Process Control

Process Control
Pressure, Flow, and Level

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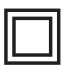
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
∿	Alternating current
⎓∿	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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Preface

Automated process control offers so many advantages over manual control that the majority of today's industrial processes use it to some extent. Breweries, wastewater treatment plants, mining facilities, and the automotive industry are just a few industries that benefit from automated process control systems.

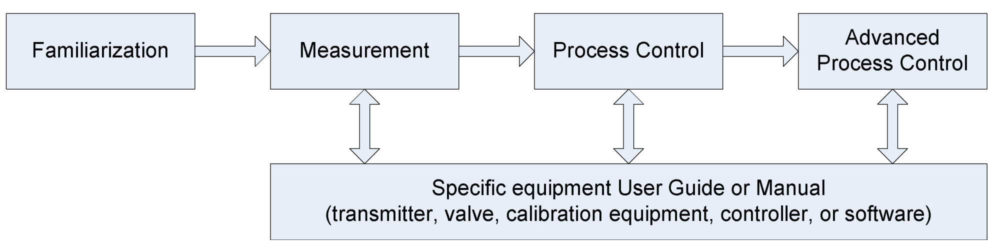
Maintaining process variables such as pressure, flow, level, temperature, and pH within a desired operating range is of the utmost importance when manufacturing products with a predictable composition and quality.

The Instrumentation and Process Control Training System, series 353X, is a state-of-the-art system that faithfully reproduces an industrial environment. Throughout this course, students develop skills in the installation and operation of equipment used in the process control field. The use of modern, industrial-grade equipment is instrumental in teaching theoretical and hands-on knowledge required to work in the process control industry.

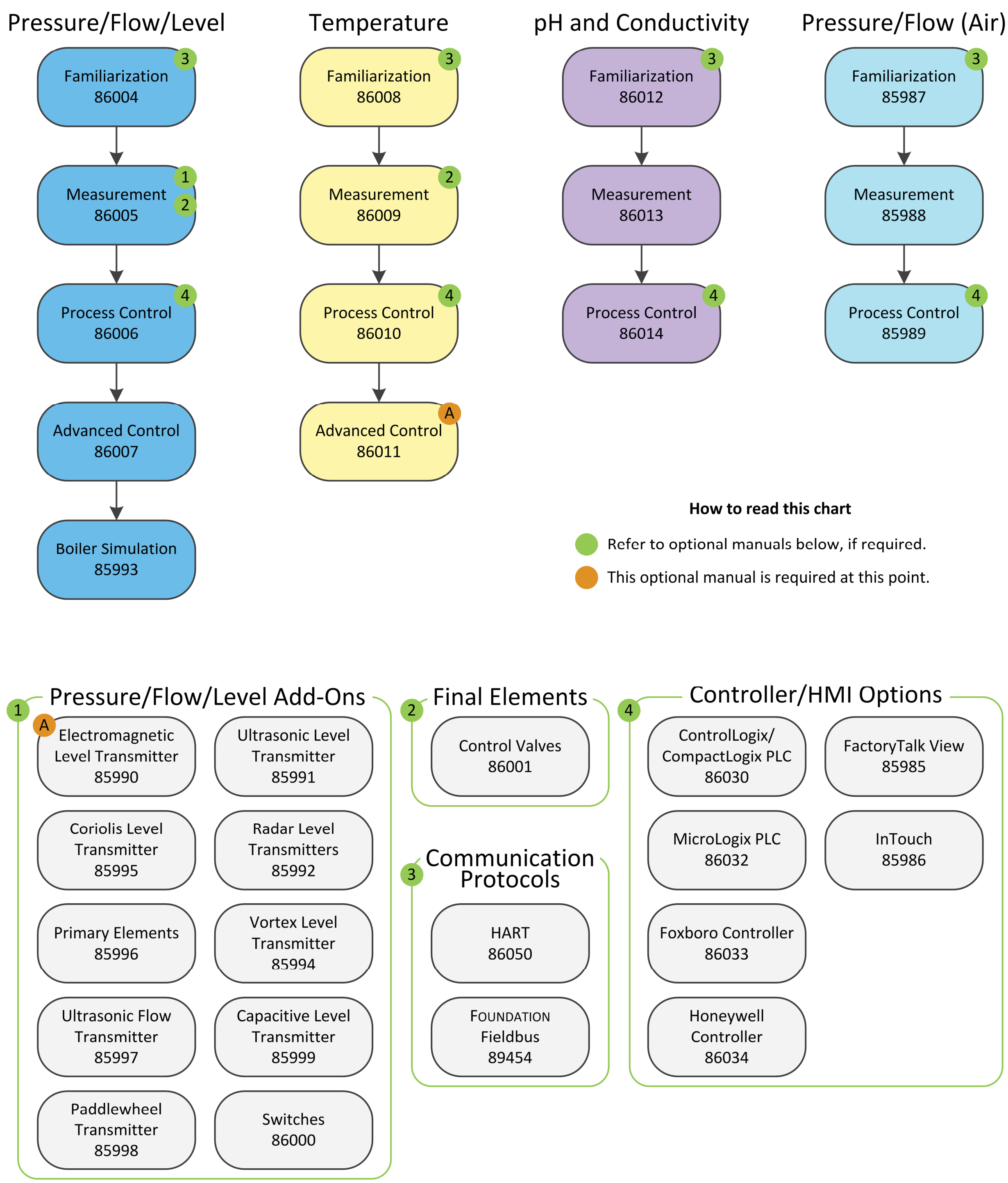
The modularity of the system allows the instructor to select the equipment required to meet the objectives of a specific course. Two mobile workstations, on which all of the equipment is installed, form the basis of the system. Several optional components used in pressure, flow, level, temperature, and pH control loops are available, as well as various valves, calibration equipment, and software. These add-ons can replace basic components having the same functionality, depending on the context. During control exercises, a variety of controllers can be used interchangeably depending on the instructor's preference.

We hope that your learning experience with the Instrumentation and Process Control Training System will be the first step toward a successful career in the process control industry.

Standard Learning Path



Manuals of the 353X Series



Preface

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Process Control Training Equipment – Pressure, Flow, and Level must have been properly installed, according to the instructions given in the user guide Familiarization with the Instrumentation and Process Control System – Pressure, Flow, and Level, part number 86004-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Tuning and Control of a Pressure Loop

EXERCISE OBJECTIVE

Familiarize yourself with the use and manual tuning of P, PI, and on-off control schemes applied to pressure loops.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Recapitulation of relevant control schemes
- Tuning with the trial and error method
  A procedure for the trial and error method. A complementary approach to trial and error tuning.

DISCUSSION

This exercise introduces three control schemes and puts them to use in a pressure process loop. This allows a comparative analysis of the different schemes in terms of efficiency, simplicity, and applicability to various situations. An intuitive method to tune controllers is also presented.

Recapitulation of relevant control schemes

A controller in proportional mode (P mode) outputs a signal ($m(t)$ – manipulated variable) which is proportional to the difference between the target value (SP: set point) and the actual value of the variable ($c(t)$ – controlled variable). This simple scheme works well but typically causes an offset. The only parameter to tune is the controller gain K_c (or the proportional band ($PB\% = 100\%/K_c$) if your controller uses this parameter instead).

A controller in proportional/integral mode (PI mode) works in a fashion similar to a controller in P mode, but also integrates the error over time to reduce the residual error to zero. The integral action tends to respond slowly to a change in error for large values of the integral time T_i and increases the risks of overshoot and instability for small values of T_i.Thus, the two parameters which require tuning for this control method are K_c (or $PB\%$) and T_i (or the integral gain, defined as $G_i = 1/T_i$).

The On-off control mode is the simplest control scheme available. It involves either a 0% or a 100% output signal from the controller based on the sign of the measured error. The option to add a dead band is available with most controllers to reduce the oscillation frequency and prevent premature wear of the final control element. There are no parameters to specify for this mode beyond a set point and dead band parameters. Note that it is possible to simulate an On-off mode with a controller in P mode for a large value of K_c (or a very small $PB\%$).

Tuning with the trial and error method

The **trial and error method** of controller tuning is a procedure for adjusting the P, I, and D parameters until the controller is able to rapidly correct its output in response to a step change in the error. This correction is to be performed without excessive overshooting of the controlled variable.

This method is widely used because it does not require the characteristics of the process to be known and it is not required bringing the process into a sustained oscillation. Another important aspect of this method is that it is instrumental in developing an intuition for the effects of each of the tuning parameters.

However, the trial and error method can be daunting to perform for inexperienced technicians because a change in tuning constant tends to affect the action of all three controller terms. For example, increasing the integral action will increase the overshooting, which in turn will increase the rate of change of the error, which will then increase the derivative action. A structured approach and experience help in obtaining a good tuning relatively quickly without resorting to involved calculations.

A good trial-and-error method is to follow a geometrical progression in the search for optimal parameters. For example, multiplying or dividing one of the tuning parameters by two at each iteration can help you converge quickly toward an optimal value of the parameter.

A procedure for the trial and error method

The trial-and-error method is performed using the following procedure (also refer to Figure 2-25 and Figure 2-26 for PI control):

1. Set the controller in the mode you want to use: P, PI, PD, or PID. Follow the instructions to adjust every parameter relevant to the mode you are using. Note that you can use the PID mode to perform any of the modes by simply setting the parameters to appropriate values (e.g. $T_d = 0$ for PI mode).

Adjusting the P action

2. With the controller in manual mode, turn off the integral and derivative actions of the controller by setting T_i and T_d.respectively to the largest possible value and 0.

The controller gain K_c is related to the proportional band: $PB\% = 100\%/K_c$.

If your controller uses the proportional band, start with a value of $PB\% = 100\%$ and replace instructions to increase K_c by a factor of two by a decrease of $PB\%$ by a factor of two.

3. Set the controller gain K_c to an arbitrary but small value, such as 1.

4. Place the controller in the automatic (closed-loop) mode.

5. Make a step change in the set point and observe the response of the controlled variable. The set point change should be typical of the expected use of the system.

   Since the controller gain is low, the controlled variable will take a relatively long time to stabilize (i.e. the response is likely to be overdamped).

6. Increase K_c by a factor of 2 and make another step change in the set point to see the effect on the response of the controlled variable.

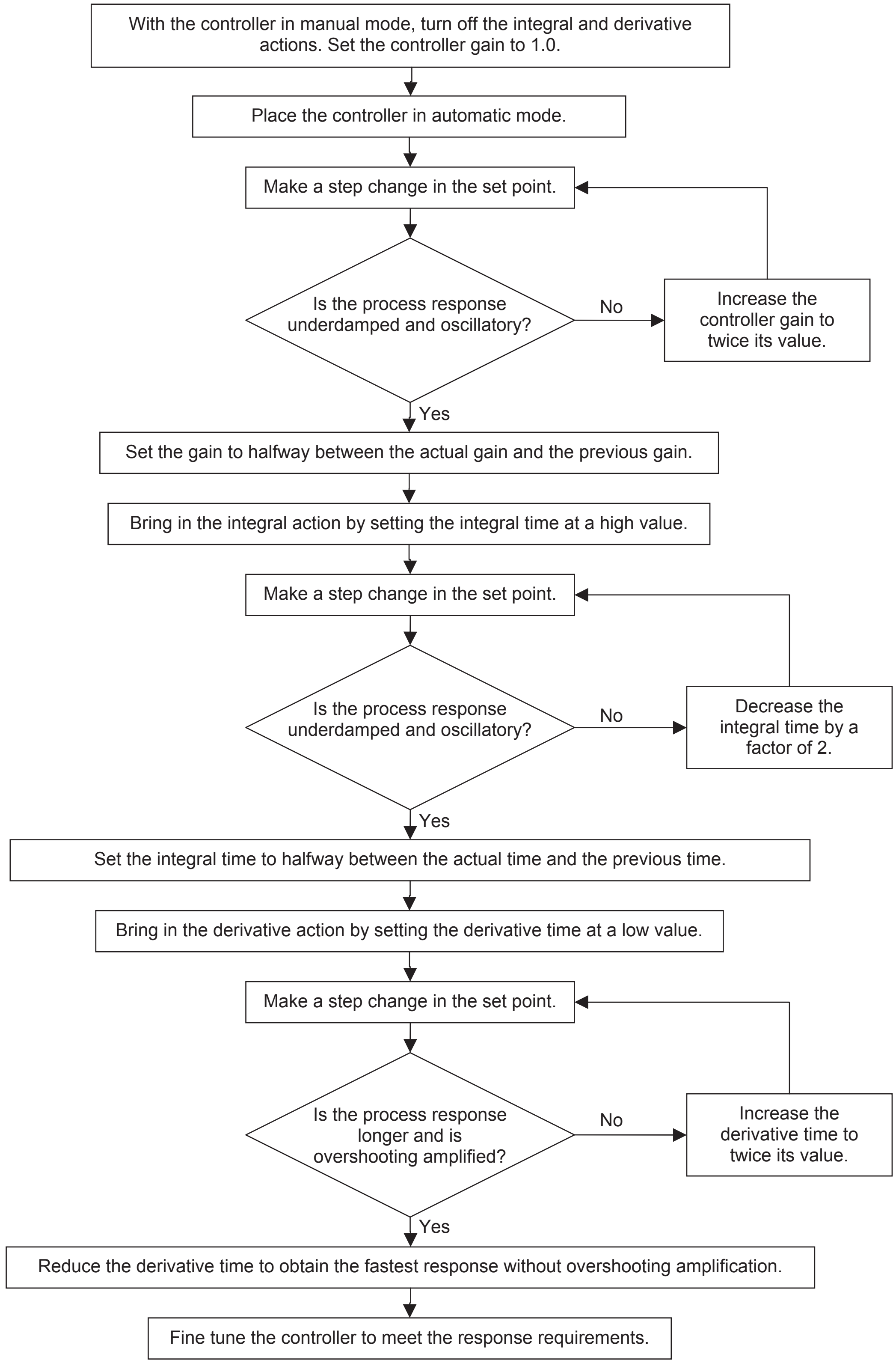


Figure 2-25. Trial-and-error tuning method.

The objective is to find the value of K_c at which the response becomes underdamped and oscillatory. This is the ultimate controller gain. Keep increasing K_c by factors of 2, performing a set point change after each new attempt, until you observe the oscillatory response.

Once the ultimate controller gain is reached, revert back to the previous value of K_c by decreasing the controller gain by a factor of 2. The P action is now set well enough to add another control action if required.

Adjusting the I action

7. Start bringing in integral action by setting the integral time T_i at an arbitrarily high value. Decrease T_i by factors of 2, making a set point change after each setting.

   Do so until you reach a value of T_i at which the response of the controlled variable becomes underdamped and oscillatory. At this point, revert back to the previous value of T_i by increasing T_I to twice its value.

   The I action is now set and you can now proceed to the adjustment of the D action if required.

Adjusting the D action

8. Start bringing in derivative action by setting the derivative time at an arbitrarily low value. Increase T_d by factors of 2, making a set point change after each setting.

   Do so until you reach the value of T_d that gives the fastest response without amplifying the overshooting or creating oscillation.

   The D action is now set.

Fine-tuning of the parameters

9. Fine-tune the controller until the requirements regarding the response time and overshooting of the controlled variable are satisfied.

A complementary approach to trial and error tuning

Another, more visual approach is to use Figure 2-26 to assist you in tuning your controller. The figure presents responses of a PI process to a step change for different combinations of parameters. A good tuning is shown in the center of the figure for 'optimal' K_c and T_i parameters. The tuning in the center is not necessarily the most appropriate for the process you want to control, but the response shown is a good target for a rough first tuning.

The figure also shows responses for detuned parameters (both above and below the 'optimal' K_c and T_i). Comparing the response you obtain for your system with the detuned responses in the figure tells you in which direction to change K_c, T_i, or both to converge towards the center case. Changing the parameters by a factor of two at every step until you get very close to the optimal value is a good method to converge rapidly.

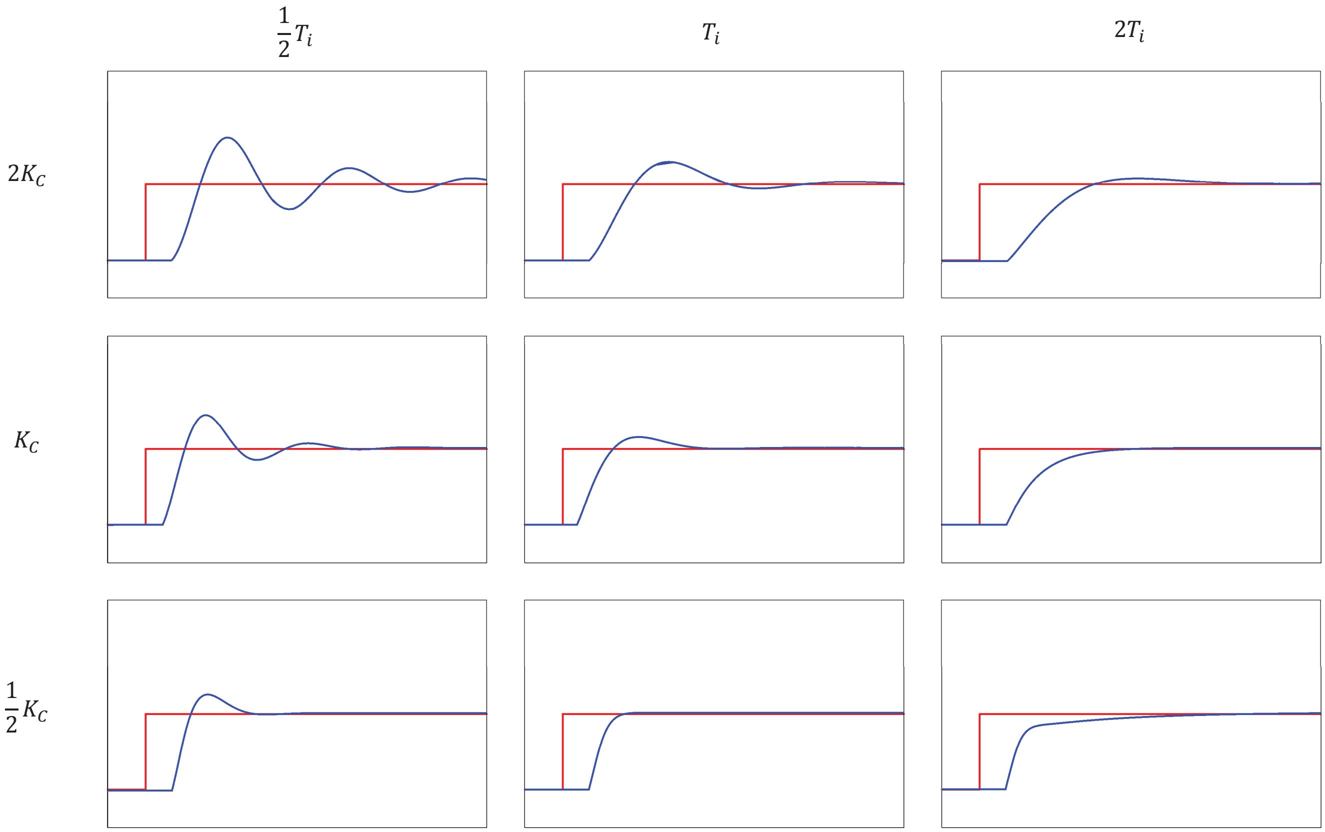


Figure 2-26. PID Tuning Chart.

Derivative action can then be added to the control scheme if required by following step 8 of the trial and error method. Then, fine-tune the parameters to optimize the control and to meet the specific requirements of your process.

Procedure Outline

The Procedure is divided into the following sections:

- Setup and connections
- Adjusting the differential-pressure transmitter
- Controlling the pressure loop
  P mode. PI mode. On-off mode.
- Analyzing the results

PROCEDURE

Setup and connections

1. Connect the equipment according to the piping and instrumentation diagram (P&ID) shown in Figure 2-27 and use Figure 2-28 to position the equipment correctly on the frame of the training system.

Table 2-2. Material to add to the basic setup for this exercise.

Name	Model	Identification
Differential-pressure transmitter (high-pressure range)	46920	PDIT 1
Solenoid valve	46951	S
Controller	----	PIC

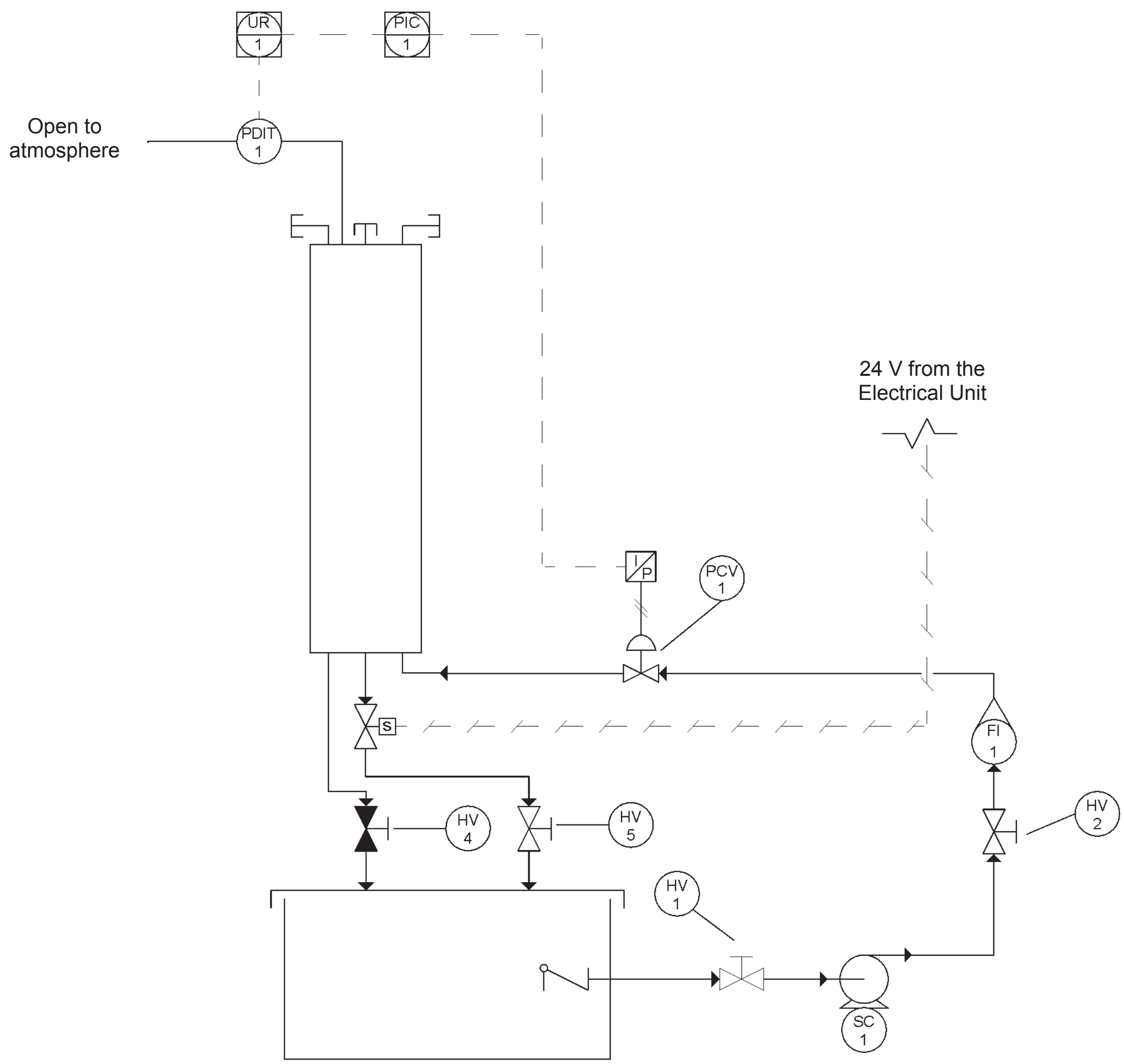


Figure 2-27. P&ID – Pressure control loop.

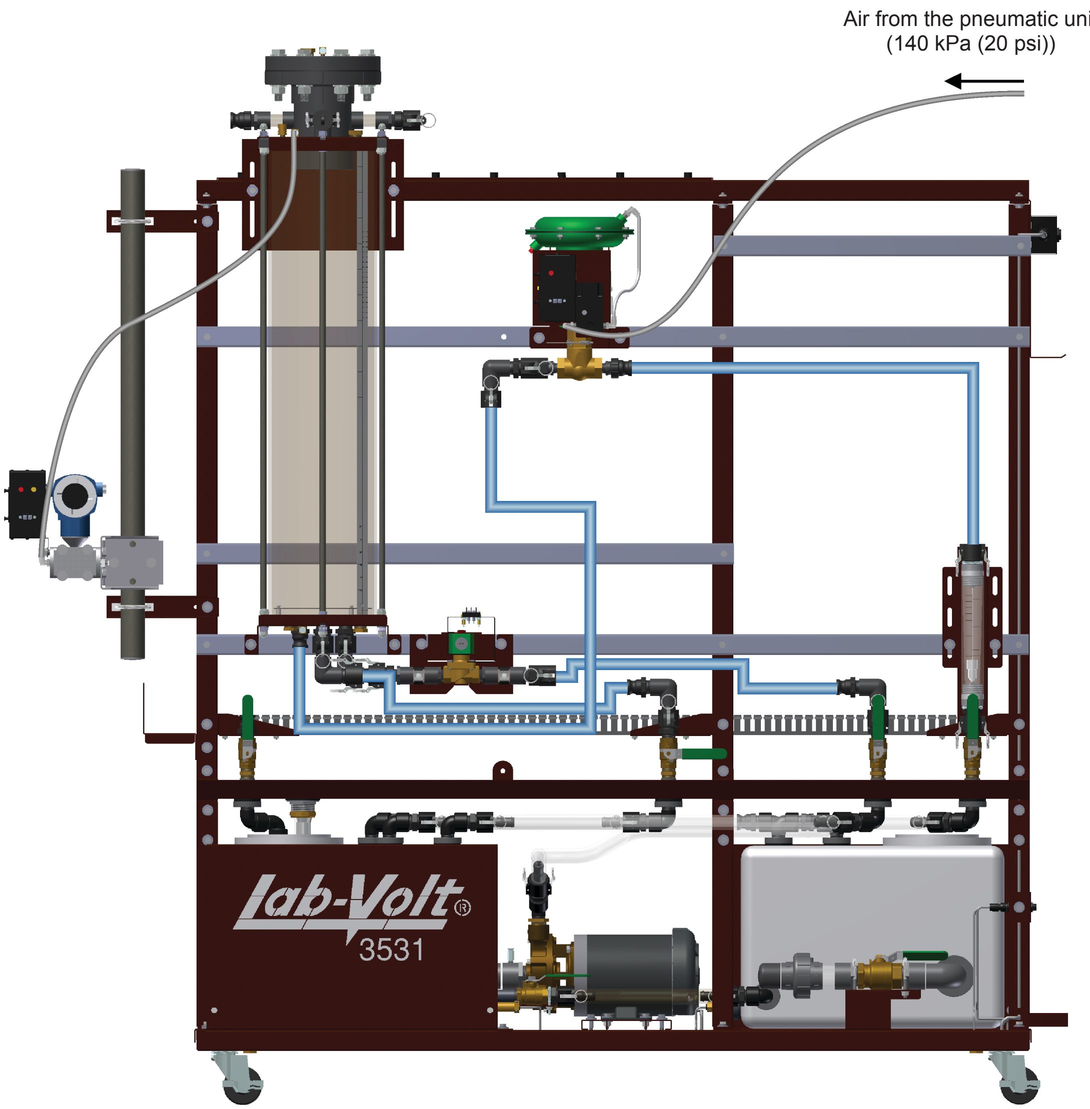


Figure 2-28. Setup – Pressure control loop.

2. Connect the control valve to the pneumatic unit.

3. Connect the pneumatic unit to a dry-air source with an output pressure of at least 700 kPa (100 psi).

4. Wire the emergency push-button so that you can cut power in case of an emergency.

5. Do not power up the instrumentation workstation yet. Do not turn the electrical panel on before your instructor has validated your setup—that is not before step 12.

The loop will react differently depending if the solenoid valve is connected or not.

6. Connect the solenoid valve so that a voltage of 24 V dc actuates the solenoid when you turn the power on in step 12.

7. Connect the controller to the control valve and to the differential-pressure transmitter. You must also include the recorder in your connections. On channel 1 of the recorder, plot the output signal from the controller and on channel 2, plot the signal from the transmitter. Be sure to use the analog input of your controller to connect the differential-pressure transmitter.

8. Figure 2-29 shows how to connect the different devices together.

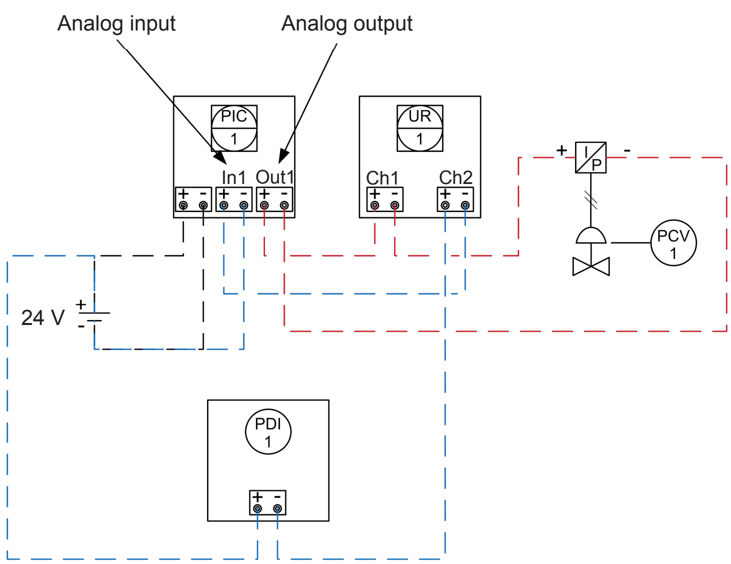


Figure 2-29. Connecting the equipment to the recorder.

9. Before proceeding further, complete the following checklist to make sure you have set up the system properly. The points on this checklist are crucial elements for the proper completion of this exercise. This checklist is not exhaustive, so be sure to follow the instructions in the *Familiarization with the Training System* manual as well.

- ☐ All unused male adapters on the column are capped and the flange is properly tightened.
- ☐ The solenoid valve under the column is wired so that the valve opens when the system is turned on.
- ☐ The hand valves are in the positions shown in the P&ID.
- ☐ The control valve is fully open.
- ☐ The pneumatic connections are correct.
- ☐ The controller is properly connected to the differential-pressure transmitter and to the control valve.
- ☐ The paperless recorder is connected correctly to plot the appropriate signals on channel 1 and channel 2.

10. Ask your instructor to check and approve your setup.

11. Remove one of the caps from the top of the column. This maintains the pressure in the column at atmospheric pressure.

12. Power up the electrical unit, this starts all electrical devices as well as the pneumatic unit. Activate the control valve of the pneumatic unit to power the devices requiring compressed air.

13. In manual mode, set the output of the controller to 0%. The control valve should be fully open. If it is not, revise the electrical and pneumatic connections and make sure the calibration of the I/P converter is appropriate.

14. Test your system for leaks. Use the drive to make the pump run at low speed in order to produce a small flow rate. Gradually increase the flow rate, up to 50% of the maximum flow rate that the pumping unit can deliver (i.e., set the drive speed to 30 Hz). Repair all leaks and stop the pump.

Adjusting the differential-pressure transmitter

Be sure to use the differential-pressure transmitter, Model 46920. This differential-pressure transmitter has a high-pressure range.

15. Make sure the impulse line of the differential-pressure transmitter is free of water and that it is connected to the pressure port at the top of the column.

16. Configure the differential-pressure transmitter so that it gives pressure readings in the desired units. Set transmitter parameters so that it sends a 4 mA signal if the pressure is 0 kPa (0 psi) and a 20 mA signal if the pressure is 32 kPa (4.6 psi).

17. Adjust the zero of the differential-pressure transmitter. The column is at atmospheric pressure because of the removed cap; therefore the transmitter will read 0 kPa (0 psi) when the pressure inside the column is equal to atmospheric pressure.

18. Replace the column cap removed in step 11. This will allow pressure to build in the column when you turn on the pump.

Controlling the pressure loop

19. Set the pump to 40.0 Hz and wait for the pressure reading to stabilize. Valve HV5 and the solenoid valve must be open.

P mode

20. Program the controller to operate in P mode. Tune the controller according to the trial and error method presented above. Record the value of K_c:

$K_c =$ _______

The PID parameters are dependent on your specific setup and cannot be expected to be adequate in every situation. The values given are indicative only and they were obtained with a Honeywell controller, Model 46961.

$K_c = 4.5$ (PD mode, with $T_D = 0$)

21. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

PI mode

22. Program the controller to operate in PI mode. Tune the controller according to the trial and error method presented above. Record the value of K_c. and T_i:

$K_c =$ _______

$T_i =$ _______

$K_c = 3$, $T_i = 0.75$, and $T_D = 0$ (PID A mode)

23. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

On-off mode

24. Program the controller to operate in On-off mode, if such a mode is available with your controller. Experiment with different values of the dead band to visualize its effects. What do you observe as the dead band increases?

The frequency of oscillation of the controlled variable decreases while the amplitude of oscillation increases.

Set the dead band to a value well suited to the process and which avoids excessive load on the control valve.

If your controller does not have an On-off mode, simply set your controller in P mode with the largest possible K_c. The dead band typically cannot be adjusted in such cases.

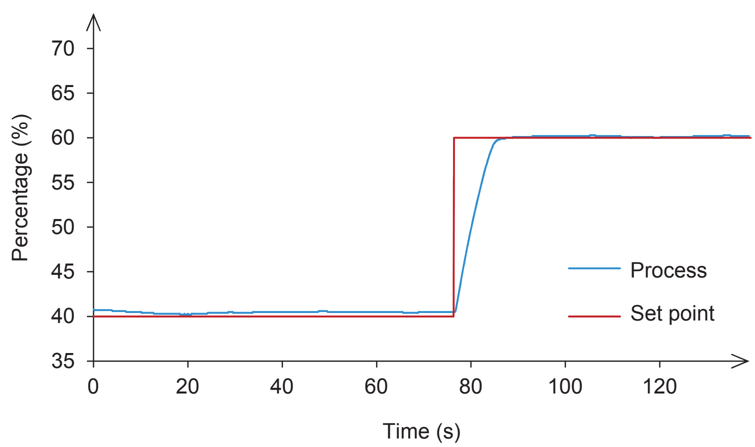
25. Record the response of the process to a step change in the set point of the controller from 40% to 60%. Transfer the data from the paperless recorder to a computer for later analysis.

26. Stop the system.

Analyzing the results

27. Plot the response of the process for each mode using spreadsheet software. Compare the efficiency of the three modes and discuss their characteristics:

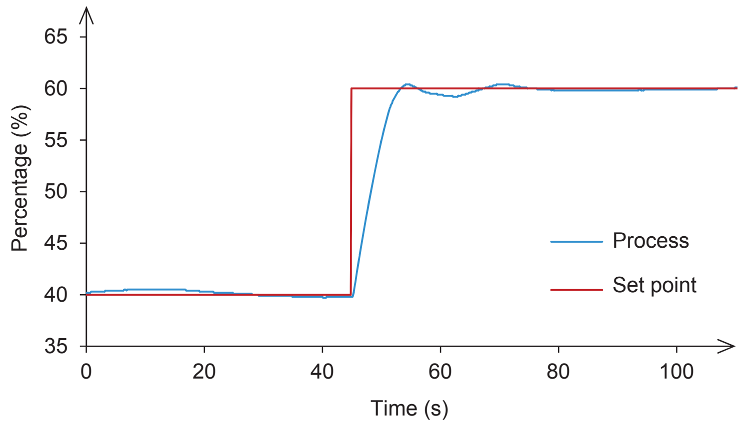
P Mode



Pressure loop response – P mode.

This mode responds quickly to the step change and stabilizes quickly to a new equilibrium value.

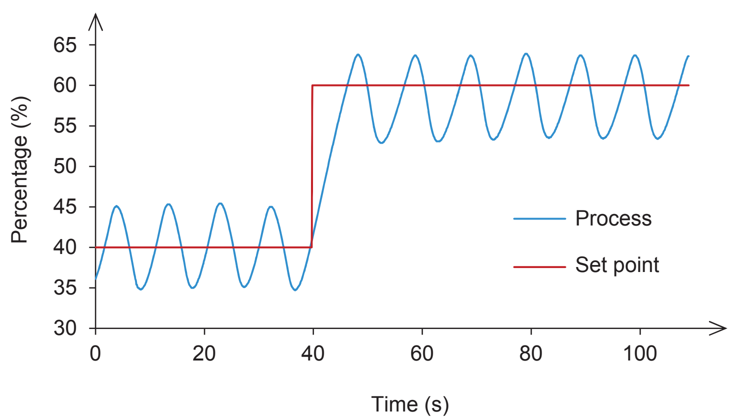
PI - Mode



Pressure loop response – PI mode.

The integral action eliminates the offset efficiently but adds some oscillation to the process response. The time required to settle to the set-point value is longer than in P mode because of the oscillations.

On-off Mode



Pressure loop response – On-off mode.

The on-off mode produces a sinusoidal response following the set point closely. The amplitude of oscillation remains large even for tight dead band settings due to the fast evolving pressure of the process. The results look the same for a "simulated" on-off mode obtained with a high-gain P mode control scheme.

Discussing the efficiency of each control mode is not straightforward as the choice of a particular mode depends on the specific requirements of the application at hand. Nonetheless, the PI mode is usually considered to be more efficient as it converges rapidly to the set point value without offsets or sustained oscillations.

CONCLUSION

In this exercise, you learned to control a pressure loop using three different control modes: P, PI, and On-off. You experimented with the trial and error method of tuning a controller and developed a feel for the behavior of the control schemes for various values of the control parameters. The next exercise will cover a different method of optimizing a PID controller and will allow you to test your control skills on a flow process.

REVIEW QUESTIONS

1. What is the advantage of adding integral action to a proportional control scheme?

   A well tuned integral action eliminates the offset typical of P-only control.

2. Why is On-off control not efficient in the experiment presented above?

   On-off control works well for slow-changing processes with large capacitance. In the experiment at hand, the pressure in the tank varies too quickly to be controlled by a two-state scheme.

3. Why does the trial and error method proceed with a factor of two change at every iteration?

   This method (geometrical progression) typically converges toward the solution faster than a fixed increment method (arithmetic progression).

4. What happens if you increase the K_c parameter in a PI control scheme?

   The response will have a larger amplitude of oscillation and will take more time to stabilize.

5. What happens if you decrease the T_i parameter in a PI control scheme?

   Same answer as question 4.

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