to compare them with those of the classical regulator, it is necessary to define evaluation criteria. These criteria must take in account at the same time the maximal amplitude of the control error and the time required for the system to follow the setpoint.

The figures from 12 to 17 show that our system has a satisfactory dynamic which quickly reacts with a static error almost zero for direct and indirect control with the use of classical PI or direct control with the use of Fuzzy PI.

We noticed that having the indirect control with two imbricated control loops improves the robustness of the system, which remains an important point especially for systems with large variations of parameters (meteorological factors). If the setpoints were changed, the response of the system remains controlled with the indirect command.

We observe that the reference powers are correctly followed in the case of the fuzzy control, which shows that the fuzzy PI controller is robust compared to the classical PI because the fuzzy controller is able to forcing the system to keep its speed with some modifications which cannot completely diverge the responses of the greatnesses.

P_s: Active power output from stator (W);
Q_s: Reactive power output of stator (VAR);
Φ_{ds}: The stator flux following axis d (Wb);
Φ_{qs}: The stator flux following axis q (Wb);
P: The number of pole pairs;
M: Magnetizing inductance (H);
L_s: Stator cyclic inductance (H);
L_r: Rotor cyclic inductance (H);
V_{ds}: The stator voltage following axis d (V);
V_{qs}: The stator voltage following axis q (V);
I_{dr}: The rotor current following axis d (A);
I_{ds}: Stator current following axis d (A);
w_s: Stator pulsation (rad/s) ;
w_r: Rotor pulsation (rad/s) ;
V_{dr} : Rotor voltage following the direct axis (V);
V_{qr} : Rotor voltage following the quadrature axis (V);
Φ_s : Stator flux (Wb);
R_s : Stator resistance per phase (Ω);
R_r : Rotor resistance per phase (Ω);
f : Friction coefficient;
C_{em} : Electromagnetic torque (N. m);
C_r: Resistant torque (N. m);
g: Slip;

VIII. CONCLUSION

In this paper, we studied the modeling and the control of the Doubly-Fed Induction Generator and analyzed tow different control systems.

We noticed that indirect control leads to an efficient and robust system compared to the direct control (simulation under MATLAB/Simulink).

We also noticed that fuzzy logic control can outperform the conventional PI control by improving the dynamic response of the system. Indeed, the fuzzy regulator reduces the difference between the reference and the result (minimal error) but with a significant response time.

Moreover, in case of using a fuzzy-logic controller, the command reference calculation is only based on two values: the error and the variation of the error.

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