



PID and ADRC Controller: A Comparative Analysis for Induction Motor Speed Regulation

Sarah Haider Abdulredha¹, Sana Khalid Abdul Hassan² and Israa Hashim Latif ³✉.

^{1,3}Department of Computer Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq

²Department of Electronic and Communications Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq

✉ These authors contributed equally to this work

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Abstract

Three-phase induction motors (IM) are widely utilized in various applications such as fans, milling machines, conveyor systems, robotics, pumps, and heavy machinery. Tasks that require precise speed control often demand additional control systems to ensure efficient and accurate operation. Unfortunately, the speed control of induction motors is a difficult problem due to system nonlinearity, parameter variations, and external disturbances. Therefore, standard proportional-integral-differential (PID) control systems are among the various techniques available for motor speed regulation. In this paper, the PID controller is used as a criteria to assess the efficacy of the proposed approach. This work specifically addresses the use of a toolbox controller for active disturbance rejection control (ADRC) to control the speed of a three-phase IM. The ADRC toolbox is a software tool (often a MATLAB/Simulink toolbox or library) designed to help users implement ADRC methods in their systems without having to code the algorithms from scratch. The speed performance of the motor was compared between PID and ADRC controllers. The evaluation was performed under steady state operation, with the intention of establishing and maintaining the speed of 1400 rpm. By simulation, the performance of the controllers in respect of rise time, settling time and the current consumption in all the simulations was analyzed conducted through MATLAB/Simulink. Simulation data indicate that the ADRC system outperforms conventional PID controllers when used with induction motors. Performance indicators such as ITAE (14.3 vs. 19.7), ISE (234.01 vs. 251.13), and RMSE (644.21 vs. 660.62) demonstrate that the ADRC system provides higher accuracy, faster response, and more efficient speed regulation control compared to the PID system. The results reveal that ADRC has better performance, especially in disturbance suppression. starting current, which contributes to extending the motor's operational lifespan. Additionally, ADRC ensures smooth acceleration of rotor speed with a lower rise time of 0.3s as well as settling time of 0.36s, allowing the system to reach steady-state speed more efficiently. ADRC is more adaptive to nonlinear and unpredictable settings than PID since it actively compensates for total disturbances and estimates them.

Keywords: *Three Phase Induction Motor, Speed Controller, ADRC Toolbox, PID, MATLAB/Simulink.*

Corresponding author: Provide the corresponding author information and publisher here. E-mail address: sarah.haider.a@nahrainuniv.edu.iq

1. Introduction

The wide use of three-phase induction motors in the modern contemporary industrial applications was due to variety of their functions and advantages. This type of motors has many remarkable properties, including structural simplicity, cost-effectiveness, durability, and robust performance despite requiring minimal maintenance [1]. The increasing in the load applied to three-phase AC induction motors will cause an increasing the slip ratio value and in the meanwhile a decreasing in the motor speed. For this, keeping the speed of a motor constant, is a crucial parameter in the different industrial contexts [2]. Without using a speed controller, will result in a corer problem, because induction motor will experience unstable speed, immoderate starting current, and poor efficiency. This unregulated operation will increase mechanical wear which leads to higher maintenance costs and reducing motor life. Additionally, the motor may not meet the load requirements,

exposing efficiency, safety risks, and possibility damage to processes or loss in products [3]. Speed control of induction motors is cosidered as a main attribute of their operational dynamics, which led to the development of many and different control methodologies concerning in improving the performance of induction motors. One of these effective strategies in speed regulation is the incorporation of a PID controller. the carefully calibrating of the PID parameters, the optimum speed can be obtained; which cosidered as a main operational component of the three-phase induction motors [4]. the various control approaches were used in achieving maximum optimum performance in these motors. Additionally, alternative control systems, such as sliding mode controllers [5], fuzzy PID controllers [6], neural network controllers [7], reinforcement learning controllers [8], and ADRC controller have been distinctively evaluated through simulation methodologies.

Induction motors have coupled torque and flux, which makes speed control difficult. In contrast to direct current (DC) motors, which

have independent, controllable torque and flux-producing components, the interaction in induction motors complicates direct control of speed [8][9].

In this paper, an ADRC toolbox is used as a controller. This can significantly contribute to control system design and offers several advantages that make it a valuable resource for practitioners and researchers. ADRC toolbox provides several benefits, such as strong resistance to external disturbances [10] and compatibility with large-scale and time-delay systems [11] which is simplified controller design by automating tasks like disturbance estimation and parameter tuning. It is robust against uncertainties, flexible across various systems, user-friendly with an intuitive interface, and supports customization. It aids learning, integrates with tools like MATLAB/Simulink, and reduces development time with pre-configured features. The toolbox acts as a bridge between the theory and practical application, streamlining the process for users who might not want to delve into the mathematical details of ADRC.

Additionally, this study accomplishes a comparative detailed study of ADRC and PID controller in means of vector control techniques. Given the inherent benefits of vector control, which is a well-established approach for AC motors, it is expected to gradually replace scalar control methods [9]. One of the main advantages of the PID controller, which considered as a long-standing and effective tool in control systems, is the widely recognition in maintaining system stability [12]. It adjusts the system's output in response to errors, thereby ensuring the desired level of stability and reliability. The controller operates based on three main parameters: proportional (K_p), integral (K_i), and derivative (K_d), which can be fine-tuned through iterative trial-and-error methods [2]. The flexibility of the PID controller allows for its implementation in various configurations PID, PI, or PD and it remains a central element in most feedback control systems [3][4]. Despite its advantages, the PID controller has limitations, one of the most notable being the prolonged time required to reduce errors and achieve a steady-state speed. This limitation highlights the need for alternative control strategies like ADRC controller due to simplify the design, simulation, and deployment of ADRC-based controllers which is a practical software tool built to facilitate the implementation of ADRC in real-world and simulated environments. [13].

In this simulation, the speed controller of an induction motor is tested under an open-loop system, a closed-loop with a PID controller, and a closed-loop with an ADRC controller. After that, a comparison is achieved between ADRC and PID controllers. Usually the open-loop control system operates without using feedback control (with constant input voltage or current), it serves as the baseline for stator current, rotor speed, and electromagnetic torque. The PID-controlled system regulates rotor speed by adjusting the input based on feedback, to minimize speed error and getting an optimize motor performance. In general, the effective ADRC- controlled system, which is known for its robustness to disturbances and uncertainties, will outperform the PID controller, because it offers a better dynamic response and more efficiency. This comparison is focusing on the basic performance metrics (rise time, settling time, starting stator current and electromagnetic torque) in

order to achieve the effectiveness and stability of each control strategy.

2. Related Works

In [5], a control algorithm that integrates PID and sliding mode control (SMC) was used in designing, simulating and analyzing the speed control of a squirrel cage induction motor (SCIM). The speed of the SCIM motor was independently controlled by separating the torque and flux components.

In [9], The Proportional-Integral (PI) controller and a Space Vector Pulse Width Modulation (SVPWM) inverter were used in controlling the induction motor's speed. This method improved the speed response and eliminates steady-state error. Also, this method accelerates the motor's rise time by reducing it by (0.012 sec) at no load and (0.046 sec) at full load.

In [11], an adaptive ADRC controller strategy is suggested in controlling the speed of the induction motors without depending on the speed sensors. The State Error Feedback Control Ratio (SEFCR) serves as the foundation for the speed controller enhancing system dynamics. A sensorless induction motor drive is proposed in [14], incorporating a simplified self-tuning fuzzy logic controller (ST-FLC) and data-driven reinforcement learning (RL) for speed estimation. Fuzzy Logic Controllers (FLCs) are shown to offer significant advantages in speed regulation for induction motor drives, resulting in a 50.5% reduction in settling time, as well as reductions in current ripples (20.4%), torque ripples (15%), and current harmonics (14.9%).

A hybrid controller, combining PID control and fuzzy logic, is proposed in [15] for speed control of an induction motor driving a non-linear load, such as a pump. The hybrid model provides improved response compared to either a fuzzy logic or PID controller used individually.

Several works [16],[17] have demonstrated that ADRC outperforms traditional controllers in terms of robustness, fast response, and reduced overshoot. Its model-independent nature makes it particularly suitable for real-time applications, where adaptability and stability are crucial.

Therefore, the motivation to adopt ADRC in this study stems from its superior disturbance rejection capability, reduced reliance on system modeling, and strong robustness under nonlinear and uncertain conditions—features that are limited or lacking in conventional methods such as PID.

3. The Three Phase Induction Motor's Operating Principle

The operating principles of a 3-phase induction motor differ in comparison with those of a one-phase motor [18]. In a 3-phase induction motor, the stator windings are arranged 120 degrees apart to create a magnetic field that rotates, as illustrated in Figure 1 [19].

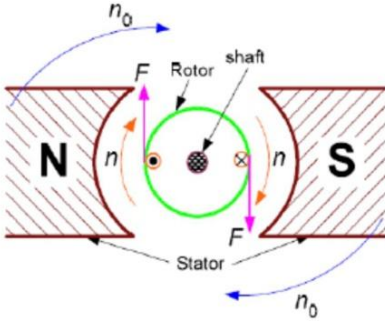


Figure 1. asynchronous motor magnetic field. [20]

The rotating magnetic field produces a current in the rotor, which causes a magnetic torque that causes the rotor to rotate. The rotor's speed is marginally slower than the synchronization speed of the rotating magnetic field. By changing the connections of the three-phase power supply, the rotor's rotational orientation can be reversed. [3][4]. The power source frequency and the number of poles dictate the motor's synchronous speed as (1).

$$n_0 = (120 \times f)/P \quad \dots(1)$$

where n_0 represents The speed of synchronous rotation in revolutions per minute (rev/min), f denotes the frequency of system source in hertz (Hz), and P indicates the pole number in the motor. Synchronous speed denotes the rate at which the stator's magnetic flux rotates, determined on the frequency of the power supply and the number of poles in the motor [18]. In industrial applications, the speed of the rotor is typically less than the speed of synchronization. The reason induction motors are often called asynchronous motors is that the rotor speed and the stator's magnetic flux speed are different the rotor speed and the stator flux speed [19], expressed as a percentage of the synchronous speed which the value typically ranges from 0.01 to approximately 0.06 of the speed of the stator flux. The slip value per unit as (2)

$$\text{slip} = s = \frac{(n_0 - n)}{n_0} p.u \quad \dots(2)$$

The rotor speed n is given as (3)

$$n = n_0(1 - s) \quad r.p.m \quad \dots(3)$$

The motor receives AC power through the stator windings, which causes the stator flux to revolve in the same direction as the supply current at a speed of n (in rev/min)

With the flux and current components in the rotating reference frame (d-q axis), the electromagnetic torque T_e produced in the induction motor may be computed as follows (4): [7]

$$T_e = (3/2) \times (P/2) \times (\psi_{ds} \times i_{qs} - \psi_{qs} \times i_{ds}) \quad \dots(4)$$

Where:

- T_e : Torque due to electromagnetic fields (Nm)
- P : Number of pole pairs
- ψ_{ds}, ψ_{qs} : d-axis and q-axis stator flux linkages
- i_{ds}, i_{qs} : stator currents on the d and q axes

The time-varying magnetic flux in an induction motor causes the rotor windings to produce the Rotor EMF Equations. Within the synchronously rotating reference frame, also known as the rotor reference frame, [6][7], the EMF formulas are written as (5)(6):

$$e_{dr} = d(\psi_{dr}/dt) - (\omega_e - \omega_r) \times \psi_{qr} \quad \dots(5)$$

$$e_{qr} = d(\psi_{qr}/dt) + (\omega_e - \omega_r) \times \psi_{dr} \quad \dots(6)$$

where:

- e_{dr} : rotor EMFs on the d and q axes
- ψ_{dr}, ψ_{qr} : Rotor flux connections
- ω_e : synchronous electrical angular speed
- ω_r : the electrical angular speed of the rotor.

The following are the rotor voltage equations in the d-q axis (7) and (8):

$$v_{dr} = R_r \times i_{dr} + d(\psi_{dr}/dt) - (\omega_e - \omega_r) \times \psi_{qr} \quad \dots(7)$$

$$v_{qr} = R_r \times i_{qr} + d(\psi_{qr}/dt) + (\omega_e - \omega_r) \times \psi_{dr} \quad \dots(8)$$

Where:

- v_{dr}, v_{qr} : The d-q axes for rotor voltages
- R_r : Rotor resistance
- i_{dr}, i_{qr} : d- axis and q-axis rotor currents

3.1. Induction Motor Drives

Induction motors, also referred to as asynchronous motors comprise two main windings: the stator winding and the rotor winding, both designed for three-phase operation. These motors are commonly used in variable-speed drives [2]. When the stator winding receives a balanced three-phase AC voltage, a magnetic flux is induced in the rotor, similar to the operation of a transformer. There are a number of ways to modify the rotor voltage, alter the frequency, and regulate the stator current, voltage, and frequency in order to change the speed (rpm) and torque of induction motors to control the motor's performance. To achieve the desired RPM and torque, it is essential to adjust parameters such as duty cycle, voltage, current, and frequency [9]. This paper aims to control an induction motor (RPM) by regulating the stator voltage. This can be accomplished using Sinusoidal the Pulse Width Modulation (SPWM) technology, combined with universal bridge components, initially controlled by a PID controller, and later by an ADRC controller.

3.2. Three-Phase Inverter DC-AC Power Converter

In applications requiring high power, 3-phase DC-AC converters, or inverters, are commonly utilized in variable frequency drive systems. The design of a three-phase inverter involves three single-phase switches, with each switch connected to a separate load output terminals which is an electrical circuit designed to transform a DC to AC voltage source, power semiconductor devices like SCRs, transistors, and MOSFETs are frequently employed in inverters to function as switches and converters [17]. A three-phase inverter uses these components to effectively convert DC power into three-phase AC power as in Figure 2 [20].

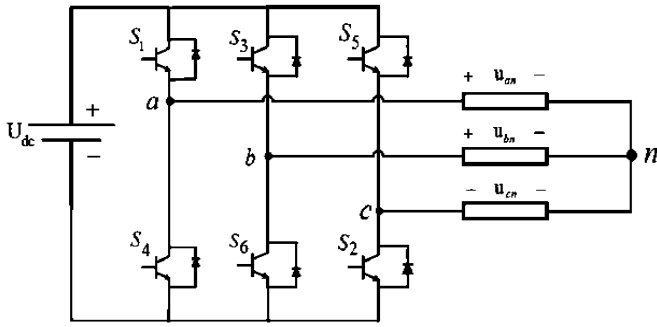


Figure 2. Circuit for converting three-phase AC to DC power [20]

4. The Proposed Controllers

4.1. ADRC Toolbox Controller

Because of the numerous internal and external disturbances that impact motor performance, the ADRC technique is ideal for managing induction motors. This study presents an open-source ADRC toolbox for MATLAB/Simulink, which is designed to simplify the implementation of high-speed controllers [21]. The ADRC-controlled system, introduced by Hahn in 1998, effectively results in strong transient responses by managing uncertainties [22]. The toolbox features a user-friendly drag-and-drop interface with customizable parameters, streamlining the application of ADRC to real-world control systems [23]. The changes in stator/rotor resistances and inductances, supply voltage fluctuations and harmonics, unmolded dynamics, and external environmental disturbances like vibrations and temperature effects are the primary causes of disturbances and perturbations in the context of an induction motor. These disruptions are intended to be estimated and rejected by ADRC's extended state observer (ESO). [24]. The ESO is fundamental, estimating both the system states and disturbances by adding a disturbance state to the system's state vector, enabling the observer to track both [24]. The Tracking Differentiator (TD) is an advanced filter that produce more accuracy of derivative estimates, enhances tracking performance, and makes ADRC more robust to noise. It enables more effective tracking of rapidly changing reference signals, especially in noisy conditions [25] [26]. The estimates from the ESO are used by the ADRC control law to calculate the control signal, applying key equations that focus on disturbance rejection and state estimation the system dynamics. The dynamics of an induction motor can be expressed mathematically as (9):

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t) \quad \dots(9)$$

Where

- $d(t)$ is the aggregate disturbance (comprising model uncertainty and external disturbances),
- $u(t)$ is the control input,
- $x(t)$ is the system state vector (e.g., motor speed , or rotor flux)
- A, B are the system matrices (depending on the system model).

The ADRC controller adjusts the control input $u(t)$ to successfully reject these disturbances by continually estimating $d(t)$ through the ESO, enhancing the induction motor speed control system's dynamic performance and robustness [25]. The ESO estimates the state $\hat{x}(t)$ and disturbances $\hat{d}(t)$ in real time [27][28]. The observer equations as (10)(11):

$$\dot{\hat{x}} = A\hat{x}(t) + Bu(t) + L_1(\hat{x}(t) - y(t)) + L_2\hat{d}(t) \quad \dots(10)$$

$$\dot{\hat{d}}(t) = -L_2(\hat{x}(t) - y(t)) - L_3\hat{d}(t) \quad \dots(11)$$

Where:

- $\hat{x}(t)$ is The estimated state, such as motor speed,
- L_1, L_2 : are the gains for the observer
- $\hat{d}(t)$: The estimated disturbance
- $y(t)$: Output that has been measured, such as actual speed
- L_1, L_2, L_3 :ESO observer gains, are adjusted according to the required bandwidth.

The ESO provides the estimated system states and disturbances that are used to build the control input $u(t)$ in ADRC. To guarantee reliable and accurate control, the controller adjusts in real time for the present system state $(x(t))$ and total disturbance $d(t)$, which are estimated by the ESO as (12).

$$u(t) = u_0(t) + \hat{d}(t) \quad \dots(12)$$

Where:

$u_0(t)$: basic PD controller with derivative and estimated state. The PD control term $u_0(t)$ as (13):

$$u_0(t) = -k_p\hat{x}(t) - K_d\dot{\hat{x}}(t) \quad \dots(13) \text{ Where:}$$

k_p : proportional gain and K_d : derivative gain.

The final ADRC control law as (14):

$$u(t) = -k_p\hat{x}(t) - K_d\dot{\hat{x}}(t) + \hat{d}(t) \quad \dots(14)$$

Where:

- $-k_p\hat{x}(t)$: lowers the error of the current (proportional control).
- $-K_d\dot{\hat{x}}(t)$: derivative control that dampens oscillations and accelerates response.
- $\hat{d}(t)$: rejects both internal and external disturbances by canceling the calculated disturbance.

These equations together form the core of the ADRC method, where the ESO estimates the system states and disturbances, and the control law uses those estimates to adjust the system's control input in real time, thereby rejecting disturbances and improving system performance. In the MATLAB/Simulink utilized ADRC Toolbox for involves a lot of efficient, simple, user- generally and friend-purpose function blocks for the engineering designers in using the ADRC concepts in the same method with little knowledge [29]. The primary objective of this study is to ease the architecture's implementation process in this paper by using ADRC toolbox where the developed block is shown in Figure 3(a), in MATLAB/Simulink, which is regarded as the prepared drag-and-drop ADRC function block, where the input signal is represented by single output u , the plant output control by y , and the reference signal by r . [29][30]. There are four mandatory parameters must be selected which is produced as shown in the Figure 3(b) where n is the order of system dynamics is an appreciation of the parameter of input gain, W_0 is the observer bandwidth and W_c is the controller bandwidth and b_0 is the critical gain [26S]. These controller parameters (n, b_0, W_c, W_0) are fine-tuned through trial and error to achieve optimal performance

while ensuring low starting current and high starting torque [33]. The optimized ADRC parameter values are $n = 2$, $b_0 = 2 \times 10^6 \text{ W} = 6100$, and $W_c = 300$.

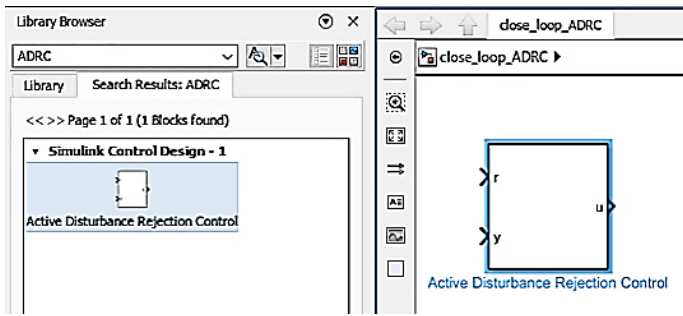


Figure 3. ADRC toolbox drag-drop ADRC block in MATLAB/Simulink.

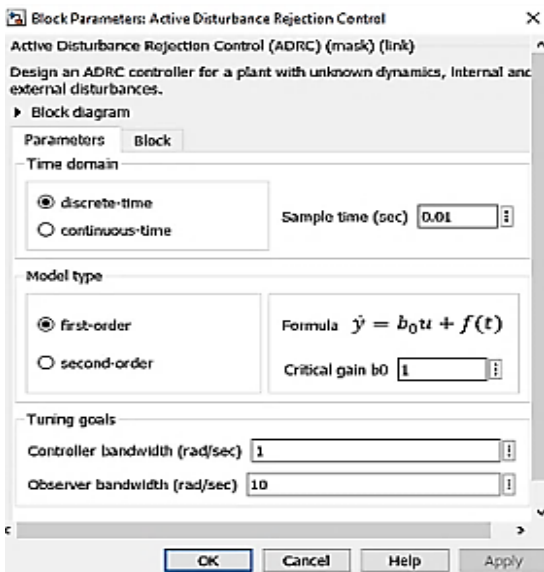


Figure 4. The setting of the parameter of ADRC toolbox block.

4.2. PID controller

The key of PID controller is a component of control systems and is widely used in many industries for its efficiency and simplicity. It works by continuously calculating an error value that represents the discrepancy between the target set point and the measured process variable [3][20]. It then executes corrective action derived from the proportional, integral, and derivative terms, which address the current, accumulated, and expected errors, respectively. This synergistic approach improves the stability and efficiency of systems [31][32]. Figure 5 explain the circuit design of the PID controller.

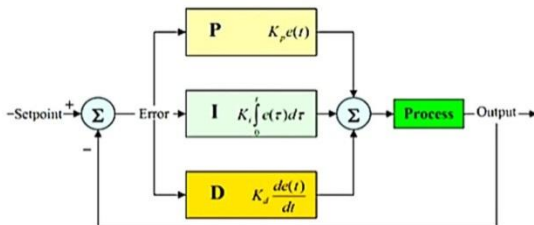


Figure 5. PID Circuit diagram [3].

The PID controller determines the control value $u(t)$ as indicated in (13), where K_p , K_i , and K_d stand for the coefficients for the proportional, integral, and derivative gains in sequential order (often referred to as P, I, and D) as (15).

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \dots (15)$$

where $u(t)$, a control signal that regulates the stator voltage through the inverter, is generated by the PID controller using $e(t)$, the resultant error. The induction motor's speed regulation is reliable and precise because to this closed-loop arrangement; the $e(t)$ is supplied as (16):

$$e(t) = SP - n \dots (16)$$

Where SP stands for the intended reference speed or set point, and n for the actual motor speed, which is determined by the synchronous speed and slip. The two are constantly tracked and contrasted.

The three elements in a control system, which are: proportional functions provide immediate corrective actions to reduce deviations from the desired value. Integral functions improve system stability by handling errors that accumulate over time and eliminating persistent steady-state errors. Differential functions shorten response times and increase system speed required to correct the mistakes, thus increasing overall efficiency. These elements work together to improve system performance by introducing corrective signals before deviation becomes too large [2][6]. The PID controller's parameters (K_p , K_d , K_i) are fine-tuned through trial and error to achieve the desired performance [34]. In this approach, the PID gains are selected based on the designer's experience and the system's response by using trial and error method. The resulting values for the PID gains are $K_p = 0.0088$, $K_d = 0.44$, and $K_i = 0.00002$.

The theoretical benefits of an ADRC system over a traditional PID controller must be discussed before providing the simulation results. Unlike the PID, which only handles defects after they happen, the ADRC uses an extended condition monitor (ESM) to forecast and control disturbances in real time. This allows the ADRC to sustain system performance in the face of external disruptions, parameter uncertainty, and changes in load torque.

While the PID does not mainly rely on preset gains intended for nominal conditions, the ADRC does not necessitate an exact mathematical model, which makes it more resilient to nonlinearities and unmolded dynamics. Additionally, the ADRC system's Tracking Differentiator (TD) increases the system's resilience to noise and its capacity to react rapidly to abrupt changes, which raises control stability and accuracy. With these theoretical benefits, ADRC should perform better when used in induction motor control systems, particularly in settings with dynamic, intricate, and ever-changing disturbances [33][20].

5. Simulation Design

5.1. Simulink Open Loop System Model

Figure 6 illustrates a Simulink model for an open-loop speed control system that uses a voltage source controlled by SPWM. The model includes a ramp function defined by a repeating sequence, with the following parameters: time values of [0, 0.1, 10] seconds and output values of [0, 50, 50] volts. The system is connected to a three-phase induction motor with specifications of 400 volts, 50 Hz, 1430 RPM, and a power rating of 5.4 HP (4 kW). In traditional scalar v/f control, additional components such as a controlled voltage source are required to adjust both the voltage magnitude and frequency,

maintaining a constant v/f ratio. This ensures proper motor operation and prevents issues like motor saturation, which could lead to overheating of the core and windings, reducing the motor's lifespan or potentially causing failure. By running this Simulink model and censoring the response of a motor's speed, valuable insights will be gain into the motor's behaviour under open-loop control state.

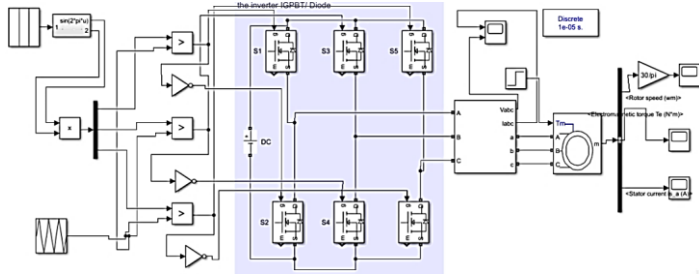


Figure 6. Simulink model of the open-loop system

5.2. Closed Loop Simulink Model with Controller

The closed-loop speed control system's Simulink model that implements a three-phase induction motor by using a PID controller, is shown in Figure 7. This model's setup presents an overview of how to use a PID controller in Simulink to control motor speed.

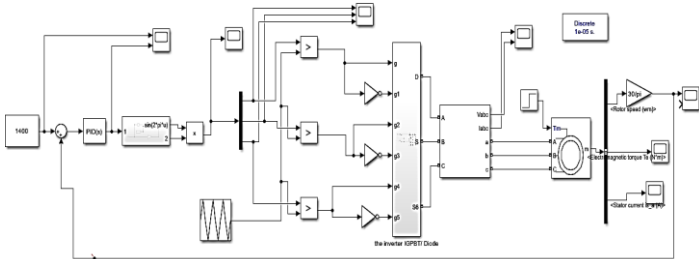


Figure 7. The Simulink model of close loop system with PID controller

The ADRC toolbox was introduced as an alternative to the traditional PID controller for adjusting motor speed. Using MATLAB/Simulink, the ADRC components are integrated to control a three-phase induction motor, targeting a reference speed of 1400 RPM, as shown in Figure 8. The results highlight the effectiveness of ADRC in managing motor speed control challenges, outperforming traditional PID controllers.

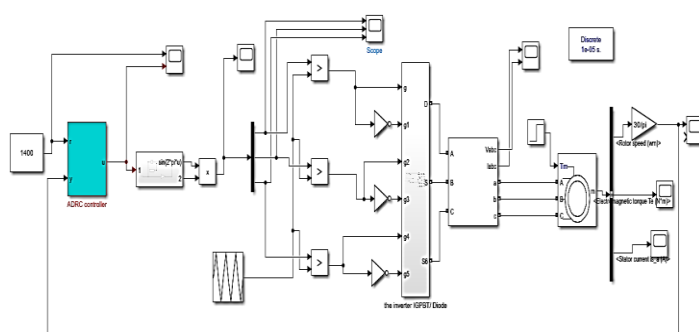


Figure 8. The Simulink model of close loop system with ADRC controller

6. Result and Discussion

Simulation results were obtained using MATLAB/Simulink software tools. The following figures display the outcomes, including the

rotor speed and electromagnetics torque results of the induction motor.

6.1. Results of an Open Loop System

In the simulation can show the results of open-loop performance of the system. In Figure 9 the stator current initially peaks at 48A before settling to 5 A. Figure 10 shows the rotor speed, increasing with slight oscillations and overshoots before settling at 1490 rad/s. Figure 11 shows the electromagnetic torque, which increases to 52 Nm with some oscillations and reaches a steady-state value of 10 Nm, consistent with the nominal load torque this higher starting torque with no feedback control. This can lead to overshooting and inefficiencies.

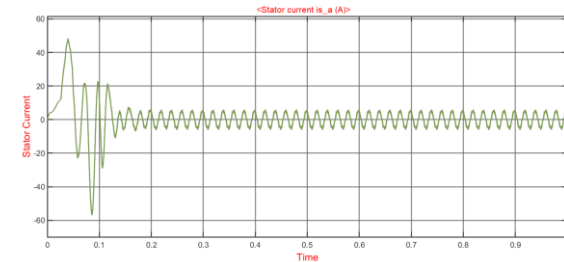


Figure9. The stator current of open loop system

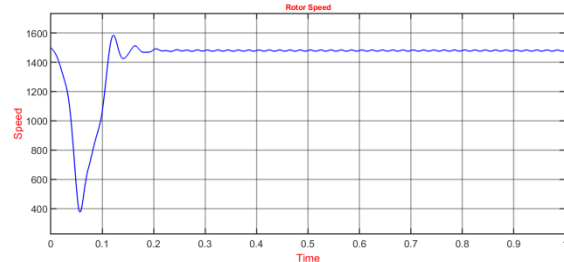


Figure 10. The rotor speed of open loop system

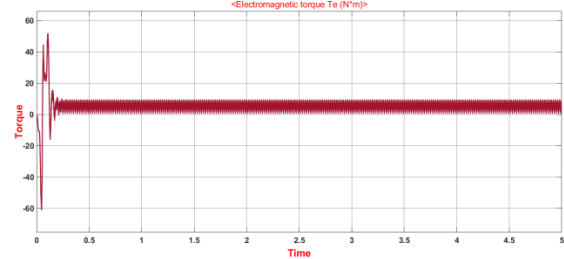


Figure 11. The electromagnetic torque of open loop system

6.2. Results of Close Loop System with PID and ADRC Controller

Figures 12(a) and 12(b) show the PID and ADRC controllers' respective stator current responses. Under the PID controller, the stator current first steadily drops to 39 A. The PID controller offers a superior reaction in the open-loop system, as evidenced by the greater beginning current of 48 A. In contrast, the ADRC controller further enhances stator current performance, as shown in Figure 12(b), where the initial current peaks at only 36 A. This demonstrates the ADRC controller's ability to reduce inrush current more effectively than both the PID controller and the open-loop system. Figure 13a and Figure 13b illustrate the rotor speed performance of the IM following an abrupt disturbance using the PID as well as ADRC controllers. In Figure 13a, the ensuing reaction exhibits considerable oscillations, with the system stabilizing only for about 0.5 seconds. This trend underscores the PID controller's constrained capacity to mitigate disruptions owing to its exclusively reactive

characteristics. It lacks a method to assess or preemptively mitigate external disruptions, leading to postponed recovery and overshoot. Conversely, Figure 13b depicts the efficacy of the ADRC controller. Although a disruption induces an initial reduction in speed, the response is markedly more fluid. The oscillations are attenuated more rapidly, and the system attains steady-state in approximately 0.35 seconds. The enhancement is ascribed to the integrated ESO in ADRC, which continuously evaluates and compensates for disturbances in real time. As a result, the ADRC exhibits enhanced transient performance, less overshoot, and expedited settling time. These results unequivocally confirm the robustness of ADRC in the face of external disturbances, highlighting its superiority over conventional PID control in situations necessitating high resilience and precision.

Figures 14(a) and 14(b) present the electromagnetic torque response for both controllers. Under PID control, as shown in Figure 14(a), the electromagnetic torque gradually reaches its peak before stabilizing at a constant value of 8 Nm, with an initial starting torque of 48 Nm. In contrast, Figure 14(b) demonstrates that the ADRC controller generates a higher starting torque of 50 Nm before settling at the same steady-state value of 8 Nm. This indicates that the ADRC controller provides improved initial torque response compared to the PID controller.

A well-designed PID controller improves performance by reducing steady-state error and inrush current, achieving a faster response compared to an open-loop system. However, while open-loop control is less expensive, it suffers from high starting currents that can impact motor lifespan. A closed-loop PID controller reduces the starting current (39 A versus 48 A in open-loop), improving steady-state performance at a higher cost. On the other hand, the ADRC controller offers even greater advantages by further reducing the starting current, ensuring a faster response time with fewer oscillations, and providing higher initial torque, making it a more efficient and robust alternative for induction motor speed control

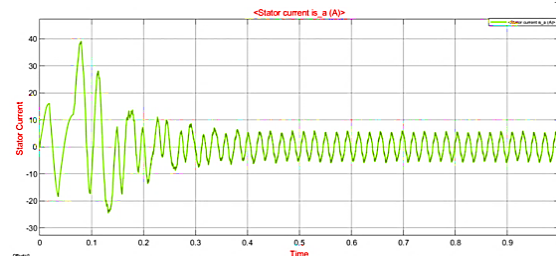


Figure 12a. The stator current of PID controller

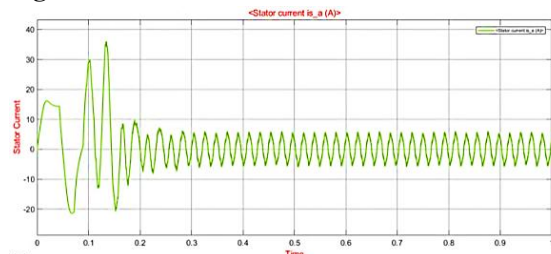


Figure 12b. The stator current of ADRC controller

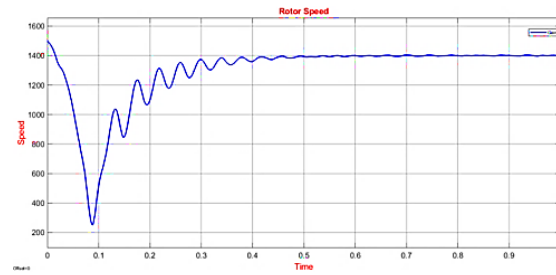


Figure 13a. The rotor speed of PID controller

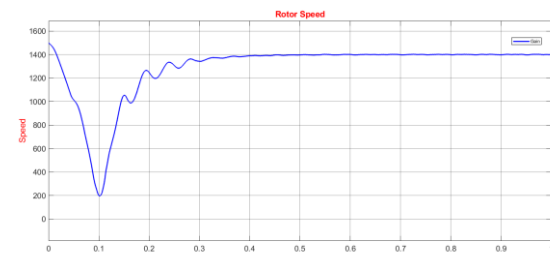


Figure 13b. The rotor speed of ADRC controller

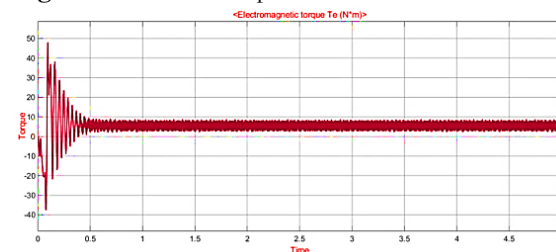


Figure 14a. The electromagnetic torque of PID controller

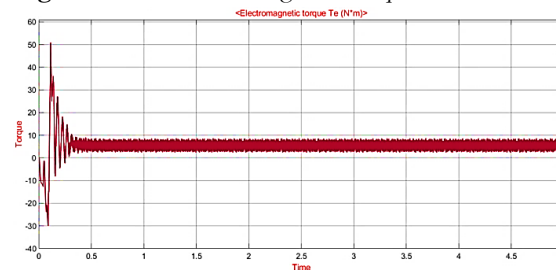


Figure 14b. The electromagnetic torque of ADRC controller

Table 1 compares the PID and ADRC controllers for induction motor speed control, highlighting ADRC's superiority in rise time, settling time, starting stator current, Electromagnetic torque, THD, ITAE, ISE, RMSE, stator current, and electromagnetic torque. Because of these benefits, ADRC is perfect for applications that need reliable, effective, and quick performance.

The findings demonstrate that, in comparison to the PID controller, the ADRC controller considerably lowers total harmonic distortion (THD). The ADRC controller achieves a THD of 271.02%, which is 87.29% lower than the THD of the PID controller, which is 358.31%.

Table 1. Performance Comparison of PID and ADRC Controlled Systems for Induction Motor Parameters

Parameter	PID	ADRC
Overshoot	0%	0%
Rise time	0.4s	0.3s
Settling time	0.5s	0.36s
Starting stator current	39A	36A
Starting Electromagnetic torque	48 N.M	50N.M
THD%	358.31%	271.02%
ITAE	19.70	14.30
ISE	251,130	234,010
RMSE	660.62	644.21

The ADRC's ESO capability of estimating a sinusoidal disturbance is evaluated that is introduced to a second-order system as the same identical sinusoidal disturbance signal utilized in the MATLAB simulation was implemented in the PID and ADRC system, ensuring coherence between the testing scenario and the estimation analysis. The observer was set with these parameters such as: system number $n=2$, known input gain $b_0 = 2 \times 10^6$, observer bandwidth $W_0 = 6100$, and control bandwidth $W_c = 300$, Figure 15 illustrates the real sinusoidal disturbance (red dotted line) in conjunction with the estimated disturbance derived from the third ESO state (blue curve). The revised plot presents strong damped oscillations in the first 0.33 seconds, following which the observer output precisely follows the actual disturbance, in contrast to idealized guesses. This modification aligns the estimating dynamics with the system's behavioral reaction, validating the ESO's efficacy under actual settings and enhancing the consistency of the ADRC's rejection of disturbances abilities. This reflects the rotor speed behavior during ADRC control, which experiences oscillatory transients prior to stabilization, as illustrated in Figure 13b.

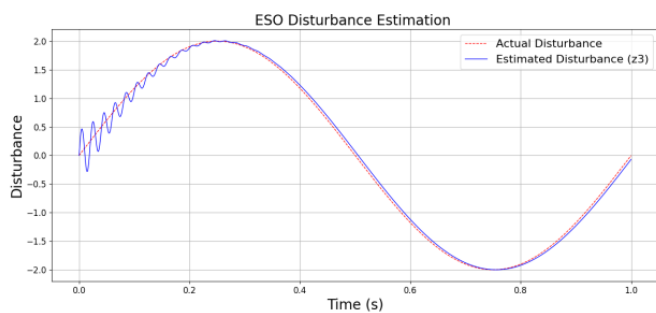


Figure 15. Using ESO to compare estimated and actual disturbance

7. Conclusion

From using MATLAB/SIMULINK The outcomes of the simulation show that the ADRC controller outperforms PID and open-loop systems in controlling induction motors. In open-loop system, the rotor speed reaches 1490 rpm but is unstable and prone to fluctuations; the starting torque is 52 Nm, resulting in higher Total Harmonic Distortion (THD) with higher starting current 48 A. Both controllers PID and ADRC controller attain zero overshoot, ensuring operational stability. The ADRC exhibits a quicker rise time 0.3 s and a shorter settling time 0.36s compared to PID's rise time of 0.4 s and settling time of 0.5 s showcasing its superior responsiveness and stabilization. Additionally, ADRC operates with a reduced stator current 36A versus PID's 39A, indicating enhanced energy efficiency and lower thermal stress. ADRC also generates a greater electromagnetic torque of 50 Nm compared to PID's 48 Nm, which improves performance under load.

Additionally, the ADRC outperforms the traditional PID controller, according to simulation data. Greater precision, quicker reaction times, and more effective speed control are demonstrated by the lower error metrics for induction motors from ADRC (ITAE (14.3 vs. 19.7), ISE (234,010 vs. 251,130), and RMSE (644.21 vs. 660.62). Furthermore, ADRC showcases a lower Total Harmonic Distortion (THD) at 271.02%, while PID has a THD of 358.31%, thereby enhancing power

quality and system reliability. Finally, after completing whole the simulations, we can obtain that the suggested system demonstrates strong performance in controlling the speed of the induction motor. Future work may focus on implementing the ADRC controller on real hardware to assess simulation findings under real-world operational conditions. Additionally, examining adaptive tuning methods for ADRC parameters could enhance its performance in a range of load and fault conditions. Integration with other state-of-the-art control techniques, such machine learning-based predictive control, may further boost resilience and efficiency for complex industrial applications

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