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The impact of Adaptive Fuzzy Logic on the regulation of induction motor speed

***Abstract**. This study presents a novel approach to developing an adaptive fuzzy logic controller to regulate the speed of a three-phase induction motor. In this paper, we introduce the motor model and various control schemes, such as vector control and PI controllers. We use simulations to test how well two fuzzy controllers, RLF3 and RLF5, can accurately track speed and ignore disturbances, and then we compare their performance to that of a PI controller. Ultimately, it was discovered that fuzzy controllers, particularly the RLF5 controller, possess the ability to diminish the PI response while also exhibiting enhanced speed, greater resilience to parameter variations, and reduced power consumption.*

***Streszczenie.** Niniejszy dokument przedstawia zaprojektowany adaptacyjny sterownik logiczny do regulacji prędkości silnika indukcyjnego trójfazowego. Przedstawiamy schematy sterowania i modele silnika, w tym sterowniki wektorowe i PI. Symulacje pokazują, że wydajność sterowników RLF3 i RLF5 w zakresie śledzenia prędkości i odrzucania zakłóceń jest porównywalna z wydajnością sterownika PI. Stwierdzono ostatecznie, że niejasne sterowniki, zwłaszcza RLF5, mogą zmniejszyć reakcję PI, jednocześnie będąc szybszymi, bardziej odpornymi na zmiany parametrów i zużywającymi mniej energii. (**Wpływ Adaptive Fuzzy Logic na regulację prędkości silnika indukcyjnego**)*

Keywords: Induction motor, Fuzzy logic control, Speed regulation, Simulation.
Słowa kluczowe: Silnik indukcyjny,Sterowanie rozmyte,Regulacja prędkości,Symulacja

Introduction

Induction motors have gained immense popularity owing to merits like sturdy build, straightforward design and cost-efficiency [1], despite exhibiting time-varying and nonlinear dynamics [2]. However, the complexity of mathematical modeling has historically hindered suitable control designs [3]. Recently, artificial intelligence techniques including fuzzy logic, neural networks and genetic algorithms are widely utilized to address limitations of classical control methods in induction machine regulation [4–6]. Fuzzy logic control has particular relevance leveraging expert knowledge rather than pure modeling [7].

Over the past three decades, knowledge-based fuzzy controllers have become ubiquitous given their simplicity, stability, accuracy and reliability [8–10]. They eliminate the need for exact system modeling by mimicking human reasoning through linguistic rule-bases.

Additionally, fuzzy logic and evolutionary computing can enable synthesis of robust induction motor controllers without precise dynamic models by overcoming constraints posed by parameter variations and nonlinearities [8–9]. Thereby they facilitate advanced techniques like field oriented control or direct torque control to leverage high-performance variable speed drives despite machine parameter instabilities [7].

This paper aims to design an adaptive fuzzy logic controller for three-phase asynchronous motor speed regulation. The fuzzy logic approach addresses the limitations of conventional controllers, especially in dealing with parametric variations. The adaptive feature of the fuzzy logic-based control unit helps overcome non-linearity in the machine without requiring complex mathematical modeling, improving overall control system performance.

Induction motor modeling

Creating regulations to monitor and improve asynchronous motors necessitates meticulous focus on modeling. The analysis of AC machines, drawing from J.C. Kron's research, frequently utilizes the Park model to develop control strategies, especially in relation to the generalized machine concept [11]. The Park model recognizes various state representations associated with control objectives and power source characteristics, which reflect the machine's dynamic behavior. Using the dynamic model representation in the state space lets you describe many different systems, such as the asynchronous machine, which is a common example of a multivariable nonlinear system [12]. The formulation of the state-space representation is as follows:

(1) $$\left[\dot{X}\right]=\frac{d\left[X\right]}{dt}=\left[A\right].\left[X\right]+\left[B\right].\left[U\right] \qquad \left[Y\right]=\left[C\right].\left[X\right]$$

Considering that control variables are voltages (vsd ,vsq) ,and state variables are currents (isd,isq) and flows (φRq , φRq).

Where: *[X]* -state vector, [U]-control vector, [A]-transition or state matrix that characterizes the engine dynamics,[B]-control input matrix,[Y]-output vector,[C]-observation matrix [3-5].

With : $[X]=[i_{sd}\ i_{sq}\ Ø_{Rq}\ \ Ø_{Rq}]^T$, $[U]=[v_{sd}\ \ v_{sq}]^T$, $[U]=[i_{sd}\ \ i_{sq}]^T$.

$$[A]=\begin{bmatrix} -\left(\frac{1}{\sigma.T_S}+\frac{1}{T_R}.\frac{1-\sigma}{\sigma}\right) & \omega_S & \frac{1-\sigma}{\sigma}.\frac{1}{M_{sR}.T_R} & \frac{1-\sigma}{\sigma}.\frac{1}{M_{sR}}.\omega_R \\ -\omega_S & -\left(\frac{1}{\sigma.T_S}+\frac{1}{T_R}.\frac{1-\sigma}{\sigma}\right) & -\frac{1-\sigma}{\sigma}.\frac{1}{M_{sR}}.\omega_R & \frac{1-\sigma}{\sigma}.\frac{1}{M_{sR}.T_R} \\ \frac{M_{sR}}{T_R} & 0 & -\frac{1}{T_R} & \omega_R \\ 0 & \frac{M_{sR}}{T_R} & -\omega_R & -\frac{1}{T_R} \end{bmatrix}$$

$$\left[B\right]=\begin{bmatrix} \frac{1}{\sigma.T_s} & 0 \\ 0 & \frac{1}{\sigma.T_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \left[C\right]=\begin{bmatrix} 1\ 0\ 0\ 0 \\ 0\ 1\ 0\ 0 \end{bmatrix}$$

Where: $T_R=\frac{L_R}{R_R}$ -Stator time constant, $T_S=\frac{L_S}{R_S}$ -Rotor time constant

We implement the control methodology and the state observer using MATLAB/Simulink. Table 1 presents a comprehensive summary of the pertinent power and parameters for the induction motor.

Table 1. Parameters of the asynchronous motor used

Grandor	Symbole	Unit
Power Nominal	P_N	1.5 Kw
Resistance Rotor	R_R	3.805 Ω
Pairs Pole of Number	p	2
Speed Nominal	n_N	1420 t_r/min
Resistance Stator	R_s	4.85 Ω
Coefficient Inductance Stator	L_s	0.274 H
Coefficient Inductance Rotor	L_R	0.274 H
Coefficient Inductance Mutual	M_{SR}	0.258 H
Moment Inertia	j	0.031 kg.m^2
Coefficient Friction	f_r	0.00114 N.s/rad

The various controllers' synthesis

The reason for selecting indirect vector control for our simulations was its straightforward implementation and robust performance. We suggest utilizing a standard PI (Proportional-Integral) controller for every regulation loop. This controller has an integral part that gets rid of any static error between the regulated variable and the set point [13] and a proportional part that changes the speed of regulation [14]. To mitigate the amplification of noise, we refrain from employing derivative actions. We are contemplating the adoption of an IP controller, a modified version of the traditional PI controller.

The IP controller aims to eliminate the impact of the zero term in the numerator of the transfer function of the control loop. IP eliminates the zero term in the numerator of the transfer function of the control loop. This prevents the controlled process response from exceeding a certain limit [14].

- **PI speed controller**

The parameters (Kpw, Kiw) will define the outer speed regulation loop. We deduce the relationship between speed and electromagnetic torque from the equation that governs the mechanics of rotating bodies.

Fig.1. depicts the functional diagram of the speed regulation.

$$\frac{\omega}{\Gamma_{em} - C_R} = \frac{1}{(f_v + j.S)} \quad (2)$$

Fig.1 illustrates the functional diagram of the speed regulation.

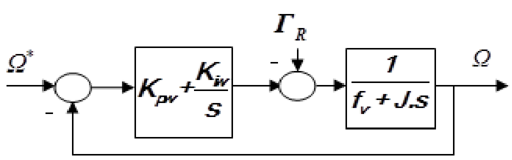

Fig.1. Outer speed regulation loop equipped with a PI controller for rotation speed

- **IP speed regulator**

Choosing an IP-type structure for rotation speed control, using a PI controller, resolves the issue of having a zero in the numerator, this results in a significant reduction in the magnitude of overshoot, as shown in Figure 2.

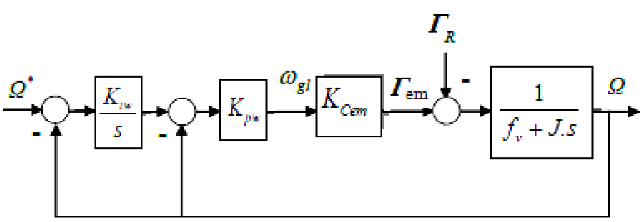

Fig.2. Outer speed regulation loop equipped with an IP structure for rotation speed control

Development of a fuzzy controller for the purpose of regulating speed

By observing the process, it becomes evident that the key factors for maintaining control are the speed error and its rate of change. Therefore, the fuzzy controller utilizes two distinct features, denoted as E and dE, as its inputs [15]. The reference torque value Γem* corresponds to the control signal increment applied to the process. A fuzzy PI controller, also referred to as a fuzzy PI [16–17], is a variant of a conventional PI controller. Figure 3 illustrates the configuration of the fuzzy controller. Figures 4 and 5 illustrate the internal configurations of RLF 3 and RLF 5, respectively.

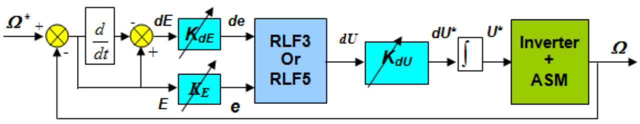

Fig.3. Fuzzy PI Controller Structure

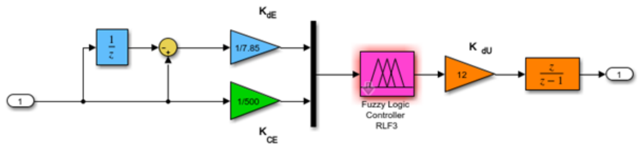

Fig.4 Internal structure of the RLF 3 regulator

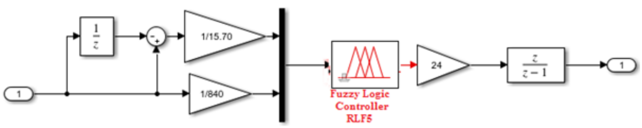

Fig.5 Internal structure of the RLF 5 regulator

The fuzzy controller's inputs at time step k are defined as:

$$E(k) = \omega^{*}(k) - \omega(k) \quad (3)$$

$$dE(k) = E(k) - .E(k-1) \quad (4)$$

The control signal is calculated through the relationship:

$$u^{*}(k) = u^{*}(k-1) + du^{*}(k) = \Gamma_{em}^{*}(k) \quad (5)$$

The fuzzy controller generates a control command *u*(k)* at every sampling period based on the two inputs *E(k)* and *dE(k)*.

- **Fuzzy controller with RLF3 and RLF5**

After conducting the trials, we included 5 fuzzy subsets (RLF3) and 3 fuzzy subsets (RLF3) in the universe of the fuzzy controller. Optimal triangular and trapezoidal membership functions (Fig. 6, 7)

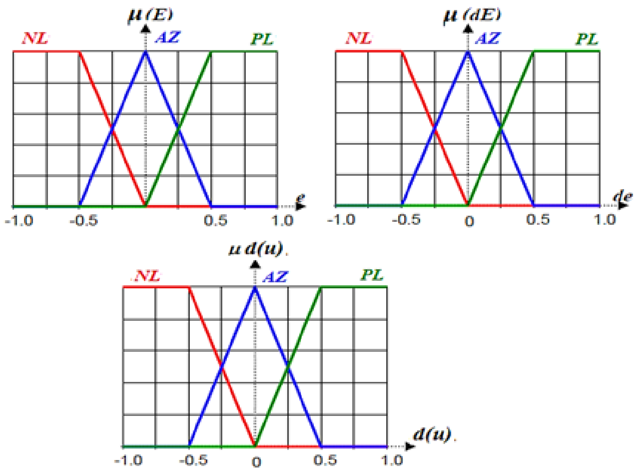

Fig. 6. Belonging functions for RLF3 controller inputs e, de or output.

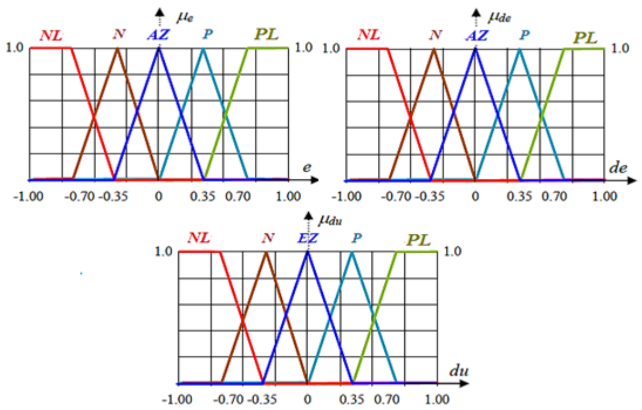

Fig. 7. Belonging functions for RLF5 controller inputs e, de or output.

Tables 2 and 3 show how the fuzzy regulators RLF3 and RLF5 work and what results they get. They give a full picture of the inference matrix

Table 2. RLF3 Inference Matrix

dE \ E	NL	AZ	PL
NL	NL	NL	AZ
AZ	NL	AZ	PL
PL	AZ	PL	PL

Table 3. RLF5 Inference Matrix

dE \ E	NL	N	AZ	P	PL
NL	NL	NL	N	N	AZ
N	NL	N	N	AZ	PL
AZ	NL	N	AZ	P	PL
P	NL	AZ	P	P	PL
PL	AZ	P	P	PL	PL

The three-dimensional image in Fig.8 shows the function du = f (e, de) in normalized coordinates for RLF3 (Fig. 8.a) and RLF5 (Fig.8.b). This shows how the controller causes the function to not be linear.

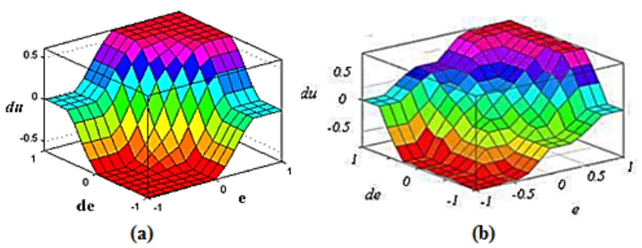

Fig.8.Characteristic surface of the RLF3 and RLF5 fuzzy controllers

Results and discussion

Fig. 9 shows indirect vector control for 3 phase AC motor speed regulation. Ziegler-Nichols method used to determine controller values for precise motor speed control (Table 4).

Table 4. Controller parameter values

Speed controllers	K_{pw}=0.775	K_{iw}=4.33
Contrôleurs de courant (i_{ds} and i_{qs})	K_{pd} =K_{pq}=24.05	K_{id} =K_{iq}=26775
Speed controllers with IP structure	K_{pw}=4.08	K_{iw}=33.65

Fig.9 depicts the implementation of indirect vector control for regulating the speed of a 3-phase AC motor. We employed the Ziegler-Nichols method to determine controller values for accurately regulating the motor speed (Table 4).

The simulations simulated a system comprising a motor and inverter, employing different controllers, namely RLF3 and RLF5. The objective was to evaluate their performance and behavior relative to the PI and IP controllers.

The simulated scenarios encompassed the initiation of the system without any load, the initiation of the system with the nominal load accompanied by sudden fluctuations, and the initiation of the system with load and changes in direction. This facilitated the examination and evaluation of the reactions in terms of both velocity and rotational force for the asynchronous motor.

Fig.10 depicts the outcomes of the RLF3 and RLF5 controllers in comparison to the conventional PI and IP controllers.

The speed curve of the asynchronous motor demonstrates that fuzzy controllers, when appropriately adjusted, can replicate the characteristic behaviors of PI and IP controllers. The plots demonstrate the remarkable response of the fuzzy controllers to vector control, specifically in decoupling torque and flow. The parameters examined exhibit a remarkably similar progression to the reference speed. This illustrates the potential of fuzzy controllers to deliver comparable outcomes while offering greater adaptability to accommodate diverse system dynamics.

The pictures numbered Fig.11 through Fig. 15 show zoomed-in views of how the speed controllers in the [motor + vector control] system we're looking at affect the system's speed. By analyzing the data presented in Figures 11 to 15, we can draw the following conclusions:

The RLF5 controller, equipped with five fuzzy subsets, demonstrates the highest speed during startup, as illustrated in Figures 11, 12, and 14. Nevertheless, the PI controller exhibits a slower response compared to the IP controller in this specific region.

RLF3 and IP reach the RLF5 controller after approximately 0.05 seconds. At the end of the transient period, the RLF3 controller outperforms the other two controllers, which subsequently demonstrate comparable progressions.

Figures 13 and 15 demonstrate the load disturbance rejection capabilities using magnified plots. The proposed fuzzy RLF3 controller and the integral-proportional (IP) controller behave similarly when the load torque changes in discrete steps. The length of the transient response and the size of the speed deviation demonstrate this similarity. Both controllers demonstrate comparable settling times following the introduction and elimination of disruptive load torques, with the ability to restore the desired speed within 0.05 seconds.

In addition, the magnified perspectives emphasize the resemblances in load impact and release between the IP and RLF3 techniques.

The suggested fuzzy logic RLF5 controller outperforms the typical PI controller by effectively disregarding disturbances and promptly restoring the motor speed to the reference value. The RLF5 controller outperforms the typical PI controller by effectively disregarding disturbances and promptly restoring the motor speed to the reference value. The PI controller speed shows notable fluctuations and extended transients when subjected to step changes in load torque. In contrast, the RLF5 fuzzy controller achieves

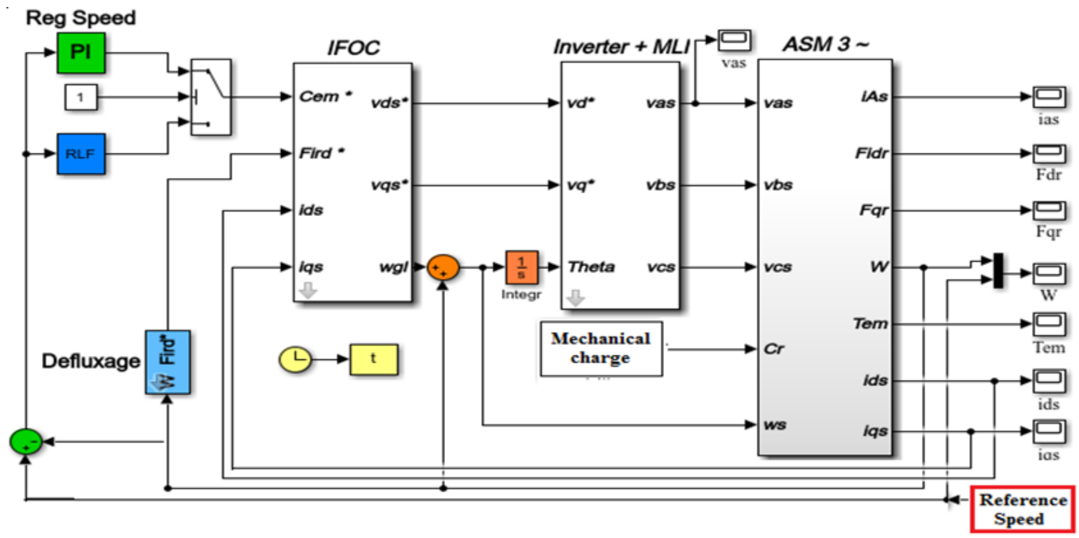

Fig.9. Block diagram of an indirect vector control for an asynchronous motor

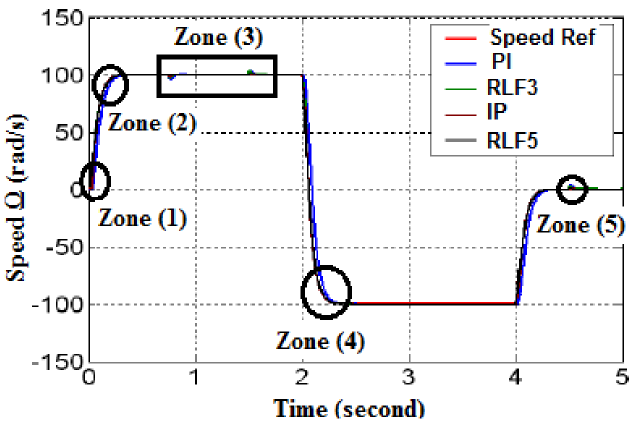

Fig.10. The different responses of the system for each controller (PI, IP, RLF3 and RLF5)

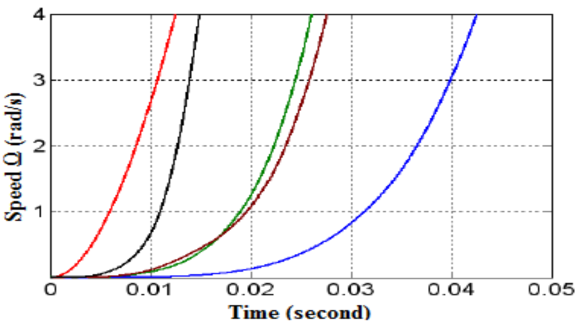

Fig. 11 . Zone (1) Zoomed

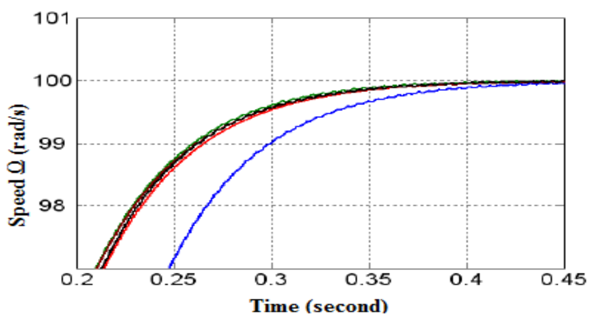

Fig. 12. Zone (2) Zoomed

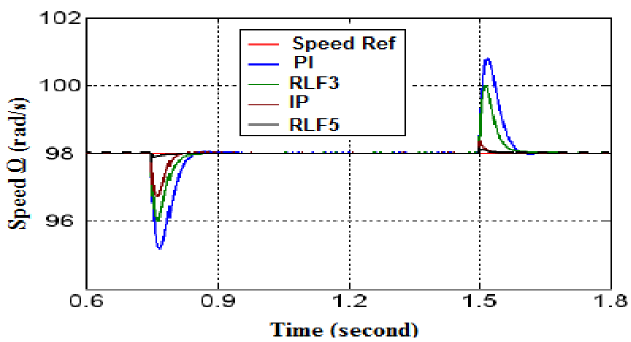

Fig.13. Zone (3) Zoomed

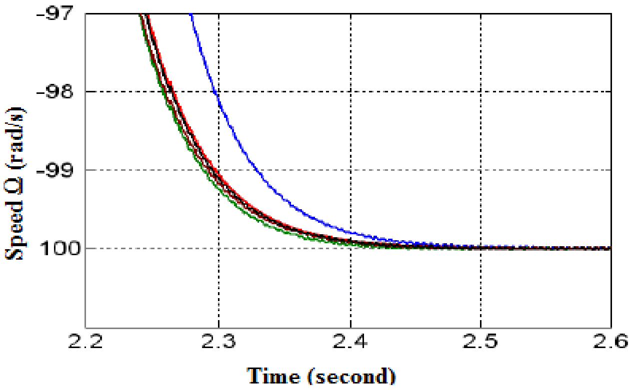

Fig.14. Zone (4) Zoomed

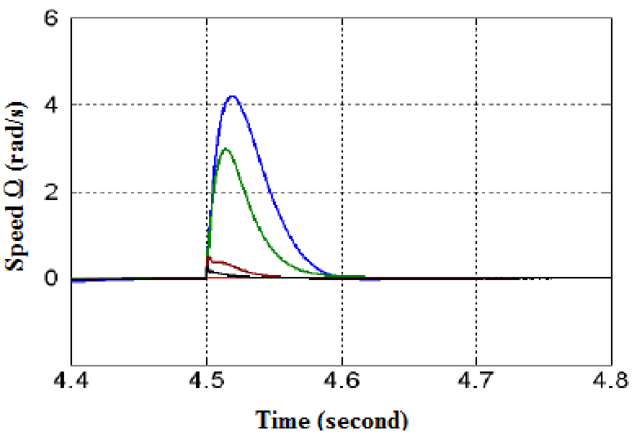

Fig.15. Zone (5) Zoomed

Conclusion

This study presents a method based on fuzzy logic for regulating the speed of three-phase asynchronous motors. Our simulations indicate that under ideal conditions, without any load or resistive torque, the performance of fuzzy controllers is comparable to that of traditional proportional-integral (PI) and integral-proportional (IP) controllers in terms of tracking and regulation. Nevertheless, the primary benefit of this innovative fuzzy method lies in its efficiency in managing shifts and fluctuations in crucial asynchronous motor parameters.

Fuzzy controllers, particularly the RLF5 and RLF3 architectures, exhibit superior performance in managing disturbances and demonstrating robustness compared to conventional PI controllers, which struggle with variations in rotor resistance and inertia torque.

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