IJE TRANSACTIONS A: Basics Vol. 33, No. 4, (April 2020) 567-574

International Journal of Engineering

Journal Homepage: www.ije.ir

Hybrid Fuzzy Reference Signal Tracking Control of a Doubly Fed Induction Generator

N. Choug*[a], S. Benaggoune[a], S. Belkacem[b]

[a] *Faculty of Technology, LSTE Laboratory, University of Mostefa Ben Boulaïd Batna 2, Algeria*
[b] *LEB Research Laboratory, Electrical Engineering Department, University of Mostefa Ben Boulaïd Batna 2, Algeria*

PAPER INFO

Paper history:
Received 01 July 2019
Received in revised form 21 January 2020
Accepted 17 March 2020

Keywords:
Doubly Fed Induction Generator
Vector Control
Reference Signal Tracking
Fuzzy Control
Parameters Uncertainly

ABSTRACT

This paper presents a hybrid scheme for the control of active and reactive powers using the direct vector control with stator flux orientation (SFO) of the DFIG. The hybrid scheme consists of Fuzzy logic, Reference Signal Tracking (F-RST) controllers. The proposed (F-RST) controller is compared with the classical Proportional-Integral (PI) and the Polynomial (RST) based on the pole placement theory. The various strategies are analyzed and compared in terms of tracking, robustness, and sensitivity to the speed variation. Simulations are done using MATLAB software. The simulation results prove that the proposed approach leads to good performances such as the tracking test, the rejection of disturbances and the robustness concerning the parameter variations. The hybrid controller is much more efficient compared to those of PI and RST controller, it also improves the performance of the powers and ensures some important strength despite the parameter variation of the DFIG.

doi: *10.5829/ije.2020.33.04a.08*

NOMENCLATURE

s, r	Stator and rotor subscripts	σ	Leakage factor
d, q	Synchronous reference frame index.	T_{em}	Electromagnetic torque
V_{sd}, V_{sq}	d and q axis stator voltages	ω_S	Synchronous speed
V_{rd}, V_{rq}	d and q axis stator voltages	P	Number of pole pairs
I_{sd}, I_{sq}	d and q axis stator currents	ω_r	Rotor speed
I_{rd}, I_{rq}	d and q axis rotor currents	**Abbreviations**	
ϕ_{sd}, ϕ_{sq}	Stator d–q frame flux	F-RST	Fuzzy Reference Signal Tracking
ϕ_{rd}, ϕ_{rq}	Rotor d–q frame flux	DFIG	Doubly Fed Induction Generator
R_s, R_r	Stator and rotor resistances	FLC	Fuzzy Logic Control
L_s, L_r	Stator and rotor self Inductances	PI	Proportional Integral
P_s, Q_s	Stator active and reactive power	VC	Vector Control
M	Mutual inductance	RST	Reference Signal Tracking

1. INTRODUCTION

In the last decades, wind energy has presented an economically viable alternative for renewable energy production similar to other renewable energy sources such as solar, hydropower, geothermal, biomass, etc. Technological progress and environmental issues have persuaded many recalcitrant opponents. A majority of installed wind turbines are of the fixed speed type, yet the number of variable speed wind turbines continues to grow [1].

The wind energy conversion system based on a doubly fed induction generator (DFIG) is the most used in large wind farms which have many advantages: variable speed operation, the decoupled control of active and reactive powers, improves the power quality and the system efficiency when a power converter of not more than 25% of the rated power is used, produce less acoustic noise and

*Corresponding Author Email: *noureddine.choug@gmail.com* (N. Choug)

Please cite this article as: N. Choug, S. Benaggoune, S. Belkacem, Hybrid Fuzzy Reference Signal Tracking Control of a Doubly Fed Induction Generator, International Journal of Engineering (IJE), IJE TRANSACTIONS A: Basics Vol. 33, No. 4, (April 2020) 567-574

its mechanical losses are smaller than other types of generators [2,3].

Vector control, based on the classic PI controller is traditionally used for the control of the active and reactive powers of the DFIG [4-7]. However, it is not always easy to obtain good performance on the process controlled by PI, especially if this process has a significant pure delay, Its dynamic characteristics vary during operation. The RST regulator is a polynomial controller based on the theory of pole placement, it has the advantage of solving the problems encountered with the PI command [8-10].

Known for its robustness and simplicity of implementation, the Sliding Mode Control (SMC) has been widely used to control a large class of nonlinear systems [11-13]. This control law represents a drawback resided in the use of the *sign* function in the control law to ensure the transition from the phased approach to that of sliding.

Artificial intelligence methods have been combined with sliding mode control to control non-linear systems with uncertainties and at least to eliminate the chattering phenomenon. Fuzzy logic control [14,17] is often used in complex systems to overcome the limitations of conventional mathematical tools.

The fuzzy sliding mode controller (FSMC) [18-19] was designed to control the powers of a DFIG. The main drawback of FSMC is the lack of systematic methods for designing fuzzy and functional rule, Lyapunov methods [20].

To overcome these drawbacks, the current trend is to integrate these tools into hybrid controllers [21-22]. The use of a fuzzy neural network offers the possibility of modeling a priori knowledge and linguistic decision rules obtained by experts in the field. Various studies show that the ANFIS neuro-fuzzy system [23], known as adaptive networks based on fuzzy inference, can quickly learn the behavior of a system with precision and this even better than the other methods. Adaptive fuzzy controller [24]. To achieve acceptable performance and effective control of active and reactive powers of DFIG, and to overcome the drawbacks of the two controllers RST and FLC, a combination between them is proposed in this article (F-RST).

The paper is organized as follows: the modeling of the DFIG and its vector control are presented. PI, Polynomial RST, fuzzy logic controllers and the possibility to obtain their hybridization are illustrated. Different tests on tracking and robustness are taken into consideration. a comparison between the results obtained by three different methods is shown. A conclusion will finish the paper.

2. MODELING OF DFIG

The Park model of DFIG is given by the equations below [8]:

$$\begin{aligned} V_{sd} &= R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \omega_s \phi_{sq} \\ V_{sq} &= R_s I_{sq} + \frac{d\phi_{sq}}{dt} + \omega_s \phi_{sd} \\ V_{rd} &= R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \omega_r \phi_{rq} \\ V_{rq} &= R_r I_{rq} + \frac{d\phi_{rq}}{dt} + \omega_r \phi_{rd} \end{aligned} \tag{1}$$

The stator and rotor flux can be expressed as:

$$\begin{aligned} \phi_{sd} &= L_s I_{sd} + M I_{rd} \\ \phi_{sq} &= L_s I_{sq} + M I_{rq} \\ \phi_{rd} &= L_r I_{rd} + M I_{sd} \\ \phi_{rq} &= L_r I_{rq} + M I_{sq} \end{aligned} \tag{2}$$

The stator powers of the DFIG are defined as:

$$\begin{aligned} P_s &= V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s &= V_{sq} I_{sd} - V_{sd} I_{sq} \end{aligned} \tag{3}$$

The electromagnetic torque is done as:

$$T_{em} = P \frac{M}{L_s} \left(I_{rq} \phi_{sd} - I_{rd} \phi_{sq} \right) \tag{4}$$

3. VECTOR CONTROL OF DFIG

By choosing a two-phase reference frame (d-q) linked to the stator rotating field and aligning the stator flux vector with the d axis we have $\varphi_{sd} = \varphi_s$ and, $\varphi_{sq} = 0$) [5,6].

The electromagnetic torque Equation (4) is then rewritten as:

$$T_{em} = P \frac{M}{L_s} \left(I_{rq} . \phi_s \right) \tag{5}$$

For medium and high power machines, the stator resistance R_s can be neglected, the stator voltages and fluxes can be rewritten as follows [7]:

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = V_s = \omega_s . \phi_s \\ \phi_{sd} = L_s I_{sd} + M I_{rd} \\ 0 = L_s I_{sq} + M I_{rq} \end{cases} \tag{6}$$

The stator active and reactive power and voltage are given by:

$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} I_{rq} \\ Q_s = \dfrac{V_s^2}{\omega_s L_s} - V_s \dfrac{M}{L_s} I_{rd} \end{cases} \tag{7}$$

$$\begin{cases} V_{rd} = R_r I_{rd} - g\omega_s L_r \sigma I_{rq} \\ V_{rq} = R_r I_{rq} + g\omega_s L_r \sigma I_{rd} + g\dfrac{MV_s}{L_s} \end{cases} \quad (8)$$

where:

$$g = \frac{\omega_s - \omega}{\omega_s} = \frac{\omega_r}{\omega_s}, \sigma = 1 - \frac{M^2}{L_s L_r}$$

Knowing relations (7) and (8), it is possible to synthesize the regulators and establish the global block-diagram of the controlled system presented in Figure 1.

Overall system control will be implemented via a power control loop with an independent controller while compensating for the perturbation terms that are present in the block diagram of Figure 1. Direct power control between the stator and the grid, shown in Figure 2.

The blocks R_d and R_q represent the controllers of the active and reactive powers.

4. CONTROLLERS SYNTHESIS

4. 1. Synthesis of PI Controller

The structure of PI controller system is represented in Figure 3:

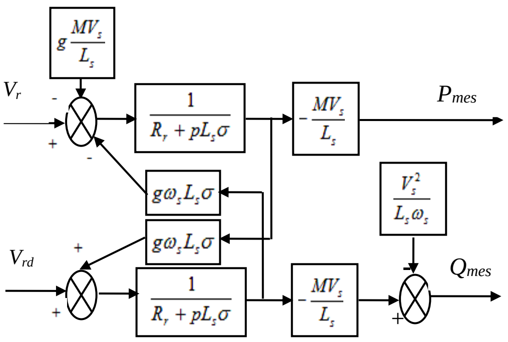

Figure 1. Block diagram of the DFIG system used for control

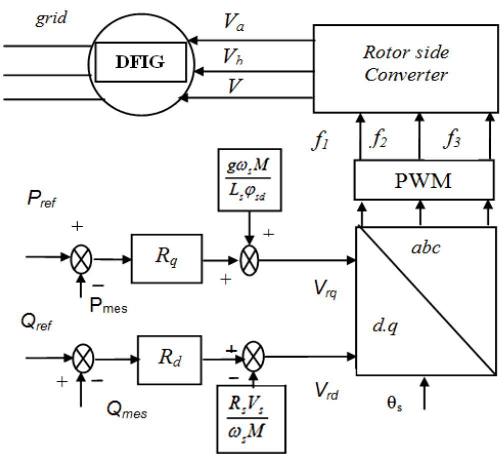

Figure 2. Vector control of DFIG

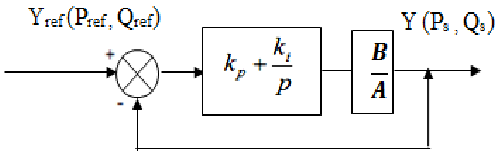

Figure 3. Structure of the PI controller

With:

$$A = L_s R_r + pL_s L_r \sigma \ , \ B = MV_s$$

The open-loop transfer function G (p) is given by:

$$G(p) = \frac{p + \frac{k_i}{k_p}}{\frac{p}{k_p}} \cdot \frac{\frac{MV_s}{L_s L_r \sigma}}{p + \frac{R_r}{L_r \sigma}} \quad (9)$$

We use the method of poles compensation for the synthesis of the controller to eliminate the zero present on the transfer function, which results in the following equality [7]:

$$\frac{k_i}{k_p} = \frac{R_r}{L_r \sigma} \quad (10)$$

Thus the closed-loop transfer function G(p) can be expressed by:

$$G(p) = \frac{1}{1 + \tau p} \quad (11)$$

With $\tau = \dfrac{L_s L_r \sigma}{k_p MV_s}$

$$k_p = \frac{\sigma L_s L_r}{\tau MV_s}, k_i = \frac{L_s R_r}{\tau MV_s} \quad (12)$$

4. 2. Synthesis of RST Controller

The block diagram of the RST controller system is represented in Figure 4: In this case, the terms A and B are expressed by:

$$A = L_s R_r + pL_s L_r \sigma \ , \ B = MV_s$$

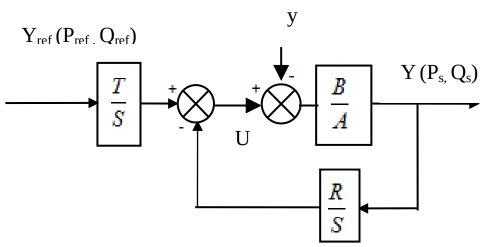

Figure 4. The block diagram of the RST controller

The principle of pole placement is to specify an arbitrary stable polynomial *D(p)* (corresponding to the denominator of the transfer functions in tracking and regulation) and to calculate S(p) and R(p) so that one obtains in accordance to the Bézout equation [8,10]:

$$D = AS + BR \tag{13}$$

With $\deg(D) = \deg(A) + \deg(S)$

For the proposed model, we obtain:

$$A = a_0 p + a_1, B = b_0, D = d_0 p^3 + d_1 p^2 + d_2 p + d_3, \quad R = r_0 p + r_1, S = s_0 p^2 + s_1 p + s_2 \tag{14}$$

Knowing that:

$$a_0 = L_s L_r \sigma \, , a_1 = L_s R_r \, , b_0 = MV_s$$

According to the robust pole placement strategy, the polynomial is written as:

$$D(p) = (p - p_c)(p - p_f)^2 \tag{15}$$

P_c=-1/T$_c$ is the pole of polynomial C and P_f=-1/T$_f$ is the double pole of the polynomial filter *F*.

The control pole is chosen arbitrarily 5 times greater than the pole of the polynomial A where:

$$p_C = 5p_A = -\frac{R_r}{L_r\sigma}, T_c = \frac{L_r\sigma}{5R_r}, T_f = \frac{1}{3}T_c = -15\frac{R_r}{L_r\sigma} \tag{16}$$

The Bezout equation leads to four equations with four unknown terms where the coefficients of *D* are related to the coefficients of polynomials *R* and *S* by the Sylvester Matrix [10]:

$$\begin{pmatrix} d_3 \\ d_2 \\ d_1 \\ d_0 \end{pmatrix} = \begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_1 & 0 & 0 \\ 0 & a_0 & b_0 & 0 \\ 0 & 0 & 0 & b_0 \end{pmatrix} \begin{pmatrix} s_2 \\ s_1 \\ r_1 \\ r_0 \end{pmatrix} \tag{17}$$

According to Equations (14), (15) and (17), we deduce the RST controller's parameters as:

$$a_0 s_0 = 1, a_1 s_0 + a_0 s_1 = -2p_f - p_c, \quad a_1 s_1 + b_0 r_0 = p_f^2 + 2p_c p_f, b_0 r_1 = -p_c p_f^2 \tag{18}$$

4. 3. Synthesis of F-RST Controller: We propose to use the combination of the two controllers previously defined, the RST during the transient regime, and that based on fuzzy logic during the steady-state.

The RST control rule is given by:

$$R(p).U(p) = T(p).Y_{ref}(p) - S(p).Y(p) \tag{19}$$

Noting that:

$$T(p).Y(p) - T(p)Y(p) = 0 \tag{20}$$

By inserting (19) in (20) and arranging the expression to update the error (*E*) we find:

$$R(p)U(p) = Y_{ref}(p)[T(p) - S(p)] + S(p)[Y_{ref}(p) - Y(p)] \tag{21}$$

The error is given by:

$$E(p) = Y_{ref}(p) - Y(p) \tag{22}$$

Using Equation (21), we get Figure 5.

The RST controller uses directly the input and the output to form the command law and the fuzzy logic one wants the error and its variation as inputs.

The control applied to the system has three components:

$$U = U_1 + U_2 + U_3 \tag{23}$$

U_1: is to improve accuracy.

U_2 has an important role in the pursuit of the instructions.

U_3: fuzzy regulator ensuring robustness.

The FLC inputs are calculated at the instant k as follows:

$$\begin{cases} E(k) = Y_{ref}(k) - Y(k) \\ \Delta E(k) = E(k) - E(k-1) \end{cases} \tag{24}$$

The control signal U_3 is obtained after integrating the output of the FLC:

$$U_3 = U_3(k-1) + \Delta U_3 \tag{25}$$

4. 3. 1 Fuzzification The selected membership functions have the trapezoidal shape at the ends and triangular shown in Figure 7:

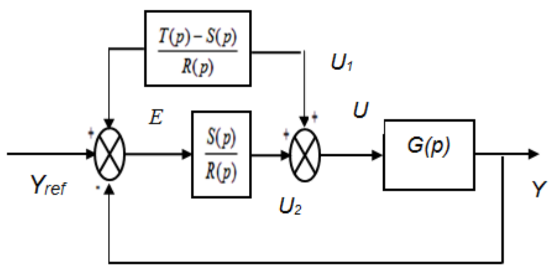

Figure 5. RST Controller with prior command

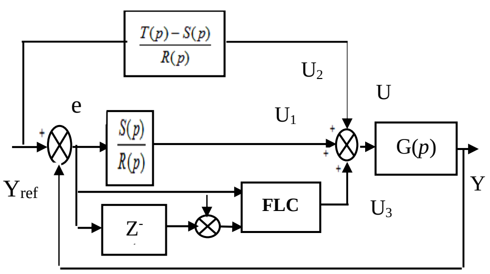

Figure 6. The block diagram of F- RST controller

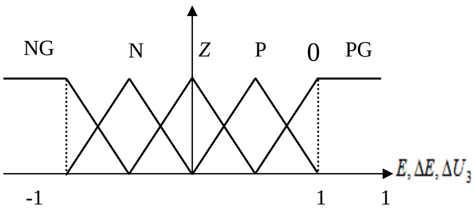

Figure 7. Membership functions for input variables E and ΔE and output ΔU_3

4. 3. 2 Fuzzy Inference System For the membership functions, they are defined by Table 1.

The linguistic variables are defined as (NB, NS, Z, PS, PB) meaning negative big, negative small, zero, positive small and positive big [15].

The fuzzy inference system is used the Mamdani type and the Max-Min method to deduce the fuzzy output, This method enabled preparing strictly linguistic rules [16].

4. 3. 3. Defuzzification For defuzzification, we use the method of the center of gravity [17], we get:

$$U_3 = \frac{\sum_{i=1}^{m} \mu(Ui) U_i}{\sum_{i=1}^{m} \mu(U_i)} \quad (26)$$

5. STABILITY ANALYSIS

In this section, we present sufficient quadratic stability conditions using the Lyapunov approach [22,23].

The most commonly used Lyapunov candidate function is defined by:

$$V(p) = p^T S(p) \quad (27)$$

For the dynamic system, The derivatives of V(p) with respect to time expressed in terms of Equation (28):

$$\dot{V}(p) = p^{\bullet T} S(p) + p^T S(p)^{\bullet} = (f(p) + b(p)u(p))^T S(p) + p^T S(f(p) + b(p)u(p)) = F(p) + B(p)u(p) \quad (28)$$

TABLE 1. Rules base for fuzzy controller

E / ΔE	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

where:

$$F(p) = f(p)^T S(p) + p^T S f(p), B(p) = b(p)^T S(p) + p^T S b(p)$$

$$B(p) = L_s R_r + pL_s L_r \sigma \;,\; F(p) = MV_s$$

Therefore,

$$\dot{V}(p) = \frac{\sum_{i=1}^{m} \mu(p) \frac{F(p)}{B(p)}}{\sum_{i=1}^{m} \mu(p)} = -\frac{L_s L_r \sigma M V_s}{\left(L_s R_r + L_s L_r \sigma p\right)^2} \quad (29)$$

$$\forall p \in P \quad \dot{V}(p) \le 0$$

It has been proved that if the Lyapunov function candidate is negatively semi-defined the closed-loop system will be globally asymptotically stable in the Lyapunov sense.

6. RESULTS AND DISCUSSION

Different methods have been studied and realized using Matlab/ Simulink. The parameters of the DFIG are reported in Table 2. The performance comparisons of the three algorithms are performed under the same operating conditions.

The active powers produced by the DFIG controlled with PI, RST, and F-RST are presented in Figures 8 and 9. In this figure, it can be noticed that the ripple is not the same for the three techniques. The F-RST is more efficient and has a very fast response time and has no overshoot over PI and RST controllers.

The stator reactive powers illustrated in Figures 10, 11 tracks the irreverence values very well; it can be seen that the hybrid algorithm shows improved performance.

6. 1. Sensitivity to the Rotor Speed Variation To verify that the measured powers remain at their set values when the speed of the DFIG varies suddenly, the mechanical speed is imposed variable at the instant t = 1s,

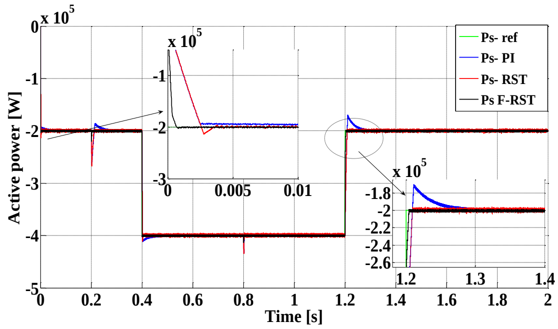

Figure 8. Active power response under PI, RST and (F-RST)

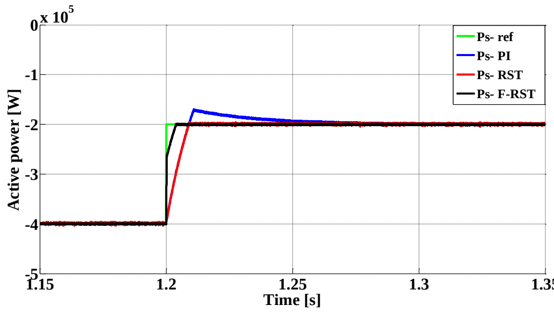

Figure 9. Zoom of active power response under PI, RST and (F-RST) strategies

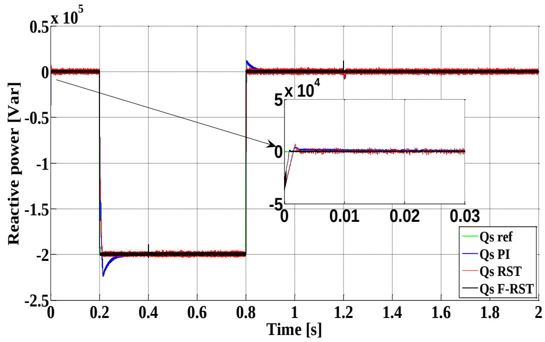

Figure 10. Reactive power response under PI, RST and (F-RST) control strategies

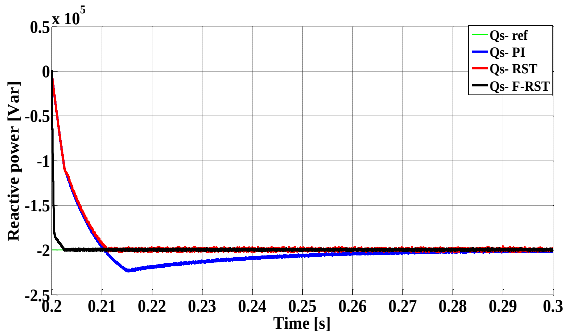

Figure 11. Zoom of reactive power response under PI, RST and (F-RST) strategies

from 170 rad/sec to 150 rad/sec.The effect of this speed variation on the active and reactive powers of the DFIG is shown in Figures 11, 12 and 13. From these results, we can say that the (F-RST) gave good dynamic and static performances for active and reactive powers compared with those of PI and RST regulators.

Parameters of the DFIG are given in Table 2.

6. 2. Robustness TEST with Parameter Uncertainty

To test the robustness against parameter uncertainty on the performances of the suggested f-rst controller, the sensitivity is tested for the three schemes for +25% variation at time t=0.6s of the rotor and stator inductances the powers are shown in Figures 14, 15, 16, 17, it can be observed from these figures. the parameter variations increase the response time of the pi and rst regulators and decrease the amplitude of the transient oscillations in the case of the f-rst.

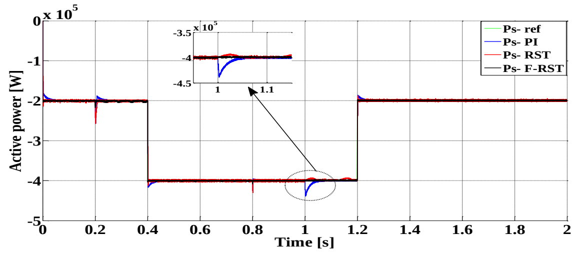

Figure 11. Simulated results of stator active power under speed variation

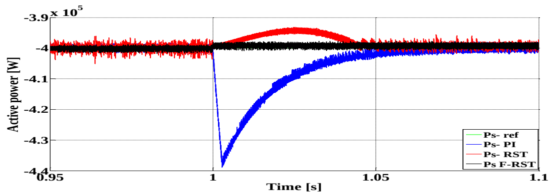

Figure 12. Zoom of active power

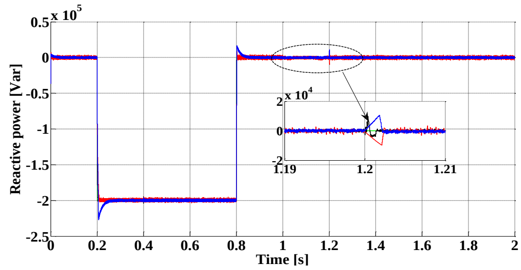

Figure13. Simulated results of stator reactive power under speed variation

TABLE 2. Parameters of the DFIG [12]

Parameters	Rated value	Unity
Nominal power	1.5	MW
Stator voltage	398	V
Stator frequency	50	Hz
Number of pairs poles	2	
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
Inertia	1000	kg m
Viscous friction	0.0024	Nm/s

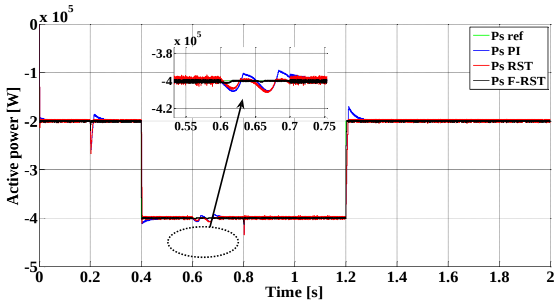

Figure 14. Stator active power during l_r variation

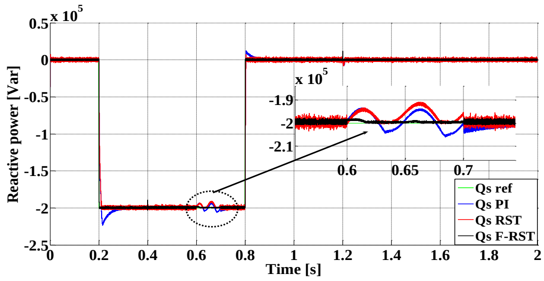

Figure 15. Tracking behavior of the stator reactive power during lr variation

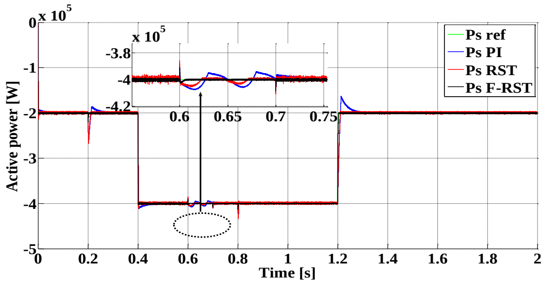

Figure 16. Simulated results of stator active power under l_s variation

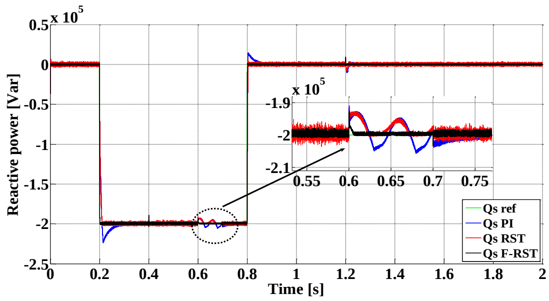

Figure 17. Simulated results of stator reactive power under l_s variation

7. CONCLUSION

In this paper, a hybrid scheme for the control of the powers using the F-RST controller for DFIG has been presented. The suggested control has been compared to the VC and RST controller. Simulation results proved that the power ripples are lower in (F-RST) compared with other controls. The efficiency of the proposed algorithm has been validated by simulation tests carried out with a 1.5 MW DFIG system. Moreover, to validate the influence of parameter uncertainty on the performances of the proposed (F-RST) algorithm, it has been shown that the suggested algorithm is robust and capable to reject the influences of uncertainty in system parameters.

8. REFERENCES

1. Tazil, M., Kumar, V., and Kong, S., "Three-Phase doubly-fed induction generator: An overview", ***IET Electric Power Application***, (2009), 75–89.
2. Ackermann, T., and Soder, L., "An overview of wind energy-status 2002" ***Renewable and Sustainable Energy Reviews***, Vol. 6, (2002), 67–128.
3. Ackermann, T. Wind Power in Power Systems. John Wiley and Sons, (2005).
4. Aydin, E., Polat, A., and Ergene, L.T., "Vector control of DFIG in wind power application". 5th international conference on renewable energy research and applications (ICRERA' 2016), Birmingham, UK, (2016).
5. Ouada, L. Benaggoune, S, and Belkacem, S, "Neuro-fuzzy Sliding Mode Controller Based on a Brushless Doubly Fed Induction Generator", ***International Journal of Engineering Transactions B: Applications*** Vol. 33, No. 2, (2020), 248-256.
6. Mahvash, H. Abbas, S. Taher, M. and Shahidehpour, M. "Enhancement of DFIG performance at high wind speed using fractional-order PI controller in pitch compensation loop" ***International Journal of Electrical Power & Energy Systems***, Vol. 104, (2019), 259-268.
7. Ghoulemallah, B., Belkacem, S., Abdesselem, C., and Said, B., "Genetic algorithm and particle swarm optimization tuned fuzzy PID controller on direct torque control of dual star induction motor", ***Journal of Central South Univ***, (2019), 251-264.
8. Doumi, M., Aissaoui, A.G., Abid. M., Tahour. A and Tahir. K., "Robust fuzzy gains scheduling of RST controller for a WECS based on a doubly-fed induction generator" ***Automatika,*** 57, (2016), 617–626. 1151-1164.
9. Linyun, X., Penghan L., Fei, W., M.and Ma, J. W., "A coordinated high-order sliding mode control of DFIG wind turbine for power optimization and grid synchronization", ***International Journal of Electrical Power & Energy Systems***, Vol. 105, (2019), 679-689.
10. Mazouz, F., Belkacem, S., Drid, S., Chrifi, A.L., and Colak I., "Fuzzy Sliding Mode Control of DFIG applied to the WECS". Proceedings of the 8th International Conference on Systems and Control, Marrakech, Morocco, (2019).
11. Zinelaabidine, B., Rachid. T., Youcef. D., and Adil. Y., "A novel direct torque control using the second-order continuous sliding mode of a doubly fed induction generator for a wind energy conversion system " ***Turkish Journal of Electrical Engineering & Computer Sciences,*** Vol. 25, (2017), 965-975.
12. Mazouz, F., Belkacem S., Harbouche Y., Abdessemed R, and Ouchen S. "Fuzzy control of a wind system based on the DFIG". International Conference on Artificial Intelligence in Renewable Energetic Systems IC-AIRES 2017, Tipaza Algeria, (2017).
13. Solat, A. R., Ranjbar. A. M., and Mozafari. B., "Coordinated control of doubly fed induction generator virtual inertia and power system oscillation damping using fuzzy logic" ***International***

Journal of Engineering-Transactions A: Basics, Vol. 32, No. 4, (2019), 536-547.

14. Rocha-Osorio, C.M., Solís-Chaves, J.S. Casella Ivan, R.S., Capovilla, C.E., Azcue Puma, J.L. and Sguarezi Filho, A.J. "GPRS/EGPRS standards applied to DTC of a DFIG using fuzzy–PI controllers", ***International Journal of Electrical Power and Energy Systems***, Vo. 93, (2017), 365-373.
15. Bounar, N., Labdai, S., Boulkroune, A.," PSO–GSA based fuzzy *sliding mode* controller for *DFIG*-based wind turbine"**, *ISA Transactions,*** Vol. 85, (2019), 177-188.
16. Benbouhenni, H., Benghanem. Z., and Belaidi. A., " Neuro-second order sliding mode control of a DFIG supplied by a two-level NSVM inverter for wind turbine system" ***Iranian Journal of Electrical and Electronic Engineering***, Vol. 14, No. 4, (2018), 362-373.
17. Horashadizadeh, S. K., H. Zadeh, S. M. Koohestani, M. R. Shekofteh, S .and Erkaya, S.?"Robust model-free control of a class of uncertain nonlinear systems using BELBIC: stability analysis and experimental validation". ***Journal of the Brazilian Society of Mechanical Sciences and Engineering***, Vol. 41, No. 8, 311, (2019). 941-964.
18. Kiran, K., J, Kanwarjit, S.S., "Real-time simulator-based hybrid controller of DFIG-WES during grid faults design and analysis", ***International Journal of Electrical Power and Energy Systems***, Vol. 116. (2020). 762-773.
19. Jyothirmayi, D., Navyasri. P., Sudhakar. N, Madhubabu. A, Ani. S and Saranya. K, "Fuzzy predictive control of variable speed wind turbines using fuzzy techniques", International Research ***Journal of Engineering and Technology,*** Vol. 31, No. 5, (2018), 3566-3571.
20. Anil, N., K.U. Prakash, G., Fernandez, C. E. "Design and implementation of interval type-2 fuzzy logic-PI based adaptive controller for DFIG based wind energy system". ***International Journal of Electrical Power and Energy Systems***, Vol. 115, (2020).
21. Saeed, K., Mahdi, S., "Adaptive fuzzy tracking control of robot manipulators actuated by permanent magnet synchronous motors". ***Computers and Electrical Engineering***, Vol, 72, (2018), 100-111.
22. Precup, R.E. Tomescu, M.L. ¸ Precup, R.E. Tomescu, M.-L. ¸"Fuzzy Logic Control System Stability Analysis Based on Lyapunov's Direct Method", ***International Journal of Computers, Communications and Control,*** Vol. IV, No. 4, (2009), 415-426.
23. Larbi, D., Edgar, N. Sanchez, and Mohammed, B, "Real-time, Neural Input-Output Feedback Linearization control of DFIG based wind turbines in presence of grid disturbances", ***Control Engineering Practice***, Vol. 83, (2019), 151-164.
24. Youb, L., Belkacem**,** S., Naceri, F., Cernat, M., and Guasch, L. P., "Design of an Adaptive Fuzzy Control System for Dual Star Induction Motor Drives", ***Advances in Electrical and Computer Engineering***, Vol. 18, No. 3, (2018), 451-464.

Persian Abstract

چکیده

این مقاله یک سیمای ترکیبی برای کنترل توان های فعال (اکتیو) و واکنشی (راکتیو) با استفاده ازکنترل مستقیم برداری را با خهت گیری شار استاتور**(**SFO**)** ناشی از *DFIG* ارائه می کند. این روش ترکیبی از کنترل کننده های منطق فازی و رد گیری **(**Tracking**)** سیگنال مرجع **(**F-RST**)** تشکیل شده است. کنترل کننده پیشنهادی **(**F-RST**)** با PI کلاسیک و RST چند جمله ای بر مبنای نظریه مکان قطب ها مقایسه شده است. استراتژی های مختلف تحلیل شده و بر حسب رد گیری، مقاوم بودن **(**Robustness**)** و حساسِت نسبت به تغییرات سرعت مقایسه شده اند. شبیه سازی ها با نرم افزار MATLAB انجام شده است. نتیج شبیه سازی ثابت می کند که شیوه ارائه شده منجر به عملکرد خوب از جمله آزمون رد گیری، رد کردن اغتشاشات،و مقاوم بودن از نظر تغییرات پارامتر ها شده است. کنترل کننده ترکیبی در مقایسه با کنترل کننده های PI و RST کارآیی تیشتری دارد و همچنین عملکرد توان ها را بهبود می بخشد و بعضی توانایی ها را علیرغم تغییرات پارامتر DFIG، تضمین می کند.