

Fuzzy Logic-Based Speed Control For Induction Motor Modeling

An Intelligent Approach to Enhancing Motor Efficiency and Performance

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Abstract:

This paper introduces a hybrid system controller that integrates a fuzzy logic controller with the vector-control method for induction motors. Instead of a conventional Proportional-Integral (PI) controller, the vector-control approach has been enhanced using a fuzzy logic controller. This hybrid controller leverages the advantages of both techniques—fuzzy logic ensures high-quality regulation, while vector control provides system stability during transient conditions and supports a broad operating range. The effectiveness of the hybrid controller has been evaluated through simulations. A comparative analysis between the proposed fuzzy logic controller and the traditional PI controller under both no-load and varying load conditions highlights its superior robustness and efficiency in achieving high-performance induction motor drive systems.

Index Terms - Indirect Vector Control, Fuzzy Logic Control, Adaptive Speed Control, Hybrid Motor Drive, Robust Control Techniques.

I. INTRODUCTION

In recent years, fuzzy control systems have gained significant traction in engineering applications. The widespread success of fuzzy control has led to increased research in the analysis and design of such systems. Ashok et al. introduced a fuzzy logic-based flexible multi-bus voltage control for power systems. Due to its ability to handle nonlinearities and its independence from plant modeling, fuzzy logic has garnered growing interest in motor control applications. The fuzzy logic controller (FLC) operates using a knowledge-based approach, relying on a set of linguistic "if-then" rules similar to human decision-making. Ramon et al. developed a rule-based fuzzy logic controller for scalar closed-loop induction motor control with slip regulation, comparing its performance with a traditional PI controller. Their work introduced a new linguistic rule table in the FLC to refine motor speed control.

The design and implementation of industrial control systems often depend on mathematical models of plants and controllers. However, in cases where controller design is complex and costly, observing expert operators to derive control rules becomes essential. In this regard, fuzzy logic plays a crucial role in controller development, as it eliminates the need for intricate hardware and relies on a defined set of rules. Induction motors, which can be controlled similarly to separately excited DC motors, have seen significant advancements in high-performance AC drive control, particularly with the introduction of vector control in the early 1970s. Due to its DC machine-like behavior, vector control is also referred to as decoupling control, orthogonal control, or transvector control. While vector control and its associated feedback processing—especially in modern sensorless vector control—are complex and require powerful microcontrollers or DSPs, this method is expected to replace scalar control and become the industry standard for AC drives.

PI controllers are widely utilized in industrial applications for plant control and generally provide satisfactory performance. However, in applications such as AC drive control, their performance may be insufficient. PI controllers cannot maintain an induction motor's speed precisely at the desired set point under disturbances or changes. As a result, advanced control strategies like fuzzy logic controllers are required to achieve superior performance. Today, fuzzy logic systems are applied across various academic and industrial domains,

including modeling, control, signal processing, and healthcare. One of the key applications of fuzzy logic is in developing innovative solutions for control challenges. This paper presents a fuzzy logic-based intelligent controller. Unlike conventional controllers that rely on complex mathematical models, FLCs utilize "IF-THEN" linguistic rules, as highlighted by Rajesh Kumar et al. (2008). This article first introduces the electrical and mechanical modeling of an induction motor, followed by an explanation of the indirect vector control block diagram. It then explores PI controllers, fuzzy logic controllers, and hybrid controllers before presenting the simulation results and discussions.

II. INDUCTION MOTOR MODELING

The electrical dynamics of an induction motor are described using a fourth-order state-space model, while its mechanical behavior is represented by a second-order system. All electrical parameters and variables are referenced to the stator. Additionally, both rotor and stator quantities are expressed in an arbitrary two-axis reference frame, as illustrated in Fig. 1.

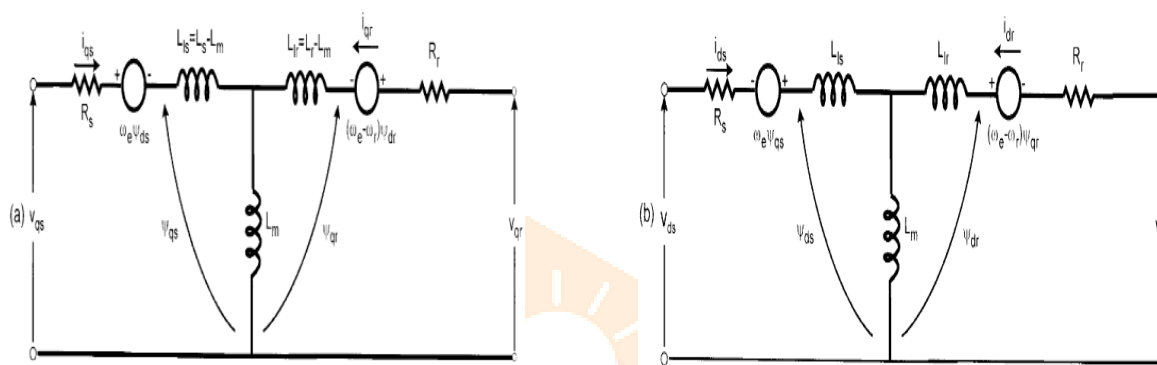


Fig 1: Stator and rotor in two-axis reference frame (a) q-axis, and (b) d-axis

III. CONTROL PRINCIPLE

In a vector-controlled drive system, the fuzzy logic controller (FLC) operates as illustrated in Fig. 1. The controller monitors the speed loop error signal and adjusts the output ΔU to ensure that the actual motor speed (ω_r) aligns with the reference speed (ω_r^*). The FLC receives two input signals: the speed error, defined as $E = \omega_r - \omega_r^*$, and the change in error (CE), which corresponds to the derivative dE/dt of the error signal. In a discrete system, this derivative is expressed as $dE/dt = \Delta E/\Delta t = CE/T_s$, where $CE = \Delta E$ within the sampling period T_s . Given a constant sampling time, CE is directly proportional to dE/dt . The controller's output ΔU in the vector-controlled drive corresponds to the variation in the quadrature-axis current reference Δi_{qs}^* . This output is then summed or integrated to generate the actual control signal U or the quadrature-axis current i_{qs}^* .

IV. HYBRID SPEED CONTROLLER

Hybrid Speed Controller

To leverage the advantages of both fuzzy logic (FL) and proportional-integral (PI) controllers, a hybrid controller known as the **Fuzzy Pre-compensated PI (FPPI) Controller** is implemented. In this approach, the FL controller is used for pre-compensation of the reference speed. This means that the reference speed signal (ω^*) is adjusted in advance based on the rotor speed (ω) to produce a modified reference speed signal ($\omega 1^*$). The primary control action is then carried out by the PI controller.

This hybrid strategy effectively mitigates common issues such as overshoot and undershoot observed in conventional PI controllers. It is particularly beneficial for applications where motor torque and speed fluctuate frequently. As per the standard approach, the FL controller receives two inputs: the speed error $e(n)^*$ and the change in speed error $\Delta e(n)$. The FL output is added to the reference speed to generate a pre-compensated reference speed δ , which serves as the input for the PI controller, as illustrated in Fig. 2.

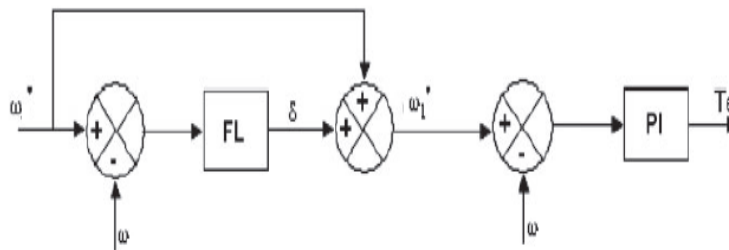


Fig.2 Hybrid Speed Controller

V. FUZZY LOGIC (FL) SPEED CONTROLLER

Fuzzy Logic (FL) Speed Controller

The PI speed controller, as discussed in the previous section, offers simple operation and ensures zero steady-state error under load conditions. However, it has several drawbacks, including overshoot during startup, undershoot when applying a load, and another overshoot upon load removal. Additionally, the PI controller relies on an accurate motor model for gain tuning and is highly sensitive to parameter variations and load disturbances. Its performance significantly deteriorates when applied to systems with considerable non-linearity.

To overcome these limitations, a **Fuzzy Logic (FL) Controller** is employed. Unlike PI controllers, the FL controller does not require an explicit drive model and is capable of handling non linearities of any complexity. The **Fuzzy Logic Controller (FLC)** consists of three main functional blocks, as illustrated in Fig. 3.

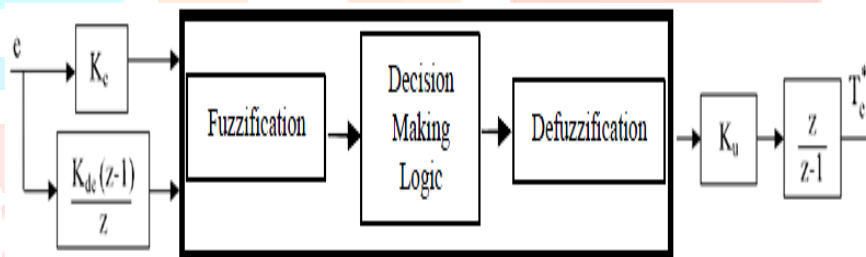


Fig.3 Fuzzy Logic Controller (FLC) Functional Block

VI. INDIRECT VECTOR CONTROL

Indirect Vector Control

The squirrel cage induction motor (IM) is analyzed using the **direct and quadrature axes (d-q) theory** in the stationary reference frame, which simplifies the analysis by reducing the number of required variables. The **block diagram of the indirect vector control technique** is shown in Fig. 4.

This control method utilizes **two control loops**:

1. **Internal Pulse Width Modulation (PWM) Current Control Loop**
2. **External Speed Control Loop**

The **induction motor** is powered by a **current-controlled PWM inverter**, which functions as a **three-phase sinusoidal current source**. The difference between the actual speed (ω) and the reference speed (ω^*)—denoted as $(\omega - \omega^*)$ —is processed by the speed controller to generate the *command torque* (T_e)* for precise motor control.

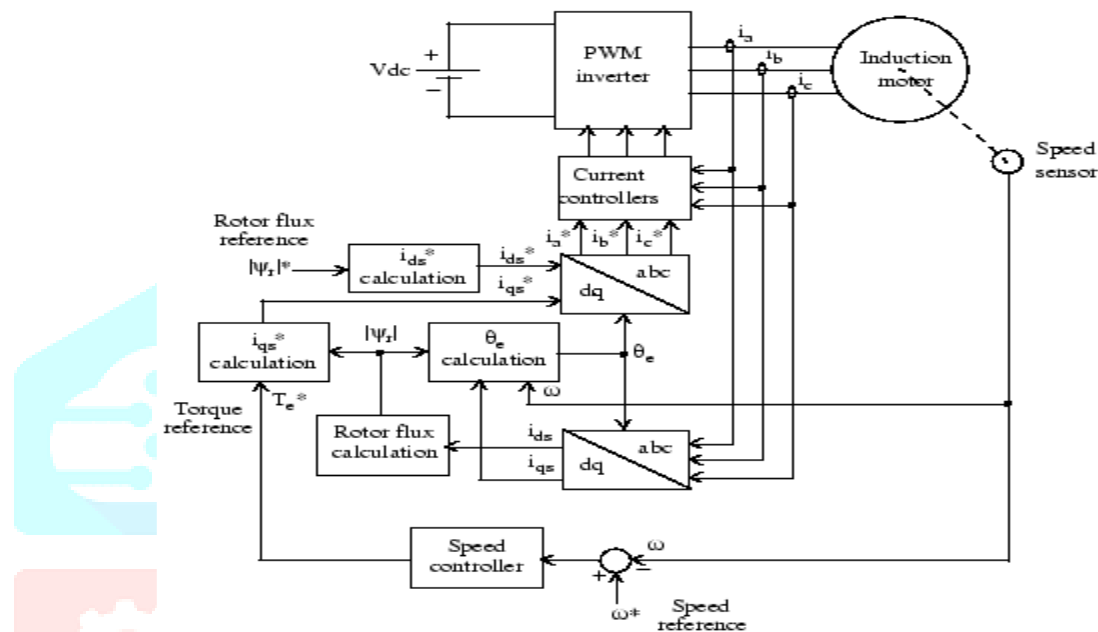


Fig 4: Block diagram of the indirect vector control technique

Fuzzy membership function

In the fuzzification block, the inputs and outputs crisp variables are converted into fuzzy variables 'e', 'de' and 'du' using the triangular membership function shown in Fig 5.

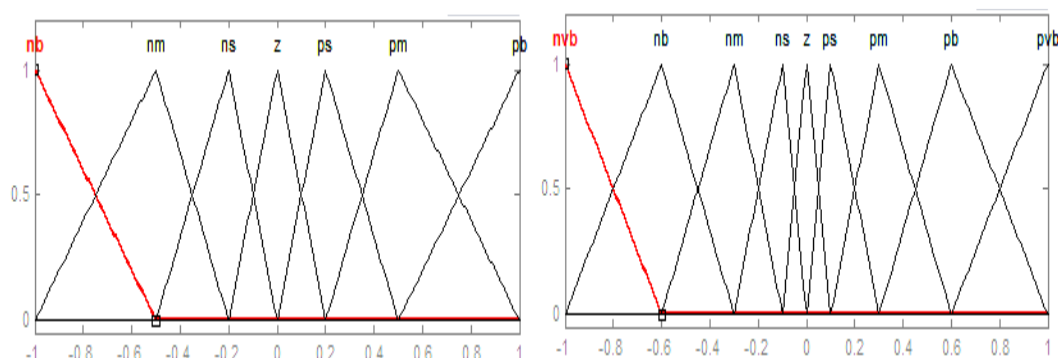


Fig 5: (a) Input membership functions, (b) Output membership function

VII. LINGUISTIC VARIABLES

The fuzzification block produces the fuzzy variables ‘e’ and ‘de’ using their crisp counterpart. These fuzzy variables are then processed by an inference mechanism based on a set of control rules contained in (7*7) table as shown in Table 3. {NVB (negative very big), NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), PB (positive big), PVB (positive very big)} (Y.Miloud et al, 2000). Shown in table.

De/e	NB	NM	NS	ZE	PS	PM	PB
NB	NVB	NVB	NVB	NB	NM	NS	ZE
NM	NVB	NVB	NB	NM	NS	ZE	PS
NS	NVB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PVB
PM	NS	ZE	PS	PM	PB	PVB	PVB
PB	ZE	PS	PM	PB	PVB	PVB	PVB

VIII. CONCLUSION

In this paper fuzzy logic controller for the control of an indirect vector-controlled induction motor was described. The drive system was simulated with fuzzy logic controller and PI controller and their performance was compared. Here simulation results shows that the designed fuzzy logic controller realises a good dynamic behaviour of the motor with a rapid settling time, no overshoot and has better performance than PI controller. Fuzzy logic control has more robust during change in load condition. The performance of PI and fuzzy controllers in speed control of IM drive are simulated. Hybridization of FL and PI controllers is done and used as a single controller by extracting the advantages present in FL and PI controllers.

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