Hybrid Controller based on Fuzzy Logic for Doubly Fed Induction Generator used in a Chain of Wind Power Conversion

Jean N. Razafinjaka and Tsiory Patrick Andrianantenaina
Department of Electricity, University of Antsiranana, Diego Suarez, Madagascar
nrazafinjaka@univ-antsiranana.edu.mg, otantikroysti@gmail.com

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Abstract: This paper deals with a study of hybridization based on fuzzy logic controller and a polynomial RST one. This new controller is applied on a Doubly-Fed Induction Generator (DFIG) dedicated in a chain of wind power conversion. These two types or controller have completely different structures: the RST controller uses directly the input and the output to form the command law and the fuzzy logic one needs the error and its variation as inputs. The new proposal consists first to make leave the a priori command from the RST structure and then to form the error and the difference of two consecutive error values for the fuzzy logic controller. The results of simulation show that this technique is realizable and leads to good performances on tracking test, disturbance rejection and robustness with respect of operating variation and parametric variation.

1 INTRODUCTION

Currently, the energy demand does not cease increasing following the various industrial productions on a side and old sources energies start to decrease on other side. In addition, reducing greenhouse gasses emission becomes an obligatory condition in the world. All these reality made the renewable resources attractive. Among these renewable sources of energy, the windmill represents a potential to bring solutions. Currently, the wind system with variable speed based on the doubly fed induction generator (DFIG) is widely used. Indeed, it has some advantages:

- The possibility to measure stator and rotor currents gives a greater flexibility and precision with the control of flow and electromagnetic torque.
- The possibility to operate with constant torque beyond nominal speed.
- Power electronics dimensioned to 30% of the nominal power output: the static inverters used are less bulky, less expensive, requiring thus a system of less heavy cooling. They generate fewer disturbances.
- The losses related to the static inverters are decreased and the system efficiency is imp-roved.

The power factor regulation is possible because the generator can be controlled.Indeed, it is possible to control independently the active and reactive powers by the reason that a converter is connected to the rotor.

Several controls applied on the DFIG have been already proposed (Adjoudj, 2011; Doumi, 2015), which give good performances. Here, a new topology obtained by hybridization of a polynomial controller and a fuzzy logic one is presented. The paper is organized as follows: first, the chain of wind power conversion is given. Then, the DFIG modelling for its vector control follows this generality. Polynomial RST, fuzzy logic controllers and the possibility to obtain their hybridization are then showed. About the simulation, different tests on tracking, disturbance rejection and robustness are taken into account. Discussions about various simulation results are made and a comparison between the results obtained by two different methods is used for the validation. A conclusion will finish the paper.

2 WIND POWER CONVERSION SYSTEM

Figure 1 shows a general scheme of the system which is composed by a turbine, multiplier, the DFIG and two converters. The turbine transforms the kinetic wind power in mechanical energy. The DFIG transforms this latest into electrical energy.

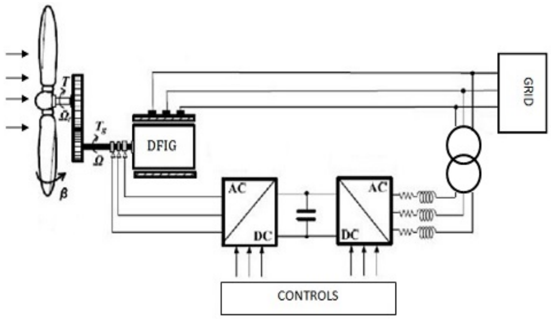


Figure 1: General scheme of wind turbine based on DFIG.

The power mechanical is

$$P = \frac{1}{2}.\rho.\pi.R_T^2.V^3.C_p \qquad (1)$$

With ρ, the air density, V, the wind velocity, R_T, the blade length and Cp, the energy extraction coefficient.

For windmills, the energy extraction coefficient C_p, which depends of the wind velocity and the turbine is usually defined in the interval (0,35÷ 0,59). The coefficient C_p is function of the specific velocity λ and the angle of the blade β. Figure 2 shows the characteristic of C_p according λ.

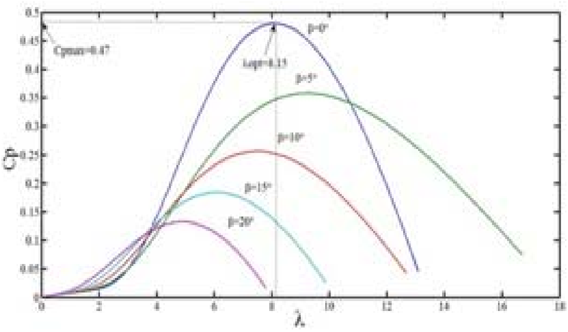


Figure 2: Coefficient C_p vs λ.

The DFIG transforms the mechanical energy to electrical one. The converters are used to transform maximal energy delivered by the windmill to the grid according the wind velocity.

The PWM command can be used for these converters. The rectifier-inverter unit can be dimensioned easily and converter power is lower than the nominal one of the generator.

3 DFIG MODELING AND ITS VECTOR CONTROL

The DFIG model is described in the referential Park. The different equations below give the global modelling of the machine.

3.1 Electrical Equations

The electrical equations give voltage expressions.

$$\begin{cases} V_{ds} = R_s.i_{ds} + \dfrac{d\phi_{ds}}{dt} - \omega_s.\phi_{qs} \\ V_{qs} = R_s.i_{qs} + \dfrac{d\phi_{qs}}{dt} + \omega_s.\phi_{ds} \\ V_{dr} = R_r.i_{dr} + \dfrac{d\phi_{dr}}{dt} - (\omega_s - \omega_r).\phi_{qr} \\ V_{qr} = R_r.i_{qr} + \dfrac{d\phi_{qr}}{dt} + (\omega_s - \omega_r).\phi_{dr} \end{cases} \qquad (3)$$

Φ, R, ω represent respectively, the flux, resistance and pulsation. The indices r, s, d, q are related to the rotor, stator and the axes.

3.2 Magnetic equations

Relation (3) gives the equations of different fluxes.

$$\begin{cases} \phi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \phi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \phi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \phi_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \qquad (4)$$

With L_s, L_r and M design respectively the stator, rotor and mutual inductances.

3.3 Torque and Power Expressions

The electromagnetic torque is expressed according to current and fluxes by:

$$C_{em} = -p.\frac{M}{L_s}(\phi_{sq}.i_{rd} - \phi_{sd}.i_{rq}) \qquad (5)$$

With p, the number of pair of poles

The active and reactive powers are:

By stator side,

$$\begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \end{cases} \tag{6}$$

By rotor side,

$$\begin{cases} P_r = V_{rd} I_{rd} + V_{rq} I_{rq} \\ Q_r = V_{rq} I_{rd} - V_{rd} I_{rq} \end{cases} \tag{7}$$

The motion equation is as:

$$C_{em} - C_r = J \frac{d\Omega}{dt} + f\Omega \tag{8}$$

3.4 DFIG Vector Control

In order to control the electricity production, a method, which not depends of active and reactive powers, is proposed. It consists to establish relations between rotor voltages delivered by the converter with active and reactive powers. Referential **d-q** related of spinning field and a stator flux aligned is adopted. So,

$$\begin{cases} \phi_{sd} = \phi_s \\ \phi_{sq} = 0 \end{cases} \tag{9}$$

Flux equations become,

$$\begin{cases} \phi_{sd} = \phi_s = L_s . i_{sd} + M . i_{rd} \\ 0 = L_s . i_{sq} + M . i_{rq} \\ \phi_{rd} = L_r . i_{rd} + M . i_{sd} \\ \phi_{rq} = L_r . i_{rq} + M\, i_{sq} \end{cases} \tag{10}$$

If the grid is supposed stable, the stator flux Φ_s is constant. Moreover, the stator resistance may be neglected: it is realist hypothesis for a generator used in windmill. Taking into account all these considerations,

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = V_s = \omega_s \phi_s \end{cases} \tag{11}$$

By the equation (8), a relation between stator and rotor currents can be established,

$$\begin{cases} i_{sd} = \dfrac{\phi_s}{L_s} - \dfrac{M . i_{rd}}{L_s} \\ i_{sq} = -\dfrac{M}{L_s} i_{rq} \end{cases} \tag{12}$$

Using relations (6) and (12), the equations of powers give,

$$\begin{cases} P_s = -V_s . \dfrac{M}{L_s} i_{rq} \\ Q_s = -V_s . \dfrac{M}{L_s} i_{rd} + \dfrac{V_s^2}{L_s . \omega_s} \end{cases} \tag{13}$$

In order to control the generator, expressions showing relation between rotor voltages and rotor currents are,

$$\begin{cases} V_{rd} = R_r i_{rd} + L_r \sigma \dfrac{di_{rd}}{dt} - g\omega_s L_r \sigma i_{rq} \\ V_{rq} = R_r i_{rq} + L_r \sigma \dfrac{di_{rq}}{dt} + g\omega_s \left(L_r \sigma i_{rd} + \dfrac{MV_s}{\omega_s L_s} \right) \end{cases} \tag{14}$$

With ***g*** and ***σ*** are denoting respectively the slip and the leakage coefficient. The expressions of g and σ are,

$$\begin{cases} g = \dfrac{\omega_s - \omega_r}{\omega_s} \\ \sigma = \dfrac{L_s . L_r - M^2}{L_s . L_r} \end{cases} \tag{15}$$

Figure 3 built by relations (11), (12), (13) and (14) shows diagram where rotor voltages are the input, active and reactive powers are the output.

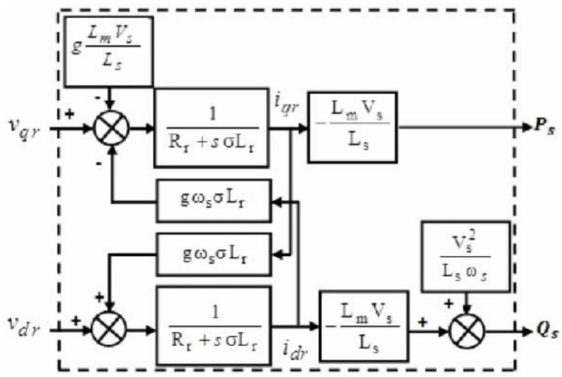


Figure 3: Diagram of the system to be controlled.

There are generally two methods to do an independent regulation of the powers:

- Direct method, which consists to neglect the coupling terms to put controller on each axe to command active and reactive powers. In this case, the controllers command directly the rotor voltages of the DFIG.
- The second method, which takes into account the coupling terms and to compensate them by using two loops permitting to control the stator powers and the rotor currents. It is based on the relations (13) and (14).

In this case, the second method is adopted. Figure 4 shows the diagram.

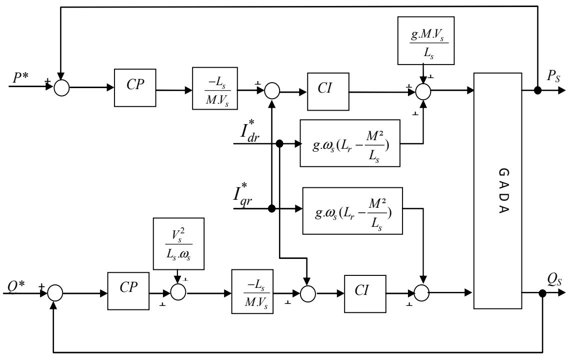


Figure 4: Indirect vector control diagram (CP and CI design power and current controllers).

Power and current loops have both, a first order transfer function. They may be represented as showed by figure 5.

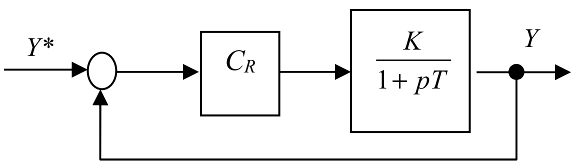


Figure 5: General schema for power and current loops.

For powers,

$$\begin{cases} K = \dfrac{M.V_s}{L_s.R_r} \\ T = \dfrac{L_s.L_r - M^2}{L_s.R_r} \end{cases} \quad (16)$$

For rotorique currents,

$$\begin{cases} K = \dfrac{1}{R_r} \\ T = \sigma \dfrac{L_r}{R_r} \end{cases} \quad (17)$$

4 THE HYBRID CONTROLLER

This new topology of hybrid controller named RST-FL is built on combination of the polynomial RST controller and the fuzzy logic one. First, the general characteristics of the RST controller is showed and followed by the presentation of the fuzzy logic controller. Based on these two types of controllers, the technique of hybridization will be studied.

4.1 Polynomial RST Controller

This type of controller is primarily digital one. It owes its name with the three polynomials which define it: R(z), S(z) and T(z). The command law is,

$$R(z).U(z) = T(z).Yc(z) - S(z).Y(z) \quad (18)$$

Where $Y_c(z)$ is the input and Y(z) the output.

The difference between T(z) and S(z) offers more possibility and it is the reason that this RST controller is called controller with two degrees of freedom. It generalizes the standard PID controller.

4.1.1 RST Synthesis

The RST synthesis is based on poles placement when a desired model $H_m(z)$ of closed loop is assigned. Figure 6 shows the basic idea. Usually, the desired model is with non-higher order model. Its poles must satisfy absolute and relative conditions of damping.

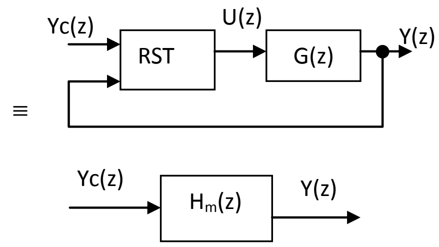


Figure 6: Basic scheme for RST synthesis.

Assume that the transfer functions G(z) and $H_m(z)$ are respectively,

$$G(z) = \frac{B(z)}{A(z)} \qquad H_m(z) = \frac{B_m(z)}{A_m(z)} \quad (19)$$

Using relations (18) and (19), the following equality can be expressed:

$$\frac{T(z).B(z)}{A(z).R(z) + B(z).S(z)} = \frac{B_m(z)}{A_m(z)} \quad (20)$$

Here R(z), T(z) and S(z) are to be calculated. Generally, R(z) is chosen as a normalized polynomial.

Resolving relation (20) with the required specifications needs zero cancellation and the desired transfer function $H_m(z)$ must satisfy some considerations:

- $H_m(1) = 1$ to ensure position error null
- The denominator is :

$$A_m(z) = z^d.P(z) \quad (21)$$

Where the d°P = 1 or d°P =2 (here, d°P denotes the degree of P(z)).

Relation (22) permits to calculate the discreet transfer function G(z) from G(p).

$$G(z) = (1 - z^{-1}).\mathbb{Z}\left\{L^{-1}\left[\frac{G(p)}{p}\right]\right\} \quad (22)$$

So,

$$G(p) = \frac{K}{1 + pT} \Rightarrow G(z) = \frac{B(z)}{A(z)} = \frac{b_o}{z - z_0} \quad (23)$$

With,

$$b_0 = K.(1 - z_0) \qquad z_0 = e^{-\frac{h}{T}} \quad (24)$$

Here, h denotes the sampling period.

Because of the expression of G(z), no zero can be cancelled. All steps to determine the polynomial RST are resumed in (Longchamp, 1992; Razafinjaka, 1991).

4.1.2 Fuzzy Logic Controller

The method built around fuzzy logic avoids modelling the system but it is clear that having knowledge of its behaviour is always useful. The reasoning is close to human perception. Nowadays, the fuzzy logic controller begins to take an important place in electrical applications. It can be used for optimization, and command (Baghli, 2005; Robyns, 2007). It is also the reason that its implementation in integrated circuits for embarked systems is currently widespread (Shuwei G., 1996), (Casciati F., 1999), (Francisco Fons, 2006). The common scheme for FLC is given in figure 7.

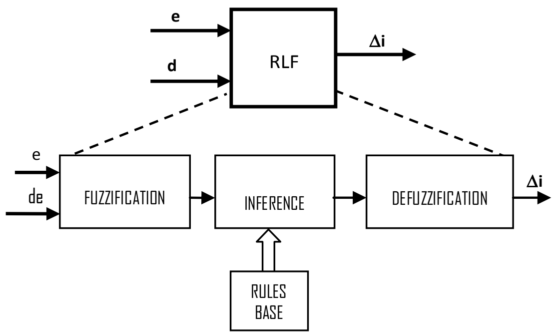


Figure 7: Structure of Fuzzy logic controller.

With e, de and Δi denote respectively the error, the error variation and the output.

The fuzzification consists in projecting a real physical variable distributed on the domains variable characterizing this variable: linguistic variable is so obtained and the fuzzification makes it possible to have a precise measurement by the membership Rules are established by the knowledge of the desired behaviour of the system. They are often as:

$$(\mathit{If}\ x_1\ \mathit{is}\ A)\ \mathit{AND}\ (x_2\ \mathit{is}\ B)\ \mathit{THEN}\ S_k = C_k \quad (25)$$

Here x_1 and x_2 are the inputs and S_k the output which is also a linguistic variable. In this paper, the Sugeno's method is chosen and C_k is chosen as constant (singleton). Membership functions may be defined for the output variable and there are several inference methods, which may be applied. To be used in a real control, these fuzzy variables must be translated into real or numerical variables: it is the function of the defuzzification block.

The Sugeno defuzzification (Tagaki, 1985) is then weighted average method.

$$S = \sum \frac{\mu(s_k).s_k}{\mu(s_k)} \quad (26)$$

For the two inputs, (e, de), the triangular and trapezoidal forms are used. The number of membership functions may be N=3, 5 or 7. Here N=3 is adopted to take into account the implementation. Simulations also show that results are not different for N=3, 5, 7. For the output, singletons are chosen.

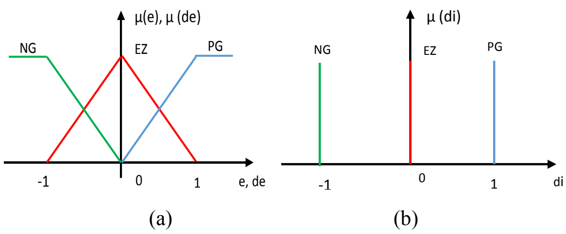


Figure 8: Membership functions. (a): inputs, (b): output.

Table 1 gives the inference matrix.

Table 1: Rules base for N = 3.

		e		
		NG	*Z*	*PG*
de	*NG*	NG	NG	Z
	Z	NG	Z	PG
	PG	Z	PG	PG

The table 1 gives 9 rules.

4.1.3 Hybrid Controller: RST-FL

Currently, hybridizations obtained with basic or old fuzzy logic are used to improve performances. Some examples may be cited here: algorithm genetic adapted by fuzzy logic (Laoufi, 2011), back stepping with fuzzy logic (Laoufi, 2011; Ezziani, 2011), maximum power point tracking (MPPT) using adaptive neuro-fuzzy inference system ANFIS (P. Siva, 2015). This last method is now well-known.

On a side, the FLC has as inputs, the error and its variation, on other side, the RST controller uses directly the input and the output as showed by relation (18). Apparently, the two topologies are definitely different. However, a possibility can be obtained on the basis of this relation. One term can be added and subscripted, for example [S(z).Y_c(z).)]

$$\begin{cases} 0 = S(z).Y_c(z) - S(z).Y_c(z) \\ R(z).U(z) = T(z).Y_c(z) - S(z).Y(z) \\ \Rightarrow R(z).U(z) = T(z).Y_c(z) - S(z).Y(z) + [S(z).Y_c(z) - S(z).Y_c(z)] \\ \Rightarrow R(z).U(z) = Y_c(z)[T(z) - S(z)] + S(z)[Y_c(z) - Y(z)] \end{cases} \quad (27)$$

The last relation can be rearranged as follows,

$$U(z) = Y_c(z).\frac{T(z) - S(z)}{R(z)} + [Y_c(z) - Y(z)]\frac{S(z)}{R(z)} \quad (28)$$

The relation (28) reveals the error and the a priori command. The transcription of this relation in functional diagram is presented by figure 9. The error is expressed as :

$$E(z) = Y_c(z) - Y(z) \quad (30)$$

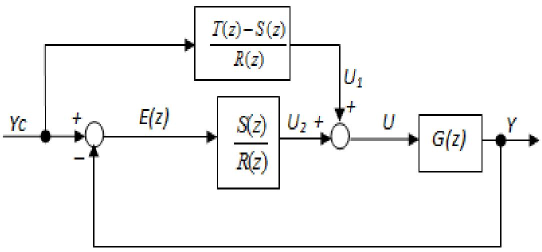


Figure 9: RST scheme with the a priori command.

Here, the command U is the sum of two components:

- U_1, which is the a priori command. It is built directly around the input and can bring its contribution for test tracking
- U_2, built by the error: difference of the input and the output.

It can be noted that this topology is always possible as long as polynomials *T(z)* and *S(z)* have same degree. Because of the presence of the error *E(z),* several topologies may be drawn from the figure 9 by inserting the FLC. Figure 10 shows the proposed combination.

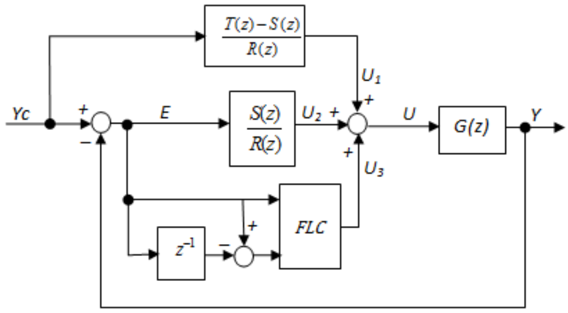


Figure 10: Basic scheme of proposed hybrid controller: RST-FL.

5 SIMULATION AND RESULTS

Simulation takes into account tracking test, disturbance rejection and robustness with respect operating and parametric variations specially the rotorique resistance variation.

For the simulation, these conditions are adopted:

- Variation of power references, P_{sref} and Q_{sref}.
- At t = 2,5 [s], Ω:167,5[rd.s^{-1}] → 178[rd.s^{-1}]
- At t = 3 [s], $R_r \rightarrow 2{*}R_r$

For the RST synthesis, an effect of perturbation compensator is chosen: m =1 and a polynomial P(z) with degree 2 is used. The results of computation are as follows (d°P = 2, h = 1[ms], m = 1).

P(z) is obtained in order to respect the relative damping condition. The analogical poles in closed loop are calculated by giving the damping factor, the pulsation and the sampling time.

Table 2: Controllers coefficients for h = 1[ms].

Powers	Currents
$\zeta = 0,6 \quad \omega_n = 1500\left[rd.s^{-1}\right]$	$\zeta = 0,6 \quad \omega_n = 50\left[rd.s^{-1}\right]$
$R(z) = z - 1$	$R(z) = z - 1$
$S(z) = 0,0712.z - 0,0346$	$S(z) = 7.z - 6,4954$
$T(z) = 0,0366.z$	$T(z) = 0,3520.z$

For FLC, no theory is applied here to determine normalization and un-normalization gains. Their determination begins by using the gains of the PI controller and then adjusted by simulations.

$$k_{de} = 8.10^{-6} \quad k_e = 2.10^{-4} \quad di = 6.10^{3} \qquad (31)$$

Simulation is made by using Matlab and Simulink. Following figures show the results
The zoom of active power curves are shown in figures 12 (a), (b) following respectively speed variation and rotorique resistance variation.

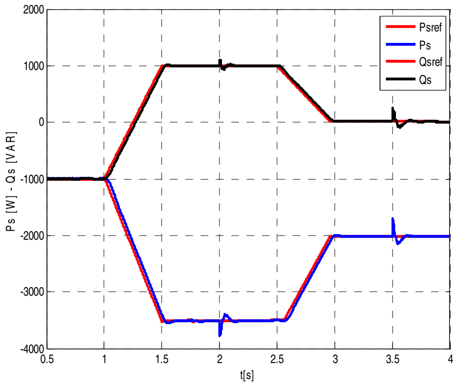
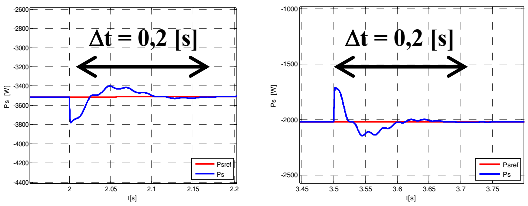


Figure 11: Active and reactive powers curves.



(a) (b)

Figure 12: Zoom on active power curves : (a) following speed variation - (b) following rotorique resistance variation.

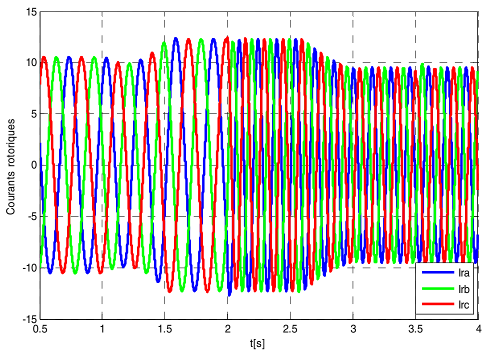


Figure 13: Rotorique currents.

Figures 11 and 12 (a)-(b) show that there are good performances. Effectively, the looped system reacts with operating and parametric variations (Δt = 0,2 [s]).

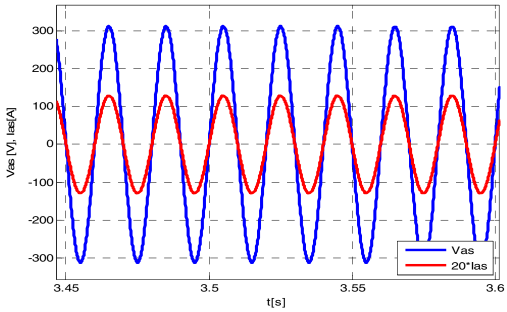


Figure 14: Statorique voltage and current when Qs = 0.

However, it can be noted that the active power loop is more sensible of rotorique variation (ΔP = 290 [W]) than the speed one (ΔP = 270 [W]).

When Q_s = 0, see Figure 14, statorique voltage and current statorique are in phase. It ensures good quality of the energy sent to the grid.

6 VALIDATIONS

Indirect validation is here adopted. It consists to compare the obtained results by the new proposed method with another published work. In (Doumi, 2015), an adaptive control based on basic fuzzy logic controller is used. The speed is maintened constant but active and reactive power references are shown in figure 15 to present test tracking and robustness in respect parameter variation, here variation of the rotorique resistance.

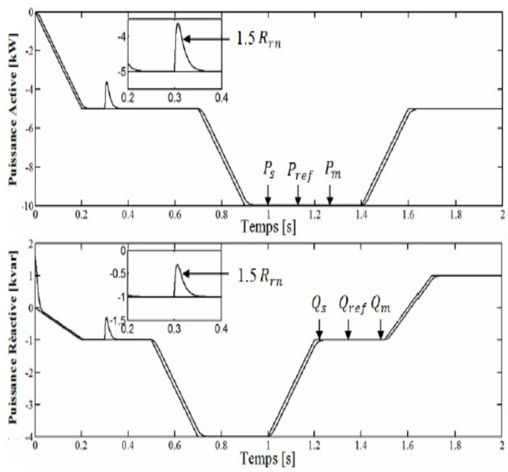


Figure 15: Simulation results obtained in (Doumi, 2015).

Comparing figures 11 and 15 shows permits to conclude that the new proposal leads to results in conformity with the method proposed in (Doumi,

2015). It may be noted that the error position is null but the error velocity depends on sampling time h.
In this work, the variation parameter is harder (*Rr → 2*Rr)*. Here, it can be noted that tracking test is better for the new method. However, it should be mentioned that the machines used in the two proposed methods have not the same characteristics.

7 CONCLUSIONS

In this paper, a new topology to obtain a hybrid controller is proposed. The hybridization consists to combine a polynomial RST and fuzzy logic controllers. The method is starting from obtaining a scheme presenting the a priori command. The simulation results show that this hybridization is realizable and leads to good performances as tracking test, disturbance rejection and robustness. The implementation needs a DSP card. An adaptive control is also possible to be implemented starting from figure 9. This option will be tested and presented later on.

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