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PERFORMANCE EVALUATION OF PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) AND FUZZY LOGIC CONTROLLER FOR ASYNCHRONOUS MACHINE SPEED CONTROL IN AN INDUSTRIAL PLANT

***1 Olusegun Bola Adesina, 2 Monsuru Ade Okandeji, 3 Olajide Blessing Olajide, 4 Saheed Akinbola Bello, 5 Adeogun Adetoyese Elijah**
[1]Department of Electrical & Electronic Engineering, Lead City University, Ibadan, Oyo State, Nigeria.
[2]Department of Computer Engineering, Federal University Wukari,, Taraba State, Nigeria.
[3]Department of Computer Engineering, Federal University Wukari, Taraba State, Nigeria.
[4]Electrical and Electronic Engineering Department, Federal Polytechnic, Ile Oluji, Ondo State, Nigeria.
[5] Department of Computer Science, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria.
Corresponding author: olajide@fuwukari.edu.ng

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Abstract: There are a number of controllers available for monitoring different characteristic of electric machines. Deciding on the choice of controller depends on its efficiency and parameter to be controlled. This research hence investigates and compares the performance of Proportional-Integral-Derivative (PID) and Fuzzy Logic Controllers (FLC) for speed control of asynchronous machine within an industrial plant. The asynchronous machine system was modelled mathematically and both controllers are designed and implemented for simulation. Settling time, overshoot, steady-state error, and robustness to disturbances are the key indicators which the comparative performance evaluation focuses. The results highlight the strengths and limitations of the controllers with emphasis on their adaptability to varying operating conditions and system parameters. Overall, this research offers a comprehensive analysis of PID and FLC in asynchronous machine speed control, providing a basis for informed decision-making in the design of control systems for industrial plants, with the ultimate goal of enhancing operational efficiency and performance.

Keywords: Fuzzy Logic, PID, Asynchronous Machine, Speed Control, Industrial Plant, Simulation, Robustness

Introduction

Induction motors play a vital role in the industrial sector especially in the field of electric drives and control. Proper monitoring and control of industrial machine speed is paramount to enabling it to achieve the desired task for a specific application. AC motors, particularly the Squirrel-Cage Induction Motors (SCIM), enjoy several inherent advantages like simplicity, reliability, low cost and virtually maintenance-free electrical drives (Prajapati and Desai, 2023; Rakib *et al.*, 2022).

However, for high dynamic performance industrial applications, their control remains a challenging problem (Zhuravlev *et al.*, 2022; Fetisovet *al.*, 2023) because they exhibit significant nonlinearities and many of the parameters, mainly the rotor resistance, vary with the operating conditions (Zhuravlev *et al.*, 2022; Denai and Attia, 2002). Generally, variable-speed drives for induction motors require both wide operating range of speed and fast torque response, regardless of load variations. The classical control is used in majority of the electrical motor drives. Conventional control makes use of the mathematical model for the controlling of the system. When there are system parametric variations or environmental disturbance, behaviour of system becomes distorted and deviates from the desired performance (Gouda, 2022; Eissa *et al.*, 2013).

In addition, usual computation of system mathematical model is difficult or impossible. To obtain the exact mathematic model of the system, one has to do some identification techniques such as the system identification and obtain the plant model. Moreover, the design and tuning of conventional controller increases the implementation cost and adds additional complexity in the control system and thus, may reduce the reliability of the control system (Naajihah and Yahya, 2022; Eissa *et al.*, 2013). Desirable control performance in both transient and steady states can be achieved even when the parameters and load of the motor vary during operation. This can be accomplished by using controllers that have adaptive or parameter identification capabilities. These controllers can adjust their parameters in real-time based on the changing conditions of the motor, ensuring optimal performance without the need for unrealistically high gains (Menghal and Laxmi, 2014)

Several papers propose different control methods to address this issue. Chen and Gong propose a new induction motor model and a simplified linearization controller method (Chen and Gong, 2023). Zhang *et al.*, (2019) present a prescribed-time tracking control scheme for robotic systems with unknown dynamics. Jia *et al.*, (2022). propose a PI controller parameter self-tuning method based on frequent-domain and time-domain indexes for a PMSM servo system. Shivam and Khadim, (2022) investigate the performance of PI and PID controllers for BLDC motors. Thus, the conventional constant gain controller used in the variable speed induction motor drives become poor when there are uncertainties in the drive such as load disturbance, mechanical parameter variations and unmodelled dynamics in practical applications. Therefore, control strategy must be adaptive and robust (Ekang *et al.*, (2023); Khelloufi and Benaicha, 2022; Xu and Hu, 2022). In recent years, Artificial Intelligent Controllers (AIC) have shown significant promise in the field of Induction Motor (IM) control (Tiwari *et al.*, 2023).

Researchers have been working on applying AIC for IM drives over the last two decades (Boutora *et al.*, 2022). Various intelligent control methods, such as fuzzy logic control, neural network control, genetic algorithm, and expert systems, have been utilized in this regard (Mencou *et al.*, 2022). The use of AIC in IM drives offers advantages such as improved performance, reduced current, torque, and flux ripples, and better efficiency (Magdy *et al.*, 2021; Saleeb *et al.*, 2022). Different techniques, including fuzzy controllers, fuzzy-PID controllers, adaptive-fuzzy-PID controllers, and ANN controllers, have been explored for IM control (Magdy *et al.*, 2021). These techniques have been compared and analysed to determine their comparative performance. The application of AIC in IM drives has the potential to enhance control accuracy and optimize the performance of the system. This is because AIC possesses particular superiorities over conventional controllers PI, PID and their adaptive versions.

Therefore, this paper presents performance analysis of conventional proportional integral controller (PID) and fuzzy logic-based controller on the speed control of an asynchronous motor drive in an extrusion industry involves decoupling of the speed and reference speed into torque and flux producing components. The dynamic performance of the Asynchronous motor drive has been analyzed for constant and variable loads.

Related Works

Various methods for speed control of induction motors have been extensively studied in the literature. Techniques such as flux-weakening control method for high-speed induction motor operation, enhancing speed control without a sensor, demonstrating improved performance through simulation (Mo *et al.*, 2024). Flux weakening control method can increase the core losses and copper losses in the motor, which may lead to higher thermal stress and thereby reduces reliability of the motor. Sony *et al.*, (2024) Proposed speed control of induction motor using fuzzy logic controller by directly controlling torque. Direct torque control scheme of induction motor is firstly used. Then, the specified rule and their membership functions of proposed fuzzy logic system was represented. A 3-phase alternating current (AC) voltage and current signals are altered into a rotating reference frame, where the stator currents are divided into their torque and flux components, to achieve precise control of motor speed and torque (Mudigondla *et al.*, 2023), this complexity may require advanced knowledge and skills, which can be a barrier for some users. Liyanage *et al.*, (2022) proposed a variable speed drive for induction motors using voltage and frequency methods, resulting in efficient speed control for three-phase induction motors. The MATLAB simulation results also described different segments and characteristic curves.

Leveraging the inherent adaptability of an ANN which useful for controlling the dynamic speed requirements in practical applications, proposed an approach to regulate the speed of a Permanent Magnet DC (PMDC) motor using an Artificial neural network (ANN), specifically a Feedforward neural network (FNN) (Thanawutthianan and Deelertpaiboon, 2024). Currently, the increasing trend of ANN adoption, along with advancements in supporting hardware, reinforces the viability of employing ANN in motor control.

Sepeeh *et al.*, (2023) proposed an improved indirect-field-oriented control (IFOC) for induction motors, integrating a convolutional neural network (CNN) as a speed controller, which enhances the control system's performance. The CNN is designed to take speed error as input and is trained offline using the back propagation algorithm. This approach minimizes the error between desired and estimated speeds, improving speed-tracking capabilities under unpredictable conditions (Sepeeh *et al.*, 2023).

Methodology

Development of Proportional Integral Differential (PID) Controller

PID controller is widely used in industrial control systems with proportional, integral, and derivative control actions. The proportional constant determines the reaction based on the current error, the integral constant determines the reaction based on the total of recent errors, and the derivative constant determines the reaction based on the rate at which the errors have been changing (Sun, 2023; Shamsuzzoha and Lloyds, 2023). PID controller is preferred in the industry due to its simplicity and ability to yield reasonable closed-loop performance (Zhou *et al.*, 2023). However, with the advancement of technology, there is a need to optimize and transform the PID controller to adapt to the control requirements of current industrial production (Zhou *et al.*, 2023).

Researchers have explored the use of intelligent algorithms and machine learning techniques to optimize PID control parameters and achieve more precise control in complex and non-linear environments (Angelli, 2022; Bien *et al.*, 2023) Additionally, there have been efforts to design PID controllers for positive systems and solve control synthesis problems using matrix decomposition and linear programming techniques. The controller transfer function block diagram of the system is shown in Figure 1

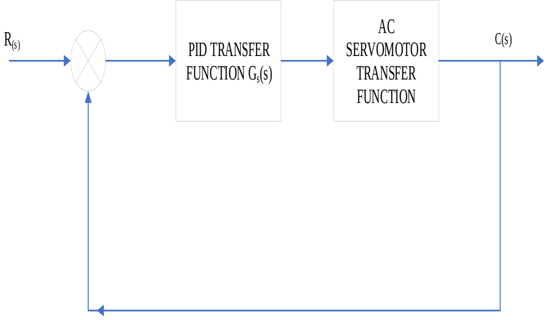


Figure 1: Block diagram of PID based servo system control mechanism.

Ziegler-Nichols suggested rules for tuning PID controllers based on experimental step response or based on the value of Kp that results in marginal stability when only proportional control action is used. The PID Controller transfer function based on Ziegler-Nichols rules for tuning PID controller is presented in equation 1 as in (Blondin, 2022).

$$G_s(s) = K_p\left(1 + \frac{1}{sT_i} + T_d s\right) = K_c\frac{(s+a)^2}{s} \qquad (1)$$

Based on the transient response characteristics of a given plant Ziegler-Nichols proposed rules for determining values of the proportional gain K_p, integral time T_i and Derivative time T_d. The rules suggest a set of value of K_p ,T_i and T_d that will give a stable operation of the system.

However, the transfer function of the armature-controlled dc motor can be deduced from the block diagram in Figure 2.

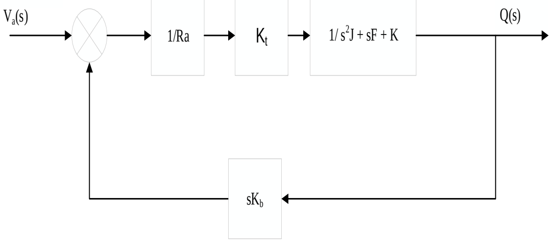


Figure 2: The block diagram for a servo system

The transfer function of the motor block diagram is derived as presented in equation 2

$$\frac{Q_{(s)}}{Va_{(s)}} = G_p(s) = \frac{K_t}{[R_a(s^2J+sF+K)+sK_tK_b]} \qquad (2)$$

Based on the provided data from literature,the final expression for servo motor transfer function is as follows:

$$G_p(\mathrm{s}) = \frac{1.2}{0.36s^3 + 1.86s^2 + 2.5s + 1} \qquad (3)$$

The forward path transfer function of the PID based servomotor system block diagram given by figure 2 above could be reduced as shown by Figure 3.

$$\frac{C(s)}{R(s)} = K_c \frac{(s+a)^2}{s} \frac{1.2}{0.36s^3 + 1.86s^2 + 2.5s + 1} \qquad (4)$$

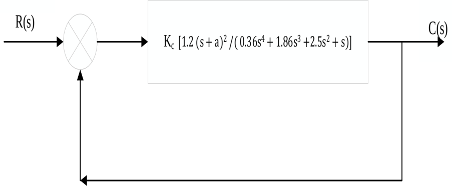


Figure 3: Reduced Block of PID based servo system control mechanism

Using an appropriate MATLAB program, 'Kc' and 'a' which are the PID controller constants were determine from Figure 4 to be 4.2 and 0.7 respectively.

Therefore, using the transfer function of the system described by figure 3 yields the overall system transfer function expressed as:

$$G_T = \frac{5.04s^2 + 7.056s + 2.469}{0.36s^4 + 1.86s^3 + 7.54s^2 + 8.056s + 2.469} \qquad (5)$$

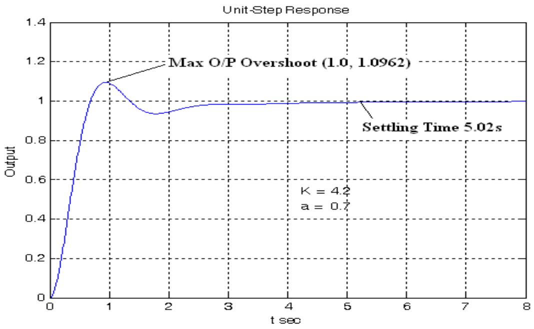


Figure 4: PID controller with Unit step input

Design of Fuzzy Logic Controller

Unlike classical control strategy, which is a point-to-point control, fuzzy logic control is a range-to-point or range-to-range control. The output of a fuzzy controller is derived from fuzzification of both inputs and outputs using the associated membership functions (Olajide *et al.*, 2021; Jeremiah *et al.*, 2020) The basic structure of a fuzzy logic controller (FLC) shown in Figure 5 assigns a fuzzy set of the control input u for each combination of fuzzy sets of K1 (Error) and K2 (Change in Error) (Senger and Kumar, 2022). The FLC design allows for the inclusion of heuristic knowledge or linguistic information about how to control a plant, rather than relying on an exact mathematical model (Li *et al.*, 2020). FLCs have been widely used in control system design, with attention given to stable behavior and optimization of performance indices (Bautista-Quintero and Dubay 2020).

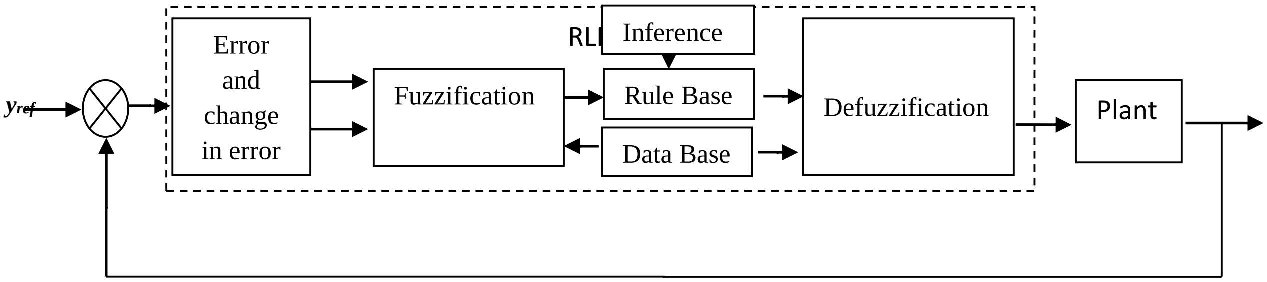


Figure 5: Basic stage of fuzzy logic controller design

The error 'e' is the first input and the second input is change in error Δe with membership functions; NB (Negative Big), NM (Negative Medium), NS (Negative small), ZR (Zero), PM (positive Medium) and PB (Positive Big). The fuzzy sets are designated by the labels with inputs assigned numerical values0, 0.25, 0.50, 0.75, and 1.The basic fuzzy rule used for the speed control of the induction motor is given in Table 1.

Table 1: Control rules for speed control of induction motor.

		Δe				
		NB	NM	ZR	PM	PB
e	NB	NB	NB	NM	NM	ZR
	NM	NB	NM	NM	ZR	PM
	ZR	NM	NM	ZR	PM	PM
	PM	NM	ZR	PM	PM	PB
	PB	ZR	PM	PM	PB	PB

The rows represent the rate of the error change 'Δe' and the columns represent the error 'e'. Each pair (e, 'Δe') determines the output level NB to PB corresponding to 'u' where 'u' is the speed control (NB, NM, ZR, PM, PB).
The triangular membership function, max-min reasoning method, and the center of gravity defuzzification method are used being the most frequently used due to their effectiveness. MATLAB SIMULINK views of the membership function editor, rule viewer, surface viewer are presented with Figures 6, 7 and 8.

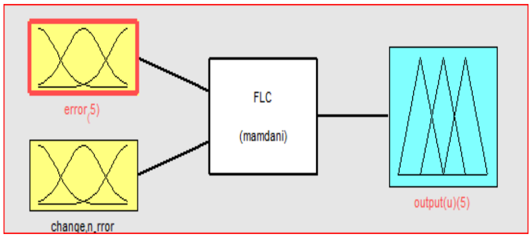
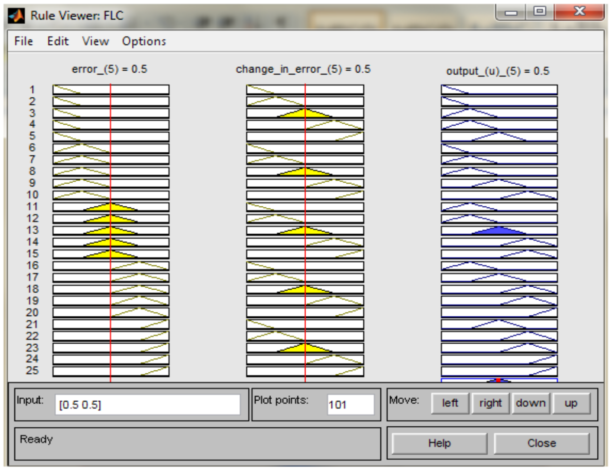


Figure 6: Membership Function Editor for 2 inputs, 1output, 25 rules



error_(5) = 0.5

change_in_error_(5) = 0.5

output_(u)_(5) = 0.5

Input: [0.5 0.5]

Plot points: 101

Ready

Figure 7: Rule Viewer at e = 0.5, Δe = 0.5 and output (u) = 0.5

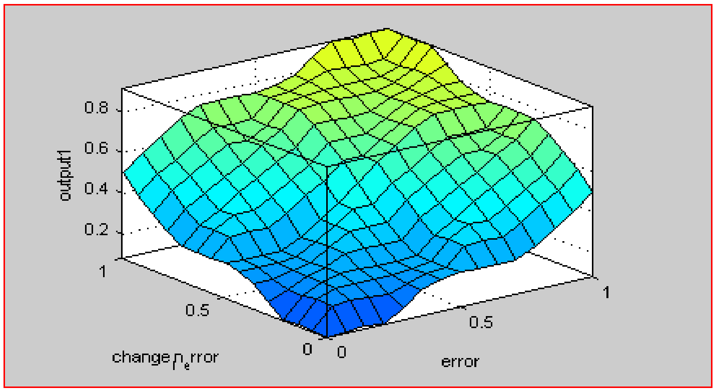


Figure 8: Surface Viewer of the Output Response (u)

Results and Discussion

Tests were carried-out on the normal servomotor system transfer function to ascertain the transient response of the system with a unit-step input perturbation using suitable MATLAB program. The same program was used to determine the most suitable values of our PID controller constants K_c and a respectively which gives a suitable operation of the system.

$$G(s) = \frac{1.2Ks^2 + 2.4Kas + 1.2Ka^2}{0.36s^4 + 1.86s^3 + [1.2K + 2.5]s^2 + [2.4Ka + 1]s + 1.2Ka^2} \qquad (6)$$

The following are the results obtained;

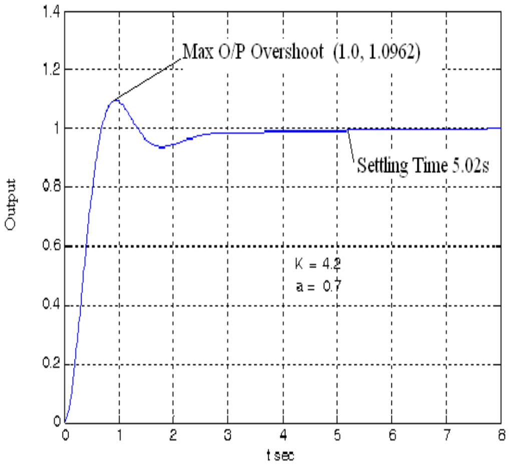


Figure 9: Transient response of the servomotor system with PID controller with unit step input.

The rise time is 1.0 sec and the settling time is 5.02 sec. Value for k, *a* and maximum outputs overshot are as follows from the command window: K = 4.2000, *a* = 0.7000 and Maximum Output Overshot = 1.0962.

The transfer function of the controller and that of the system to controller after supplying the values of 'K' and '*a*' arrived at on the command window was also perturbed with a unit step response to better the effect of PID controller on the motor system control. The response curve obtained using MATLAB program is shown in Figure 10

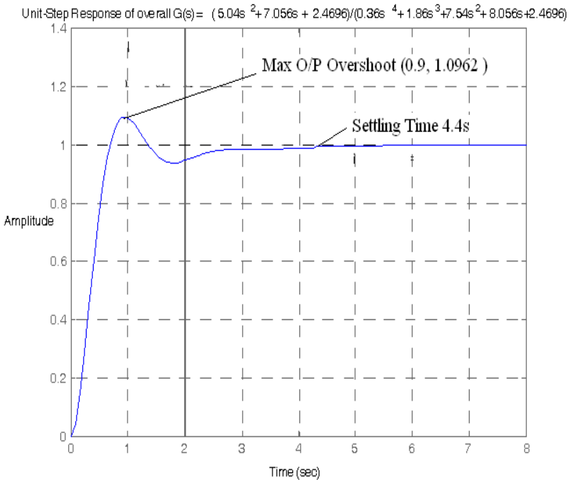


Figure 10: Unit Step Response of the Overall System Transfer Function with PID Controller.

The rise time reduced from 1.0 sec to 0.9 sec also the settling time reduced to 4.4 sec from 5.02 sec, these show that PID controller has a fairly moderate control over the initial response of the system given the motor response which indicate a reduction in the instability in the system.

The fuzzy logic controller block diagram was constructed on the already well-known set parameters of an AC Asynchronous motor characteristic. FLC fine tuning was carried out to ensure a better control of the servomotor system, setting our constant for best result as compared with other controllers. Below is the FLC simulation block diagram.

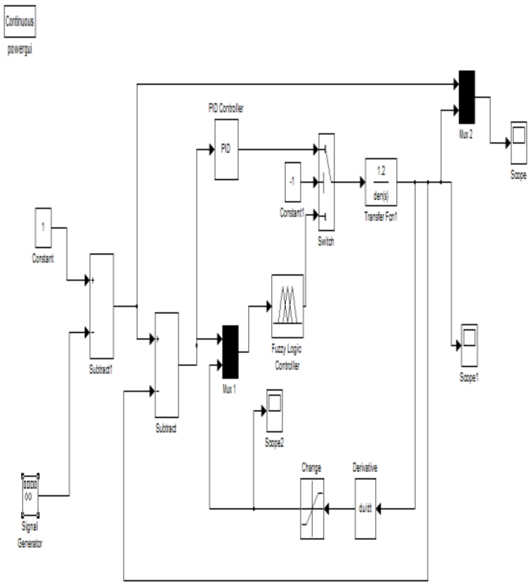


Figure 11: Fuzzy Logic Controller Simulink Block Diagram

A unit step and square wave signal were fed into the block diagram with the designed FLC. The comparator compares the reference signal to that of output signal from the FLC on the motor and also that of the PID controller.

The switch alternate between the signals that will get to the comparator scope, the scope views the output signal from either the PID or FLC controller in the simulation block diagram.

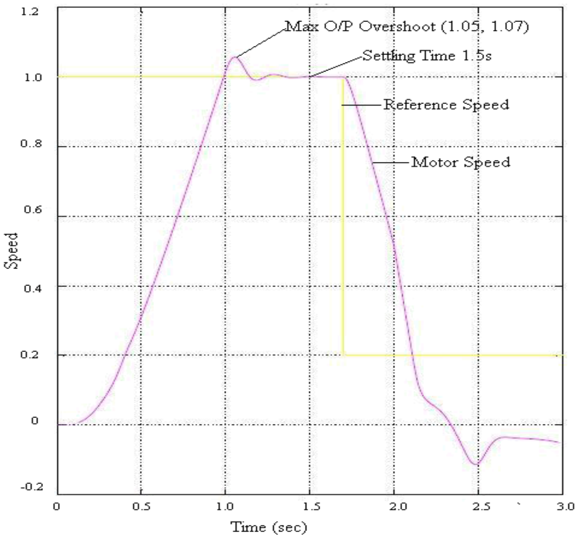


Figure 12: Square Wave Input at Comparator End with PID Controller.

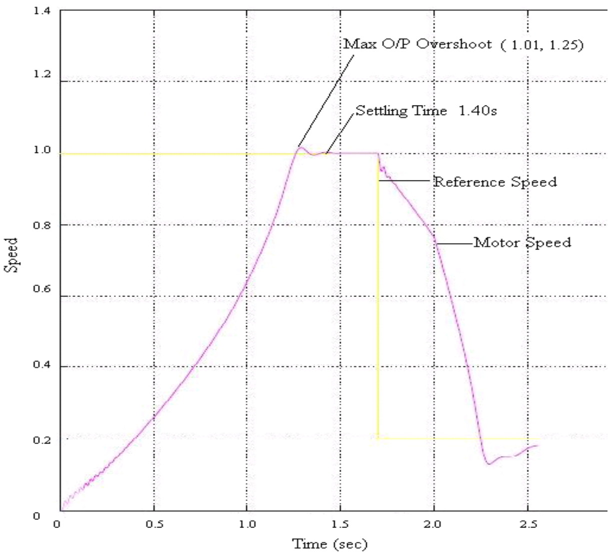


Figure 13: Square Wave Input at Comparator End with Fuzzy Logic Controller

Table 2 shows the comparison between PID and FLC. Fuzzy Logic Controller gives a better response when the reference speed is changed. It can be observed from Figure 10 that the PID controller diverges from the new reference speed and does not attain a steady state when it is very less as compared to the base speed or greater than the base speed. The Fuzzy Logic Controller on the other hand attains a steady state. Even though this attained speed is not exactly equal to the new reference speed, it is very much close to it.

Table 2.0: Comparison between PID and FLC

Parameter	PID Controller	FLC
Settling Time (sec)	1.50	1.40
Overshoot	1.05	1.01

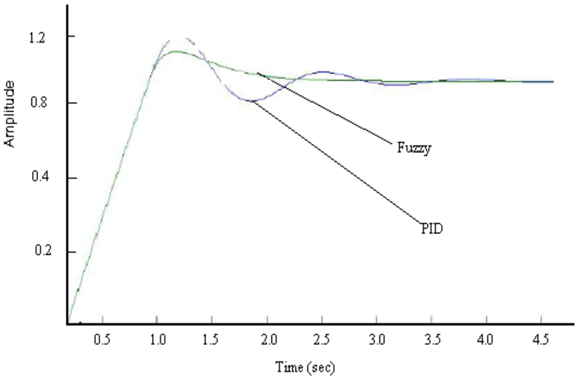


Figure 14: Comparison of Speed for PID and FLC

The result shown above indicates the best possible tuning of our simulation block diagram with FLC controller in use, showing that the fuzzy logic controller has an excellent controllability over the speed control of three-phase AC induction motor over the conventional PID controller.

Conclusion

The controller attempts to attain a certain level of human intelligence by utilizing the linguistic variables instead of numerical ones and complex mathematical computations are completely avoided, which relieves the designer from using cumbersome techniques with desirable results. Controller can be implemented in different practical applications of induction motors, the feasibility and effectiveness of the controller in the corresponding applications can be studied and changes can be made according to the system requirement so as to achieve an optimum value for the rise time, settling time and peak overshoot. Fuzzy Logic Controllers are adjudged to be more effective in terms of settling time and overshoot.

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