Nonlinear control of a doubly fed induction generator for wind energy conversion

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Abstract—**This paper deals with a variable speed device to produce electrical energy on a power network, based on a doubly-fed induction generator (DFIG) used in wind energy conversion systems. In the first place, we developed a model of the doubly fed induction machine. In order to control the power flowing between the stator of the DFIG and the power network, a control law is synthesized using two types of controllers : adaptive fuzzy logic and sliding mode. Their respective performances are compared in terms of power reference tracking, response to sudden speed variations, sensitivity to perturbations and robustness against machine parameters variations.**

Key words **—Doubly fed induction generator (DFIG), nonlinear controller, adaptive fuzzy logic, sliding mode.**

I. INTRODUCTION

Wind energy is the most promising renewable source of electrical power generation for the future. Many countries promote the wind power technology through various national programs and market incentives. Wind energy technology has evolved rapidly over the past three decades with increasing rotor diameters and the use of sophisticated power electronics to allow operation at variable speed [1]. Doubly fed induction generator is one of the most popular variable speed wind turbines in use nowadays. It is normally fed by a voltage source inverter.

In recent years, dozens of work was done by researchers on the control of DFIG using a simplified model of the latter by negligence the stator resistance. This assumption, although it has been proven that it is a realistic approximation for medium power machines used in wind energy conversion, but in reality, the model does not reflect reality because this parameter still exists and it can not be neglected. To overcome this drawback, in this work and in contrast to previous work, we used a real model of DFIG, ie without negligence in this resistance.

A lot of works have been presented with diverse control diagrams of DFIG. These control diagrams are usually based on vector control notion with conventional PI controllers as proposed by Pena et al. in [2]. The similar conventional controllers are also used to realize control techniques of DFIG when grid faults appear like unbalanced voltages [3,4] and voltage dips [5]. It has also been shown in [6,7] that glimmer problems could be resolved with suitable control strategies. Many of these works prove that stator reactive power control can be an adapted solution to these diverse problems.

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 power. After modeling the DFIG and choosing the appropriate *d-q* reference frame, active and reactive powers are controlled using two types of nonlinear controllers: adaptive fuzzy logic and sliding mode. The two controllers are compared in terms of power reference tracking, sensitivity to perturbations and robustness against machine parameters variations. Wind energy is the most promising renewable source of electrical power generation for the future. Many countries promote the wind power technology through various national programs and market incentives. Wind energy technology has evolved rapidly over the past three decades with increasing rotor diameters and the use of sophisticated power electronics to allow operation at variable speed [1]. Doubly fed induction generator is one of the most popular variable speed wind turbines in use nowadays. It is normally fed by a voltage source inverter.

II. THE DFIG MODEL

The dynamic voltages and fluxes equations of the DFIG in the synchronous *d-q* reference frame are given by :

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d}{dt}\psi_{ds} - \omega_s \psi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d}{dt}\psi_{qs} + \omega_s \psi_{ds} \\ V_{dr} = R_r I_{dr} + \dfrac{d}{dt}\psi_{dr} - \omega_r \psi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d}{dt}\psi_{qr} + \omega_r \psi_{dr} \end{cases}, \quad \begin{cases} \psi_{ds} = L_s I_{ds} + M I_{dr} \\ \psi_{qs} = L_s I_{qs} + M I_{qr} \\ \psi_{dr} = L_r I_{dr} + M I_{ds} \\ \psi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (1)$$

The stator and rotor angular velocities are linked by the following relation : $\omega_s = \omega + \omega_r$.

This electrical model is completed by the mechanical equation :

$$C_{em} = C_r + J\frac{d\Omega}{dt} + f\Omega \quad (2)$$

Where the electromagnetic torque C_{em} can be written as a function of stator fluxes and rotor currents :

$$C_{em} = p\frac{M}{L_s}(\psi_{qs}I_{dr} - \psi_{ds}I_{qr}) \quad (3)$$

III. Control strategy of the DFIG

In order to easily control the production of electricity by the wind turbine, we will carry out an independent control of active and reactive powers by orientation of the stator flux. This orientation will be made in this work with a real model of the DFIG, i.e. without negligence of the stator resistance [6].

By choosing a reference frame linked to the stator flux, rotor currents will be related directly to the stator active and reactive power. An adapted control of these currents will thus permit to control the power exchanged between the stator and the grid. If the stator flux is linked to the d-axis of the frame we have :

$$\psi_{ds} = \psi_s \text{ and } \psi_{qs} = 0 \quad (4)$$

and the electromagnetic torque can then be expressed as follows :

$$C_{em} = -p\frac{M}{L_s}\psi_{ds}I_{qr} \quad (3)$$

By substituting (4) in (1), the following rotor flux equations are obtained :

$$\begin{cases} \psi_s = L_s I_{ds} + MI_{dr} \\ 0 = L_s I_{qs} + MI_{qr} \end{cases} \quad (6)$$

In addition, the stator voltage equations are reduced to :

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_s \\ V_{qs} = R_s I_{qs} + \omega_s \psi_s \end{cases} \quad (7)$$

By supposing that the electrical supply network is stable**,** having for simple voltage V_s, which led to a stator flux ψ_s constant**.** This consideration associated with Eq. 5 shows that the electromagnetic torque only depends on the *q*-axis rotor current component. With these assumptions, the new stator voltage expressions can be written as follows :

$$\begin{cases} V_{ds} = R_s I_{ds} \\ V_{qs} = R_s I_{qs} + \omega_s \psi_s \end{cases} \quad (8)$$

Using (6), a relation between the stator and rotor currents can be established :

$$\begin{cases} I_{ds} = -\frac{M}{L_s} I_{dr} + \frac{\psi_s}{L_s} \\ I_{qs} = -\frac{M}{L_s} I_{qr} \end{cases} \quad (9)$$

The stator active and reactive powers are written :

$$\begin{cases} P_s = V_{ds}I_{ds} + V_{qs}I_{qs} \\ Q_s = V_{qs}I_{ds} - V_{ds}I_{qs} \end{cases} \quad (10)$$

By using (1), (7), (9) and (10), the statoric active and reactive power, the rotoric fluxes and voltages can be written versus rotoric currents as :

$$\begin{cases} P_s = \frac{\omega_s \psi_s M}{L_s} I_{qr} - \frac{V_s^2}{R_s} + \frac{\omega_s^2 \psi_s^2}{R_s} \\ Q_s = -\frac{\omega_s \psi_s M}{L_s} I_{dr} + \frac{\omega_s \psi_s^2}{L_s} \end{cases} \quad (11)$$

$$\begin{cases} \psi_{dr} = (L_r - \frac{M^2}{L_s})I_{dr} + \frac{M\psi_s}{L_s} \\ \psi_{qr} = (L_r - \frac{M^2}{L_s})I_{qr} \end{cases} \quad (12)$$

$$\begin{cases} V_{dr} = R_r I_{dr} + (L_r - \frac{M^2}{L_s})\frac{dI_{dr}}{dt} - g\omega_s(L_r - \frac{M^2}{L_s})I_{qr} \\ V_{qr} = R_r I_{qr} + (L_r - \frac{M^2}{L_s})\frac{dI_{qr}}{dt} + g\omega_s(L_r - \frac{M^2}{L_s})I_{dr} + g\omega_s\frac{M\psi_s}{L_s} \end{cases} \quad (13)$$

In steady state, the derivatives in (10) are equal to zero, which gives:

$$\begin{cases} V_{dr} = R_r I_{dr} - g\omega_s(L_r - \frac{M^2}{L_s})I_{qr} \\ V_{qr} = R_r I_{qr} + g\omega_s(L_r - \frac{M^2}{L_s})I_{dr} + g\omega_s\frac{M\psi_s}{L_s} \end{cases} \quad (14)$$

The third term, which constitutes cross-coupling terms, can be neglected because of their small influence. These terms can be compensated by an adequate synthesis of the regulators in the control loops.

IV. Controllers Synthesis

In this section, we have chosen to compare the performances of the DFIG with two different nonlinear controllers : adaptive fuzzy logic and sliding mode.

Based on relations (9), (11) and (14), the control system can be designed as shown in Fig. 1. The blocks R_{Idr} and R_{Iqr} represent rotor currents regulators, respectively I_{dr} and I_{qr}.

A. Adaptive fuzzy logic controller (AFLC)

When the conventional controllers, such as the Proportional Integral (PI) does not allow to obtain extremely high performances and that we do not have an important computing power to establish a standard predictive regulation, the fuzzy logic control proves to be an interesting approach. This type of control, approaching the human reasoning that makes use of the tolerance,

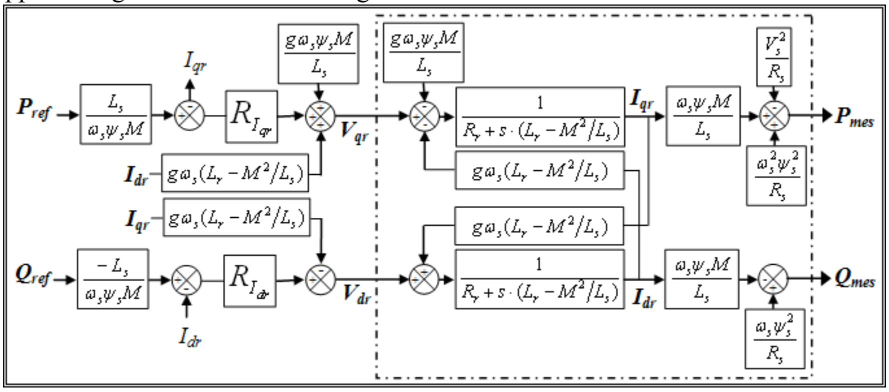

Figure 1. Power control of DFIG.

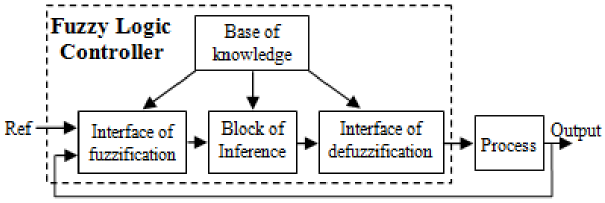

Figure 2. Structure of fuzzy logic controller.

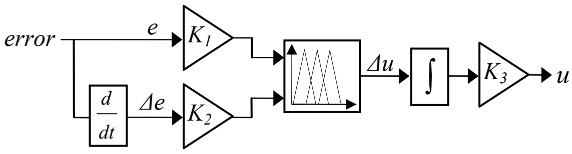

Figure 3. Block diagram of fuzzy logic controller.

uncertainty, imprecision and fuzziness in the decision-making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system just by incorporating the experts' knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations).

The main preference of the fuzzy logic is that is easy to implement control that it has the ability of generalisation. The approach of the basic structure of the fuzzy logic controller system is illustrated in Fig. 2 [8,9].

Input and output are non-fuzzy values and the basic configuration of the fuzzy logic controller (FLC) is featured in Fig. 3.

In the system presented in this study, Mamdani type of fuzzy logic is used for the currents controllers [9]. The command signals are the errors ($e(k)$, $e'(k)$) and change rate of errors ($\Delta e(k)$, $\Delta e'(k)$). Currents errors ($e(k)$, $e'(k)$) are calculate with comparison between currents references ($I_{dr\text{-}ref}$, $I_{qr\text{-}ref}$) and currents signals feedback (I_{dr}, I_{qr}). Currents errors and currents errors changing are fuzzy controller's inputs, so must currents errors changing ($\Delta e(k)$, $\Delta e'(k)$) are be calculated.

As it's shown by Fig. 2, fuzzy logic controller is based on three well known blocs: Fuzzyfication bloc, block of rule bases and defuzzyfication block, whose function is following briefly explained. The fuzzyfication stage transforms crisp values from a process into fuzzy sets. The second stage is the fuzzy rule bases which expresses relations between the input fuzzy sets of linguistic description rules A, B and the output fuzzy set C in the form of "IF A and B – THEN", and the defuzzyfication stage transforms the fuzzy sets in the output space into crisp control signals.

For the two proposed fuzzy controllers, the universes of discourses are first partitioned into the seven linguistic variables NB, NM, NS, EZ, PS, PM, PB, triangular membership functions are chosen to represent the linguistic variables and fuzzy singletons for the outputs are used.

The fuzzy rules that produce these control actions are reported in Table 1.

We use the following designations for membership functions:

-NB: Negative Big, -NM: Negative Middle,
-NS: Negative Small, - EZ: Equal Zero,
-PS: Positive Small, -PM: Positive Middle,
-PB: Positive Big.

These choices are described in Fig. 4.

TABLE I.
MATRIX OF INFERENCE

ΔE \ E	NB	NM	NS	EZ	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	EZ
NM	NB	NB	NB	NM	NS	EZ	PS
NS	NB	NB	NM	NS	EZ	PS	PM
EZ	NB	NM	NS	EZ	PS	PM	PB
PS	NM	NS	EZ	PS	PM	PB	PB
PM	NS	EZ	PS	PM	PB	PB	PB
PB	EZ	PS	PM	PB	PB	PB	PB

The application of the fuzzy logic regulators constitutes a powerful tool for the complex processes control. But its capacity of robustness remains fairly limited because it loses its property for the significant parametric variations.

Very recently, a new form of the adaptive control seemed remedy for this problem; it is called behavior model control (BMC). Its principle is to impose on the process a behavior comparable to that of a model chosen beforehand, in spite of the risks and the significant disturbances which affect the process during its operation. It requires at least two regulators, a model and the process (Fig. 5).

According to a reference variable y_{ref}, a principal regulator $C_{pl}(s)$ delivers a size of regulation u_{reg}. The size from the principal regulator u_{reg} is applied to a model

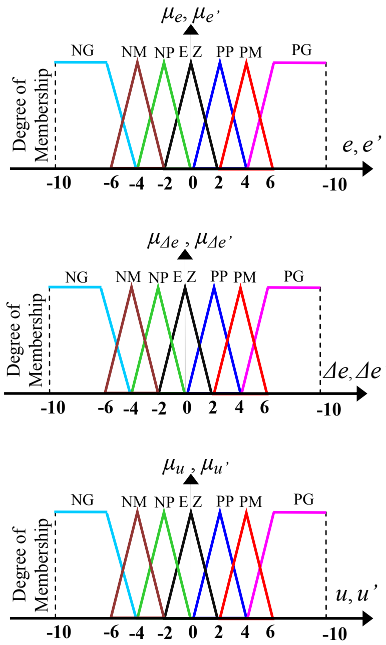

Figure 4. Fuzzy sets and its memberships functions.

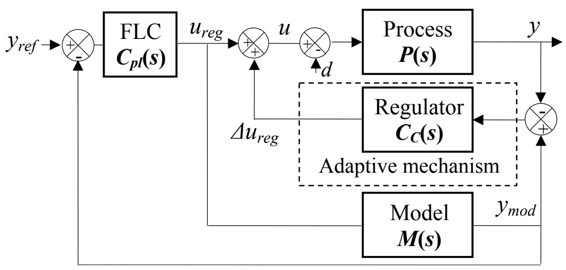

Figure 5. Behavior model control (functional diagram).

chosen beforehand $M(s)$, called model of behavior, this last defines an output variable y_{mod}. A second regulator called regulator of adaptation $C_C(s)$, use the difference between the output of the process y and that of the model y_{mod} to define the complementary size of control Δu_{reg}. By cancelling the error ($y - y_{mod}$), the behavior of the process becomes similar to that of the model.

This complementary order will be added to the size u_{reg} then provided to process $P(s)$. So this auxiliary control increases the robustness of the total control, it rejects indirectly various disturbances facilitate the synthesis of traditional control and allows the linearization of a non-linear process through linear model [10].

It should be noted that the principal regulator is used to eliminate the error between the reference size y_{ref} and that from the output, which can as well be the output of the model y_{mod} or that of the process y.

We proceed now the application of the behavior model fuzzy control to regulate the rotor currents of the DFIG. We call it: **behavior model fuzzy control**, because all the regulators used for its design are fuzzy regulators.

By the combination of the two control diagrams given by figures 2 and 5, we can build the block diagram expressed by Fig. 6. The model "$M(s)$" used in the control loops of the two rotor currents is the same one, the choice of this model went on the transfer functions of the machine which connect the control voltages to the measured currents (Eq. 15).

$$M(s) = \frac{1}{R_r + s\cdot(L_r - M^2 / L_s)} \qquad (15)$$

According to the bloc diagram given by Fig. 6, we need two fuzzy regulators for each loop of current : two principal regulators $\boldsymbol{C_{pl}(s)}$ which remain the same ones used in session (4.1) and two regulators of adaptation (of behavior) $\boldsymbol{C_c(s)}$. These latter make it possible to cancel the errors between the output currents of the DFIG (I_{dr}, I_{qr}) and those of the models (I_{drm}, I_{qrm}).Thus it's very convenient to use these errors and their derivative like inputs for these correctors. By integrating the outputs of the latter, one obtains the correction signals (ΔI_{dr}, ΔI_{qr}), which make it possible the DFIG to have a behavior comparable to that of the model.

The internal structure of the adaptation regulators "FLC $\boldsymbol{C_c}$" is identical to that of the principal Regulators, i.e. it is composed of three blocks: Fuzzification, Inference and the deffuzification.

Just as for the design process of the principal regulators, each input is represented by seven vague sets. What leads to a base of rules made up of forty-nine (49) rules. The method of inference used is that of Mamdani (Max Min).Whereas the defuzzification is carried out by the centre of gravity method.

B. *Sliding mode controller*

The sliding mode technique is developed from variable structure control to solve the disadvantages of other designs of nonlinear control systems. The sliding mode is a technique to adjust feedback by previously defining a surface. The system which is controlled will be forced to that surface, then the behaviour of the system slides to the desired equilibrium point.

The main feature of this control is that we only need to drive the error to a "switching surface". When the system is in "sliding mode", the system behaviour is not affected by any modelling uncertainties and/or disturbances. The design of the control system will be demonstrated for a nonlinear system presented in the canonical form [11] :

$$\dot{x} = f(x,t) + B(x,t)V(x,t), x \in R^n,\ V \in R^m,\ ran(B(x,t)) = m \qquad (16)$$

with control in the sliding mode, the goal is to keep the system motion on the manifold S, which is defined as :

$$S = \{x : e(x, t)=0\} \qquad (17)$$

$$e = x^d - x \qquad (18)$$

e is the tracking error vector, x^d is the desired state, x is the state vector. The control input u has to guarantee that the motion of the system described in (16) is restricted to belong to the manifold S in the state space. The sliding mode control should be chosen such that the candidate Lyapunov function satisfies the Lyapunov stability criteria :

$$\vartheta = \frac{1}{2} S(x)^2, \tag{19}$$

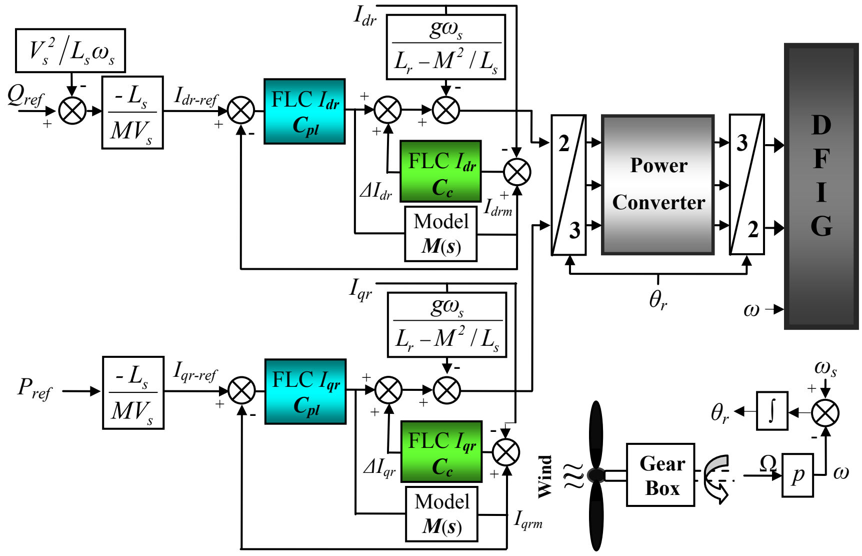

Figure 6. Bloc diagram of the adaptive fuzzy logic control of the DFIG.

$$\dot{\vartheta} = S(x)\dot{S}(x). \tag{20}$$

This can be assured for :

$$\dot{\vartheta} = -\eta |S(x)| \tag{21}$$

η is strictly positive. Essentially, equation (19) states that the squared "distance" to the surface, measured by $e(x)^2$, decreases along all system trajectories. Therefore (20), (21) satisfy the Lyapunov condition. With selected Lyapunov function the stability of the whole control system is guaranteed. The control function will satisfy reaching conditions in the following form :

$$V^{com} = V^{eq} + V^n \tag{22}$$

V^{com} is the control vector, V^{eq} is the equivalent control vector, V^n is the correction factor and must be calculated so that the stability conditions for the selected control are satisfied.

$$V^n = K\ \mathrm{sat}((S(x)/\delta) \tag{23}$$

sat$((S(x)/\delta)$ is the proposed saturation function, δ is the boundary layer thickness. In this paper we propose the Slotine method :

$$S(X) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e \tag{24}$$

λ is a positive coefficient and n is the relative degree.

B.1. Application to the DFIG control

The rotor currents which are linked to active and reactive powers by Eq.11 have to track appropriate current references, so a sliding mode control based on the above Park reference frame is used. The sliding surfaces representing the error between the measured and references rotor currents are given by this relation [4]:

$$\begin{cases} S_d = I_{dr-ref} - I_{dr} \\ S_q = I_{qr-ref} - I_{qr} \end{cases} \tag{25}$$

V_{dr} and V_{qr} will be the two components of the control vector used to constraint the system to converge to S_{dq}=0. The control vector U_{dqeq} is obtained by imposing $\dot{S}_{dq} = 0$ so the equivalent control components are given by the following relation :

$$U_{eqdq} = \begin{bmatrix} \left(L_r - \frac{M^2}{L_s}\right)\dot{I}_{dr\_ref} + g\omega_s\left(L_r - \frac{M^2}{L_s}\right)I_{qr} \\ \left(L_r - \frac{M^2}{L_s}\right)\dot{I}_{qr\_ref} + g\omega_s\left(L_r - \frac{M^2}{L_s}\right)I_{dr} + R_r I_{qr} + \frac{gMV_s}{L_s} \end{bmatrix} \tag{26}$$

To obtain good performances, dynamic and commutations around the surfaces, the control vector is imposed as follows :

$$U_{dq} = U_{eqdq} + K \cdot \mathrm{sat}(S_{dq}) \tag{27}$$

The sliding mode will exist only if the following condition is met :

$$S \cdot \dot{S} < 0 \tag{28}$$

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, simulations are realized with a 1.5 MW generator coupled to a 398V/50Hz grid. The machine's parameters are given next in appendix. In the objective to appraised the performances of the controllers, three categories of tests have been realized : pursuit test,

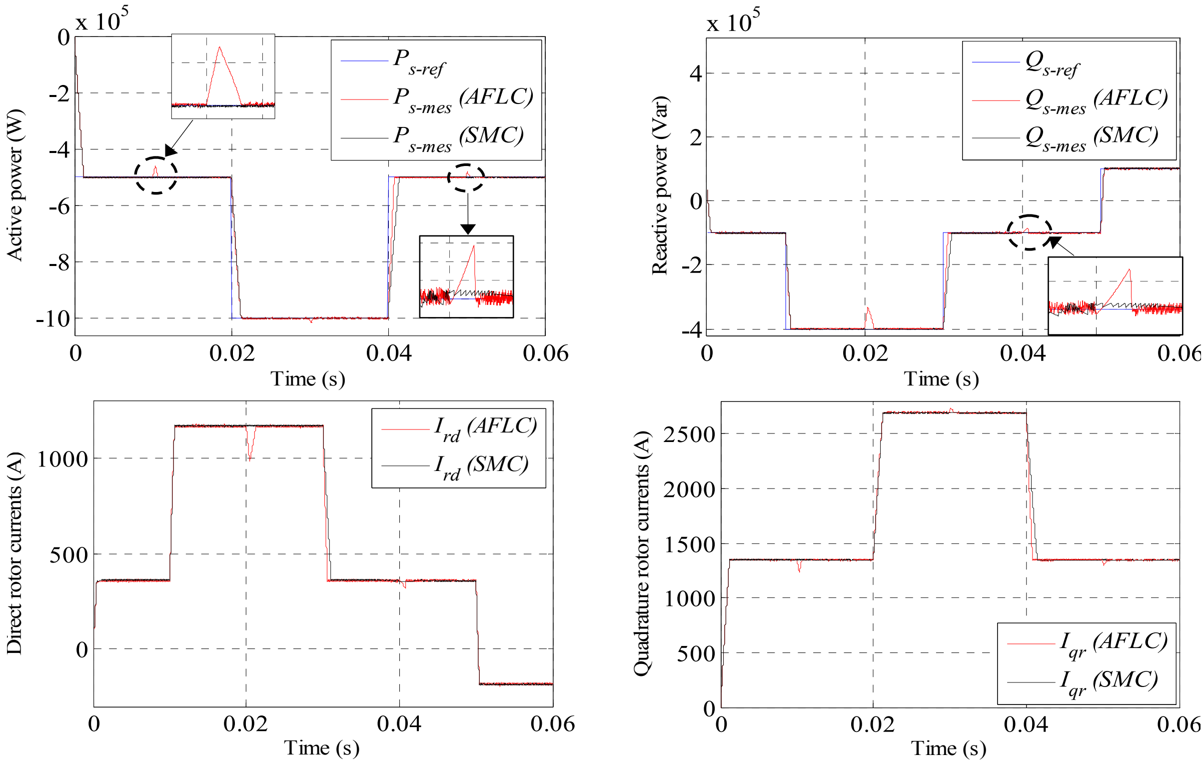

Figure 7. Reference tracking.

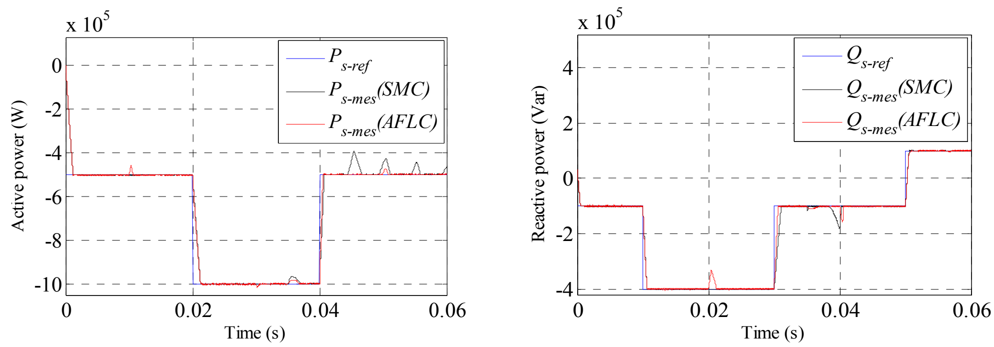

Figure 8. Effect of a speed variation.

sensitivity to the speed variation and robustness facing variations of the machine's parameters.

A. Pursuit test

This test has for goal the study of the two controller's behaviors in reference tracking, while the machine's speed is considered constant at its nominal value. The simulation results are presented in Fig. 7. As it's shown by this figure, for the two controllers, the active and reactive generated powers tracks almost perfectly their references. In addition and contrary to the AFLC controller where the coupling effect between the two axes is very clear, we can notice that the SMC controller ensures a perfect decoupling between them. Therefore we can consider that the sliding mode controller has a very good performance for this test.

B. Sensitivity to the speed variation

The goal of this test is to analyze the influence of a speed variation of the DFIG on active and reactive powers. For this objective and at time = 0.035s, the speed was varied from 150 rad/s to 75 rad/s. The simulation results are shown in Fig. 8. This figure express that the speed variation produced osciallions only on the curves of the active powers for the two controllers, but this effect is more important on the SMC controller than on the AFLC one. We can notice that the AFLC controller has a nearly perfect speed disturbance rejection, indeed; only very small power variations can be observed (fewer than 5%). This result is attractive for wind energy applications to ensure stability and quality of the generated power when the speed is varying.

C. Robustness

In order to test the robustness of the used controllers, the machines' parameters have been intentionally modified with overkill variations: the values of the stator and the rotor resistances R_s and R_r are doubled and the values of inductances L_s, L_r and M are divided by 2. The machine is running at its nominal speed. The gotten

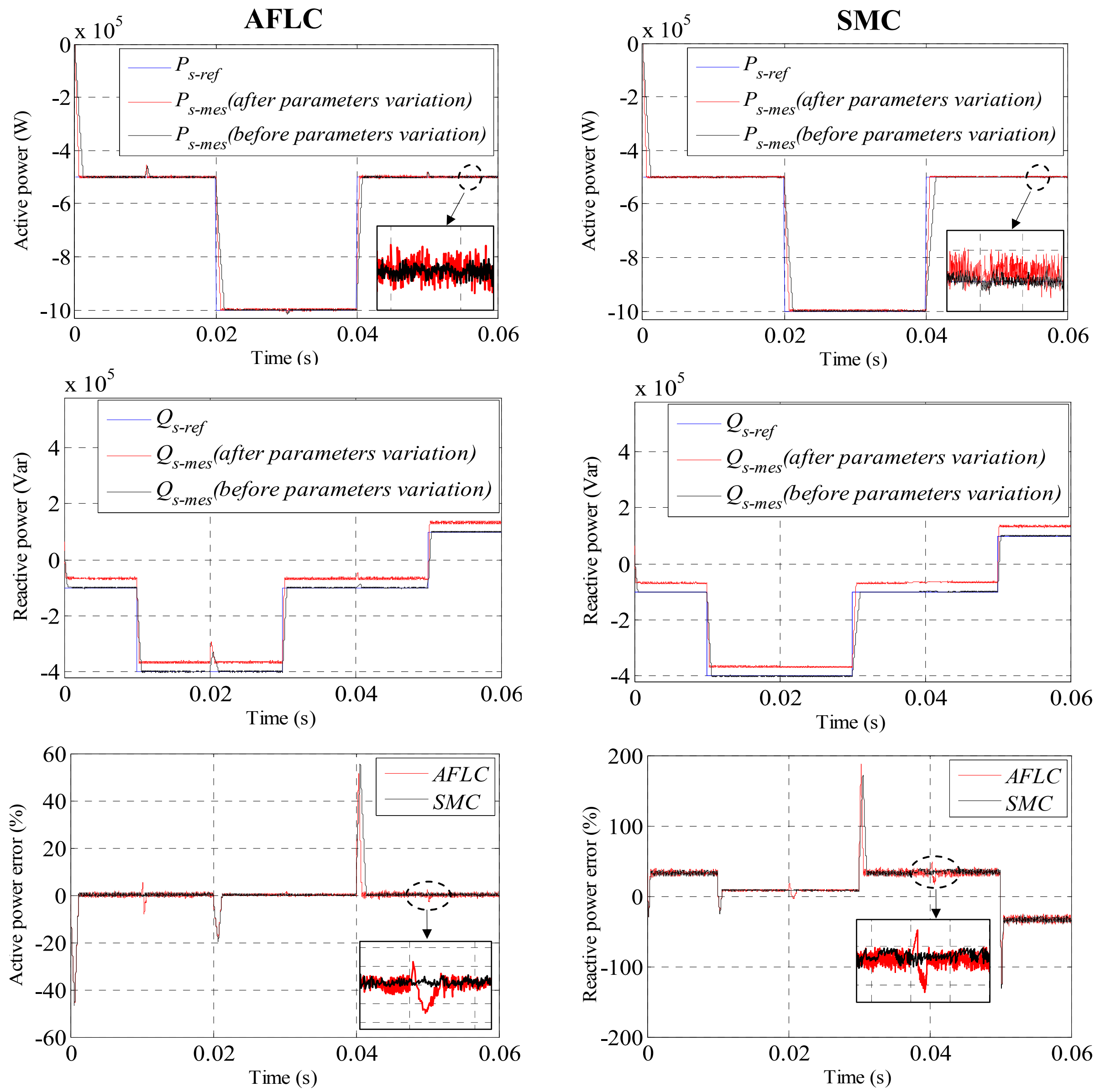

Figure 9. Effect of machine's parameters variation on the DFIG control.

results are represented on Fig. 9. As it's shown by these figures, we notice that the parameters variations of the DFIG create a clear effect on the responses of the two controllers especially on the reactive powers such as static errors are appearing on their curves and this is due to the absence of the powers control loops. On the other hand we can also see that parameters variations generated oscillations (see the errors curves) on active and reactive powers curves which are more significant for AFLC controller than for SMC one. This result enables us to conclude that this last control type is slightly more robust.

VI. CONCLUSION

The modeling, the control and the simulation of an electrical power electromechanical conversion system based on the doubly fed induction generator (DFIG) connected directly to the grid by the stator and fed by a power converter on the rotor side has been presented in this study. Our objective was the implementation of a robust decoupled control system of active and reactive powers generated by the stator side of the DFIG, in order to ensure of the high performance and a better execution of the DFIG, and to make the system insensible with the external disturbances and the parametric variations. In the first step, we started with a study of modeling on the doubly fed induction generator. In second step, we adopted a vector control strategy in order to control statoric active and reactive power exchanged between the DFIG and the grid. Contrary to the previous work carried out on the DFIG where the researchers always neglect the stator resistance to facilitate its control, in our work this resistance was not neglected in order to return the system studied near to reality. In third step, two different controllers are synthesized and compared. In term of power reference tracking with the DFIG in ideal conditions (no parameters variations and no disturbances), the SMC ensures a perfect decoupling between the two axes comparatively to the AFLC where the coupling effect between them is very clear.

When the machine's speed is modified (witch represents a perturbation for the system), the impact on the active and reactive powers values is important for SMC controller whereas it is almost negligible for AFLC one. A robustness test has also been investigated where the machine's parameters have been modified. These changes induce time-response variations with the two controllers. The static error of about 10% appears on the reactive power but it is due to the absence of the powers control loops and it can be numerically compensated in future works.

From all these results, we can say that each controller has advantages and disadvantages, an idea to join together the two techniques of control in the system prove very interesting and can make it more powerful, especially with the addition of the loops for the powers control.

APPENDIX

TABLE II.
MACHINE PARAMETERS.

Parameters	Rated Value	Unity
Nominal power	1.5	MW
Stator voltage	398	V
Stator frequency	50	Hz
Number of pairs poles	2	
Nominal speed	100	rad/s
Stator resistance	0.012	Ω
Rotor resistance	0.021	Ω
Stator inductance	0.0137	H
Rotor inductance	0.0136	H
Mutual inductance	0.0135	H

TABLE III.
LIST OF SYMBOLS.

Symbol	Significance
$V_{s,abc}$, $V_{r,abc}$	Three-phase stator and rotor voltages,
$I_{s,abc}$, $I_{r,abc}$	Three-phase stator and rotor currents,
V_{ds}, V_{qs}, V_{dr}, V_{qr}	Two-phase stator and rotor voltages,
ψ_{ds}, ψ_{qs}, ψ_{dr}, ψ_{qr}	Two-phase stator and rotor fluxes,
I_{ds}, I_{qs}, I_{dr}, I_{qr}	Two-phase stator and rotor currents,
R_s, R_r	Per phase stator and rotor resistances,
L_s, L_r	Per phase stator and rotor inductances,
M	Mutual inductance,
p	Number of pole pairs,
g	Generator slip,
ω_s, ω_r	Stator and rotor currents frequencies (rad/s),
ω	Mechanical rotor frequency (rad/s),
P_s, Q_s	Active and reactive stator power,
C_{em}	Electromagnetic torque.

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