A Comparative Analysis and Performance Evaluation of an Improved Novel Hybrid PI Based Fuzzy Logic Controller for Induction Motor Speed Regulation

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Abstract –*A 45-year review of the literature on power electronics and electrical machines reveals a recurring pattern of circuit construction, loss, and reinvention. The concerns need to be addressed because they have resulted in substantial time and effort waste, continuous legal conflicts, the long-term loss of good ideas, and ongoing losses of time. With the aid of comparison analysis and performance evaluation utilizing a hybrid proportional plus integral (PI) based fuzzy logic controller (FLC), this research paper provides speed regulation of induction motor (IM) drives Multi converter designs are widely employed in high-power applications, according to an analysis of the power electronics and industrial controls literature published over the preceding three decades. The development of induction machine drive technology for future applications involves a number of difficulties, both present and emerging. Industrial best practices for induction motor torque management are emerging, including FLC, field-oriented control (FOC) and direct torque control (DTC). The speed regulation method is frequently required in the energy-saving control system in order to start and stop the equipment. These techniques are regulating speed for both electrical and mechanical. This research seeks to contribute to a comprehensive comparison and performance evaluation of increased speed regulation of induction motor utilizing PI based FLC in MATLAB/Simulink. MATLAB/Simulink software was utilized in the design of the suggested controller, which underwent testing under a range of operating situations, such as rapid changes in reference speed and load disturbance. The transient response to step adjustments in the torque and flux command, as well as torque and current ripple, are assessed for PI-based fuzzy logic speed control methods for induction motors. The suggested controller performed better than the traditional PI controller, according to the results.*

Keywords – PI Controller, Fuzzy Logic Control, Torque Control, Speed Control, Induction Motor Drive.

1. INTRODUCTION

Induction motors are widely used in industry as well as home appliances. Due to simple structure, reliability and high efficiency, induction motors are easy to maintain. Induction Motors have historically been used primarily for applications which require a constant speed [1]. DC drives have predominated in variable speed applications. With the development of power electronics devices like gate turn-off thyristor (GTO), switched power transistors (MOSFET and IGBT) are responsible for Control of high voltage and current. This makes a path for control of induction motor drive [1-2]. IGBT and GTO-enabled induction motor drives are more sophisticated and expensive than conventional DC drives of comparable rating. Only AC drives can offer a superior answer when dealing with high power and high voltage. Additionally, in terms of power rating, axial length, maintenance, and design and service requirements, AC drives demonstrate a greater number of applications than DC drives. With the advancement of solid-state power devices and microprocessor technology, modern motor drives are using switching power converters more and more frequently to convert and supply the required energy to the motor.

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Pulse width modulation (PWM) signals are sent to the power transistors' gates by a switching power converter, which then controls the amount of energy that reaches a motor. PWM methods for driving three-phase VSIs significantly contribute to the control of induction motors by regulating the switching devices. The essential concept of VSI is therefore to regulate the frequency and voltage of the AC output from a fixed DC source voltage. PWM techniques also provide the inverter's output waves with high efficiency, low distortion, reduced harmonics, minimal switching loss, easy implementation, and quick computation times [3–4]. Induction motor drives are becoming commonly employed with speed control in high performance drive systems. Induction motor speed regulation has been achieved by a variety of control techniques, including vector control, scalar control, proportional integral (PI), proportional derivative (PD), and proportional integral derivative (PID) control [5].

In 1936, Taylor Instrument Company introduced the PI, PD, and PID typical controllers for the first time. While most motors are made to run at a steady speed and have a steady output, many uses for electric motors in current technology call for varied speeds. A variable frequency drive (VFD) adjusts the voltage and frequency for regulate the induction motor.

With a VFD, the output of the system is regulated by directly varying the speed or torque of the motor. Additionally, it can control the motor's ramp-up and ramp-down at start and stop. Reduced demand causes the motor to run more slowly and consume less power relative to energy consumed, which boosts efficiency and conserves energy. VFD is used in many rotating machines, such as fans, pumps, and compressors respectively.

In 1965, Zadeh created the fuzzy logic controller (FLC). Its popularity in recent years has been facilitated by its updated online management, which is based on adaptive modelling with unanticipated event changes in systems. IM drives' predictive torque control has been enhanced by the use of multi-objective fuzzy decision making [6], the Kalman filter covariance technique [7], and the finite-control set model predictive control [8-9]. Researchers controlled the speed of induction motors using conventional methods for several decades. These controllers demonstrated stability in performance and simplicity in design, much like the traditional PI controller. Nevertheless, the mathematical model of an induction motor is still needed by conventional controllers. Additionally, in the event of a load disruption or abrupt change in the reference speed, they can create overshoot or a lengthy settling time. Fuzzy logic and other intelligent control techniques have been widely employed in induction motor control to overcome these shortcomings. Both traditional control theory and artificial intelligence theory serve as the foundation for these control systems.

The best aspects of FLC and PI are combined in this creative control scheme are, PI based FLC performs better in steady-state conditions than a conventional PI controller because it primarily functions in a transient state, providing a quick dynamic reaction and extending the stability limits of the system. A weighting expert system based on FLC is used to aggregate the outputs from the two nonlinear controllers in order to decide the control action. Using this structure leads to better performances as compared to using the PI controller by itself. Experimental verifications show that this control method is successful. This research investigates the motor's steady state and transient properties of the IM dynamic model. This work presents a thorough assessment of the literature on the energy-saving uses of PI-Based FLC in electrical motors. Finding opportunities for energy savings and factoring in the expenses of using FLC in the current electrical motor applications is the goal.

The application of FLC in electric drives and, theoretical context of proposed novel PI based FLC are covered in Section II. Section III presents the mathematical modelling, simulation model of proposed novel PI based FLC, results and discussions of the proposed research. Section IV covers the conclusions of the proposed novel research.

2. FUZZY LOGIC CONTROL SYSTEM

Fuzzy control utilizes the principles of fuzzy logic theory, initially introduced by Zadeh. Fuzzy controllers operate based on a set of rules formatted as if–then statements. These rules can incorporate multiple variables on either the condition or conclusion side. Consequently, fuzzy control does not necessitate a mathematical model of the system, making it applicable to nonlinear systems. The design of a fuzzy controller is illustrated in Figure 1 [10].

1. Fuzzification

Fuzzification is the process of converting precise values into degrees of membership within fuzzy sets' linguistic terms. The singleton fuzzifier is the most widely employed method for this purpose [11-13].

2. The fuzzy inference (FI) engine

The fuzzy inference system handles decision-making in FI system. It explains decision rules using the if-then and the connectors OR or AND. A fuzzification unit is a device that converts sharp data into fuzzy input and makes it easier to use different fuzzification algorithms [14].

3. Defuzzification

The mathematical method of defuzzification involves converting fuzzy values into crisp values.

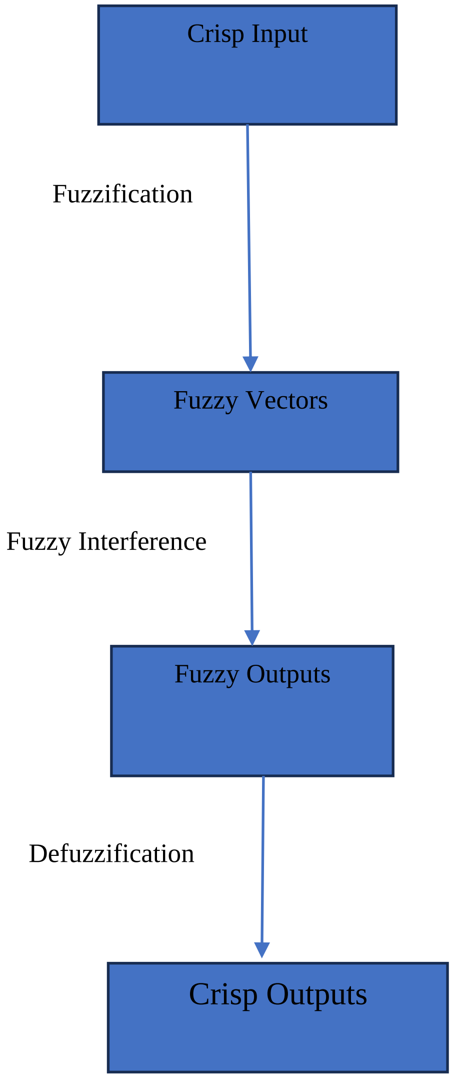

Figure 1: Fuzzy Logic Control System.

4. Fuzzy Logic-Based Controller

Contemporary electric drives require constant shaft speed monitoring of the motor to guarantee that it follows specified pathways. This can be accomplished by developing a fuzzy control system. Fuzzy control converts linguistic control tactics into an automatic control approach by using a fuzzy rule-based system to automate control operations that would otherwise require human skill [15-16]. One of the key characteristics of an FLC is its ability to offer high-performance control without necessitating a comprehensive mathematical model of the system. The following stages can be used to outline the implementation of an FLC.

5. Speed control using FLC

A FLC uses the motor speed error (E) and its derivative, which shows the change in speed error (CE), as the two primary input variables for controlling motor speed. The controller's output is the voltage applied to the motor divided by its frequency (CF) [17-20]. The definitions that follow relate to both the speed error and the change in speed mistake.

$$E = V_{ref} - V_{act} \quad (1)$$

$$CE = \frac{dE}{dt} \quad (2)$$

3. FLC FOR THE PROPOSED SYSTEM

Fig. 2 provides an overview of the knowledge database containing all PI based fuzzy rules for the proposed research in MATLAB/Simulink. A simplified fuzzy inference system using triangular and symmetrical membership functions was developed to fuzzy logic control induction motors as shown in fig. 2. With values ranging from [-0.5, 0.5] the fuzzy control system's variances in frequency, speed error, and speed error variation were all scaled into a single discourse universe [21-24]. This resulted in a simultaneous mapping of all variables using unique membership functions as a result of this proposed method.

The proposed PI based fuzzy controller has two inputs and one output, explained below [25-28]:

$$e(x) = \omega^{*}(x) – \omega(x\text{-}1) \quad (3)$$

$$de = \frac{e(x)}{T} - \frac{e\,(x-1)}{T} \quad (4)$$

Where, de is derived from the error approximated with Sampling Period T.

The output of the regulator is calculated by [29]:

$$C_{ref.}\,(x) = C_{ref.}(x\text{-}1) + \Delta u(x) \quad (5)$$

The MATLAB Simulation model for the proposed PI based fuzzy logic controller's simulation diagram is displayed in fig. 3. Here, a comparison is made between the induction motor speed and the reference speed in order to calculate the speed error. To provide an output of frequency variation, the fuzzy controller uses this as one of its inputs. This signal is multiplied by the voltage-sourced inverter's previous frequency to obtain the fundamental frequency. The remaining control is identical to the PI controllers. A full diagram of the Simulink Flux speed and torque estimation block can be found in Fig. 3.

The set point, which represents the intended motor speed, and the feedback signal, which represents the actual motor speed, are the two inputs of the proposed control system. The induction motor's speed is controlled by the FLC. The three-phase inverter receives the output from the FLC and uses it to create a waveform with varying voltage and frequency that regulates the motor's speed.

Over the past ten years, the use of FLC has increased noticeably in recent years. Fuzzy logic can be applied to resolve problems involving membership functions with values between 0 and 1, ambiguity, and uncertainty. As a result, if a trustworthy source of expert information is unavailable or if the controlled system is too complex to extract the necessary decision rules from, developing a fuzzy logic controller may be difficult, time-consuming, or even impossible in some circumstances. The controller might need to be adjusted if the necessary professional experience is not readily available.

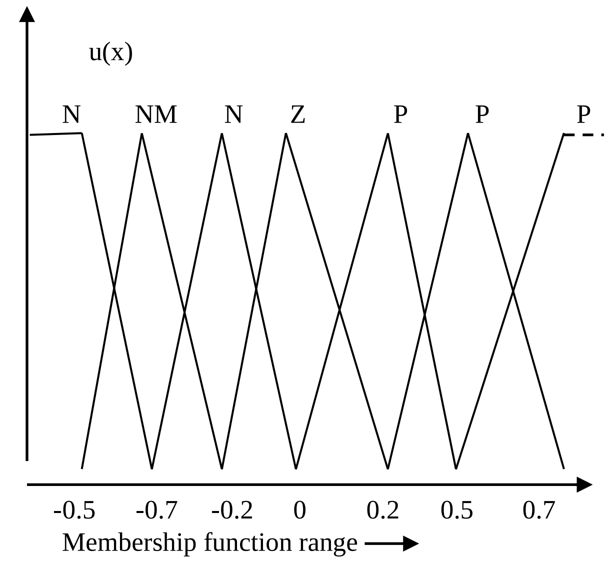

Fig. 2- Membership function of PI based fuzzy control system.

3.1 Result And Discussion

The approach immediately draws the motor speed to the reference speed and uses a proportional integral controller to quickly modify the motor speed based on speed errors. The simulation results demonstrate the developed controller's excellent performance, which has very minimum overshoot. PI and FLC were used in a number of simulation studies to control the induction motor's speed. Different operating circumstances, including applied load and reference speed, were used in the simulations. The speed response is displayed in fig. 5. An analysis and comparison of PI and FLC's performance were conducted. In fig. 6, the magnetic flux is present the dynamic response. Also, in fig. 6 and 11, the flux estimator provides the speed estimation response. Therefore, it may be concluded that PI based FLC control of the IM is better than standard controller management. A FLC provides a better dynamic response with PI controller for nonlinear systems. This result shows that the steady state response of the system and this is equal to the load flux and the speed which is approaches the reference speed.

It may be observed that the speed reaction is more superior and better than when using a PI controller. The rotor current simulation results are displayed in Fig. 9. Here, the speed response is observed to be superior to the other controllers, and the speed settles in less than 0.369 sec. Therefore, it may be concluded that PI based FLC control of the IM is better than standard controller management. A FLC provides a better dynamic response with PI controller for nonlinear systems.

Fig. 8 and 11 shows the trajectory of reference torque, output torque and flux estimator and discrete RMS value using PI based fuzzy logic controller. After that the value of controller gains k_p is 12.2 and k_i is 1.6. At 50 Hz frequency the value of Stator and rotor resistance are 0.537 Ω and 0.6313 Ω. At this frequency the rated voltage is 400V, 7.5 Kw and rated speed is 800 rpm. The suggested controller is compared to PI-FLC, Fuzzy-PD, Fuzzy-FOC, and Fuzzy-PID controllers by comparative analysis. After comparing the value of PI based fuzzy logic Controller rise time is 0.0568920 second. Value of PI based fuzzy logic controller settling time is 1.5 second and value of PI based fuzzy logic controller overshoot is 1.4 second.

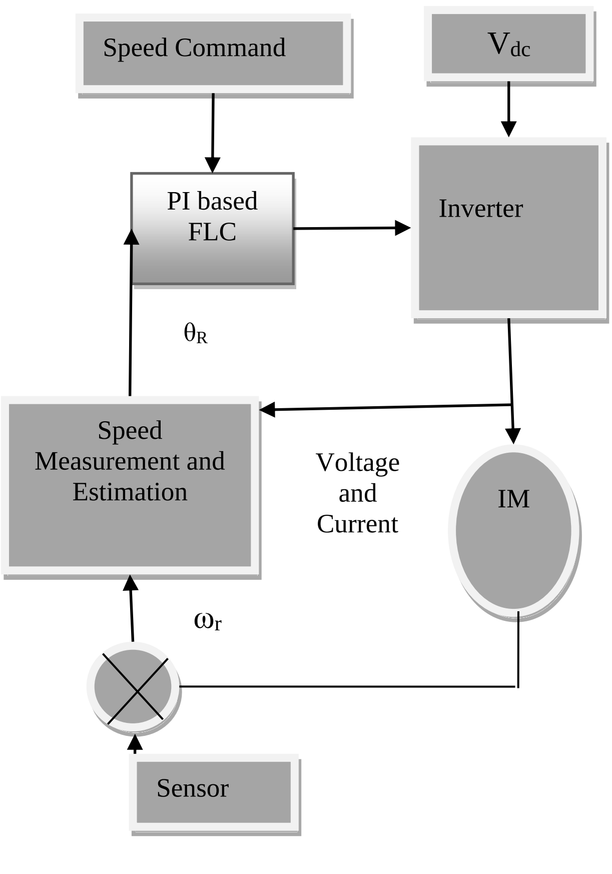

Fig. 3 - MATLAB/Simulink model of closed-loop control for IM using PI Based FLC control.

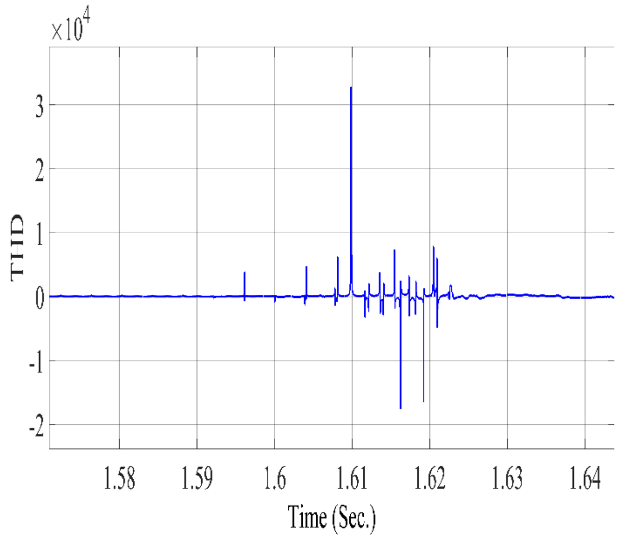

Fig. 4. - Simulation result of total harmonic distortion (THD) vs time using PI based FLC.

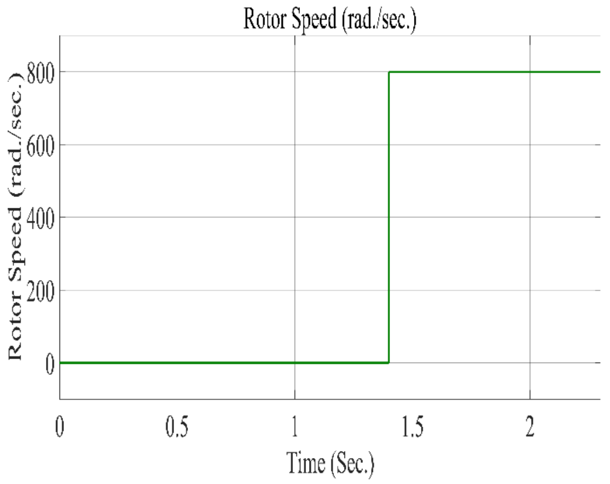

Fig. 5 - Simulation result of rotor speed vs time using PI based FLC.

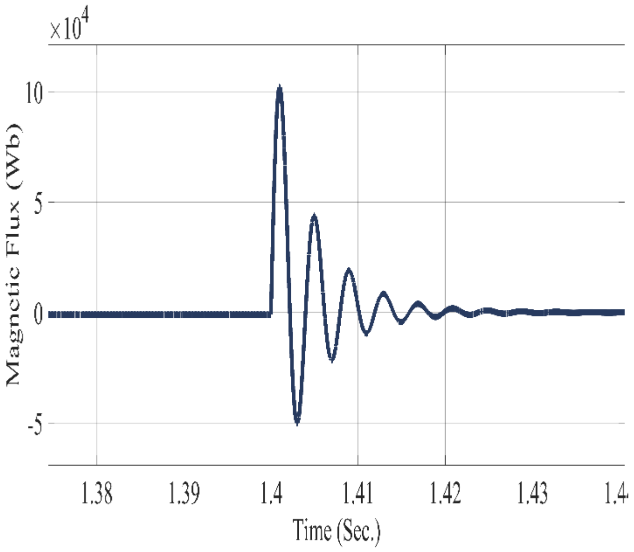

Fig. 6 - Result of magnetic flux vs time using PI based FLC.

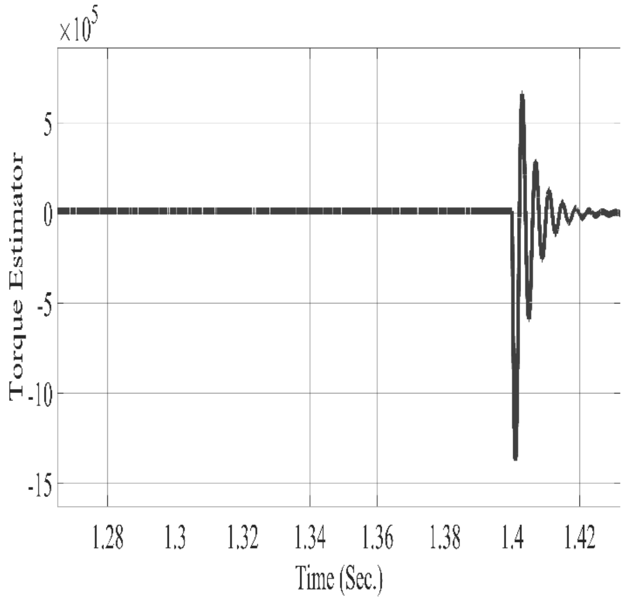

Fig. 7 - Simulation result of torque estimator vs time for speed estimation.

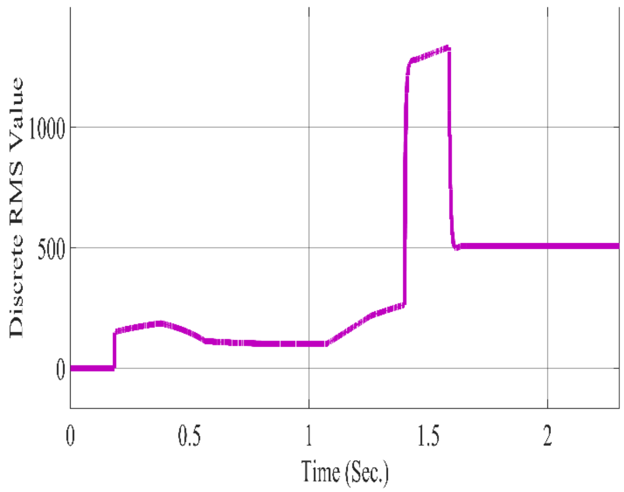

Fig. 8 - MATLAB/Simulink result of discrete RMS value vs time using PI based FLC.

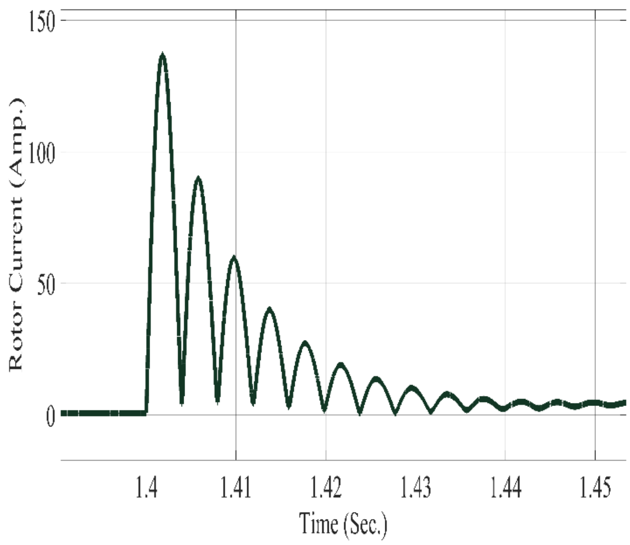

Fig. 9- Rotor current vs time using PI based FLC in MATLAB.

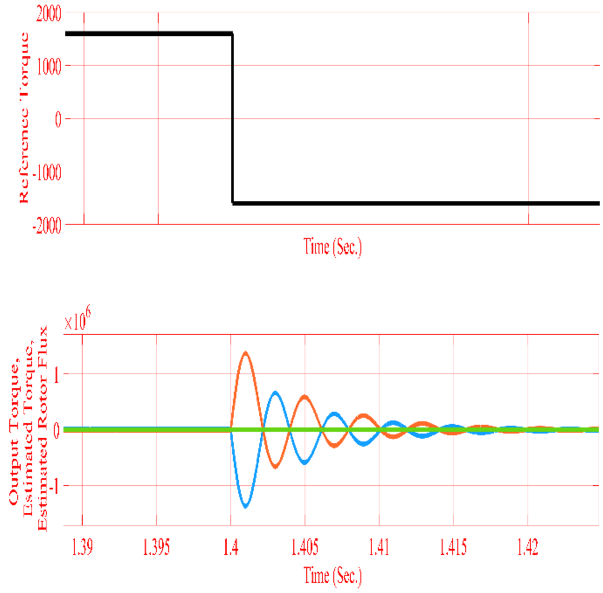

Fig. 10 – Trajectory of reference torque, output torque and estimated rotor flux vs time using PI based FLC.

The preceding table makes it evident that, as compared to PI response for multistep speed input, FLC demonstrated a faster rising and settling time, with the exception of the rise time at 800 rpm. Consequently, FLC outperformed PI controller in terms of performance. The three-phase induction motor's speed regulation and fast response time with virtually no overshoot or steady state error were other abilities displayed by FLC.

The final determinant of the output waveform's quality is the sine wave's smoothness, which is reliant on the harmonic components. Therefore, in order to assess the quality of the inverter output waveform, it is imperative that the harmonic components be analyzed. To achieve this, a number of simulation-based experiments were conducted to examine the output voltage's harmonic components.

4. CONCLUSION

In this paper a PI based FLC system for three-phase induction motor speed regulation is done. It gives an overview of relevant research and describes the fuzzy logic controller's construction in depth. This research explains the use of MATLAB/Simulink software to simulate the three-phase voltage source inverter and FLC for proposed model. In terms of handling the various uncertainties, this technique is used in the speed controller development. This controller uses a PI based FLC and this system is suggested while accounting for a various factor, including overshoot, settling time, and rise time. The motor rotor speed is taken into consideration when measuring the various discussed parameters and MATLAB software is used to obtain the simulation findings. The findings demonstrated that the suggested method required less time than the conventional method. A comparative analysis is carried out, emphasizing on rise time, settling time, overshoot, and performance, between the various conventional controllers and the proposed controller. Hence, the suggested technique has been shown to work better in terms of settling time, speed regulation, and overshoot. In future work various optimization techniques can be used with PI based FLC for enhancing the speed of induction motor.

NOMENCLATURE

E = IM speed error

V_{ref} = Desired IM speed

V_{act} = Actual measured IN speed

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