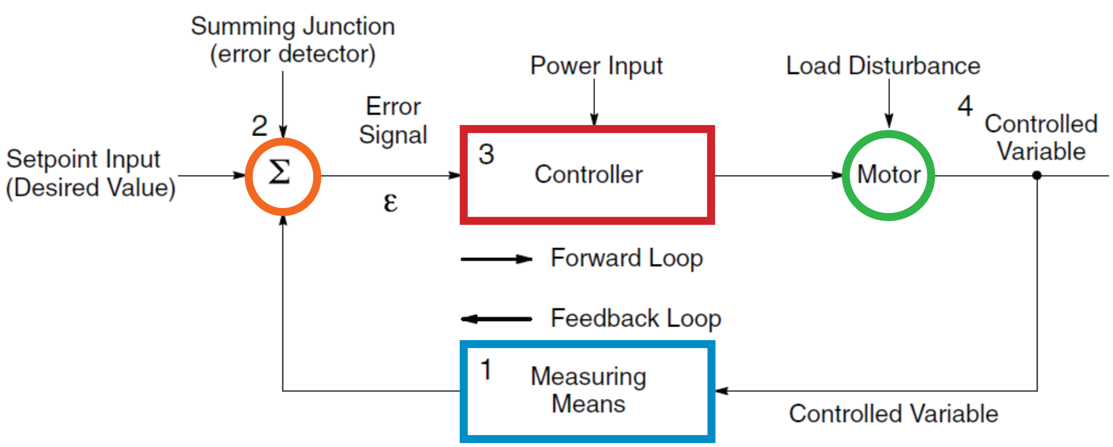
BOOK 3 Classroom Basics

Understanding Process Control



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INTRODUCTION

Upon completion of this book, the student will have a good understanding of the important issues of process control as it relates to centrifugal pumping, including; Variable Frequency Drive Operation, Open and Closed Loop Systems, Feedback Loop , Proportional, Integral and Derivative Algorithm and Gain. This knowledge will serve as the foundation for learning to effectively use centrifugal pumping in liquid process scenarios.

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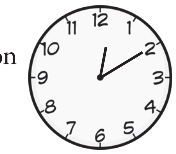

Lesson 1: Define Process Control

Student will be introduced to what process control is, why it is important, and how it is accomplished.

Process control is the ability to manipulate or control an operation on a consistent basis to produce reliable desired outcomes. In pumping, this means controlling a pump to produce desired flow and/or pressure results in the system in which it is operating. This usually means the system environment offers "feedback" information to the pump so that it can automatically adjust how it runs in order to properly meet the situation requirements.

Process control is extensively used in industry and enables mass production of continuous processes such as oil refining, paper manufacturing, chemical formulation, electric power production and many other industries. Process control enables automation which allows a small staff of operating personnel to operate a complex process from a central control room.

Centrifugal pumps are used extensively in industry to direct the flow of fluids for countless processes. Controlling and integrating this flow is now typically handled by a programmable Variable Frequency Drive (VFD). VFDs can be programmed to control the speed of the electric motor driving the pump, essentially making it a variable speed unit to meet very particular pumping needs. It also can be part of a larger control scheme where many pumps are controlled and scheduled automatically to produce a desired final result. Feedback Loops are a part of process control that provide information to the VFD regarding adjustments that need to be made to the pump speed to enable it to maintain the desired end result.

Let's start with a simple operation that illustrates developing process control.

Focus 1: Watering the Lawn

Figure 1.1: Watering the Lawn

You move to a new house with a dry-looking lawn. You decide to water it by connecting a hose to your water supply, turning it on and hand spraying it by walking around the property. The next day you do it again. Since you have better things to do than spend your time walking around the lawn, you add an oscillating lawn sprinkler to the end of the hose and set an alarm for yourself to move it every half hour. Notice that you are establishing a "process" and "controlling" it to accomplishing the "result" of watering the lawn. Each day the lawn needs water, so you repeat this process. Finally, you tire of this "monitor and move" operation, so you have a sprinkler system installed which covers your whole lawn. The system has a control on it so you can set the time of day you want the sprinkler to come on and how long it should run. Your process is now perfectly automated to come on at a pre-set time and water the lawn for a fixed amount of time.

You are very pleased with yourself until later that week you notice your lawn sprinkler is on during a driving rainstorm. Ouch! The process wasn't getting any "feedback" that it wasn't needed, so it came on as scheduled. That's when you decide to install a moisture sensor on your lawn that is connected to your sprinkler. If the moisture level of the lawn was reading high enough, it signaled the sprinkler not to launch during the programmed launch time. It also sensed when the moisture level was high enough during sprinkling to shut the sprinkler system off early. Now you have a "process" that is "controlled" automatically with proper "feedback", which accomplishes the mission of watering the lawn in a reliable, convenient, repeatable and cost effective manner.

Pumps can be operated in a similar fashion; from basic manual control at constant speed, all the way to fully automatic control using a variable speed controller tied to some sort of system "feedback loop". A pump driven by an electric motor can be controlled by a variable frequency drive. Why is this important? It offers greatly improved fluid processing control while using the electricity to drive it much more efficiently. These two factors improve the end use result while saving substantially on energy. Let's find out how this happens. The following lessons will introduce topics that build toward better understanding of pumping process control.

Skill Builder

Lesson 1, Focus 1

You install a yard light that is activated by a manual switch. You decide to put it on an automatic timer so that is comes on and goes off at prescribed times. As the seasons change, it gets darker earlier and stays darker later resulting in times where the field is too dark to use. What sort of "feedback" from your environment would help this situation?

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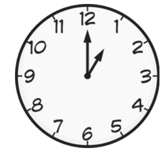
1 hr



Lesson 2: Electric Motor Operation; a Pump's Driving Force

In this lesson, the student will learn important characteristics of electric motors which drive pumps. Topics will include electric motor components, electrical frequency, single and three phase motors. Understanding these basic elements helps a student to understand how an electric motor is controlled in a process control environment.

Focus 1: Components of an Electric Motor

The electric motor is considered the workhorse of industrial processes; most machines are driven by them. Electric motors can be divided into Alternating Current (AC) and Direct Current (DC) motors. AC motors are the most commonly used motors in industrial processes and will be our focus.

An AC electric motor has two major components; the stator and the rotor. The stator is a round, fixed frame with a series of wire coils or "windings" evenly spaced around its periphery. These windings are energized by an AC electrical source, which drive the rotor. The rotor features "windings" which are magnetically influenced by the stator coils, causing the rotor to spin.

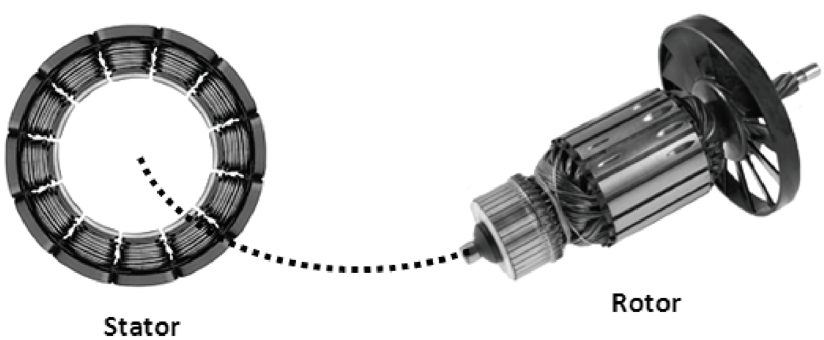


Figure 2.1: Motor Components

An electric motor's rotational speed is based upon how many windings or poles the motor has in its stator and the frequency of the AC electrical source powering the motor.

We'll discover that when the number of poles increases, the RPM decreases. Increase the frequency, the speed increases. So what? Actually, this is the key to controlling motor speed to get the desired pumping results in a liquid process environment. You can't change the number of poles in a motor once it is built, but you can change the frequency of the electrical power source driving it. A Variable Frequency Drive, or VFD, is a device designed to take advantage of these facts to optimize a pump's performance. The following concepts will build toward the understanding what a VFD is and how it works in conjunction with an electric motor to drive a pump effectively.

Focus 2: What is Electric Frequency

You may be familiar with the terms "Alternating Current" (AC) power and "Direct Current" (DC) power. Alternating Current (AC) is what is used around the world to power most industries and commercial electrical energy systems.

Looking at graphs of both, we see DC voltage is a flat line while AC is a sinusoidal or symmetric wave along a zero axis. AC repeats itself consistently over a given period of time. We call each fully repeated wave form a cycle and we call the number of times the cycle repeats itself in a time span of a second to be its frequency in cycles per second. The term hertz (hz) is used as the designator for cycles per second. When electric power is generated at a power plant and delivered to its end-use location, the power is delivered at a constant frequency, such as 50 or 60 hz. So, frequency depends on the rotational speed of the power plant generator and is based on 360° of generator rotation. Increase the generator speed and the frequency goes up; reduce it and it goes down.

So, it stands to reason that the frequency of the AC signal is directly related to the rotational speed of the electric motor it powers. Please keep in mind that these curves could be for voltage or for current, so keep an eye out for that if you study other materials related to electric power.

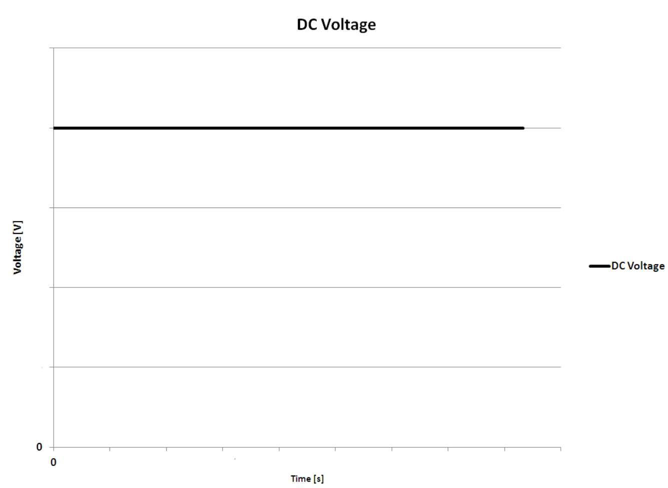


Figure 2.2: DC Voltage

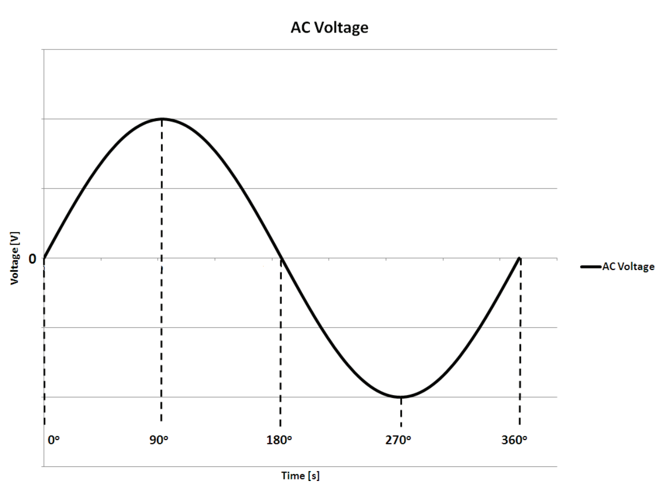


Figure 2.3: AC Voltage

Skill Builder

Lesson 2, Focus 2

If your alternating current electrical power source operates as shown in the graphs, what are the frequencies of each power source?

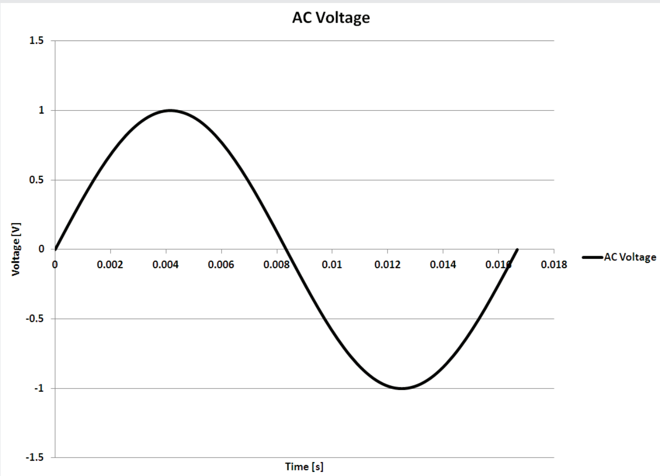


Figure 2.4

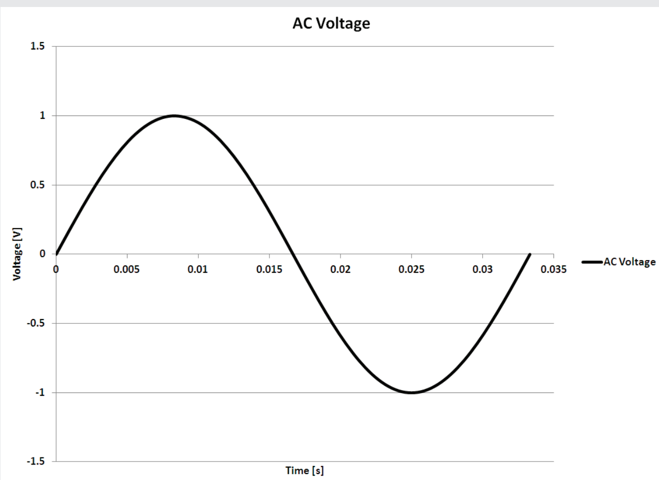


Figure 2.5

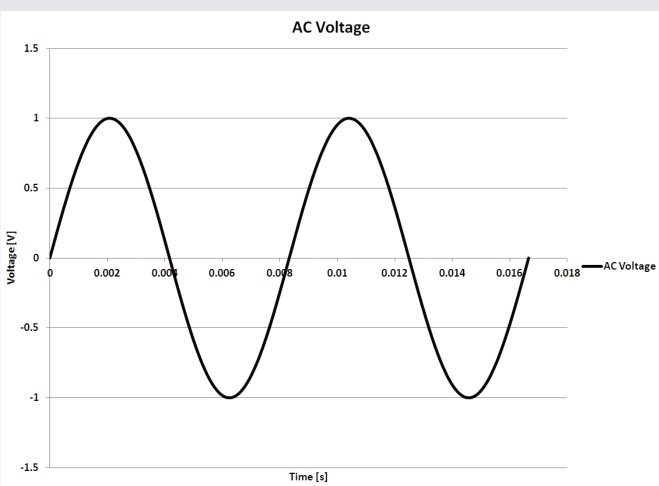


Figure 2.6

Focus 3: RPM as a Function of Frequency in a Single Phase

If we look at a cross section of simple single phase, 2 pole motor stator (the part that remains stationary), it contains 2 windings (or poles). As the AC waveform that supplies the windings rises from zero to its maximum positive voltage, the upper pole has what is called a north polarity, while the lower one has a south polarity (remember playing with a bar magnet in school, where one end was labeled north and one south-one attracted to a metallic object, one repelled).

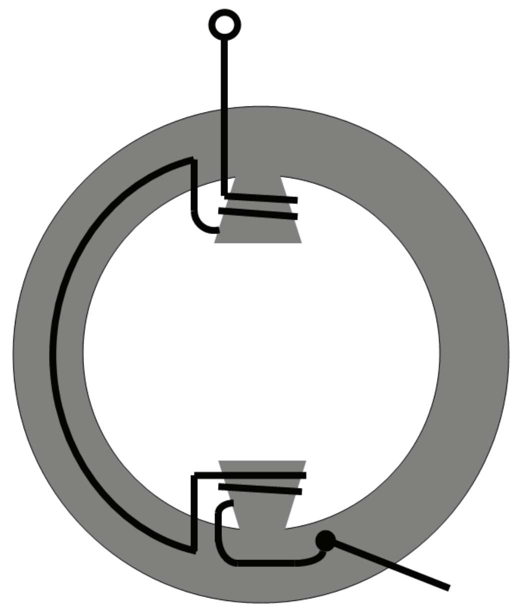


Figure 2.7: Single Pole Motor

When the waveform changes direction and begins to fall, the poles change polarity and then change again when the wave begins to rise again. These polarity changes in the stator send magnetic fields by induction to the motor's rotor (the part that ultimately turns the motor's shaft to drive the pump). These magnetic fields oppose magnetic fields already set in the rotor (either by permanent magnets or electromagnets), causing the rotor to spin (hence the name rotor). One AC wave cycle will cause the motor to complete one rotation. So, if the AC frequency was 60 cycles per second (60 Hz), the motor would spin at 60 cycles per second x 1 motor turn per cycle x 60 seconds per minute = 3600RPM. If it was 20 Hz, the motor would spin 1200 RPM.

If we increased the number of poles in a motor to 4, the rotational speed of the motor would be half that of the two pole. How's that? When you wire up 2 more poles in a series configuration, it takes 2 AC power cycles to spin the rotor around the whole stator one time, thus the increase in time to make one full rotation. So, at 60 Hz, the rotational speed would be 60 cycles per second x 1 revolution every 2 cycles x 60 seconds per minute = 1800 RPM. The following handy equation will allow you to compute the rotational speed of a motor if the power supply frequency and the number of motor poles is known:

$$RPM = \frac{frequency \times 120}{\#\, of\ \ poles}$$

Skill Builder

Lesson 2, Focus 3

You have a single-phase motor with 6 poles. Your power supply is 25 Hz. What RPM will your motor run?

What will the motor RPM be if you change power supply to 60 Hz?

Focus 4: Three Phase Motors

Remember our discussion about frequency and RPM in a single phase motor. Think back to the poles connected in series. Large power output motors actually have 2 more sets of these poles that are individually wired to be driven by one of three electrical feeds from what is called a three phase power source (verses a single feed from a single phase power source). Simply put, each set of poles is wired in series and are offset from each other by 120^o (360^o divided by 3) to provide a symmetric application of the sinusoidal wave form. This allows more power to be applied to the motor, thus being able to drive a larger load with a compact motor size. Three phase power has many details which we won't get into here, but we do recommend checking out other texts on three phase power to gain a deeper understanding. Figure 2.8 shows the 3 sinusoidal wave output of a 3 phase generation system; each wave is displaced from each other by 120^o.

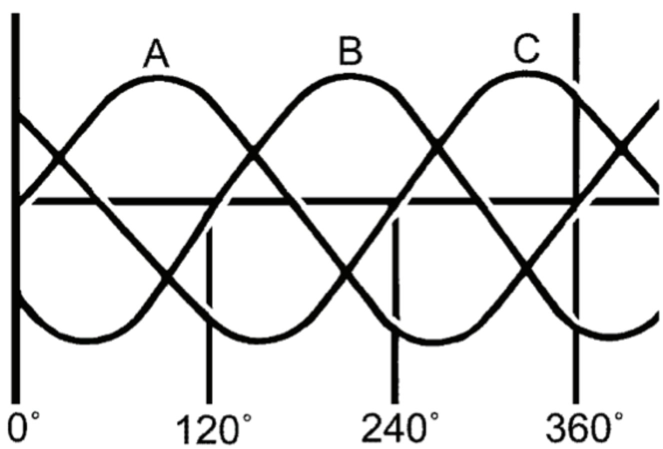


Figure 2.8: Three Phase Waveform

Here is what a cross-section looks like for an 8 pole, 3 phase motor. If you look at the stator, you see 8 sets of 3 poles (again, also known as windings or coils). The rotor has 8 windings.

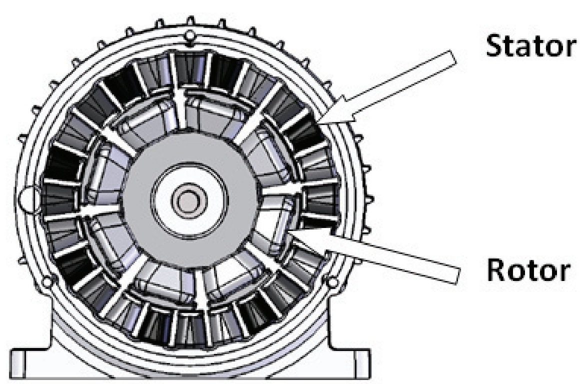


Figure 2.9: Three Phase Motor Cross-Section

Skill Builder

Lesson 2, Focus 4

You have a 3 phase electric motor with a total of 24 poles in the stator and 8 windings in the rotor. You supply it with 60 hz, 3 phase power. What RPM will your motor run? How about if the power supply was now 50 Hz?

Knowledge Certification Quiz: Lesson 1 and 2

1. What is process control?

2. Where is process control used?

3. An industrial pump is typically driven by an electric motor. In a process control environment, what is the device that controls the electric motor?

4. An electric motor consists of 2 major parts. Name them and describe their function.

5. Electric power can be provided in what 2 forms? What is the difference between the two?

6. For AC power, what does the term frequency mean? What term designates frequency?

7. What dictates the frequency of electric power?

8. In a 2 pole single phase electric motor, one AC cycle will cause the motor to spin how many revolutions?

9. If the power supplied to the two-pole, single phase motor was 60 hz, what would be the Revolutions per Minute (RPM) of the motor? What if your motor was 4 pole?

10. Single phase AC power has one sine wave. How many does three phase AC power have? How many degrees will each wave offset from each other based on 360 degrees per revolution?

11. If you count up the total number of poles in an 8 pole, 3 phase electric motor stator, how many poles do you actually have? In this instance, how many windings does the rotor have?

12. You have a 3 phase electric motor with a total of 36 poles in the stator and 12 windings in the rotor. Your power supply is 50 Hz, 3 phase power. What RPM will your motor run? What is the motor RPM if you could change the power supply to 70 Hz?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

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Your Signature Date

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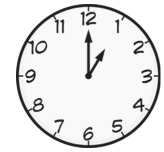
Lesson Duration:
1 hr



Lesson 3: Variable Frequency Drives-The Heart of Pumping Process Control

In this lesson, the student will learn about the Variable Frequency Drive (VFD), the device which controls the speed of an electric motor at any point of the motor's operating range.

A Little History: Variable Speed (Frequency) Motor Operation

Electric motor operation using a variable electric frequency has been in use for a long time, but the focus back in the early days was on the AC power generator at the power plant. If the generator rotational speed changed, the output frequency followed suit. At that time, frequency changes were limited using this method because the generator still cranked out the same voltage level, but wound up with a higher effective voltage (this is an issue we'll touch on later in Focus 5). Needless to say, variable speed capabilities for motors were pretty crude and complicated. Back then, a multi-pole motor could be wired to allow switches to vary the number of poles that would be in operation at any given time. The motor's rotational speed could be changed by manipulating these switches either manually or by some sort of sensor or relay. Other mechanical methods were employed to accomplish speed changes; some so cumbersome as to resemble a "Rube Goldberg" contraption (Never heard of Rube Goldberg? Check it out-you're in for a treat that will make you smile!).

Today, electronics in the form of a Variable Frequency Drive (VFD) help us to vary the speed of an electric motor with relative ease, while providing excellent precision. In the next section, we will be introduced to the components that make up a VFD and explain their roles in making it work.

Skill Builder

Lesson 3

What was accomplished when poles in the motors were wired so they could be switched on and off during its operation?

Introducing the Variable Frequency Drive (VFD)

As mentioned in the last lesson, the Variable Frequency Drive (VFD) is today's technology for controlling the speed of an electric motor. A VFD allows precise motor speed control while substantially reducing the pump motor's electric power requirements. While we could treat a VFD as a black box and just tell you that it works, that wouldn't be any fun. To get a better feel for what is going on, we will show how this technology works in a step by step fashion. Our remaining discussion will focus on 3 phase motors controlled by a 3 phase VFDs.

Figure 3.1: Commercial VFD (left) with electric motor
(courtesy of ABB Group)

Focus 1: Rectifier

As we said earlier, AC power is the predominant power type for numerous reasons. However, it is a difficult task to try to change the frequency of an AC sine wave power source when working with AC. Using Figure 3.1 as a reference, the first thing a VFD does is convert the AC sine wave into a DC wave (A to B) Now, some of this explanation may get a little complicated, but try to stick with it as it will make more sense as everything comes together. The VFD uses an electronic circuit called a diode bridge to limit the travel of the AC sine wave to one direction only (flips all negative waves to positive direction). So, the incoming AC voltage is converted to DC voltage by the diodes. The sine wave changes from a three phase wave to a single wave form . Because the magnitude of the signal is in one direction, a DC circuit thinks it's a DC signal with "ripples" on the top. So, when a 3 phase VFD accepts 3 separate AC input phases, it converts them to a single DC output.

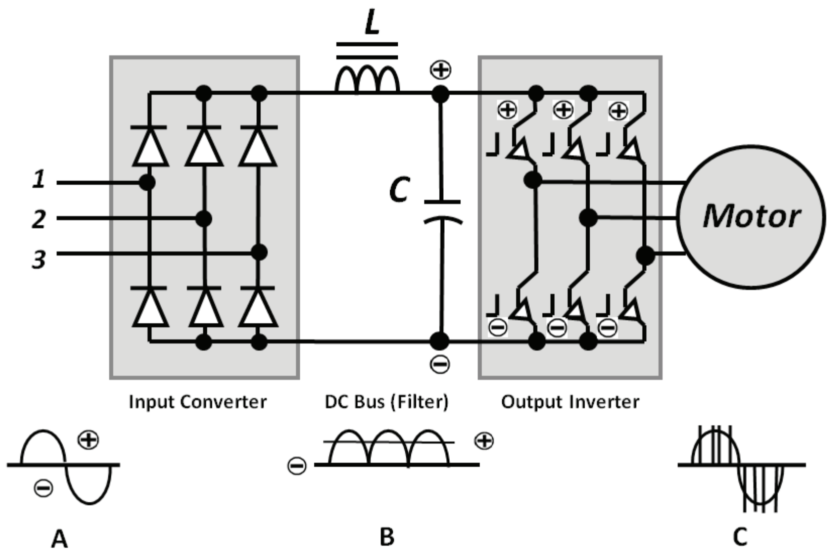


Figure 3.2: AC Rectifier Circuit

Lesson 3, Focus 1

The term VFD stands for what?

What does the rectifier in the VFD do?

What is the name of the electric circuit that limits the travel of an AC sine wave to one direction?

Focus 2: Direct Current Bus (DC Bus)

For those new to electricity, the DC Bus is not something you ride on to go to DC, but rather a part of the VFD that uses capacitors and an inductor to filter the AC "ripple" voltage from the converted DC, before it enters a section called the Inverter (next section). If you look at the AC sine wave coming out of the diode bridge, you see that waves all stay positive and the wave is chopped. The capacitor section takes this chopped wave form and smoothes out this "ripple" into a controllable DC voltage. It so happens this voltage will be the square root of 2 times the incoming voltage, i.e. a 480 volt system will have a 650-700 volt DC voltage. By the way, the DC Bus also includes filters to prevent something called harmonic distortion that can feed back into the power source supplying the VFD. If you're not an electrical engineer, don't fret; this is just some of the "black box" effect the engineers figured out that was needed – just know that it works.

Skill Builder

Lesson 3, Focus 2

What does the capacitor section of the DC Bus do to the wave form that comes out of the rectifier?

Focus 3: Inverter

The inverter is the heart of the VFD. It uses 3 sets of high-speed switching transistors to take the output from the DC bus to create DC pulses that look like squared-off versions of the three phases of the AC sine wave (see C in Figure 3.1). These pulses dictate the voltage and frequency of the sine wave. The term inverter or inversion refers to "reversal" and simply refers to the up and down motion of the generated wave form. Today's modern VFD inverters use a technique known as "Pulse Width Modulation" (PWM) to control or regulate the voltage and frequency (this will be discussed in greater detail in the next section). Within the Inverter is the Insulated Gate Bipolar Transistor (IGBT), which is the actual switching (pulsing) component of the inverter. The IGBT converts the DC voltage from the rectifier/DC bus section back to a "Pulse Width Modulated" (PWM) wave form to send to the motor. The PWM wave form simulates the AC waveform in short pulses. In the electronics world, a transistor can serve 2 functions; it can act as a signal amplifier or as a switch that can simply turn a signal on and off. It features a high switching speed capability while offering lower heat generation. The high switching speeds provide very good AC wave emulation accuracy. This also produces less heat which reduces heat sink cooling requirements and thus provides a smaller package. Since the Variable Frequency Drive controls both the frequency (number of time above and below the zero crossing of the sine waves) and the duration of the on/off, we can send the desired voltage and frequency for the most efficient energy usage. That will be covered next.

Focus 4: Output of the Inverter

Figure 3.3 shows a close up of the wave form generated by the inverter of a PWM VFD overlaid on a true AC sine wave (take a minute to review all that alphabet soup if you've forgotten what they stand for).

The inverter output is actually a series of rectangular pulses with a fixed height and adjustable width. In our illustration, there are 3 sets of pulses; a wide set in the middle and a narrow set at the beginning and end of both positive and negative portions of the AC sine wave. If you add up the areas of the pulses, they equal the EFFECTIVE VOLTAGE (which we will cover shortly) of the true sine wave. If we were to chop off the portions above or below the true AC sine wave and use them to fill in the blank spaces under each curve, the result would be almost a perfect match. This is the way a VFD controls voltage going to a motor.

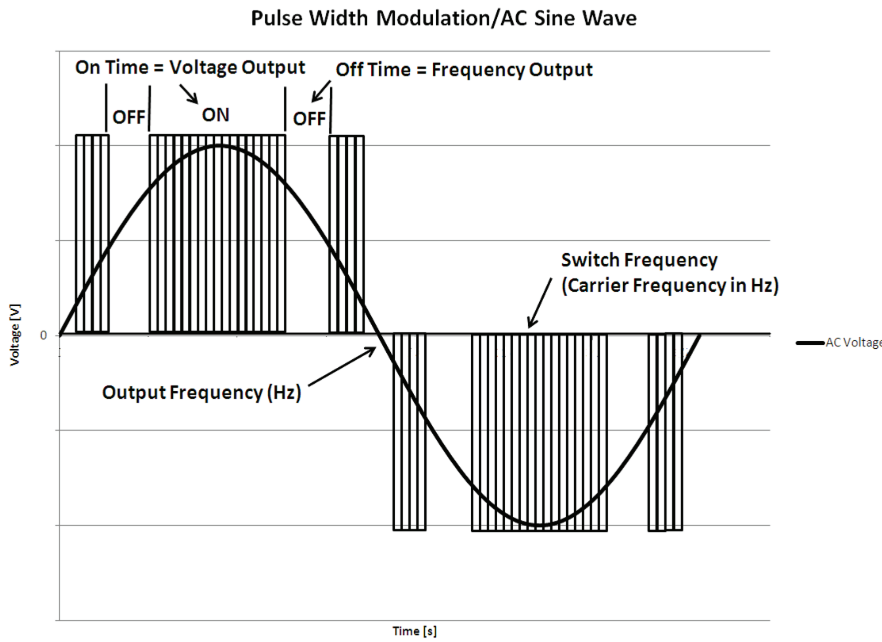


Figure 3.3

When you add up the width of the pulses and the blank spaces between them, this determines the frequency of the wave (Pulse Width Modulation-PWM) seen by the motor. If the pulse was continuous, without blank spaces, the frequency would still be correct, but the voltage would be much greater than that of the true AC sine wave. The VFD will vary the height and width of the pulse and the width of blank spaces between them to accomplish the desired voltage and frequency. Although it is internally complex, the result is elegantly simple.

One last thing for those who really understand electricity: because this is essentially DC now, people who understand how induction motors work may wonder about how a DC signal can "induce a current" in a motor's rotor. Without going into detail, just know that the wide DC pulses shown in Figure 3.2 are actually made up of hundreds of individual pulses. This on and off motion of the inverter output allows induction by way of DC to happen.

Skill Builder

The inverter takes the output signal from the DC bus and does what with it?

What is the device in the inverter that does that?

What is the technique called which controls or regulates the voltage and frequency?

Focus 5: Effective Voltage

As we have seen, AC power is rather complex. If you think about it, one complexity is that it changes voltage continuously; going from zero to some maximum positive voltage, then back to zero, then to some maximum negative voltage and then back to zero. So, how can we tell the actual voltage that is applied to a circuit? Good question!

Figure 3.3 shows a 60 Hz, 120V sine wave. If you look at the peak voltage of the sine wave, it is 170 V. How can this be called a 120V wave if the voltage is 170V? During one cycle, it starts at 0V, rises to 170V and then falls again to 0V. It continues to fall to -170V and then rises back up to 0V. It turns out that the area under the light gray rectangle, whose border is 120V, is equal to the sum of the areas under the positive and negative portions of the curve. Is 120V the average voltage? No. If you average all the voltage values at each point across the cycle, it would yield 108V. Why is it then that a voltage meter will measure 120V? Here is where "Effective Voltage" comes in.

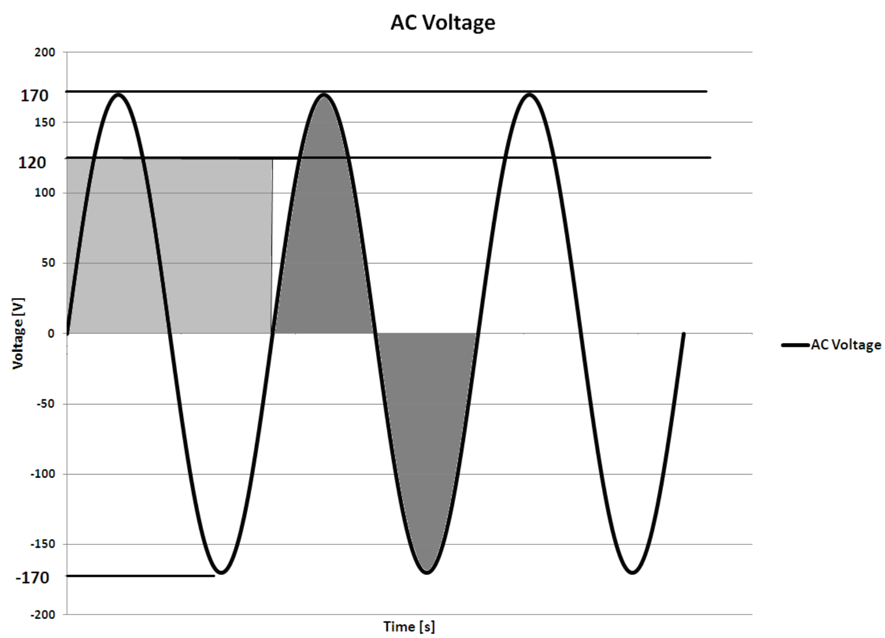


Figure 3.4

If you were to measure the heat produced by a DC current flowing through a resistor, you would find that it is hotter than the equivalent AC current going through it. This is due to the fact that AC does not maintain a constant value through the cycle (as we have shown). Now, if you did this in a controlled laboratory setting and found that a particular DC current caused a temperature rise of 100 degrees, the equivalent AC circuit would generate a 70.7 degree rise, or about 70.7% of the DC value. Therefore the effective value of the AC is 70.7% of the DC. It also turns out that the effective value of an AC voltage is equal to the square root of the sum of the square of the voltage across the first half of the curve. If the peak voltage is 1 and you were to measure each of the individual voltages from 0 to 180 degrees, the effective voltage would be 0.707 of the peak voltage. So, 0.707 of the peak voltage of 170V is 120V. This effective voltage is also known as the root mean square or RMS voltage. It follows then that the peak voltage will be 1.414 of the effective voltage. So, let's say you have a measured 230V AC , this would have an effective Voltage of 325V. A measured 460V has a peak voltage of 650V.

Why do we need to know this? Is it just extra torture for no good reason? No. It's actually meant to give you a better understanding of what a VFD has to go through to work effectively. In addition to varying frequency, a VFD must also vary voltage, even though voltage has nothing to do with the speed an AC motor operates. Stick with this-it will make sense in a minute.

If you plot a 460V wave form at 50 Hz and then again at 60 Hz, you see a distinct difference (see Figure 3.5). Both have a peak voltage of 650V (1.414 x measured voltage), but the 50 Hz curve spreads out further during the cycle. If you look at the first half of each curve, the 50 Hz curve is larger. Remember when we discussed the area under the curve as being proportional to the effective voltage; this means the effective voltage is higher. This increase in effective voltage becomes even more pronounced as frequency gets smaller. So, if a 460V motor were operated at these higher voltages, it could hurt the lifespan of that motor substantially. Consequently, the VFD must always vary the peak voltage with respect to the frequency in order to maintain a constant effective voltage which the motor is designed to run on. The lower the operating frequency, the lower the peak voltage; the higher operating frequency, the higher the voltage.

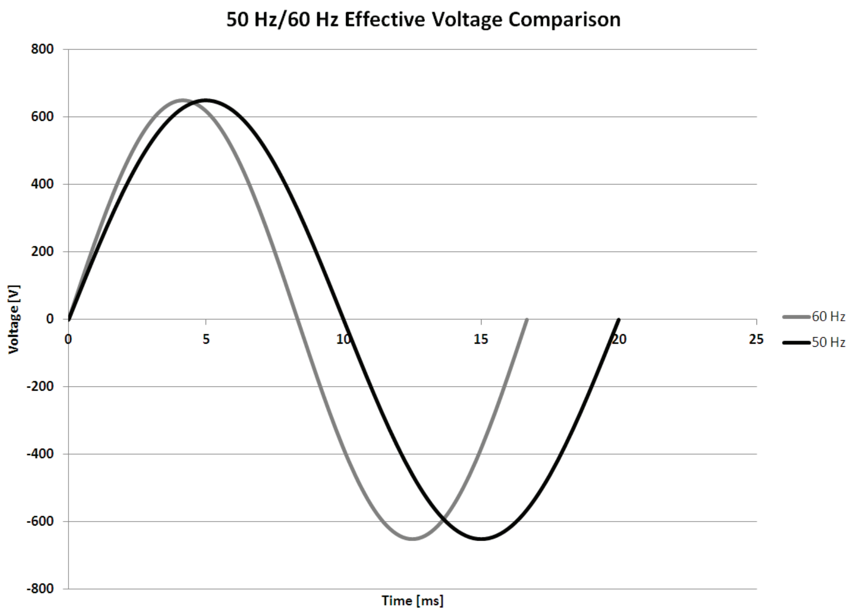


Figure 3.5

This should give you a better understanding of how a VFD controls the speed of a motor. As you will discover, most VFD's can control a motor speed either manually using a keypad or multi-position switch. They also can be set up to be controlled by sensors (pressure, flow, temperature, level, etc.) to automate the process. So a VFD is a pretty remarkable piece of equipment in terms of what it has to do and what it must keep track of to do it.

Skill Builder

Lesson 3, Focus 5

The term Effective Voltage is also known as what?

Let's say you have a peak voltage of 500V. What would be your effective voltage for an AC system?

If you are running a peak voltage of 640 V at 60 Hz and decide to have it run at 50 Hz, what happens to the effective voltage? Is this an issue with your motor?

Knowledge Certification Quiz: Lesson 3

1. What does the term VFD stand for?

2. A rectifier in a VFD converts an AC sine wave to what?

3. A diode does what to an AC sine wave?

4. The AC ripple voltage generated by the diode is converted to a DC voltage by what?

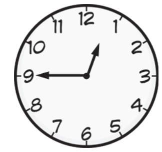
5. What does the inverter do?

6. The term Effective Voltage is also known as what?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature ______________________ Date ______________________

Approximate
Lesson Duration:
45 min.



Lesson 4: Variable Speed Applications in Pumping

In this lesson, the student will look at some examples of typical situations that use Variable Frequency Drives (VFDs) to accomplish objectives.

There are essentially 3 situations VFD's are used for in pumping;

1. maintain constant pressure

2. maintain constant flow

3. provide or react to variable flow

They not only offer a very good way to perform these tasks, but do so with a significant reduction in power consumption over other methods. Let's use some typical application examples from VFD manufacturers to see how this works.

Focus 1: Constant Pressure

Just as the name indicates, constant pressure is a situation where pressure is maintained at a specific level in the system, even though the flow may be changing. Good examples of constant pressure would be booster pump systems in large commercial and industrial applications. A pressure transducer in the system sends a signal back to the VFD to change pump speed in order to keep pressure constant.

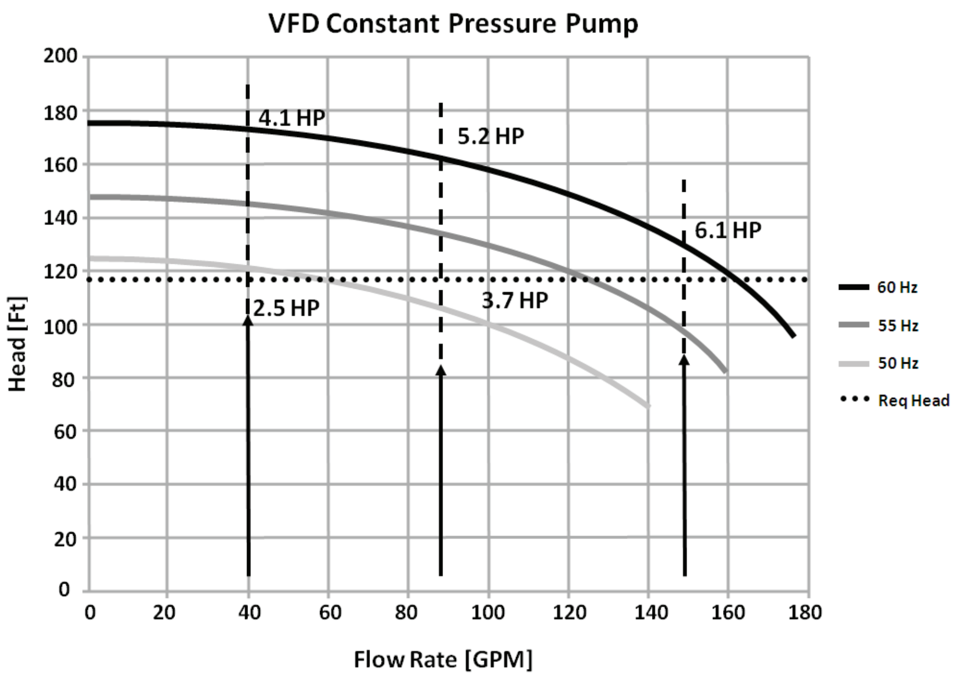


Figure 4.1

Figure 4.1 is a typical example of a simplex (single) booster pump in a constant pressure application. When you plot the Total Dynamic Head (TDH) of the pump at different operational speeds based on frequency (in our case 60, 55 and 50 Hz), your performance curves map out as shown.

Let's start with the 60 Hz curve; If you want to maintain a constant head of 120' (dotted line) at 60 Hz, notice that where those two lines cross yield a flow rate of 150 GPM, while consuming 6.1 HP to do it. This is typically called the "design point"; the maximum flow rate you'll have to meet while maintaining that constant pressure head.

Now let's look at the 55 and 50 Hz curves. The dotted horizontal line is still the same constant pressure head to be maintained at the various flow rates. If you look closely, you can see that at about 53 Hz the pump can provide 100 GPM at the design head and at 50 Hz it can provide about 50 GPM. It becomes apparent that over a relatively small frequency range of 50 to 60 Hz, the pump will provide 50 to 150 GPM at 120'. Remember that the VFD produces not only 50, 55, and 60 Hz pulses, but also each individual (and fractional) Hz in between. It can settle on the optimum frequency for the particular need. This yields a significant savings in the power required if the flow requirements drop lower than the "design point" flow. The brake BHP requirement at 53 Hz (100 GPM) drops to 3.8 or 58% of design point HP. At 50 Hz (50 GPM), it drops to 2.4 HP or just 39% of that at the design point.

Now, we could use a pressure reducing valve (PRV) to maintain a constant pressure of 120 feet as flow demand decreases and take advantage of the centrifugal pump's reduced power consumption as its flow moves towards the left of the capacity curve (remember, we are on the 60 Hz curve when we do this). But, at the 100 GPM point on the 60 Hz curve the power requirement is 5.2 HP (compared to only 3.8 HP if we lowered the operating frequency down to approximately 53 Hz). At 50 GPM, the PRV control requires 4.1 HP on the 60 Hz curve, or 72% more than an optimized VFD frequency. In a constant pressure application, the VFD offers precise and flexible control plus an increased power savings over mechanical constant pressure devices. Because centrifugal pumps follow the laws of affinity, a relatively small change in frequency (speed) can result in a substantial reduction in power.

If you have not studied the affinity laws for centrifugal pumps, they state that;

1. Capacity varies directly as the change in speed
2. Head varies as the square of the change in speed
3. Brake horsepower varies as the cube of the change in speed.

Skill Builder

Lesson 4, Focus 1

1. For a constant pressure flow situation, can the flow be changing and still achieve constant pressure?

2. What do you call the maximum required combination of pressure and flow for this situation?

3. If you can back off of flow while still maintaining the pressure design point, can a VFD be useful in this situation? Would a Pressure Reducing Valve (PRV) work better? Why?

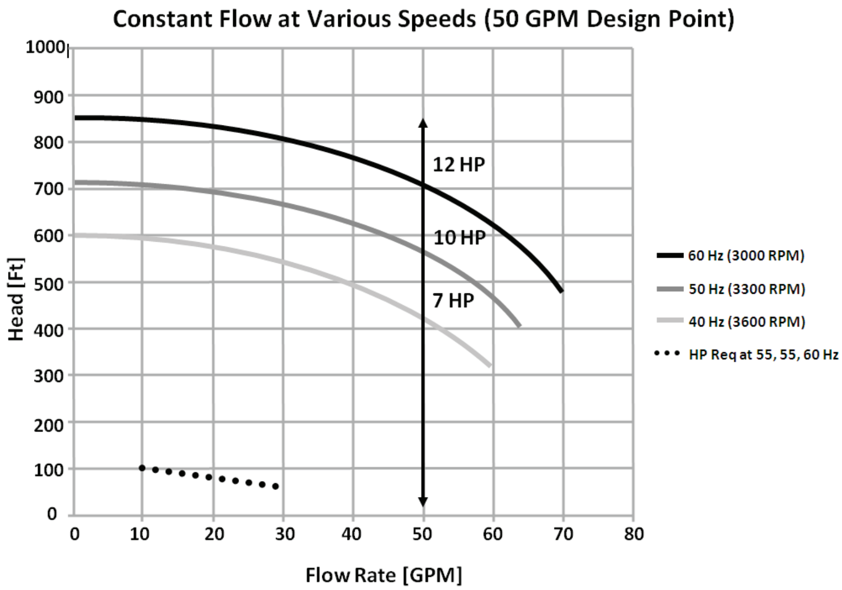


Figure 4.2

Focus 2: Constant Flow

Figure 4.2 shows a constant flow application (vertical line at 50 Gallons per Minute). These applications require flow to remain constant regardless of the pressure fluctuations the system may encounter. A flow meter is usually employed to control VFD output and, in turn, motor speed. Examples of constant flow include maintaining levels in tanks at various elevations, manufacturing processes, and the operation of nearby and remote irrigation zones. Each of the multiple components served by these applications require similar flows but, differences in elevation, back pressure, and pipe line friction may require different pressures to maintain those flows. The system is designed for the highest pressure component of the application so that the VFD can reduce motor speed for the lower pressure component and save energy in doing so. Otherwise, a throttling valve that kept flow constant based on pressure would be in use. Motor electrical consumption would remain similar to the set point usage. If you examine the graphed pump curves closely, just like you did for the constant pressure analysis, you will see the opportunities presented when pressure does not have to be maintained at one specific "design point" to maintain the flow set point.

Skill Builder

Lesson 4, Focus 2

1. Can you name three constant flow applications?

2. What types of situations cause challenges to maintaining steady flow?

3. If you didn't have a VFD, what less sophisticated means of controlling flow would you have to use? What is one major problem with using it?

Focus 3: Variable Flow

Variable Flow applications might also be called variable flow / variable pressure because neither remains constant. For your information, most are circulation applications and deal only with pipe line friction as flow changes. A major application area is that of chilled water circulation in large air conditioning systems (HVAC) where cooling demand is always changing. Since the chilled water flows in a circulation loop, the only pressure component that changes is that due the friction caused by the flowing water. VFD output is controlled by a flow meter, temperature transmitter, or directly by the chiller controls. The cooling tower pump is often controlled by the same circuit.

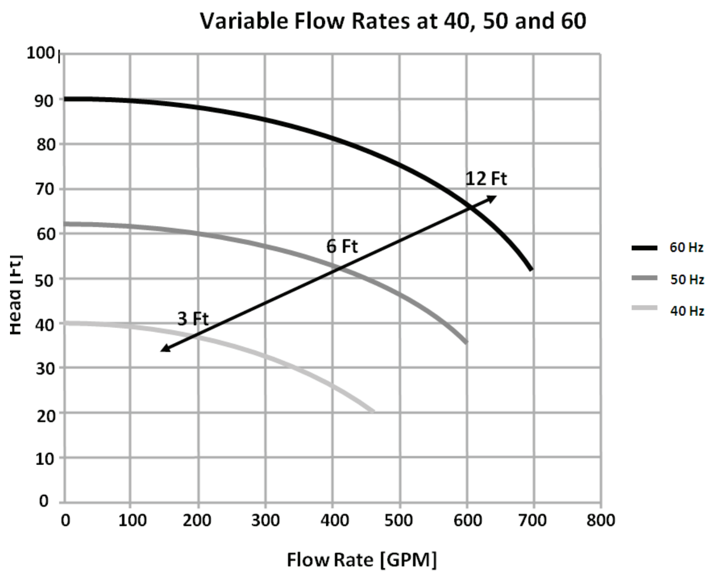


Figure 4.3

Figure 4.3 is a depiction of a variable flow, chilled water application. The straight upwardly-sloped line shows flow points on the various frequency curves and the additional pressure (in Head) required to over-come friction as flow increases. Please note that the straight line could be curved depending on the design. Since friction is not a linear function, it may have some curvature based upon the calculated friction in the circulation loop. In the past, multi speed motors were used for this application. Large swimming pools also use a similar design for circulation through a filter. Again, power savings are achieved as the flow is decreased by the VFD.

Focus 4: Soft Start

A final advantage that will be touted in VFD application benefits is the Soft Start/Stop option. This option allows the pump and motor to be started at a lower frequency (say 30 hz) and then "ramped" up to run speed over a period of a second or more. The result is a significant reduction in the starting current required by the motor, verses it just starting and ramping right up to 60 Hz. Equate it to stomping your engine throttle to the floor verses gently pushing on it to slowly ramp up your speed. The former requires much more energy input all at once and creates more stress than the latter. Some utilities require that motors over a certain HP undergo a soft start. With the VFD, it's just part of the package. In addition to a lower inrush current, mechanical stress on the motor and pump are also greatly reduced. In a normal "across the line" start, the motor rotor and pump rotating element go from motionless to the motor's rated RPM in about one second! And, soft start/stop virtually eliminates a phenomenon called water hammer in almost any pumping system (you might want to read up on that).

Skill Builder

Lesson 4, Focus 3 and 4

1. Variable flow situations are mainly concerned with what 2 issues?
2. Can you name a situation where variable flow control is needed?
3. What typically can be used in a variable flow application if a VFD is not used?
4. Can you describe what a motor soft start is?

Knowledge Certification Quiz: Lesson 4

1. Name 3 situations where VFDs are used in fluid pumping.
2. In a "constant pressure" fluid pumping scenario, what feedback sensor is used to "talk" with the VFD?
3. In a "constant flow" fluid pumping scenario, what feedback sensor is used to "talk" with the VFD?
4. What happens to a pump performance curve if the driving frequency is lowered?
5. In a variable flow pumping scenario, can both pressure and flow be changing at the same time?
6. Name an application that has variable flow requirements.
7. What does the term "soft start" mean regarding electric motors?

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

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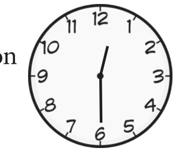
Your Signature Date

Approximate Lesson
Duration: 30 min.



Lesson 5: Process Control Logic

In this lesson, students will expand their knowledge of Lesson 1 to better understand the logic of Process Control in pumping.

Way back in Lesson 1, we gave a general definition for Process Control:

Process control is the ability to manipulate or control some form of operation on a consistent basis to produce reliable desired outcomes. In pumping, this means controlling a pump to produce desired flow and/or pressure results in the system in which it is operating. This usually means the system environment offers "feedback" information to the pump so that it can automatically adjust how it runs in order to properly meet the needs of the situation.

We want to expand this discussion to show how processes differ in necessary control schemes to get the job done most efficiently. This means we will look at ever increasing capabilities to fill a need. We'll use various examples from different scenarios to make the point, but will use this building block knowledge to ultimately focus on pumping fluid.

Focus 1: Open Loop Control: A Return to Watering the Lawn

Remember in lesson 1 when we talked about adding the sprinkler system to your lawn? When it was strictly operating on a timer, which turned it on and off at preset times (even if it was raining outside), the "process" environment this control scheme worked in is known as "open loop" control. Open loop control works well as long as the event it controls is repetitive and no damage could result from its action. If your sprinkler activates while it's raining, the water is wasted but no damage occurs. Open loop controls are also simple and inexpensive. The key characteristic of open loop control is that the controller has no clue what is going on within the system. It simply follows its instructions, to the letter, regardless of its surroundings.

Focus 2: Closed Loop Control: The Heating System

While the lawn sprinkler can run relatively well in an open loop manner, your home heating system would not. If open loop control was used, you would experience times when it was too warm and others when it was too cold as the heater would start and stop based on a simple timer cycle. To combat this problem you need "feedback" to the heater based on the desired temperature and the actual measured temperature at any point in time. Your heating system could then make its own decision when to start and how long to run. In the typical home heating system, this is accomplished with a thermostat. When the temperature drops below a certain predetermined level, the thermostat starts the heating system and runs it at its full capacity until the temperature rises to the thermostat setting. The thermostat then stops the heating system and waits to begin another cycle. This is a simple example of "closed loop" control. More specifically, it is known as "on/off, closed loop control" as the heater is either fully on or fully off and there are no intermediate settings. The key characteristic of the closed loop controller is that it receives some form of feedback as to what is going on within the system and can therefore make more "intelligent" decisions. The downside is that when you look at an operational graph of the system, you see that it is not very precise. If it's above the desired temperature, it shuts off; if below, it turns on. This looks something like Figure 5.1.

To take this discussion a little further. This type of control is known as Dead Band control. The controller allows the signal to oscillate between a low and high set point (the Dead Band) so that the furnace isn't constantly turning on and off for short durations. When the low set point is reached, the controller calls for an increase. When it reaches the high set point, it calls for a decrease. Now, the problem with this is that there is usually a delay between the time the final control element changes (in this case, temperature) and the time the sensor reads the measurement (called PV or Process Variable). This delay is called lag time and unless the sensor is very fast, the control element very responsive and the physical distance between them is very short, the measured values will both overshoot the high and low set points. Many methods have been tried to remediate the problem and these schemes are called control algorithms. The most common control algorithm is PID; Proportional, Integral and Derivative control. The Proportional value determines the reaction to the current error. The Integral Value determines the reaction based on the sum of the recent errors. The Derivative value determines the reaction to the rate at which the error has been changing. The output of the controller to the final control element is the weighted sum of these 3 values.

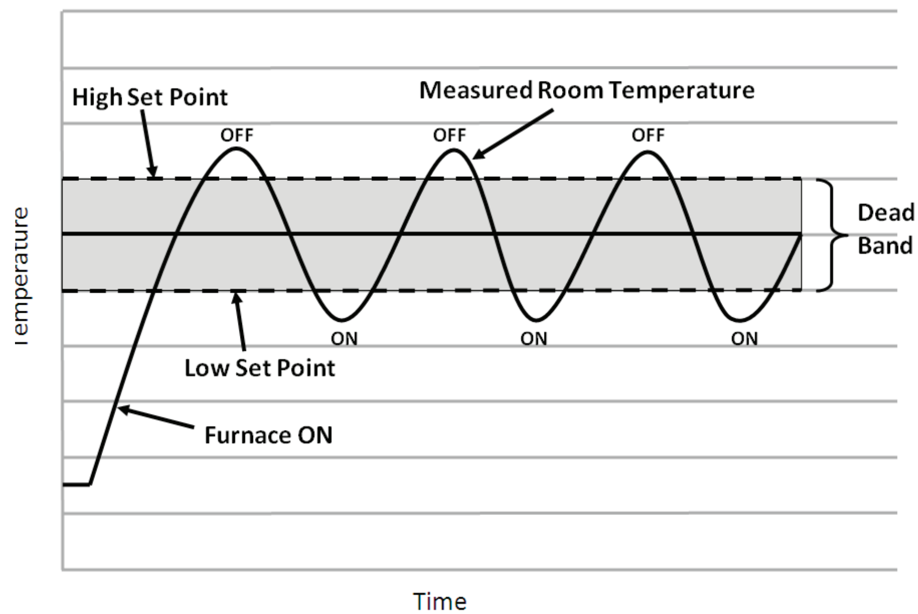


Figure 5.1

Focus 3: Getting a Better Feel for Controller Logic (Hand-Controlling the Process).

Let's think about something you're very familiar with; controlling water temperature using hot and cold faucets. You turn these on and touch the water to feel the temperature. Based on the feedback, the faucets are adjusted until the water reaches the desired temperature.

Touching the water is what we call a process variable-it's the difference between what the temperature of the water currently is and what we want it to be. In control lingo, this difference can be called the error. You determine that the water is too hot or too cold and also by how much.

Knowing the magnitude of the error, you change the faucet positions. When you first do this, you might turn the hot valve on just slightly if you want warm water; or you may turn it on full-blast if you want very hot water. You're doing this in relation or proportion to how far off you think the temperature is from where you want it to be. Keep this in mind as this will be something we will be talking about later called Proportional Control. Now, if the hot water isn't coming fast enough, you may try to speed up the process by opening the hot water valve more, checking temperature, and doing this more as time goes by. You're in essence looking at the past history of how the temperature was changing based on your input and adjusting it quicker. This would be an example of Integral Control.

Now, if you make too big a change when the error is small, you can overshoot your target (water gets too hot). If you kept doing this, (being ham-handed, without good control over yourself) you would repeatedly overshoot your goal. If you think about it in a graphical form, you would create a wavy pattern that would oscillate around the set-point temperature. If the oscillations increase as time goes on, you have what's called an unstable system (and an unstable operator). If they remain at a constant level or decrease, the system is considered marginally stable.

If you have some finesse and control, you want to gradually converge your faucets so the desired water temperature is reached. You do this by settling down or tempering your ham-handed oscillations (being in tune with rate of change you are applying to the faucets) as you move forward. This can be thought of as an example of Derivative control.

Once you get it the way you want it (zero error), no changes will need to be made unless the system experiences a disturbance. Maybe someone else just turned on their faucet next to you and is using some of your warm water stream, which makes yours cooler. This increases your error and you have to react. This is the way a controller functions in industry.

After going through all of that, the good news is that a PID Controller can successfully replace the human being. Whew! We'll talk about that next.

Skill Builder

Lesson 5

1. What is the main difference between open-loop control and closed-loop control?

2. When your heating thermostat is set at 70, but your room temperature is 65, what is this difference known as?

Knowledge Certification Quiz: Lesson 5

1. How could you convert a yard light from an "open loop" control to a "closed loop" control?

2. What does an ON-OFF Control Loop mean?

3. Does an ON-Off Control Loop maintain an accurate set-point result? Why or Why Not?

4. Referring to the controlling water temperature with your hand example in the text, list 2 other processes that would work similarly.

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

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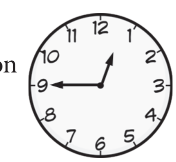
Your Signature Date

Lesson 6: The PID Controller-The Brains and Logic of Pump Process Control

Approximate Lesson Duration: 45 min.



In this lesson, the student will learn about the PID control algorithm for process control and its functionality.

Focus 1: PID Control Overview

PumpLabTM uses something called a Proportional-Integral-Derivative Controller, or PID for short, to control the on-board Variable Frequency Drive (VFD) which ultimately controls the speed of the motor driving our pump. This PID controller changes the speed of the pump, in very specific ways, after receiving "feedback" from the system in which the pump is operating in. How this works and why this is important is what we want to learn now. Let's ease into this a step at a time as we build toward a quality understanding of PID Control. A proportional-integral-derivative controller (PID controller) is a common control-loop feedback controller widely used in industrial control systems.

When a process loop is created by adding feedback (from a variable such as airflow, pressure, or level) and sent to the VFD, regulation of the variable is possible through the PID loop control. A PID controller calculates an "error" value; the difference between what we are measuring in the process (process variable) and our desired setting (set-point).

The VFD's PID controller determines the proper reaction to the error; the changes between the system set-point and its actual state as measured by feedback. The controller attempts to minimize the error by adjusting the process control inputs.

Figure 6.1 shows a basic schematic diagram of a closed-loop system using a feed-back controller to control error.

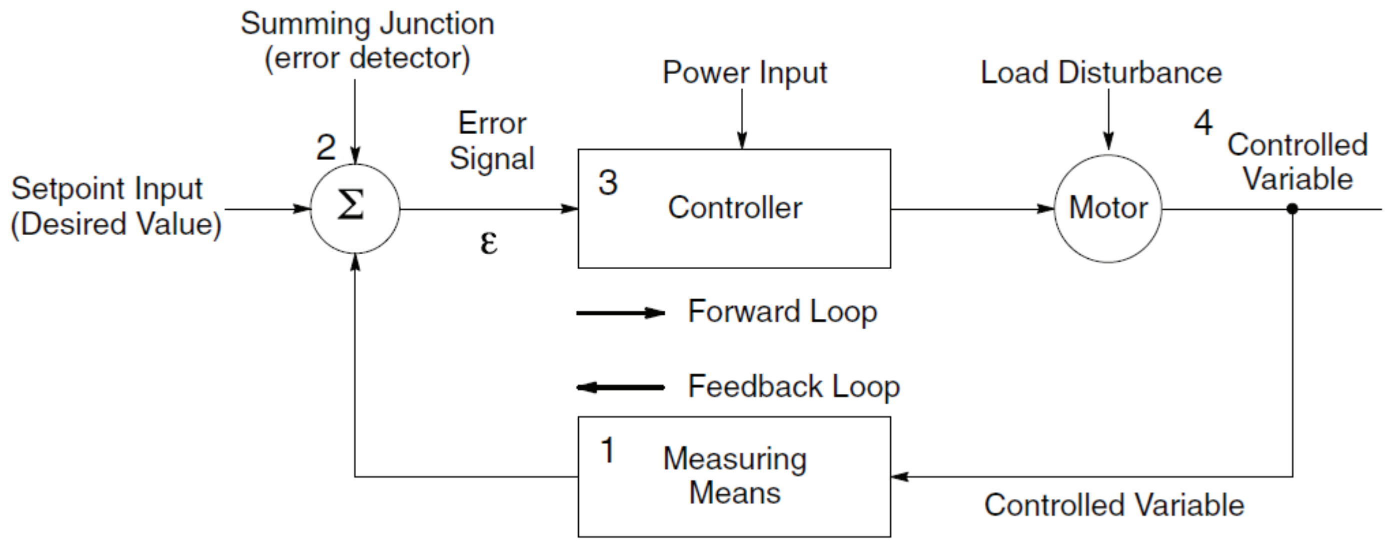


Figure 6.1: Block diagram of a closed loop control system. The basic premise of this scheme is to adjust the motor condititions in order to minimize the error signal.

The PID controller logic consists of an algorithm (a programmed calculation formula for solving a problem in a finite number of steps), that has three separate constant parameters: the proportional, the integral and derivative values, denoted P, I, and D. Basically, these values can be interpreted in terms of time: P depends on the present error, I on the accumulation of past errors, and D is a prediction of future errors, based on current rate of change. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve, a damper, or the power supplied to a heating element. In the case of PumpLabTM, this is used to control the speed of the pump and is accomplished through a software program that is executed by a PLC (programmable logic controller) built into the VFD. You may also hear algorithms being referred to as instructions, procedures, functions or programming. The general control algorithm is laid out as follows:

$$A_{out} = K_p \varepsilon + K_i \int \varepsilon \Delta t + K_d \frac{\Delta \varepsilon}{\Delta t}$$

Figure 6.2: General PID Control Algorithm

Furthermore, by tuning the three parameters with something called Gain in the PID controller algorithm, the controller can provide control action designed for specific process requirements (we'll talk more about Gain shortly). The response of the controller can be described in terms of how the controller responds to an error, the degree to which the controller overshoots the set-point and the degree of system oscillation. Please note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability. You try to get it tuned to be the most effective over the full course of operation. Let's get into more detail about how each element we discussed works.

Looking at Figure 6.3, the black line plots the proportional signal trying to react to a change in an input signal in order to maintain a set point (zero line). You see that it shoots upward, overshoots, turns toward the set point, then undershoots. It continues this pattern in a diminishing fashion until it is settled on the set point.

The integral function measures the areas under the curves (errors) and the derivative function measures the rate of change of that curve as it moves along to the right. In essence, these two functions measure how much error the proportional algorithm has in getting to the set point for this application and uses that information to apply measures to speed up the proportional signal response and to reduce that error. We'll explore each element of PID in greater detail next.

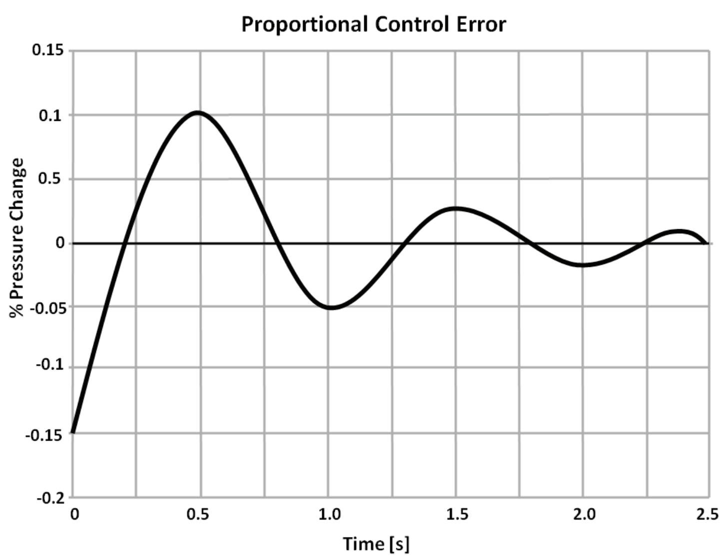


Figure 6.3: Proportional Control Error

Lesson 6, Focus 1

Skill Builder

1. Is a PID controller meant for open or closed loop operation?
2. Does a PID controller need any feedback to work effectively? Why?
3. What is an algorithm?

Focus 2: Proportional Control (The P in PID)

Remember how you added control elements to your lawn sprinkler to get it automated and react intelligently to the current lawn moisture situation? Let's take a similar approach with your heating system.

Your old home heating system used a basic closed loop, on/off thermostat, as described earlier. One day the old furnace died, so you had the local dealer install a brand new one. He brought you up to speed on the latest technology and showed you that the new thermostat can transmit the actual measured temperature in the room back to the heating system controller. He also showed you that your new heating system can vary its output based upon the temperature it receives from the thermostat. In your case, your new furnace has 4 gas burners that can be controlled so only one or two burners can be operating (an electric furnace could control a number of heating elements). A variable speed fan in the unit also helps the control of heat.

As the temperature in the room approaches its' "set point" the heater would not necessarily turn off but, instead, reduce its output (turn off some burners) and attempt to keep the room at the desired temperature. If the temperature drops, it would increase its output (turn on more burners) and if the temperature increases it would either reduce its output or shut off completely. Furthermore, these changes in output would be in "proportion" to the change in temperature. A small change in temperature results in a small change in output while larger changes in temperature would lead to proportionally larger changes in heat output. The heating system example is one of "proportional, closed loop" control and is the "P" in "PID". Figure 6.4 shows how the proportional control smoothly changes the system output to get the existing low temperature back to the desired set-point. (Notice that it doesn't quite make it to the set point. This is known as offset in industry and is one of the reasons we need more than proportional control to effectively establish the best results in process control. This will be addressed in the next section.

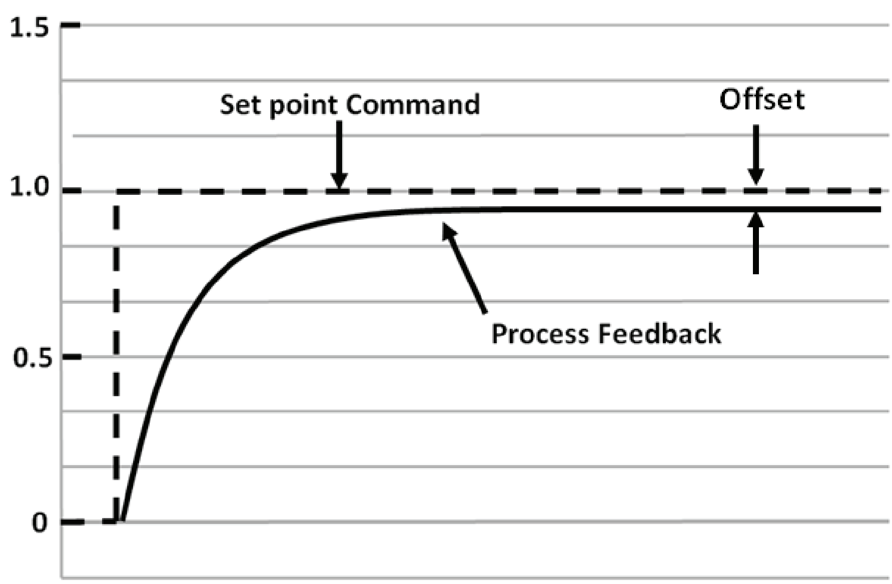


Figure 6.4: Proportional Control Curve

Proportional control is used in systems where the feedback measurement tends to change slowly. Another example you may be familiar with is your car's cruise control-it also operates by proportional control. The controller monitors your speed and changes the throttle setting in proportion to the change in speed it sees. These devices work very well on level and slightly inclined roads but you have probably noticed that they do not work as well on a steep incline. A steep incline will decrease your speed quickly but the controller reacts in its normal fashion and speed will remain well below the set point until, ultimately, the transmission drops into a lower gear and the speed set point is once again reached. If the steep incline continues, this cycle will repeat itself a number of times.

Proportional control is very common for pumps used in process plants. Some processes use a grouping of pumps that can collectively or individually come on or drop off to adjust output based on what is needed. Multiple pump booster systems use multiple pressure switches to bring additional pumps on line based upon changes in system pressure.

$$A_{out} = \boxed{K_p \varepsilon} + K_i \int \varepsilon \Delta t + K_d \frac{\Delta \varepsilon}{\Delta t}$$

$$A_{out} = K_P \cdot \varepsilon$$

$where:$

A_{out} = controller output

K_P = proportion al gain

ε = error signal

Figure 6.5: Proportional Component (with Gain Factor) of PID Control Algorithm

Looking at formula in Figure 6.5, the proportional term produces an output value that is "proportional" to the existing error being experienced by the system. The proportional response can be adjusted by multiplying the error by a proportional gain constant.

A high proportional gain can result in a large change in the output for a given change in the error. If it's too high, the system can become unstable; too low and the reaction might not be adequate enough, especially if your system does experience a disturbance. Based on theory and industrial practice, the proportional part of the PID controller should contribute the majority of the output change.

Proportional control is also used in some simple VFD pumping applications where a finite number of different flows or pressures are required by some process. For example, a process may require three different flow rates based upon the number of machines operating at a given time. If a single pump can provide all three flows at different speeds, the VFD can use proportional control to vary its output frequency and satisfy the application's requirements. This is a good example of "proportional, closed loop" control and is the P in PID control. Figure 6.6 shows different proportional control reactions in conjunction with various Gain factors. We will cover Gain in more detail in a later Focus.

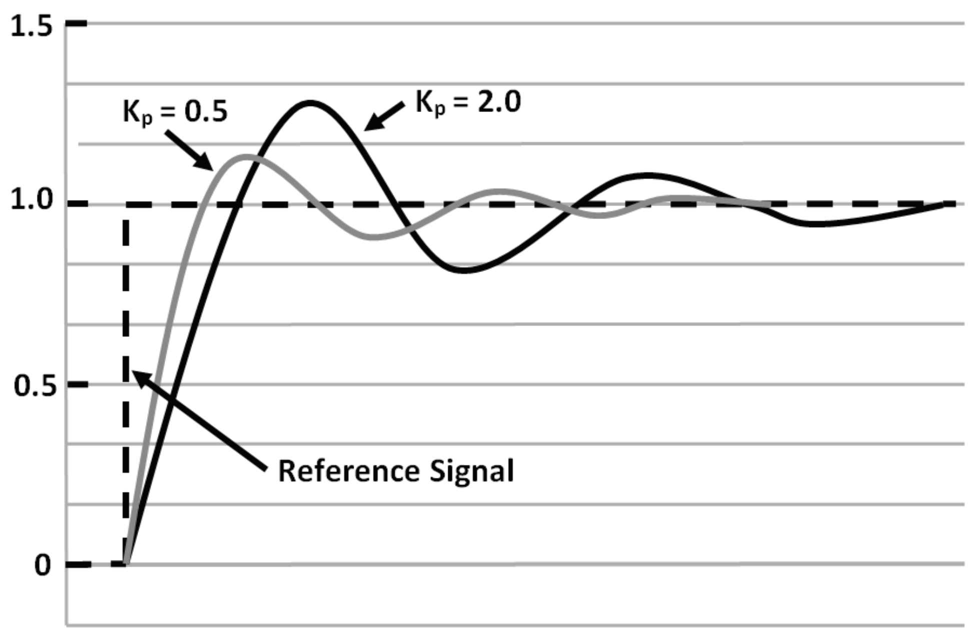


Figure 6.6: Proportional Responses based on various magnitudes of gain

Skill Builder Lesson 6, Focus 2

1. Is proportional control best used in systems where feedback changes rapidly?

2. An automobile uses a proportional controller algorithm for its cruise control. Does this work well on terrain with lots of hill? Why?

Focus 3: Integral Control (The I in PID)

If changes in your process are gradual and there's lots of time for Proportional Control to react, then proportional control usually works great. But most of the time, changes occur fairly quickly (maybe even abruptly); proportional can't respond fast enough or with the right magnitude. It tries, but inevitably it can't keep up, and starts over-reacting. This creates instability in the process to the point where the process losses control. In this situation, the proportional control algorithm needs some assistance. One of these assists is provided by Integral Control.

In pumping applications, proportional control is usually satisfactory to maintain the flow requirements if conditions are fairly steady, with no sudden changes and if small offsets are tolerable.

Proportional control, by itself, is not dependent on time in a control process. Consequently, the process usually will reach a steady state condition where the error signal just stays there and doesn't change with time. In other words, the controller output would never bring the controlled variable exactly equal to the setpoint. You would always have some small amount of error. This is often called offset. Offsets are steady state errors that proportional control can't overcome alone. The Integral term senses this long term offset, and corrects the controller output to reduce the effect of offset (return to Figure 6.4).

The contribution of the integral term is proportional to "how big the error is and how long it lasts". It adds up all the instantaneous errors (areas under the curves-errors) over time and corrects the offset the system experiences with proportional-only control. A gain factor is applied to affect how the controller reacts.

Keep in mind that in a typical process, a VFD is tasked to respond to a single condition, such as a change in pressure or flow in the system. It is usually fed a signal from a pressure or flow transducer strategically placed to tell the VFD what the situation is so it can adjust its operation to maintain a required set point.

$$A_{out} = K_p \varepsilon + \boxed{K_i \int \varepsilon \Delta t} + K_d \frac{\Delta \varepsilon}{\Delta t}$$

$$A_{out} = K_I \int \varepsilon \, \Delta t$$

where :

A_{out} = controller output

K_I = integral gain

ε = process error

Δt = increment of time

Figure 6.7: Integral Component (with Gain Factor) of PID Algorithm

The integral term accelerates the movement of the process towards the setpoint and eliminates the steady-state error (offset) that occurs with a proportional-only controller. Integral gain can be set to change how quickly the integral response occurs. Figure 6.8 shows 2 different responses to a desired set point; one responds gradually and meets the set point curve smoothly, the other responds much more quickly, but overshoot and oscillates until it settles on the set point.

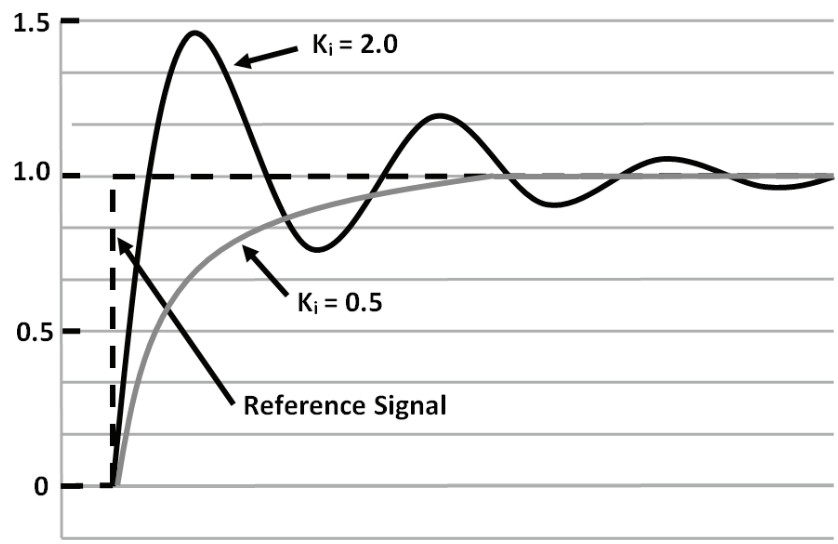


Figure 6.8: Integral responses based on various magnitudes of gain

Skill Builder

Lesson 6, Focus 3

1. Integral Control assists Proportional Control by doing what?

Focus 4: Derivative Control (The D in PID)

The derivative responds to the rate of change of the process error (take a moment and think about that). It reduces overshoot of the process control during sudden large disturbances. The differential element is only responsive during transient conditions (when conditions change) and is not active for steady state errors because their rate of change is zero. Just like with proportional and integral functions, applying a gain factor to the derivative function results in different responses.

$$A_{out} = K_p\varepsilon + K_i\int \varepsilon\Delta t + \boxed{K_d\frac{\Delta\varepsilon}{\Delta t}}$$

$$A_{out} = K_D\frac{\Delta\varepsilon}{\Delta t}$$

where:

A_{out} = controller output

K_D = derivative gain

$\frac{\Delta\varepsilon}{\Delta t}$ = change in error with time

Figure 6.9: Derivative component (with Gain Factor) of PID Algorithm

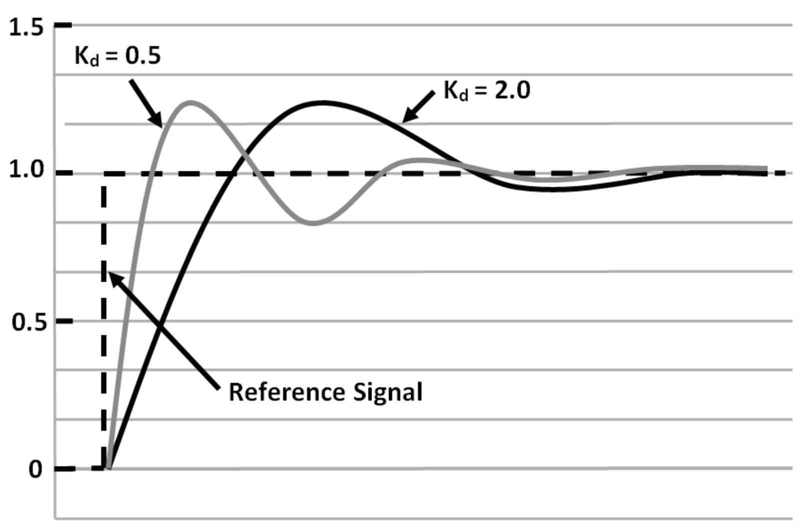


Figure 6.10: Derivative responses based on various derivative gain factors.

Skill Builder

Lesson 6, Focus 4

1. What does the derivative portion of the control algorithm respond to?

Focus 5: Putting It All Together: PID Control

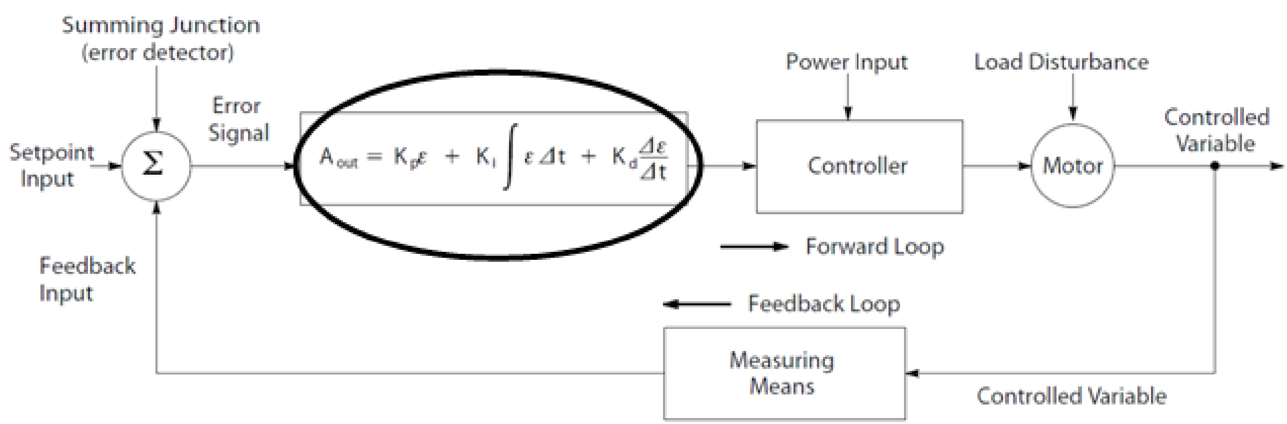


Figure 6.11: Closed loop control system showing the three components of PID control output.

If we look at Figure 6.11, it shows a full PID algorithm imbedded in a control loop. All 3 elements can contribute to controlling errors in the system, which is depicted in Figure 6.12.

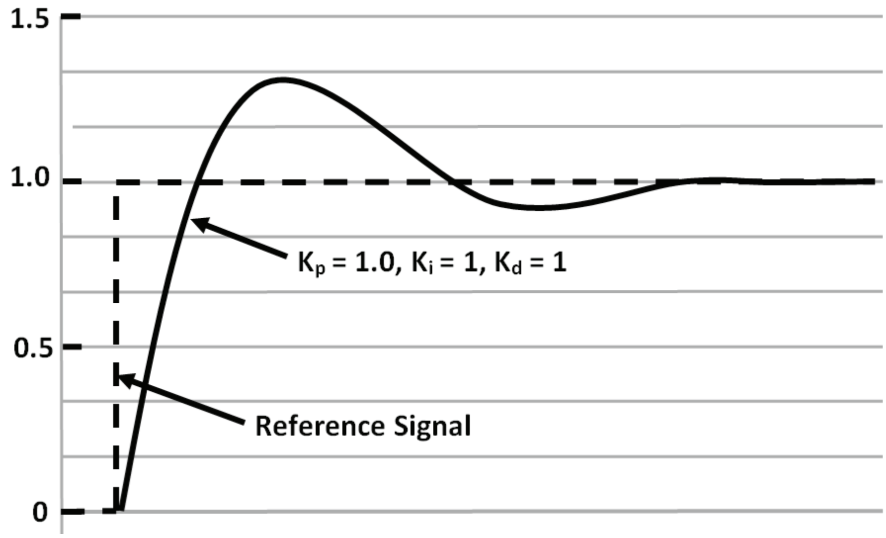


Figure 6.12: A system response using PID Control

Interestingly enough, in most pump applications, proportional and integral control (PI control) is sufficient for maintaining process control. The proportional control will amplify the output in proportion to the error signal and the integral control amplifies the output based on the accumulation of error with time. Proper selection of the gains for these two control elements is critical to the success of any closed loop control application. Figure 6.13 shows the response curves of the PumpLabTM centrifugal pump system when reacting to a step change of the pressure setpoint using differing values of proportional and integral gain. In this figure, the importance of proper gain settings is easily recognized.   Imagine a traffic cop monitoring the flow of traffic (in this situation, the proportional algorithm of the VFD controller) with his or her radar gun, trying to keep it from speeding off in one direction or another. You may like to refer to it as the "how much function". It does this by keeping track of the errors that occur and using that information to correct those errors in the future. Almost every time a VFD attempts to bring a change in system pressure back to the set point, it makes a mistake; that is, it initially misses the set point. There are many reasons for this; the way the algorithm was written for the application, data sampling rate, etc.

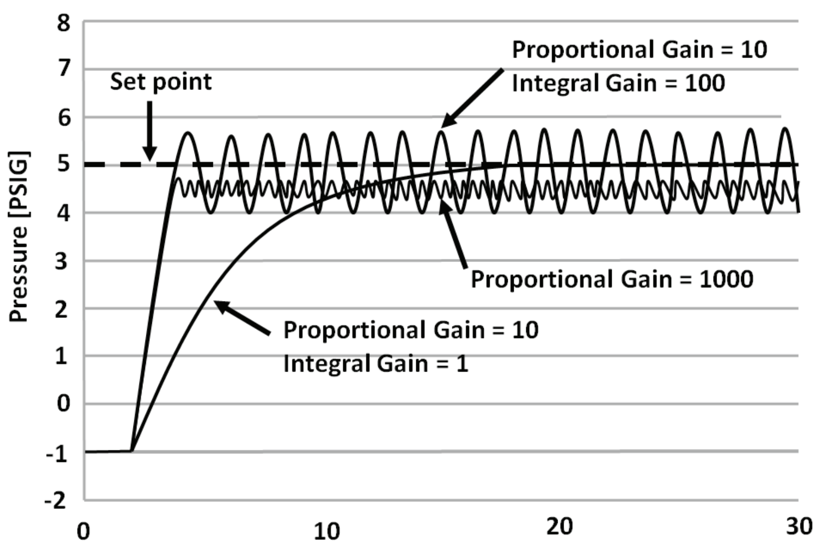


Figure 6.13: Pressure response of the PumpLabTM to a step change in the pressure setpoint using differing values of the proportional and integral gain.

Skill Builder

Lesson 6, Focus 5

1. What is the basic job of the Integral and Derivative functions?
2. What does the integral function do?
3. What does the derivative function do?

Knowledge Certification Quiz: Lesson 6

1. What is a control algorithm?

2. What is the primary attribute of proportional control?

3. What is the primary attribute of integral control?

4. What is the primary attribute of derivative control?

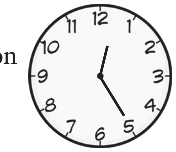
5. Can you have just a proportional algorithm for control?

6. Name a common proportional algorithm application.

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature ______________________   Date ______________________

Approximate Lesson
Duration: 25 min.



Lesson 7: Tuning Methodologies-An introduction to Gain

In this lesson students will learn about applying Gain to a control algorithm to optimize response.

Focus 1: Introduction to Gain

As we have discussed, the response of each PID control element can be adjusted by multiplying the error for each control element by a constant called gain. This constant can be changed during the operation of the system until the optimum response is reached. In the PID algorithm, the K elements signify the gain factors

The process of setting the optimal gains for P, I and D to get an ideal response from a control system is called tuning. There are different methods for tuning a PID loop, including; manual tuning (also known as a trial and error method), the Ziegler Nichols method, and tuning software.

$$A_{out} = K_p\varepsilon + K_i\int \varepsilon\Delta t + K_d\frac{\Delta\varepsilon}{\Delta t}$$

Figure 7.1: Control Algorithm

Focus 2: Manual Tuning-Trial and Error

The gain settings of a PID controller can be obtained by trial and error method. Once an engineer understands the significance of each gain parameter, this method becomes relatively easy. In this method, the I and D gain terms are set to zero first and the proportional gain is increased until the output of the loop oscillates (does not settle). As one increases the proportional gain, the system becomes faster, but care must be taken not make the system unstable. Once P has been set to obtain a desired fast response (with oscillations), the integral term is increased to stop the oscillations. The integral term reduces the steady state error, but increases overshoot. Some amount of overshoot is always necessary for a fast system so that it could respond to changes immediately. The integral term is tweaked to achieve a minimal steady state error. Once the P and I have been set to get the desired fast control system with minimal steady state error, the derivative term is increased until the loop is acceptably quick to its set point. Increasing the derivative term decreases overshoot and yields higher gain with stability but would cause the system to be highly sensitive to noise. Often times, engineers need to tradeoff one characteristic of a control system for another to better meet their requirements.

Focus 3: The Ziegler-Nichols Method

The Ziegler-Nichols method is another popular method of tuning a PID controller. It is very similar to the trial and error method wherein I and D are set to zero and P is increased until the loop starts to oscillate. Once oscillation starts, the ultimate gain K_u and the period of oscillations T_u are noted. The P, I and D are then adjusted as per the tabular column shown below.

Ziegler-Nichols Method			
Control Type	K_p	K_i	K_d
PID	$0.6\ K_u$	$2/T_u$	$0.125\ T_u$

Table 7.1- Ziegler-Nichols tuning, using the oscillation method

Focus 4: PID Tuning Software

Modern process facilities, especially with complex processes, can also utilize PID tuning and loop optimization software to ensure consistent results. These software packages will gather the data, develop process models of the system and suggest optimal tuning. There are a variety of programs available, including custom application developments.

Skill Builder

Lesson 7

1. Can you name three methods of applying gain to a PID process?
2. Can you just use P&I in a control system to get adequate control?

Knowledge Certification Quiz: Lesson 7

1. *What is gain?*
2. *What is the process called of setting optimal gains to get the desired control responses?*
3. *What does gain improve for each element of the control algorithm*

I certify that I have answered all certification quiz questions correctly and am ready for the next lesson.

Your Signature ____________________ Date ____________________

Notes:

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