International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-4, February 2020

# Fuzzy Logic Control Contribution to the Rotor Speed Control of the Doubly Fed Induction Generator

**Sadoune Zouhair, El Kachani Abderrahmane, Chakir El Mahjoub**

***Abstract: This paper presents the control of the wind energy system (WES), based on the doubly fed induction machine in generating mode (DFIG) using Artificial Intelligence (AI) technique based on fuzzy logic control. The performances of the conventional Integral Proportional (PI) and Fuzzy-PI controllers are compared with respect to the speed variation of the generator. The objective of the control strategy based on Fuzzy-PI controller is to ensure perfect tracking of the rotor speed and control the current regulation loops. The performances of the fuzzy-PI controller are studied via simulation on the Matlab/Simulink. We obtained perfect results that show the value of using a fuzzy PI controller.***

***Keywords: Fuzzy-PI controllers, Wind energy turbine (WES), doubly fed induction generator (DFIG).***

## I. INTRODUCTION

Most industrial wind turbines (WTs) operate at variable speeds. This type of operation can increase energy efficiency and reduce mechanical loads. These control algorithms allow controlling the active and reactive powers produced by the WT every moment.

Currently, the market for variable speed wind generators has been oriented towards power levels greater than 1 MW, especially to make the maximum wind potential. These WTs often use the doubly fed induction generator (DFIG) as a generator. Indeed, the most connection diagram of this generator is to connect the stator directly to the electric power grid, while the rotor is fed through two static converters back-to-back (the first side machine CSM and the second side grid CSG).Today most WTs installed around the world use the DFIG because it operates at a variable speed, the control of active and reactive powers is independent and economical side these WTs have low-cost converters [1]. This means fewer switching losses, a lower converter production cost and a reduction in the size of the passive filters implying reduced costs.

**Revised Manuscript Received on February 28, 2020.**
* Correspondence Author

**Sadoune Zouhair***, Department of Physics, Ibn Tofail University, Kenitra, Morocco. E-mail: sadoune.zouhair@gmail.com

**El Kachani Abderrahmane**, Department of Physics, Ibn Tofail University, Kenitra, Morocco. E-mail: abderrahmane.el.kachani@uit.ac.ma

**El Mahjoub Chakir**, Department of Physics, Ibn Tofail University, Kenitra, Morocco. E-mail: mahchakir@yahoo.fr



Conventionally, the active and reactive power control of DFIG is based on indirect vector control with the use of PI (Proportional Integral) controller [1, 2]. This technique is based on decoupling the rotor current between active and reactive components. Therefore, classical PI controllers are the most commonly used in the control of industrial systems; recently in the control of WTs equipped with DFIG [1-4].

However, setting the PI controllers is difficult for nonlinear systems. Another major disadvantage of this regulator is that its performance strongly depends on the parameters of the DFIG [5, 6].

Artificial intelligence techniques are currently known for their great potential to solve problems related to industrial processes, in particular, the control, estimation and identification of the parameters of the variant systems. Among these techniques are the fuzzy logic and the neural networks that are increasingly applied in the control of the induction machine and the adaptation of its vector control. The goal of Artificial Intelligence (AI) is to design systems that can reproduce the behavior of humans in their reasoning activities. Different AI techniques exist today in the literature, such as genetic algorithms, evolutionary algorithms, fuzzy logic and neural networks, and so on.

In our study, we are interested in the fuzzy logic technique to synthesize controllers robust to the parametric variations of DFIG, to replace conventional PI controllers. Simulation results are presented to increase the efficiency of these controllers in solving the problem of robustness and compare their performance.

## II. WT BASED ON DFIG

### A. Modeling of WT based on DFIG

The studied WT model is composed of [7]:

- Aerodynamic model;
- Pitch system, generates the pitch angle from pitch reference βref;
- The mechanical system;
- The generator and power converters, which converts the generator torque into an electric power grid current;
- Control system, allows controlling the generator torque, reactive power references a pith angle.

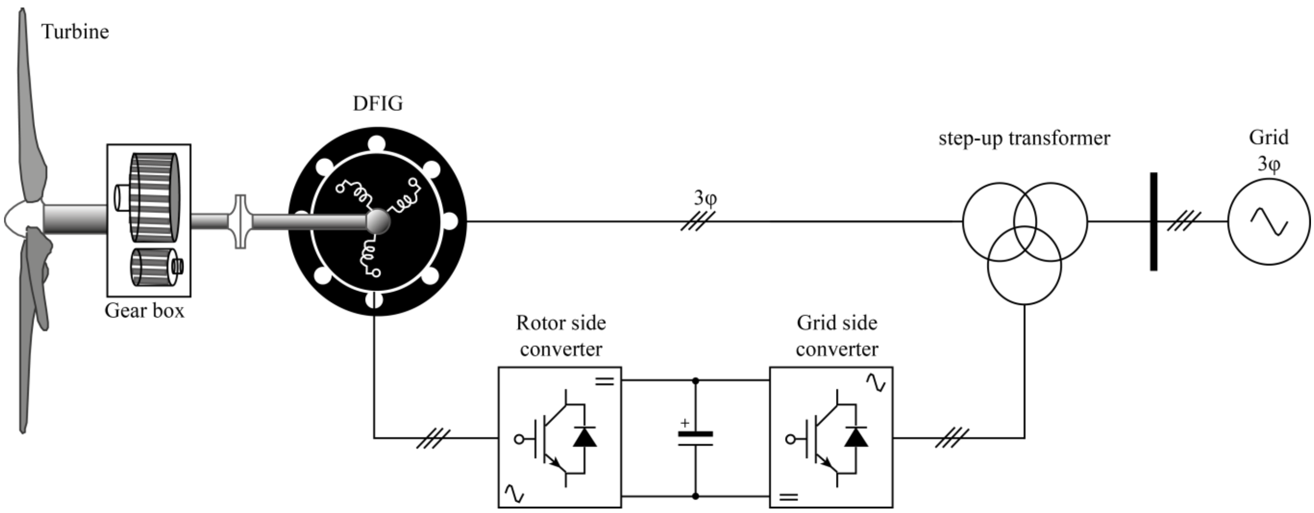


**Fig. 1 .The system connected to the electrical grid**

### B. The electrical configuration of a variable speed WT based on DFIG

The wind conversion system based on DFIG showed in Figure 1 consists of a WT, a DFIG, a DC bus, two static power converters, and a three-phase current filter. The WT drives the DFIG at a variable speed of rotation through a gearbox. The stator of the DFIG is directly connected to the electrical grid while the rotor is connected to the grid via two bidirectional static converters cascaded through a DC bus [7].

### C. Aerodynamic model

The aerodynamic model allows extracting maximum power from a given wind speed by optimizing the tip-speed-ratio λ. The power of wind is expressed by.

$$P_v = \frac{1}{2}\rho A_1 V_v^3 \quad (1)$$

Where ρ is the air density

The power of the turbine is expressed by:

$$P_t = \frac{1}{2}\rho\pi R^2 V_v^3 C_p \quad (2)$$

Where $C_p$ is the power coefficient and $R$ is the radius of the WT.

The power coefficient $C_p$ is defined by

$$\lambda = \frac{R\Omega_t}{V_v} \quad (3)$$

Most used power coefficient expression is

$$C_p = k_1\left(\frac{k_2}{\lambda_i} - k_3\beta - k_4\beta^{k_5} - k_6\right)\left(e^{k_7/\lambda_i}\right) \quad (4)$$

$$\lambda_i = \frac{1}{\lambda + k_8} \quad (5)$$

Where R is the length of the blades and $\Omega_t$ is the angular speed of the turbine.

The rotor torque is defined by:

$$T_t = \frac{P_t}{\Omega_t} = \frac{\rho\pi R^2 V_v^3}{2\Omega_t} C_p = \frac{\rho\pi R^3 V_v^2}{2\lambda} C_p = \frac{\rho\pi R^3 V_v^2}{2} C_t \quad (6)$$

Where $C_t$ is the coefficient of torque

Figure 2 shows the coefficient of torque and the power in function of the wind speed curves of a three blades WT, which is actual 2.4 MW.

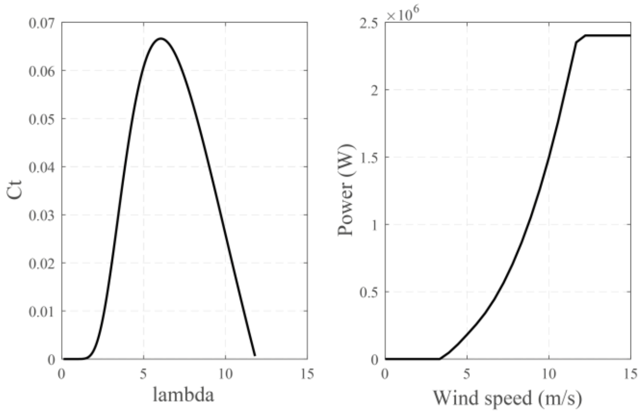


**Fig. 2. Curves of the coefficient of torque and power**

## III. DYNAMIC MODELING OF THE DFIG

The equation of frequency of stator voltages and currents ωs, is expressed as follows [8]:

$$\omega_s = \omega_r + \omega_m \quad (7)$$

The relationship of electric speed is expressed as a function of mechanical speed and the number of pole pairs:

$$\omega_m = p\Omega_m \quad (8)$$

With, p is the number of pole pairs

The slip s of the machine is expressed as follows:

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{\omega_r}{\omega_s} \quad (9)$$

The DIFG is represented in the Park model (*d-q*) whose equations are established in a frame linked to the rotating field as follows:

- The stator voltages

$$\begin{cases} V_{sd} = R_s \cdot i_{sd} + \dfrac{d\varphi_{sd}}{dt} - \omega_s \cdot \varphi_{sq} \\ V_{sq} = R_s \cdot i_{sq} + \dfrac{d\varphi_{sq}}{dt} + \omega_s \cdot \varphi_{sd} \end{cases} \quad (10)$$

- The rotor voltages

$$\begin{cases} V_{rd} = R_r \cdot i_{rd} + \dfrac{d\varphi_{rd}}{dt} - (\omega_s - \omega_r)\cdot \varphi_{rq} \\ V_{rq} = R_r \cdot i_{rq} + \dfrac{d\varphi_{rq}}{dt} + (\omega_s - \omega_r)\cdot \varphi_{rd} \end{cases} \quad (11)$$

- The stator magnetic field

$$\begin{cases} \phi_{sd} = L_s \cdot i_{sd} + L_m \cdot I_{rd} \\ \phi_{sq} = L_s \cdot i_{sq} + L_m \cdot I_{rq} \end{cases} \quad (12)$$

- The rotor magnetic field

$$\begin{cases} \phi_{rd} = L_r \cdot i_{rd} + L_m \cdot I_{sd} \\ \phi_{rq} = L_r \cdot i_{rq} + L_m \cdot I_{sq} \end{cases} \quad (13)$$

- The electromagnetic couple

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s}\left(\phi_{sq}\cdot i_{rd} - \phi_{sd}\cdot i_{rq}\right) \quad (14)$$

### A. Speed control loop

To control the DFIG, it is more judicious to choose the reference (*d-q*) linked to the stator rotating field, which is relative to the frequency of 50 Hz (frequency of the electric power grid). Therefore, the Park frame will be synchronized with the stator filed

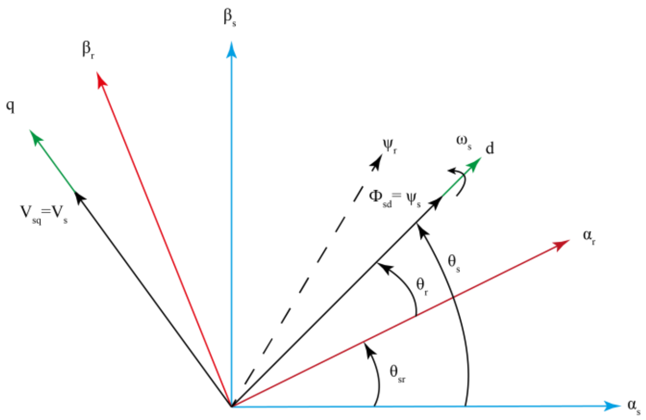


**Fig.. 3 Orientation of the stator field**

Often in the case of a medium and high power of the DFIG, the stator resistance is neglected during the synthesis of the DFIG model under the assumption the orientation of the stator field [9]

- By thus adopting the assumption of a negligible stator resistance Rs and that the stator field is oriented along with the axis d, we deduce:

$$\begin{cases} \phi_{sq} = 0 \\ \phi_{sd} = \psi_s \end{cases} \quad (15)$$

$$\begin{cases} V_{sd} = 0 \\ V_{sq} = V_s = \omega_s \psi_s \end{cases} \quad (16)$$

$$\begin{cases} V_{sd} = L_s \cdot i_{sd} + L_m \cdot i_{rd} \\ 0 = L_s \cdot i_{sq} + L_m \cdot i_{rq} \end{cases} \quad (17)$$

From Equation (17), the equations of the stator currents is expressed as follows,

$$\begin{cases} i_{sd} = \dfrac{\psi_s}{L_s} - \dfrac{L_m}{L_s} i_{rd} \\ i_{sq} = -\dfrac{L_m}{L_s} i_{rq} \end{cases} \quad (18)$$

By replacing in equation (13) the rotor currents and stator current of the expression (18), we obtain

$$\begin{cases} \phi_{rd} = \sigma L_r i_{rq} + \dfrac{L_m}{L_s}\psi_s \\ \phi_{rd} = \sigma L_r i_{rq} \end{cases} \quad (19)$$

With the Blondel dispersion factor

$$\sigma = 1 - \left(\frac{L_m^2}{L_s L_r}\right) \quad (20)$$

By replacing the expression (19) in equation (11), we obtain:

$$\begin{cases} V_{rd} = R_r i_{rd} + \sigma L_r \dfrac{di_{rd}}{dt} - s\omega_s \sigma L_r i_{rq} \\ V_{rq} = R_r i_{rq} + \sigma L_r \dfrac{di_{rq}}{dt} - s\omega_s \sigma L_r i_{rd} + s\dfrac{L_m V_s}{L_s} \end{cases} \quad (21)$$

In steady-state, the derivatives of the rotor current disappear, so we can write:

$$\begin{cases} V_{rd} = R_r i_{rd} - s\omega_s \sigma L_r i_{rq} \\ V_{rq} = R_r i_{rq} - s\omega_s \sigma L_r i_{rd} + s\dfrac{L_m V_s}{L_s} \end{cases} \quad (22)$$

Replacing (16) in (14), the torque of the DFIG will have for expression will be expressed

$$T_{em} = -\frac{3}{2} p \frac{L_m}{L_s}\psi_s i_{rq} = -\frac{3}{2} p \frac{L_m V_s}{L_s \omega_s} i_{rq} = K_T i_{qr} \quad (23)$$

Then, the quadratic rotor current is proportional to the torque. Therefore, we can control the latter by the rotor current and, consequently, the generator speed.

Figure 4 illustrates the closed-loop system of the $\omega_m$ loop, we consider that the current loop has been tuned much faster than the external loops. Therefore, the system can be controlled by choosing the gains of the fuzzy-PI controller.

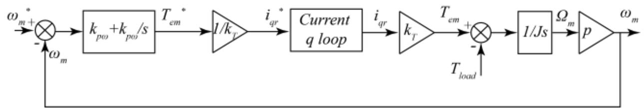


**Fig. 4. Equivalent closed-loop system of ωm loop**

## IV. DESIGN OF FUZZY LOGIC CONTROLLER OF THE WT

Fuzzy logic is a versatile logic where the truth values of variables - instead of being true or false - are real values between 0 and 1. In this sense, it extends classic Boolean logic with partial truth values1. It consists of taking into account various numerical factors to arrive at a decision that we wish to accept.

This technique combines the notions of "fuzzy subset" and "theory of possibilities".

It is an approach modeled on human reasoning rather than rigid calculations; for ill-defined problems, the human being is irreplaceable. It suits control problems that cannot be easily represented by mathematical models: weak model, parameter variation problem, very complex plants and good qualitative understanding of plant or process operation.

A fuzzy logic control consists of four steps:

- Fuzzification: the transformation of variables into fuzzy variables (also called linguistic variables)
- The fuzzy inference: construction of rules (and results) based on linguistic variables, attribution of veracity to each rule, then the aggregation of rules to obtain a unique (linguistic) result
- Defuzzification: the passage from a linguistic result to a quantified result [10] [11] [12].

The looped system can be represented in figure 5, it is made up of a fuzzy logic controller, the process with the presence of disturbance d which modifies the state of the output. The process variable which must be set is present at the input of the system, it is compared with the image of the output provided by the sensor. The signal obtained at the output of the comparator will make it possible to control the action chain composed of two main elements, the PI-fuzzy controller and the plant. The role of the PI-fuzzy controller is to adapt the error signal to obtain an optimal response from the plant. In the event of disturbing phenomena acting on the output quantity forcing it to deviate from its desired value, the sensor reports to the PI-fuzzy controller on the state of the output and the correction process is triggered by the PI-fuzzy controller to bring the output quantity at its desired value.

The proposed PIFLC structure is shown in figure 6 which is a combination of the FLC and the PI controller. It includes more tuning parameters ($G_{de}$, $G_e$, $K_p$, and $K_i$).

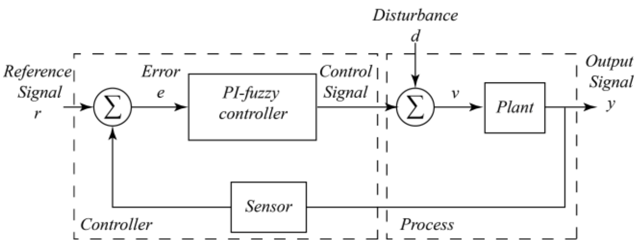


**Fig. 5. Structure of the control system**

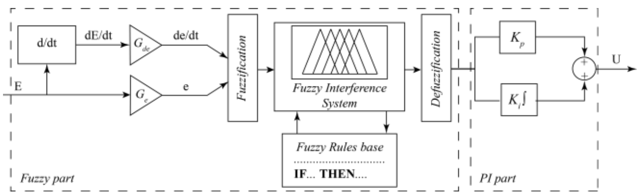


**Fig. 6. structure of proposed Fuzzy-PI controller**

Taking the output of the system, the control signal of the Fuzzy-PI controller is given by:

$$u = K_p U + K_i \int U dt \qquad (24)$$

Where U is the output of the controller.

Considering the Fuzzy-PI controller essentially as a nonlinear static input/output mapping, the controller action can be written as

$$\frac{du}{dt} = K_p \cdot \frac{de}{dt} + K_i \cdot e \qquad (25)$$

For this work, triangular shaped membership functions has been chosen. Figure 7 shows the membership functions for the controller inputs on the interval [-3, 3] (i.e., error (e) and derivative of the error (de)) and the controller outputs on the interval [0, 1] (i.e., proportional gain (kp) and integral gain (ki) for the Fuzzy-PI controller). In figure 7 seven linguistic variables (NB, NM, NS, ZO, PS, PM, PB) are adopted for each of the three input/output variables. Where NB is a linguistic variable which means Negative Big, NM: Negative Medium, NS: Negative Small, ZO: Zero, PS: Positive Small, PM: Positive Medium and PB: Positive Big, The fuzzy rules are summarized in Table I.

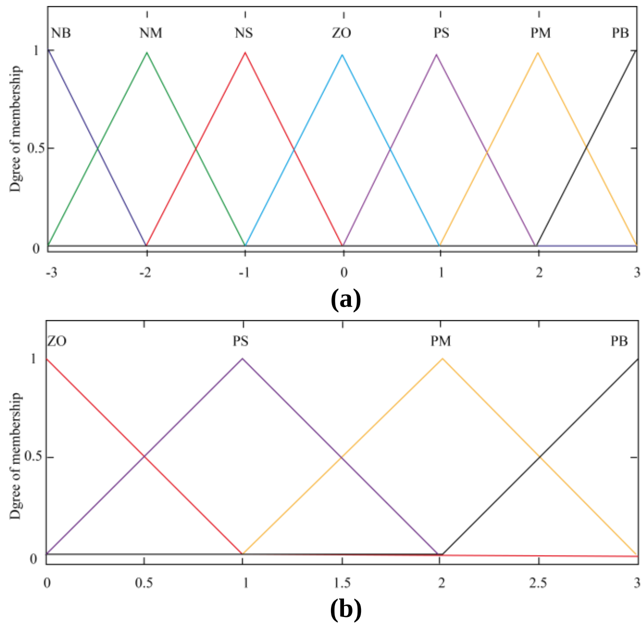


**Fig. 7: Membership functions for (a) e and de, and (b) Kp and Ki of the Fuzzy-PI controller.**

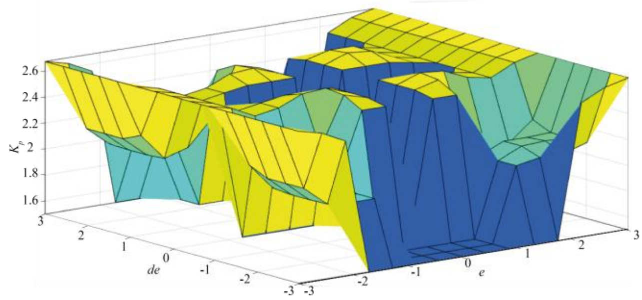


**Fig. 8: Variation of gain (Kp)**

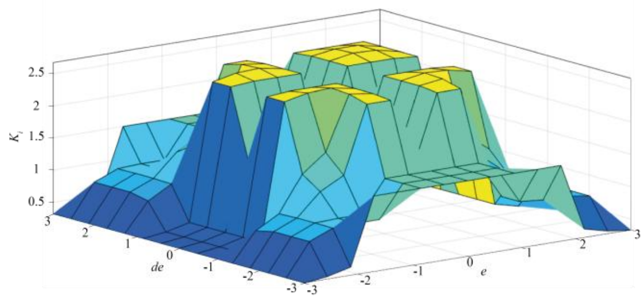


**Fig. 9: Variation of gain (Ki)**

The highly nonlinear variation of the gains Kp and Ki with e and de is shown in Fig. 8 & 9. Fig. 8 and 9 reflect the desirable characteristics of Kp and Ki as a function of e and de.

**Table I. Fuzzy Rules**

| de/dt (pu) | e(pu) NB | NM | NS | ZO | PS | PM | PB |
|---|---|---|---|---|---|---|---|
| **NB** | NB | NB | NB | NM | NM | NS | ZO |
| **NM** | NB | NB | NM | NM | NS | ZO | PS |
| **NS** | NB | NM | NM | NS | ZO | PS | PM |
| **ZO** | NM | NM | NS | ZO | PS | PM | PM |
| **PS** | NM | NS | ZO | PS | PM | PM | PB |
| **PM** | NS | ZO | PS | PM | PM | PB | PB |
| **PB** | ZO | PS | PM | PM | PB | PB | PB |

## V. SIMULATION RESULTS AND DISCUSSIONS

The performance of the proposed control system was evaluated with Simulink for a 2 MW WT based on DFIG. The simulated system is shown in figure 10 The 2 regulators are tested by two different benchmark; the first is the reference tracking, the second is the robustness against variations of the parameters. The generator and turbine parameters used in the simulation are listed in Table II.

The generator is tested with a speed of 1500 rpm. The results show that the fuzzy logic controller presents has a faster response in comparison with the Proportional integral controller as shown in figure 11.

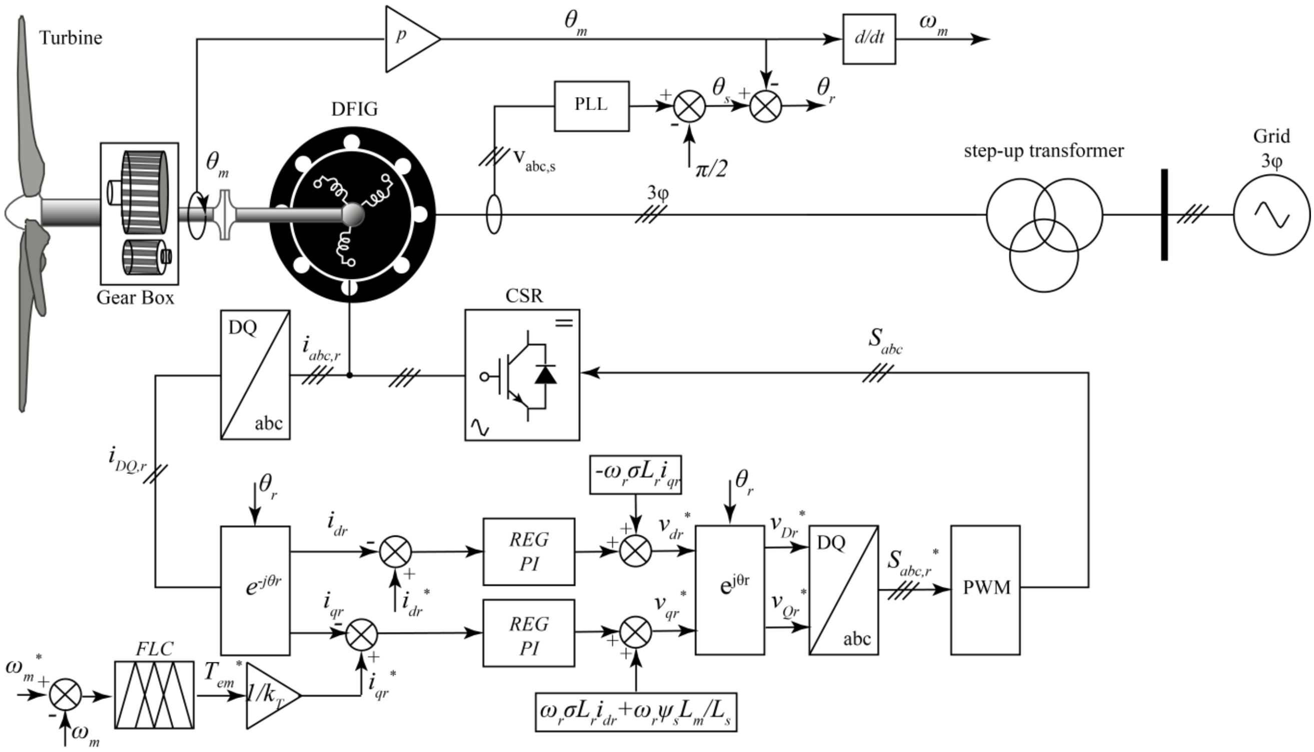


**Fig. 10. Complete Fuzzy-PI controller of DFIG**

**Table II. Parameter Values Of The Dfig**

| Parameters | Designations | Values |
|---|---|---|
| $P_s$ | Rated stator power (W) | $2.10^6$ |
| f | Stator frequency (Hz) | 50 |
| n | Rated rotational speed (rev/min) | 1500 |
| $V_s$ | Rated stator voltage (V) | 690 |
| $I_s$ | Rated stator current (A) | 1760 |
| $T_{em}$ | Rated torque (N.m) | 12732 |
| p | Pole pair | 2 |
| $R_s$ | Stator resistance (ohm) | $2.6\ 10^{-3}$ |
| $R_r$ | Rotor resistance referred to stator (ohm) | $2.9\ 10^{-3}$ |
| $L_m$ | Magnetizing inductance (H) | $2.5\ 10^{-3}$ |

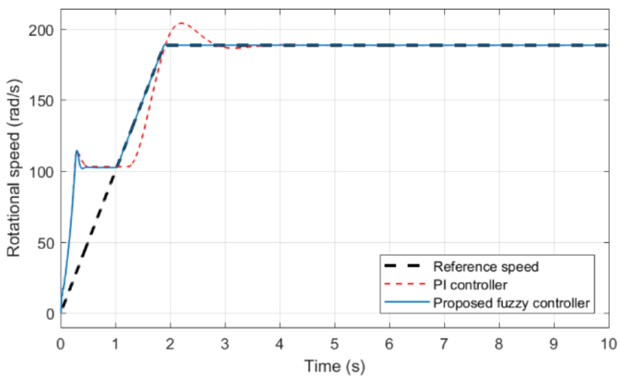


**Fig. 11. Dynamic Responses to the speed for reference speed 157 rad/s**

These results obtained show that the system with a classical PI controller with fixed values of gains Kp and Ki, it is difficult to perfectly track the reference speed values.

Retrieval Number: B6846129219/2020©BEIESP
DOI: 10.35940/ijitee.B6846.029420
Journal Website: www.ijitee.org



Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

As shown in figures 12 & 13 the quadratic rotor current is proportional to the electromagnetic torque. Therefore, to control the torque and the speed of the generator we can just control the rotor current.

Therefore, we can see that the two components of the rotor current independently used to control the electromagnetic torque. Maintaining the current loops, a speed loop has been added.

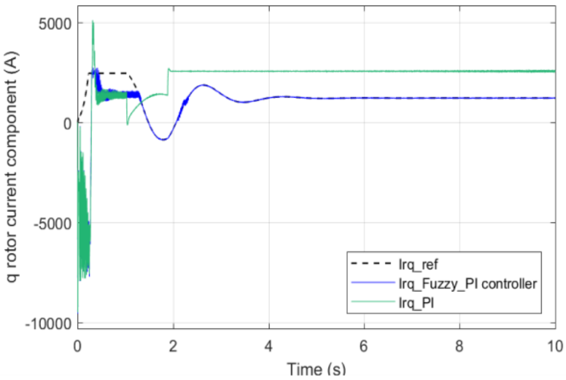


**Fig. 12. Dynamic response to the q rotor current component**

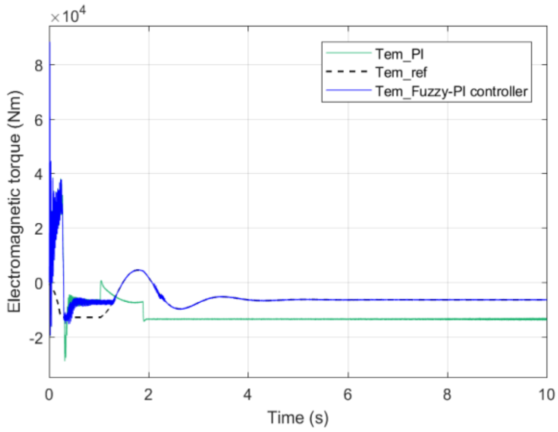


**Fig. 13. Electromagnetic torque responses to the reference**

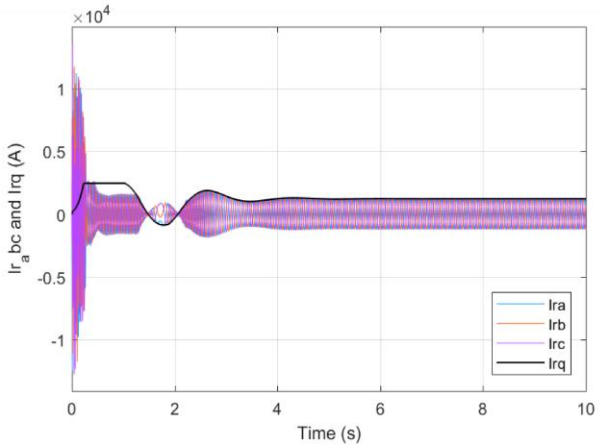


**Fig. 14. abc rotor currents**

As shown in figure 15, we have settled the rotor *idr* current to zero, to minimize rotor winding and the rotor side converters. To get these results we increase the stator winding.

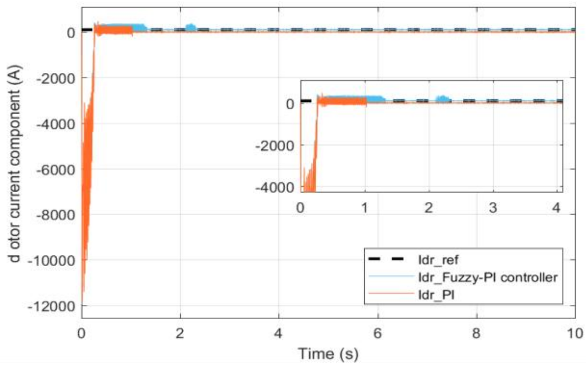


**Fig. 15. Dynamic Response to the d rotor current component**

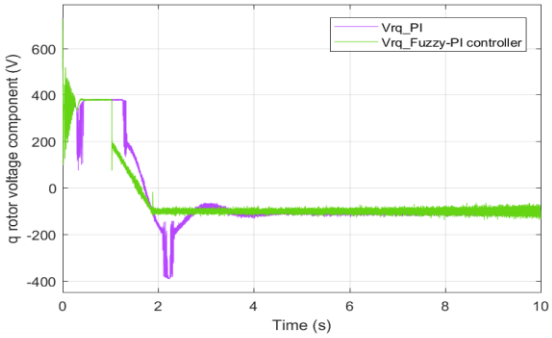


**Fig. 16. q rotor voltage component**

As shown in figures 17 & 18. The stator voltages is maintained constant due to direct connection of the generator to the grid. The electromagnetic torque is maintained constant. The variation of the speed causes a variation of the rotor currents and rotor voltages.

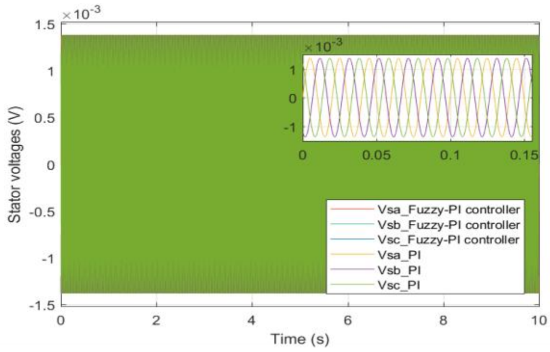


**Fig. 17. abc Stator voltages**

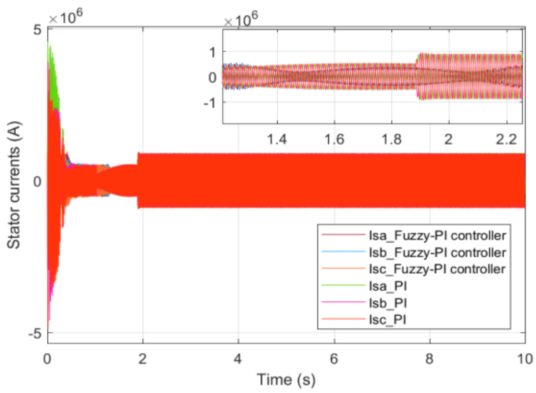


**Fig. 18. abc Stator currents**

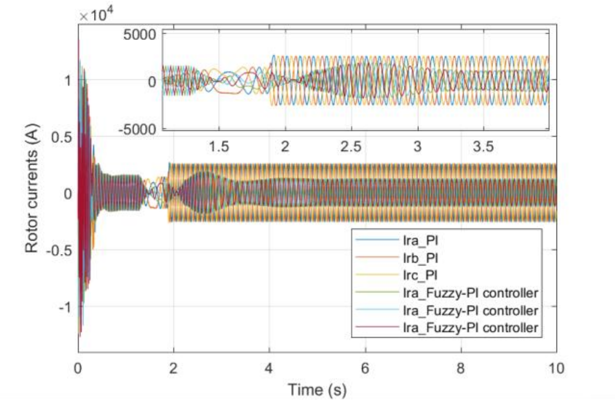


**Fig.19. abc Rotor voltages**

## VI. CONCLUSION

In this paper, the robust fuzzy-PI controller of DFIG based on artificial intelligence technology has been exposed. The first results of this research action demonstrate the digital validation of the low control strategy originally based on the fuzzy logic to improve the performance of the WES based on DFIG. The results obtained show the effect of the variation of the parameters on the performance of the controllers, which explains why the performance of the PI controller degrades with the variation of the parameters, while the Fuzzy-PI controller presents satisfactory performance concerning disturbances. because when the parameters change the fuzzy controller gains changes by adjusting the fuzzy rules. The results proved that the fuzzy-PI controller has improved the system's reference tracking capability, hence improving the robustness of the system.

According to the simulation results obtained, it can be said that intelligent controllers bring significant robustness to the control of the DFIG with regard to parametric variations of the DFIG.

For comparison, the fuzzy controller has the advantage in terms of attenuation of the transient regime overruns compared to the classical PI controller.

## REFERENCES

1. B. Hopfensperger, D.J. Atkins, and R. Lakin, "Stator-Flux-Oriented Control of a DFIM with and without Position Encoder", IEEE Proc. on Elec. Power App., Volume 147, Number 4, page 241 - 250, 2000.
2. M. Yamamoto and O. Motoyoshi, "Active and Reactive Power Control for WRIG", IEEE Trans. on Power Electronics, Volume 6, Number 4, page 624 - 629, 1991.
3. A. Tapia, G. Tapia, J.X. Ostolaza, and J.R. Sáenz, "Modeling and Control of a Wind Turbine Driven DFIG", IEEE Trans. on NRG Conversion, Volume 18, Number 2, page 194 - 204, 2003.
4. G. Tapia, A. Tapia, and J.X. Ostolaza, "Proportional–Integral Regulator Based Approach to Wind Farm Reactive Power Management for Secondary Voltage Control", IEEE Trans. NRG Conversion, Volume 22, Number 2, page 488 - 498, 2007.
5. A. Meroufel, Y. Djeriri, A. Massoum et A. Hammoumi, "Commande Vectorielle par les Réseaux de Neurones Artificiels de l'Energie d'une MADA Intégrée à un Système Eolien', Journal des EnR, Volume 13, Number, page 669 - 682, 2010.
6. Y. Djeriri, A. Meroufel and M. Allam, "Artificial Neural Network-Based Robust Tracking Control for DFIG Used in WECS", JARST, Volume 2, Number 1, page 173-181, 2015.
7. G. Abad, J. Lopez Miguel A. Rodriguez, L. Marroyo, G. Iwanski, DFIG (IEEE Press, 2011, page 25).
8. H. Abu-Rub, M. Malinowski, K. Al-Haddad, Power electronics for renewable energy systems, transportation and industrial application" IEEE Press. , page 271, 2014.
9. A. Tapia, G. Tapia, J.X. Ostolaza, and J.R. Sáenz, "Modeling and Control of a Wind Turbine Driven DFIG", IEEE Trans. on Energy Conversion, Vol. 18, Number 2, page 194 - 204, 2003.
10. E. Koutroulis, K. Kalaitzakis, et N. C. Voulgaris, "Development of a microcontroller-based, photovoltaic maximum power point tracking control system", IEEE Trans. Power Electr., volume 16, Number 1, page 46-54, 2001.
11. H. Buhler, "Réglage Par Logique Floue", Presses Poly-techniques et Universitaires Romandes CH-1015 Lau-sanne. 1994.
12. A. Ait Laachir, A. El Kachani, A. Niaaniaa, MB Sedra, E. CHAKIR, T. Jarou, "MPPT Using Adaptive Fuzzy Logic control for Photovoltaic System", IJERA, Volume 5, page 65-70, 2015

## AUTHORS PROFILE

**Sadoune Zouhair** Received the "Electrical Energy degree" from Polytechnic Faculty of Mons, Belgium, in 2009. He received with honors the Ph.D. degree in physics (Piezoelectricity), Faculty of science, Rabat, Morocco in 2013. He has been a Professor at Faculty of Science, Ibn Tofail University, Kenitra, Morocco. His current area of interest is related to Electrical engineering.

**El Kachani Abderrahmane** is a PhD student in Electrical Engineering at Faculty of sciences in SIMO Laboratory, Kénitra, Morocco. He graduated a Master in electrical engineering. He has been preparing, under the direction of Chakir El mahjoub a thesis in electrical engineering. His research interests include the electric power sources based on energy renewable and active power filters.

**Chakir El mahjoub** is a professor of nuclear physics at Ibn Tofail University. He received Doctorat degree in nuclear physics from University Mohamed V, Rabat, Morocco He is a member of the SIMO laboratory team, Kenitra. He supervised several theses in Physics and applications.