



RESEARCH ARTICLE

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A ROBUST FUZZY-PI CONTROLLER FOR DOUBLY FED INDUCTION MACHINES USING 12 LINGUISTIC VARIABLES

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ABSTRACT

This study focuses on the development of a robust nonlinear control strategy for the Doubly-Fed Induction Machine (DFIM), with the objective of improving its performance in variable-speed drive applications. This approach combines vector control with intelligent techniques, specifically Type-1 Fuzzy Logic, utilizing 12 linguistic variables, to address the shortcomings of traditional control methods. Conventional vector control often faces challenges, including oscillations, sluggish response, and diminished efficiency across different load and speed scenarios. The introduction of fuzzy logic enhances the adaptability and robustness of the control system, thereby significantly improving its dynamic response and steady-state performance. We conducted an extensive simulation to evaluate the effectiveness of the proposed fuzzy-vector control strategy. The results demonstrate that the integration of fuzzy logic reduces oscillations and improves load-driving capability across a range of speeds. Additionally, it enhances response time, mitigates derivation issues, and minimizes flux ripples and fluctuations in electromagnetic torque. Overall, the findings suggest that fuzzy logic surpasses traditional vector control, offering a more reliable and efficient solution for modern DFIM applications.



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I. INTRODUCTION

Asynchronous motors are widely preferred in industrial settings for a variety of reasons. Key attributes include cost-effectiveness, reduced weight, durability, and simple construction that requires minimal maintenance [1]. A notable example of an asynchronous motor is the doubly fed induction machine (DFIM), which is frequently employed in industrial applications. This machine is distinguished by unique features that set it apart from other motors in its category. The DFIM is structured as a three-phase system with a wound rotor that can be powered by two separate voltage sources: one connected to the stator and the other to the rotor [2]. This design provides an efficient solution for high-performance, variable-speed drives, enabling operations at very low speeds. From a control standpoint, these motors pose challenges that challenge/complicate the application of classical control theory [3-6]. The dynamics of these systems are marked by nonlinearity, coupled multivariable interactions, and time-varying elements, in addition to an inaccessible rotor.

Over the past forty years, significant efforts have been dedicated to developing effective control strategies for the dynamic behavior of induction motors [7]. A range of methods for controlling induction machines has been explored, with flux-oriented vector control (FOC) being one of the foremost advancements. The FOC was first introduced in the early 1970s by F. Blaschke and Hass (1970) [8]. The fundamental objective of the FOC is to establish a decoupling mechanism between magnetic flux and electromagnetic torque, in a manner analogous to the operation of a separately excited DC machine. This technique is known for its impressive dynamic performance; however, it is susceptible to parametric variations, particularly those associated with rotor resistance, which directly influences the flux orientation angle. FOC can be categorized into two types: direct control, which requires precise knowledge of the actual rotor flux modulus and phase, and indirect control, which depends on the estimation of the rotor flux position. Consequently, various control strategies have been developed to enhance robustness against these variations, including nonlinear control via input-output linearization, direct torque

control (DTC), sliding mode control, backstepping control, and fuzzy logic control techniques, among others [9-11]. Fuzzy logic has emerged as an effective approach due to its distinctive characteristics, particularly its ability to generate efficient control laws without the necessity for extensive modeling. Unlike traditional controllers and state feedback controllers, fuzzy logic controllers do not rely on precise mathematical relationships. Instead, they make inferences based on a set of rules derived from linguistic variables. This allows them to incorporate the knowledge of operators involved in a technical process [12]. The effectiveness of fuzzy logic in enhancing the control robustness of nonlinear systems has been well-documented, particularly its capability to address modeling errors and parametric variations, which are crucial factors.

These properties have been demonstrated in numerous theoretical and practical studies [13-16]. This study presents an approach that combines fuzzy logic with the oriented stator flux vector control of the doubly fed induction machine (DFIM). The objective of this integration is to develop an innovative adaptive control system that utilizes fuzzy logic with 12 linguistic variables. The implementation of this system is expected to enhance the dynamic performance of the doubly fed induction motor. The structure of the paper is as follows: The second section of this text presents a comprehensive analysis of the DFIM mathematical model within the (d, q) reference frame. This section addresses the design presentation of the Fuzzy SMC-PI controller. The fourth section discusses the simulation results, while the final section, Section 5, provides a conclusion and explores future research directions. This work aims to enhance DFIM control, with possible applications in renewable energy systems, industrial drives, and other high-performance electromechanical systems [17].

II. MODELING OF DFIM

The matrix representation below outlines the dynamic model of the doubly fed induction motor in the (d, q) reference frame, incorporating both electrical and mechanical dynamics [1], [18], [19].

$$\dot{X} = AX + BU \tag{1}$$

Where:

$$X = [\varphi_{sd} \quad \varphi_{sq} \quad I_{rd} \quad I_{rq}]^T; \quad U = [V_{sd} \quad V_{sq} \quad V_{rd} \quad V_{rq}]^T;$$

$$[A] = \begin{bmatrix} -\frac{1}{T_s} & \omega_s & \frac{M}{T_s} & 0 \\ -\omega_s & -\frac{1}{T_s} & 0 & \frac{M}{T_s} \\ \alpha & -\beta\omega & -\delta & (\omega_s - \omega) \\ \beta\omega & \alpha & -(\omega_s - \omega) & -\delta \end{bmatrix}; [B] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_r} \end{bmatrix}$$

With:

$$\sigma = 1 - \frac{M^2}{L_r L_s}; T_r = \frac{L_r}{R_r}; T_s = \frac{L_s}{R_s}; \alpha = \frac{M}{\sigma L_r L_s T_s}; \beta = \frac{M}{\sigma L_r L_s}; \delta = \frac{1}{\sigma} \left(\frac{1}{T_r} + \frac{M^2}{L_s T_s L_r} \right)$$

The equations for mechanics and electromagnetism are as follows:

$$J \frac{d\Omega}{dt} = C_{em} - C_r - f\Omega \tag{2}$$

$$C_{em} = P \frac{M}{L_s} (\varphi_{sq} I_{rd} - \varphi_{sd} I_{rq}) \tag{3}$$

The objective of controlling active and reactive powers is crucial for regulating the power output of wind turbines. To achieve this, it is essential to establish equations that connect rotor voltages to the energetic and reactive stator powers [20], [21]. By selecting a (d, q) reference frame that is aligned with the rotating stator region and placing the stator flux vector along the d-axis, we derive the following results: $\varphi_{sd} = \varphi_s$ and $\varphi_{sq} = 0$. Assuming a stable electrical network and negligible stator resistance, the equations simplify to

$$V_{sd} = 0, V_{sq} = V_s, \text{ and } V_{sq} = V_s / \omega_s.$$

The above equations can be adapted to the simplifying assumptions as follows:

$$\begin{cases} I_{sd} = \frac{\varphi_s}{L_s} - \frac{M}{L_s} I_{rd} \\ I_{sq} = -\frac{M}{L_s} I_{rq} \end{cases} \tag{4}$$

$$\begin{cases} \varphi_{rd} = \left(L_r - \frac{M^2}{L_s} \right) I_{rd} + \frac{M V_s}{\omega_s L_s} \\ \varphi_{rq} = \left(L_r - \frac{M^2}{L_s} \right) I_{rd} \end{cases} \tag{5}$$

$$\begin{cases} V_{rd} = R_r I_{rd} + \left(L_r - \frac{M^2}{L_s} \right) \dot{I}_{rd} - g \omega_s \left(L_r - \frac{M^2}{L_s} \right) I_{rq} \\ V_{rq} = R_r I_{rq} + \left(L_r - \frac{M^2}{L_s} \right) \dot{I}_{rq} + g \omega_s \varphi_{rq} + g \frac{M V_s}{L_s} \end{cases} \tag{6}$$

The method used for power control involves eliminating coupling phrases and utilizing an independent regulator for each axis. This allows for separate management of active and reactive power. This technique is referred to as the direct approach, where electricity regulators exert direct control over rotor voltages [22].

III. FUZZY LOGIC CONTROL APPLIED TO DFIM

The use of artificial intelligence techniques, particularly fuzzy logic, is widely recognized for its considerable potential in addressing challenges pertaining to industrial processes, estimation, and identification of the parameters of varying systems. These tools can be employed judiciously to address specific issues associated with modelling errors and the absence of knowledge regarding the model of the controlled system. In this context, the PI controller is replaced by a fuzzy controller (Fuzzy Logic Controller "FLC"). It can thus be concluded that a fuzzy PI has the capacity to enhance the dynamic and static performance of a loop control. This is especially evident in the context of enhancing the resilience of a control system against modelling errors and parametric variations, which are frequently unavoidable [12], [23].

III.1 PI-TYPE FUZZY CONTROLLER

As demonstrated in Figure 1, the configuration of a non-adaptive gain PI-type fuzzy controller is illustrated. The PI-type corrector is constructed by integrating the fuzzy motor output, as illustrated in Figure 1. It is imperative to acknowledge that S_{PI} signifies the output of the PI-type fuzzy controller.

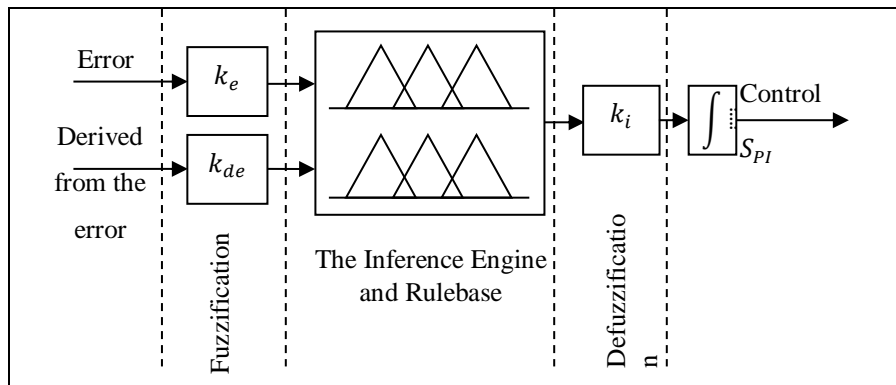


Figure 1: Fuzzy PI controller.
Source: Authors, (2025).

A fuzzy controller defines a static non-linear mapping between inputs and outputs. The controller's action is represented by equation [19].

$$u = k_e \cdot e + k_{de} \cdot \frac{de}{dt} \tag{7}$$

The Fuzzy-PI output is as follows:

$$y = \int k_i \cdot u \tag{8}$$

Where:

- k_e : the gain of error;
- k_{de} : the gain of derivative error;
- k_i : the integral factor;
- u : the fuzzy output.

The fuzzy-PI controller is utilized in the vector control of the doubly-fed induction motor (DFIM), as illustrated in Figure 2.

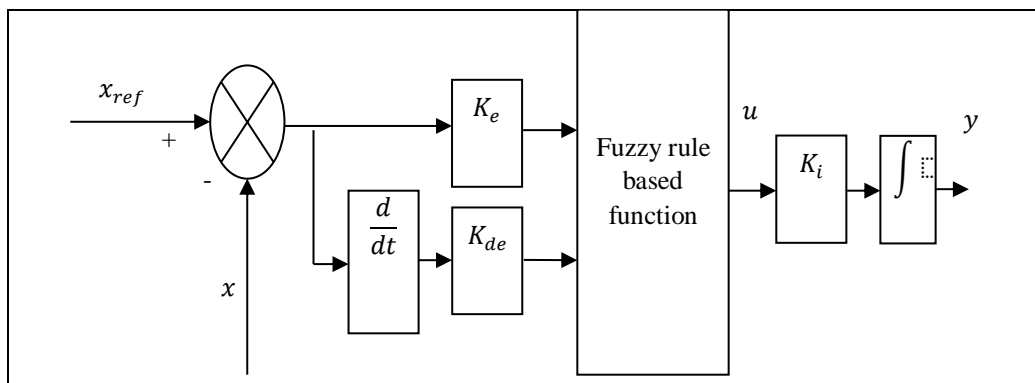


Figure 2: Block diagram of Fuzzy-PI controller.
Source: Authors, (2025).

III.2 FUZZY LOGIC WITH 12 LINGUISTIC VARIABLES

The internal structure of fuzzy logic is comprised of three constituent components. The subsequent processes are known as fuzzification (F), inference (I) and defuzzification (D). As illustrated in Figure 2, the block diagram integrates the error e and its derivative, Δe . The selection of linguistic variables is denoted as follows:

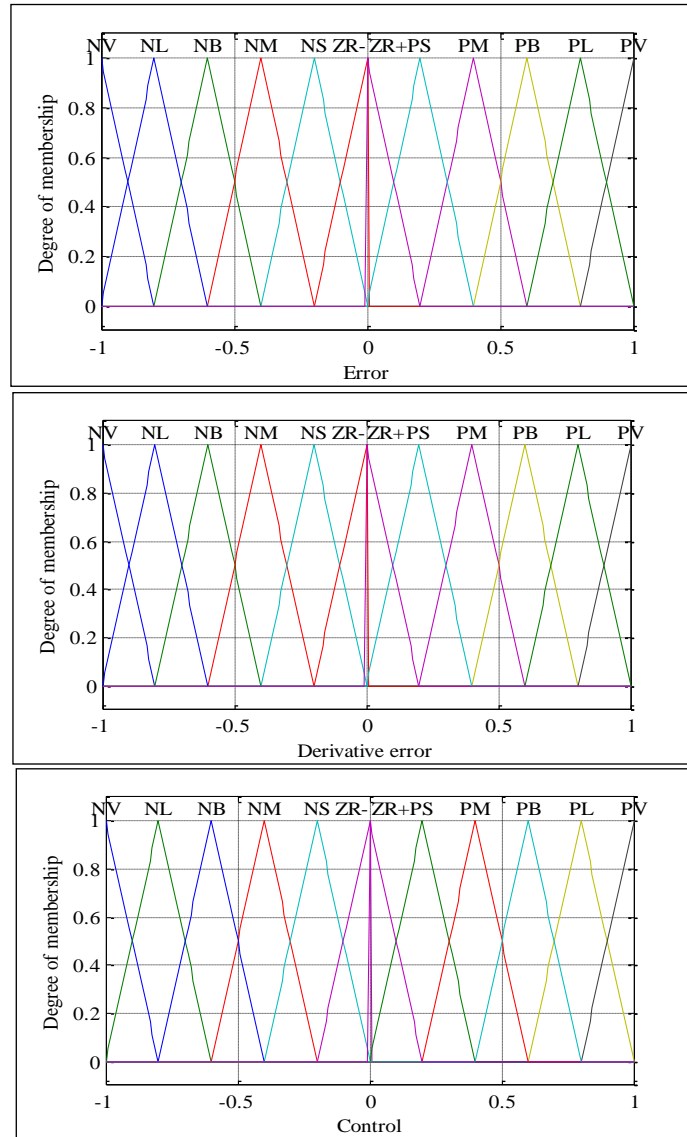


Figure 3: Membership functions used by the proposed control. Source: Authors, (2025).

The rules for inferring the output variable related to the current adjustment are organized in the table below. The inference method used is Mamdani's "min-max" approach.

Table 1: Decision rule table for the speed controller.

Control		Error											
		NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV
Derivative of Error	NV	NV	NV	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR-
	NL	NV	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR-	ZR+
	NB	NV	NV	NV	NV	NV	NL	NB	NM	NS	ZR-	ZR+	PS
	NM	NV	NV	NV	NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM
	NS	NV	NV	NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB
	ZR-	NV	NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL
	ZR+	NV	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV
	PS	NL	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV	PV
	PM	NB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV	PV	PV
	PB	NM	NS	ZR-	ZR+	PS	PM	PB	PL	PV	PV	PV	PV
	PL	NS	ZR-	ZR+	PS	PM	PB	PL	PV	PV	PV	PV	PV
	PV	ZR-	ZR+	PS	PM	PB	PL	PV	PV	PV	PV	PV	PV

Source: Authors, (2025).

As illustrated in Figure 4, the fuzzy controller under consideration incorporates 12 linguistic variables, which are based on the stator flux orientation of the doubly-fed induction machine. The diagram under consideration features a fuzzy system that utilizes 12 linguistic variables for the purpose of speed regulation, in conjunction with three proportional-integral controllers: one for flux control and two for current control.

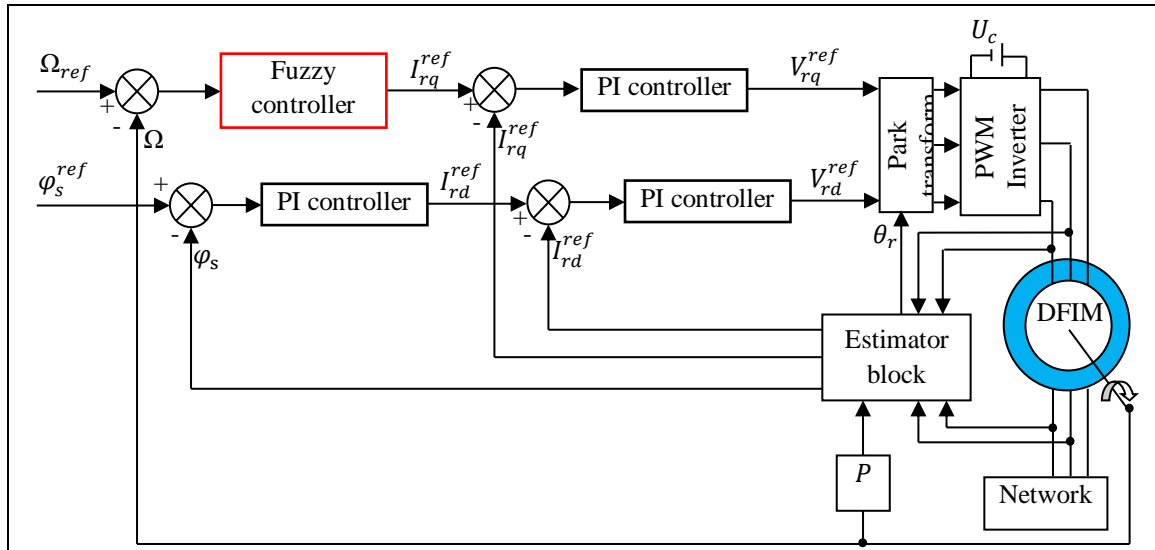


Figure 4: Structure of fuzzy with 12 linguistic variables Control for DFIM.
Source: Authors, (2025).

IV. SIMULATION RESULTS

The results of the grouped simulation are displayed in Figure 5. The findings indicate that variations in load have a minimal impact on speed and control currents. It is evident that both the electromagnetic torque and speed exhibit a high degree of correlation with the set point, thereby ensuring effective decoupling between the flux and torque.

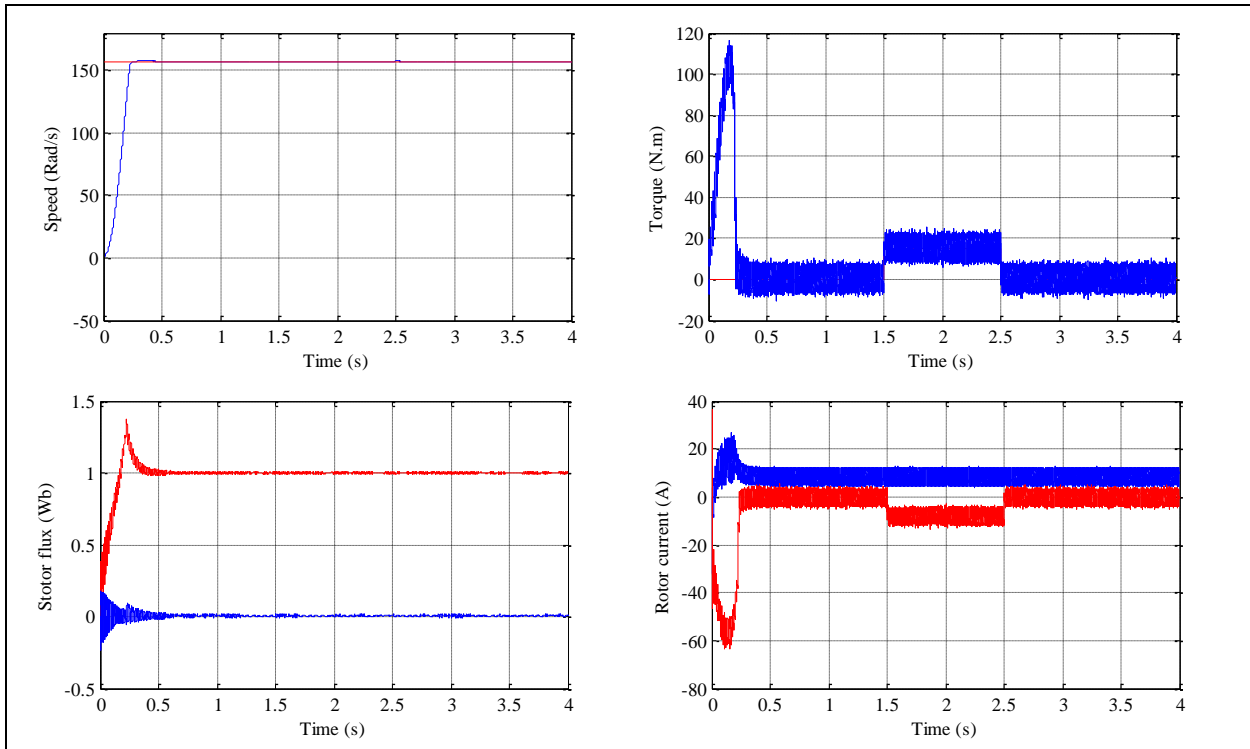


Figure 5: Simulation results when the load varies.
Source: Authors, (2025).

To evaluate the robustness of the control system against significant changes in the speed reference, we introduced an increase in the speed reference to 157 rad/s, followed by a decrease to a low speed of 50 rad/s. It was observed that the decoupling phenomenon continued to occur, demonstrating the effectiveness of the control system in handling substantial variations in speed.

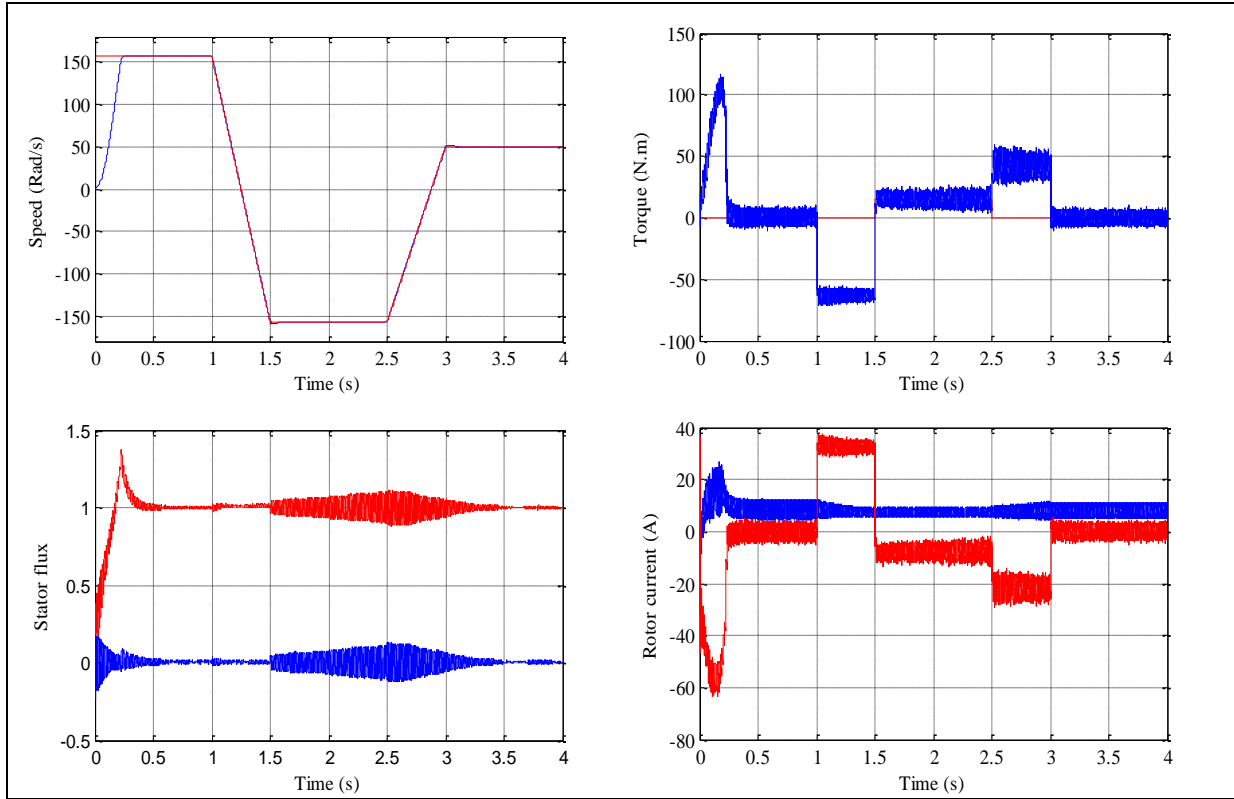


Figure 6: Simulation results when varying the speed.

Source: Authors, (2025).

V. CONCLUSIONS

The findings indicate that the fuzzy controller demonstrates superior performance, both in terms of tracking and regulation. The system has been engineered to ensure highly accurate tracking of the reference speed, with zero static error. In comparison with the PI structure, the fuzzy controller demonstrates a substantially reduced tracking error, thereby emphasising its optimal adaptation to the control. It is also observed that the stator flux orientation is perfectly achieved and that disturbances are effectively rejected. The fuzzy approach is distinguished by its superior performance in terms of speed deviations and disturbance rejection times. A thorough investigation was conducted into the evolution of rotational speed responses to variations, which culminated in the determination that the fuzzy controller exhibits superior performance. Despite these variations, its behavior in terms of tracking and regulation remains remarkable.

VI. APPENDIX

Table 2: Parameters of the DFIM.

Parameters	Value	Parameters	Value
Nominal power	$P_n = 4 \text{ KW}$	Nominal current	$I_n = 15/8.6 \text{ A}$
Stator voltage	$U_{sn} = 380 \text{ V}$	Nominal mechanical speed	$\Omega_n = 1440 \text{ rpm}$
Rotor voltage	$U_{rn} = 220 \text{ V}$	Nominal stator and rotor frequencies	$\omega_{sn} = 50\text{Hz}$
Pole pair number	$P = 2$	Rotor self inductance	$L_r = 0.1568 \text{ H}$
Stator resistance	$R_s = 1.2 \Omega$	Mutual inductance	$M = 0.15 \text{ H}$
Rotor resistance	$R_r = 1.8 \Omega$	Moment of inertia	$J = 0.2 \text{ Kg. m}^2$
Stator self inductance	$L_s = 0.1554 \text{ H}$	Friction coefficient	$f = 0.001 \text{ IS}$

Source: Authors, (2025).

VII. AUTHOR'S CONTRIBUTION

Conceptualization: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Methodology: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Investigation: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Discussion of results: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Writing – Original Draft: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Writing – Review and Editing: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Resources: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Supervision: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

Approval of the final text: Herizi Abdelghafour, Abed Ahcene and Rouabhi Riyadh.

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