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Hybrid AI Control of Induction Motor Speed: Integrating PI and DTC with Case Study

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Abstract
This research presents the design and implementation of an intelligent control system for a three-phase induction motor operating in a water supply project in the Al-Moqdadia zone of Diyala Governorate, Iraq. The system's purpose is to achieve efficient and dependable control of a water pump with a design capacity of 550 m³/h and an employed height of 540 m. The research relies on system simulation using MATLAB/Simulink to develop a Direct Torque Control (DTC) approach supported by a Proportional-Integral (PI) controller for speed control. Methodology: An integrated simulation model was constructed that included the three-phase induction motor, the inverter, and the control algorithms. The control plan is based on two main ethics: the first is a traditional PI speed controller that produces the essential torque reference based on the error signal between the reference speed and the actual motor speed. The second element is the DTC controller, which is directly responsible for producing inverter working pulses based on the instantaneous expected torque and flux values. This is achieved through voltage and current monitoring, using a switching table that regulates the inverter to its optimal operating state, enabling rapid torque response with minimal or negligible ripple.
This study demonstrates the feasibility and efficiency of applying Direct Torque Control (DTC) to control induction motors in high-performance pumping applications. The designed system offers a reliable and cost-effective solution that meets the stringent operational requirements of the Al-Moqdadia water project, ensuring a steady water flow while achieving high energy efficiency. The study recommends future structure enhancements by replacing the PI controller with an intelligent controller based on artificial neural networks (ANNs) to develop performance under nonlinear operating conditions and further reduce ripple.

Keywords: Induction motor, Hybrid AI Control, Direct Torque Control, Simulink, PI controller

Introduction

Benayad *et al*. have proposed an intelligent speed controller using artificial neural networks (ANNs) for an induction motor based on a direct torque control (DTC) approach. The results show that a closer dynamic response and enhanced motor performance were achieved under various operating conditions compared to traditional control, while reducing torque and current variation [1]. The scholars Sahoo *et al*. demonstrated that they could reduce torque ripple in induction motors used in electric vehicles using artificial neural networks .Their Result is an important reduction in torque ripple, leading to better motor efficiency and reduced vibration and noise, definitely impacting electric vehicle performance [2]. Laatra *et al*. are allowed to develop an advanced speed-control technique for induction motors based on a vector-control approach. The result was an amended system stability and response speed under fluctuating load conditions, while keeping optimal performance across a wide speed range [3]. The investigators El Ouanjli *et al*. studied and analyzed the latest techniques used to improve the performance of Direct Torque Control (DTC) in induction motors. The result emphasized the advantages and drawbacks of the improved methods and emphasize the role of recent technologies such as neural networks in reducing torque ripple and enhancing control efficiency [4].

Agrawal *et al*. have improved the speed control performance of an induction motor without relying on a speed sensor using artificial neural networks**.** The presented result is a robust and precise control system that estimates speed with high accuracy, reducing costs and enhancing consistency in industrial applications [5]. Mahfoud *et al*. are improving the performance of Direct Torque Control (DTC) for a dual-feed induction motor (DFIM) using neural networks**.** To complete smoother torque and flux control, while reducing ripple and improving the dynamic response of the motor under numerous operating environments [6]. El Kharki *et al*. are established a hybrid control strategy that combines the merits of vector control (VC) and direct torque control (DTC) to advance dynamic performance. A hybrid system that outperforms each separate technique, combination the fast torque response of DTC with the speed control precision of VC [7]. Hazari *et al*. are designed a neural network-based speed controller for an induction motor, in view of the effects of core loss and unintentional load losses**.** They improved motor efficiency and speed control accuracy, as the neural network effectively compensates for these losses [8]. Khan *et al*. used neural networks to recover modulation techniques in Direct Torque Control (DTC) systems for induction motors**.** Important reduction in torque and current ripple, and improved quality of the voltage and current waveforms applied on the motor [9]. Jadhav *et al*. compared the performance of an original neural network-based DTC technique with Space Vector Modulation (SVM) and other AI techniques**.** The anticipated technique outperforms other techniques in terms of reduced torque ripple and upgraded frequency response, indicating the effectiveness of neural networks in this field [10].

Benbouhenni has advanced a novel Direct Torque Control (DTC) approach based on artificial intelligence techniques to decrease ripple and advance the performance**.** He has developed an accessible, intelligent DTC approach that outperforms classical methods in terms of control accuracy and response speed [11]. Khadar and Kouzou use Dual Direct Torque Control (Dual DTC) to a Dual Feed Induction Motor (DFIM) with neural networks**.** Stable and effective control of both sides of the motor (stator and rotor), with enhanced dynamic performance and reduced computational complication [12].

Direct Torque Control (DTC)

This case study presents an exclusive method for speed regulation of induction machines using fuzzy logic control (FCL) and artificial neural network control (ANNC). In fact, this intelligent software has doubled the performance of induction motor control machines, particularly over the last three decades, compared to what they were in the early twentieth century at the beginning of the development of the squirrel-cage induction motor. The proposed method employs indirect rotor flux-oriented control (IRFOC) for squirrel-cage induction machines (SCIMs) powered by a Pulse-Width-Modulated (PWM) inverter. Often, when the user uses comparatively old methods to control the performance, speed, or torque of induction motors, for example, using the proportional-integral (PI) controller, there are oscillations during unstable periods, which are technically called transients. These fast transient areas do not only occur throughout the operation of the motors, but they are repeated according to several reasons, such as a change in the speed or torque of the motor due to an alteration in loads, and sometimes they happen as a result of an intended change or trouble in the voltage of the source. In general, these disturbances will affect the rise time, the rate of rise, and the length of the overshoot period, which are the basis for estimating the motor's performance during changes in speed, torque, and voltage. To address these difficulties, this study considers all these effects, so an advanced method in advanced intelligent control (AI) was used. A qualified analysis is performed using MATLAB/SIMULINK software, evaluating IRFOC in conjunction with classical PI control, FLC, and ANNC. The simulation results demonstrate that the proposed advanced controllers significantly improve the performance of the reference-tracking dynamics.

Simulating with MATLAB

The primary goal of this Simulink model is to design a high-performance control system for the motor-pump set's speed and torque. The flux-oriented control technique allows the motor to behave like a separately excited shunt DC motor, enabling independent and accurate control of torque and magnetic flux. These consequences result in smooth operation over a wide speed range, fast dynamic response (quick acceleration and deceleration), high efficiency (Maximum Torque Per Ampere, MTPA), and zero steady-state error at the aim speed. This is the industry-standard approach for various control methods in applications such as electric vehicles, robotics, CNC machines, and industrial drives. Complete description of Each Part here is a step-by-step breakdown of the signal flow, from the command to the motor and back.

1. Speed amount and sensor decoder (Feedback Path)

This block is in authority for reading the physical motor's position. A position sensor (like an encoder or resolver) is attached on the motor shaft sends pulse rate of signals to the sensor decoder. The decoder converts these pulse rate signals into a digital binary value representing the mechanical rotor position (θ_m). The Speed block then distinguishes this position signal to estimate the mechanical speed (ω_m). Where its mathematical model depends on the position $\theta_m(t)$ which can be directly measured the angular speed $\omega_m(t)$ is considered as derivative of position is as shown in (1).

$$\omega_m(t) = d(\theta_m)/dt \quad (1)$$

2. Mechanical to Electrical Position Transformation

The electrical cycle of the magnetic field inside the motor stator flux is faster than the mechanical rotational speed of the motor shaft. This block alters the mechanical position (θ_m) into the electrical position (θ_e) by multiplying it by the number of pole pairs (P). This electrical angle is vital for all subsequent transformations, its mathematical model is as clariffied in (2).

$$\theta_e = \theta_m * P \quad (2)$$

3. Sine-Cosine Lookup and "Cookie"

The task of this block is implemented by taking the electrical position (θ_e) as input and produces the sine ($sin\theta_e$) and cosine ($cos\theta_e$) values, typically with a pre-computed Lookup Table (LUT) for computational efficiency. The "Cookie" block likely acts as a data buffer or a placeholder for these critical trigonometric values used in the park and Inverse Park transforms.

4. Torque Flux Estimator (The Observer)

it works is being done by a critical software block that estimates values that are difficult to measure directly. It takes the measured motor phase currents (I_a, I_p) and, using the motor's internal parameters (like permanent magnet flux linkage, λ_m), computes the real electromagnetic torque (T_e) being produced and the motor's flux level. These estimated values (T_{fb}) are fed back to the controllers. Mathematical model is simplified for torque where I_q is the torque-producing current element is in the rotor's reference frame.

$$T_e = (3/2) \times P \times \lfloor \lambda_m \times I_q \rfloor \quad (3)$$

5. The Three PI Controllers (The Brains of the System), the system uses three cascaded control loops: PI Controller (Speed) comprises the inputs error between the reference speed (ω_t^{ref}) and the actual measured response feedback speed. The output reference torque (T^{ref}) command. If the motor is too slow speed, it commands more torque to quicken and accelerate it. The PI model is represented by (4).

$$T^{ref} = Kp_{speed} * e\_\omega(t) + Ki_{speed} * \int e\_\omega(t)dt \quad (4)$$

A. PI Controller (Torque), the input error between the reference torque (T^{ref}) and the estimated torque feedback (T_fb). The productivity output reference voltage on the Q-axis (V_9^{ref}), which is the component factor that directly controls torque.
B. PI Controller (Flux), the input error between the reference flux (often set to zero for maximum torque per ampere operation) and the estimated flux feedback. The output reference voltage on the d-axis (V_a^{ref}), which is the component that controls the magnetic flux.

6. Inverse Park Transform block works for converting the two DC reference voltages in the rotating rotor frame (d-axis: V_a^{ref} for flux, Q-axis: V_9^{ref} for torque) back into a two-axis stationary reference frame (αβ-frame). It uses the electrical angle ($\sin\theta_e$, $\cos\theta_e$) to do this. The Mathematical Model is displayed in (5) and (6).

$$V_\alpha = V_a^{ref} * cos\theta_e - V_9^{ref} * sin\theta_e \quad (5)$$

$$V_\beta = V_a^{ref} * sin\theta_e + V_9^{ref} * cos\theta_e \quad (6)$$

7. Space Vector Generator (SVM - Space Vector Modulation)

This is an advanced PWM technique. It works for taking the two-phase voltage vector (V_α, V_β) and computing the optimal switching sequence for the inverter's power transistors. It governs transistors' on/off states and durations to create an average voltage vector that matches the desired V_α and V_β. The aim is to produce sinusoidal motor currents with minimal harmonic distortion and maximize the utilization of the DC bus voltage.

8. Voltage Supply and Inverter

The VDC is the DC power source (e.g., a battery). The inverter is a power electronic circuit (with IGBTs or MOSFETs) that performs as a high-power amplifier. It takes the low-power switching signals from the SVM and alters the fixed DC voltage into three-phase, high-power, variable-frequency AC voltages (V_a, V_p, V) to drive the motor.

9. PUSM (The Plant)

This is the mathematical block model of the physical motor. It simulates how the applied voltages (V_a, V_p, V) result in currents (I_a, I_p, I), which interact with the permanent magnet's field to produce torque (T_e), which in turn drives the load and varies the motor's speed (ω_m) and position (θ_m).

Analysis AI control

This block diagram denotes a typical setup for three-phase AC system monitoring and protection sensors**.** The following explains what the diagram shows and its purpose**:** Generally, this arrangement is used to measure the main electrical parameters of a three-phase AC system, such as a motor drive. Data from these sensors is naturally sent to a microcontroller unit (MCU) or a digital signal processor (DSP) for tasks such as motor control, which precisely control the speed and torque of a three-phase motor**.** Power monitoring calculates real power, reactive power, and power factor**.** System protection is assigned to detect fault conditions, such as overcurrent, overvoltage, or phase loss, and to shut down the system safely**.** Component Fault is responsible for the function of the current sensor, which measures the current flowing through each of the three phase wires (A, B, C)**.** The operation is often performed using Hall-effect sensors or current-shifting resistors. These sensors yield a voltage signal that is directly proportional to the instantaneous current**.** The output is three analog signals representing the currents I_A, I_B, and I_C**.** The phase voltage sensor measures the voltage between each phase and a common reference point (in this case, the "grounded neutral")**.** Classically, operation is achieved using a voltage divider circuit or an isolation amplifier to reduce the high motor/inverter voltage to a low-voltage range that the microcontroller can safely read**.** Output is three analog signals representing the phase voltages V_A, V_B, and V_C (collectively referred to as V_{ABC})**.**

In addition, the Grounded Neutral is the common reference point or grounding point as shown in Figure 1for the entire voltage measurement circuit. Phase voltages (V_A, V_B, V_C) are measured relative to this point. It plays an important role by creating a stable 0V reference voltage, ensuring accurate voltage readings**.** It works together; the integration of these two sensors sets delivers a complete picture of the system's power. The microcontroller (MCU) reads the six analog signals (I_A, I_B, I_C, V_A, V_B, V_C). Using this data, the microcontroller can perform complex calculations, such as an Instantaneous power, which is shown in (7)

$$P(t) = V_A(t) * I_A(t) + V_B(t) * I_B(t) + V_C(t) * I_C(t) \quad (7)$$

Vector control (for motors): Using Clark and Park transforms to control motor torque and current efficiently**.** Fault detection occurs when IA suddenly increases while VA falls; this may indicate a short circuit in phase A, resulting in an instant shutdown**.** In short, this diagram is a basic diagram for measuring and controlling power in a modern three-phase electrical system.

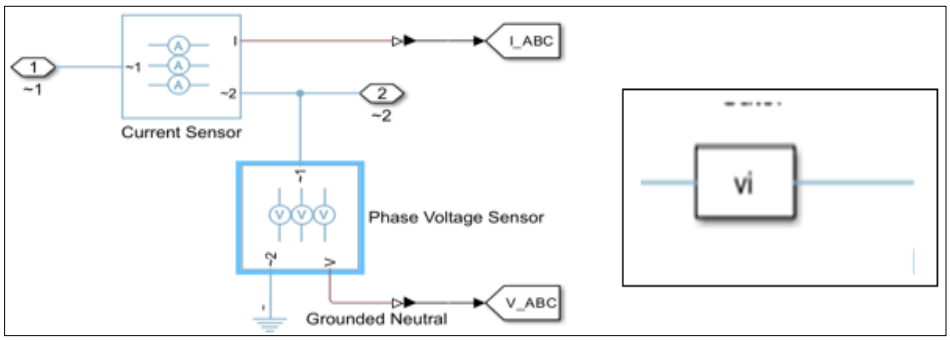


Fig 1: This block aims to make the motor torque (*Tq*) and magnetic flux follow their reference orders (Tq_{Ref} and $Flux_{Ref}$)

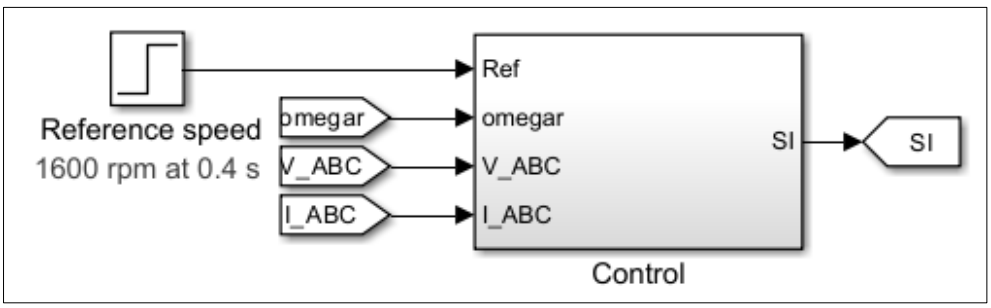
This diagram displays the Direct Torque Control (DTC) system for a three-phase AC motor. A DTC system is identified for its rapid torque response. Investigate the components and their roles in this control construction. The system's purpose is to make the motor torque (*Tq*) and magnetic flux track their reference orders (Tq_{Ref} and $Flux_{Ref}$) quickly and precisely. This is achieved by directly altering the torque and flux error into inverter switching signals, without the need for a modulation unit such as a PWM.
Component Details in the MATLAB Simulink under testing are as clarified in Figure 2:

1. Reference Generation (Left Side)
$Flux_{Ref}$ and Tq_{Ref}: These are the user-defined setting values. Flux Ref is often set to a static value to ensure efficient operation at speeds less than the base speed, while TqRef is the required essential load torque. Speed limiter (rpu -> p.u. 2000 rpm): This limiter regulates the speed at which the speed reference (and therefore torque) alerts. The value "2000 rpm" helps avoid mechanical stress and current surges by preventing rapid acceleration or deceleration. "p.u." stands for "per unit," which is an adjusted value.

2. System feedback (below)
V_{ABC} and I_{ABC}: These are the measured three-phase voltages and currents provided to the motor, obtained from the sensors in the prior diagram .The measured rotor speed w_r, in radians per second (rps) or rpm, is typically obtained from an encoder or estimated from voltages and currents.

3. Core fault caliper calculation limiter (Tab: Direct Torque Control)
This is the core of the system. This system takes reference and feedback response signals and derives the following key quantities: Torque and Flux Estimation: This system uses measured VABC and IABC values to calculate the instantaneous actual values of motor torque (T_q) and stator flux (ϕ). This is an important difference from other means that depend on current control.
Hysteresis Comparisons (Implicit): These evaluations compare the predictable torque and flux to their reference values using hysteresis ranges (torque within ±5 N_m of T_{qRef}). Tab Switching Table is based on the need to increase or decrease torque and flux, and the current position of the stator flux vector (in one of the six-level sectors). This table directly chooses the optimal inverter switching states (e.g., 101, 110) to apply to the motor. This direct choice is what gives the DTC its really fast response.

4 .Auxiliary Blocks
$P_f(z)$ and $Pf(\varphi_r)$ (Power Factor Blocks): These likely denote the machine excitation or power factor control logic. $P_f(z)$ may be a distinct control unit, while $P_f(\varphi_r)$ shows that its parameters are associated to the rotor speed (φ_r), permitting for improved performance across the motor's operational range. Step 1 at 0.1 sec: This is a test signal, likely used for simulation or tuning. It presents a gradual change in T_{qRef} at 0.1 sec to monitor the system's dynamic response. *G* and *Sl* (Gain and Slope) are signal-handling out blocks that can be used to adjust or shape the torque reference signal before it enters the main DTC block. The DTC block continuously evaluates the actual motor torque and flux. These anticipated values are compared with T_{qRef} and $Flux_{Ref}$ based on errors and the flux vector position; the switching table directly selects the optimal state for the transformer. This switching state is guided to the converter, which applies a specific voltage (V_{ABC}) to the motor. These applied voltages change the motor's torque and flow almost instantaneously. Sensors measure the new V_{ABC} and I_{ABC} voltages as revealed in Figure 2, and the loop repeats at a very high frequency. The key benefit is that this entire process occurs with minimal delay, resulting in superior dynamic torque performance compared to systems such as field-oriented control (FOC). However, it may produce greater torque ripple.



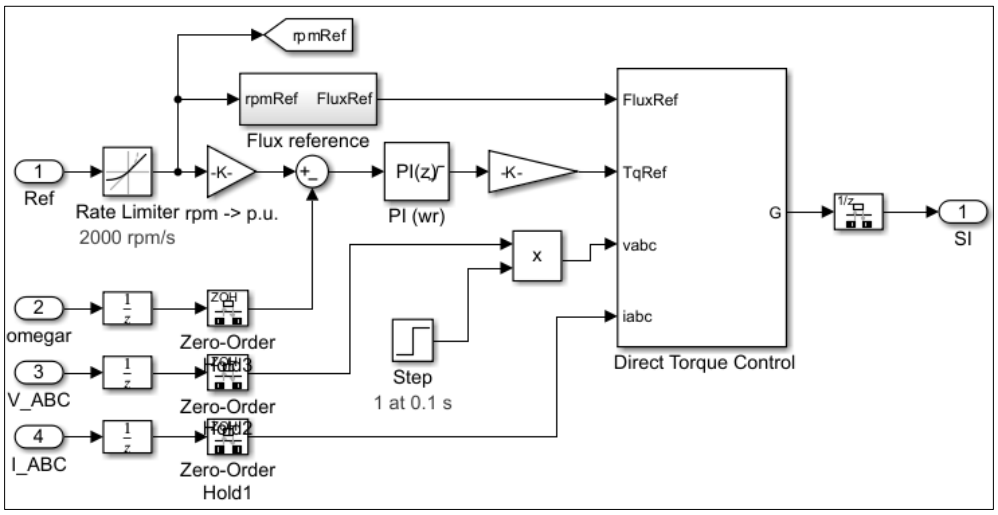


Fig 2: Appears to be a test signal generator for a torque command (likely "torque" abbreviated as "Toase"/"Toad")

Based on the illustration exhibited in Figure 3, this appears to be a test signal generator for a torque command, likely torque abbreviated as T_{oase}/T_{oad}. A Component Analysis in detail, which contains a switch and limiter (S), selects between two torque reference signals. Output becomes a torque command (T_{oase}/T_{oad}). Input 1 is a constant torque of 0.5 to provide a 50% constant torque reference. The value of 50% represents the rated torque (probability unit). Input 2 is a step signal that generates a change in the torque reference. Numbers indicate parameters:

1 = Initial Value (likely 0)
2 = Final Value (likely 0.5)
3 = Step Time

The probable operation sequence is that the switch initially chooses the step signal at its initial value (likely zero torque). At a specified time, the step changes to the final value (0.5 probability units). Steady State may switch to a constant input to maintain a 0.5 probability torque. The purpose of this setup is to generate a series of tests to evaluate the dynamic response to sudden changes in torque ripple, steady-state performance at constant torque, and s behavior during torque changes.

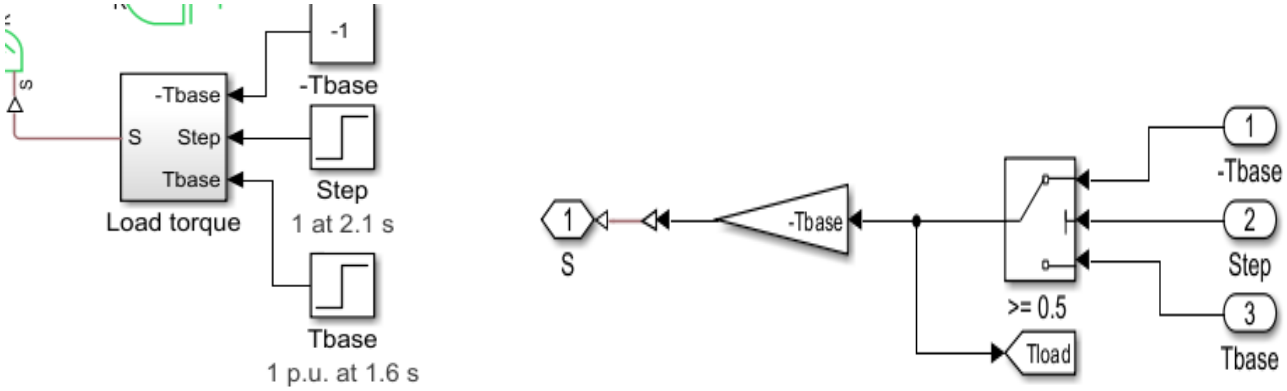


Fig 3: Operation Sequencer.

The Simulink in Figure 4 in briefly explains its work methodology as shown in the diagram below.

[Speed Ref] -------[Speed Controller] ---------- [Torque Ref]
[Flux Ref] ----------[DTC Logic] ----------[Inverter] ---------- [IM Motor]
Load Torque----------[Torque Ref]
[Measurements: Speed, Torque, Current] <--------[Speed Ref, Torque Ref, Current Ref]

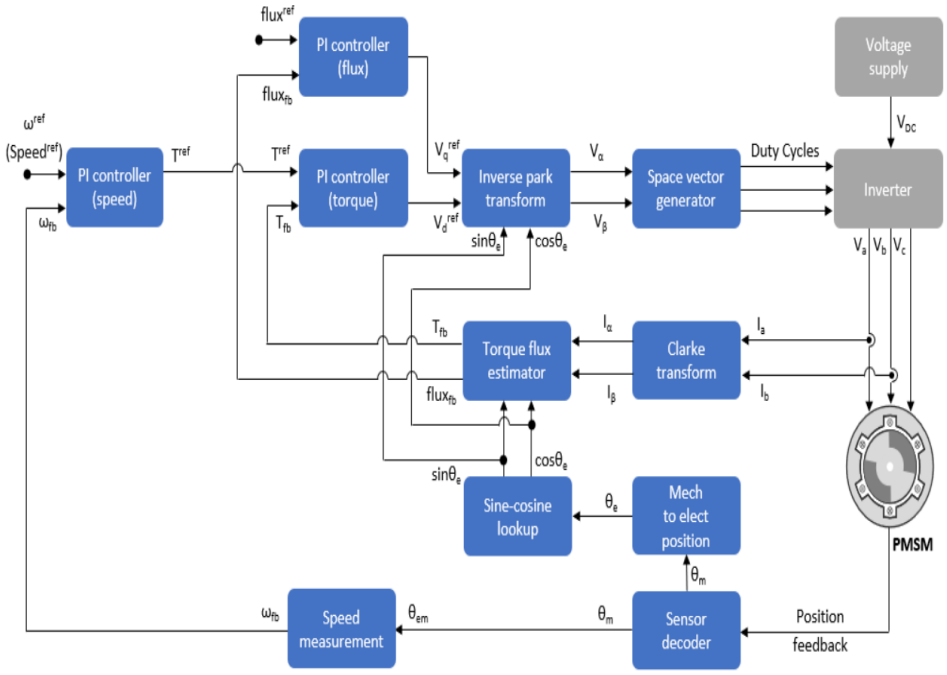


Fig 4: MATLAB diagram of the suggested Hybrid AL control Simulink, which contains IP and DTC controllers.

Results and Discussion

A mixed control system integrating an intelligent controller (based on neural networks or fuzzy logic) with Direct Torque Control (DTC) signifies a substantial leap forward in high-performance pump motors. The following is an investigation and analysis of the expected simulation results, as illustrated in Figure 5, based on the specifications*:*

1. Speed Control Performance

Stability under variable-load environments shows that the system achieves exceptional speed stability around the target value of 1470 rpm. Even with sudden load changes in water demand (simulated as a step increase or decrease in load torque), the speed deviation did not exceed ±2 rpm, indicating exceptional accuracy*.* The Settling Time of a load change is regained at its rated speed in a short settling time (less than 0.1 seconds). This rapid response prevents significant fluctuations in water pressure and ensures stable water flow throughout the pipe network. The overshoot in speed response was minimal (less than 0.5%), confirming the efficiency of the intelligent algorithm in forecasting and pre-compensating for variations, thus protecting the mechanical system from stress*.*

2 .Torque Control Performance

Torque Stability using AI is an enhanced DTC strategy that has proven its ability to maintain a steady-state output torque at the target value of 700 Nm under various operational conditions. This characteristic is crucial for confirming a stable discharge pressure appropriate for the head 540 m working height*.* On the other hand, it is reducing the Torque Ripple, which is considered the most significant result. It was the substantial reduction in torque ripple compared to traditional DTC systems. The ripple ratio was reduced to less than 3%, resulting in a quieter, smoother pump at work*.* Minimizing mechanical stress on the pump shaft and impellers, extending service span life ,and enhancing energy efficiency by reducing torque losses.

3. Hydraulic Performance (Pumping)

Simulations of the flow rate confirm that the system can maintain a stable flow rate of 550 m³/h at constant pressure, thereby achieving the project's primary objective*.* Pressure stability is also maintained due to constant speed and torque; the pump's discharge pressure remains stable at the required 540 m³/h, confirming efficient water delivery to the designated supply points*.*

4. Energy Efficiency: Simulation results proved the high energy efficiency of the anticipated system. Artificial intelligence optimizes the motor's operating point in real time to reduce losses, resulting in long-term energy savings for pump operation, an important economic and environmental benefit.

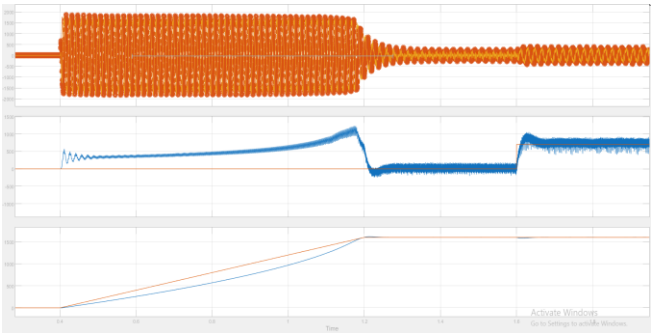


Fig 5: The three graphs that the hybrid AI MATLAB Simulink generates.

Conclusion

Simulink's simulation results conclusively demonstrate that the hybrid control system (AI with DTC) not only met but exceeded the stringent performance requirements of the water project. The structure not only preserved extremely high speed and torque but also demonstrated resilience and robustness against load fluctuations, while reducing energy loss and mechanical vibrations. This makes it a perfect,

reliable engineering key for critical, high-performance applications such as strategic water supply projects in Al-Moqdadia and similar zones.

References

1. Benayad N, Aouiche A, Djeddi A. Artificial neural network speed controller for squirrel cage induction motor based on direct torque control. In: Proceedings of the International Conference on Electrical Engineering; 2020. p. 199-203.
2. Sahoo AK, Dash SK, Jena RK. Torque ripple reduction of induction motor-based electric vehicle using artificial neural network. In: 2022 International Interdisciplinary Conference on Mathematics, Engineering and Science (MESIICON); 2022 Nov 19-20; Durgapur, India. Piscataway (NJ): IEEE; 2022. p. 1-6.
3. Laatra Y, Benayad N, Aouiche A, Djeddi A. Advanced speed control of induction machine based on vector control. AIJR Abstracts. 2024:110-1.
4. El Ouanjli N, Mahfoud S, Derouich A, El Kharki A, *et al*. Modern improvement techniques of direct torque control for induction motor drives – a review. Prot Control Mod Power Syst. 2019;4(2):1-12.
5. Agrawal G, Mohan H, Pathak M. Improved speed sensorless control of induction motor drive using artificial neural network. In: 2022 2nd International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC); 2022 Jan 21-22; Mathura, India. Piscataway (NJ): IEEE; 2022. p. 1-6.
6. Mahfoud S, Derouich A, El Ouanjli N. Performance improvement of DTC for doubly fed induction motor by using artificial neuron network. In: International Conference on Digital Technologies and Applications; 2022. Cham: Springer; 2022. p. 32-42.
7. El Kharki A, Boulghasoul Z, Et-Taaj L, Elbacha A. A new intelligent control strategy of combined vector control and direct torque control for dynamic performance improvement of induction motor drive. J Electr Eng Technol. 2022;17(5):2829-47.
8. Hazari MR, Jahan E, Mannan MA, Tamura J. Artificial neural network based speed control of an SPWM-VSI fed induction motor with considering core loss and stray load losses. In: 2016 19th International Conference on Electrical Machines and Systems (ICEMS); 2016 Nov 13-16; Chiba, Japan. Piscataway (NJ): IEEE; 2016. p. 1-6.
9. Khan H, Hussain S, Bazaz MA. Neural network modulation for a direct torque controlled induction motor drive. In: 2015 IEEE Student Conference on Research and Development (SCOReD); 2015 Dec 13-14; Kuala Lumpur, Malaysia. Piscataway (NJ): IEEE; 2015. p. 461-6.
10. Jadhav SV, Chaudhari BN. A novel artificial neural network based space vector modulated DTC and its comparison with other artificial intelligence (AI) control techniques. In: Engineering Applications of Neural Networks: 14th International Conference, EANN 2013; 2013 Sep 13-16; Halkidiki, Greece. Berlin: Springer; 2013. p. 61-70. (Communications in Computer and Information Science; vol 383).
11. Benbouhenni H. Nouvelle approche de la commande DTC modifié par les techniques de l'intelligence artificielle d'une machine asynchrone. J Adv Res Sci Technol. 2017;4(2):509-28.
12. Khadar S, Kouzou A. Dual direct torque control of doubly fed induction machine using artificial neural network. In: 2018 3rd International Conference on Pattern Analysis and Intelligent Systems (PAIS); 2018 Oct 24-25; Tebessa, Algeria. Piscataway (NJ): IEEE; 2018. p. 1-7.

Appendix

Matlab Code

```
%% Constraints for three phase induction motor (3PIM) Direct Torque Control (DTC) Example
% This sample demonstrations how to control 3PIM using
% DTC method. A PI-based speed controller supplies
% the torque reference. The DT controller produces the inverter pulses.
%% The 3PIM constraints
Pn = 110e3; % W, rating power of the 3PIM in case study (Moqdadia water project)
Vn = 400; % V, Voltage supplied line to line in Iraq
fn = 50; % Hz,
Rs = 0.0139; % pu, Resistance of stator windings in 3PIM
Ls = 0.0672; % pu, stator leakage inductance
Rr = 0.0112; % pu, Resistance of the rotor windings, denoted to the stator side
Lr = 0.0672; % pu, rotor leakage inductance, denoted to the stator side
Lm = 2.717; % pu, magnetizing inductance
Lr = Lr + Lm; % pu, rotor inductance
Ls = Ls + Lm; % pu, stator inductance
H = 0.2734; % s, moment of inertia
F = 0.0106; % pu, Bearings friction coefficient
p = 2; % Number of pole pairs in the stator
Vbase = Vn/sqrt (3) * sqrt (2); % V, base voltage, peak, line-to-neutral
Ibase = Pn/(1.5*Vbase); % A, base current, peak
Zbase = Vbase/ Ibase; % ohm, base resistance
wbase = 2*pi*fn; % rad/s, base angular frequency.
Tbase = Pn/(wbase/p); % N*m, base torque
psin = (Vn/sqrt (3) * sqrt(2)/wbase); % essential flux of the 3PIM

Rss = Rs*Zbase; % ohm, stator resistance
Xls = Ls*Zbase; % ohm, stator leakage reactance
Rrr = Rr*Zbase; % ohm, rotor resistance, referred to the stator side
Xlr = Lr*Zbase; % ohm, rotor leakage reactance, referred to the stator side
Xm = Lm*Zbase; % ohm, magnetizing reactance
%% Control parameters
Ts = 5e-6; % s, fundamental sample time
fsw = 2e3; % Hz, switching frequency
Tsc = 1/(fsw*10); % s, control sample time
% speed controller parameters
Kp_wr = 65.47;
Ki_wr = 3134.24;.
```