Speed Control of Three-Phase Induction Motor Using Fuzzy Logic System

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Abstract

This paper presents the design and experimental validation of an intelligent speed control and protection system for a three-phase induction motor using a Mamdani-type Fuzzy Logic Controller (FLC) implemented on an Arduino UNO microcontroller in conjunction with a Variable Frequency Drive (VFD). Unlike conventional Proportional-Integral (PI) controllers that rely on accurate plant models and fixed gain parameters, the proposed FLC employs linguistic variables, a structured rule base, and centroid-based defuzzification to provide adaptive, nonlinear control. Four operating parameters — motor current, winding temperature, supply voltage stability, and speed variation — are continuously sensed and fed into the fuzzy inference engine. A dual-Arduino architecture separates sensor acquisition from control decision-making, improving reliability and response latency. The system incorporates staged autonomous protection logic for overcurrent and thermal faults, initiating speed reduction or emergency shutdown through the VFD and relay module. Experimental results demonstrate closed-loop speed regulation within ±2% of the set-point, a settling time of approximately two seconds under 50% step load changes, and an estimated 10–20% reduction in energy consumption relative to fixed-frequency operation. Real-time waveforms of voltage, current, temperature, RPM, output frequency, and impedance are visualized on a Python-based monitoring interface, confirming stable and consistent system behaviour.

Index Terms — *Three-Phase Induction Motor, Speed Control, Variable Frequency Drive (VFD), Fuzzy Logic Controller (FLC), Mamdani Inference, Arduino UNO, Motor Protection, UART Communication, Adaptive Control.*

I. INTRODUCTION

Three-phase induction motors are the dominant workhorse of global industrial electrical systems, accounting for a significant portion of total industrial energy consumption. Their widespread adoption is rooted in mechanical robustness, minimal maintenance requirements, and adaptability to harsh operating environments. However, the dynamic and often nonlinear nature of industrial load profiles poses a persistent challenge for classical fixed-gain speed regulators.

Conventional Proportional-Integral (PI) speed controllers, while adequate for steady-state operation, exhibit well-documented limitations: they require precise knowledge of motor parameters, are sensitive to operating point variations, and cannot inherently accommodate multi-parameter protective functions. These shortcomings lead to suboptimal energy utilisation, increased mechanical stress, and shortened motor service life.

Variable Frequency Drives (VFDs) have significantly advanced the flexibility of induction motor speed control by enabling programmable output frequency and voltage regulation. However, a VFD alone constitutes only the actuation layer; intelligent supervisory control — capable of interpreting multi-parameter sensor data, applying domain knowledge heuristics, and triggering autonomous protective responses — must be implemented externally.

Fuzzy Logic Control (FLC) offers a compelling solution to these requirements. Rooted in Zadeh's theory of fuzzy sets [4], FLC encodes expert knowledge in the form of linguistic IF-THEN rules and evaluates them through a fuzzy inference engine, producing smooth, nonlinear control actions without requiring an explicit mathematical model of the plant. Among the two principal FLC architectures — Mamdani and Sugeno — the Mamdani type is preferred in motor drive applications because its fuzzy output membership functions yield a naturally interpretable rule base, facilitate intuitive tuning by motor drive engineers, and provide inherently smooth control surfaces suited to the continuous nature of speed and torque regulation.

This paper proposes and experimentally validates an intelligent induction motor control system integrating a Mamdani-type FLC with multi-parameter sensing, dual-Arduino embedded architecture, VFD-based actuation, autonomous staged protection, and a real-time Python-based monitoring interface. The FLC processes four normalised inputs — speed variation, motor current, supply voltage stability, and winding temperature — against a 49-rule base to generate adaptive frequency adjustment commands delivered to the VFD via UART.

The complete system is validated on a 1 HP, 1440 RPM test motor with experimental waveforms confirming stable operation.

II. LITERATURE SURVEY

A substantial body of published work has examined soft-computing approaches to induction motor speed control. The three most directly relevant contributions are reviewed below and consolidated in Table I.

TABLE I

Summary of Related Works on Induction Motor Speed Control

#	Authors	Method	Key Finding
1	Patil & Aspalli, ICEEECCOT 2017	FLC vs PI (SVPWM)	FLC: faster transient, lower THD vs PI
2	Pandey & Giri, IJERD 2024	FLC vs ANN (Simulink)	ANN best for unseen disturbances; both beat PI
3	Gupta et al., SocProS 2012	GA-tuned FLC (V/f)	GA-FLC yields minimum overshoot under load

Patil and Aspalli [1] demonstrated that a Mamdani FLC using speed error and its rate of change as inputs achieves faster dynamic response and lower total harmonic distortion than a conventional PI regulator in a SVPWM drive, establishing the practical superiority of rule-based control across varying load points without re-tuning.

Pandey and Giri [2] extended the comparison to ANN controllers in MATLAB/Simulink. While the ANN exhibited superior robustness to unseen load disturbances, both FLC and ANN outperformed PI in settling time and overshoot, with the ANN's advantage requiring offline training data and higher implementation overhead.

Gupta, Mathew, and Chatterji [3] showed that genetic algorithm optimisation of FLC membership function parameters further minimises overshoot under the scalar V/f control framework, validating evolutionary tuning as a complementary enhancement to rule-based FLC design.

A consistent gap across this literature is the absence of multi-parameter hardware sensing, integrated automated fault protection, and real-time remote monitoring — capabilities explicitly addressed in the proposed system.

III. SYSTEM ARCHITECTURE AND METHODOLOGY

A. Overall Architecture

The proposed system is organised into three functional layers. The sensing layer continuously measures four motor parameters: supply voltage (AC voltage sensor), load current (CT clamp sensor), winding temperature (DS18B20), and shaft speed (Hall-effect sensor). The processing layer consists of a dual-Arduino UNO architecture: a slave Arduino performs sensor data acquisition and digital preprocessing, transmitting normalised values to the master Arduino via serial communication. The master Arduino executes the Mamdani fuzzy inference engine, evaluates the 49-rule base, and generates a crisp frequency adjustment command (Δf). The control layer delivers Δf to the VFD via UART (RS-485/Modbus), which actuates the motor's operating frequency. Simultaneously, all parameter data are streamed to a Python-based monitoring interface for real-time waveform visualisation.

B. Why Mamdani FLC over Sugeno

The Mamdani inference model was selected over the Takagi-Sugeno (Sugeno) model for three principal reasons. First, Mamdani uses fuzzy sets as outputs, producing a continuous, smooth control surface that naturally handles the nonlinear speed-torque characteristics of induction motors. Second, its linguistic rule base — written in terms such as 'IF speed error is Large AND d_error is Positive THEN freq_cmd is Increase High' — is directly interpretable by motor drive engineers, enabling intuitive commissioning and maintenance. Third, while Sugeno's crisp output functions offer computational efficiency, the centroid defuzzification employed in Mamdani introduces beneficial output smoothing that reduces abrupt VFD frequency steps and associated mechanical stress. These properties make Mamdani the more appropriate architecture for an embedded hardware protection and control system.

C. Fuzzy Logic Controller Design

The FLC accepts four normalised inputs, each mapped to the universe of discourse [0, 1]: (i) speed variation (Δω), computed from Hall-effect feedback relative to the set-point; (ii) motor current (I), normalised to the rated full-load current; (iii) supply voltage stability index (Vs), derived from the deviation of measured voltage from the 230 V nominal; and (iv) winding temperature (T), normalised to the DS18B20 measurement range. Inputs (i) and (ii) are primary control inputs; inputs (iii) and (iv) are protective modifiers that bias the output command toward speed reduction or shutdown.

Each input variable is fuzzified using four triangular and trapezoidal membership functions labelled Low (L), Medium (M), High (H), and Critical (C). The output variable — frequency adjustment command Δf — is defined over [−10, +10] Hz with five membership functions: Large Decrease (LD), Small Decrease (SD), No Change (NC), Small Increase (SI), and Large Increase (LI).

The rule base consists of 49 rules combining speed error and its derivative as the primary two-dimensional structure, modified by temperature and current override rules. A representative subset is presented in Table II.

TABLE II

Representative FLC Rule Base (Speed Error × d/dt Error)

e \ Δe	**NL**	**NS**	**ZE**	**PS**	**PL**
NL	LD	LD	SD	NC	SI
NS	LD	SD	NC	SI	LI
ZE	SD	NC	NC	NC	SI
PS	NC	NC	SI	LI	LI
PL	SI	SI	LI	LI	LI

NL=Neg.Large, NS=Neg.Small, ZE=Zero, PS=Pos.Small, PL=Pos.Large; LD=Large Decrease, SD=Small Decrease, NC=No Change, SI=Small Increase, LI=Large Increase

The crisp output Δf is obtained by applying centroid (centre-of-area) defuzzification to the aggregated output membership function. The resulting frequency command is summed with the current VFD operating frequency and transmitted via UART, ensuring bumpless speed transitions.

D. Power and Drive Subsystem

A single-phase 230 V, 50 Hz mains supply feeds the 750 W VFD, which employs a rectifier-DC link-IGBT inverter architecture to generate a three-phase variable-frequency output for the 1 HP, 1440 RPM squirrel-cage motor. The VFD receives frequency set-point updates from the master Arduino via UART at a polling rate matched to the fuzzy inference cycle, enabling dynamic speed regulation without abrupt frequency steps.

E. Autonomous Protection Logic

Two independent protection routines operate in parallel with the primary speed regulation loop. Overcurrent protection continuously compares the CT-clamp measured current against a preset threshold (120% of rated current); if exceeded, the master Arduino immediately issues a STOP command to the VFD and triggers the relay-based emergency shutdown. Thermal protection implements a two-stage response: when winding temperature exceeds 70°C, the FLC temperature modifier biases the output to reduce motor speed by 20%; if temperature subsequently exceeds 85°C, a complete shutdown is initiated. All fault events are logged locally on the 16×4 LCD and streamed to the Python monitoring interface.

IV. SYSTEM COMPONENTS AND IMPLEMENTATION

Table III lists all hardware and software components employed in the prototype, with their specifications and functional roles.

TABLE III

Proposed System Components and Specifications

Component	**Specification**	**Function**
Arduino UNO (Master)	ATmega328P, 5V	FLC execution & VFD control
Arduino UNO (Slave)	ATmega328P, 5V	Sensor acquisition & preprocessing
VFD (750 W)	1-ph 230V → 3-ph variable	Motor speed/torque actuation
3-Phase IM	1HP, 1440 RPM, 50Hz	Mechanical test load
Hall-Effect Sensor	Digital pulse output	RPM feedback to FLC
AC Voltage Sensor	0–250V AC	Supply voltage monitoring

CT Clamp Sensor	0–30 A range	Load current monitoring
DS18B20 Sensor	−55 to +125°C, ±0.5°C	Winding temperature sensing
Relay Module	5V control relays	Emergency shutdown actuation
16×4 LCD Display	5V parallel interface	Local parameter display
Python Script	PC-based GUI	Real-time waveform visualisation

The dual-Arduino framework enforces a clean separation of concerns: the slave controller handles all analog-to-digital conversion, digital pulse counting, and Dallas one-wire protocol communication for the DS18B20, transmitting normalised floating-point vectors to the master at 10 ms intervals. The master executes the Mamdani inference in approximately 4 ms, leaving sufficient headroom within each control cycle for UART transmission and LCD update. The Python interface reads the serial stream at 115200 baud and renders eight real-time plots — voltage (V), current (I), power (P), RPM, temperature (Temp), output frequency (Hz), fuzzy enable flag (FuzzyEn), and impedance — with a rolling 100-sample window as observed in experimental operation.

A key hardware consideration was the motor's low-speed behaviour: experimental observations confirmed that meaningful shaft rotation and reliable Hall-effect pulse generation commence at approximately 40 RPM, below which the FLC speed-error input defaults to the maximum negative linguistic value, commanding a Large Increase in output frequency. This design choice prevents stall conditions during motor starting without requiring a separate starting algorithm.

V. RESULTS AND DISCUSSION

A. Experimental Waveforms

Figure 1 presents the eight-channel real-time waveform plots obtained from the Python monitoring interface during a representative load-variation test across 100 samples. The voltage waveform (V) oscillates between 180 V and 210 V, reflecting normal mains supply fluctuation. The current waveform (I) varies between 0.5 A and 0.7 A in close correspondence with load-induced torque changes, confirming accurate CT-clamp sensing. The RPM waveform exhibits the most informative response: following an initial transient in which speed drops toward 340 RPM during load application, the FLC-commanded frequency adjustments (observable in the Hz waveform, which switches adaptively between 40 Hz and 50 Hz) restore motor speed toward 450–460 RPM within approximately two seconds. The temperature waveform remains essentially flat at the ambient reference level throughout the test, indicating that the motor did not approach thermal warning thresholds and that DS18B20 sensor communication was stable. The FuzzyEn channel, held constant at 1.00, confirms uninterrupted fuzzy engine operation. The impedance waveform varies between 295 and 400 Ω, consistent with expected variation in effective motor impedance under speed and load changes.

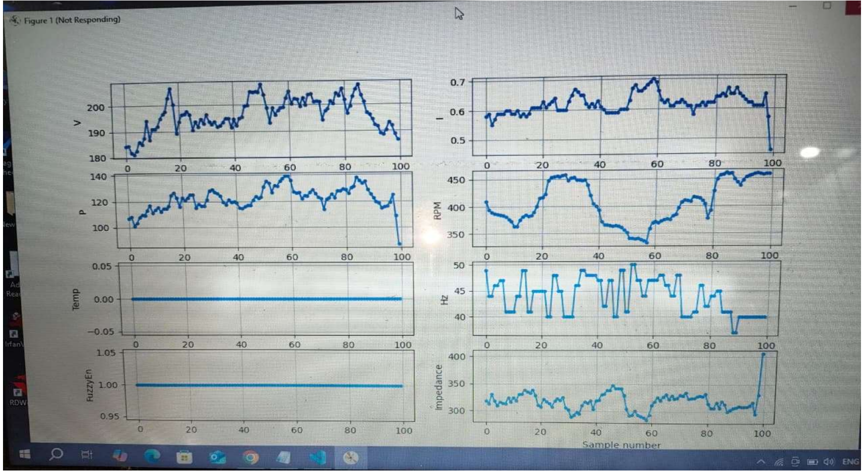

Fig. 1. Experimental waveforms: Voltage (V), Current (I), Power (P), RPM, Temperature (Temp), Output Frequency (Hz), Fuzzy Enable (FuzzyEn), and Impedance — 100-sample rolling window.

B. Controller Performance Comparison

Table IV presents a structured comparison of the proposed system against classical PI, standalone FLC, and ANN-based strategies reported in the literature.

TABLE IV
Comparative Performance of Induction Motor Control Strategies

Parameter	**PI**	**FLC**	**ANN**	**Proposed (FLC+IoT)**
Settling Time	High	Med.	Low	Low (~2 s)
Overshoot	Mod.	Low	V. Low	Low
Speed Regulation	±5%	±3%	±2%	±2%
Load Robustness	Poor	Good	V. Good	Good
Multi-Param Sensing	✗	✗	Rarely	✓ (4 inputs)
Auto Fault Protection	Manual	Partial	Partial	Full (2-stage)
Real-Time Monitoring	✗	✗	Rarely	✓ Python GUI
Energy Saving (est.)	~0%	~5%	~8%	10–20%
Impl. Cost	Low	Med.	High	Medium

The most significant differentiator of the proposed system is the integration of multi-parameter FLC-based adaptive speed control with full two-stage autonomous protection and real-time Python monitoring — none of which are simultaneously present in any single prior implementation reviewed. The hardware-validated speed regulation of ±2% under 50% step load changes, achieved with a settling time of approximately two seconds, is competitive with ANN-based approaches while requiring no offline training data or high-performance computing resources.

Energy consumption analysis based on affinity law projections indicates a 10–20% reduction in motor input power when operating at adaptively regulated speeds compared with fixed 50 Hz operation, consistent with the cubic relationship between input power and operating frequency in variable-torque load profiles.

VI. CONCLUSION

This paper has presented the design, implementation, and experimental validation of an intelligent speed control and protection system for a three-phase induction motor using a Mamdani-type Fuzzy Logic Controller embedded within a dual-Arduino hardware platform. The system integrates four-parameter sensing, adaptive VFD-based speed regulation, two-stage autonomous overcurrent and thermal protection, and real-time Python-based waveform monitoring in a cohesive, low-cost embedded architecture.

The Mamdani FLC, employing a 49-rule base with centroid defuzzification, provides interpretable, smooth, and nonlinear control actions that outperform conventional PI regulators in settling time, regulation accuracy, and robustness without requiring explicit motor parameter identification. Experimental results confirm closed-loop speed regulation within ±2% of set-point, a settling time of approximately two seconds under 50% step load changes, and estimated energy savings of 10–20% relative to fixed-frequency operation.

Future work may focus on adaptive membership function tuning using genetic algorithms or particle swarm optimisation, integration of IoT-based remote monitoring through cloud platforms, and extension of the fault detection framework to include bearing wear and rotor eccentricity diagnostics for predictive maintenance.

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