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RESEARCH ARTICLE

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IMPLEMENTATION AND COMPARATIVE ANALYSIS OF A FUZZY LOGIC CONTROLLER FOR INDUCTION MOTOR VECTOR CONTROL

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ABSTRACT

Indirect vector control of induction motor (IM) drives operates on the principle of decoupling the stator current into independent torque and flux-producing components. This paper presents the implementation of a Fuzzy Logic Control (FLC) scheme for an IM, based on its dynamic d-q model. An intelligent Fuzzy Logic Controller is designed using a knowledge-based rule set to achieve robust and efficient drive control. The performance of the proposed FLC is rigorously compared against a conventional fixed-gain Proportional-Integral (PI) controller. Key performance metrics include settling time and the dynamic response to sudden load disturbances. Furthermore, the harmonic spectrum of the output current is evaluated for both control strategies. The steady-state performance of the IM drive is analyzed, and comparative results are presented to demonstrate the superiority of the fuzzy logic-based approach.

I. INTRODUCTION

For over a century, induction motors (IMs) have been a cornerstone of industrial electromechanical conversion due to their exceptional simplicity, rugged construction, and high efficiency. The invention of this asynchronous machine significantly propelled the transition from direct current (DC) to alternating current (AC) systems in the generation, transmission, and distribution of electrical energy. A primary advantage of the induction motor is the absence of sliding electrical contacts, which results in a robust and maintenance-friendly design[1]. Despite decades of research into efficient speed control methodologies for induction motors, solutions available until recent years remained unsatisfactory, often compromising on complexity, cost, efficiency, or dynamic performance.

The advancement of semiconductor technology over the past two decades has provided the necessary impetus, making static frequency converters economically viable and enabling widespread adoption of adjustable-speed drives for numerous applications. Control complexity presents a fundamental challenge. Separately excited DC drives benefit from independent control of flux and torque, leading to a relatively simple control structure [2]. In contrast, induction motors require the coordinated, nonlinear control of both the magnitude and phase of the stator current. This complexity can be mitigated through vector control, or field-oriented control (FOC). This technique resolves the stator flux linkages onto a rotating reference frame, effectively decoupling the flux and torque-producing components.

By requiring the instantaneous position of the flux linkages, FOC enables control of the AC induction motor that is analogous to the control of a separately excited DC motor. Conventional drive systems typically employ fixed-gain Proportional-Integral (PI) controllers .However, these controllers exhibit significant limitations, including sensitivity to parameter variations and poor disturbance rejection, often resulting in prolonged settling times following load transients. Consequently, numerous adaptive control techniques have been proposed to enhance robustness and performance[3]. In recent years, fuzzy logic control (FLC) has emerged as a powerful methodology for managing complex, nonlinear systems. Fuzzy set theory has fostered active and fruitful research, leading to its successful application in motor control.

Prior works present comprehensive surveys of FLC and describe general methodologies for its construction and performance assessment. Furthermore, discusses comprehensive procedures and guidelines for defining input parameters and constructing fuzzy logic rule bases. Additional methodologies for the design and theoretical analysis of FLCs are proposed in including explanations of the relationship between control resolution and the fuzzification of variables, as well as guidance for designing and tuning scaling gains[4]. In this context, the present paper proposes the design and implementation of an intelligent controller based on Fuzzy Logic for induction motor drives. The principal advantage of an FLC is its independence from a precise mathematical model of the plant; instead, it leverages a foundation of IF-THEN linguistic rules derived from expert knowledge and operational experience[5].

II. INDUCTION MOTOR MODELING

The dynamic analysis and modeling of rotating field machines are underpinned by well-established theoretical frameworks. This work considers a standard induction motor model characterized by a uniform air gap and a sinusoidally distributed magnetomotive force (mmf). For analytical simplicity, the effects of magnetic saturation and variations in machine parameters are neglected.The dynamic model of the induction motor is developed using a reference frame transformation. The three-phase electrical quantities (abc-frame) are transformed into an equivalent two-phase system within a direct and quadrature (d-q) rotating reference frame. This transformation is derived based on the principle of power invariance, which necessitates that the total power calculated in the two-phase model must be identical to that of the original three-phase system.The magnetomotive forces (mmfs) along the d and q axes are obtained by mathematically resolving the mmfs of the three stator phases onto these orthogonal axes. The formal mathematical relationship governing the transformation between the d-q axes currents and the a-b-c phase currents is given as follows:

$$i_{ds} = \frac{2}{3} V_d \left(i_{as} - \frac{i_{bs}}{2} - \frac{i_{cs}}{2} \right) \tag{1}$$

$$i_{qs} = \frac{1}{\sqrt{3}} \left(i_{cs} - i_{bs} \right) \tag{2}$$

Where ias, ibs and ics are the three phase currents and Vd is the dc link voltage at the inverter input. These equations are also applicable to the voltage and flux linkage transformation Applying this transformation to the three phase quantities . The electrical model of the induction motor is expressed by the matrix equation (3) in stationary reference frame.

$$\begin{pmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{pmatrix} = \begin{pmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_r & R_r + L_r p \end{pmatrix} \begin{pmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{pmatrix} \tag{3}$$

Where vds, vqs, ids, iqs Rs, Ls, Rr, Lr, Lm and θr are the d-q axes voltages and currents, stator resistance, stator inductance, rotor resistance, rotor inductance, mutual inductance betweenthe stator and rotor windings and the rotor position respectively. The stator and rotor flux linkages in the synchronous reference frames are defined as:

$$\begin{aligned} \varPhi_s &= L_s \bar{I}_s + L_m \bar{I}_r \\ \varPhi_r &= L_r \bar{I}_r + L_m \bar{I}_s \end{aligned} \tag{4}$$

Where $\Psi_{s,}\Psi_r, I_s$ and I_r are the stator and rotor flux-linkage Space vector and the stator and rotor current space vector, all in stationary reference frame. The electromagnetic torque obtained from machine flux linkages and currents is as:

$$T_e = \frac{3}{2} \frac{P}{2} L_m \left(i_{qs} \varPhi_{dr} - i_{ds} \varPhi_{qr} \right) \tag{5}$$

Where Te, P, Φdr, Φqr are the electromagnetic torque, number of poles, rotor d-q axes fluxes respectively. The Electromagnetic dynamic equation describing the mechanical model of the induction motor is given by:

$$T_e = J \frac{\omega_n}{dt} + T_l + B\omega_n \tag{6}$$

Where J, T1, B, ωm are the moment of inertia of motor and Load , the load torque, the friction coefficient and the mechanical speed. The equations (3) and (6) form the mathematical model equations of a three phase induction motor.

II.1 INDIRECT VECTOR CONTROL

The structure of the indirect vector control method is illustrated in Figure 1. In contrast to the direct vector control approach, this method operates as a feedforward control scheme, as it relies on the indirect estimation of the slip speed for field orientation

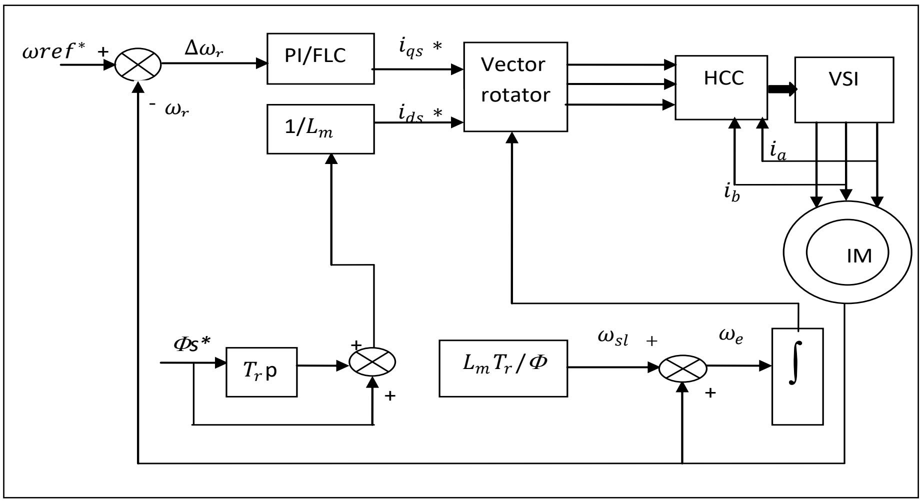

Figure 1: Indirect Vector Control Scheme.
Source: Authors, (2026).

The speed error, with the help of a PI controller or any other intelligent controller, is converted into a torque controlling current component iqs*, of the stator current. This current component t is used to regulate the torque along with the slip speed

$$i^*_{qs} = k_p\Delta\omega_r + k_i\int \Delta\omega_r dt \tag{7}$$

Similarly the flux producing current component ids*, is obtained from the stator flux linkage reference value and is given by the following equation:

$$\Phi_s^* = \frac{R_r L_m}{R_r + Lp} i_{ds}^* \tag{8}$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\Phi_s^* i_{qs}^* \tag{9}$$

$$\omega_{sl} = \omega_e - \omega_r = \frac{R_r}{L_r}\frac{i_{qs}^*}{i_{ds}^*} \tag{10}$$

The slip speed, together with the feedback rotor speed, is integrated to obtain the stator reference flux linkage space vector position θe.

$$O_e = \int(\omega_{sl} + \omega_r)dt \tag{11}$$

The position of the stator flux space vector is utilized to transform the two-phase direct and quadrature (d-q) axis current components back into three-phase quantities. These transformed currents serve as the reference command signals. The actual three-phase currents measured from the induction motor are continuously compared against these reference values. The resulting current errors are processed by two-level hysteresis band controllers. The hysteresis controllers regulate the motor currents by constraining them within a predefined hysteresis band. This control strategy ensures the machine achieves its required dynamic performance. Furthermore, the flux reference is maintained constant at its rated value for operation up to the base speed of the motor.

III. FUZZY LOGIC CONTROLLER

Fuzzy Logic implementation requires no exact knowledge of A model. The block diagram implementation of a FLC is shown in Figure 2. It involves the use of the concept of fuzzy subset and rule based modeling. By permitting certain amount of imprecision, complex solutions are modeled with ease[6].

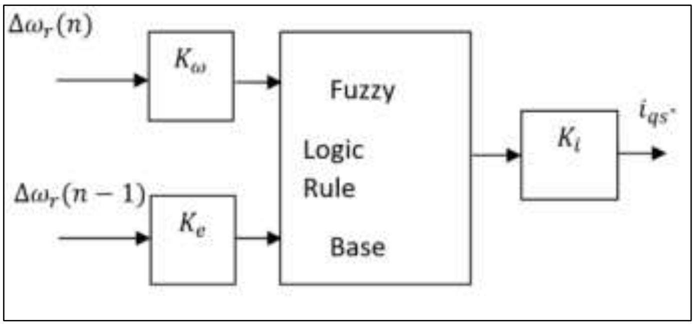

Figure 2: Fuzzy Logic Based Controller block.
Source: Authors, (2026).

III. 1 CONCEPT OF FUZZY LOGIC

The idea of formulating the control algorithms by logical rules introduced the implementation of human understanding and human thinking in control algorithms. The lack of analytical description makes the fuzzy control conceptually different from conventional control [7-9]. One defines a subset with the aid of a characteristic function which describes membership in the subset. Let X be the universe of discourse and let S b e a subset of X. The characteristic function associated with S is a mapping

$$f_s : X \to \{0,1\} \tag{12}$$

In the framework of fuzzy set theory the characteristic function is called the membership function associated with the fuzzy subset A. A fuzzy logic controller is describe d by a knowledge-based system consisting of IF. THEN rules with vague predicates and a fuzzy logic inference mechanism. The present fuzzy logic controller adopted is of the Mamdani Controller type[10].The speed error and the change in the speed error are given as inputs to the FLC. The torque producing current component t is the output. A knowledge rule base which simulates the performance of the system is defined. The rule base acts upon the inputs to produce the given outputs.

III. 2 CONCEPT MEMBERSHIP FUNCTION

The Fuzzy Logic Controller initially converts the crisp error and change in error variables into fuzzy variables and then are mapped into linguistic labels. Membership functions are associated with each label consists of two inputs and one output. The linguistic labels are divided into seven groups. They are:NH-negative high, N-Negative, NL-negative low, Z-zero, PL-positive low, P-positive, PH-positive high. Each of the Inputs and the output contain membership functions with all these seven linguistics. This method of formulation of control algorithms allows implementing heuristic strategies [11-14]. A straightforward source of deriving the linguistic control strategies are human experience and understanding, which essentially contain the model of the control system in an implicit form.

III. 3 CONCEPT KNOWLEDGE RULE BASE

The mapping of the fuzzy inputs into the required output is derived with the help of a rule base as given in Table 1. Each rule of the FLC is characterized with an IF part, called the antecedent, and with a THEN part called the consequent. The antecedent of a rule contains a set of conditions and the consequent contains a conclusion. If the conditions of the antecedents are satisfied, then the conclusions of the consequent apply. Considering the first rule, it can be interpreted as: IF change in speed error is NH and change is speed is NH, THEN the output will be NH.

Table 1: Knowledge Rule Base.

E CE	NH	N	NL	Z	PL	P	PH
NH	NH	NH	NH	NH	NL	NL	Z
N	NH	NH	N	N	N	Z	PL
NL	NH	N	NL	NL	Z	PL	P
Z	NH	N	NL	Z	PL	P	PH
PL	N	NL	Z	PL	PL	P	PH
P	NL	Z	PL	P	P	PH	PH
PH	Z	PL	P	PH	PH	PH	PH

Source: Authors, (2026).

III. 4 DEFUZZIFICATION

Generally the output obtained is fuzzy in nature and has to be Converted into a crisp value by using any Defuzzification technique.

IV. RESULTS AND DISCUSSIONS

In the following, we will present the results of the essential parameters of our machine, we will be particularly interested in the currents of the machine as well as the torque and the speed to highlight the efficiency of our fuzzy controller compared to a classic PI controller. The current response of the machine for both case i.e. PI and FLC is presented in the Fig.3 and Fig.4

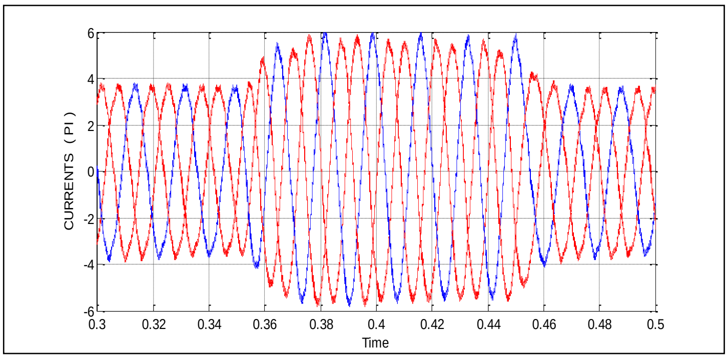

Figure 3: Stator currents response for PI.
Source: Authors, (2026).

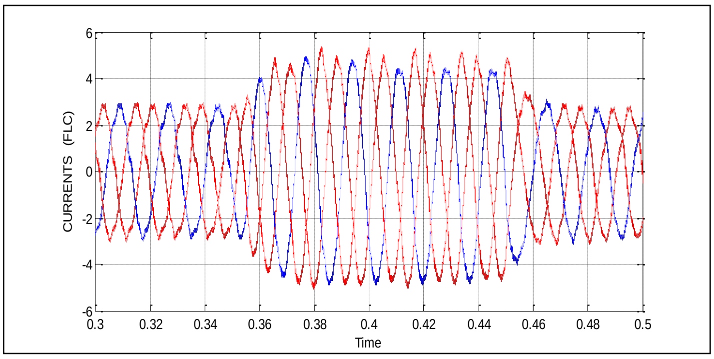

Figure 4: Stator currents response for FLC.
Source: Authors, (2026).

Figure 3, 4 presents a comparative analysis of the machine's current response under both Proportional-Integral (PI) and Fuzzy Logic Control (FLC) schemes. The graphical results clearly indicate that the FLC strategy exhibits significantly greater robustness to load disturbances compared to the conventional PI controller. The torque response for both cases of classical controllers is shown simultaneously in Figure 5.

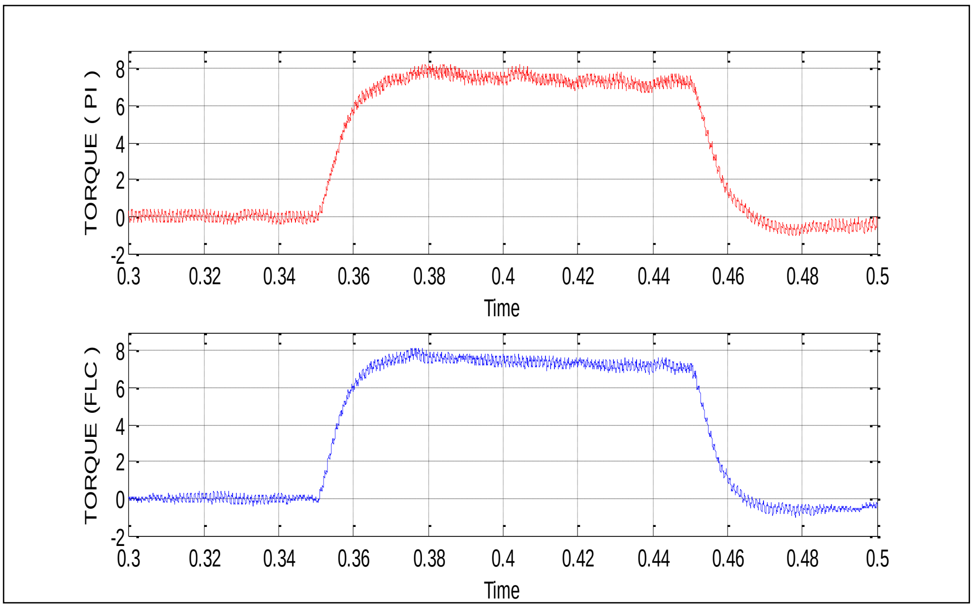

Figure 5: Torque response for PI and FLC.
Source: Authors, (2026).

The waveform indicates that the Fuzzy Logic Controller (FLC) achieves a significant reduction in current ripple and a markedly quicker dynamic response to load transients compared to the PI controller. Figure 6 (a,b) shows the speed response for both PI and fuzzy controllers.

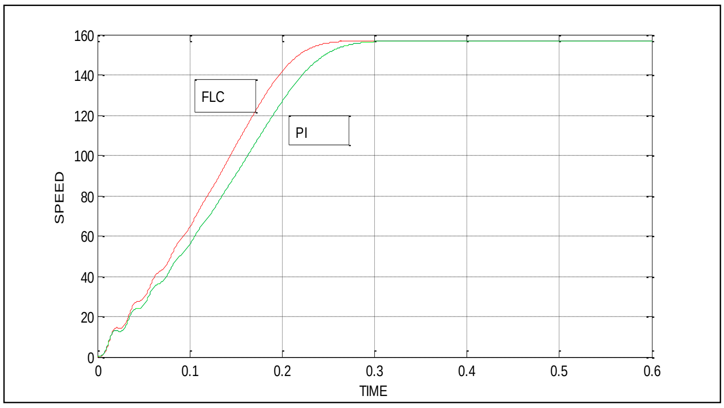

Figure 6 (a): Speed response for PI and FLC.
Source: Authors, (2026).

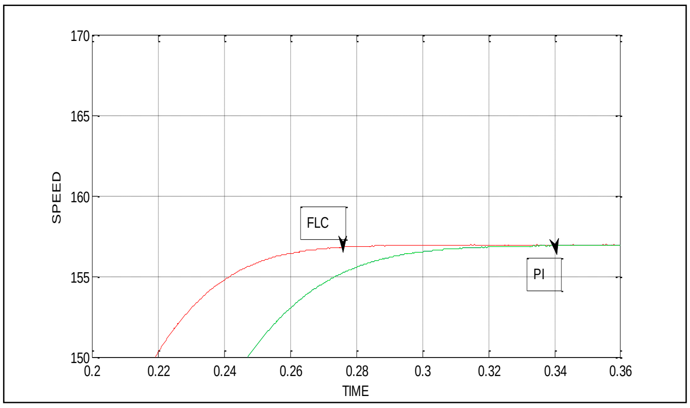

Figure 6 (b): Speed response for FLC (0.275sec) and PI(0.34sec).
Source: Authors, (2026).

When a load is applied at 0.35 sec the speed response for Both controller are as shown in Fig.6 (c),

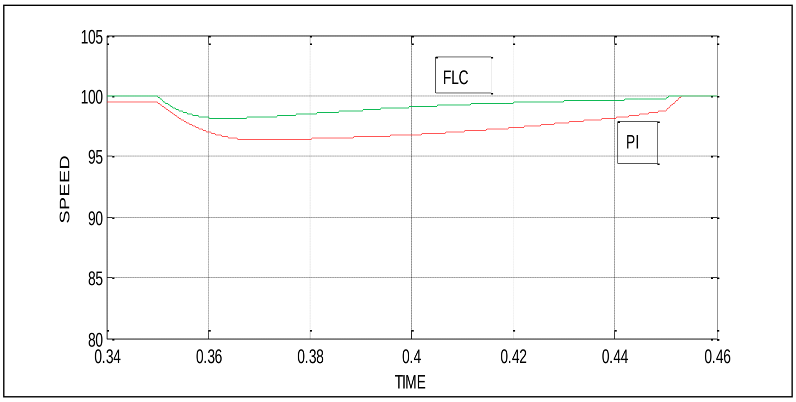

Figure 6 (c): Speed response for FLC and PI with andWithout load impact .
Source: Authors, (2026).

The dynamic response to a load torque application at t = 0.35 s is detailed in Fig. 6(c). This analysis confirms that the FLC strategy results in a smaller speed deviation and a quicker recovery compared to the PI controller.

V. CONCLUSIONS

This paper presents the implementation of a Fuzzy Logic Controller (FLC) for an indirect vector-controlled induction motor drive. The drive system was simulated using both a conventional Proportional-Integral (PI) controller and the proposed FLC to facilitate a comparative analysis. The performance of both controllers was evaluated and compared under dynamic operating conditions. Simulation results demonstrate that the FLC-based strategy achieves a significantly faster settling time and superior overall performance compared to the PI controller.

VI. AUTHOR’S CONTRIBUTION

Conceptualization: Salim Mahdab and Mohamed Fekir.
Methodology: Salim Mahdab.
Investigation: Salim Mahdab and Mohamed Fekir.
Discussion of results: Salim Mahdab.
Writing – Original Draft: Salim Mahdab.
Writing – Review and Editing: Salim Mahdab and Mohamed Fekir.
Resources: Salim Mahdab.
Supervision: Author Salim Mahdab.
Approval of the final text: Author Salim Mahdab and Mohamed Fekir.

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APPENDIX

The parameters of 3 phase Induction Motor, in SI units are:

P = 1.5kW,
Rs = 4.85Ω,
Rr = 3.805Ω
Ls = 0.274H,
Lr = 0.274H,
Lm = 0.258H
J = 0.031kg.m2,
f = 0.001136Nm/rd/s