Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.53, p. 154-161. May/June., 2025.
DOI: https://doi.org/10.5935/jetia. v11i53.1640

RESEARCH ARTICLE OPEN ACCESS

TIYPE 2 FUZZY CONTROL OF DFIG FOR WIND ENERGY CONVERSION SYSTEMS

Kouadria Mohamed Abdeldjabbar[1], Kouadria Selman[2] and Bouzid Mohamed Amine [3]

[1] Department of Electrical Engineering Abdelhamid Ibn Badis University Mostaganem, Algérie.
[2] Laboratoire de Génie électrique et des plasmas, Université Ibn Khaldoun Tiaret, Algérie.
[3] Laboratory Computer Engineering and Energy Engineering Ibn Khaldoun University, Algérie.

[1]https://orcid.org/0000-0002-5001-4131, [2]https://orcid.org/0000-0001-7179-2146, [3]https://orcid.org/0000-0002-1696-8388

Email: mohamedabdeldjabbar.kouadria@univ-mosta.dz, kouadria.selman@univ-tiaret.dz, bouzid19amine@gmail.com

ARTICLE INFO

Article History
Received: February 14, 2025
Revised: May 20, 2025
Accepted: June 15, 2025
Published: June 30, 2025

Keywords:
Wind Energy Conversion System (WECS),
Doubly Fed Induction Generator (DFIG),
Direct control,
Indirect control,
Type-2 fuzzy logic controller,

ABSTRACT

This study develops and designs a Type 2 fuzzy controller technique for application in wind turbines directly linked to the grid and incorporating variable-speed doubly fed induction generators (DFIG).
Type 2 fuzzy theory is proposed with the aim of enhancing system performance. Unlike Type 1 fuzzy systems, it accommodates a wide range of uncertainties and dynamic nonlinearities that may constrain the system's operational efficiency.
Type 2 fuzzy logic provides an effective approach to managing linguistic uncertainty by modeling the ambiguity and limited reliability of information, thereby reducing the overall level of uncertainty within the system.
Both Type 1 Fuzzy Logic Control (T1FLC) and Type 2 Fuzzy Logic Control (T2FLC) techniques were employed in direct and indirect modes. The two control methods were developed, their performances were evaluated, and the most effective control method in terms of reference tracking and robustness was identified. This comparative analysis is derived from a series of tests performed under identical conditions during both transient and steady-state operations of the system.
The simulation results demonstrate that the proposed method exhibits significant resilience to parameter variations and unstructured uncertainties.

I. INTRODUCTION

Over the past few decades, global interest in renewable energy sources has grown considerably. At this stage, electricity generation using wind turbines is among the most promising sustainable energy alternatives [1].

Wind energy is a promising technology for electricity generation due to its well-known environmental advantages over conventional generation systems [2]. To effectively exploit the potential of wind energy, Doubly Fed Induction Generators (DFIGs) play a crucial role [3]. With their advanced technology and design, DFIGs are specifically designed to convert wind energy into electrical energy with remarkable efficiency [4]. They achieve this by using a rotor or blade system that interacts with the force of the wind, converting its kinetic energy into usable electricity [5]. The electricity generated by DFIGs is intelligently integrated into the existing grid.

Type-2 fuzzy sets have recently been included into Fuzzy Logic Systems (FLS) across a range of application fields.

This study focuses on controlling the electrical power produced by the DFIG using a Type-2 Fuzzy Logic Controller (T2FLC). The control method aims to manage the active and reactive power transfer between the stator and the grid, considering variations in rotor resistance, inductance, tip speed ratio, and power coefficient [6-8].

When handling external disturbances, uncertainties, and nonlinearities in nonlinear systems like WEC Systems, robust control is an essential component of renewable energy technology [9].

In recent years, various control methodologies based on T2FLC theory for DFIG have been proposed. In this section, several studies will be presented to show the different applications.

In [10], the authors offer an innovative control technique that employs interval type-2 fuzzy sets for enhanced grid synchronization of DFIG-based wind energy conversion systems. The methodology's distinctive three-dimensional membership function architecture provides parametric adaptability to accommodate stochastic variations and measurement inaccuracies inherent in distributed generation environments.

In [11], the authors presents an adaptive control architecture for DFIG rotor-side converters, where interval type-2 fuzzy logic dynamically optimizes proportional-integral (PI) controller parameters. This methodology demonstrates enhanced robustness against generator parameter variations and grid disturbances compared to conventional PI implementations.

Another method proposed in [12], where a neuro-fuzzy controller for DFIG that uses adaptive sliding mode to regulate power. To improve the efficiency of the suggested control technique, the parameters of the type-2 fuzzy system membership functions are trained online using sliding mode control (SMC) theory.

In [13], the authors use a Type 2 adaptive fuzzy controller approach to evaluate the efficiency of the system in maximizing power generation from wind turbines with variable-speed doubly-fed induction generators connected directly to the grid. The control technique is employed to sustain the optimal value of the stator's reactive power.

Another method for regulating a DFIG in hyposynchronous mode has been discussed in [14]. The approach relies on maximum power point tracking (MPPT). To regulate Ird and Irq, a novel class of fuzzy logic known as adaptive type-2 fuzzy logic control has been created as an alternative to standard proportional integral derivative (PID) controllers. A three-level neutral point clamped (NPC) converter was used to provide power to the rotor side converter (RSC).

Another architecture combines type-2 fuzzy logic control with sliding mode control (SMC) has been presented in [15]. It was used to control effectively the active and reactive powers of the DFIG. This technique reduces chattering and increase the system's performance in speed monitoring and stator side power regulation.

In this work, we will propose a T2FLC strategy. The structure of this paper is organized as follows: In Section II, we present the mathematical model of the wind turbine system, which comprises DFIG driven by a variable pitch turbine. This system is regulated through rotor variables using two bidirectional Pulse Width Modulation (PWM) converters, allowing for effective management of power output and operational efficiency. In Sections III and IV, the control strategy and synthesis of the type 2 fuzzy logic control algorithm (direct and indirect modes) is discussed. Section V presents and discusses the simulation results, using Matlab/Simulink software, along with an evaluation of the proposed controller's effectiveness. Finally, we conclude the reported work.

II. SYSTEM MODELLING

The wind energy conversion system examined in this study utilizes a Doubly Fed Induction Generator (DFIG). From a system perspective, the conversion chain consists of three key interacting components, each modeled separately: the wind turbine, gearbox, and DFIG topology. As illustrated in Figure 1, the rotor is linked to the grid through a back-to-back AC-DC-AC PWM converter, while the stator is directly connected to the grid.

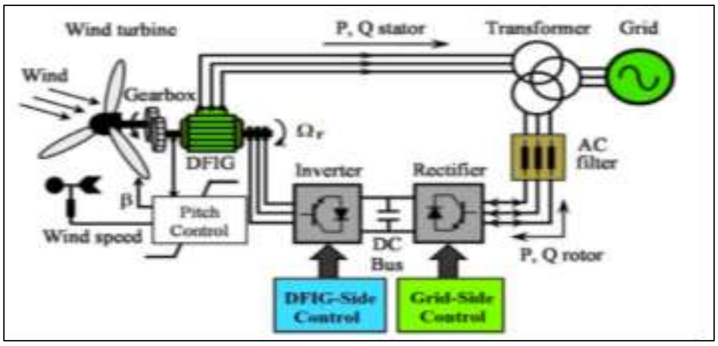


Figure 1: Wind energy conversion system.
Source: Authors :[16].

II.1 WIND TURBINE

The aerodynamic power generated by a wind turbine is determined by several key factors, including wind speed, turbine design, and its geometric characteristics. The relationship can be mathematically described using the following equation[17],[18]:

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

Then the aerodynamic torque is given by:

$$T_{aer} = \frac{P_{aer}}{\Omega_t} \tag{2}$$

In this context, ρ denotes the air density, which has a value of ρ = 1.225 kg/m³. R refers the length of the blade in meters (m), and V indicates the wind velocity in meters per second (m/s). The power coefficient C_p (λ, β), depends on two factors: the pitch angle of the turbine (β, in degrees°) and the tip speed ratio (TSR), represented as λ.

The tip speed ratio (λ) is expressed as:

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

where Ω_t represents the angular shaft speed of the wind turbine.

The power coefficient C_p and the tip speed ratio λ are related by the following function:

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\,\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068 \tag{4}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08.\beta} - \frac{0.035}{\beta^3+1} \tag{5}$$

The turbine is connected to the generator shaft via a gearbox, which has a gear ratio G selected to ensure that the generator shaft operates within a specified speed range:

$$\begin{cases} T_g = \frac{T_{aer}}{G} \\ \Omega_t = \frac{\Omega_m}{G} \end{cases} \tag{6}$$

Where T_g the driving torque of the generator and Ω_m is the generator shaft speed, respectively.

II.2 DYNAMIC MODEL OF A DFIG

The electrical expressions in the (d, q) reference frame are written as follows [19], [20]:

$$\begin{cases} V_{ds} = R_s.I_{ds} + \dfrac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ V_{qs} = R_s.I_{qs} + \dfrac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \\ V_{dr} = R_r.I_{dr} + \dfrac{d\Phi_{dr}}{dt} - (\omega_s - \omega)\Phi_{qr} \\ V_{qr} = R_r.I_{qr} + \dfrac{d\Phi_{qr}}{dt} + (\omega_s - \omega)\Phi_{dr} \end{cases} \quad (7)$$

Where R_s and R_r stand for the phase resistances of the stator and rotor, respectively.
ω = Ω p. is the electrical speed and p is the number of pair poles.
The expressions for the stator and rotor fluxes in the (d, q) reference frame are:

$$\begin{cases} \Phi_{ds} = L_s I_{ds} + M I_{dr} \\ \Phi_{qs} = L_s I_{qs} + M I_{qr} \\ \Phi_{dr} = L_r I_{dr} + M I_{ds} \\ \Phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (8)$$

Where L_s and L_r represent the stator and rotor self-inductances, respectively, while M denotes the mutual inductance between windings. Additionally, I_{ds} ,I_{qs},I_{dr}, and I_{dr}correspond to the direct and quadrature components of the stator and rotor currents, respectively.

The following expression expresses the electromagnetic torque of the DFIG:

$$Tem = \frac{PM}{Ls}\left(\Phi_{qs} I_{dr} - \Phi_{ds} I_{qr}\right) \quad (9)$$

The model of the DFIG can be represented using state equations in the synchronous reference frame, with the d-axis aligned with the orientation of the stator flux, as indicated in the equation below:

$$\begin{cases} V_{ds} = 0 \\ V_{qr} = V_s = \omega_s \Phi_{ds} \end{cases} \quad (10)$$

The stator's active and reactive powers, together with those that are provided to the grid, are described as follows:

$$\begin{cases} P_s = V_{ds}.I_{ds} + V_{qs}.I_{qs} \\ Q_s = V_{qs}.I_{ds} - V_{ds}.I_{qs} \end{cases} \quad (11)$$

Here are the formulas for rotor voltages as a function of rotor currents:

$$\begin{cases} V_{dr} = R_r.I_{dr} + \sigma.L_r.\dfrac{dI_{dr}}{dt} - g.\omega_s.\sigma.L_r.I_{qr} \\ V_{qr} = R_r.I_{qr} + \sigma.L_r.\dfrac{dI_{qr}}{dt} + g.\omega_s.\sigma.L_r.I_{dr} + g.\dfrac{M.V_s}{L_s} \end{cases} \quad (12)$$

where the DFIG's dispersion coefficient is denoted by

$$\sigma = \left(1 - \frac{M^2}{L_s L_r}\right).$$

III. CONTROL OF THE STUDIED SYSTEM

This section will discuss the utilization of a Type 2 Fuzzy Logic controller (T2FLC)to manage the active and reactive power DFIG.

III.1 DIRECT CONTROL OF THE DOUBLY FED INDUCTION GENERATOR

Figure 2 illustrates the block design of the DFIG that shows the direct control technique. By using separate regulators on each axis and ignoring the coupling factors, this method allows the active and reactive powers to be separately controlled.

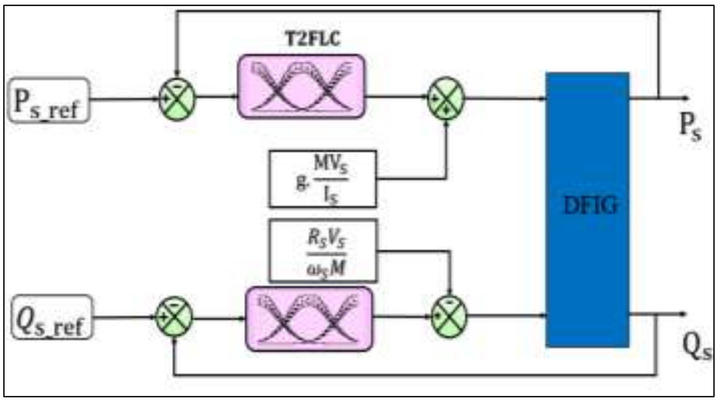


Figure 2: Direct control of the DFIG.
Source: Authors, (2025).

III.2 INDIRECT CONTROL OF THE DOUBLY FED INDUCTION GENERATOR

The indirect control strategy for the DFIG is depicted in Figure. 3. This method focuses on addressing the coupling terms and compensating for them by utilizing a dual-loop system designed to regulate both power output and rotor currents. This technique, referred to as the indirect method, facilitates the management of rotor currents, which is crucial for safeguarding the DFIG by limiting excessive currents and enhancing the operational flexibility of the machine.

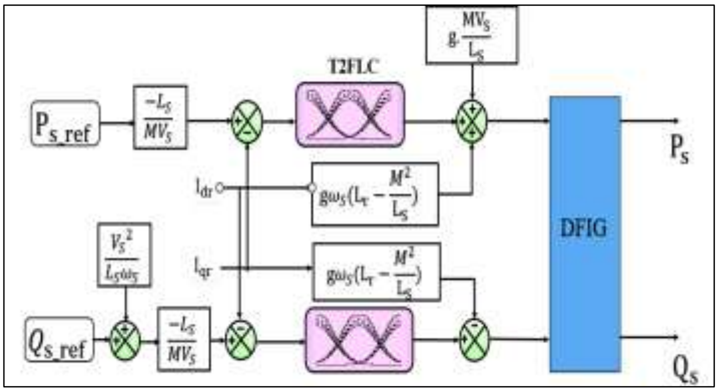


Figure 3: Indirect control of the DFIG.
Source: Authors, (2025).

IV. TYPE-2 FUZZY LOGIC CONTROL SYNTHESIS

Artificial intelligence methods are widely recognized for their significant potential in addressing industrial process challenges, especially in areas such as control, parameter estimation, and system identification [21]. Fuzzy logic, a notable technique within artificial intelligence, is increasingly utilized for controlling induction machines and adapting their vector control -

[22]. The overarching goal of artificial intelligence is to develop systems capable of emulating human reasoning behavior in various cognitive tasks [23].

Type-2 fuzzy logic is an advancement of classical fuzzy logic that expands upon type-1 fuzzy logic. This novel logic will allow us to integrate uncertainties into the regulations, positively influencing the system's output under examination [24]. Type-2 fuzzy logic is particularly efficacious in scenarios when establishing precise membership functions for a fuzzy system proves challenging.

A Type 2 fuzzy system is structured similarly to a Type 1 fuzzy system, consisting of a fuzzification block, a rule base, and an inference mechanism. The primary difference lies in the output, which introduces a reduction block before the defuzzification block in Type 2 systems [25], [26].
Figure 4 shows the Type-2 fuzzy logic controller's structure:

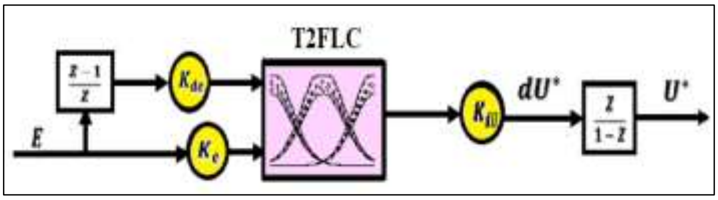


Figure 4: Schematic diagram of T2FLC.
Source: Authors, (2025).

The controller continuously analyzes the error signal and its derivative within the active and reactive power control loops. Based on this analysis, it adjusts the output U to ensure that the active power Ps aligns with its desired reference value P_s^*, while also ensuring that the reactive power Qs matches its corresponding reference value Q_s^*. Each Type-2 fuzzy controller processes two input signals: the error signal E and its derivative dE/dt. These signals undergo normalization using their specific scaling factors, K_e for the error and K_{de} for its derivative. The control output signal U is computed by multiplying the rate of change du/dt by the output scale factor K_{dU}, followed by integration to produce the final command signal.

The primary goal of this control method is to enhance the effectiveness of the results obtained through Type-1 fuzzy control. By implementing this advanced approach, the system can achieve significantly lower static errors, ensuring a more accurate response. Additionally, it provides a robust and swift reaction to changes, which is crucial for maintaining stability and efficiency in dynamic operating conditions.

The defuzzification employs the center of gravity method, and the controller block is founded on a Mamdani-type inference system. A distinctive set of criteria was established to ascertain the appropriate defuzzification procedure according to the quantity of input/output parameters. We implemented this control utilizing the Type-2 fuzzy control technique and integrated it into our system. Three Gaussian fuzzy sets represent the error and its variance in the membership functions of the fuzzification block. Our choice of three Gaussian fuzzy sets aligns with the defuzzification block, which determines the order variation.

Figure 5a illustrates the error, Figure 5b depicts the rate of change of the error, and Figure 5c presents the corresponding control action. Table 1 offers a comprehensive summary of the inference rules employed to identify the control variable.

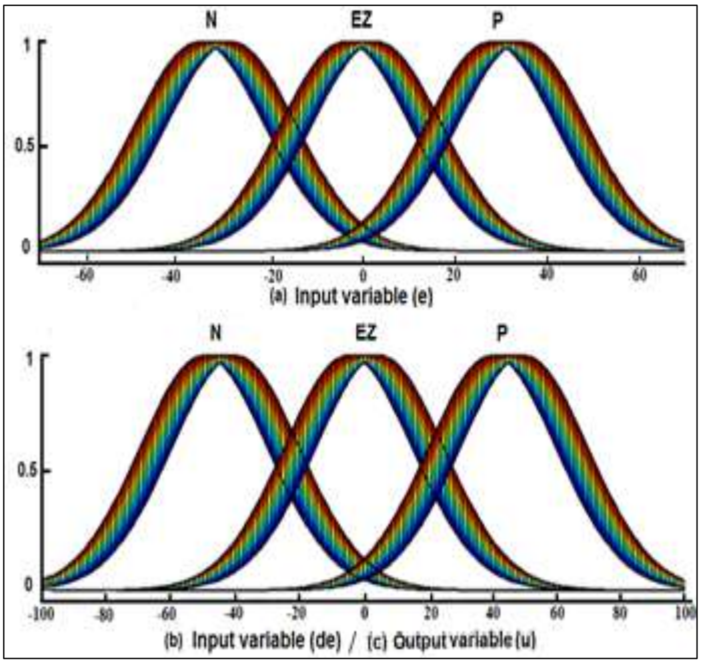


Figure 5: T2FLC membership functions.
Source: Authors : [25].

Table 1: Inference Rules for the T2FLC.

Control		**Error**		
		N	**EZ**	**P**
Rate of change of error	N	N	N	EZ
	Z	N	EZ	P
	P	Z	P	P

Source: Authors : [26].

V. SIMULATIONS AND RESULTS

We conduct comparative MATLAB/Simulink simulations to evaluate the dynamic performance of Type-1 (T1FLC) and Type-2 (T2FLC) fuzzy logic controllers in achieving decoupled active/reactive power regulation for DFIG-based wind turbines. The experimental framework utilizes the wind turbine specifications and DFIG electrical parameters detailed in Appendix A, with particular focus on transient response characteristics during grid interconnection scenarios.

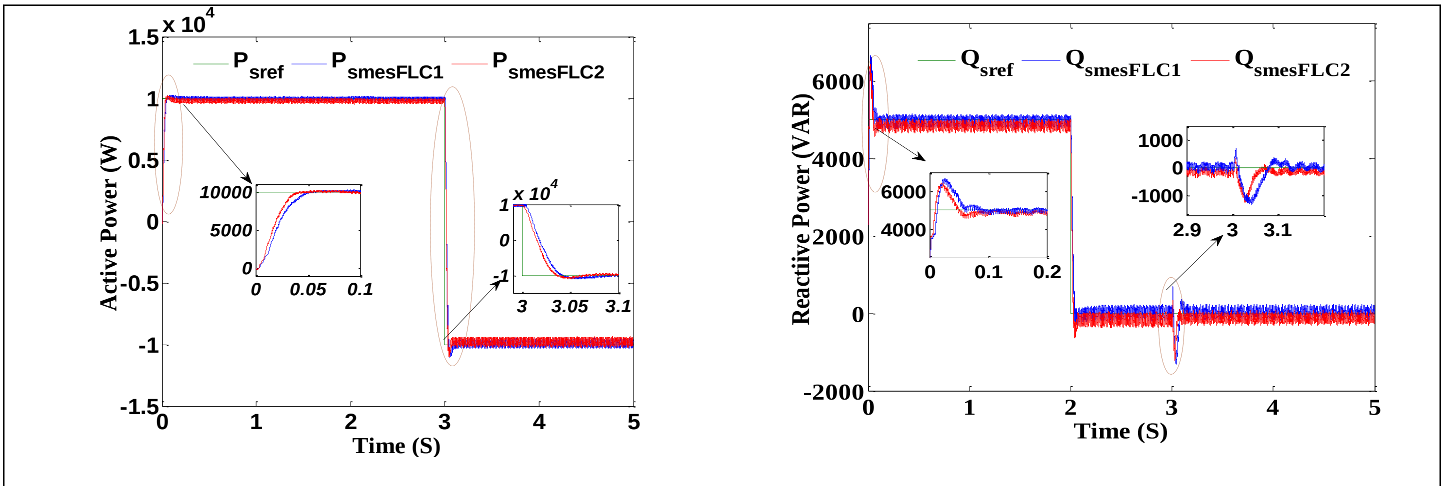
Case I: Setpoint Tracking Test

This evaluation investigates DFIG performance under controlled rotational speed (1440 rpm) during bidirectional active/reactive power transitions:
At t = 3 sec: an active power step (P_{ref}) changes from 1M W to -1MW.

At t=2 sec: a reactive power step (Q_{ref}) changes from 0 var to -5000 var

Concerning this initial test, Figures 6 and 7 illustrate the results of the simulations for the two DFIG power control methods, the direct and indirect techniques.

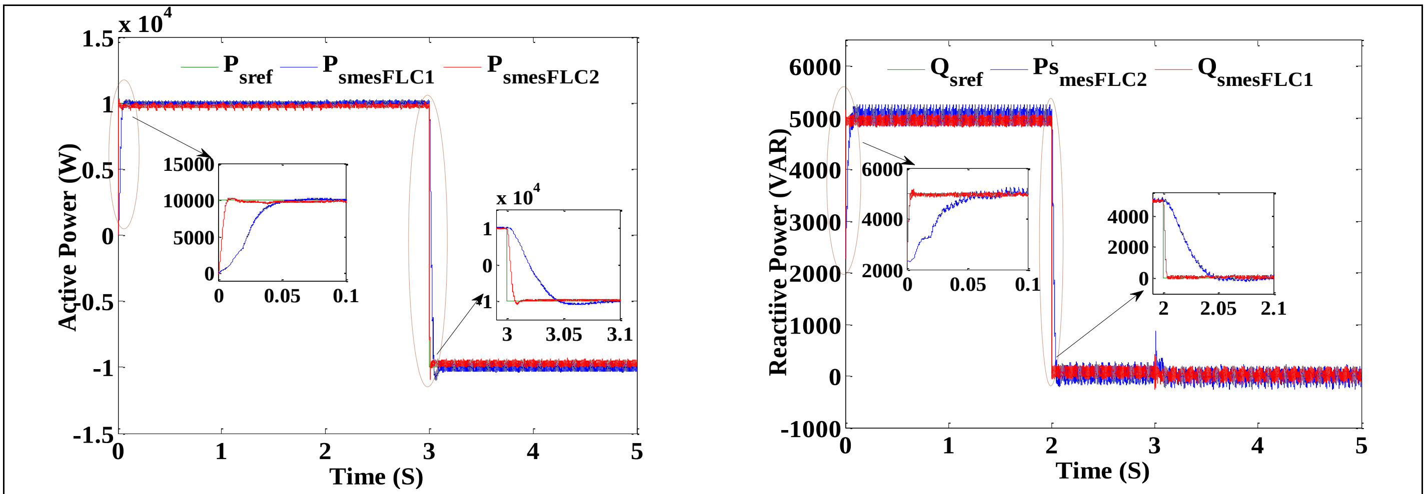
The results indicate that the DFIG effectively rejects disturbances and maintains to the power set points for both active and reactive power for both control methods.



(a)Stator Active Power (b) Stator Reactive Power

Figure 6: Direct control of the DFIG (setpoint tracking).
Source: Authors, (2025).

As shown in Figure 6, for both power control methods (T2FLC and T1FLC), the reactive and active powers of the DFIG closely follow their reference values. However, in the direct control approach using the T1FLC controller, the coupling effect between the two axes is evident. In contrast, the T2FLC controller effectively ensures decoupling between them.



(a) Stator Active Power (b) Stator Reactive Power

Figure 7: Indirect control of the DFIG (setpoint tracking).
Source: Authors, (2025).

The simulation results show in Figure 7 demonstrate that both controllers effectively achieve decoupling, power regulation, and accurate tracking of the reference values. Consequently, the suggested control technique for each converter, as well as the established simulation model, can be validated. Furthermore, a comparison between the results of the T2FLC and T1FLC controllers reveals a strong similarity in their dynamic behavior.

Table 2 provides a comprehensive summary of the controllers' performance, highlighting factors such as decoupling, response time, and power tracking ability.

Table 2: Step response of the controllers.

Active power				
Performances	**Direct control**		**Indirect control**	
	T1FLC	**T2FLC**	**T1FLC**	**T2FLC**
Rise time(s)	1.5758e+3	1.3501e+3	148.9657	271.6274
Overshoot (%)	13.3101	13.0162	33.6529	13.8152
SettlingTime	4.9956e+5	4.9990e+5	3.0140e+5	4.9413e+4
Reactive power				
Performances	**Direct control**		**Indirect control**	
	T1FLC	**T2FLC**	**T1FLC**	**T2FLC**
Rise time(s)	1.4752e+3	0.4000e+3	77.8339	149.6292
Overshoot (%)	5.8596e+3	2.4317e+3	4.1447e+3	3.7551e+3
SettlingTime	4.9998e+5	4.9998e+5	5.000e+5	4.9998e+5

Source: Authors, (2025).

The simulation results, under nominal conditions of operation show that the designed T2FLC and T1FLC control strategy can achieve satisfactory performance. It is possible to individually regulate active and reactive power, with the power responses closely following their reference values.

Case II: Real wind profile

To assess the system's dynamic behavior, regulating the DFIG with a realistic wind speed profile is crucial. This simulation was conducted using the wind profile presented in Fig. 8, where the mean wind velocity fluctuates between 7.5 m/s and 15 m/s. This wind speed profile was rescaled and processed over 5 seconds, as illustrated in Fig. 9 and 10, to align with the simulation and ensure the controllers operated at maximum efficiency. The T2FLC controller exhibited a faster response time and reduced undershoot compared to the T1FLC controller.

Figures 9 and 10 depict the simulation results obtained from direct and indirect control implemented on the DFIG, utilizing the MPPT control technique for the complete wind turbine system.

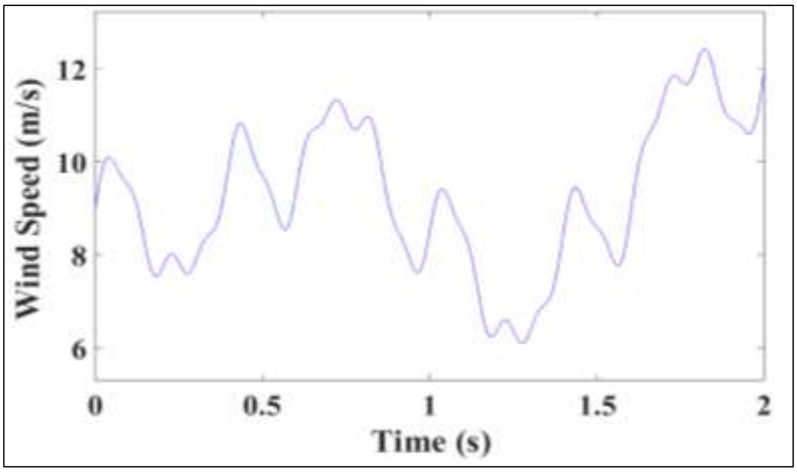
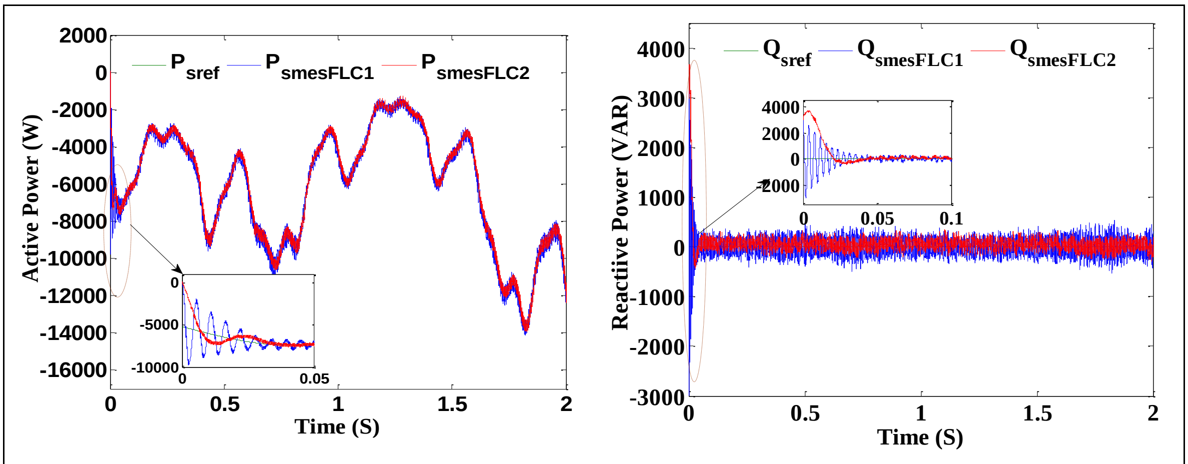


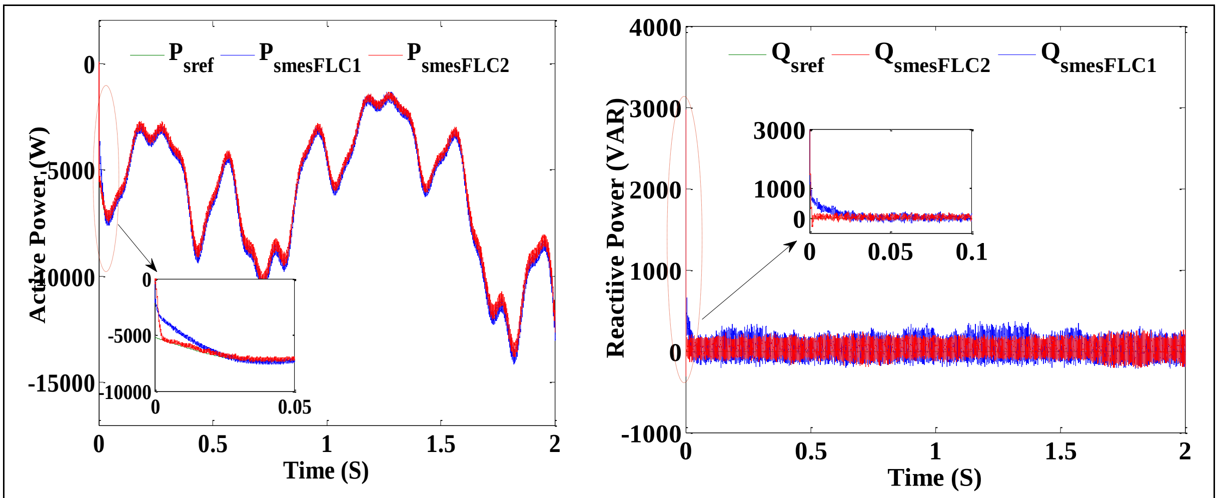
Figure 8: Wind Profile.
Source: Authors, (2025).



(a) Stator Active Power (b) Stator Reactive Power

Figure 9: Direct control of the DFIG (Real wind profile).
Source: Authors, (2025).

As illustrated in Fig. 9b, the reactive power waveforms for the evaluated control techniques maintain a reference value of Q_{ref} = 0 Var. The T2FLC demonstrated improved performance, featuring lower overshoot, minimal undershoot, and better damping characteristics compared to the T1FLC.



(a) Stator Active Power (b) Stator Reactive Power

Figure 10: Indirect control of1 the DFIG (Real wind profile).
Source: Authors, (2025).

We assessed the decoupling of reference active and reactive powers under varying wind speed conditions by obtaining suitable dynamics.

To optimize wind turbine efficiency, the MPPT control method enables the stator's active power to correspond with the turbine's mechanical power, which fluctuates with wind variations. The reactive power is null as we aim for operating at a unity power factor.

The results clearly indicate that the T2FLC provides enhanced performance regarding maximum power tracking and system stability restoration.

Compared to the two controllers, the T2FLC demonstrates exceptional performance in terms of rise time, overshoot, and settling time. It is particularly notable for its low overshoot when compared to the T1FLC controller. However, it does show a noticeable undershoot.

Table 3 provides a summary of the dynamic and static performances of the two controllers.

Table 3: Step response of the controllers.

Active power				
Performances	**Direct control**		**Indirect control**	
	T1FLC	**T2FLC**	**T1FLC**	**T2FLC**
Rise time(s)	1.7018e+5	7.0800e+4	1.7006e+5	1.7003e+5
Overshoot (%)	14.7001	21.6464	15.1533	16.3602
SettlingTime	1.9997e+5	1.9990e+5	1.9997e+5	1.9995e+5
Reactive power				
Performances	**Direct control**		**Indirect control**	
	T1FLC	**T2FLC**	**T1FLC**	**T2FLC**
Rise time(s)	83.5158	951.5273	170.5732	77.8431
Overshoot (%)	2.1221e+3	0.8012e+3	1.7387e+3	1.7233e+3
SettlingTime	2.0000e+5	2.0000e+5	2.0000e+5	2.0000e+5

Source: Authors, (2025).

VI. CONCLUSIONS

This study designs a Type-2 Fuzzy Logic Controller (T2FLC) to independently regulate active and reactive power exchange in a Doubly Fed Induction Generator (DFIG)-based Wind Energy Conversion System (WECS). The research further evaluates and contrasts the efficacy of Type-1 and Type-2 fuzzy logic control strategies to identify optimal solutions for maintaining reliability and adaptability amid parameter fluctuations and shifting operational setpoints. Rigorous testing was conducted under consistent operating conditions, analyzing both steady-state and transient behaviors of the system. The primary objective is to identify controllers that deliver consistent stability and high performance across varying scenarios. Results conclusively demonstrate that the T2FLC outperforms its Type-1 counterpart (T1FLC) in the examined WECS, exhibiting superior dynamic response, robustness, and operational effectiveness under diverse conditions.

VII. APPENDIX

Table 4: Wind power parameters.

Components	Parameter Name	Rated Value
P	Nominal power	1.5 MW
U	Nominal voltage	380/690 V
F	Frequency	50 HZ
n	Rotation speed	1440 tr/min
R	Wind Radius	35.25 m
G	speed multiplier gain	90
Rs	Stator Resistance	0.455 Ω
Rr	Rotor Resistance	0.62 Ω
l_{0s}	Stator leakage inductance	0.084 H
l_{0r}	Rotor Leakage Inductance	0.081 H
M	Main inductance	0.078 H
j	Inertial	0.3125 $kg\ m^2$
f	Viscous coefficient	$6.73.10^{-3}N.m.s^{-1}$
p	Pole pairs number	2

Source: Authors : [19].

VIII. AUTHOR'S CONTRIBUTION

Conceptualization: Kouadria Mohamed Abdeldjabbar, Kouadria Selman and Bouzid Mohamed Amine.
Methodology: Kouadria Mohamed Abdeldjabbar, Kouadria Selman and Bouzid Mohamed Amine.
Investigation: Kouadria Mohamed Abdeldjabbar, Kouadria Selman and Bouzid Mohamed Amine.
Discussion of results: Kouadria Mohamed Abdeldjabbar, Kouadria Selman and Bouzid Mohamed Amine.
Writing – Original Draft: Kouadria Mohamed Abdeldjabbar.
Writing – Review and Editing: Kouadria Mohamed Abdeldjabbar and Bouzid Mohamed Amine.
Resources: Kouadria Selman.
Supervision: Kouadria Selman and Bouzid Mohamed Amine.
Approval of the final text: Kouadria Mohamed Abdeldjabbar, Kouadria Selman and Bouzid Mohamed Amine.

IX. REFERENCES

[1] Bošnjaković, M., Katinić, M., Santa, R., & Marić, D. (2022). Wind Turbine Technology Trends. Applied Sciences, 12(17), 8653. https://doi.org/10.3390/app12178653

[2] Sukanta Roga, Shawli Bardhan, Yogesh Kumar, Sudhir K. Dubey, Recent technology and challenges of wind energy generation: A review, Sustainable Energy Technologies and Assessments, Volume 52, Part C, 2022, 102239, https://doi.org/10.1016/j.seta.2022.102239.

[3] SINGH, Pradeep, ARORA, Krishan, et RATHORE, Umesh C. Energy Storage Systems with Artificial Intelligence Techniques in Doubly Fed Induction Generator Based Wind Energy Conversion System—An Overview. Intelligent Circuits and Systems for SDG 3–Good Health and well-being, p. 403-418.

[4] B. Desalegn, D. Gebeyehu, et B. Tamrat, « Wind energy conversion technologies and engineering approaches to enhancing wind power generation: A review », Heliyon, vol. 8, nº 11, nov. 2022, https://doi:10.1016/j.heliyon.2022.e11263.

[5] Tan, J. D., Chang, C. C. W., Bhuiyan, M. A. S., Nisa'Minhad, K., & Ali, K. (2022). Advancements of wind energy conversion systems for low-wind urban environments: A review. Energy Reports, 8, 3406-3414. https://doi.org/10.1016/j.egyr.2022.02.153

[6] S. R. Mosayyebi, S. H. Shahalami and H. Mojallali, "Fault Ride-Through Capability Improvement in a DFIG-Based Wind Turbine using Modified ADRC," in Protection and Control of Modern Power Systems, vol. 7, no. 4, pp. 1-37, October 2022, https://doi:10.1186/s41601-022-00272-9

[7] Verma, P., K., S., & Dwivedi, B. (2021). Comprehensive investigation on doubly fed induction generator-Wind farms at fault ride through capabilities: technical difficulties and improvisations. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 47(1), 3621–3653. https://doi.org/10.1080/15567036.2020.1857476

[8] Sonam Gupta, Anup Shukla, Improved dynamic modelling of DFIG driven wind turbine with algorithm for optimal sharing of reactive power between converters, Sustainable Energy Technologies and Assessments, Volume 51, 2022, https://doi.org/10.1016/j.seta.2022.101961.

[9] Sahu, S., & Behera, S. (2022). A review on modern control applications in wind energy conversion system. Energy & Environment, 33(2), 223-262. https://doi.org/10.1177/0958305X21995929

[10] S. Krishnama Raju and G. N. Pillai, "Design and Implementation of Type-2 Fuzzy Logic Controller for DFIG-Based Wind Energy Systems in Distribution Networks," in IEEE Transactions on Sustainable Energy, vol. 7, no. 1, pp. 345-353, Jan. 2016, https://doi:10.1109/TSTE.2015.2496170.

[11] Kanasottu Anil Naik, Chandra Prakash Gupta, Eugene Fernandez, Design and implementation of interval type-2 fuzzy logic-PI based adaptive controller for DFIG based wind energy system, International Journal of Electrical Power & Energy Systems, Volume 115, 2020, https://doi.org/10.1016/j.ijepes.2019.105468.

[12] Moradi, H., Alinejad-Beromi, Y., Yaghobi, H. and Bustan, D. (2019), Sliding mode type-2 neuro-fuzzy power control of grid-connected DFIG for wind energy conversion system. IET Renewable Power Generation, 13: 2435-2442. https://doi.org/10.1049/iet-rpg.2019.0066

[13] Hosseini, S. M., & Manthouri, M. Type 2 adaptive fuzzy control approach applied to variable speed DFIG based wind turbines with MPPT algorithm. Iranian Journal of Fuzzy Systems, 19(1), 31-45. (2022), https://doi:10.22111/ijfs.2022.6549

[14] F. Amrane, A. Chaiba and B. Francois, "Suitable power control based on type-2 fuzzy logic for wind-turbine dfig under hypo-synchronous mode fed by multi-level converter," 2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B), Boumerdes, Algeria, 2017, pp. 1-6, https://doi:10.1109/ICEE-B.2017.8191983.

[15] Zouggar, E. O., Chaouch, S., Abdeslam, D. O., & Abdelhamid, L. (2019). Sliding control with fuzzy type-2 controller of wind energy system based on doubly fed induction generator. Instrumentation, Mesure, Métrologie, 18(2), 137-146. https://doi:10.18280/i2m.180207

[16] Kouadria, Selman, et al. "Improved control strategy of DFIG-based wind turbines using direct torque and direct power control techniques." Journal of Renewable and Sustainable Energy 10.4 (2018).

[17] Balat, M. (2009). A Review of Modern Wind Turbine Technology. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 31(17), 1561–1572. https://doi.org/10.1080/15567030802094045

[18] Kouadria, Abdeldjabbar Mohamed, et al. Power Quality Enhancement in Off-Grid Hybrid Renewable Energy Systems Using Type-2 Fuzzy Control of Shunt Active Filter. In: Bi, Y., Kapoor, S., Bhatia, R. (eds) Intelligent Systems and Applications. Studies in Computational Intelligence, vol 650. Springer, Cham 2016. https://doi.org/10.1007/978-3-319-33386-1_17

[19] Kouadria, M. A., Kouadria, S., & Chaib, H. (2024). Sliding mode control for doubly fed induction generators system-based a wind turbine. STUDIES IN ENGINEERING AND EXACT SCIENCES, 5(2), e7199. https://doi.org/10.54021/seesv5n2-139

[20] X. Liu and X. Kong, "Nonlinear Model Predictive Control for DFIG-Based Wind Power Generation," in IEEE Transactions on Automation Science and Engineering, vol. 11, no. 4, pp. 1046-1055, Oct. 2014, https://doi:10.1109/TASE.2013.2284066

[21]I. Ahmed, G. Jeon and F. Piccialli, "From Artificial Intelligence to Explainable Artificial Intelligence in Industry 4.0: A Survey on What, How, and Where," in IEEE Transactions on Industrial Informatics, vol. 18, no. 8, pp. 5031-5042, Aug. 2022, https://doi:10.1109/TII.2022.3146552.

[22] M. A. Hannan, J. A. Ali, P. J. Ker, A. Mohamed, M. S. H. Lipu and A. Hussain, "Switching Techniques and Intelligent Controllers for Induction Motor Drive: Issues and Recommendations," in IEEE Access, vol. 6, pp. 47489-47510, 2018, https://doi:10.1109/ACCESS.2018.2867214
.

[23] VERNON, David. Artificial cognitive systems: A primer. MIT Press, 2014.

[24] N. N. Karnik, J. M. Mendel and Qilian Liang, "Type-2 fuzzy logic systems," in IEEE Transactions on Fuzzy Systems, vol. 7, no. 6, pp. 643-658, Dec. 1999, https://doi:10.1109/91.811231.

[25] Kouadria, M. A., Allaoui, T., & Denaï, M. (2015). High performance shunt active power filter design based on fuzzy interval type-2 control strategies. Int. Rev. Autom. Control (I. RE. A. CO.), 8(5), 322.

[26] Kouadria, A. M., Allaoui, T., Denaï, M., & Pissanidis, G. (2015, November). Grid power quality enhancement using fuzzy control-based shunt active filtering. In 2015 SAI Intelligent Systems Conference (IntelliSys) (pp. 646-650). IEEE.