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*Original Article*

# Optimization of PI Controller on Level Control of Hopper Tank System with PSO Technique

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***Abstract —*** *Regulating the usage of hazardous chemicals in the manufacturing of medicines is critical in industries. Therefore it is required to regulate the level in the nonlinear tank and to avoid the wastage of chemicals used for its preparation. The research deals with the control of the level for a nonlinear hopper process tank. The main benefit of the hopper tank system is that it can able to store more quantity and also provides an easy flow of materials. To provide a better performance analysis, Fractional-Order PI (FOPI) is compared with the Particle Swarm Optimization method to optimize the PI controller parameters like* $K_p$ *&* $K_i$*. The Optimized PI controller gain parameters provide the fastest settling time and reduce error using performance indices. The servo and regulatory responses were analyzed with different individual region-based control and combined region-based control of hopper tank system to achieve minimized settling time and minimized ISE, IAE & ITAE error values of process response.*

**Keywords —** *Nonlinear Hopper Tank process, Fractional Order PI control, Particle Swarm Optimization, Servo-Regulatory response, Multi-Region Model.*

## I. INTRODUCTION

The use of controllers in industries plays a major role in the control of manipulated variables. In general Proportional integral control was used to control these variables. The important gain parameters like Proportional gain and integral gain are varied based on the setpoint value, and the load disturbances occur in the process, which is said to be servo regulatory change or disturbance. Both linear and nonlinear process was used in industries. In this research work, the nonlinear hopper tank system used in petroleum industries was considered, and the level is too maintained to avoid the wastage of costlier petroleum products. It may have uncertainty while dealing with the plant operation, but it can reduce by tuning the gain values. When the process fails to work properly due to the nonlinear behavior, the controller regains its parameters and maintains the constant controlled output. Therefore, the Hopper nature process is used up for the current study. Owing to its shape, the raw resources can be easily removed or disposed of in a hopper tank, and the work process can be done very quickly. It is capable of handle the storage quantity while large storing of process materials. It is because of the cylindrical shape which is present at the top of the hopper tank. Due to the top portion increased quantity of materials can be loaded in larger amounts, in view of the necessities. It gives a fast and sanitized tidy-up. The unprocessed substance might comprise solvents, viscous fluids, slurries, and solids. To beat up the rusting & protect the process material, liquid movement routinely ought to be there possible through using utilizing the lower part portion of the conical element introduced at the bottom of the design structure. The novelty of this work is based on the design procedure with the combination of the conical tank with the cylindrical tank. The implementation of controller techniques with Fractional-order PI controller & to improve the controller parameters like Particle swarm optimization Technique is used.

Suresh Manic Kesavan et al. [1] developed the real-time implementation simple PID Controller tuning method for both open and closed-loop feedback operations using servo-regulatory response. Marshiana, D et al. [2] designed the FOPI controller for the conical process tank using the down order calculus method. The nonlinear system designed performed by digital algorithm [10] based dead beat controller provides better implementation when contrasted among the analog PID algorithm. It is stated that many of the chemical industries [11] use conical or hopper tank systems for easy flow of materials without any loss. Saravanakumar, G et al. [3] proposed an internal Model-Based P+I+D controller design for a conical container level system. The Stable Operating point is used for different regions for the identification of the process model using the process reaction curve method. Sarif, B. Mabu[4] presents the procedure for acquiring the FOPDT model utilizing Sundaresan and Krishnaswamy technique and execution correlation of PID control device for IMC –PID technique and reduces the error using ISE, IAE. Venkatesan, M. et al. [5] presented a comparative study on the characteristics and performances of Sliding Mode controller using Sliding Mode Luenberger observer. Ravi, V. Ret. al [6] proposed a multivariable process-based PID controller design for an interacting two first-order conical tank system to determine its effectiveness on its operating ranges. The above model has compared with

Gain Scheduling Adaptive Controller over GA tuned multi-region-PI controllers had highlighted [7]. Optimization of the Genetic algorithm [8] based linear model predictive algorithm approach used for a 2 tanks conical interacting model was validated during Matlab simulation. The decentralized PI [9] controller combined with the decouplers used for the stability investigation of TCTILS to reduce the intelligence property of the conical tank process.

Kesavan et al. [12] worked on the real-time realization of a PID controller for a conical section of the hopper tank and optimized the performance with the error criteria for various tuning methods. Murugananthan, V et al. [13] highlighted the performance of modified IMC with other techniques using error criterion and time-domain analysis for a nonlinear hopper tank system. Alfi et al. [14] present a technique to discover the best possible control parameters with the APSO algorithm. Inertia weights are adjusted based on the feedback taken from the particle best memories. Fister, Dušan, et al. [15] states that the PID controller is used for reducing the error value using the tuning process. It was optimized using PSO based evolutionary and intelligent algorithm. J.Zhao et.al[16] analyzed the improved output performance of a PID control by applying a robust parameter under bounded model uncertainty to decrease peak overshoot and greater control progress. To improve the PID value PSO method is pertained to unravel the nonlinear, non-differentiable crisis. D.Kalpana et.al[17] proposed FOPI controller for relay based feedback system by comparing with integer order PI controller for load rejection and set point tracking methods. Pamela.D et.al[18] discuss about the control of temperature for a nonlinear system using intelligent controllers to reduce the overshoot and to obtain an suitable output. Jauregui.C et al[19] simulated the results of ZN method for comparison with PSO to obtain the optimal parameters by providing a lowest value of IAE for a conical level control.

## II. RESEARCH MATERIALS AND METHODS

### *A. System Identification of Hopper Tank*

The Hopper tank system identification was developed by considering the following assumptions. 1) Liquid Level as Control variable and 2) Inlet flow as a manipulated variable. The first order transfer function with dead time[24] for the process tank ie., hopper tank is was accomplished by having the process terms, for example, gain of the system Ks, time constant parameter T and process dead time is td. Figure 1 outlines the schematic perspective on the created hopper tank process.

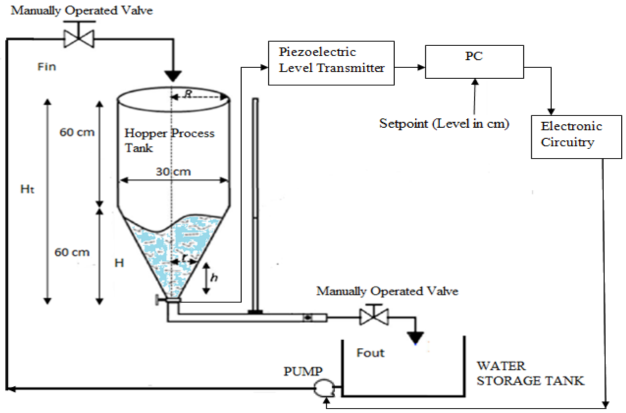


**Fig.1: Schematic Feedback Arrangement of Hopper Tank System**

The mass balance relationship of conical part of hopper tank dynamic is
Inlet flow rate-Outflow rate=Rate of accumulation

$$f_i - f_o = A\frac{dh_i}{dt} \qquad (1)$$

But, outflow rate of the tank,

$$f_o = a\sqrt{2gh_i}$$

$$f_o = b\sqrt{h_i}$$

So, Equation (1) becomes,

$$f_i - b\sqrt{h_i} = A\frac{dh_i}{dt} \qquad (2)$$

Where A=Area at Height $h_i(t)$, a= Conical outlet area, b= Constant, g = Gravitational force, 980cm$^2$/sec.
Applying partial differentiation based Linearization on equation (1)

$$\partial f_i - \frac{b}{2\sqrt{h_i}}\partial h_i = A \qquad (3)$$

Applying Laplace transform and rearranging the equation (3) in the form of First order Expression,

$$G(s) = \frac{\partial h_i}{\partial f_i} = \frac{K_s}{(Ts+1)} \qquad (4)$$

Therefore Transfer function of Hopper tank with conical region is approximated to a Transfer function by way of first order system with dead time which differs concerning the liquid height.

$$G(s) = \frac{K_s}{(Ts+1)} e^{-t_d s} \qquad (5)$$

Where, $K_s=2\sqrt{h_i}/b$; $b=a\sqrt{2g}$; $T=(2A\sqrt{h_i})/b$; $K_s$=Process Gain; T =Time constant;
a=Area of Conical outlet; $h_i$= Hopper tank nominal height;
A=Nominal area of tank on $h_i$ ; b= Discharge constant.

**TABLE 1: Specifications for Hopper Tank System**

| | |
|---|---|
| Total Height of Hopper tank ($H_t$) | 120 cm |
| Height of conical shape of tank | 60cm |
| Height of cylindrical shape of tank | 60cm |
| Conical section maximum radius (R) | 15cm |
| Conical outlet radius($r_b$) | 1.25 cm |
| Nominal radius (r) | $Rh_i/H_t$ |
| Level transmitter | Piezo-electric Level Transmitter |

Based on the single system identification, various regions [12] are identified and its corresponding transfer function was developed and shown in Table 2. The hopper tank specifications are represented in Table 1.

**TABLE 2: Representation of Region based Transfer Function model**

| Regions | Level Operating Range (cm) | Transfer function Model |
|---|---|---|
| Region 1 | 0-15cm | $G_i(s) = \frac{0.03542}{(1.548s+1)} e^{-0.9s}$ |
| Region 2 | 15-30cm | $G_{ii}(s) = \frac{0.05013}{(8.9175s+1)} e^{-4.8s}$ |
| Region 3 | 30-45cm | $G_{iii}(s) = \frac{0.06170}{(24.572s+1)} e^{-11.20s}$ |
| Region 4 | 45-60cm | $G_{iv}(s) = \frac{0.07130}{(50.03s+1)} e^{-19.50s}$ |
| Region 5 | 60-100cm | $G_v(s) = \frac{0.0920}{(65.029s+1)} e^{-24.25s}$ |

### *B. Fractional Order PI (FOPI) Controller Tuning Technique*

The conception of FOPIC was proposed by podlubny in 1997. In this technique, he demonstrated that in comparison with a conventional PI controller this method provides the improved response when it is used to control the fractional order systems. Monje (2004) presented an optimization technique. In this, the parameters of the FOPI such that the tuned values are satisfied based on the predefined design specifications. The ${}_aD^q{}_t$ is said to be a differ integral operator known as fractional calculus. It is a combination of two operators held to be as differentiation and integration. This operator notation for single expression is defined with fractional derivative & fractional integral. The mathematical expression for fractional calculus is distinct as

$$D_t^a = \begin{bmatrix} \frac{d^q}{dt^q} & q > 0 \\ 1 & q = 0 \\ \int_a^t (d\tau)^{-q} & q < 0 \end{bmatrix} \qquad (6)$$

Where, q = Fractional Order. It can likewise be a complex number; a, t= Fractional integer limits.

The Fractional order derivatives defined by using descriptive of "Riemann–Liouville", "Grunwald–Letnikov" & "Caputo". The general FOPID controller model[19] is given by

$$(s) = K_p + K_I \frac{1}{s^\lambda} + K_d s^\mu \, ; \quad (\mu \& \lambda > 0) \qquad (7)$$

Where, $G_{pid}(s)$ -Controller transfer function; $s^\lambda$ is the integrator term & $s^\mu$ is the derivative term. If λ and μ are fractional value then it is FOPID technique. So transfer function model of FO-PI controller[26] is known by

$$G_{pi}(s) = K_p + K_I \frac{1}{s^\lambda} \, ; \quad (\lambda > 0) \qquad (8)$$

This fractional $PI^\lambda$ controller can be used as a conventional controller in some special cases. It can be anticipated that the control performance of the process can be improved by $PI^\lambda$ controller. The most significant advantage of the $PI^\lambda$ controller is described by the mathematical model of fractional order method to offer enhanced control of dynamical systems. The benefit of using this technique is the parameters changes occur by this controlled system are less sensitive. The process dynamics is conveniently described by the normalized dead time, **τ**= Delay time /(Delay time +T). The following control parameters are designed based on the model

$$\lambda = \begin{cases} 0.7 & if \quad \tau < 0.1 \\ 0.9 & if \quad 0.1 \le \tau < 0.4 \\ 1.0 & if \quad 0.4 \le \tau < 0.6 \\ 1.1 & if \quad \tau \ge 0.6 \end{cases} \qquad (9)$$

FOPI controller tuning rule for hopper tank is given below,

$$K_p = \frac{0.2978}{K(\tau+0.00007)} \quad \& \; T_i = T\left[\frac{0.8578}{(\tau^2-3.402\tau+2.405)}\right] \qquad (10)$$

The limitation of FOPI method is the fractional value limits the process operation.

### *C. PI Controller Design using Particle Swarm Optimization Technique*

The evolutionary calculation called PSO was first proposed by Elberhat and Kennedy in 1995 to take care of different Real -Valued Optimization issues. Levenberg-Marquardt algorithm used to achieve fast Convergence rate and to avoid local minima problem. PSO is an incredible strategy for accomplishing the best arrangement in a nonlinear framework. The PSO procedure is created based on the regular practices of gatherings of birds and every up-and-comer arrangement is related with a speed at a D-dimensional space [27]. The competitor arrangements, called "particles", then, at that point "fly" through the hunt space.

First and foremost, a populace with the size of particles is made. Then, at that point, the speed of each particle is continually changed by the relating particle's experience and the particle's partners' encounters. It is normal that the particles will move towards better arrangement regions. The Particle fitness will be surveyed by objective limits of optimization issue [20]. For every cycle, the speed of each particle would be determined by

$$v_i^{n+1} = wv_i^n + c_1 r_1 (Pbest_i^n - x_i^n) + c_2 r_2 (Gbest^n - x_i^n) \quad (12)$$

Subsequent to ascertaining the speed, each particle new position will be determined by,

$$x_i^{n+1} = x_i^n + v_i^{n+1} \quad (13)$$

where $x_i^n$ is the position of the particle i in n$^{th}$ cycle, $Pbest_i^n$ is the best past position of this particle (retained by each molecule), $gbest^n$ is past position of best among n$^{th}$ emphasis of every particles, w is weight of moment of inertia, c1 and c2 are speed increase coefficients& are known as cognitive& social boundaries correspondingly. At long last, r1& r2 are random numbers with the range of 0 to 1. The PSO calculation is utilized in this analysis because of its simple execution, vigor, global combination ability and minimal required calculation time [21]. Tuning the PSO-PI parameters impressively influences the optimization performance as shown in Figure 2.

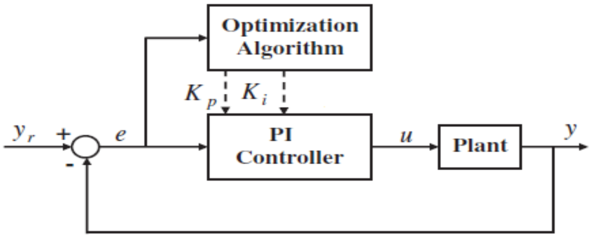


**Fig. 2: PI Controller Design with PSO**

Accordingly, picking the legitimate boundaries works on the Algorithm's viability. In the Level control of Hopper tank framework, the best upsides of the Kp and Ki parameters will be distinguished to create small or zero error. The design parameters of PSO-PI tuning [21] technique is shown in table 3.

**TABLE 3: Design Parameters of PSO Tuning Technique**

| | |
|---|---|
| Size of the Swarm (No. of Birds) | 60 |
| Maximum no. of birds steps | 60 |
| Dimension of the Problem ($K_p$ , $K_I$) | 2 |
| Cognitive and Social parameters (C1, C2) | C1=0.2 & C2=1.5 |
| Momentum of inertia | 0.95 |
| No. of iteration | 150 |

## III. RESULTS AND PERFORMANCE ANALYSIS

In this section a detailed analysis of the results obtained by the various proportional-integral controller parameters for a nonlinear hopper tank system. The methods discussed here are Fractional Order-PI and Particle Swarm Optimization tuning techniques. The FOPI method is a conventional controller technique and the PSO method is used to optimize the controller parameters to reach its settling point with minimized error. The controller gain values for region-based transfer function are publicized in Table 4.

**TABLE 4: Parameters of PI Controller with PSO-PI&FOPI**

| S. No | Operating Region | PSO-PI | | FO-PI | |
|---|---|---|---|---|---|
| | | $K_P$ | $K_i$ | $K_P$ | $K_i$ |
| 1 | Region-1 | 28.456 | 16.230 | 26.38 | 17.69 |
| 2 | Region-2 | 21.331 | 2.183 | 22.454 | 2.26 |
| 3 | Region-3 | 20.198 | 0.753 | 19.08 | 0.82 |
| 4 | Region-4 | 21.273 | 0.393 | 19.75 | 0.401 |
| 5 | Region-5 | 16.409 | 0.237 | 15.42 | 0.235 |

The Individual region based level control responses using FOPI and PSOPI tuning techniques were publicized in Figure 3 & 4 respectively. The fastest settling time after applying setpoint changes and load changes can be analyzed using these methods.

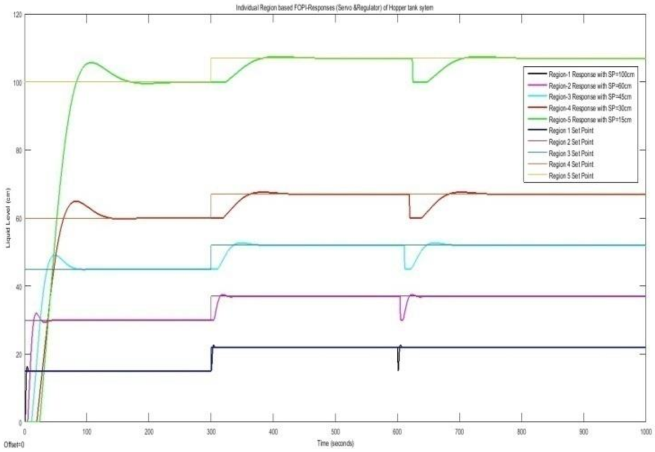


**Fig. 3: Individual Region based Level Control Responses with FOPI**

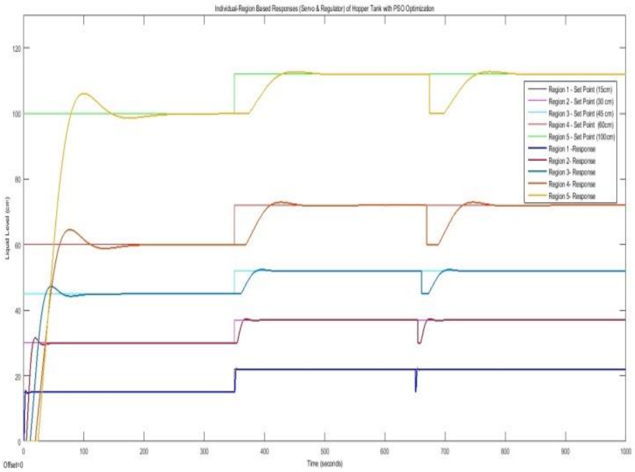


**Fig. 4: Individual Region based Level Control responses with PSO-PI**

The performance of the controlled output is determined by reducing the error using Time Integral Criteria methods like ISE, IAE & ITAE[22]. Time Domain Parameters like Peak overshoot, Settling time, and Rise time acts as deciding factors for identifying the best-suited controller for the hopper level process. Table 5 represents the performance of Fractional-Order PI controller with individual region-based level control [25] of hopper tank system. Particle Swarm Optimization Technique based performance indices among Individual region-based level control are publicized in Table 6. From all the Individual regions of performance indices, it clearly indicates that PSO-PI provides Minimum Settling time and reduced error values while compared with FOPI.

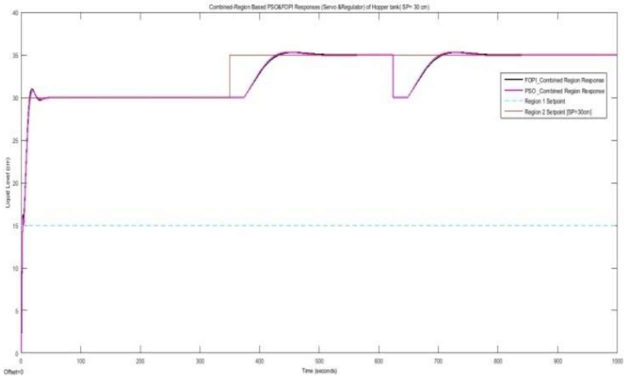
**TABLE 5: Individual Region based Performance Indices Analysis with FOPI**

| Operating Region | FO-PI (Individual Region Model) | | | | | |
|---|---|---|---|---|---|---|
| | Time Integral Performances | | | Time Domain Parameters Analysis | | |
| | ISE | IAE | ITAE | Settling Time (Ts) Sec | Peak Overshoot (%) | Rise Time (Tr) Sec |
| Region -1 | 331.90 | 29.55 | 25.81 | 5.60 | 9.04 | 1.46 |
| Region -2 | 6936 | 311.7 | 2141 | 28.1 | 15.1 | 6.65 |
| Region -3 | 37150 | 1097 | 17210 | 72.10 | 9.16 | 18.4 |
| Region -4 | 1.141e$^{+5}$ | 2492 | 6.586 e$^{+5}$ | 118 | 8.5 | 31.9 |
| Region -5 | 3.996e$^{+5}$ | 5159 | 1.640 e$^{+5}$ | 144 | 5.70 | 42.40 |

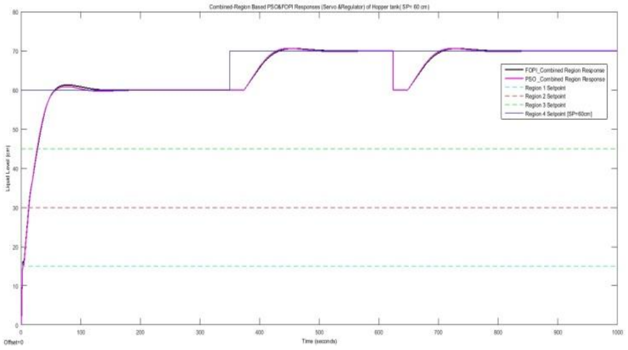
**TABLE 6: Individual Region based Performance Indices Analysis with PSO**

| Operating Region | PSO-PI (Individual Region Model) | | | | | |
|---|---|---|---|---|---|---|
| | Time Integral Performances | | | Time Domain Parameters Analysis | | |
| | ISE | IAE | ITAE | Settling Time (Ts) Sec | Peak Overshoot (%) | Rise Time (Tr) Sec |
| Region -1 | 323 | 27.55 | 20.18 | 4.35 | 4.2 | 1.46 |
| Region -2 | 6820 | 295.7 | 1723 | 24.6 | 5.15 | 7.8 |
| Region -3 | 36480 | 1044 | 16300 | 57.7 | 5.05 | 18.4 |
| Region -4 | 1.12 e$^{+5}$ | 2422 | 65150 | 103 | 7.62 | 29.8 |
| Region -5 | 3.908 e$^{+5}$ | 5062 | 1.565 e$^{+5}$ | 131 | 6.06 | 39.6 |

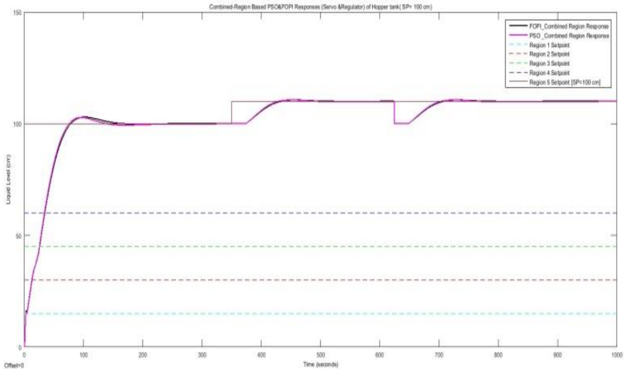
The individual region provides the level output of the hopper tank under the concept of Respective region model. The combined region provides the précised response of hopper tank level control system based on the combination all-region models (Multiple Regions). The Combined Region level control [25] responses for three different combinations (setpoint at 30cm, 60cm, and 100cm) are shown in Figure 5.



**(a)**



**(b)**



**(c)**

**Fig. 5: Servo Regulatory Response of Combined Region: (a) Nominal setpoint of 30cm (b) Nominal setpoint of 60cm (c) Nominal setpoint of 100cm**

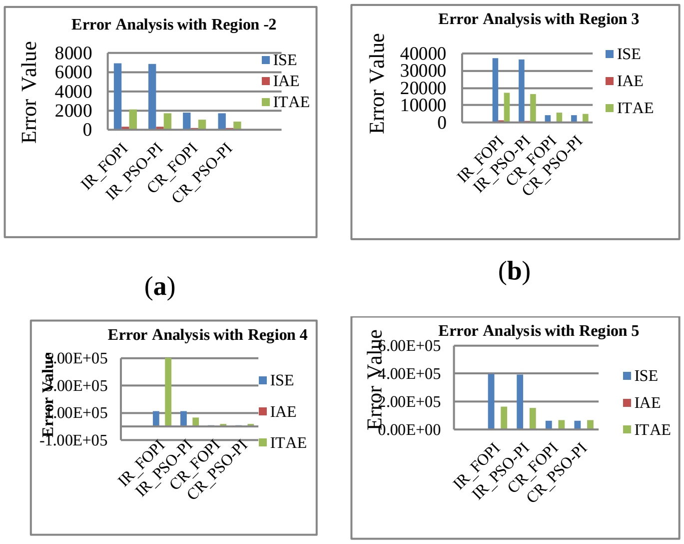
When the regions are combined it provides an ultimate faster response than that individual model. The combined model-based level control parameter analysis with time-domain and time integral of FOPI & PSO-PI are shown in tables 7&8 respectively. When the regions are combined, PSO-PI provides an ultimate faster response (Minimum settling time) and reduced Time integral error values while compared with Combined FOPI model-based level control.

**TABLE 7: Combined Region based Parameter Analysis with FOPI**

| Operating Region | FO-PI (Combined Region Model) | | | | | |
|---|---|---|---|---|---|---|
| | Time Integral Performances | | | Time Domain Parameters Analysis | | |
| | ISE | IAE | ITAE | Settling Time (Ts) Sec | Peak Overshoot (%) | Rise Time (Tr) Sec |
| Region -1 | 331.90 | 29.55 | 25.81 | 5.60 | 9.04 | 1.46 |
| Region -2 | 1799 | 155.9 | 1071 | 26.58 | 8.152 | 9.87 |
| Region -3 | 4128 | 365.5 | 5733 | 60 | 2.58 | 24.81 |
| Region -4 | 7129 | 622.9 | 16860 | 86.06 | 2.58 | 37.55 |
| Region -5 | 63930 | 2063 | 66580 | 124 | 2.95 | 58 |

**TABLE 8: Combined Region based Parameter Analysis with PSO**

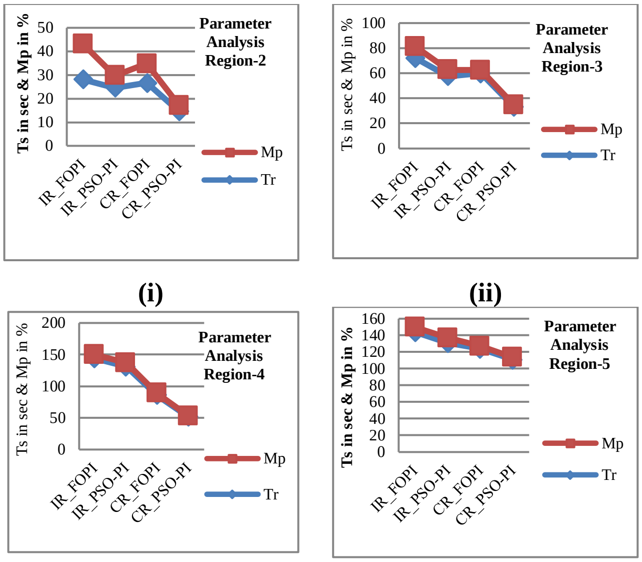
| Operating Region | PSO-PI (Combined Region Model) | | | | | |
|---|---|---|---|---|---|---|
| | Time Integral Performances | | | Time Domain Parameters Analysis | | |
| | ISE | IAE | ITAE | Settling Time (Ts) Sec | Peak Overshoot (%) | Rise Time (Tr) Sec |
| Region -1 | 323 | 27.55 | 20.18 | 4.35 | 4.2 | 1.46 |
| Region -2 | 1730 | 147.9 | 861.3 | 14.62 | 2.58 | 10.81 |
| Region -3 | 4053 | 347.9 | 5100 | 33.50 | 1.531 | 23.80 |
| Region -4 | 6952 | 605.5 | 16290 | 51.45 | 1.531 | 37.56 |
| Region -5 | 62520 | 2025 | 65620 | 111 | 2.58 | 56.41 |



**(a)** **(b)**

**(c)** **(d)**

**Fig. 6: Error analysis chart using Time Integral Criteria: (a) Region -2 (b) Region -3 (c) Region -4 (d) Region-5**



**(i)** **(ii)**

**(iii)** **(iv)**

**Fig.7: Analysis of Time Domain Parameters: (i)Region-2 (ii)Region-3 (iii)Region-4 (iv)Region-5**

Performances indices Comparison chart on Settling time & peak overshoot of FOPI & PSO-PI methods with Individual and combined region-based level control are being represented in figure 7. The bar chart illustrations of error analysis using FOPI and PSO-PI for Individual and Combined regions are exposed in figure 6. The aim is to maintain the tank liquid level, which is attained as a result of providing the fastest settling time with help of combined region-based Level control. From the Performance indices figures 6&7, it clearly indicates that the minimized time integral errors and fastest settling time is achieved by combined region-based level control with PSO-PI technique compared with FOPI tuning technique.

## IV. CONCLUSION

The wastage of materials was the major problem in industries that can be avoided by applying controller tuning techniques. The Particle Swarm Optimization technique is being used to Control the liquid Level of nonlinear Hopper tank with individual and combined region-based models. The FOPI controller provides a good response while considering the conventional controllers. But Optimization of proportional gain and integral gain results in better output when compared with the FOPI controller. Evaluations are made with individual regions and combined region responses based on the time domain parameters ($T_{r,}$ $M_{p)}$ and time integral performance criterion (ISE, IAE&ITAE) to reduce the error and to improve the performance. Combined region-based level control reduces around 40%-60% of error values while comparing with Individual region-based level control for both FOPI & PSO-PI. It was analyzed from the results that the Combined region model-based Particle Swarm Optimization method of PI controller tuning provides enhanced performance with minimum settling time(14.62, 33.50, 51.45& 111seconds) and error values when evaluated with FOPI controller settling time (26.58, 60, 86.06& 124seconds) for both individual and combined region-based hopper tank level control system.

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