

# Introduction to Process Control

## Introduction

To study the subject of industrial process control effectively, you must first gain a general understanding of its basic principles. To present these control principles clearly and concisely, an intuitive approach to process control is used. First, however, some basic definitions and concepts of process control are presented.

## Definition of Process Control

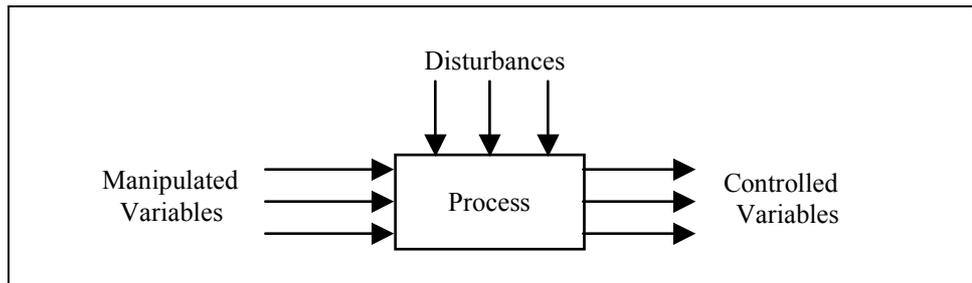
The operations that are associated with process control have always existed in nature. Such “natural” process control can be defined as any operation that regulates some internal physical characteristic that is important to a living organism. Examples of natural regulation in humans include body temperature, blood pressure, and heart rate.

Early humans found it necessary to regulate some of their external environmental parameters to maintain life. This regulation could be defined as “artificial process control” or more simply as “process control,” as we will refer to it in this book. This type of process control is accomplished by observing a parameter, comparing it to some desired value, and initiating a control action to bring the parameter as close as possible to the desired value. One of the first examples of such control was early man’s use of fire to maintain the temperature of his environment.

The term *automatic process control* came into wide use when people learned to adapt automatic regulatory procedures to manufacture products or pro-

cess material more efficiently. Such procedures are called automatic because no human (manual) intervention is required to regulate them.

All process systems consist of three main factors or terms: the manipulated variables, disturbances, and the controlled variables (Figure 1-1). Typical manipulated variables are valve position, motor speed, damper position, or blade pitch. The controlled variables are those conditions—such as temperature, level, position, pressure, pH, density, moisture content, weight, and speed—that must be maintained at some desired value. For each controlled variable there is an associated manipulated variable. The control system must adjust the manipulated variables so the desired value or “set point” of the controlled variable is maintained despite any disturbances.



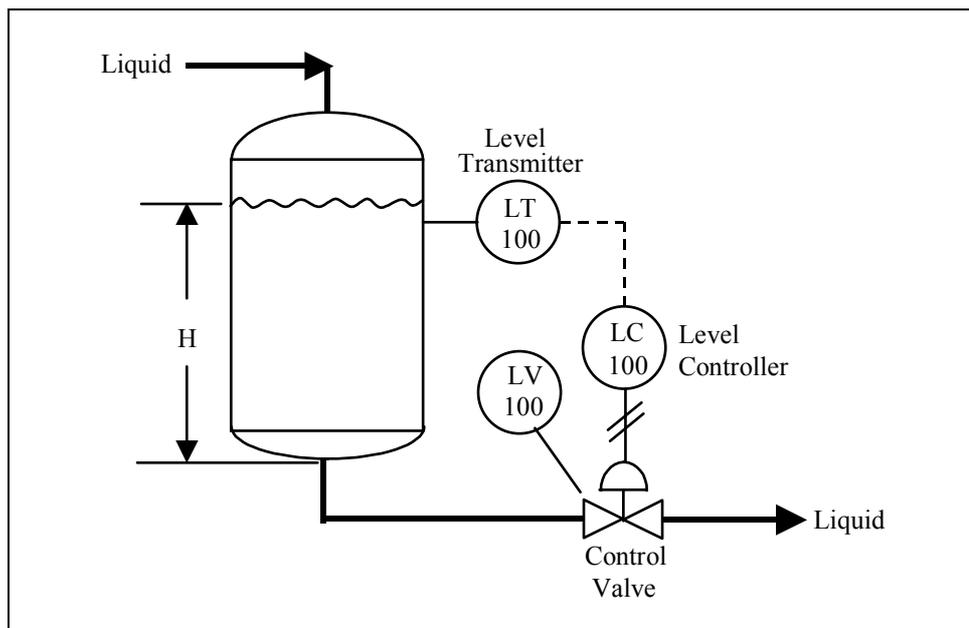
**Figure 1-1. Process control variables**

Disturbances enter or affect the process and tend to drive the controlled variables away from their desired value or set point condition. Typical disturbances include changes in ambient temperature, in demand for product, or in the supply of feed material. The control system must adjust the manipulated variable so the set point value of the controlled variable is maintained despite the disturbances. If the set point is changed, the manipulated quantity must be changed to adjust the controlled variable to its new desired value.

For each controlled variable the control system operator selects a manipulated variable that can be paired with the controlled variable. Often the choice is obvious, such as manipulating the flow of fuel to a home furnace to control the temperature of the house. Sometimes the choice is not so obvious and can only be determined by someone who understands the process under control. The pairing of manipulated and controlled variables is performed as part of the process design.

## Elements of a Process Control System

Figure 1-2 illustrates the essential elements of a process control system. In the system shown, a level transmitter (LT), a level controller (LC), and a control valve (LV) are used to control the liquid level in a process tank. The purpose of this control system is to maintain the liquid level at some prescribed height ( $H$ ) above the bottom of the tank. It is assumed that the rate of flow into the tank is random. The level transmitter is a device that *measures* the fluid level in the tank and converts it into a useful measurement signal, which is sent to a level controller. The level controller *evaluates* the measurement, compares it with a desired set point ( $SP$ ), and produces a series of corrective actions that are sent to the control valve. The valve *controls* the flow of fluid in the outlet pipe to maintain a level in the tank.



**Figure 1-2. Process level control: Example**

Thus, a process control system consists of four essential elements: *process*, *measurement*, *evaluation*, and *control*. A block diagram of these elements is shown in Figure 1-3. The diagram also shows the disturbances that enter or affect the process. If there were no upsets to a process, there would be no need for the control system. Figure 1-3 also shows the input and output of the process and the set point used for control.

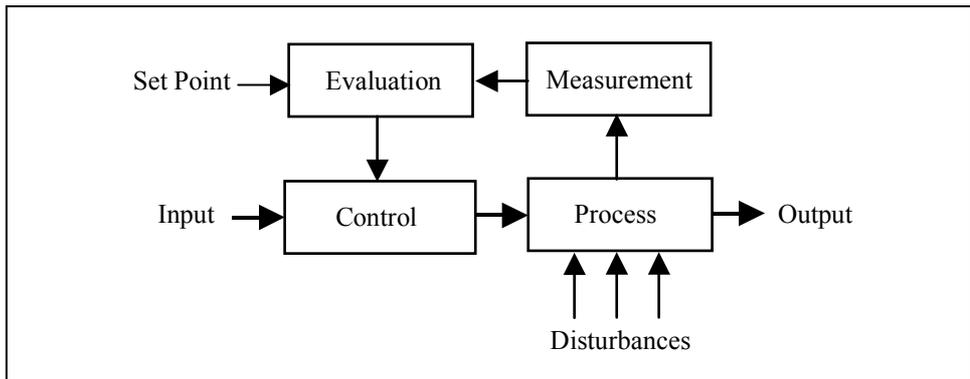


Figure 1-3. Four elements of a control system

## Process

In general, a process consists of an assembly of equipment and material that is related to some manufacturing operation or sequence. In the example presented in Figure 1-2, the process whose liquid level is placed under control includes such components as a tank, the liquid in the tank, the flow of liquid into and out of the tank, and the inlet and outlet piping. Any given process can involve many dynamic variables, and it may be desirable to control all of them. In most cases, however, controlling only one variable will be sufficient to control the process to within acceptable limits. One occasionally encounters a multivariable process in which many variables, some interrelated, require regulation.

## Measurement

To control a dynamic variable in a process, you must have information about the entity or variable itself. This information is obtained by measuring the variable.

Measurement refers to the conversion of the process variable into an analog or digital signal that can be used by the control system. The device that performs the initial measurement is called a *sensor* or *instrument*. Typical measurements are pressure, level, temperature, flow, position, and speed. The result of any measurement is the conversion of a dynamic variable into some proportional information that is required by the other elements in the process control loop or sequence.

## Evaluation

In the evaluation step of the process control sequence, the measurement value is examined, compared with the desired value or set point, and the amount of corrective action needed to maintain proper control is deter-

mined. A device called a *controller* performs this evaluation. The controller can be a pneumatic, electronic, or mechanical device mounted in a control panel or on the process equipment. It can also be part of a computer control system, in which case the control function is performed by software.

## Control

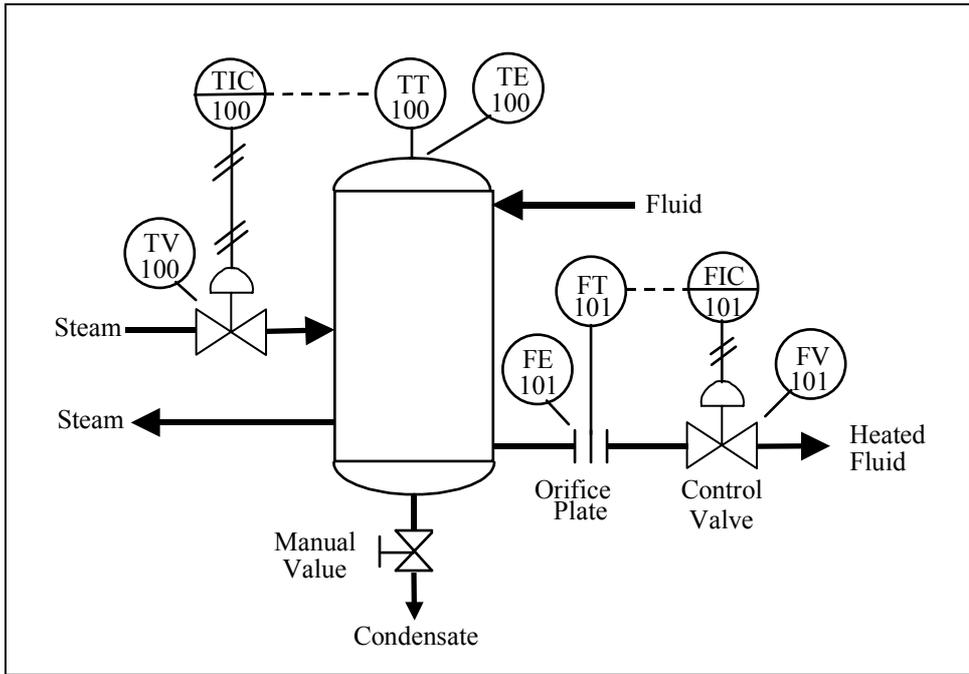
The control element in a control loop is the device that exerts a direct influence on the process or manufacturing sequence. This final control element accepts an input from the controller and transforms it into some proportional operation that is performed on the process. In most cases, this final control element will be a control valve that adjusts the flow of fluid in a process. Devices such as electrical motors, pumps, and dampers are also used as control elements.

## Process and Instrumentation Drawings

In the measurement and control field, a standard set of symbols is used to prepare drawings of control systems and processes. The symbols used in these drawings are based on the standard ISA-5.1-1984 (R1992) Instrumentation Symbols and Identification, which was developed by ISA. A typical application for this standard is process and instrumentation diagrams (P&IDs), which show the interconnection of the process equipment and the instrumentation used to control the process. A portion of a typical P&ID is shown in Figure 1-4.

In standard P&IDs, the process flow lines, such as process fluid and steam, are indicated with heavier solid lines than the lines that are used to represent the instrument. The instrument signal lines use special markings to indicate whether the signal is pneumatic, electric, hydraulic, and so on. Table A-1 in Appendix A lists the instrument line symbols that are used on P&IDs and other instrumentation and control drawings. In Figure 1-4, two types of instrument signals are used: double cross-hatched lines denote the pneumatic signals to the steam control valve and the process outlet flow control valve, and a dashed line is used for the electrical control lines between various instruments. In process control applications, pneumatic signals are almost always 3 to 15 psi (i.e., pounds per square inch, gauge pressure), and the electric signals are normally 4 to 20 mA (milliamperes) DC (direct current).

A balloon symbol with an enclosed letter and number code is used to represent the instrumentation associated with the process control loop. This letter and number combination is called an instrument identification or instrument *tag number*.



**Figure 1-4. P&ID: Example**

The first letter of the tag number is normally chosen so that it indicates the measured variable of the control loop. In the sample P&ID shown in Figure 1-4, T is the first letter in the tag number that is used for the instruments in the temperature control loop. The succeeding letters are used to represent a readout or passive function or an output function, or the letter can be used as a modifier. For example, the balloon in Figure 1-4 marked TE represents a temperature element and that marked TIC is a temperature-indicating controller. The line across the center of the TIC balloon symbol indicates that the controller is mounted on the front of a main control panel. No line indicates a field-mounted instrument, and two lines mean that the instrument is mounted in a local or field-mounted panel. Dashed lines indicate that the instrument is mounted inside the panel.

Normally, sequences of three- or four-digit numbers are used to identify each loop. In our process example (Figure 1-4), we used loop numbers 100 and 101. Smaller processes use three-digit loop numbers; larger processes or complex manufacturing plants may require four or more digits to identify all the control loops.

Special marks or graphics are used to represent process equipment and instruments. For example, in our P&ID example in Figure 1-4, two parallel lines represent the orifice plate that is used to detect the discharge flow from the process heater. The two control valves in the figure also use a

special symbol. See Appendix A for a more detailed discussion of the instrumentation and process symbols that are used on P&IDs.

## General Requirements of a Control System

The primary requirement of a control system is that it be reasonably stable. In other words, its speed of response must be fairly fast, and this response must show reasonable damping. A control system must also be able to reduce the system error to zero or to a value near zero.

### System Error

The system error is the difference between the value of the controlled variable set point and the value of the process variable maintained by the system. The system error is expressed in equation form by the following:

$$e(t) = PV(t) - SP(t) \quad (1-1)$$

where

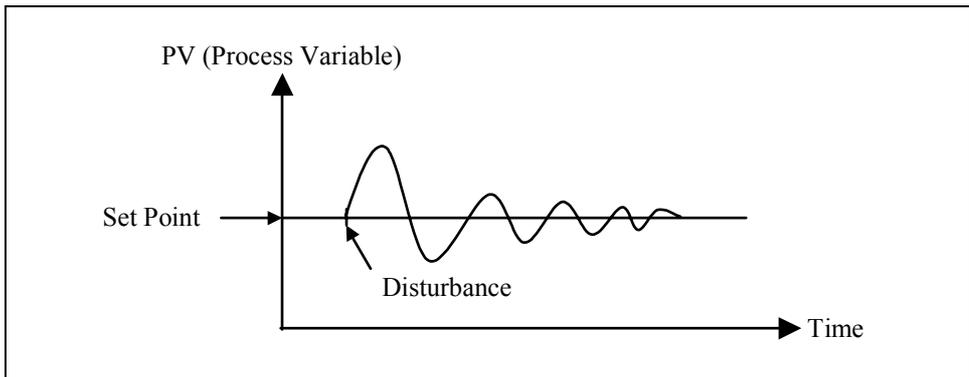
- $e(t)$  = system error as a function of time ( $t$ )
- $PV(t)$  = the process variable as a function of time
- $SP(t)$  = the set point as a function of time

### System Response

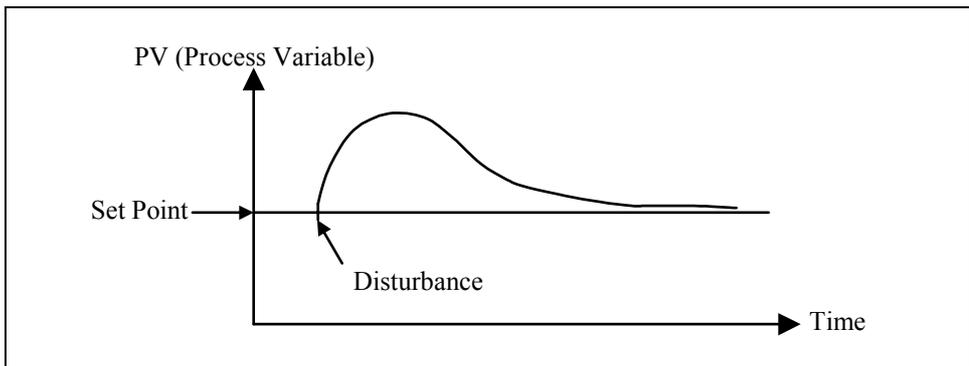
The main purpose of a control loop is to maintain some dynamic process variable (pressure, flow, temperature, level, etc.) at a prescribed operating point or set point. System response is the ability of a control loop to recover from a disturbance that causes a change in the controlled process variable.

There are two general types of good response: underdamped (cyclic response) and damped. Figure 1-5 shows an underdamped or cyclic response of a system in which the process variable oscillates around the set point after a process disturbance. The wavy response line shown in the figure represents an acceptable response if the process disturbance or change in set point is large, but it will not be an acceptable response if the change from the set point is small.

Figure 1-6 shows a damped response where the control system is able to bring the process variable back to the operating point with no oscillations.



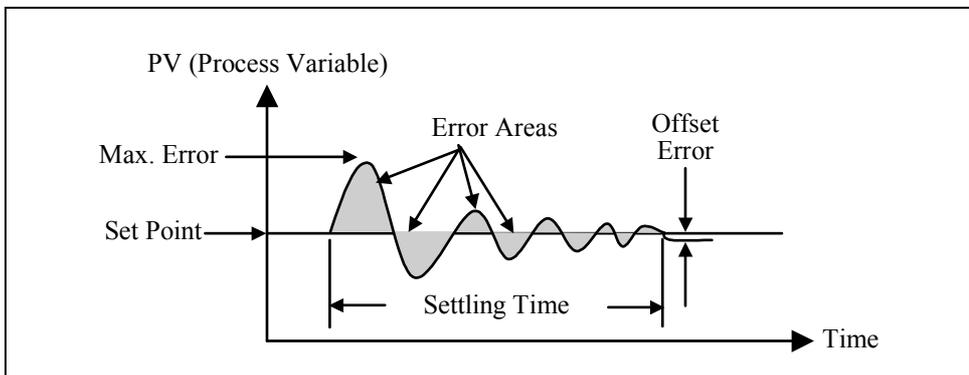
**Figure 1-5. Cyclic response to process disturbance**



**Figure 1-6. Damped response to process disturbance**

## Control Loop Design Criteria

Many criteria are employed to evaluate the process control's loop response to an input change. The most common of these include settling time, maximum error, offset error, and error area (Figure 1-7).



**Figure 1-7. Evaluation of control loop response**

When there is a process disturbance or a change in set point, the *settling time* is defined as the time the process control loop needs to bring the process variable back to within an allowable error. The *maximum error* is simply the maximum allowable deviation of the dynamic variable. Most control loops have certain inherent linear and nonlinear qualities that prevent the system from returning the process variable to the set point after a system change. This condition is generally called *offset error* and will be discussed later in this chapter. The *error area* is defined as the area between the response curve and the set point line as shown by the shaded area in Figure 1-7.

These four evaluation criteria are general measures of control loop behavior that are used to determine the adequacy of the loop's ability to perform some desired function. However, perhaps the best way to gain a clear understanding of process control is to take an intuitive approach.

## Intuitive Approach to Process Control Concepts

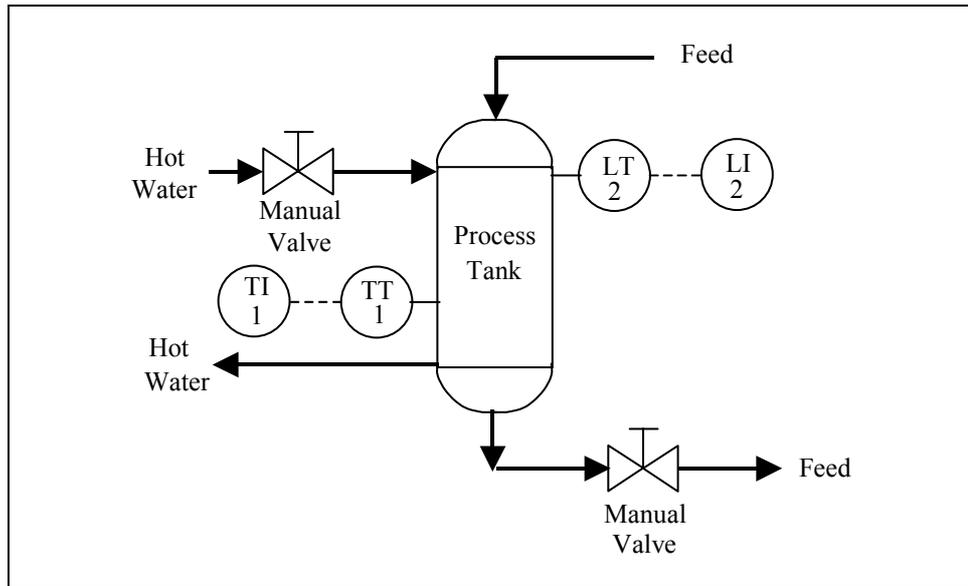
The practice of process control arose long before the theory or analytical methods underlying it were developed. Processes and controllers were designed using empirical methods that were based on intuition ("feel") and extensive process experience. Most of the reasoning involved was nonmathematical. This approach was unscientific trial and error, but it was a successful control method.

Consider, for example, an operator looking into an early metal processing furnace to determine whether the product was finished. He or she used flame color, amount of smoke, and process time to make this judgment. From equally direct early methods evolved most of the control concepts and hardware used today. Only later did theories and mathematical techniques emerge to explain how and why the systems responded as they did.

In this section, we will approach the study of control fundamentals in much the same way that control knowledge developed—that is, through a step-by-step procedure starting from manual control and moving to ever-increasing automatic control.

Suppose we have a process like that shown in Figure 1-8. A source of feed liquid flows into a tank at a varying rate from somewhere else in a process plant. This liquid must be heated so that it emerges at a desired temperature,  $T_d$ , as a hot liquid. To accomplish this, hot water, which is available from another part of the plant, flows through heat exchanger coils in the tank. By controlling the flow of hot water, we can obtain the desired tem-

perature,  $T_d$ . A further process requirement is that the level of the tank must neither overflow nor fall so low that it exposes the heater coils.



**Figure 1-8. Example process – using manual valves**

The temperature is measured in the tank, and a temperature transmitter (TT-1) converts the signal into a 4-20 mA direct current (DC) signal to drive a temperature indicator (TI-1) mounted near the hot water inlet valve. Similarly, a level indicator (LI-2) is mounted within the operator's view of the hot feed outlet valve (HV-2).

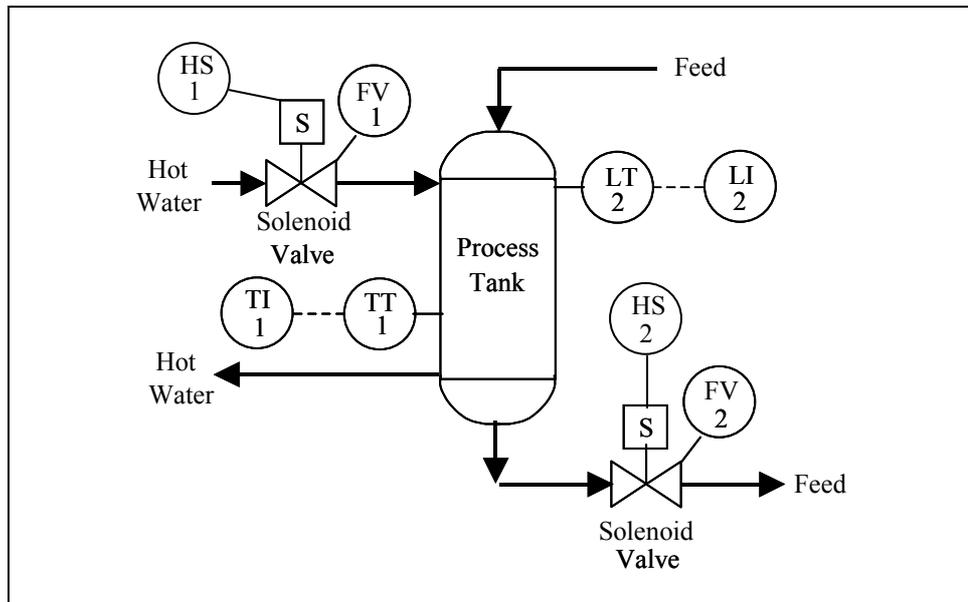
Suppose a process operator has the task of holding the temperature,  $T$ , near the desired temperature,  $T_d$ , while making sure the tank doesn't overflow or the level get too low. The question is how the operator would cope with this task over a period of time. He or she would manually adjust the hot water inlet valve (HV-1) to maintain the temperature and occasionally adjust the outlet valve (HV-2) to maintain the correct level in the tank.

The operator would face several problems, however. Both indicators would have to be within the operator's view, and the manual valves would have to be close to the operator and easy to adjust.

## On/Off Control

To make the operator's work easier, suppose we install electrically operated solenoid valves in place of the manual valves, as shown in Figure 1-9. We can also install two hand switches (HS-1 and HS-2) so the solenoid

valves can be operated from a common location. The valves can assume two states, either fully open (on) or fully closed (off). This type of control is called two-position or *on/off control*.



**Figure 1-9. Sample process: Solenoid valves**

Assume for the moment that the level is holding steady and that the main concern is controlling temperature. The operator has been told to keep the temperature of the fluid in the tank at 100°F. He or she compares the reading of the temperature indicator with the selected set point of 100°F. The operator closes the hot water valve when the temperature of the fluid in the tank rises above the set point (Figure 1-10). Because of process dead time and lags the temperature will continue to rise before reversing and moving toward the set point. When the temperature falls below 100°F, the operator opens the hot water valve. Again, dead time and lags in the process create a delay before the temperature begins to rise. As it crosses the set point, the operator again shuts off the hot water, and the cycle repeats.

This cycling is normal for a control system that uses on/off control. This limitation exists because it's impossible for the operator to control the process exactly with only two options.

This on/off type of control can be expressed mathematically as follows:

$$e = PV - SP \quad (1-2)$$