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A Hybrid Pi-ANN Framework for Non-Linearity And Performance Analysis of the Torque and Speed of an Induction Motor

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ABSTRACT

Induction motors are crucial in industrial settings due to their reliability and efficiency in converting electrical energy into mechanical energy. Their extensive application across various industries underscores the necessity for ongoing research and development. However, the performance of induction motors are notably affected by nonlinearities caused by factors such as magnetic saturation, thermal variations, and fluctuating load conditions. When handling dynamic variations in control systems, traditional proportional-integral (PI) controllers struggle to adapt quickly and effectively due to their inherent limitations. In contrast, standalone Artificial Neural Network (ANN) models possess a greater capacity for handling these variations but often demand substantial training data and computational resources for optimal performance. Hybrid control systems that combine Proportional-Integral (PI) controllers with artificial neural networks (ANNs) have been designed to effectively manage nonlinear disturbances encountered during motor operations. To assess the efficiency of this hybrid control system, simulations were executed using MATLAB/Simulink, focusing on a model of a 3-phase, 5-horsepower induction motor. The results showed that the hybrid control system outperformed traditional PI controllers in terms of torque ripple, speed overshoot, settling time, and steady-state error, demonstrating the potential for improved motor performance and stability in real-world applications. In conclusion, the integration of artificial neural networks (ANNs) with traditional control methods has proven to be a promising approach for enhancing motor control systems.

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INTRODUCTION

An induction motor is an AC motor that operates through electromagnetic induction, generating a rotating magnetic field to drive the rotor, which in turn causes the motor to rotate. This design ensures efficient operation across various industrial and commercial applications, including metalworking, woodworking, and general-purpose machinery, press-forming, weaving, sewing, hoisting, and earth-moving equipment [1].

The construction of IM are primarily divided into two parts, the stator and rotor, in addition to its low cost, minimal maintenance requirements, ruggedness, excellent starting torque, and comparatively high efficiency. The stator is the stationary part of the motor that generates a rotating magnetic field, while the rotor is the rotating part that interacts with this field to produce mechanical motion. These features make induction motors suitable for a wide range of industrial and commercial applications, from

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pumps and fans to conveyor belts and compressors. In addition, there are also two primary types of rotors: squirrel-cage and wound-rotor, although this article focuses on the squirrel-cage kind due to its simplicity and reliability [2].

In applications where the need for automation is diminish, industrial machines (IMs) often operate without advanced control systems, depending primarily on manual intervention from human operators. This approach can lead to cost reductions for businesses that do not necessitate elaborate automated solutions. However, to maintain the reliability and efficiency of IMs in environments lacking automatic control mechanisms, it is crucial to have a clear understanding of their operational dynamics, and providing adequate training for operators is essential to ensure optimal performance in such settings [3]. Research into the operating modes of induction motors (IM) is vital due to its implications on starting characteristics, fault detection, and diagnosis. Ongoing studies concentrate on fault detection, condition monitoring, and practical diagnostics in these systems, highlighting the importance of further exploration in this field to improve the efficiency and reliability of induction motors in various applications. Furthermore, advancements in technology and data analysis techniques have opened up new possibilities for enhancing the performance and lifespan of IMs through more accurate monitoring and diagnosis methods [4].

The study of the dynamic operating modes of the induction motor in low-inertia drives helps optimize performance and efficiency, ultimately leading to improved overall system performance. By understanding and analyzing electromagnetic transient phenomena, engineers can develop control strategies that enhance the motor's response to varying operating conditions, resulting in better precision and accuracy in critical applications, and advancements in control algorithms and sensor technology have further improved the capabilities of low-inertia drives, making them essential components in modern automation systems, particularly in industries where rapid and precise movements are required [5]. Induction motor applications necessitate sophisticated control methods for high-accuracy drives, effectively managing nonlinear and coupled motors with time-variant parameters. While PID controllers are favored for their design simplicity, stability, and robustness, alternatives like model predictive control (MPC) and fuzzy logic control have also been employed to enhance speed regulation, torque control, and energy efficiency in induction motor drives [6].

The shift towards enhancing the functionality and performance of electric drives has led to the adoption of advanced controllers that outperform traditional ones, particularly in nonlinear and complex systems like induction motors. In conventional designs for rotor field-oriented control (RFOC) of induction motors, a proportional integral (PI) controller is utilized. However, this controller introduces several challenges, including increased overshoot and oscillations in speed and torque, due to its inability to adapt effectively to changes in system dynamics and external disturbances [7]. Advanced control strategies, particularly model predictive control (MPC), are being investigated for induction motor speed control to enhance performance and robustness in the face of varying operating conditions and disturbances. These strategies involve optimizing control inputs over a finite time horizon based on a dynamic model of the system, allowing for improved response to changing conditions and disturbances compared to traditional control methods [8].

Using vector control technology, induction motors can achieve independent control of speed and torque, akin to the operation of separately excited DC motors. This is accomplished through classical Field-Oriented Control (FOC), which employs a Proportional-Integral (PI) controller designed to regulate the speed of the induction motor drive effectively while also maintaining precise control over the torque output. The implementation of the PI controller ensures that the motor maintains stable performance throughout its operational range, enhancing its efficiency and responsiveness to varying load conditions [9]. Conventional speed control methods struggle with accuracy and performance, particularly under load

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disturbances, and classical linear control is effective only at a single operating speed. In contrast, fuzzy logic provides a means to emulate human-like reasoning in control systems, allowing for the design of fuzzy controllers that utilize linguistic descriptions for process control for improved accuracy and robustness across a wide range of operating conditions [10].

PROBLEM STATEMENT

Induction motors are expected to provide smooth, accurate torque and speed tracking. In reality, their behavior is non-linear due to factors like magnetic saturation, thermal induced resistance changes, and load inertia variations. These factors can lead overheating and distortions, motor failure and mechanical stress as well as reduction in the overall motor’s efficiency. Conventional Proportional Integral (PI) controllers are widely used for induction motor control due to their simplicity. However, they struggle with the motor's inherent non-linearities such as parameter variations, magnetic saturation, and load disturbances leading to suboptimal torque and speed performance under dynamic conditions.

While artificial neural networks (ANNs) can model non-linearities, they lack the straightforward stability and zero steady-state error of PI control. This research addresses the gap by developing a hybrid PI-ANN framework. The core problem is to systematically analyze and quantify how this hybrid architecture improves non-linearity compensation and dynamic performance (overshoot, settling time, torque ripple) compared to conventional PI control, thereby establishing a robust method for high-performance induction motor drives. Hence, there is need to develop a robust, sensor-less framework for accurate, real-time torque and speed estimation with superior transient and steady state performance

The Paper Organization

The paper is organize as follows: Section I presents the introduction of the research work, section II presents the overall methodological structure of the system, the dynamic model of the induction motor, and Section III presents the details of the developed framework. The simulation results obtained from the torque and speed of the induction motor in different conditions are presented in Section IV. Section V presents the conclusion and future scope of the work.

METHODOLOGY STRUCTURE

This study proposes a hybrid control framework that combines a traditional proportional-integral (PI) regulator with an artificial neural network (ANN) to improve control and management of non-linearity in induction motor torque and speed. The approach aims to leverage the advantages of PI regulation alongside ANN capabilities for enhanced motor dynamic performance. Key components of the methodology include system modeling, design of the hybrid PI-ANN structure, and ANN training, all intended for MATLAB/Simulink implementation. Performance evaluations demonstrate the framework's effectiveness in managing asynchronous motor operations under varied load and speed transients, showcasing improved torque and speed response compared to traditional PI controllers.

Induction Motor Dynamic Model

To enhance the analysis of the three-phase squirrel-cage induction motor's dynamic behavior and eliminate time-varying inductances, the motor is modeled in the synchronously rotating d-q frame. This approach offers a comprehensive understanding of motor performance across different operating conditions, facilitating the investigation of torque production, speed control, and efficiency optimization. By incorporating both mechanical and electromagnetic dynamics, this model serves as a foundational tool for developing control strategies aimed at improving the motor's overall performance and efficiency. The dynamic equations are constructed in three phases and illustrate the electrical and mechanical interactions within the motor. These interactions are crucial for precisely forecasting the motor's performance in practical scenarios.

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Voltage Equations: The voltage equations describe the relationship between the stator and rotor voltages, taking into account the motor's electrical characteristics.

$$V_{ds} = R_s * i_{ds} + \frac{d(\psi_{ds})}{dt} - \omega_e * \psi_{qs} \quad (1)$$

$$V_{qs} = R_s * i_{qs} + \frac{d(\psi_{qs})}{dt} + \omega_e * \psi_{ds} \quad (2)$$

$$V_{dr} = 0 = R_r * i_{dr} + \frac{d(\psi_{dr})}{dt} + (\omega_e - \omega_r) * \psi_{qr} \quad (3)$$

$$V_{qr} = 0 = R_r * i_{qr} + \frac{d(\psi_{qr})}{dt} + (\omega_e - \omega_r) * \psi_{dr} \quad (4)$$

Flux Linkage Equations: The flux linkage equations describe the relationship between the stator and rotor flux linkages, providing insight into the motor's magnetic behavior.

$$\psi_{ds} = L_s * i_{ds} + L_m * i_{dr} \quad (5)$$

$$\psi_{qr} = L_r * i_{qr} + L_m * i_{qs} \quad (6)$$

The electromagnetic torque equation relates the motor's torque output to the current flowing through the stator windings, allowing for accurate prediction of the motor's rotational force.

$$T_e = \left(\frac{3}{2}\right) * \left(\frac{P}{2}\right) * \left(\frac{L_m}{L_r}\right) * (\psi_{dr} * i_{qs} - \psi_{qr} * i_{ds}) \quad (7)$$

Where: R_s and R_r are Stator and rotor resistances, Ls, Lr and Lm are Stator, rotor, and magnetizing inductances, ωe and ωr are Electrical and rotor angular speeds, ψ is the Flux linkages, Te and TL are Electromagnetic and load torques, J is the Moment of inertia, B is friction coefficient and P is the Number of poles

Induction Motor (Im) Parameters

The motor nominal parameters for the five horsepower (5 HP) simulation are shown in Table 1.

Table 1: Induction motor parameters

S/N	Motor parameter	Parameter Value
1.	Power Rating	3700 W
2.	Poles (P)	4
3.	Stator Resistance (Rs)	0.405 Ω
4.	Rotor Resistance (Rr)	1.05 Ω
5.	Stator Inductance (Ls)	0.65H
6.	Rotor Inductance (Lr)	0.0065 H
7.	Magnetizing inductance (LM)	0.115H
8.	Moment of Inertia (J)	0.05kg·m²,
9.	Voltage (Line-Line)	415V
10.	Frequency (F)	50Hz
11.	Power Rating	3700 W
12.	Friction Coefficient (B)	0.0025 N·m·s

The Developed Framework

The developed hybrid PI-ANN framework integrates a proportional-integral (PI) controller with an artificial neural network (ANN) to enhance the real-time estimation and performance analysis of induction motor torque and speed. The framework is systematically divided into two components: the first component elaborates on the structure and operational mechanisms of the PI controller, while the second component delves into the ANN model, which is specifically designed for torque and speed estimation in induction motors.

The Pi Control Loop

Field-Oriented Control (FOC) is necessary for precise AC motor management because standard Proportional-Integral (PI) control does not provide the required coordinate transformations. FOC allows for independent control of torque and flux through the use of PI loops in the dq-frame. While it is possible to implement a PI closed-loop controller without

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FOC, doing so would lead to significantly inferior performance in induction motors compared to using FOC in conjunction with PI controllers [12]. The field-oriented control (FOC) serves as the foundational framework that enables the operation of alternating current (AC) motors to be managed in a manner similar to direct current (DC) motors, providing precise control over speed and torque [13].

The PI component focuses on the feedback control loop of a proportional-integral (PI) controller used to regulate motor torque and speed. It explains the mechanism by which the PI controller modifies the motor input voltage according to the error signal derived from the difference between desired and actual torque/speed values. This is crucial for achieving precise control and stability across varying operating conditions, ensuring optimal performance and efficiency of the induction motor.

Outer Loop (Speed)

A PI (Proportional-Integral) controller operates within an outer loop system where it performs the crucial task of comparing a specified reference speed with the actual measured speed obtained from the feedback of the motor. This comparison is essential for maintaining optimal performance, as it assesses the discrepancy between desired and actual speeds. Based on the difference, the PI controller generates a torque reference signal, which is then utilized by the inner loop control system to make necessary adjustments to the motor's operation.

Inner Loop (Speed)

Inner Loop (Current/Torque) utilizes two distinct PI controllers to regulate the d-axis (flux) and q-axis (torque) currents for precise control of motor torque and speed. These controllers compute the error between the current values transformed by Field-Oriented Control (FOC) and the desired reference values, ultimately generating the necessary voltage outputs (Vd, Vq) to achieve the targeted performance.

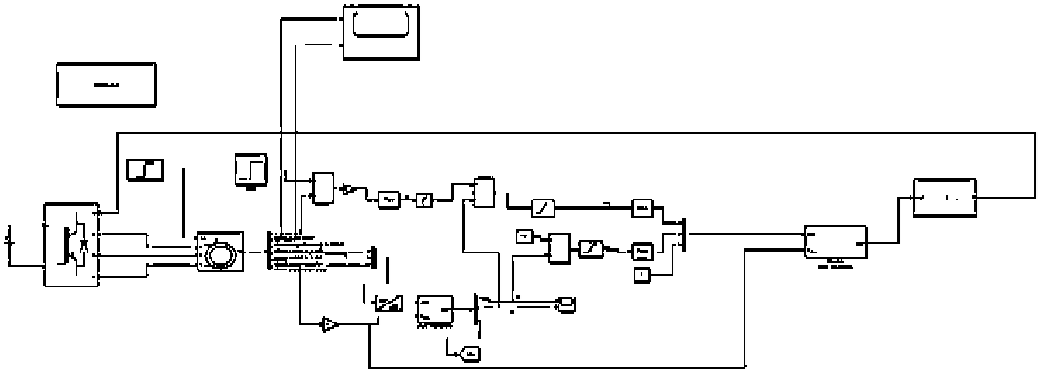

Fig. 1.1: PI Control Model of Induction Motor

Fig: 1.1 depicts the PI induction motor model, which is sensitive to the parameter's variation, and provide a baseline estimate based on the fundamental motors model.

The ANN Estimator

The Artificial Neural Network (ANN) Estimator leverages the output from the Proportional-Integral (PI) controller along with various motor parameters as inputs. This combination enables the real-time prediction of both the torque and speed of the induction motor, allowing for precise control and monitoring of its performance. In high-performance motor drives, the ANN is usually used to estimate variables that are difficult to measure directly in real-time, such as torque and speed. Levenberg-Marquardt is the algorithm commonly utilized for training due to its effectiveness in applications related to speed control and parameter estimation within motor control systems.

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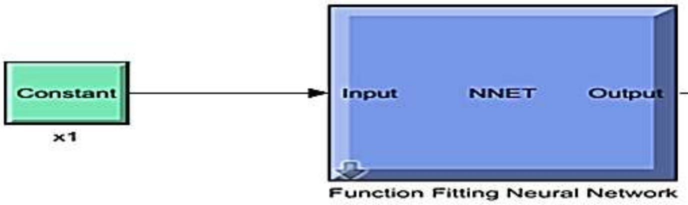

Fig. 1.2: ANN Regression Model

Fig: 1.2 depicts an ANN regression model, The (ANN) estimation tool is designed to perform multiple essential functions, including data modeling, prediction, and analysis, within its designated framework, which includes the following:

1. Inputs (x) and Target (y)
   Stator Currents: (i{sa}, i{sb}) or converted d-q frame currents (i{sd}, i{sq}).
   Stator Voltages: (v{sd}, v{sq}).
   Reference Speed/Torque: To provide the network with the desired operating point.
2. Target (y): Electromagnetic Torque (Te) and Rotor Speed (omega, r)

Fig. 1.3: PI-ANN Hybrid Model of Induction Motor

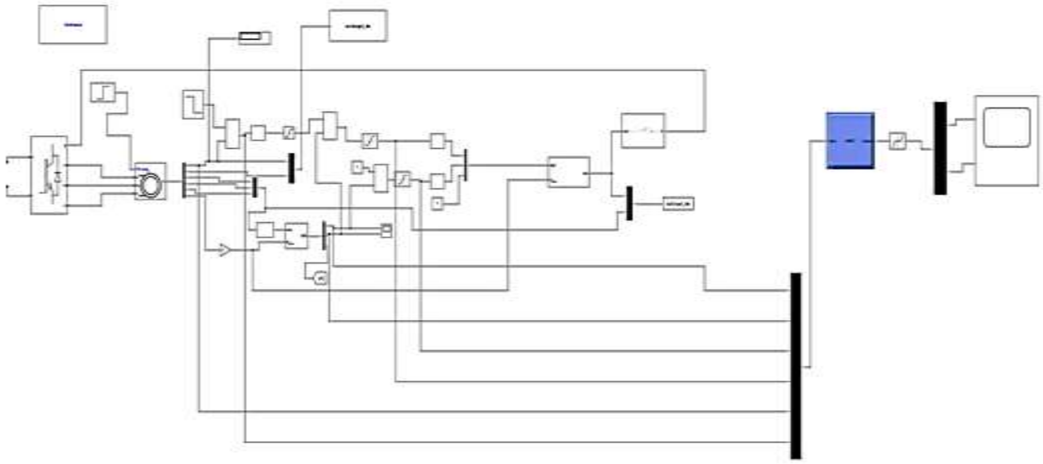

Fig. 1.3: PI-ANN Hybrid Model of Induction Motor

Fig: 1.3 depicts the PI-ANN hybrid induction motor model, the power Stage consists of a DC source connected to a three-phase Voltage Source Inverter (VSI) for driving an induction motor. The standard three-phase industrial supply is rated at 415V, representing the root mean square (RMS) value. The relationship between line-to-line RMS voltage (V{L-L,rms}) and peak voltage (V{peak}) is established.

$$V_{peak} = \sqrt{2} \times V_{L(rms)} \quad (8)$$

DISCUSSION AND RESULTS FOR HYBRID FRAMEWORK INDUCTION MOTOR MODEL

The developed hybrid control framework for an induction motor was evaluated with MATLAB/Simulink. This configuration typically consists of a power electronic inverter stage, an induction machine plant, and a hybrid controller designed to improve the nonlinearity responses of the motor's mechanical output.

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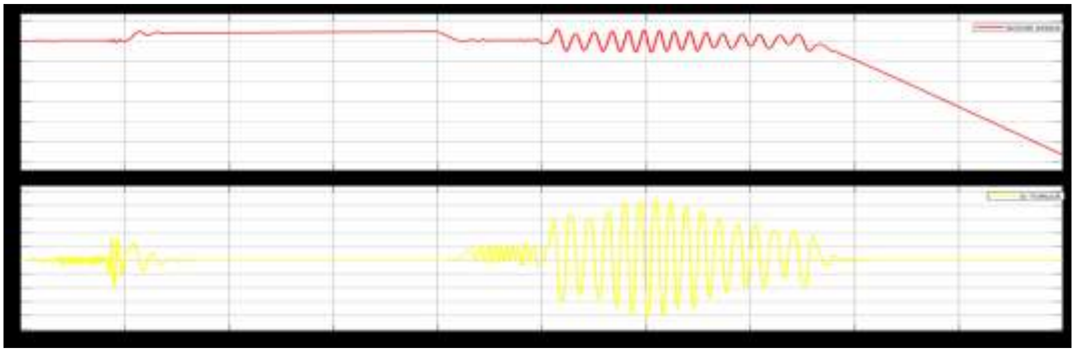

Fig 1.4 Waveform of an induction motor with PI controller

Analysis of Speed Responses

The motor exhibits efficient PI controller tracking with little chattering as it quickly accelerates from 0 rpm to a reference speed and maintains a steady performance between 0.5 and 2 seconds. On the other hand, a disturbance at about two seconds causes a brief decrease in speed along with a discernible oscillation. The PI controller raises the current to produce more torque in order to offset this load disturbance. The system does not completely return to the initial reference speed, despite a droop at the end indicating a partial speed recovery. This behavior highlights that while the PI controller provides reasonable regulation, the system demonstrates nonlinearity characterized by slower recovery and oscillatory motion.

Analysis Torque Response

There is a notable high-magnitude spike in torque at t=0 during the induction motor's starting phase, typical when no load is applied, where it stabilizes near zero consistent with constant-speed operation and friction losses. At t=2 seconds, a load disturbance induces significant oscillations in torque between approximately +150 and -150 Nm. This behavior in a PI-controlled system indicates the controller is responding to load or reference speed changes but lacks adequate damping for stabilization. Eventually, the torque stabilizes at a higher positive value to counterbalance the imposed load torque, demonstrating the system's ability to adapt to disturbances. However, it highlights the need for further tuning of the controller parameters to enhance response time and improve overall stability.

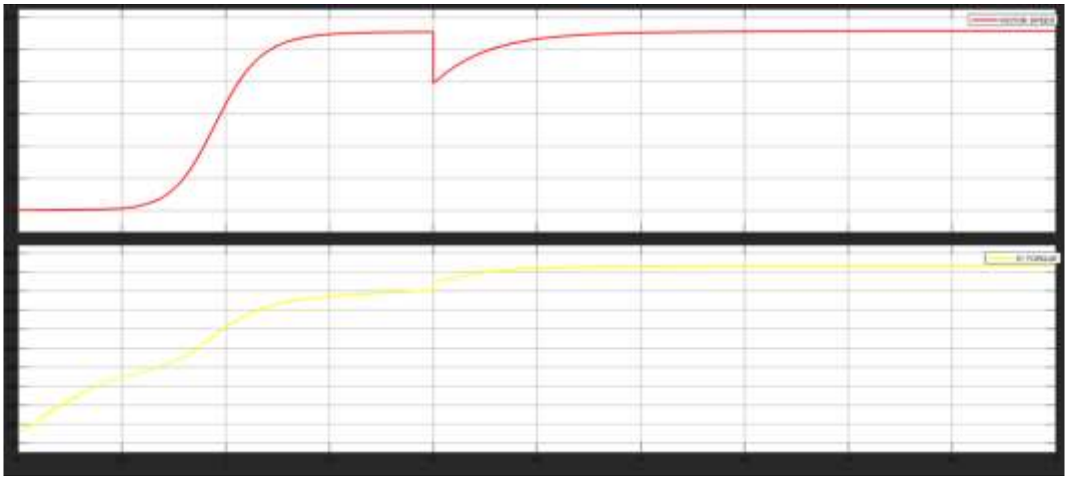

Fig 1.5 Waveform of an Induction Motor with PI-ANN Framework

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Analysis of Speed Responses

The rotor speed in Fig. 1.5 exhibits an exponential rise towards a steady-state reference, characterized by a smooth acceleration profile. The implementation of an ANN compensated PI controller proves effective in mitigating the inherent inertia and non-linearity typically associated with conventional PI controllers during the start-up phase. These points to a comparatively damped system that is potentially optimized to avoid high inrush currents or mechanical strain on the motor that could lead to premature wear and tear.

The system achieves stabilization between 1.2 and 2 seconds, successfully reaching a steady state without ripples or overshoot. However, there is a brief momentary dip in speed before a swift recovery occurs, indicating the application of a load torque step. The hybrid PI-ANN architecture exhibits robust performance by restoring the set-point speed in about 0.5 seconds, highlighting the effectiveness of integrating both components to handle sudden dynamic changes. This approach improves performance and addresses nonlinearity in induction motor control, which a standard PI controller may not manage effectively alone.

Analysis of Torque Responses

A high initial torque is produced as shown in Fig.1.5 to counteract inertia and facilitate rapid motor acceleration, and the smooth profile suggests that the PI-ANN hybrid effectively curtails the high-frequency issues typically present in pure hysteresis or basic switching controllers. When a dynamic load change occurred at t = 2s, there was a simultaneous decrease in speed and an increase in torque to meet the higher mechanical demand. This "step-up" signifies that the controller is operating in a closed-loop mode, successfully balancing the power demand to sustain the desired speed. The initial dip in speed indicates that a load disturbance was introduced, causing the motor to decelerate due to an increase in load.

The torque waveform is remarkably clean; however, induction motors usually exhibit high-frequency ripples in torque due to inverter switching; the PI-ANN hybrid appears to be filtering or suppressing these oscillations effectively. Even with the sudden change, the speed does not dip significantly before rising, and the torque settles quickly without hunting or sustained oscillation. This hybrid framework resolves the motor's inherent nonlinearity, essential for stable and efficient operation. Its real-time torque adjustment demonstrates the effectiveness of the PI-ANN hybrid system in controlling performance under varying conditions, ensuring smooth control even with load variations.

Table 2: The performance of PI-ANN controller

Performance Metrics	**PI Controller**	**PI-ANN Controller**
Settling time	High	Low
Torque ripples	High	Low
Overshoot	High	Low
Undershoot	High	Low
Steady state error	High	Low

Table 2 depicts the quantitative performance metrics of the PI-ANN controller from the simulation result. The table compares the performance **of** the PI controller and the PI-ANN controller. The PI-ANN controller notably enhance performance across all metrics.

CONCLUSION

This research presents a hybrid proportional-integral and artificial neural network (PI-ANN) framework aimed at improving induction motor torque and speed control. The developed system successfully addresses the challenges posed by non-linearity and dynamic complexities in motor control, leading to enhanced performance. The proposed PI-ANN framework demonstrates superior adaptability and robustness compared to traditional control methods, making it a promising solution for optimizing motor control systems. Compared to a standalone proportional-integral (PI) controller, this hybrid framework leads to a significant reduction in overshoot, enhances torque response, and provides quicker recovery from

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disturbances with minimal deviation. By combining the stability of classical PI control with the advanced mapping characteristics of artificial neural networks, the proposed system significantly enhances both transient and steady-state performance of the motor control system.

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