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Advanced golden jackal optimization-based fractional-order integral terminal sliding-mode (FO-ITSM) controller for level control of the conical tank system

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ABSTRACT
This article examines a conical tank nonlinear system's level control. A crucial component of facilities like milk processing plants and sugarcane mills is the conical tank. The fluid drains entirely due to the conical shape of the tank. The conical form of the system causes nonlinear dynamics. The conical tank nonlinear system transfer mechanism is not easily accessible, and different operating heights require different transfer mechanisms, making controller design difficult. Developing the Fractional-Order Integral Terminal Sliding-Mode (FO-ITSM) Controller system for Advanced Golden Jackal Optimisation (GJO) based conical tank systems is the main objective of this paper. This is utilised to deliver real-time liquid level management in non-linear conical systems. The dynamics of these models make it possible to identify the conical tank system that produces control signals from liquid samples taken at reference levels with greater accuracy. This system, which is employed on multiple platforms, maintains and controls the liquid level while meeting all design specifications, including time constant, no overshoot, less settling, and rise time. For research simulation work, MATLAB software's FOMCON toolbox is utilised.

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1. Introduction

One of the fundamental issues in progression trades is the management of liquid level [1] and flow in the tank. Liquids must be propelled, held in tanks, and then propelled to alternative tank in the process industries. The liquid will frequently undergo chemical or fraternization behavior in the tanks, but there must always be control over the fluid level there. In process industries, the controlling liquid level is a crucial and frequent operation. In this particular level process, the level of liquid is kept at a consistent rate in a conical tank. By regulating the input flow into the tank, this is accomplished. The inflow into a tank is the altered constant, and the range in the tank is the control strategy. There are numerous uses for conical tanks in the process industries, including the concrete mixing, food, hydrometallurgical and wastewater treatment sectors.

Fractional controllers are now often utilized [2] in recent years. The differentiator or integrator is either absent or present in typical Proportional Integral Derivative Controller (PID) controllers, also known as proportional–integral (PI) and proportional-derivative (PD) regulators; that is, their respective powers are either 0 or 1. Nonetheless, the powers of the derivative and integral actions in the FOPID regulator may be non-integers, such as 0.1 or 1.2. Fractional Order Proportional Integral Derivative Controller (FOPID) controllers are able to weigh the advantages and disadvantages of the integrator and differentiator due to their versatility. CRONE, N-integer and FOMCON toolboxes are examples of toolboxes used to emulate fractional controllers. In this work, fractional controllers and fractional transfer functions are simulated using the FOMCON toolbox. The non-integer order of the fractional regulator makes tweaking the controller parameters more difficult, even if it offers greater design freedom than other controllers. The FOPID regulator was proposed by Podlubny [3,4].

For a miscellaneous range of industries including storage, manufacturing and the service sector, liquid level control is considered to be the most important scheme. If the level in the process tank is too high or keep on increasing with respect to time, may cause damage to process equipment thus affecting the product quality. In the other case, if the level is too low, it may cause deterioration to the overall process performance. Owing to these factors, control of level in the process tank has become a mandatory requirement in the manufacturing industries to enhance production, safety and product excellence. Most of the manufacturing processes in the real world are of multivariable and nonlinear nature. In linear systems, such as rectangular

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tank interacting and non-interacting systems, the control of liquid level will be easier, since the dynamics of the tank does not vary. But the control of liquid levels in conical and spherical tanks is difficult, since the cross-sectional area varies with respect to height.

IMC is used in the process control business, which deals with big time constants and long dead times. Integral Sliding Mode Controller (IMC) can be configured with either a 1-degree of freedom (DOF) or a 2-DOF (dual loop) design [5]. [5,6] addresses the use of fractional IMC-based PID controllers for conical tank height control. Applications of the FOIMC are covered in [7,8]. Fractional Order Integral Sliding Mode Controller (FOIMC) offers a simpler controller design and iso-damping in contrast to integer-order IMC. For systems with a range of time delays, [8,9] offers mathematical equations for adjusting the setting parameters of fractional filter-based FOIMC. The latest advancements in fractional order IMC are presented in [10,11].

The process of regulator constraint adjustment is crucial when the controller configuration is finalized. Zeigler–Nichols and Cohen–Coon approaches are utilized to tune the process control problems. Soft computing performances like fuzzy logic, neural systems and genetic optimizations, as well as swarm intelligence performances like PSO, ant colony and GWO have recently gained popularity as tuning strategies for multiple-purpose nonlinear optimization difficulties with or without restrictions. An approach for nonlinear multi-objective minimization problems based on swarm intelligence is called particle swarm optimization (PSO) outlines the PSO optimization in [12]. A FOPID regulator for a First Order Plus Dead Time (FOPDT) system is designed in [13] using the PSO algorithm [14–17]. The grey wolf optimization is utilized in [18] to minimize different combinations of objective functions, and the regulator constraints are adjusted for FOPID and PID controllers. The bee colony optimization algorithm's pseudo-code is provided in [19]. Ant Colony Optimization (ACO) is alternative modern soft computing method. A thorough overview of ACO applications is provided in [20].

Fractional-order integral terminal sliding-mode (FO-ITSM) is utilized to regulate the height of the conical tank, and the golden jackal optimization (GJO) algorithm is used to adjust the FO-ITSM's parameters. The goal of choosing this challenge is to create a FO-ITSM using GJO methods. The trial-and-error-based design's errors are removed by the GJO algorithm. For a variety of systems, the empirical formulae-based controller parameter design may not be applicable, and occasionally it may not produce acceptable outcomes. The GJO can be programmed, thus a large range of constraints and goal functions can be used during the tuning process. Because the FO-ITSM is fractional, nonlinear equations must be introduced when altering the regulator constraints. Fortunately, the GJO algorithm makes this process simple. The following is the paper's contribution.

- The GJO technique is utilized to regulate the FO-ITSM controller constraints. Based on integral absolute error (IAE), integral time absolute error (ITAE) and integral square error (ISE) three distinct goal functions are utilized to optimize the regulator constraints.
- At the conclusion of the tuning procedure, the algorithms present the optimal controller parameters while minimizing the objective function.
- The conical tank system is controlled using a GJO constructed on a FO-ITSM. A FO-ITSM based on a fractional filter was not used in previous conical tank system studies.

The article is planned as follows: the first section clarifies why this project is needed and introduces the topic. The second section contains the proposed methodology. Third section explains the proposed algorithm of liquid level control in conical tank. Section 4 contains the results of simulation studies as well as a discussion of the findings. Finally, Section 5 has the conclusion.

2. Proposed methodology for the liquid level control in the conical tank system

As demonstrated in [4], the nonlinear conical tank arrangements are extremely inconsistent. Therefore, complex and sophisticated control methods are needed for the modelling, investigation and regulation of these nonlinear systems. The nonlinear mechanism of a real-time FOPID controller leads to chattering issues [2]. While FOPID controllers are useful for managing nonlinear systems, real-time applications must be tuned carefully to avoid chattering problems. Because the system is nonlinear, control strategies designed for particular operating situations may not translate effectively to other scenarios. Reduced toughness and adaptability. Liquid level regulation is a successful function of FOPID-based systems, which constitute most intelligent systems. The Sliding Mode Controller (SMC)-based FOPID controller controls the time domain specifications, something that most current systems are unable to do.

The suggested block diagram for the conical tank arrangement's level control is displayed in Figure 1. The level-based control in a conical tank system is one of the main challenges in the processing industries. This is because the pressure generated by the elevated upper tank creates a potential energy difference that drives the flow of liquid. The pump speed is given by Spj. The noise control valves are given by Nc2 and Nc4. A lower tank's liquidity level is given as Ll. The surface area of outflow in the lower tank system is represented

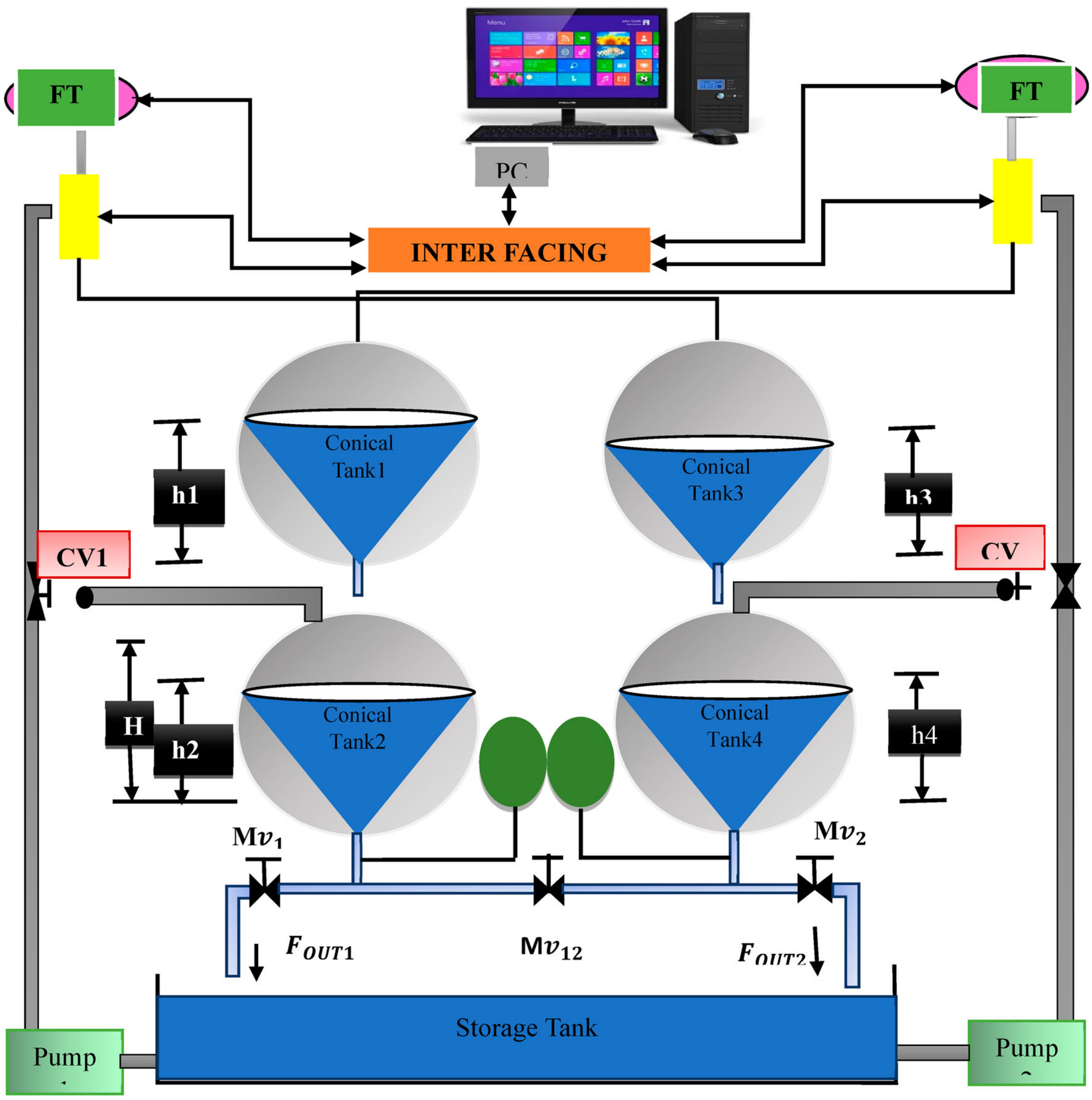

Figure 1. Proposed block diagram of liquid level control in the conical tank system.

by CSoi. The upper tank system's surface area and flow are represented by CSui and Fi, respectively. The ability to perform better and have favourable time domain functional features in the liquid level organization is the main benefit of integrating the suggested FO-ITSM with a GJO system. In order to provide a nonlinear system uncertainty in the event of interruptions, a sliding mode regulating mechanism was developed. For an effective exhibition of this intricate technique, set point (SP) tracking capability to preserve the SP standards while the development of an outside interference is studied. Furthermore, the proposed study work bounds and minimizes mistakes. Simulation was accomplished to estimate the suggested controller's execution in managing the range of liquid in the conical tank.

Level control in a conical tank system is one of the benchmark challenges of process industries. Because of the four tanks arranged in a conical configuration and the variation in the tank's radius, the conical tank system is regarded as an incredibly nonlinear process. A conical tank's radius changes from top to bottom. The configuration of the conical tanks used in the study is shown in Figure 1. Four conical tanks (TANK1, TANK2, TANK3, TANK4) with a height of 50 cm (H) and a radius of 25 cm (R) are utilized in the process. Chemical processing takes place in the third and fourth tanks, while the first and second tanks are utilized for storage. The third and fourth tanks are used for mixing and blending chemicals. The MV_12 valve that connected those tanks. Through the MV_12 valve's opening, liquids move from TANK2 to TANK4.F_IN1 represents the input flow in TANK2, while F_IN2 represents the input flow in TANK4. The purpose of F_OUT2's output flow is to regulate the flows from R2 to pump 1. Differential pressure transmitters (DPT) estimate these fluid heights. This is where the liquid level in Tanks 3 and 4 will be managed. Control valves are indicated by CV1 and CV2. A storage tank holds the raw materials. Magnetic Flow Transmitters (MFT) can measure the input flows F_IN1 and F_IN2. Current signals (4–20 mA) from the DPT and MFT were transferred and made it to the PC's interface unit. Later

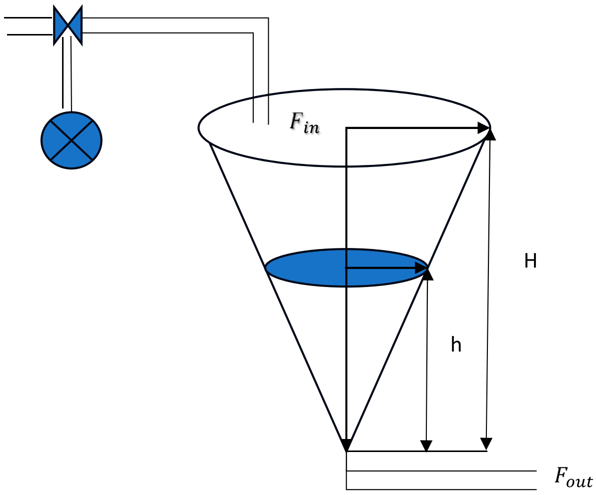

Figure 2. Conical tank system.

implementation takes into account the PC's sophisticated control architecture. The control signal generates a 4–20 mA current signal, which is then transmitted to the SMART control valves to produce a specific flow to Tanks 1, 2, 3 and 4.

2.1. Conical tank system

The range of liquid in the conical-shaped tank used in this level method is intended to remain constant. By regulating the input flow into the tank, this is accomplished. The inflow into a tank is the operated variable and the range in the tank is the control variable. The system's schematic diagram can be seen in Figure 2.

The conical system height control problem involves adjusting the input flow Fin rate to control the height h. Since h is the output variable and Fin is the input variable for this control problem, the transfer mechanism would be $G(s) = h(s)/F_{in}(s)$. Analysing the changing aspects of the organization yields the transfer mechanism.

$$F_{in} - F_{out} = \frac{A(h_1)dh_1}{dt} \tag{1}$$

$$\tan\theta = \frac{R}{H} \tag{2}$$

At any level,

$$h_1(\tan\theta) = \frac{r}{h_1} \tag{3}$$

where F_{in} is the inlet flow frequency; F_{out} is the outlet flow frequency; h is the altitude of the liquid at any other level and r is the liquid's perimeter radius at height h.

The tank's cross-sectional area at each level is dependent on the fluid altitude. Based on the symmetries of the tank, the relation of proportionality $r/R = h/H$ can be written. The formula for the tank's cross-sectional measurement for radius r is:

$$A(h) = \pi r^2 \tag{4}$$

Table 1. Dimensions of the conical tank.

Constraints	Value
H	50 cm
R	25 cm
h_s	30 cm
B	6.27
V	liters

Employing the proportionality relationship,

$$A(h) = \pi R^2 h^2 / H^2 \tag{5}$$

The expression for the discharge Fout, which is a non-linear arrangement of altitude h, is as follows:

$$F_{out} = a\sqrt{2gh} = b\sqrt{h} \tag{6}$$

In which a and b are factors of proportionality, gravity is represented by g and $b = a\sqrt{2g}$. Using the material equilibrium equation,

$$F_{in} - F_{out} = A(h)\frac{dh}{dt} \tag{7}$$

Using Equations (2) and (3) in Equation (4),

$$\frac{dh}{dt} = \frac{F_{in} - b\sqrt{h}}{\frac{\pi R^2 h^2}{H^2}} \tag{8}$$

The dimensions of the conical tank are demonstrated in Table 1.

3. Mathematical analysis of the proposed methodology

In this part, the analysis of developed fractional order integral sliding mode regulator and GJO has been discussed.

3.1. Proposed FO-ITSM controller

Let's have a look at the subsequent FO-ITSM variable to develop the suggested robust controller:

$$\sigma = S + AD^{\beta-1}S_I \tag{9}$$

with $\Lambda > 0, 0 < \beta < 1$. The sliding variable (SV) S is given in (9) and S_I can be designed as:

$$D^{\beta}S_I = sign(S)|S|^{\alpha} \tag{10}$$

with preliminary range

$$S_I(0) = -\frac{1}{A}D^{1-\beta}S(0) \tag{11}$$

It is evident from Equations (9)–(11) that $\sigma(0) = 0$. Thus, the period of arriving to the sliding exterior $\sigma = 0$ is eliminated.

The FO-ITSM Controller flow with the GJO algorithm is depicted in Figure 3. Two sliding variables are combined in the suggested recursive form terminal sliding variable. The network routes will be limited to the sliding exterior $\sigma = 0$, and subsequently to the origin in FnT, provided that a suitable control input is built in a way that establishes the sliding mode, that is, $\tau = 0$. Compared to traditional terminal sliding mode (TSM) control, the reaching phase (RP) is negated due to the inherent beginning condition. Furthermore, the integral TSM is easier to implement practically since it only uses two layers of sliding assorted, as opposed to the three levels used in high-order sliding mode control. Furthermore, the suggested sliding assorted provides extract degree to improve the nonlinear system's overall performance tracking.

Now compute σ's temporal derivative, i.e.

$$\dot{\sigma} = \dot{S} + AD^{\beta}S_{I\beta} \tag{12}$$

Consider the sliding variable S is given by

$$S = \dot{Z}_n + k_n sign(Z_n)|Z_n|^{\mu_n} + \cdots + k_1 sign(Z_1)|Z_1|^{\mu_1}$$

where μj and κj $(j = 1, 2, \ldots, n)$ are positive constants

Now,

$$\begin{aligned}\dot{\sigma} &= \ddot{Z}_n + k_n\mu_n|Z_n|^{\mu_n-1}\dot{Z}_n \\ &\quad \ldots k_n\mu_n|Z_1|^{\mu_1-1}\dot{Z}_1 + AD^{\beta}S_{I\beta}\end{aligned} \tag{13}$$

Consider the following nonlinear organization

$$\begin{cases}\dot{Z}_1 = Z_2 \\ \dot{Z}_2 = Z_3 \\ \vdots \\ \dot{Z}_{n-1} = Z_n \\ \dot{Z}_n = F(Z) + G(Z)U + D(Z,t)\end{cases} \tag{14}$$

where the state vector is $Z = [Z_1, Z_2, \ldots, Z_n]^T \in R^n$ and the control input is $U \in \mathbb{R}$. Moreover, $F(Z)$ and $G(Z) \neq 0$ are two recognized nonlinear functions, while $D(Z,t)$characterizes external and uncertainties disturbances.

One way to express the FO switching law is as

$$\begin{aligned}D^{\lambda}U_1 + TU_1 &= -(\Upsilon_d + \Upsilon_T + \xi_0)D^{\lambda-1} \\ &\quad \times sign(\sigma) - K_f D^{\lambda-1}\sigma \qquad (15) \\ &= -D^{\lambda-1}[(\Upsilon_d + \Upsilon_T + \xi_0)sign(\sigma) - K_f\sigma] \qquad (16)\end{aligned}$$

Following a quick computation, one has

$$\dot{U}_1 + TD^{1-\lambda}U_1 = -(\Upsilon_d + \Upsilon_T + \xi_0)sign(\sigma) - K_j\sigma \tag{17}$$

Since the Laplace transform of Equation (17) is

$$sU_1(s) - U_1(0) + Ts^{1-\lambda}U_1(s) - T_s^{-\lambda}U_1(0) = \xi_I(s) \tag{18}$$

with non-negative constant $U_1(0) = U_1(0, \sigma(0))$, then Equation (18) can be defined as

$$U_1(s) = \frac{\xi_I(s)s^{-1} + U_1(0)s^{-1} + s^{-1-\lambda}U_1(0)}{1 + Ts^{-\lambda}} \tag{19}$$

Since $U_1(t, \sigma)$ is locally Lipschitz with regard to σ, the unique resolution of (19) results from the possessions of the inverse Laplace transform as well as the distinctiveness and reality theorem of fractional equivalences. The answer to (15) is provided by:

$$\begin{aligned}U_1(t) &= U_1(0)t^{-\lambda}E_{-\lambda,-\lambda+1}(-Tt^{-\lambda}) \\ &\quad + U_1(0)E_{-\lambda}(-Tt^{-\lambda}) \\ &\quad + \int_0^t (t-\tau)^{-\lambda}E_{-\lambda,-\lambda+1} \\ &\quad \times (-T(t-\tau)^{-\lambda})\xi_I(\tau)d\tau\end{aligned} \tag{20}$$

where $E_{-\lambda}(-Tt^{-\lambda})$ and $E_{-\lambda,-\lambda+1}(-Tt^{-\lambda})$ are Mittag-Leffler functions.

Using the circumstances $\Upsilon_T > T\delta$ and from (14) and (20), under the circumstances $U_1(0) = 0$, one obtains $\Upsilon_T \geq T, \Upsilon_d \geq T$ and $|U_1|_{Max} \geq T|U_1(t)|$, which in turn implies $T|U_1(t)| \leq \Upsilon_T$. The terminal sliding manifold (14)'s fractional derivative is

$$\begin{aligned}D^{\lambda}\sigma &= D^{\lambda}D(Z) + D^{\lambda}U_1 \qquad (21) \\ &= D^{\lambda}D(Z) - D^{\lambda-1}[(\Upsilon_d + \Upsilon_T + \xi_0) \\ &\quad \times sign(\sigma) - K_f\sigma] - TU_1 \qquad (22)\end{aligned}$$

Now analyse the Lyapunov function and the resulting derivative of its time as $\gamma = \frac{1}{2}\sigma^2$ and $\dot{\gamma} = \sigma\dot{\sigma} = \sigma D^{1-\lambda}(D^{\lambda}\sigma)$ one gives

$$\begin{aligned}\dot{\gamma} &= \sigma D^{1-\lambda}\{D^{\lambda}D(Z) - D^{\lambda-1}\} \\ &\quad \times [(\Upsilon_d + \Upsilon_T + \xi_0)sign(\sigma) - K_f\sigma] - TU_1\end{aligned} \tag{23}$$

The finite-time constancy of (23) could be shown by rewriting it as

$$\dot{\gamma} = \sigma\dot{\sigma} \leq -\xi_0|\sigma| - K_f\sigma^2 \tag{24}$$

$$\dot{\gamma} \leq -2K_f\gamma - \sqrt{2}\xi_0\gamma^{\frac{1}{2}} \tag{25}$$

By integrating (25) from t_0 to t_c and after a simple calculation, it yields

$$t_0 \text{ to } t_c \leq -\int_{\gamma(t_{x0})}^{0} \frac{\gamma^{-\frac{1}{2}}}{2K_f\gamma^{\frac{1}{2}} + \sqrt{2\xi_0}} \tag{26}$$

$$= \frac{1}{K_f}\ln\frac{2K_f\gamma^{\frac{1}{2}}t_{x0} + \sqrt{2\xi_0}}{\sqrt{2\xi_0}} \tag{27}$$

However, this suggests that under a finite length of time, one has $\sigma = 0$, and under this condition, the network's routes will also converge to zero in FnT. In reality,

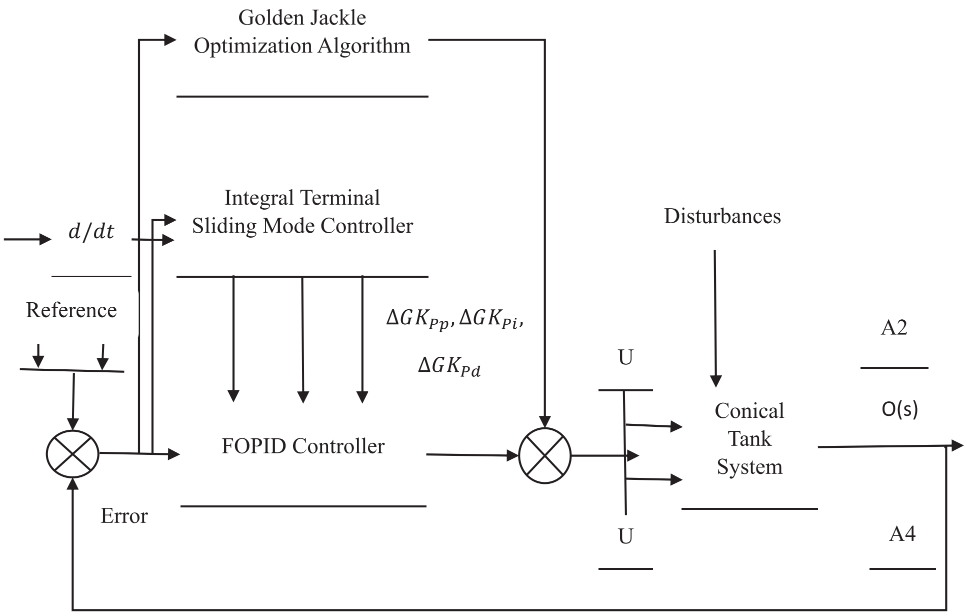

Figure 3. Flow of the FO-ITSM controller with GJO.

Lemma 2 states that the SV in a FnT will converge to zero if $\sigma = 0$,

$$\sigma = S + AD^{\beta-1}S_{I\beta} = 0 \tag{28}$$

$$D^{\beta}S_{I\beta} = sig(S)^{\alpha} \tag{29}$$

Hence one has

$$D^{\beta}S_{I\beta} = sig(-AD^{\beta-1}S_{I\beta})^{\alpha} \tag{30}$$

This, following a quick computation, suggests

$$\dot{S}_{I\beta} = -A^{\alpha}sig^{\alpha}(S_{I\beta}) \tag{31}$$

the moment of confluence t_s is represented by

$$t_s = \frac{|\sigma(0)|^{1-\alpha}}{A(1-\alpha)} \tag{32}$$

Ultimately, one may determine the settling time as

$$T_{FnT} \le t_s + t_S + t_c$$

3.2. Proposed golden jackal algorithm for level control in the conical tank system

Muhammad Mohsin Ansari and Nitish Chopra developed the GJO, a swarm intelligence programme that imitates the natural hunting patterns of golden jackals. Male and female golden jackals typically hunt together. The three steps of a golden jackal's hunting process are: (1) penetrating for and imminent the prey; (2) surrounding and frightening the prey until it stops moving and (3) lunging in its direction.

The golden jackal's hunt is represented mathematically by the subsequent equation ($|E| > 1$):

$$Y_1(t) = Y_M(t) - E|Y_M(t) - rl.Prey(t)| \tag{33}$$

$$Y_2(t) = Y_{FM}(t) - E|Y_{FM}(t) - rl.Prey(t)| \tag{34}$$

where the current iteration is denoted by t, the prey's position vector is represented by $Prey(t)$, $Y_M(t)$ represents the position of the male golden jackal, and $Y_{FM}(t)$ shows the position of the female. The male and female golden jackals' revised positions are denoted by $Y_1(t)$ and $Y_2(t)$. E, or the prey's avoiding energy, is computed as follows:

$$E = E_1.E_0 \tag{35}$$

$$E_1 = c_1.\left(1 - \left(\frac{t}{T}\right)\right) \tag{36}$$

where T is the highest possible number of repetitions, c1 is the standard constant set to 1.5, E_0 is a random integer in the range [−1, 1], representing the prey's beginning power, and E_1 is the prey's diminishing power.

In Equations (33) and (34), $|Y_M(t) - rl.Prey(t)|$ is the distance among the golden jackal and prey, and "rl" represents the random number vector that the Levy flying function computes.

$$rl = 0.05.LF(y) \tag{37}$$

$$LF(y) = 0.01 \times \frac{\mu \times \sigma}{\left|v^{\frac{1}{\beta}}\right|} \tag{38}$$

$$\sigma = \left\{\frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\frac{\Gamma(1+\beta)}{2} \times \beta \times (2^{\beta-1})}\right\}^{\frac{1}{\beta}} \tag{39}$$

where β is the standard constant, set at 1.5, and u and v are random numbers in (0, 1).

$$Y(t+1) = \frac{Y_1(t) + Y_2(t)}{2} \tag{40}$$

Algorithm 1: Proposed GJO for level control of the conical tank system

Inputs: Set parameters of GJO
The maximum number of iterations T and the population size N
Outputs: Update the level of liquid in conical tank
Initialize the liquid level of conical tank system ($Y_i (i = 1, 2, \ldots, N)$
While ($t < T$)
Determine the prey's fitness values.
Y_1 = best prey individual
Y_1 = second best prey individual
Initialize FO-ITSM parameters
Evaluate the objective function and get best parameters
Set iteration count t = 1
Update FO-ITSM parametrs
for
Update best parameters
if($|E| \leq 1$)
Update best liquid level in conical tank arrangement
if($|E| \leq 1$)
Update best liquid level in conical tank arrangement
end for
t = t+1
end while
returnY_i

Hence, according to the male and female golden jackals, $Y(t+1)$represents the prey's updated position.

The escaping energy is reduced when the golden jackals harass their prey. The following is the precise prototypical ($|E| \leq 1$) of the golden jackals encircling and consuming their prey:

$$Y_1(t) = Y_M(t) - E|rl.Y_M(t) - rl.Prey(t)| \quad (41)$$

$$Y_2(t) = Y_{FM}(t) - E|rl.Y_{FM}(t) - rl.Prey(t)| \quad (42)$$

The recommended controller with GJO algorithm efficiently assurances the asymptotic stability for the global optimization of the whole system. FO-ITSM regulating parameters ($\lambda, \beta, K_{PP}, K_{PI}, K_{PD}$) were selected through the application of the trial-and-error technique. Tf(e), where ER is the transfer mechanism, and o(s) is the organization output during the error phase for the suggested FO-ITSM controller. The related system gains, with integral and derivative values, are GKpp, GKp1 and GKpD, where IP is the fractional component of the prime portion. DP functions as the controller's fractional component's integral and derivative parts. Equation (43) provides the FO-ITSM system with a time domain representation.

$$v_p(t) = GK_{PP}er_s(t) + GK_{P1}D^{-\beta}er_s(t) + GK_{PD}D^{\lambda}er_s(t) \quad (43)$$

4. Results and discussion

The FO-ITSM regulator assistances in liquid control for conical tank systems at non-minimum phase, $0 \prec IP1 + IP2 \prec 1$, where IP1 = 0.45 and IP2 = 0.4. The control valves for noise are given by Nc2 and Nc4. The ratios of Nc2 and Nc4 are provided for the control valves. The data gathered from these characteristics is used to calculate the precision of the controller with the observer. Table 2 represents the modelling parameter of four regions.

Table 2. Modelling parameter of four regions.

Region	1	2	3	4
Flow rate (cm^3/s)	0–20	21–40	41–55	56–100.85
Height h1 (cm)	1.843	5.756	14.34	31.34
Height h2 (cm)	1.672	5.548	14.566	30.65
Height h3 (cm)	1.767	5.898	14.876	31.76
Height h4 (cm)	1.899	5.976	14.987	32

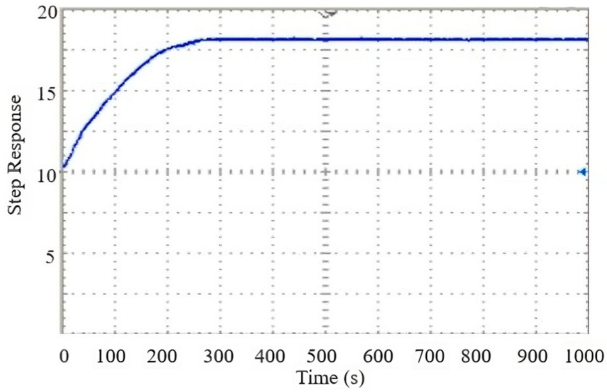

Figure 4. Step response of the conical tank architecture.

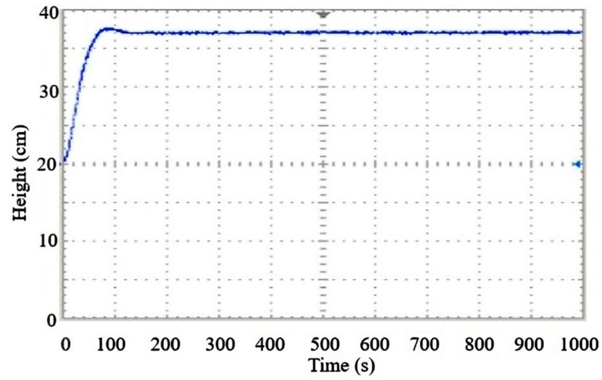

Figure 5. Conical tank SP tracking.

Figure 4 represents the step response of conical tank architecture where the height is 17.6 cm. Figure 5 shows the SP tracking of the conical tank, which represents the range of height is 38 cm. Figure 6 represents the control efforts for SP tracking in conical tank system. The conical tank regulator's robustness verification is depicted in Figure 7.

The conical tank arrangement is simulated using the Matlab 2021a platform in order to complete a successful statistics gathering phase. The input standards comprises the signals for pumps 1 and 2 with the voltages vp1(k) and vp2(k). Tanks 2 and 4's liquid level output signals were collected. The bottom tanks' liquid contents are L2 and L4. The dataset is described that exhibits an amplitude level change from 0 to 1 in response to variations in the input voltage. Tanks two

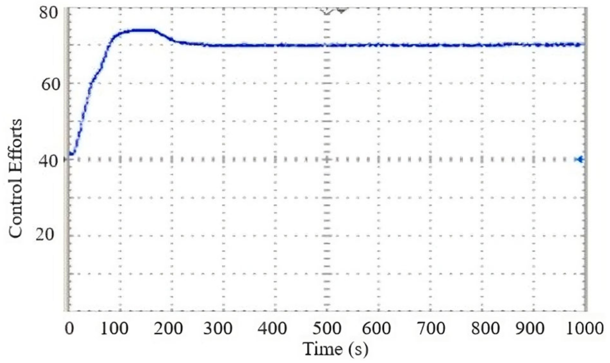

Figure 6. Control efforts for SP tracking in the conical tank system.

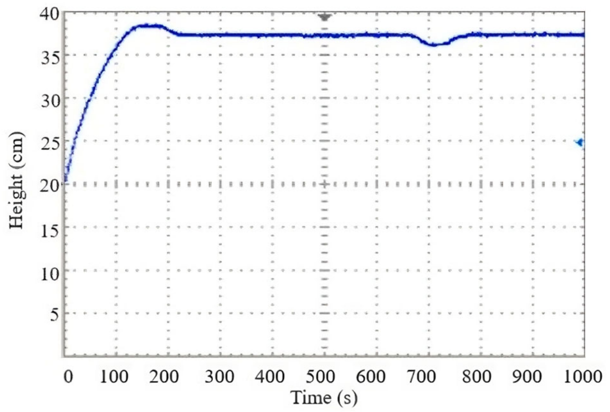

Figure 7. Robustness validation of the conical tank controller.

and four have their control valves opened. The suggested FO-ITSM controller's goal is to settle in less than 15 s.

4.1. Simulation results of PID controller

The connected conical tank system with PID regulator's simulation findings and performance comparisons at the steady-state functional point of 17 cm, both in the occurrence and nonappearance of turbulences, are the main topics of this part. Level responses for four regions were attained using a PID controller; Figure 8 shows the results in the absence of disturbances, and Figures 9–11 show the results in the occurrence of disturbances.

4.2. Simulation results of fuzzy-SMC controller

The simulation findings and performance comparisons of the connected conical tank system with fuzzy-SMC regulator at the stable state operation of 30 cm, both with and without disturbances, are the main topics of this part. The fuzzy SMC controller was used to generate the level responses for four regions, which are displayed in Figure 12 when there are no disturbances and in Figures 13–15 when there are disturbances.

4.3. Simulation results of FFOPID controller for the operating point of 32 cm

The simulation findings and performance comparisons of the connected conical tank system with FFOPID regulator at the stable state operation of 32 cm, both with and without disturbances, are the main topics of this part. The values of *Kp*, *Ki* and *Kd* that were obtained are 5.63, 2.14 and 0.98, respectively.

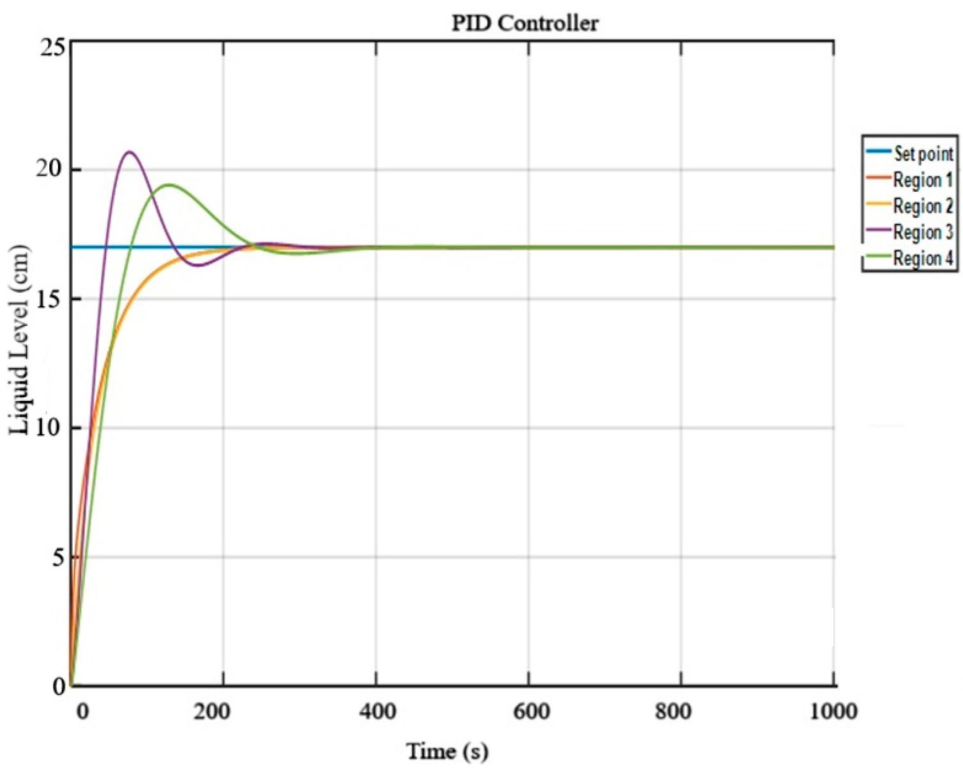

Figure 8. Comparative level response of four regions at SP = 17 cm using the PID controller in the absence of disturbance.

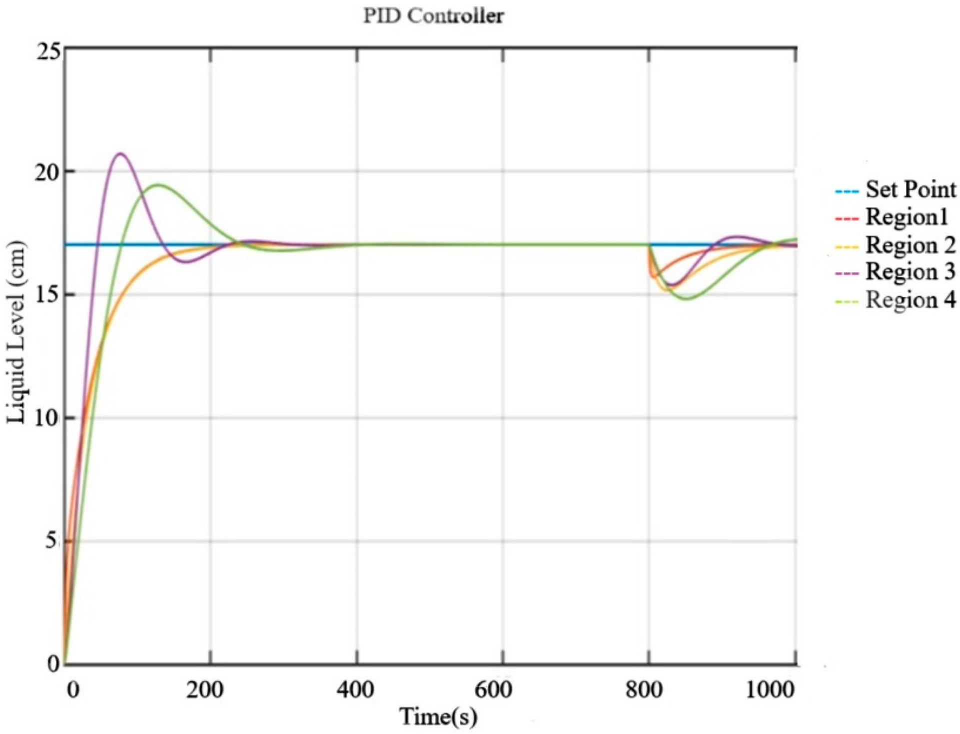

Figure 9. Comparative level response of four regions at SP = 17 cm using the PID controller in the presence of disturbance of 15 lph at t = 800 s.

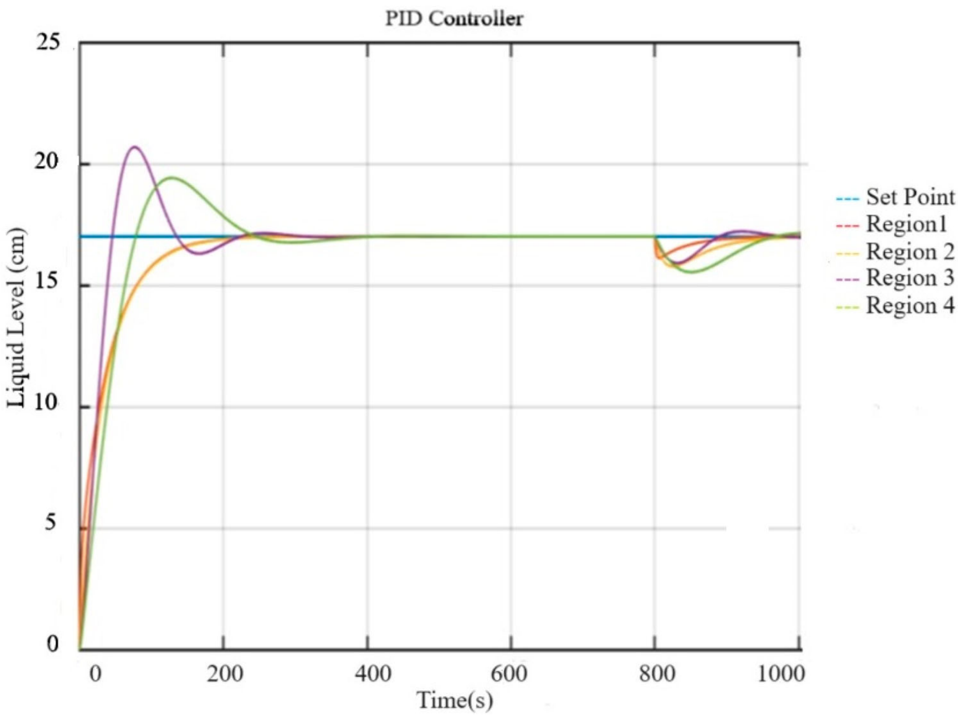

Figure 10. Comparative level response of four regions at SP = 17 cm using the PID controller in the presence of disturbance of 10 1ph at t = 800 s.

Four regions' level responses were acquired using the FFOPID Controller; the results are displayed in Figures 16 and 17, respectively, in the nonappearance of disturbances and in the occurrence of disturbances (Figures 18 and 19).

After obtaining time domain stipulations such settling time, rise time, overshoot and peak time, the data are presented in Table 3. The FFOPID controller is deduced to have a rise time of 14.3 s, a peak time of 22.2 s, a settling time of 14.1 s and a 0.006% overrun in the case of Region 1 based on the table. Region 2 has a 0.002% overshoot, a rise time of 20.8 s, a peak time of 21.5 s and a settling time of 30.9 s. The peak time, rise time, settling time

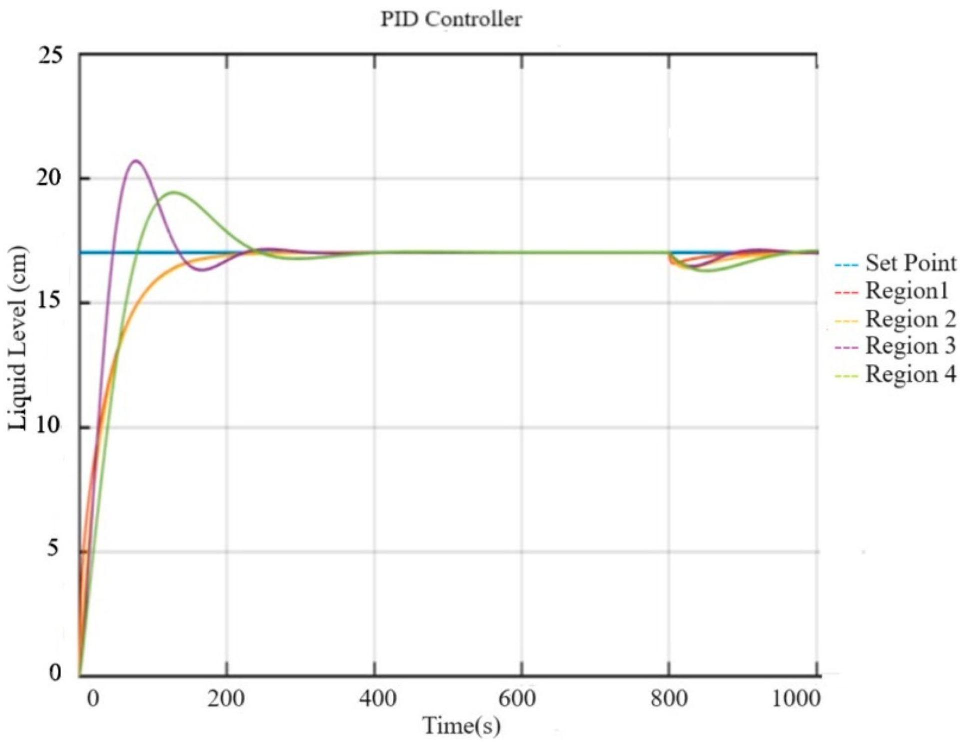

Figure 11. Comparative level response of four regions at SP = 17 cm using the PID regulator in the occurrence of disturbance of 5 1ph at t = 800 s.

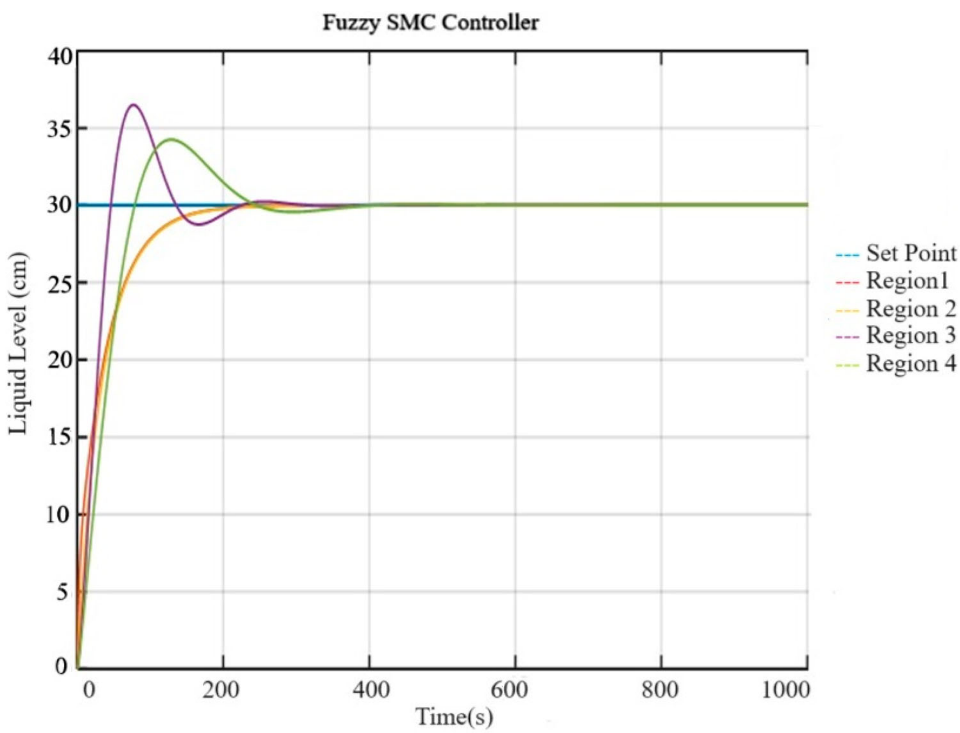

Figure 12. Comparative level response of four regions at SP = 30 cm using the fuzzy-SMC controller in the absence of disturbance.

and overshoot for Region 3 are 21.3, 12.1, 28.1 s and 1.432% overshoot, respectively. Rising at 12.9 s, peaking at 11.4 s, settling at 50.6 s and overshooting by 2.091% is Region 4. In a similar manner, Table 4 displays the time integral parameters for each of the four areas employing the FFOPID Controller, including ISE, IAE and ITAE.

4.4. Simulation results of FFOPID controller for SP tracking

In the occurrence of disturbances, SP tracking for the FFOPID regulator to regulate the liquid level was carried out. The designed regulator was able to reach the SP at the first functional point of 8 cm. Later, at time

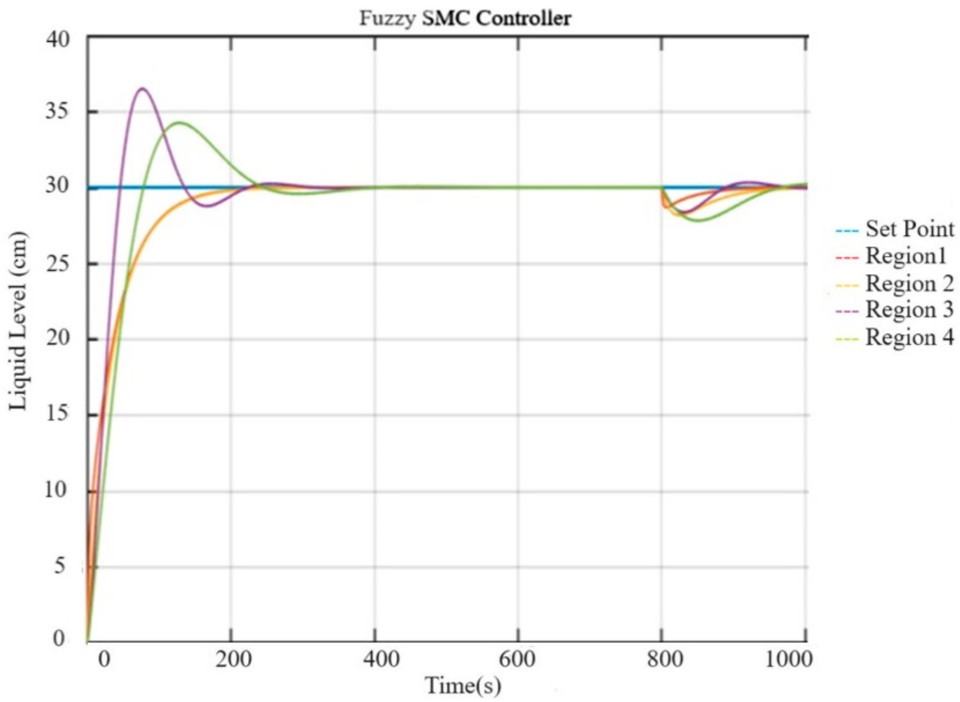

Figure 13. Comparative level response of four regions at SP = 30 cm using the fuzzy-SMC controller in the presence of disturbance of 15 1ph at t = 800 s.

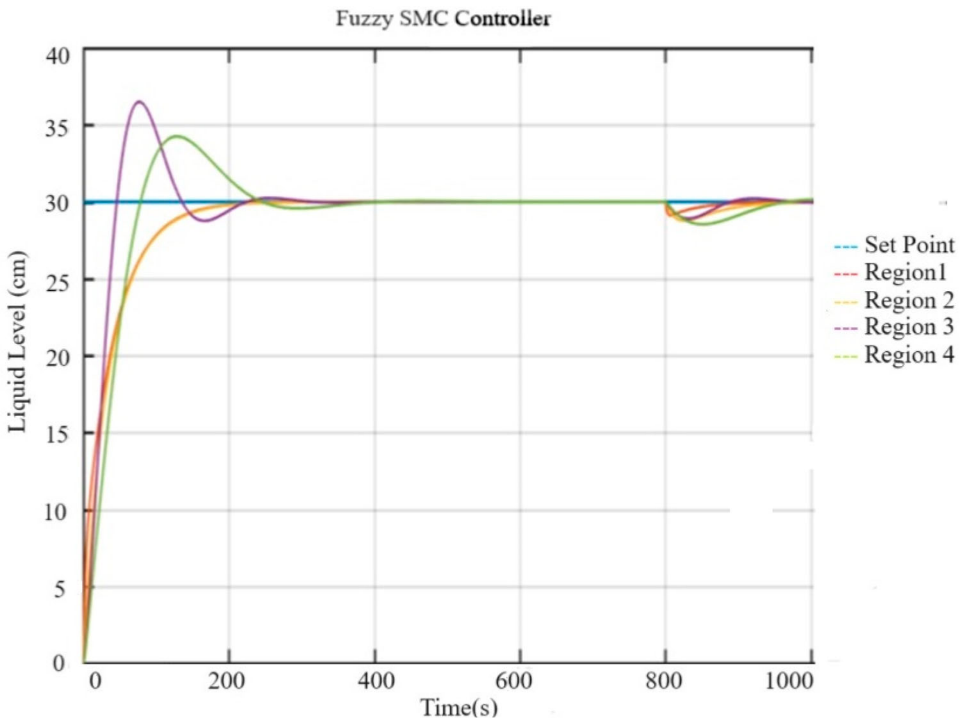

Figure 14. Comparative level response of four regions at SP = 30 cm using the fuzzy-SMC controller in the presence of disturbance of 10 lph at t = 800 s.

t = 500 s, the functional point was adjusted to 32 cm, as seen in Figure 20.

4.5. Simulation results of FO-ITSM controller for the operating point of 17 cm

The conical tank system with FO-ITSM Controller at stable state operation of 17 cm, both in the nonappearance and presence of disturbances, is the subject of this section's simulation results and performance comparisons. Level responses for four regions were acquired using the FO-ITSM Controller; Figure 21 shows the regions in the absence of disturbances, while Figures 23 and 24 show the regions in the presence of disturbances, respectively.

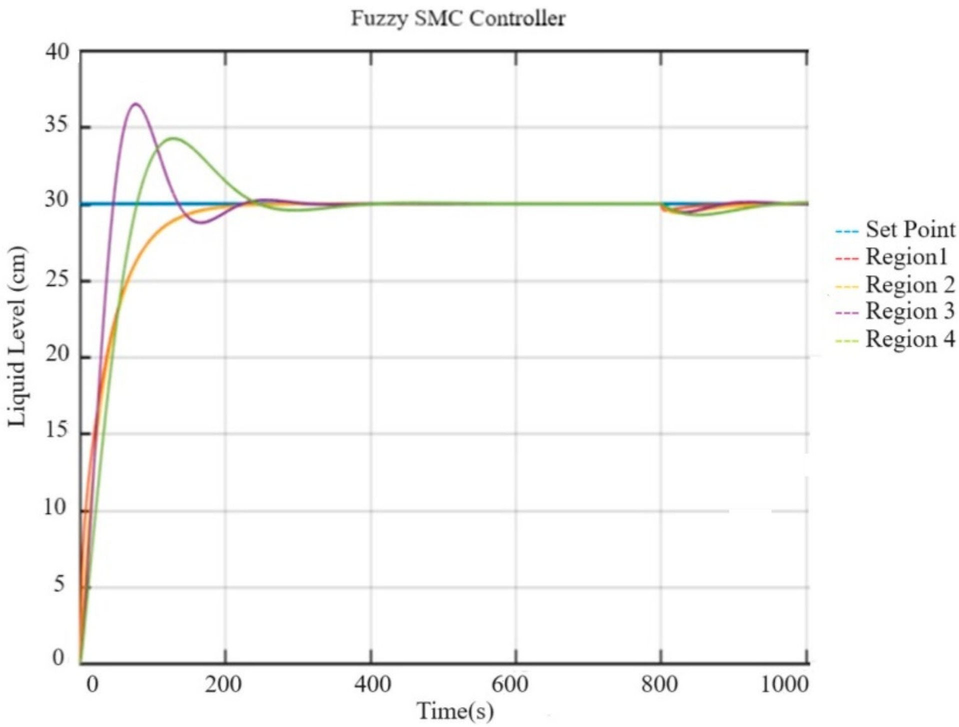

Figure 15. Comparative level response of four regions at SP = 30 cm using the fuzzy-SMC controller in the occurrence of disturbance of 5 lph at t = 800 s.

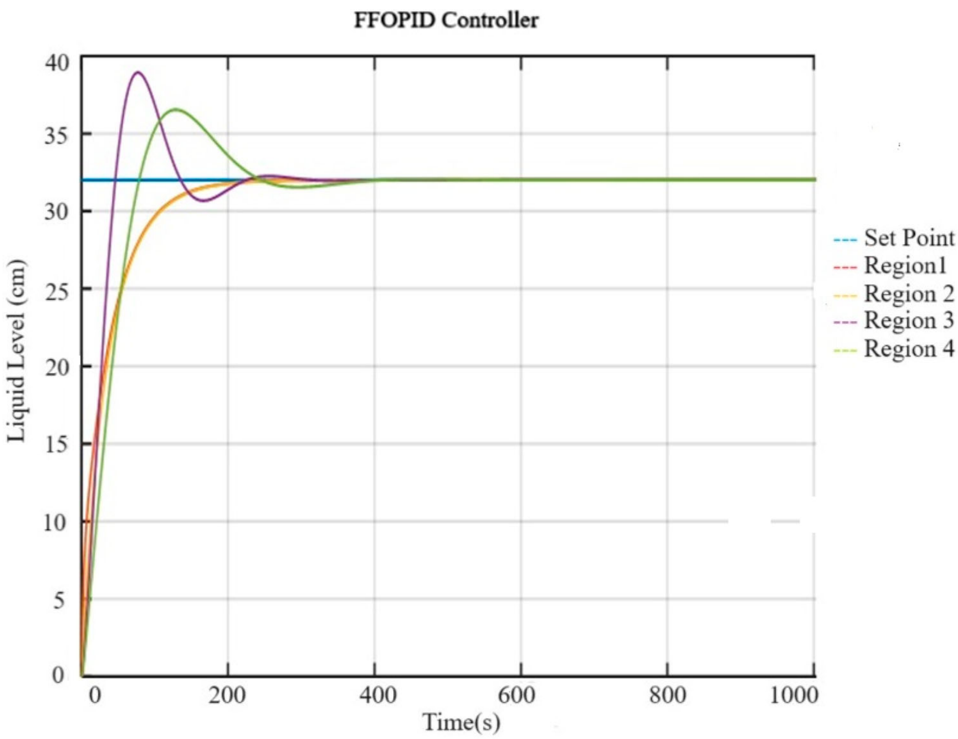

Figure 16. Comparative level response of four regions at SP = 32c m using the FFOPID controller in the absence of disturbance.

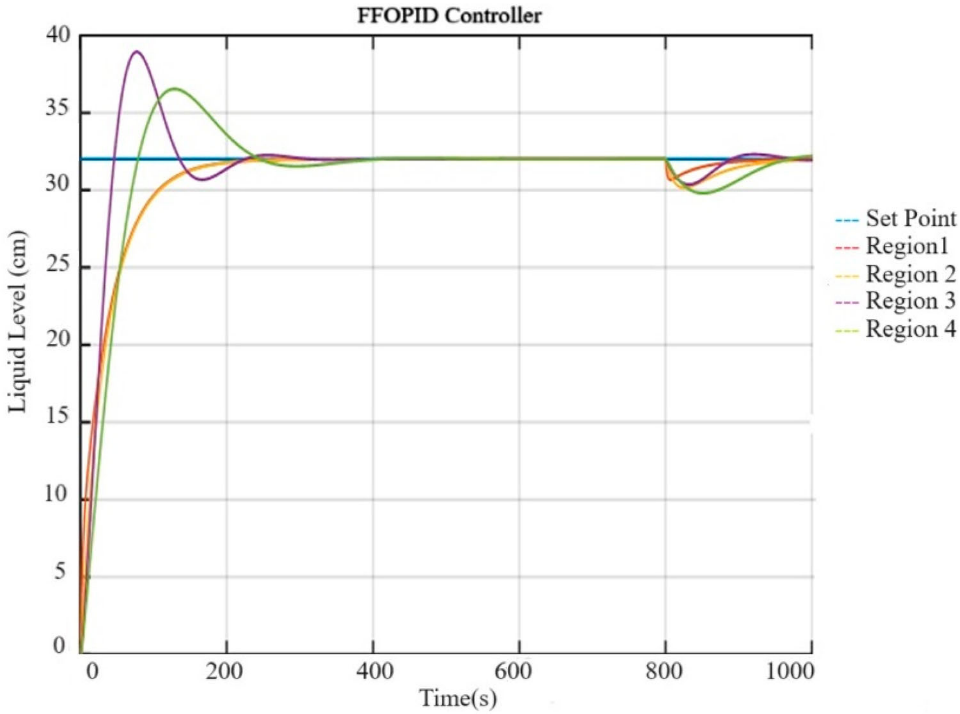

Figure 17. Comparative level response of four regions at SP = 32 cm using the FFOPID regulator in the occurrence of disturbance of 15 lph at $t = 800$ s.

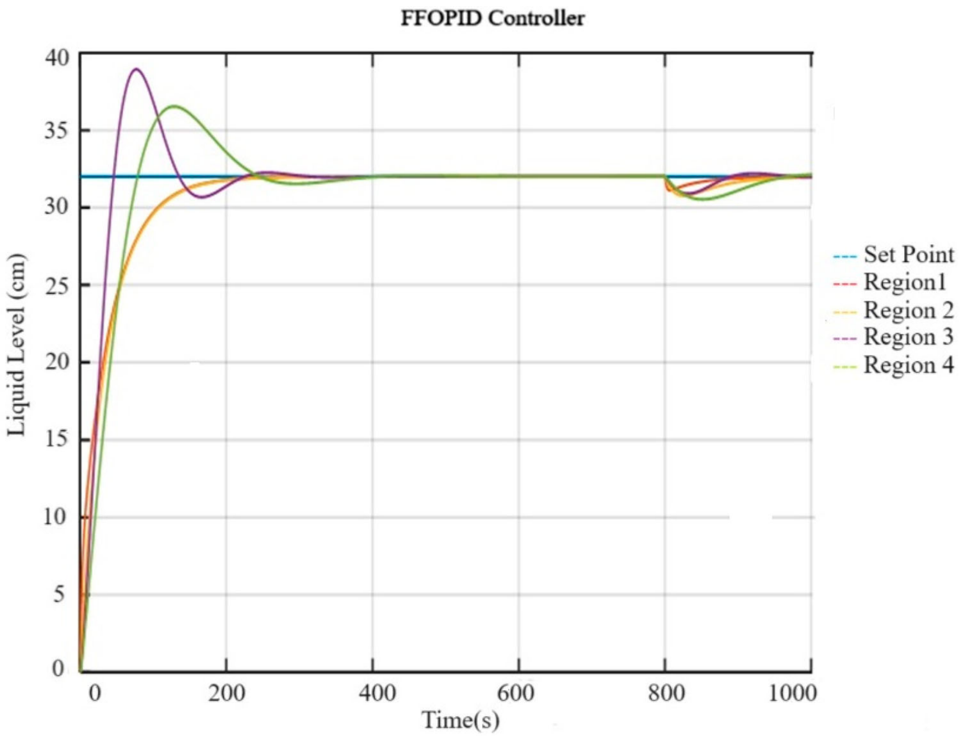

Figure 18. Comparative level response of four regions at SP = 32 cm using the FFOPID regulator in the occurrence of disturbance of 10 lph at $t = 800$ s.

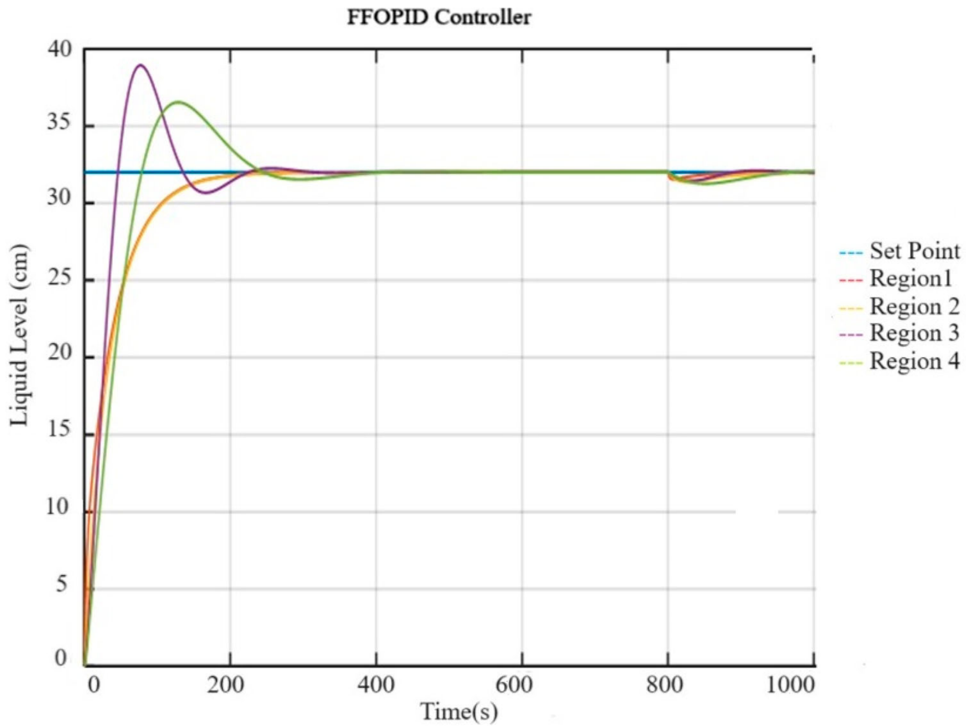

Figure 19. Comparative level response of four regions at SP = 32 cm using the FFOPID controller in the occurrence of disturbance of 5 lph at $t = 800$ s.

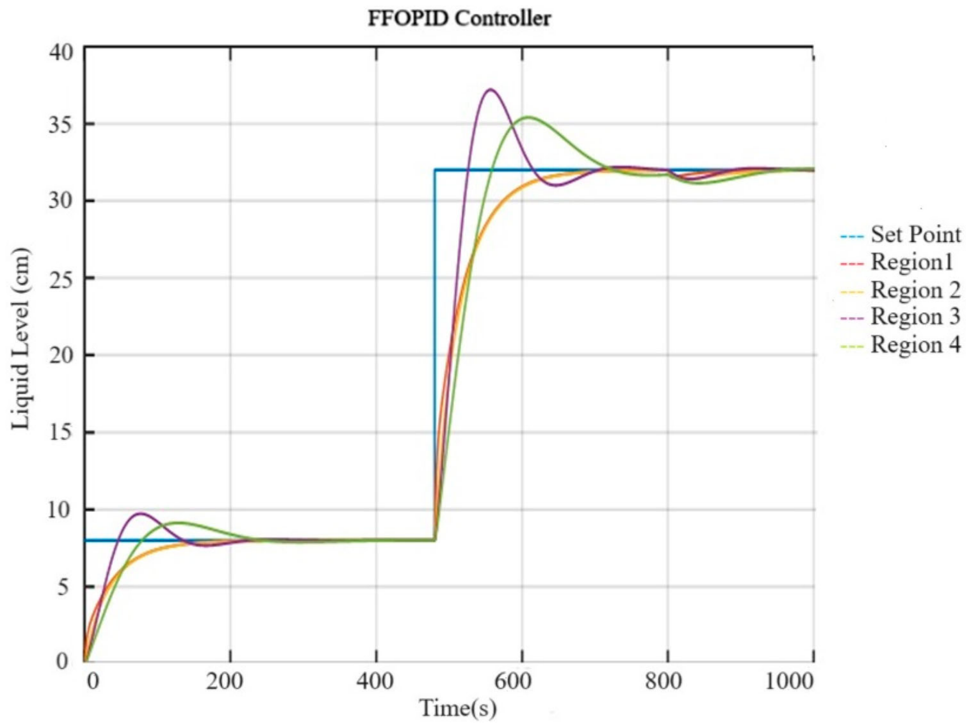

Figure 20. SP tracking performance of the FFOPID regulator in the occurrence of disturbance.

Table 3. Time domain specifications with FFOPID regulator.

Region		Region 1	Region 2	Region 3	Region 4
Time domain	Rise time (s)	14.3	20.8	12.1	12.9
	Settling time (s)	14.1	30.9	28.1	50.6
	Peak time (s)	22.2	21.5	21.3	11.4
	Over shoot (%)	0.006	0.002	1.432	2.091

Table 4. Time integral performance with FFOPID controller.

Region		Region 1	Region 2	Region 3	Region 4
Performance indices	IAE	$3.176e^1$	$4.832e^1$	$5.12e^1$	$8.114e^1$
	ISE	$14.232e^1$	$23.178e^1$	$44.132e^1$	$79.734e^1$
	ITAE	$38.231e^2$	$71.217e^2$	$90.542e^2$	$159.276e^2$

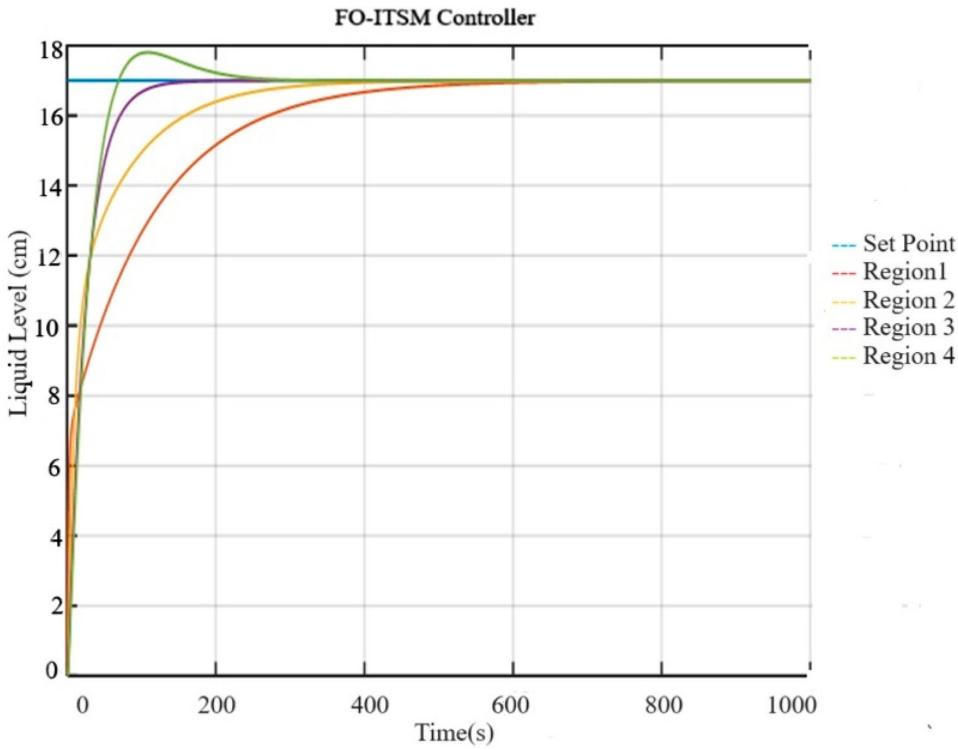

Figure 21. Comparative level response of four regions at SP = 17 cm using the FO-ITSM controller in the absence of disturbance.

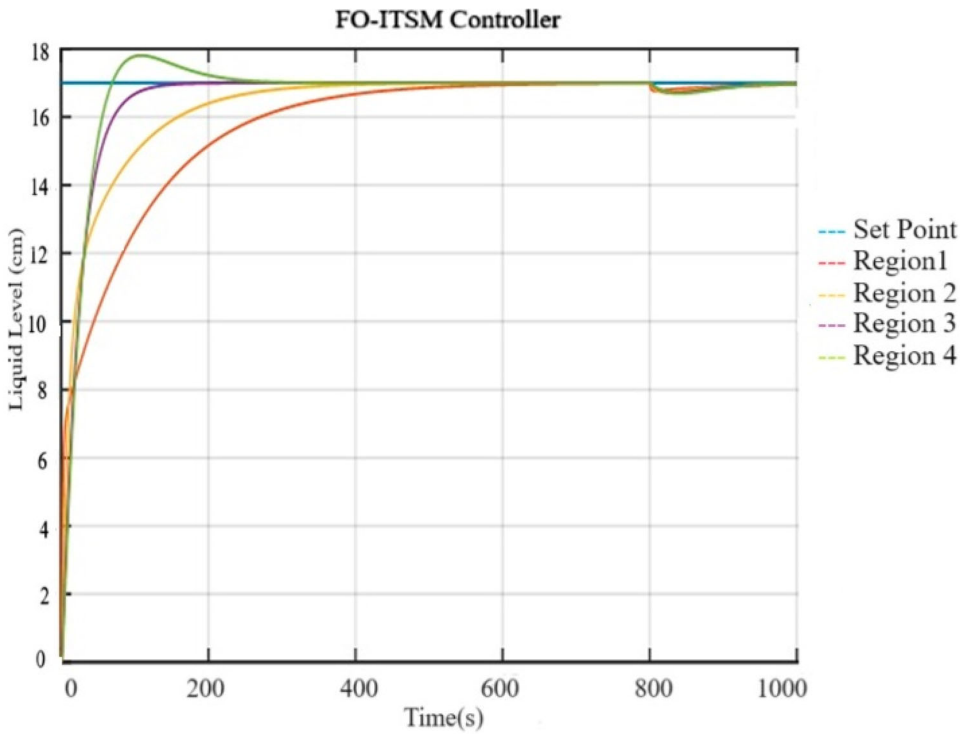

Figure 22. Comparative level response of four regions at SP = 17 cm using the FO-ITSM controller in the presence of disturbance of 15 lph at $t = 800$ s.

Table 5 displays the simulation results with the FO-ITSM controller along with the error, undershoot, peak, settling and overshoot values. With a 0% overshoot, 0% undershoot, peak time of 0.002 ms and settling time of 0.001 ms rise in time. Consequently, the steady-state error is decreased by the proposed FO-ITSM controller. When compared to alternative approaches,

Table 5. Simulation results with FO-ITSM controller with GJO.

S.No	Parameters	FO-ITSM-based GJO
1	Settling Time	0.001s
2	Peak Overshoot	0%
3	ITAE	4.974s
4	IAE	4.564s
5	ISE	8.564s

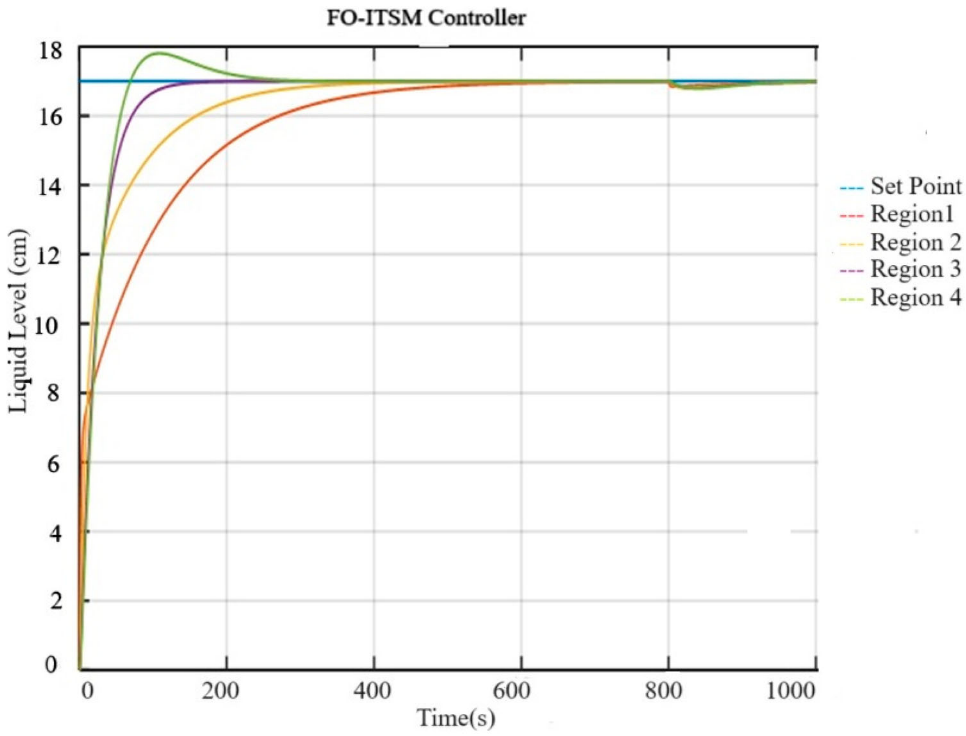

Figure 23. Comparative level response of four regions at SP = 17 cm using the FO-ITSM controller in the presence of disturbance of 10 lph at $t = 800$ s.

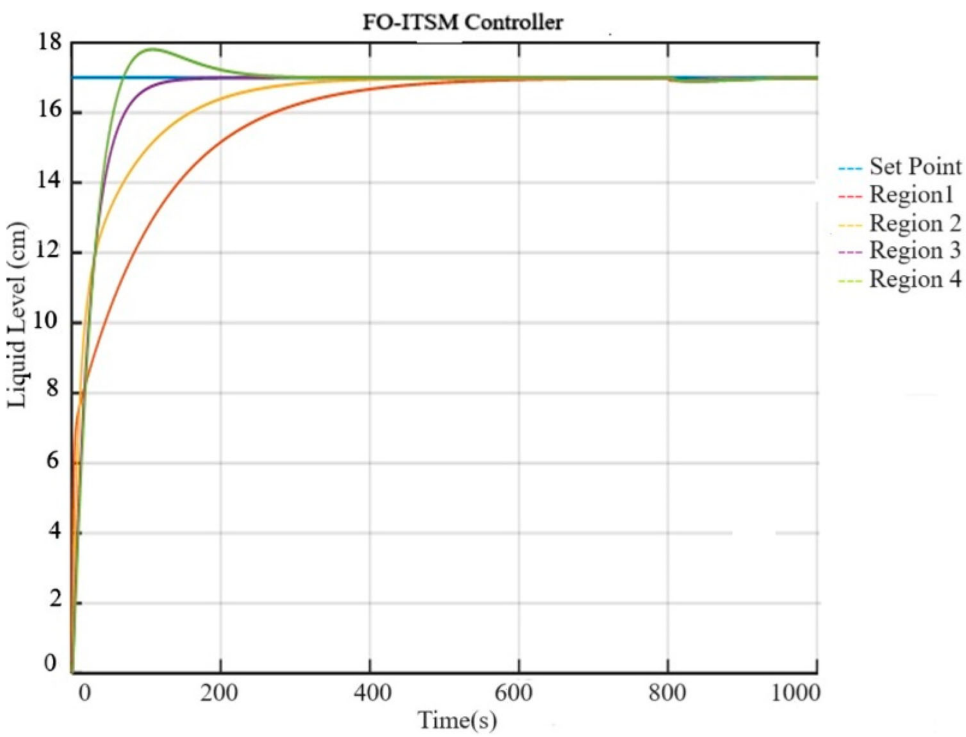

Figure 24. Comparative level response of four regions at SP = 17 cm using the FO-ITSM controller in the presence of disturbance of 5 lph at $t = 800$ s.

the ITAE, ISE and IAE performance numbers are lower. Comparison of the proposed system with various methodology is represented in Table 6.

5. Conclusion

The suggested FO-ITSM controller, which regulates the liquid level in a conical tank system, is part of this innovative research project. The GJO technique is used to train and comprehend the dynamic properties of the four-tank system based on the received reference signal. The necessary goals, which included preserving and controlling the intended liquid level in every tank, meeting the physical input restrictions, and significantly reducing errors, have all been accomplished by these control processes. All of the control

Table 6. Comparison of proposed system with various methodology.

Controller	Peak time (s)	Rise time (s)	Settling time(s)	Overshoot (%)	Undershoot (%)
PID	4.98 s	4.65 s	1.98 s	16%	11.54%
Fuzzy-SMC	4.23 s	4 s	1.77 s	12.34%	8.22%
FFOPID	3.78 s	3.98 s	1.54 s	2.34%	5.34%
FO-ITSM-based GJO (Proposed)	1.95 s	1.68 s	0.001 s	0%	0%

strategies described for the nonlinear interacting conical system have been created and implemented successfully using MATLAB/SIMULINK. FO-ITSM systems provide exceptional quality even in settings with high loads and noise levels. Together with the recommended FO-ITSM, simulation control systems based on PID, fuzzy-SMC and FFOPID were also implemented in order to successfully demonstrate the control performance. With a 0% undershoot and 0% overshoot, the rise time is approximately 1.68 s, the settling time is 0.001 s and the peak time is 1.95 s. simulation data show that the developed regulator performs significantly improved with no undershoot or overshoot. Notably, the FO-ITSM controller's results show which control method delivers the highest system performance with disturbance rejection and takes the least amount of time to reach the required stable level in both tanks. In order to confirm that weight values converge to the right values, the tank system will eventually be changed in simulation using a super twisting method to learn the coefficient learning rate. It can be further extended to six tanks with cross coupling and decoupling effect of considerations, which makes the problem more challenging.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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