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Design of PI controller for Liquid Level System using Siemens Distributed Control System

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***Abstract:** The PI controller design for a liquid level system using the weighted geometric center method is discussed. Every real-time process have dead time. This dead time leads to the generation of oscillation in the system response. The oscillation generated due to dead time introduces instability in system performance. This paper presents a tuning method based on calculating a geometric center in the stability region for a higher order system. In this, the stability region calculated by plotting (K_p, K_i)-plane based on boundary locus stability technique. Further centre point computed in the stability locus by a geometric center method. This center point will provide K_p, K_i value for tuning the PI controller. The First Order Plus Dead Time (FOPDT) process considered to elaborate the method for computing the tuning parameters. A nonlinear time-delay system and a plant having time-delay response are controlled in simulation. The performance of the newly obtained PI controller based on weighted geometric center method is compared with the existing results to show the usefulness of the control scheme. Moreover, disturbance rejection ability of the newly obtained PI controller based on weighted geometric center method is demonstrated by applying disturbances. In addition, the designed controller implemented using Siemens DCS PCS7 V8.1 platform.*

***Keywords:** PI controller, weighted geometric center, stability boundary locus, Siemens Distributed Control System.*

I. INTRODUCTION

Since past years, many researchers have proposed various tuning and controller design methods. Fang, J et al., 2009 proposed a knocker sum operations method to define the stability boundary locus making use of Kronecker sum operation [1]. Padmashree et al., 2004 used coefficient matching of corresponding first power of *s* in given polynomial for both numerator and denominator by specifying the initial jump [2]. Scientists have researched many important results based on computations of stable P, PI, and PID controllers after the work through (Ho et al., 1991) [3]. Bekker et al., 1992 focused on characterizing stable PI and PID controllers through linear programming [4]. Ackermann et al., 2001 gave method that is determined by coordinating coefficient concerning powers of s within the numerator and that in the denominator [5]. This strategy gives straightforward conditions for setting of controller parameters. Mudi et al., 2011 gave a dynamic set-point weighting based PI controller design method for the higher-order system [6]. Rahimian and Tavazoei, 2011 has shown a method using centroid computation of stability boundary loci [7]. Shamsuzzoha & Skogestad, 2010 in their work used closed-loop experimental method for PID controller tuning [8]. Veronesi et al., 2010 shows a comparison of PI controller implementation in simulation and real-time by the use of a Distributed Control System [9]. C. Onat et al., 2012 gave new proposal on PI tuning method established on stabilizing controller parameters area for the time delay techniques. The concept is weighted geometric center of stabilizing controller in a region specified by parameters calculated by the computation technique used [10]. C.B.Kadu et al., 2016 proposed a stability evaluation procedure for designing a PID controller for time prolong system validated with actual-time experimentation with Interacting method [11]. C.B.Kadu et al., 2018 illustrated a decentralized Sliding Mode Controller (SMC) design for time lengthen TITO systems. In this, the creator has designed a corrector with the observer to support the accuracy of extending ahead prediction. SMC with PI surface designed to regulate and track unsure process control systems [12, 13].

In this paper, a simple method has been adopted for the design of PI controller based on weighted geometric center method [10]. The applicability of the newly obtained PI controller based on weighted geometric center method is demonstrated through four simulation examples. The performance of the newly obtained PI controller based on weighted geometric center method is compared with the existing results to show the usefulness of the control scheme. Moreover, disturbance rejection ability of the newly obtained PI controller based on weighted geometric center method is demonstrated by applying disturbances. The paper is structured as follows. Section 2 summarizes the mathematical calculations for computing the PI controller gains. Simulation outcome are illustrated in section 3 situated on the proposed method. Concluding remarks are given in part 4.

II. DESIGN OF PI CONTROLLER

A. Computation of Stability Region

In this paper, a method to obtain region of stability utilizing the stability boundary locus is proposed [10]. The one-input, one-output control closed loop system is as shown in Fig.1

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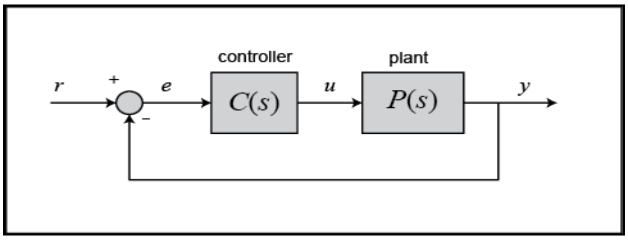

Fig.1: Simple control system

$$G_1(s) = G_{p1}(s)\,e^{-\theta s} \tag{1}$$

Where P(s) is a system under control and C(s) is a PI controller of the form,

$$C(s) = K_p\,.s + \frac{K_i}{s} \tag{2}$$

The crisis is to find the region of stability, which includes the entire parameters of the PI controller in Eq.2, as a way to stabilize the given plant. The Closed loop characteristic polynomial P(s) of the method, i.e., the numerator of [1 + C(s) G(s)], is

$$P(s) = s.D_u(s) + (K_p.s + K_i)N_u(s).e^{-\theta s} \tag{3}$$

Then decompose numerator and denominator polynomials of G_{P1} (s) in Eq.3 as even and odd parts, and substituting s = $j\omega$ gives

$$G_{p1}(s) = \frac{N_{ue}(-\omega^2) + j\omega N_{uo}(-\omega^2)}{D_{ue}(-\omega^2) + j\omega D_{uo}(-\omega^2)} \tag{4}$$

To simplify ($-\omega^2$) will be dropped in subsequent equations. Thus, resulting closed-loop characteristic polynomial of Eq.3 is

$$P(\omega) = P_{R1}(\omega) + jP_{I1}(\omega) \tag{5}$$

Where

$$P_{R1}(\omega) = \left(K_i N_{ue} - K_p\,\omega^2 N_{uo}\right)\cos(\omega\theta) + \omega\left(K_i N_{uo} + K_p N_{ue}\right)\sin(\omega\theta) - \omega^2 D_{uo} \tag{6}$$

$$P_{I1}(\omega) = -\left(K_i N_{ue} - K_p \omega^2 N_{uo}\right)\sin(\omega\theta) + \omega\left(K_i N_{uo} + K_p N_{ue}\right)\cos(\omega\theta) - \omega D_{ue} \tag{7}$$

The couple of equations are determined by comparing real and imaginary parts of P (ω) to zero,

$$Q(\omega).K_p + R(\omega).K_i = X(\omega) \tag{8}$$

$$S(\omega).K_p + U(\omega)K_i = Y(\omega) \tag{9}$$

Where

$$Q(\omega) = \omega N_{ue}\sin(\omega\theta) - \omega^2 N_{uo}\cos(\omega\theta) \tag{10}$$

$$R(\omega) = N_{ue}\cos(\omega\theta) + \omega N_{uo}\cos(\omega\theta) \tag{11}$$

$$S(\omega) = \omega N_{ue}\cos(\omega\theta) + \omega^2 N_{uo}\sin(\omega\theta) \tag{12}$$

$$U(\omega) = \omega.N_{uo}\cos(\omega\theta) - N_{ue}\sin(\omega\theta) \tag{13}$$

$$X(\omega) = \omega^2 D_{uo} \tag{14}$$

$$Y(\omega) = -\omega D_{ue} \tag{15}$$

Thus by solving Equations 8-15, the results PI controller parameters as,

$$K_p = \frac{(\omega^2 N_{uo} D_{uo} + N_{ue} D_{ue})\cos(\omega\theta)}{-\left(N_{ue}{}^2 + \omega^2 N_{uo}{}^2\right)} + \frac{\omega(N_{uo} D_{ue} + N_{ue} D_{uo})\sin(\omega\theta)}{-\left(N_{ue}{}^2 + \omega^2 N_{uo}{}^2\right)} \tag{16}$$

$$K_i = \frac{\omega(\omega^2 N_{uo} D_{uo} + N_{ue} D_{ue})\sin(\omega\theta)}{-\left(N_{ue}{}^2 + \omega^2 N_{uo}{}^2\right)} - \frac{\omega^2(N_{uo} D_{ue} + N_{ue} D_{uo})\cos(\omega\theta)}{-\left(N_{ue}{}^2 + \omega^2 N_{uo}{}^2\right)} \tag{17}$$

The stability locus (K_p, K_i, ω) is constructed in (K_p, K_i) plane by altering the values of ω from zero to infinity. For this reason, an actual root boundary is bought with the aid of substituting s = zero in P(s) of Eq.3. Hence, this special boundary is determined as

$$K_i = 0 \tag{18}$$

Consider a FOPDT model

$$G_1(s) = \frac{N_u(s)}{D_u(s)}.e^{-\theta s} = \frac{1}{s+1}.e^{-0.5s} \tag{19}$$

Here, the goal is to obtain all stabilizing values of K_p and K_i that make the closed-loop approach in Fig.1 steady. The next equations are determined after equating the real and imaginary part of attribute equation to zero.

$$\omega = K_p\omega.\cos(0.5\omega) - K_i\,\sin(0.5\omega) \tag{20}$$

$$-\omega^2 = K_p.\omega.\sin(0.5\omega) + K_i\cos(0.5\omega) \tag{21}$$

The plotting of the steadiness boundary locus is performed by using cooperative inspecting of Eq.20 and Eq.21 for every value of ω_i. The Fig.2 shows stable K_p and K_i values for the range of ω_i [0, ω_i]. The frequency of intersection is determined as 3.67 rad/s.

Computation of Geometric Center Point

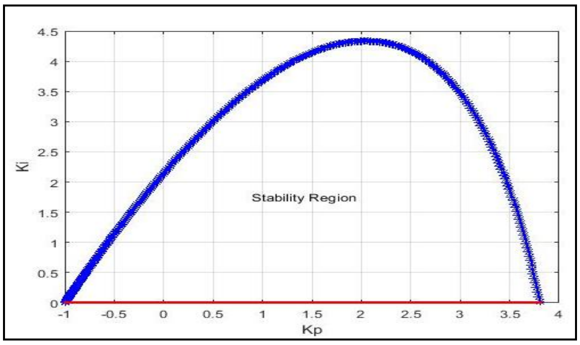

Fig. 2: Stability Region

Fig.3 shows the factor founded stability boundary locus for a FOPTD system. Every (K_p, K_i) features are marked by way of

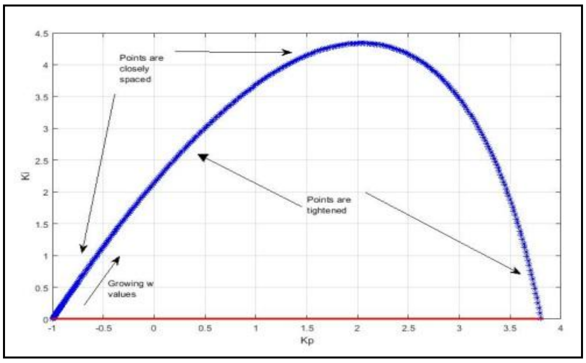

Fig. 3: Stability boundary locus

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altering ω from 0 to 3.67 with step size of 0.01. The distance between each point is different. The facets are closely spaced at small ω values. By way of growing the values of ω they emerge as far away and then tighten across the peak factor of stability.

$$K_{pw} = \frac{1}{n}\sum_{j=1}^{n} K_{pj} \tag{22}$$

$$K_{iw} = \frac{1}{2n}\sum_{j=1}^{n} K_{ij} \tag{23}$$

B. Liquid Level System

A liquid level system as shown in Fig.4 is considered for demonstration and validation of developed controller. It consists of two tanks each with Level transmitters LT1 and LT2 resp. A pump driven by 230 V, 50Hz motor using a VFD, controls the inlet flow of the tank. To simulate this a distributed control system of Siemens PCS7 V8.1 software is used The hardware configuration consists of: Simatic Microbox PC, Interface module (IM 153-2), Digital Inputs (DI-32,DI-16), Digital Outputs (DO-32,DO-16), Analog Inputs HART(AI-8), Analog Outputs HART(AO-8).The system designed consists of two parts as Design of Controller and Design of mimics

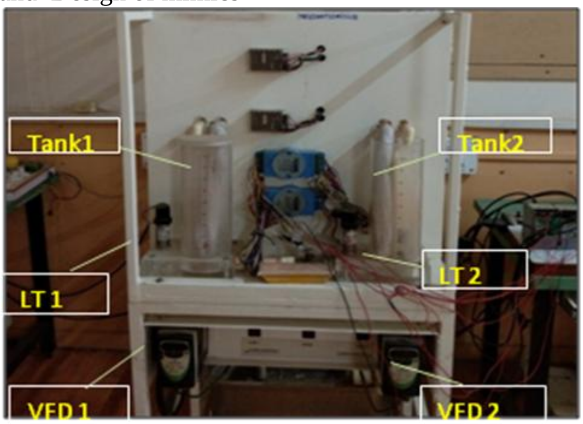

Fig. 4: Liquid Level System

Fig. 5: Siemens PCS7 Control Panel

D. Distributed Control System

1. Design of Controller

The logic is developed using CFC (Control Function Chart). To control speed of pump, the inbuilt PI controller of Siemens is used. The parameters of PI controller are obtained in example 4. The input signal of 4-20mA from level transmitters (LT1 & LT2) is given to the PI controller and the analog controller output of 0-10v applied to VFD to control speed of pump. The VFDs ensure the smooth control of the pump operation. To execute the logic algorithms are written using a sequential function chart (SFC).Fig.6 and Fig.7 show the CFC programming for pump and PID control respectively and Fig.8 shows the SFC.

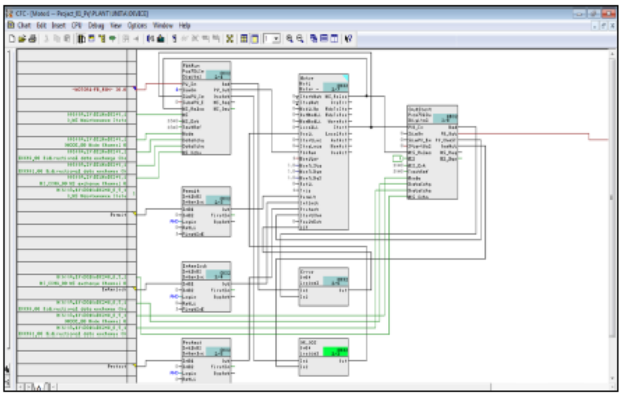

Fig. 6: Motor CFC

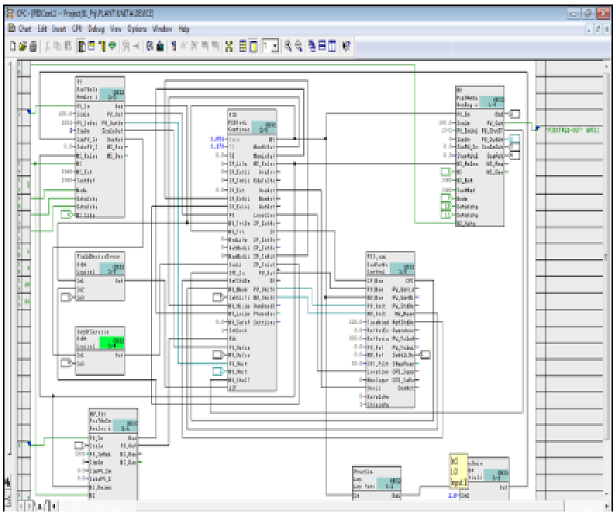

Fig.7: PID CFC

2. Design of Mimics

The Fig.9 shows the mimic of a coupled tank system. In this, faceplates for PID and pump and VFD are developed. Fig.10 and Fig.11 shows the faceplate of PID and pump control, respectively. The set point tracking shown in Fig. 12

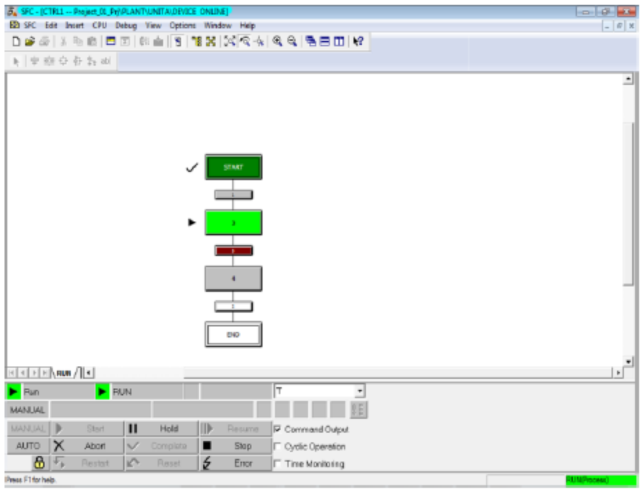

Fig. 8: SFC for speed control

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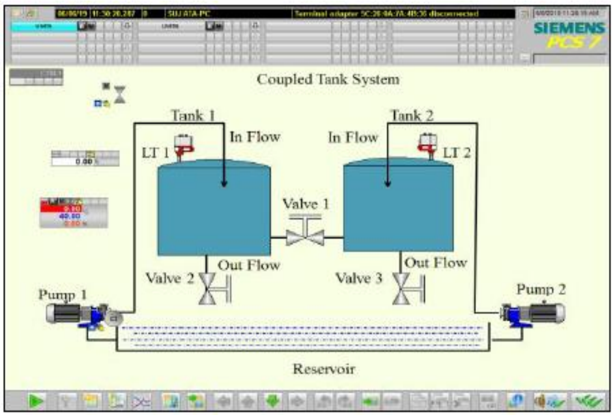

Fig. 9: SCADA screen for speed control of Pump

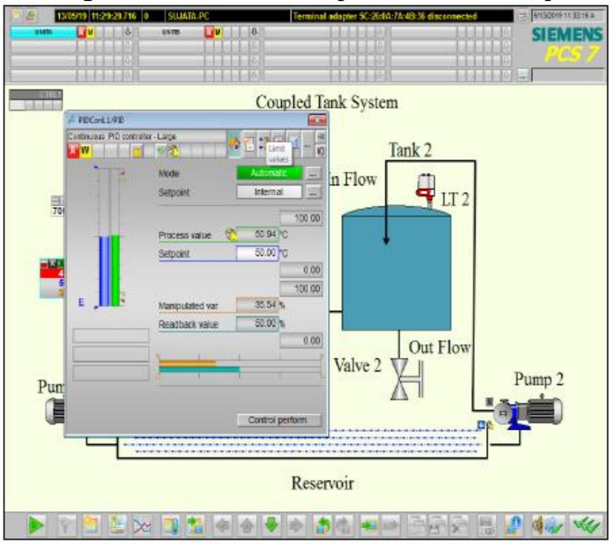

Fig. 10: Motor Control Faceplate

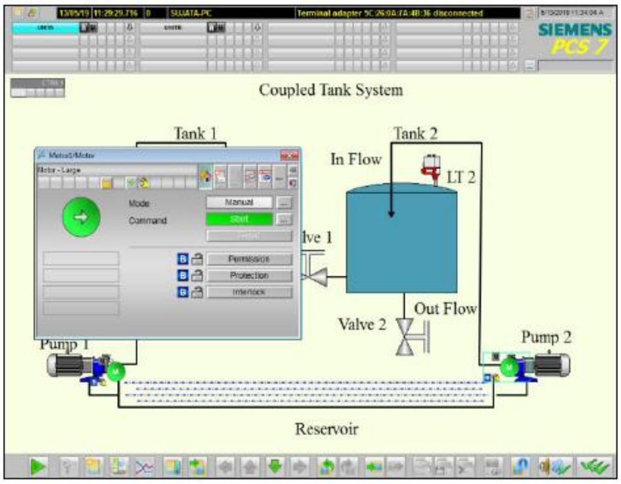

Fig. 11: Motor Control Faceplate

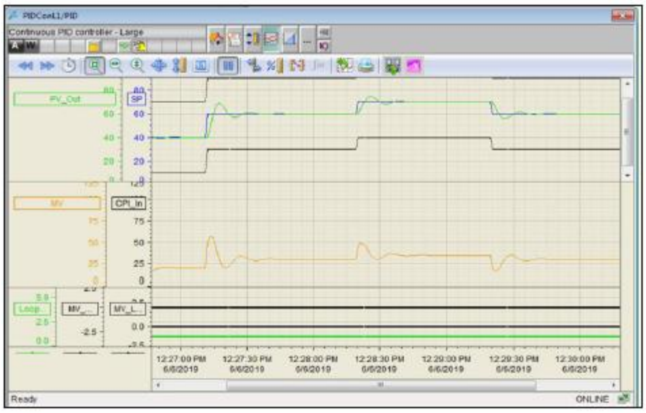

Fig. 12: Speed control trend showing a change in speed

III. RESULTS AND DISCUSSION

To demonstrate the performance of the designed controller three examples along with liquid level system are illustrated. Firstly, an example of FOPDT system is considered. The second example taken is of Second Order Plus Dead Time (SOPDT) system and then Third Order Plus Dead Time (TOPDT) system and lastly real-time liquid level system is considered. The PI controller designed using weighted geometric center method shows good performance than the conventional PI controller. In addition, the designed controller implemented using Siemens DCS PCS7 V8.1 platform.

Example: 1

Transfer function of the system given by eq.24 is considered

$$G_1(s) = \frac{1}{s+1}e^{-s} \qquad (24)$$

The PI controller parameters computed by using eq.22 and eq.23 are obtained as Kp = 0.4368 and Ki = 0.4674. The parameters

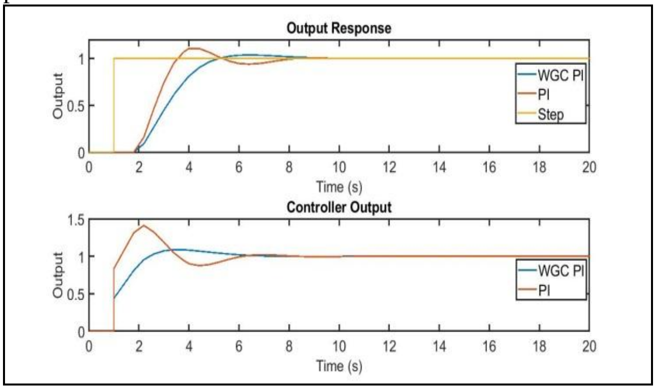

Fig 13: Output response and controller effort for Ex-1

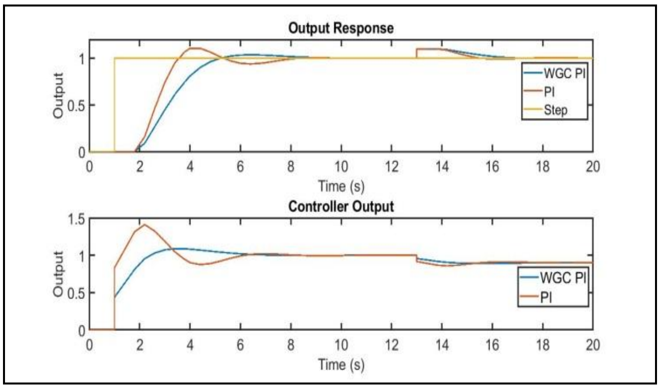

Fig. 14: Output response for disturbance input at t=13s for Ex-1

for the auto tune PID controller as, Kp= 0.8333 and Ki=0.6003. Fig 13 and Fig.14 shows the output response and control signal of the system without and with a disturbance input given at t=13s respectively. Performance of the newly obtained PI controller based on weighted geometric center method is compared with auto-tuned PI controller and summarized in Table I, where M_p, *Ts*, *Tr* and *u (s)* denote the maximum percentage overshoot, settling time, rise time, and control signal, respectively.

Table I: Transient Specifications for Ex-1

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Controller	M_p (%)	T_s (sec)	T_r (sec)	$u(t)$
WGC PI	3.6	6.5	1.3	1.088
Conventional PI	9.9	8.9	0.2	1.428

It can be observed from Table I that the newly obtained PI controller based on weighted geometric center method outperforms the auto-tuned PI controller in terms of maximum overshoot and settling time.

Example: 2

Transfer function of the system given by eq.24 is considered

$$G_1(s) = \frac{1}{s^2 + 2s + 1} e^{-s} \qquad (25)$$

The PI controller parameters computed by using eq.22 and eq.23 are obtained as Kp = 0.5168 and K_i = 0.308. The parameters for the auto tune PID controller as, Kp = 0.877 and K_i =0.3890. The Fig 15 and Fig.16 shows the output response and control signal of the system without and with a disturbance input given at t=13s respectively. The Table II shows the transient response characteristics. It is evident

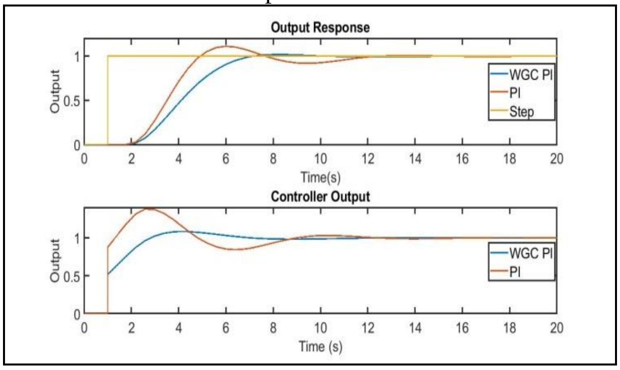

Fig 15: Output response and controller effort for Ex-2

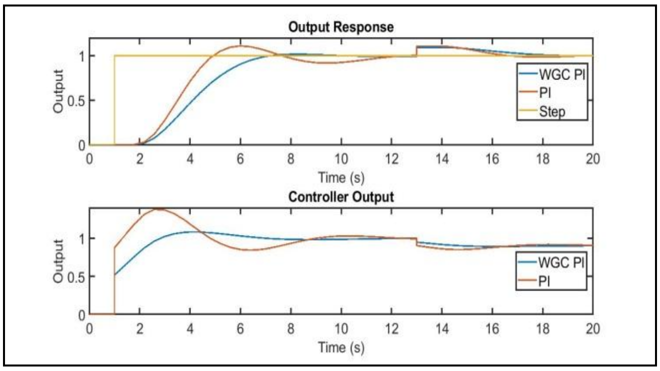

Fig. 16: Output response for disturbance input at t=13s for Ex-2

from the results, the fast response with small overshoot are obtained with the minimum control signal.

Table II: Transient Specifications for Ex-2

Controller	M_p (%)	T_s (sec)	T_r (sec)	$u(t)$
WGC PI	1.7	18.28	5.593	1.084
Conventional PI	11	28.51	3.305	1.386

Example: 3

Transfer function of the system given by eq.24 is considered

$$G_1(s) = \frac{1}{s^3 + 6s^2 + 11s + 6} e^{-0.5s} \qquad (26)$$

The PI controller parameters computed by using eq.22 and eq.23 are obtained as Kp = 3.6554 and Ki = 2.5716. The parameters for the auto tune PID controller as, Kp = 5.5743 and Ki=3.1023. The Fig 17 and Fig.18 shows the output response and control signal of the system without and with a disturbance input given at t=34.5s respectively. It can be observed from Table III that the newly obtained PI controller based on weighted geometric center method outperforms the auto-tuned PI controller in terms of maximum overshoot, rise time, settling time and lesser controller efforts.

Table III: Transient Specifications for Ex-3

Controller	M_p (%)	T_s (sec)	T_r (sec)	$u(t)$
WGC PI	2.5	6.69	1.99	6.827
Conventional PI	10.6	11.55	1.54	8.458

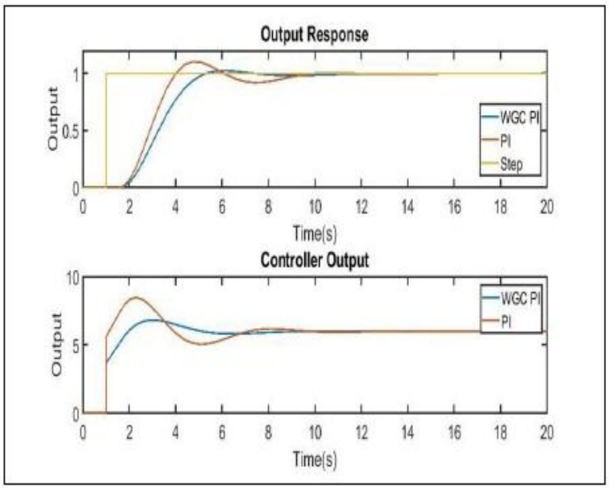

Fig.17: Output response and controller effort for Ex-3

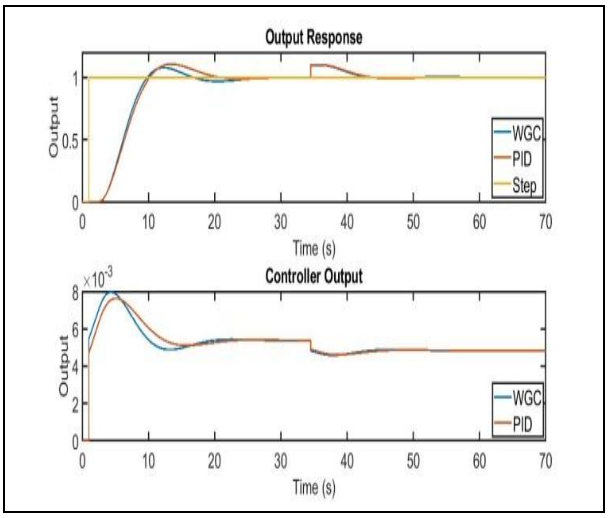

Fig.18: Output response for disturbance input at t=34.5s for Ex-3

Example: 4 Liquid level system

Consider the transfer function of liquid level system given by eq.25 [13]

$$G_1(s) = \frac{142}{s^3 + 5.33s^2 + 4.378s + 0.764} e^{-1.5s} \qquad (27)$$

The PI controller parameters computed by using Eq.22 and Eq.23 are obtained as K_p = 0.005443 and K_i = 0.00108. The output response and control signal shown in Fig.19. The Fig.20 shows the output response of the system when a disturbance input is applied at t=16s. The Table IV shows transient response characteristics. It is evident that, the newly designed controller outperforms the conventional PI controller in terms of Maximum overshoot, Settling time, Rise time and with almost similar efforts.

Table IV: Transient Specifications for Ex-4

Controller	M_p (%)	T_s (sec)	T_r (sec)	$u(t)$
WGC PI	7.58	16.98	4.16	0.0080
Conventional PI	10.8	29.61	4.49	0.0079

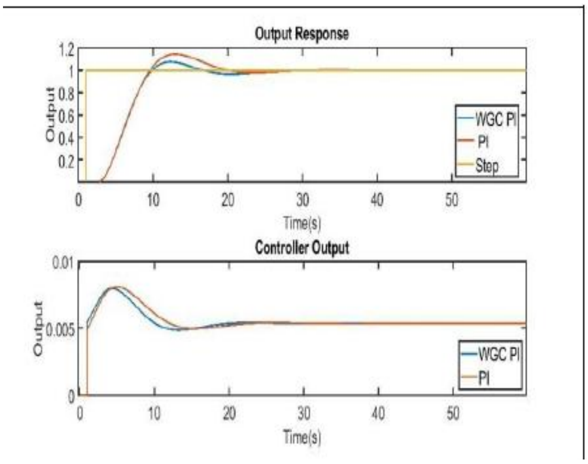

Fig.19: Output response and controller effort for Ex-4

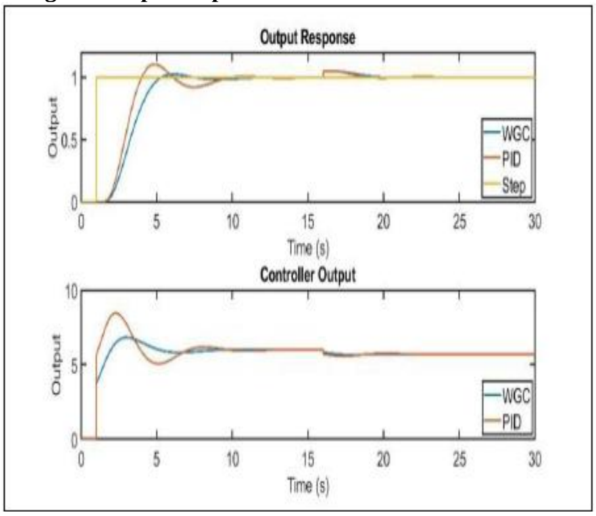

Fig. 20: Output response for disturbance input at t=16s for Ex-4

IV. CONCLUSION

This paper, is aimed toward imparting the inspiration of weighted geometrical center point for calculating the region of stability for PI control. A nonlinear time-delay system and a plant having time-delay response are controlled in simulation. The performance of the newly obtained PI controller based on weighted geometric center method is compared with the existing results to show the usefulness of the control scheme. Moreover, disturbance rejection ability of the newly obtained PI controller based on weighted geometric center method is demonstrated by applying disturbances. The simulation study show that the weighted geometrical center method gives a special point with good performance in terms of rise-time, settling time and overshot with minimal requirement of controller efforts.

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