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Design and implementation of PID based flow rate control using PLC

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ABSTRACT

Industrial systems require efficient techniques to observe the stable operation of various industrial processes and to achieve optimal control. Considering the importance of industrial processes, Proportional Integral and Derivative (PID), Adaptive PID, and fuzzy logic are the most utilized control systems. Programmable Logic Controller (PLC) is a low-cost solution for the industrial processes requiring control and having the flexibility of graphical user interface. In this paper, an experimental study on flow rate control system for water flowing in a vessel is realized and implemented using Proportional (P), Proportional Derivative (PD), Proportional Integral (PI), and PID controllers with Programming Logic Controller (PLC). For optimal control, the constants for the PID controller are calculated based on Zeigler-Nichols (ZN) rules. ZN tuning rules can be used to find controller constants where the plant dynamics are not available. The experimental analysis is performed to validate the theoretical concepts. The achieved results and analysis demonstrate that the process variable, which is water inflow rate 4.92L/minute, is equal to the set point without any overshoot and remains controllable at every set point change.

1. Introduction

In the recent decades, conventional PID controllers and related methods have been upgraded in terms of system components and tuning methods. These controllers have been extensively used with industrial systems including electric, hydraulic, and pneumatic systems [1-3]. To use a PID controller in an application, first desired output response of a system is determined through an arbitrary input signal. Then, the process called tuning defines the parameters of a PID controller. There have been various PID tuning techniques have been implemented and applied by researchers in various PID control structures [4-7]. It is not possible to realize an analytical approach for the plants which have unknown mathematical models owing to the difficulty in finding controller parameters. To address this problem suitable option is to select experimental methods to tune the PID controller [8, 9].

PID controller is also known as a three-term controller. It is an upgraded version of Proportional (P), Proportional Integral (PI), and Proportional Derivative (PD) controllers. PID controller compounds the properties of these controllers, which can be employed for stability of any industrial process. It is a continuous type controller, which outputs a continuous value as compared to a digital controller in which output can only have two values 1 and 0. The continuous process could be a refining gasoline process or any other chemical industry processes. A PID controller can be implemented by mechanical, pneumatic, and electronic control systems. It can also be realized using PLC. PID controller can be analytically expressed by Eq. 1.

$$K_P E_P + K_P \int K_i\, E_P dt + K_P\, K_d\, \frac{dE_P}{dt} + P(\text{o}) \qquad (1)$$

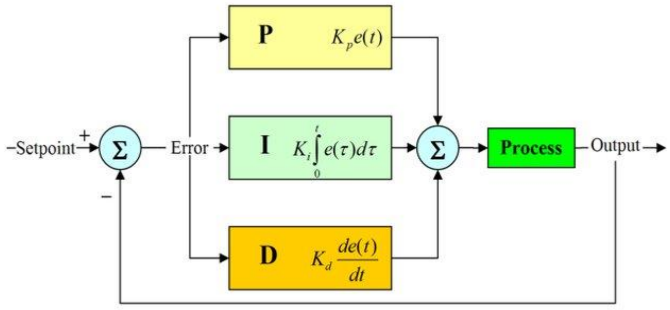


Fig. 1. Simplified diagram of PID [20]

Fig. 1 depicts the simplified block diagram of non-interacting PID [20]. It contains proportional amplifier, integral amplifier, derivative amplifier, and two summing points. At the first summing point, difference between the measured variable and the set-point (SP) results in error value as output. The KP amplifies the error and Kp value, which is again amplified by the Ki and Kd amplifiers. Moreover, at the second summing point, a resultant of three amplifiers is generated. Subsequently, the generated output by the controller is supplied as the input to the control element, which brings the process variable (PV) near to the set-SP. The Kp amplifier suppresses the current error, the Ki minimizes the offset, and the Kd minimizes fluctuations in PV.

When, the Ki and Kd amplifiers are connected in series with each other. Then, the PID is considered as interacting in which the Ki control lags the Kp control, and the Kd control leads the Ki action and aggregate effect is a vector sum as depicted in Fig. 2.

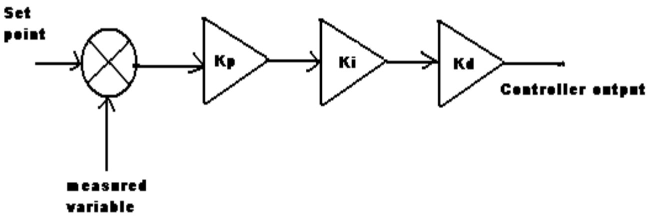


Fig. 2. PID Controller

Generally, it generates the output signal in such a way as to bring error at zero. It tracks the error value by computing the difference between SP and PV. In the same way, a digital type controller is to be implemented so that continuous value is converted into digital value as expressed in Eq. 2.

$$M_n = K_{Pn} + K_{in} + K_{dn} \qquad (2)$$

where, the Mn represents output, K_{Pn} is the output of proportional term, K_{in} is the output of the integral term, and K_{dn} is the output of the derivative term.

Among various techniques, the Zeigler and Nichols (Z-N) and Cohen _Coon tuning rules put up an educated guess for the tuning parameter values which provide the initial point for tuning the controller. Such tuning of parameters of PID controller can be done by on-site engineers through performing various experiments on a process plant [10-12]. ZN rules are used on the process where mathematical model is unknown. Controller constants realized based on ZN rules can be used to control a process parameter to achieve initial stability and then fine tuning can be performed.

According to Z-N close loop method, the tests are to be conducted at the time of commissioning of the process plant to find PID constants. Keeping only proportional gain (Kp) at the minimum and the other two integral time (Ki) and derivative time (Kd) equal to zero, the process is to be brought in the close loop and observing the behaviour of flow rate in cyclic nature. Record the Kp value at which these oscillations are achieved as Ku (ultimate gain). Measure the period of variations inflow rate as period (Pu) [6].

After knowing the values of Ku and Pu, the controller parameters can be calculated by putting the values given in Table 1. This allows to find controller parameters and observe initial stability in the process loop, and after that fine-tuning of controller constants could be done.

Table 1

Controller parameter calculation using ZN approach

Controller Type	Proportional Gain	Integral Time	Derivative Time
P	Ku/2	-	-
PI	Ku/2.2	Pu /1.2	-
PID	Ku/1.7	Pu/2	Pu /8

Similarly, PLC has been considered as the best possible solution for the industrial processes, which require an automatic or intelligent control, compared to old relay logic owing to easy programming without any change of relays, timers, counters, and physical connections. Industries in developing countries prefer PLC over dedicated controllers, if required number of I/Os is limited. Among various industrial applications, temperature, level, flow, and pressure are the most common parameters which are controlled using PID controller [13]. Moreover, PID in conjunction with PLC could be employed for real processes having analog I/O cards [14].

Flow control is one of the trending and evolving subfields of fluid mechanics. There has been various research available related to flow control including drag reduction and mixing enhancement [15-17]. However, there have been limited studies related to the stability of the control system. In [18], authors have experimentally tuned the PID-based temperature control system through PLC by calculating PID parameters through Z-N rules by manual tuning and automatic tuning. It is observed that initial stability can be observed in the process and the system can track changes with set-point change and with external disturbance. In [19] authors have employed PID controller to control the flow of oil through controlling the vibration of the pumping motor. The Lyapunov stability theorem was used to validate the essential conditions for the asymptotic stability of the controller. To reduce the impact of vibration on the motor torsional actuator is used. The numerical simulations were performed to validate theoretical concepts which demonstrated the effectiveness of the controller in improving the flow rate.

Compared to the aforementioned researches, in this investigation, a flow rate control system is implemented using PID through PLC. The controller parameters are determined based on Z-N rules for observing initial stability in the process and these methods are implemented through PLC to determine whether the analogue methods of finding controller constants can be realized through PLC or not. Contributions of this study can be summarized as under.

(i) Determining PID controller parameters for flow rate control experimentally (manual method and automatic through PLC).

(ii) Realization of the process control using PLC.

(iii) Monitoring the initial stability of the controller for the flow rate control.

The investigation is intended for the implementation of an effective system for various flow rate control applications.

The remainder of this paper is organized as follows, Section 2 reports the methodology used to carry out this research, Section 3 reports the experimental setup and tests to find P, PI, and PID controller constants, and Section 4 presents the results and discussion. Finally, conclusions are provided in Section 5.

2. Methodology

Initially the controller parameters are determined through Z-N rules by two methods. Manual and automatic by PLC by performing the close loop tests on the experimental test setup. The controller parameters are determined through the two approaches based on Z-N rules includes the close loop test manually and the other one is PLC-based automatically (PLC itself suggests the controller constants for the Kp, Ki, and Kd values).

In the next phase, the P, PI and PID controllers are realized on the process by adjusting the set point of flow rate and observing how the controllers try to achieve the desired set point of process variable i.e. flow rate.

3. Experimental Setup

The experimental setup used in this investigation includes the industrial process system Flow, Level, Temperature and Pressure (FLTP) with S-7 200 PLC with the Microwin software, and power supply module. The test setup is shown in Fig. 3, and its process and instrumentation diagram is shown in Fig. 4.

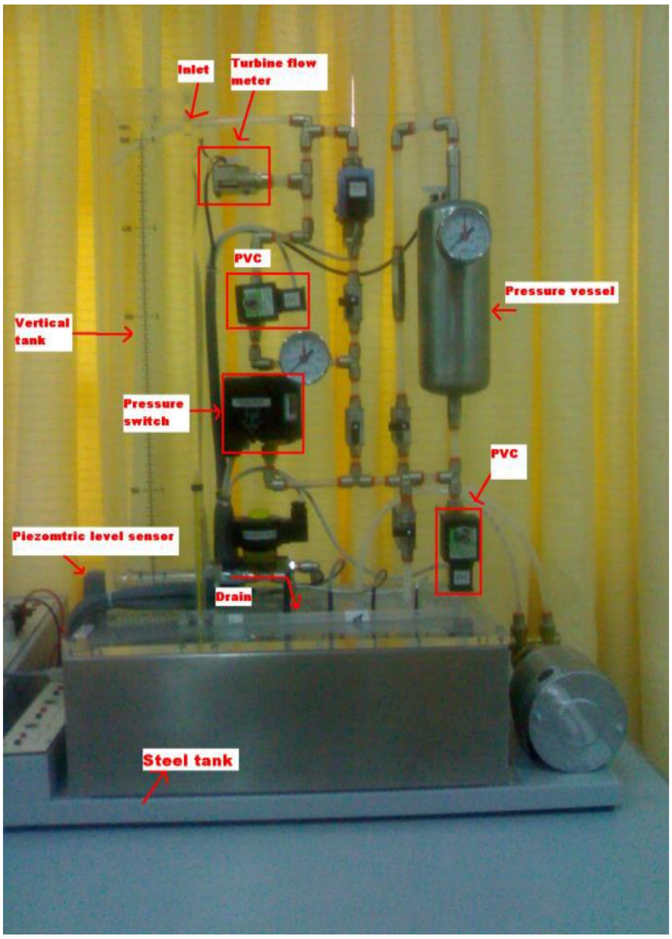


Fig. 3. FLTP module

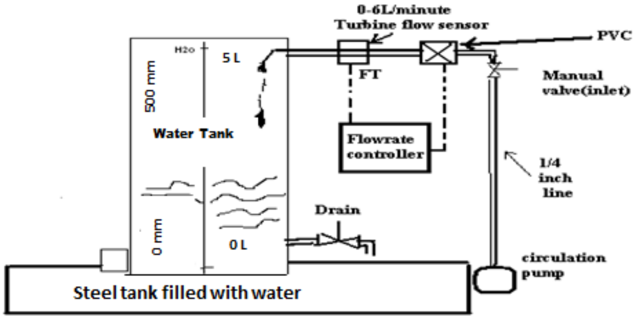


Fig. 4. Process and instrumentation diagram

The close loop setup of FLTP process plant in Fig. 3 with PLC and other devices used is shown in Fig. 5. The steel tank at the base shown in Fig. 3 is already filled with water that is pumped through a circulation pump already switched on manually at the time of applying desired set point. A proportional valve (PVC) operating on 0-10V DC is installed on a ¼ inch line of plastic tubing. This valve allows controlling the water inflow rate from the steel tank from ground to the vertical Plexiglas tank having capacity of 5 litres (5L). The flow of water is measured by a digital turbine flow meter measuring 0-6 litre/min and producing ON-OFF pulses. A signal conditioner is used to convert these pulses to a homogenous output voltage 0-10V dc as analogue input to the PLC. Manual valves are used to disturb the water inflow as shown in Fig. 3 installed in the same line of PVC in ¼ inch line.

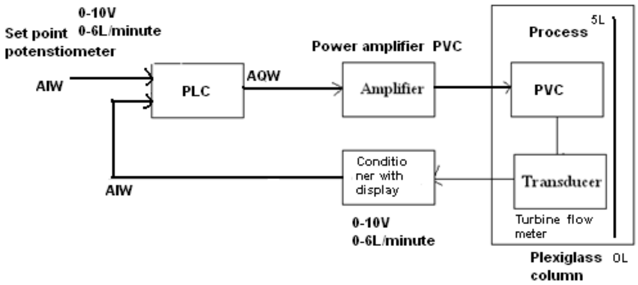


Fig. 5. PLC and plant connected in loop

3.1 Manual Test To Find Controller Parameters

Fig. 5 represent the PLC connected in a closed loop showing external set-point as an analogue input (AIW), analogue output (AQW), and measured process variable through signal conditioner as feedback. The SP and flow rate are to be connected as two analogue inputs between 0-10Vdc for the range of 0-6L/minute. The relay-based output (AQW) generated by the PLC is connected to an amplifier which amplifies the PLC signal matching to PVC. The measured process variables as flow rate, SP and the controller output can be analysed on the control panel in the Microwin software of S7-200 PLC.

After putting the PLC in a close loop, the controller parameters are determined through manual test or automatic turning. The SP is to be adjusted as zero and the program block is downloaded to PLC. The PLC is to be brought in run mode. For close loop manual testing, insert the Kp value equal to 1, Ti as infinity, Td as zero, manually in PLC and observe the oscillations inflow rate when step change is introduced at SP with increasing the Kp value until the sustained oscillations are achieved inflow rate. Display of the SP in green and its label is at the left side, controller output in blue and values are shown at right side (0-32000 equal to 0-10V) at right side, and flow rate which is the process variable in red colour (0-100 equals to 6L/minute) are shown in Fig. 6 and 7.

It can be observed in the response curves depicted in Fig. 6 and 7, at the left side in which 0-100 represents 0-6L/minute. The SP value starting at 3.6L/min and it is increased from 2.1L/min at 35s with the manually fixed proportional gain (Ku) of 2.5 of controller at PLC. The water flow rate in the water tank and output of the controller both demonstrate fluctuations in the opposite directions when the loop is turned on. The measured period of oscillations Pu is 6s and 3s in Fig. 6 and 7, respectively. This is performed with only proportional gain adjusted from 1 to 2.5 as Ku of 2.5 to achieve sustained oscillations in process variable. Performed approximately 15 tests and based on these results the controller parameters were computed using Z-N rules in Table 1, and the results are provided in Table 2 and 3. The table provide the P, PI, and PID controller constants.

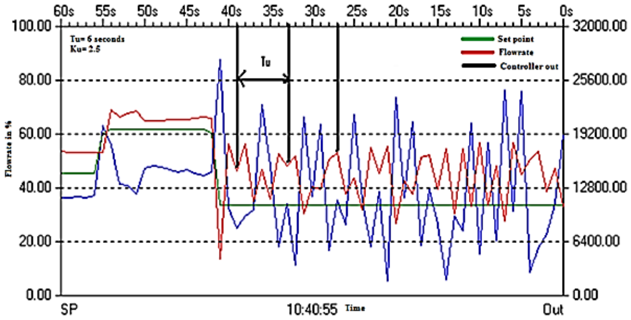


Fig. 6. Response of process variable, controller output in manual test showing sustained oscillations of process variable with Pu of 6s

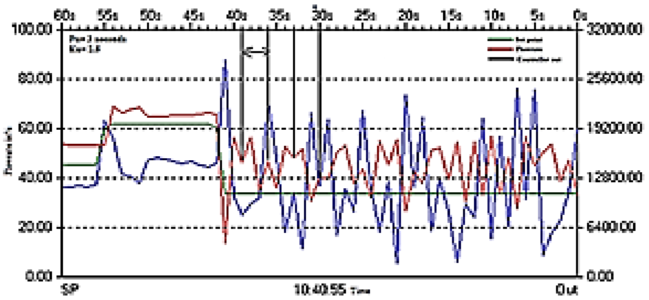


Fig. 7. Response of set-point, and controller output during manual test showing sustained oscillations of process variable with Pu of 3s

Table 2

Controller constants based on 2.5 Ultimate gain and ultimate period of 6s

Controller Type	Proportional gain	Integral Time	Derivative Time
P	1.25	-	-
PI	1.1364	5s	-
PID	1.5	3s	0.75s

Table 3

Controller constants based on 2.5 Ultimate gain and ultimate period of 3s

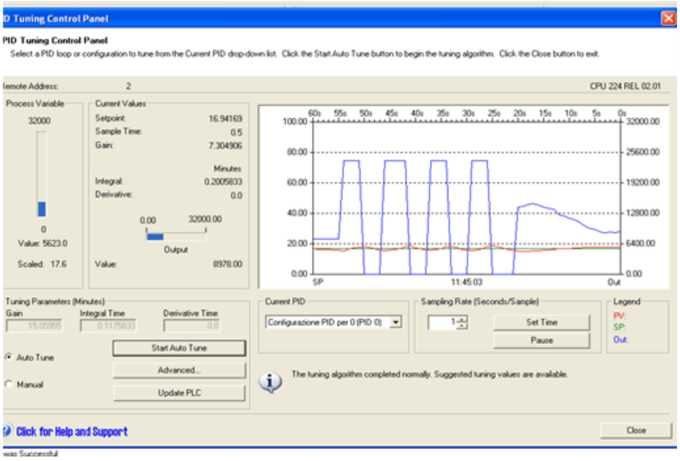
Controller Type	Proportional Gain	Integral Time	Derivative Time
P	1.25	-	-
PI	1.1364	2.5s	-
PID	1.5	1.5s	0.37s

3.2 Automatic Test To Find Controller Parameters

For automatic tuning, the PLC automatically applies SP and increases the Kp value for sustained oscillations. The PLC-based automatic tuning determines the constants for PID (Kp, Ti, and Td) using three kinds of responses (slow, medium, and fast). Automatic tuning is initialized on the control panel shown in Fig. 7 with an observation of process parameters which are process variable (PV), SP, and controller output. The PLC generates relay output to observe small variations in PV and based on those variations the automatic tuning wizard determines the controller type (P, PI, and PID) required for the specific loop and its contestants. Hysteresis is used in automatic tuning for reducing the noise in comparison to erratic switching of controller output in the manual tuning. In this way, the wear and tear of the control valve can be avoided in comparison to manual testing in which repeated tests are to be performed. The process loop should remain in closed loop in automatic tuning as well as manual tuning. To start automatic tuning, the PLC is brought in run mode and initial gain values are inserted and downloaded first to PLC. Initializing the PID tuning control panel displays the parameters and suggested PID constants by choosing auto-tuning. The panel is depicted in Fig. 9.

The setting of the advance auto-tuning parameters is shown in Fig. 10. The check box automatically determines values for hysteresis and deviation is selected. Initial step output value, which is 0.100, and watchdog time 7200s is inserted in other options. The output response speed (fast, medium, slow, and very slow) is to be selected in dynamic response options.

In Fig. 8, controller output in blue colour and measured process variable (flow rate) in red colour are the two parameters are to be observed in the automatic tuning panel during tuning. The initial SP (flow rate) is in green colour, which is to be fixed already before initiating the automatic tuning. The water level in the Plexiglas tank is to be observed and the output of the controller should remain stable when the loop is opted for automatic tuning. In this method, first hysteresis and deviation are calculated by the PLC. Then, a relay output is generated to open and close the proportional valve control (PVC) for the determination of controller parameters. The PID controller constants suggested by PLC automatically were Kp = 0.52, Ti = 0.021min, and Td = 0.01min with selection of fast response and hysteresis adjustment automatically. The values are given in Table 4.



D Tuning Control Panel

PID Tuning Control Panel

Select a PID loop or configuration to tune from the Current PID drop-down list. Click the Start Auto Tune button to begin the tuning algorithm. Click the Close button to exit.

lemote Address: 2

CPU 224 REL 02.01

Process Variable: 32000 … 0; Value: 5623.0; Scaled: 17.6

Current Values
Setpoint: 16.94169
Sample Time: 0.5
Gain: 7.304906
Integral (Minutes): 0.2005833
Derivative (Minutes): 0.0
Output: 0.00 … 32000.00; Value: 8978.00

Tuning Parameters (Minutes)
Gain: 15.05955
Integral Time: 0.1175833
Derivative Time: 0.0

● Auto Tune
○ Manual

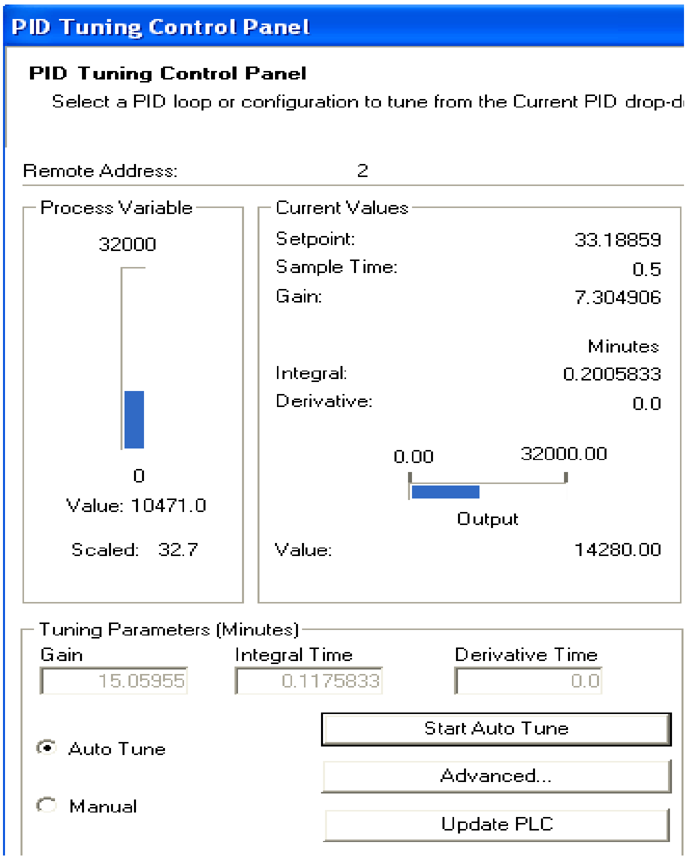
Current PID: Configurazione PID per 0 (PID 0)

Sampling Rate (Seconds/Sample): 1

The tuning algorithm completed normally. Suggested tuning values are available.

was Successful

Fig. 8. PID tuning control panel



PID Tuning Control Panel

PID Tuning Control Panel

Select a PID loop or configuration to tune from the Current PID drop-d

Remote Address: 2

Process Variable: 32000 … 0; Value: 10471.0; Scaled: 32.7

Current Values
Setpoint: 33.18859
Sample Time: 0.5
Gain: 7.304906
Integral (Minutes): 0.2005833
Derivative (Minutes): 0.0
Output: 0.00 … 32000.00; Value: 14280.00

Tuning Parameters (Minutes)
Gain: 15.05955
Integral Time: 0.1175833
Derivative Time: 0.0

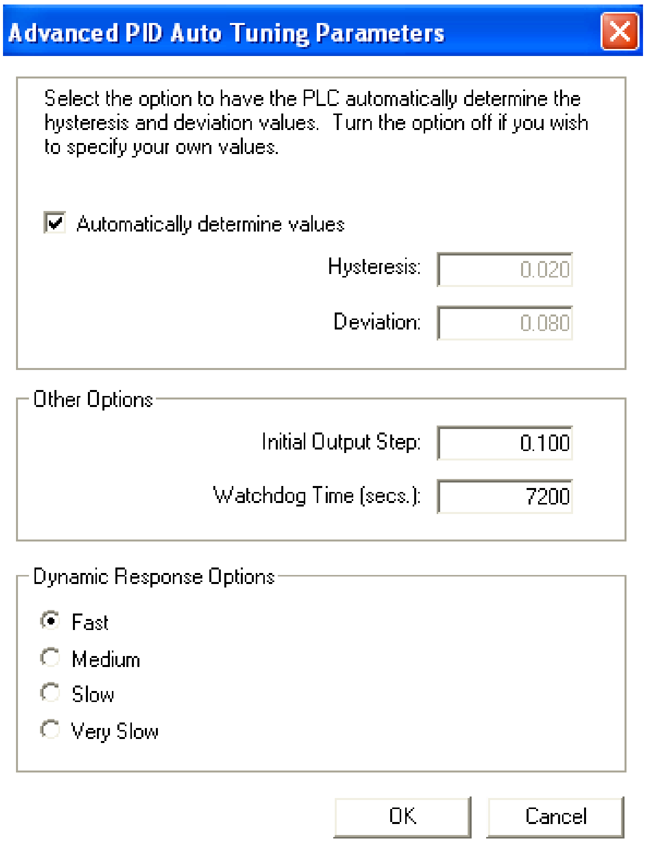
● Auto Tune
○ Manual

Fig. 9. Start auto tune panel

Table 4

PID constants suggested by PLC self-tuning

PID parameters	Value
Proportional gain Kp	0.52
Integral time Ti	0.021min
Derivative time Td	0.01min



Advanced PID Auto Tuning Parameters

Select the option to have the PLC automatically determine the hysteresis and deviation values. Turn the option off if you wish to specify your own values.

☑ Automatically determine values

Hysteresis: 0.020

Deviation: 0.080

Other Options

Initial Output Step: 0.100

Watchdog Time (secs.): 7200

Dynamic Response Options

● Fast
○ Medium
○ Slow
○ Very Slow

Fig. 10. Advanced PID tuning parameters panel

4. Results and Discussion

The flow rate control was realized by the controller constants determined manually as given in Table 2 and Table 3. The automatic flow control was realized by the self-tuning of PLC and the constants are given in Table 4. The P and PI control actions are realized based on manually calculated results and PID control was realized on based on the self-tuned constants suggested by PLC software. The performance of different actions is compared as under.

4.1 Realization of P Control (Manually Tuned)

Based on the performed tests, the closed loop P controller was realized with Kp = 1.25, Ti = ∞, and Td = 0, the response representing the offset error is presented in Fig. 11. Initially, the flow rate is 12% (0.72L/min) greater than SP. The flow rate of water remained 5.65% (0.339L/min) as the SP is varied to 2.5L/min and that is greater than the SP. It can be observed that the P controller is unable to suppress the offset error between SP and the PV.

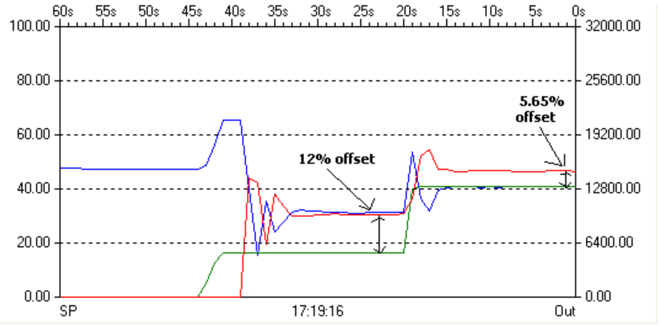


Fig. 11. P control action

4.2 PI Controller Realization (Manually Tuned Loop)

With controller constants Kp=1.13636 and Ti = 5s shown in Fig. 12, the SP was changed in four steps and the PV (flow rate) was following the trend line of the desired values and also depicted the overshoot when the PV crossed the SP. Whenever, SP was changed, initially there were four cycles of PV and after every SP change there was only one oscillation in PV and then it became stable. It can be seen from the figure that the controller output and process are also stable.

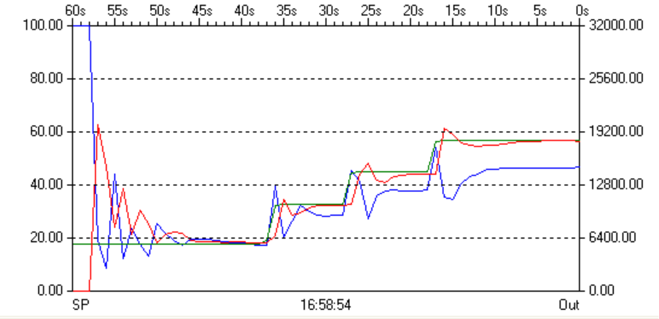


Fig. 12. PI control action with Kp=1.13636 and Ti=5s

However, with the controller constants Kp as 1.1364 and Ti as 2.5s in Fig. 13, the SP is equal to 3.6L/min at the end of the graph, which is 60% of the total flow rate of 6L/min. The PV which is water flowing into the tank is approximately 3.6L/min. It can be observed that incoming flow of water into the tank is tracking the change in the SP smoothly.

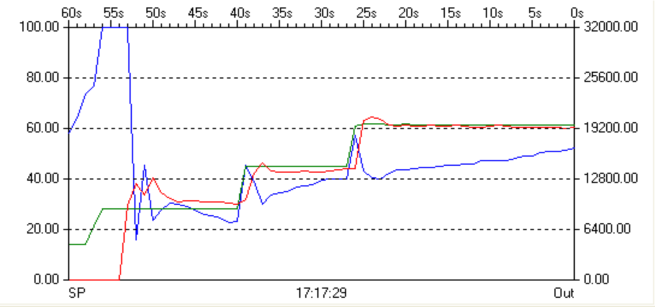


Fig. 13. PI control action with Kp=1.13636 and Ti=2.5s

4.3 Realization of PID Control (Self-Tuned Loop) By PLC

Based on the suggested PID constant through the automatic tuning wizard by PLC given in Table 4, the PID controller was tested on flow rate control loop. Keeping the loop stable and in running conditions the values of PID constants Kp = 0.52, Ti = 0.021min, and Td = 0.01min were entered in PLC. The achieved close loop response is shown in Fig. 14, which is highly desirable, showing no overshot, no offset, and no oscillations. As shown in the graph, the inflow rate of water in the tank is almost equal to the desired SP, which is approximately 4.92L/min. It can be observed in Fig. 14, that the incoming flow rate of water is tracking every variation in the SP and the controller output is changing in the opposite direction of PV with a stable change.

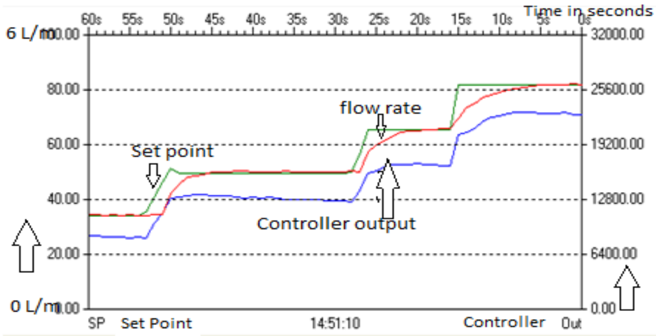


Fig. 14. Auto tuned flow loop

5. Conclusion

In this paper, an experimental study is carried out on flow rate control loop by finding PID constants and putting the loop (process plant, measuring sensors, and PLC) in operation has given stable results. It was observed that manually tuned loops based on Z-N rules the P and PI control can be observed on flow rate control for a plant with an unknown mathematical model. Proportional control has provided the flowrate control with an offset error of 5.65%. PI control loop displayed very less amount of offset error between set point and flowrate. However, loop tuning performed automatically through GUI of PLC wizard has yielded better results compared to the manually tuned loop in terms of having lesser overshoot, offset error, and set-point tracking. The automatic tuning takes less time as compared to manual tuning in which repeated tests are to be performed to achieve sustained oscillations and then calculate controller constants. The experimental method is useful to tune the process loops in industrial applications for achieving stability where plant mathematical models are not available or unknown.

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