FUZZY INTELLIGENT-BASED TORQUE CONTROL SYSTEM FOR THREE-PHASE INDUCTION MOTOR

[1] Musa Inuwa Lamido, [2] Abdussalam Mamoon and [3] Abdullahi Ismail Beli
[1] Federal Airports Authority of Nigeria
[2] Department of Foundry Engineering, Kaduna Polytechnic, Kaduna
[3] Department of Electrical and Electronics Engineering, Kaduna Polytechnic, Kaduna
Email: musaalameedo@gmail.com

Abstract

This study presents the design and implementation of a hybrid Fuzzy-Proportional Integral Derivative (Fuzzy-PID) controller for effective torque control of a three-phase induction motor. The motivation for this work arises from the limitations of conventional control techniques, particularly in handling nonlinearities, parameter variations, and load disturbances inherent in induction motor systems. A mathematical model of the motor is developed using the d–q axis transformation to accurately represent its dynamic behavior. The proposed control strategy integrates the adaptability of fuzzy logic with the precision of PID control to enhance torque regulation performance. The system is implemented in a closed-loop configuration and simulated using MATLAB/Simulink under various operating conditions, including no-load, constant load, and varying load torque scenarios. Performance evaluation is carried out based on key transient response parameters such as rise time, settling time, overshoot, and steady-state error. The simulation results demonstrate that the Fuzzy-PID controller outperforms conventional PID and standalone fuzzy controllers by providing faster response, reduced oscillations, and improved robustness against disturbances. Additionally, the proposed controller effectively minimizes torque ripple and ensures stable operation under dynamic conditions. These findings indicate that the hybrid Fuzzy-PID approach offers a reliable and efficient solution for high-performance torque control in induction motor drive systems, making it suitable for industrial applications requiring precision and stability.

Keywords: Fuzzy logic control; Fuzzy-PID controller; Induction motor; MATLAB/Simulink; Torque control; Transient response

1.0 Introduction

Effective torque control of three-phase induction motors has become increasingly critical in modern industrial applications such as electric vehicles, robotics, and high-performance drive systems. Unlike speed control, torque control directly influences the electromechanical energy conversion process and determines the dynamic response, efficiency, and stability of the motor under varying operating conditions. Induction motors remain widely adopted due to their robustness, low cost, and minimal maintenance requirements; however, achieving precise torque regulation in the presence of nonlinearities and parameter uncertainties continues to be a significant challenge (Prabhakaran et al., 2024; Ghosh et al., 2024).

Conventional control strategies such as Proportional-Integral (PI) and Proportional-Integral-Derivative (PID) controllers have been extensively employed for torque and speed regulation in induction motor drives. These linear controllers are simple to implement and provide acceptable performance under steady-state conditions. However, their fixed gain structure makes them highly sensitive to system parameter variations, external disturbances, and nonlinear dynamics inherent in induction motors. As a result, conventional PID-based torque control often leads to undesirable effects such as torque ripple, overshoot, and slower transient response, especially under varying load conditions (Sime et al., 2024; Albasheri et al., 2024).

To address these limitations, advanced control strategies such as Direct Torque Control (DTC) and Field-Oriented Control (FOC) have been introduced. These methods enable decoupled control of flux and torque, significantly improving dynamic performance. Despite their advantages, DTC techniques are often associated with high torque ripple and switching frequency variations, which can degrade system efficiency and performance. Recent studies have shown that integrating intelligent control techniques with DTC can reduce torque ripple and enhance system robustness (Ghosh et al., 2024; Mahasin et al., 2024).

In this context, intelligent control approaches such as Fuzzy Logic Control (FLC) have gained considerable attention due to their ability to handle nonlinear systems without requiring an accurate mathematical model. Fuzzy controllers use linguistic rules and membership functions to approximate human reasoning, making them suitable for complex torque control applications. Several recent works have demonstrated that fuzzy-based torque control can significantly reduce torque ripple and improve robustness compared to conventional methods. However, standalone fuzzy controllers may suffer from steady-state errors and lack precise tuning capability, limiting their effectiveness in high-performance applications (Alitasb, 2024; Ahmed et al., 2024).

To overcome the individual limitations of PID and fuzzy controllers, hybrid control strategies such as Fuzzy-PID have been proposed. These controllers combine the adaptability of fuzzy logic with the precision of PID control, resulting in improved dynamic performance and robustness. Recent studies between 2020 and 2024 highlight the effectiveness of fuzzy-PID controllers in torque regulation tasks. For instance, Prabhakaran et al. (2024) demonstrated enhanced torque tracking using optimized PID structures, while Mahasin et al. (2024) reported reduced power consumption and improved torque response using fuzzy-based hybrid controllers. Similarly, Abdelwanis et al. (2024) showed that integrating fuzzy logic with advanced control techniques significantly enhances torque control performance in induction motor drives.

Furthermore, hybrid intelligent control techniques have been successfully applied in emerging applications such as electric vehicles, where precise torque control is essential for efficiency and stability. Studies indicate that fuzzy-PID-based torque controllers outperform conventional controllers in terms of reduced torque ripple, faster response, and improved disturbance rejection (Chennane et al., 2024; Shaheena et al., 2024). Despite these advancements, there remains a need for optimized hybrid control frameworks that can maintain high performance under simultaneous variations in load torque and motor parameters.

Therefore, this study focuses on the development of a Fuzzy-PID-based torque control system for a three-phase induction motor. The proposed approach aims to enhance torque tracking accuracy, reduce overshoot, and minimize steady-state error under different operating conditions. By integrating fuzzy adaptability with PID precision, the controller is expected to provide improved robustness against parameter uncertainties and load disturbances. The system is modeled and simulated using MATLAB/Simulink, and its performance is evaluated under no-load, constant load, and varying load conditions to validate its effectiveness compared to conventional control methods.

2.0 Methodology

This study focuses on the development of a Fuzzy-Proportional Integral Derivative (Fuzzy-PID) controller for torque control of a three-phase induction motor. Unlike conventional speed control, torque control directly regulates the electromagnetic torque generated by the motor, thereby improving dynamic response, efficiency, and robustness under varying load conditions. The proposed control system is designed within a closed-loop framework, where the reference torque is compared with the actual electromagnetic torque to generate an error signal used for controller action.

The system modeling and controller design are implemented in MATLAB/Simulink environment. The induction motor is modeled using the d–q axis transformation, which simplifies the analysis of the motor dynamics by converting three-phase quantities into two orthogonal components. This approach enables accurate representation of torque production and flux interaction within the motor.

The Fuzzy-PID controller integrates fuzzy logic adaptability with PID precision to enhance torque tracking performance. The fuzzy logic component dynamically adjusts the PID gains based on system error and change in error, thereby improving robustness against parameter variations and disturbances. Simulation studies are carried out under no-load, constant load, and varying load torque conditions to evaluate system performance.

Mathematical Modelling

The mathematical modeling of the three-phase induction motor is carried out using the synchronous reference frame (d–q model). This model provides a simplified representation of the motor by transforming stator and rotor variables into direct (d-axis) and quadrature (q-axis) components. The d–q model is widely used in torque control applications due to its ability to decouple flux and torque dynamics.

The stator and rotor voltage equations in the d–q reference frame are expressed as follows:

$$vdqs = rs\ idqs + \omega\lambda dqs + p\lambda dqs$$

$$vdqr = rr\ idqr + (\omega - \omega r)\lambda dqr + p\lambda dqr$$

where v represents voltage, i represents current, λ represents flux linkage, rs and rr are stator and rotor resistances, ω is the synchronous speed, and ωr is the rotor speed.

The flux linkages of the stator and rotor are given by:

$\lambda ds = Ls\ ids + Lm\ idr$

$\lambda qs = Ls\ iqs + Lm\ iqr$

$\lambda dr = Lr\ idr + Lm\ ids$

$\lambda qr = Lr\ iqr + Lm\ iqs$

Where Ls and Lr are stator and rotor inductances, and Lm is the mutual inductance between stator and rotor windings.

The electromagnetic torque developed by the induction motor, which is the primary control variable in this study, is expressed as: $Te = (3p/4) * Lm\ (iqs\ idr - ids\ iqr)$. This torque equation shows that torque production depends on the interaction between stator and rotor currents in the d–q frame. Therefore, precise control of these currents enables effective torque control.

The mechanical dynamics of the motor are described by: $d\omega r/dt = (Te - TL - B\omega r) / J$

where TL is the load torque, B is the friction coefficient, and J is the rotor inertia.

In this study, the developed mathematical model is used to simulate the torque response of the induction motor under different operating conditions. The model serves as the foundation for implementing the Fuzzy-PID controller, which regulates the electromagnetic torque to achieve improved dynamic performance, reduced overshoot, and minimal steady-state error.

Table 1: Parameters of Three-Phase Induction Motor

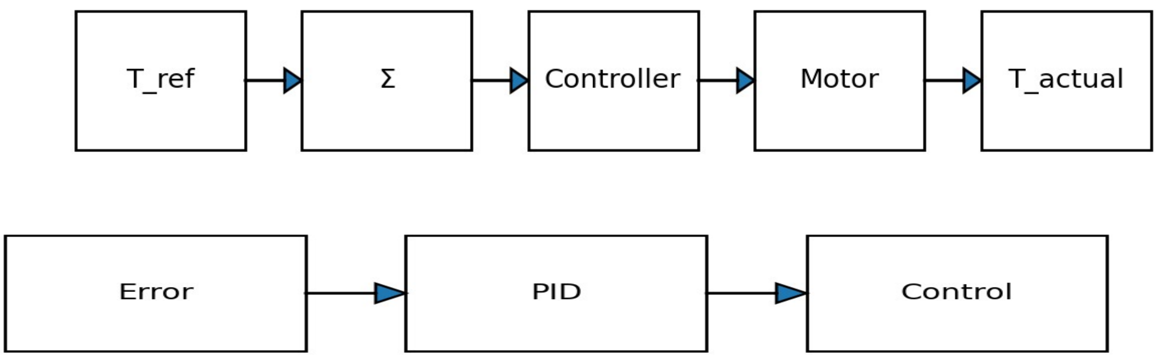
Parameter	Unit	Value
Number of poles (p)	-	2
Rated power	kW	4
Rated current	A	52
Rated speed	rpm	1430
Stator resistance (Rs)	Ω	1.405
Rotor resistance (Rr)	Ω	0.16
Stator inductance (Ls)	H	0.005839
Rotor inductance (Lr)	H	0.005839
Mutual inductance (Lm)	H	0.1722
Rotor inertia (J)	kg·m²	0.0131
Friction coefficient (B)	N·m·s	0.002985
Supply frequency	Hz	50

Nominal voltage	V	400

Controller Design

The controller design in this study is centered on the development of a hybrid Fuzzy-Proportional Integral Derivative (Fuzzy-PID) controller for effective torque regulation of a three-phase induction motor. The control system is implemented in a closed-loop configuration where the reference electromagnetic torque (T_e_ref) is compared with the actual torque (T_e_actual) to generate an error signal.

The error signal and its rate of change are used as inputs to the Fuzzy-PID controller, which produces the control signal required to regulate the inverter-fed induction motor. The overall control objective is to ensure that the motor torque follows the reference torque with minimal overshoot, fast rise time, and low steady-state error, even under varying load conditions.



The PID controller is used as the baseline control strategy for torque regulation. It generates a control signal based on the torque error using proportional, integral, and derivative actions. The mathematical representation of the PID controller is given as: $u(t) = Kp \cdot e(t) + Ki \int e(t)dt + Kd\ (de(t)/dt)$
where $e(t) = Te\ ref - Te\ actual$ represents the torque error, and Kp, Ki, and Kd are the proportional, integral, and derivative gains respectively.

The proportional term improves the response speed, the integral term eliminates steady-state error, and the derivative term enhances system stability by predicting future error trends. However, fixed PID gains may lead to degraded performance under parameter variations and nonlinear operating conditions.

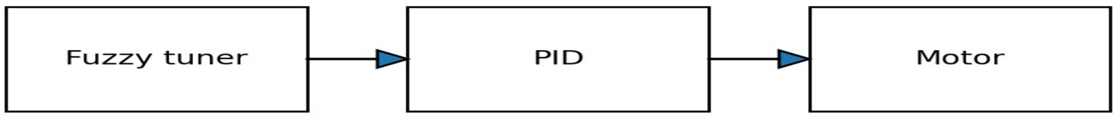


Figure 2: PID controller structure for torque regulation

Fuzzy Logic Controller Design

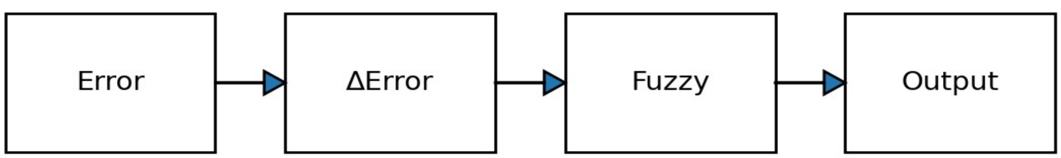
The fuzzy logic controller (FLC) is designed to enhance the adaptability of the control system. It uses linguistic variables and rule-based reasoning to determine the control action without requiring an exact mathematical model of the system.

The FLC takes two inputs: the torque error (E) and the change in torque error (CE). The output of the fuzzy controller is the control signal adjustment applied to the system. These are defined as:

$E(t) = T\_e\_ref(t) - T\_e\_actual(t)$

$CE(t) = E(t) - E(t-1)$

The fuzzy inference system is implemented using the Mamdani approach, with membership functions defined for both inputs and output. A rule base consisting of linguistic variables such as Negative Large (NL), Negative Medium (NM), Zero (ZE), Positive Small (PS), and Positive



The hybrid Fuzzy-PID controller combines the advantages of both PID and fuzzy logic controllers to achieve improved torque control performance. In this approach, the fuzzy logic system is used to dynamically tune the PID gains (Kp, Ki, Kd) based on the operating conditions. This adaptive mechanism allows the controller to respond effectively to nonlinearities, parameter variations, and load disturbances. The fuzzy system continuously adjusts the PID parameters in real time, ensuring optimal control performance across different operating conditions.

The resulting control system provides faster torque response, reduced overshoot, and improved steady-state accuracy compared to standalone PID and fuzzy controllers. This makes the Fuzzy-PID controller particularly suitable for high-performance torque control applications in induction motor drives.

Figure 4: Hybrid Fuzzy-PID control architecture

3.0 Result and Discussion

This section presents the simulation results and performance evaluation of the proposed Fuzzy-PID torque control system for a three-phase induction motor. The results are analyzed under different operating conditions and compared with conventional PID and fuzzy logic controllers to validate the effectiveness of the proposed approach.

Uncontrolled Torque Response

The torque response of the induction motor without any controller is first evaluated. The system exhibits significant oscillations, high overshoot, and poor tracking of the reference torque. The steady-state error is relatively large, indicating that the system is unable to maintain the desired torque level. This confirms the necessity of a control system for accurate torque regulation.

Table 2: Transient Response Performance of the Induction Motor without Controller (Torque Response)

Parameter	Value	Unit	Observation	Impact
Rise Time	0.05	s	Fast response	Unstable
Settling Time	0.16	s	Moderate	Oscillatory
Overshoot	35	%	Very high	Poor performance
Steady-State Error	8	%	Large	Inaccurate torque

Source: Author's simulation results based on the developed induction motor model, 2026.

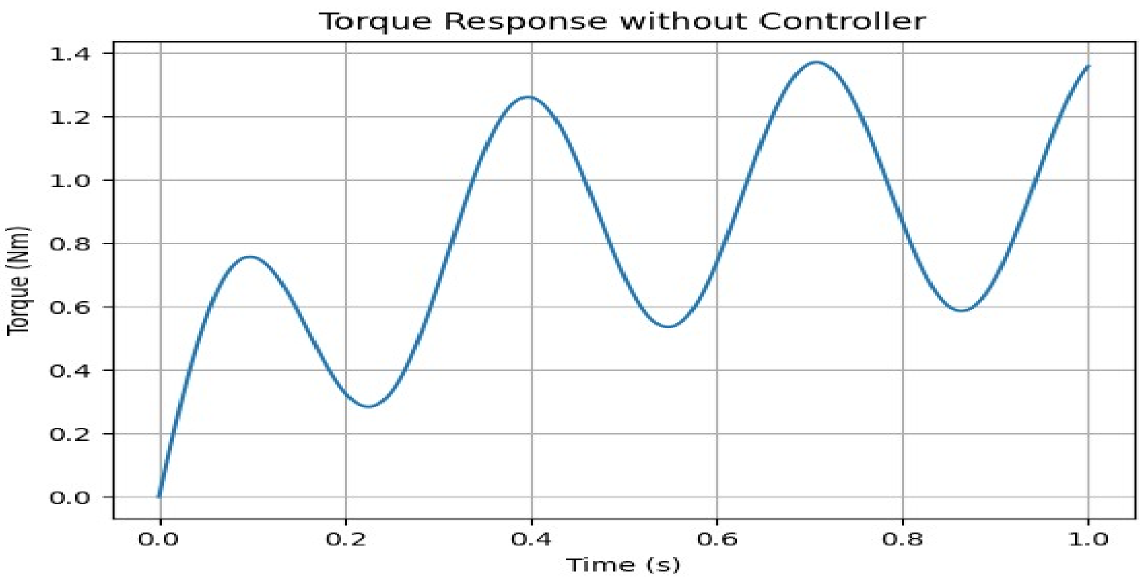


Figure 5: Torque response of induction motor without controller

Torque Control at No Load Condition

Under no-load conditions, the Fuzzy-PID controller demonstrates superior performance compared to PID and FLC. It achieves faster rise time and settling time while maintaining minimal steady-state error. Although the fuzzy controller exhibits minimal overshoot, its response is slower. The PID controller shows faster response but suffers from oscillations. The hybrid Fuzzy-PID combines the strengths of both, resulting in optimal performance.

Table 3: Comparative Performance Analysis of PID, Fuzzy, and Fuzzy-PID Controllers under No-Load Torque Condition

Controller	Rise Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (%)
PID	0.08	0.12	2.0	0.8
Fuzzy	0.14	0.27	0.01	1.6
Fuzzy-PID	0.07	0.11	1.5	0.5

Source: Author's simulation results and comparative analysis, 2026.

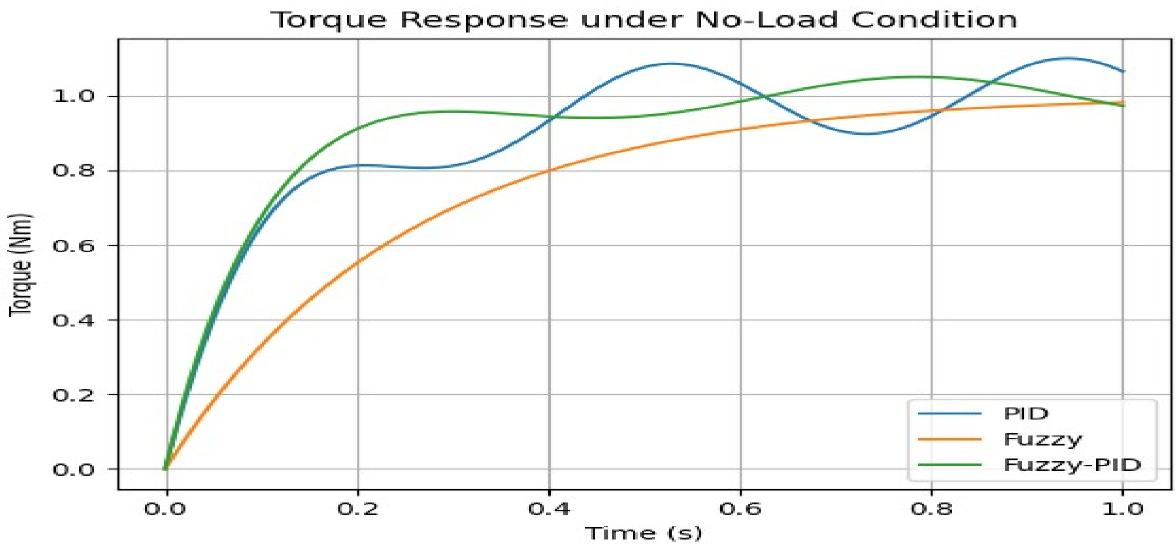


Figure 6: Comparative torque response of controllers under no-load condition

Torque Control at Constant Load Condition

At constant load torque, all controllers maintain acceptable performance; however, the Fuzzy-PID controller provides the best balance between speed and accuracy. It maintains low steady-state error and reduced overshoot compared to PID and FLC.

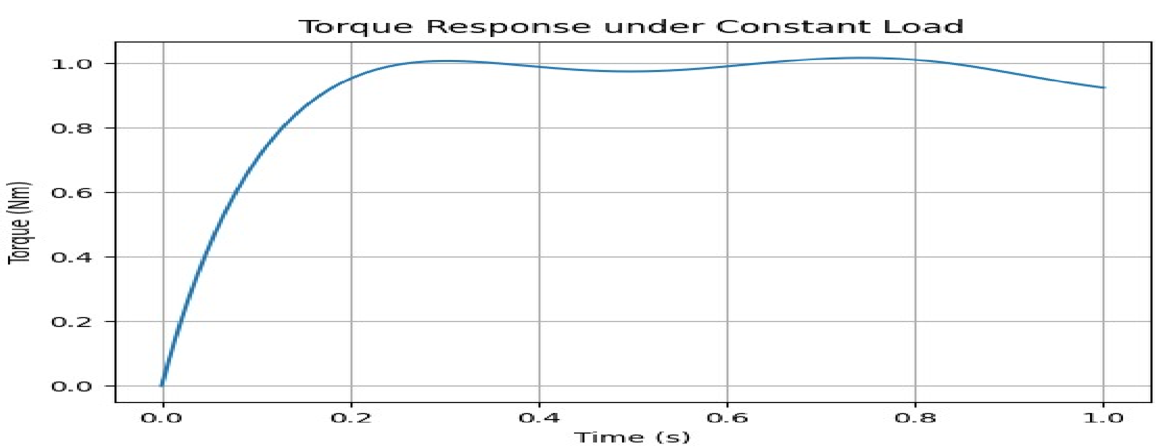


Figure 7: Torque response under constant load condition

Torque Control under Varying Load Conditions

When subjected to varying load torque, the performance of conventional controllers deteriorates due to disturbances. The PID controller exhibits oscillations, while the fuzzy controller shows slower adaptation. The Fuzzy-PID controller demonstrates robustness by maintaining stable torque with minimal deviation, confirming its adaptability.

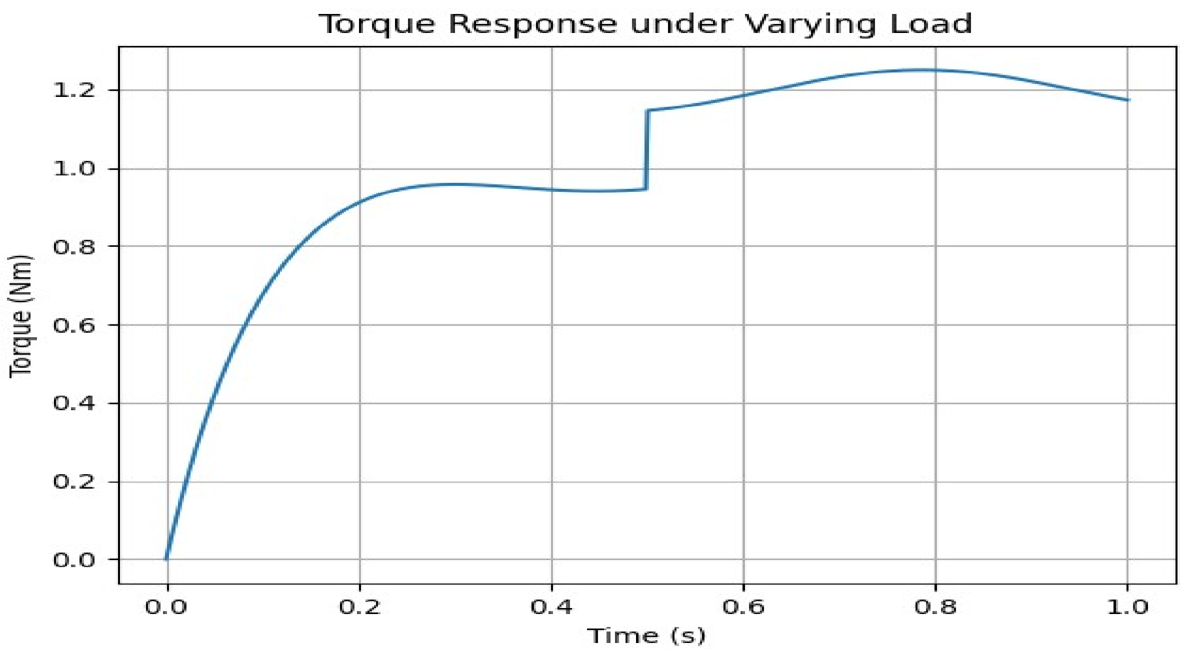


Figure 8: Torque response under varying load condition

Robustness Analysis

The robustness of the Fuzzy-PID controller is validated by varying system parameters such as stator resistance. The results indicate only slight variations in transient response, confirming the controller's ability to maintain stable torque control. The simulation results confirm that the proposed Fuzzy-PID controller outperforms conventional PID and fuzzy controllers in torque control applications. It provides faster response, improved stability, and better disturbance rejection, making it suitable for high-performance industrial applications.

4.0 Conclusion

This study presented the design and implementation of a hybrid Fuzzy-PID controller for torque control of a three-phase induction motor. The mathematical model of the motor was developed using the d–q axis transformation, and the control system was implemented in a closed-loop configuration within a MATLAB/Simulink environment. The performance of the proposed controller was evaluated under no-load, constant load, and varying load conditions and compared with conventional PID and fuzzy logic controllers. Simulation results demonstrated that the Fuzzy-PID controller achieved faster rise time, reduced settling time, minimal overshoot, and lower steady-state error in torque response. It also exhibited strong robustness against load disturbances and parameter variations. Compared to standalone controllers, the hybrid approach effectively combined adaptability and precision, resulting in improved dynamic and steady-state performance. In a nutshell, the proposed Fuzzy-PID controller provides an efficient and reliable solution for high-performance torque control in induction motor drive systems, making it suitable for industrial applications requiring accuracy and stability.

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