Hybrid fuzzy sliding mode control of a doubly-fed induction generator speed in wind turbines

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Abstract

The aim of this paper is hybrid fuzzy sliding mode control of a Doubly Fed Induction Generator (DFIG) in the form of a wind turbine. This type of control is introduced to avoid the major disadvantage of variable structure systems, namely the chattering phenomenon. Variable structure ensures the high dynamic of convergence and robustness towards parametric variations and disturbances. Fuzzy control is introduced here in order to remove residual vibrations in high frequencies. That approach is used to control the mechanical speed and the reactive power exchanged between the stator circuit and the grid. Those variables are decoupled through vector control. The feasibility of this work is proven by mathematical and simulation models based on MATLAB.

Keywords: Sliding Mode, Fuzzy Logic, DFIG, Rotor speed Control, Robustness, Hybrid control

1. Introduction

Wind power has attracted much interest as a suitable source of renewable energy. The mechanical power generated by the wind turbine is transformed into electrical power by an induction generator and is fed into the main grid through stator windings. The most widely adopted generator in terms of a wind turbine with variable-speed system is the DFIG. That system consists that the stator circuit is directly connected to the grid, while the rotor circuit is connected to the grid through an AC/DC/AC converter via slip rings enabling control of the rotor voltage of the induction machine in magnitude and phase angle [1–3]. The fundamental feature of the DFIG is that the power processed by the power converter is only a fraction of the total wind turbine power, and therefore its size, cost and losses are much smaller than they are with a full-scale power converter [2]. The converter is designed so that the DFIG can operate in a limited variable-speed range (Fig. 1). The gear-box ratio is set so the nominal speed of induction generator corresponds to the middle value of the rotor speed range of the wind turbine [1, 2]. To start with the rotor speed reference establishment, it is important to consider the mechanical power P_{mec} developed by a wind turbine, which depends directly on the blade radius R, the power coefficient C_p and the wind speed V hitting the blades of the generator [1, 2]

$$P_{mec} = \frac{1}{2}C_p(\lambda) \ A \ V^3 \qquad (1)$$

and

$$\lambda = \frac{R\,\omega}{V}$$

where: ω—rotational speed; λ—tip speed ratio; ρ—air density and A—area of the turbine blades in m².

According to the analysis developed in many papers [1, 3, 4], for any given wind speed, there is a rotation speed ω which corresponds to the optimal mechanical power that can be generated by the turbine, as seen in Fig. 2. Additionally, it is important to consider that when wind speed changes the rotation speed must be adapted so as to extract the maximum power. That speed is the reference value and it equation for obtaining the target power is available.

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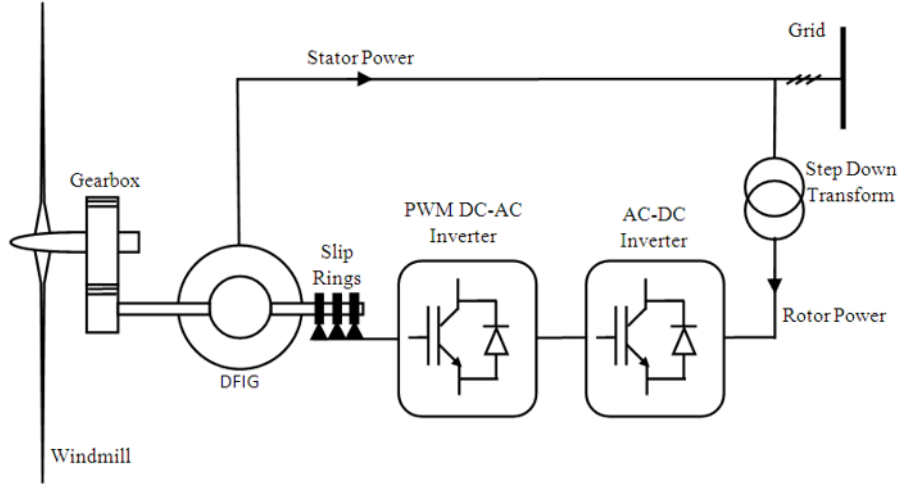
Figure 1: Wind Energy Conversion System Using a Doubly Fed Induction Generator
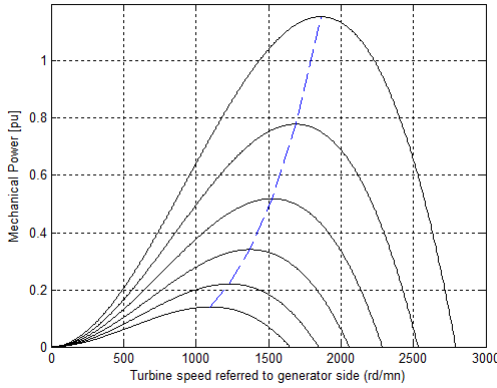

Figure 2: Wind turbine characteristics for several wind speeds

In this paper, the control of rotor speed and reactive power exchanged between the stator of DFIG and the grid are investigated independently. Several works have been developed in this direction using several controllers [1, 3–6]. In our case after modelling the machine in $d-q$ reference frame, rotor speed and reactive power are controlled using fuzzy sliding mode theory. It is a question of using a fuzzy supervisor that allows gradual commutation between two laws of control; first by sliding mode which acts primarily during the transitory step, and secondly by fuzzy logic which lasts for the duration of the permanent step. Their performances are discussed in terms of reference tracking and robustness against variations in parameters.

In this paper, a dynamic model of the DFIG in $d-q$ reference is presented followed by the vector control technique to achieve decoupled control of torque and reactive powers. Then, sliding mode and fuzzy logic controls of the DFIG are independently introduced. The combination

of these controllers is achieved by means of a fuzzy supervisor, allowing gradual commutation between them. Finally, performances and robustness of the proposed command are tested on a wind turbine using a DFIG of 1.5 kW.

2. Mathematical modeling of DFIG

The idea of this DFIG control is to establish stator outputs such as three-phase voltages and operate the output power fed into the grid via stator windings. The general model wound rotor induction generator is similar to any fixed-speed induction generator. The application of Park's transformation allows a dynamic model in d-q reference to be written as follows [7]:

- Electric equation

$$
\begin{cases}
v_{ds} = \mathrm{R_s} i_{ds} + \frac{d\Phi_{\mathrm{ds}}}{dt} - \omega_{\mathrm{s}} \Phi_{\mathrm{qs}} \\
v_{qs} = \mathrm{R_s} i_{qs} + \frac{d\Phi_{\mathrm{qs}}}{dt} + \omega_{\mathrm{s}} \Phi_{\mathrm{ds}} \\
v_{dr} = \mathrm{R_r} i_{dr} + \frac{d\Phi_{\mathrm{dr}}}{dt} - (\omega_{\mathrm{s}} - \omega) \Phi_{\mathrm{qr}} \\
v_{qr} = \mathrm{R_r} i_{qr} + \frac{d\Phi_{\mathrm{qr}}}{dt} + (\omega_{\mathrm{s}} - \omega) \Phi_{\mathrm{dr}}
\end{cases}
\tag{2}
$$

$$
\begin{cases}
\Phi_{\mathrm{ds}} = \mathrm{L_s} i_{ds} + \mathrm{M} i_{dr} \\
\Phi_{\mathrm{qs}} = \mathrm{L_s} i_{qs} + \mathrm{M} i_{qr} \\
\Phi_{\mathrm{dr}} = \mathrm{L_r} i_{dr} + \mathrm{M} i_{ds} \\
\Phi_{\mathrm{qr}} = \mathrm{L_r} i_{qr} + \mathrm{M} i_{qs}
\end{cases}
\tag{3}
$$

- Mechanic equation

$$
T_e - T_r = \frac{\mathrm{J}}{\mathrm{P}} \frac{d\omega}{dt} + \frac{\mathrm{f}}{\mathrm{P}}.\omega
\tag{4}
$$
$$
T_e = \mathrm{P} \frac{\mathrm{M}}{\mathrm{L_s}} \left(i_{qr} \Phi_{\mathrm{ds}} - i_{dr} \Phi_{\mathrm{qs}} \right)
$$

- Power equation

$$
\begin{cases}
P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \\
Q_s = v_{qs} i_{ds} - v_{ds} i_{qs}
\end{cases}
\tag{5}
$$

3. Stator flux oriented control

To achieve decoupled stator reactive power and rotor speed control, we choose in the d-q reference-frame the stator flux aligned with the d-axis, so we have $\Phi_{ds} = \Phi_s$ and $\Phi_{qs} = 0$ [6–9]. Assuming the condition of small stator resistors and constant stator flux, the stator voltage is consequently aligned with the q-axis. The dynamic model will be simplified as follows:

- Stator and rotor voltages

$$\text{while} \quad \sigma = 1 - \frac{M^2}{L_s L_r}$$

$$\begin{cases} v_{ds} = 0 \text{ and } v_{qs} = v_s = \omega_s \Phi_{ds} \\ v_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - \sigma L_r (\omega_s - \omega) i_{qr} \\ v_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \sigma L_r (\omega_s - \omega) i_{dr} + s\frac{Mv_s}{L_s} \end{cases} \quad (6)$$

- Stator reactive power

$$Q_s = \frac{v_s^2}{L_s \omega_s} - \frac{M}{L_s} v_s i_{dr} \quad (7)$$

- Mechanical equation

$$\frac{d\Omega}{dt} = \frac{1}{J}\left(T_e - T_r - f.\Omega\right) \quad (8)$$

where: $T_e = P\frac{M}{L_s} i_{qr}\Phi_{ds}$

Now, knowing relations (6), (7) and (8), it is possible to synthesize the regulators and draw up a global block-diagram of the controlled system [1, 6, 7]. Block Controllers 1 and 2 in Fig. 3 represent reactive power and rotor speed regulators respectively. The aim of these regulators is to obtain high dynamic performances in terms of reference tracking, sensitivity to perturbations and robustness. To realize these objectives, the hybrid fuzzy sliding mode controller is studied.

4. Hybrid control synthesis

For a given wind turbine, some relations exist between the wind speed, the generator's rotating speed and the available mechanical power. If the wind speed is measured and the mechanical characteristics of the wind turbine are known, it is possible to deduce in real-time the theoretical rotor speed to achieve maximum power generated [3, 4, 6]. It is then possible to control the generator using this rotor speed as reference. Therefore the reactive power is controlled to establish a desired power factor.

4.1. Sliding mode control

The sliding mode controller does not need accurate mathematical models like classical controllers, but requires knowledge of the parameter variation range to ensure stability and satisfy reaching conditions.

A. Reactive power loop: The reactive power is controlled via d-axis voltage. The sliding surface is chosen in the first order as follows:

$$S_Q = Q_{ref} - Q_s \quad (9)$$

In the first derivative of this surface, there appears the input command $'v'_{dr}$

$$\dot{S}_Q = \dot{Q}_{ref} + \frac{M}{L_s}v_s\left(\frac{1}{\sigma L_r}v_{dr} - \frac{R_r}{\sigma L_r}i_{dr} + (\omega_s - \omega)i_{qr}\right) \quad (10)$$

The equivalent command is added to ensure an asymptotic convergence of the system towards the sliding surface. In our case it is omitted because, during the permanent mode, only the fuzzy logic component is applied. The hitting command $'v_{d'SM}'$ is deduced so that the surface is always attractive. A sufficient condition to achieve this behavior is to select a control strategy such as:

$$\frac{d}{dt}\left(\frac{1}{2}S_Q^2\right) \leq -\eta|S| \quad \text{and } \eta \geq 0 \quad (11)$$

thus ensuring that

$$v_{dSM} = -K_Q\, sign(S_Q) \quad K_Q > 0 \quad (12)$$

B. Rotor speed loop: In exactly the same way, the rotor speed is controlled via q-axis voltage. The sliding surface is chosen in the second order as follows:

$$S_\Omega = \frac{d}{dt}(\Omega_{ref} - \Omega) + \lambda(\Omega_{ref} - \Omega) \quad (13)$$

where λ is a positive constant.

In the first derivative of this surface, there appears the input command $'v'_{qr}$.

$$\dot{S}_\Omega = \ddot{\Omega}_{ref} + f\dot{\Omega} + \lambda\left(\dot{\Omega}_{ref} - \dot{\Omega}\right) \quad (14)$$

$$-P\Phi_s\frac{M}{J\sigma L_s}\left(v_{qr} - R_r i_{qr} - \sigma L_r(\omega_s - \omega)i_{dr} - s\frac{Mv_s}{L_s}\right)$$

In the same way, the hitting command $'v'_{qSM}$ is deduced so that the surface S_Ω is always attractive, as follows:

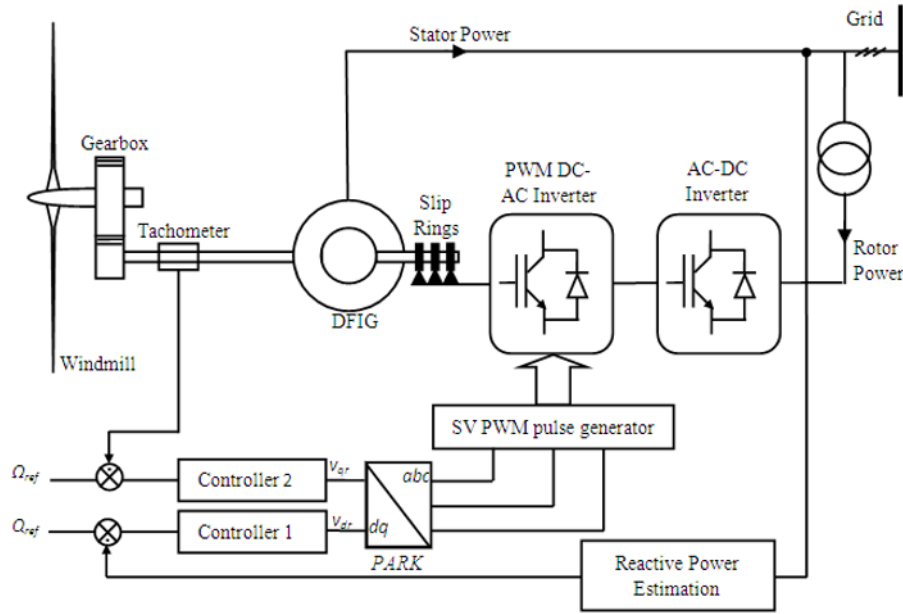$$v_{qSM} = -K_\Omega\, sign(S_Q) \quad K_\Omega > 0 \quad (15)$$

Figure 3: Global block-diagram of Power Reactive and Rotor Speed control

4.2. Fuzzy logic control

Recently, fuzzy logic (FL) controllers have generated a good deal of interest in certain applications. The advantages of FL over the classical controllers are: it does not need an accurate mathematical model, it can work with imprecise inputs, it can handle non-linearity and it is more robust than classical nonlinear controllers. With fuzzy logic, it is possible to use linguistic information from a human expert describing the dynamic behavior of the system around certain points. This information can be reformulated in the form of a collection of fuzzy rules If-Then [10]. In our case, we adopt for the fuzzy controller the error and its change $\Delta \tilde{x}$ as inputs and the change-in-command ΔU_{FL} as output. Thus, the jth fuzzy rule is given by:

If $\tilde{x}$ is A_0^j and $\Delta \tilde{x}$ is A_1^j then $\Delta \hat{U}_{FL}$ is C^j

where j=1, m and m is the number of rules, A_0^j, A_1^j are corresponding membership functions and C^j is the jth output membership function center .

The overall output of the fuzzy systems with centroid defuzzification using sum-prod inferencing can be obtained as:

$$\Delta \hat{U}_{FL} = \frac{\sum_{j=1}^{m} C^j \left(\mu_{A_0^j} (\tilde{x}) . \mu_{A_1^j} (\Delta \tilde{x}) \right)}{\sum_{j=1}^{m} \left(\mu_{A_0^j} (\tilde{x}) . \mu_{A_1^j} (\Delta \tilde{x}) \right)} \quad (16)$$

where $\mu_{A_1^j} (.)$ is the fuzzy membership function of A_l^j and l=1,2
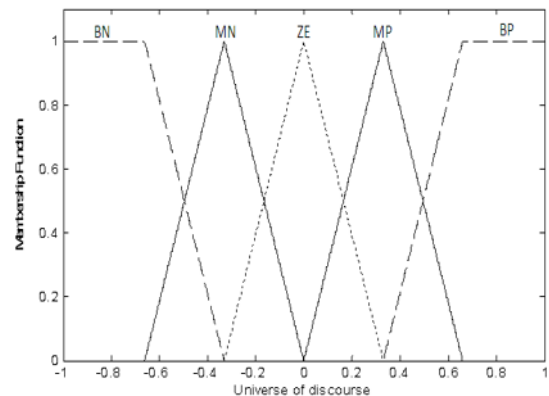

Figure 4: Membership functions chosen for FL Controllers

To synthesize the FL controller of the two variables Reactive Power and the Rotor Speed, we have divided the universe of the error and the change-in-error into five units: BN (Big Negative), MN (Medium Negative), ZE (Zero), MP (Medium Positive), and BP (Big Positive). The inputs corresponding to membership functions are chosen triangular, as shown in Fig. 4., and the sum-prod rule of inference is used.

The control rules must be designed using a technical knowledge base such that the stability of the global control system is ensured and the trajectory of the states always turns toward and does not cross the sliding surface on the phase plane. The control rules are extracted from Table 1.

Table 1: The Rules Matrix of the controllers

$\tilde{x}$	BN	MN	ZE	MP	BP
$\triangle\tilde{x}$					
BN	BN	BN	BN	MN	ZE
MN	BN	MN	MN	ZE	MP
ZE	BN	MN	ZE	MP	BP
MP	MN	ZE	MP	MP	BP
BP	ZE	MP	BP	BP	BP

Table 2: The Rules Matrix of the supervisor

$\tilde{x}$	ZE	MP	BP
$\triangle\tilde{x}$			
ZE	BP	BP	MP
MP	BP	BP	MP
BP	BP	MP	ZE

4.3. Implementation of hybrid control

In order to guarantee the robustness of the closed loop and a fast dynamic response with best possible performances, we propose using a combination of the two controllers previously defined, sliding mode controller during the transitory mode, and fuzzy logic controller in the permanent mode. The first controller ensures convergence of the system towards its permanent mode, with insensitivity towards external disturbances and structural uncertainties and a fast dynamic of convergence. The second takes over in the permanent mode in order to ensure a practically null static error without the chattering phenomenon. To avoid instantaneous passage from one controller to another, we will use a gradual commutation in the following form [10]:

$$U = \alpha.U_{FLC} + (1 - \alpha).U_{SMC} \tag{17}$$

where α is a factor generated by a fuzzy supervisor having the same inputs as the fuzzy controller.

The rules of the supervisor are constructed so that the output takes "0" when the system is far from the desired trajectory and "1" when the system is near to the desired trajectory (the error and its derivative converge towards zero). The control rules are given by Table 2.

The inputs corresponding membership functions are also chosen triangular (Fig. 5) and the sum-prod compositional rule of inference is used.
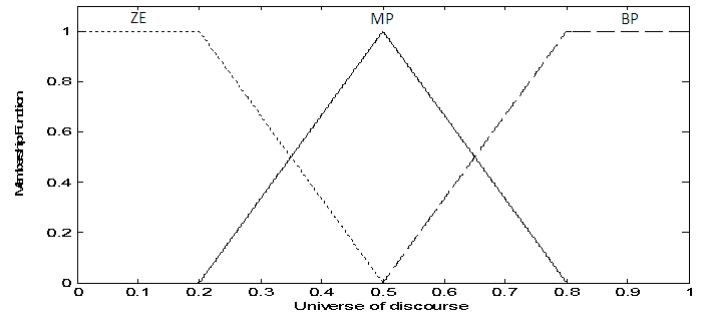

Figure 5: Membership functions chosen for supervisors

4.4. Stability of hybrid control

Hybrid system stability analysis relies on classical Lyapunov stability theory. For conventional control systems, demonstrating stability depends on the existence of a continuous and differentiable Lyapunov Function. In the hybrid system case, stability is provided using multiple Lyapunov functions to compose a single continuous and differentiable Lyapunov Function that can be used to demonstrate stability.

Suppose that each subsystem has an associate Lyapunov function. To guarantee the stability of the global system is to provide a methodology for switching between subsystems. The strategy taken in this work is to give the biggest weight for the subsystem which has the smallest value of Lyapunov function.

5. Simulation results

The structure of the suggested hybrid control is illustrated in Fig. 6. The three blocks SMC, FLC and the fuzzy supervisor have as inputs:

- the error of rotor speed and its change-in-error for the speed loop,

- the error of reactive power and its change-in-error for the reactive power loop,

These three blocks have as outputs U_{FLC}, U_{SMC} and α respectively. Finally, we can establish the block-diagram of the rotor speed and reactive power control using the hybrid approach controllers.

Some simulations were done to test the dynamic performance of the control system described above and were compared with the case of varying some parameters. Simulations were investigated with a 1.5 kW generator connected to a 220V/50Hz grid. The machine's parameters were: R_s=4.85Ω; R_r=3.805Ω; L_s=0.274H; L_r=0.0.274H; M=0.258H; J=0.031kg.m; f=0.008N.m.s^{-1}
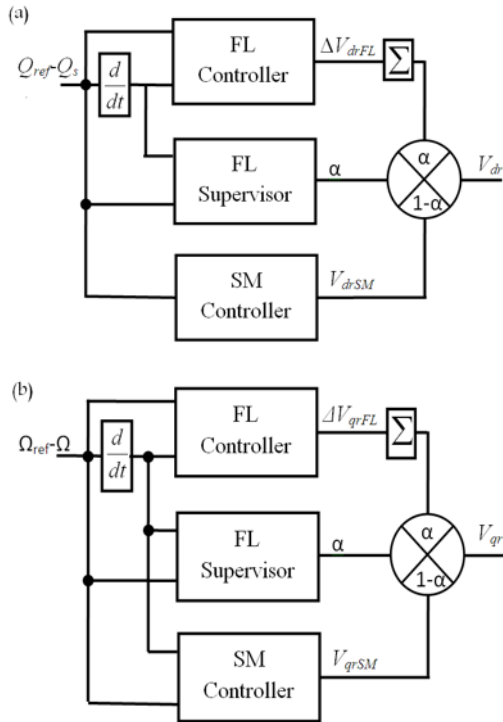
Figure 6: Hybrid Fuzzy Sliding Mode structures for Reactive Power (a) and Rotor Speed (b).

The regulators will be tested in reference tracking and robustness against parameter variations.

5.1. Reference tracking and sensitivity to perturbation

Assuming that the rotor speed ensuring the optimal mechanical power is 159 rad/mn under a unit power factor ($Q_{ref} = 0$). At time 1 s the wind speed increases, hence the rotor speed reference must increase and take 164rad/s to establish the optimal mechanical power according to equation (1). Between 2 s and 3 s, we change the power factor by changing the reactive power reference to −1 kVAR and then revert to a unit power factor again. At 4 s the wind speed decreases, hence the rotor speed reference must decrease and reach 159 rad/s. Controlled variables in the continuous line follow exactly the references in the broken line (Fig. 7 and 8).

The effects of the reactive power step on the rotor speed response due to the cross-coupling and non linearity in modelling are perfectly rejected. Almost all performances are obtained with the effects of the rotor speed step on the reactive power response.

5.2. Robustness

In order to test the robustness of the two controllers, the rotor resistance value is varied. When calculating controllers we assumed rotor resistance to be 3.805 Ω. Then
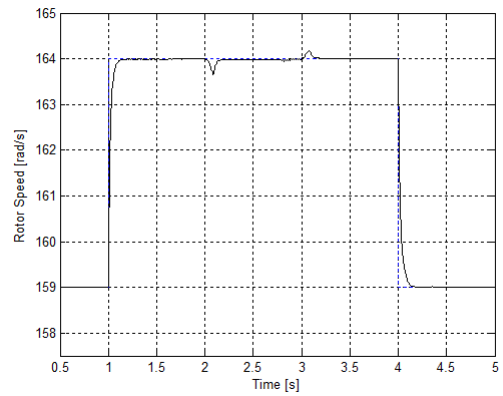

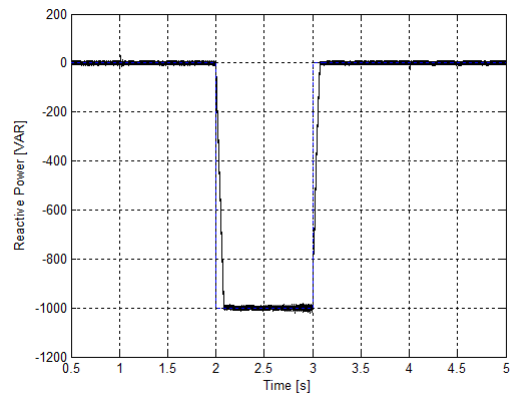Figure 7: Rotor speed response using Hybrid FL SM controller

Figure 8: Reactive power response using Hybrid FL SM controller

its value was doubled to 7.61 Ω. We imposed a rotor speed step of 164 rad/s at time 1 s while keeping the reactive power constant and at another time we imposed a reactive power step of −1000 VAR at time 1 s while keeping the rotor speed constant. Then we observed the response obtained with the hybrid controller (Fig. 9 and 10). It is clear that the controller is robust. The rotor speed and the reactive power follow their references with a time response and some overshoot, more than without R_r variation.

6. Conclusion

This paper presents Hybrid Fuzzy Sliding Mode Control of Reactive Power and Rotor Speed in a DFIG and performance evaluations. After presenting a description of a Doubly Fed Induction Generator with variable wind speed and fixed frequency of the grid, we established a two-phase power mathematical model of the DFIG. In order to control the rotor speed and the stator reactive power exchanged between the DFIG and the grid, a hybrid fuzzy sliding mode approach using vector control strategy
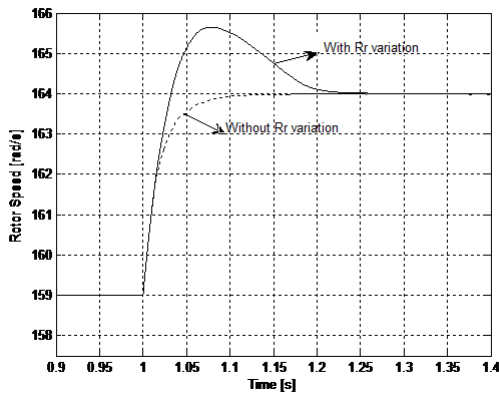
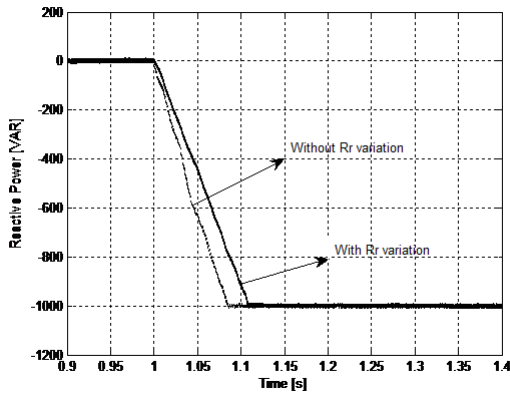Figure 9: Rotor Speed response with 100% R_r variation

Figure 10: Reactive power response with 100% Rr variation

was developed and presented. Simulations were investigated with this type of controller and they showed very interesting performances in terms of reference tracking, sensitivity to perturbation and robustness under parameter variation.

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Nomenclature

ω_s, ω	The grid and rotor angular frequency (electrical speed), respectively
Ω	Mechanical Rotor Speed
$\Phi_{qs}, \Phi_{ds}, \Phi_{qr}, \Phi_{dr},$	The three-phase stator and rotor flux linkages in the d-q reference frame, respectively
$\tilde{x}, \Delta\tilde{x}$	error and change in error, respectively
A_i^j	The jth membership function of the ith input variable
C^j	The jth output membership function centre
$i_{qs}, i_{ds}, i_{qr}, i_{qr}, i_{dr},$	The three-phase stator and rotor currents in the d-q reference frame, respectively
$L_s, L_r,$	The cyclic inductances of stator and rotor windings, respectively
$P_s, Q_s,$	The stator active and reactive powers, respectively
R_s, R_r	The stator and rotor resistors of machine per phase, respectively
T_e, T_r	Electromagnetic and resistant torque

$v_{qs}, v_{ds}, v_{qr}, v_{dr}$	The three-phase stator and rotor voltages in the d-q reference frame, respectively
AC, DC	Alternative Current and Direct Current respectively
J, f	Inertia and viscous friction
M	Magnetizing inductance
P	Number of pole pairs.
PWM	Pulse Width Modulation
s	Slip frequency
SMC, FLC	Sliding Mode and Fuzzy Logic Controllers, respectively