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PERFORMANCE INVESTIGATION OF A WIND POWER SYSTEM BASED ON DOUBLE-FEED INDUCTION GENERATOR: FUZZY VERSUS PROPORTIONAL INTEGRAL CONTROLLERS

OMAR KHALED KRINAH[1], RACHID LALALOU[1], ZAHIR AHMIDA[2], SOUFIENE OUDINA[3]

Keywords: Doubly-fed induction generator; Fuzzy logic controller; Maximum power point tracking; Conversion system; Wind turbine; Modeling; Converters.

This paper presents a comparative control performance study based on different combinations of classical proportional-integral (PI) and intelligent fuzzy logic controllers. The control settings were used to control both active and reactive powers to achieve the optimum operation of a double-feed induction generator (DFIG) integrated into a wind power conversion system with maximum power point tracking (MPPT). For this purpose, a mathematical model of the conversion system (wind turbine-DFIG) is established. The active and reactive powers at the output of the DFIG are controlled separately to achieve a better power factor. The complete model of the wind energy conversion system is simulated and tested in the Matlab-Simulink environment. The results obtained are compared to PI controllers. The study clearly shows the effectiveness of introducing the fuzzy technique in the control loops.

1. INTRODUCTION

The current technological development in renewable energy makes the double-feed asynchronous machine apparent for use as an asynchronous generator mounted on the wind turbine. Several types of asynchronous machines have been used in this field, the asynchronous dual-feed machine has several advantages over the others, its control is done through the stator and the rotor via the static power converters, but only its control is complex. The development of new methods and the development of algorithms, and industrial system development are modeled by a set of nonlinear differential equations called the state model. The vector control is applied to this type of machine so that its order becomes simpler. In several applications, the classical proportional-integral (PI) control is used to control the active and reactive power of the wind system, this type of control is easy to apply. Still, also these performances depend on the precision of the parameters used in the calculation of the coefficients Kp and Ki of the regulator [1].

The field of electric power production has seen significant developments, and important steps have been made toward replacing relatively conventional energy sources with renewable energies [2]. The use of wind energy has grown significantly over the last decade, and the exploitation of these energies reduces the disadvantages and risks of fossil and nuclear energy, as they preserve the environment and natural resources.

Because a wind energy conversion system uses a clean and renewable energy source for generating electricity, significant investments and research efforts have been made in this field to improve the yield through technological innovation [3, 4].

There are several techniques for controlling the active and reactive powers in the DFIG, in this study, we apply the classical control PI technique to the whole system, then we use the technique of fuzzy control on the DFIG, and finally, we make a comparison between the fuzzy versus PI control techniques. Also, an MPPT technique is applied to the wind turbine system to ensure maximal power provided by the turbine to the generator DFIG.

Several research projects in this field have been carried out to operate DFIG-based wind turbines under the right conditions. Control based on the orientation of the field by the decoupling of the components of the rotor currents d, q, makes it possible to control the active and reactive powers provided by the DFIG with acceptable performances. The use of PI controllers is limited by the sensitivity to variation of DFIG parameters [5].

Several researchers have introduced smart techniques into conventional vector control to achieve good performance.

The proposed control technique is applied with flux alignment on the d-axis and using fuzzy controllers to control the stator currents and the powers at the generator output. The advantage of a fuzzy controller is that it is robust and straightforward to design and does not require a mathematical model of the system to create it [6].

2. STRUCTURE OF THE WIND ENERGY CONVERSION SYSTEM

The overall wind turbine system with the dual feed induction generator used in this research is shown in Fig. 1.

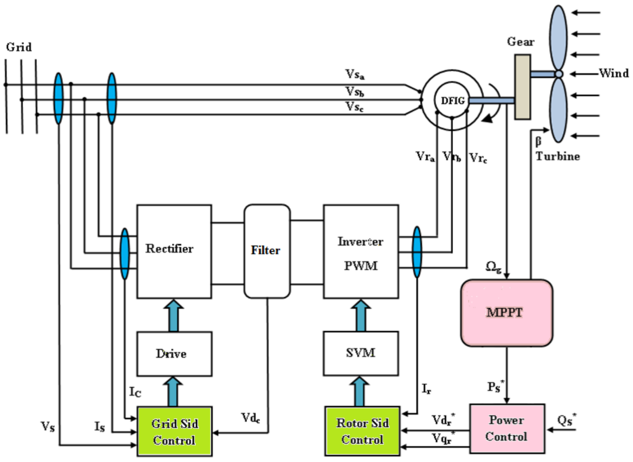

Fig. 1 – General structure of the wind energy conversion system.

This structure contains a turbine to transfer the kinetic energy of wind into mechanical energy, a speed multiplier, DFIG. The wind turbine ensures the conversion of the

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[1] Laboratoire d'électrotechnique de Skikda, université 20 aout 1955 Skikda, Algeria, E-mail : r.lalalou@univ-skikda.dz
[2] Laboratoire de recherche en électronique de Skikda, Université 20 Août 1955 Skikda, Algeria
[3] Laboratoire d'Automatique de Skikda, Université 20 Août 1955 Skikda, Algeria

kinetic energy of the wind into electrical energy; this operation depends on the wind speed, the density of the air, and the area swept by the rotor [7].

The stator of the DFIG is connected directly to the electrical network; on the other hand, the rotor is connected to the latter by a rotor side converter (RSC), which is used to control the active and reactive power, and the grid side controller that regulate the direct current (dc) link voltage, The wind turbine ensures the transfer of wind energy into mechanical energy and the DFIG converts this mechanical energy into electrical energy. The rotor side converter RSC controls the active and reactive power, and the grid side controller regulates the dc-link voltage.

3. MATHEMATICAL MODEL OF THE WIND TURBINE

The power of the wind turbine as a function of the wind speed and the length of the blades can be expressed by [8]:

$$P_V = \frac{1}{2}\rho\pi R^2 v^3. \tag{1}$$

The aerodynamic power available on the shaft is presented in the following relation [9, 10]:

$$P_a = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)v^3, \tag{2}$$

where the speed ratio λ, which indicates the ratio between the speed of the turbine (Ω_t) and the wind speed, is given by the following expression:

$$\lambda = \frac{\Omega_t}{v} R, \tag{3}$$

where R is the rotor radius, and Cp is the power coefficient, Cp (λ,β) depends on the speed ratio and the angle of displacement of the blades.

The torque of the turbine can be expressed as a function of the aerodynamic power and the speed of the turbine by:

$$T_t = \frac{P_a}{\Omega_t} = \frac{1}{2}\frac{\rho\pi R^2 C_P(\lambda,\beta)v^3}{\Omega_t}. \tag{4}$$

The fundamental equation of the dynamics which determines the variation of the mechanical speed from the total mechanical torque on the generator shaft can be defined by the following expression [1, 12]:

$$J\frac{\mathrm{d}\Omega_g}{\mathrm{d}t} = T_t - T_{em} - \Omega_g f, \tag{5}$$

where: $\Omega_t = \frac{\Omega_g}{G}$, $T_{em} = \frac{T_t}{G}$, G is the gain of the multiplier, J is the total moment of inertia, f is the coefficient of viscous friction of the generator, Ω_g is the mechanical speed of the generator.

4. MATHEMATICAL MODEL OF THE DFIG

The doubly-fed induction generator can be mathematically modeled as differential equations. Three-phase stator and rotor voltages can represent in the form of matrix equations as follows:

$$\begin{cases} [V_{abcs}] = R_s[i_{abcs}] + \frac{\mathrm{d}}{\mathrm{d}t}[\varphi_{abcs}] \\ [V_{abcr}] = R_r[i_{abcr}] + \frac{\mathrm{d}}{\mathrm{d}t}[\varphi_{abcr}] \end{cases}. \tag{6}$$

The stator and rotor fluxes are expressed as a function of the currents in the following matrix equations:

$$\begin{bmatrix} \varphi_{abcs} \\ \varphi_{abcr} \end{bmatrix} = \begin{bmatrix} [L_s] & [L_m] \\ [L_r] & [L_m] \end{bmatrix} \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix}, \tag{7}$$

With the application of the Park transformation related to the stator rotating field leads to its equations represented as follows [13–15]:

The electrical equations:

$$\begin{cases} V_{ds} = R_s i_{ds} + \frac{\mathrm{d}}{\mathrm{d}t}\varphi_{ds} - \omega_s\varphi_{qs} \\ V_{qs} = R_s i_{qs} + \frac{\mathrm{d}}{\mathrm{d}t}\varphi_{qs} + \omega_s\varphi_{ds} \\ V_{dr} = R_r i_{dr} + \frac{\mathrm{d}}{\mathrm{d}t}\varphi_{dr} - (\omega_s - \omega_r)\varphi_{qr} \\ V_{qr} = R_r i_{qr} + \frac{\mathrm{d}}{\mathrm{d}t}\varphi_{qr} + (\omega_s - \omega_r)\varphi_{dr} \end{cases} \tag{8}$$

The magnetic equations:

$$\begin{cases} \varphi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \varphi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \varphi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \varphi_{qr} = L_s i_{qr} + L_m i_{qs} \end{cases} \tag{9}$$

The equation of the electromagnetic torque:

$$T_{em} = P\frac{L_m}{L_s}(\varphi_{qs} i_{dr} - \varphi_{ds} i_{qr}), \tag{10}$$

where V is the voltage, I is current, φ is the flux, R is the resistance, L is inductance, M is the mutual inductance, T_{em} is the electromagnetic torque, and P is the pole pair number. The active and reactive power stator and rotor are expressed by the following equations [16]:

$$\begin{cases} P_S = V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_S = V_{qs} i_{ds} - V_{ds} i_{qs} \\ P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \\ Q_r = V_{qr} i_{dr} - V_{dr} i_{qr} \end{cases}. \tag{11}$$

5. MAXIMUM POWER POINT TRACKING (MPPT)

The MPPT strategy is to extract the maximum available power from the wind, Fig. 2. To achieve this objective, the speed of the turbine must be controlled and adjusted to have a mechanical reference speed corresponding to an optimum velocity ratio (λ_{opt}). There are several techniques for controlling the speed of rotation. This paper proposes the technique of PI controller. The block diagram of the turbine with MPPT is represented in Fig. 4 [17, 18].

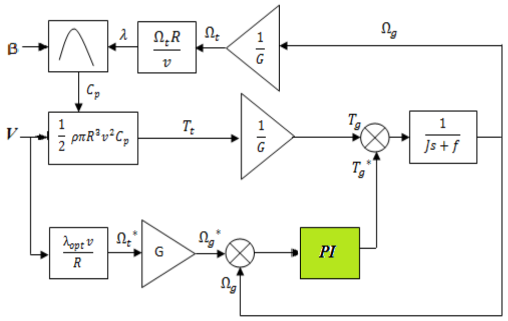


Fig. 2 – Block diagram of the turbine with MPPT.

6. **INDIRECT ACTIVE AND REACTIVE POWER CONTROL**

The strategy of indirect power control by the orientation of the stator flux is applied to obtain a simple mathematical model of the DFIG; this allows independent control of the active and reactive powers. Under the assumptions of constant stator voltage, constant flux is constant, and neglecting the effect of the stator resistance, the following expressions hold [19, 20]:

$$\begin{cases} V_{ds} = V_s, V_{qs} = 0 \\ \varphi_{ds} = 0, \varphi_{qs} = -\varphi_s = -\dfrac{V_s}{\omega_s} \end{cases}. \tag{12}$$

The relationship between the stator and rotor currents is expressed as:

$$\begin{cases} i_{ds} = -\dfrac{L_m}{L_s} i_{dr} \\ i_{qs} = -\dfrac{1}{L_s}\varphi_s - \dfrac{L_m}{L_s} i_{qr} \end{cases}. \tag{13}$$

The equation of the electromagnetic torque becomes:

$$\begin{cases} P_s = -\dfrac{3}{2}\dfrac{L_m}{L_s} V_s i_{dr} \\ Q_s = \dfrac{3}{2 L_s \omega_s} V_s^2 + \dfrac{3}{2}\dfrac{L_m}{L_s} V_s i_{qr} \\ T_{em} = -\dfrac{3}{2} P \dfrac{L_m}{L_s} \varphi_s i_{dr} \end{cases}. \tag{14}$$

Given these equations, the active and reactive powers depend on the i_{dr} and i_{qr} current, respectively. The block diagram of the indirect control of the active and reactive powers by the orientation of the stator flux is presented in Fig. 3.

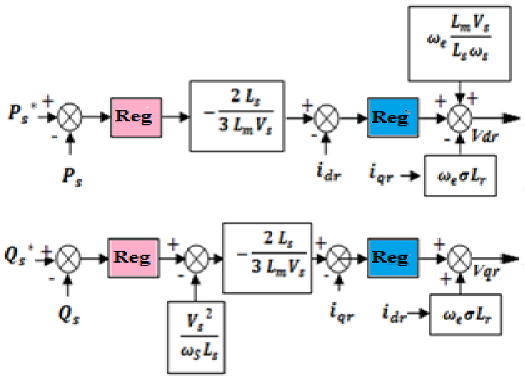


Fig. 3 – Block diagram of indirect control active and reactive power.

7. **FUZZY CONTROL FOR ACTIVE AND REACTIVE POWER**

Fuzzy logic control is excellent in dealing with imprecise, nonlinear, or time-varying systems with uncertain or unknown parameters and structure variation. it is relatively easy to implement. Indeed it does not need any mathematical model of the controlled system, making it popular for control, estimation, and optimization problems. This is achieved by converting the linguistic control strategy [21–23]. The membership functions of these variables are shown in Fig. 4.

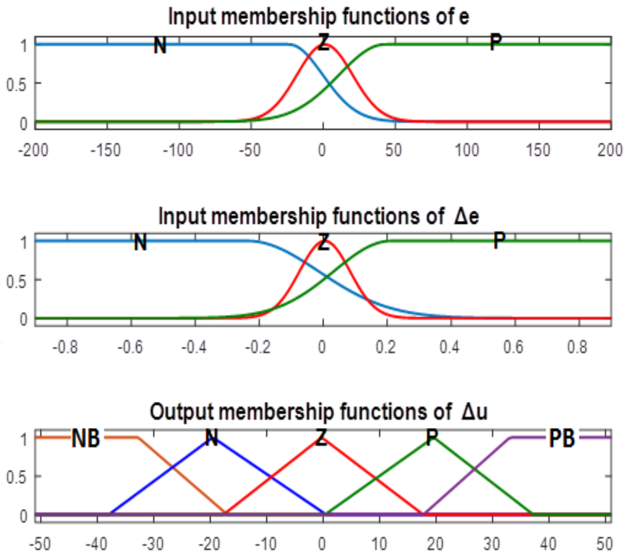


Fig. 4 – The membership functions.

8. **DC (DIRECT CURRENT) VOLTAGE CONTROL**

The main objective of the converter on the network side is to ensure an adjustable dc voltage used to supply the converter on the rotor side. An alternating three-phase source supplies this rectifier through low-pass filters, and their output is connected with the inverter through a continuous bus [24, 25], Fig. 5.

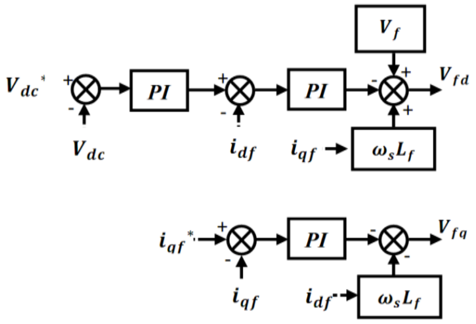


Fig. 5 – Block diagram of the dc voltage control.

10. **SIMULATION RESULTS**

Implementing the previously studied wind turbine system with a power of 1.5 MW in the software MATLAB-Simulink allowed us to obtain the following simulation results through several tests.

A wind profile is applied in the first test (Fig. 6). We note the performance of the MPPT strategy in which the speed follows its reference value with a fast response time.

The second test, it's the simulation of dc bus voltage with the different combinations between the fuzzy logic controller and the PI controller.

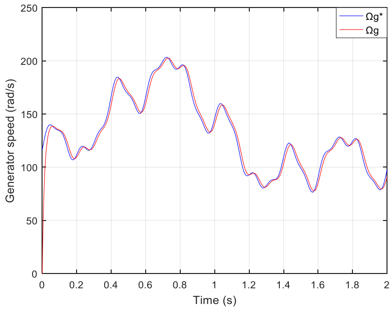


Fig. 6 – Simulation of a wind profile and generator speed.

Figure 7 shows an applied wind profile. The combinations between the fuzzy logic controller and PI controller in the loop of power and current, The variation in wind speed causes a variation in the active power of the stator, the negative sign of this power means that it is charged to the grid by the DFIG; the reactive power follows its set point with a small disturbance which gives a power factor close to the unit, the values of the stator powers illustrate the good tracking behavior and the performance of the proposed technique for the defined references (*Q**, *P**, *Vdc**), The stator current has follows the variation of the wind speed. The simulation results show that the active and reactive powers of the stator were controlled by the direct and quadrature rotor currents, so they are controlled independently; the response of the electromagnetic torque is stable but variable with the variation of the active power. The reactive power follows their zero-reference value.

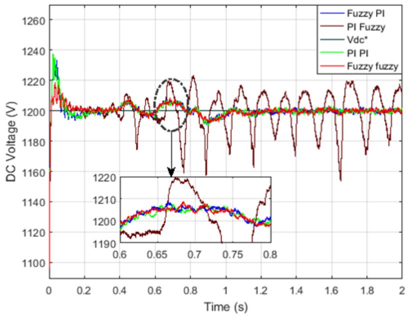
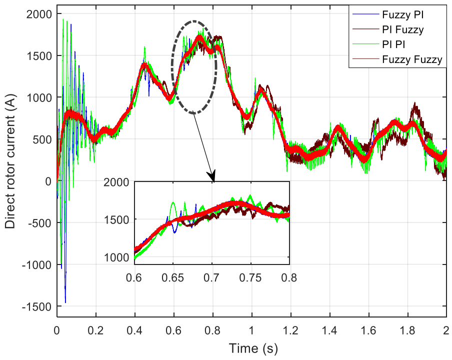


Fig. 7 – Simulation of the dc voltage control.

Figure 8 shows the error of the active and reactive powers with the different combinations between the fuzzy logic controller and the PI controller in the external power loop and the internal current loop; we notice that the power error is minimal in the fuzzy combination blurs, which proves that this combination is the best among of the four combinations used.



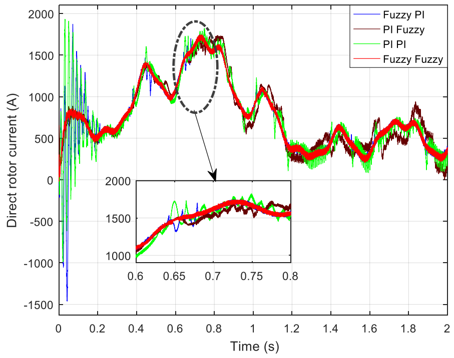


Fig. 8 – Simulation of direct and quadratic current with different combinations between fuzzy logic and PI controller.

Figure 9 displays the four combinations between the two fuzzy controllers and PI in the loop of powers and currents; we notice that the two fuzzy-fuzzy combinations and PI-PI are best. And to have the mesh generator combination between both we did a robustness test by varying the resistance of the DFIG rotor by twice the nominal value.

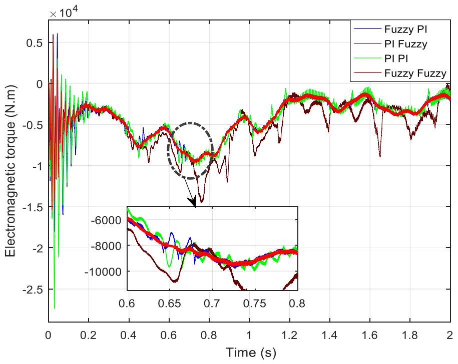
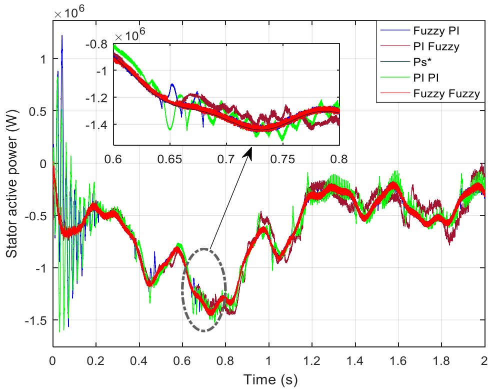


Fig. 9 – Simulation of the electromagnetic torque with different combinations between fuzzy logic and PI controller.

The simulation results show that the proposed methods for the PI and fuzzy control algorithm have good active and reactive power responses provided by DFIG, only the choice of the fuzzy controller does not depend on machine parameters such as stator and rotor time constant, which improves the robustness of the proposed control.

Finally, Fig. 10 to Fig. 12, a comparison between the fuzzy control and the conventional control of the power produced by the stator of the DFIG shows that the power error is minimal in the case of the fuzzy control, which justifies the efficiency of the control technique fuzzy on the control of the active and reactive powers supplied to the electrical network by the DFIG.



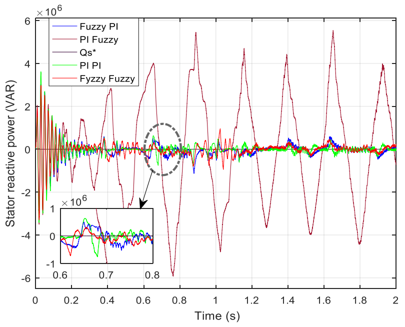


Fig. 10 – Simulation of the active and reactive power with different combinations between fuzzy logic and PI controller.

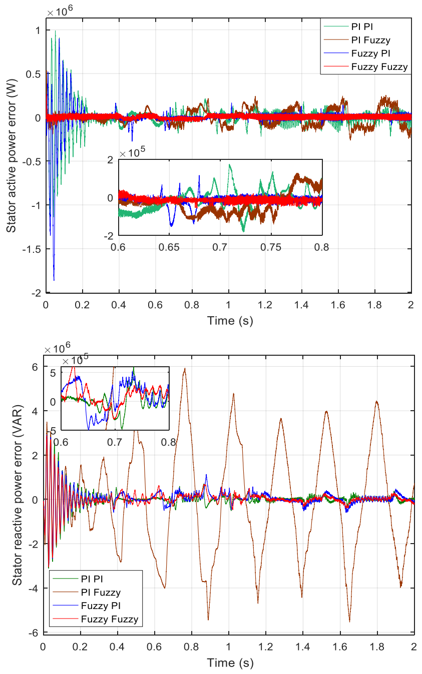


Fig. 11 – Simulation, the error of stator active and reactive power with different combinations between fuzzy logic and PI controller.

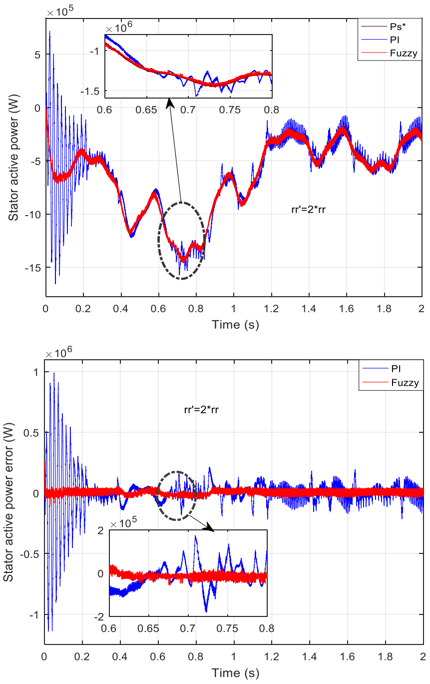


Fig. 12 – Simulation, the robustness of the fuzzy and PI controller in the active power.

11. CONCLUSION

In this paper, a classical (PI) and modern (fuzzy) control strategy has been applied to a variable speed wind energy conversion system based on the double feed induction generator (DFIG). For this purpose, a mathematical model of the wind turbine and the DFIG is presented; the independent control of the active and reactive power of the stator is performed by the stator flux orientation technique.

A strategy to maximize available wind energy (MPPT) based on a PI controller was applied. Subsequently, the two control techniques (PI and fuzzy) were used to control the active and reactive power separately with a power factor close to the unit.

The complete system has been tested on MATLAB-Simulink software. The simulation results obtained show the good performance of the wind system. After a comparative study between the two power control techniques at the output of DFIG, the combinations between the fuzzy logic controller and PI controller in the power and current loop show that the fuzzy-fuzzy combination is the best or error and robustness point of view.

Table 2

Wind turbine and DFIG parameters

The wind turbine parameters	
Air density	1.225 kg/ m^3
power coefficient	0.4412
optimal speed ratio	7.05
blade diameter	70 m
Number of blades	3
Moment of inertia	1000 kg .m^2
friction coefficient	0.0024 N.m. s^{-1}
Gearbox ratio	90
The DFIG parameters	
Rated power	1.5 MW
Stator voltage	690 V
Stator frequency	50 Hz
Stator resistance	0.012 Ω
Rotor resistance	0.021Ω
Stator inductance	0.0137 H
Rotor inductance	0.0136 H
Mutual inductance	0.0135 H
The pair of poles Number	2
Dc link voltage	1200 V

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REFERENCES

1. F. Amrane, A. Chaiba, S. Mekhilef, *High performances of grid-connected DFIG based on direct power control with fixed switching frequency via MPPT strategy using MRAC and neuro-fuzzy control*, J. of Power Technologies., **96**, *1*, pp. 27–39 (2016).
2. M. Bezza, B.EL. Moussaoui, A. Fakkar, *Sensorless MPPT fuzzy controller for DFIG wind turbine*, Energy Procedia., **18**, pp. 339 – 348 (2012).
3. W.C. de Carvalho, R.P. Bataglioli, R.A.S. Fernandes, D.V. Coury, *Fuzzy-based approach for power smoothing of a full-converter wind turbine generator using a supercapacitor energy storage*, Electric Power Systems Research, **184**, pp. 106287–96 (2020).
4. A. Asri, Y. Mihoub, S. Hassaine, P.O. Logerais, T. Allaoui, *Intelligent maximum power tracking control of a PMSG wind energy conversion system*, Asian J Control., pp. 1–11 (2019).
5. S. Bayhan, S. Demirbas, H. Abu-Rub, *Fuzzy-PI-based sensorless frequency and voltage controller for doubly fed induction generator connected to a dc microgrid,* IET Renewable Power Generation. **10 Iss**, *8*, pp. 1069–1077 (2016).
6. K. Bedoud, M.A. Rachedi, T. Bahi, R. Lakel, *Adaptive fuzzy gain scheduling of PI controller for control of the wind energy conversion systems*, Energy Procedia., **74**, pp. 211 – 225 (2015).
7. M. El Azzaoui, H. Mahmoudi, *Fuzzy-PI control of a doubly fed induction generator-based wind power system,* Int. J. Automation

and Control. **11**, *1*, pp. 54–66 (2017).

8. S. Tamalouzt, K. Idjdarene, T. Rekioua, R. Abdessemed, *Direct torque control of wind turbine driven doubly fed induction generator*, Rev. Roum. Sci. Techn.– Électrotechn et Énerg., **61**, *3*, pp. 244–249 (2016).
9. T. Chia-Sheng, H. Chih-Ming, L. Kai-Hung, *Design of novel intelligent controller for doubly-fed induction generator-driven wind turbine to improve transient control performance*, Electric Power Components and Systems., **0**, *0*, pp. 1–12 (2020).
10. A.M. Eltamaly, H.M. Farh, *Maximum power extraction from wind energy system based on fuzzy logic control*, Electric Power Systems Research, **97**, pp. 144–150 (2013).
11. S. Ghulam Kaloi, W. Jie, H.B. Mazhar, *Active and reactive power control of the doubly fed induction generator based on wind energy conversion system*, Energy Reports, **2,** pp. 194–200, 2016.
12. Z. Tir, O.P. Malik, M.N. Hashemnia, *Intelligent control of a brushless doubly-fed induction generator*, Int. J. of System Assurance Engineering and Management, **10**, *1*, pp. 326–338 (2019).
13. C.M. Rocha-Osorio, J.S. Solís-Chaves, I.R.S. Casella, C.E. Capovilla, J.L. Azcue Puma, A.J. Sguarezi Filho, *GPRS/EGPRS standards applied to DTC of a DFIG using fuzzy – PI controllers*, Electrical Power and Energy Systems, **93**, pp. 365–373 (2017).
14. L. Saihi, Y. Bakou, F. Ferroudji, B. Berbaoui, L. Djilali, *MPPTF & pitch fuzzy controller of a wind turbine system using DFIG*, 1st Int. Conf. on Sustainable Renewable Energy Systems and Applications (ICSRESA), Tebessa, Algeria December 04-05 (2019).
15. B. Ouamri, Z. Ahmed-Foitih, *Comparative analysis of robust controller based on classical proportional-integral controller approach for power control of wind energy system,* Rev. Roum. Sci. Techn.– Électrotechnique. et Énerg., **63**, *2*, pp. 210–216 (2018).
16. K. Imran, Z. Kamran, U. Waqar, S. Ul Islam, I. Muhammad, H. Sadam, H. Je Kim, *Dynamic modeling and robust controllers design for doubly fed induction generator-based wind turbines under unbalanced grid fault conditions*, Energies., **12**, *3*, 454–77, (2019).
17. E. Marouane, M. Hassene, *Modeling and control of a wind system based doubly fed induction generator: optimization of the power produced*, J. of Electrical & Electronic Systems., **4**, *1*, pp. 304–314 (2015).
18. K. Ouhaddach, H. El Fadil, A. Senhaji Malih, L. Ammeh, *New MPPT optimizer for wind turbine energy sources*, Int. Conf. on Automation, Control Engineering and Computer Science (ACECS) Proceedings of Engineering and Technology – PET, **20,** pp. 59–64 (2017).
19. H. Guolian, J. Zhuo, Y. Yu, Z. Jianhua, *Variable universe fuzzy controller used in MPPT based on DFIG wind energy conversion system*, 28th Chinese Control and Decision Conference (CCDC), China, pp. 5871–75 (2016).
20. D. M'hamed, A. Abdel Ghani, T. Ahmed, A. Mohamed, *Commande adaptative d'un système éolien*, Rev. Roum. Sci. Techn. – Électrotechnique. et Énerg., **60**, *1*, pp. 99–110 (2015).
21. C. Zafer, L. Murat, Ç. Ertuğrul, B. Necaattin, *Control of pitch angle of wind turbine by fuzzy PID controller*, Intelligent Automation & Soft Computing., **22**, *3*, pp. 463–471 (2016).
22. H. Ehsan, S. Ghazanfar, *Output power leveling for DFIG wind turbine system using intelligent pitch angle control*, Automatika, **58**, *4*, pp. 363–374 (2018)
23. B. Samir, K. D. Saheb, *Fuzzy robust control of double fed induction generator with parameter uncertainties*, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **61**, *4*, pp. 367–371 (2016).
24. S. Arezki, M. Boudour, *Study and regulation of dc bus voltages of wind-photovoltaic system,* Rev. Roum. Sci. Techn.– Électrotechn. et Énerg., **59**, *1*, pp. 35–46 (2014).
25. N. Ibrahima, S.M. Sondes, S.B. Ilhem, B.M Alioune, T. Lamine, *An adaptive dc-link voltage control for doubly fed induction generator wind turbine system*, 3rd International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, October 29-31 (2018).