

Fundamentals of HVAC Control Systems

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Foreword



Welcome to the ASHRAE Learning Institute's Fundamentals of HVAC&R eLearning System Series.

This is a Course Reader to accompany the Fundamentals of HVAC Control Systems online modules. To help you learn at the convenience, this Course Reader is also available to you as an eBook with the online Course Modules.

The Course Reader will provide you with background information to help you develop in-depth knowledge of the Fundamentals of HVAC Control Systems, to improve your skills in HVAC&R and to earn the 47PDHs/4.7CEU's awarded for successful completion of the Fundamentals of HVAC Control Systems Learning course.

We look forward to working with you and helping you achieve maximum results from this course.

Introduction to HVAC Control Systems

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Study Objectives of Chapter I

Chapter 1 introduces basic control concepts. It begins with a discussion of why controls are required in HVAC systems and a brief history of the development of control products. Next, we introduce the concept of a control loop, the basic building block of all control systems, and the various control strategies and algorithms used in control loops. After studying this chapter, you should understand:

Why controls are necessary in HVAC systems.

The difference between open and closed control loops.

How two-position, floating, and modulating control loops work.

Proportional control.

Integral and derivative control action in modulating control loops.

How to tune control loops.

The difference between direct acting and reverse acting.

Difference between normally open and normally closed.

How controlled devices may be sequenced using a single controller.

1.1 Why Do We Need Controls?

We need controls and control systems because, in our modern age of technology, they make our lives more convenient, comfortable, efficient, and effective. A control enables equipments to operate effectively and sometimes gives the ability to change their actions as time goes on and conditions or occupancies change. Controls can be devices used to monitor the inputs and regulate the output of systems and equipments. You use controls every day. For example, when you shower in the morning you sense the water temperature and manually modulate the hot and cold water valves to produce the desired temperature. When you drive to work, you monitor your speed using the speedometer and manually control the accelerator of your car to maintain the desired speed. When you get to your office, you sense a shortage of light so you manually switch on the overhead lighting.

These are all examples of closed-loop manual controls. The term *manual* means that you (a person, rather than a device) are acting as the controller; you are making the decisions about what control actions to take. The term *closed-loop* means that you have feedback from the actions you have taken. In these examples, the feedback comes from your senses of touch and sight: as you open the hot water valve in your shower, you can sense the temperature of the water increase; when you depress the accelerator, you can see that your speed is increasing by viewing the speedometer; and when you turn on the light, you can see that the brightness in the space has increased.

Your car may also be equipped with cruise control, to automatically maintain speed on a clear road, which is an example of an *automatic* control. An automatic control is simply a device that imitates the actions you would take during manual control. In this case, when you press the set-button on the cruise control panel, you are telling the controller the speed you desire, or the set point. The controller measures your speed and adjusts the position of the accelerator to attempt to maintain the car's speed at set point – the desired speed – just as you do when you manually control the speed.

You may notice that your cruise control system is able to maintain your car's speed at a given set point more precisely than you can manually. This is generally because you are not paying strict attention to controlling your speed; you must also steer, watch for traffic and perform all of the other functions required for safe driving. This is one reason why we use automatic controls: we do not have the time or desire, or perhaps the ability, to constantly monitor a process to maintain the desired result.

Controls of heating, ventilating and air-conditioning, and refrigerating (HVAC&R) systems are analogous in many ways to the controls we use to drive our cars. Just as we use speed as an indicator of safe driving, we generally use dry bulb temperature (the temperature that a common thermometer measures) as an indicator of comfortable thermal conditions. Just as speed is not the only factor that affects driving safety, temperature is not the only factor that affects our perception of thermal comfort. But like speed is the major factor in driving, temperature is the major factor in comfort and is readily measured and controlled. Your car's engine was designed to bring the car up to speed quickly, to drive it up a hill, or to carry a heavy load. But because we do not need this peak power output all of the time, we need a control

device (the accelerator) that can regulate the engine's power output. The same can be said of HVAC systems. They are generally designed to handle peak cooling or heating loads that seldom, if ever, take place, so we must provide controls that can regulate the system's output to meet the actual cooling or heating load at a given time.

We use *automatic* controls for HVAC systems in place of manual controls, just as we might use cruise control to control the speed of our car. Automatic controls eliminate the need for constant human monitoring of a process, and therefore they reduce labor costs and provide more consistent, and often improved, performance.

The ultimate aim of every HVAC system and its controls is to provide a comfortable environment suitable for the process that is occurring in the facility. In most cases, the HVAC system's purpose is to provide thermal comfort for a building's occupants to create a more productive atmosphere (such as in an office) or to make a space more inviting to customers (such as in a retail store). The process may also be manufacturing with special requirements to ensure a quality product, or it may be a laboratory or hospital operating suite where, in addition to precise temperature and humidity control, the HVAC system must maintain room pressures at precise relationships relative to other rooms. With all of these systems, the HVAC system and its controls must regulate the movement of air and water, and the staging of heating, cooling, and humidification sources to regulate the environment.

Another capability that is expected of modern control systems is energy management. This means that while the control systems are providing the essential HVAC functions, they should do so in the most energy efficient manner possible.

Safety is another important function of automatic controls. Safety controls are those designed to protect the health and welfare of people in or around HVAC equipment, or in the spaces they serve, and to prevent inadvertent damage to the HVAC equipment itself. Examples of some safety control functions are: limits on high and low temperatures (overheating, freezing), limits on high and low pressures, freezestats, over current protection (e.g. fuses), and fire and smoke detection.

I.2 A Brief History of Controls

The first efforts at automatic control were to regulate space-heating systems. The bimetallic strip was the first device used; it controlled boiler output by opening and closing the boiler door, or a combustion air damper to control the rate of combustion. These devices were known as regulators. Other applications were to control steam radiators and steam heating coils. (Most steam radiators at that time were turned on and off by hand.)

Dr. Andrew Ure was probably the first person to call his regulator a thermostat and we still use this name 150 years later. These devices were soon used to control temperatures in incubators, railway cars, theaters, and restaurants.

Two other devices were developed to compete with the bimetallic strip. The first was a mercury thermometer column, having a contact low in the mercury and one or more contacts above the top of the column. Increasing temperature

caused the mercury to rise and make contact with an upper electrode, thereby completing the circuit. This extremely accurate thermostat was nonadjustable.

The second device, a mercury switch uses a drop of mercury in a small, sealed glass tube with contacts at one or both ends. The horizontal glass tube is concave upwards, must be mounted level, and will make or break a circuit with a slight impulse from a bellows or bimetal sensor. This slight impulse is multiplied by the mass of the moving mercury. This device (discussed in Chapter 4) still is used to control countless HVAC systems.

Refrigeration systems used thermostats to cycle the motor driving the compressor, or to open and close valves to modulate capacity. The first refrigeration systems controlled the flow of refrigerant by hand. When smaller automatic equipment was developed, high side floats, low side floats, and constant pressure valves (automatic expansion valves) came into use.

These early control devices were generally electric; their function was to make or break an electric circuit that turned on a fan or pump, opened a valve or damper, etc. Some early controls (particularly burner controls on furnaces and boilers) were self-powered; meaning they drew their energy from the process itself rather than from an external source such as electricity. The need for inexpensive modulating controls (controls that could regulate output over a continuous range rather than cycling from full-on to full-off) lead to the development of pneumatic controls that use compressed air as the control power rather than electricity.

Pneumatic controls are inherently analog (modulating). With the invention of the electron tube, analog electronic controls were developed. These controls now use analog solid-state (semiconductor) devices to provide the desired control functions. Finally, with the emergence of powerful and inexpensive microprocessors, digital controls were developed. Digital controls (often called direct digital controls or DDC) use software programmed into circuits to effect control logic.

These five control system types—self-powered controls (described in Chapter 6), electric controls (Chapter 7), pneumatic controls (Chapter 8), analog electronic controls (Chapter 9), and digital controls (Chapter 10)—are the basis of modern control systems. Most control systems today use a combination of the five system types and are more accurately called hybrid control systems.

All of the various types of hardware used in temperature control systems (in the past, currently, and in the future) are based on the same fundamental principles of control. While the technology used to implement these principles may change, the fundamental concepts generally remain the same. These principles are the subject of the rest of this chapter.

(The historical information in this section is from the ASHRAE publication, *Heat and Cold: Mastering the Great Indoors*.)

1.3 Control Loops

The process of driving your car at a given speed is an example of a control loop. You use your speedometer to measure your car's speed. If you are below the desired speed, you press the accelerator and observe the response. If you continue below the desired speed, press the accelerator some more. As you approach the desired speed, you start to release the accelerator so that you do not overshoot it.

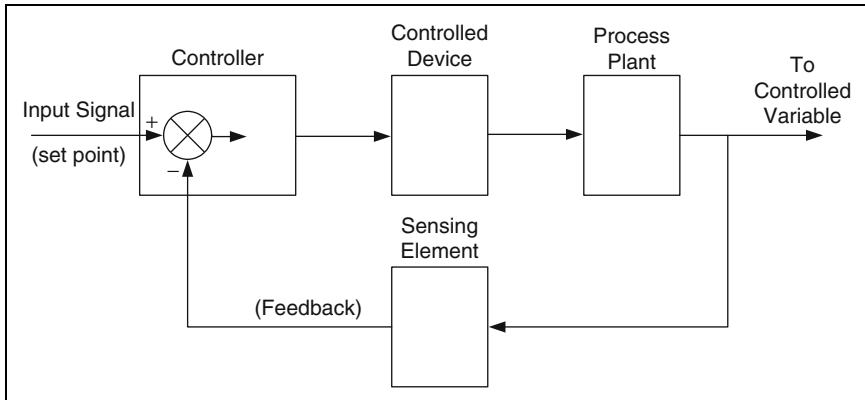


Figure 1-1 Diagram of Control Loop

In this example, you are acting as the controller making the control decisions whether to press or release the accelerator. The car's speed is the controlled variable and the speedometer is the sensor that measures the current value or control point of the controlled variable. The accelerator is the controlled device and your car's engine is the process plant.

Figure 1-1 shows this exchange of information schematically (see also *Table 1-1*).

It is called a control loop because information flows in a circle from the sensor (the speedometer) measuring the controlled variable (speed) to the controller (you), where the current value of the controlled variable (the control point) is compared to the desired value or set point. The controller then makes a control decision and passes that on to the controlled device (the accelerator) and to the process plant (the car's engine). This then has an effect on the current value or control point of the controlled variable, starting the process all over again. All control loops include these essential elements.

Figure 1-2 illustrates the components of a typical HVAC control loop.

Shown in *Figure 1-2* is an air-heating system utilizing a heating coil provided with steam, hot water, or some other heating source. Cold air is forced through the system using a fan and heated to some desired temperature to maintain its set point.

The intent of this control is to maintain a desired supply air temperature. As described in *Figure 1-2* and *Table 1-1*, the sensor measures the temperature of the supply air (the controlled variable) and transmits this information to the controller. In the controller, the measured temperature (the control point) is compared to the desired temperature (the set point). The difference between the set point and the control point is called the error. Using the error, the controller calculates an output signal and transmits that signal to the valve (the controlled device). As a result of the new signal, the valve changes position and changes the flow rate of the heating medium through the coil (the process plant). This, in turn, changes the temperature of the supply air. The sensor sends the new information to the controller and the cycle is repeated.

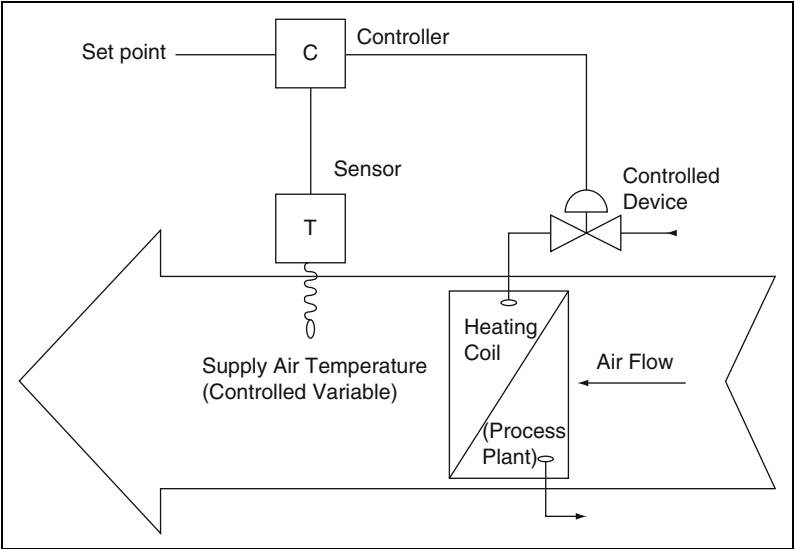


Figure 1-2 Simple Heating System

Table 1-1 Control Comparison for Automobile and Heating

Term	Automobile Example	Heating System Example	Definition
Controller	You	The device that provides a signal to the valve	The device that provides a signal to the controlled device in response to feedback from the sensor
Sensor	Speedometer	Supply air temperature sensor	The device that measures the current status of the controlled variable
Controlled device	The accelerator	The control valve	The device that changes the operation of the process plant in response to a control signal
Controlled variable	The car speed	The supply air temperature	The signal that the sensor senses
Process plant	The car engine	The heating coil	The device that produces the change in the controlled variable
Input signal (set point)	Desired speed	Supply air set point	This is the reference or desired input that is compared to the controlled variable

Both of these examples are called closed-loop or feedback-control systems because we are sensing the controlled variable and continuously feeding that information back to the controller. The controlled device and process plant have an effect on the controlled variable, which is sensed and fed to the controller for comparison to the set point and a subsequent response in the form of a change in controller output signal.

An open-loop control system does not have a direct link between the value of the controlled variable and the controller: there is no feedback. An example of an open-loop control would be if the sensor measured the outside air temperature and the controller was designed to actuate the control valve as a function of only the outdoor temperature. The variable (in this case, the supply air temperature or perhaps the temperature of the space the system served) is not transmitted to the controller, so the controller has no direct knowledge of the impact that valve modulation has on these temperatures modulating the valve.

Another way of defining an open-loop is to say that changes to the controlled device (the control valve) have no direct impact on the variable that is sensed by the controller (the outdoor air temperature in this case). With an open-loop control system, there is a presumed indirect connection between the end-result and the variable sensed by the controller.

If the exact relationship between the outdoor air temperature and the heating load was known, then this open-loop control could accurately maintain a constant space temperature. In practice, this is rarely the case, and therefore simple open-loop control seldom results in satisfactory performance. For this reason, almost all HVAC continuous-control systems use closed control loops.

Open-loop control, in the form of time-clocks, or occupancy sensors, are very common but they are on/off and not continuous controls. One form of open-loop control commonly used is called reset control. In reset control, an open-loop is used to provide a varying set point for a closed control loop. For example, an open-loop can be arranged to adjust the heating supply water temperature based on outside temperature, as shown in [Figure 1-3](#). As the outside temperature falls, the open-loop output rises based on a predetermined schedule, shown in the table in [Figure 1-3](#). This open-loop output provides the set point for the boiler.

The advantage of this reset control is that the capacity of the heating system increases as the load increases, greatly improving controllability. This use of one control loop to provide input to a second control loop is generally called cascading and other examples will be mentioned later in the course.

These examples describe the essential elements in any control loop: sensor, controller, controlled device, and process plant. Very few control systems are as simple as these examples, but every control system must include these

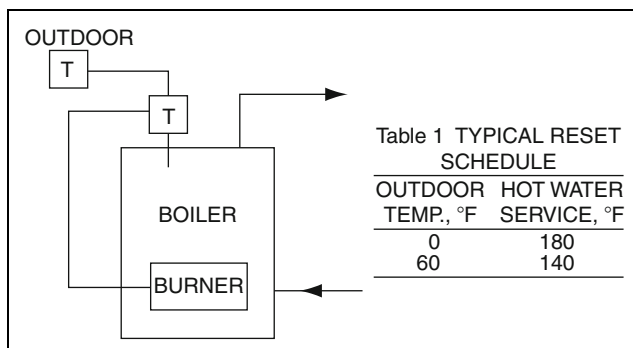


Figure 1-3 Boiler Reset Control

essential elements. In Chapter 5, we will describe more complex systems, but all of them will be based on elementary control loops. Behind any apparent complexity, there must be an elementary system or systems.

Sometimes the sensor and controller are combined in one package. This sensor/controller combination is commonly called a stat, such as a thermostat, humidistat, or pressure stat. These devices still contain the individual control elements (the sensor and the controller); they have simply been mounted into a single enclosure.

Common controlled devices include control valves, which are used to control the flow of water or steam, and control dampers, which are used to control the flow of air. These devices and their proper selection are discussed in Chapter 3. Motor starters, relays, and variable speed drives are also common control devices; they are discussed in Chapter 2.

Common controlled variables include the temperature, humidity, pressure, and velocity of air in conditioned spaces and in ductwork, and the temperature, velocity, and pressure of water in hydronic heating and cooling systems. Sensors used to measure these variables come in a variety of types with varying degrees of accuracy. The accuracy of the measurement naturally affects the accuracy of control. Sensors are discussed in Chapter 4.

Typically, between the controller and the controlled device, there is an actuator attached to the controlled device through connectors called the linkage. Actuators are devices that convert the signal from the controller into a physical force that causes the controlled device (damper or valve) to move. Actuator characteristics vary by the type of control system used and are discussed in Chapters 6–10.

This section introduced some fundamental terms used in control systems. It is very important that these terms are well understood so that you understand the remaining sections of this chapter. The following is a summary of key terms:

Controlled variable: the property that is to be controlled, such as temperature, humidity, velocity, flow, and pressure.

Control point: the current condition or value of the controlled variable.

Set point: the desired condition or value of the controlled variable.

Sensor: the device that senses the condition or value of the controlled (or “sensed”) variable.

Sensed variable: the property (temperature, pressure, humidity) that is being measured. Usually the same as the controlled variable in closed-loop control systems.

Controlled device: the device that is used to vary the output of the process plant, such as a valve, damper, or motor control.

Process plant: the apparatus or equipment used to change the value of the controlled variable, such as a heating or cooling coil or fan.

Controller: the device that compares the input from the sensor with the set point, determines a response for corrective action, and then sends this signal to the controlled device.

Control loop: the collection of sensor, controlled device, process plant, and controller.

Closed-loop: a control loop where the sensor is measuring the value of the controlled variable, providing feedback to the controller of the effect of its action.

Open-loop: a control loop where the sensor is measuring something other than the controlled variable. Changes to the controlled device and process plant have no direct impact on the controlled variable. There is an “assumed” relationship between the property that is measured and the actual variable that is being controlled.

1.4 Control Modes

The purpose of any closed-loop controller is to maintain the controlled variable at the desired set point. All controllers are designed to take action in the form of an output signal to the controlled device. The output signal is a function of the error signal, which is the difference between the control point and the set point. The type of action the controller takes is called the control mode or control logic, of which there are three basic types:

- two-position control
- floating control
- modulating control

Within each control-mode category, there are subcategories for each of the specific control algorithms (procedures, methods) used to generate the output signal from the error signal, and other enhancements used to improve accuracy.

The various control modes and subcategories are simply different ways of achieving the desired result: that the controlled variable be maintained at set point. It is often a difficult task because the dynamics of the HVAC system, the spaces it serves, and the controls themselves can be very complex. There are generally time lags between the action taken by the controller and the response sensed by the sensor.

For instance, in the heating system depicted in [Figure 1-2](#), it takes time for the valve to move when given a signal from the controller; then it takes a little more time for the water to begin to flow. If the coil has not been used for a while, it will take time to warm its mass before it can begin warming the air. If the sensor was located in the space served by the system (as opposed to in the supply duct, as shown in [Figure 1-2](#)), there would be even more time delays as the air travels down the duct to the diffusers and begins to mix with and warm the air in the space. There will be a delay as the air warms the surfaces in the space (the space envelope, walls, and furnishings) before it warms the surfaces and the air near the sensor. There can also be a delay as the sensor itself takes time to warm up and reach a new steady-state condition, and there may be a delay in transferring that information back to the controller. Finally, the controller can take time to compare the sensor signal to the set point and calculate a response. The effect of all these delays is called the system time constant. If the time constant is short, the system will react quickly to a change in the controlled device or process plant; if the time constant is long, the system will be sluggish to changes in the controlling devices.

Another factor that affects the performance of a controller is the system gain. As shown in [Table 1-2](#), the controller gain describes how much the controlled device will change for a given change in the controlled device and process plant.

Table 1-2 Controller Gain

Controller Setting	Controller Gain	Control Action
Open valve from 0 to 100% for a 1°F change in measured variable	Higher	Small change in measured variable creates a big change in output. 1°F causes controller to request 100% valve opening
Open valve from 0 to 100% for a 5°F change in measured variable	Lower	Large change in measured variable required to create a significant change in output. 1°F causes controller to request only 20% valve opening

The gain of the controller is only part of the issue. The capacity of the controlled device also influences the system gain. Thus, at full load, if full output just matches the requirement, then the controller gain is the same as the system gain. However, let us imagine that the required output is met with the controlled device only half open. In effect, the system capacity is twice what is required. The system gain is now the controller gain divided by the system overcapacity i.e., the gain is doubled. Thus, system gain is a function of controller gain and a function of how much capacity the system has relative to the load the system experiences. A system with a high gain means that a small change in the signal to the controlled device will cause a large change in the controlled variable. In the extreme case, the system is said to be oversized and good control is virtually impossible as even a small change in measured variable produces a huge change in output. The outdoor reset shown in [Figure 1-3](#) is an example of adjusting the system capacity to avoid the effect of overcapacity at low loads.

If all of these time delays and gains are fairly linear and consistent, the controller can generally be adjusted (tuned) to provide accurate control, but, there may be nonlinearities, such as hysteresis (delay, or uneven response) in the control valve. In this example, this is a delay caused by friction that binds the actuator or valve stem, thereby preventing a smooth, linear movement. There may also be changes to the system that change its gain, such as a varying hot water supply temperature to the heating coil, or a varying airflow rate through the coil. These complications can be handled with varying degrees of success and accuracy by the various control modes described in the following sections.

Two-position Control

The simplest and probably most common control mode is two-position control. It applies to systems that have only two states, such as On and Off for a fan or pump, or Open and Closed for a valve or damper. Small HVAC systems, such as the furnaces and air conditioners found in most residences, are examples of two-position systems. Systems that only have two states of operation are almost always controlled using two-position controls.

[Figure 1-4](#) shows the action of a two-position control of a heating thermostat for the heating system.

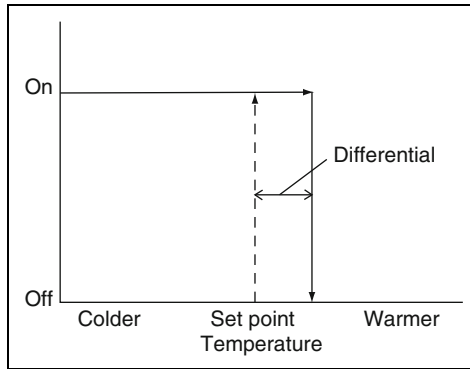


Figure 1-4 Two-position Control Diagram for a Heating System

Figure 1-5 shows what happens with this control when the controller responds to supply air that is colder than the desired set point at about 50% load.

The two positions in this case are the valve full-open (allowing full flow of hot water or steam through the coil) and the valve full-closed (no flow). Along the vertical axis is the value of the controlled (or “sensed”) variable (the supply air temperature), while time is on the horizontal axis.

Looking again at *Figure 1-2* and starting at the left of *Figure 1-5*, because the air entering the coil is colder than the desired set point, the air temperature sensed by the supply temperature sensor begins to fall. Just as it falls below the set point (represented by the lower dashed horizontal line in the figure), the controller causes the valve to open. The heating medium flows to the coil, but the air temperature will not rise immediately because it takes time for the actuator to open the valve and for the coil mass to begin to warm before it starts to warm the air. So the air temperature continues to fall below the set point before it turns around and begins to rise.

The valve will stay open until the supply air temperature rises by the control differential above the set point. The control differential is a fixed difference in sensed value between the open and closed commands; it is represented in *Figure 1-5* by the difference between the set point and the higher dashed line

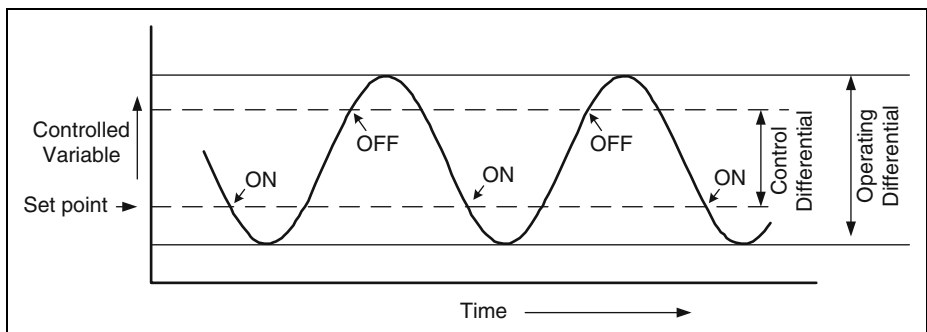


Figure 1-5 Two-position Heating Control

horizontal line. When the air temperature intersects this line, the controller closes the valve. Again, there is a time delay before the air temperature begins to fall because the heating medium in the coil and the coil itself must first cool off. Eventually, the air temperature falls until it reaches the set point again, and the cycle is repeated. In this example, the set point is shown to be the on-point (the point where the valve is opened) and the set point plus control differential is the off-point (where the valve is closed). It is also common to show the set point as being the midpoint between the on-point and off-point because this is the average condition of the controlled variable as the valve cycles opened and closed. In practice, however, the set point for a typical two-position thermostat (the point set by adjusting the set point knob) is usually either the on-point (as shown in [Figure 1-5](#)) or the off-point. It very seldom corresponds to the midpoint of the differential.

The overshoot and undershoot caused by the time delays result in the operating differential. This is depicted in [Figure 1-6](#) by the two solid horizontal lines marking the difference between the maximum and minimum temperature seen by the controlled variable. The operating differential always will be greater than the control differential.

It is not possible to remove the natural time-delays and thermal lag inherent in all real HVAC systems, but it is possible to reduce the difference between operating differential and control differential through the use of anticipation devices. One type of heat anticipator common in single-zone heating thermostats is a small resistance heater placed adjacent to the temperature sensor. This heater is energized when the heating is turned on and provides a false reading that causes the sensor to respond more rapidly. This causes the heater to be shut off before the actual space temperature rises above the control differential, reducing the overshoot and thus reducing the operating differential. This is depicted in [Figure 1-6](#).

The same device can be used to provide anticipation for cooling as well, except that in this case the heater is energized during the off-cycle. This causes

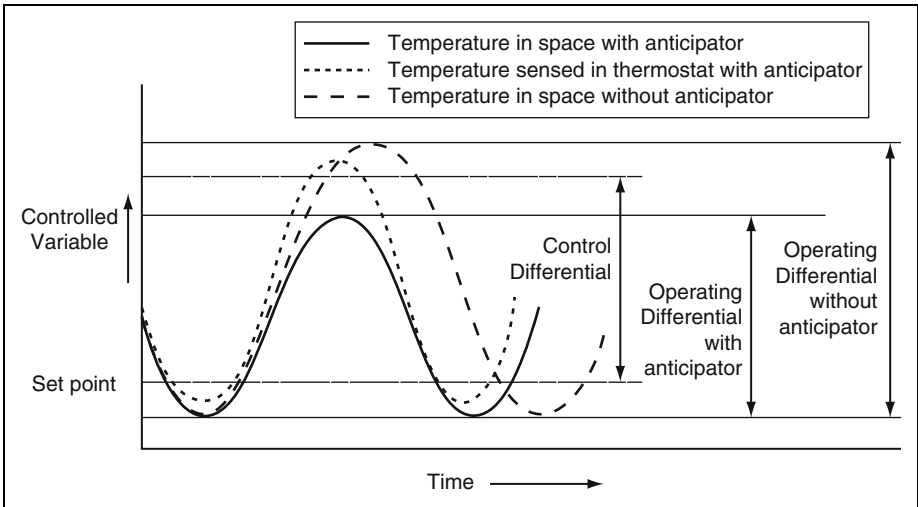


Figure 1-6 Two-position Control with Anticipator

the sensor signal to rise more quickly above set point, which then turns the cooling on more quickly, again reducing the operating differential.

Despite the use of anticipation devices, the very existence of a control differential results in temperature fluctuations. The air temperature is only at the desired condition (the set point) for a few moments. Control could be made more accurate by decreasing the control differential, but too small a differential will result in rapid cycling, called short-cycling. Short-cycling usually leads to inefficiencies in the heating or cooling system, and almost always shortens the life of equipment.

The ability of two-position control to function well (its ability to maintain the controlled variable near set point with a reasonable operating differential without short-cycling) is a function of the system gain, which is a function of the design of the HVAC system the control system. The capacity of the process plant (the heating or cooling system) must not greatly exceed the actual load experienced. If it does, then either the control differential must be increased, resulting in an unacceptably wide operating differential, or the system must be allowed to short-cycle. As with many control applications, the control system cannot compensate for a poor HVAC system design.

Where a wide variation in load is expected, if the system gain is too high due to process plant capacity that far exceeds the load at any given time, an HVAC system with continuously varying capacity or multiple capacity steps should be used. Systems with continuous capacity are controlled using either floating or modulating controls, as discussed in the next two sections. Systems with multiple capacity steps are controlled by step controls.

Step control is actually a series of two-position controls controlling the same controlled variable but at slightly different set points. Step control is used to control systems with multiple stages of capacity, such as multi-speed motors (high-low-off), multi-stage gas burners (high-fire, low-fire, off), or multi-stage refrigeration systems (multiple compressors, multi-speed compressors, or compressors with cylinder unloading). *Figure 1-7* shows how a step controller

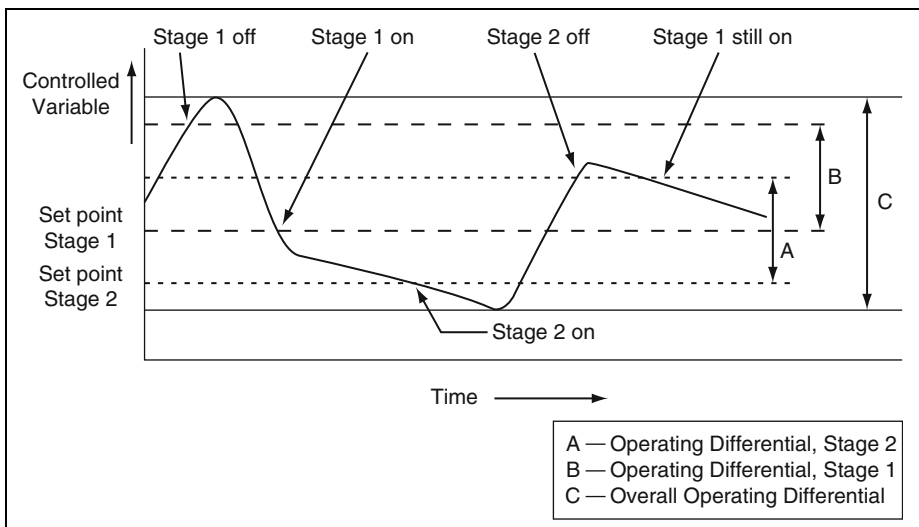


Figure 1-7 Step Control

might operate with a heating system that had two heating stages for a total of three operating positions (high-fire, low-fire, and off).

As the temperature falls below the Stage 1 set point, the first step of heating is turned on. If this were enough capacity to handle the load, the temperature would cycle around this set point and its control differential just as it would with two-position control. If, as depicted in [Figure 1-7](#), the temperature were to continue to fall below the Stage 2 set point, the second heating stage would be turned on. Operation is then just like two-position control around this set point. Note that the control operating ranges overlap; the temperature at which the first stage comes on is lower than the temperature at which the second stage goes off. The set points and control differentials could have been set for nonoverlapping ranges where the first-stage on-point was equal to or above the second stage off-point. However, overlapping the ranges reduces the overall operating differential without using small operating differentials for each stage. In this way, fine control can be provided without short-cycling stages.

Floating Control

Floating control (also called “tri-state” control) is similar to two-position control, but the system it controls is not limited to two states. The system must have a modulating-type controlled device, typically a damper or valve driven by a bi-directional actuator (motor). The controller has three modes: drive open, idle (no movement), or drive closed.

Like two-position control, floating control has a set point and a control differential. Some floating controllers have, instead, two set point adjustments, an upper set point and a lower set point. The control differential is then the difference between the two set points.

When the supply air temperature falls below the lower line of the differential (in [Figure 1-8](#)), the controller starts to drive the control valve open, thereby increasing the flow of the heating medium through the coil. Because of the time delay in moving the valve and the normal thermal lags, the supply air temperature will continue to fall below the differential, but eventually it will start to rise. When it rises above the differential, the valve is no longer driven

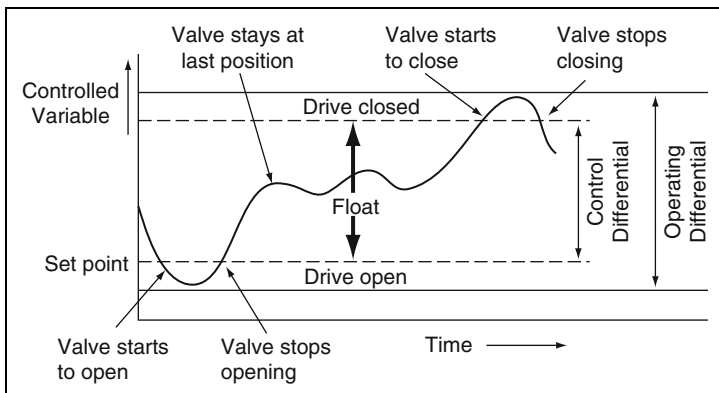


Figure 1-8 Floating Control

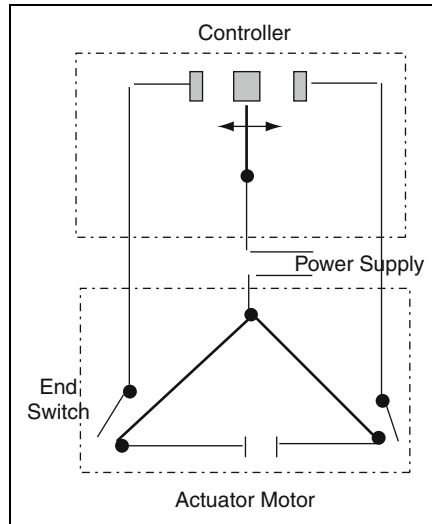


Figure 1-9 Floating Diagram with Actuator

open; it is left in the position it was in just when the temperature rose above the lower range of the differential.

While the temperature is within the differential range, the valve position will not move. If the temperature rises above the upper line of the differential, the controller will begin to drive the valve closed, thereby decreasing the flow of the heating medium through the coil. Again, the valve stops moving in whatever position it happens to be in once the temperature returns to within the differential. The air temperature will “float” within the differential range, which is how this control logic was given its name. Basically, as shown in [Figure 1-9](#), a drive signal is applied to drive the actuator to either its open or closed position as the controller monitors its feedback.

Because the controlled device is variable rather than two-position, floating control can have a smaller control differential than two-position controllers without instability or excessive cycling. As with two-position control, floating control will have an operating differential that exceeds the control differential due to thermal lags and other time delays. In fact, the overshoot/undershoot can be even more severe because the valve timing (the time it takes to drive the valve from full-open to full-closed) must be relatively slow to prevent unstable control. (If the valve closes too quickly, the system will essentially behave as a two-position control.) For this reason, anticipation devices as described for two-position controls are especially desirable for floating controls.

Modulating Control

Can you imagine driving a car using two-position control? When your speed falls below the desired speed, you would fully depress the accelerator, and then release it at some differential above the desired speed. The results would be very jerky. To control speed precisely in a car, given the variation in power

required from accelerating onto the freeway to coasting down a residential lane, a system of continuously varying capacity control is required: the accelerator. Many HVAC systems face similar widely varying loads and are also fitted with continuous or nearly continuous capacity capability. When controlling systems with this capability, you can improve the accuracy of control by using modulating control logic, the subject of this section.

Note that just because the system has a continuously variable output capability it does not limit you to using modulating controls. You could still drive your car with two-position control by alternately pressing and releasing the accelerator (although with not very satisfactory results). Early cruise control systems used floating control logic to control speed (as do some poor drivers, it seems). Conversely, systems that are inherently two-position or multi-position (such as staged refrigeration systems) are not limited to using two-position controllers. As we will see below, these systems can also benefit from modulating control techniques.

Modulating control is sometimes called analog control, drawing on the parallel between modulating/two-position and analog/digital. For many years, the term *proportional control* was used to mean modulating control because the controllers at that time were limited to proportional control logic (described below). Modern modulating controls use more sophisticated algorithms that go beyond simple proportional logic.

Remember that automatic controls simply imitate the human logic you would apply during manual control. To understand some of the control logic you use without consciously thinking about it, imagine you are trying to drive your car at a constant speed. While the road is flat or at a steady slope you can maintain a constant speed while pressing the accelerator to a fixed position. As you start to climb a hill, you begin to lose speed, so you begin to press the accelerator some more. If you slowed only a little below your desired speed, you may only press the accelerator a little more. The further you fall below the desired speed, the more you would press the accelerator.

After a while, you may find that you are no longer decelerating, but the speed you are maintaining, while constant, is still below that desired. The longer you stay below the desired speed, the more inclined you are to press the accelerator more to get back up to speed. However, let us say that, before you get up to speed, the terrain changes and you start to go down a hill. Your speed begins to increase toward the desired speed, but at a rate that you sense is too fast. To prevent from shooting past the speed you desire, you begin to back off of the accelerator even though you are still below the desired speed. As the terrain changes, you continuously go through many of these same thought processes over and again.

While you certainly do not think of them this way, the thought processes you use to drive your car can be approximated mathematically as:

$$\begin{aligned} V &= V_0 + V_p + V_i + V_d \\ &= V_0 + K_p e + K_i \int e \, dt + K_d \frac{de}{dt} \end{aligned} \quad (\text{Equation 1-1})$$

In this expression, V is the output of the controller. Using our example, V is how much you press the accelerator.

The first term on the right-hand side of the equation, V_0 , is called the offset adjustment. It is the amount you have to press the accelerator when you are driving on a flat road or a road with a steady slope, and to keep your car cruising steadily at the speed you desire.

The second term, V_p , is called the proportional term. It is proportional to the error e , which is the difference between actual speeds and the desired speed or set point. When you sense that the further you are from the desired speed, the more you should press the accelerator, you are using proportional control logic.

The third term, V_i , is called the integral term. It is proportional to the integral of the error over time. For those of you not familiar with calculus, the integral term is essentially a time-weighted average of the error; how much are you away from set point multiplied by how long you have been that way. In our example, when you sensed that you stayed below the desired speed for too long and thus pressed the accelerator more to increase speed, you were using integral control logic.

The last term V_d is called the derivative term. It is proportional to the derivative of the error with respect to time. Again, if you are not familiar with calculus, the derivative term is essentially the rate of change of the error; how fast you are approaching or going away from set point. In our example, when you sensed that you were approaching the desired speed too quickly and thus started to back-off the accelerator, you were using derivative control logic.

These three terms can be seen graphically in [Figure 1-10](#). The proportional term varies proportionally to the error: how far we are from set point. The integral term is proportional to the time-weighted average of the error, which is the area under the curve (the hatched area in the figure) and represents both how long and how far we have been away from set point. The derivative term is proportional to the slope of the error line; how quickly we are approaching or going away from set point. Now let us examine each of these terms to see how they affect control accuracy.

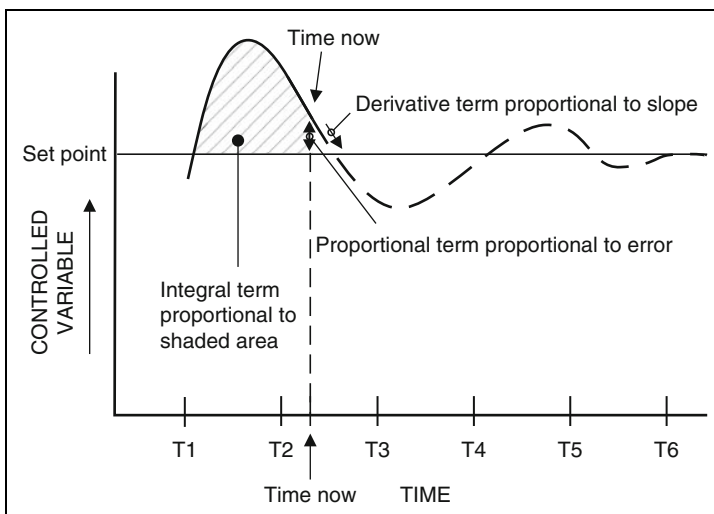


Figure 1-10 Proportional, Integral, and Derivative Control

First, if we remove the integral and derivative terms from [Equation 1-1](#), we get:

$$V = V_0 + K_p e \tag{Equation 1-2}$$

This is the mathematical expression of proportional-only control logic. Proportional control is the simplest and most common modulating control logic. Virtually, all pneumatic thermostats, most pneumatic controllers, and most analog electronic controllers use it.

[Figure 1-11](#) shows a typical proportional system response to start-up or change of set point. The system will respond by approaching the set point and then overshooting, due to the time delays and thermal lag mentioned under two-position control. Overshoot and undershoot will decrease over time until, under stable loads, the system levels out at some continuous value of the error (called offset or droop).

Continuous offset under steady-state conditions (constant load) is an inherent characteristic of proportional control. Proportional control will only keep the controlled variable exactly at set point under one specific load condition; at all others, there will be droop or offset.

Applying proportional logic and [Equation 1-2](#) to the heating coil depicted in [Figure 1-2](#), you can see the following.

If we were at a steady load, then we would require a certain flow of the heating medium that would exactly match that load. To get that flow rate, we would have to open the valve to a certain position. That position is determined by the signal from the controller V in [Equation 1-2](#).

If we assume that we were exactly at set point, then the second term in [Equation 1-2](#) would be zero because the error e would be zero, so the control signal would be equal to V_0 (our offset adjustment). For this specific load, we could adjust V_0 so that the desired flow rate is achieved and could maintain zero offsets. However, because V_0 is a constant, we can only maintain this condition at this precise load. If we were at a steady load that was higher, for example, we would need to open the valve more, requiring a larger signal V . To increase the value of V , the second term of [Equation 1-2](#) would have to be

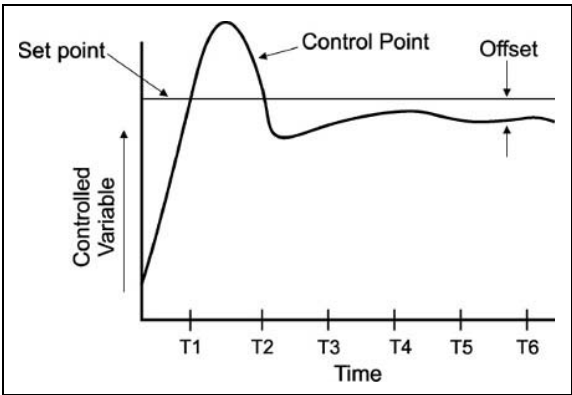


Figure 1-11 Proportional-only Control

nonzero, meaning our error would have to be nonzero. This error is the offset or droop.

The amount of the offset is a function of the constant K_p (the controller proportional gain). The larger the gain is, the smaller the offset. However, increasing the gain to minimize offset must be done with care because too high a gain may result in instability and a rapid oscillation around the set point (called *hunting*). This is because the larger gain causes the valve signal to be larger when there are small values of error, thereby causing the system to overreact to small changes in load. This overreaction causes an even larger error in the other direction, which again causes a large change in the valve signal, and we overshoot in the other direction. Adjusting the gain for stable control (minimal offset without hunting) is called tuning the control loop and is discussed further in [Section 1.5](#).

A more common way of expressing the proportional gain is the term *throttling range*. The throttling range is the amount of change in the controlled variable that causes the controlled device to move from one extreme to the other, from full-open to full-closed. It is inversely proportional to the proportional gain. Applying integral logic along with proportional logic has the effect of minimizing or eliminating offset. This is called proportional plus integral (PI) control logic, expressed mathematically as:

$$V = V_0 + K_p e + K_i \int e \, dt \quad (\text{Equation 1-3})$$

The longer the error persists, the larger the integral term becomes, so that the effect is always to drive the value of the controlled variable toward the set point and eliminating offset. This is shown in [Figure 1-12](#).

The sensitivity of the control logic is now a function of both the proportional gain K_p and the integral gain K_i . Just as with proportional control, it is possible to have unstable control if the gains are too high; they must be tuned for the application.

One disadvantage of including the integral term is an effect called *windup*. This is caused when the control loop is operating but the controlled device

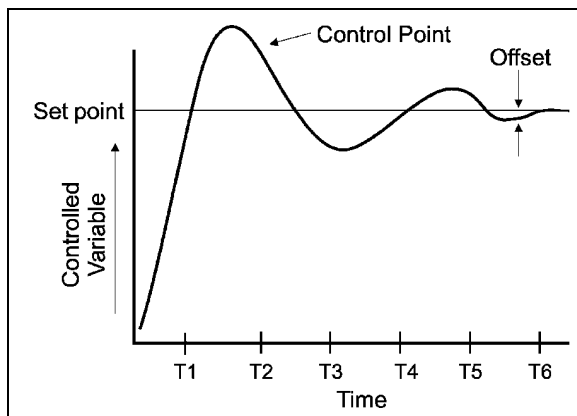


Figure 1-12 Proportional Plus Integral Control

is disconnected or otherwise not able to control the controlled variable, such as when a system is turned off at night. In this case, the controlled variable cannot be maintained at set point, so the integral term becomes larger and larger. When the system is turned on, the value of V is fully in one direction and the system will usually overshoot the set point. It takes time for the integral term to fall because of the long period that the system was far from set point. This effect (windup) causes the system to be temporarily unstable.

The problem can be mitigated by simply disabling the controller when the system is turned off (the preferred solution), by adding derivative control (discussed below), or by any number of anti-windup devices or algorithms commonly used with analog electronic controllers. A common anti-windup algorithm is to use proportional logic only until the system has been on for a period of time.

PI control is available with many pneumatic and analog electronic controls. It is virtually standard on digital control systems.

Using all three terms of [Equation 1-1](#) is called proportional plus integral plus derivative (PID) control logic. Adding the derivative term reduces overshooting. It has the effect of applying “brakes” to overreacting integral terms. Typically, derivative control has a very fast response, which makes it very useful in such applications as fast acting industrial processes and rocketry. However, because most HVAC system responses are relatively slow, the value of derivative control in most HVAC applications is minimal. Including the differential term may complicate the tuning process, and cause unstable responses. For these reasons, derivative control logic is *normally not used* in most field HVAC applications. (Note that the generic control loop, particularly in digital control applications, is often referred to as a PID loop, even though the derivative function is typically unused.)

While PID logic is generally applied to systems with continuous or modulating capacity capability, it may also be applied to systems with staged capacity capability to improve the accuracy versus two-position control logic. The way this is usually done is by applying a modulating control loop to the controlled variable, the output of which (V) is a “virtual” output (an output that does not actually control a real device). Then, step control logic is applied to a second control loop using the signal V as its controlled variable. The output of this second loop sequences the capacity stages of the equipment. Using PID logic in this manner can result in a smaller operating differential than using step control logic, particularly if the system has many steps of control (four or more).

Pulse-width Modulating, and Time-proportioning Control

Another type of modulating logic applied to an on-off type output is pulse-width modulation (PWM). The output is based on movement in a series of discrete steps, but it simulates true modulation quite well. Here, the output of the controller is a series of pulses of varying length (see [Figure 1-13](#)) that drive the controlled device (such as a stepping motor driving a valve or damper, or on-off control of an electric resistive heater). The output signal of the control loop (V) defines the length of the pulses rather than the position of the controlled device as it does with true modulating control. If the actual position of the controlled device must be known, as it may be for some control schemes, a feedback device that senses actuator position must be provided and fed back to the control system as another input.

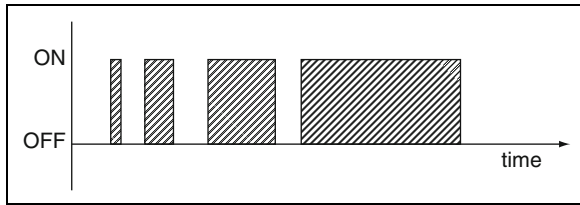


Figure I-13 Pulse-width Modulation

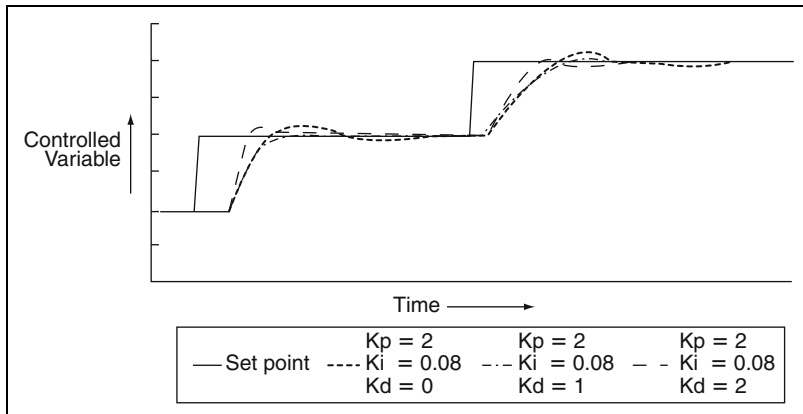


Figure I-14 Time-proportioning Control

A variation on PWM is time-proportioning control (see [Figure 1-14](#)). Like PWM, the output is a series of on/off pulses, but the time cycle is fixed and the percentage of on-time and off-time during that cycle period is varied.

I.5 Gains and Loop Tuning

When you first started driving, chances are your actions were jerky, you applied too much gas when starting up, and overcompensated by releasing the accelerator too quickly or pressing too hard on the brakes. This is an example of an overly responsive control loop. As you gained experience driving, you effectively were tuning your control loop, subconsciously adjusting the sensitivity to which you responded to error, the difference between actual speed and desired speed. The adjustments depend to a certain extent on the car you are driving, the sensitivity of its accelerator and brakes, and the power of its engine. When you drive a different car, you must retune your driving control loop to adjust to these changes in system responsiveness.

HVAC system control loops must be similarly tuned. Every loop is a little different because the system to which it is applied is different. You can use the same controller to control the heating coil serving a small hotel room and to control a heating coil serving a huge warehouse. But the time constants of the two systems will be very different, so the controller gains must be adjusted, or tuned, to suit the two applications.

The effect of loop tuning can be seen in [Figures 1-15–1-17](#) which show, respectively, P-proportional, PI, and PID control loops with various gains.

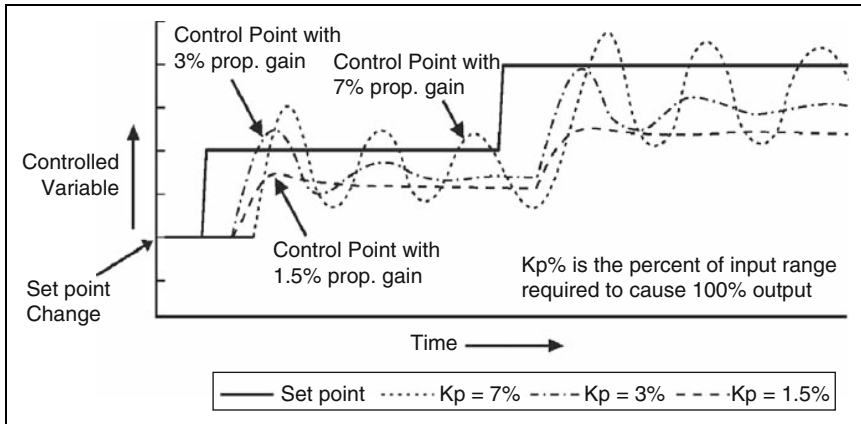


Figure I-15 Proportional Control

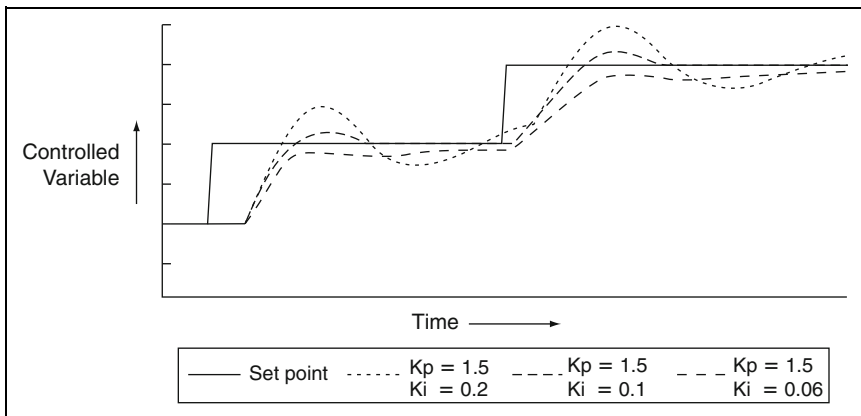


Figure I-16 Proportional–Integral Control

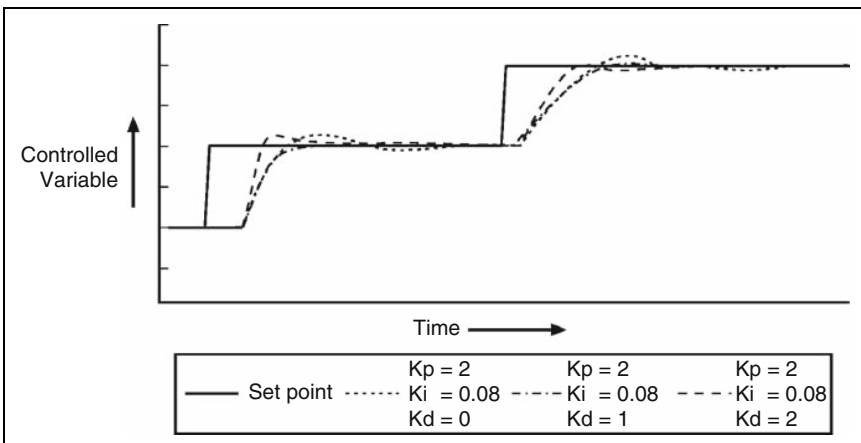


Figure I-17 Proportional–Integral–Derivative Control

These figures show how the controller responds to step changes in set point. Except when a system is first started each day, it is unlikely in most HVAC applications to abruptly change set points in this way. But the response would be similar to large changes in heating and cooling loads, as might occur when an assembly room is quickly occupied, for instance. As can be seen by the curves, the accuracy and stability of the control can be optimized by selecting the proper proportional, integral, and derivative gains.

Loop tuning is currently somewhat of an art and is usually done empirically by trial-and-error. The technique is typically to tune the proportional gain first, then adjusting the integral gain to eliminate offset. (As noted above, the derivative gain is usually not used, at least partly because it complicates this tuning process.) The PID gains are initially set to values based on rules-of-thumb, manufacturer recommended values, or learned from experience with similar applications. The control technician will then observe the system in action and adjust the gain upward until oscillation is detected. If trend logging is available, the performance should be viewed over time. The gain adjustments will then be backed off to about one-half of the high value. (Note: defined performance of PID values may perform differently from one manufacturer to another.) The more experienced the technician is, the more precisely and more quickly the loop will be tuned. This procedure, while not optimum, will usually provide reasonable results.

More precise loop tuning techniques can be applied, but usually the process is too cumbersome to be done manually. Some digital control systems include automatic loop tuning software that applies these more rigorous loop-tuning techniques to automatically tune loops without input from the technician.

Proportional- or P-control logic assumes that processes are linear; the function that describes the error has the same characteristics independent of operating conditions. Most real processes are nonlinear and thus PID logic may be very difficult to set up to maintain zero error under all conditions.

For instance, when the valve serving the heating coil in [Figure 1-2](#) is opened only slightly, the supply temperature will rise very quickly. This is an inherent characteristic of steam or hot water heating coils. After the valve is opened 50%, opening it further has little impact on the supply air temperature. If we tune the loop to maintain excellent control when water (or steam) flow rates are high, it may be too sluggish and will provide poor control when water (or steam) flows are low. Conversely, if we tune the loop when flows are low, it may be too responsive and become unstable when flows are high.

To mitigate this problem, loops could be dynamically self-tuned, meaning the gains could be automatically and continuously adjusted to maintain precise control regardless of operating conditions. Some digital control systems have this capability and more systems are expected to as more “robust” (fast responding) self-tuning techniques are developed. Dynamic self-tuning also reduces commissioning time because it eliminates the need for manual tuning.

Another means to mitigate the nonlinearity problem is through the use of *fuzzy logic*, which is a relatively new alternative to PID control logic. Fuzzy logic imitates human intuitive thinking by using a series of fuzzy, almost intuitive, if-then rules to define control actions. Neural networks are another technique for self-tuning using artificial intelligence to “learn” how a system behaves under various conditions and the proper response to maintain control. More information on *fuzzy logic*, *artificial intelligence*, and *neural networks* can be obtained in more advanced control classes and texts.

1.6 Control Actions and Normal Position

Controllers may be direct acting (DA) or reverse acting (RA). These terms describe the control action or direction of the controller output signal relative to the direction of a change in the controlled variable. Direct acting means that the controller output increases as the value of the controlled variable increases. Reverse acting means that the controller output decreases as the value of the controlled variable increases. For example, a cooling valve is to control discharge air temperature at a set point. If the discharge air temperature is above set point the valve signal may be increased to open the valve to allow more cold water to flow through the coil. We would call this “direct acting,” as when the temperature being controlled is above set point, we would increase the signal to the valve; we would say “temperature up, signal up,” which depicts direct acting. Similarly, controlling heat is typically reverse acting: if the temperature was below set point, the signal would be increased or turned on. We would say “temperature down, signal up.”

The term *control action* must be used with care because it is used in practice to describe many different control system characteristics. The term is used most commonly as above to describe the direction of the output signal relative to the direction of change of the controlled variable. But it is also frequently used to describe what is termed here as the control mode (for example, two-position action, floating action, modulating, etc.). It can also be used to describe the type of control logic used for modulating control (for example, proportional action, integral action, etc.).

[Figure 1-18](#) shows how direct acting and reverse acting signals look using proportional control logic. The signal varies in direct proportion to the error signal, as described mathematically in [Equation 1-2](#). The magnitude of the slope of the line is the proportional gain while the sign of the slope is positive for direct acting and negative for reverse acting. The throttling range is the

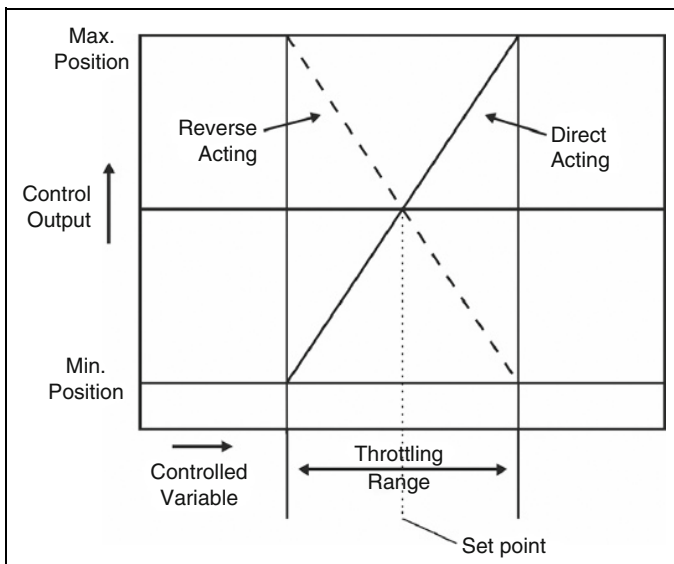


Figure 1-18 Proportional Control

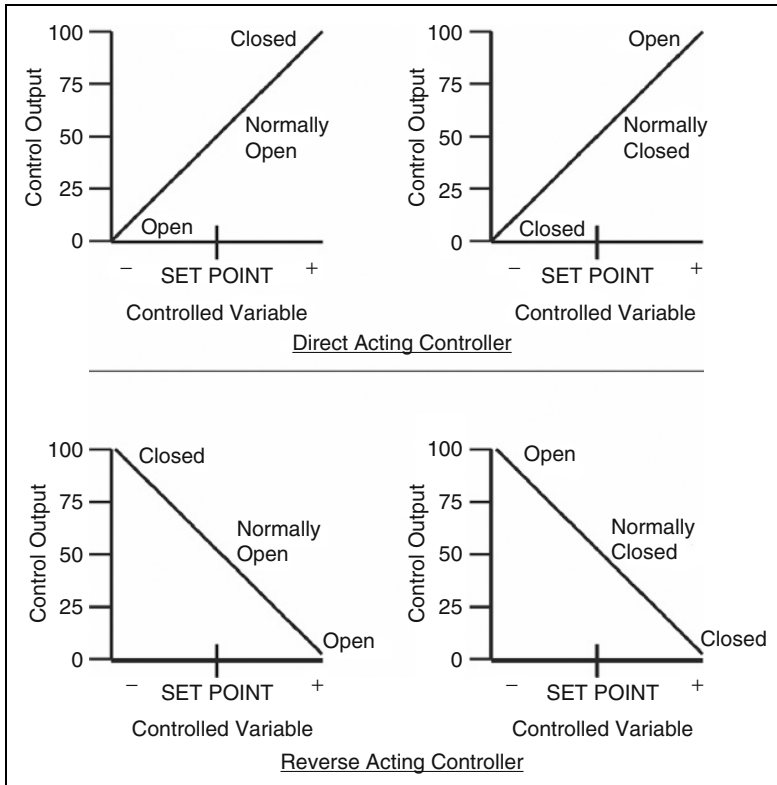


Figure 1-19 Control Action and Normal Position

difference in the value of the controlled variable to cause the controlled device to go from full-open to full-closed (see also [Figure 1-19](#)). Note how the set point is depicted as being in the center of the throttling range rather than at one extreme, as we depicted it for two-position and floating controls ([Figures 1-4–1-8](#)). This is a typical representation of proportional control logic. However, in practice, proportional controllers can be calibrated so that the set point (as it is set using the set point adjustment knob on the controller) is represented by any point within the throttling range (for example, that corresponding to fully open, fully closed, or any place in between).

Controlled devices (such as dampers, valves, and switches) may be normally open (NO) to flow through the process plant or normally closed (NC) to flow. These terms describe the so-called normal position of the damper, valve, or contact, which is the position it assumes when connected to its actuator but with no power (electricity or control air) applied.

Devices with normal positions must have some self-powered means of actuation, generally a spring built into the actuator or relay solenoid. The spring closes or opens the device when control power is removed. For example, a normally closed damper is one that is configured so that the spring in the actuator automatically closes the damper when the power to the actuator is removed or shut-off. If the actuator has no spring to return the damper to its normal position, the damper will simply stay in the last position it was in

before power was removed. This type of damper/actuator does not have a normal position. The spring power must be large enough to do the job of returning the device to the intended position.

With three-way valves (valves that divert a stream of water or compressed air into two streams, or that mix two streams into one), one port is called the common port (the entering port for the diverting valve, or the leaving port for the mixing valve – the port which has continuous flow). The common port is open to the normally open port and closed to the normally closed port when control power to the valve actuator is removed. Whether a three-way valve is normally open or normally closed to flow through the controlled device depends on how the three ports are piped. (See Chapter 3 for schematics and more discussion of control valves.)

It is important to note that the normal position of a controlled device does not refer to its position during normal (everyday) operation. For instance, an outdoor air damper may be configured to be normally closed when in fact it is usually open during normal fan operation. The term *normal* here strictly refers to the position when control power is removed.

The use of spring-return actuators and other devices that have a specific normal position can be used to return the system to a fail-safe position should control power fail. For instance, hot water valves on outdoor air intake coils are typically configured to be normally open to the coil so that if control power fails, full hot water flow will go through the coil, thus preventing coil freezing or freezing of elements downstream.

The normal position can also be used as a convenient means to affect a control strategy. For instance, the inlet guide vanes on a supply fan and the outdoor air intake dampers to a fan system may be configured to be normally closed with the power source to the actuator or controller interlocked to the supply fan. (The term *interlocked* here means the power source is shut off when the supply fan is off and vice versa.) Thus, when the supply fan shuts off at night, the inlet guide vanes and the outdoor air damper will automatically close. This saves the trouble of adding controls that would actively shut the inlet guide vanes and outdoor air dampers when the fan turns off, as would be required if actuators without spring-return were used.

In most cases, the spring-return affects how the controlled device responds to a control signal. In general, when the control signal is reduced or removed (zeroed), the device moves towards its normal position. An increase in the control signal will cause the device to move away from its normal position. For this reason, the normal position must be coordinated with the control action of the controller and the nature of the process plant.

For example, in the heating system shown in [Figure 1-2](#), if the valve is configured normally open, the controller (and thermostat) must be direct acting. This is because the valve will start to move toward its normal position as the control signal from the controller reduces. To close the valve, the control signal must be increased to its maximum value. Thus, as the air temperature in the duct rises, we want the control signal to rise as well so that the valve will close and reduce the amount of hot water passing through the coil, preventing the air from overheating.

If we replaced the heating coil in [Figure 1-2](#), with a chilled water-cooling coil and the same normally open control valve, the controller would have to be reverse acting. This is because as the temperature of the air rises, we want the valve to open to increase the flow of chilled water. For the valve to open,

Table I-3 Required Control Action

Normal Position		
Application and Controlled Device	NO	NC
Heating valve or damper	DA	RA
Cooling valve or damper	RA	DA

the control signal must fall. Because this is the opposite direction of the temperature change, a reverse acting controller is required.

The relationship of control action to normal position for heating and cooling applications is shown in [Table I-3](#).

These relationships are also shown schematically in [Figure 1-19](#) for proportional controls.

In most applications, you would first select the desired normal position for the device based on what might be perceived as the fail-safe position, then select the controller direction (reverse acting or direct acting) that suits the normal position selected and the nature of the process plant (for example, whether the system is to provide heating or cooling). If there is a conflict (for example, you would like to use a normally open heating valve with a reverse-acting controller), a reversing relay may be added to change the action of the controller. Reversing relays (discussed in Chapter 8) have the effect of reversing the control action of the controller.

I.7 Control Range and Sequencing

The output from a control loop, V in [Equations 1-1–1-3](#), can be scaled to yield values in a given range by adjusting the gains relative to the error. For instance, we may want a control loop output to range from 0% to 100%, with 0% corresponding to a fully closed controlled device for a direct-acting loop (or fully open for a reverse-acting loop) and 100% corresponding to full-open (full-closed for reverse acting). As we shall see in later chapters, the output from a pneumatic controller generally ranges from 3 psi to 13 psi while an electronic controller output can range from 2 Vdc to 12 Vdc.

For a controlled device to work with a given controller, it must operate over the same control range as the controller output, or a subset of that range. The control range is the range of control signal over which a controlled device will physically respond. For instance, for a pneumatic controller with a 3 to 13 psi output range, the controlled device must have a control range within that output range. Typical control ranges for pneumatic devices are 3 to 8 psi, and 8 to 13 psi. At each end of the control range, the device is fully in one direction (for example, fully open or fully closed for a valve or damper). For instance, a normally open pneumatic control valve with a control range of 3 to 8 psi will be fully open at 3 psi and fully closed at 8 psi. The control span is the difference between the signals corresponding to the extremes of the control range. In this pneumatic control valve example, the control span is 5 psi (8 psi minus 3 psi).

By properly selecting controlled devices with the proper control range and proper normal position, devices can be sequenced using a single controller.

Sequencing means that one device is taken from one extreme of its control range to the other before doing the same with the next device.

Energy codes typically require that the valves have a control range that is nonoverlapping. In this case, we would select the heating valve to have a control range of 0%–50%, and a cooling valve to operate from 50% to 100%. This would cause the heating valve to go from full open to full closed when the controller output goes from 0% to 50%, then from 50% to 100%, the chilled water valve to go from full closed to full open. The ASHRAE Standard 90.1-2004 requirement is even more stringent than just not overlapping:

6.4.3.1.2 Dead Band. Where used to control both heating and cooling, zone thermostatic control shall be capable of providing a temperature range or dead band of at least 5°F within which the supply of heating and cooling energy to the zone is shut off or reduced to a minimum.

To provide this 5°F requirement one would normally use a different strategy which will be covered later in the course.

For instance, suppose we wish to sequence a heating and cooling valve to control supply air temperature using a direct-acting controller with an output that ranges from 0% to 100% (see *Figure 1-20*).

The normal position of the chilled water valve must be opposite that of the hot water valve. This will cause one to open as the other closes using the same control signal. In this case, because the controller is direct-acting, the hot water valve must be normally open while the cooling coil valve must be normally closed. If, for any reason, we also wanted the cooling valve to be normally open as well, we could do so provided we also add a reversing relay between the controller and the valve. But this adds to cost and complication, and generally should be avoided if possible. Another way to accomplish this is with an electronic actuator which has a switch that allows the actuator to drive clockwise or counterclockwise as the control signal increases depending on the position of the switch.

1.8 Controls Documentation, Maintenance, and Operations

All control systems should be documented with written sequences, parts lists, data sheets, damper and valve schedules, control drawings, marked site plan locations for all controls and remote devices, and points lists where applicable. This documentation must be kept in a safe and accessible place for the life of the systems and building. After the installation is complete, total documented performance testing and commissioning, clean up and fire caulking of all penetrations should be made. Training sessions should be set up for all affected parties to participate in. All control systems require periodic maintenance, adjustments, calibration checks, and testing in order to stay in operation properly. Most often, this should be performed on a quarterly or semi-annual basis at minimum. Some standards have specific maintenance requirements such as ASHRAE Standard 62.1-2004 requirement that outdoor air dampers and actuators to be visually inspected or remotely monitored every 3 months. Records of all repairs and maintenance should be kept. You should refer to ASHRAE Standard 180 (to be published) for further details on this subject.

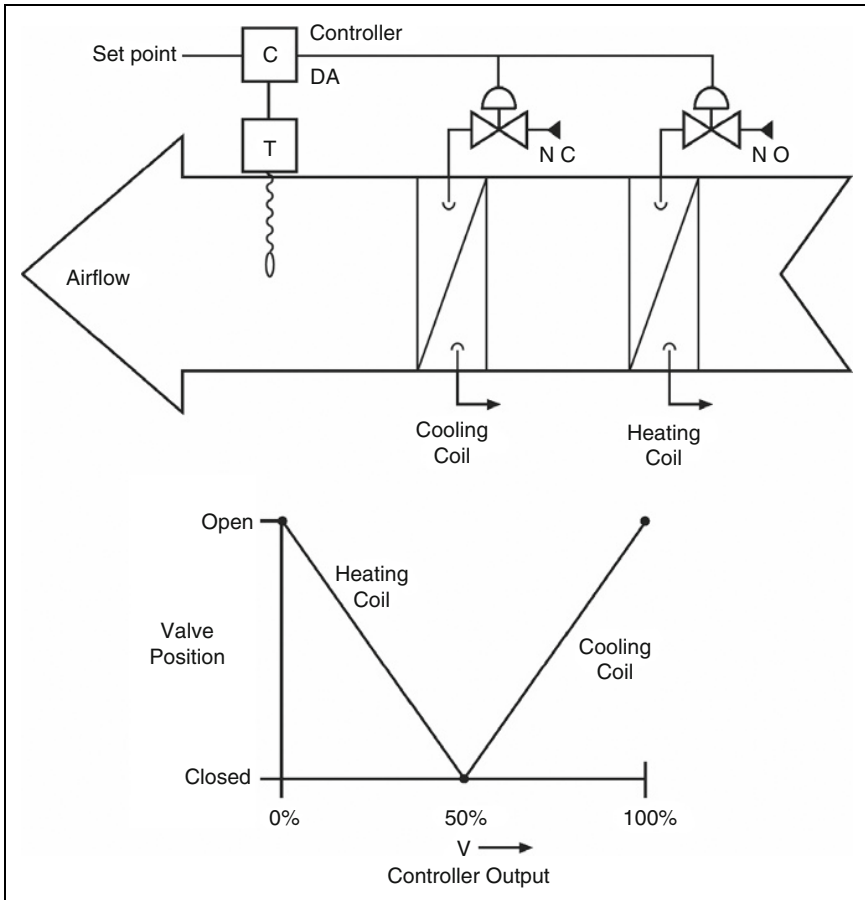


Figure I-20 Sequencing

The Next Step

In the next chapter, we will learn about electricity fundamentals. Relays, transformers, motor starters, and other electrical devices play a role in almost all control systems, so it is important to understand the fundamentals of electrical circuits before going into detail about specific control hardware.

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Chapter 2

Basics of Electricity

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 - 2.2 AC Circuits
 - 2.3 Transformers and Power Services
 - 2.4 Relays
 - 2.5 Motors and Motor Starters
 - 2.6 Variable Speed Drives
 - 2.7 Relay Logic and Ladder Diagrams
- The Next Step

Study Objectives of Chapter 2

This chapter introduces simple electrical circuits and common devices used to provide and control electrical power in HVAC systems. It is not intended to be a comprehensive course in electrical engineering, nor does it address electronics. (An understanding of electronics is important if the internal operation of analog electronic controllers and microprocessors is to be understood, but generally it is not necessary for most control applications.) This chapter is included because virtually all HVAC control systems will have relays, transformers, starters, and other electrical devices as a part of them. Many control systems are composed almost entirely of relays, so it is important to understand relay logic and how to read ladder diagrams of electrical devices.

After studying this chapter, you should be able to:

- Understand basic electricity concepts and simple electrical circuits.
- Understand the mathematical relationships between power, voltage, current, and resistance.
- Understand how a relay works, why relays are used, and the symbols used to show normally open and normally closed contacts.
- Understand how transformers work and why they are used in power services and control systems.
- Understand what motor starters are and where they are used.

Understand why variable speed drives are used and the principles upon which many of them work.
 Become familiar with Boolean logic and relay logic.
 Learn to read ladder diagrams.

2.1 Simple Circuits and Ohm's Law

Electrical force is one of the primary forces interconnecting matter. Elementary particles such as protons and electrons have electrical charges. Particles of like charge repel each other while those with opposite charges attract. If two bodies of opposite charge are held apart, an electrical potential is created between them. If the bodies are then interconnected by material, loosely bound electrons in the material will be caused to move; a motion we call an electric current. Some materials (such as metals like copper) are more conducive to electrical flow. They are called conductors. Materials such as ceramics, rubber, and plastics offer a high resistance to free electron movement; they are called insulators.

Figure 2-1 shows a simple electrical circuit.

The battery creates an electrical potential across it, also called an electromotive force (EMF) or voltage V . The wires connect the battery to the device we wish to power, called the load, which has a resistance R to electrical flow. When the switch shown is closed (when it connects the wires entering and leaving the switch together), an electrical circuit is formed. The result is that electrical current I , will flow around the circuit. The magnitude of the current will be a function of the voltage V and the resistance R . The battery provides the electrical potential energy to move the electrical current through the resistance.

The circuit might be understood better by using an analogy. *Figure 2-2* shows a water tank with a pipe connecting it to the ground.

The height of the water tank is analogous to the electrical voltage; the higher the tank, the higher its "voltage" or energy potential. Gravitational force rather than electrical force is the source of the energy potential. Water flow

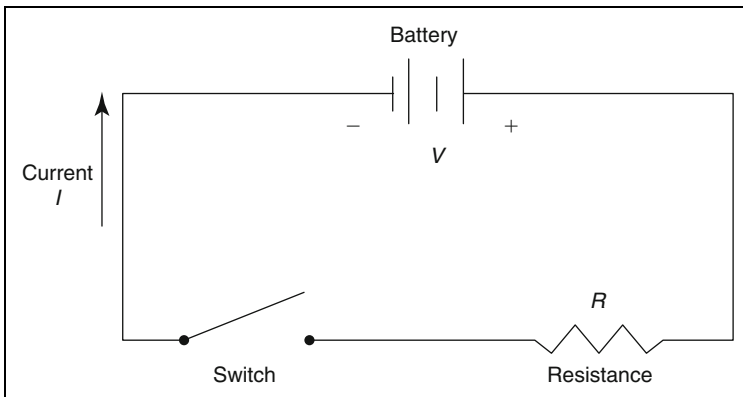


Figure 2-1 Simple Electrical Circuit

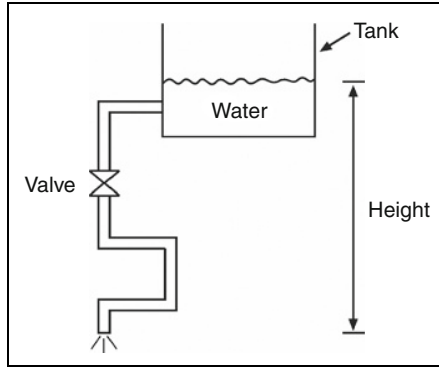


Figure 2-2 Water Tank Analogy

is analogous to electrical current and the shut-off valve is analogous to the switch. When the valve is closed, no water flows. When the valve is opened, water will flow through the pipe down to the ground due to the force of gravity. The rate of water flow (the “current”) is a function of the height of the tank (the “voltage”) and the frictional resistance to flow in the pipe, analogous to the resistance to electricity flow in our electrical circuit.

In this analogy, we close the valve increasing the resistance to stop the flow of water while we open the switch increasing the resistance to stop the flow of electricity. We will come across the same process when dealing with water and pneumatic control air valves and switches in the following chapters. Just remember that an open electrical switch allows no current to flow while a closed hydronic or pneumatic valve allows no fluid to pass.

The mathematical relationship relating the current, voltage, and resistance is expressed as:

$$V = IR \quad (\text{Equation 2-1})$$

where V is the voltage (in volts), I is the current (in amperes, or amps for short), and R is the resistance (in ohms, abbreviated Ω). This is called Ohm’s law, named after George S. Ohm who was the first to express the relationship in 1826. Sometimes the letter E or e is used to represent the electrical potential instead of V . Others use E to represent electrical potential across a battery, and use V to represent voltage drop across a load. In this text, V is used for both purposes, which is common in general engineering practice.

For a practical example, often used in the field, if you wanted to convert a 0–20 mA signal to be 0–10 VDC, then you would put a 500 ohm resistor across the circuit, hence the new voltage would equal the 0.02 A times the 500 ohms which is 10 VDC.

You can imagine that if you added another pipe from the tank to the ground in our water tank example, you would still get the same flow rate through the first pipe no matter whether the valve through the second was opened or closed (see [Figure 2-3](#)).

This is called parallel flow because the two pipes are in parallel with each other (side by side). The same is true with electricity. The electrical potential

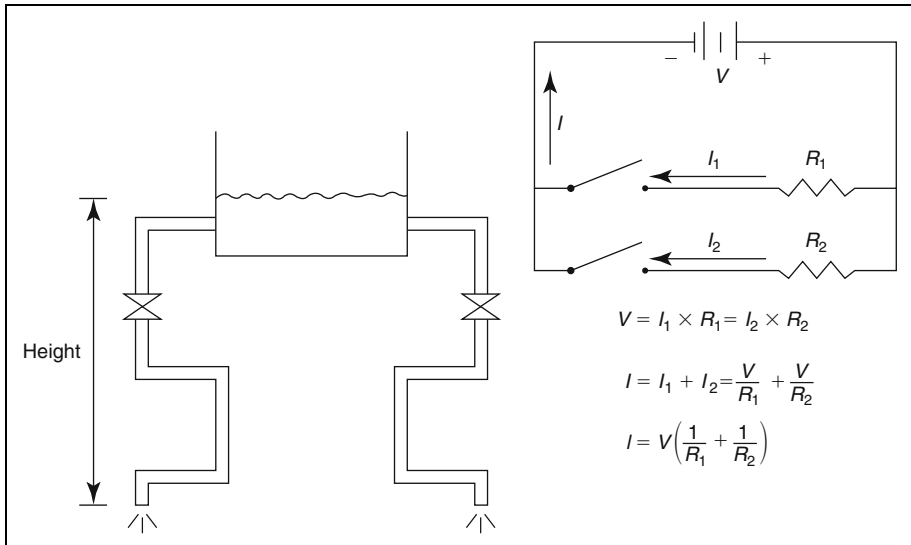


Figure 2-3 Parallel Circuits

across each resistor in [Figure 2-3](#) is still the same, V . Therefore, from Ohm's law we know that the current must still be the same:

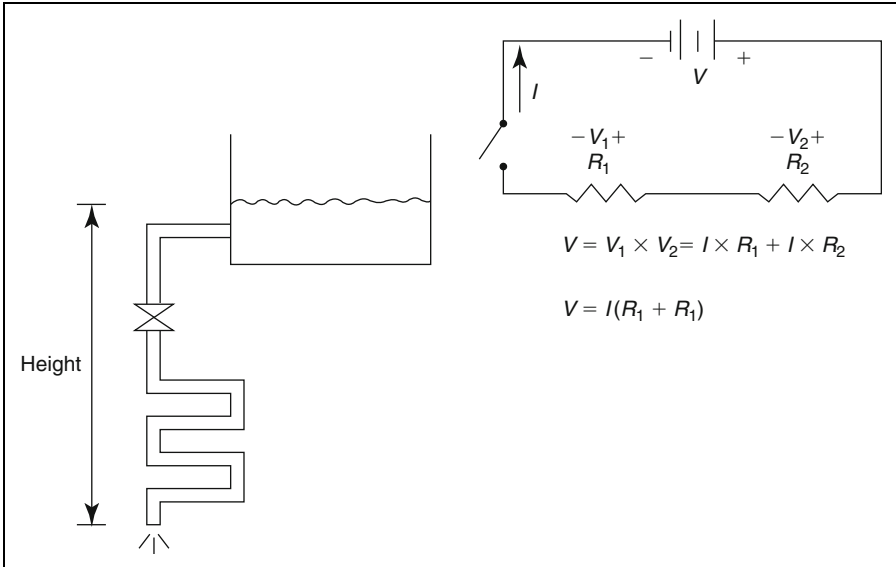
$$I = \frac{V}{R} \quad (\text{Equation 2-2})$$

Of course, the total current from the battery is now increased. Just as our water tank will drain faster when we add the second pipe, our battery will "drain faster," or use more current, when there are two parallel circuits. If the resistances (R_1 and R_2) in [Figure 2-3](#) were equal we would get twice the current (flow).

$$I = \frac{V}{R} + \frac{V}{R} = \frac{2V}{R} \quad (\text{Equation 2-3})$$

If we took that same added piping and placed it in series with (added it to the end of) the original piping, the water would have to follow a longer and more circuitous route from the tank to the ground, see [Figure 2-4](#).

We can imagine then that the water flow rate would go down because we increased the resistance to flow. Again, the same is true in the analogous electric circuit. The electrical potential is split between the two loads (resistors), so the current must fall. We know that the voltage drop across the first resistor plus that across the second must add up to the total battery voltage. Because the voltage drop must be equal to $I \times R$ from Ohm's law and the current through each resistor must be the same (just as the water flow through the two pipe sections in series must be the same), and if the resistances (R_1 and R_2) in [Figure 2-3](#) were equal we would get $\frac{1}{2}$ the current (flow).

**Figure 2-4** Series Circuits

$$I = \frac{V}{R + R} = \frac{V}{2 \times R} \quad (\text{Equation 2-4})$$

So the current is cut in half when we put the two identical resistance loads in series. The amount of overall potential energy stored in our water tank is a function of the amount of water in the tank and its height above the ground. If we double its height, we double the amount of stored energy because now we can get twice as much flow through our pipe. If we double the volume of water in the tank, we also double the energy stored because it will last twice as long once we start to drain it. So the energy stored is then the product of the height and the volume of water.

The rate at which we discharge the energy (called the power) is then the product of the height and the rate at which water flows out of the tank. Using our analogous electrical terms, electrical power (P) in watts is then:

$$P = IV \quad (\text{Equation 2-5})$$

Using Ohm's law to substitute for $V = IR$, this can also be expressed as:

$$P = I \times R \times I$$

$$P = I^2 \times R \quad (\text{Equation 2-6})$$

2.2 AC Circuits

In the previous section, we looked at a simple circuit using a battery maintaining a constant electrical potential or voltage that resulted in a constant current through the circuit. This is referred to as a direct current (dc) circuit because the current is constant and flows only in one direction. But the electrical systems serving our homes and buildings are not dc systems. Rather, they are alternating current (ac) systems.

Alternating current is produced by varying the electrical potential (the voltage) in a sinusoidal fashion, as shown in [Figure 2-5](#). The voltage varies from positive (+V) to negative (-V). In the simple circuit shown in [Figure 2-6](#), the alternating voltage causes a corresponding alternating current that swings back and forth in the same sinusoidal fashion as the voltage. When you measure the ac voltage you measure the “root mean square,” rms voltage which for a pure sine wave is 0.707 times the peak voltage.

The time it takes for the oscillation to go through a full cycle (from peak to peak) is called the cycle time, measured in cycles per second or Hertz (Hz). Common ac power sources in the United States are 60 Hz, while those in many other countries are 50 Hz.

Ohm’s law and the formula for power derived for dc circuits in the previous section also apply to the simple ac circuit shown in [Figure 2-6](#). However,

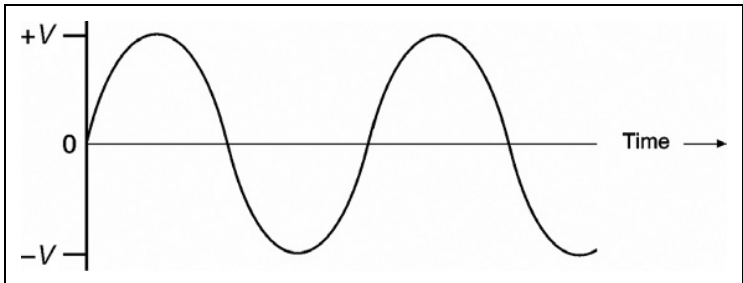


Figure 2-5 Alternating Voltage

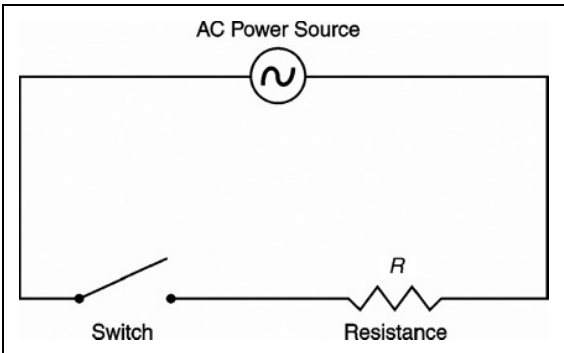


Figure 2-6 Simple AC Circuit

ac circuits are never so simple in real applications. The rms current in an ac circuit with resistance is given by the rms voltage divided by the resistance ("root mean square voltage" means the effective average voltage). Two other elements – capacitance and inductance – come into play, which make ac circuits more complicated.

In the circuit shown in [Figure 2-7](#), we have a capacitor in series with a resistor. A capacitor, as its symbol implies, is two parallel plates typically separated by a nonconducting material called a dielectric. If we applied a dc (constant) voltage across the capacitor by closing the switch, the current would start as it would if the capacitor was not in the circuit, as electrons begin to move due to the electrical potential from the battery. However, as electrons collect on the plates of the capacitor, they begin to repel other electrons and the flow diminishes. This is shown in the graph on the right of [Figure 2-7](#).

Quickly, the current would drop to near zero, actually a very low amount called *leakage* due to the very low but still non-zero conductivity of the dielectric. At this point, energy is stored in the capacitor, and is fully charged. The capacitor can be thought of as a storage device. We measure its size using the term capacitance (C), which is a function of the size of the plates, their separation distance, and the properties of the dielectric.

As [Figure 2-7](#) indicates, a capacitor is like an open switch in a dc circuit once steady-state is reached, which is why it does not play a part in most dc systems. But when a capacitor is placed in an ac circuit, the result is very different. The alternating voltage simply allows the capacitor to charge, then discharge, then charge again. While no electrons actually pass through the capacitor, there is still current flow back and forth through the load just as it would if the capacitor was not there.

The only difference is that the capacitor causes a time delay in the current. It takes time to charge and discharge the capacitor plate, so current and the voltage become out of phase, as shown in [Figure 2-8](#). Another effect that has an impact on ac circuit current flow is inductance, which is a resistance to current change caused by magnetic induction. As current flows through a wire, a magnetic field is created around it, as shown in [Figure 2-9](#) (with current directional arrows shown as the direction electrons follow, flowing from positive to negative).

If we wound the wire into a spiral, the magnetic fields from the wires would align inside the spiral, creating a strong magnetic field in the center.

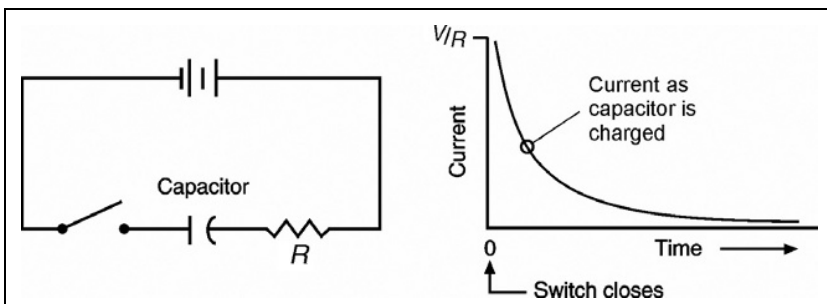


Figure 2-7 Capacitor in DC Circuit

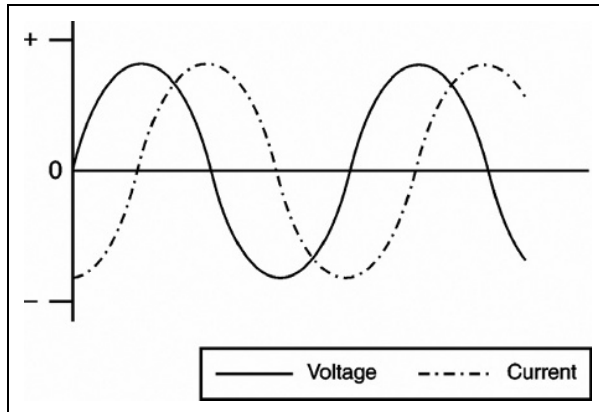


Figure 2-8 Voltage and Current Out of Phase, Current Lagging

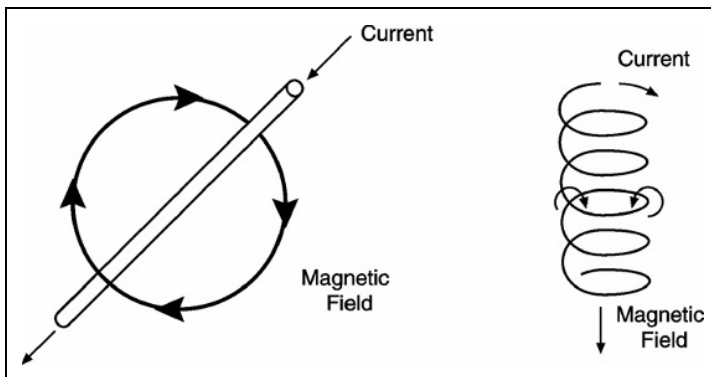


Figure 2-9 Magnetic Field

This principle is used in many electrical devices (such as solenoids, relays, and electromagnets).

The interaction goes the other way as well; if a changing magnetic field passes through a conductor, it induces an electromotive force perpendicular to the magnetic field. This phenomenon, discovered by Hans Oersted in 1820, can affect the current in a circuit, as can be seen in [Figure 2-10](#). When the switch is closed, current begins to flow through the circuit. The rising (changing) magnetic field in the coil (the inductor) creates an electrical potential that is opposite to that of the battery. This potential, called back-EMF, cancels part of the potential of the battery, effectively retarding flow in the circuit. Eventually, as the current reaches steady-state, the back-EMF begins to die away because the current is no longer changing. Once steady-state is reached, the inductor has no impact on the dc circuit, as can be seen in [Figure 2-10](#).

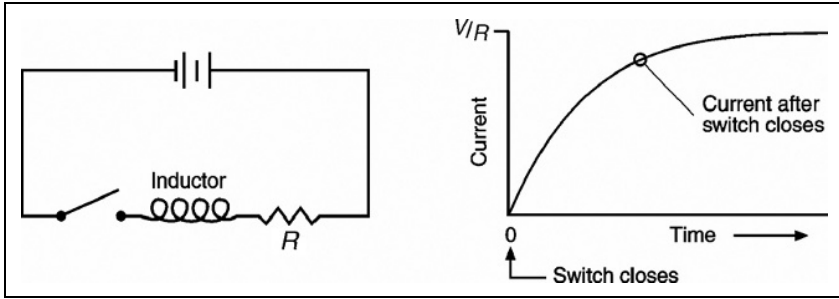


Figure 2-10 Inductor in DC Circuit

When the switch opens the current flow will abruptly stop. A large EMF (voltage) will be generated as the energy stored in the magnetic field in the coil starts to collapse. Depending on the size of the current flowing before the switch was opened, this can lead to arcing (sparking) across the contacts and generating electromagnetic interference (EMI) (electrical radiated energy), which can affect sensitive electronics.

Things are very different in ac circuits because the current is always changing. The back-EMF always acts to retard the change in current whether the change is an increase or a decrease. The ability of the inductor to resist changes in current is measured in terms of its inductance L .

The impact of inductance on current flow is to push the voltage and current oscillations out of phase with each other, like the capacitor did. However, while the capacitor causes current to lead voltage, the inductor causes the current to lag voltage, as can be seen by the graphs on the right of [Figures 2-7 and 2-10](#). The effects are opposite and in fact may tend to cancel each other.

The capacitance and inductance effects on current flow are collected into a factor called impedance, Z , which is analogous to resistance in a dc circuit:

$$V = I \times Z \quad (\text{Equation 2-7})$$

Capacitance and inductance effects exist even where we do not want them to. For example, alternating current running in one circuit will induce current in other adjacent circuits, and poorly made wiring connections will create a capacitance between the contacts. The fact that these effects are always present is why there are no simple and purely resistive ac circuits, such as the one shown in [Figure 2-6](#).

The power used in ac circuits is computed like that for dc circuits: it is equal to the product of voltage times the corresponding current. However, when the current and voltage are out of phase, as in [Figure 2-7](#), the peak voltage and peak current do not occur at the same time. We can still relate the power to the rms current and rms voltage, but a factor must be added to account for the phase offset. This factor, called the power factor, varies from 0 (180° out of phase) to 1 (in phase):

$$P = V_{\text{rms}} \times I_{\text{rms}} \times PF \quad (\text{Equation 2-8})$$

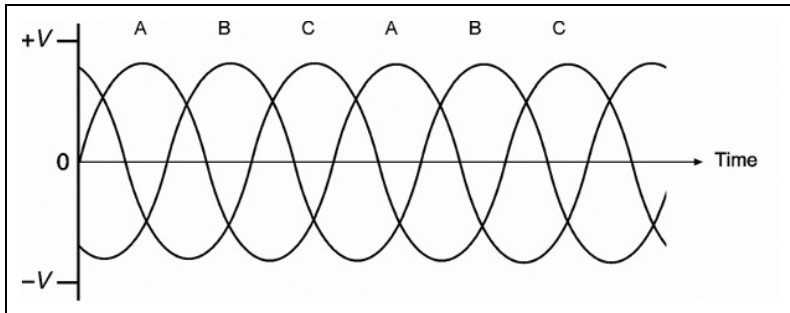


Figure 2-11 Three-phase Voltage

Because power plants, transmission lines, transformers, and other distribution equipment have to be sized for the maximum current, utilities often impose an added charge to users that have very low power factors. A low power factor is typically caused by an inductive device such as a motor. Capacitors, which as noted above have an opposite effect on current/voltage phase shifts as inductors, can be used to correct power factor in these instances.

Most larger buildings are served by three-phase power services (discussed in the next section), typically with four wires, three of which are hot and one that is neutral (grounded at the service entrance or distribution transformer). The three hot wires have ac voltages that are 120° out of phase with each other, as shown in [Figure 2-11](#). Three-phase (abbreviated to 3ϕ) power is used because it is convenient for motors (it causes a naturally rotating field that starts a motor turning in the right direction) and it reduces the amount of current required for the same amount of power. The power equation for a three-phase circuit is:

$$P = V_{\text{rms}} \times I_{\text{rms}} \times PF \times \sqrt{3} \quad (\text{Equation 2-9})$$

2.3 Transformers and Power Services

A power transformer is a device that is used primarily to convert one ac voltage to another. Based on the principle that alternating current in an inductor electromagnetically induces an electrical potential in adjacent conductors, transformers can interconnect two circuits without any electrical connection between them. A transformer is shown schematically in [Figure 2-12](#). It is essentially composed of coiled wiring (inductors) in each circuit which is connected by an electromagnetic field. Current flow in the primary circuit induces a voltage across the secondary coil.

If the number of coils in the primary circuit differs from the secondary, then the induced voltage will differ from the primary. The secondary voltage will be higher or lower by the ratio of the number of turns in each system. For instance, if there are four times as many windings on the primary side of the transformer as there are on the secondary, the voltage on the secondary

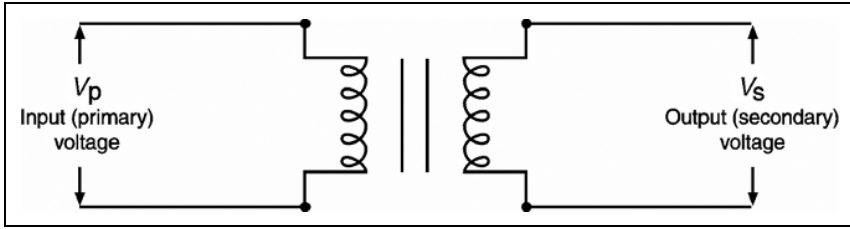


Figure 2-12 Transformer

will be $\frac{1}{4}$ that on the primary side. By varying winding ratios, transformers can be used to boost or reduce the voltage in the secondary circuit. If it boosts the voltage it is called a step-up transformer; if it drops the voltage it is called a step-down transformer.

The transformer's capacity is rated in VA (volt-amps) or kVA (kilovolt-amps), which are roughly equal to the product of the voltage times the maximum current required on either side of the transformer. The primary and secondary voltages are specified as rms voltage. This will be larger than the power (wattage) requirement because of the power factor shown in [Equation 2-9](#).

The ease with which voltage can be boosted and reduced with ac systems is the main reason they are used for power distribution instead of dc power. The higher the voltage, the lower the current is for the same power output. Therefore, with ac systems, power from power plants can be transmitted to the communities they serve at very high voltages (low current), thereby allowing the use of smaller wiring and reducing power losses in transmission lines. This reduced current at high voltages is very significant as the power loss in transmission is proportional ([Equation 2-6](#)) to the square of the current $P = I^2R$. Doubling the voltage and halving the current provides the same power but the losses are reduced to $.5 \times .5 = .25$ or 25%. The voltage can then be reduced using a transformer at the building service entrance to a lower, safer voltage to power lights and motors, and all the other power consuming devices in the building.

Three-phase transformers have three secondary, or output, windings. These windings may be connected in two ways – Delta or Wye [Figure 2-13](#). In the Delta connection, the ends of the three windings are connected together and the same voltage is available across each phase. In the Wye connection, the three phases are all connected at one end: a common point. This point, called common or neutral, is usually grounded. The Wye connection provides a phase-to-phase voltage and a phase-to-common $1/\sqrt{3}$ times the phase-to-phase voltage.

The typical commercial building is provided (downstream of the utility transformer) with either a 208 V, 230 V, 480 V (or other), three-phase, four-wire service from which various voltages can be obtained depending on which wires are used. The voltages available with two of these service types are shown in [Figure 2-14](#). When there is a 480-V service, there typically will be one or more transformers in the building that step down the voltage to 120 V, which is the voltage used by most common household and office plug-in appliances in North America.

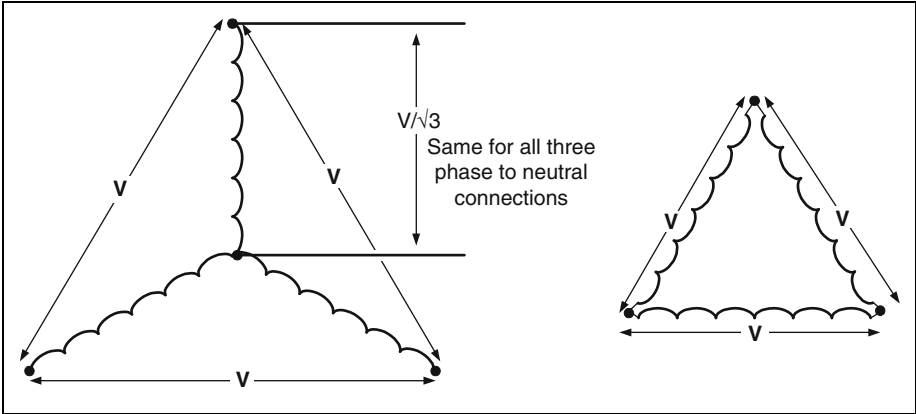


Figure 2-13 Delta and Wye Connected Three-phase Transformer Outputs

The lowest voltage available with typical services is still higher than that needed for typical control systems. Control systems use very little power, so the cost advantages offered by higher voltages (lower current, smaller wire sizes) are negligible. Therefore, control systems typically are powered by another step-down transformer producing 24 V. This is sufficiently low that

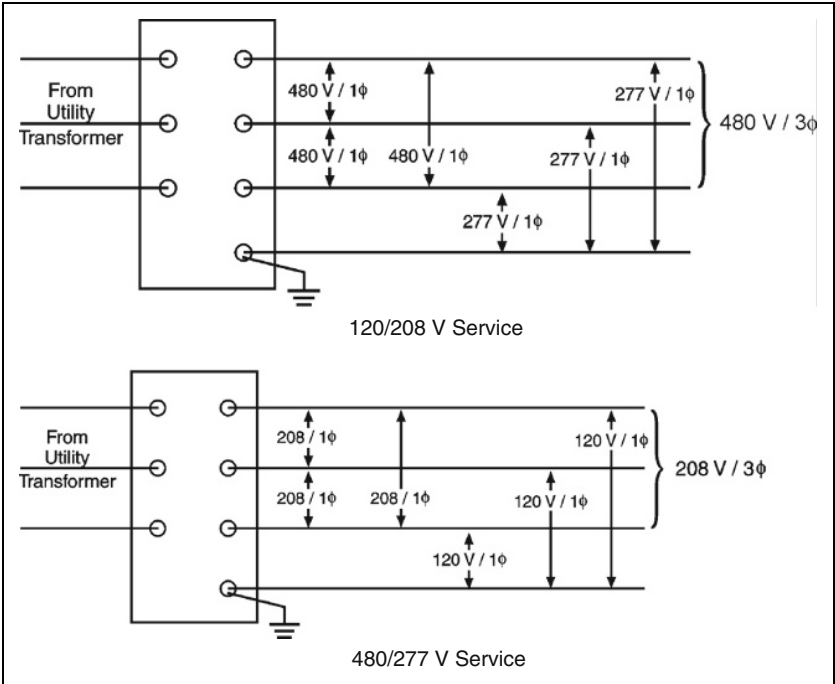


Figure 2-14 Four-wire Wye Connected Transformer Outputs

most building codes do not require many of the expensive protection devices (such as conduit and junction boxes) that are required for higher voltage circuits. This reduces installation costs. Typically, control transformers are small (less than 75 VA), which places them in a lower cost electrical code category (NEC Class 2, which includes power systems rated at less than 30 V and 100 VA).

2.4 Relays

A *relay* is an electrical *switch* that opens and closes under control of another electrical circuit. The electromagnetic relay with one or more set of contacts was invented by Joseph Henry in 1835. There are many types of relays used in controls, which will be discussed in later chapters. In simple electrical circuits, the term refers to a device that delivers an on/off control signal. In a sense, the relay is a type of remote-controlled switch.

Figure 2-15 shows a type of electromagnetic relay. It works by taking advantage of the magnetic force that results from current flow. Wire is wound around an iron core. When current is allowed to pass through the wire in either direction (when a voltage is placed across leads labeled A and B in the diagram), a magnetic field is formed in the iron. Iron is highly permeable to magnetic fields; much like copper is highly conductive to current flow. The result is that an electromagnet is created. The magnet attracts the metal armature (sometimes called a clapper), which is allowed to move toward the magnet, causing the contacts to close (connect to each other), connecting leads labeled C and D in the schematic. The contacts are often called “dry” contacts because they are electrically isolated from other circuits, including the circuit that energizes the relay, and hence they have no source of voltage in and of themselves. The relay solenoid coil is represented as a circle while the relay contact is represented in wiring diagrams by two parallel lines.

Figure 2-16 shows two simple circuits with a relay interconnecting the two. When the manual switch in the first circuit is closed, the relay is energized,

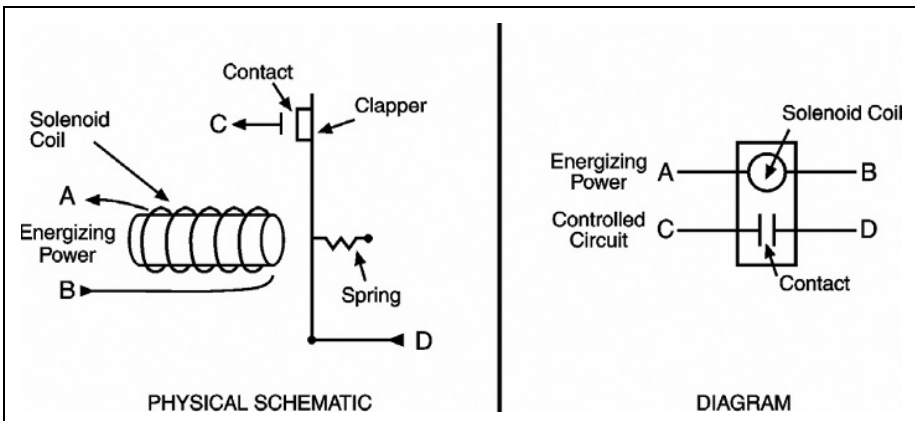


Figure 2-15 Electromagnetic Relay

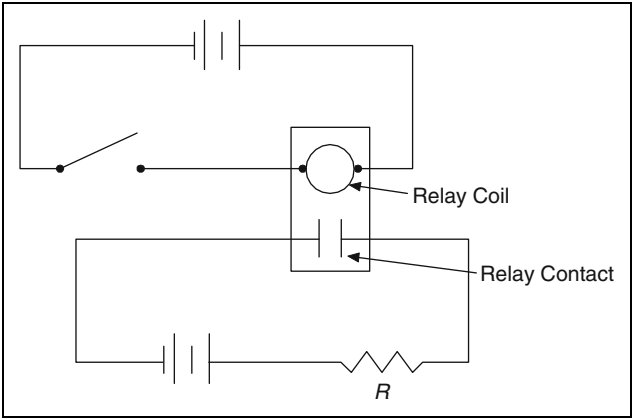


Figure 2-16 Simple DC Circuit with Relay

which closes the relay contacts in the other circuit. In this way, the switch closure “information” was transferred from the first circuit to the second circuit without requiring that the two be electrically interconnected. Because they are separate, the voltage in the first circuit may be different from the voltage in the second, or the power may be from different sources. This is a common reason for using a relay.

Relays that have more than one contact are called multipole relays. Each pole (contact) is electrically isolated from the other, so each may be used to control a different circuit. Each pole is energized and de-energized at the same time, and they work in unison.

Multipole relays are represented in two ways. For simple diagrams, the relay contacts may be grouped under the relay coil so it is clear the contacts are controlled by that coil, as shown in [Figure 2-17](#). When the drawing gets more complicated, this type of representation can crowd the drawings and make it confusing. In this case, the relays and contacts are labeled. For example, a three-pole relay R1 has contacts labeled R1-1, R1-2, and R1-3. In this

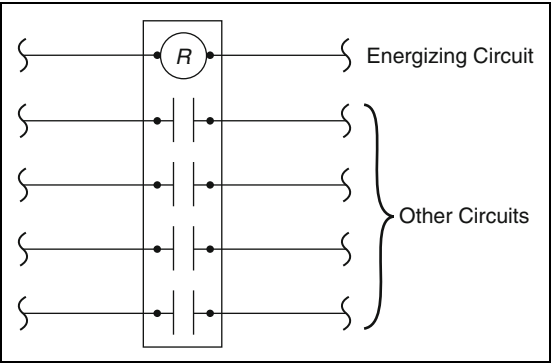


Figure 2-17 Multipole Relay

way, the contacts may appear anywhere in the diagram without having to show wires running back to the relay.

In Chapter 1, when speaking of controlled devices such as valves and dampers, the term *normal position* referred to the state of the device when control power was removed. For a general purpose relay, the *normal position* refers to the state of the contact when the relay is not energized. Thus, a normally open contact, N.O., is open when the relay is not energized (no current is allowed to flow through it) and closes when the relay is energized. Normally open contacts are shown in [Figures 2-15–2-17](#). A normally closed contact, N.C., (represented diagrammatically as a contact with a slash through it) operates in an opposite manner to the normally open contact; it is closed when the relay is not energized and opens when the relay is energized. Normally open and normally closed contacts are shown in [Figure 2-18](#).

Relay contacts may be single-throw or double-throw. A single-throw contact is much like a two-way control valve controlling a fluid, while the double-throw contact is much like a three-way valve. [Figure 2-18](#) shows both types of contacts used in simple circuits to turn on pilot lights. The contact on the double-throw relay has a common terminal that is simultaneously switched to the normally open terminal when the relay is energized and to the normally closed terminal when the relay is de-energized.

In [Figure 2-18](#), when the manual switch is closed, the relay is energized, causing all the normally open contacts to close and all the normally closed contacts to open, turning on the red (R) pilot lights and turning off the green (G) pilot lights. When the switch is open, the relay is de-energized, closing the normally closed contacts and opening the normally open contacts, turning on the green pilot lights and turning off the red pilot lights.

Relays are commonly used as control logic devices and they are discussed in more detail in Chapter 4.

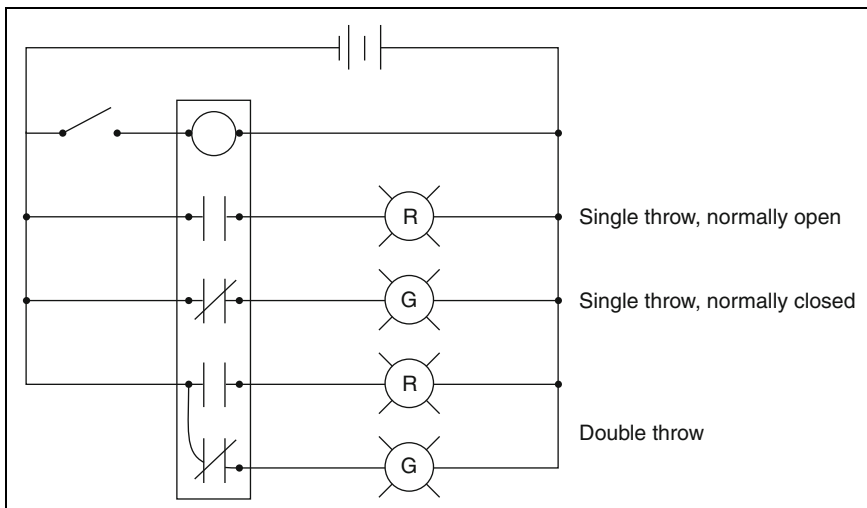


Figure 2-18 Single- and Double-throw Contacts

2.5 Motors and Motor Starters

Electric motors are devices that convert electric energy into mechanical energy by causing a shaft to rotate. The shaft can then be connected to a device such as a fan or pump to create useful work. The rotation in the shaft is caused by the interaction of two magnetic fields in the motor: one produced by the fixed part of the motor (the stator) and the other produced by the rotating part (the rotor) which is connected to the shaft. The magnetic fields are created either by fixed magnets or, more commonly, by an electromagnet created by a winding in which current flows. The most common type of motor is an ac induction motor. (A more complete discussion of motor types is beyond the scope of this course.)

Small motors used for HVAC applications tend to be powered using single-phase services, usually 120 V, 208 V, and 277 V in North America. Motors that are 5 horsepower (hp) and larger are typically three-phase motors, usually 208 V or 480 V.

Motors are generally controlled by a motor starter that serves two functions:

- *Start/stop control.* Motors require some means to connect power to them when they are required to operate, and to disconnect power when they are not. Starters may be manual (basically a large switch) or they may be automatic. The automatic type typically uses a magnetic contactor, using a concept similar to the electromagnetic relay described above. More recently, solid-state (electronic) starters have begun to be used, particularly on large motors such as those used on chillers.
- *Overload protection.* Electric motors are not inherently self-limiting devices. The device they are driving may operate in a fashion that causes the motor to draw more current than it was designed to handle. This is called overloading. There are other causes of high motor current such as motor insulation resistance breakdown, low voltage to the motor, voltage phase imbalance, etc. When high motor current occurs, the motor windings will overheat, damaging the insulation that protects the windings, resulting in motor burn-out. To protect against this, electrical codes generally require that motors be protected from thermal overload.

A current sensing device called an overload relay provides overload protection. When the relay senses an overload condition, it drops out the motor contactor and the motor shuts off. A common overload device is a small electric resistance heater in series with the motor that warms a bimetallic strip in a manner similar to the warming of the windings in the motor caused by the same current. At high temperatures, the bimetallic strip warps and breaks a contact, tripping the motor. In [Figure 2-19](#), the normal operating current is shown as just over 5 A. If the current rises to a steady current above 9 A the thermal overload protection will trip the motor off. The thermal overload takes time to respond just as the motor takes time to heat up, so the thermal overload trip does not trip due to the high, 25 A, startup inrush current.

However, there are situations such as a short circuit or a locked rotor (rotating part of motor is jammed and cannot rotate) when very high currents can flow and instant tripping is required. This is called over-current protection.

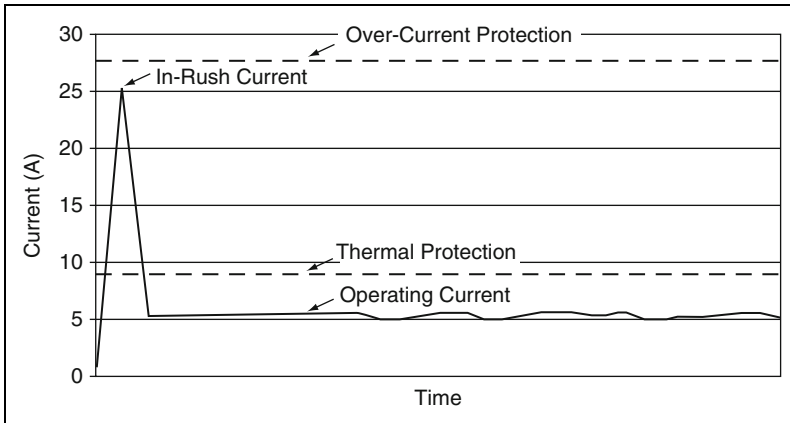


Figure 2-19 In-Rush Current and Overload Protection

The over-current devices (fuses, and circuit breakers) are primarily intended to protect against short-circuits. These devices must be set to trip at relatively high currents due to the in-rush current typical of motors when they are first started. This temporary in-rush current is much higher than the overload current. For this reason, over-current protection cannot protect against overload.

Some single-phase motors have internal thermal overload protection, a small switch that requires either manual or automatic reset, depending on the type used. For these motors, starters are not required and a simple line-voltage contact (such as a thermostat) may be used. All other motors will require starters, most commonly the automatic magnetic type.

An across-the-line magnetic starter for a three-phase motor is shown in [Figure 2-20](#). To start the motor, a voltage is placed across the contactor coil (basically a relay device). Provided the overload relays are not tripped, the coil will energize and close the three contacts, connecting the incoming power to the motor. The motor will start operation in a direction. Always check for proper rotation of the motor in relation to what it is connected to, i.e. a fan blade or pump impeller: if the rotation is backward, simply swap two of the three-phase wires and re-terminate the contacts, and the motor direction will reverse.

The contactor often is fitted with one or more auxiliary contacts that are added poles that close and open along with the motor contacts. These can be used to interlock other equipment to this motor or to provide an indication that the motor has been started (lighting a remote pilot light, for instance). Make sure the voltage/amp ratings of the interlocked device will agree with the voltage going through those auxiliary contacts. For discussion purposes, often these auxiliary contacts are used to interlock other devices such as fans, pumps, dampers, and smoke dampers. Always be aware of the amperage ratings of these auxiliary contacts so that the number of interlocked devices you connect to them does not exceed their ratings for current, wire size, wire insulation value (600 V rating), and voltage, especially if you are using low voltage (24 V) over a long distance always size the wire appropriately.

Another concern is the minimum ampere rating of the auxiliary contacts. If the amperes are below the minimum rating, the contacts will not be cleaned

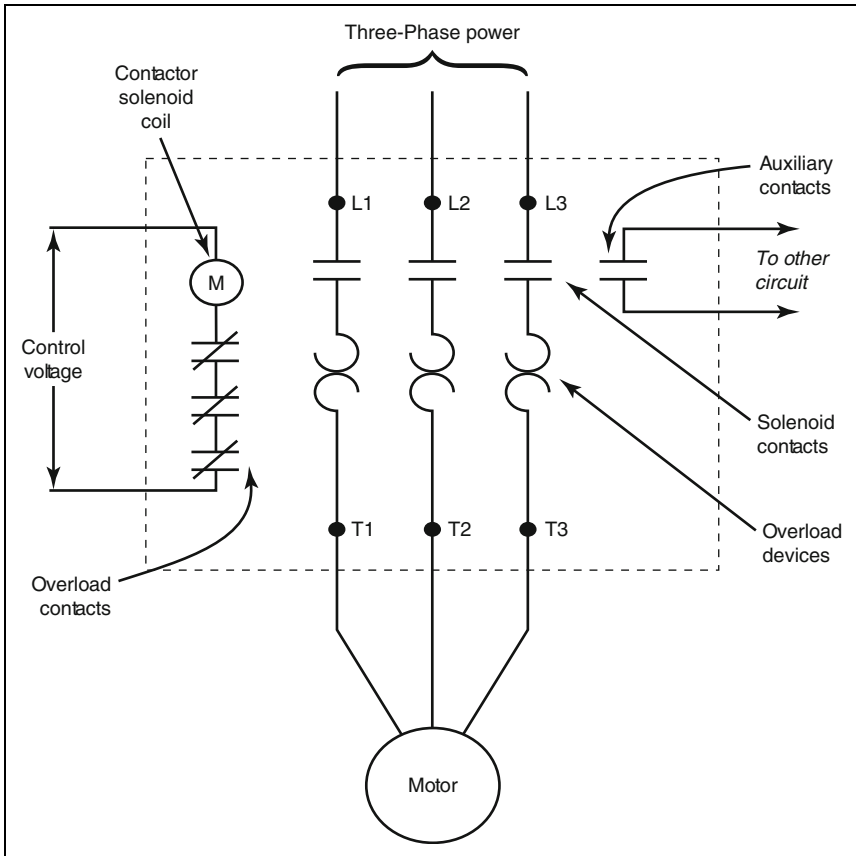


Figure 2-20 Across-the-line Magnetic Motor Starter

and erratic operation will occur. Remember, the wire insulation value, typically 600 V for commercial applications, must always match the highest value used if you are using it in conduit or in panels. In [Figure 2-20](#), the control power comes from a source external to the starter, potentially a dedicated control circuit. It is better practice to draw the control power from within each starter itself. In that way, any interruption in the control circuit will only affect that one motor, whereas with a common control circuit serving many motors, a loss of control power would cause all of the motors to be inoperative.

Control power can be taken directly from two legs of the incoming power or one leg and the neutral. This is common with 208 V three-phase starters because 120 V can be achieved between any leg and the neutral (note: this is only true for Wye connected loads with the center common, or neutral). With 480 V starters, the resulting control voltage would be higher, and it is more common to see a control transformer mounted in the starter to step-down the voltage to 120 V or, less commonly, 24 V (see [Figure 2-21](#)).

The use of 24-V transformers would appear to be more economical because it would allow for less expensive installation of any remote control contacts.

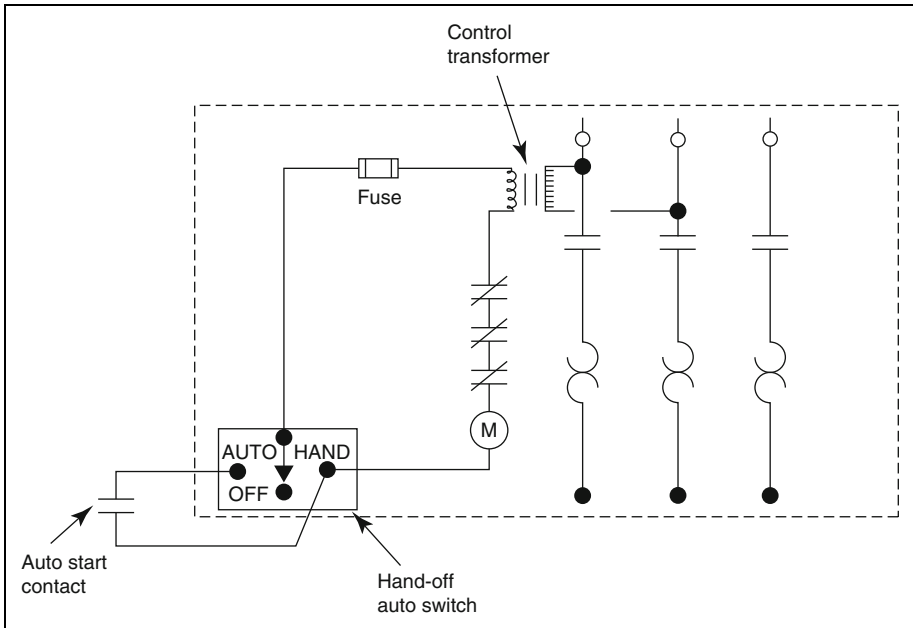


Figure 2-21 Magnetic Starter with H-O-A Switch

However, the amperage required to pull in the contactor at 24 V, termed VA, can be very high so the cable size is uneconomic and 120+ V is used. The wiring to any remote devices must be sufficiently sized to ensure that the voltage drop in the wiring does not result in an insufficient voltage at the contactor coil. To avoid this potential problem, many commonly practiced starter control transformers are 120–480 V.

Make note that the fire alarm start-stop relay, F/A, should always break the magnetic coil directly and before any other safety device: Life safety always takes first, and absolute, priority.

Also shown in [Figure 2-21](#) is a starter-mounted hand-off-auto (H-O-A) switch. The motor can be started manually by switching the H-O-A switch to the hand or on position. When in the auto position, the motor starts only when the remote contact closes. This might be a start/stop contact at an energy management system panel or simply a thermostat or other two-position controller.

There are many other types of starters in addition to the across-the-line starters shown in [Figures 2-20](#) and [2-21](#). For instance, larger motors (larger than 75 hp to 100 hp on 480 V services) are typically served by reduced-voltage starters that are designed to “soft-start” the motor to limit the in-rush current. However, the controls system designer often does not know and seldom cares what type of starter or motor is used. Only the control circuit side of the starter is of importance to the design of the control system. For this reason, the starter is often depicted without any of the power-side wiring, such as in [Figure 2-22](#). You may also note the different way the H-O-A switch is represented in [Figure 2-22](#) as compared to [Figure 2-21](#). Both styles are commonly used.

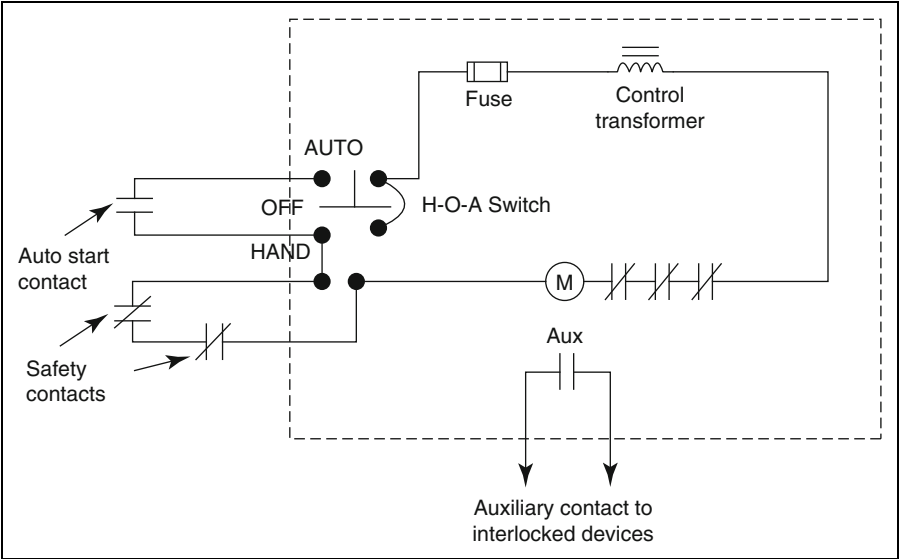


Figure 2-22 Generic Magnetic Starter with H-O-A Switch and Auxiliary Contact

Figure 2-22 includes wiring to safety enabling devices (such as a smoke detector, firestat, fire alarm device, or freeze-stat) that will stop the motor when either of the normally closed contacts open (upon detection of smoke or when freezing temperature air is sensed at a coil, for instance). These safety contacts are wired so that they can stop the motor whether the H-O-A switch is in either the hand or auto position.

Figure 2-23 shows a starter circuit using momentary contact pushbuttons to manually start and stop the motor. When the normally open start button is

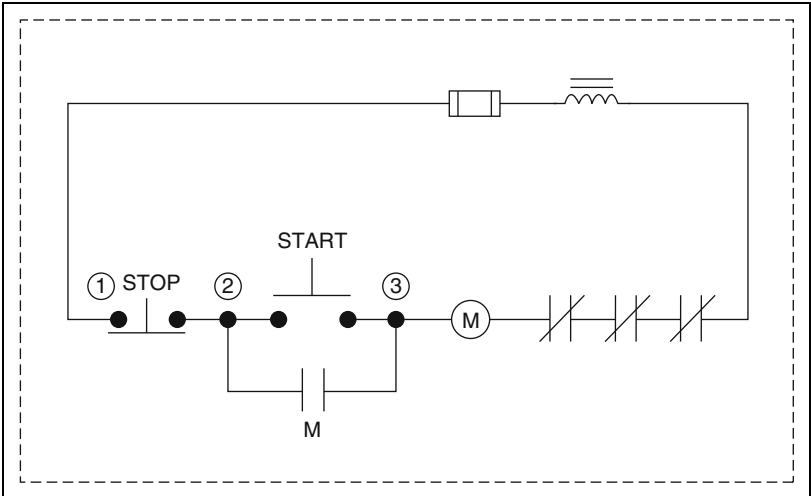


Figure 2-23 Generic Magnetic Starter with Manual Start/Stop Buttons (Three-wire)

depressed, the magnetic starter coil is energized, then the holding contact (an auxiliary contact of the starter coil) maintains power to the coil. When the normally closed stop button is pressed, power to the coil is removed, dropping out the holding contact so that when the button returns to its closed position, the motor stays off. This starter wiring is often called a three-wire control circuit because if the buttons were external to the starter, three wires would have to be run from the buttons to the starter, connecting at the points labeled 1, 2, and 3 in [Figure 2-23](#). (The H-O-A switch approach shown in earlier diagrams is similarly called a two-wire control circuit because only two wiring connections would have to be made if the switch were remotely mounted.)

The two-wire (H-O-A) and three-wire (pushbutton) starter control circuits have two significant differences:

- First, if the motor was running and control power was interrupted and then resumed, a motor controlled by a two-wire circuit would restart. With the three-wire design, the holding coil would drop out when control power was lost, so the motor will only restart if the start button is pressed again.
- Second, the three-wire circuit can only be started and stopped using the pushbuttons. With the two-wire design, a single remote contact (such as a timeclock contact) can be used to start and stop the motor. For this reason, the two-wire approach is more common in HVAC control applications.

Sometimes an HVAC fan must serve double duty as part of the life safety system. For instance, in case of fire, a supply and return fan system may be used to exhaust smoke from one area of a building while pressurizing other areas to prevent smoke migration. The fan will generally be controlled by a fireman's control panel that is part of the life safety system, but a lot of times it is controlled from the fireman's panel as well as from the HVAC control system. For smoke control, most codes allow for the design engineer to design an "engineered smoke control" system that will allow for fans to operate during a fire condition. Typically, the HVAC control system controls it in the automatic side, and a manual switch and control is provided at the fireman's control panel location so that it can be overridden by the attending fire official on site. Typically, the HVAC control panel and fireman's panel are remotely located in a common location of the building. The design of these smoke control systems is complex and intricate, and much coordination is needed between the mechanical and electrical fields of expertise, both in design and during construction.

[Figure 2-24](#) shows how these controls might be wired. The life safety system can command the fan to be off or on. These commands must take precedence over the automatic control of the system and any manual control at the H-O-A switch. When the off-relay shown is energized, the fan cannot run regardless of the H-O-A switch position or the demands of the automatic control system. When the on-relay is energized, the fan will run regardless of the H-O-A switch position and, the way this example is wired, regardless of the freeze-stat contact status. Wiring the freeze-stat in this manner allows the fireman to keep the fan on, even when the weather is freezing; this is valid control logic if life safety concerns are felt to override the concern about damaging

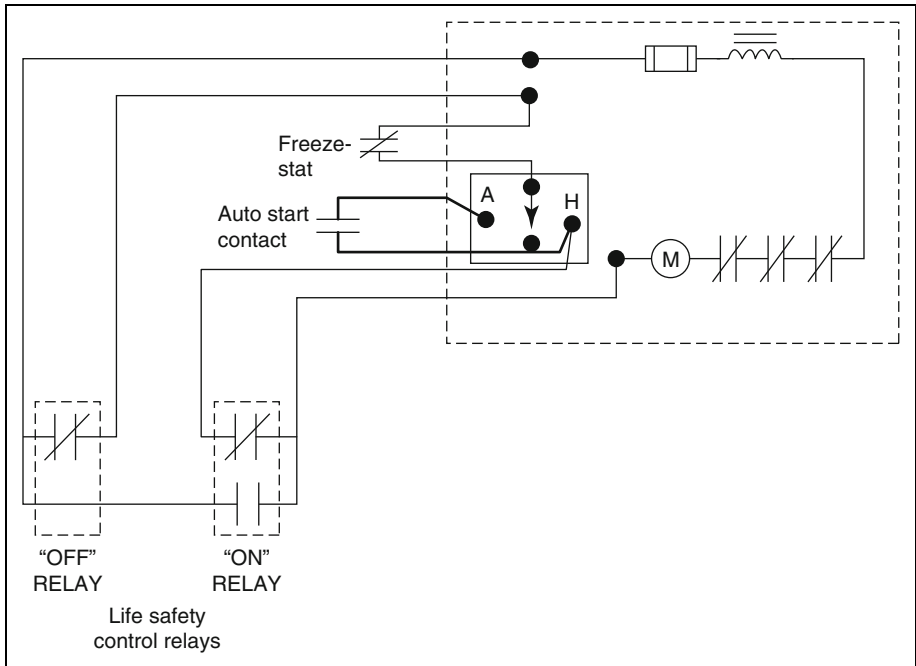


Figure 2-24 Magnetic Starter with Life Safety Fan Wiring

the cooling coil. The wiring between the starter and the fireman's control is generally provided by the life safety contractor, while the wiring connecting the starter to normal HVAC control systems, freeze stat and auto start contact in [Figure 2-24](#), is usually provided by the controls contractor. The HVAC system designer must make this distinction clear in bid documents.

2.6 Variable Speed Drives

Variable speed drives (VSDs), also called adjustable speed drives (ASDs), are devices that can vary the speed of a normally fixed speed motor. In HVAC systems, they are used primarily to control fans in variable air volume systems instead of other devices such as inlet vanes and discharge dampers. Variable speed drives are more energy efficient than these other devices (their main advantage), but they also reduce noise generation at part-load, allow fans to operate at much lower loads without causing the fan to operate in surge (an unstable condition that can result in violent pulsations and possibly cause damage to the fan), and reduce wear on mechanical components such as belts and bearings. Variable speed drives are also used to control pumps on variable flow pumping systems and to control refrigeration compressors in centrifugal chillers.

Many types of variable speed drives have been used over the years, starting with dc drives used primarily in industrial applications, and mechanical

drives that varied sheave diameter. One of the most important developments in recent years has been the advancement of variable frequency drive (VFD) technology. These drives use solid-state electronic circuitry to adjust the frequency and voltage of the power to the motor, which in turn varies the speed.

The most common VFDs used in HVAC applications are inverters using sine-coded pulse-width-modulation (PWM) technology. A schematic of the PWM is shown in [Figure 2-25](#). The PWM works by first converting the incoming ac power to dc using a diode bridge rectifier. The voltage is then filtered, smoothed and passed on to the PWM inverting section. The inverter consists of high speed bipolar transistors that control both voltage and frequency sent to the motor.

The output, shown in [Figure 2-26](#), consists of a series of short-duration voltage pulses. Output voltage is adjusted by changing the width and number of the voltage pulses while output frequency is varied by changing the length of the cycle. The waveform that is produced has the required voltage and frequency to produce the desired motor speed and torque, but it is not as smooth as the incoming sinusoidal source. For this reason, motors should be specifically chosen with adequate design and construction to withstand the less smooth power source.

Do you remember earlier in the chapter when we noted that when we measure the voltage and current in a pure sinewave ac circuit we are measuring the rms value? In most situations, being clear about rms does not matter as the waveform is close to a sinewave. As you can see in [Figure 2-26](#) the waveform is not a sinewave. A standard meter may read substantially high or low in this

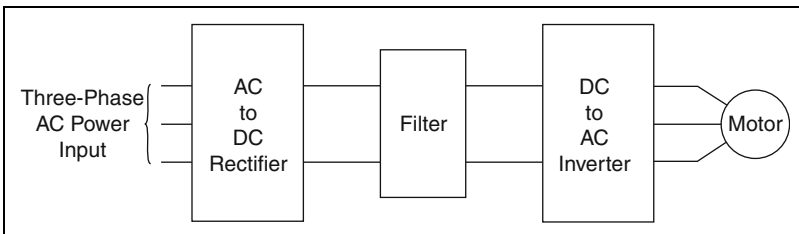


Figure 2-25 Inverter Variable Frequency Drive

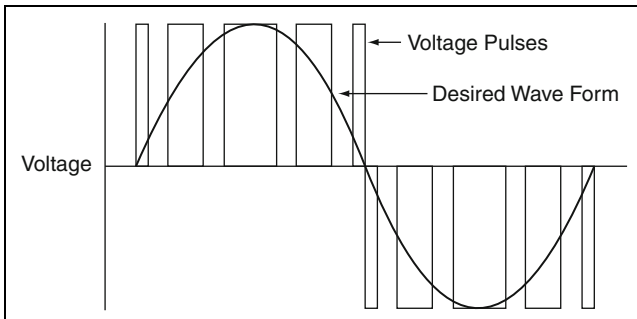


Figure 2-26 Sine-coded PWM Waveform

nonsinewave situation. With the output of a VFD it really matters that you use a meter designed to give you “true rms” readings. Meters are sold as “true rms” meters and are more costly than those which need the true sinewave input.

Variable speed drives (VSDs) take the place of a starter. They have both starting capability and overload protection built in. In fact, the microprocessor controls in most drives provide additional protection against other faults (such as under-voltage, over-voltage, ground-fault, loss of phase, etc.). Variable speed drives also provide for soft-start of the motor (if so programmed), reducing in-rush current and reducing wear on belts and sheaves.

While a starter is not required when a VSD/VFD is used, one may be provided as a back up to the drive so that the motor can be run at full speed in case the drive fails. A schematic of how a bypass starter might be wired is shown in [Figure 2-27](#). Bypass starters were considered almost a requirement in the early days of VSDs and VFDs but now, as drives have improved in reliability, the need for bypass starters is a lot less critical. If a bypass is required, sometimes the use of multiple drives being fed from one similarly sized bypass is desirable, and reduces the cost of buying multiple bypasses. When using a bypass starter, it is important to consider how well the system will operate at full speed. For instance, in a VAV fan application, operating the fan at full speed may cause very high duct pressures at low airflow rates, potentially damaging the duct system. Some new VSDs have what are called electronic bypasses, which are speed selectable and do not have to run at full speed. (These electronic bypasses are not independent; therefore, they use the same contactors and overloads, as does the VSD, so they are not totally

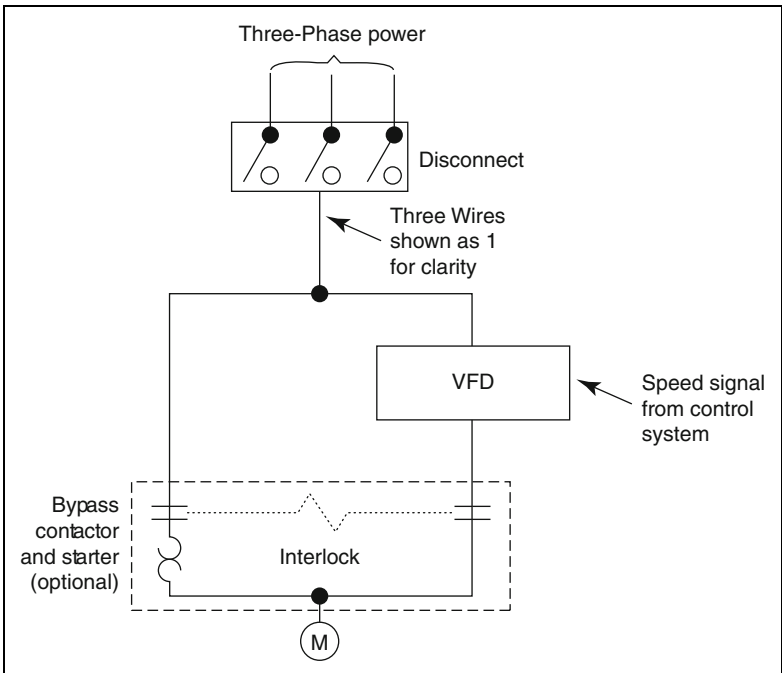


Figure 2-27 Variable Speed Drive with Optional Starter

independent.) Some other means of relieving the air pressure or reducing fan speed should be provided. These complications, along with the added costs involved, must be weighed against the potential benefit of bypass starters.

2.7 Relay Logic and Ladder Diagrams

Relays may be used to implement control sequences using Boolean logic. Boolean logic is a way of making decisions using two-position switches or states. A switch may be opened or closed, also expressed as On or Off, 1 or 0. This is the way digital computers work; in fact, the name *digital* is derived from the discrete on/off states. The first digital computer was constructed of a huge mass of electromagnetic relays, now long since replaced with semiconductor devices.

Boolean logic or relay logic can be used in simple control sequences. For instance, suppose we wish to turn on a pilot light if either fan A or fan B was on. To sense the fan's status, we could install a differential pressure switch across the fan. The contact would be open if the fan pressure was low and closed if the fan pressure was high. To make the light turn on if either fan was on (if either pressure switch contact were closed), we would wire the two contacts in parallel ([Figure 2-28](#), line 1). If we want to turn on the light only if both fan A and fan B were on, the contacts would be wired in series ([Figure 2-28](#), line 2).

Using Boolean logic notation, if turning on the light was labeled event C, then these two sequences could be written:

If (A or B) then C (parallel wiring – line 1)
 If (A and B) then C (series wiring – line 2)

Suppose we wanted the light to turn on when either fan was on, but not if both were on together. Instead of the on/off contacts used above, we could use single-pole double-throw (SPDT) contacts ([Section 2.4](#)). [Figure 2-29](#) shows

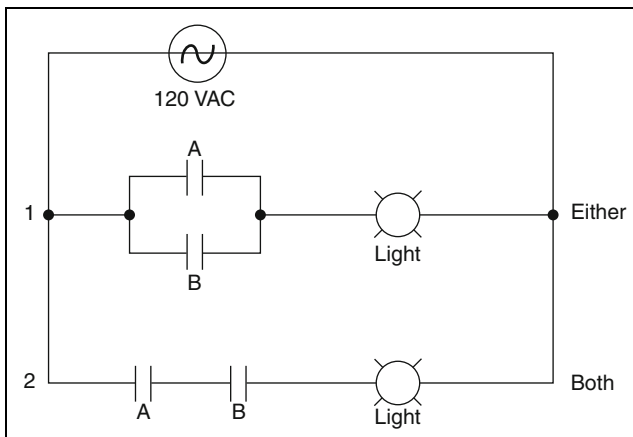


Figure 2-28 Simple Relay Logic

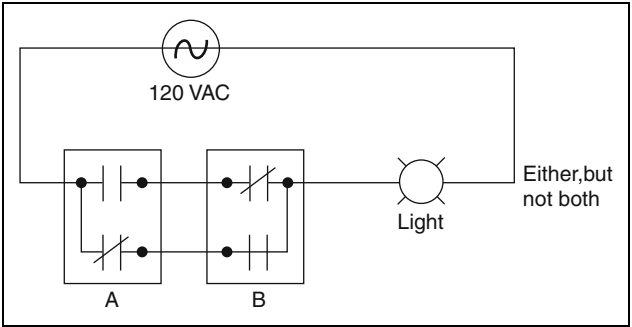


Figure 2-29 Relay Logic with Double-throw Contact

how the double-throw contacts can be used to turn on the light if either but not both fans is on. This would be represented in Boolean format as:

If (A or B) and NOT (A and B) then C

While the fan status contacts in the previous example are from a current sensing relay, the same type of double-throw configuration is also typical of almost any relay or switching device, such as most two-position thermostats and differential pressure switches.

An application similar to the previous example using switches instead of contacts is the three-way switching arrangement common in households, where a light must be switched from either of two locations. We would like the light to change states (go on or off) if either switch is switched. If single throw switches were used in parallel (like [Figure 2-28](#), line 1), then either switch could turn the light on, but both would have to be off for the light to go off. If the switches were wired in series (like [Figure 2-28](#), line 2), either switch could turn the light off, but both would have to be switched on for the light to go on. The solution is shown in [Figure 2-30](#) using single-pole double-throw switches.

Ladder diagrams are a type of wiring diagram used to convey control logic such as relay logic and, typically, to show how devices are to be physically wired in the field. [Figures 2-28–2-30](#) are examples of elementary ladder diagrams. The name comes from the diagram’s resemblance to a ladder. The “rungs” of the ladder are wires interconnecting control contacts (such as relay contacts, thermostats, switches, etc.) to loads (relays, starter coils, etc.) across

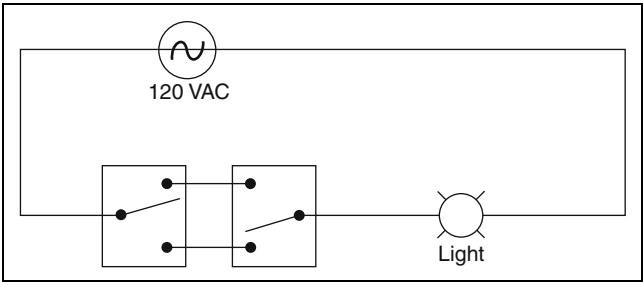


Figure 2-30 Three-way Light Switch

the control power voltage potential represented by the two vertical lines on the left and right.

Figure 2-31 shows many of the symbols used in ladder diagrams to represent commonly used HVAC devices. Many of these devices have already been introduced. One group which has not been introduced is the time delay relay. Often equipment needs to operate in sequence or to have a delay before action is taken.

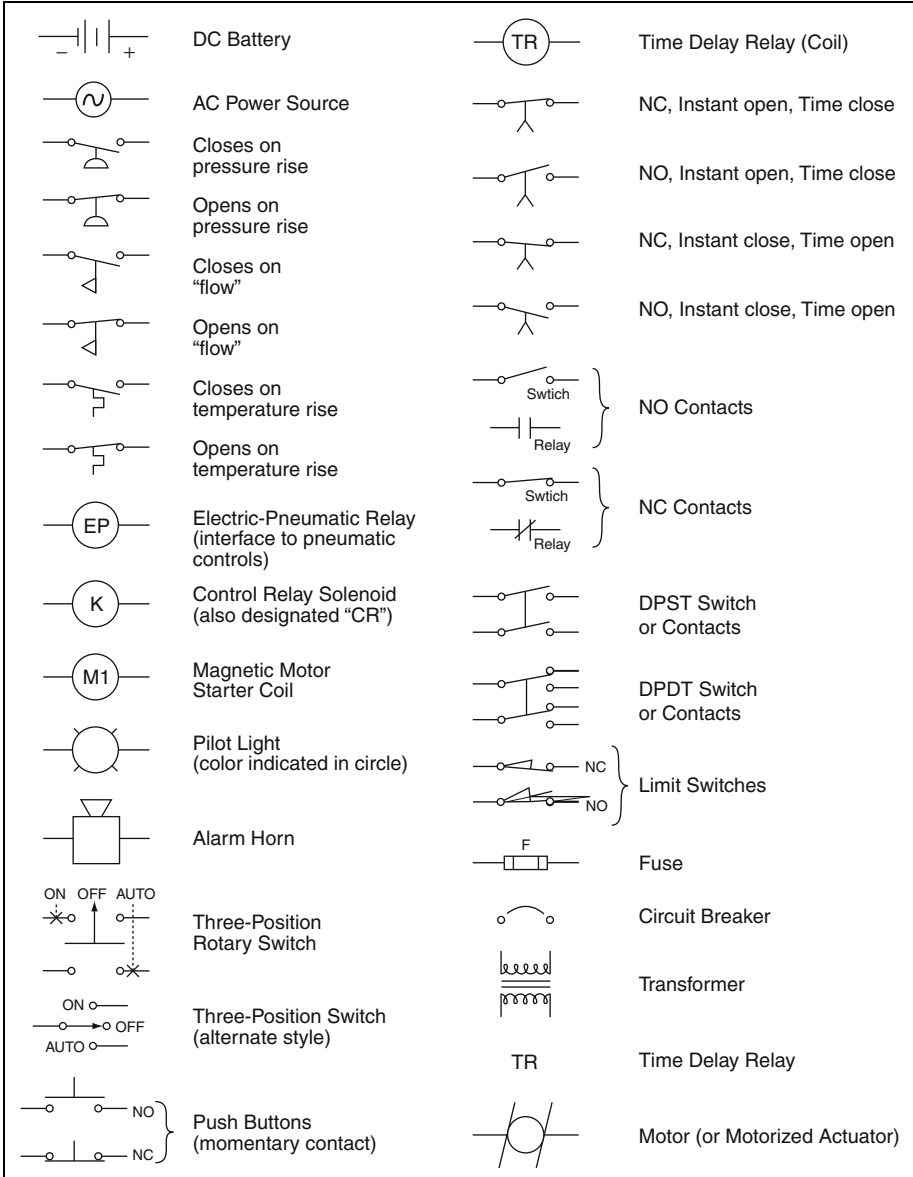


Figure 2-31 Symbols for Electrical Logic Devices

Consider, for example, a simple ventilation unit with a normally closed outside air damper. On startup we may want the damper to be open before the fan starts. We can achieve this with a normally open, time to close, relay supplying the fan starter. When the system is powered on the damper will open while the timer on the fan relay runs and then closes, powering the fan.

Ladder diagrams can have “bugs,” inadvertent errors that cause an unexpected result. Most commonly, these bugs are caused by unintentional voltage feedback. A very simple example is shown in [Figure 2-32](#). We would like to start two heating fan-coil units from a timeclock contact (TC) provided the spaces they serve are below 70°F, as indicated by the two space thermostats shown. We would also like to start fan-coil 1 if the space temperature dropped below a night low limit thermostat set point (55°F), so we add a parallel connection to the relay that starts fan-coil 1. The bug in this design is that when the night low limit thermostat closes, the contacts of the other thermostats in the space will also be closed because their set points are even higher. This will allow the voltage to feed back through the space thermostats so that if the space served by fan-coil 2 was below 70°F, fan-coil 2 would also start. This was not our intention.

To avoid this problem, another relay could be added, as shown in [Figure 2-33](#). As this example demonstrates, care must be taken to avoid feedback when there are multiple, parallel paths to switch a device.

[Figure 2-34](#) is a somewhat more complicated example of a ladder diagram. On more complicated diagrams, such as this, it is common to number the lines for reference. When a relay contact is used in a given line, the line number that the relay coil is on should be referenced (the numbers on the right side of [Figure 2-34](#) in parentheses) to make it easier for the reader to follow the logic.

The example shown in [Figure 2-34](#) is for a simple system consisting of a fan-coil, secondary hot water pump and a toilet exhaust fan, all serving a single space. The following is the control logic this diagram represents:

The fan and pump may be started and stopped manually or automatically using hand-off-auto switches. In the auto position, the fan shall start based on the timeclock or by the night low-limit thermostat (set to 55°F

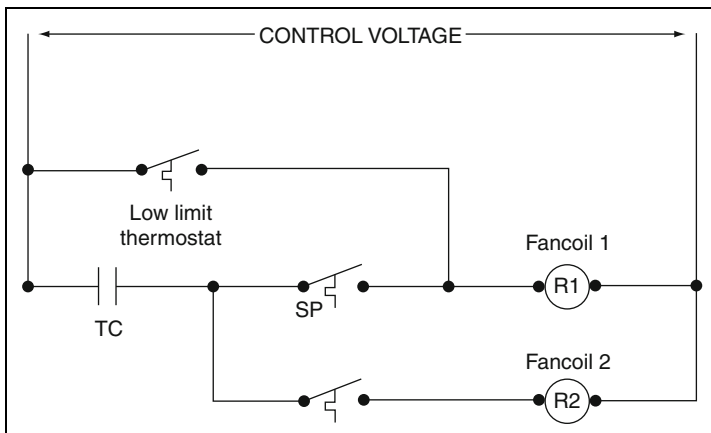


Figure 2-32 Voltage Feedback Bug

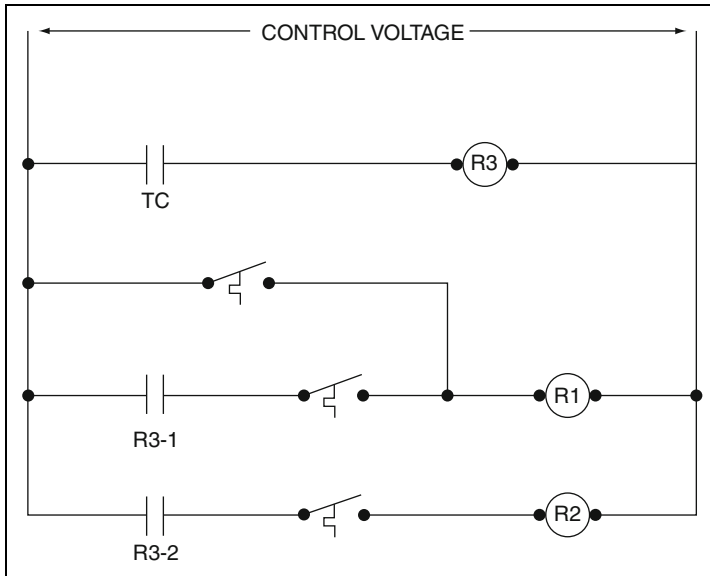


Figure 2-33 Correction for Voltage Feedback

with a 3°F differential). If either the freeze-stat or discharge smoke detector trip, the fan shall stop whether in hand or auto mode. In the auto position, the pump shall start whenever the fan is on, as indicated by an auxiliary contact at the fan starter, and the outdoor air temperature is less than 65°F. When the pump is on, the pneumatic thermostat controlling the hot water control valve (not shown because these are not electrical devices) shall be enabled via an electric-pneumatic (EP) valve. The 120-V toilet exhaust fan shall be started by the timeclock after first opening its discharge damper (powered by a 120-V two-position actuator) and allowing 30 s for the damper to fully open.

A load is energized when the contacts connecting the device to the left-hand power lead to the right-hand lead all close. For instance, looking at [Figure 2-34](#), lines 3 and 4, and assuming the H-O-A switch is in the auto position, for the starter coil for the fan-coil (M1) to energize, we would first have to close either contact R1-1 (one of the contacts from relay R1) or the night low-limit thermostat contact (which closes on a fall in temperature below set point, 55°F in this example). That would pass the control voltage through the auto terminal of the H-O-A switch and up to the two safety contacts, the smoke detector and freeze-stat. These contacts are normally closed; meaning they would open in the event of a safety fault (for example, when smoke is detected or when freezing temperatures at the coil inlet are detected). Assuming these safeties are satisfied, the control voltage is passed on to the starter coil. The circuit is complete if all the overload contacts are satisfied, energizing the coil, which would start the fan motor. At the same time, the coil's auxiliary contact is closed. This contact is used to start the hot water pump.

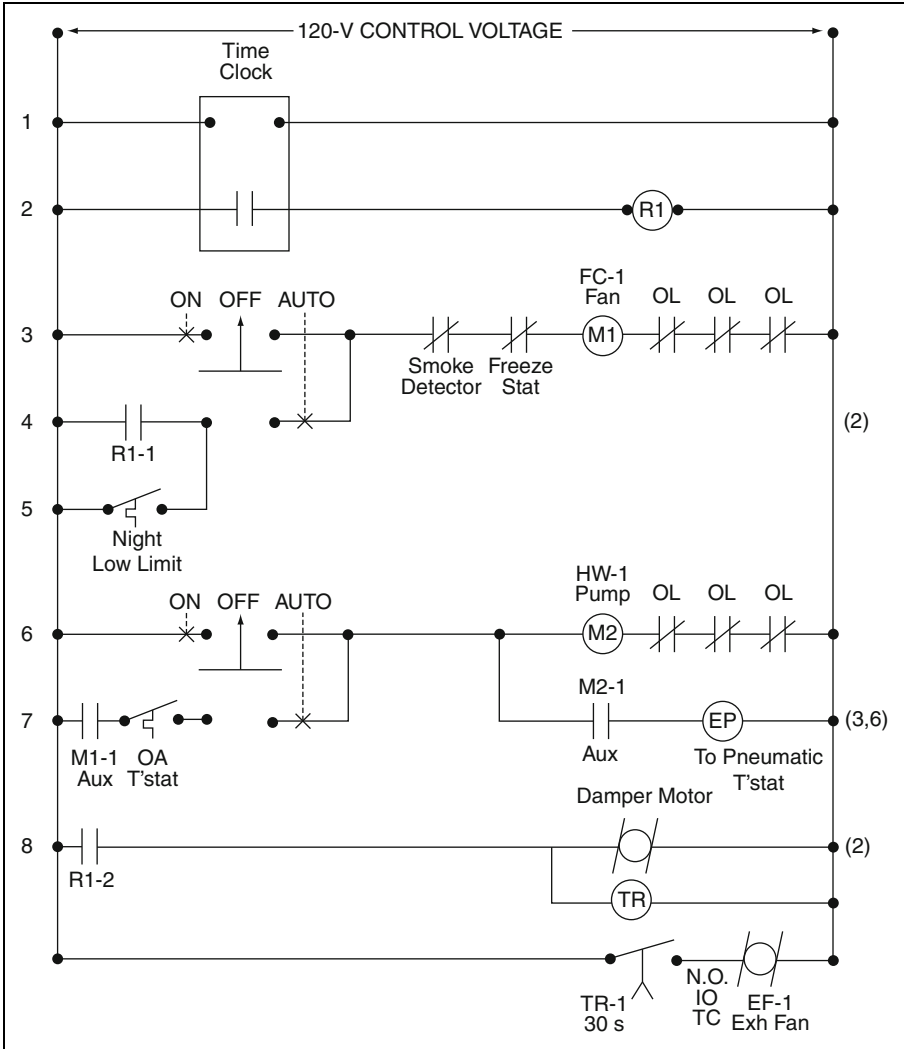


Figure 2-34 Ladder Diagram

While [Figure 2-34](#) clearly conveys the desired control logic, it actually is a poorly constructed diagram. For instance:

- The diagram implies that there is a single source of control power for all the devices shown. While this is possible, it is not likely. The motor starters probably each have their own control transformers while the toilet exhaust fan is probably served by its own power circuit. To avoid this confusion, it is important that ladder diagrams be consistent with the actual power sources used. In this example, the drawing would have to be broken into several stacked ladders, one for each control voltage source.

- The physical location of devices is not clear. The diagram implies that all the devices are in the same panel. In reality, the timeclock and perhaps the EP valve are in a control panel; the H-O-A switches, overloads, and starter coils are in the individual motor starters; and the thermostats are in other remote locations. This problem is often avoided by labeling devices and terminal numbers to show location.

While the ladder diagram is a convenient means of conveying control logic, it is often a poor representation of the physical layout of the system, as this example illustrates. In most cases, HVAC design engineers will never need to develop a ladder diagram as part of the control system description. Written logic sequences and system schematics, along with coordination details and specifications, are usually sufficient to satisfactorily convey the design intent and division of responsibility to the bidding contractors. Where there may be confusion in some wiring responsibility, a detail such as that shown in [Figure 2-24](#) should be added to the plans, but a ladder diagram seldom is required.

Ladder diagrams are probably most commonly used with factory installed controls associated with packaged air conditioners and chillers. However, even in this application, they are becoming obsolete as control system designs migrate towards digital controls. With digital controls (as we will learn in Chapters 10–12), much of the control logic is implemented in software, thereby obviating the need for many of the relays and controllers found in electric control systems.

The Next Step

In the next chapter, we will learn about control valves and control dampers, two of the most common controlled devices used in HVAC systems. The proper selection and sizing of control valves and dampers are critical to the performance of the control system. As these devices have very specific operating characteristics we can often choose the control methodology to best suit these characteristics.

Control Diagrams and Sequences

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Study Objectives of Chapter 9

This chapter introduces how control systems are designed and how the design intent is conveyed using control diagrams (schematics), damper and valve schedules, parts lists, and written control sequences. Electric controls are drawn on ladder diagrams, which were covered in Chapter 2, Section 2.7. The process of designing a control system must begin with an understanding of what is to be controlled and how it is to be controlled before selecting the type of control device hardware required to implement the desired logic. The hardware selection (be it self-powered, electric, analog electronic, pneumatic, or digital) will be a function of the requirements of the process, the accuracy and reliability required, cost desired, etc. More advanced control strategies are discussed in other courses and in the ASH-RAE Handbooks.

After studying this chapter, you should be able to:

Comprehend design concepts that will result in a workable and flexible control system.

Understand the responsibilities of the various designers and contractors in the typical control system design and construction process.

Know how to create a control diagram using standard symbols.

Comprehend the guidelines for writing a control sequence.

9.1 Control Systems Design Criteria

Designing HVAC control systems, like designing HVAC systems themselves, is a science but allows for different approaches. Every designer's style differs and there are many right ways to control the same system.

The critical first step towards success is to be absolutely clear about the objective. For example, an office air-conditioning system has temperature, humidity, and outside air requirements to achieve during occupied hours. If groups of offices are to be in a single control zone identify the fact. It may well have requirements for setback temperature and humidity control in OFF hours as well as particular performance in case of fire/smoke alarm or fire department control. Having these requirements written down, and agreed with the client, makes for a solid foundation for controls design. This is particularly the case with large client organizations and larger design offices, where people with different views and expectations often join the project well after the design decisions have been made.

There are several basic requirements for systems:

- The control system must meet the needs of the process.
- The control system should control the process as directly as possible.
- The control system must be designed to work with the HVAC system, and vice versa.
- The HVAC control system should minimize energy consumption.
- The HVAC control system should maintain indoor air quality requirements.
- The cost of the HVAC control system must meet the budget.
- The control system must be designed for maximum simplicity. As Albert Einstein once said: "Everything should be as simple as possible, but not simpler."

The simplest systems have the best chance of being operated as intended. This is not to say that we must compromise the design goals expressed above for the sake of simplicity. The designer must balance the need for complexity with the reality that complex systems are the most likely to work incorrectly due to "bugs" in the design and the most likely to be misunderstood by the facility operator or repair technician who must make the system operate in the field. The ability of the maintenance team and available support should be considered when making design and equipment choices. A school which is one of many in a large city school district is very different from a school in a remote community, where maintenance expertise is very limited and any maintenance items may have to be flown in.

Even the simplest of control systems requires good documentation and training. Some control systems are necessarily complex because the HVAC system or the process it serves is complex. It is very important to have an effective training and useable documentation.

Operators that follow in years to come must be able to find out and understand how the system is designed to operate, and where components are physically located. Therefore, detailed explanations of the design intent should be included on plans. All software and programming must be turned over to the end-user and copies kept in the operations room as well as in another safe place. As-built drawings and data sheets must be transmitted

through the design and contractor channels to the end-user files. Careful attention to depicting locations of all sensors, thermostats, communication lines, power wiring/tubing, pilot lights, valves, dampers, PRV's, relays, switches, etc., on the as-built and maintenance and operation documents should be done. All cables, wires, and tubes should be marked permanently with a marker, in at least two places, and documented on the control diagrams or point lists. It is a good idea for the engineer to specify and follow up to verify compliance. In any but the simplest system, formal commissioning pays off in initial performance and in ongoing operation and energy consumption.

9.2 Control Systems Design Process

The controls system designer must be able to convey not only the design intent (how the system is supposed to operate), but also who is responsible for performing the work and who is required to construct the control system.

Today, the advent of more complex control systems, and the variation in system architecture from one manufacturer to another, has led to more performance-based designs and specifications. In a performance-based design, the operational characteristics that are desired are specified and the control system provided can provide a number of solutions in order to control the system to meet this requirement. Ultimately, in most cases, the contractor is responsible for interpreting the intent of the contract documents, and the contractor shall direct his staff, subcontractors and suppliers to comply.

Controls Contractor: The controls contractor is part of the controls design-and-construct team, along with the HVAC engineer. The controls contractor may also be the control system vendor, the manufacturer, and/or distributor of the parts and components.

It is very important that the firm installing the electrical and mechanical controls is duly licensed and insured to do the work, as well as authorized and trained by the controls manufacturer. For additional information on the responsibilities and actions required at various stage of the design and construction process, readers are encouraged to read *ASHRAE Guideline 1, Commissioning HVAC Systems*.

9.3 Control Diagrams and Symbols

ASHRAE has published Standard 134-2005 Graphic Symbols for Heating, Ventilating, Air-Conditioning, and Refrigerating Systems, which includes standard symbols to be used in the controls industry: a sample of symbols can be seen in [Figure 9-1](#). Many organizations have developed their own library of graphic symbols and it is wise to include on the controls drawings a key to their meaning to avoid any misunderstandings.

The symbols cover four sections: air handling, piping, controls, and equipment. The graphic symbol may have two types of information added about particular variations of device and detail about the device function. For example, a coil symbol may have CC – to indicate Cooling Coil – or HC – to indicate Heating Coil. Alternatively, the coil can be marked with a $\ominus$ for cooling

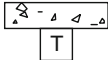
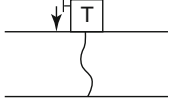
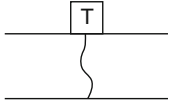
Controller	Symbol	Filename
Thermostat, wall mounted		C 15970.001
Thermostat, duct mounted, low limit, manually reset		C 15970.005
Thermostat, duct mounted, averaging		C 15970.002
Thermostat remote bulb		C 15972.003
Electric-pneumatic transmitter		C 15972.018
Electric-pneumatic transducer		C 15960.001
Controller, adjustable (variable) speed drive		C 15970.018

Figure 9-1 Sampling of Symbols > From ASHRAE Standard 134-2005

and $\oplus$ for heating. An example of indicating unction is with a thermostat, which may be marked as DA – Direct Acting – or RA – Reverse Acting.

Some of the graphic symbols are quite detailed and could be misread. Included in the figure is an example: thermostat, duct mounted, low limit, manually reset. Be sure to include the details in the specification or parts list so that you are not relying on detailed interpretation of the drawing to obtain what you want. Also note that not all symbols are unique, as in the abbreviation VFD for variable frequency drive and symbol ASD for adjustable speed drive, as shown in the figure.

When making up symbols, be sure to follow the overall convention of controller devices (thermostats, controllers) being in a square or rectangular box, and sensors and transmitters in a hexagonal box.

In this chapter, the diagrams are mostly generic; as they do not define the type of controls hardware (electric, electronic, pneumatic, and digital) and lines are used to indicate an interconnection between devices without defining whether they represent wiring or tubing.

Generic control diagrams are generally acceptable for most HVAC designs for bidding purposes because they, along with the written sequence of controls described in the next section, should sufficiently define the requirements of the control system. (The generic diagrams for digital control systems take on a slightly different appearance than the generic drawings here; if digital controls are to be used, diagrams should be tailored for that purpose and we will cover them in later chapters.)

9.4 Control Sequences

Controls are simply devices that try to duplicate the human thought process. With HVAC system controls, the controls are designed to carry out the thoughts and desires of the HVAC system designer. Because the HVAC system designer is probably not the person who will detail the controls system design, possibly not the person who will program and commission the system, and seldom the person who must operate and maintain the system for years to come, it is imperative that the designer convey his or her thoughts, about how the system is supposed to perform, clearly and without ambiguity. This is done through a written sequence of operation, also called a written control sequence.

Note that there are two fundamentally different ways of specifying a control system: performance and detail. In the performance specification the resulting performance is set out and described but the means to achieve this performance is left open. In the detailed specification, the components and how they are to be connected are all defined. “The temperature control shall maintain $73 \pm 2^\circ\text{F}$ ” is a performance specification and “Supply and install a model ABC temperature sensor and XYZ controller” is a detail specification. Many designers use a mix of the approaches, allowing the contractor freedom except where the designer wants a specific product for performance, reliability, client wishes, or other reason. For the HVAC designer following the performance specification approach, a clearly written sequence of operation is essential because it is the means of conveying the desired control system’s performance to the controls vendor or contractor.

Some guidelines for writing control sequences:

- Break the sequence into logical parts. First divide the system into major subsystems, such as air handlers, chiller plant and boiler plant, CAV, VAV, reheat coils, exhaust fans, isolation rooms, hoods, air flow monitors, etc. Then further subdivide each of these parts into individual control blocks, such as start/stop (how and when will the equipment run), and a block for each controlled device and/or controlled variable. In the previous chapter the variable volume system controls were in three parts: fan start/stop, air velocity control by inlet guide vanes, and temperature and mixed air control. Although the parts interconnected, they each operated as a separate subsystem.
- When specifying an HVAC control loop, be sure it is clear what the control point and controlled device are, and how the set point is determined. Typical devices to control are temperature, pressure, carbon dioxide level, humidity, carbon monoxide level, filter pressure drop, flow, and velocity.

If certain control logic (such as P, PI), resets, and direct/reverse acting are required for acceptable performance, it also should be specified.

- Many HVAC control loops will need to have some type of enabling and disabling interlock. This is important because PID control loops, which are enabled when the equipment they control are “off”, can develop “integral windup” due to the long periods of time with its controlled variable signal is away from its set point. To solve this, the control loop can be turned on and off with a status control point tied to the status of the equipment controlled, allowing for the control loop to be turned on and off with respect to its equipment being on or off. This allows for the control loop to start working closer to its target set point immediately upon its equipment starting.
- Always state the required or desired set point and range for control loops. Many times, this information is left up to the operator to set because set points are generally adjustable. But the control sequence should at least provide a guideline of the range of set points that the system was designed to provide, and that will result in acceptable performance.
- In general, each controlled variable should be controlled by a single control loop. If various devices affect a given controlled variable and a control loop is provided for each, the control loops would have to be coordinated to be sure that only one is operational at any given time. For example, supply air temperature control for a system with an economizer should have a single controller that sequences the chilled water valve and economizer dampers. One controller should be used for each process. All sensors that directly control the controlled devices should be wired to that controller, where feasible. If two controllers are used instead of one, they must be enabled and disabled in sequence so that one does not “fight” the other. Some extra sensors may be required, that will wire to both controllers, if they directly conflict with its operation. Also, if one controller loses power or communication, or if sensors and/or devices wired to them affect other controllers, then this practice should be avoided. Generally, all control loops and sensors should have the capability to sense and alarm when there is a suspected and/or sensed failure and/or out-of-bounds response. In rare cases, where industrial high accuracy control is required, double loops or cascaded loops may be used.
- For each controlled device, state not only how it should be controlled when the system is normally operating, but also how the device is to be controlled when the system is shut off normally (such as by time schedule) or in an emergency (such as by a smoke detector, or fire alarm, or bad weather). For instance, when an air handler shuts off, typically it is better to have the outdoor air dampers to close to avoid infiltration and possible coil freezing. Also, two-way control valves to close to reduce pumping energy and piping losses may be desirable. If so, this must be specifically stated in sequences.
- Specify the normal position of a controlled device if it is important to the design. For instance, we may want all heating valves to be normally-open to prevent freeze-ups in cold weather. If so, this must be stated in sequences (or on schematics). If a normal position is not critical to the design, do not require one because with some hardware types (particularly electric and electronic controls) this will increase first-costs.

- Specify the wiring and installation methods required such as plenum wiring only (plenum wiring has low flame and smoke generation properties that are sufficiently limited for them to be approved for plenum use), conduit required, or a combination. Tell the contractor where to mount the devices, such as on the ducts, on the walls and at what height, on the top of the pipes, in the ceilings, etc.
- It is important that control sequences be as specific and detailed as possible. All sequences should answer the questions who, what, when, where, how, and how much?

9.5 Example Applications

In this section, written sequences and generic control diagrams are discussed for many typical HVAC applications. These applications, with some variations, will be the basis of further examples to demonstrate how different control system hardware and software types are applied.

These examples are written from the perspective of the HVAC system design engineer who is attempting to convey the design intent and operating sequence to a controls vendor/contractor (who will actually design more intricate details of the controls upon its formal submittal and as-builts) and to future system operators.

Typical Single-Zone System

Figure 9-2 shows a single-zone unit with hydronic heating and cooling coils. A fan coil unit can also be a simple single-zone system.

To develop a sequence of controls, the controlled devices, which are: the supply fans' motor; the hot water valve; the chilled water valve; and the outdoor air damper must be identified. The controlled variable is the temperature of the room being conditioned by this air handler. A room thermostat (a sensor and controller in the same enclosure) is used as the controller.

In addition, two safety devices are provided: a duct smoke detector and a freeze-stat. The smoke detector is required by most building codes (depending on equipment size) to shut off the fan when smoke is detected to prevent its recirculation to occupied spaces. The freeze-stat is typically required to shut down the fan and/or outside air damper in cold climates to prevent coil freeze-ups should the hot water system fail. For this system, the sequence might read:

- Start/stop. The system shall start and stop based on the time schedule set on the timeclock. (Modern timeclocks will have a total annual format with holiday and temporary day programming. Specify how many times each day that this start-stop occurs, such as on at 7 a.m. and then off at 8 p.m.) (If operation is desired after the normally scheduled "on" time, an "override or bypass" switch to allow is required for overriding and should be added to the diagram.)
- Heating/cooling control. Heating and cooling shall be controlled to maintain room temperature at set point (typically 70–75°F, adjustable) by a single set point proportional room thermostat modulating two-way

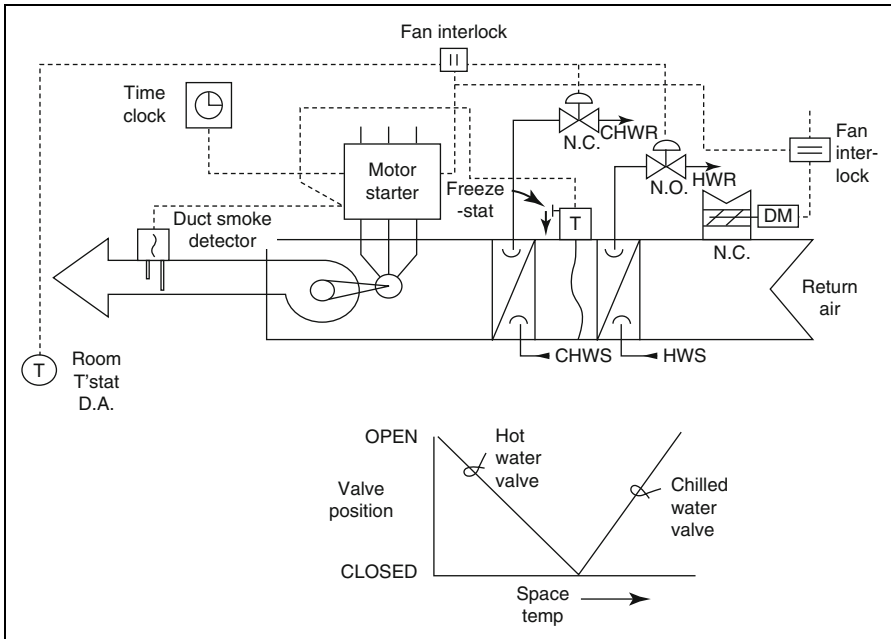


Figure 9-2 Typical Single-Zone Air Handler

control valves. On a call for cooling, the cooling coil control valve shall open. Upon a call for less cooling, the cooling coil control valve shall close. On a continued call for less cooling (call for heating) the heating coil control valve shall modulate open. When the fan is off, the hot water and chilled valves shall close.

- **Outdoor air damper.** The outdoor air damper shall open whenever the fan is energized and close when the fan is off. To maintain building pressurization, the exhaust fans for the general common areas and the toilets can be interlocked together with the operation of the OA damper. (Note: the exhaust fans should stay on and the OA dampers should stay opened during occupied periods.)

The control schematic does not show the wiring details of the fan starter, nor does it indicate the starter components required such as H-O-A (hand-off-automatic) switches and control transformers. They could be shown here, but it is usually more convenient to specify the requirements in a motor control diagram or in a generic starter detail. The timeclock should be mounted in a temperature control panel (TCP), and its physical panel location should be specified or shown on HVAC plans and in the specs. (If there are several panels, they are generally numbered (TCP-1, 2, etc.), as are control valves and control dampers (V-1, D-1, etc.).

The normal position of valves and dampers should be specified on schematics or in control sequences (but not both, to avoid potential conflicts). A schematic was selected here because it makes the written sequence more

understandable. In this example, the hot water valve was selected to be normally open so that if the controller fails, for some reason, hot water flow could be made to flow through the coil by simply removing its control power. This might be used to prevent a coil freeze-up, or in cold climates it can be considered life safety. The controller must be direct-acting to correspond to the normally open hot water valve and the heating medium. This may or may not be included in the diagram and written sequence. If it were not specified, the controls vendor would be responsible for making the selection.

To correspond with the action of the controller above, the chilled water valve must be normally-closed. It also must have a control range that is sequenced with that of the heating valve. The control ranges may be shown on schematics, but their selection is often left up to the controls vendor or contractor.

For information, hot water pre-heat coils or electric heat is used to prevent the freezing of coils and other devices in cold weather. When heat is not available, sometimes just flow through the coils is initiated by the control system when freezing conditions apply, so that the coils can use the heat in the "piping system" to slow down the freezing effect. Heating reheat coils can also be useful to provide for dehumidification when needed and allowed by code.

On many systems, the designer will specify alarms that will advise the owner and operator that a control system or equipment failure has occurred, so a fast response and repair can be initiated.

In practice, many valves and actuators are now designed to permit the controlled device to be normally-open or normally-closed depending on what the designer wants.

The sequence specifies that the flow of hot and chilled water be shut off when the fan is not running, potentially reducing pump energy, piping, and coil heat losses. This could be done most conveniently by using normally-closed valves so that we need only interlock the valve's power source to the supply fan to close it when the fan is off. To do this, using a normally-open valve, some means of driving the valve closed when the fan is off must be provided. This would be a hardware requirement implied by specifying that the valve be normally-open but shut when the fan is off. (For cooling systems, it is advisable to shut off the cooling valve when the fan system is off, as it may produce condensate and waste energy when not being used.)

Using a single controller (thermostat) means we have a single set point for both heating and cooling. To save energy, we may wish to have a lower set point in the winter than in the summer. For instance, we may want to maintain the space at 70°F for heating and 75°F for cooling. Between these two set points, we would want both valves closed. This is called the controller deadband, which is the range over which a change in controlled variable causes no changes to any controlled device. To create a deadband using proportional controls, we could adjust the control ranges over which the chilled and hot water valves operated to create a gap in between them. Using pneumatic controls as an example, we could operate the hot water valve over a 2–6 psi range and the chilled water valve over a 10–14 psi range, leaving a gap from 6–10 psi where both valves were closed. The temperature range that corresponds to this signal range would depend on the throttling range of the controller. Typically, pneumatic thermostats are adjusted to provide a 2.5-psi per °F throttling range, which would mean the 4 psi gap between 6 psi and 10 psi would correspond to a temperature dead band of about 1.6°F, or 2°F, which could be 70–72°F.

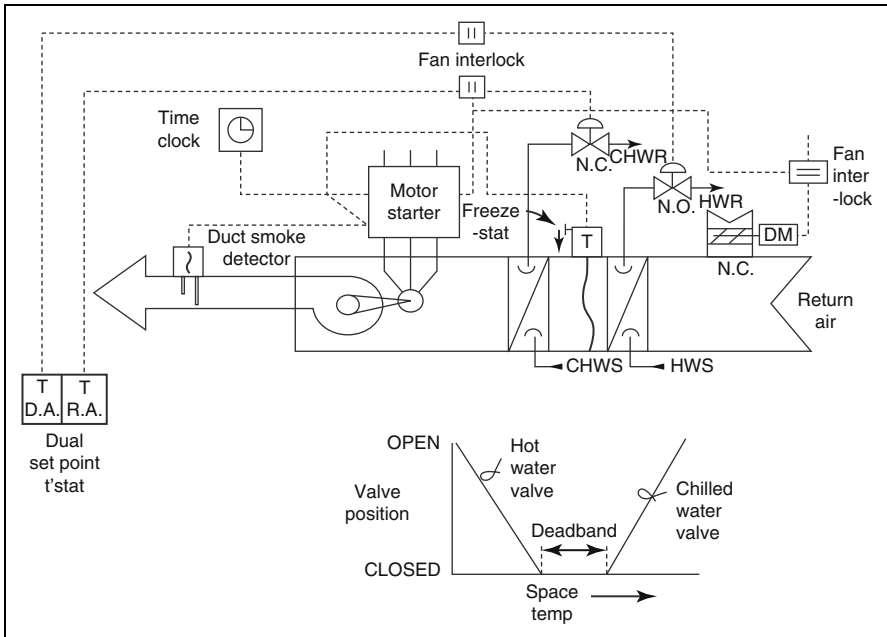


Figure 9-3 Single-Zone Unit with Dual Set point Thermostat

Another way to create a deadband is to use a deadband thermostat. This is a thermostat designed to provide a fixed output signal over a selected range of temperature that defines the deadband. Pneumatic deadband or hesitation thermostats are examples of this type of controller.

More commonly, simply using two thermostats, one for heating and one for cooling (as depicted in [Figure 9-3](#)), achieves deadband. Typically, the two thermostats are housed in the same enclosure. Common residential heating/cooling thermostats and dual set point electric or pneumatic thermostats are good examples of this type of controller. Dual output electronic controllers are similar except they generally use a single temperature-sensing element feeding both of the two controllers. Because each controller has its own set point, virtually any deadband can be achieved with this design. Unfortunately, in some cases it may be possible to overlap the two set points; for example setting the heating thermostat to 75°F while setting the cooling thermostats to 70°F. This would cause both valves to be opened at the same time, and the heating and cooling coils would “fight” with one another. To prevent this energy waste, many dual set point thermostats have physical stops that ensure that the cooling set point always exceeds the heating set point. (Digital controllers typically have similar limits programmed into software.)

Another advantage of using dual thermostats is that they can each have different control actions, which allow unlimited flexibility in selecting the normal position of the control valves. For instance, if we want both valves to fail open, we could use a direct-acting heating thermostat and a reverse-acting cooling thermostat.

Note that the problem of overlapping can also occur when two thermostats controlling separate equipment are mounted near each other. Two, or more,

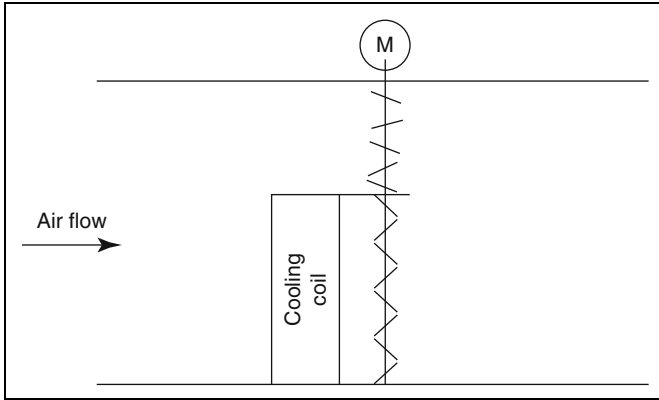


Figure 9-4 Face and Bypass Damper Arrangement

self-contained units that can both heat and cool installed in the same room is an example.

Typical Constant Air Volume System with Face and Bypass Dampers

For each air-handling unit, its chilled water valve shall be modulated to maintain discharge air temperature set point at 55°F (adjustable) unless it is in its heating mode.

Face and bypass dampers are used to vary the volume of air through a coil or bypassing it. The arrangement is shown in [Figure 9-4](#). Due to the relatively higher resistance of the coil, the bypass damper is much smaller than the coil damper. The dampers here are shown as being driven by a single motor with the bypass well open and the coil flow somewhat closed off.

The face and bypass damper for this example is around the cooling coil. (Note, it can be around the heating coil or both for other designs.)

The face and bypass damper shall modulate to maintain a room or return air set point of 72°F (adjustable). As room or return air temperature rises above set point, the actuator shall command open face damper (more air flow across cooling coil) while closing bypass damper, until the desired return air temperature set point is achieved.

As the room or return air temperature falls below the set point 72°F (adjustable), the chilled water valve will be commanded closed, and face and bypass dampers shall be positioned to bypass position. On continued drop in room temperature, the face and bypass shall go to the full bypass position, and the hot water valve or electric heat shall be modulated or staged on as required to maintain heating set point.

Provide a minimum of 1°F of deadband where no control action occurs. Provide a fail-safe position for the face and bypass (F&B) damper to position itself. When the F&B damper is in the full face or full bypass position it is sometimes advisable to close the valve that is not being used. (Note, for example, in a cold climate, the fail-safe position may be in the bypass position.)

The supply fan and outdoor air damper/interlocked exhaust fans shall be controlled on and off together, on its own separate occupied time schedule.

Typical Constant Air Volume System with Multiple Zones or Reheat

The AHU is constant volume, and may or may not have inlet vanes or VFD to maintain its volume during filter loading. It typically has a main AHU cooling coil section that modulates in order to maintain its supply air temperature set point, often set at 55°F. In the reheat model, a thermostat in each room that is served reheats the cold air.

In the multi-zone model, a face and bypass damper arrangement, one for each zone, modulates its air stream through an electric or hydronic-heating coil and/or through the cold deck face, in response to a room thermostat/humidistat. Hot and cold air streams are mixed by the damper arrangement to control the zone temperature.

Typical Variable Air Volume System

The systems in the previous examples supply a constant volume of air to the space, with supply air temperature sometimes varying to satisfy space heating and cooling loads. Variable air volume (VAV) systems do the opposite. They maintain nearly constant supply temperatures while modulating the volume of air supplied to the zone.

Figure 9-5 shows a basic VAV AHU system which includes:

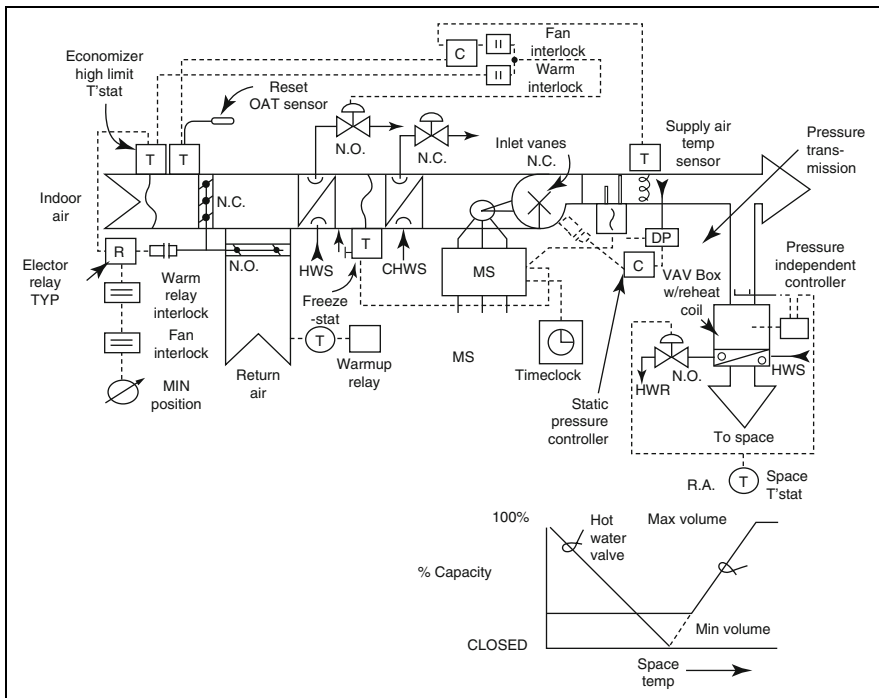


Figure 9-5 Typical VAV Systems AHU

- Supply air temperature control. During normal operation, the supply air temperature shall be maintained at set point by sequencing the chilled water valve, economizer dampers and hot water valve. The supply air temperature set point shall be reset based on outdoor air temperature as follows:

Outdoor air temperature	Supply air temperature
65°F	55°F
55°F	60°F

- Static pressure control. Whenever the fan is commanded on, duct static pressure shall be maintained at set point by modulating inlet guide vanes using PI logic. (VSDs are replacing inlet vanes in most cases these days.) The inlet vanes should be ramped very slowly in order not to cause undue turbulence or noise.

The pressure static high limit, PSHL, device stops the fan to avoid damage to the ductwork from a failed or closed damper downstream of the fan. Sometimes, if the vanes are not closed at shutdown, and the fan starts up under a full load this may happen prematurely. Also, if changes are made to the pressure relationships in the building, these high limit set points may have to be adjusted.

The PSHL is usually manual reset, and may initiate an alarm report. Take care to mount it, label it, and mark its location carefully, as it will need to be located someday for resetting.

The system in [Figure 9-5](#) uses inlet vanes for static pressure control, but the concept is the same regardless of which type of control device is used. Duct static pressure is measured in the main supply duct out near the extreme end of the system of VAV boxes. The further out in the system the sensor is located, the lower the set point can be, thereby reducing fan energy.

The static pressure set point is typically confirmed by the controls and air-balancing technicians with all VAV boxes open to their design maximum airflow rates. For systems with a large diversity factor (those for which the sum of VAV box design air flow significantly exceeds the fan design air flow) it may be necessary to reduce or shut-off the air flow to zones nearest the supply fan until the sum of the actual zone air flows approximates the fan design supply air flow rate. This will provide a more realistic approximation of actual operating conditions.

Some VAV systems use a return fan in addition to the traditional supply fan in order to effect building pressurization and deal with large pressure drops in return ducts. Controls need to work together in these supply/return fan systems in order to maintain their independent pressure set points and building pressurization goals.

PI control (proportional plus integral) is specified for static pressure control. In systems operating over a wide air volume range, the proportional gain must be fairly low (throttling range fairly high) to provide stable control. This can lead to offset (droop), as explained in Chapter 1, with proportional-only controls. The addition of integral logic can eliminate this offset.

- Economizer. Economizer control shall be disabled when the outdoor air temperature is greater than the outdoor air high limit thermostat set point (67°F with a 3°F differential). The signal to the outdoor air damper shall

be the larger of the signal from the supply air controller and the signal corresponding to minimum outdoor air intake required for ventilation (to be established and verified by the balancing and/or commissioning contractor in the field).

The controller modulates the cooling control valve, economizer dampers and heating control valve in sequence to maintain the supply air temperature at a fixed set point. The economizer could be controlled by a separate mixed air controller, but using a single controller reduces first-costs and eliminates the complication of having to coordinate the actions of the two controllers so that they do not “fight” each other.

The sequencing of the components is accomplished by selecting sequential control ranges, shown schematically in [Figure 9-6](#). The economizer function is very good about providing energy savings using outdoor conditions that are useful in helping to satisfy the cooling and heating loads inside the building. At the controller output signal corresponding to full cooling, the chilled water valve is full open. The economizer outdoor air damper may also be fully open depending on outdoor conditions. The control system will examine the outdoor temperature and humidity conditions, and use the appropriate amount of outside air to assist the conditioning of the space. (In the figure, it is assumed that the economizer high limit will shut off the economizer before full load is reached: the usual case.) As the cooling loads decrease, or when the set point is being satisfied, the chilled water valve begins to close. When it is fully closed after the load falls or the set point is completely satisfied, the signal to the economizer dampers, in sequence, falls, reducing the supply of cool outdoor air and therefore the space (or supply air temperature) becomes satisfied. As the load falls further, outdoor air is reduced until its minimum is reached after which the heating valve opens.

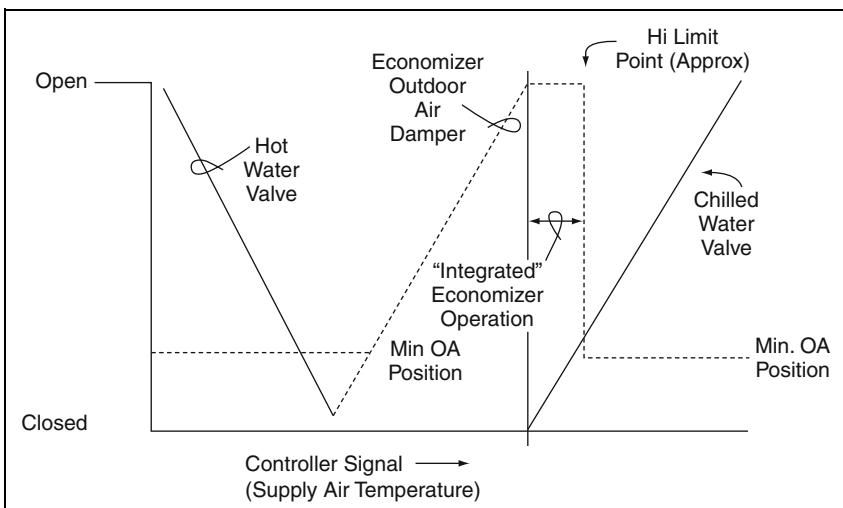


Figure 9-6 Chilled Water, Economizer, and Hot Water Sequencing

As explained in Chapter 1, sequencing outputs require both coordinating control ranges and coordinating normal position and control action. It is typically desirable for the outdoor air damper to be normally closed. In this way, the controller signal can be interlocked to the fan so that the damper will automatically shut when the fan is off. If the outdoor damper is normally closed, then the controller must be direct acting because, on a rise in supply air temperature, the output from the controller must also rise to bring in more outdoor air. The chilled water valve also must be normally closed because an increase in controller signal, which corresponds to an increase in the call for cooling, must cause the valve to open. The hot water valve then must be normally open.

For VAV systems such as this one, reheating of supply air will occur at the VAV boxes when zones require heat. To reduce this inefficiency, the supply air temperature set point may be reset. Various strategies have been used for reset control. The use of outdoor air temperature to reset supply air temperature is one of those strategies, used in this example.

This is shown graphically in [Figure 9-7](#). Below 55°F outdoor air temperature, the supply temperature is constant at 60°F. Above 65°F, the set point is fixed at 55°F. In between these outdoor air temperature limits, the supply air temperature set point varies linearly from 55°F to 60°F.

Reset of outdoor air temperature is usually a reliable strategy, as long as interior zones, those that may still require cooling even in cold weather, have been designed for the warmer supply air temperatures that can occur due to the reset schedule (in this case 60°F). Care should be exercised in deciding on resetting strategies, as sometimes this resetting process can cause more problems than it solves.

The operations staff of the building and the control designer should be aware that relative humidity is affected by decisions about temperature ([Harriman et al 2001](#)). Consider hot and humid climates, where almost constant dehumidification is necessary almost all year long; when there is a reset, in these climates it is important to also look at the load in the building, the inside and outside humidity and the inside and outside temperatures, before there is a reset. Indoor air quality can be compromised if proper indoor temperature and humidity are not constantly maintained.

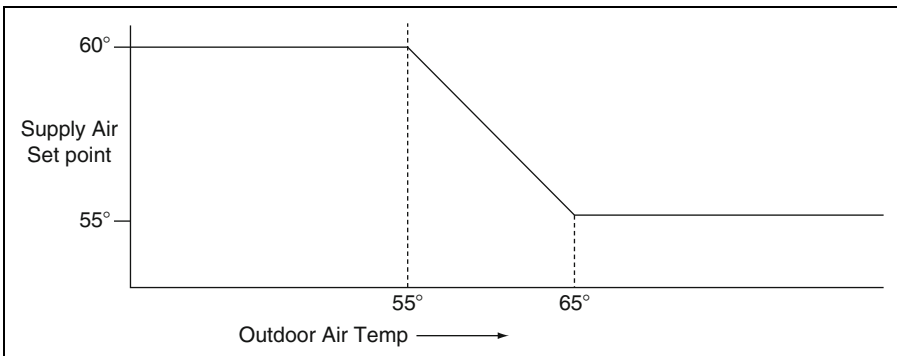


Figure 9-7 Reset Schedule

The above specification and discussion are written in narrative, descriptive language. Many organizations now use plain language – short simple sentences and bulleted items as the following example, which is modified from CtrlSpecBuilder.com. This system is similar to the variable volume system above with the addition of controlling the relief fan by building pressure compared to outside pressure and it has more alarms than we have previously considered.

Variable Air Volume – AHU – Sequence of Operations:

Run Conditions – Scheduled: The unit shall run based upon an operator adjustable schedule.

Freeze Protection: The unit shall shut down and generate an alarm upon receiving a freezestat status. Manual reset shall be required at operator panel.

High Static Pressure Shutdown: The unit shall shut down and generate an alarm upon receiving a high static pressure shutdown signal. Manual reset shall be required at operator panel.

Supply Air Smoke Detection: The unit shall shut down and generate an alarm upon receiving a supply air smoke detector status.

Supply Fan: The supply fan shall run anytime the unit is commanded to run, unless shutdown on safeties. To prevent short cycling, the supply fan shall have a user definable (1–10 min) minimum runtime.

Alarms shall be provided as follows:

- Supply Fan Failure: Commanded on, but the status is off.
- Supply Fan in Hand: Commanded off, but the status is on.

Supply Air Duct Static Pressure Control: The controller shall measure duct static pressure and modulate the supply fan VFD speed to maintain a duct static pressure set point. The speed shall not drop below 30% (adjustable).

- The initial duct static pressure set point shall be 1.5 in H₂O (adjustable).

Alarms shall be provided as follows:

- High Supply Air Static Pressure: If the supply air static pressure is above 2.0 in H₂O (adjustable).
- Low Supply Air Static Pressure: If the supply air static pressure is less than 1.0 in H₂O (adjustable).
- Supply Fan VFD Fault.

Return Fan: The return fan shall run whenever the supply fan runs. Alarms shall be provided as follows:

- Return Fan Failure: Commanded on, but the status is off.
- Return Fan in Hand: Commanded off, but the status is on.
- Return Fan VFD Fault.

Building Static Pressure Control: The controller shall measure building static pressure and modulate the return fan VFD speed to maintain a building static pressure set point of 0.05 in H₂O (adjustable) above outside pressure. The return fan VFD speed shall not drop below 30% (adjustable).

Alarms shall be provided as follows:

- High Building Static Pressure: If the building air static pressure is 0.1 in H₂O (in H₂O is inches of water, just the same as 'in wg' that we used earlier in the text) (adjustable).
- Low Building Static Pressure: If the building air static pressure is -0.05 in H₂O (adjustable).

Supply Air Temperature Set point - Optimized:

- The initial supply air temperature set point shall be 55°F (adjustable) when the outside temperature is above 65°F.
- As outside temperature drops from 65°F to 55°F, the set point shall incrementally reset up to 60°F (adjustable) and remain at 60°F for temperatures below 55°F.

Cooling Coil Valve: The controller shall measure the supply air temperature and modulate the cooling coil valve to maintain its cooling set point.

The cooling shall be enabled whenever:

- Outside air temperature is greater than 60°F (adjustable).
- AND the economizer (if present) is disabled or fully open.
- AND the supply fan status is on.
- AND the heating (if present) is not active.

The cooling coil valve shall open to 50% (adjustable) whenever the freezestat is on.

Alarms shall be provided as follows:

- High Supply Air Temp: If the supply air temperature is above 58°F (adjustable).

Heating Coil Valve: The controller shall measure the supply air temperature and modulate the heating coil valve to maintain its heating set point.

The heating shall be enabled whenever:

- Outside air temperature is less than 65°F (adjustable).
- AND the supply fan status is on.
- AND the cooling is not active.

The heating coil valve shall open whenever:

- Supply air temperature drops from 40 °F to 35 °F (adjustable).
- OR the freezestat is on.

Alarms shall be provided as follows:

- Low Supply Air Temp: If the supply air temperature is below 50°F (adjustable).

Cooling Coil Pump: The recirculation pump shall run whenever:

- The cooling coil valve is enabled.
- OR the freezestat is on.

Alarms shall be provided as follows:

- Cooling Coil Pump Failure: Commanded on, but the status is off.
- Cooling Coil Pump in Hand: Commanded off, but the status is on.

Economizer: The controller shall measure the mixed air temperature and modulate the economizer dampers in sequence to maintain a set point 2°F (adjustable) less than the supply air temperature set point. The outside air dampers shall maintain a minimum adjustable position of 20% (adjustable) open whenever occupied.

The economizer shall be enabled whenever:

- Outside air temperature is less than 65°F (adjustable).
- AND the outside air enthalpy is less than 22 Btu/lb (adjustable)
- AND the outside air temperature is less than the return air temperature.
- AND the outside air enthalpy is less than the return air enthalpy.
- AND the supply fan status is on.

The economizer shall close whenever:

- Mixed air temperature drops from 40°F to 35°F (adjustable)
- OR the freezestat is on.
- OR on loss of supply fan status.

The outside and exhaust air dampers shall close and the return air damper shall open when the unit is off.

Minimum Outside Air Ventilation: When in the occupied mode, the controller shall measure the outside airflow and modulate the outside air dampers to maintain the proper minimum outside air ventilation, overriding normal damper control. On dropping outside airflow, the controller shall modulate the outside air dampers open to maintain the outside airflow set point (adjustable).

Humidifier Control: The controller shall measure the return air humidity and modulate the humidifier to maintain a set point of 40% rh (adjustable). The humidifier shall be enabled whenever the supply fan status is on.

The humidifier shall turn off whenever:

- Supply air humidity rises above 90% rh.
- OR on loss of supply fan status.

Alarms shall be provided as follows:

- High Supply Air Humidity: If the supply air humidity is greater than 90% rh (adjustable).
- Low Supply Air Humidity: If the supply air humidity is less than 40% rh (adjustable).

Prefilter Differential Pressure Monitor: The controller shall monitor the differential pressure across the prefilter.

Alarms shall be provided as follows:

- Prefilter Change Required: Prefilter differential pressure exceeds a user definable limit (adjustable).

Final Filter Differential Pressure Monitor: The controller shall monitor the differential pressure across the final filter.

Alarms shall be provided as follows:

- Final Filter Change Required: Final filter differential pressure exceeds a user definable limit (adjustable).

Mixed Air Temperature: The controller shall monitor the mixed air temperature and use as required for economizer control (if present) or preheating control (if present).

Alarms shall be provided as follows:

- High Mixed Air Temp: If the mixed air temperature is greater than 90°F (adjustable).
- Low Mixed Air Temp: If the mixed air temperature is less than 45°F (adjustable).

Return Air Humidity: The controller shall monitor the return air humidity and use as required for economizer control (if present) or humidity control (if present).

Alarms shall be provided as follows:

- High Return Air Humidity: If the return air humidity is greater than 60% (adjustable).
- Low Return Air Humidity: If the return air humidity is less than 30% (adjustable).

Return Air Temperature: The controller shall monitor the return air temperature and use as required for set point control or economizer control (if present).

Alarms shall be provided as follows:

- High Return Air Temp: If the return air temperature is greater than 90°F (adjustable).
- Low Return Air Temp: If the return air temperature is less than 45°F (adjustable).

Supply Air Temperature: The controller shall monitor the supply air temperature.

Alarms shall be provided as follows:

- High Supply Air Temp: If the supply air temperature is greater than 60°F (adjustable).
- Low Supply Air Temp: If the supply air temperature is less than 45°F (adjustable).

Of particular note in this plain language specification is the use of AND and OR logic, Boolean logic:

The economizer shall be enabled whenever:

- Outside air temperature is less than 65°F (adjustable).
- AND the outside air enthalpy is less than 22 Btu/lb (adjustable)
- AND the outside air temperature is less than the return air temperature.
- AND the outside air enthalpy is less than the return air enthalpy.
- AND the supply fan status is on.

The economizer shall close whenever:

- Mixed air temperature drops from 40°F to 35°F (adjustable)
- OR the freezestat is on.
- OR on loss of supply fan status.

This style of presentation is very clear and easy to follow, particularly where many control choices are being made.

CtrlSpecBuilder.com is a website providing noncopyright specifications and drawings for common equipment based on direct digital controls. You can use it as a base for either DDC or non-DDC controls. Let us now return to the descriptive style and move from the VAV supply system to the VAV box. [Figure 9-8](#) shows a control sequence for a VAV box, with a detailed discussion of the philosophy behind each item.

- VAV boxes. Room temperature shall be controlled by modulating the air volume damper and the reheat valve, or electric heater, in sequence as indicated in the [Figure 9-8](#). Volume shall be controlled using a pressure-independent controller. The maximum and minimum cooling volume, as well as a heating minimum, shall be as indicated on equipment schedules. For units with electric heat, care should be taken to specify an air-proof switch (so the heater cannot come on without airflow to avoid overheating),

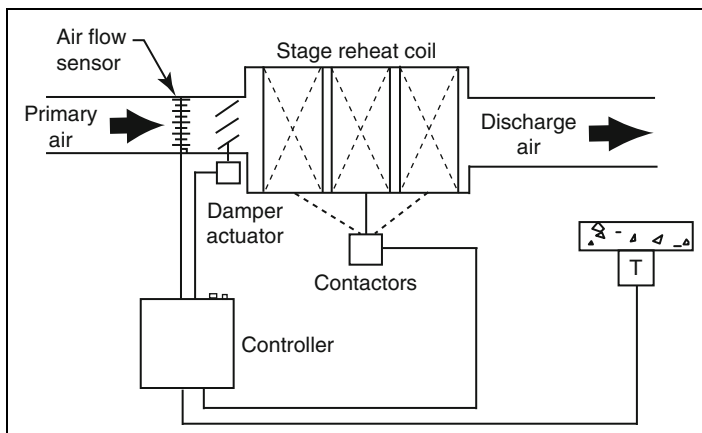


Figure 9-8 VAV Box Control Diagram

as well as thermal protection at the electric heater, so that potential fire conditions can be avoided. Power for the control system may be wired via a low voltage transformer attached to the electric heater, or, in the case of hot water heat, the power would be provided externally. This sequence references pressure-independent control.

Early “pressure-dependant” VAV systems simply used a damper mounted in the ductwork that was directly controlled by the space thermostat. As space temperature increased, the VAV damper opened. As the temperature in the space fell, the VAV damper closed until at zero loads (when the thermostat was satisfied) the VAV box would shut completely, with some (and sometimes, significant) leakage. If a minimum flow was required, the damper could be linked so that it would not close all the way to shut-off.

This type of control is called pressure-dependent because the amount of air supplied to the space is a function of the pressure in the supply air system, not just of the thermostat signal. A change in system pressure could cause the supply air to the space to change, and velocities to increase, possibly causing noise and overcooling or under cooling the space before the thermostat is able to compensate. This change in supply air pressure could be caused by the opening and closing of VAV boxes in the system causing severe airflow fluctuation.

This pressure-dependant control is rarely used as it has caused so many problems in the larger systems. In some smaller systems, where noise, accuracy, ventilation effectiveness, and comfort are not as important, it is still used occasionally. The first cost is typically much more economical than pressure-independent systems.

To overcome this problem, pressure independent controls were developed. These controls use two cascading control loops, meaning the control loops are chained together with the output of one establishing the set point of the other. The first loop (the space thermostat) controls space temperature. The output from this loop is fed to the second controller as the reset signal, setting the airflow set point required to cool the space. The set point range can be limited to both a minimum (cool and heat) and maximum airflow rate. The second controller modulates the VAV damper to maintain the air volume at this set point.

Air volume, velocity times its fixed duct area (CFM), is measured using a velocity pressure averaging and amplifying sensor that often has fairly sophisticated configurations (such as rings or crosses), so that accurate measurements of air velocity can be made even if inlet duct configurations are not ideal and even when flows are low. (See the ASHRAE Handbooks for more information on this subject.) Its operation is ‘independent’ of the changing supply duct pressure, although it still requires an acceptable range of duct static pressure in order to operate normally, usually 1–2 in of water column pressure.

The availability of the maximum volume limit is very useful during system balancing. The VAV box can be set to maintain the design air flow rate to the zone while the balancer adjusts manual volume dampers to achieve the desired distribution of air among the rooms served by the zone. The maximum volume limiter is also useful in preventing excess supply that can be noisy and objectionable. This might occur during early morning operation when spaces are warm and require greater than design airflow to cool down.

The capability to limit minimum volume is important to ensure that adequate airflow is provided to maintain minimum ventilation rates for acceptable indoor air quality. The thermal loads in the space (which dictate the

amount of air supplied by the VAV box) are not always in synch with the ventilation requirements, which are a function of occupancy and the emission rates of people, pollutants from furnishings and office equipment.

The minimum volume control can be used to ensure that sufficient supply air is provided regardless of thermal load; this also promotes and maintains proper building pressurization as long as the exhaust and ventilation operation (and volumes) are coordinated into the control system as well. Pressure-independent box controls are preferred over pressure-dependant for many reasons, including both minimum and maximum flow rates can be controlled regardless of duct pressure, and flow rates are a function of available duct pressure.

Minimum volume control is also essential for reheat boxes (where used to provide space temperature or heating), which must be able to maintain a minimum flow and temperature to effectively heat the space. Reheat boxes behave like cooling-only boxes when the space is warm. As the space cools, the air volume slows to its minimum amount, and while maintaining minimum volume the air is reheated.

The reheat box function is also used to heat the cold air flowing into the room when the room thermostat is calling for heat. The volume cannot be too low or the air supplied will be too warm and buoyant, and will not mix well with the air in the space, resulting in discomfort and possibly inadequate ventilation in the occupied zone.

Remember the supply air from the VAV fan system is cool so, before any useful heating can take place, the air must first be reheated up to the space temperature to provide heating. Some VAV box controllers have the ability to control to dual minimum set points: one during cooling operation to maintain minimum ventilation rates, and a higher set point during peak heating operation.

Some control systems allow the supply air to be reset based on the return air from the spaces so that energy can be conserved during intermediate temperature and low-humidity conditions. Other triggers include a change in the heating water temperature, or outside air temperature. Some VAV controls have a discharge air temperature controller/sensor at its exit so that under-cooling and over-heating can be avoided. These discharge temperatures can also be used to reset the discharge air temperature control back at the AHU, and are excellent information for troubleshooting temperature complaints of the occupants.

Typical Constant Air Volume System, with Variable Speed Fan for Filter Loading

A variation of the VAV delivery system described in the last few pages is the constant air volume system that uses variable speed fans to account for increasing pressure drop across the filters as they load up with dirt. This form of control is used in healthcare buildings, laboratories and clean rooms, as the amount of air delivered to the space must be constant, so that precise building pressurization can be maintained. The air delivery to the space may still be thru VAV boxes, but the VAV boxes are used as constant air volume (CAV) boxes, with the maximum and minimum volumes set at the same value. The supply air feeding the boxes is again typically 55°F. In some operating suites, the supply air can be as low as 48°F. Normally, the CAV box will have some type of reheat: either hot water or electric. The thermostat and/or humidistat for the room will control the reheat, and maintain its room temperature set point.

Care should be taken to make sure there is enough reheat energy available at each CAV box to perform its job, and that the supply air temperature does

not get too cold for the application. In retrofit jobs, a common mistake is to reuse existing reheat devices that have inadequate capacity to supply the proper amount of reheat. This is especially true if a new, colder, supply air temperature is being utilized. The CAV box controller has its minimum and maximum set point as the same value, so it modulates in order to maintain its airflow set point.

Back at the air handler unit, the variable speed drives, or vanes, on the supply fan modulate to maintain the static pressure set point in the supply duct. As the filters load up their resistance increases, the VFDs modulate the fan speed higher to overcome the added resistance of the filter, maintaining a constant static pressure in the ductwork, as sensed by its supply duct static pressure sensor, typically $\frac{2}{3}$ to $\frac{3}{4}$ of the distance from the fan to the end of the duct.

Now, over to the return and outside air ducts. In this example the exhaust fans are separate and they are in the space operating stand-alone, interlocked to the AHU, and constant speed. (Note that if this exhaust fan is serving washrooms Using [Figure 9-9](#) as a guide drawing, there needs to be a specific amount of outside air flowing into the AHU while the unit is on. There are many methods that good designers can come up with to achieve this ([Chen & Demster 1996](#))).

First, measure and monitor the outside airflow into the AHU. Install an airflow-measuring device in the outside air ductwork to measure this flow. Flow is the (average) speed of the air times its (flow) area, so there needs to be a high enough velocity of air so that the velocity pressure sensor is accurate, and locate the sensor in a place where there is good nonturbulent flow. Place the VFD and fan in the return duct and put a static pressure sensor into the mixed air plenum. With the all return and outside duct dampers open, and the supply fan running at its supply duct pressure set point, the outside air flow is tested, adjusted and balanced into the unit using the return fan VSD modulating to a mixed air plenum static pressure.

The engineering economics concept here is clear; with all of the dampers open, the fan is not wasting energy trying to overcome damper pressure drop; and therefore there are energy savings with the use of the VSD over the traditional damper modulation. Now, once the proper ventilation outside airflow is reached, that mixed air plenum pressure becomes the set point for the return fan VSD to maintain, and the supply fan VSD modulates to maintain its set point and that will change the mixed plenum pressure and cause the

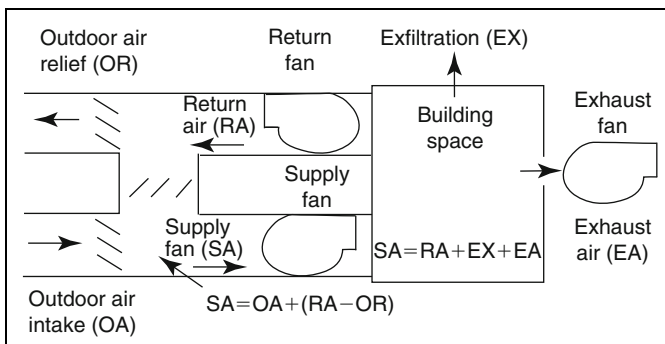


Figure 9-9 Schematic showing SA, RA, and EA Relationships

return fan to track it. There is an OA monitor in the duct that can monitor and record the measured OA flow, and its damper could be made automatic over a small range in order to make small adjustments. If further monitoring of OA effectiveness is desired, a CO₂ sensor in the return air duct can be used to monitor its value and record its trend. For operating suites and clean rooms, it may be desirable to have room pressurization sensors in the space as well, in order to monitor pressurization effectiveness.

Chiller Plant, Pumps, and Boilers – Monitoring and Control

Chiller and boiler plant control systems consist of controllers, sensors, relays, transducers, valves, and dampers that operate the plant and its equipment, as well as optimize it for energy conservation, efficiency, and functionality.

On a demand for cooling, the chilled water system shall be enabled. First the chillers respective chilled water primary pump may be energized and then the chillers respective condenser water pump (or condenser fan system) may be energized, then, several minutes later, after flow is proven at the pumps/fans/chiller, the respective chiller shall be enabled to operate and produce chilled water to the HVAC&R system. The internal controls of the chiller shall operate each chiller to produce the required chilled water supply temperature. The control system shall monitor the common supply and return temperatures and provide a constant common supply water temperature, typically 40°F (adjustable).

If the chiller plant has cooling towers as a source of condenser heat rejection, then the condenser water supply temperature shall be controlled to optimize the plant energy use (check with chiller manufacturer for recommended set point values and allowable drop in temperature at times of low enthalpy outside air) by staging the cooling towers as necessary and cycling the cooling tower fans as required. If cooling tower fans are controlled using variable speed drives, then their speed can be varied in order to meet the demand. Deadbands and time limits shall be set up such that the fans do not cycle unnecessarily.

Some cooling tower plants have a bypass loop and internal sumps that allows bypassing of water around the towers in order to maintain minimum set points during cold and below freezing ambient conditions.

On a call for heating, the plant control system shall start the boiler primary pump, and then the boiler shall be started–stopped. The boiler primary pump shall be operated at least 10 min before and after boiler is energized. A high limit temperature sensor will operate the circulating pumps until the boiler internal temperature is at or below its set point. The boiler discharge temperature control is integral to the boiler and is provided by the manufacturer. If multiple boilers are used, a control routine that starts and stops them is used to maintain an adjustable set point temperature of water in the loop or storage tank while maintaining an appropriate return water temperature. In addition, some boiler plant controllers monitor outside temperature, and provide higher hot water supply temperature set points to be available during extreme cold ambient conditions.

Primary pumping systems are used frequently and are described above. In some designs, secondary pumps are used. Secondary pumps receive their water flow from the primary loop usually via a coupling “header” as shown in [Figure 9-10](#).

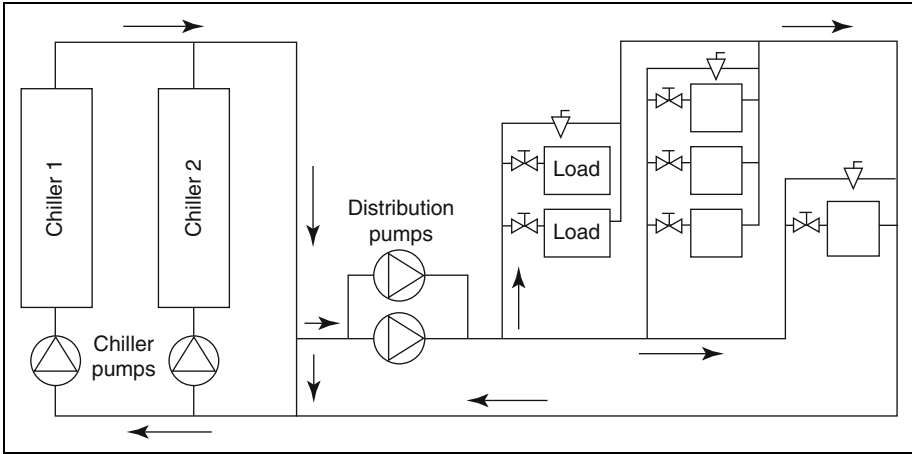


Figure 9-10 Primary Secondary Pumping System

The primary loop (chillers and pumps) provides the “header” with a constant flow of chilled water. The secondary loop, via its secondary distribution pumping system, takes water from the primary loop as needed for the hydronic systems it serves. The secondary pumps may be controlled in order to provide adequate flow to the secondary piping loop, using a water pressure or flow sensor. They can be constant speed pumps with a bypass arrangement, or the motor speed can be controlled by a variable speed drive, less energy waste. Control valves are typically two-way when variable flow secondary control systems are used.

Secondary pumps, as with any dual equipment scenarios, shall be rotated from lead to lag typically on a daily basis. When a failure is sensed, the lag (or redundant backup) pump can automatically take over.

A flow meter and appropriate temperature sensors, in the secondary loop, can be used to monitor its flow readings and calculate energy usage. Flow meters can be used to monitor make-up water flows in order to trend water usage and identify potential leaks.

When the outside air temperature is above/below an appropriate temperature (adjustable), the chiller/boiler plant may be disabled/enabled. An override feature that will override this outside temperature shutdown should be installed and available.

For maintenance or out-of-service times, the control system will sense the abnormal off and/or alarm condition of a chiller, boiler, fan or pump and bring on its next in series in order to maintain its set points. All alarms should be monitored by an alarm providing visible or audible alarm.

Temperature and Humidity Monitoring and Control

The use of temperature/humidity monitoring and control devices is very important in today’s design of HVAC systems. Whenever possible, the use of both is desirable. When the humidity drops too low in the space, a humidifier is switched on in order to add a spray of steam, or atomized water, into the airstream in order to add water vapor and increase the relative humidity.

During periods of high humidity, the control system typically activates the cooling systems in order to cool the airstream below its dewpoint temperature so that the water vapor will condense on the cooling coil and be removed by the drain pan. Further dehumidification and adjustment of the relative humidity downwards can be obtained by reheating the cold airstream with some acceptable heat source, such as hot gas reheat, recovered heat, heat load of the building, lights, energy wheel, face and bypass, etc. (see ASHRAE Standard 90 for more information).

It is advisable to limit cycling of the cooling coil. Too much cycling of the cooling coil will not allow enough time for the condensate to drain from the coil, resulting in the condensate entraining itself back into the air stream of the supply ductwork, causing energy waste and potentially, IAQ problems.

Continuous monitoring, and recording, of temperature and humidity can be very useful when it comes to resolving problems and detecting poor performance.

Carbon Dioxide Control

In ordinary outside air, it is generally found that the carbon dioxide, CO_2 , concentration is 350–450 parts per million (ppm), this is called the “background” CO_2 level. In city areas with high traffic volumes the level may be substantially higher. People breathe, inhaling air and absorbing oxygen and exhaling CO_2 . The rate of carbon dioxide production depends on activity level and is quite consistent in the population. The higher the activity level the greater the CO_2 production.

A person in an enclosed space with no ventilation would continuously add to the CO_2 level. If ventilation is provided then, after a while, there will be a balance:

Background level in > Addition from person to raise concentration > Higher Concentration out

The process is shown in [Figure 9-11](#). Note that the process is the same for one or many people with more than one person producing proportionally more CO_2 and needing proportionally more ventilation. For the ASHRAE Standard 62.1, default ventilation rate in an office is 17 cfm. The increase in concentration is about 620 ppm. If the background level was 350 ppm then the steady concentration in the office would be $350 + 620 = 970$ ppm. In the



Figure 9-11 Ventilation Air Collecting CO_2 from Occupants

case of a fully occupied auditorium, the ASHRAE Standard 62.1 default ventilation rate is 5 cfm and the increase in concentration is 2100 ppm providing a steady state level of $350 + 2100 = 2450$ ppm.

Note that the added concentration increases in proportion to the number of people for a fixed ventilation rate. Thus halving the population density in an office will result in the added CO₂ concentration dropping from +620 ppm to +310 ppm. Similarly, an increase in ventilation rate for the same occupancy will proportionally drop the added CO₂. For example, increasing the office rate from 17 cfm to 20 cfm per person will drop the rate to $+620 \times 17/20 = +527$ ppm.

This increase in CO₂ concentration can be used to control the ventilation rate. In the high population density auditorium situation, the level of CO₂ can be used as a surrogate (equivalent to) for occupant numbers and the ventilation rate adjusted to maintain a maximum CO₂ concentration. In the lower density office situation Standard 62.1 requires a ventilation rate significantly based on area per occupant and using CO₂ is more complex than we are covering in this course.

More detailed discussions and requirements can be found in ASHRAE Standard 62-2004 and ASTM Standard D6245.

Exhaust Fan Control

Exhaust fan controls are often thermostats or interlock relays specified with little thought as to when they are needed to operate. A typical example is the electrical room provided with a manually set thermostat with a range of 60–80°F. It gets set at 60°F and the fan runs continuously for the life of the building wasting energy.

Just as for the main system, you should be establishing what service is required. This may mean simply linking the exhaust fan in with the main system. However, for any system that operates out of occupied hours to maintain temperature or humidity the exhaust fan operation is probably not required.

The designer should provide a schedule showing each exhaust fan, its specified design parameters, and its intended control and interlock methodology. Care should be taken to ensure that these exhaust fans do not operate when the main HVAC systems are off, unless needed, as this can cause negative pressurization and cause unconditioned outside air to enter the building and cause IAQ problems. Where used for conditioning equipment rooms, a room thermostat should be used to turn the fan on and off to maintain its exposed temperature set point. In storage rooms, where sensitive materials are being stored, a thermostat and humidistat may be used in order to operate the exhaust fans and supplemental dehumidification/humidification equipment to maintain the space temperature and humidity requirements.

Toilet exhaust fans are usually interlocked to their respective HVAC system and its OA damper operation; sometimes the toilet exhaust is supplementally interlocked to a light switch. In garages and spaces where hazardous or toxic gases/fumes can gather, exhaust fans are operated continuously, or can be controlled by a high limit gas/fume-sensor/controller. For chiller plants where refrigerants are used, refrigerant gas monitors are set up to operate exhaust fans and/or open dampers/doors when their set points are exceeded.

In boiler rooms, exhaust and supply fans can be used in conjunction for exhaust of fumes and to also provide combustion air for the boilers.

For medical isolation rooms where harmful bacteria or germs etc., may exist, exhaust fan systems, coordinated with supply fan systems, are set up to maintain their individual room pressurization set points, either negative or positive, and should have a room pressurization monitor and alarm panel installed in each room. Visual and audible alarms should be initiated when set points are violated, and when the fans fail. In a lot of cases, depending on what the intended use of the room is, these exhaust fans may not be switched off for any reason, including fire alarm initiation. Isolation room fan sizing and controls should allow for controlling the pressure in the isolation room in situations when the ambient pressure changes, such as during strong storms such as hurricanes or tornados.

For flammable storage and/or explosion-proof areas, where the fumes are typically more dangerous and flammable than normal building exhaust, they are typically controlled using an “explosion-proof” or “nonspark producing” control device. The controls are typically constantly working and respond automatically to their temperature and gas/fume concentration set points by staging the exhaust fans on and off. In addition, visual and audible alarms should be initiated when crucial or safety set points are exceeded, and/or when the fans fail.

In almost all cases, exhaust fans need to be specified to be interlocked with the building fire alarm system to meet all local, state and national codes. Typically, all fans are stopped when the fire alarm system is in alarm, with the exception of engineered smoke control fans and some isolation room fans.

Fume Hood Control

Fume hoods are typically used in laboratories to collect and exhaust fumes. The cross-section of a hood in [Figure 9-12](#) has a vertical sash which can be raised and lowered as necessary. The horizontal air velocity into the hood is, typically, maintained at a constant velocity of 80–100 fpm whatever the sash height.

When the hoods are not operating, the room control is much the same as a normal occupancy for a variable air volume controlled room. When the hoods are operating, the control system senses the flows and pressures in the room, hoods, and ducts in and out, and makes adjustments to maintain the temperature, humidity, and pressurization of the room. The objectives for control in laboratory hoods are for the capture and containment of fumes and harmful gases, to maintain acceptable room pressurization, to maintain acceptable temperature and humidity set points, and to ventilate the space in order to preserve dilution of contaminants. Many conditions can affect performance and speed of response from the control system. There are great cost differences between desired levels of control for these systems; the designer needs to know and account for the accuracy and reliability of controls required for the process.

Variable air volume air handling systems are often employed in modern laboratory and hood systems. A fast and stable control system for the hoods, exhaust fans, supply fans, and all HVAC equipment is suggested. The airflows required are determined by the highest demand of the minimum

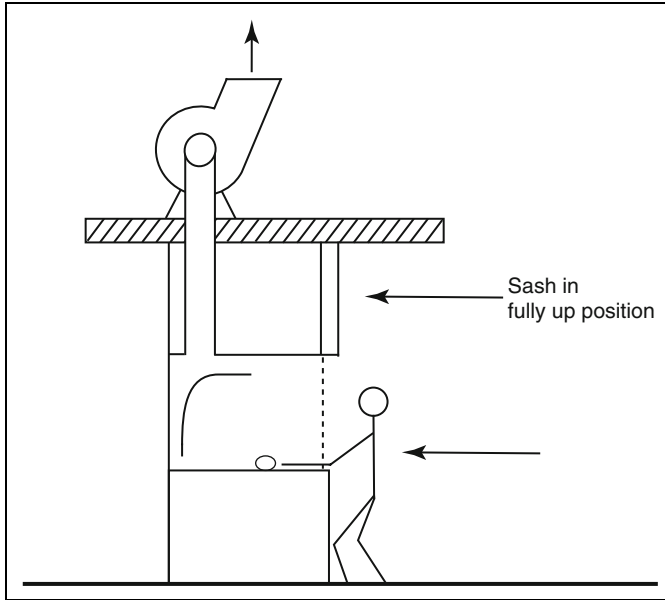


Figure 9-12 Rising Sash Fume Hood

ventilation rates prescribed, the cooling or heating loads required, and the total amount of exhaust from the hoods themselves. The airflow in and out of the room is controlled to meet these needs. Sometimes, the airflow required is below the amount needed to cool or heat the room to its comfort settings; therefore, the room supply air must be increased to meet the load. The lab control system must react to exhaust additional air through a “general exhaust” damper or air valve to compensate and maintain room pressurization and hood equilibrium.

Typically, the room is kept at a slight negative with respect to its adjacent corridors. Controlling the total supply air to be a little less than the total exhaust is what performs this. There are, however, situations where a positive pressure laboratory is required based on the type of experimentation being done.

Now as the hood sash opens and closes, the hood’s exhaust volumetric flow is varied as a linear function of the sash opening percentage (which is an indication of the hood face velocity). Typically, there is a minimum flow that takes precedence when the sash is below 20% open. This relationship between the maximum and minimum flows is called the turndown ratio; for example if the maximum flow is 500 cfm and the minimum is 100 cfm, and the supply air is offset by 100 cfm, then the turndown ratio required is 400:100 cfm, or 4:1. This maintains a constant face velocity into the opening of the hood. A constant face velocity is a key element in successful hood control. Typical set points of acceptable face velocities range from 60 to 120 fpm. A maximum of plus/minus 5% set point control should be maintained at all times. Unstable or excess velocities can cause adverse effects, such as loss of containment, turbulence, eddy currents, glass breakage, blow out of heat candles, and leakage from the hood. The control system should have less than 1s response timings.

There has been much research on control design and implementation. Many other factors such as occupancy in the fume hood areas, usage of the hood, cross drafts, sash positions, operator position, diversity of conditions, and placement of instrumentation, as well as temperature and humidity have a dramatic effect on some aspects of its ultimate control need for sophistication.

Condensate Management and Control

One source of microbial growth is improperly installed and nonfunctional condensate removal from cooling coil drip pans. Controls include drain pan float switches that shut down the fans and/or cooling systems when they sense an overfull drain pan. There are pipe sensors that fit in the condensate piping that sense a 'too wet' or 'too dry' condition, and stop their systems as well as provide alarming that can provide early detection of problems. To detect and alarm carryover in coils, a moisture sensor can be placed in the ductwork downstream of the cooling coil or humidifier to detect its alarm condition. Provide monitoring of the drain pan overflow and alarm the controller when tripped. To stop the condensate, stop the fan, or stop the DX cooling or close the cooling valve. If available, provide a sensor in the condensate pipe exit point so that it can sense the "lack" of moisture removal, which can predict that there is a problem with coil operation or at the drain pan.

Ventilation Monitoring and Control

The accurate and proper monitoring and control of ventilation into the system and into the occupied spaces of the building is very important and at the center of today's most urgent issues in HVAC controls and instrumentation. There are many ways to control the outside air entering the system, and the most successful is the direct monitoring with an airflow-monitoring device. A velocity-sensing probe is installed in the outside air duct. Depending on the size, and arrangement, of the duct, air-straightening vanes may be necessary. Follow the manufacturers' recommendations on mounting, but in general they need to be installed in a piece of duct with at least five diameters of straight length. The more tubes used, the more accurate and dependable the measurement. In general, one sensing tube per 2 ft² of duct is a rule of thumb. The velocity needs to be sufficient to create a readable and reliable differential pressure across the velocity tube, so in many cases the OA duct is downsized. This velocity tube reading is then multiplied by the area of the duct to get airflow in cubic feet per minute (cfm). The designer sets the amount of ventilation airflow in accordance with the local Code, current ASHRAE Standard 62.1, experience, expertise, and her/his best judgment. The airflow is monitored and controlled to this set point by modulating dampers, a fan, a variable speed fan motor, vanes, etc. Some means of documentation should be kept of these ventilation airflows in a permanent record.

Now that the proper amount of ventilation is being delivered to the supply fan, it needs to be delivered to the spaces in a proportional, appropriate and effective manner.

Filtration Monitoring and Control

Digital or analog differential pressure sensors, mounted across each filter bank, should monitor filter loading. When the differential pressure high limit is exceeded, a visual and audible alarm should be initiated. On medical systems, duct mounted visual exposed "Magnehelic™" differential pressure gauges, visible, with set point markings may be required. In some cases where the filters are concealed, a visible alarm light is required to signal dirty and ineffective filters. The manufacturer should provide the maximum dirty filter resistance and the alarm set point should be specified. For example, the filter resistance alarm set point might be 80% of the manufacturers' stated final resistance.

Outside Air Monitoring and Control

In some areas, the quality of the outside air is sometimes not acceptable. Sensors that can detect levels of gases such as carbon monoxide, sulfur dioxide, ammonia, acetylene, methane, propane, benzene, formaldehyde, hydrocarbons, HFC-CFCs, etc., are employed and installed in the intakes, ducts and spaces to provide protection against the introduction of sources of contamination such as garbage containers, gas sources, sewage, bird nesting areas, standing water, pesticides, cooling towers, etc. Typically, if the outside air is not acceptable, the control system can sense it with sensor devices, provide visual and audible alarms, and shut down the ventilation control fans and dampers for that period of time. You should consult the latest edition and addenda for ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, for specific requirements.

DX – Direct Expansion Systems

Some areas use DX (direct expansion) HVAC systems in their buildings. These systems use refrigerants and reciprocating, scroll and/or screw compressors to produce the cooling. The controls for these DX systems consist of manufacturer-provided unit controls which are installed and wired at the factory to operate the internal components, and there are building control devices that are field installed and wired to control the area of the building for space temperature and humidity. Sometimes they are all packaged into one large piece of equipment, called "package units" or "through the wall units", or sometimes the fan and airside equipment is separate from the compressor and condenser equipment, and this is called a "split system".

Control of the DX equipment is very similar to any other unit, but there is a potential for much colder coil temperatures since the refrigerants being used are being "directly" exposed to the airstream at the cooling coil. These refrigerants are interacting with the airstreams at very low temperatures, as low as 0–20°F. This means that the speed of response is much faster than for chilled water, and the potential for "freezing up" the coil is great.

First, the designer must establish an almost constant airflow and load across that cooling coil. It is not advisable to have variable flow across DX coils, unless approved by the manufacturer, as this could cause freezing. If reduced airflow to the space is needed, a bypass duct is used and supply air is routed to the return so that the airflow across the coil is constant. As the load

changes, unloading devices and control schemes are used that have a sufficiently low minimum capacity. This will allow the unit controls to match and control to the changing load conditions.

When possible, specify a form of recoverable or waste heat for the unit, such as hot gas bypass/reheat, so that the controls can adjust the temperature and relative humidity of the leaving air stream. Sometimes this hot gas is also used to heat the potable water for a building.

Controls can be mounted in the control panel on the wall of the mechanical room or inside the units. The controller should control the stages of DX cooling in order to maintain the discharge air temperature at set point, using the stages of cooling and hot gas bypass/reheat where possible. The response of the DX cooling effect is very fast, and unloading and multiple staging controls is necessary to effectively stage the effect. The staging should also have a time delay between starts, so once a stage is turned completely off, it is typically not turned back on for 3–5 min. The supply air temperature set point that we are staging to maintain can have some resets embedded inside it, such as being adjusted by the return or outside air temperature.

For cold climates, a heating coil in the pre-heat position may be specified to protect the chilled water coils from freezing in the winter. Alternatively, the coils must be drained and dried or filled with antifreeze. For hot and humid climates, a reheating coil after the cooling coil may be required to provide reheat after the reduced air delivery required to produce dehumidification effects.

Water Source Heat Pumps

A very popular and effective design involves water source heat pumps. A supply of water is continuously pumped around the building with DX units connected to it, as shown in *Figure 9-13*. Each DX unit has the ability to pump heat out of the water and into the zone or to cool the space and reject heat to the circulating water. The system is particularly attractive in buildings with high internal cooling loads and perimeter heating loads. The system enables the excess heat in some areas to be used in cool areas needing heating, load transfer. The DX units operate as above, but their source of energy for heat and cool rejection is water, not the ambient air. The efficiency and capacity of the heat pump is greatly enhanced since it is not restricted by extreme ambient conditions. This circulating water source is typically maintained between 60 and 90°F year round, depending on the environmental and design conditions.

The pipe loop is typically connected to a boiler for heat when needed and a heat rejection evaporative cooling unit or chiller. The source of water for heating and cooling may also come from a lake, or a geothermal well/bore and pump system. Certainly, proper water treatment control is required for each of these scenarios. The evaporative cooler/cooling tower fans are controlled to maintain the water temperature set point as required. Variable speed fans are frequently used to save energy and improve control performance by modulating the speed of the cooling tower fans to maintain the condenser water temperature set point of the condenser water. A tower bypass valve can also be modulated in order to bypass water around the tower to mix return water with its supply water to maintain the condenser water temperature set point.

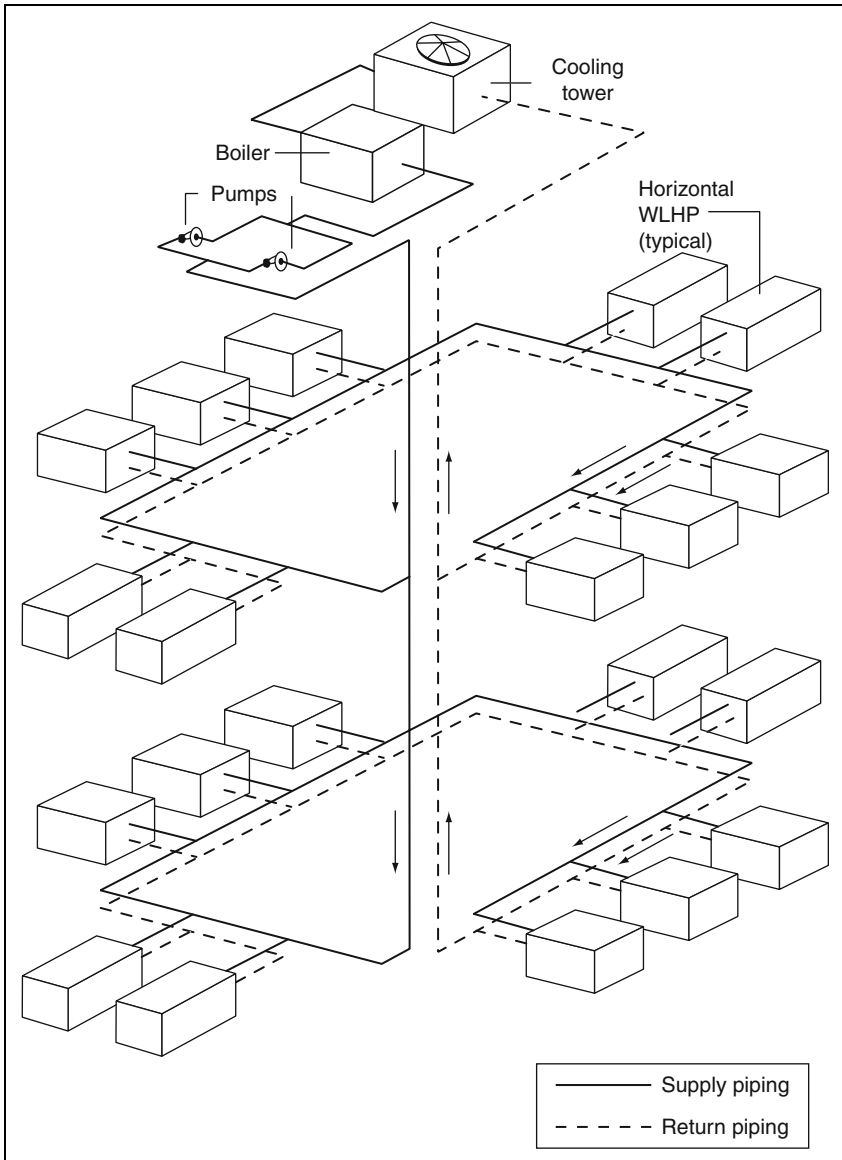


Figure 9-13 Heat Recovery System Using Water-to-Air Heat Pumps in a Closed Loop

In mild climates, a tower sump water heater may be cycled in order to temper the condenser water during cold ambient conditions to prevent basin freezing. In colder climates the cooling tower drains to an indoor sump avoiding the heater energy use and reduced reliability of depending on a heater to prevent freezeup.

Each heat pump unit can have a water valve that opens and closes upon operation of the unit. The water valve should be normally open and fail-safe

(open to the coil) if possible. If a water valve is not used, then the water flows through the coil at all times. The pumping system is typically variable speed and provides enough water to the heat pumps as required by a water pressure sensor and control algorithm. If there is variable flow, then a two-way control valve should be used (if variable flow is not used, then three-way valves are required). A water pressure sensor at/near the end of the piping loop is provided to control the pump and maintain its pressure set point.

If the loop water temperature rises above or below its alarm set point, a visible and audible alarm shall be initiated, and the heat pumps affected should be stopped until the alarm is resolved. Back up and redundant equipment is suggested to be available to control any major parts of the HVAC&R system, such as pumps, tower fans, heat exchangers, back-up electric heat, etc.

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