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Performance Analysis of Different Pulp Consistency Models Using Particle Swarm Optimization Based Proportional Integral Derivative Controller

Abstract: *In this paper, an attempt has been made to design a PSO based classical PID Controller for controlling stock consistency, one of the most important papermaking parameters used as a single input single output (SISO) system. Various transfer function models of this parameter reported in the literature have been employed. These transfer functions are actually developed from experimental data from real systems i.e. paper industry. Out of so many tuning techniques for controller settings, the Ziegler-Nichols (ZN), Internal Model Control (IMC)& Tyreus –Luyben (TL) techniques are mostly used in industries. These controller tuning methods usually produce large overshoot, larger settling time slower dynamics and less comparative stability. Therefore, modern heuristics approach such as Particle Swarm Optimization (PSO) is proposed to examine its suitability in enhancing the capability of traditional techniques. For comparison purposes, the simulation with ZN –PID, TL-PID, and IMC-PID are also presented. The analysis reveals that the PSO-based PID approach in most of the situations provides better optimal performance pertaining to overshoot, frequency response & relative stability (gain Margin and phase Margin), and low-performance index values of given process models of stock consistency.*


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Key Words: *Particle Swarm Optimization (PSO), Paper Machine, Stock Consistency, Internal Model Control (IMC), Zeigler – Nichols (ZN), Tyreus Luyben (TL).*

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Introduction

All chemical process industries need accurate measurement and control of their process parameters. Pulp and Paper is not an exception. For controlling process parameters, the majority of the process industries use classical Proportional Integral Derivative (PID) still today. Paper mills also employ PID control for controlling a number of parameters notably flow, level, pH, temperature and consistency. Out of the aforesaid parameters, consistency is widely used in various stages of pulp and paper stock processing stages till formation wires in the wet end of the paper machine begin. However, because of the complexity of the consistency control process caused by its nonlinear nature, PID controller even as Single Input Single Output (SISO) does not give satisfactory performance. It requires frequent tuning to adjust controller parameters to control consistency. It is well known that the PID controller has three parameters, the proportional gain (K_P), integral time (T_T) and derivative time (T_D). In industrial practice, these are frequently termed as K_P, K_i(product of K_P and $1/_{TI}$) and K_d(product of K_p and T_D).Three are a large number of tuning techniques available in the literature, notably time domain, frequency domain, and model-based strategies. Industry uses them according to their scope, convenience, experience, and judgment. Even rule of thumb, online trial or error or computer simulation techniques are also used. Empirical tuning methods like Zeigler-Nichols(Z-N) (closed and open loop) tuning techniques, Cohen and Coon (C-C) open loop tuning and their modifications have been a widely used method as a benchmark for performance evaluation of different tuning methods and control strategies. These are called pseudo-standards developed based on experimental data and experience gathered from settings of similar loops in various chemical industries. They result in responses with large overshoot, fairly under damped with significant oscillatory action and are sensitive to uncertainty. In spite of limitations, they give reasonable first guesses of settings of the values of the controller's adjustable parameters and useful as a place to start. Responses with ZN tuning are found slightly better than those with the C-C setting. Instead of optimal, it gives inflection point in sigmoidal shape, S shape or delta shape response curve of an over damped system. Tyreus –Luyben method (1997) is also a modified technique based on continuous cycling method like ZN techniques and are more conservative than ZN tuning method. It results in less oscillatory response and is less sensitive to changes in process condition. Therefore, these techniques need retuning before applied to control single input single output (SISO) system. In the current control system design, an optimization technique is often proposed to tune the control parameters to determine optimal performance [1, 2]. Model-based tuning techniques such as IMC tuning relations and Integral Error Criteria are the other alternative methods of tuning. They optimize the closed loop response for a simple model and a specified disturbance or set point change. The optimum settings minimize an integral error criterion. To improve the capabilities of classical PID for enhanced performance, several Artificial Intelligence (AI) based tuning techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have also been suggested. The objective of this paper is to present a PID control design for analysis of performance using ZN, T-L, Integral Error criteria, and PSO for control of headbox stock consistency as a SISO system. The performances of the proposed PSO based controller has been compared with those of conventional PID controllers designs using ZN, T-L, Integral of Square Error and IMC techniques.

Controller Design

Figure 1 represents a simplified general closed-loop feedback control system loop for controlling any process parameter of any plant as a SISO system, where C(s) represents controllers' transfer function and G(s) represents process transfer function. The transfer function is in the feedback loop has been considered unity. To analyze the system one needs to know transfer function models of the consistency process parameter. These are generally not available to the designer as process dynamics in a real system (plant) is mostly unknown. Therefore, one requires experimental data from a real plant to develop a model through the process identification technique.

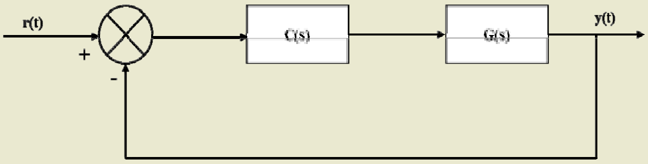

Fig.1 General Representation of the closed-loop system

Table-1 Transfer functions of Consistency Control Process in Paper mill

Sl. no.	Transfer functions	Reference& Details
Sys 1 (FOPDT)	$G_1(s)=\dfrac{-2.035}{3.84s+1}e^{-6.84s}$	[1]Consistency Control loop NC4A (pp.187)*
Sys 2 (FOPDT)	$G_2(s)=\dfrac{0.03}{10s+1}e^{-5s}$	[1] Consistency dynamics based on open loop bump tests and dead time varying between 5 – 30 seconds(pp.262)*
Sys 3 (FOPDT)	$G_3(s)=\dfrac{-1.4}{3s+1}e^{-3s}$	[1]Blending of Softwood(Pine) and Hardwood pulps for ratio control((pp.394) *
Sys 4 (FOPDT)	$G_4(s)=\dfrac{-2.08}{5s+1}e^{-5s}$	[1]Pine wood consistency NIC-104 dynamics –open loop bump test(pp. 397)*
Sys 5 (FOPDT)	$G_5(s)=\dfrac{-1.93}{3.51s+1}e^{-5.7s}$	[2] EnTech, Emerson process management, 2002.
Sys 6 (SOPDT)	$G_6(s)=\dfrac{-5.775\,e^{-005}s\;+0.001847}{s^2+0.01496s+0.004918}e^{-5s}$	Determined based on 3000 data points obtained from industry with ABB-DCS system [3]
Sys 7 (SOPDT)	$G_7(s)=\dfrac{0.08726\,s\;+0.1846}{s^2+0.4394s+0.2404}e^{-3s}$	Determined based on 1000 data points obtained from industry with ABB-DCS system [4]

* *Bill Bialkowski and Fred Thomasson in1994 TAPPI Process Control Symposium in New Orleans and solved using Simulation Software, VisSim*

Transfer Function models

In this investigation, seven number of process transfer function models for stock consistency have been taken into consideration [1,2]. These are depicted in Table 1.

The first four were based on experimental data on real control loop of consistency of softwood pulp or of hardwood consistency or both as their blends obtained from 5 % bump test. The dynamic models based on realistic process operation included first order Pade's approximation (dead time) developed by Bill Bialkowski and Fred Thomasson using Simulation Software (VisSim) [1]. The fifth Consistency control loop dynamic specification was developed by, M/s EnTech, Emerson process management [2]. The dynamics of consistency parameter were also determined based on data from one of the largest paper mill using process identification technique based on point data of ABB-DCS (Distributed Control System), installed in Tamil Nadu Newsprint Limited (TNPL). The last two open loop transfer functions have been developed as second order with dead time (SOPTDT) systems.

Performance Indices

For a PID- controlled system, there are often four performance indices to analyze the system performance: Integral of Square Error (ISE), Integral of Absolute Error (IAE), Integral of Time-weighted Absolute Error (ITAE) and Integral of Time-weighted Square Error (ITSE). They are defined as follows [14, 15]:

$$ISE = \int_0^\infty e^2(t)dt \qquad ....(1)$$

$$IAE = \int_0^\infty |e(t)|dt \qquad ....(2)$$

$$ITAE = \int_0^\infty t|e(t)|dt \qquad ....(3)$$

$$ITSE = \int_0^\infty te^2(t)dt \qquad ....(4)$$

For optimum values of PID control parameters, any of the performance indices have to be minimum. For the PSO-based PID tuning, these performance indices (equations 1-4) will be used as the objective function. In other words, the objective in the PSO-based optimization is to seek a set of PID parameters such that the feedback control system has minimum performance index.

Considering the advantages and limitations of various techniques available for PID controller tuning, ZN, modified ZN known as Tyreus-Luyben (TL), and Internal Model Control (IMC) have been found more relevant for comparison purposes. These tuning methodologies are termed as ZN-PID, IMC-PID, and TL-PID. Now with the implementation of PSO, the new tuning methodology will be named as PSO-PID. Optimization Algorithm of PSO is discussed below:

Particle swarm optimization algorithm

Particle Swarm Optimization (PSO) concept is used to optimize the nonlinear function [5-11]. It is related to evolutionary computation just similar to the Genetic Algorithm (GA). A Swarm is an apparently disorganized collection (population) of moving individual that tends to cluster together while each individual seems to be moving in a random direction. The population is initialized by assigning random position and velocities. Each particle keeps track of its best highest fitness position. At each time step, each particle stochastically accelerates towards its pbest & gbest for an individual particle, best in population respectively. Each particle has access to some information like current, personnel, global solution & positions. One gets optimize solution in terms of PSO position & velocity. PSO position & velocity update equations are expressed asunder:

Position: $x_{id} = x_{id} + v_{id}$

Updated position: $x(k+1) = x_i(k) + v_i(k+1)$

Velocity: $v_{id} = w_* v_{id} + c_{1*} rand\left(p_{id} - x_{id}\right) \cdot$

$$+ c_{2*} rand\left(p_{gd} - x_{id}\right)$$

Original velocity updated equation:

$$v_i(k+1) = inertia \ + \ cognitive \ + \ social$$

Where; w: inertia weight, c_1& c_2: Acceleration factors, $p_{id} - x_{id}$: individual particle fitness (pbest); $p_{gd} - x_{id}$: Global particle fitness (gbest), rand: random functions, d: dimension

The basic PSO is developed from research on swarms such as fish schooling and bird flocking [5-11]. After it was firstly introduced in 1995 [5], a modified PSO was then introduced in 1998 to improve the performance of the original PSO [3]. A new parameter called inertia weight is added [6]. This is a commonly used PSO where inertia weight is linearly decreasing during iteration in addition to another common type of PSO which is reported by Clerc [8]. The PSO based PID controller tuning parameters are shown in table-2.

Table-2 PSO based Controller Tuning Parameters for process models

Controller Tuning Parameters	$G_1(s)$	$G_2(s)$	$G_3(s)$	$G_4(s)$	$G_5(s)$	$G_6(s)$	$G_7(s)$
K_p	-0.33556	7.4806	-0.4633	-0.51201	-0.12376	0.015283	0.32137
K_i	-0.04471	1.0207	-0.1136	-0.051678	-0.02957	0.16121	0.034587
K_d	-0.36715	1.3985	-0.6214	-0.53277	-0.2408	0.03181	6.7689

Implementation of PSO

The tuning of PID controller parameters can be accomplished by developing an algorithm of intended tuning methods to ensure optimal control performance at nominal operating conditions. For PSO-PID tuning as already indicated, PSO is used to tune PID controller parameters (Kp, Ki, Kd) using different pulp consistency models, given in table-1. Initially, Particle Swarm Optimization Technique produces an initial swarm of particles in search space represented by a matrix. Each particle represents a candidate solution for PID parameters. An optimum set of PID controller parameters can yield good system response and result in minimization of performance indices (equations 1-4).

Result Analysis

This section presents the comparative analysis of the responses obtained for all process models taken into consideration for this work. Comparisons are made in terms of Rise Time (RT), Overshoot (OS), Settling Time (ST), Gain Margin (G.M.) and phase margin(PM). It is well-known that the latter two are the parameters in frequency response methods indicating relative stability. The results presented in this section have been obtained through the MATLAB/SIMULINK simulation of the designed control systems. Figure 2 represents a comparison of step responses of process model G1(s). The relevant time domain and frequency domain values are depicted in table 3.

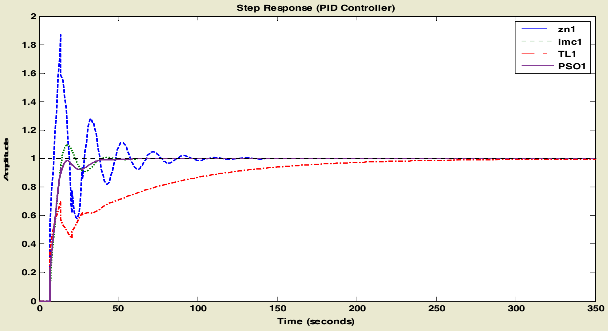

Fig. 2 Step response comparison of G1(s)

Figure 3 shows step responses of the system with G2(s) for all four PID controllers. The relevant time response, frequency response and performance index values of G2(s) are given in table 5 and 6. From these tables, it is noticed that for the case of G2(s) also, PSO – PID controller yields optimal performance in terms of overshoot, relative stability and but not in terms of performance indices.

From table 3, it is observed that the PSO – PID controller yields no overshoot and gives optimal relative stability. Though TL – PID controller also produces no overshoot, its rise time and settling time are more than those from PSO – PID controller. The performance indices of G1(s) are shown in table 4. Here also, PSO – PID produces minimum integral errors in all four performance indices.

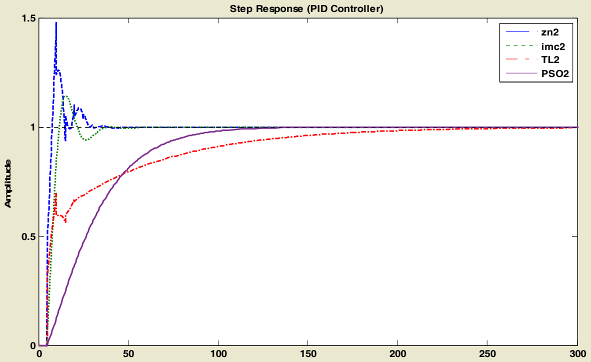

Fig. 3 Step response comparison of G2(s)

Table-3 Step response performance values for G1(s)

Tuning Technique	Rise Time (sec)	Overshoot (%)	Settling Time (sec)	Gain Margin (dB)	Phase Margin (deg)
PSO - PID	6.51	0.0	35.8	7.29	68.9
IMC –PID	6.27	9.72	36.69	6.14	63.4
ZN – PID	1.88	87.16	91.88	2.15	31.6
TL – PID	110.79	0.0	219.67	7.01	113

Table-4 Performance Indices G1(s) based on integral Errors

System	Controller	ISE	IAE	ITAE	ITSE
$G_1(s)$	**PSO-PID**	8.42	10.99	85.96	38.15
	ZN-PID	10.5835	18.8126	391.4582	99.1133
	IMC-PID	8.6889	11.4026	93.888	40.8793
	TL-PID	16.8174	42.6811	2570	421.5165

Table- 5: Step response performance values for G2(s)

Tuning Technique	Rise Time (sec)	Overshoot (%)	Settling Time (sec)	Gain Margin (dB)	Phase Margin (deg)
PSO - PID	55.32	0.0	98.74	22.4	77.1
IMC –PID	5.40	14.24	33.24	7.0	55.3
ZN – PID	2.18	47.82	27.16	4.63	49.6
TL – PID	88.33	0.0	190.37	8.51	115

Table-6 Performance Indices G2(s)

Controller	ISE	IAE	ITAE	ITSE
PSO-PID	20.26	32.66	816.13	292.33
ZN-PID	5.6026	7.7465	47.4279	18.3347
IMC-PID	6.7743	9.2568	65.5868	25.4531
TL-PID	11.1741	31.675	1720	215.9126

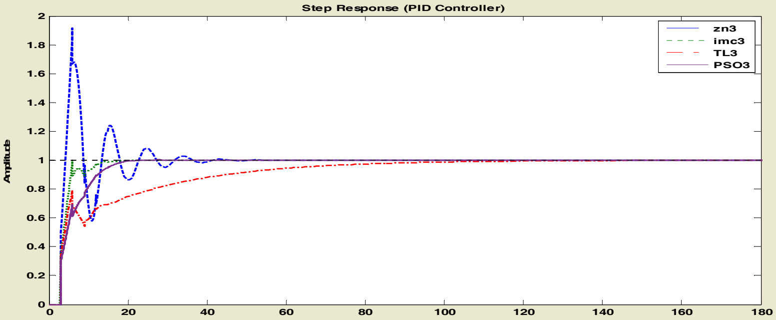

Fig. 4 Step response comparison of G3(s)

Figure 4 is a comparison of step responses among four controllers with G3 transfer function. Time and frequency response values of G3(s) is shown in Table 7. From the values presented in these tables, it is observed that PSO – PID yields low overshoot than those from ZN – PID controller. However, the rise time and settling time are better than the TL – PID controller. Also, PSO – PID gives optimal relative stability (as shown by the gain margin and phase margin of G3(s) in table 7). As far as performance index is concerned, PSO – PID gives optimal results. Table 8 presents the performance index values of G3(s).

Table-7 Step response performance values for G3(s)

Tuning Technique	Rise Time (sec)	Overshoot (%)	Settling Time (sec)	Gain Margin (dB)	Phase Margin (deg)
PSO-PID	9.37	0.23	17.68	10.2	74.5
IMC –PID	2.55	0.0	13.09	7.34	69.0
ZN – PID	0.89	91.82	35.10	2.37	26.3
TL – PID	41.64	0.0	87.20	7.2	116

Table-8 Performance Indices G3(s)

Controller	ISE	IAE	ITAE	ITSE
PSO-PID	4.21	6.33	29	11.14
ZN-PID	4.8809	8.287	69.578	20.3339
IMC-PID	3.448	4.488	13.4792	6.3559
TL-PID	5.996	15.6206	379.7196	54.028

The step responses of G4(s) and G5(s) are compared in figure 5 and figure 6 respectively. The respective time and frequency domain values are given in table 9 and 11 for both process models respectively. Similarly, the performance index values of the process models have been depicted in table 10 and table 12. From these tables, it is observed that it gives zero overshoot and better relative stability.

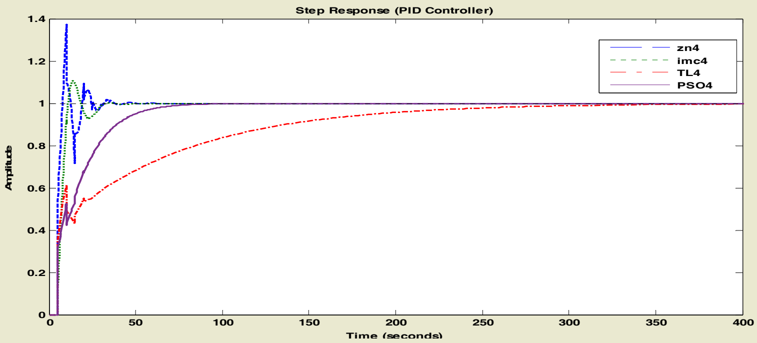

Fig. 5 Step response comparison of G4(s)

Also, the performance index values are minimum for G4(s) and G5(s) as compared to all other controllers. Though, the rise time and settling time are better for IMC – PID and ZN – PID controllers, but PSO – PID yields better gain margin and optimal phase margin values. Though the phase margin of TL – PID is better among all controllers, it gives a higher rise and settling time.

Table-9 Step response performance values for G4(s)

Tuning Technique	Rise Time (sec)	Overshoot (%)	Settling Time (sec)	Gain Margin (dB)	Phase Margin (deg)
PSO-PID	34.2	0.0	63.9	9.91	85.9
IMC –PID	4.85	10.56	29.32	6.71	60.5
ZN – PID	2.22	37.42	29.38	4.26	63.5
TL – PID	131.51	0.0	257.16	8.1	119

Table-10 Performance Indices G4(s)

Controller	ISE	IAE	ITAE	ITSE
PSO-PID	9.66	17.66	285.92	78.68
ZN-PID	5.4057	7.4224	46.5719	16.5994
IMC-PID	6.4239	8.485	52.0308	22.3981
TL-PID	17.3337	48.1278	3.47E+03	543.1689

The following figure (Figs. 7and 8) and tables (tables 13 and 14) present the analysis of the result of process model G6(s) and G7(s) which are ABB – DCS based SOPDT models. For G6(s) process model, the comparison of step responses is shown in figure 7 and the corresponding time and frequency response values are given in table 13. PSO – PID controller produces low overshoot and lower settling time as compared to other controllers. However, the relative stability is comparatively low as compared to IMC and TL based PID controllers. IMC – PID controller has a low rise time but its settling time is more than PSO – PID.

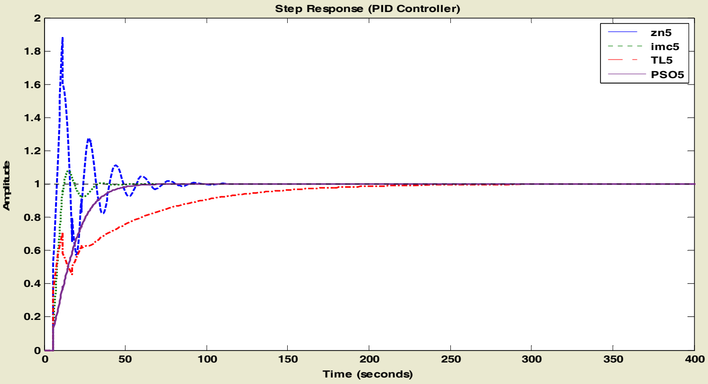

Fig. 6 Step response comparison of G5(s)

Table-11 Step response performance values for G5(s)

Tuning Technique	Rise Time (sec)	Overshoot (%)	Settling Time (sec)	Gain Margin (dB)	Phase Margin (deg)
PSO – PID	27.23	0.0	48.88	17.2	74.1
IMC –PID	5.22	7.90	30.53	6.47	63.8
ZN – PID	1.59	87.93	70.90	2.17	30.5
TL – PID	90.82	0.0	181.23	7.02	114

Table-12 Performance Indices G5(s)

Controller	**ISE**	**IAE**	**ITAE**	**ITSE**
PSO-PID	11.5	17.52	218.93	87.01
ZN-PID	8.8593	15.7476	272.4974	69.7586
IMC-PID	7.1295	9.2304	59.8296	27.3275
TL-PID	13.6054	34.7942	1.74E+03	278.804

Performance index values of G6(s) are given in Table 14. From this table, it is noticed that PSO – PID and IMC – PID controllers have nearly equal values (except for ITAE), where IMC – PID controller performs better as compared to PSO – PID. Similarly, the comparison of performances of controllers has been done for SOPDT process model G7(s). The step responses of G7(s) are compared in fig. 8. Table 15 depicts time and frequency response values of G7(s). Here, PSO – PID performs better than ZN and TL based PID controllers in terms of rise time and settling time. Also, the overshoot due to PSO – PID controller is very low. As far as relative stability is concerned, PSO – PID yields better gain and phase margin as compared to the other three PID controllers. The performance index values of G7(s) are presented in table 16, from where it is found that the PSO – PID controller has better performance indices as compared to ZN and TL based PID Controllers.

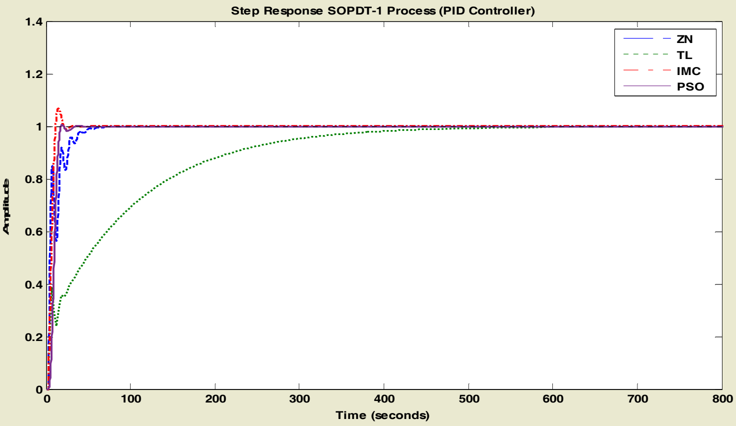

Fig. 7 Step response comparison of G6(s)

Table-13 Step response performance values for G6(s)

Tuning Technique	**Rise Time (sec)**	**Overshoot (%)**	**Settling Time (sec)**	**Gain Margin (dB)**	**Phase Margin (deg)**
PSO-PID	8.38	0.52	16.30	8.43	64.6
IMC –PID	6.56	6.88	19.15	13.1	61
ZN – PID	14.46	0.0	47.16	5.35	37.9
TL – PID	216.54	**0.0**	390.98	10.2	105

Table-14 Performance Indices G6(s)

Controller	**ISE**	**IAE**	**ITAE**	**ITSE**
PSO-PID	6.01	7.96	57.22	15.09
ZN-PID	5.2335	9.9936	114.7866	25.4058
IMC-PID	5.0104	6.7985	30.7067	14.3164
TL-PID	34.0973	84.342	8.84E+03	1.77E+03

Table-15 Step response performance values for G7(s)

Tuning Technique	**Rise Time (sec)**	**Overshoot (%)**	**Settling Time (sec)**	**Gain Margin (dB)**	**Phase Margin (deg)**
PSO-PID	177.62	0.13	349.74	27.2	91.0
IMC –PID	9.53	4.20	30.50	9.91	61.2
ZN – PID	177.86	0.0	473.474	21.7	35.0
TL – PID	2028.2	0.0	3580	26.4	82.1

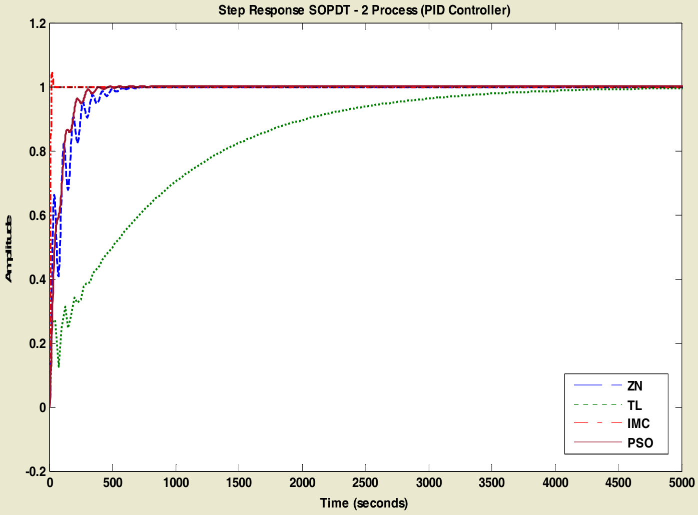

Fig. 8 Step response comparison of G7(s)

Table-16 Performance Indices G7(s)

Controller	ISE	IAE	ITAE	ITSE
PSO-PID	38.52	77.13	6.10E+03	1.47E+03
ZN-PID	40.3372	95.2487	1.15E+04	2.41E+03
IMC-PID	8.47	10.9575	8.24E+01	3.93E+01
TL-PID	262.5314	418.8194	1.29E+05	7.01E+04

A summary of time responses, frequency response and performance index values obtained using PSO based PID controller for all seven process models have been given in table 17. It is amply clear from the table that PSO gives better performance than the other three in terms of optimum settings, robustness, and relative stability. Thus it can be suitably used as robust tuning techniques for PID control for consistency control in the paper industry.

Table-17 Summary of PSO – PID responses

System	Rise time (sec)	Percent overshoot,%	Settling time(sec)	Gain Margin (dB)	Phase margin (deg)	Performance indices (ISE, IAE, ITAE,ITSE)
$G_1(s)$ (FOPTD)	6.51	0.0	35.8	7.29 highest	68.9 (high)	All lowest
$G_2(s)$ (FOPTD)	55.32	0.0	98.74	22.4 (highest)	77.1 (high)	Low
$G_3(s)$ (FOPTD)	9.37	0.23 (very low)	17.68	10.2 (highest)	74.5 (high)	Low
$G_4(s)$ (FOPTD)	34.2	0.0	63.9	9.91 (highest)	85.9 (high)	Low
$G_5(s)$ (FOPTD)	27.23	0.0	48.88	17.2 (highest)	74.1 (high)	Low
$G_6(s)$(SOPTD,)	8.38	0.52 (very low)	16.30	8.43(moderately high)	64.6 (high)	Mod. low
$G_7(s)$(SOPTD,)	177.62	0.13 (very low)	349.74	27.2 (highest)	91.0 (highest)	Mod. low

Conclusions

In this paper, an attempt has been made to use an AI-based tuning technique in order to improve the performance of the PID controller to control process parameters. AI-based controller should not only provide better tuning but also optimize the parameters.

Among the AI based controllers, PSO based PID is one of the recent innovations in robust controller design techniques. Therefore, present paper examined the suitability of PSO based design technique. At the same time, this paper has also presented the design of PID controllers using ZN, TL, and IMC. Seven different stock consistency models reported in the literature have been considered for simulation purpose. These models have been developed based on data from the Pulp and Paper Industry. Out of the 7 models, five are first order plus time delay (FOPTD) and the other two are second order plus time delay (SOPTD).The simulated results have been obtained through MATLAB and SIMULINK Software.

Comparison of performances of proposed PID controllers has been done on the basis of time response, frequency response, and performance index values. It is evident from the analysis of data that there should be a compromise among between stability, robustness and optimum values of performance indices for the four different controllers. It is evident from the simulation results that the conventional PID controls using ZN and Tyreus- Luyben (TL), Internal Model Control (IMC) tuned PID controller, the responses of pulp consistency dynamics produce generally high overshoot and low relative stability (gain margin and phase margin), but Particle swarm optimization (PSO) tuned PID controller provides better performance and relative stability for both FOPTD and SOPTD systems, particularly for ABB-DCS based model.

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