Design and Implementation of Water Level Control Using Gain Scheduling PID Back Calculation Integrator Anti Windup

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Abstract—**Conventional PID controller is a simplest known controller and has been used in almost all process industries for controlling process parameter at desired set point. However, the weakness of the controller is largely depend on the parameter of the controlled object. As the dynamics process of a water tank is nonlinear, it also has nonlinear behaviour between the input and output. This paper demonstrates that Gain Scheduling PID with Back Calculation Integrator Antiwindup enables to enhance the response of automatic water level control system performance. A mathematical model of a first order tank system is considered and simulated to determine fine tunes and schedules for the controller parameter based on trial and error experiment so as to adapt with all operating points. The system performance comparison of various setpoint given to the system is performed to prove that the Gain Scheduling PID with Back Calculation Integrator Antiwindup outpaces conventional PID controller.**

Keywords— conventional PID, non linear behaviour, Back Calculation Integrator Anti Windup, Gain Scheduling.

I. Introduction

PID controller has been widely used for industrial control in any application of controlling process since a long time ago. According to the survey in 1989, 90% of process in industries uses the conventional PID controller [1]. The reason of why the use of PID controller in the industry is wide spread is due to its simplicity and ease of returning online feature of PID controller [2-8]. Although many aspect of a control system can be understood based on linear theory, some nonlinear effect must be accounted [1]. All actuator have limitations e.g a motor has limited speed, a valve cannot be more than fully open, water pump has maximum flow rate, etc. In some cases, such a control with wide range of operating condition, it may happen that control signal from controller reaches the actuator limits. When this condition occurs, the feedback loop is broken because the actuator will stay at its limit independently of the process output. PID controller, which has integrating action will continue to be integrated and the integral term may become very large. It is then required a long period before it returns to normal condition. One of the weaknesses of PID controller is that it largely depends on the parameters of the controlled object [5], whereas an industrial process control system consist of many constraints such as nonlinearity, inertial lag, time delay, time varying parameter and many more factors. Gain scheduling is a technique that deals with nonlinear processes, processes with time variations or situations where the requirements on the control change with the operating conditions [1]. Since the process of nonlinear behavior performing at various operating points, the objective of designing this controller is to obtain an enhanced control performance at all operating points.

This paper organized as follows. Section 1 gives a brief introduction of the experiment. Section 2 explains a brief base theory of Gain Scheduling and Back Calculation Integrator Anti Windup controller. Section 3 provides mathematical model of the tank process in order to simulate and observe the characteristic of the system. Section 4 describes the experimental set up and its implementation of conentional PID and Gain Scheduling PID with back calculation integrator anti windup controller. Section 5 shows the result the system response of both controller. Conclusion is given in section 6.

II. System Description

A. Gain Scheduling Controller

In several conditions it is known that the dynamics of a process is varied with the operating condition. The parameter changes in dynamics are what we called nonlinearities. Gain Scheduling is a method that deals with nonlinear processes, needed to change the control parameter with the operating conditions. Also, it is required to find measurable variable that correlated with changes in dynamic process, called scheduled variable. It can be the control signal or measured system response. Thus, gain scheduling can be understood as a feedback control system which the feedback gains are adapted by using feedforward compensation. When scheduling variables are determined, the controller parameters are calculated by using some design method e.g PID controller. The controller then tuned for each operating condition.

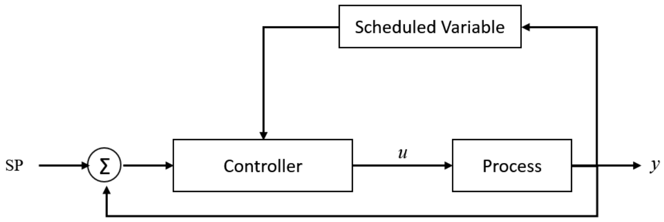


Fig. 1. Block Diagram of Gain Scheduling controller

B. Back Calculation Integrator Anti Windup

Integrator windup may occur because the change of large setpoint, large disturbance, or equipment error. It also happened when the selectors are used to control one actuator. One of several types of integrator windup is back calculation. It works as follows : when the control signal work in actuator limits, the integral is recalculated so that its new value gives an output at the saturation limit. The system has extra feedback path used to measured error signal (e_s) by measuring the different between the output of the controller (v) and the actuator output (u). The signal is zero if there is no saturation, so it will not have any effect if the actuator does not saturate.

C. Mathematical Model

The water level process is a single tank system, which consist of a tank of uniform volume to which attached a flow reistance *R* (valve). Assume :

q_0 , the volumetric rate of flow through the resistance is conneted to the head of tank.

$$q_0(t) = h / R \tag{1}$$

The accumulation of mass in the tank is the difference between the input flow rate and output flow rate, given by :

$$q(t) - q_0(t) = A\, dh / dt \tag{2}$$

Substitute (4) and (5) :

$$q(t) - h / R = A\, dh / dt \tag{3}$$

Apply Laplace transformation,

$$Q(s) = 1 / R\, H(s) + As\, H(s) \tag{4}$$

The transfer function of system is

$$H(s) / Q(s) = R / (RAs + 1) \tag{5}$$

From the experiment it is observed :

A = 450 cm^2, h = 30 cm, q =8.625 cm^3/s, q_0 = 31.275 cm^3/s

Using the values of the parameter above, the transfer function of the system derived as follows :

$$G(s) = H(s) / R(s) = 1 / (450\, s + 1.0425) \tag{6}$$

III. Controller Design and Implementation

The experimental set up of the tank system is made up of the crossbar-shape tank with the dimension of 15 cm x 30 cm x 30 cm. Water from reservoir is pumped by CBA pump with specification of 5 bar maximum pressure, 1.6 L/min of maximum cap flow, operating voltage of 12-15 volt, and 2.1 A of maximum current. The level of the tank is measured by the PING Parallax ultrasonic sensor having a measurement range of (3-200) cm. Arduino UNO board is used as the main controller combined with motor driver L298P to drive the PWM of water pump.

Fig. 2. Experimental set up of water tank system

A. Gain Scheduling PID Controller with Back Calculation Integrator Antiwindup Design

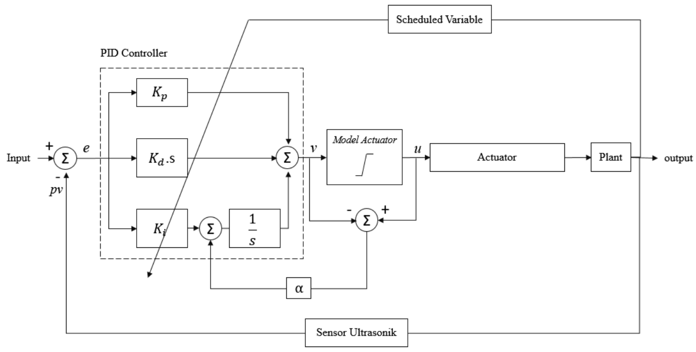


Fig. 3. Block Diagram of Gain Scheduling PID with Back Calculation Integrator Antiwindup

Figure 4 shows the block diagram of the controller, consist of three main part i.e conventional PID controller, added up by Back Calculation Integrator Antiwindup to prevent instability, and Gain Scheduling to enhance the performance at any desired operating condition.

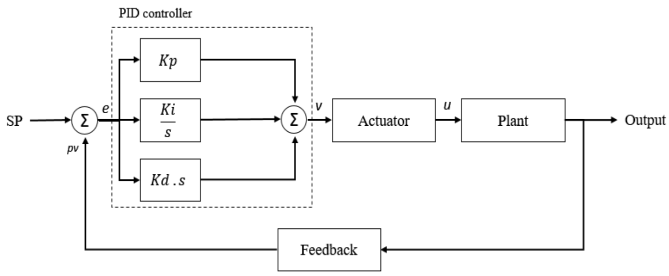


Fig. 4. Block Diagram of conventional PID

Figure 5 is block diagram of conventional PID system. To implement the controller using Arduino, we need to change the system into discrete of PID form. Below is the equation of the discrete PID form :

$$PID(z) = P(z) + I(z) + D(z) \quad (7)$$

where,

$$P(z) = K_p \,.\, E(z) \quad (8)$$

$$I(z) = K_i \,/\, (1\text{-}z^{-1}) \,.\, E(z) \quad (9)$$

$$D(z) = K_d \,.\, (1\text{-}z^{-1}) \,.\, E(z) \quad (10)$$

Let (1), (2), and (3) transform to the discrete form,

$$P(n) = K_p \,.\, e(n) \quad (11)$$

$$I(n) = K_i\, e(n) + I(n\text{-}1) \quad (12)$$

$$D(n) = K_d\, (e() - e\,(n\text{-}1)) \quad (13)$$

Then equations above are represented to codes below,

P = K_p . *error*

I = K_i . *Σerror*

D= K_d . *delta error*

where,

Σerror = present error + previous error

delta error = present error – previous error.

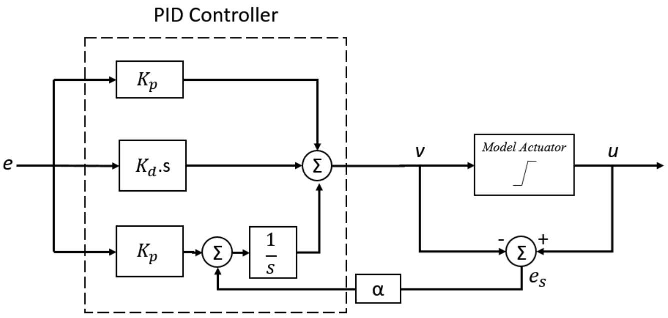


Fig. 5. Block Diagram of Back Calculation Integrator Antiwindup

Figure 5 shows a block diagram of PID controller with back calculation integrator antiwindup. When the actuator saturates, the signal e_s is different from zero and the integrator output is driven towards a value so that the integrator input becomes zero. The integrator input is :

$$\alpha \,.\, e_s + K_i \,.\, e \quad (1)$$

$$e_s = \text{-}(K_i \,.\, e) \,.\, \alpha \quad (2)$$

where $e_s = u - v$.

Substitute (1) and (2) to find v

$$v = u_{lim} + (K_i \,.e) \,.\, \alpha \quad (3)$$

u_{lim} is the saturation valye of controled variable. Since e_s and u_{lim} have same sign , the value v is always greater than u_{lim} so that it will prevent the integrator from winding up.

B. Tuning of PID controller

Controller tuning is a compromise between the requirement desire for fast and stable control. In this section, the parameter of PID controllers are derived from trial and error method. PID parameters K_p, K_i, K_d, are changes so that it will be found the best system response at all operation condition. The trial and error method step through the system from proportional to integral to derivative. Each coefficient of the PID controller is set to zero, the proportional component is considered by increasing its value scaling by a factor of one until it oscillated. Then the integral parameter K_i is increased until steady oscillations obtained by scaling it value by the factor of 10. Next brings up the derivative parameter by scaling it by a factor of one as well as the proportional.

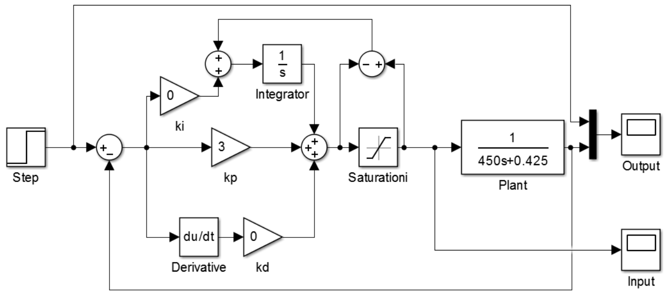


Fig. 6. Simulation of the system

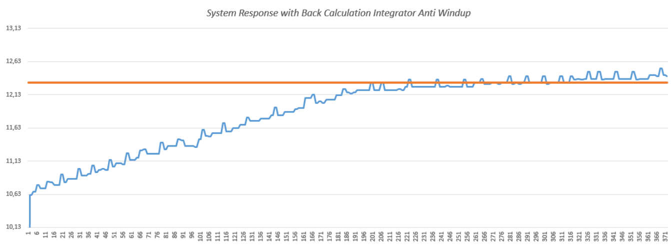
It may resulting some noises in the real implementation of the system, but it can be used as the refference to understand the characteristic of the system so that we can determining the best tuned parameter. The tuned parameter then will be used as scheduled variable as follows :

TABLE I. PID SCHEDULED PARAMETER

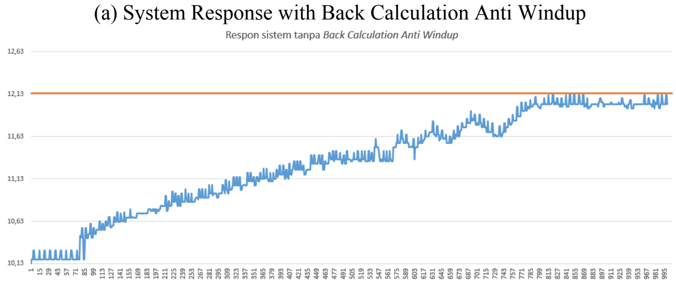
Condition	PID Parameter		
	K_p	K_i	K_d
13-16 cm	1	0.5	1
17-20 cm	1	0.4	2
21-23 cm	2	0.5	3

IV. RESULT AND ANALYSIS

The designed controller is now examined for its ability to control the level of water tank system compared to the conventional PID. The PID controller is tuned, where K_p, K_d, and K_i as shown at table 1.



(a) System Response with Back Calculation Anti Windup



(b) System Response without Back Calculation Integrator Antiwindup

Fig. 7. System Response of PID Controller

Figure 7 (a) represents the response of the PID controller with back calculation integrator antiwindup which has rise time of 34.6 second. It is different with the system response without back calculation integrator antiwindup which has rise time of 156 second shown in figure 7 (b) . It is evident from the response shown in figure 7 PID controller with back calculation integrator antiwindup could track the setpoint with minimal rise time and settling time than the conventional PID.

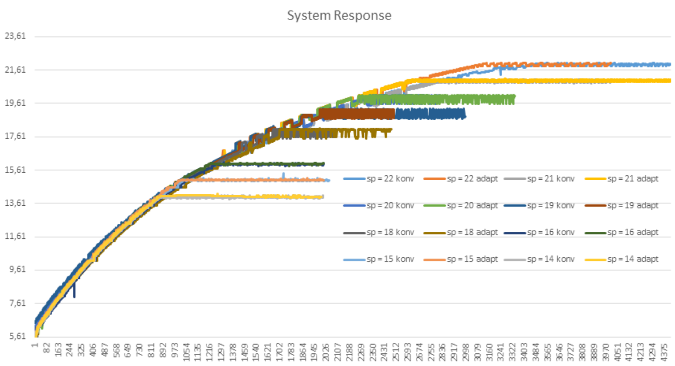


Fig. 8. System Response of Conventional PID Controller and Gain Scheduling PID at several setpoint

Figure 8 shows the system response of Gain Scheduling PID versus conventional PID at several setpoint. At (14-16) cm, (18-20) cm, and (21-22) cm the trajectory plotted at 400, 1200, and 1600 second respectively. Table II below represents the details of the system response.

TABLE II. COMPARISON OF TRANSIENT RESPONSE

Setpoint	**Transient Response**					
	Rise Time (s)		***Settling Time (s)***		***Overshoot (cm)***	
	Conv	GS PID	Conv	GS PID	Conv	GS PID
13 cm	129.6	125	136	135.6	0	0
14 cm	162.4	155.2	167	164.6	0.6	0.01
15 cm	184.8	182	200.2	194.8	0	0
16 cm	253.4	242.8	264	246.8	0	0.05
19 cm	410.4	396.4	413.2	400.2	0.15	0.13
20 cm	462. 4	449.8	471.8	450.6	0.06	0.06
21 cm	572.4	522.4	583	525	0.03	0.01
22 cm	696.8	623.2	712.8	628.2	0	0

It is evident from the system response of Gain Scheduling PID is better than the conventional PID at rise time, settling time, and overshoot. Based on the experiment at 8 different setpoints given to the system, Gain Scheduling PID has better performance.

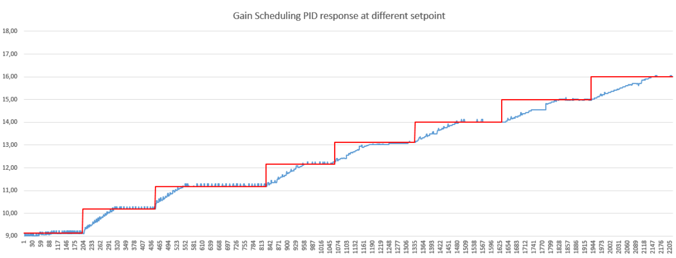


Fig. 9. System Response of Gain Scheduling PID at different setpoint

Figure 9 represents the graph and prove that Gain Scheduling PID controller with back calculation integrator antiwindup could track the setpoint at different operating points. Based on the experiment, given from 9.18 cm to 16.18 cm, the response are obtained detailed below

TABLE III. SYSTEM RESPONSE

Initial point	***Setpoint***	***Rise Time***	***Settling Time***
9.18 cm	10.18 cm	23.2 second	27.2 second
10.18 cm	11.18 cm	21 second	29 second
11.18 cm	12.18 cm	24.8 second	28.2 second
12.18 cm	13.18 cm	28 second	38 second
13.18 cm	14.18 cm	29.4 second	33.2 second
14.18 cm	15.18 cm	39.8 second	44.2 second
15.18 cm	16.18 cm	40.8 second	46 second

V. CONCLUSION

Gain scheduled PID controller with Back Calculation Integrator Antiwindup can adapt with water tank which has nonlinear characteristic at various operating points. Gain Scheduling PID is performed better than the conventional PID controller i.e it has faster rise time and settling time. Controller proves that it is robust enough for changes in the process variables and keep it on the setpoint given by user.

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