Fuzzy Control with Adaptive Gain of DFIG based WECS

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ABSTRACT

In this paper, a direct vector control using fuzzy logic controller with adaptive gain for a doubly fed induction generator (DFIG) based wind energy conversion system (WECS) is presented. The performance of fuzzy controllers is characterized by unsatisfactory performance: (wide overshoot, excessive oscillations and sensitivity to parametric variations). We propose a robust method, where the control gain will be continually adapted with the use of a set of fuzzy rules; we only consider the gain adaptation of the command. I mean the value of the gain will be determined by a rule base defined by the error and the variation of the error. Finally, the control of the active and reactive powers using a fuzzy logic controller with adaptive gain is simulated using software Matlab/Simulink, studies on a 1.5 MW DFIG wind generation system compared with the conventional fuzzy logic controller. Performance and robustness results obtained are presented and analyzed.

KEY WORDS

Wind energy conversion system ; Vector control ; Fuzzy logic controller ; Adaptive fuzzy logic controller.

I. INTRODUCTION

Sustainable development and renewable sources of energy are now attracting the interest of several research teams. Thus, the development of wind turbines represents a major investment in the field of technological research. Wind energy can contribute significantly to new energy sources that do not emit greenhouse gases [1-3]. Currently, variable-speed wind turbine systems have turned to power levels greater than 1 MW, in particular to take full advantage of the wind farm on the site of implantation. Because of their advantages, doubly fed induction generators are generally used in such installations [4-7]. That hase many advantages: Primarily, the variable speed generation (± 30% around the speed synchronism), the decoupled control of active and reactive powers, produce less acoustic noise and its mechanical losses are smaller than other types of generators [8-11]. This paper discusses the control of electrical power exchanged between the stator of the DFIG and the power network by controlling independently the active and reactive powers. Today, new control techniques that are more competitive, more able to overcome the nonlinearities of the systems and more adapted to the resolution of robustness problems are proposed for the research. In particular, fuzzy logic is another interesting alternative. After modeling the whole system, active and reactive powers provided by the DFIG are controlled using two types of controllers: fuzzy logic controller with adaptive control gain and conventional fuzzy logic controller. The paper is organized as follows, modeling of wind energy conversion system (WECS) based on a doubly fed induction generator (DFIG) in section 2. Control of active and reactive power of DFIG in section 3, section 4 is the synthesis of the two controllers and their performance are compared. The results and discussion of simulations obtained are presented in section 5. Finally, conclusion of this work in section 6.

II. WIND ENERGY CONVERSION SYSTEM MODELING

The WECS consists of the turbine that drives the DFIG at a variable speed of the gearbox. The stator is directly connected to the grid while the rotor is connected to the via two bidirectional converters in cascade via a continuous DC link, as shown in Fig. 1.

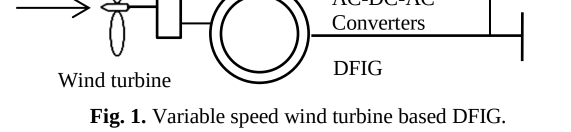


Fig. 1. Variable speed wind turbine based DFIG.

A. *WIND MODELING*

The wind speed can be modeled in deterministic form by a sum of several harmonics by: [14]:

$$V_v(t) = A + \sum_{n=1}^{i}(a_n \sin(b_n w_v f)) \tag{1}$$

with: *A* is constant, a_n,b_n $w_v$and, represent respectively the amplitude and the pulsation of the wind sample.

From equation 1 we can note that :

$$V_v(t) = 8 + 0.4\sin(1.47t) + 2\sin(0.56665t) + \sin(5.75t) + 0.8\sin(4.266t) \tag{2}$$

B. *MODELING OF THE TURBINE*

The aerodynamic power captured by a wind turbine is written in the following form:

$$P_{aero} = \frac{1}{2}\rho\pi R^2 V_v^3 C_p(\lambda,\beta) \tag{3}$$

The tip-speed ratio λ is expressed as follows:

$$\lambda = \frac{\Omega_{turb}.R}{V_v} \tag{4}$$

For a wind turbine of 1.5 MW, the expression of the power coefficient is:

$$C_p(\lambda,\beta) = \left(0.5 - 0.167(\beta - 2)\right)\sin\left(\frac{\pi(\lambda+0.1)}{10-0.3\beta}\right) - 0.00184(\lambda - 3)(\beta - 2) \tag{5}$$

The aerodynamic torque is expressed as follows:

$$T_{aero} = \frac{1}{2\Omega}\rho\pi R^2 V_v^3 C_p(\lambda,\beta) \tag{6}$$

The aerodynamic torque is given by the following equations:

$$T_g = \frac{T_{aero}}{G} \tag{7}$$

$$\Omega_{turb} = \frac{\Omega_{mec}}{G} \tag{8}$$

The mechanical equations of the system can be described by:

$$J_T \frac{d\Omega_{mec}}{dt} = T_{mec} = T_g - T_{em} - f\Omega_{mec} \tag{9}$$

With: $J_T = \frac{J_{turb}}{G^2} + J_g$

C. *MODELING OF THE DFIG*

The modelling of the DFIG is described in the d-q reference frame as: [11]:

$$\begin{cases} V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s\varphi_{sq} \\ V_{sq} = R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s\varphi_{sd} \\ V_{rd} = R_r I_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r\varphi_{rq} \\ V_{rq} = R_r I_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r\varphi_{rd} \end{cases} \tag{10}$$

The stator and rotor flux can be expressed as:

$$\begin{cases} \varphi_{sd} = L_s I_{sd} + M I_{rd} \\ \varphi_{sq} = L_s I_{sq} + M I_{rq} \\ \varphi_{rd} = L_r I_{rd} + M I_{sd} \\ \varphi_{rq} = L_r I_{rq} + M I_{sq} \end{cases} \tag{11}$$

The electromagnetic torque is expressed in terms of currents and fluxes by:

$$T_{em} = p\frac{M}{L_s}(I_{rq}\varphi_{sd} - I_{rd}\varphi_{sq}) \tag{12}$$

III. CONTROL OF ACTIVE AND REACTIVE POWERS OF DFIG

By aligning the q-axis of synchronous rotating reference frame on stator flux vector, the following equations can be written: $\varphi_{sd} = \varphi_s, \varphi_{sq} = 0$

The electromagnetic torque of equation (12) is then written as follows

$$T_{em} = p\frac{M}{L_s}(I_{rq}\varphi_{sd}) \tag{13}$$

The stator voltage and flux can be simplified as:

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = V_s = \omega_s \varphi_s \\ \varphi_{sd} = L_s I_{sd} + M I_{rd} \\ 0 = L_s I_{sq} + M I_{rq} \end{cases} \quad (14)$$

The stator powers and rotor voltage are written as follows:

$$\begin{cases} P_s = -V_s \frac{M}{L_s} I_{rq} \\ Q_s = \frac{V_s^2}{L_s \omega_s} - V_s \frac{M}{L_s} I_{rd} \end{cases} \quad (15)$$

$$\begin{cases} V_{rd} = R_r I_{rd} - g w_s L_r \sigma I_{rq} \\ V_{rq} = R_r I_{rq} + g w_s L_r \sigma I_{rd} + g.\frac{M.V_s}{L_s} \end{cases} \quad (16)$$

Block diagram of the electrical system to be regulated given by the Fig. 2:

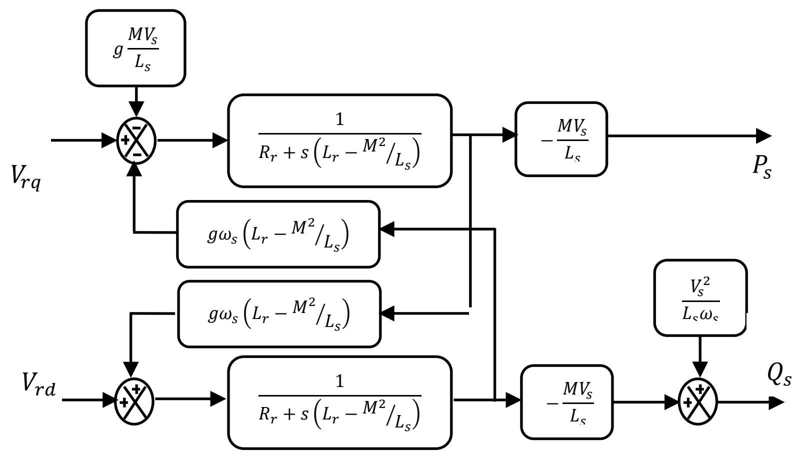


Fig. 2. Block diagram of the system to be regulated.

IV. DESCRIPTION OF FUZZY LOGIC CONTROLLER

The structure of a fuzzy control can be broken down into three modules:

The first module deals with the inputs of the system called fuzzification, which means the operation of transforming a numerical quantity into a fuzzy quantity.

The second module consists of the inference engine and the rule base. This module consists of rules of type: (If ..., Then ...) and which enables to pass degrees of belonging of the quantities of inputs to the degrees of belonging to the fuzzy subset of the control quantity. The inference engine will enable to generate a conclusion from the inputs and the active rules. It then calculates the degrees belonging to the fuzzy subset corresponding to the control of the system.

The last module consists of the defuzzification interface. It transforms a fuzzy size into a digital size. Several defuzzification strategies exist, the most used are: (center of gravity method, weighted heights method, average maximums method) [18-21].

A. *FUZZY CONTROLLER DESIGN OF ACTIVE AND REACTIVE POWERS*

In the system , two independent conventional fuzzy logic controllers are used to produce the desired the reference rotor voltages for controlling the stator active and reactive powers , the design of FLC goes through three main distinct steps, as shown in Fig. 3.

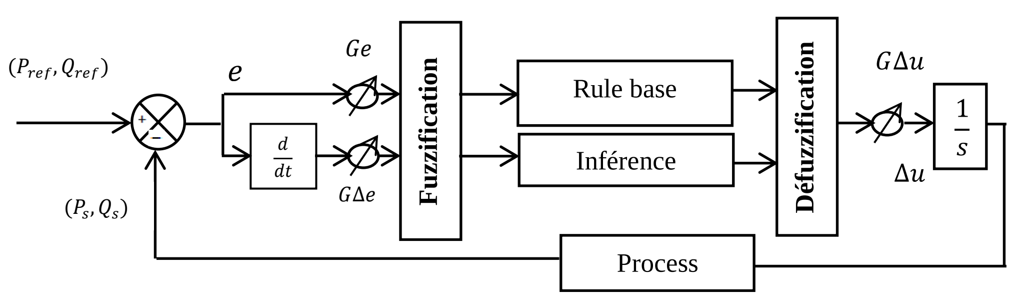


Fig. 3. Diagram of conventional FLC of active and reactive powers.

In the above diagram, the FLC inputs are calculated at time k as follows:

$\boldsymbol{e}$: Error, it is defined by:

$$e(k) = \left(P_{sref}, Q_{sref}\right)(k) - (P_s, Q_s)(k) \tag{17}$$

Δe : The derivative of the error it is approximated by:

$$\Delta e(k) = \frac{e(k)-e(k-1)}{T_e} \tag{18}$$

The output of the regulator is given by:

$$V_{r,dq}(k) = V_{r,dq}(k-1) + \Delta u(k) \tag{19}$$

The gains $G_e, G_{\Delta e}$, and $G_{\Delta u}$ are the gains that allow changing the sensitivity of the fuzzy regulator without changing the fuzzy structure. They are used to transform the physical values of the inputs into a normalized domain [-1 1] called discourse universe.

For the membership functions, we chose for each variable the triangular and trapezoidal shapes as shown in Fig. 4.

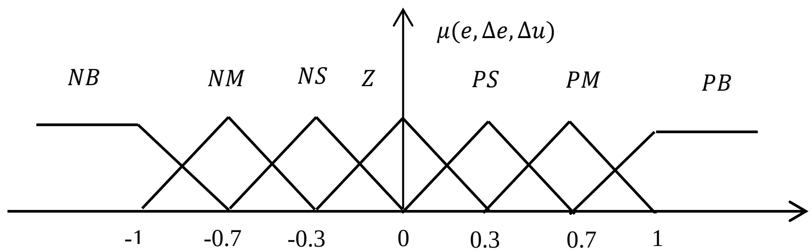


Fig. 4. *Membership functions for input variables, e, Δe and output Δu.*

To simplify the description of the inferences, we use an inference matrix, see Table 1.

$\boldsymbol{e, \Delta e}$	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NP	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PP	PM	PB	PB	PB	PB

Table. 1. Basic control of active and reactive power.

The inference method used is the method (Max-Min) which is easy to implement.
For defuzzification, we use the center of gravity method to obtain [5]:

$$\mathrm{dV_{r,dq}} = \frac{\sum_{i=1}^{m} u(\mathrm{dV_{r,dq}})\mathrm{dt}}{\sum_{i=1}^{m} u(\mathrm{dV_{r,dq}})} \tag{20}$$

B FUZZY CONTROLLER DESIGN WITH CONTROL GAIN ADAPTATION

In most studies done on fuzzy control, the gain associated with control variation when it is constant, it gives low results. In order to avoid the problem of instability in transient regime, the variations will be parameters.

To adapt fuzzy algorithm to each situation while ensuring a good stability of the system, the gain of the variation of the command is considered as a fuzzy variable. A decision table will be based on the error and error variation, see Table 2 as well as the associated membership function see Fig. 5.

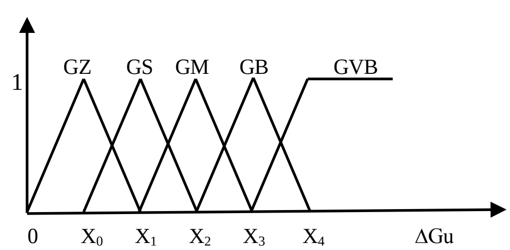


Fig. 5. Memberships function of control gain.

e / Δe	NB	NM	NS	Z	PS	PM	PB
NB	GVB	GVB	GB	GM	GS	GZ	GZ
NM	GVB	GB	GM	GS	GZ	GZ	GZ
NS	GB	GM	GS	GZ	GZ	GZ	GS
Z	GM	GS	GZ	GZ	GZ	GS	GM
PS	GS	GZ	GZ	GZ	GS	GM	GB
PM	GZ	GZ	GZ	GS	GM	GB	GVB
PB	GZ	GZ	GS	GM	GB	GVB	GVB

Table. 2. The decision on the gain of the control variation.

The diagram of the fuzzy controller taking into account the adaptation of the gain of the control becomes Fig. 6.

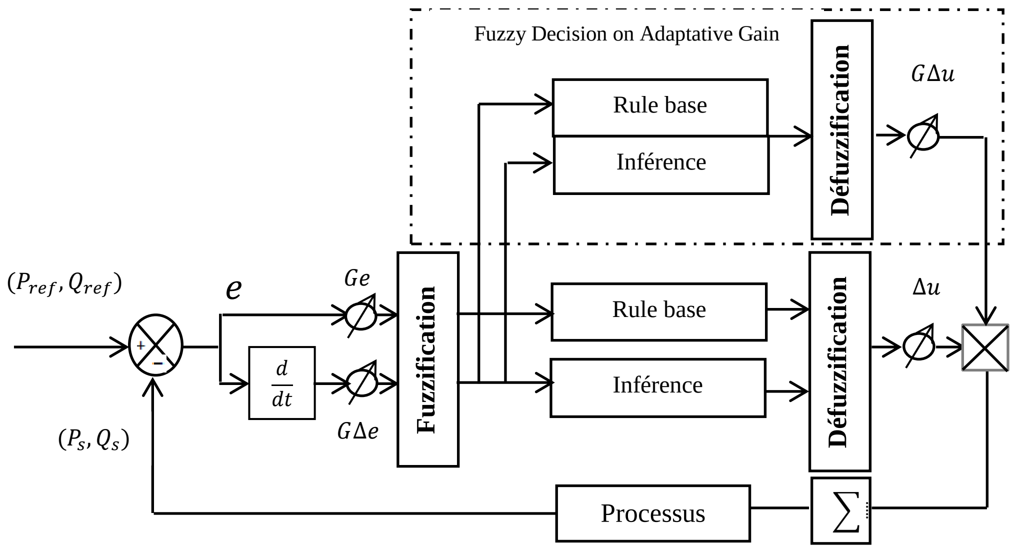


Fig. 6. Diagram of fuzzy controller with adaptive gain of active and reactive powers.

From the order decision table, the variation of the order between the moments T_k and T_{k+1} is given by:

$$U_{k+1} = U_k + G_{\Delta U_{k+1}} * \Delta U_{k+1} \quad (21)$$

V. SIMULATION RESULTS AND DISCUSSIONS.

In order to validate the results obtained through the different approaches, it is necessary to make a comparison of the static and dynamic characteristics of the two control techniques under the same operating conditions and in the same simulation configuration. Simulation studies of the DFIG-based training system were performed using MATLAB / Simulink. The parameters of a wind turbine and a DFIG are presented in Table.3.

During the first test, the active power is a function of the wind speed as shown in Fig. 7, the stator reactive power is set zero to ensure unity power factor at the stator side in order to optimize the quality of the energy returned to the grid. The average wind profile is around 8.5m/s applied to the turbine for 5 s.

We have represented on the Fig. 7 the profile of the wind which submits this wind turbine during the simulation time and the Fig. 8 is the speed of the generator ω_{mec} (tr/min).

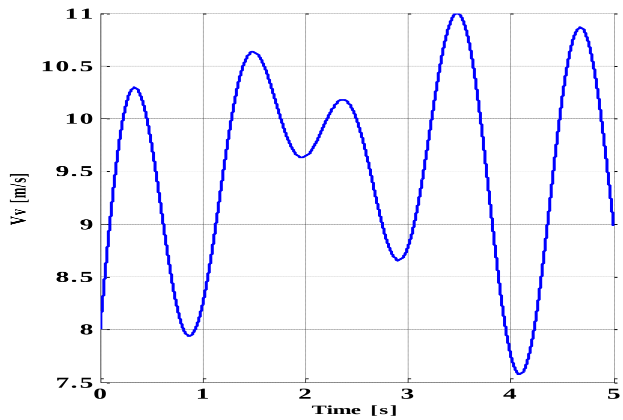


Fig. 7. Wind turbine speed

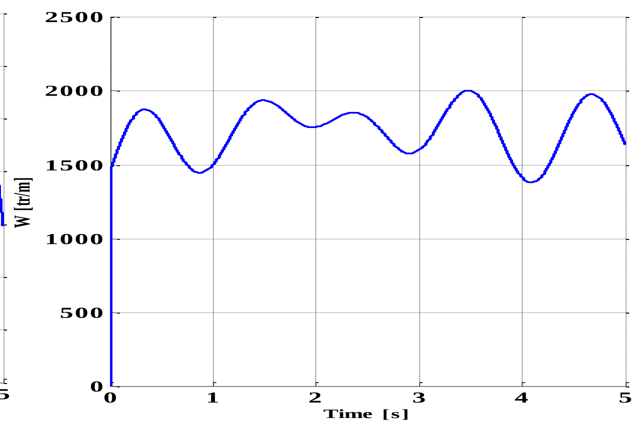


Fig. 8. Mechanical speed.

Fig. 9 and 10 represent the results of the active and reactive powers for the two proposed controllers. We notice that the responses by the adaptive fuzzy controller are more satisfactory, better response time without overshoot, low transient oscillations and well follow-up of the reference compared to the conventional fuzzy controller.

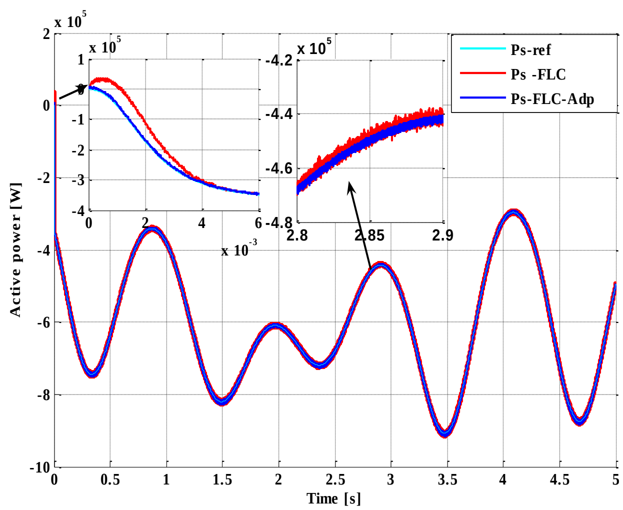


Fig. 9. Active power.

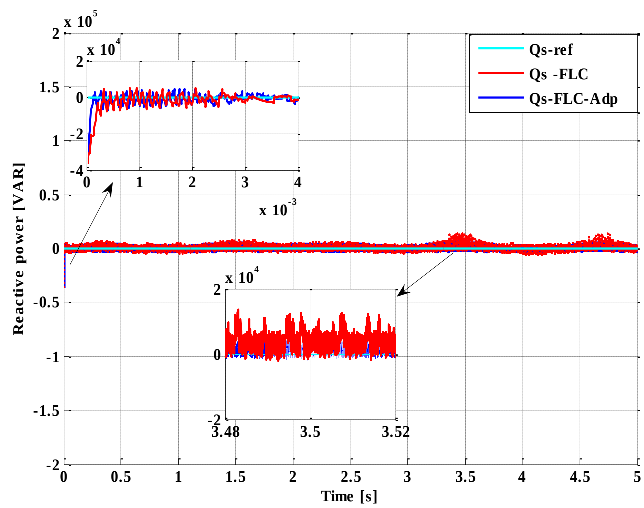
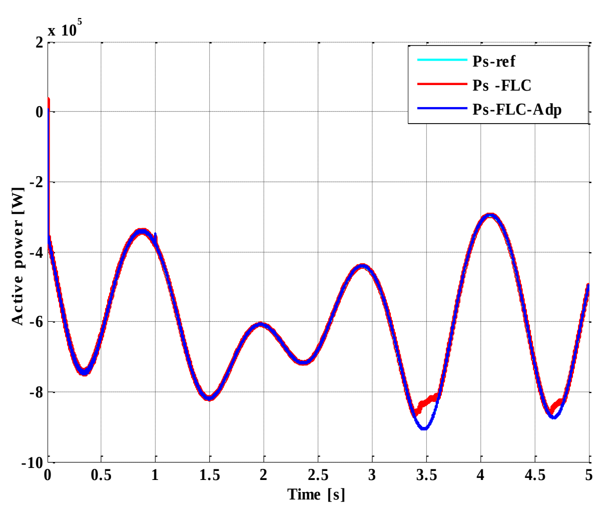
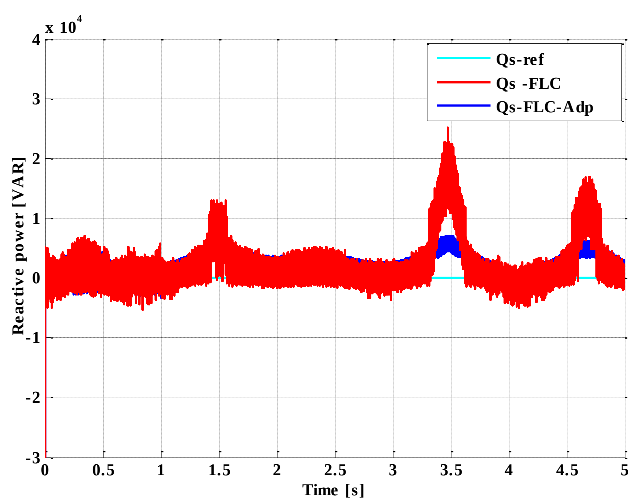


Fig. 10. Reactive power.

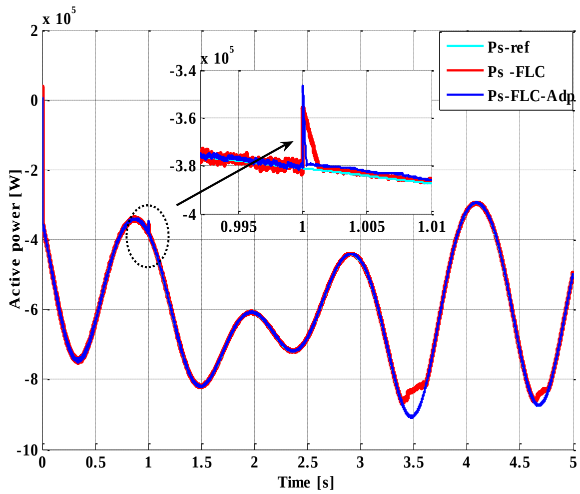




In order to test the influence of the variation of wind speed for both strategies. We will make an increase of the inductances (+25 % of Ls ,Fig. 11 and 12) and decrease of the mutual inductance (-30% of M, Fig. 13 and 14). In the variations of the stator and mutual inductances, we notice a divergence in the pursuit of power for the conventional fuzzy regulator, the proposed controllers are more efficient.

Fig. 11. Active power (Variation of Ls +25%).

Fig. 12. Reactive power (Variation of Ls +25%).



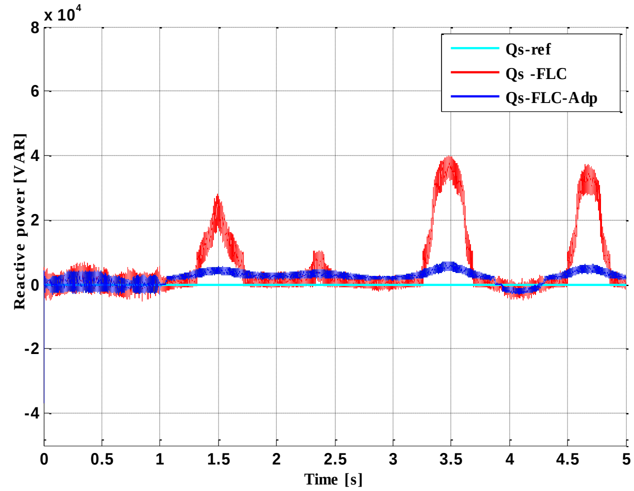


Fig. 13. Active power (Variation of M -30%).

Fig. 14. Reactive power (Variation of M -30%).

VI. CONCLUSION

In this paper, adaptive fuzzy control for DFIG has been presented. The suggested control has been compared to fuzzy control. Simulation results demonstrate that the power ripples and total harmonic distortion are lower in adaptive fuzzy control compared with classical control. The effectiveness of the proposed controller was verified using simulation tests with a 1.5 MW DFIG. Moreover, the proposed controller was examined for DFIG parameter variations it has been demonstrated that the suggested algorithm gives better performance.

The advantages of the suggested algorithm are highlighted by the following points:

1. Good robustness against the machine's parameter
2. Stability and the convergence towards the equilibrium

Table. 3. Parameters of DFIG wind turbine [16].

Parameters	Rated value	Unity
Nominal power Pn	1.5	Mw
Stator voltage Vs	398	V
Stator frequency fs	50	Hz
Number of pairs poles P	2	
Stator resistance Rs	0.012	Ω
Rotor resistance Rr	0.021	Ω
Stator inductance Ls	0.0137	H
Rotor inductance Lr	0.0136	H
Mutual inductance M	0.0135	H
Gearbox ratio G	90	
Rotor diameter R	35.25	m
Inertia Jt	1000	Kg m2
Viscous friction F	0.0024	Nm/rad

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