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Modeling and control of a high-quality electro-hydraulic actuator driven via an induction motor under intelligent indirect vector control

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HIGHLIGHTS

- The smart PIFLC & IVC controller demonstrated superior performance
- Smart PIFLC & IVC outperformed PI controllers and V/f in cost, stability, and response
- PIFLC & IVC achieved a low starting current of 15A
- Energy savings of 15% were obtained, improving efficiency with an 80V reduction
- The steady-state error in PIFLC & IVC was minimal at 0.024

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ABSTRACT

Due to its excellent energy efficiency and broad speed range, the variable-speed electro-hydraulic drive is an appealing driving principle in many contemporary industrial applications. A primary control of linear motion is via a variable-speed electric motor driving a hydraulic actuator via a constant displacement pump. One of the most commonly used controllers for the speed control of induction motors is the Proportional Integral (PI) type. However, the traditional PI controller has some disadvantages, such as the high starting overshoot, sensitivity to controller gains, and sluggish response due to sudden disturbance. An intelligent controller based on PI Fuzzy logic set theory is introduced to the electro-hydraulic system to overcome these defects. This paper presents a study on the speed control of an indirectly controlled vector-controlled induction motor driving an electro-hydraulic actuator. Various speed control techniques like voltage-frequency control, sinusoidal pulse width modulation PI control, indirect field control, and fuzzy logic PI control were applied in the electro-hydraulic system and simulated by Matlab/Simulink environment for performance analysis and comparison. The results prove that the indirect field-oriented control technique with PI fuzzy logic control provides better speed control of the induction motor, especially with high dynamic disturbances, by reducing the steady state error to (0.024), overshooting to (0.2%) and Settling time to (0.3s). This, in turn, will improve the performance of the proposed electro-hydraulic system.

1. Introduction

Electro-hydraulic system (EHS) covers all combinations of electrical (electronic) signal processing with hydraulic drives. The EHS consists of high-power hydraulic devices such as pumps, valves, and actuating cylinders or motors with fast response electronically controlled drives [1]. In many engineering applications, electro-hydraulic components are often employed [2–5]. Also, they can be applied for low-rise lifting purposes [6-9].The variable-speed electro-hydraulic drive (speed-regulated electric motor squirrel cage induction motors (SCIM) in conjunction with a hydraulic constant pump) has significantly improved with the improvements in frequency converters [10-13].

Due to its low cost, straightforward construction, durability, and high reliability, the three-phase induction motor (IM) has a very wide variety of applications in industries for electrical AC drives [14,15]. For AC drives, responsiveness to changes in command speed and torques requires strong dynamic performance. The vector control system is capable of meeting these needs [16,17]. For high-performance applications, the control of an IM has changed with the introduction of the vector control approach to resemble that of an independently excited DC motor. By adjusting the necessary field-oriented parameters, this technique allows for the independent control of the field and torque of three-phase IM (decoupling) [16].

Due to its simplicity and stability, the typical Indirect Vector Control (IVC) method used to regulate the IM uses a conventional PI controller in the outer speed loop. The drive's performance will deteriorate due to overshoot, oscillation of the motor speed, oscillation of the torque, and extended settling times caused by unexpected changes in the load circumstances or

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environmental variables. The PI regulator can be replaced with an intelligent controller based on fuzzy logic to solve this issue [17,18]. Compared to traditional controllers, the fuzzy logic controller (FLC) offers a few benefits, such as easy control, low cost, and the ability to build without knowing the precise mathematical model of the plant [19]. One of the good features of fuzzy controllers over traditional PI controllers in driving IMs is that they reach the final response and steady-state conditions [20].

For many years, the control of electro-hydraulic systems has attracted considerable interest from researchers. Kutlu and Güner [21] employed a digital proportional derivative (PD) and an FLC in an electro-hydraulic system with an asymmetric cylinder. The findings revealed that the FLC is less susceptible to changes in system parameters. Scheidl and Manhartsgruber [22] performed a singular perturbation analysis on a 10^{th}-degree non-linear model of an electro-hydraulic system comprising a servo valve and a hydraulic cylinder. A fuzzy PD-based self-learning fuzzy controller created by Deticek [23] is utilized for position control in an electro-hydraulic system. Jones et al. [24] created an adaptive self-learning FLC to improve the tracking performance of an electro-hydraulic system.

The Variable Voltage Variable Frequency (VVF) controller-based energy-saving method created by Bing et al. [25] for a hydraulic system is intended to increase the effectiveness of how hydraulic elevators use their energy. The hydraulic system's accumulator pressure is used as an energy storage and release unit, reducing the amount of installed energy and energy consumption. To avoid this disadvantage, Cochoy et al. [26] used the valve-pump parallel control, where the control valve is installed in parallel on the main circuit. Also, to enhance the flight's dynamic characteristics, Rongjie et al. [27] utilized the parallel control to electro-hydraulic actuators (EHA), which are position servo systems.

A unique electro-hydraulic drive principle for speed control was created by Xu et al. [28] and is helpful for practical use. Xu et al. [13] introduced a pump/valve coordinate control of the independent metering system for mobile machinery that is also a valve-pump series control and can function in various modes. Bingbing et al. [29] modeled and analyzed a valve-controlled system in which the accumulator worked as the oil-supplying component and had a sustained pressure decline.

The research studies [30,31] developed a method for estimating both external disturbances and unknown parameters using an extended disturbance observer. The extended disturbance observer is driven by state estimation and tracking errors, and its efficacy in various electro-hydraulic systems has been demonstrated. Wrat et al. [32] examined the impacts of two distinct control techniques used to regulate the actuator's position in a hydraulic system while controlling the main pump's swash plate angle and electric motor speed. The swash plate control approach performed better in simulation and experimentation than other methods regarding responsiveness and dynamic properties.

Based on research on a system that included counterbalance valves with time-varying negative loads and a variable meter-out flow control valve, Jin and Wang [33] produced a stable controller. The controller modifies the actuator's velocity and the load state to change the pump displacement. This lowers the actuator's intake pressure, which minimizes power consumption. This is appropriate for applications like excavator booms, where the load and flow must change dynamically while the machine is in use.

To lessen vibrations that may be produced by the hydraulic system and the actuator after the stroke, Hoshi et al. [34] investigated the impact of adding an accumulator. Hashim et al. [35] practically studied the effect of changing the bulk modulus of elasticity on the performance of conventional electrohydraulic systems. Mohammed et al.'s experimental study [36,37] reported on the proportional valve and fixed displacement pump-based regulation of hydraulic elevator speed using a conventional PI controller. This control relied on regulating the proportional solenoid valve to regulate the flow rate, which in turn controlled the speed of the hydraulic cylinder or the speed or the elevator going up and down. Li and Zhang [38] employed an FLC to modify the impedance rules' values to enhance the functionality of an electro-hydraulic actuator. The impedance control with fuzzy logic established the velocity command of adaptive robust velocity control.

In the literature, many technologies are employed to control the speed of IMs. Some studies employed scalar V/f control [39-41]. Other studies used advanced techniques. A new controlling strategy based on an Artificial Neural Network (ANN) was presented by Yadav et al. [15] to improve the speed control of an IVC for IM drive. Ojha et al. [16] presented a speed control scheme of an IVCIM drive. Dahmardeh et al. [14] introduced a unique Direct Torque Control (DTC) technique and Stator-Flux Oriented Control (SFOC) system to improve the general performance of three-phase IM drives.

To improve the comprehensive performance of the complex speed regulation process in any electro-hydraulic system, the advanced techniques employed for efficient speed control of IM can be combined with any hydraulic system to implement a new type of high-quality electro-hydraulic control scheme. The present paper presents a new pump control system in the electro-hydraulic system using IM. Investigated is the use of PI-fuzzy logic and indirect vector control (IVC) to achieve intelligent IM drive speed control, thus controlling the flow rate of hydraulic fluid into, through, and out of the gear pump, thus improving the overall system. Based on fuzzy set theory, the suggested intelligent system's analysis, design, and simulation have been carried out using MATLAB and Simulink.

2. Theoretical analysis

The intelligent speed control for a three-phase IM, which drives an electro-hydraulic system loaded by a hydraulic hoist, is shown in the overall system block diagram in Figure 1and is based on PI fuzzy logic.

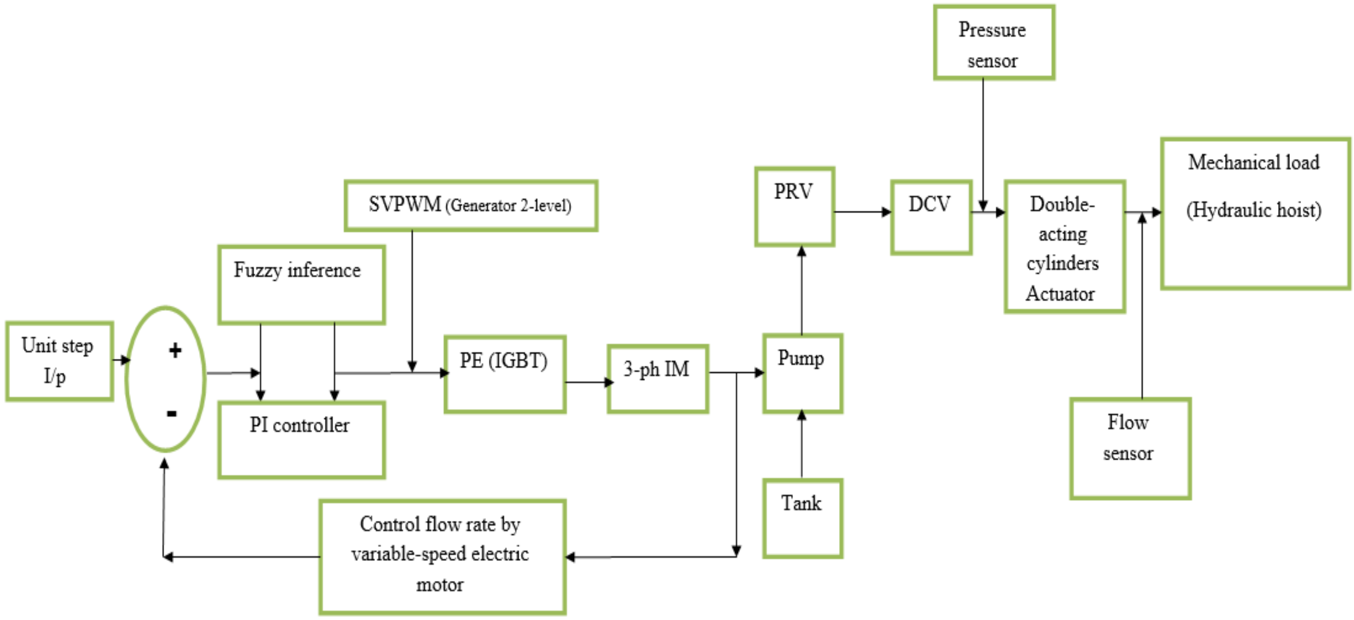

Figure 1: PI-fuzzy control of electro-hydraulic system

The following subsections will detail the modeling of the major parts of the proposed electro-hydraulic system that were completed in the MATLAB/Simulink environment. The following are some assumptions that should be considered when conducting the analysis:

1) Information 1 on the hydraulic pump's dynamics, as well as information on the driving motor and valves.
2) Neglected are the frictional and leakage losses occurring in the cylinder, pump, and valve.
3) It does not take into account how temperature affects fluid characteristics.
4) Any uncertainty in system parameters was not considered because the research work was limited to the MATLAB program, and here, the results and measurements are given perfectly and without any error rate.

2.1 Hydraulic Pump

Fixed-displacement pump (gear pump) is represented with the following Equations (1-5) [42]:

$$q = D.\omega - k_{leak}.P \tag{1}$$

$$T = \frac{D_p}{\eta_{mech}} \tag{2}$$

$$k_{leak} = \frac{k_{HP}}{v.\rho} \tag{3}$$

$$k_{HP} = \frac{D.\omega_{nom}(1-\eta_V).v_{nom}.\rho_{nom}}{p_{nom}} \tag{4}$$

$$P = P_P - P_T \tag{5}$$

The Hagen-Poiseuille formula [43] may be used to calculate the leakage flow, which is derived from the presumption that it is linearly proportional to the pressure differential across the pump in Equation (6):

$$P = \frac{128\,\mu}{\pi d^4} q_{leak} = \frac{\mu}{k_{HP}} \tag{6}$$

where $\mu = v\,\rho$.

Since data sheets rarely include information on the mechanical efficiency of pumps, this efficiency is calculated from the total and volumetric efficiencies on the presumption that the hydraulic efficiency is negligibly low from Equation (7):

$$\eta_m = \frac{\eta_t}{\eta_V} \tag{7}$$

Hydraulic power is the real force that a pump applies to a fluid. In Equation (8) the hydraulic power formula is:

$$P_h = P * Q_a \tag{8}$$

2.2 Directional control valve (DCV)

A DCV is a valve whose main purpose is to control flow through a specific route. Flexible (4-way valves with 3-position types) start-stop-reverse options are offered as seen in Figure 2.

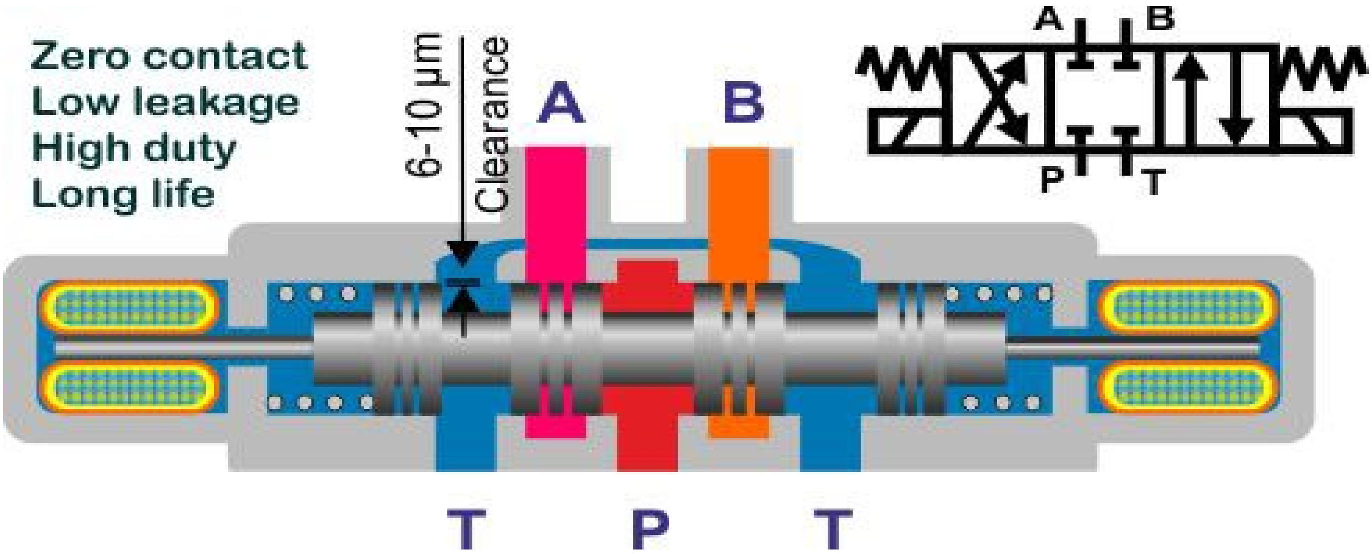

Figure 2: Directional control valve [42]

2.3 Proportional pressure relief valve (PPRV)

According to [44], the inertial force acting on the PPRV's valve spool is as follows in Equation (9):

$$m\frac{dw_m}{dt} = \Delta PA - C\dot{x} - K_1 - F_s \quad (9)$$

The inertial force of the load is represented by the first term in this equation. The second term in this equation is the force that the loading pump pressure exerts on the relief valve's valve spool. The third term in this equation is viscous friction loss. The fourth term in this equation is the variable spring force. The final term in this equation is the force that the spring's pre-compression exerts on the valve spool.

2.4 Actuator

The mechanical energy produced by an actuator comes from fluid energy. The flow inside the actuator is given by Equation (10) [43]:

$$K\frac{dP}{dt} + Aw_m + \frac{P_L}{R_{lkga}} = Q_{in} \quad (10)$$

The first phrase refers to the flow of compressible fluid, the second to the flow that drives the actuator, the third to the flow that causes leaks in the actuator, and the fourth to the flow that enters the actuator. By rearrangement (10), the following is the load pressure operating within the actuator express in Equation (11):

$$P_L = \frac{1}{K}\int\left(Q_{in} - \frac{P_L}{R_{lkga}} - Aw_m\right) \quad (11)$$

According to [45], the actuator's force balance Equation (12) is as follows:

$$P_L A = m\frac{dw_m}{dt} + K_1 X + \beta v + F_L \quad (12)$$

In this equation, the first term is the pressure force acting within the actuator against the external load, followed by the inertial force associated with the load, the spring force resulting from the stiffness of the actuator, the friction force acting between the piston and the fluid trapped within the clearances, the fourth term, and the external load acting upon the actuators. All the previous equations were simulated using Matlab simulation. Table 1 provides an example of the hydraulic system's simulation parameters.

Table 1: Simulation parameters for the hydraulic system

Hydraulic system specifications	
Components	**Specification**
Hydraulic fluid block	Fluid: Skydrol LD-4 Relative amount of trapped air: 0.005 System temperature: 60 ºC Viscosity 7.12831 cst
Fixed pump displacement	Pump displacement: 4×10^{-6} m^3/rad Volumetric efficiency: 92% Total efficiency: 80% Nominal pressure: 50×10^5 pa Angular velocity: ω_m = 188 rad/sec Kinematic viscosity: 18 cst Fluid density: 900 kg/m^3
Pressure relief valve	Max. pass area: 2×10^{-4} m^2 Valve pressure setting: 3×10^7 pa Regulation range: 3×10^6 pa Flow discharge coefficient: 0.7 Critical Reynolds no.: 12 Leakage area: 1×10^{-12} m^2
4-way directional valve	Valve passage max. area: 5×10^{-4} m^2 Max. opening: 0.005 m Critical Reynolds no.: 12 Leakage area: 1×10^{-9} m^2
Double-acting hydraulic cylinder	Piston area A, B: 0.125 m^2 Piston stroke: 0.5 m Dead volume A, B: 1×10^{-4} m^3 Specific heat ratio: 1.4
Load	Backhoe actuation system (Hydraulic hoist): motion divided into 3 mechanisms (penetration, separation and secondary separation) = 3 DOF manipulator represented by: Spring: 1000 N/m Damping coefficient: 100 N×s/m Mass: 100 kg

3. Intelligent motor drive control

Through the PI-fuzzy logic system, the speed and voltage (V/f) of three-phase IM are controlled, thus achieving quick and efficient access to the required steady-state for the electro-hydraulic system.

3.1 Induction motor model

The three-phase IM delivers electromagnetic torque to a fixed displacement pump as a mechanical energy converter. Using the asynchronous machine model block, the IM is simulated. The windings of the stator and rotor are Y-linked with internal neutral. For a single squirrel cage IM, a fourth-order state-space model of the motor's electrical component and a second-order system model of the mechanical component is used [44]. The electromagnetic motor torque T_e is given as Equation (13):

$$T_e = 1.5\, p\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \tag{13}$$

The mechanical system of the three-phase IM is given as Equations (14,15):

$$\frac{d}{dt}\omega_m = \frac{1}{2H}\left(T_e - f_v \omega_m - T_m\right) \tag{14}$$

$$\frac{d}{dt}\theta_m = \omega_m \tag{15}$$

3.2 PID controller

PID controller is a generic control loop feedback mechanism widely used in industrial control systems [45]. The PID controller is made to provide the PWM generator with the necessary control signals. The motor speed is used as feedback when compared to the desired speed. The PID controller provided the error signal as input. By modifying the process control inputs, the controller tries to reduce the error [6]. The three independent constant parameters—Proportional P, Integral I, and Derivative D—are used in the PID controller method. It is based on the accumulation of prior errors, P is based on the current error e, and D is a forecast of coming errors, as Equation (16) [46]:

$$u(t) = k_p\, e(t) + k_i \int_0^t e(t) + k_d \frac{de(t)}{dt} \tag{16}$$

The PI controller is typically used for applications requiring speed control, as stated in Equation (17):

$$u(t) = k_p\, e(t) + k_i \int_0^t e(t) \tag{17}$$

3.3 Indirect vector control (IVC) system

The IVC is the favored option for high-performance drives [16,17,47]. The IVC approach is similar to direct vector control in most respects, except for the rotor angle θ_e is created indirectly (by estimation) using the measured speed ω_r and the slip-speed omega ω_{sl}. The following dynamic Equations (18-21) [47] must be considered while applying the IVC approach.

$$\theta_e = \int \omega_e\, dt = \int (\omega_r + \omega_{sl}) dt = \theta_r + \theta_{sl} \tag{18}$$

The torque component of the current i_{qs} should be on the q-axis for decoupling control, and the stator flux component of the current i_{ds} should be aligned on the d-axis, which leads to $\psi_{qr} = 0$ and $\psi_{dr} = \psi_r$, as show in Equation (19):

$$\frac{L_r}{R_r}\frac{d\psi_r}{dt} + \psi_r = L_m i_{ds} \tag{19}$$

As well, the slip speed can be calculated as in Equation (20):

$$\omega_{sl} = \frac{L_m}{\psi_r}\frac{R_r}{L_r} i_{qs} = \frac{R_r}{L_r}\frac{i_{qs}}{i_{ds}} \tag{20}$$

It has been discovered that using the aforementioned slip angular speed command to make field orientation would result in perfect decoupling. The constant rotor flux ψ_r and $d\psi_r/dt = 0$ can be used in place of (19), causing the rotor flux to be set as in Equation (21):

$$\psi_r = L_m i_{ds} \tag{21}$$

This controlled approach drives the IM as a separately excited DC motor to achieve excellent dynamic performance. The phasor diagram of the IVC method of an IM is shown in Figure 3.

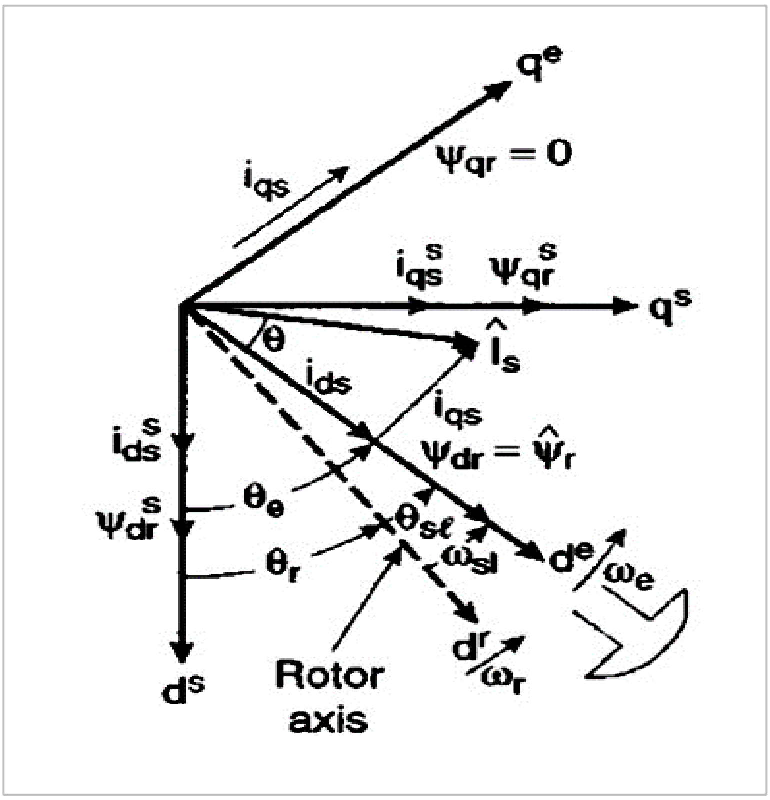

Figure 3: Phasor diagram indirect vector control method of Induction motor [48]

3.4 Fuzzy logic control (FLC)

The FLC's simplicity and adaptability make it appropriate for many industrial applications. In the FLC, linguistic description rules based on expert knowledge describe a fuzzy system's dynamic behavior [5]. Expert knowledge often takes the form of "IF (a set of conditions are satisfied) THEN (a set of consequences can be inferred)". They are sometimes called "fuzzy conditional statements" since the antecedents and consequents of these IF-THEN rules are linked to fuzzy ideas (linguistic words). According to our definition, a fuzzy control rule is a fuzzy conditional statement with an application domain condition as the antecedent and a control action for the system under control as the consequent. Fuzzy control rules essentially offer a practical means of defining control policy and knowledge areas. Furthermore, the antecedents and conclusions of these rules may incorporate several linguistic factors. In this situation, the system will be called a single input, single output (SISO) fuzzy system. Figure 4 shows the fuzzy logic design in MATLAB (AWS).

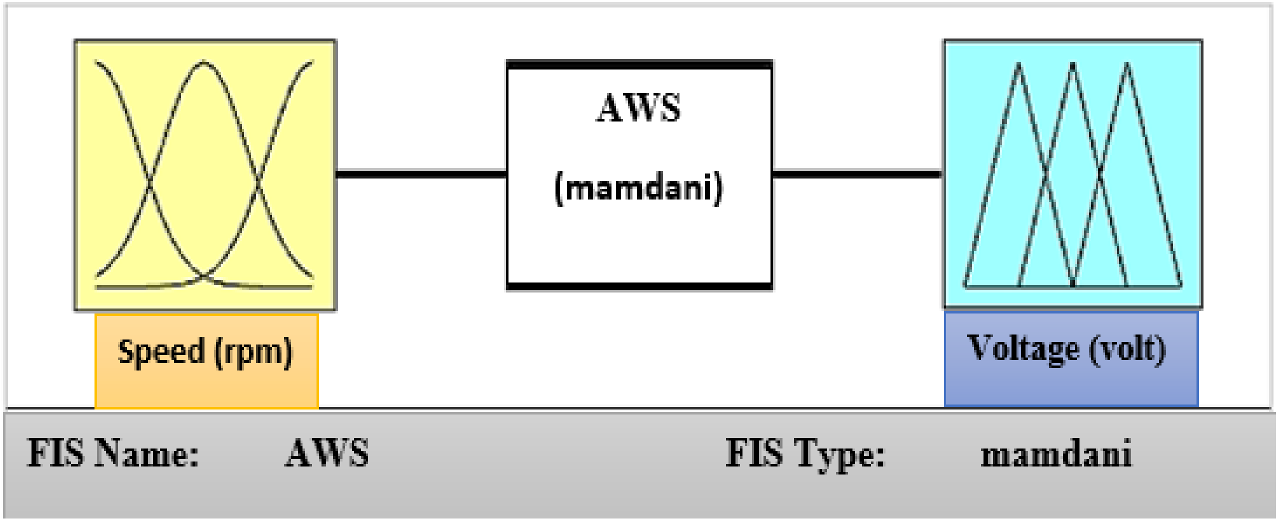

Figure 4: Fuzzy logic design

Some basic rules of FLC are made to operate the system:

1) If the speed is slow, then the voltage is up
2) If the speed is right, then the voltage is no change
3) If the speed is high, then the voltage is down

Figures 5 and 6 show the input and output membership functions.

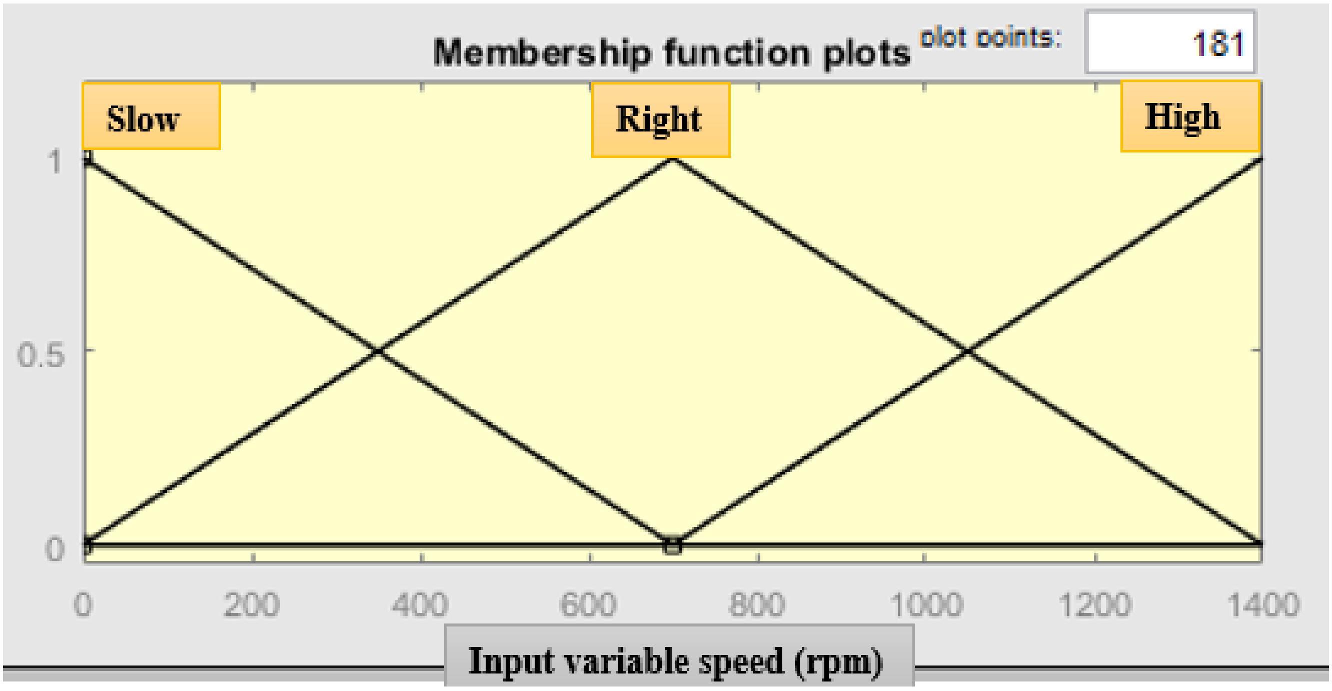

Figure 5: I/P membership (s peed)

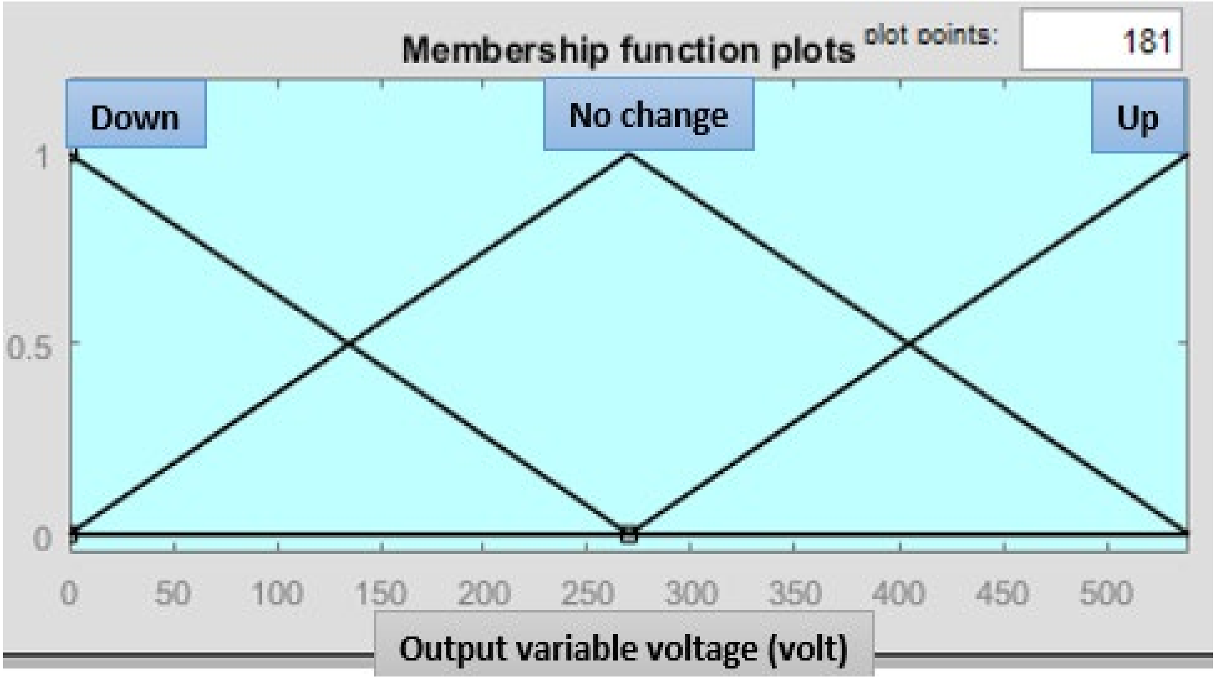

Figure 6: O/P membership (voltage)

After several attempts, we found that choosing nine memberships was best for the electro-hydraulic system's performance. Table 2 shows the Rules for Fuzzy Controller, which in turn shows the relationship between input and output membership functions.

Table 2: Relation between Input and Output membership functions

Speed / Voltage	Slow	Right	High
Down	Down	Down	Down
No change	No change	No change	No change
Up	Up	Up	Up

Figure 7 shows the curve between voltage and speed in fuzzy logic design. A voltage of 540V drove the IGBT inverter since the IVC technique lowers the voltage, which lowers the power and preserves energy. The required voltage may be decreased from 620 V to 540 V using the following formulae, saving 80 V. This indicates that, as compared to SPWM, the DC utilization factor using the SVM is raised by 15%.

To generate an AC peak voltage of 310 V using the SPWM approach, a DC voltage of 620 V must be supplied. With the SVM approach, a 540 DC voltage is sufficient to generate 310 V of peak voltage since the technology adds an extra DC value of 80 V, reducing the required supply and allowing for source voltage savings. The following Equations (22,23) illustrate the above text in the proposed new mathematical model. From the proposed simulation model, it is concluded that:

For SPWM $V_{dc} = 620V$

$$V_{ac} = \frac{m_a V_{dc}}{2} \tag{22}$$

$$V_{ac} = \frac{620}{2} = 310V$$

For SVM $V_{dc} = 540V$

$$V_{ac} = \frac{1.15\, m_a V_{dc}}{2} \tag{23}$$

$$V_{ac} = \frac{1.15 * 540}{2} = 310V$$

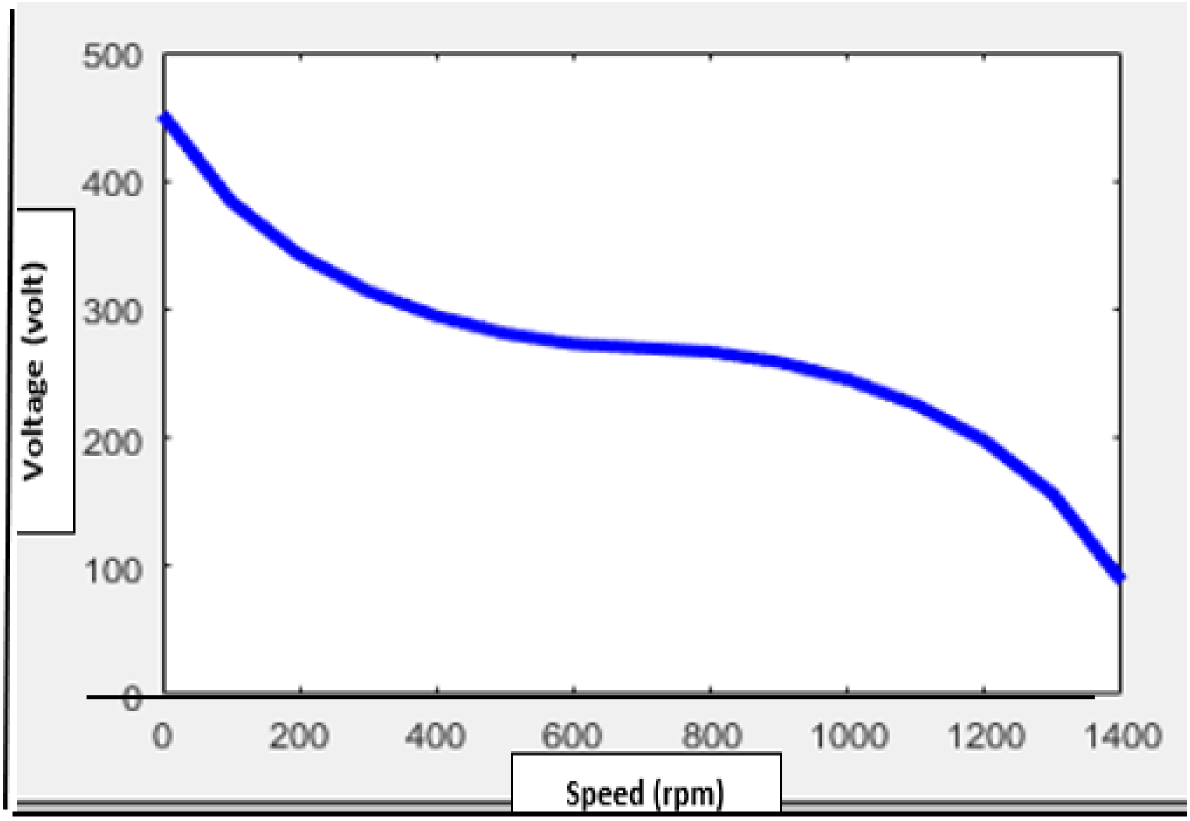

Figure 7: Curve between voltage and speed in fuzzy logic design

Table 3 demonstrates the simulated parameters of the electric system.

Table 3: Simulation parameters of the electric system

Electric system	
Components	**Specification**
Induction motor	3-ϕ, single squirrel cage model, 4 kW, 400 V, 50 Hz, 1430 rpm, 4 poles
PI controller	k_p = 1500, k_i = 6
Fuzzy logic controller	I/P: Speed & O/P: Voltage
Power electronic devices	IGBT Universal Bridge, Diodes Snubber resistance R_s =10^5 Ω Snubber capacitance, $C = \infty$ No. of bridge arms = 3
SVPWM (Generator 2-level)	Data type of input reference vector: α, β components Operation mode: unsynchronized PWM frequency: 5000 Hz Sample time: 0

Finally, after writing all the mathematical models of the parts used in the research system, we show in Figure 8 the flow chart that shows the work of the overall system with the mathematical models.

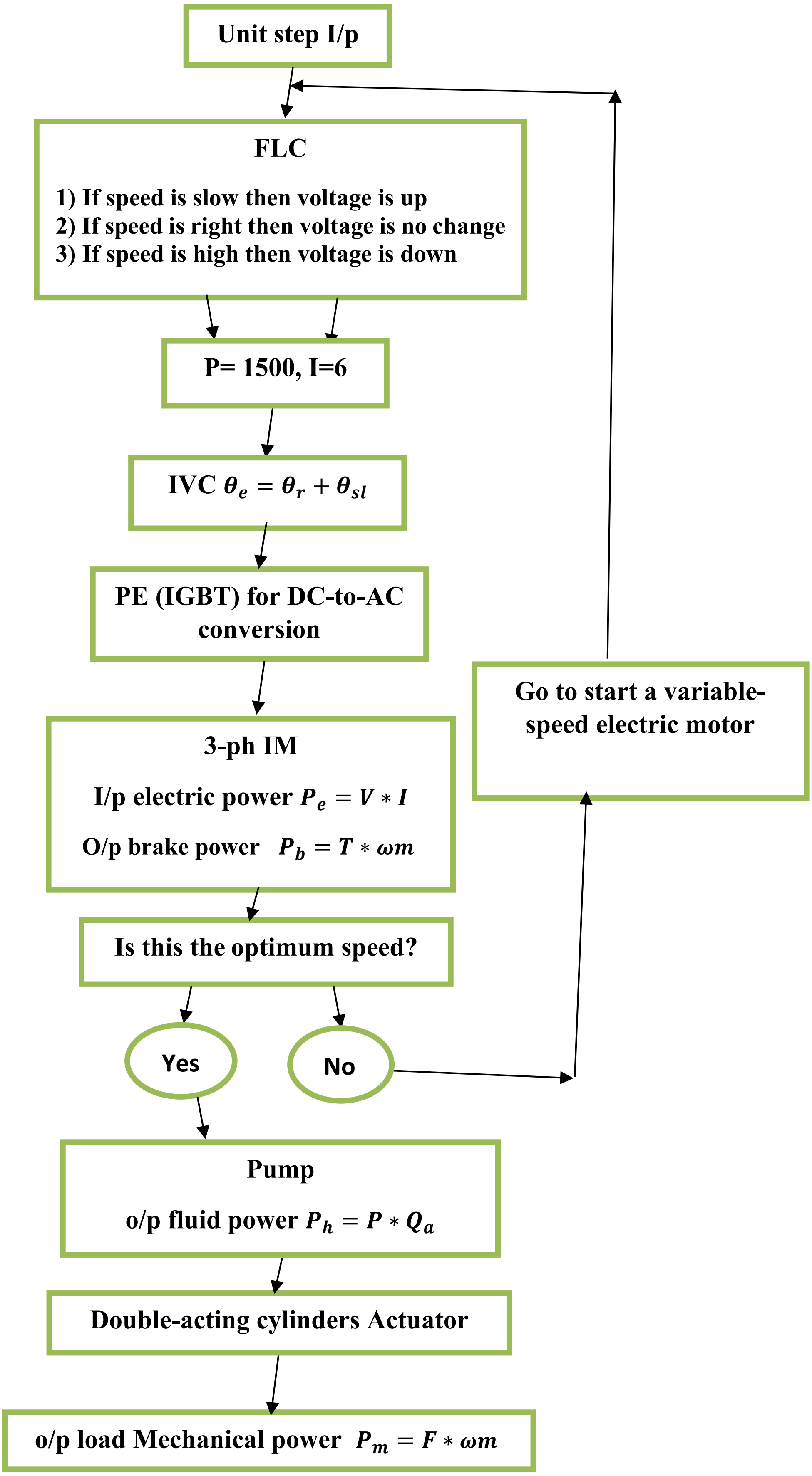

Figure 8: Flow chart of system operation

4. Simulation model

The whole electro-hydraulic system has been built, as shown in Figure 9. It comprises two main systems: the electrical and hydraulic systems. The electric system, shown in Figure 10 comprises a three-phase squirrel cage IM with a PI-fuzzy logic controller (PIFLC) system, an SVPWM generator, and an IGBT universal bridge. The main aim of this system is to control the speed of the IM to supply the required mechanical movement (torque) to the fixed displacement pump, which is necessary to adjust the hydraulic flow rate in the 3-DOF hydraulic manipulator.

The hydraulic system model shown in Figure 11 consists of hydraulic fluid, a tank, lines, a fixed displacement pump (gear pump), a check valve, a proportional pressure relief valve (PDCV), a relief valve, a double-acting cylinder, directional control valve (DCV), a passion sensor, flow rate sensor, pressure sensor, and load application (3-DOF hydraulic hoist).

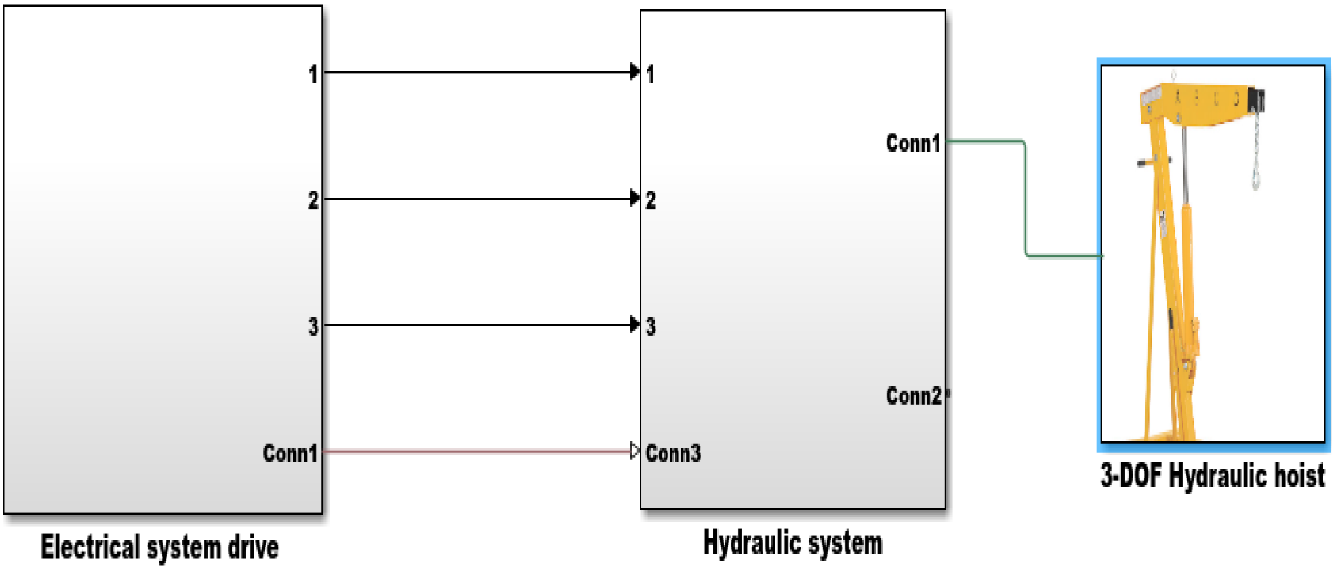

Figure 9: Electro-hydraulic system

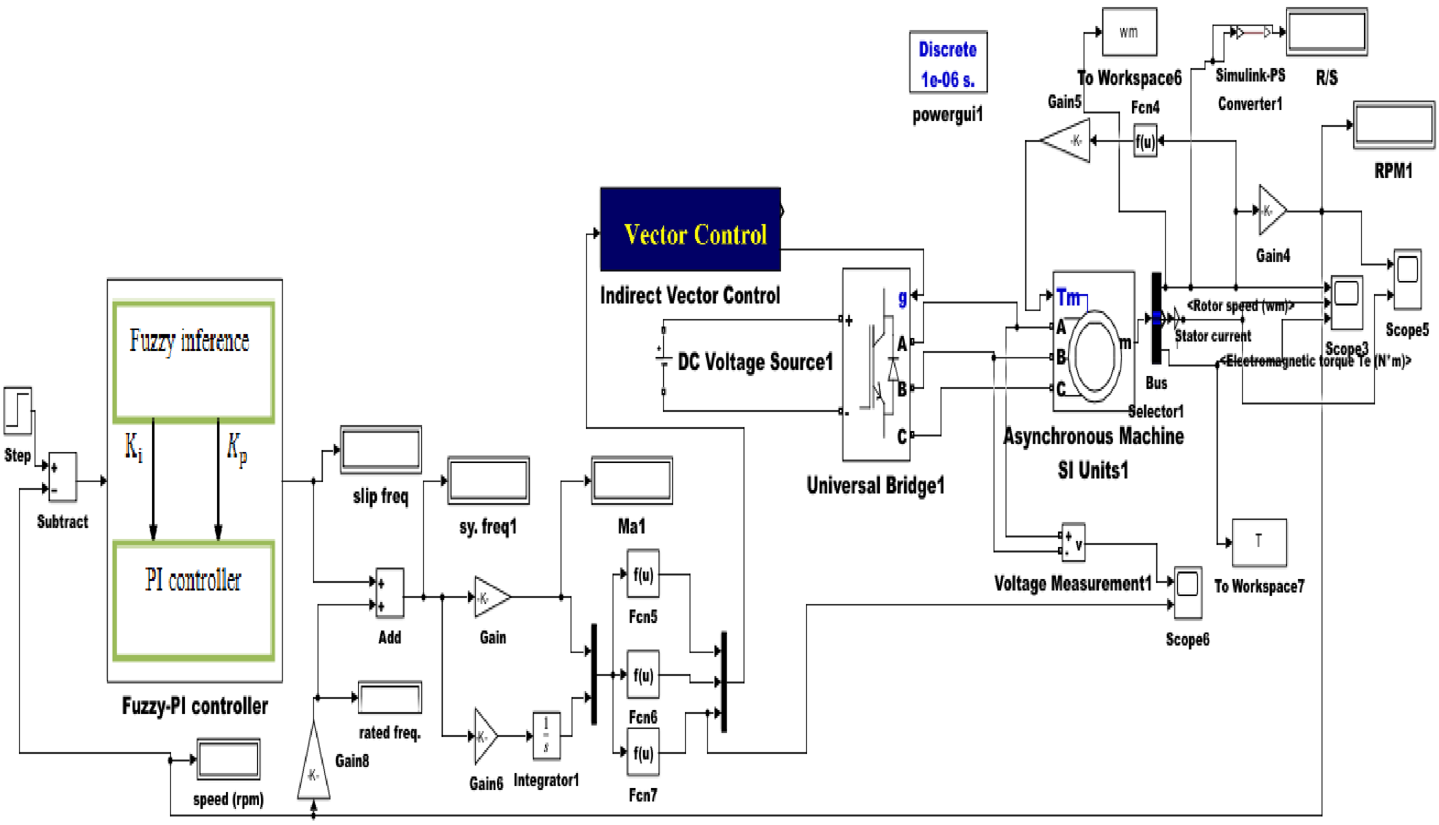

Figure 10: Electrical system with (PIFLC , IVC)

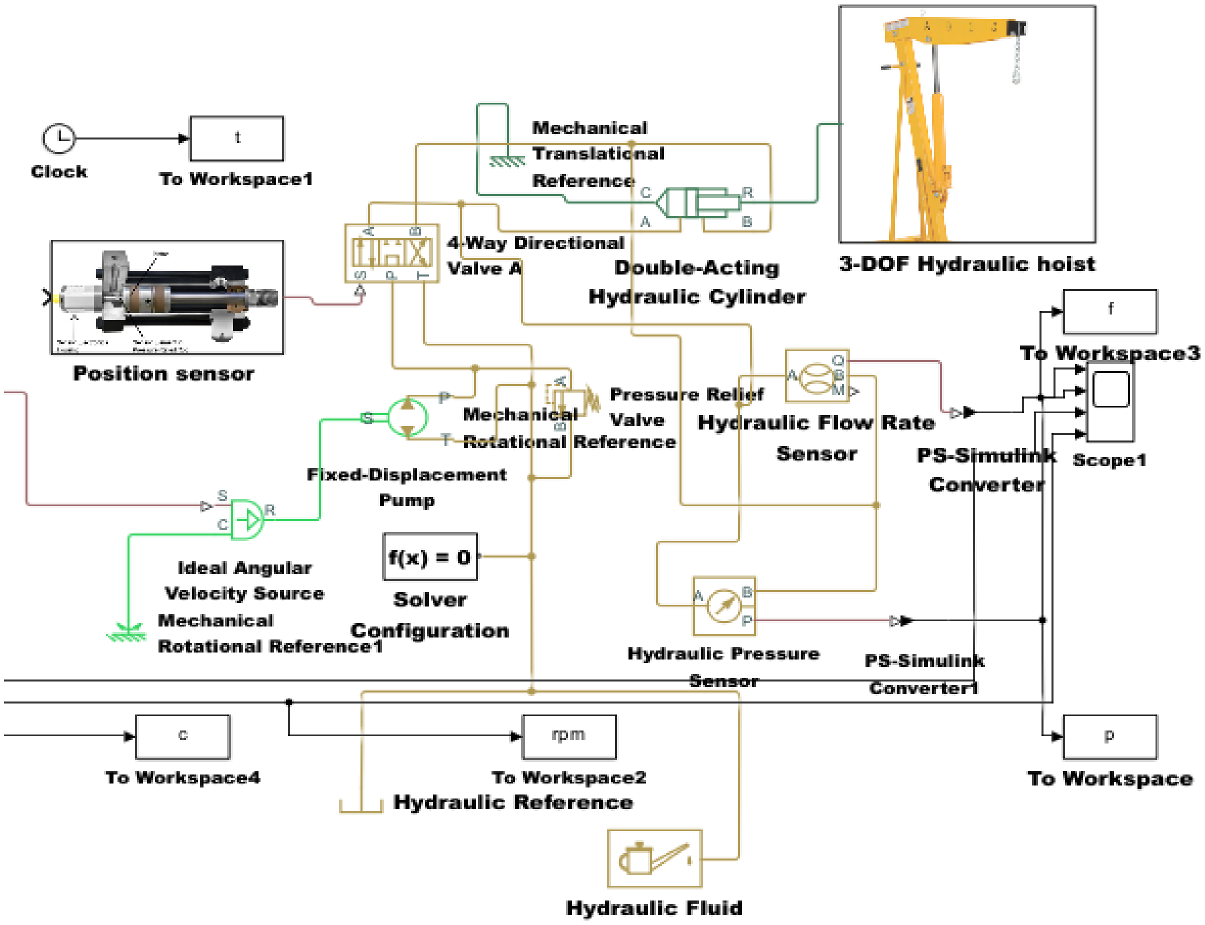

Figure 11: Hydraulic system

5. Results and discussion

In the current study, the PI-fuzzy logic control (PIFLC) technique was used with indirect vector control (IVC). Compared to traditional controllers, the PIFLC offers a few benefits, such as easy control, low cost, and the ability to build without understanding the entire mathematical model of the plant. The IVC (FOC) technique is easy to implement using digital processors. After comparing them with conventional PI and V/f techniques, the results proved that the system performance using PIFLC with IVC technique is better than the traditional PI control regarding the starting current. Figure 12A shows the difference between the current and speed curves at the transition state up to stability when the blue plots represent the current and speed waveforms under V/f control, and the red plots represent the waveforms under PI control.

In contrast, the black plots represent the waveforms with PIFL control. In the transition state, when using the PIFLC with IVC technique, the starting current stabilizes at 15 A, while in the conventional PI controller, the starting current is high, reaching 80 A. Meanwhile, for the V/F control, the current in the transition state reaches 35 A before all currents stabilize at a value of 12A. This, in turn, will protect the motor from the negative effects of drawn currents and improve its performance, and, accordingly, it will improve the performance of the entire hydraulic system.

It is important to note that the low beginning current obtained using the current study PIFLC with IVC technique is crucial. By decreasing the beginning current amount, the induction motor is shielded from the many harmonics produced by the high starting current. Hence, these harmonics cause the motor to malfunction, harming the control system and preventing the electro-hydraulic system from operating entirely.

According to the source speed that was given, which was 1400 rpm, Figure 13D shows the IM's speed in the PIFLC with IVC is steady, regular, oscillates without overshooting, and is equal to 1400 rpm (146.5 r/s) in the transitional stage—the outcome of Affinity law's direct relationship between speed and flow rate shown in Equation (24) [42]:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \tag{24}$$

This means that the 6×10^{-4} m^3/sec flow becomes regular, as shown in the flow rate curve in Figure 13C. The pressure disturbance decreases, which leads to a decrease in pressure drop and an improvement in the general performance of the electro-hydraulic system, thus resulting in more energy saving, as shown in the pressure curve in Figure 13B. The speed curve in Figure 13D was previously explained in the speed comparison curve in Figure 12 (B,C).

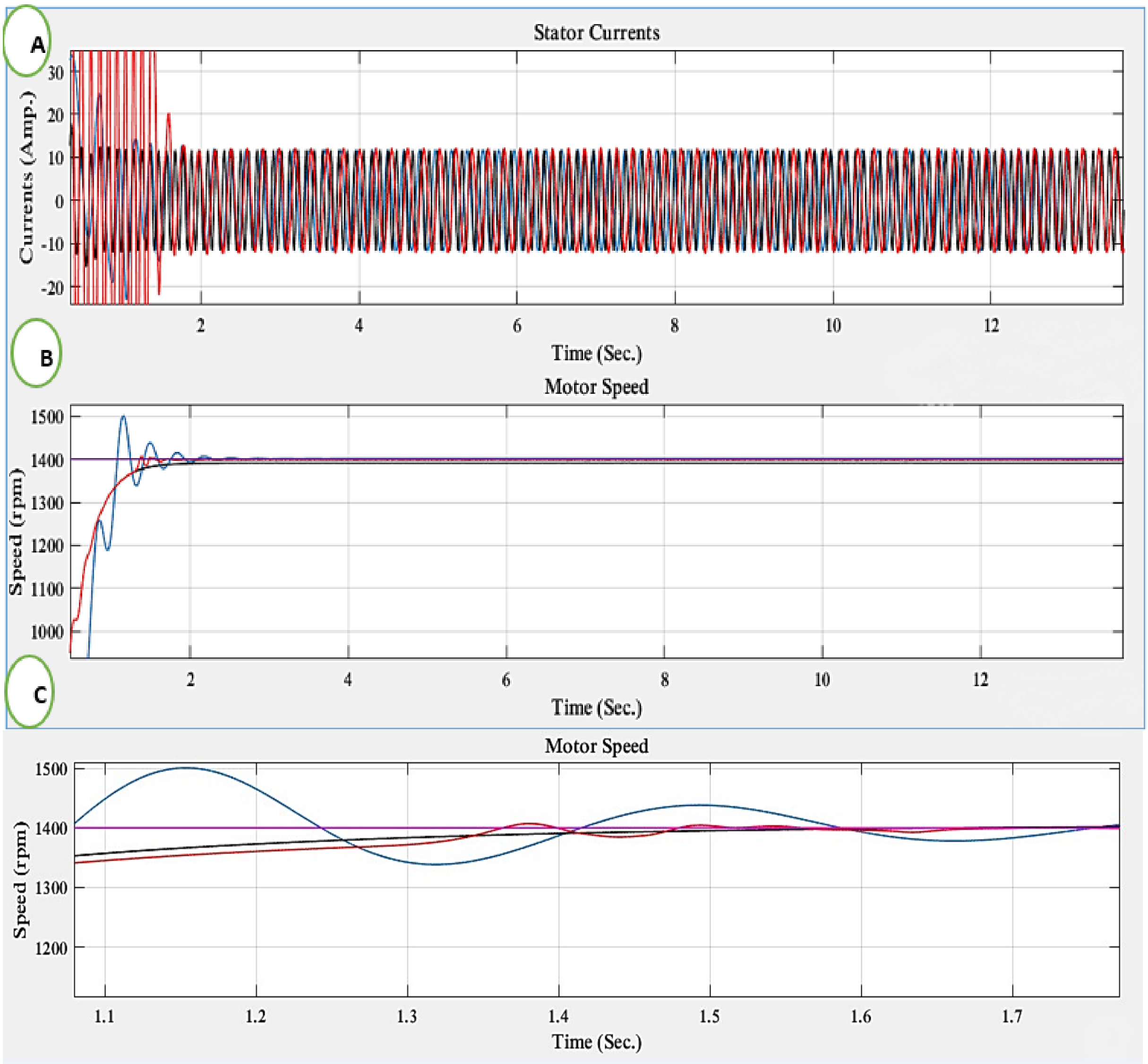

Figure 12: Dynamic response of motor currents and speeds for three control techniques

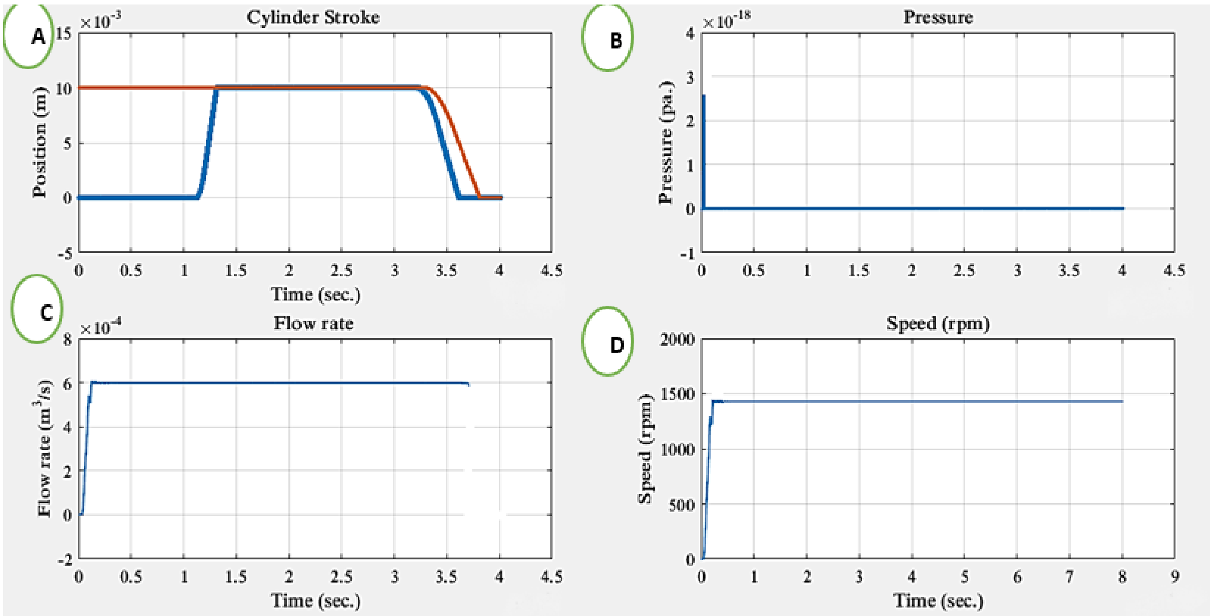

Figure 13: Electro-hydraulic system performance under PIFLC with IVC technique

It should be mentioned that the research's approach (PIFLC with IVC) is the first of its type for controlling an electro-hydraulic system to regulate pipe flow basis and with system requirements. This is the first time it's happened. It is also a very good approach regarding how easy it is to build the fuzzy system mathematical model developed for the study. It is a digital approach that differs from other analog approaches in that it produces results with great precision and saves a substantial amount of energy, improving efficiency significantly.

This contrasts with the work of other researchers [15,16] who have not employed all of the suggested research techniques in this way. Instead, these researchers are satisfied with using control techniques solely to regulate the motor's speed without connecting the motor to other applied systems to assess the control systems' effectiveness.

In the PI control of the speed at the transitional state, it suffers from a little turbulence and irregularity, as its value reaches 1420 rpm (148.6 r/s) before it stabilizes, as shown in the speed curve in Figure 14D, which leads to a slight disturbance in the flow of 6.2×10^{-4} m^3/sec and a slight vibration before settling as shown in the flow rate curve in Figure 14, consequently, the pressure imbalance affects the stability of the electro-hydraulic system before it returns to a steady state, as shown in the pressure curve in Figure 14B.

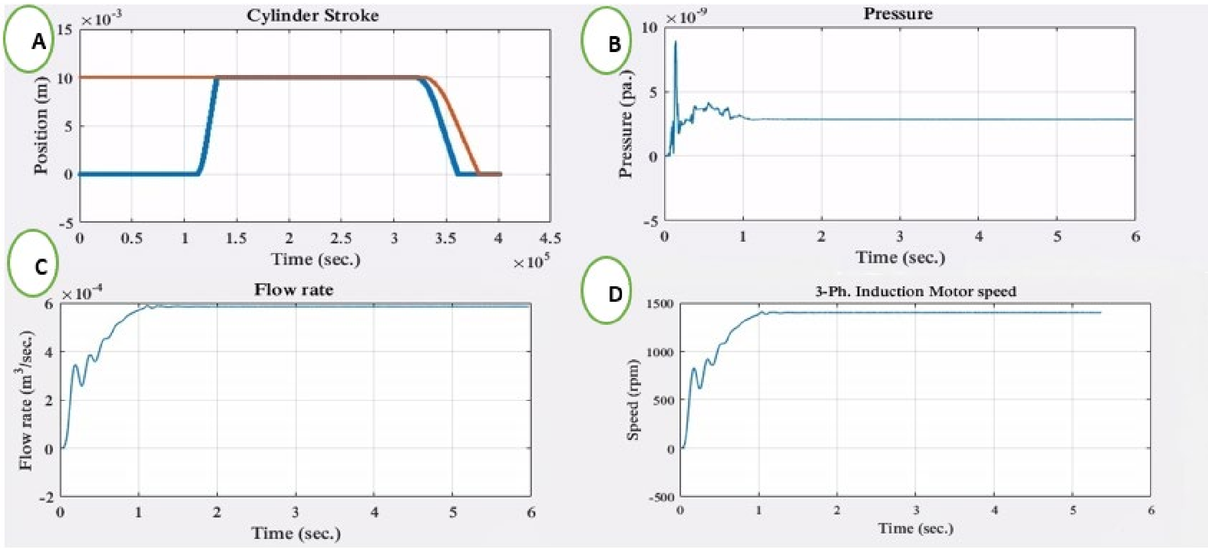

Figure 14: Electro-hydraulic system performance by PI control

Finally, and in general, all the pressure generated during the system's operation achieves the appropriate acceleration required for the overall system.

The speed controlled by the V/f technique will suffer from high turbulence as the speed reaches 1500 rpm (157 r/s), which affects the stability of the flow rate of 6.5×10^{-4} m^3/sec, as shown in the speed and flow rate curve in Figure 15D,15C and this, in turn, leads to pressure drop then vibration in the electro-hydraulic system, and thus the occurrence of leaks and corrosion of moving parts and system failure sometimes as shown pressure curve in Figure 15B.

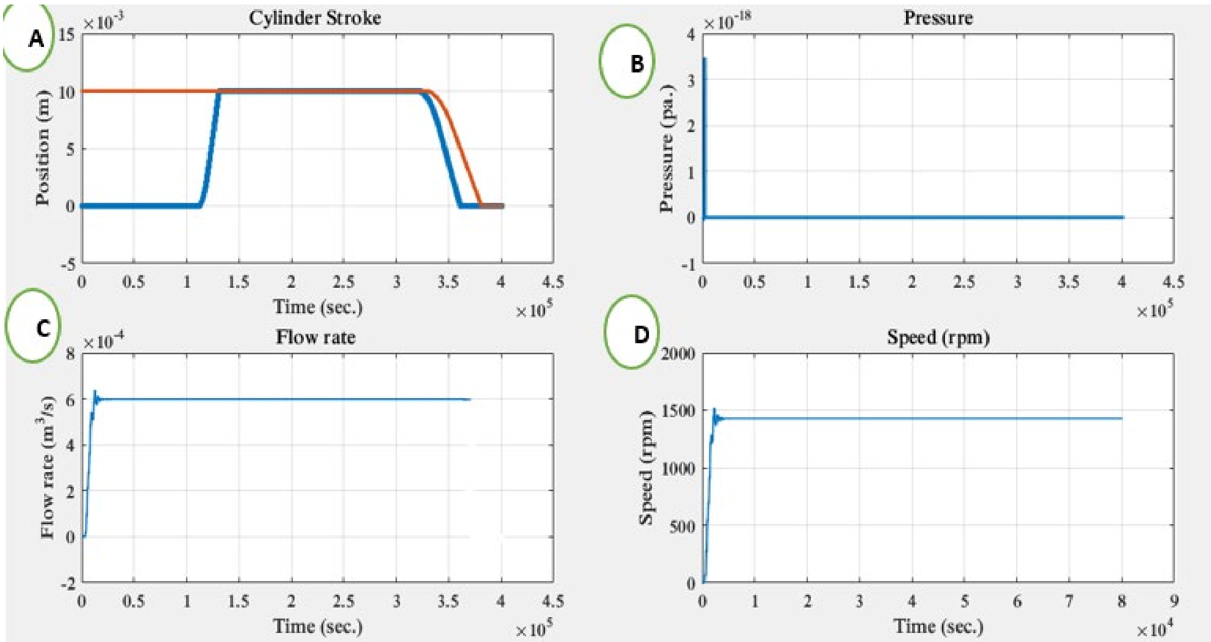

Figure 15: Electro-hydraulic system performance under V/f control technique

The expansion cylinder stroke time and retraction cylinder stroke times for position sensors at 150 bar pressure were 3.75 sec and 3.55 sec, respectively. There is a variation in the time taken for the expansion and contraction strokes due to the piston's area changing between the two strokes. This changes the applied force, turning a static head into a dynamic head. The cylinder strokes are shown in part A of the Figures (13A, 14A ,15A).

Three control techniques and their responses appear in Table 4.

Table 4: System performance parameters of the step response under three controller types

Controller Type	Rise time (s)	Settling time (s)	Overshoot (%)	Stead-state error
PI	1	1.6	0.71428	0.393
V/f	0.5	2	7.142	0.486
PIFLC & IVC	0.15	0.3	0.2	0.024

The results recorded in Table 4 showed that the steady-state error in PIFLC with IVC is very small (0.024) compared to other cases V/F (0.486) & PI controller technique (0.393) because the time required to reach a steady-state is much less in the first control method (PIFLC with IVC) compared to the other two control methods (V/F & PI), as the settling time for the PIFLC with IVC control is (0.3s). In contrast, the settling time for the V/f control is (2s), and the PI control is (1.6s). Several simulation experiments were conducted on indirect vector-controlled induction motor drives under varied operating situations using V/F, PI controllers, and intelligent controllers (PIFLC with IVC) based on fuzzy logic. We compared and studied the steady state errors and the timing response.

For all states of the V/F, PI, and PIFLC with IVC-based controller, Figures (13-15). display speed response, pressure drop, and flow rate at the same time of cylinder stroke. The PIFLC and IVC controllers demonstrated superior performance in steady-state error, rise time, settling time, overshoot, and transient process time.

6. Conclusion

For indirect vector speed-controlled PWM voltage source inverter drive-fed induction motors, the performance of an intelligent controller using PI fuzzy logic has been confirmed and compared to that of a traditional PI controller and V/f control. Some conclusions can be drawn from the results obtained.

1) The simulation results showed the fuzzy logic controller's excellent dynamic performance and resilience throughout the transient period. After several attempts, I found that choosing nine memberships is best for the electro-hydraulic system performance.
2) The proposed smart controller showed superior performance compared to the PI controller and V/f technique in terms of lower cost, good stability, fast response, and thus good performance.
3) The system response overshoots when the PI controller is used, necessitating additional settling time to reach the target value. At the same time, the motor speed under the PIFLC with IVC is steady, regular, and oscillates without overshooting, especially when starting.
4) It can be inferred that using PIFLC with IVC for various load conditions enhances and smooths out motor torque and stator current ripples.
5) A low starting current of 15A when using PIFLC with IVC compared with a very high starting current of 80A for conventional PI controller while it has a current of 35A using V/F control.
6) Due to the flow rate approaching uniform laminar flow, the electro-hydraulic actuator system using PIFLC with IVC will be much less brittle, vibrate less, last longer, leak less hydraulic oil, and have a lower degree of pressure drop.
7) The simulation results prove that the indirect field-oriented control technique with PI fuzzy logic controller provides better speed control of the induction motor by reducing the steady state error to (0.024), overshooting to (0.2%), and Settling time to (0.3s).

Nomenclature

A: Orifice passage area (m^2)
C. Damping coefficient (N.s/m)
d: Diameter (m)
D: Pump displacement (m)
D_p: Volume displacement rate (m)
FOC: Field-oriented control
H. Inertia constant of the rotor/load set
i_{qs}, i_{ds}: Currents aligned with q-axis & d-axis
IVC: Indirect vector control
k_{HP}: Hagen-Poiseuille coefficient
Leak: Leakage coefficient
k_p, k_i, k_d: Proportional, integral & derivative coefficients
K_1: Spring stiffness linked with the actuator (N/m)
L_m: Motor magnetizing inductance (H)
p: Motor pole pair
PIFLC: PI fuzzy logic control
T_e: Electromagnetic torque (N.m)
T_m: Mechanical torque on the shaft (N.m)
SPWM: Sinusoidal pulse width modulation
FVf_v: Viscosity coefficient of rotor friction
F_L: External load acting upon the actuator (N)
F_s: Force due to the pre-compression of the spring (N)
ω: Pump angular velocity (r/s)
ω_e: Reference frame speed (r/s)
ω_{nom}: Pump nominal angular velocity (r/s)
ω_m: Angular velocity of the rotor (r/s)
ω_r: Measured speed (r/s)
ω_{sl}: Slip speed (r/s)
v: Kinetic viscosity of the fluid (St)
v_{nom}: Nominal fluid kinematic viscosity
η_m, η_V: Pump mechanical & volumetric efficiencies
η_t: Total efficiency

P: Discharge pressure (pa)
PT, PP: Gauge pressures
P_L, P_h: Load power & Hydraulic power (W)
q: Pump delivery
q_{leak}: Leakage flow
Q_a: Actual flow rate for hydraulic pump (m^3/sec)
Q_{in}: Inlet flow reaching the actuator (m^3/sec)
K: Constant of the compressible fluid flow
R_{lkga}: Resistance of leakage flow
R_r, L_r: Rotor resistance (Ω) & inductance (H)
T: Torque at the pump driving shaft
μ: Fluid dynamic viscosity (Pa.s)
β: Friction coefficient
θ_e: Theta generated (New rotor angle)
θ_r: Measured angle (Original rotor angle)
θ_{sl}: Slip angle
ρ: Fluid density (kg/m^3)
ρ_{nom}: Nominal fluid density (kg/m^3)
$\varphi_{ds}, \varphi_{qs}$: Stator fluxes referred to d-axis & q-axis (Wb)
θ_m: Angular position of the rotor (m)
ψ_r: Rotor flux
ΔP: Pressure difference (pa)

Author contributions

Conceptualization, A. hassan. J. Mohammed. and W. Hashim.; methodology, A. hassan. J. Mohammed. and W. Hashim.; software, A. Hassan.; validation, A. hassan. and J. Mohammed.; formal analysis, A. hassan. and J. Mohammed.; investigation, A. hassan. J. Mohammed. and W. Hashim.; resources, A. hassan. J. Mohammed. and W. Hashim.; data curation, A. hassan. and J. Mohammed.; writing—original draft preparation, A. hassan.; writing—review and editing, J. Mohammed. and W. Hashim.; visualization, A. hassan.; supervision, J. Mohammed. and W. Hashim.; project administration, A. hassan J. Mohammed. and W. Hashim. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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