Optimized Pi Control Of Induction Motor Using Fuzzy Logic: A Simulation Approach

Integrating Fuzzy Logic for Efficient Motor Speed and Torque Control

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Abstract:

Fuzzy control has been extensively utilized in industrial applications, particularly in scenarios where conventional control design techniques face challenges. One of the critical factors in real-time fuzzy control applications is the number of fuzzy rules, as it directly influences system efficiency and computational complexity. This study is driven by the growing industrial demand for highly reliable, efficient, and low-complexity controllers. The proposed fuzzy controller is designed using multiple fuzzy controllers with a reduced number of fuzzy rules, ensuring optimal control performance while maintaining simplicity. The effectiveness of the proposed fuzzy controller is analyzed and compared with that of conventional fuzzy controllers. Fuzzy logic control offers a robust solution by effectively handling errors in control operations, managing system nonlinearities, and demonstrating resilience to system parameter variations. The comparative analysis highlights the advantages of the proposed approach in enhancing system performance and reliability.

***Index Terms** - Fuzzy Logic Control, PI Controller, Induction Motor, Torque Optimization, Genetic Algorithm.*

I. Introduction

An **induction motor** is a type of electric motor that generates power through electromagnetic induction. It derives its name from its operating principle, where **alternating current (AC) voltages** are induced in the rotor circuit by the rotating magnetic field of the stator. Induction motors are primarily constructed using **copper, steel, and aluminum**, making them more expensive than universal motors but significantly enhancing their durability and performance.

The **design of an induction motor** closely resembles that of a **three-phase synchronous motor**. It consists of a **rotor**, typically a laminated cylindrical structure with slots for windings. These windings can be classified into three main types:

- **Squirrel-cage rotor**: Comprising copper bars running along the rotor length, connected at both ends by rings. The rotor bars are skewed rather than straight to minimize noise.
- **Slip-ring rotor**: Instead of bars, it contains windings connected to slip rings. When the slip rings are short-circuited, the rotor behaves similarly to a squirrel-cage rotor.
- **Solid-core rotor**: Made from solid steel, it generates the necessary current for rotation through induced electromagnetic energy.

An **induction motor**, also referred to as an **asynchronous motor**, operates by transferring electromagnetic energy via **inductive coupling** between the stator (primary winding) and the rotor (secondary winding), with an **air gap** separating the two. In **three-phase induction motors**, energy is transferred from the stator to either a **wound rotor** or a **short-circuited squirrel-cage rotor**, both of which are self-starting by design.

Due to their **ruggedness, reliability, and cost-effectiveness**, **three-phase squirrel cage induction motors** are widely used in industrial applications. **Single-phase induction motors** are also commonly employed for smaller loads. Traditionally, AC motors have been used for **fixed-speed applications**, but with advancements in technology, they are increasingly integrated into **variable-frequency drive (VFD) systems**. This is particularly beneficial for **variable-torque applications**, such as **centrifugal fans, pumps, and compressors**, where VFDs contribute significantly to energy savings. As a result, **squirrel cage induction motors** remain the most widely used choice for both **fixed-speed and VFD-driven applications** across various industries.

II. Equivalent Circuit

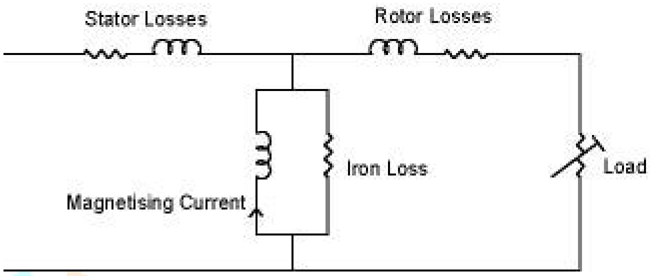

Fig.1 Circuit for Induction Motor

An **induction motor** can be analyzed similarly to a **transformer**, with its equivalent circuit consisting of various components. The **stator circuit** includes **leakage reactance, copper losses (resistance), iron loss, and magnetizing inductance**, where the iron loss and magnetizing elements function as **shunt components**. Similarly, the **rotor circuit** comprises **leakage reactance, rotor copper losses, and shaft power**, all treated as **series components**.

By adjusting the rotor parameters according to the **effective turns ratio**, the transformer element in the equivalent circuit can be eliminated, simplifying the analysis. From this equivalent circuit, it is evident that the **magnetizing current and iron loss** are **voltage-dependent** rather than **load-dependent**. Additionally, the **full-voltage starting current** of a motor is influenced by both **voltage and speed**, but remains **independent of load**.

The **magnetizing current** varies based on motor design. In **small motors**, it can be as high as **60%**, whereas in **large two-pole motors**, it typically falls within **20-25%**. At the **design voltage**, the iron core approaches **saturation**, leading to a **nonlinear increase** in **magnetizing current and iron loss** with small voltage increments. As a result, even minor voltage increases can cause a **significant rise in magnetizing current and iron loss**, i006Dpacting motor efficiency.

III. Genetic Algorithms

Genetic Algorithms (GAs) are adaptive search techniques inspired by **Darwin's principle of natural selection**, where only the fittest individuals survive and reproduce. In GAs, a population of candidate solutions is represented by **chromosomes**, each assigned a **fitness value** that determines its likelihood of survival and reproduction. The **evolutionary process** occurs over multiple iterations (or generations) and consists of four key operations:

1. **Selection** – Prioritizes individuals with higher fitness for reproduction, increasing their chances of passing on their genetic material.
2. **Reproduction** – Generates offspring based on selected parent chromosomes.
3. **Crossover** – Exchanges genetic characteristics between selected parents, producing new offspring with a mix of traits.
4. **Mutation** – Introduces random genetic variations in a small percentage of the population, enhancing diversity and preventing premature convergence.

The **evolutionary cycle** in GAs systematically directs the search process toward more promising regions within the solution space. GAs offer several advantages:

- **Global search capability**, making them effective for complex optimization problems.
- **Robustness**, as they do not require a precise mathematical formulation.
- **Applicability** to a wide range of optimization tasks, including ill-structured problems.
- **Efficiency**, often yielding near-optimal or optimal solutions within a reasonable time frame.

Due to these strengths, Genetic Algorithms have become widely used in fields such as **machine learning, engineering optimization, artificial intelligence, and industrial control systems**.

IV. Fuzzy Logic Control

A **Fuzzy Logic Control (FLC) system** mimics human reasoning by applying approximate rather than precise logic to decision-making. Unlike traditional control methods that require accurate mathematical models, **FLC operates on linguistic "if-then" rules**, similar to how a human operator would reason based on experience and intuition.

FLC has gained significant popularity in **motor control applications** due to its ability to handle **nonlinearities** and its independence from explicit plant modeling. The control process involves three main steps:

1. **Understanding and Characterizing System Behavior** – Using expert knowledge to define system responses.
2. **Designing the Control Algorithm** – Developing fuzzy rules that describe the relationship between inputs and outputs.
3. **Simulation and Debugging** – Testing the controller, modifying fuzzy rules, and refining performance iteratively.

Fuzzy Logic Controllers operate in a **knowledge-based** manner, where control decisions are derived from predefined **fuzzy linguistic rules** rather than exact mathematical equations. If the system's performance is unsatisfactory, adjustments can be made by **modifying fuzzy rules**, eliminating the need for complex reprogramming.

Due to its **flexibility, adaptability, and robustness**, FLC is widely used in **industrial automation, robotics, and motor drive systems**, offering a **more intuitive and efficient** approach to process control.

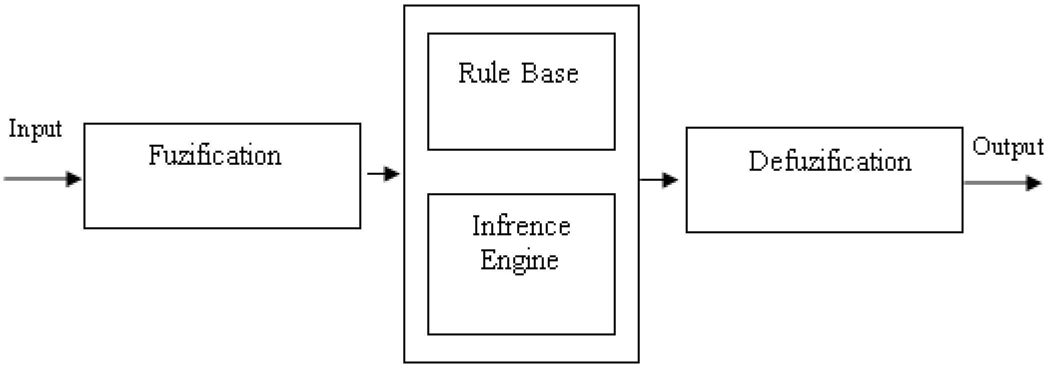

Fig.2: Fuzzy Logic Control system

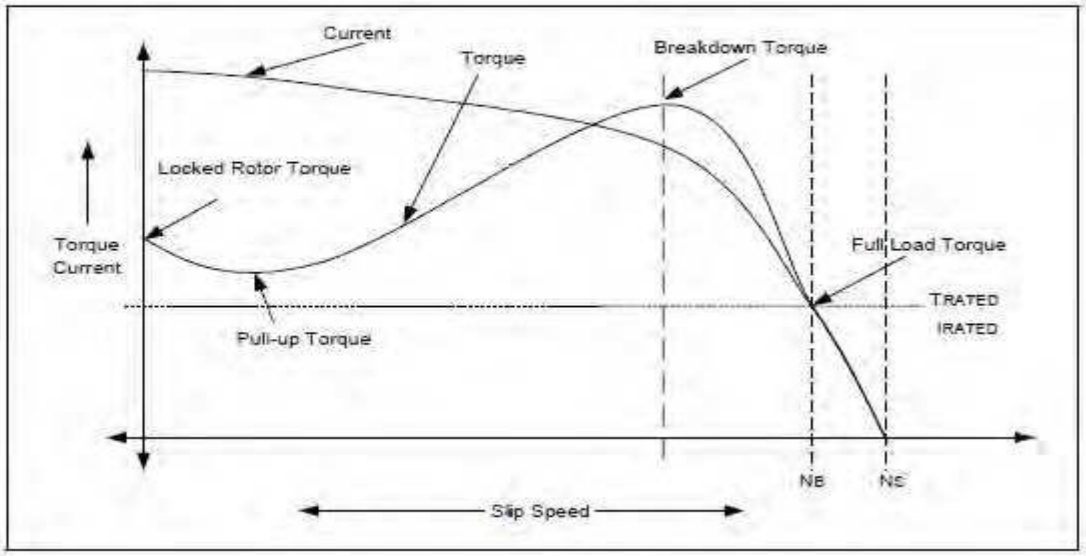

Fig 3. Speed vs Torque

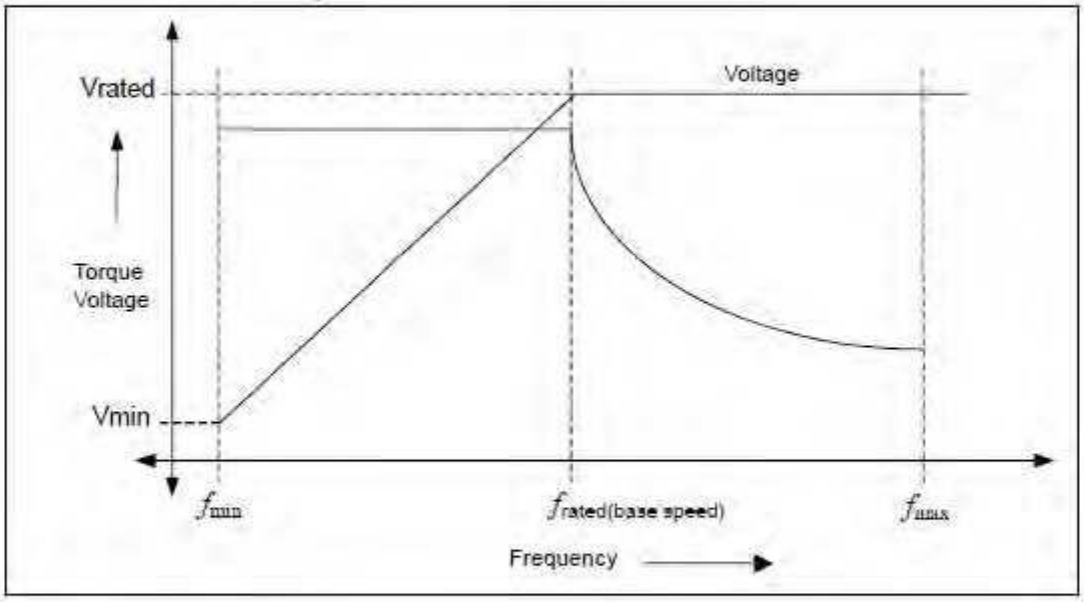

Fig 4. Frequency VS Torque Voltage

V. Speed-Torque Characteristics of an Induction Motor

Figure 3 illustrates the typical **speed-torque characteristics** of an **induction motor**, showing how the motor draws **rated current** and delivers **rated torque** at its base speed. The relationship governing the induction motor's operation is given by:

Stator Voltage(V)∝Stator Flux(ϕ)×Angular Velocity(ω)\text{Stator Voltage} (V) \propto \text{Stator Flux} (\phi) \times \text{Angular Velocity} (\omega) V∝ϕ×2πfV \propto \phi \times 2\pi f ϕ∝Vf\phi \propto \frac{V}{f}

This relationship makes **constant V/f control** the most commonly used **speed control method** for induction motors.

Figure 4 further illustrates the relationship between **voltage, torque, and frequency**. At **low frequencies and low voltages**, the **voltage drop across the stator impedance** reduces the available voltage, leading to insufficient torque generation. To compensate for this, a **higher-than-proportional voltage must be applied at lower speeds** to maintain adequate torque output.

This method ensures **stable and efficient motor operation**, making it widely used in **industrial applications** that require **variable-speed control** of induction motors.

VI. FUZZY PI CONTROL

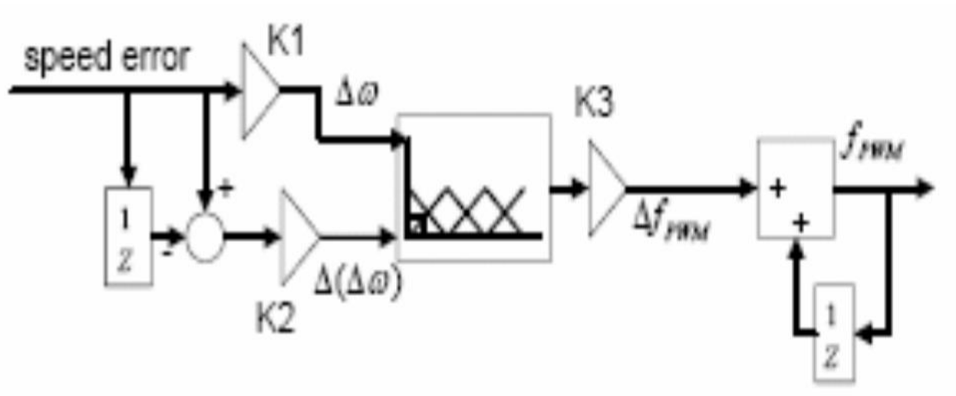

Fig.5 PI Fuzzy Control

Fuzzy Rule Base and Speed Control Mechanism

Each **training dataset** generates a corresponding **fuzzy rule**, which is stored in the **fuzzy rule base**. As each **input-output data pair** is processed, new rules are continuously generated. The **fuzzy knowledge base** is typically represented as a **two-dimensional table**, which the **fuzzy reasoning mechanism** can reference during operation.

The **speed error** is determined by comparing the **reference speed** with the **feedback speed signal**. Both the **speed error** and the **rate of change of speed error** serve as **inputs to the fuzzy controller**.

To ensure effective fuzzy logic control, input variables undergo **normalization**, using membership functions within a defined range. The **normalization factors**, denoted as **K1 and K2**, play a crucial role in optimizing the **algorithm's efficiency** and **response time**, as illustrated in **Figure 5**. Proper normalization directly influences the controller's **accuracy** and its ability to achieve **faster convergence**.

Rule Base for Controlling Speed

	Speed Error							
		NL	NM	NS	ZZ	PS	PM	PL
Speed Error Vari Ation	NL	NL	NL	NL	NM	NM	NS	ZZ
	NM	NL	NM	NM	NS	NS	ZZ	PS
	NS	NM	NM	NS	NS	ZZ	PS	PS
	ZZ	NM	NS	NS	ZZ	PS	PS	PM
	PS	NS	NS	ZZ	PS	PS	PM	PM
	PM	NS	ZZ	PS	PS	PM	PM	PL
	PL	ZZ	PS	PM	PM	PL	PL	PL

Table.1 Speed Error Variation Vs Speed Error

The **array implementation** significantly enhances **execution speed**, as **run-time inference** is reduced to a **table lookup**, which is much faster—especially when the correct entry is quickly located without excessive searching.

A common **application** of a **table-based fuzzy controller** is in systems where the **inputs** are **error** and **change in error**. This type of controller can be **embedded** in a **larger system**, such as a **vehicle**, where the **control table** is preloaded into a **lookup mechanism**.

The **fuzzy logic controller** operates based on the **control rules** outlined in **Table I**. A total of **49 fuzzy rules** are generated and stored in the **fuzzy control system database**. Notably, the results indicate **similar performance trends**, but for precise **performance evaluation**, key statistical measures such as **mean relative error** and **standard deviation (STD)** with respect to **reference speed** were calculated.

As shown in **Table V**, under a **ramp reference input**, the **fuzzy controller** demonstrates a **lower error** compared to the **PID controller**, reinforcing its effectiveness in handling system variations.

IV. RESULTS AND DISCUSSION

Fuzzy logic is an effective technique for incorporating **human-like reasoning** into a **control system**. A **fuzzy controller** is designed to **mimic human deductive thinking**, allowing it to infer conclusions based on available knowledge. Unlike traditional control methods, fuzzy control primarily operates using **fuzzy linguistic descriptions**, making it well-suited for handling **nonlinear and complex systems**.

The proposed **fuzzy-based speed controller** successfully delivers **maximum torque** across the entire speed range, ensuring **optimal performance**. In **steady-state conditions**, the **efficiency** of the **induction motor** improves significantly. The **PID and PI gains** were fine-tuned to achieve **optimal performance** during **step-up and step-down reference changes**. The **PI controller gain parameters** were carefully adjusted, demonstrating **effective performance** in both **PI and PID controllers**, as illustrated in **Fig. 6**.

Additionally, the **load torque** applied to the **induction motor rotor shaft** varies from approximately **2.2 Nm at 800 RPM** to **3.9 Nm at 1800 RPM**, further validating the controller's effectiveness in maintaining **stable and efficient motor operation**.

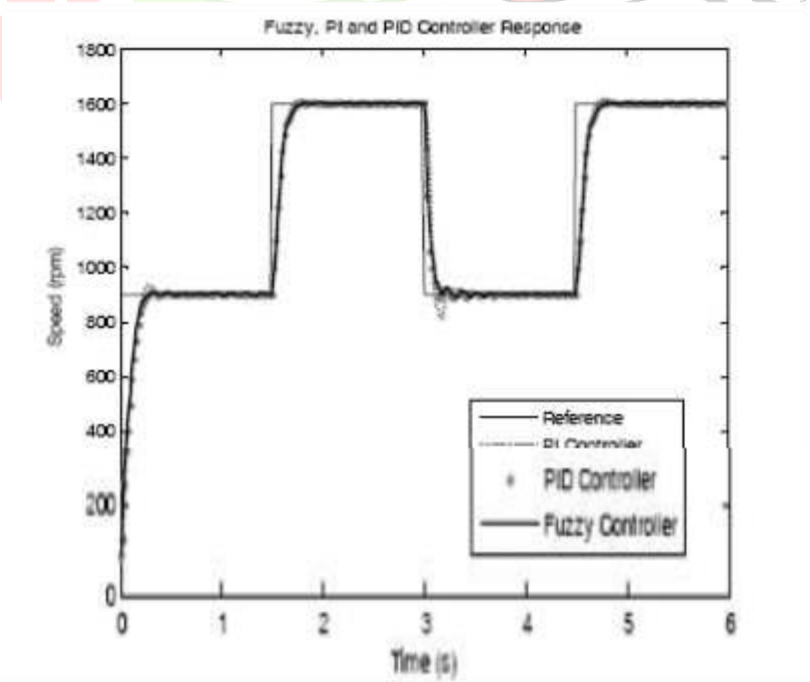

Fig.6 .Fuzzt PI and PID controller Process

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