Design and Implementation of GSO Based PI Controller for Non Linear Spherical Tank System

T. Geetha[a], **S. Somasundaram**[b]

[a,b]Department of Electronics and instrumentation Engineering, Annamalai university, Chidambaram, Tamil Nadu, India
Email:[a]geetha22.1988@gmail.com

Article History: Received: 10 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 28 April 2021

Abstract: From literature point of view process parameter control for non linear process found to be issue in process control industries. The main dilemma lies on managing liquid level in globular tank which is non linear in nature owing to its area disparity in cross section consequent to the change in shape. System identification is made with black box model which is nonlinear and approximated to first order plus dead time model using the worst case model parameter criterion. Group Search Optimization based Proportional Integral controller is implemented to control the non linear system. The real time work is implemented in MATLAB using VMAT-01 module. The servo and regulatory responses of GSO based proportional integral controller intended for different operating region is noted and results are compared with the algorithms such as Big Bang - Big Crunch optimization, Particle swarm optimization and Bacterial Foraging optimization . The most admirable controlling method is determined based on indices such as reduced overshoot, better set point tracking, disturbance rejection , lower performance indices, faster settling time and rise time.

Keywords: PI Controller, nonlinear system, optimization, spherical tank

1. Introduction

Generally designing a Non-linear process controller is really a challenge when compared to linear processes in industries. Mostly in process control industries the liquids are initially stored in tanks & again pumped to a new tank. Often liquids are processed by chemical treatment and level of the liquid ought to be kept in control. High level of the liquid causes damage to the equipment or hazardous material likewise low level leads to disturbances in sequential operations. Thus, control of the fluid level is an essential factor and is common in process industries[1]. Spherical tanks are widely used in metallurgical industries, cement industries, petro-chemical industries, paper making etc for several applications. The unique shape contributes to enhanced draining of solid mixtures, gelatinous fluids deposited at the lower tank part. The level control in the spherical tank level is a hard-hitting task in view of its non-linearity and frequently varying cross section. Due to this process industries need a traditional control technique to control the tank level. Although there is a eloquent development in advanced process control schemes, traditional PID (Proportional + Integral + Derivative) controllers are extensively proposed for industrial control phenomena considering robust performance and ease in implementation [2]. The PID controller design with the traditional method is complex, model oriented and time delaying for a nonlinear system. Even though the PI/PID controller possesses few flexible parameters tuning them during real time process requires dreary plant tests to acquire enhanced controller setting. Hence a closed-loop mode is employed in this paper to improve performance. Therefore it is essential to employ evolutionary algorithms in controller design for the nonlinear process. The process used to find the preeminent resolution for a particular hitch is called as optimization. The PI controller outperforms PID controller in limiting the noise in industrial processes [3]. Group Search optimization based PI tuning is utilized due to its capability to find optimized controller parameters with a minimal computation time, accuracy, and memory size compared with other methods. The real time replica is intended to control fluid level in spherical tank. Process model is interfaced with real time using VMAT-01 module in MATLAB. Operating points for the non-linear spherical tank system is chosen as 30cm, 60cm and 72cm and corresponding mathematical models are derived using the black box modelling technique and using worst case model parameter criterion the desired FOPTD model is identified. For the proffered model, PI parameters are evaluated by means of GSO algorithm. The output of the GSO-PI controller is compared with tuned optimization algorithms.

2.Experimental Setu

The real time set up includes a spherical tank, a water tank, rotameter, a DPT, pump, I/P converter, a air operated control valve, a VMAT-01module for interfacing and a computer. The model is developed using Simulink blockset in MATLAB software and linked with VMAT-1module

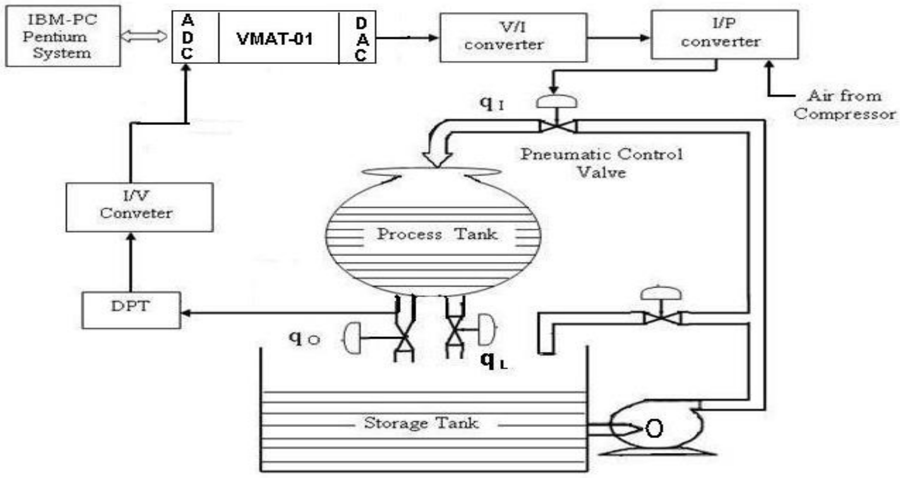

Fig 1. Spherical tank set up

Figure 2 represents spherical tank experimental set up. The air control valve controls the waterflow from the reservoir in the spherical tank. The fluid level in the tank is monitored through a DPT whose output varies from (4-20) mA & same is fed to the interfacing VMAT-01 module. After computation of the specified algorithm an output in the form of current signal varying from (4-20) mA is sent to I/P converter, further I/P converter converts the current signal to pressure signal which controls the actuation of the Pneumatic valve for feeding the water in a controlled manner to the tank, this happens as a continuous closed loop process . Air for the Actuation of valve is being fed through a Air compressor which is always maintained at 6kg pressure.

Fig 2 Real time experimental setup of a Spherical tank

3. Identification

Various types of System Identification persist to find the model of the process, of which Mathematical modeling & Black Box modeling are considered to be most reliable.

3.1 Mathematical Modeling

Fundamental physical & chemical laws such as law of conservation of energy, mass, momentum etc form the base for mathematical modeling. To study the same engineers work on their engineering skills to make Judgment from the actual assumptions made in reality. The development of a model incorporating basic phenomena in the process needs lot of skill & practice.

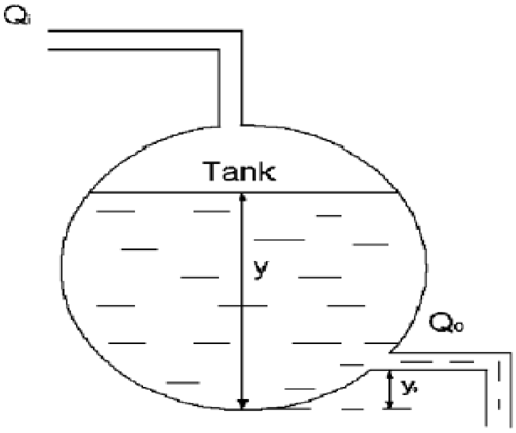

Figure.3 Structure of spherical tank

The volume equation of the above tank is computed using the radius & height of the tank, for the volume in the tank V is formulated as

$$v = \int_{r-h}^{r} A\,dx \quad (1.1)$$

Where, 'A' represents the cross-sectional area in the location 'X' from the mid of the sphere. The integral lower limit is X = r - h the point where the liquid is and integral upper limit is 'r' representing the lower end of the sphere. So, the 'A' at any location 'X' is calculated as follows

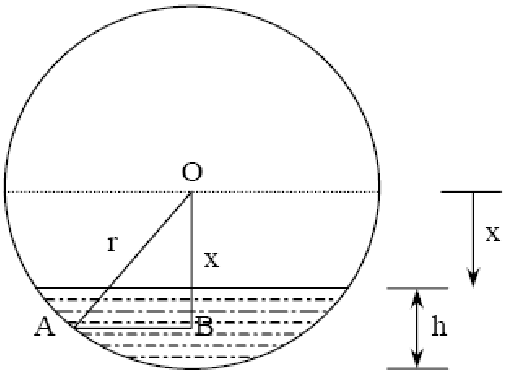

Fig.3.2 Obtaining the volume equation for liquid in the tank

From figure.3.2, for a location 'x',

OB=X and OA = r , Then

$$AB = \sqrt{OA^2 - OB^2}$$

$$= \sqrt{r^2 - x^2}$$

Where AB is the radius of the area 'X', so the area at location 'X' is

$$A = \pi AB^2 = \pi(r^2 - x^2)$$

Applying the same in volume equation

$$V = \int_{r-h}^{r} \pi(r^2 - x^2)dx = \pi\left[r^2x - \frac{x^3}{3}\right]_{r-h}^{r}$$

$$V = \pi\left[(r^2r - \frac{r^3}{3}) - (r^2(r-h) - \frac{(r-h)^3}{3})\right]$$

$$V = \frac{\pi h^2(3r-h)}{3} \quad \text{and} \quad \frac{dv}{dh} = \pi(2hr - h^2)$$

In terms of Inflow & Outflow the mathematical model is given as

$$Q_i(t) - Q_o = \pi R^2\left[1 - \frac{(R-y)^2}{R^2}\right]\frac{dy}{dt}$$

$$\frac{dy}{dt} = Qi(t) - Qo(t)/\pi(2Ry - y2)$$

Where

$$Q_o = c_d\alpha\sqrt{2g(y - y_o)}$$

Figure 3 portrays a spherical tank with dynamic characteristics being non- linear and is illustrated in terms of differential equation of order one. Wherein radius of tank is denoted as ‘R’ and variation of water level in terms of its outflow and inflow cause is denoted as ‘y’.

Based on relations, it is obvious that water level rise time is rapid at top and lower end while mild at the middle part. According to Bernoulli relation, tank outflow is comparative to root square of liquid level height.

3.2 Black Box Modeling

The Spherical tank is initially filled up with water at range (0-45cm), with fixed rate of water inflow & outflow. For every unit sample time, the output (4-20mA) from DPT (Differential Pressure Transmitter) is being noted down & sent to system via RS-232 serial port employing interfacing module VMAT-01.

Using the open loop method output response is noted for input variable. The three process parameters Kp, τp, θ can be anticipated through single step test. The process gain is calculated by

$$Kp = \frac{\Delta}{\delta} \tag{1.2}$$

$$Kp = \frac{Change\ in\ process\ output}{Change\ in\ process\ input} \tag{1.3}$$

Smith evaluated the FOPTD transfer function model values by making the response of the actual system and that of the model to coincide at two points 28.3% & 63.2% which expresses the parameters time constant θ and time delay τ ie the time span between the input change occurrence & corresponding significant output response is recorded. Two point method is utilized here for estimating the process parameters, time taken for the process output to reach 28.3% and 63.2% are used respectively. The time delay and the time constant is obtained from the equation (1.4) and (1.5)

$$\tau_p = 1.5\,(t_{63.2\%} - t_{28.3\%}) \tag{1.4}$$

$$\theta = (t_{63.2\%} - \tau_p) \tag{1.5}$$

The intention is to find the model of the system which reaches steady state at fixed inflow & outflow rate, for this the open loop response of the spherical tank process is recorded between the span of the operating points (region) from 30% to 45%. A step size increment of 5% is given in input flow rate & corresponding readings of the output are collected until a new steady state is reached. The same procedure is carried out at all operating regions & the model parameter values such as process gain (Kp), time constant (τ), and time delay (t_d) are noted. The real time data confined to be FOPDT model and strictures of the same are charted in table (1.1).

Table 1.1 Black box model of spherical tank on different operating points

S.No	Operating region	Kp	T	t_d
1	30 – 35	2.94	3450	250
2	35 – 40	3.788	4500	300
3	40 – 45	5.294	5850	150

From this the FOPTD model for spherical tank system is as provided like below

$$G(S) = \frac{5.294}{3450} e^{-300s} \tag{1.6}$$

Based on this model a Stable PI controller parameter is obtained based on Optimization techniques.

4.. Controller Design

4.1.. Group Search Optimization Algorithm

GSO Group search optimization Algorithm is enthused by group living theory & was developed by Gustavo-De-Souza in 2011. In GSO, a group consists of Producer, Scroungers and Rangers. Producer is the member with a best potential area, possessing the finest fitness value among the group. The rest other members in the group are the scroungers & rangers. GSO algorithm follows one producer model ie a single producer is assumed at every searching drum , which finds the resources & other members in the group use the output path explore by the producer.

In the search process or in the next drum if the scrounger finds better resource than the previous one then it will toggle as a producer and all the scroungers and the preceding producers in searching drum will now perform scrounging strategies. Producer and scroungers have phenotypic characteristics so they can toggle among the two roles [4] [5]. All possible sets of decision variables are adjusted so as to minimize the objective function f(x), & evaluate the controller's performance in terms of Integral Square Error (ISE) error criteria which integrates the square of the error over time .This algorithm continuously adjusts K*c*, K*i* until f(x) is minimized. The optimal values having minimal errors are termed as Global best solution. .The constraints limit the decision values within the range where L - [min(*kc*) min(*ki*)] is the lower bound value and U- [max(*kc*) max(*ki*)] is the upper bound value containing minimum and maximum K*c*, K*i* values.

The initial head angle φ° of apiece inhabitant is set to be π/4. The maximum pursuit angle θ_{max} is fit to be $\pi/(a^2)$. The maximum turning angle α_{max} is fit to be $\theta_{max}/2$. The maximum pursuit distance is $l\max \in R^1$ & it is derived from

$$l_{max} = \| U - L \| = \sqrt{\sum_{i=1}^{n} (U_i - L_i)^2} \tag{1.7}$$

It is likely to derive appropriate results by fine tuning the φ°, θ_{max}, l_{max} and α_{max}.

In GSO, head angle is reminded by producer during the initiation of production, the search is easily performed by turning head to a fresh angle. The scanning procedure of GSO is a cut down direct search method, component of search orientation introduced by white crappie scanning is performed in n dimensional space characterize by maximum pursuit angle θmax ϵ R_1 & maximum pursuit distance lmax ϵ R_1. Bounded search space strategy is adopted to confine the search within the constraints [6]. If suppose a member is found at outer surface of the searching space then, it will return back by setting the variables that violated the boundary criteria within the search space. GSO works well for all the FOPTD models.

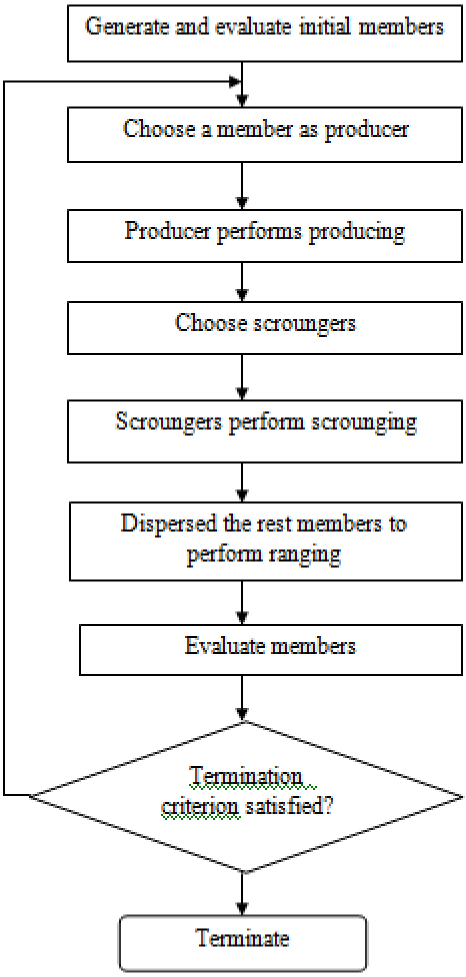

Fig.4.1 Flowchart of the GSO Algorithm

The step wise procedure of the flowchart has been prescribed below:

Step 1: Randomly initialises the group until one valid member if found in the feasible area

Step 2: The fitness of all members is calculated, & the member who finds the best resource is chosen as producer.

Step 3: Producer performs the producing strategy.

Step 4: Scroungers are chosen randomly from the remaining group members.

Step 5: Scroungers then carry out the scrounging activity in the path of producers.

Step 6: The remaining members in the group are identified as Rangers & they carry out the ranging strategy in arbitrary direction.

Step 7: Evaluation of the member is carried out.

Step 8: If the Termination criterion is satisfied, the process ends else the process continues in a loop proceeding back to step 2.

4.2.. Particle Swarm Optimization Algorithm

The Particle swarm optimization algorithm (PSO) is a population based speculative search algorithm introduced in 1995 by Kennedy & Eberhart. It is a venerable optimization methodology & primitive approach for finding the optimal PID controller parameters from the search space, it is easy to implement & can swiftly converge to a good solution [7]. Alike to the genetic algorithm (GA), PSO is a population based method and it exhibits the form of an algorithm by population which is continually personalized until satisfies the termination criteria. In PSO algorithms, the population P= {p1....pn} of the Feasible solution is termed as swarm, whereas the feasible solution p1...pn are called as particles. The objective function f:Rd ->R is called the fitness function: it measures the performance of each particle to examine for the best value during the running of the process[8]. Optimization algorithm is performed until either utmost iteration numbers are completed, or desired fitness value attained. Since minimal value of the objective function is considered, the reciprocal of error gives the fitness value. For each iteration, the finest in the midst of 100 particles are chosen as potential solution.

4.3.. Big Bang - Big Crunch Optimization Algorithm

BB-BC algorithm is carried out as two junctures, Big Bang and Big Crunch. Big Bang phase is a depository of energy dissipation actions in view of randomness and disordering, this phase signifies large space exploration. The Big Crunch phase is a method that arbitrarily splits up the particles and puts them into an order; this phase signifies best solution exploitation. The Big Bang phase trailed by Big Crunch phase selects centre of mass point through best member method [9] which aims to decline computational time, at the same time having quick convergence, sustaining search diversity and solutions quality. The population formed in the Big Bang phase will be steadily reduced in this phase. First iteration ends subsequent to Big Crunch phase. Second iteration has a tapered search interval around centre of mass point and Big Bang phase runs in this interval.

BB-BC algorithm is used to find the best kp-ki gains for an FOPDT system, the predefined parameters such as population size & iteration number were chosen & the best performance is evaluated with minimum settling time & without any overshoot. The gains of the controller are obtained by

$$Kp = \frac{(0.395 - 0.425u)\tau}{kL} \qquad (1.8)$$

$$Ki = \frac{0.395 - 0.725u}{kL} \qquad (1.9)$$

4.4. Bacterial Foraging Optimization Algorithm

Bacterial Foraging Optimization Algorithm (BFOA) is put forth by Kevin passino in 2002. Application of animal searching strategy for a swarm of *E*.coli bacteria in multi-optimal function optimization is base inspiration behind this algorithm. Every entity bacterium sends signals to others for communication [10]. The aim of BFOA is imitating the bacterial chemotactic movement in the boundary of search space [11].

Chemotaxis process personates the E.coli cell movement by swimming and dipping through flagella. Organically a bacterial E.coli moves among two ways. Bacterial E.coli can swim in the similar direction upto a phase of time or it can tumble. It operates in these two modes until its existence.

Swarming is a process in which unique group behaviour is noticed among numerous motile species of bacteria containing E.coli and S [12]. Cluster of E.coli cells organize them in the form of the travelling ring via stirring through nutrient gradient and infuse a matrix which is semisolid exhibiting unit nutrient chemo-effect.

Reproduction involves the destruction of unhealthy bacteria in due course when the healthy bacteria which is set to be having minimal significance of objective function asexually cracks into two bacteria and gets positioned in similar position thus ensuring constant swarm volume.

Eliminational-Dispersal process involves steady and impulsive changes in the confined surrounding which makes the bacterium population to live, it might happen over different reasons. Actions can take place such that the cluster of bacteria in a region is killed or detached to a fresh part of the environment. To stimulate this occurrence in BFOA few bacterium are selected randomly with a least probability whereas the new bacterium replacements are initialized in random manner within the search space. Elimination process has the ability of probably destroying chemotactic progress also they support the chemotaxis process and scattering might locate the bacterium in the vicinity of better food sources. The PI gain tuning steps are based on BFA presented[13].

5. Experimental Results

5.1 Real Time Experimental Analysis Of Optimization Based Pi Controller

Using the experimental set up servo response of spherical tank altitude course is attained for shift in supposed operating spot for 60% with raise and drop off in set point at different time interval +/-5% & +/-10% as revealed in figure 5.1 to 5.4.The GSO based PI controller provides best results when compared to PSO BF & BG based PI controllers with minimal overshoot ,faster rise time & minimal settling time & also the performance index are found to be minimal for GSO based PI controller as tabulated in table 5.1 to 5.4 where IAE, ISE values & time domain specifications are evident as minimal. The GSO controller provides highly stable output at different operating points of the progression over intact span of tank.

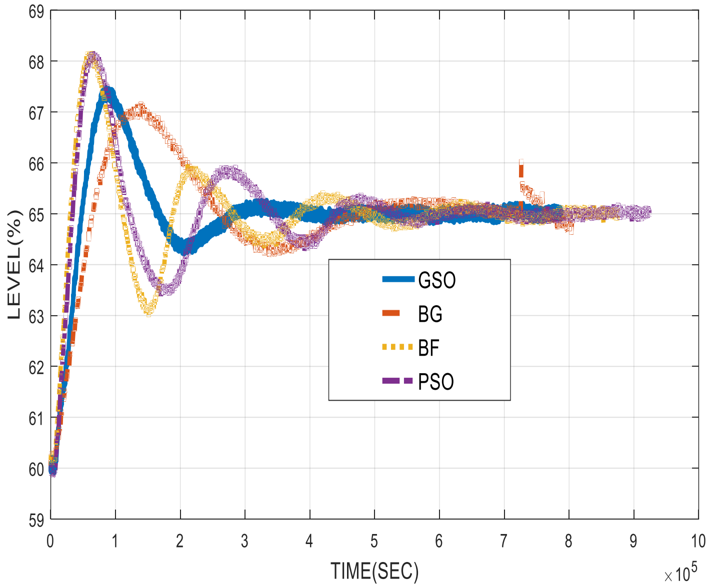

Fig 5.1 Servo Response of spherical tank height progression for 5% augments in Set summit from nominal operational indicate of 60% via Optimization techniques

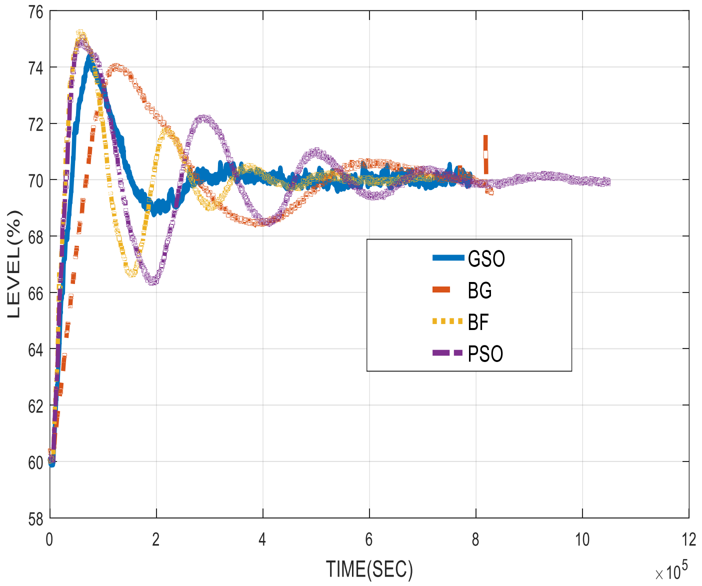

Fig 5.2 Servo Response of spherical tank height progression for 10% augments in Set summit from nominal operational indicate of 60% via Optimization techniques

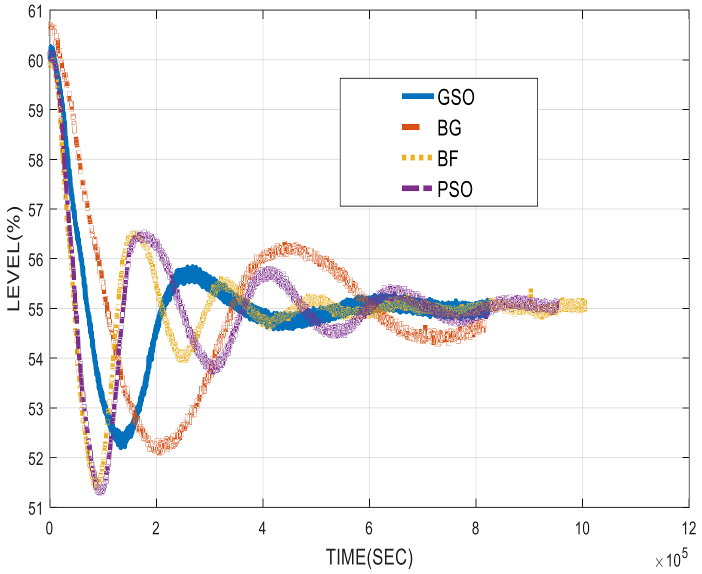

Fig 5.3 Servo Response of spherical tank height progression for 5% decrease in Set summit from nominal operational indicate of 60% via Optimization techniques

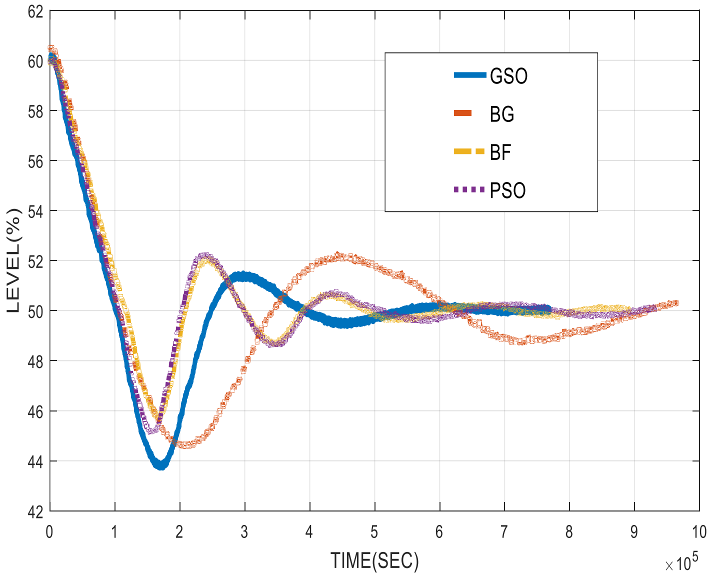

Fig 5.4 Servo Response of spherical tank height progression for 10% decrease in Set summit from nominal operational indicate of 60% via Optimization techniques

S.No	METHOD	ISE	IAE	R.S	O.S	S.T
1	GSO	8.618 e^{+04}	4.534e^{+04}	0.4x10^5	3.38	3
2	BF	9.510e^{+04}	5.3389e^{+04}	0.3x10^5	4.615	4.5
3	BG	1.557e^{+05}	6.3003e^{+04}	0.6x10^5	3.230	6.5
4	PSO	1.0667e^{+05}	6.0256e^{+04}	0.3x10^5	4.615	5.5

Table 5.1 Performance Index of spherical tank level route for 5% Increase in Set indication from nominal functioning condition of 60% employing Optimization techniques

S.No	METHOD	ISE	IAE	R.S	O.S	S.T
1	GSO	$2.522\ e^{+05}$	$7.009e^{+04}$	$0.4x10^5$	5.71	$2.8x10^5$
2	BF	$3.1208e^{+05}$	$8.6963e^{+04}$	$0.3x10^5$	7.28	$4.5x10^5$
3	BG	$4.8756e^{+05}$	$1.2148e^{+05}$	$0.65x10^5$	5.71	$7.5x10^5$
4	PSO	$3.9393e^{+05}$	$1.2536e^{+05}$	$0.3x10^5$	7.28	$7\ x10^5$

Table 5.2 Performance Index of spherical tank level route for 10% Increase in Set indication from nominal functioning condition of 60% employing Optimization techniques

S.No	METHOD	ISE	IAE	R.S	O.S	S.T
1	GSO	$1.352\ e^{+05}$	$6.179e^{+04}$	$0.9x10^5$	4.9	$4x10^5$
2	BF	$1.2903e^{+05}$	$6.558e^{+04}$	$0.5x10^5$	6.9	$6x10^5$
3	BG	$2.599e^{+05}$	$1.068e^{+05}$	$1.2x10^5$	5.45	$8.5x10^5$
4	PSO	$1.5530e^{+05}$	$7.6337e^{+04}$	$0.5x10^5$	6.9	$8x10^5$

Table 5.3 Performance Index of spherical tank level route for 5% decrease in Set indication from nominal functioning condition of 60% employing Optimization techniques

S.No	METHOD	ISE	IAE	R.S	O.S	S.T
1	GSO	$6.282\ e^{+05}$	$1.27e^{+05}$	$1.1x10^5$	11	$5x10^5$
2	BF	$5.495e^{+05}$	$1.1871e^{+05}$	$1.2x10^5$	8.2	$6x10^5$
3	BG	$8.800e^{+05}$	$2.009e^{+05}$	$1.1x10^5$	10.2	$9.1x10^5$
4	PSO	$5.3917e^{+05}$	$1.2183e^{+05}$	$1.2x10^5$	8.5	$7x10^5$

Table 5.4 Performance Index of spherical tank altitude route for 10% decrease in Set indication from nominal functioning condition of 60% employing Optimization techniques

Regulatory response of spherical tank indication works at 60% nominal operating provision when subjected to sudden opening of the tank output valve up to 50% is recorded in figure 5.5 to 5.8. The GSO PI controller yields better performance measures in comparison with other conventional controllers in correspondence to the disturbance caused as given in table 5.5 .This proves the fact that GSO PI controller acts upon effectively even in uncertain conditions & control the level in the tank without causing any disturbance to the process involved.

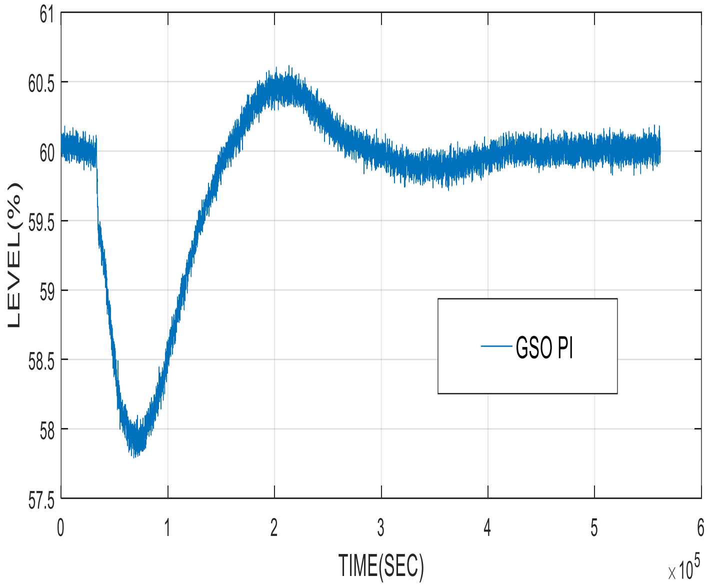

Fig 5.5 Regulatory Response of spherical tank level process for 50% Output valve opening

At nominal functional condition of 60% via GSO PI controller

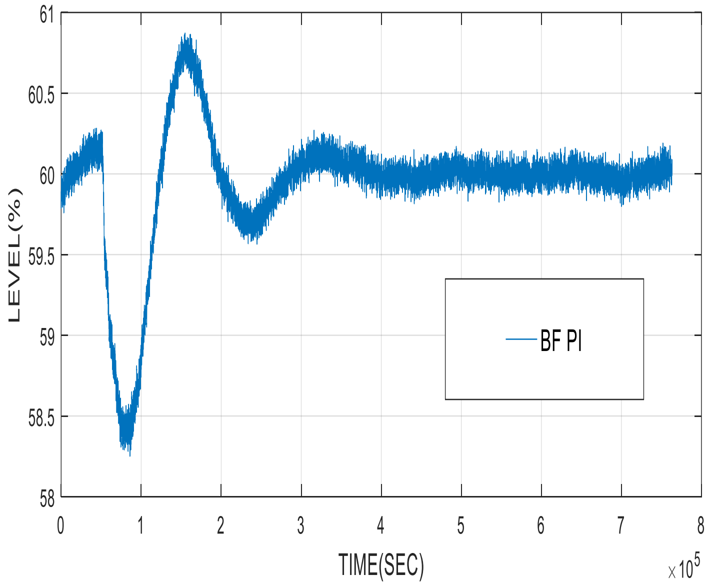

Fig 5.6 Regulatory Response of spherical tank level process for 50% Output valve opening

At nominal functional condition of 60% via BF PI controller

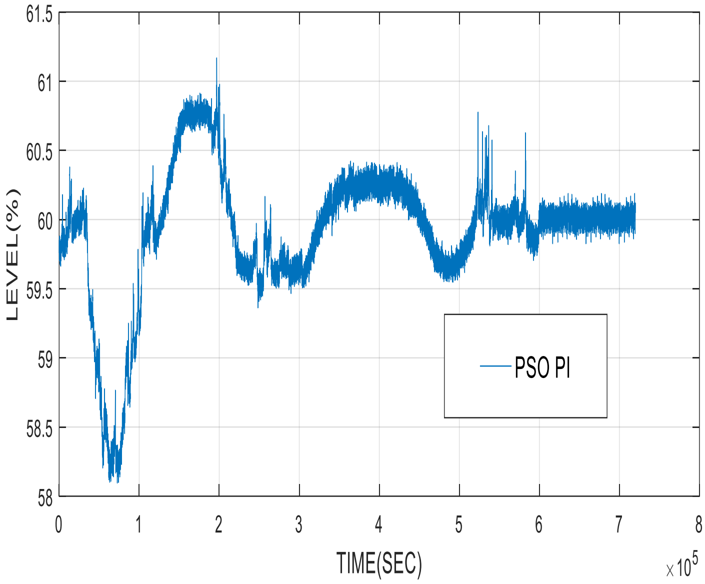

Fig 5.7 Regulatory Response of spherical tank level process at 50% Output valve opening At nominal functional condition of 60% via PSO PI controller

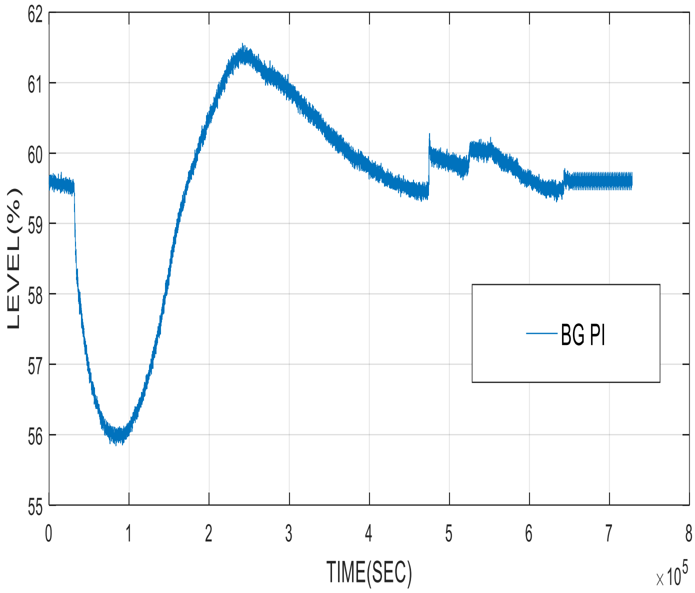

Fig 5.8 Regulatory Response of spherical tank level process for 50% Output valve opening At nominal operating point of 60% using BG PI controller

S.No	METHOD	ISE	IAE	O.S(%)	S.T
1	GSO	1.4839 e^{+04}	$2.0131e^{+04}$	0.5	2.8
2	BG	$1.5708e^{+05}$	$6.5996e^{+04}$	1.5	Nil
3	BF	$1.5018e^{+04}$	$2.0332e^{+04}$	0.8	3.5
4	PSO	$2.6201e^{+04}$	$3.2463e^{+04}$	0.9	6

Table 5.5 Performance Index of spherical tank level process for 50% Output valve opening

At nominal operating point of 60% using Optimization techniques

6.- Conclusion

In the present work Spherical tank is taken for the experimental study & an FOPTD model is obtained using the worst case model parameter criteria for level control at different operating regions. Design and execution of concurrent GSO based PI controller is done & compared with PSO, BF, & BG based PI controller. Based on real time results, it is proposed that, GSO based PI controller outperforms the other comparison controllers which is evident from the servo & regulatory responses which reflects its efficiency in terms of performance measures & time domain specifications.

References

1. Ackermann, J., and Kaesbauer, D. (2001). Design of robust PID controllers. Proc. in: European Control Conference, Porto,522-527.
2. Astrom, K.J., and Hagglund, T. (1995). PID controllers: Theory, Design, & Tuning (2nd ed.). ISA, R. Triangle Park, NC.
3. Bekker, J.E., Meckl, P.H., and Hittle, D.C. (1992). A tuning method for first-order processes with PI controllers. ASHRAE Transactions, 99, 2.
4. C. J. Barnard and R. M. Sibly, “Producers and scroungers: A general model and its application to captive flocks of house sparrows,” Animal Behavior, vol. 29, pp. 543–550, 1981.
5. J. Najemnik and W. S. Geisler, “Optimal eye movement strategies in visual search,” Nature, vol. 434, pp. 387–391, Mar. 2005.
6. S. He, Q. H. Wu, and J. R. Saunders, “A novel group search optimizer inspired by animal Behavioral ecology,” in Proc. 2006 IEEE Congr. Evol. Comput., Vancouver, BC: Sheraton Vancouver Wall Center, Jul. 2006, pp. 1272–1278.
7. Eberhart RC, Kennedy J. A new optimizer using particle swarm theory. In: Proceedings on international symposium on micro machine and human science. USA: IEEE Service Center; 1995. p. 39–43.
8. S. M. Giriraj Kumar , R. Sivasankar , T. K. Radhakrishnan , V. Dharmalingam & N. Anantharaman (2008) Particle Swarm Optimization Technique Based Design of Pi Controller for a Real-Time Non-Linear Process, Instrumentation Science & Technology, 36:5, 525-542.
9. Ugur Yildrim, IIhan Mutlu and Mehmet T. Söylemez (2015) An Optimal Robust Tuning Method for First Order plus Dead Time Systems with Parameter Uncertainty, IFAC-PapersOnLine 48-14 (2015) 126–131.
10. Alam, M., Claviez, M., Oesterhelt, D., & Kessel, M. (1984), Flagella and motility behaviour of square bacteria. The EMBO Journal,13(12).2899 2903.
11. Berg, H. C. (1993). Random Walks in Biology , New Expanded Edition. Princeton, NJ: Princeton University press.
12. Berg, H. C., & Brown, D. A. (1972). Chemotaxis in Escherichia Coli Analysed by Three Dimensional Tracking. Nature, 239, 500 504.
13. Ahmed G. Agamy, Ali H. Kasem Alaboudy, Member, IEEE, Hossam E. Mostafa, Member, IEEE, and Mahmud Y. Fekry(2011), Bacterial Foraging-Based PI Controller of Inverter-Based Distributed Generator : IEEE Service Center p.1 – 7.