Model Reference Adaptive Control based on Fuzzy Logic for Doubly Fed Induction Generator used in a Chain of Wind Power Conversion

Jean N. RAZAFINJAKA, Tsiory P. ANDRIANANTENAINA

***Abstract*—**
This paper deals with a study of a model reference adaptive control (MRAC) based on fuzzy logic controller and polynomial RST one. This new proposal is applied on the controls powers of a doubly fed induction generator (DFIG) used in a chain of wind power conversion. The wind system is envisaged to be connected to the grid. Simulations are made by using MATLAB platform. The results show that this new method is realizable and leads to good performances on tracking test, disturbance rejection and robustness in respect with parameters variation, especially rotorique resistance variation. Indirect validation by comparison with a method suggested by other authors permits to conclude the effectiveness of the new method.

***Index Terms*—Adaptive control, fuzzy logic, DFIG, RST controller , model reference**

I. INTRODUCTION

Currently, the energy request does not cease increasing and old sources energies start to decrease. In addition, reducing greenhouse gasses emission becomes an obligatory condition in the world. All these reality made renewable resources attractive. Among these renewable sources of energy, the windmill represents a potential to bring solutions. Currently, windmill system with variable speed based on the DFIG is widely used. Indeed, it presents more advantages. Several controls applied on the DFIG have been already proposed as [1], [2], [3], which give good performances. Here, a MRAC using fuzzy logic and a polynomial RST is adopted. The paper is organized as follows: first, the chain of wind power conversion is given. The DFIG modeling and its vector control follow this generality. Polynomial RST, fuzzy logic and MRAC are then showed. About the simulation, different tests are taken into account. Discussions from various simulation results are presented. An indirect validation by comparison and a conclusion will finish the paper.

II. WIND POWER CONVERSION SYSTEM

Fig.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 total kinetic is,

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

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) [3].

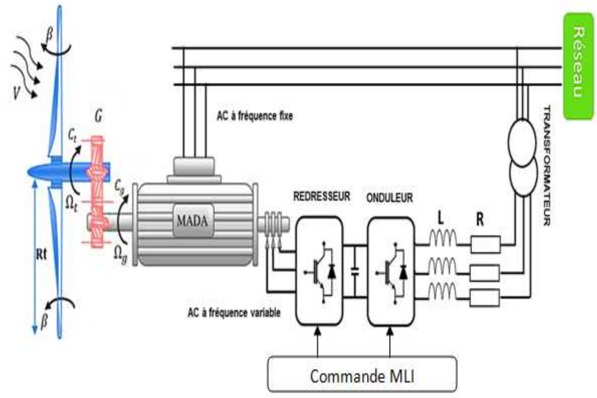

Fig.1: General scheme of wind turbine based on DFIG.

The coefficient C_p is function of the specific velocity λ and the angle of the blade β. Fig.2 shows the characteristic of C_p according λ.

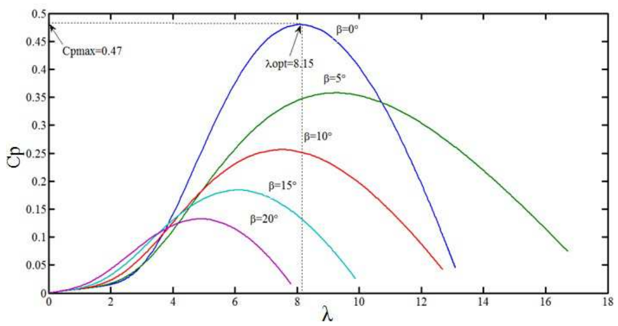

Fig.2: Characteristic of C_p vs. λ.

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.

Manuscript received on February 2016

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III. DFIG MODELING AND ITS VECTOR CONTROL

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

A. *Electrical equations*

The electric equations give voltage expressions.

$$\begin{cases} V_{ds} = R_s.i_{ds} + (d\phi_{ds}/dt) - \omega_s.\phi_{qs} \\ V_{qs} = R_s.i_{qs} + (d\phi_{qs}/dt) + \omega_s.\phi_{ds} \\ V_{dr} = R_r.i_{dr} + (d\phi_{dr}/dt) - (\omega_s - \omega_r).\phi_{qr} \\ V_{qr} = R_r.i_{qr} + (d\phi_{qr}/dt) + (\omega_s - \omega_r).\phi_{dr} \end{cases} \quad (2)$$

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.

B. *Magnetic equations*

Relation (3) gives the equations of different fluxes.

$$\begin{cases} \phi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \phi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \phi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \phi_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \quad (3)$$

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

C. *Torque and powers expressions*

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

$$C_{em} = -p(M/L_s).(\phi_{sq} i_{rd} - \phi_{sd} i_{rq}) \quad (4)$$

With p, the number of pair of poles

The active and reactive powers are:

By stator side,

$$\begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \end{cases} \quad (5)$$

By rotor side,

$$\begin{cases} P_r = V_{rd} I_{rd} + V_{rq} I_{rq} \\ Q_r = V_{rq} I_{rd} - V_{rd} I_{rq} \end{cases} \quad (6)$$

The motion equation is as:

$$C_{em} - C_r = J(d\Omega/dt) + f.\Omega \quad (7)$$

With *f*, the coefficient of viscous friction, C_r, resisting torque and Ω, the angular mechanical speed.

D. *Vector control of the DFIG*

The control of active and reactive powers can be reached by the control of rotor flux of the DFIG. This technique consists in maintaining reactive flux of armature in squaring with rotor flux. To control independently active and reactive powers, direct and transverse rotor voltages must be controlled separately in an uncoupled mode by introducing compensation terms. Referential (d, q) related of spinning field and stator flux aligned are adopted. So,

$$\begin{cases} \phi_{sd} = \phi_s \\ \phi_{sq} = 0 \end{cases} \quad (8)$$

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

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = V_s = \omega_s \phi_s \end{cases} \quad (9)$$

By equations (8) and (9, relations between rotorique and statorique currents can be established,

$$\begin{cases} i_{sd} = \dfrac{\phi_s}{L_s} - \dfrac{M.i_{rd}}{L_s} \\ i_{sq} = -\dfrac{M}{L_s} i_{rq} \end{cases} \quad (10)$$

Using relations (5) and (10), power equations are as follows,

$$\begin{cases} P_s = -V_s.(M/L_s).i_{rq} \\ Q_s = -V_s.(M/L_s).i_{rd} + (V_s^2/(L_s.\omega_s)) \end{cases} \quad (11)$$

In order to control the generator, relations between rotorique currents and voltages are given,

$$\begin{cases} V_{rd} = R_r i_{rd} + L_r \sigma (di_{rd}/dt) - g\omega_s L_r \sigma i_{rq} \\ V_{rq} = R_r i_{rq} + L_r \sigma (di_{rd}/dt) + g\omega_s \left(L_r \sigma i_{rd} + (MV_s/\omega_s L_s) \right) \end{cases} \quad (12)$$

Where g and σ are denoting respectively the slip and the leakage coefficient.

$$g = (\omega_s - \omega_r)/\omega_s \quad , \sigma = (L_s.L_r - M^2)/L_s.L_r \quad (13)$$

Fig. 3 built from relations (9), (10), (11) and (12) shows the diagram where rotor voltages are the input and active and reactive powers are the output.

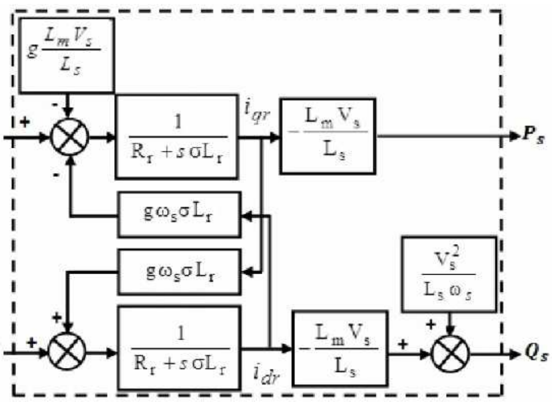

Fig.3: System diagram to be controlled.

In this paper, the direct method (DTC) is adopted. It consists to neglect the coupling terms to insert controller on each axe in order to command active and reactive powers. In this case, the controller commands directly the rotor voltages of the DFIG.
Powers loop have a first order transfer function.

$$G(p) = K/(1+pT) \quad (14)$$

With,

$$\begin{cases} K = (M.V_s / L_s.R_r) \\ T = \sigma.(L_r / R_r) \end{cases} \quad (15)$$

IV. MRAC WITH POLYNOMIAL RST AND FUZZY LOGIC

The techniques of adaptive control can bring solutions to the problem of parametric variations, which may generate bad performances or even instability.
For these techniques, the controller adapts itself to the conditions of system operating. Several configurations are already available [4], [5], [6] presenting direct or indirect schemes.
In this work, fuzzy logic and RST controller are adopted. The technique consists to the parallelization of two loops:

1) The direct loop provided with a polynomial controller RST
2) The adaptive loop, with fuzzy logic

The reference model generates a desired output $\hat{Y}$. It is then compared with the effective output Y to produce the signal correction resulting of the adaptive mechanism. Fig.4 gives a synoptic diagram.

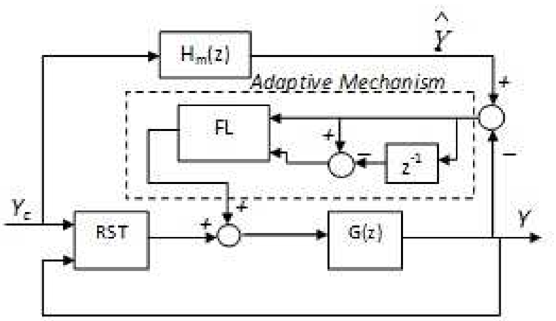

Fig.4 Fig. 4: Synoptic diagram for MRAC

A. The polynomial RST controller

The RST controller is primarily a digital controller. It generalizes the standard PID and owes its appellation with the three polynomials R(z), S(z) and T(z) which define it. The command law is,

$$R(z).U(z) = T(z).Y_c(z) - S(z).Y(z) \quad (16)$$

The RST synthesis is based on poles placement where a desired model $H_m(z)$ in close loop is chosen. Fig.5 shows the basic idea. Usually the desired model is with non-high order. Its poles must satisfy absolute and relative conditions of damping.

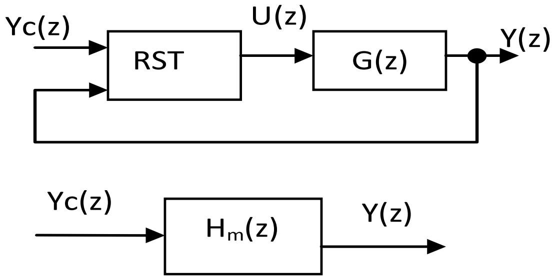

Fig. 5: Basic scheme for RST synthesis

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

$$\begin{cases} G(z) = B(z)/A(z) \\ H_m(z) = B_m(z)/A_m(z) \end{cases} \quad (17)$$

Using relations (16) and (17), the following equality can be expressed,

$$T(z).B(z)/[A(z).R(z) + B(z).S(z)] = B_m(z)/A_m(z) \quad (18)$$

Here R(z), T(z) and S(z) are to be determined. Generally R(z) is chosen as a normalized polynomial. Resolving the equation (18) with required specifications needs zero cancellation and the desired transfer function $H_m(z)$ must satisfy some considerations:

1) $H_m(1) = 1$ to ensure the position error nul ($e_p = 0$)
2) The denominator: $A_m(z) = z^{d.} P(z)$

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

Relation (19) gives the discreet function transfer G(z) from G(p),

$$G(z) = (1 - z^{-1}).Z\left\{L^{-1}\left[G(p)/p\right]\right\} \quad (19)$$

So,

$$G(z) = B(z)/A(z) = b_o/(z - z_0)$$
$$\begin{cases} b_o = K.(1 - z_0) \\ z_0 = \exp(-h/T) \end{cases} \quad (20)$$

Here, **h** denotes the sampling time.

Because of the expression of G(z), no zero can be cancelled. All steps for polynomial RST synthesis are resumed in [4] and [7].

B. Fuzzy Logic Controller (FLC)

Using fuzzy logic avoids modeling the system but it is clear that having knowledge of its behavior is always useful. The reasoning is close to human perception. Nowadays, fuzzy logic controller begins to take an important place in electrical applications. It can be used for optimization and command [8], [9], [10]. The common scheme for FLC is given in figure 6.

The fuzzification consists in projecting a real physical variable distributed o the variable domains to characterize the variables: linguistic variables are so obtained and the fuzzification makes it possible to have a precise measurement by the membership degree of the real variable to each fuzzy subset.

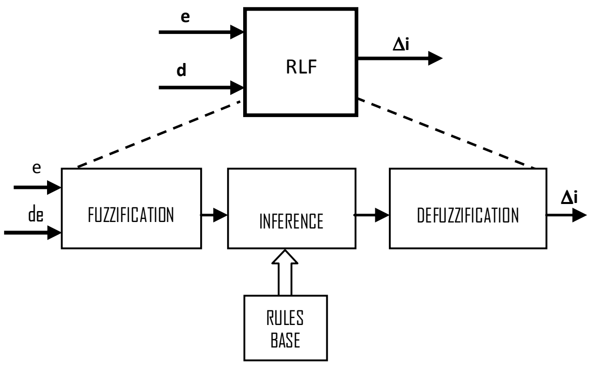

Fig. 6: Structure of fuzzy logic controller

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

Generally, the inference method is a logical operation by which one admits a proposal under the terms of its relation with other proposals, held for true. At this stage, rules are established by the knowledge of the desired behavior of the system. The rules are often as follows,

Rule k: (IF x_1 is A) AND (x_2 is B) THEN $S_k = C_k$ (21)

Here x_1 and x_2 are the inputs and S_k the output which is also a linguistic variable. There are several inference methods which may be applied.

The result of aggregation of the inference rules gives still fuzzy variables. To be used in a real control, these fuzzy variables must be translated into real or numeric variables: it is the function of the defuzzification block.

In this paper, Sugeno's methods are chosen: a singleton is used as membership function of the rule consequent combined by (max-min) method for rule evaluation. Thus, in relation (21), C_k is a constant. The Sugeno's defuzzification uses the weighted average method [11].

$$S = \sum (\mu(s_k).s_k / \mu(s_k)) \quad (22)$$

For the two inputs (e, de), triangular and trapezoidal membership functions are used. For the output, singletons are chosen.

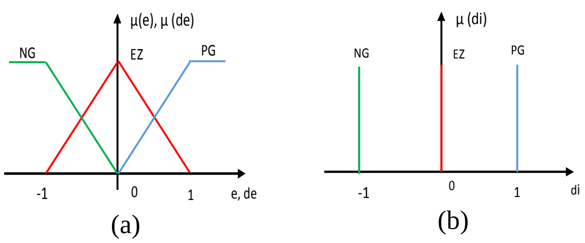

Fig. 7: Membership functions. (a): inputs (b): output

Table 1 gives the inference matrix. The table gives 9 rules. For example,

R_1: (IF e =NG) AND (de = NG) THEN (Δi = NG) (23)

TABLE I. RULES FOR N = 3.

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

V. SIMULATION AND RESULTS

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

1) Variation of power references: P_{sref} and Q_{sref}
2) At t = 4,5 [s], Rr → 2*Rr ⇒ $\tau_r \rightarrow \tau_r/2$

For the RST synthesis, an effect or perturbation compensation (m = 1) is chosen, and a polynomial P(z) with degree 2 is used.

$$\begin{cases} h = 5\,[ms] \quad d°P = 2 \quad \omega_n = 150\,[rd.s^{-1}] \quad \zeta = 0,707 \quad m = 1 \\ R(z) = z - 1 \\ S(z) = 0,006z - 0,0028 \\ T(z) = 0,0032 \end{cases} \quad (21)$$

For the FLC, normalization and un-normalization gains are determined by experiences.

$$\begin{cases} k_{de} = 8.10^{-5} \\ ke = 2.10^{-4} \\ di = 3.10^{3} \end{cases} \quad (22)$$

Following figures give the simulation results.

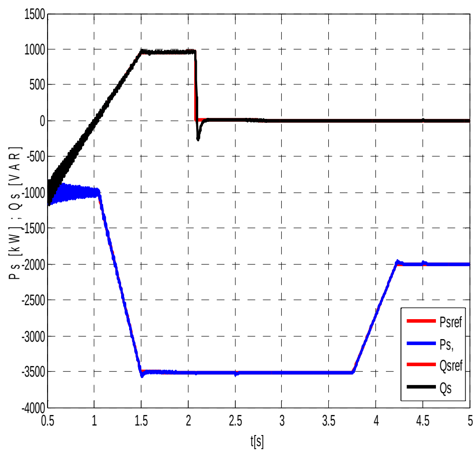

Fig. 8 : Active and reactive power curves.

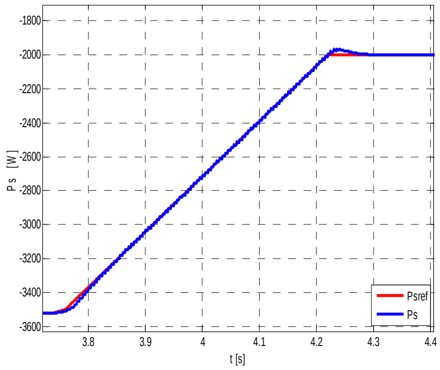

Fig. 9: Active power curve showing set point tracking

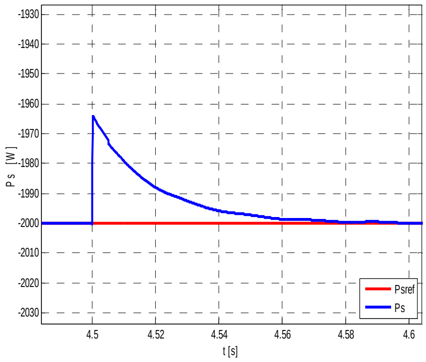

Fig.10: Zoom, t = 4,5 [s] Rr → 2*Rr

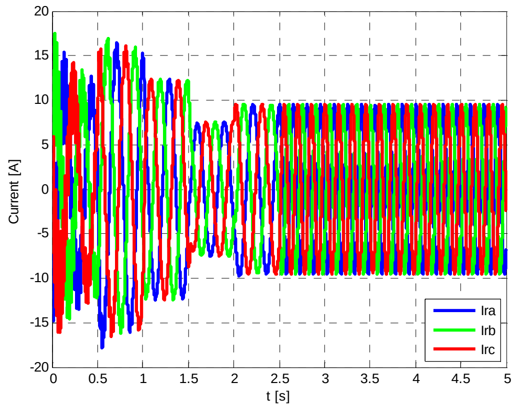

Fig. 11: Rotorique currents curves

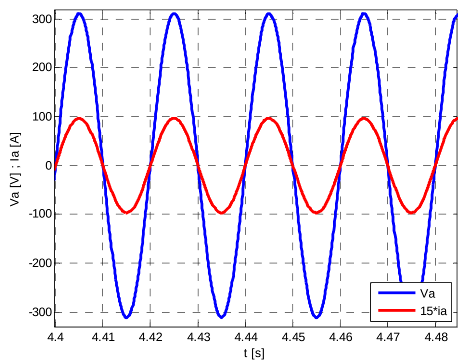

Fig. 12: Statorique voltage and current when Qs = 0.

The results show that the proposed topology leads to good performances

$$\begin{cases} D_1 = 1{,}9\ \% \\ t_P = 4{,}235\ [s] \end{cases} \qquad \begin{cases} t = 4{,}5[s] \quad R_r \rightarrow 2*R_r \\ \Delta t = 0{,}077[s] \\ \Delta P = 36\ [W] \end{cases}$$

The references P_{sref} and Q_{serf} are well followed. There is a rapid regulation.

When $Q_s = 0$, rotorique voltage and rotorique current are purely sinusoidal and in phase. It ensures a good quality of the energy injected into the grid.

VI. VALIDATIONS

Indirect validation is here adopted. It consists to compare the obtained results by the new proposed method with another published work. In [12], an adaptive control based on basic fuzzy logic controller is also 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.

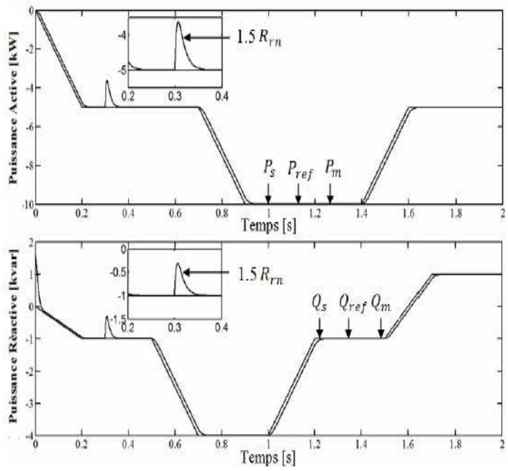

Fig. 13: Simulation results obtained in [12]

Comparing figures 8, 9 and 13 permits to conclude that the new proposal leads to results in conformity with the method proposed in [12].
In both cases, the position error is null but the velocity error is better with the MRAC RST-FLC. It must be noted that this kind of error depends on sampling time h.
However, it may be mentioned that the machines used in the two proposed methods have not the same characteristics.

VII. CONCLUSION

In this paper a MRAC using polynomial RST controller with Fuzzy logic one is proposed to be applied on DFIG used in a chain of wind power conversion. Simulation results present that the proposed method leads to good performances as tracking test, disturbance rejection and robustness in respect of parameters variation especially with rotorique resistance variation. The indirect validation consisting by comparison with a method proposed by others authors shows that the results are in conformity and permits to conclude the reliability of the MRAC method.

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