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Reconditioning and Enhancement of Automatic Pressure Control Equipment for Servo and Regulatory Processes

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Abstract

Control Systems have taken essential parts widely from industrial world to military equipment. Control systems in the industrial world determine the quality, speed, cost and efficiency of the manufacturing process known as the Process Control System (PCS). The core of the Control System is conditioning (actuators) and reading conditions (sensors). By synergizing those parts with the coordination of the controller, the process value (PV) can be obtained according to the condition of the set point (SP). To get the proper control characteristics, i.e. the fastest possible response, the lowest possible oscillation and offset (error steady state/ESS), an understanding of the concept of a closed loop control system with a continuous scheme is developed. In this regard, the Automatic Control Laboratory under the Pneumatic and Hydraulic Laboratory at the Department of Mechanical Engineering - POLBAN considered to provide students with an introduction to Automatic Instrumentation and Control. The briefing covered the introduction, mechanism and operation of Automatic Instrumentation and Control systems. Therefore, tools were required as a medium for achieving the above competencies, one of which was the modernization of pressure regulators in order to strengthen the Laboratory. Through this research, a rejuvenation and modernization of the control system were carried out by applying a proportional, integral and differential (PID) control system. It was based on a programmable logic controller (PLC) equipped with a human machine interface (HMI) to make it easier to enter set points and PID parameters, to be practical in operation and effective in monitoring and data acquisition. The result of the pressure regulator modernization had the ability to include servo control process (getting a certain value) and regulatory control process (maintaining a certain value) with a continuous closed loop scheme. The modernized pressure control system could be utilized as a prototype demonstration of the system in an actual environment to study and observe the Proportional, Integral and Differential (PID) control system along with the process of determining the parameters Kp, Ti and Td as Practicum equipment.

Keywords: sensor; actuator; PLC; PID control; process.

1. Introduction

The development of instrument and control system technology in industry is growing rapidly, the PID (Proportional Integral Derivative) control system [1] is the preferred technology to be implemented in the needs of the control process in the world of industry, defense and security. The application of Automatic Instrumentation and Control systems in the Process Industry is related to economic aspects. The focus is on producing quality product according to criteria in a short time so that production costs are reduced, and the efficiency of machine time is increased. In response to this, through a vocational higher education institution at the Bandung State Polytechnic in the Department of Mechanical Engineering [2], a curriculum was designed to support similar process control activities. Moreover, the activities were carried out through an educational approach to the introduction, mechanism and operation of Automatic Instrumentation and Control Systems that can be varied and set to determine the response of certain measurable phenomena. By implementing this stages, vocational students can master or expert in the field of process control before going into the Industrial world [3].

Educational teaching tools for practicum that support teaching and learning activities on instrumentation and process control are available at the Pneumatic, Hydraulic and Mechatronics Laboratory, Mechanical Engineering Department, Bandung State Polytechnic [4]. The tool in question is a pressure control simulator equipped with pressure transducer and actuator features in the form of a pneumatic servo valve, as shown in

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Figure 1. Preliminary activities were conducted to check the sensor components, actuators, and mechanical components in general. The results were still functioning properly, but there was a control system installed, which was an old type that had been discontinued, and it was not functioning so that the tool could not be used for teaching and learning activities with practicum [5].

Figure 1. Pressure regulator practicum tool

One of the developing and widely needed technologies is Automatic Instrumentation and Control given in several study programs in the Department of Mechanical Engineering [4]. In line with this matter, Automatic Instrumentation and Control props were required, which provided a more complete and comprehensive understanding of lectures in theory and practice. The purpose of this laboratory capacity improvement research activity was to modernize tools by reconditioning and enhancing of automatic pressure control equipment for servo and regulatory processes.

2. Experimental Methods

Through laboratory capacity building research, funded by schemes with internal institutional research budget allocations, a modernization of pressure regulators was done with Proportional, Integral and Differential (PID) control systems, program bases with programmable logic controllers (PLC) and human machine interfaces (HMI) that can simplify the process of inputting set points and PID parameters. The operation was practical and effective in monitoring and data acquisition. Instruments, actuators, and controllers used were the same as industry standard components that were easy to obtain information. The tool could be utilized by students so that they can be skillful, proficient and adaptive in facing problems in the industry [6].

Modernization of equipment covered inventory types, technical specification sensors, existing actuators inventory, and control systems replacement (controllers) that had been discontinued. After determining the selection of the control system used, the next step was equipping communication devices that help students to practice in studying Automatic Instrumentation and Control. Modernized equipment testing was carried out to obtain information on the performance and feasibility of the pressure control system as a simulation tool for teaching and learning activities through automatic instrumentation and control practice.

The research method was applied with modernization to strengthen the pneumatic, hydraulic and mechatronics laboratories. The flow chart of activities was illustrated in Figure 2.

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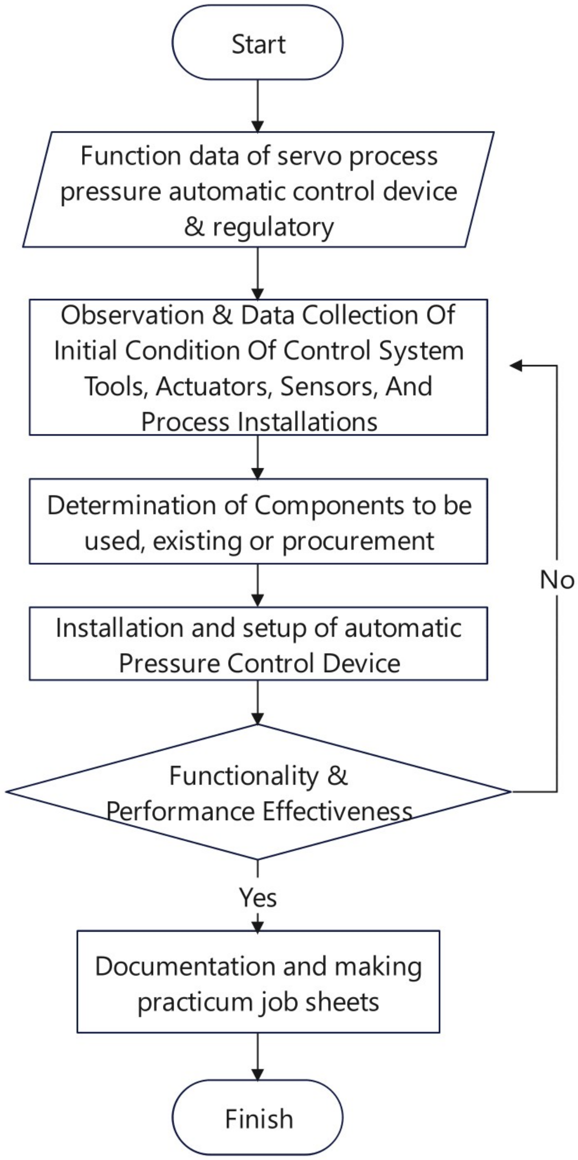

Figure 2. Activity flowchart

2.1. Pressure Regulating System initial conditions (existing)

The performance data of the existing device was tested, by means of signal treatment in the form of an electric current of 4÷20 mA fed to the electric servo valve [7]. The control signal response results were in a pneumatic signal of 20÷100 kPa. The pneumatic signal was the input feed of the pneumatic servo valve that could open the main valve from 0÷100% opening. The existing equipment available was shown in Figure 3.

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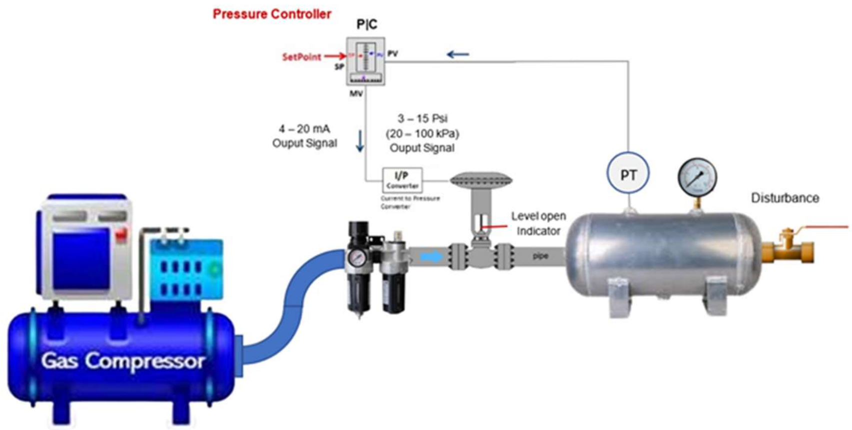

Figure 3. Schematic of initial condition formation Pressure regulator

2.2. Pressure Regulator System after reconditioning

The purpose of modernizing the Pressure Regulator tool in the pneumatics, hydraulics and mechatronics laboratory, Mechanical Engineering Department, was to activate practical tools by migrating the control system (controller), which originally used a microcontroller base to a PLC base. PLC allowed users to obtain the preferred control characteristics as shown in Figure 4.

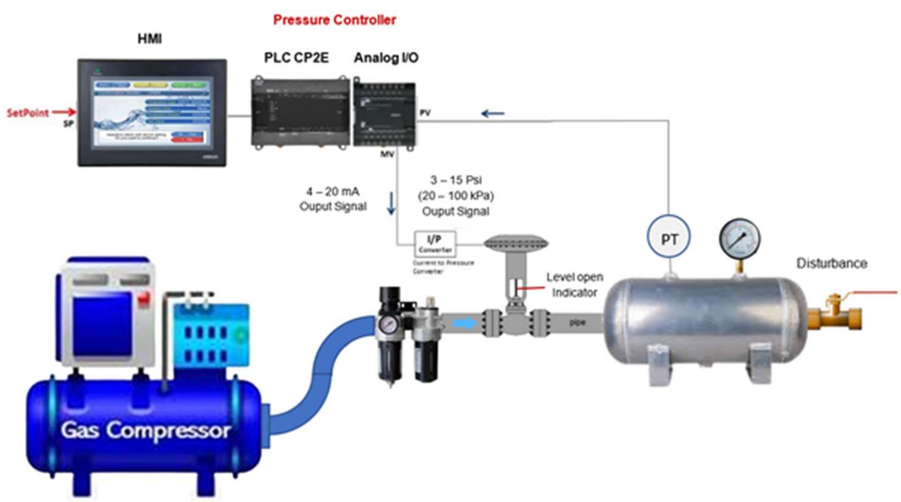

Figure 4. Schematic of the formation after reconditioning the pressure regulator

The current PLC did not feature analog input and output ports; hence, an analog input/output (I/O) module was required as an Analog to Digital Conventer (ADC) and Digital to Analog Conventer device conversion. To simplify the operation of the reconditioned pressure regulator, it was also necessary to equip it with human and machine communication tools, known as Human Machine Interfaces (HMI). This tool allowed the user to facilitate communication with the machine, by entering the set point (SP), Proportional, Integral and Differential (PID) parameters [8]. The configuration of the HMI, controller and I/O ports was shown in Figure 5.

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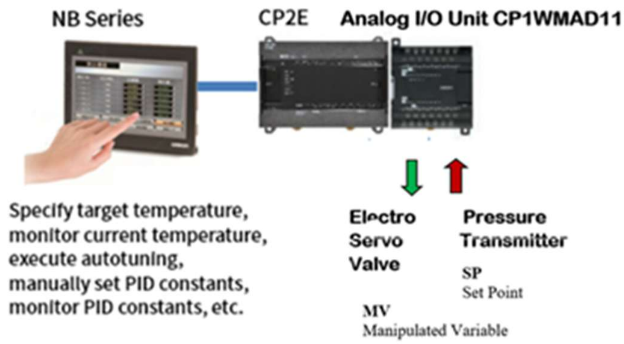

Figure 5. HMI configuration – controller – module I/O

3. Results and Discussion

The results and discussion were composed in accordance with the flowchart of activities shown in Figure 2, which consisted of 6 stages.

3.1. Function Data of Automatic Control Tool Pressure Servo & Regulatory Processes

Tools that can show the interaction between control system components were required in the teaching and learning activities for the practicum of automatic control courses. The ability of the tool to perform servo and regulatory processes was in line with the expected conditions (Figure 6).

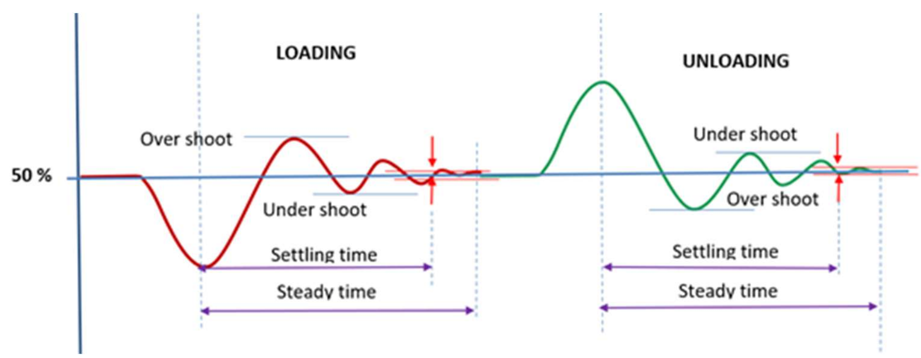

Figure 6. Regulatory process in control systems

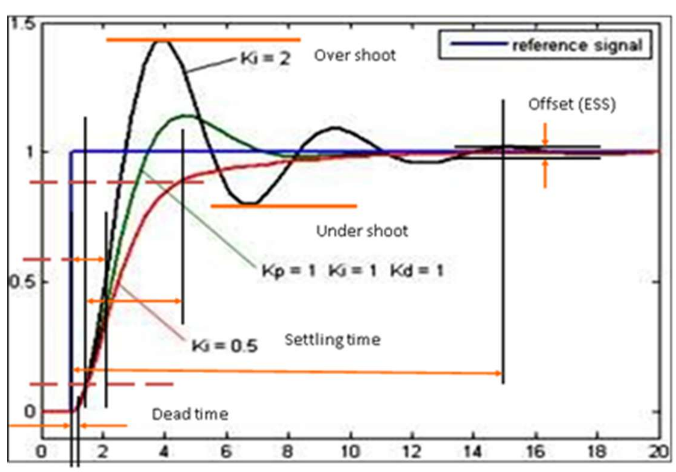

Figure 7. Response characteristics of automatic control systems

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Meanwhile, tool performance information was in the form of quality control, such as speed of response (deadtime, rise time, settling time, steady time) and process value oscillations (over shoot, undershoot, offset/ESS) [9], as illustrated in Figure 7.

3.2. Observation & data collection of equipment initial conditions

Migration of the pressure control system replacement was required. The initial condition data must be known; thus, it could monitor the initial performance of the entire system. From the observation results, performance information from the plant and sensors could be obtained [10].

3.3. Actuator

The plant (controlled system) consisted of two important parts, namely the actuator and the process. The actuator got a manipulated variable (MV) signal that had the main function to adjust the process in order to produce a process value (PV). Furthermore, the process value was matched with what the user wanted in the form of a set point (SP), the Installation block in Figure 8.

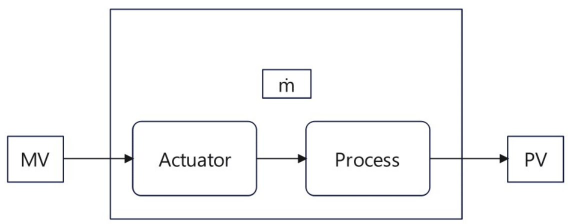

Figure 8. Installation block diagram of pressure regulator

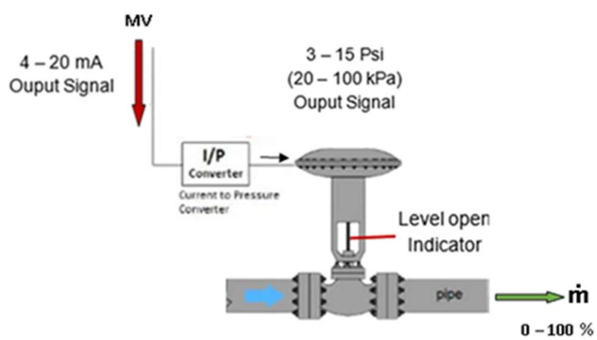

Figure 9. Actuators on pressure regulator installations

Tests were carried out by providing a manipulated variable signal (MV) in the form of variations in electric current in the range of 4-20 mA. According to the industry standard signal on the Electronic Servo Valve, the range of 4-20 mA can produce a pressure of 20-100 kPa. Therefore, the Electronic Servo Valve was also referred to as a converter from current to pressure (I/P Converter), as shown in Figure 9. Simulation of control signals (MV) used 4-20 mA electric current simulator tools.

Signals in the form of pressure changes (20-100 kPa) resulting in the conversion from current to pressure given as input to the Pneumatic Servo Valve. The input of Pneumatic Servo Valve was used as a control signal for opening the valve that supplied air into the tank in the form of a mass flow rate ($\dot{m}$) with units of kg/s. The mass flow rate through the main valve filling the tank could also be interpreted in quality as a 0-100 % valve opening.

This mass flow rate was employed to fill the tank, which allowed the tank pressure to be as the preferred value at the set point (SP). The cause of the pressure in the tank depended on the accumulation of air mass

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contained in the space in the tank (tank volume) based on the ideal gas equation approach. The amount of mass (m) contained in the tank depended on the speed of the incoming mass flow rate ($\dot{m}$) over at certain time (t).

$$P = \frac{m}{V} RT \quad (1)$$
$$m = \dot{m}t \quad (2)$$

where P is Tank pressure (Pa), 1 bar = 10^5 pa, m is Mass of air in the tank, R is Ideal gas constant 287 J/kg.K, and T is Temperature in Kelvin.

The test results were listed in Table 1 with the current varied using a current simulator, and the pneumatic signal was in the form of pressure measured with a pressure gauge with an accuracy factor of 0.05 bar. For valve opening, it could be observed through the valve stem increase indicator on a scale of 0-100 %.

Table 1. Initial condition check of the actuator in the pressure regulator system

No.	Manipulated Variable (mA)	I/P Conversion (kPa)	Opening Level (%)
1	0.00	0.00	0.00
2	4.00	30.00	0.00
3	8.20	55.00	12.50
4	12.00	85.00	25.00
5	16.00	100.00	50.00
6	20.00	105.00	50.00

The initial test results according to Figure 10, there was a deviation in the conversion of electric current (mA) to the output of the electro servo valve in the form of pressure (kPa).

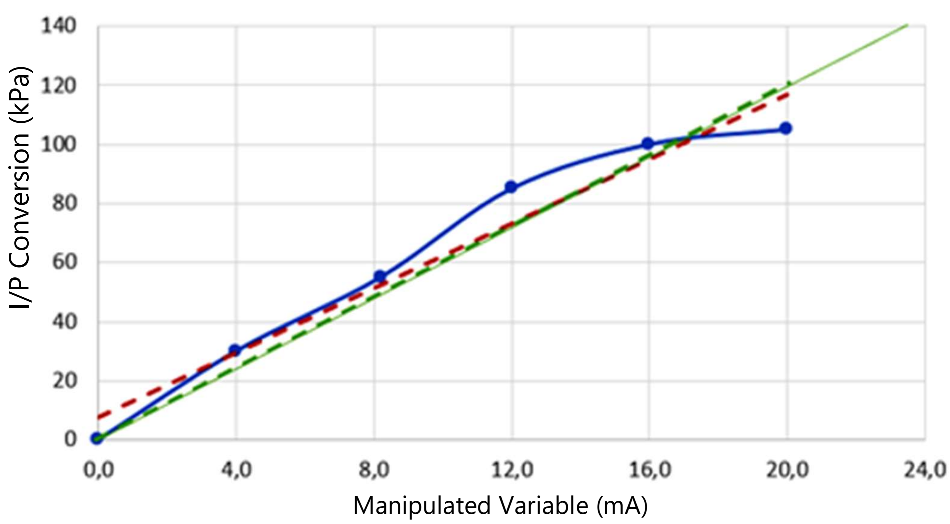

Figure 10. Manipulated variable (mA) dan I/P conversion (kPa) before reconditioning

The initial test result of the pressure control equipment showed that the electro servo valve components did not require reconditioning steps in the form of resetting and calibration.

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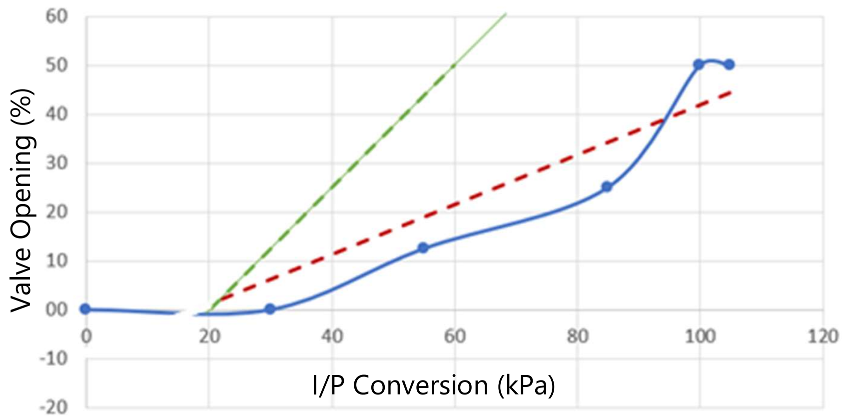

Figure 11. Correlation of I/P conversion (kPa) with valve opening (%) before reconditioning

Another component that was applied to the test was the pneumatic servo valve component, which had the function of converting 20-100 kPa pneumatic signals from the electro servo valve output into 0-100 % openings on the main valve. Testing the pneumatic servo valve produced a performance graph shown in Figure 11.

Observations on the pneumatic servo valve test revealed actual performance deviations. Hence, the need for tuning and calibration to achieve performance is close to ideal conditions. Calibration included offset and gain to get performance close to the ideal line [11] as shown in Figure 12.

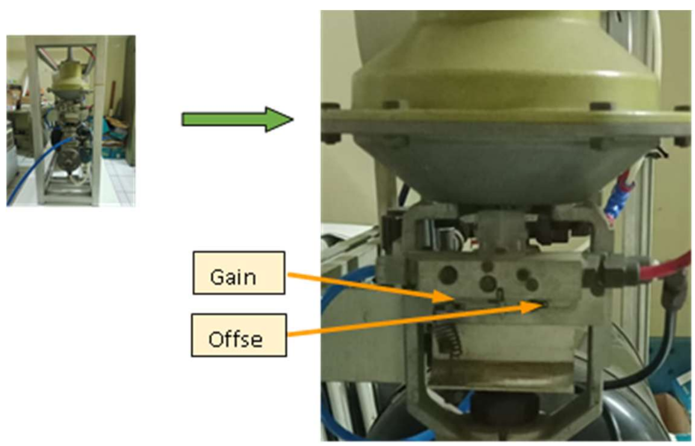

Figure 12. Fluid-mechanical calibration of pneumatic servo valve

3.4. Pressure Transmitter

The development of a pressure regulator used pressure transmitter (PT) with a working area of 0-4 bar. As a result, the transmitter could emit an electric current of 4-20 mA . The performance of the pressure transmitter must be observed to ensure that it was still operating properly. The test results were shown in Figure 13.

Examination of the pressure transmitter used in the pressure setting produced a graph showing good conditions. The available pressure transmitter could be employed and did not need to be recalibrated or replaced. The working area of the pressure transmitter was at a pressure threshold of 4 bar, so in its use, the set point was limited to 0-4 bar.

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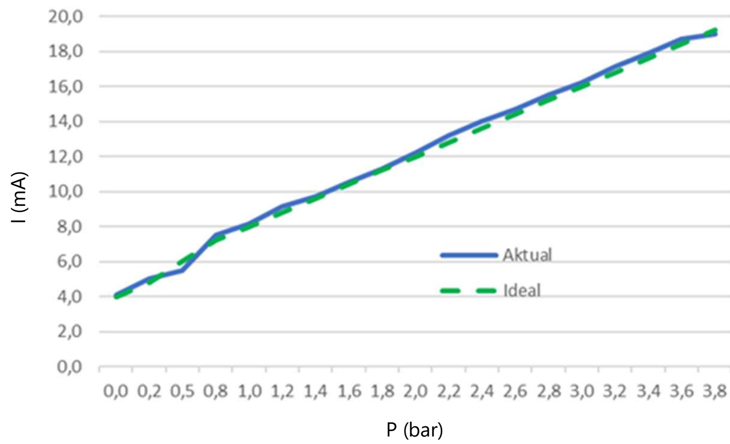

Figure 13. Pressure transmitter test results, I (mA) vs P (bar)

3.5. Determination of Components to be Used; Existing or Procurement

Determination of the components used and some components added and replaced through procurement, had been conducted preliminary testing as shown above. Observations and tests determine the components used and those added or replaced were shown in Table 2.

Table 2. Condition of pressure automatic control components

No.	Components	Condition (%)	Status
1	Electro Servo Valve	90	In use
2	Pneumatic Servo Valve	55	In use
3	Pressure Transmitter	95	In use
4	Pressure gauge	95	In use
5	Piping and Valves	80	In use
6	Tank	95	In use
7	Controller	100	Replacing the
8	Port I/O	100	control system and
9	HMI	100	operation panel
10	Power Supply 24 VDC	100	In use

From Table 2, condition of tools and components in the plant could be used without replacement. Despite components with 55% of normal conditions, this would not directly affect the servo or regulatory process. This however affected the speed of response known as rise time, which was the time required for the process value to catch up with the tuning point.

Replacements were made to the control and communication systems between the equipment and the operator. The control system was replaced using a PLC with PID programming capabilities. In addition to having these capabilities using a PLC, a device (Human Machine interface) could also be used; thus, it was more communicative in the equipment operation. The use of PLC also allowed communication between devices using Ethernet network communication so that it could be developed as Industry 4.0 learning [12].

3.6. Installation and Setup of Automatic Pressure Control Devices

The installation step was done after ensuring the condition of the components and determining the components used. A slight modification was executed for the placement of the operator interface device and the tool in the form of an HMI (Human Machine interface) touch screen to facilitate the operation of the tool. The placement of the control system including equipment modifications, which consisted of a CPU unit, Port I/OT Module The appearance of the HMI was shown in Figure 14.

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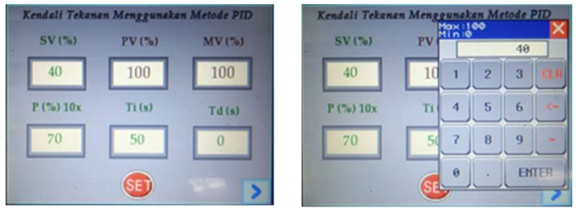

Figure 14. Input display of tuning points, PID parameters and process

3.7. Testing the suitability of the function and performance of the tool

Testing was done to see the pressure regulator system had worked properly based on the PID control scheme. There were three parameters set in PID control, Kp as proportional control gain (%), Ti as integral response time (s), and Td as differential response time (s). Generally, the proportional gain was used to speed up the response, the integral response time used to eliminate the offset, and the differential response time used to dampen the oscillation with the results shown in Table 3.

Table 3. Effect of Kp. Ki and Kd parameters on PID control

Response	Rise Time	Overshoot	Setting Time	Steady state error
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Decrease
Kd	Small Change	Decrease	Decrease	No Change

As in $K_d = K_p T_d$ and $K_i = \frac{K_p}{T_i}$

Testing was carried out by inputting the set value (SV) through the HMI followed by PID settings in Kp (%), Ti (s) and Td (s).

3.7.1 Pressure Regulatory with Closed Loop Scheme On-Off Servo Process

This scheme employed arithmetic operations in the form of proportional correction calculations (Kp), Integral (Ti) and Differential (Td) [13]. The controller would decide to signal (MV) of 4 mA (Off condition) and 20 mA (On condition) [14], as shown in Figure 15. The high quality of the settings could be measured by the faster response, the smallest possible oscillation and the smallest possible offset/error steady state (ESS) [15]. The test data could be seen in Table 4.

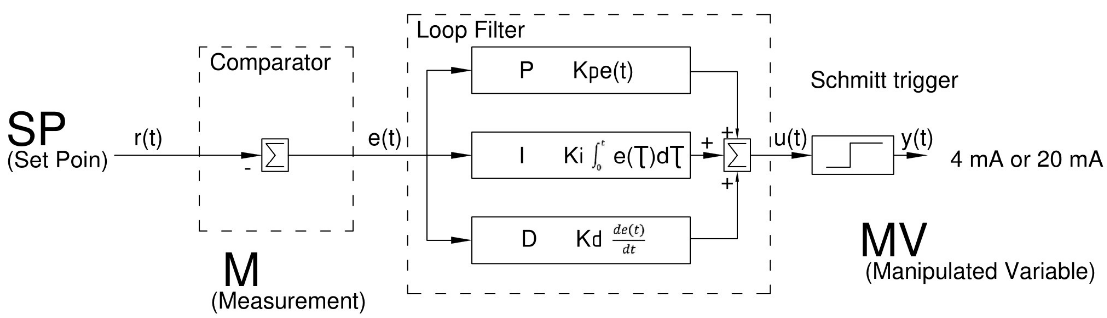

Figure 15. Schematic of closed loop on-off controller

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Table 4. Servo process with Kp, Ti and Td variants

No.	SP1 (%)	SP2 (%)	t (s)	PID
1	20	40	58.31	Kp=100 %, Ti=10 s, Td=10 s
2	20	60	204.07	
3	20	40	50.50	Kp=150 %, Ti=10 s, Td=10 s
4	20	60	126.04	
5	20	40	63.23	Kp=100 %, Ti=8 s, Td=10 s
6	20	60	175.55	
7	20	40	61.54	Kp=100 %, Ti=10 s, Td=8 s
8	20	60	145.61	

The observation results from Table 4 were then processed into a pressure regulatory response graph. The graph could show the effect of determining the parameters Kp, Ti and Td on the speed of response of the pressure control system. There were 4 variants of PID parameters, each of which showed the response time required to change SV_1 to SV_2 as shown in Figure 16.

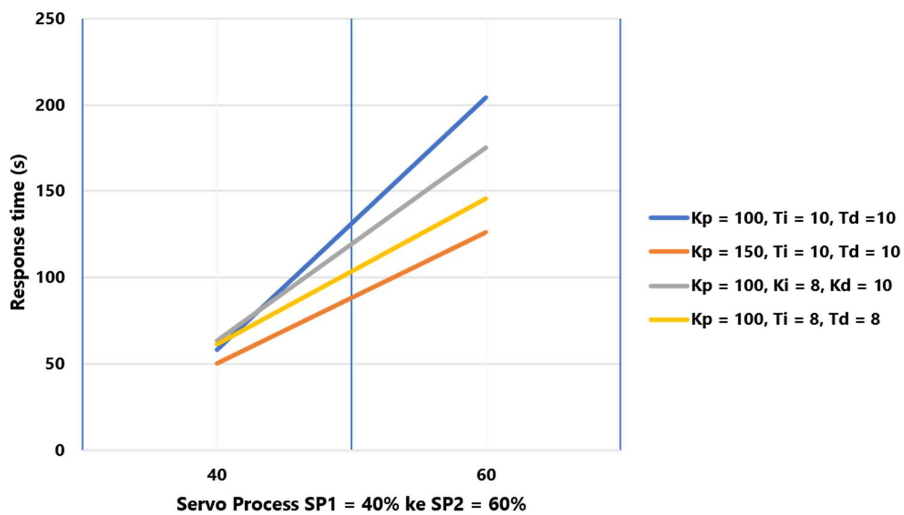

Figure 16. Response time with variants of Kp, Ti and Td

From the examination of Pressure Regulator function showed that the equipment had functioned properly and was in line with the concept of setting using a controller with PID operation. PID parameter settings as in Kp = 150 %, Ti = 10 s and Td = 10 s had the fastest servo process time to reach the destination SP (SP2) in 50.5 s to change from SP1 = 20 % to SP2 = 40 % and took 126.04 s to change from SP1 = 20 % to SP2 = 60 %.

Furthermore, Kp = 100 %, Ti = 10 s and Td = 8 s showed the impact of adding differential operation gain from Td = 10 s to Td = 8 s (Kd ≈ Td). The addition of Kd gain accelerated the speed to achieve stability. In the test, it was obtained that the servo process time reached the destination SP (SP2) in 61.54 s to change from SP1 = 20 % to SP2 = 40 % and took 145.61 s change from SP1 = 20 % to SP2 = 60 %.

On the other hand, the addition of Integral gain (Ki ≈ 1/Ti) with the parameter set Kp = 100 %, Ti = 8 s and Td = 10 s in the test showed a faster response compared to the parameter set Kp = 100 %, Ti = 10 s and Td = 10 s. This was in accordance with the concept of regulatory using a controller with PID operation in Table 3 about the impact of integral gain (Ki) together with proportional gain (Kp) affects the response of the process value (PV).

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3.7.2 Pressure Regulatory with Closed Loop Scheme Continous Servo Process

Arithmetic operations in this scheme were employed in the form of proportional (Kp), Integral (Ti) and Differential (Td) correction calculations [16]. The results of the arithmetic operation would enter the signal conditioner to translate the results of the PID operation into a signal (MV) [17] of 4 mA to 20 mA, as seen in Figure 17.

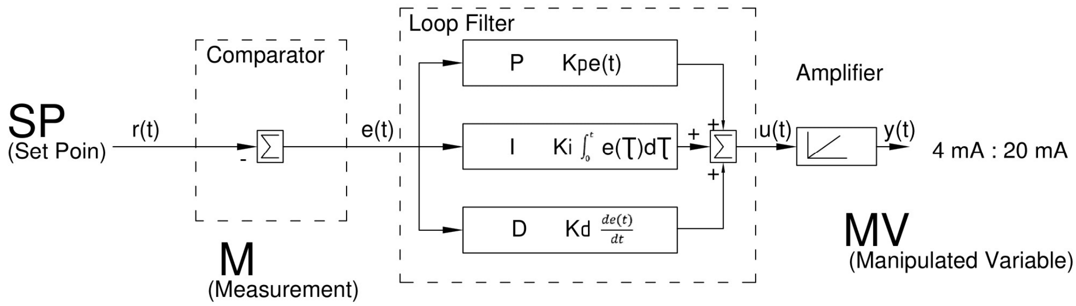

Figure 17. Closed-loop on-off controller schematic

Observations of the pressure setting servo process were presented in Table 5. The observation results were provided through a graph of the response time to changes in the initial set value (SV_1) to the final set value (SV_2).

Table 5. Pressure regulator system response with PID parameter variation

No.	Kp (%)	Ti (s)	Td (s)	RT (s)	ST (s)	OS (%)	US (%)
1	100	10	10	10.16	140	59	44
2	150	10	10	10.20	145	61	43
3	150	8	10	10.81	160	60	44
4	100	8	10	9.76	147	58	44
5	100	10	8	10.40	100	59	44
6	150	10	8	10.50	110	61	43

a) Effect of changing Kp (Proportional gain)

From the test results, the effect of Kp would be evaluated by comparing data number 1 to number 2 shown in Figure 18. By raising Kp from 100 % to 150 % percent, the system response became larger, and there was an over shoot from 59 % to 61 %. In addition to the increase in over shoot, the time to get steady time (ST) also increased from 140 to 145 s. Based on the results, it could be seen that raising the Kp value must be followed by operating Ti and Td with the right values.

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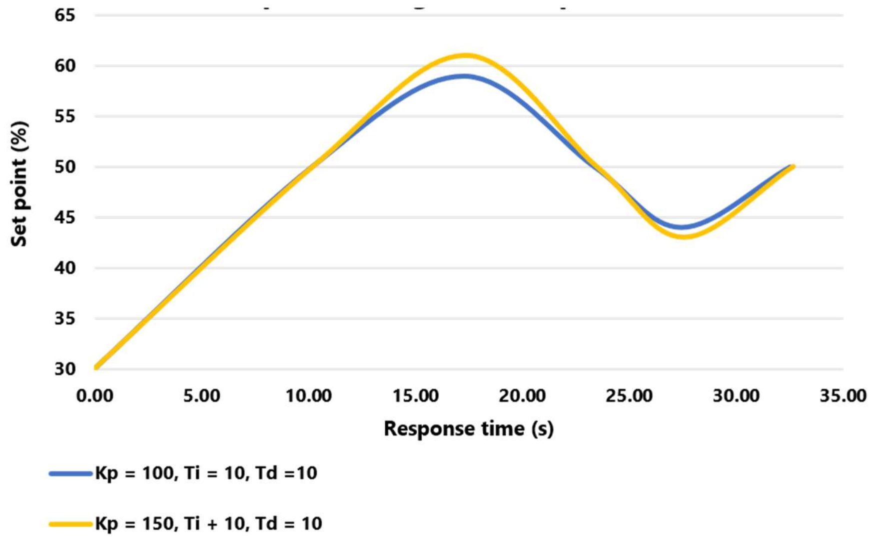

Figure 18. Effect of increasing Kp value on pressure regulator response

b) Effect of changes in Ti (Time respon integral)

The effect of changes in Ti was tested by increasing the gain Ki, which meant lowering the price of Ti from 10 to 8 s. The effect of changes in the value of Ti was done by comparing data number 1 as a reference to data number 3 and 4. The results of the observations were depicted in the graphs shown in Figure 19. By increasing Ki, which was done by decreasing the value of Ti, the system response became faster to get the intended value (SP2), but there was an increase in time to reach steady state from 140 to 147 s. This happened since the addition of Kp and Ki together would respond to errors that occurred as the preferred difference (SP) with the process value (PV) that occurred more responsively.

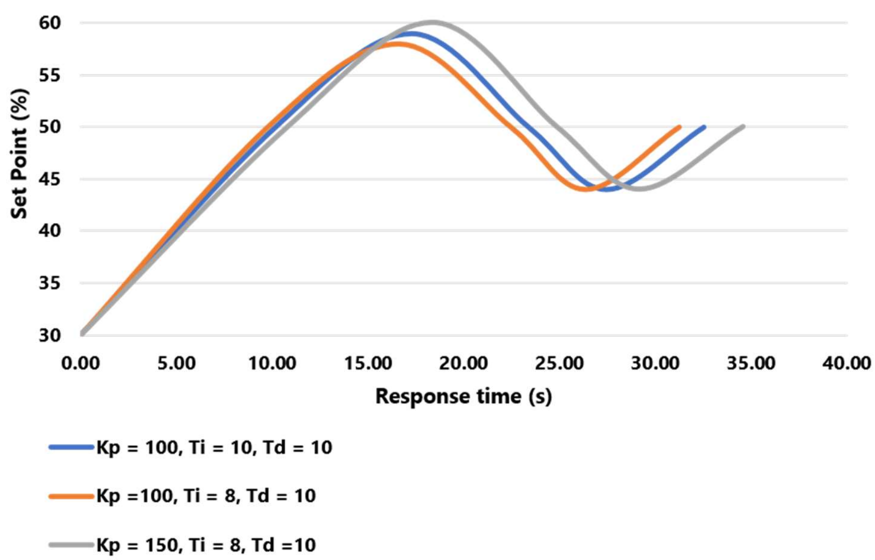

Figure 19. Effect of decreasing Ti value on pressure regulator response

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c) Effect of changes in Td (Time response differential)

The effect of changing Td could be seen by comparing data no. 1 as a reference to data no. 5 and data no. 6. The observation results were graphically depicted in Figure 20. By lowering Td from 10 to 8 s, the system response became faster to reach steady state (TS) from 140 to 100 s. Likewise, increasing Kp from 100 % to 150 % by lowering Td got a faster time to reach steady state (TS) from 140 to 110 s.

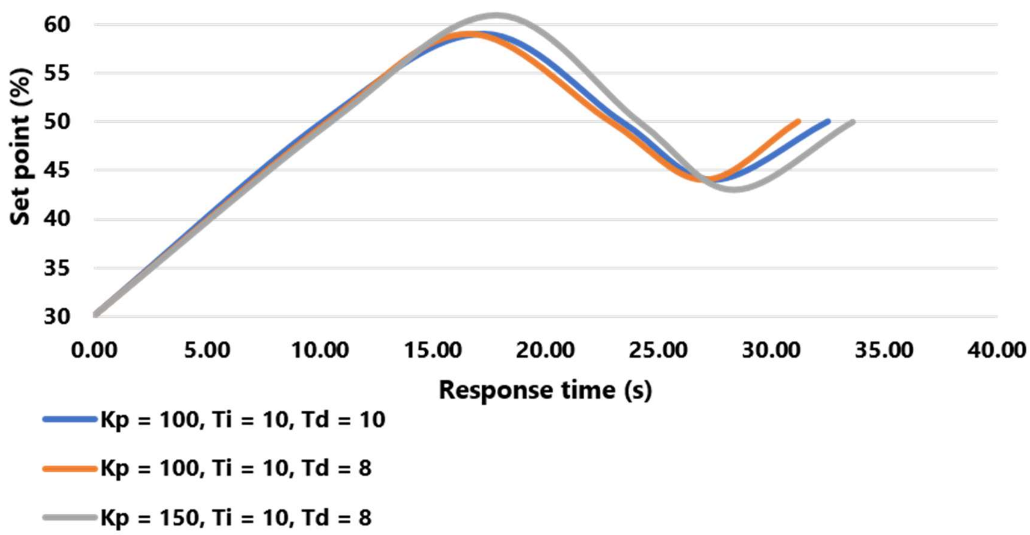

Figure 20. Effect of decreasing Ti value on pressure regulator response

3.7.3 Pressure regulator with closed loop scheme Continuous regulatory process

In the process of observing the regulatory process in pressure regulator, the process value (PV) was set at 50 %. Changing the PID parameters observed the ability of the pressure regulator to maintain/regulate the value that had been achieved. Observations were made by providing disturbance to the pressure regulator system by loading and unloading. The observation results were presented in graphical form in Figure 21 from the observation data in Table 6.

Table 6. Testing the Regulatory process on the Pressure Regulator

	Loading			Unloading	
	PV (%)	t (s)		PV (%)	t (s)
Kp=150 Ti=10 Td=10	50	0.00	Kp=150 Ti=10 Td=10	50	0.00
	30	5.10		60	5.10
	50	12.50		50	12.00
	58	17.50		47	15.60
	50	23.75		50	19.20
	46	27.50		56	24.00
	50	32.50		50	31.00
	50	91.00		50	249.00

The process was conducted with PID parameters Kp value = 150%, Ti = 10 s and Td = 10

a) Recovery process from loading

During loading, the process value (PV) decreased to a value of 30 %, or decreased about 20 %, and would be immediately responded to the control system in order to recover to the same process value as the set point (SP) value of 50 %. The recovery process occurred overshoot or excess response by 8 %, or the process value had

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reached 58 %, whereas in the reverse process over shoot occurred under shoot (US) by 4 % or had returned down to the process value of 46 %.

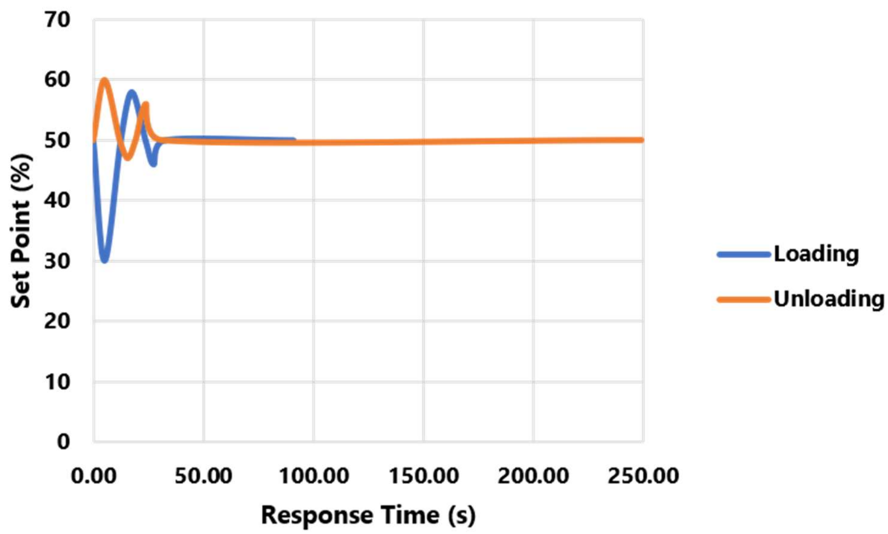

Figure 21. Regulatory process with loading and unloading

b) Recovery process from unloading

The response of the pressure regulator was also observed when the load was removed or released in the pressure regulatory process. At the time of unloading, the process value (PV) would rise to a value of 60 % or an increase of about 10 % and would be immediately responded to the control system in order to recover to the same process value as the set point (SP) value of 50 %. In the recovery process, there was an overshoot or excess response of 3 %, or the process value had dropped to 47 %. On the other hand, in the reverse process of overshoot, there was an under shoot (US) of 6 % or had dropped back to the process value of 56%.

From the two experimental results, it could be seen that the control system could recover the process value (PV) by 50% with different response characteristics. The time required to reach a steady state in the loading regulatory process was 91 s while for the reverse process it reached 249 s. This was influenced by the speed of the air leaving the tank slower than the speed of the pneumatic servo valve filling the tank. This condition could be different when applied to flow regulatory or temperature regulatory.

4. Conclusion

The usage of PLC as a controller with HMI as a communication device could facilitate the operation of the pressure regulator in inputting set point (SP) values and PID parameters. It also enables process monitoring since the communication was more interactive and attractive. In controllers that did not have analog outputs could use pressure regulatory with On-Off closed loop schemes with process values (PV) having upper and lower limits depending on the system device (hardware) and programming (software). The response characteristics of pressure regulator with a continuous closed loop scheme depended on the system device in the form of a time constant (T), which was proportional to the rise time (RT) value and the PID parameter value. In the regulatory process, the pressure regulator characteristics had a different response between loading and unloading due to the capacity differences between the flow entering the pneumatic servo valve and the flow leaving the tank. Future recommendation about the study is to obtain the optimal value of PID parameters. Besides, tuning needs to be done associated with the characteristics of the pressure regulating device in the form of Dead Time (L) information, where the time required to respond to the control signal (MV) and actuator characteristics in the form of time constant (T).

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