An Hybrid Control Based on Fuzzy Logic and a Second Order Sliding Mode for MPPT in Wind Energy Conversion Systems

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Abstract: This paper deals with power control of a grid connected variable speed wind turbine system, based on doubly fed induction generator. In this paper we propose a novel control scheme of the rotor side converter, that is based on indirect control of power consist currents and powers control loops. The two loops of rotor currents: direct and quadrature component are controlled by the technique of the second order sliding mode using the super-twisting algorithm in order to eliminate the chattering phenomenon. A fuzzy logic controller is applied to the active and to the reactive powers loops exchanged between the stator of the doubly fed induction generator and the grid to track the maximum power point. In order to maintain the voltage of the DC-link constant of the grid side converter, the classical proportional integral controller is used. The proposed control strategy, which combines the second order sliding mode and fuzzy logic, is applied to a 1.5 MW three blade wind turbine shows robustness for variations in the wind speed.

Keywords: Hybrid control, Second Order Sliding Mode Controller (SOSMC), Fuzzy Logic Controller (FLC), Proportional Integral (PI), Wind turbine, Doubly Fed Induction Generator (DFIG), Maximum Power Point Tracking (MPPT).

Nomenclature

P_s,Q_s	The stator active and reactive powers.
P_s^*, Q_s^*	The reference values of the stator powers.
P_r,Q_r	The rotor active and reactive powers.
R_g,L_g	The grid resistance and inductance.
GSC	The grid side converter.
RSC	The rotor side converter.
DFIG	The doubly fed indication generator.
SOSMC	The second order sliding mode control.
MPPT	The maximum power point tracking.
FLC	The fuzzy logic control.
PI	The proportional integral.
P_a	The extracted power from the wind.
σ	The leakage factor.
C_P	The power coefficient.
λ	The tip speed ratio.

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β	The angle of blade.
P_{vent}	The wind power.
ρ	The air density.
V	The wind speed.
R	The radius of the wind.
Ω_t	The rotor speed of the wind turbine.
Ω_{mec}	The mechanical speed of the DFIG.
Ω^*_{mec}	The reference values of the mechanical speed of the DFIG.
G	The gain multiplier.
λ_{cpmax}	The tip speed ratio max.
J	The inertia.
f	The friction coefficient.
T_{em-ref}	The electromagnetic torque.
V_{dr}, V_{qr}	The rotor voltage components.
i_{dr}, i_{qr}	The rotor current components.
i^*_{dr}, i^*_{qr}	The reference values of the rotor currents.
ϕ_{dr}, ϕ_{qr}	The rotor flux components.
R_r, L_r	The rotor resistance and inductance.
M	The mutual inductance.
L_s, R_s	The stator resistance and inductance.
ω_r, ω_s	The stator and the rotor pulsation.
ϕ_{ds},ϕ_{qs}	The stator flux components.
g	The slip.
v_s	The grid voltage.
$V_{dr\ eq}$,$V_{qr\ eq}$	The equivalent control of the rotor voltage.
$V_{dr\ ST}$, $V_{qr\ ST}$	The continuous control.
e_1, e_2	The error of the rotor currents.
e_3, e_4	The error of the active and the reactive powers.
S	The sliding surface.

1. Introduction

Much of the wind turbines installed today for electrical power generation are used with variable speed wind turbines and are equipped with double fed induction generators (DFIG) as shown in Figure 1.

And the DFIG has several advantages including variable speed operation in this point there are two possible operation modes: sub-synchronous and super-synchronous [1 -3].

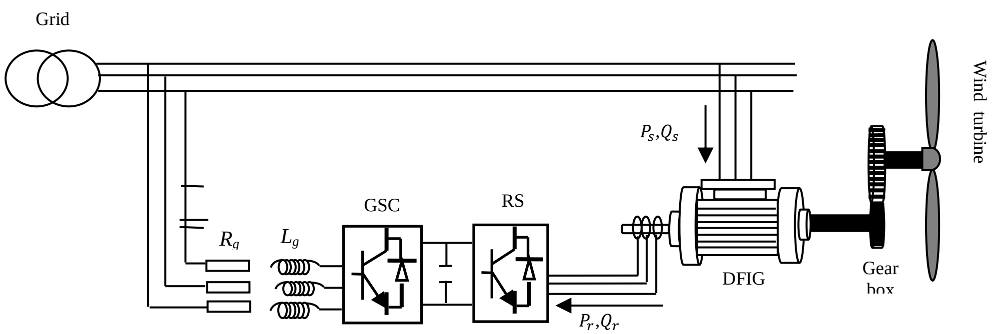


Figure 1. The general structure of a double fed wind generator.

Different schemes and regulators can be used to control the powers converter of the DFIG. The proportional integral (PI) controller is one of the most used of regulating the rotor currents and the stator powers generation in the DFIG. In this case, the used system is composed by tow stator powers loops and tow currents loops. However, this controller has the same weakness such as the uncertainty on some behavior parameters of the generator, turbine and external disturbances caused by unpredictable wind speed.

To improve dynamic behavior of wind turbine system, and overcome this difficulty, we adopt, in this work, the variable structure control strategy exactly, the sliding mode control as a control approach.

The sliding mode control has received much attention in the field of electrical drives control [4 - 8]. In this method, the response of control system depends only on the sliding surface.

Despite the robustness of this control, the first sliding mode control faces the main problem of discontinuous control what inevitably results in a chattering phenomenon [5].

Even, if different methods have been applied out recently to reduce the chattering, few papers [9 - 13] present the solution for second order sliding mode control. In these approaches, sliding surfaces are chosen so that they will be compatible with the errors in reactive power and electromagnetic torque as is described in references [9 - 11], where, the sliding surfaces are chosen coinciding with the errors in the stator active and reactive powers as in references [12 - 13].

The reproach to this approach is that it does not incorporate the rotor currents loops, that is why we suggest in this work the use of the control strategy with two stator powers loops and two rotor currents loops.

In this paper, a second order sliding mode control strategy is applied to the two rotor current loops using the super-twisting algorithm technique in order to improve the chattering phenomenon and where the active and the reactive powers are controlled using fuzzy logic regulators.

2. Wind turbine modeling

The mechanical power extraction from the wind is given as follow:

$$P_a = C_P.P_{vent} = C_P(\lambda, \beta).\frac{\rho.\pi.R^2.V_{vent}{}^3}{2} \quad (1)$$

Figure 2 shows the variation of the C_P with respect to the given values of the tip speed ratio λ and the blade pitch angle β:

$$C_P = 0.5 - 0.167.(\beta - 2).\sin\left[\frac{\pi.(\lambda + 0.1)}{(18.5 - 0.3.\beta)}\right] - 0.00184.(\lambda - 3).(\beta - 2) \quad (2)$$

where

$$\lambda = \frac{\Omega_t.R}{V_{vent}} \quad (3)$$

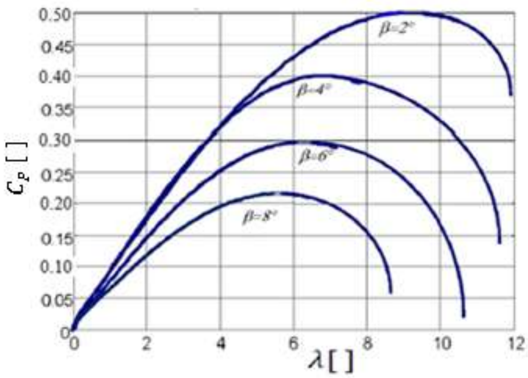


Figure 2. The turbine characteristic with maximum power point tracking.

The Maximum Power Point Tracking (MPPT) method is applied to the wind turbine, in order to generate the maximum electrical power from the wind. the structure of this control strategy as shown in Figure 3.

To obtain the maximum wind capture and the maximum power output, Figure.2 shows that the maximum ($C_P = 0.5$) is reached at tip speed ratio($\lambda = 9$) at β constant and equal to two degrees: ($\beta = 2°$), where the rotor speed (Ω_{t-ref}) is given by the following formula.

$$\Omega_{t-ref} = \frac{\lambda(C_{P\,max}).V_{vent}}{R} \quad (4)$$

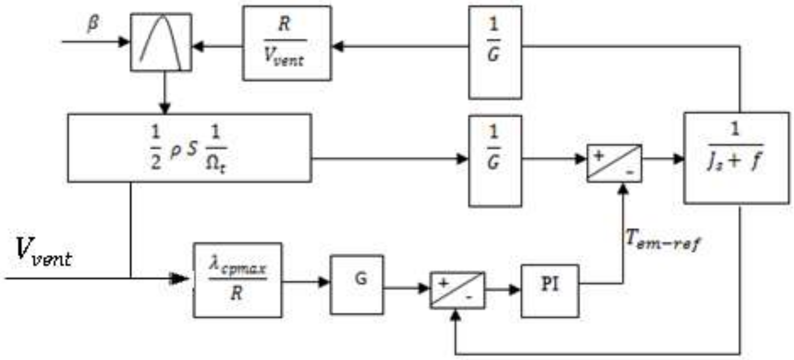


Figure 3. The diagram block of the maximizing power with speed control.

3. Modeling and control of the double fed indication generator

The generator dynamics model is given by the following system of equations:

$$V_{dr} = R_r.i_{dr} + \frac{d\,\phi_{dr}}{dt} - \omega_{sl}.\phi_{qr} \quad (5)$$

$$V_{qr} = R_r.i_{qr} + \frac{d\,\phi_{qr}}{dt} - \omega_{sl}.\phi_{dr} \quad (6)$$

where:$\omega_{sl} = \omega_s - \omega_r$

$$\phi_{dqr} = L_r.i_{dqr} + M.L_{dqs} \quad (7)$$

By substituting equation (7) into the rotor voltage equations given in (5) and (6), the rotor direct current and quadrature current components will be written as:

$$\frac{di_{dr}}{dt} = g_1 - \frac{M}{L_s.\sigma.L_r}\frac{d|\phi_s|}{dt} + \frac{1}{\sigma.L_r}.V_{dr} \quad (8)$$

$$\frac{di_{qr}}{dt} = g_2 + \frac{1}{\sigma.L_r}.V_{qr} \quad (9)$$

where:

$$g_1 = \frac{R_r}{\sigma.L_r}.i_{dr} + \omega_{sl}.i_{qr} \quad (10)$$

$$g_2 = \frac{R_r}{\sigma.L_r}.i_{qr} - \omega_{sl}\left(i_{dr} + \frac{M}{\sigma.L_s.L_r}.|\phi_s|\right) \quad (11)$$

The stator active and the reactive powers and the rotor voltages can be written according to the rotor currents as:

$$P_s = -\frac{v_s.M}{L_s}.i_{qr} \quad (12)$$

$$Q_s = \frac{v_S^2}{\omega_s.L_s} - \frac{v_s.M}{L_s}.i_{dr} \quad (13)$$

$$V_{dr} = R_r . i_{dr} + s . L_r . \sigma . i_{dr} - g . \omega_s . L_r . i_{qr} . \sigma \quad (14)$$

$$V_{qr} = R_r . i_{qr} + s . L_r . \sigma . i_{qr} + g . \omega_s L_r . i_{dr} . \sigma + \frac{g . M . v_s}{L_s} \quad (15)$$

We note that, in equations (12) and (13), the stator active power depend only on the rotor current i_{qr} and the stator reactive power depend only on the rotor current i_{dr}.

According to equations (12), (13), (14) and (15), we have realized the overall structure of the field oriented control of the DFIG, based on an indirect control with tow stator powers loops and tow rotor currents loops. Where the two loops (powers and rotor currents) are controlled by the traditional PI controllers.

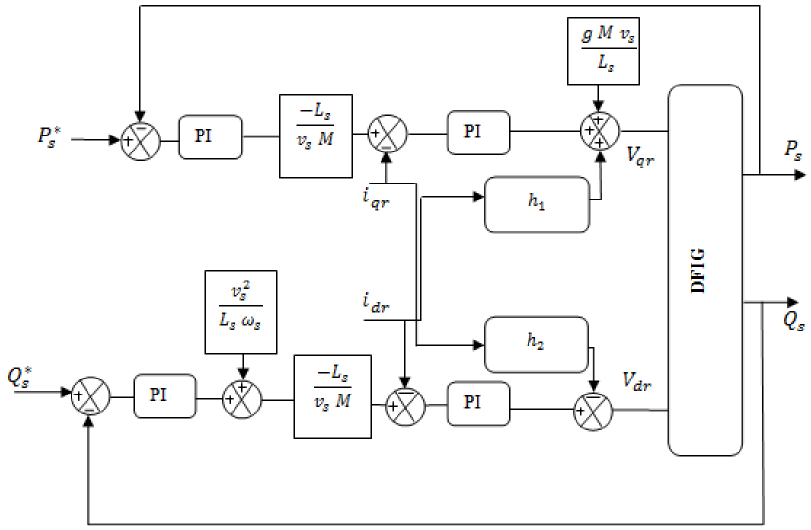


Figure 4. The block diagram of the DFIG control (two power loops and two currents loops) using PI controllers.

we note that:

$h_1 = g . \omega_s . L_r . \sigma . i_{dr}$

$h_2 = g . \omega_s . L_r . \sigma . i_{qr}$

4. Hybrid control of the double fed indication generator:

In our system, the two loops of the rotor currents (direct and quadrature components) are controlled by the technique of the SOSMC. The fuzzy logic controller is applied to the stator active and to the reactive powers loops exchanged between the stator of the DFIG and the grid.

A. The Second Order Sliding Mode Design

A.1 The Sliding Surfaces

Our goal is to make the direct and the quadrature components of the rotor currents control closer to their reference where we have applied the indirect control of powers. The sliding surface is given by:

$$S = \left[S(i_{dr}) \quad S(i_{qr}) \right].$$

We define the rotor currents errors, respectively, as follow:$e_1 = (i_{dr}^* - i_{dr})$ and $e_2 = (i_{qr}^* - i_{qr})$, where the i_{dr}^* and i_{qr}^* are, respectively, the reference values of the direct and the quadrature components of the rotor currents. As described in references [11 - 12], the sliding mode of the rotor currents surfaces can be used in their integral form:

$$S\ (i_{dr}) = e_1 + c_d \int e_1\ dt \tag{16}$$

$$S\ (i_{qr}) = e_2 + c_q \int e_2\ dt \tag{17}$$

Where c_d and c_q are the positive control gains.
The main condition in the second order sliding mode is achieving the following equality:

$$\frac{dS\ (i_{dr})}{dt} = \frac{dS\ (i_{qr})}{dt} = 0 \tag{18}$$

The substitution of equation (18) in (16) and in (17) gives of equations:

$$\frac{dS(i_{dr})}{dt} = -\frac{di_{dr}}{dt} + c_d.e_1 \tag{19}$$

$$\frac{dS(i_{qr})}{dt} = -\frac{di_{qr}}{dt} + c_q.e_2 \tag{20}$$

The substitution of equation (8) and (9) into (19) and (20) leads to:

$$\frac{dS(i_{dr})}{dt} = g_1 - \frac{M}{L_r.L_s.\sigma}\frac{d|\phi_s|}{dt} + \frac{1}{\sigma.L_r}.V_{dr} + c_d.e_1 \tag{21}$$

$$\frac{dS(i_{qr})}{dt} = g_2 + \frac{1}{\sigma.L_r}.V_{qr} + c_q.e_2 \tag{22}$$

Let's define two functions F_1 and F_2 as follow:

$$F_1 = g_1 - \frac{M}{L_r.L_s.\sigma}\frac{d|\phi_s|}{dt} + \frac{1}{\sigma.L_r}.V_{dr} + c_d.e_1 \tag{23}$$

$$F_2 = g_2 + \frac{1}{\sigma.L_r}.V_{qr} + c_q.e_2 \tag{24}$$

Then, we obtain the following equations systems:

$$\frac{dS\ (i_{dr})}{dt} = F_1 + \frac{V_{qr}}{\sigma.L_r} \tag{25}$$

$$\frac{dS\ (i_{qr})}{dt} = F_2 + \frac{V_{dr}}{\sigma.L_r} \tag{26}$$

The Variable Structure Control Law

The aim of the use of a SOSMC, is to control the rotor voltage applied to the rotor side converter. The rotor controlled voltage may be derived according to the control law:

$$V_{dr} = V_{dr\ ST} + V_{dr\ eq} \tag{27}$$

$$V_{qr} = V_{qr\ ST} + V_{qr\ eq} \tag{28}$$

Equivalent Control

Gives in equation (25) and (26) can be generalized by the following expression:

$$\frac{dS}{dt} = F + B.V_r \tag{29}$$

with

$F = [F_1 \quad F_2]^T, V_r = [V_{dr} \quad V_{qr}]^T$ and $B = \frac{1}{\sigma.L_r}$

The equivalent control of equations (27) and (28) is given by the substitution of equation (18) in (25) and in (26) and are represented as follow:

$$\begin{bmatrix} V_{dr\ eq} \\ V_{qr\ eq} \end{bmatrix} = -B^{-1}\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} \tag{30}$$

So the equivalent command takes the following form:

$$V_{dr\,eq} = \sigma . L_r \left(-g_1 + \frac{M}{L_s.\sigma.L_r} \frac{d|\phi_s|}{dt} - c_d.(e_1) \right) \quad (31)$$

$$V_{qr\,eq} = -\sigma . L_r . \left(g_2 + c_q.(e_2) \right) \quad (32)$$

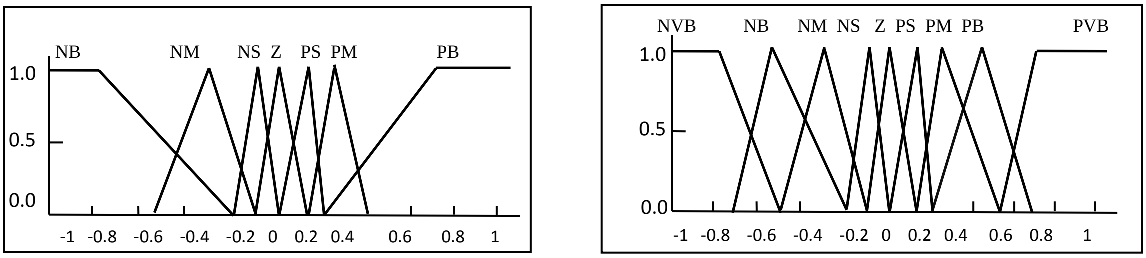
The Super-Twisting Algorithm
The super-twisting algorithm is defined as follow:

$$V_{dr\,ST} = \delta_q |S(i_{qr})|^{(1/2)} sat\left(S(i_{qr})\right) - w_q \int sat\left(S(i_{qr})\right) dt \quad (33)$$

$$V_{qr\,ST} = \delta_d |S(i_{dr})|^{(1/2)} sat\left(S(i_{dr})\right) - w_d \int sat\left(S(i_{dr})\right) dt \quad (34)$$

where:
δ_d, δ_q, w_d and w_q are the positive control gains.

Fuzzy Controller of Active and Reactive Powers
The active and the reactive powers errors are respectively given by: $e_3(P_s) = (P_s^* - P_s)$ and $e_4(Q_s) = (Q_s^* - Q_s)$.



a. The inputs b. The output

Figure 5. The membership functions of inputs and output variables.

5. Application

The proposed technique of control based on hybrid SOSMC and FLC is applied to a high wind energy conversion system use a double fed indication generator. The overall structure of this system is shown in Figure 6.

The parameters of the adopted double fed indication generator are given in the following table.

Table 1. The machine parameters.

Parameters	Units	Value
The nominal power	[MW]	1.5
The stator voltage	[V]	690
The stator frequency	[Hz]	50
The number of poles pairs	[ ]	2
The stator resistance	[Ω]	0.012
The rotor resistance	[Ω]	0.021
The stator inductance	[H]	0.0137
The rotor inductance	[H]	0.0136
The mutual inductance	[H]	0.0135
The inertia	[Kg.m²]	1000
The friction coefficient	[N.m.s/rad]	0.0024

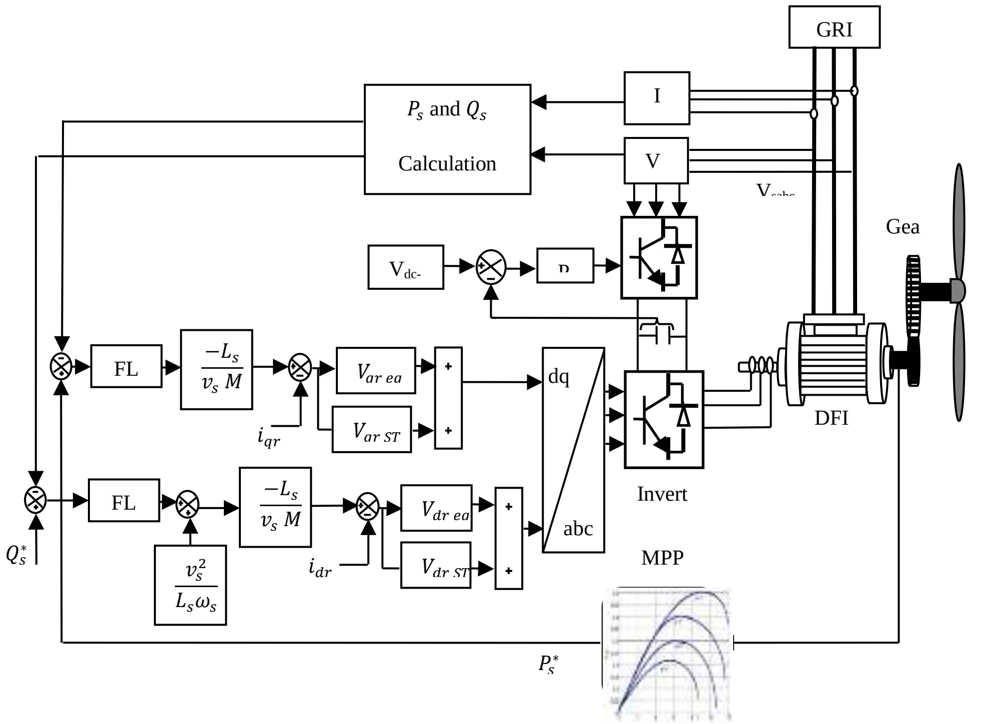


Figure 6. The schematic diagram of the proposed SOSMC and FLC for a grid connected to a DFIG.

The parameters of the selected wind turbine are given in Table 2

Table 2. The wind turbine parameters.

Parameters	Units	Value
The tip speed ratio max $\lambda(C_{P\ max})$	[ ]	9
The power coefficient $C_{P\ max}$	[ ]	0.5
The radius of the wind	[m]	35.25
The gain multiplier	[ ]	90
The air density	[kg/m^3]	1.225

6. Simulation Results

Dynamical performances of the system are obtained when we propose the change of the step in wind speed as shown in Figure 7.

Simulations realized under Matlab software have been done with the main parameters of the DFIG simulation model and are presented in Table I. Table II gives the wind turbine parameters.

The simulations results are obtained with a stator reactive power equal to zero (Q_s = 0 VAR).

The figures below show the simulations results of the system control considered firstly with classic PI controllers then with the proposed fuzzy logic and the second order sliding mode control technique.

The evolution of the quadrature component of rotor current i_{qr}, shown in Figure 8.a, reaches its referential value in a negligible response time and equal to 0.001s when compared to the 0.4s obtained for the response time with a classic PI controllers given in Figure 8. b. Thus, the evolution of i_{qr} is sensitive to the wind speed variations between t = 5s and t = 14s.

In opposite to that, Figure 8.a, shows well the robustness of the rotor current face to the wind speed variations.

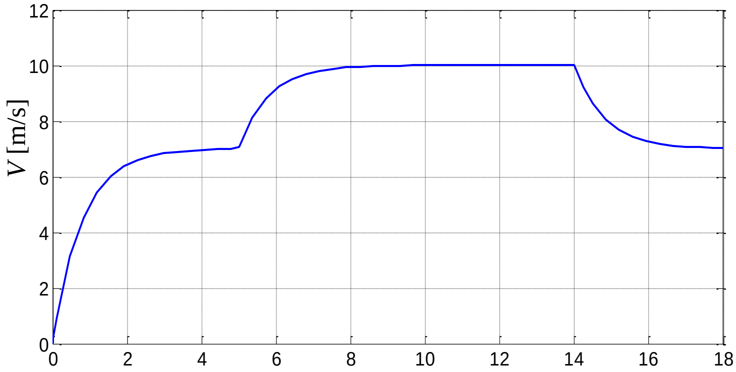
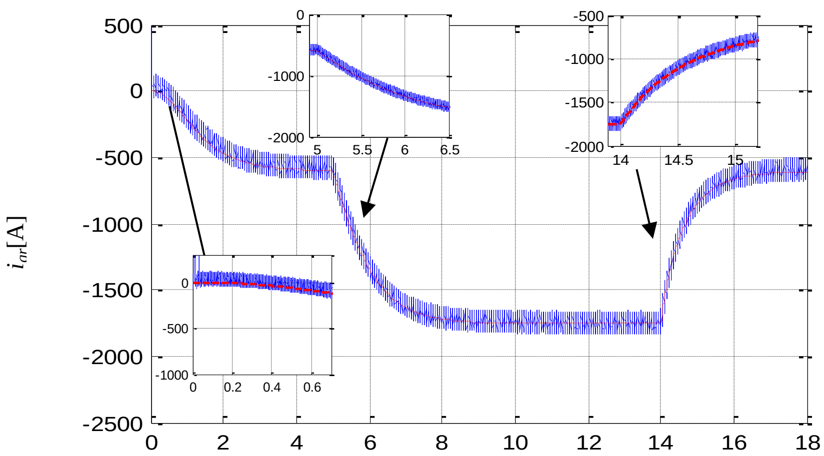
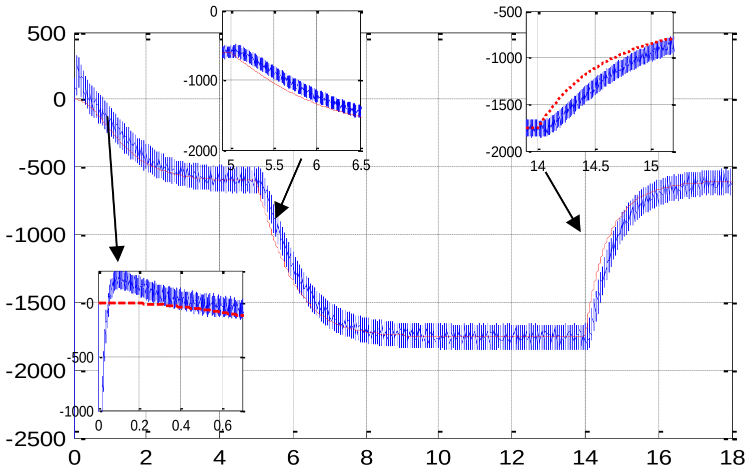


Figure 7. The wind speed applied to wind turbine



a. In Fuzzy and SOSMC case



b. In PI controllers case.

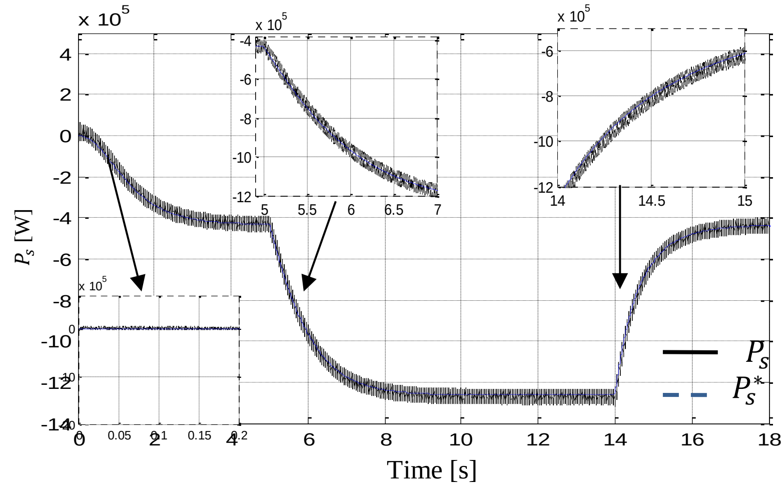
Figure 8. The quadrature component of the rotor currents

The simulation results in Figure 9.a and Figure 10.a show that the active and the reactive generated powers track almost perfectly their references when using the fuzzy and the SOSM controllers, contrary to the PI regulators case. Where the coupling effect between the two axes appears clearly in Figure 9.b and in Figure 10.b. We deduct that the fuzzy and the SOSM controllers ensure a perfect decoupling between the two axes.

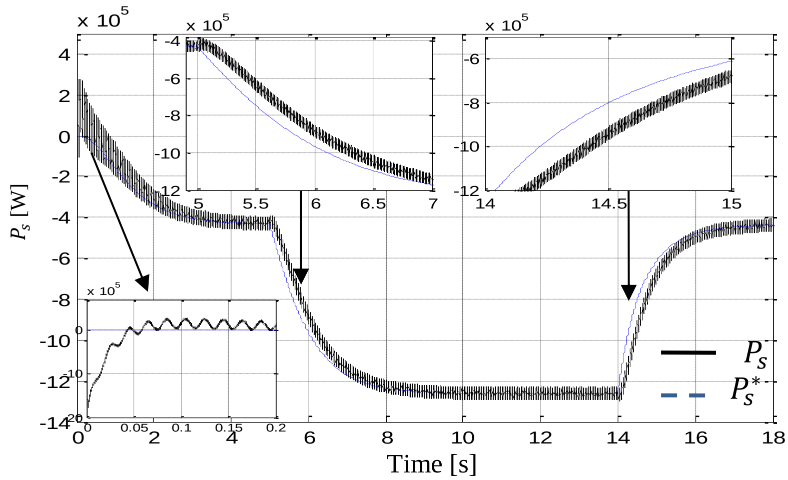
Also, Figure 9.a and Figure 10.a, show that the stator active and the reactive powers follow the reference value with zero steady state error, contrary to the PI regulators case where the coupling effect between the two axes appears clearly. This result proves that the fuzzy and the SOSM controllers are more robust.

These results show also the regulation performance using the fuzzy and the SOSM controllers.

The evolution of the stator active power, presented in Figure 9.a, shows that the power reaches its reference value in a negligible time. And Figure 9.b confirm that the response is faster compared to the classical PI controllers witch gives a response time equal to 1.2s. The stator active power variation, presented in Figure 9.b, shows that it is sensitive to the wind speed variation. However, Figure 9.a, shows that the robustness of the fuzzy and the SOSM controllers of the stator active power towards wind speed variation.

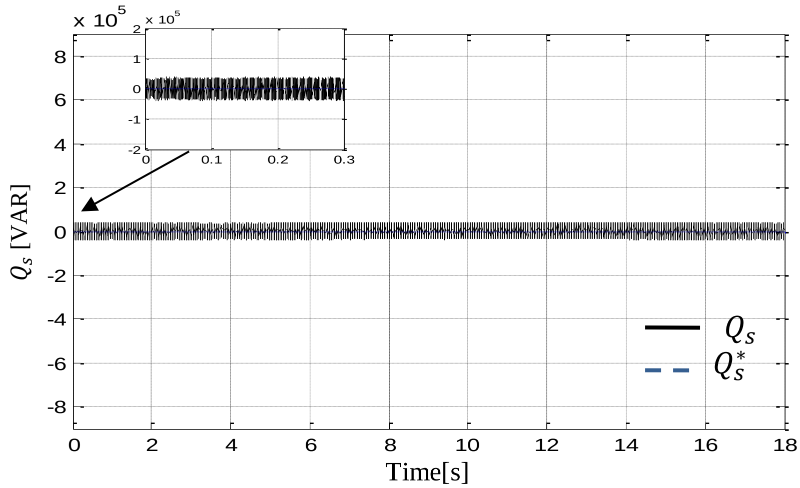


a. In Fuzzy and SOSMC case.

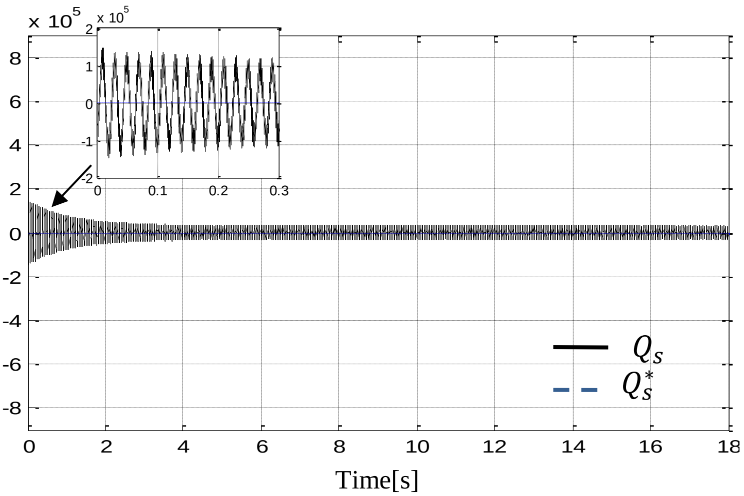


b. In PI controllers case.

Figure 9. The stator active power as a function of time



a. In Fuzzy and SOSMC case.

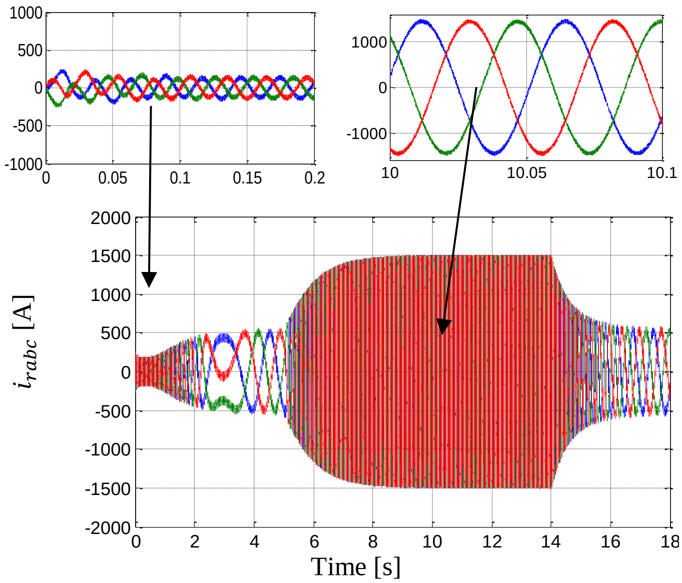


b. In PI controllers case.

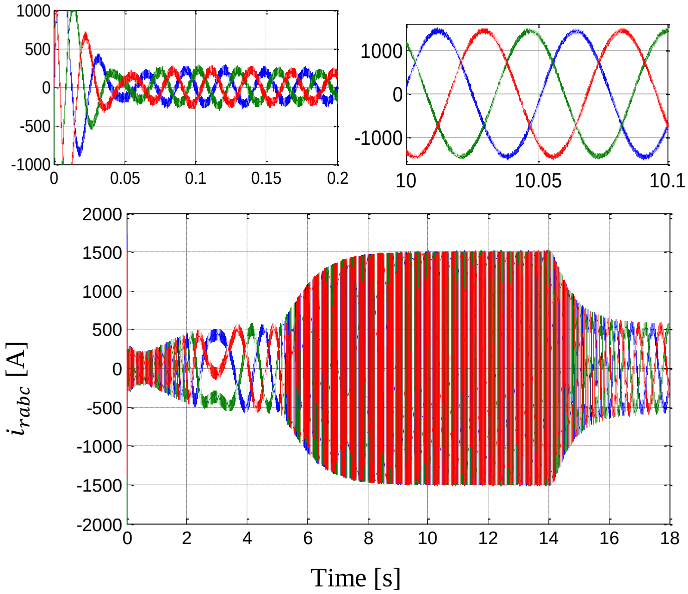
Figure 10. The stator ractive power as a function of time.

Figure 11 shows that the rotor currents took their sinusoidal shape. Their temporary profiles are perfectly adapted to the rotor speed variation and therefore to rotor frequency as they directly depend on the rotational speed of the wind while switching from hypo-synchronous to hyper-synchronous mode.

Our results confirm that "the Power coefficient" presented in Figure 12 and "the tip speed ratio" presented in Figure 13, not change remarkably and their values remain almost equal to their optimal reference values, respectively, equal to $C_P = 0.5$ and $\lambda = 9$.



In Fuzzy and SOSMC case



b. In PI controllers case.

Figure 11. The rotor currents as a function of time.

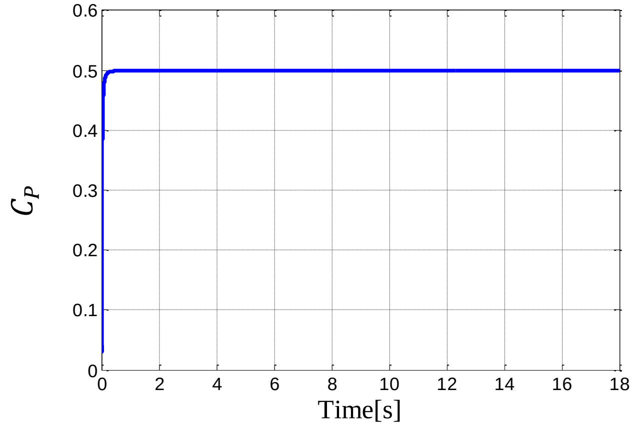


Figure 12. The power coefficient C_P.

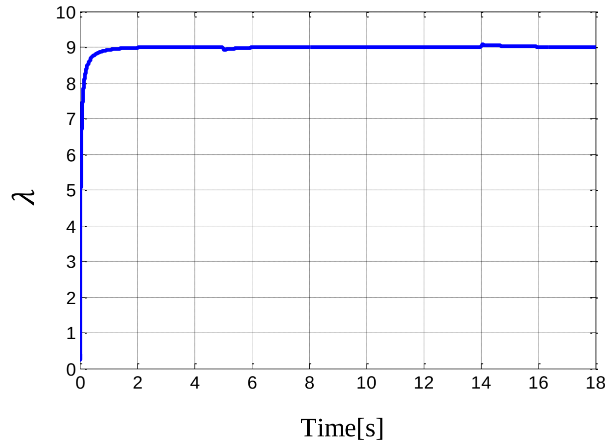


Figure 13. The tip speed ratio λ.

Figure 14 shows that the mechanical speed follows its optimal reference indicating that the "maximum point tracking" is achieved.

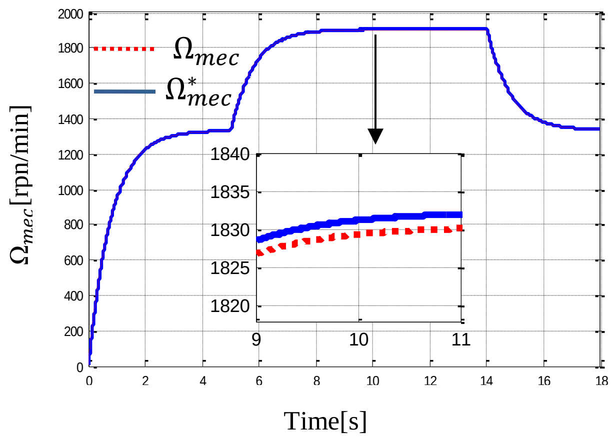


Figure 14. The mechanical speed and its reference.

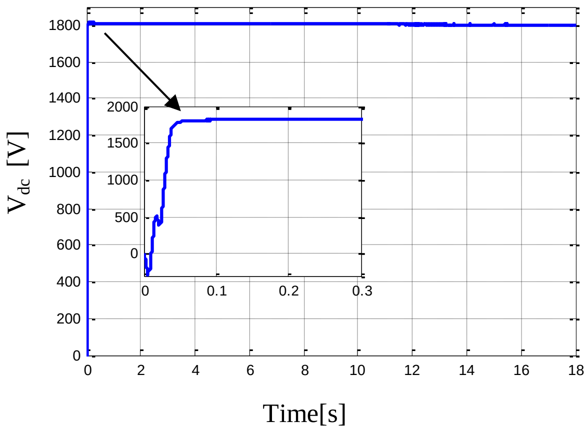


Figure 15. The DC–link voltage.

7. Conclusion

In order to control the active and the reactive powers exchanged between the doubly fed induction generator and the electrical grid used in wind energy conversion system, an hybrid control is proposed.

The proposed control is composed by a coupled model based on fuzzy logic and a second order sliding mode controllers, applied to a doubly fed induction generator. This model used to control the rotor currents. The system performance are compared to the conventional PI controllers.

Simulation results obtained confirm that stability and the precision of our hybrid control. The results demonstrate the independent control of the active and the reactive powers and improve the response time of the combined system: Wind Turbine-DFIG. The obtained results show also that the proposed control ensures a perfect decoupling between the two axes comparatively to the PI regulators and where the coupling effect is appears clearly. The same results confirm also that the proposed fuzzy and the second order sliding mode controllers are more robust towards wind speed variations.

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