## CHAPTER 15

# FUNDAMENTALS OF CONTROL

AUTOMATIC HVAC control systems are designed to maintain temperature, humidity, pressure, flow, power, lighting levels, and safe levels of indoor contaminants. Automatic control primarily modulates, stages, or sequences mechanical and electrical equipment to meet load requirements and provide safe operation of the equipment. It can use digital, pneumatic, mechanical, electrical, and electric control devices; human intervention is limited to starting and stopping equipment and adjusting control set points.

This chapter focuses on the fundamental concepts and devices normally used by a control system designer. It covers (1) control fundamentals, including terminology; (2) the types of control components; (3) the methods of connecting these components to form various individual control loops or subsystems; and (4) commissioning, operation, and maintenance. Chapter 46 of the *ASHRAE Handbook—Applications* discusses the design of controls for specific HVAC applications.

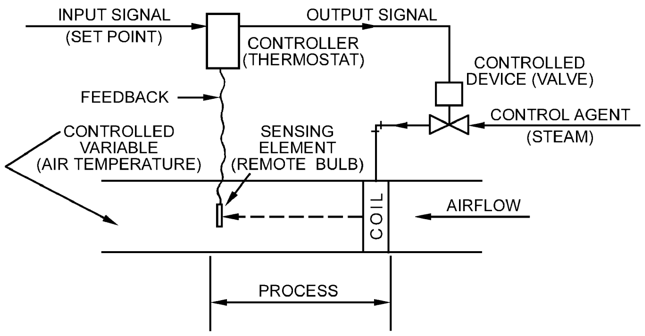

**Fig. 1 Discharge Air Temperature Control**
(Example of Feedback Control)

## TERMINOLOGY

A **closed loop** or **feedback** control measures actual changes in the controlled variable and actuates the controlled device to bring about a change. The corrective action continues until the variable is brought to a desired value within the design limitations of the controller. This arrangement of having the controller sense the value of the controlled variable is known as **feedback**. Figure 1 shows a feedback control.

An **open loop** control does not have a direct link between the value of the controlled variable and the controller. An open loop control anticipates the effect of an external variable on the system and adjusts the set point to avoid excessive offset. An example is an outdoor thermostat arranged to control heat to a building in proportion to the calculated load caused by changes in outdoor temperature. In essence, the designer presumes a fixed relationship between outside air temperature and the heat requirement of the building and specifies control action based on the outdoor air temperature. The actual space temperature has no effect on this controller. Because there is no feedback on the controlled variable (space temperature), the control is an open loop.

Figure 1 illustrates the components of the typical **control loop**. The **sensor** measures the controlled variable and transmits to the controller a signal (pneumatic, electric, or electronic) having a pressure, voltage, or current value proportional to the value of the variable being measured. The **controller** compares this value with the set point and signals to the controlled device for corrective action. A controller can be hardware or software. A **hardware controller** is an analog device that continuously receives and acts on data. Thermostats, humidistats, and pressure controls are examples of hardware controllers. A **software controller** is a digital device that receives and acts on data on a sample-rate basis. Digital algorithms are examples of software controllers.

The **set point** is the desired value of the controlled variable. The controller seeks to maintain this set point. The **controlled device** reacts to signals received from the controller to vary the control agent. The controlled device may be a valve, a damper, a heating element, or a motor driving a pump or a fan.

The **control agent** is the medium manipulated by the controlled device. It may be air or gas flowing through a damper; gas, steam, or water flowing through a valve; or an electric current.

The **process** is the air-conditioning apparatus being controlled. It reacts to the output of the control agent and effects the change in the controlled variable. It may be a coil, fan, or humidifier.

The **controlled variable** is the temperature, humidity, pressure, etc., being controlled.

A control loop can be represented in the form of a **block diagram**, in which each component is modeled and represented in its own block. Figure 2 is a block diagram of the control loop shown in Figure 1. The flow of information from one component to the next is shown by lines between the blocks. The figure shows the set point being compared to the controlled variable. The difference is the **offset error**, also known as offset drift, deviation, droop, or steady-state error. The offset error is fed into the controller, which sends a control signal to the controlled device. In this case, the controlled device is a valve that can change the amount of steam flow through the coil of Figure 1. The amount of steam flow is the input to the next block, which represents the process. From the process block comes the controlled variable, which is temperature. The controlled variable is sensed by the sensing element and fed to the controller as feedback, completing the loop.

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The preparation of this chapter is assigned to TC 1.4, Control Theory and Application.

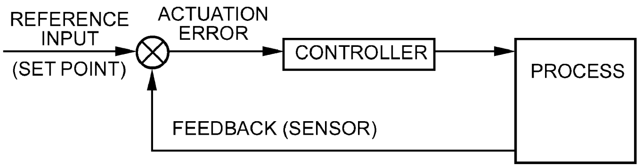

**Fig. 2 Block Diagram of Discharge Air Temperature Control**

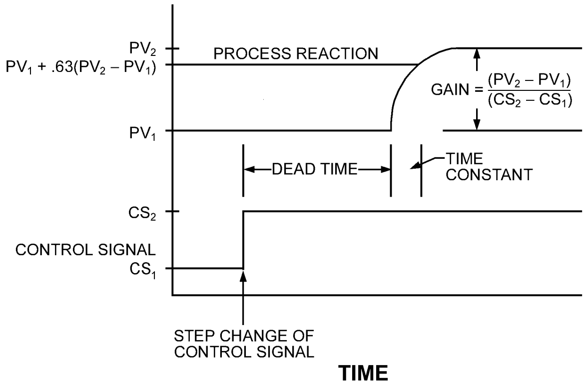

**Fig. 3 Process Subjected to a Step Input**

Each component of Figure 2 can be represented by a **transfer function**, which is an idealized mathematical representation of the relationship between the input and the output variables of the component. The transfer function must be sufficiently detailed to cover both the dynamic and static characteristics of the device. The dynamics of the component are represented in the time domain by a differential equation. In environmental control, the transfer function of many of the components can be adequately described by a first-order differential equation, implying that the dynamic behavior is dominated by a single capacitance factor. For a solution, the differential equation is converted to its Laplace transform or *z*-transform.

The **time constant** is defined as the time it takes for the output to reach 63.2% of its final value when a step change in the input is effected. Components with small time constants alter their output rapidly to reflect changes in the input; conversely, components with a larger time constant are sluggish in responding to changes in the input.

**Dead time** is a phase shift that can cause control and modeling problems. Dead time (or **time lag**) is the time between a change in the process input and when the change affects the output of the process. Dead time can occur in the control loop of Figure 1 due to the transportation time of the air from the coil to the space. After a coil temperature is changed, there is dead time while the affected supply air travels the distribution system and finally reaches the sensor in the space. The mass of air within the space further delays detection of the coil temperature change. Dead time can also be caused by a slow sensor, or a time lag in the signal from the controller. If the dead time is small, it may be ignored in the model of the control; if it is significant, it must be considered.

The **gain** of a transfer function is the amount the output of the component changes for a given change of input under steady-state conditions. If the element is linear, its gain remains constant. However, many control components are nonlinear, and have gains that depend on the operating conditions. Figure 3 shows the response of the first-order-plus-dead-time process to a step change of the input signal. Notice that the process shows no reaction during the dead time, followed by a response that resembles a first order exponential.

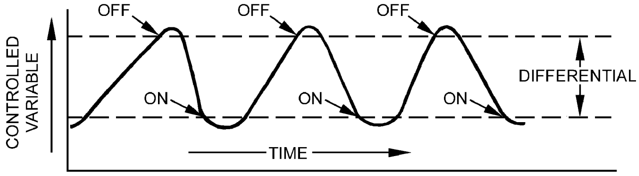

**Fig. 4 Two-Position Control**

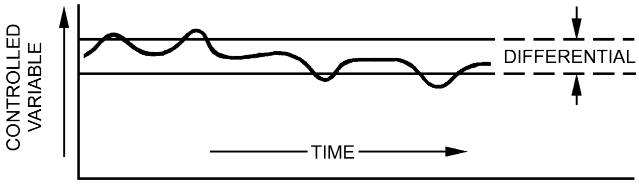

**Fig. 5 Floating Control Showing Variations in Controlled Variable as Load Changes**

## TYPES OF CONTROL ACTION

Closed loop controls are commonly classified by the type of corrective action the controller is programmed to take when it senses a deviation of the controlled variable from the set point. Both hardware and software controllers can be classified according to the following most common types of control action.

### Two-Position Action

The control device shown in Figure 4 can be positioned only to a maximum or minimum state (e.g., on or off). Because two-position control is simple and inexpensive, it is used extensively for both industrial and commercial control. A typical home thermostat that starts and stops a furnace is an example of two-position action.

**Controller differential**, as it applies to two-position control action, is the difference between a setting at which the controller operates to one position and a setting at which it operates to the other. Thermostat ratings usually refer to the differential (in degrees) that becomes apparent by raising and lowering the dial setting. This differential is known as the **manual differential** of the thermostat. When the same thermostat is applied to an operating system, the total change in temperature that occurs between a "turn-on" state and a "turn-off" state is usually different from the mechanical differential. The **operating differential** may be greater due to thermostat lag or hysteresis or to heating or cooling anticipators built into the thermostat.

**Anticipation Applied to Two-Position Action.** This common variation of strictly two-position action is often used on room thermostats to reduce the operating differential. In heating thermostats, a heater element in the thermostat is energized during "on" periods, thus shortening the on-time because the heater warms the thermostat. This is known as **heat anticipation**. The same anticipation action can be obtained in cooling thermostats by energizing a heater thermostat at "off" periods. In both cases, the percentage of on-time is varied in proportion to the load, while the total cycle time remains relatively constant.

**Timed Two-Position Action.** This action occurs when a heating or cooling element is turned on for a time interval proportional to the deviation from set point. For example, an element may be turned on for two minutes and off for one minute when the deviation from set point is 3°F. This is similar to incremental action applied to floating control, except the time interval is usually shorter for incremental action.

## Floating Action

In floating action, the controller can perform only two operations—moving the controlled device toward either its open or closed position, usually at a constant rate (Figure 5). Generally, a neutral zone between the two positions allows the controlled device to stop at any position when the controlled variable is within the differential of the controller. When the controlled variable falls outside the differential of the controller, the controller moves the controlled device in the proper direction. In order to function properly, the sensing element must react faster than the actuator drive time. If not, the control functions the same as a two-position control.

**Incremental Action.** This action is a variation of floating control. Incremental action varies the pulse action to open or close an actuator depending on how close the controlled variable is to the set point. As the controlled variable comes close to the set point, the pulses become shorter. This action allows closer control using floating motor actuators.

## Modulating Control

With modulating control, the output of the controller can vary infinitely over the range of the controller. The following terms are used to describe this type of control:

- **Throttling range** is the amount of change in the controlled variable required to cause the controller to move the controlled device from one extreme to the other. It can be adjusted to meet job requirements. Throttling range is inversely proportional to proportional gain.
- **Control point** is the actual value of the controlled variable at which the instrument is controlling. It varies within the throttling range of the controller and changes with changing load on the system and other variables.
- **Offset**, or error signal, is the difference between the set point and the actual control point under stable conditions. This is sometimes called drift, deviation, droop, or steady-state error.

The following are the three typical modulating control modes:

**Proportional Action.** In proportional action, the controlled device is positioned proportionally in response to changes in the controlled variable (Figure 6). A proportional controller can be described mathematically by

$$V_p = K_p e + V_o \tag{1}$$

*where*

$V_p$ = output of controller
$K_p$ = proportional gain (inversely proportional to throttling range)
$e$ = error signal or offset
$V_o$ = offset adjustment parameter

The output of the controller is proportional to the difference between the sensed value, the controlled variable, and its set point. The controlled device is normally adjusted to be in the middle of its control range at set point by using an offset adjustment. This control is similar to that shown in Figure 1.

**Proportional plus Integral (PI) Action.** This type of control improves on simple proportional control by adding another component to the control action that eliminates the offset typical of proportional control (Figure 7). **Reset action** may be described by

$$V_p = K_p e + K_i \int e d\theta + V_o \tag{2}$$

*where*

$K_i$ = integral gain
$\theta$ = time

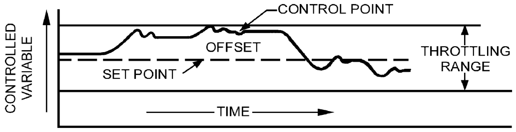

**Fig. 6 Proportional Control Showing Variations in Controlled Variable as Load Changes**

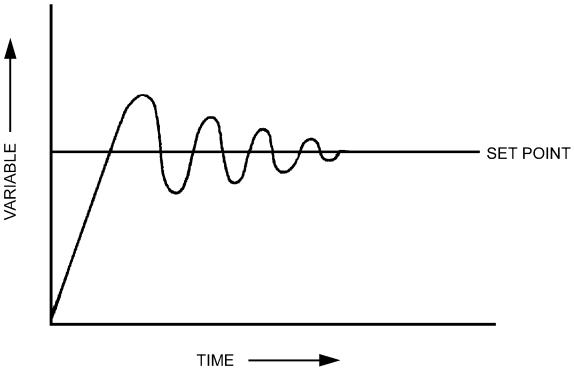

**Fig. 7 Proportional plus Integral (PI) Control**

The second term in Equation (2) implies that the longer error *e* exists, the more the controller output will change in attempting to eliminate the error. Proper selection of proportional and integral gain constants increases stability, and eliminates offset, giving greater control accuracy. PI control can also improve energy efficiency in applications such as VAV fan control, chiller control, and hot and cold deck control of the air handler.

**Proportional-Integral-Derivative (PID) Action.** This type of control is PI control with a derivative term added to the controller. It varies with the value of the derivative of the error. The equation for PID control is

$$V_p = K_p e + K_i \int e d\theta + K_a \frac{de}{d\theta} + V_o \tag{3}$$

*where*

$K_a$ = derivative gain of controller
$de/d\theta$ = time derivative of error

Adding the derivative term gives some anticipatory action to the controller, which results in a faster response and greater stability. However, the derivative term also makes the controller more sensitive to noisy signals and harder to tune than a PI controller. Most HVAC control loops perform satisfactorily with PI control alone. **Adaptive control**, or self tuning, is a form of digital PID control, where the gain factors ($K_p$, $K_i$, and $K_a$) are continuously or periodically modified automatically to compensate for the control loop offset.

## Fuzzy Logic

Fuzzy logic control offers an alternative to traditional control algorithms. A fuzzy logic controller uses a series of "if-then" rules that emulates the way a human operator might control the process. Examples of fuzzy logic might include

1. IF the room temperature is high AND the rate of change is decreasing, THEN increase cooling a little.
2. IF the room temperature is high AND the rate of change is increasing, THEN increase cooling a lot.

The designer of a fuzzy logic controller must first define the rules and then define such terms as *high*, *increasing*, *decreasing*, *a lot*, and *a little*. The room temperature, for instance, might be mapped into a series of functions that include *very low, low, OK, high,* and *very high*. The "fuzzy" element is introduced when the functions overlap and the room temperature is, for example, 70% high and 30% OK. In this case, multiple rules are combined to determine the appropriate control action.

## CLASSIFICATION BY ENERGY SOURCE

Control components may be classified according to the primary source of energy as follows:

- **Pneumatic components** use compressed air, usually at a pressure of 15 to 20 psig, as an energy source. The air is generally supplied to the controller, which regulates the pressure supplied to the controlled device.
- **Electric components** use electrical energy, either low- or line-voltage, as the energy source. The controller regulates electrical energy supplied to the controlled device. Controlled devices in this category include relays; electromechanical, electromagnetic, and hydraulic actuators; and solid-state regulating devices. Components that include signal conditioning, modulation, and amplification in their operation are classified as **electronic**.

  A **digital controller** receives electronic signals from the sensors, converts the electronic signals to numbers, and performs mathematical operations on these numbers inside a microprocessor. The output from the digital controller takes the form of a number, which is then converted to an electronic signal to operate the actuator. The digital controller must sample its data because the microprocessor requires time for other operations than reading data. If the sampling interval for the digital controller is properly chosen to avoid second- and third-order harmonics, there will be no significant degradation in control performance due to sampling.
- **Self-powered components** apply the power of the measured system to induce the necessary corrective action. The measuring system derives its energy from the process under control, without any auxiliary source of energy. Temperature changes at the sensor result in pressure or volume changes of the enclosed media that are transmitted directly to the operating device of the valve or damper. A component using a thermopile in a pilot flame to generate electrical energy is also self-powered.

This method of classification can be extended to individual control loops and to complete control systems. For example, the room temperature control for a particular room that includes a pneumatic room thermostat and a pneumatically actuated reheat coil would be referred to as a pneumatic control loop. Many control systems use a combination of controls and are called **hybrid** systems.

## COMPUTERS FOR AUTOMATIC CONTROL

Computers can perform the control described in this chapter. Chapter 39 of the *ASHRAE Handbook—Applications* covers computer components and some of the ways computers are being used in the HVAC control industry.

# CONTROL COMPONENTS

This section groups components by their function in a complete control system. The section on Controlled Devices considers the controlled device or final control element, examples of which are relays, valves, and dampers. Actuators, which are used to drive the valve or damper assembly, are also covered.

The section on Sensors considers the sensing element that measures changes in the controlled variable. Some of the sensor types included are temperature, humidity, flow, and pressure. While many other sensors are available, these represent the majority of those found in HVAC control systems.

The section on Controllers reviews various controllers. Controllers are classified according to energy source; pneumatic, electric/electronic, and digital. They are also classified according to the control action they cause to maintain the desired condition (set point)—two-position, floating, proportional, proportional plus integral (PI), or proportional plus integral plus derivative (PID). Thermostats (devices that combine a temperature sensor and controller in a single unit) are also described as well.

Fundamental control systems can be constructed using only the components described in the first three subsections. In practice, however, a fourth group is sometimes necessary. The section on Auxiliary Control Devices covers transducers, switches, power supplies, and air compressors.

## CONTROLLED DEVICES

A controlled device regulates the flow of steam, water, electricity, or air in an HVAC system. Water and steam flow regulators are known as **valves**, and airflow control devices are called **dampers**; both devices perform essentially the same function and must be properly sized and selected for the particular application. The control link to the valve or damper is called an **actuator** or **operator**. This device uses electricity, compressed air, or hydraulic fluid to power the motion of the valve stem or damper linkage through its operating range.

### Valves

An automatic valve is designed to control the flow of steam, water, gas, or other fluids. It can be considered a variable orifice positioned by an electric or pneumatic actuator in response to impulses or signals from the controller. It may be equipped with a throttling plug or V-port specially designed to provided a desired flow characteristic.

Renewable composition disks are common. They are made of materials best suited to the media handled by the valve, the operating temperature, and the pressure. For high pressure or for superheated steam, metal disks are often used. Internal parts, such as the seat ring, throttling plug, or V-port skirt, disk holder, and stem, are sometimes made of stainless steel or other hard and corrosion-resistant metal for use in severe service.

Various types of automatic valves include the following:

A **single-seated valve** (Figure 8A) is designed for tight shutoff. Appropriate disk materials for various pressures and media are used.

A **double-seated** or **balanced valve** (Figure 8B) is designed so that the media pressure acting against the valve disk is essentially balanced, reducing the actuator force required. It is widely used where fluid pressure is too high to permit a single-seated valve to close. It cannot be used where a tight shutoff is required.

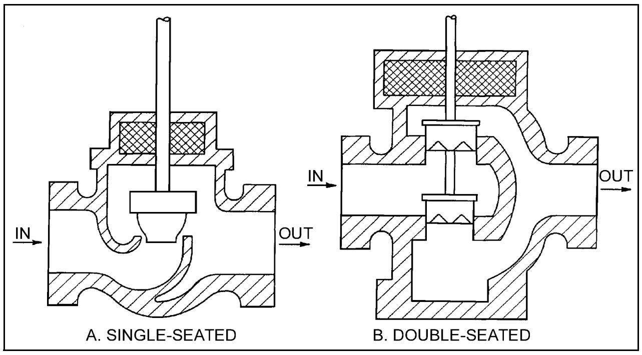

**Fig. 8 Typical Single- and Double-Seated Two-Way Valves**

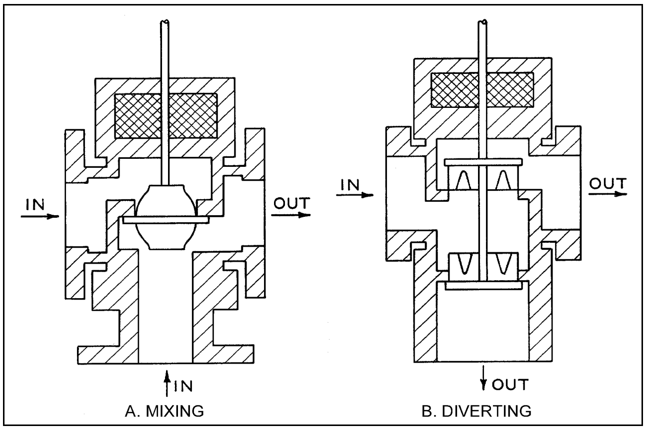

**Fig. 9 Typical Three-Way Mixing and Diverting Valves**

A **three-way mixing valve** (Figure 9A) has two inlet connections and one outlet connection and a double-faced disk operating between two seats. It is used to mix two fluids entering through the inlet connections and leaving through the common outlet, according to the position of the valve stem and disk.

A **three-way diverting valve** (Figure 9B) has one inlet connection and two outlet connections and two separate disks and seats. It is used to divert the flow to either of the outlets or to proportion the flow to both outlets.

A **butterfly valve** consists of a heavy ring enclosing a disk that rotates on an axis at or near its center and is similar to a round single-blade damper. In principle, the disk seats against a ring machined within the body or a resilient liner in the body. Two butterfly valves can be used together to act like a three-way valve for mixing or diverting.

**Flow Characteristics.** The performance of a valve is expressed in terms of its flow characteristics as it operates through its stroke, based on a constant pressure drop. Three common characteristics are shown in Figure 10 and are defined as follows:

- **Quick opening.** Maximum flow is approached rapidly as the device begins to open.
- **Linear.** Opening and flow are related in direct proportion.
- **Equal percentage.** Each equal increment of opening increases the flow by an equal percentage over the previous value.

Because the pressure drop across a valve seldom remains constant as its opening changes, actual performance usually deviates from the published characteristic curve. The magnitude of the deviation is determined by the overall design. For example, in a system arranged so that control valves or dampers can shut off all flow, the pressure drop across a controlled device increases from a minimum at design conditions to the total pressure drop at no flow. Figure 11 shows the extent of the resulting deviations for a valve or damper designed with a linear characteristic, when selection is based on various percentages of total system pressure drop. To allow for adequate control by valve or damper, the design pressure drop should be a reasonably large percentage of the total system pressure drop, or the system should be designed and controlled so that the pressure drop remains relatively constant.

**Selection and Sizing.** Higher pressure drops for controlled devices are obtained by using smaller sizes with a possible increase in size of other equipment in the system. Because sizing techniques are different for steam, water, and air, each is discussed separately.

***Steam Valves.*** Steam-to-water and steam-to-air heat exchangers are typically controlled through regulation of steam flow using a two-way throttling valve. One-pipe steam systems require a line-size, two-position valve for proper condensate drainage and steam flow, while two-pipe steam systems can be controlled by two-position or modulating (throttling) valves.

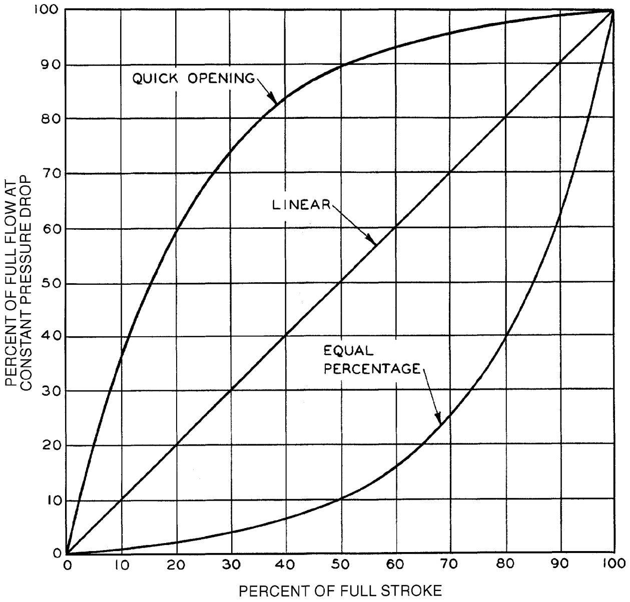

**Fig. 10 Typical Flow Characteristics of Valves**

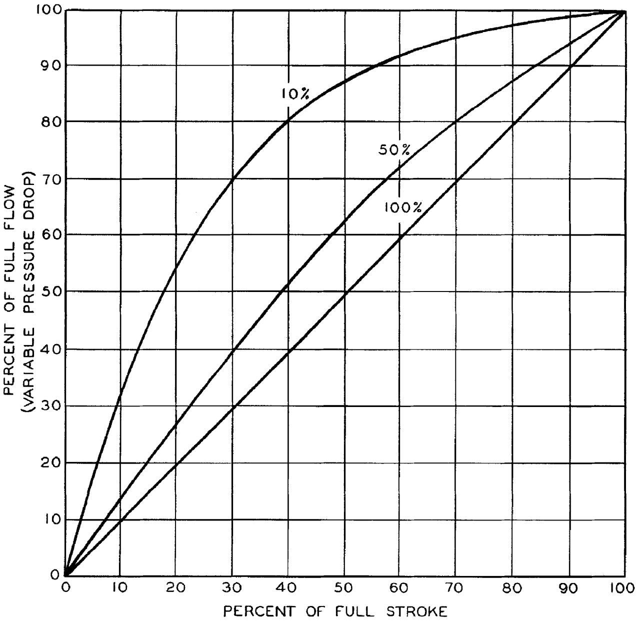

**Fig. 11 Typical Performance Curves for Linear Devices at Various Percentages of Total System Pressure Drop**

***Water Valves.*** Valves for water service may be two- or three-way and two-position or proportional. Proportional valves are used most often, but two-position valves are not unusual and are sometimes essential. While it is possible to design a water system in which the pressure differential from supply to return is kept constant, it is seldom done. It is safer to assume that the pressure drop across the valve increases as it modulates from fully open to fully closed. Figure 12 shows the effect in a simple system with one pump, one two-way control valve, and a heat exchanger. The system curve represents the pressure loss in the piping and heat

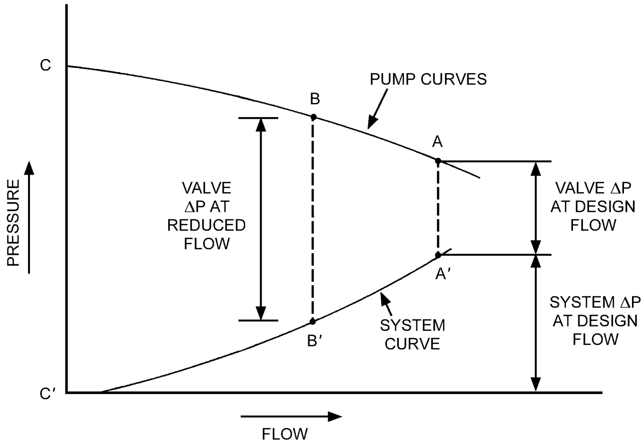

**Fig. 12 Pump and System Curves with Valve Control**

exchanger at various flow rates. The pump curve is the typical curve for a centrifugal pump. At design flow rates, the valve is selected for a specific pressure drop A – A′. At part load, the valve must partially close to provide a higher pressure drop B –B′. The ratio between the design pressure drop A – A′ and the zero Flow pressure drop C – C′ influences the control capability of the valve.

**Equal percentage valves** provide better control at part load, particularly in hot water coils where the heat output of the coil is not linearly related to flow. As flow is reduced, a greater amount of heat is transferred from each unit of water, counteracting the reduction in flow. Equal percentage valves are used in an attempt to linearize the heat transfer from the coil with respect to the control signal.

Two-way control valves should be sized to provide from 20 to 60% of the total system pressure drop. The valve operator should be sized to close the valve against the full pump head pressure to ensure complete shut off during no-flow condition.

For additional information on control valve sizing and selection, see Chapters 12 and 42 of the *ASHRAE Handbook—Systems and Equipment*.

**Actuators.** Valve actuators include the following general types:

- A **pneumatic valve actuator** consists of a spring-opposed, flexible diaphragm or bellows attached to the valve stem. An increase in air pressure above the minimum point of the spring range compresses the spring and simultaneously moves the valve stem. Springs of various pressure ranges can sequence the operation of two or more devices, if properly selected or adjusted. For example, a chilled water valve actuator may modulate the valve from fully closed to fully open over a spring range of 3 to 8 psig, while a sequenced steam valve may actuate from 8 to 13 psig.

  Two-position pneumatic control is accomplished using a two-position pneumatic relay to apply either full air pressure or no pressure to the valve actuator. Pneumatic valves and valves with spring-return electric actuators can be classified as normally open or normally closed.

  A **normally open valve** assumes an open position, providing full flow, when all actuating force is removed.

  A **normally closed valve** assumes a closed position, stopping flow, when all actuating force is removed.
- **Springless pneumatic valve actuators**, which use two opposed diaphragms or two sides of a single diaphragm, are generally limited to special applications involving large valves or high fluid pressure.
- An **electric-hydraulic valve actuator** is similar to a pneumatic one, except that it uses an incompressible fluid circulated by an internal electric pump.
- A **solenoid** consists of a magnetic coil operating a movable plunger. Most are for two-position operation, but modulating solenoid valves are available with a pressure equalization bellows or piston to achieve modulation. Solenoid valves are generally limited to relatively small sizes (up to 4 in.).
- An **electric motor** actuates the valve stem through a gear train and linkage. Electric motor actuators are classified in the following three types:

  **Unidirectional**—for two-position operation. The valve opens during one half-revolution of the output shaft and closes during the other half-revolution. Once started, it continues until the half-revolution is completed, regardless of subsequent action by the controller. Limit switches in the actuator stop the motor at the end of each stroke. If the controller has been satisfied during this interval, the actuator continues to the other position.

  **Spring-return**—for two-position operation. Electric energy drives the valve to one position and a spring returns the valve to its normal position.

  **Reversible**—for floating and proportional operation. The motor can run in either direction and can stop in any position. It is sometimes equipped with a return spring. In proportional control applications, a feedback potentiometer for rebalancing the control circuit is also driven by the motor.

## Dampers

**Types and Characteristics.** Automatic dampers are used in air-conditioning and ventilation to control airflow. They may be used (1) for modulating control to maintain a controlled variable such as mixed air temperature or supply air duct static pressure; or (2) for two-position control to initiate operation such as opening minimum outside air dampers when a fan is started.

**Multiblade** dampers are available in two arrangements—parallel blade and opposed blade (Figure 13). They are used to control flow through large openings typical of those in air handlers. **Parallel-blade dampers** are adequate for two-position control and can be used for modulating control when the pressure drop remains relatively constant (i.e., outdoor air and return air dampers on air-handling unit mixing boxes). However, **opposed-blade dampers** are

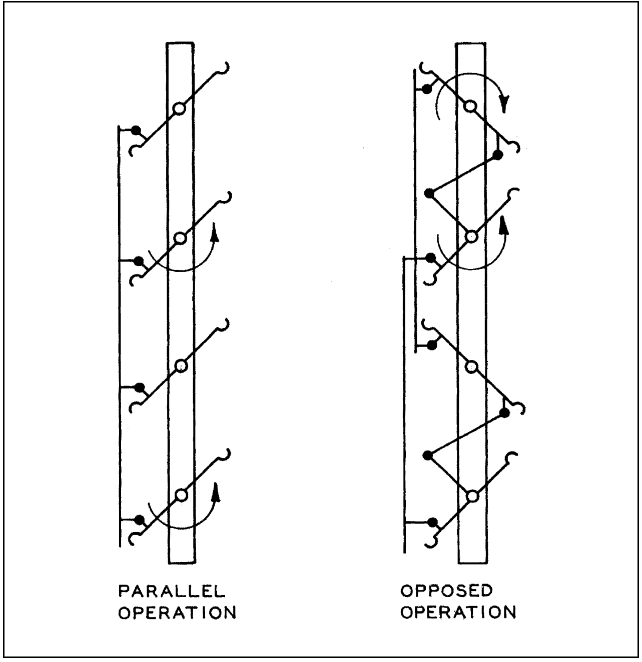

**Fig. 13 Typical Multiblade Dampers**

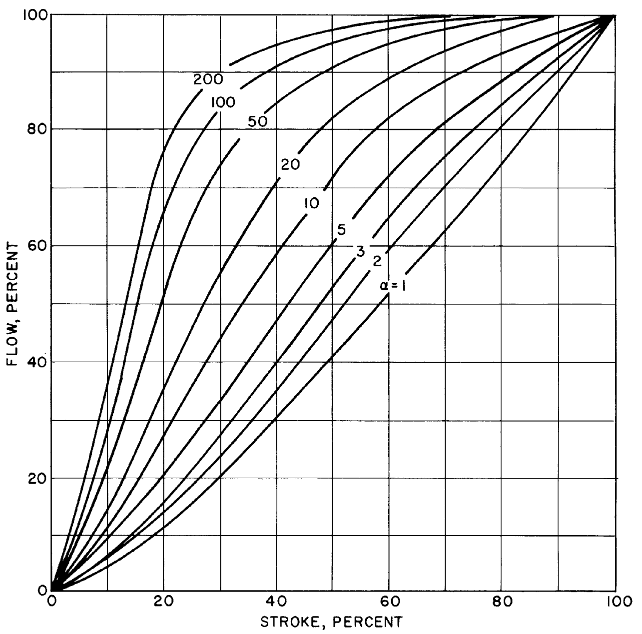

**Fig. 14 Characteristic Curves of Installed Parallel-Blade Dampers**

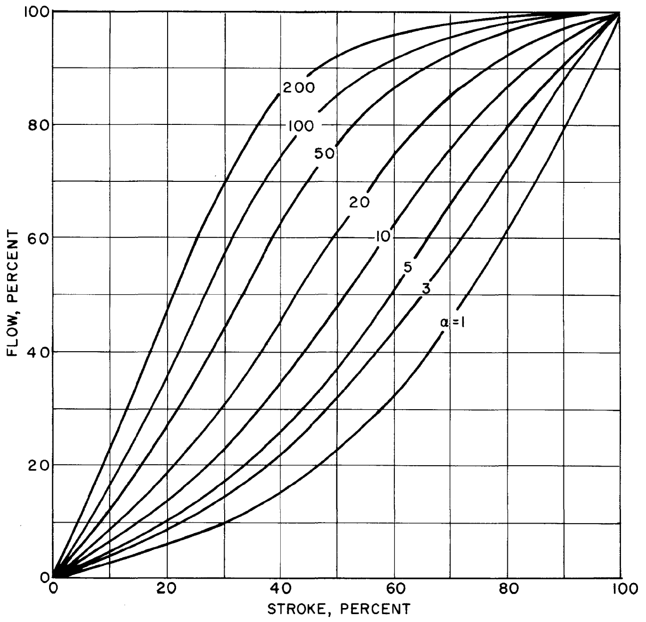

**Fig. 15 Characteristic Curves of Installed Opposed-Blade Dampers**

preferable for throttling control because they normally provide better control when the ratio of the pressure drop between closed and fully open is large (Figures 14 and 15). In these figures, α is the ratio of the system pressure drop to the drop across the damper at maximum (fully open) flow. **Single-blade dampers** are typically used for flow control at the zone.

Damper leakage is a concern, particularly where tight shutoff is necessary to reduce energy consumption significantly. Also, outdoor air dampers in cold climates must close tightly to prevent coils and pipes from freezing. Low-leakage dampers cost more and require larger actuators because of the friction of the seals in the closed position; therefore, they should be used only as necessary.

**Actuators.** Either electricity or compressed air is used to actuate dampers.

- **Pneumatic damper actuators** are similar to pneumatic valve actuators, except that they have a longer stroke or the stroke is increased by a multiplying lever. Increasing the air pressure produces a linear motion of the shaft, which, through a linkage, moves the crank arm to open or close the dampers.
- **Electric damper actuators** can be unidirectional, spring-return, or reversible. A **reversible** actuator, which has two sets of motor windings, is frequently used for accurate control in modulating damper applications. Energizing one set of windings turns the actuator output shaft clockwise; energizing the other turns the shaft counter-clockwise.

  When neither set of windings is energized, the shaft remains in its last position. The simplest form of control for this actuator is a floating point controller, which causes a contact closure to drive the motor clockwise or counter-clockwise. This type of actuator is available with a wide range of options for rotational shaft travel (expressed in degrees of rotation) and timing (expressed in the number of seconds to move through the rotational range). In addition, a variety of standard electronics signals from electronic controllers, such as 4–20 mA (dc) or 0–10 V (dc), can be used to control this type of modulating actuator.

  A two-position **spring-return** actuator moves in one direction when power is applied to its internal windings; when no power is present, the actuator returns (via spring force) to its normal position. Depending on how the actuator is connected to the dampers, this action opens or closes the dampers. A modulating actuator may also have spring-return action.

**Actuator Mounting.** Damper actuators are mounted in different ways, depending on the size, and accessibility of the damper, and the power required to move the damper. The most common method of mounting electric actuators is directly over the damper shaft with no external linkage. Actuators can also be mounted in the airflow on the damper frame and be linked directly to a damper blade; or they can be mounted outside the duct and connected to a crank arm attached to a shaft extension of one of the blades. On large dampers, two or more actuators may be needed. In this case, they are usually mounted at separate points on the damper. An alternative is to install the damper in two or more sections, each section being controlled by a single damper actuator; however, proper flow control is easier with a single modulating damper. Positive positioners may be required for proper sequencing. A small damper with a two-position spring-return actuator may be used for minimum outside flow, with a large damper being independently controlled for economy cycle cooling.

## Positive Positioners

A pneumatic actuator may not respond quickly or accurately enough to small changes in control pressure due to friction in the actuator or load, or to changing load conditions such as wind acting on a damper blade. Where accurate positioning of a modulating damper or valve in response to load is required, positive positioners should be used. A positive positioner provides up to full supply control air pressure to the actuator for any change in position required by the controller (Figure 16). An increase in branch pressure from the controller (A) moves the relay lever (B), which opens the supply valve (C). This allows supply air to flow into the relay chamber and the actuator cylinder, moving the pistons. A linkage and spring (D) transmit the piston movement to the other end of lever (B), and when the force due to movement balances the control force, the supply valve closes, leaving the actuator in the new position. A decrease in control pressure allows the exhaust valve (E) to open until a new balance is obtained.

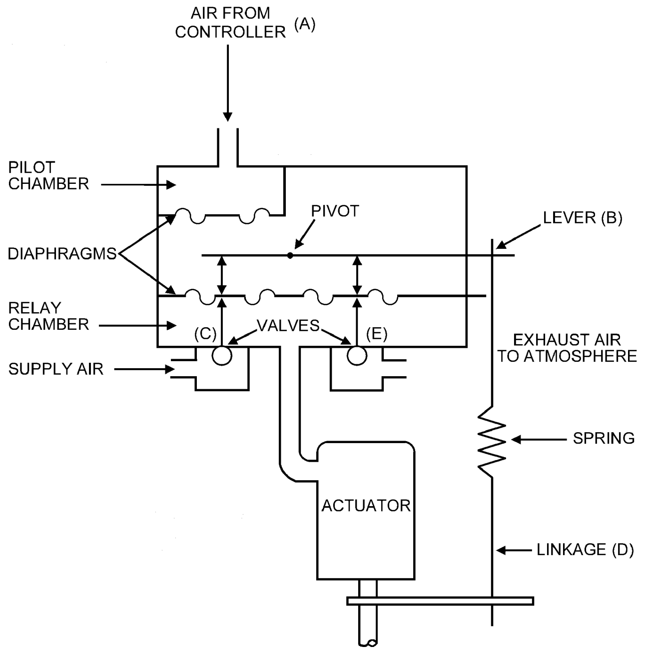

**Fig. 16 Pilot Positioner (Positive Positioner)**

A positive positioner provides finite and repeatable positioning change and permits adjustment of the control range (spring range of the actuator) to provide a proper sequencing control of two or more controlled devices.

## SENSORS

A sensor is a device that responds to a change in the controlled variable. The response, which is a change in some physical or electrical property of the primary sensing element, is available for translation or amplification by mechanical or electrical signal. This signal is sent to the controller.

Chapter 46 of the *ASHRAE Handbook—Applications* and manufacturer's catalogs and tutorials include information on specific applications. In selecting a sensor for a specific application, the following should be considered:

- **Operating range of controlled variable.** The sensor must be capable of providing an adequate change in its output signal over the expected input range.
- **Compatibility of controller input.** Electronic and digital controllers accept various ranges and types of electronic signals. The specific controller to be used must be considered in the selection of an electronic sensor; if this is not known, an industry standard signal, such as 4–20 mA (dc) or 0–10 V (dc), should be used.
- **Accuracy and repeatability.** For some control applications, the controlled variable must be maintained within a narrow band around a desired set point. Both the accuracy and the sensitivity of the sensor selected must reflect this requirement. However, even an accurate sensor can not maintain the set point if (1) the controller is unable to resolve the input signal, (2) the controlled device can not be positioned accurately, (3) the controlled device exhibits excessive hysteresis, or (4) disturbances drive its system faster than the controls can regulate it.
- **System response time (or process dynamics).** Associated with a sensor/transducer arrangement is a response curve, which describes the response of the sensor output to change in the controlled variable. If the time constant of the process being controlled is short, and stable accurate control is important, the sensor selected must have a fast response time.
- **Control agent properties and characteristics.** The control agent is the medium to which the sensor is exposed, or with which it comes in contact, for measuring a controlled variable such as temperature or pressure. If the agent corrodes the sensor or otherwise degrades its performance, a different sensor should be selected, or the sensor must be isolated or protected from direct contact with the control agent.
- **Ambient environment characteristics.** Even when the sensor's components are isolated from direct contact with the control agent, the ambient environment must be considered. The temperature and humidity range of the ambient environment must not reduce the accuracy of the sensor. Likewise, the presence of certain gases, chemicals, and electromagnetic interference (EMI) can cause component degradation. In such cases, a special sensor or transducer housing can be used to protect the element, while ensuring a true indication of the controlled variable.

### Temperature Sensors

Temperature-sensing elements fall into three general categories: (1) those that use a change in relative dimension due to differences in thermal expansion, (2) those that use a change in state of a vapor or liquid, and (3) those that use a change in some electrical property. Within each category, there are a variety of sensing elements to measure room, duct, water, and surface temperatures. Temperature-sensing technologies commonly used in HVAC applications are as follows:

- A **bimetal element** is composed of two thin strips of dissimilar metals fused together. Because the two metals have different coefficients of thermal expansion, the element bends and changes position as the temperature varies. Depending on the space available and the movement required, it may be straight, U-shaped, or wound into a spiral. This element is commonly used in room, insertion, and immersion thermostats.
- A **rod-and-tube element** consists of a high-expansion metal tube containing a low-expansion rod. One end of the rod is attached to the rear of the tube. The tube changes length with changes in temperature, causing the free end of the rod to move. This element is commonly used in certain insertion and immersion thermostats.
- A **sealed bellows element** is either vapor-, gas-, or liquid-filled. Temperature changes vary the pressure and volume of the gas or liquid, resulting in a change in force or a movement.
- A **remote bulb element** is a bulb or capsule that is connected to a sealed bellows or diaphragm by a capillary tube; the entire system is filled with vapor, gas, or liquid. Temperature changes at the bulb cause volume or pressure changes that are conveyed to the bellows or diaphragm through the capillary tube. The remote bulb element is useful where the temperature measuring point is remote from the desired thermostat location.
- A **thermistor** is a semiconductor that changes electrical resistance with temperature. It has a negative temperature coefficient (i.e., the resistance decreases as the temperature increases). Its characteristic curve of temperature versus resistance is nonlinear over a wide range. Several techniques are used to convert its response to a linear change over a particular temperature range. With digital control, one technique is to store a computer "look-up table" that maps the temperature corresponding to the measured resistance. The table breaks the curve into small segments, and each segment is assumed to be linear over its range. Thermistors are used because of their relatively low cost and the large charge in resistance possible for a small change in temperature.
- A **resistance temperature device (RTD)** is another sensor that changes resistance with temperature. Most metallic materials increase in resistance with increasing temperature. Over limited ranges, this variation is linear for certain metals such as platinum,

copper, tungsten, and nickel/iron alloys. Platinum, for example, is linear within ±0.3% from 0 to 300°F. The RTD sensing element is available in several forms for surface or immersion mounting. Flat grid windings are used for measurements of surface temperatures. For direct measurement of fluid temperatures, the windings are encased in a stainless steel bulb to protect them from corrosion.

## Humidity Sensors

Humidity sensors, or **hygrometers**, are used to measure relative humidity, dew point, or absolute humidity of ambient or moving air. Two types that detect relative humidity are mechanical hygrometers and electronic hygrometers.

A **mechanical hygrometer** operates on the principle that a hygroscopic material, usually a moisture-sensitive nylon or bulk polymer material, retains moisture and expands when exposed to water vapor. The change in size or form is detected by a mechanical linkage and converted to a pneumatic or electronic signal. Mechanical sensors using hair, wood, paper, or cotton do not match the performance of moisture-sensitive nylon or bulk polymer sensors and are not widely used.

**Electronic hygrometers** can use either resistance or capacitance sensing elements. The resistance element is a conductive grid coated with a hygroscopic (water-absorbent) substance. The conductivity of the grid varies with the water retained; thus, the resistance varies according to the relative humidity. The conductive element is arranged in an alternating current excited Wheatstone bridge and responds rapidly to humidity changes.

The capacitance element is a stretched membrane of nonconductive film. It is coated on both sides with metal electrodes and mounted in a perforated plastic capsule. The response of the sensor's capacity to rising relative humidity is nonlinear. The signal is linearized and temperature is compensated in the amplifier circuit to provide an output signal as the relative humidity changes from 0 to 100%.

The **chilled mirror humidity sensor** determines dew point rather than relative humidity. Air flows across a small mirror in the sensor. A thermoelectric cooler lowers the surface temperature of the mirror. The mirror surface condenses until it reaches the dew point of the air. The condensation from the surface reduces the amount of light reflected from the mirror compared to a reference light level.

**Dispersive infrared (DIR) technology** can be used to sense absolute humidity or dew point. It is similar to technology used to sense carbon dioxide or other gases. **Infrared water vapor sensors** are optical sensors that detect the amount of water vapor in air based on the infrared light absorption characteristics of water molecules. Light absorption is proportional to the number of molecules present. The output of an **infrared hygrometer** is typically a value of absolute humidity or dew point. They can operate in diffusion or flow-through sample mode. This type of humidity sensor is unique in that the sensing element (a light detector and an infrared filter) is behind a transparent window that is never exposed directly to the sample environment. As a result, this sensor has excellent long-term stability and life and fast response time, is not subject to saturation, and operates equally well in very high or low humidity. Previously used solely for high-end applications, infrared hygrometers are now commonly used in HVAC applications because they cost about the same as mid-range accuracy (1 to 3%) humidity sensors.

## Pressure Transmitters and Transducers

A pneumatic pressure transmitter converts a change in absolute, gage, or differential pressure to a mechanical motion using a bellows, diaphragm, or Bourdon tube mechanism. When corrected through appropriate links, this mechanical motion produces a change in the air pressure to a controller. In some instances, the sensing and control functions are combined in a single component, a **pressure controller**.

An electronic pressure transducer may use the mechanical actuation of a diaphragm or Bourdon tube to operate a potentiometer or differential transformer. Another type of transducer uses a strain gage bonded to a diaphragm. The strain gage detects the displacement resulting from the force applied to the diaphragm. Electronic circuits provide temperature compensation and amplification to produce a standard output signal.

## Flow Rate Sensors

Orifice plate, pitot tube, venturi, turbine, magnetic flow, vortex shedding, and Doppler effect meters are used to sense fluid flow. In general, the pressure differential devices (orifice plates, venturi and pitot tubes) are less expensive and simpler to use but have limited range; thus, their accuracy depends on how they are applied and where in a system they are located.

More sophisticated flow devices, such as turbine, magnetic, and vortex shedding meters, usually have better range and are more accurate over a wide range. If an existing piping system is being considered for retrofit with a flow device, the expense of shutting down the system and cutting into a pipe must be considered. In this case, a noninvasive meter, such as a Doppler effect meter, can be cost-effective.

## Indoor Air Quality Sensors

Indoor air quality control can be divided into two categories—ventilation control and contamination protection. Ventilation control measures levels of carbon dioxide or other contaminants in a space and controls the amount of outdoor air introduced into the occupied space. Demand control of ventilation helps maintain proper ventilation rates at all levels of occupancy. Typical control set point levels for carbon dioxide are 800 to 1000 ppm. ASHRAE *Standard* 62 provides further information on ventilation for acceptable indoor air quality.

Contamination protection sensors monitor levels of hazardous or toxic substances and issue warning signals and/or initiate corrective actions through the building automation system (BAS). Sensors are available for many different gases. The carbon monoxide (CO) sensor is one of the most common. The CO sensor is used to control and alarm CO levels in parking garages. Oxygen depletion sensors are used to measure, alarm, and initiate ventilation purging in enclosed spaces that house refrigeration equipment to prevent suffocation of occupants upon a refrigeration leak. The application of these sensors determines the type selected, the substances monitored, and the action taken.

## Lighting Level Sensors

Analog lighting level transmitters packaged in various configurations allow control of ambient lighting levels using building automation strategies for energy conservation. Some examples include ceiling-mounted indoor light sensors used to measure room lighting levels; outdoor ambient lighting sensors used to control parking, general exterior, security, and sign lighting; and interior skylight sensors used to monitor and control light levels in skylight wells and other atrium spaces.

## Power Sensing and Transmission

Passive electronic devices that sense the magnetic field around a conductor carrying current allow low-cost instrumentation of power circuits. A wire in the sensor forms an inductive coupling that powers the internal function and senses the level of the power signal. These devices can provide an analog output signal to monitor current flow or operate a switch at a user-set level to turn on an alarm or other device.

## CONTROLLERS

A controller compares the sensor's signal with a desired set point and regulates an output signal to a controlled device. Digital controllers perform the control function using a microprocessor and control algorithm. The sensor and controller can be combined in a single instrument, such as a room thermostat, or they may be two separate devices.

### Pneumatic Receiver-Controllers

Pneumatic receiver-controllers are normally combined with pneumatic elements that use a force or position reaction to the sensed variable to obtain a variable output air pressure. The control mode is usually proportional, but other modes such as proportional-plus-integral can be used. These controllers are generally classified as nonrelay, relay direct, or reverse-acting.

The nonrelay pneumatic controller uses low-volume output. A relay-type pneumatic controller actuates a relay device that amplifies the air volume available for control. The relay provides quicker response to a variable change.

Direct-acting controllers increase the output signal as the controlled variable increases. Reverse-acting controllers increase the output signal as the controlled variable decreases. A reverse-acting thermostat increases output pressure when the temperature drops.

### Electric/Electronic Controllers

For two-position control, the controller output may be a simple electrical contact that starts a burner or pump, or one that actuates a spring-return valve or damper actuator. Single-pole, double-throw (SPDT) switching circuits are used to control a three-wire unidirectional motor actuator. SPDT circuits are also used for heating and cooling applications. Both single-pole, single-throw (SPST) and SPDT circuits can be modified for timed two-position action.

Output for floating control is a SPDT switching circuit with a neutral zone where neither contact is made. This control is used with reversible motors; it has slow response and a wide throttling range.

Pulse modulation control is an improvement over floating control. It provides closer control by varying the duration of the contact closure. As the actual condition moves closer to the set point, the pulse duration shortens for closer control. As the actual condition moves farther from the set point, the pulse duration lengthens.

Proportional control gives continuous or incremental changes in output signal to position an electrical actuator or controlled device.

### Digital Controllers

A microprocessor in the digital controller executes control algorithms on one or multiple control loops. This controller is fundamentally different from pneumatic or electronic controllers in that the control algorithm is stored as a set of program instructions in memory (software or firmware). The controller itself calculates the proper control signals digitally rather than using an analog circuit or mechanical change.

A digital controller can be either single-loop or multiloop. Interface hardware allows the digital computer to process signals from various input devices such as electronic temperature, humidity, or pressure sensors described in the section on Sensors. Based on digitized equivalents of the input voltage or current signals, the control software calculates the required state of the output devices, such as valve and damper actuators and fan starters. The output devices are then positioned to the calculated state via interface hardware that converts the digital signal from the computer to an analog voltage or current required to position the actuator or energize a relay. It is common in both new and retrofit applications to use an additional interface device to convert the analog voltage or current into a pneumatic signal, which operates a pneumatic actuator. Such devices are called **electronic-to-pneumatic (E/P) transducers**.

The operator enters parameters such as set points, proportional or integral gains, minimum on and off times, or high and low limits, but the control algorithms stored in the computer's memory make the control decisions. The computer scans the input devices, executes the control algorithms, and then positions the output device(s), in a stepwise scheme. Digital controllers can be classified with regard to the way control algorithms are stored in memory (such as in firmware and software) and their ability to communicate to higher level devices such as terminals and computers.

**Firmware and Software.** Preprogrammed control routines, known as firmware, are typically stored in permanent memory such as electrically erasable programmable read-only memory (EEPROM). The operator can modify parameters such as set points, limits, and minimum off times within the control routines, but the program logic cannot be changed without replacing the memory chips.

User-programmable controllers allow the algorithms to be changed by the user. The programming language provided with the controller can vary from (1) a derivation of a standard language (such as Pascal or BASIC) to (2) a custom language developed by the controller's manufacturer to (3) graphically based programming. Preprogrammed routines for proportional, proportional plus integral, Boolean logic, timers, and so forth, are typically included in the language. Standard energy management routines may also be preprogrammed and may interact with other control loops where appropriate.

Digital controllers can be furnished with both preprogrammed firmware and user-programmed routines. These routines can automatically modify the parameters of the firmware according to user-defined conditions to accomplish the sequence of control designed by the control engineer.

**Operator Interface.** Some digital controllers are designed for dedicated purposes and are adjustable only through manual switches and potentiometers mounted on the controller. This type of controller cannot be networked with other controllers. An example is the programmable room thermostat. A **direct digital controller** can have manual adjustable features, but it more typically is adjusted through a built-in LED or LCD display, a hand-held device, or a terminal or computer. The DDC controller can communicate digitally, which allows remote connection to other controllers and to higher level computing devices and host operating stations.

A **terminal** allows the user to communicate with the controller and, where applicable, modify the program in the controller. Terminals can range from hand-held units with an LCD display and several buttons to a full-size console with a video monitor and keyboard. The terminal can be limited in function to allow only the display of sensor and parameter values or powerful enough to allow changing or reprogramming the control strategies. In some instances, a terminal can communicate remotely with one or more controllers, thus allowing central displays, alarms, and commands. Usually, hand-held terminals are used by technicians for troubleshooting, and full consoles at a fixed location are used to monitor the entire digital control system.

### Thermostats

Thermostats combine sensing and control functions in a single device. Microprocessor-based thermostats have many of the features described in the following paragraphs.

- The **occupied-unoccupied** or **dual-temperature room thermostat** controls at a reduced temperature at night. It may be indexed (changed from occupied to unoccupied) individually or in groups by a manual switch or time switch from a remote point. Some electric units have an individual clock and switch built into the thermostat.
- The **pneumatic day-night thermostat** uses a two-pressure air supply system—the two pressures often being 13 and 17 psig, or 15 and 20 psig. Changing the pressure at a central point from one

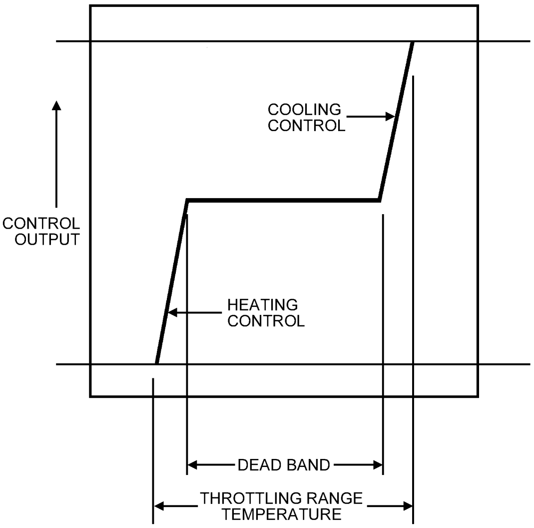

Fig. 17 Dead Band Thermostat

value to the other actuates switching devices in the thermostat that index it from occupied to unoccupied or vice versa.

- The **heating-cooling** or **summer-winter thermostat** can have its action reversed and its set point changed by indexing. It is used to actuate controlled devices, such as valves or dampers, that regulate a heating source at one time and a cooling source at another.
- **Multistage thermostats** are arranged to operate two or more successive steps in sequence.
- A **submaster thermostat** has its set point raised or lowered over a predetermined range in accordance with variations in output from a master controller. The master controller can be a thermostat, manual switch, pressure controller, or similar device.
- A **dead band thermostat** has a wide differential over which the thermostat remains neutral, requiring neither heating nor cooling. This differential may be adjustable up to 10°F. The thermostat then controls to maximum or minimum output over a small differential at the end of each dead band (Figure 17).

## AUXILIARY CONTROL DEVICES

Auxiliary control devices for electric systems include

- **Transformers** to provide current at the required voltage.
- **Occupancy sensors** to automatically adjust controlled variables based on occupancy such as lighting, ventilation rate, and temperature.
- **Signal transducers** to change one standard signal into another. The popularity of digital control and other electric-based control systems has generated a variety of transducers. The variables usually transformed include voltage [0–10, 0–5, 2–10 V (dc)], current [4–20 mA], resistance [0–135 Ω], pressure (3–15, 0–20 psig), phase cut voltage [0–20 V (dc)], pulse-width modulation, and time duration pulse. Signal transducers allow the use of an existing control device in a retrofit application.
- **Electric relays** to control electric heaters or to start and stop burners, compressors, fans, pumps, or other apparatus for which the electrical load is too large to be handled directly by the controller. Other uses include time-delay and circuit-interlocking safety applications.
- **Potentiometers** for manual positioning of proportional control devices, for remote set point adjustment of electronic controllers, and for feedback.
- **Manual switches**, either two-position or multiple-position with single or multiple poles.
- **Auxiliary switches** on valve and damper actuators for selecting a sequence of operation.

Auxiliary control devices for pneumatic systems include

- **Air compressors** and accessories, including dryers and filters, to provide a source of clean, dry air at the required pressure.
- **Electropneumatic relays**, electrically actuated air valves for operating pneumatic equipment according to variations in electrical input to the relay.
- **Pneumatic-electric switches**, which are actuated by the pressure from a controller to permit a controller actuating a proportional device to also actuate one or more two-position devices.
- **Pneumatic transducers**, which are used to reverse the action of a proportional controller, select the higher or lower of two or more pressures, average two or more pressures, respond to the difference between two pressures, add or subtract pressures, and amplify or retard pressure changes.
- **Positive positioning relays** to ensure accurate positioning of a valve or damper actuator in response to changes in pressure from a controller.
- **Switching relays**, which are pneumatically operated air valves used to divert air from one circuit to another or to open and close air circuits.
- **Pneumatic switches**, which are manually operated devices used to divert air from one circuit to another or to open and close air circuits. They can be two-position or multiple- position.
- **Gradual switches**, which are proportional devices used to manually vary air pressure in a circuit.

Auxiliary control devices common to both electric and pneumatic systems include the following:

- **Step controllers** to operate several switches in sequence by means of a proportional electric or pneumatic actuator. They are commonly used to control several steps of refrigeration capacity. They may be arranged to prevent simultaneous starting of compressors and to alternate the sequence to equalize wear. These controllers may also be used for sequenced operation of electric heating elements and other equipment.
- **Power controllers** to control electric power input to resistance heating elements. The final controlled device may be a variable autotransformer, a saturable-core reactor, or a solid-state power controller. They are available with various ratings for single- or three-phase heater loads and are usually arranged to regulate power input to the heater in response to the demands of the proportional electronic or pneumatic controllers. However, solid-state controllers may also be used in two-position control modes.
- **Clocks** or **timers** to turn apparatus on and off at predetermined times, to switch control systems from day to night operation, and to regulate other time sequence functions.
- **Transducers**, which consist of combinations of electric or pneumatic control devices, may be required. For these applications, transducers are used to convert electric signals to pneumatic output or vice versa. Transducers may convert proportional input to either proportional or two-position output.

The electronic-to-pneumatic (E/P) transducer is used in many applications. It converts a proportional electronic output signal into a proportional pneumatic signal (as illustrated in Figure 18) and can be used to combine electronic and pneumatic control components to form a control loop, as illustrated in Figure 19. Electronic components are used for sensing and signal conditioning, while pneumatic components are used for actuation. The electronic controller can be either analog or digital.

The E/P transducer presents a special option for retrofit applications. An existing HVAC system with pneumatic controls can be retrofitted with electronic sensors and controllers while retaining the existing pneumatic actuators (Figure 20).

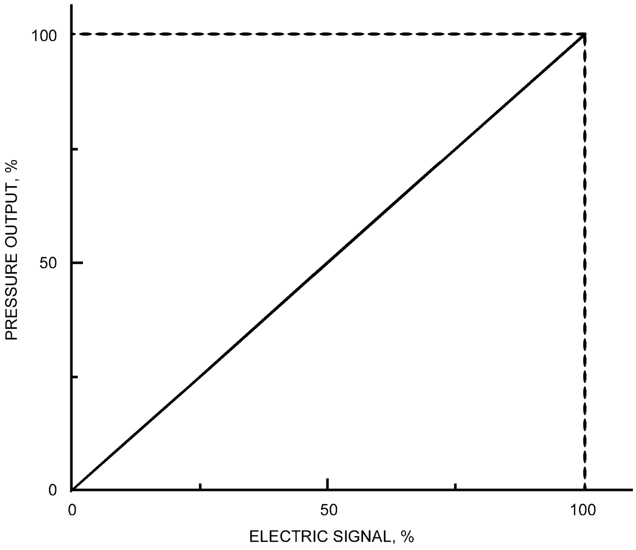

**Fig. 18** Response of Electronic-to-Pneumatic (E/P) Transducer

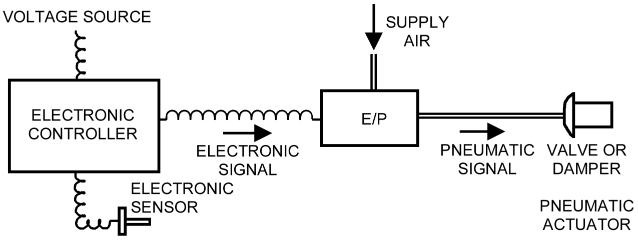

**Fig. 19** Electronic and Pneumatic Control Components Combined with Electronic-to-Pneumatic (E/P) Transducer

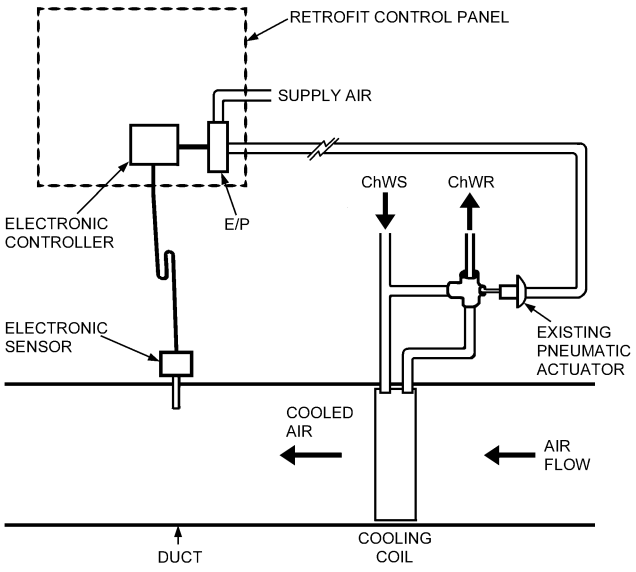

**Fig. 20** Retrofit of Existing Pneumatic Control with Electronic Sensors and Controllers

# COMMUNICATION NETWORKS FOR BUILDING AUTOMATION SYSTEMS

A **building automation system (BAS)** is a centralized control and/or monitoring system for many or all building systems (e.g., HVAC, electrical, life safety, security). A BAS may link together information from control systems actuated by different technologies.

One important characteristic of direct digital control (DDC) is the ability to share information. Information is transferred (1) between controllers to coordinate their action, (2) between controllers and building operator interfaces to monitor and command systems, and (3) between controllers and other computers for off-line calculation. This information is typically shared over communication networks. DDC systems nearly always involve at least one network and commonly involve more than one. A **network** is a set of connections between controllers, routers, bridges, and computers that enables them to exchange digital information.

## COMMUNICATION PROTOCOLS

A **protocol** is a set of rules that define the communication behavior of each element in a communication network. The word may describe the communication at one layer of the network [e.g., **Internet protocol (IP)**, which defines the network layer in the Internet suite of protocols], or it may refer to the entire communication process. In discussions of BASs, most communication needs are described in terms of the entire process, but it is sometimes necessary to discuss the protocols at a particular layer.

There is great interest in open protocols for BASs to facilitate communication among devices from different suppliers. Although there is no commonly accepted definition of "openness," the Institute of Electrical and Electronics Engineers defines three classes of protocols (IEEE *Standard* 802):

- **Standard protocol.** Published and controlled by a standards body. Examples include BACnet by ASHRAE, LonTalk by Electronic Industries Alliance, and TCP/IP by Internet Engineering Task Force.
- **Public protocol.** Published but controlled by a private organization.
- **Private protocol.** Unpublished; use and specification controlled by a private organization. Examples include the proprietary communications used by many building automation devices.

Multivendor communication is possible with any of these three classes, but the challenges vary. Specifying a common protocol does not ensure that the end user's requirement for interoperability is met. The engineer may select an open protocol and specify the interaction between devices. This limits the bidders, but assures the engineer of certain communication characteristics. On the other hand, the engineer can specify the required interoperation and put the burden on the suppliers to select combinations of products that meet the need. This is likely to result in a wider range of options, but they may be more difficult to compare.

## THE OSI NETWORK MODEL

ISO *Standard* 7498-1 presents a seven-layer model of information exchange called the **Open Systems Interconnection (OSI) Reference Model** (Figure 21). Most descriptions of computer networks, especially open networks, are based on this reference model. The layers can be thought of as steps in the translation of a message from something with meaning at the application layer, to something measurable at the physical layer, and back to meaningful information at the application layer.

The layered approach to network design is valuable because it allows developers to take advantage of existing standards such as IP at the network layer or Electronic Industries Association (EIA)

| | |
|---|---|
| **7** Application Layer | Window between applications and network. |
| **6** Presentation Layer | Coordinates representation of information between different applications. |
| **5** Session Layer | Synchronizes and structures exchange of data messages between specific users. |
| **4** Transport Layer | Converts data messages into packets for transmission, and converts received packets into messages. Responsible for data message error recognition and recovery, and ensures reliable delivery of messages. |
| **3** Network Layer | Addressing and routing packets independent of media and topology. |
| **2** Data Link Layer | Responsible for point-to-point reliability. Media access. Representation of bits and bytes as physical signals. Organizes bits into data packets. |
| **1** Physical Layer | Electrical characteristics of devices and conductors. |

**Fig. 21 OSI Reference Model**

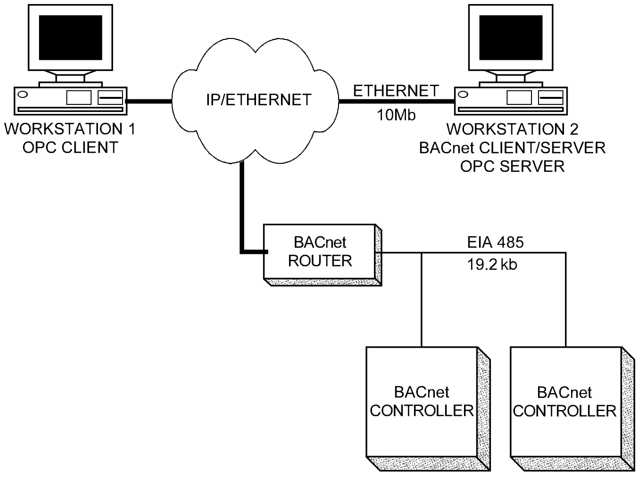

**Fig. 22 Portion of a BAS Network**

*Standard* 485, a signaling standard, at the physical layer without becoming tied to one technology.

The full seven-layer model does not apply to every network, but it is still used to describe the aspects that do fit. When describing DDC networks that use the same technology throughout the system, the seven-layer model is relatively unimportant. For systems that employ various technologies at different points in the network, the model helps describe where and how the pieces are bound together.

The portion of network shown in Figure 22 illustrates how the OSI Reference Model describes communications. The system includes a number of controllers on a BACnet network and several operator workstations connected by an ISO 8802-3 backbone or local area network (LAN), in this case an Ethernet. A BACnet router links the BACnet controllers to the Ethernet.

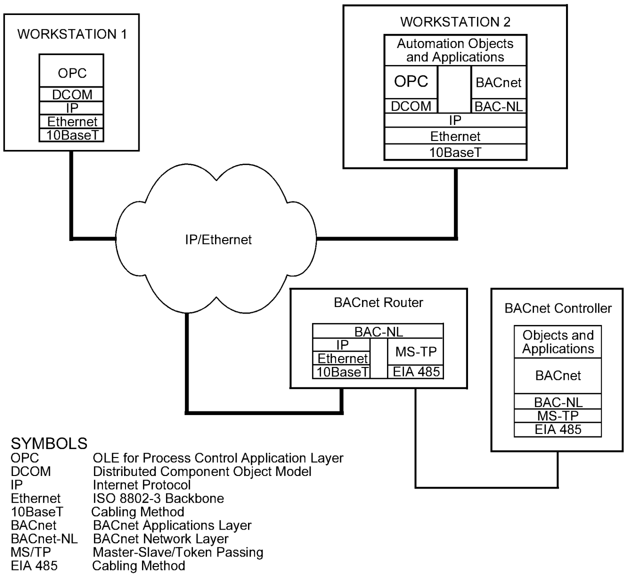

**Fig. 23 Network Layers in BAS Devices**

Figure 23 shows the network layers in each device that make communication possible. Workstation 2 and the BACnet controller both show communication stacks with BACnet at the application layer; however, these devices do not communicate directly because they use different protocols at the lower layers. If the stacks are different at any layer, a device that bridges the gap is required. The BACnet router shows two stacks. One matches the physical, data link, and network layers of the BACnet controllers; the other matches the bottom three layers of the BACnet stack on Workstation 2. The BACnet network layer is the common layer that delivers BACnet messages from one end of the router to the other. When a message reaches the router, it travels up through the stack. The router reformats it and sends the same message out through the other stack to the other network. This makes it possible for application data to pass between the controller and BACnet devices on the Ethernet. Bushby (1998) described this process more fully.

Both workstations contain an OPC stack. **OPC** (OLE for process control) is a standard for communicating automation data between computers or processes; it is based on distributed component object model (DCOM) technology. DCOM is a software development standard that facilitates interchangeability of software components.

The workstations communicate with each other over the Ethernet with OPC messages. Workstation 2 and the BACnet router communicate with each other over the Ethernet using BACnet messages. Although they are on the same network, Workstation 1 and the BACnet router do not communicate directly with each other because their protocol stacks do not match at the upper layers. If BACnet data is required at Workstation 1, it must pass through the OPC server on Workstation 2.

## NETWORK STRUCTURE

Often, a single DDC system applies several different network technologies at different points in the system. For example, a relatively low-speed, inexpensive network with relatively primitive functions may link a group of room controllers to a larger equipment controller. A faster, more sophisticated network links the large controller to its peers and to an operator's workstation. Several workstations communicate over a high-speed, relatively expensive, general-purpose office automation network. Figure 24 illustrates this sort of high-speed **hierarchical** network. Structures like it have been popular in DDC for years. Frequently, the network hierarchy corresponds roughly to a hierarchy related to the control function of the devices. Variations on this hierarchical structure will continue to emerge. The opposite extreme is a completely **flat** network architecture. A flat architecture links all the devices through the same network without altering any other hierarchy that exists among the devices. A flat architecture is more viable in small systems than in large ones due to the considerations discussed in the following paragraph.

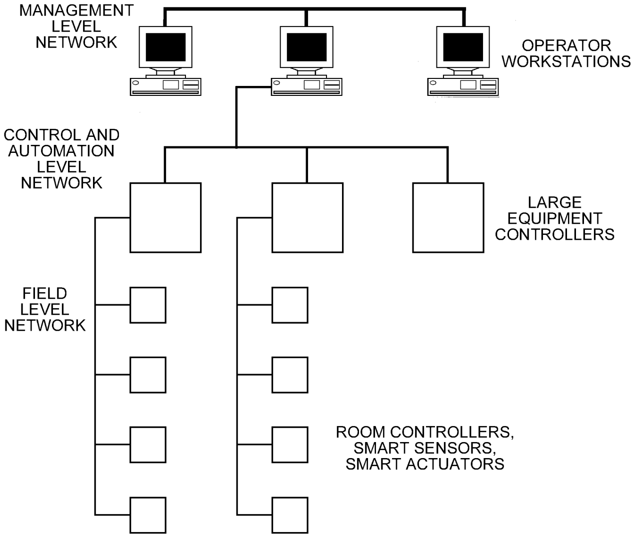

**Fig. 24 Hierarchical Network**

Network structure sometimes affects the cost, operation, and opportunities for expansion of a BAS. The structure can affect the reliability and failure modes of the system. It may be appropriate to separate sections of a network in order to isolate failures. Structure can affect the way devices load the information carrying capacity of the network. It can isolate one busy branch from the rest of the system. It can isolate branches from the high-speed backbone. Structure affects the cost of the system because it determines the mix of low-speed and high-speed devices. Network structure can influence system data security and access control. The relative merits of one structure versus another depend on the communication functions required, the hardware and software available for the task, and cost. For a given job, there is probably more than one suitable structure. Product capabilities change quickly. Engineers who choose to specify network structure must be aware of new technologies to take advantage of the most cost-effective solutions.

## Connections Between Networks and Network Segments

Some BAS networks use other networks to connect segments of the BAS. This occurs

- Within a building, using the information technology network
- Between buildings, using telephone lines
- Between buildings, using the Internet

In each case, the link between BAS segments must be considered part of the BAS network when evaluating function, security, and performance. The link also raises new issues. The connecting segment is likely to be outside the control of the owner of the BAS, which could affect availability of service. It may mean that traffic and bandwidth issues have to be addressed outside the facilities department.

The connection may be **switched** (dial-up) or **dedicated**. In the case of a switched connection, the function of the network depends on which segment may dial the other and the circumstances that trigger the call. Switched connections are most commonly used to handle remote buildings or to serve a remote operator (i.e., one who is on call over the weekend).

## Transmission Media

The transmission medium is the foundation of the network. It is usually, but not always, cable. In cases where physical cable connection is not possible or practical, devices may transfer information using wireless technologies, such as radio waves or infrared light. However, this section covers only physical cabling media.

**Table 1 Comparison of Fiber Optic Technology**

| | Multimode Fiber | Single-Mode Fiber |
|---|---|---|
| Light source | LED | Laser |
| Cable designation (core/cladding diameter) | 62.6/125 | 8.3/125 |
| Transmission distance | 660 ft | 980 ft |
| Data rate | >10 gigabit/s and increasing | Even higher |
| Relative cost | Less per connection, more per data rate | More per connection, less per data rate |

**Twisted-Pair Copper Cable.** A twisted-pair cable consists of multiple twisted pairs (typically 24 AWG) of wire covered by an overall sheath or jacket. Varying the number of twists for each pair relative to the other pairs in the cable can greatly reduce crosstalk (interference between signals on different pairs).

**In shielded** twisted pair (STP) cable, each wire pair, as well as the combined grouping of all pairs, is covered with a layer of shielding to minimize interference-related problems. STP cable performs better than **unshielded** twisted pair (UTP) cable in environments where a high level of immunity and/or a low level of emissions is critical. It also allows less crosstalk than UTP. However, STP requires a more labor-intensive installation, and any break or improper grounding of the shield reduces its overall effectiveness.

Category 5 (defined by TIA/EIA *Standard* 568-A) UTP cable is currently the most common medium. RJ-45 jacks and plugs are specified and have standard pinouts. This cable is rated at up to 1 gigabit per second for 330 ft and can be used over much longer distances for lower speed applications (e.g., EIA *Standard* 485).

**Fiber Optic Cable.** Fiber optic cable uses glass or plastic fibers to transfer data in the form of light pulses, which are typically generated by either a laser or an LED. Fiber optic cable systems are classified as either single-mode fiber or multimode fiber systems. Table 1 compares their characteristics.

Light in a fiber optic system experiences less energy loss than electrical signals traveling through copper and no capacitance. This translates into greater transmission distances and dramatically higher data transfer rates. With the rapid advances in this technology, the data transfer rate of a fiber cable imposes no limits on a BAS. Fiber optics also have exceptional noise immunity. However, the necessary conversions between light-based signaling and electricity-based computing make fiber optics more expensive per device, which sometimes offsets the other advantages.

**Structured Cabling.** TIA/EIA *Standard* 568-A, Commercial Building Telecommunications Cabling Standard, permits cable planning and installation to begin before the network engineering is finalized. It supports both voice and data. The standard was written for the telecommunications industry, but cabling is gaining recognition as building infrastructure, and the standard is being applied to BAS networks as well.

TIA/EIA *Standard* 568-A specifies **star topology** (each device individually cabled to a hub) because connectivity is more robust and management is simpler than for busses and rings. If the wires in a leg are shorted, only that leg fails, making fault isolation easier; with a bus, all drops would fail.

The basic structure specified is a **backbone**, which typically runs from floor to floor within a building and possibly between buildings. The **horizontal cabling** runs between the distribution frames on each floor and the information outlets in the work areas. The maximum length of horizontal cabling recommended is 330 ft.

## SPECIFYING BAS NETWORKS

Specifying a DDC system includes specifying a network. The many network technologies available deliver many performance levels at many different prices. A rational selection requires an assessment of the requirements (i.e., what information will pass between devices and at what rates). In some cases, the new equipment is required to interface with existing devices, which may limit networking options.

### Specification Method

As with other aspects of an HVAC system, an engineer must choose a method of specification. The Construction Specification Institute lists four methods. The following list relates those methods to BAS networks.

- **Descriptive.** Calls out the exact properties of the products. Properties could include communication protocols and data transfer rates.
- **Performance.** Tells what result is required and the criteria by which performance will be verified. Allows bidders to propose products to meet the need.
- **Reference standard.** Requires products to conform to an established standard. Does not oblige contractor to meet end user's needs not addressed in the standard.
- **Proprietary.** Calls out brand names. May be necessary in expansion of existing systems.

To write a descriptive network specification, the designer must know the details of network technology. To succeed with any specification, the designer must articulate the end user's needs. Typically, a performance-based specification results in the best value for the customer (Ehrlich and Pittel 1999).

### Communication Tasks

Determining network performance requirements means identifying and quantifying the communication functions required. Ehrlich and Pittel (1999) identified five basic communication tasks. To establish network requirements, the specifier must elaborate on each basic task. They are listed here along with some of the questions an engineer can use to identify the client's needs.

**Data Exchange.** What data passes between which devices? What control and optimization data passes between controllers? What update rates are required? What data does an operator need to reach? How much delay is acceptable in retrieving values? What update rates are required on "live" data displays? Within one system, the answers may vary according to the use of the data. Which set points and control parameters do operators need to adjust over the network?

**Alarms and Events.** Where do alarms originate? Where are they logged and displayed? How much delay is acceptable? Where are they acknowledged? What information must be delivered along with the alarm? (Depending on the design of the system, alarm messages may be passed over the network along with the alarms.) Where are alarm summary reports required? How and where do operators need to adjust alarm limits, etc?

**Schedules.** For the HVAC equipment that runs on schedules, where can the schedules be read? Where can they be modified?

**Trends.** Where does trend data originate? Where is it stored? How much will be transmitted? Where is it displayed and processed? Which user interfaces can set and modify trend collection parameters?

**Network Management.** What network diagnostic and maintenance functions are required at which user interfaces? Data access and security functions may be handled as network management functions.

Bushby et al. (1999) refer to the same five communication tasks as **interoperability areas** and list many more specific considerations in each area.

## APPROACHES TO INTEROPERABILITY

In the surge toward interoperability, many approaches have been proposed and applied, each with varying degrees of success under various circumstances. The field changes quickly as product lines emerge and standards develop and gain acceptance. The building automation world continues to evaluate the options project by project.

Typically, an interoperable system uses one of two approaches: standard protocols or special-purpose gateways. With a standard, the supplier is responsible for compliance with the standard; the system specifier or integrator is responsible for interoperation. With a gateway, the supplier takes responsibility for interoperation. The majority of integrated building automation systems currently depend on gateways, especially where the job requires interoperation with existing equipment. Bushby (1998) addressed this issue and some of the limitations associated with gateways. To date, interoperability by any method requires solid field engineering and capable system integration; the issues extend well beyond the selection of a communication protocol.

### Standard Protocols

Several standard protocols have been applied successfully in building automation systems. Their different characteristics make some more suited to particular tasks than others. The European Committee for Standardization (CEN) discusses characteristics of protocols appropriate for different building functions (CEN 1999). Table 2 lists some of the applicable standard protocols..

**Table 2 Some Standard Communication Protocols Applicable to BAS**

| Protocol | Definition |
|---|---|
| BACnet | ASHRAE *Standard* 135 |
| LonTalk | EIA *Standard* 709.1 |
| PROFIBUS FMS | EN 50170:1996 Volume 2 |
| EIB | ENV 13154-2 Annex C |
| EIBnet | ENV 18321-2 |

### Gateways and Interfaces

Rather than conforming to a published standard, a supplier can design a specific device to exchange data with another specific device. This typically requires cooperation between two manufacturers. It can be simpler and more cost-effective than for both manufacturers to conform to an agreed-upon standard. Sometimes the device is developed for one particular installation; other times it is an off-the-shelf product. In either case, the communication tasks must be carefully specified to ensure that the gateway performs as needed.

Choosing a system that supports a variety of gateways may be a way to maintain a flexible position as products and standards continue to develop.

# COMMISSIONING

A successful control system requires a proper start-up and testing, not merely the adjustment of a few parameters (set points and throttling ranges) and a few quick checks. With the services of an experienced control professional, the typical DDC system can be used effectively in the commissioning process to test and document the peformance of the HVAC system. In general, the increased use of VAV systems and digital controls has increased the importance of and need for commissioning.

Design and construction specifications should include specific commissioning procedures. In addition, commissioning should be coordinated with testing, adjusting, and balancing (TAB) because each affects the other. The TAB procedure begins by checking each control device to ensure that it is installed and connected according to approved drawings. Each electrical and pneumatic connection is verified, and all interlocks to fan and pump motors and primary heating and cooling equipment are checked. *ASHRAE Guideline* 1 explains how commissioning starts with project conception and continues for the life of the building.

## TUNING

The systematic tuning of controllers improves the performance of all controls and is particularly important for digital control. First, the controlled process should be controlled manually between various set points to evaluate the following questions:

- Is the process noisy (rapid fluctuations in controlled variable)?
- Is there appreciable hysteresis (backlash) in the actuator?
- How easy (or difficult) is it to maintain and change set point?
- In which operating region is the process most sensitive (highest gain)?

If the process cannot be controlled manually, the reason should be identified and corrected before the controller is tuned.

Tuning selects control parameters that determine the steady-state and transient characteristics of the control system. HVAC processes are nonlinear, and characteristics change on a seasonal basis. Controllers tuned under one operating condition may become unstable as conditions change. A well-tuned controller (1) minimizes the steady-state error for set point, (2) responds quickly to disturbances, and (3) remains stable under all operating conditions. Tuning proportional controllers is a compromise between minimizing steady-state error and maintaining margins of stability. Proportional plus integral (PI) control minimizes this compromise because the integral action reduces steady-state error, while the proportional term determines the controller's response to disturbances.

### Tuning Proportional, PI, and PID Controllers

Popular methods of determining proportional, PI, and PID controller tuning parameters include closed- and open-loop process identification methods and trial-and-error methods. Two of the most widely used techniques for tuning these controllers are ultimate oscillation and first order plus dead time. There are many optimization calculations for these two techniques, but the most widely used is the Ziegler-Nichols, which is given here.

**Ultimate Oscillation (Closed-Loop) Method.** The closed-loop method increases the gain of the controller in proportional-only mode until the equipment continuously cycles after a set point change (Figure 25, where $K_p = 40$). Proportional and integral terms are then computed from the cycle's period of oscillation and the $K_p$ value that caused cycling. The ultimate oscillation method is as follows:

1. Adjust control parameters so that all are essentially off. This corresponds to a proportion band (gain) at its maximum (minimum), the reset (repeats per minute) to maximum (minimum), and derivative to its minimum.
2. Adjust the manual output of the controller to give a measurement as close to midscale as possible.
3. Put the controller in automatic.
4. Slowly and gradually increase the proportional constant effect (this corresponds to reducing the proportional band or increasing the proportional gain) until the observed oscillations neither grow nor diminish in amplitude. If the response saturates at either extreme, start over at Step 2 to obtain a stable response. If no oscillations are observed, change the set point and try again.
5. Record the proportional band as $\text{PB}_u$ and the period of the oscillations as $T_u$.
6. Use the recorded proportional band and oscillation period to calculate controller settings as follows:

Proportional only:

$$\text{PB} = 1.8(\text{PB}_u) \qquad \text{percent} \qquad (4)$$

Proportional plus integral (PI):

$$\text{PB} = 2.22(\text{PB}_u) \qquad \text{percent} \qquad (5)$$

$$T_i = 0.83T_u \qquad \text{minute per repeat} \qquad (6)$$

Proportional plus integral plus derivative (PID):

$$\text{PB} = 1.67(\text{PB}_u) \qquad \text{percent} \qquad (7)$$

$$T_i = 0.50T_u \qquad \text{minute per repeat} \qquad (8)$$

$$T_d = 0.125T_u \qquad \text{minute} \qquad (9)$$

**First-Order-plus-Dead-Time (Open-Loop) Method.** The open-loop method introduces a step change in input into the opened control loop. A graphical technique is used to estimate the process transfer function parameters. Proportional and integral terms are calculated from the estimated process parameters using a series of equations.

The value of the process variable must be recorded over time, and the dead time and time constant must be determined from it. This can be accomplished graphically as seen in Figure 26. The first-order-plus-dead-time method is as follows:

1. Adjust the controller manual output to give a midscale measurement.
2. Arrange for the recording of the process variable over time.
3. Move the manual output of the controller by 10% as rapidly as possible to approximate a step change.
4. Record the value of the process variable over time until it reaches a new steady state value.
5. Determine the dead time and time constant.
6. Use the dead time (TD) and time constant (TC) values to calculate PID values as follows:

$$\text{Gain} = \frac{\%\ \text{change in controlled variable}}{\%\ \text{change in control signal}} \qquad (10)$$

Proportional only:

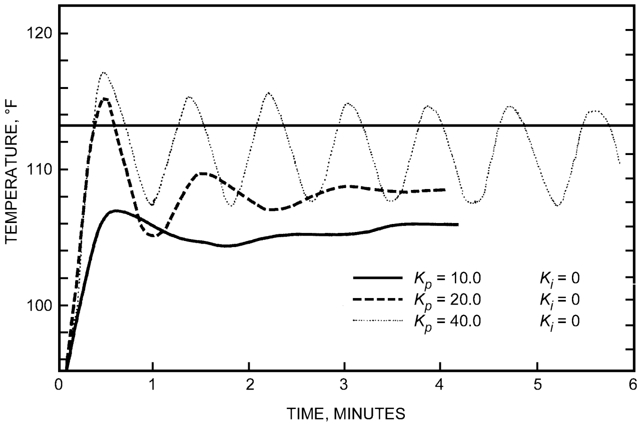

**Fig. 25 Response of Discharge Air Temperature to Step Change in Set Points at Various Proportional Constants with No Integral Action**

$$\text{PB} = \text{Gain}/(\text{TC}/\text{TD}) \tag{11}$$

Proportional plus integral (PI):

$$\text{PB} = 0.9(\text{Gain})/(\text{TC}/\text{TD}) \tag{12}$$

$$T_i = 3.33(\text{TD}) \tag{13}$$

Proportional-integral-derivative (PID):

$$\text{PB} = 1.2(\text{Gain})/(\text{TC}/\text{TD}) \tag{14}$$

$$T_i = 2(\text{TD}) \tag{15}$$

$$T_d = 0.5(\text{TD}) \tag{16}$$

**Trial and Error Method.** This method involves adjusting the gain of the proportion-only controller until the desired response to a set point is observed. Conservative tuning dictates that this response should have a small initial overshoot and quickly damp to steady-state conditions. Set point changes should be made in the range where controller saturation, or output limit, is avoided. The integral term is then increased until changes in set point produce the same dynamic response as the controller under proportional control, but with the response now centered about the set point (Figure 27).

### Tuning Digital Controllers

In tuning digital controllers, additional parameters may need to be specified. The digital controller sampling interval is critical because it can introduce harmonic distortion if not selected properly. This sampling interval is usually set at the factory and may not be adjustable. A controller sampling interval of about one-half the time constant of the controlled process usually provides adequate control. Many digital control algorithms include an error dead band to eliminate unnecessary control actions when the process is near set point. Hysteresis compensation is possible with digital controllers, but it must be carefully applied because overcompensation can cause continuous cycling of the control loop.

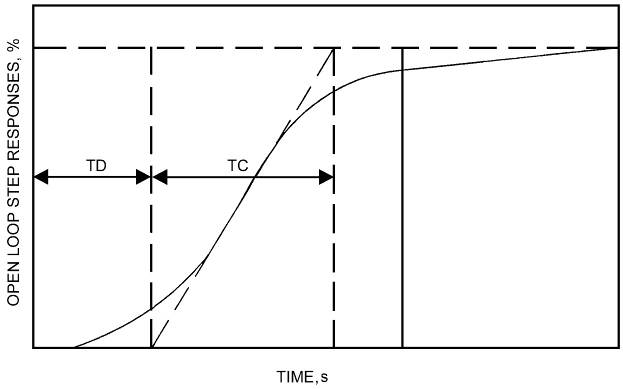

**Fig. 26 Open Loop Step Response Versus Time**

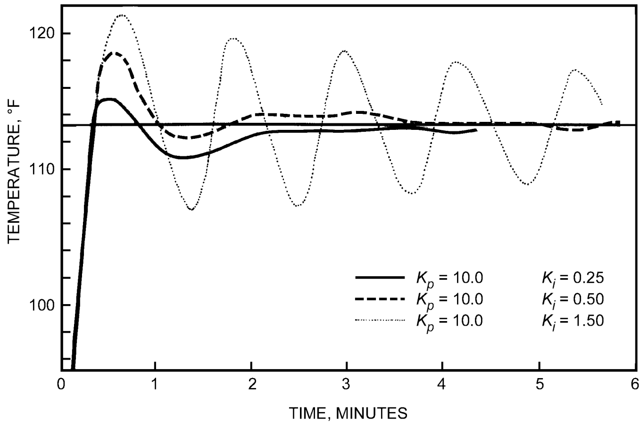

**Fig. 27 Response of Discharge Air Temperature to Step Change in Set Points at Various Integral Constants with Fixed Proportional Constant**

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