Experimental Studies on Step Response of Water Level Control System with P, PI and PID Control Mechanisms

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Abstract - *Water use has been increasing worldwide by 1 % per annum, impelled by a combination of population growth, socio-economic development and changing consumption patterns. Water supply with high precision is constantly a dominant field to study. As the Government of Eritrea has started numerous water supply projects in and around the capital city, Asmara, this work is primarily focused on sustaining water level in the storage tank which inherently determines the discharge rates in the supply lines. Ziegler Nichols model known as 'The Process Reaction Method' is employed to determine the optimal PID parameters with minimal step input value of 30 %. P, PI and PID controllers' response characteristics are examined with incremental changes in the step inputs from 0 to 90 %. Proportional control system has resulted into improved response times but generated increased steady state errors. PI controller headed to higher overshoot values due to rapid damping with larger dead time and response times despite of the fact that the error decreased gradually relative to P controller. PID controller minimized the steady state error progressively, and the overshoot values are fewer in contrast with PI controller. However, the response times are little higher than the P controller, PID controllers are proved as efficient to handle the error attractively.*

Key Words: Water Level Control, Step response of P, PI, PID Controllers, Ziegler Nichols model and Optimization of PID Parameters

1. INTRODUCTION

Water is a vital element of human life. It is crucial not only to sustain life on earth for drinking purposes of all living species but also utilized in several domestic, industrial and agricultural processes. [1] Water use has been increasing worldwide by about 1 % per year since the 1980s, driven by a combination of population growth, socio-economic development and changing consumption patterns. Global water demand is expected to continue increasing at a similar rate until 2050, accounting for an increase of 20 to 30 % above the current level of water use, mainly due to raising demand in the industrial and domestic sectors.[2] Misuse and poor management practices of water resources leads to severe consequences on sustainability of our environment. The Government of Eritrea (GOE) has initiated several water supply projects like Toker River Water Supply Project, to alleviate the critical water supply shortage and meet the future needs of the City of Asmara (population of 500,000). On behalf of the GOE, Natural Resources Consulting Engineers, Inc. (NRCE), acting as Project Manager in conjunction with General Development, Engineering and Construction Company. The pre-design phase addressed a number of unknowns associated with the project, particularly concerning the type of water treatment system to use, the requirements for the connection of the pipeline to the existing distribution system in Asmara. [3] The concept of the project includes the pumping of treated water to the central storage tanks that must be placed at comparatively higher elevations followed by supply water to the households by gravity through connecting them with the existing water distribution lines in the city. This study focuses on how to maintain the required level in the storage tanks to provide sufficient pressure in the discharge pipelines. Other words, in beverage and other process industries, regulated water supply with high precision can be achieved by connecting the systems with a suitable controller. The operation of a control valve that is connected with a well-designed controller determines the controlled discharge of water to a specific process.

The idea of PID control is surprisingly simple. It has to do with knowledge of the past, knowledge of the present, and predictions of the future just like how we make decisions in our life. The functions of the individual proportional, integral and derivative controllers complement each other. Proportional control action given by the current error, while Integral control action works based the past error, and derivative action predicts the rate of change and mitigates the error not to occur in the future. If they are combined it is possible to make a system that responds quickly to changes (derivative), tracks required positions (proportional), and reduces steady state errors (integral).[4]

The equation of PID controller is

$$U_n(s) = K_c\left[1 + \frac{1}{\tau_i s} + \tau_d s\right]E(s)$$

Where, $E(s) = SP(s) - MV(s)$

The following is the block diagram representation of the PID controller equations.

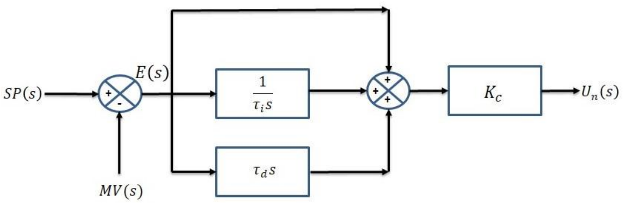

Fig.1 Block diagram of PID controller

In the above diagram *SP* is set point, *MV* is measured variable, U_n is controller output, and *E* is error. The parameter τ_i is the integral time and the parameter τ_d is the derivative time. Sometimes the proportional gain K_C is included in the individual terms and following used, some controllers designing companies do not use the name of proportional gain, instead the name proportional band, PB is used and it can be expressed as % PB = 100/ K_C

2. MATERIALS & METHODS

Materials: Ambient Air, Water, which was collected from the supply lines of Mai-Nefhi College of Engineering and Technology that are connected from the source of Mai-Nefhi water treatment plant.

Experimental System: Table top frame structure for XPO PCT System provided by Matrix Global Pvt Ltd.

The system has three different resource panels, Instrumentation power supply panel (EMT8), Signal conditioning panel (SCP), and Computer Interface Panel (CIP). The trainer is equipped with two tanks mounted one vertically in the front side & other horizontally on rear side of the trainer. The second tank serves as primary reservoir and it has a capacity of 70 lit which must be filled with water to at least 80 percent of the tank prior to the experimentation. The other tank performs for level control function. There is one centrifugal pump of ½ HP mounted on backside of the trainer to draw water from sump tank to the process tank. It is piped with ½ inch reinforced tube and has a bypass valve (V1) as well as one shut off valve (V2) to control water delivery to the process. There are three (V7, V8 and V9) ¼ inch drain valves at the bottom of level tank continuously operated during the level experiment.

Bubbler method was applied using a pressure sensor to measure water column pressure in the level tank. AFR1 supplies necessary air pressure to the sensor sensing water column height. The sensor is mounted inside the computer interface panel (CIP). A blue colored polyurethane tube taps the back pressure of water column from T junction and straight connected to CIP panel to be coupled with sensor port to avoid any pressure leakage. The system is provided with two AFR (Air filter regulator) units because the incoming pressure from compressor is in the range of 0 to 6 bars. I to P converter operates on 0 to 1.4 bar, to reduce pressure from 6 to 1.4 bar, we are using AFR1 while AFR2 operates to reduce 1.4 bar to 1 psi (0.06 bar).

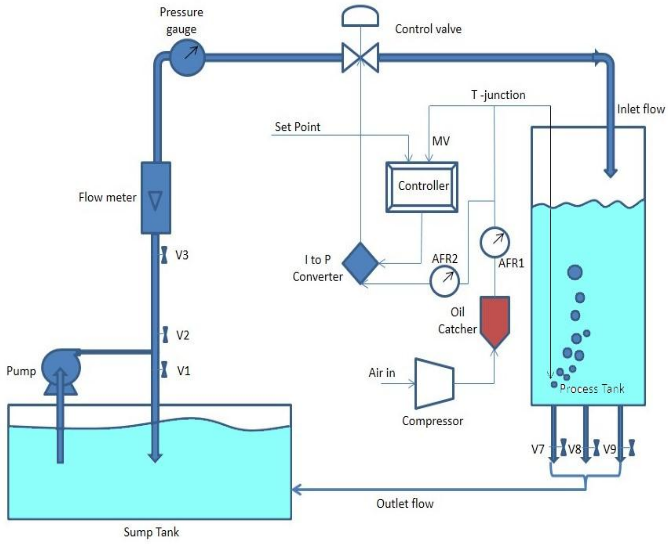

Fig -2: Schematic diagram of experimental set up for water level control in the process tank

The control valve used in this setup is of ½ inch port size, action-air to close, consists of 10 sq. inch diaphragm, and stroke length of 14.3 mm with an air supply of 3 to 15 psi. I to P converter is coupled at the output of AFR2 with the specifications of 4 to 20 mA input and 3 to 15 psi output and the output is given to the control valve by polyurethane plastic tube for control action.

Methods:
The selection of PID controller design parameters K_C, τ_i and τ_d were estimated by using one of the Ziegler and Nichols devised empirical method which is known as the "The Process Reaction Method". This method is based on the assumption that the open-loop step response of the most process control systems has an S-shape, called the process reaction curve as shown in Chart-1. The process reaction curve may be approximated to a time delay D (also called a transportation lag) and a first order system of maximum tangential slope R as shown in Chart-1 [5] The system was first operated for the open loop configuration to determine the PID parameters to control the water level in the tank.
Procedure for the open loop control system operation: Connected the pump motor to the power supply panel (EMT8). Opened the valves V1, V2, V3, V8 & V9 while V7 kept closed. Attached compressor at input of Oil Catcher unit on backside of the process board. The output of oil catcher goes to input to the AFR1 then it was adjusted to 1.4 bar air pressure on pressure gauge.

Wiring sequence for the open loop control system operation: Pump L-14 EMT8, Pump N-15 EMT8, LEVEL O/P (16 SCP) – CIP CH1, CIP6 – CIP9, CIP 10- (+ve) of I to P, (-ve) of I to P-

CIP 20, CIP CH0 – FIXED 1.25 V (14 of CIP) manually by setting pot P1.

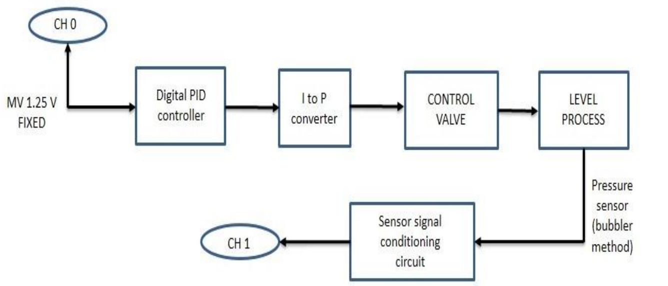

Fig.3 Block diagram of open loop control configuration

Accessed the main window of PID CONTROLLER software on PC. This control panel includes the required information that must be given for the estimation of optimal PID parameters by using the Process Reaction Method. By providing the sufficient information as shown in Fig.4 and Fig.5, followed by running the pump we observed the response plot for steady state to accomplish, and later gathered the data from the saved file for further analysis.

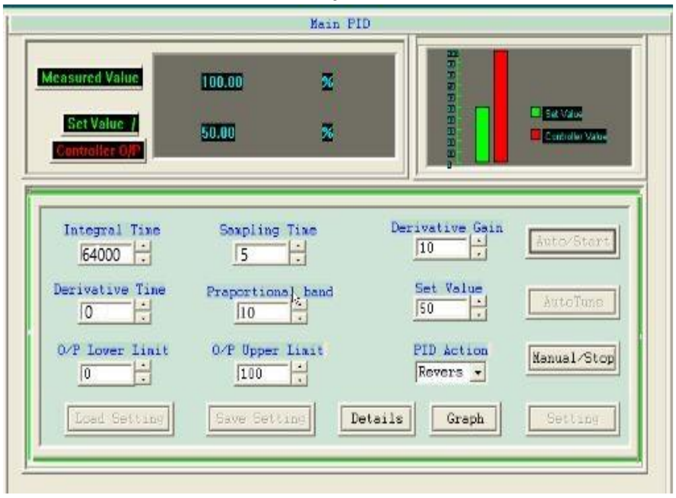

Fig.4 Parameters set on PID software main window for open-loop study

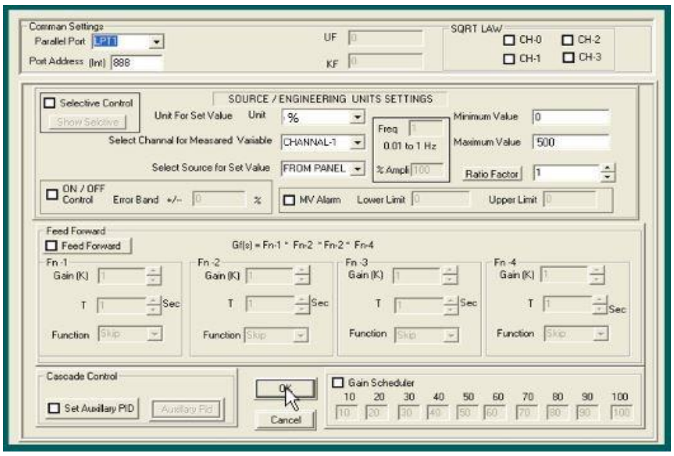

Fig.5 Parameters set on PID software setting window for open-loop study

Procedure for the closed loop control system operation: The operation remains similar with open loop study of the system except few changes which are mandate to make in wiring sequence and in setting the calculated PID parameters that are shown in the Table.1 according to the control mechanism applied. For this case, the setting window was kept similar with the open-loop system study as shown in Fig.4

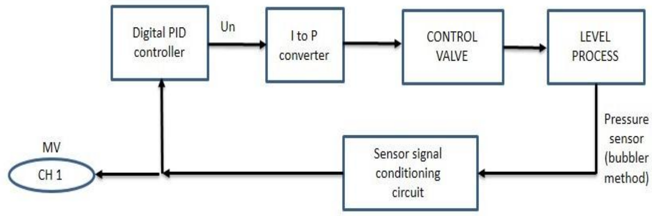

Fig.6 Block diagram of closed loop control configuration

Wiring sequence for the closed loop control system operation: Pump L-14 EMT8, Pump N-15 EMT8, LEVEL O/P (16 SCP) – CIP CH1, CIP6 – CIP9, CIP 10- (+ve) of I to P, (-ve) of I to P- CIP 20.

Table.1 Parameters set on PID main window for the study of closed –loop controllers response

Controller Type	τ_i	T_s	K_d	τ_d	PB%	Set Value
P	64000	1	10	0	10	30,50,70 and 90
PI	100	1	10	0	10	30,50,70 and 90
PID	60	1	10	15	10	30,50,70 and 90

3. RESULTS AND DISCUSSIONS

Experimental Results: Calculation of PID parameters was performed in terms of transportation lag (Dead time) D and maximum tangential slope value R according to the Ziegler Nichols empirical relations given in the table. An experiment on open loop system was conducted at min step value of 30 as input and the optimal derivative gain value of 10 to observe the optimal process reaction curve with a sampling time (T_s) of 5 sec. The response curve as shown in figure was analysed for the estimation of D and R. The value of D can be directly obtained from the plot as

$$D = Number\ of\ samples \times Sampling\ time$$
$$= 6 \times 5 = 30\ sec$$

R can be estimated indirectly from the relation of

$R = K/T$, where, $K = \frac{\Delta\, Output}{\Delta\, Input} = 0.4315$ and

$T = Number\ of\ sample\ \times Sampling\ time$
$= 48 \times 5 = 240\ sec$

The controller parameters as a function of R and D to acquire an optimum response curve for the closed loop controllers were calculated and given in the Table.2

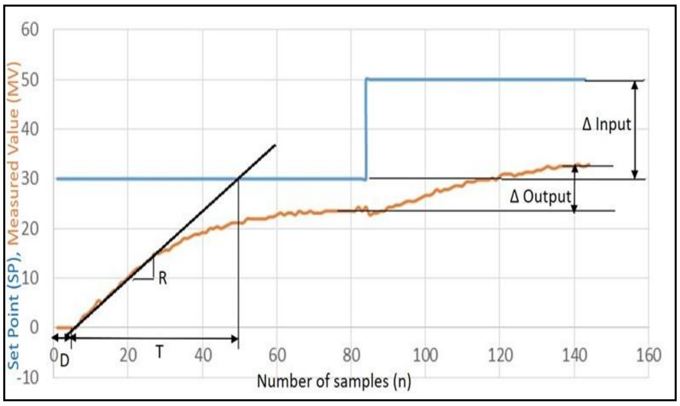

Chart -1: Open-loop system response plotted for the step input values of 30 and 50 to determine PID parameters.

Step Response of WLC System with P control mechanism was obtained by providing the respective parameters from the Table.2 It was identified as the delay time of 17 sec for the initial step value of 30 and it was not significant in the successive changes in set values as they were not studied as the initial set values.

Table.2 Ziegler Nichols PID parameters using the Process Reaction Method

Controller Type	K_c	Calculated K_c	τ_i	Calculated τ_i	τ_d	Calculated τ_d
P	*1/RC*	18.54	-------	-------	-------	-------
PI	*0.9/RC*	16.68	*D/0.3*	100	-------	-------
PID	*1.2/RC*	22.25	*2D*	60	*0.5D*	15

It was also studied that the overshoot and rise time were irrelevant parameters for any proportional controller as the system never meet the desired set value, instead it produced a static error which was observed as gradually increasing with increase in step input values. The response times of proportional controller for all step changes were faster in comparison with other control mechanisms as shown in Table.3.

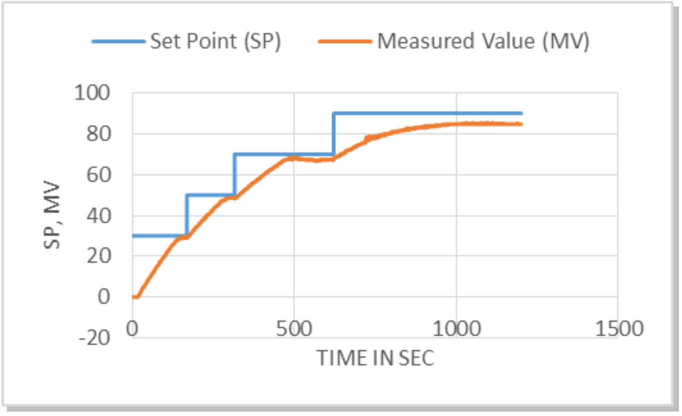

Chart-2: P Controller response plotted for the subsequent step changes 30, 50, 70 and 90

Table.3 Estimated characteristic parameters of P controller for subsequent changes in step inputs

Step Changes in Input	Dead time (sec)	Rise time (sec)	Overshoot (%)	Steady state Error	Response time (sec)
30	17	NA	NA	0.59	136
50	NA	NA	NA	1.38	126
70	NA	NA	NA	2.55	288
90	NA	NA	NA	5.30	355

Step Response of WLC System with PI - control mechanism was studied corresponding to 30, 50 and 70 step input values. Unlike P and PID controllers, in PI controller the response time seems too tardy for 90 Step value.

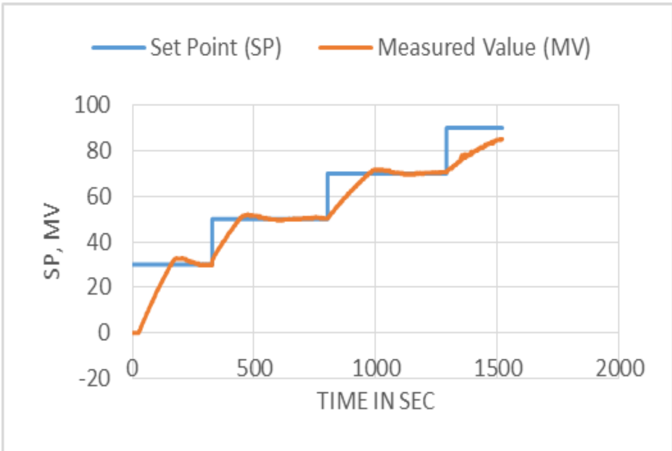

Chart-3: PI Controller response plotted for the subsequent step changes 30, 50, 70 and 90

Estimated characteristic parameters such as rise time, overshoot, response time and steady state errors for three step input values of 30, 50 and 70 are furnished in the Table.4 for PI controller.

Table.4 Estimated characteristic parameters of PI controller for subsequent changes in step inputs

Step Changes in Input	Dead time (sec)	Rise time (sec)	Overshoot (%)	Steady state Error	Response time (sec)
30	26	129	8.467	-2.54	248
50	NA	108	8.8	-1.76	451
70	NA	166	8.8	-1.76	460
90	NA	NA	NA	NA	NA

Step Response of WLC System with PID - control mechanism was developed with subsequent step changes in the input values of 30, 50, 70 and 90 as shown in the figure. And their respective characteristic variables are assessed and listed below in the Table.5

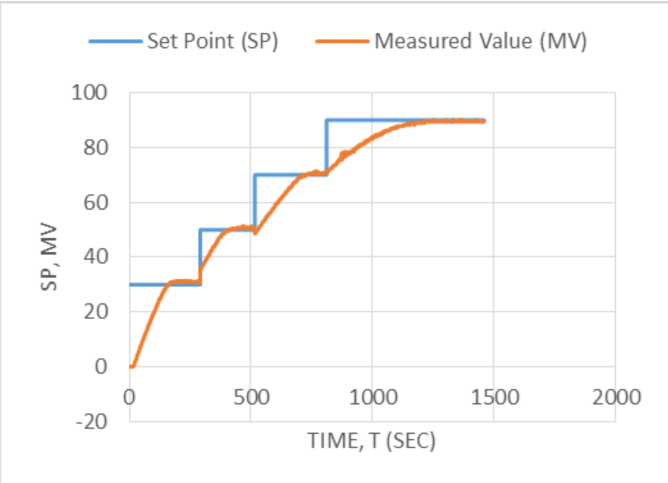

Chart-4: PID Controller response plotted for the step changes 30, 50, 70 and 90

Table.5 Estimated characteristic parameters of PID controller for subsequent changes in step inputs

Step Changes in Input	Dead time (sec)	Rise time (sec)	Overshoot (%)	Steady state Error	Response time (sec)
30	17	161	4.567	-0.98	255
50	NA	108	6.85	-0.58	136
70	NA	194	6.85	-0.58	220
90	NA	454	0.95	+0.19	415

Result Analysis:

Prior to determine the characteristics of the open loop system, the effect of derivative gain (K_d) was observed with 1, 10 and 20 values, it has produced the minimum transportation lag and less damping in the case of 10 when we compare with 1, and 20 values. Derivative gain 1 produced larger delay time but later the process was faster while for 20, the system has minimal dead time but sluggish in response.

At lower step value (30), PI controller caused to larger error of -2.54, with higher delay time of 26 sec as shown in the Chart-5 & 6. Step response characteristics of P, PI, and PID are measure for successive changes in the step inputs from 0 to 30, 30 to 50, 50 to 70 and 70 to 90 with predetermined PID parameters.

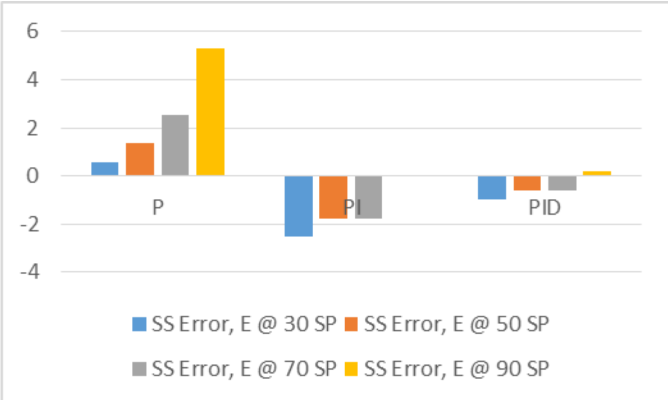

Chart-5. Steady state Error estimated for 30, 50, 70 and 90 Step changes for P, PI and PID controllers

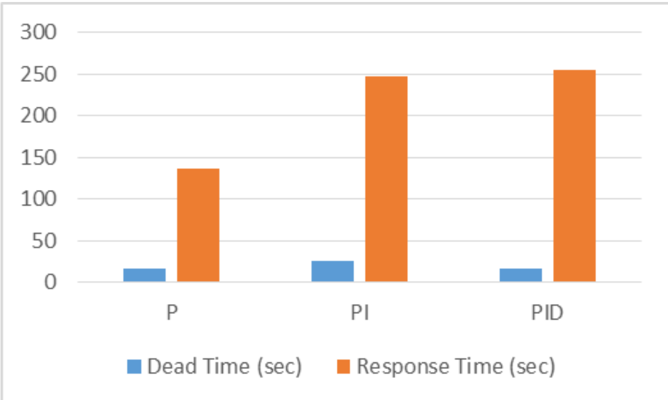

Chart-6. Comparision of Dead time and Response times for P, PI and PID controllers at step input value of 30

It is identified that the higher response times in PI controllers caused from their larger overshoot values, whereas P controller generated stable increments in the errors but PID controller has more response time than P controller and lesser damping unlike PI controller as shown in Chart-7. PID also recognized with gradual cutback in the error values whilst moving towards higher step changes. PID controller holds the best performance with respect to PI controller in terms of transportation lag, overshoot, response time and eliminating error.

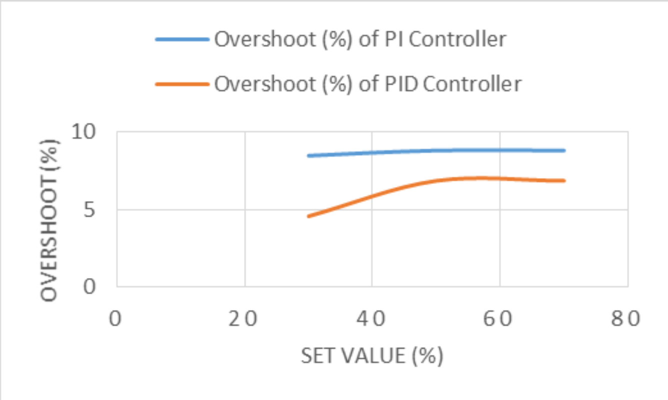

Chart-7. Comparative study of Overshoot (%) in PI and PID Controllers

The rise times for PI controller were shorter in comparison with PID controller because of it higher damping nature.

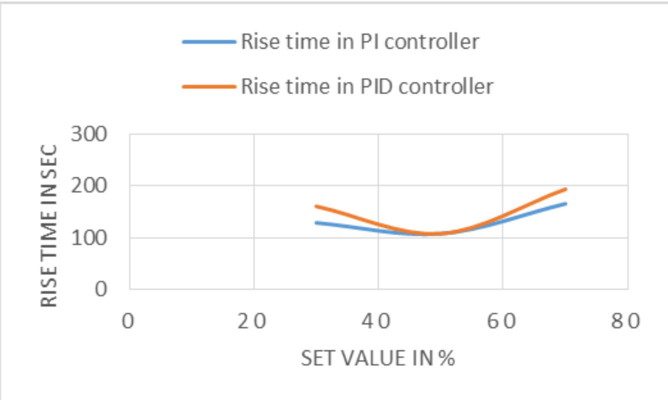

Chart-8. Comparative study of Rise time (sec) in PI and PID Controllers

4. CONCLUSIONS

The study of water level control has been established with P, PI and PID control mechanisms. Proportional control system has resulted into improved response times with minimal dead time but the steady state error has amplified regularly to a bigger one as the step inputs changes from zero to higher set values. PI controller headed to higher overshoot values due to rapid damping with larger dead time and response times but the error was gradually decreased with respect to P controller. Rise times in PI control device are quite earlier relative to both P and PID controllers. PID controller minimized the steady state error progressively, and the overshoot values are fewer in contrast with PI controller. Though the ultimate response times are fewer in the case of P controller but it couldn't diminish the error, instead PID controller proved as optimum controller by reducing the error significantly with reasonably faster response times.

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REFERENCES

[1] Beza Negash Getu,"Water Level Controlling System using PID controller" IJAER, Volume 11, pp. 11223-11227, Number 23, 2016.

[2] UN World Water Development Report-2019, available at

https://www.unwater.ord/publications/worl-water-development-report-2019/

[3] "Adi Nefas Water Treatment Plant and Treated Water Pipeline, Eritrea" NRCE-Project Report available at https://nrce.com/project/adi-nefas-water-treatment-plant-and-treated-water-pipeline-eritrea/

[4] "Technical Manual of Process Control Trainer (PCT)" provided by Matrix Global Private Limited, version 1.5, 2009.

[5] Ronald S. Burns, "Advanced Control Engineering", Butterworth and Heinmann publishers, page no. 1st edition, 2001.