



# Drives 101

## Lesson 4

### Application Terminology for a VFD



Screw Compressor  
VFD must be CT or VT?

This lesson covers the application terminology associated with a Variable Frequency Drive (VFD) and describes each term in detail.

When applying a Variable Frequency Drive (VFD) to a particular application, a number of terms are involved. This lesson attempts to clarify most of those terms.

Here is the basics outline for this lesson.

#### **Outline: Application Terminology**

1. Application Curves
2. Starting Torque
3. Open or Closed Loop
4. Closed Loop and PID
5. Different Types of VFDs

**Note:** There are other names for a VFD such as Adjustable Frequency Drive (AFD); Variable Speed Drive; Adjustable Speed Drive; Inverter and Frequency Converter. The name VFD is consistently used through out this lesson.



## Outline

### Application Terminology

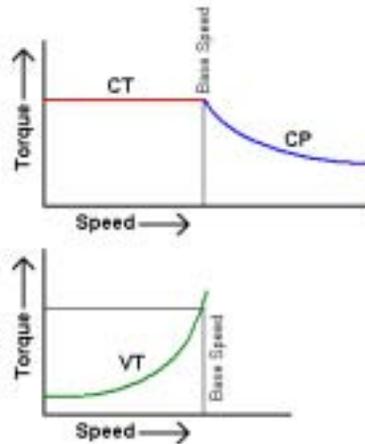
1. Application Curves – CT, CP, VT
2. Starting Torque – HO, Breakaway, NO
3. Open or Closed Loop
4. Closed Loop & PID – Action, Setpoint, Offset, Proportional, Integral, Derivative
5. Different Types of VFDs

This module covers some of the application terminology used with variable frequency drives (VFD). This terminology becomes very important for selecting the correct VFD and programming the correct settings needed for an application.

Applications include terms such as Constant Torque (CT), Constant Power (CP) and Variable Torque (VT). Starting Torque is also covered, which uses High Overload (HO), Breakaway Torque, and Normal Overload (NO). Terms such as speed open loop, speed closed loop and process closed loop are also covered. Terms in the process closed loop, also explore action, setpoint and PID terminology.

The last part covers a summary of the different types of VFDs. It shows the Volts/Hz, Voltage Vector, Flux Vector as they compare to a DC Servo in terms of response, accuracy and speed range. A more detailed explanation of each type is scheduled for a later lesson.

# 1. Application Torque Curves

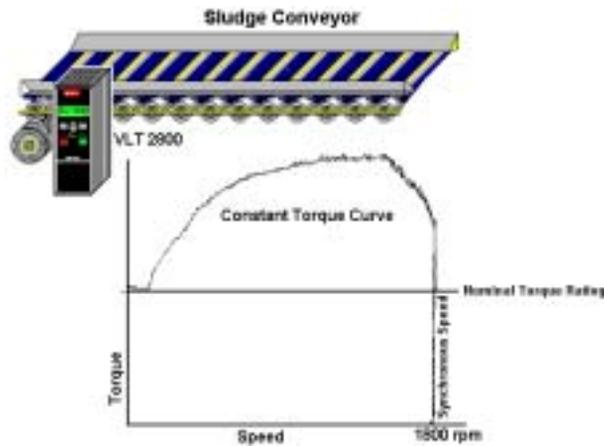


This part of the lesson covers the application terminology associated with a VFD, starting with application torque curves.

## VFD Application Terminology

1. **Application Torque Curves**
  - a) Constant Torque (CT)
  - b) Constant Power (CP)
  - c) Variable Torque (VT)
2. Starting Torque
3. Open or Closed Loop
4. Closed Loop & PID
5. Different Types of VFDs

## 1. a) Constant Torque (CT)



- CT are the majority of industry applications
- Torque stays relatively constant from 5Hz to 60Hz.
- AC motors have low torque at slow speeds.

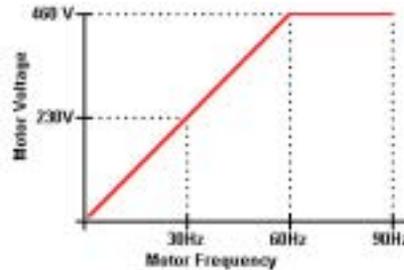
The graph above shows Torque in relationship to Speed. This graph was made when the VFD and loaded motor, were running at Synchronous Speed, 60 Hz, 1800 rpm on a 4-pole 3-phase AC motor. The speed of the VFD was slowly turned down to 0 Hz. Notice that the torque drops down to its nominal rating on an AC induction motor at the lower speeds, 5Hz or less.

**Constant Torque** applications require a constant level of torque throughout a process regardless of different speeds. The vast majority of industrial applications for a VFD are constant torque. Any applications that involve conveyors, mixers, elevators, feeders, hoists, bottling machines, screw compressors, and numerous others, are constant torque. In waste water, sludge conveyors are CT.

In the picture above constant torque must be maintained on the sludge conveyor. Notice that the torque curve drops when the speed is reduce below a minimum speed of about 5Hz. To compensate for this drop, some VFDs can perform “motor tuning” which matches the VFD settings to a particular motor. This “tuning” allows for more precise calculations by the VFD giving more torque throughout the CT curve, but particularly noticeable is the torque boost at those slow speeds from 1 to 10Hz.



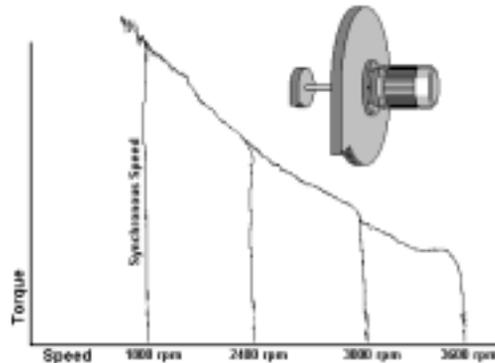
## Volts per Hertz Chart



- In order to keep a constant torque which is directly related to current, the voltage going from the VFD to the motor is increased as the speed increases. In the example above on a 460Vac motor, 460 Volts is only sent to the motor when the speed reaches 60Hz.

Constant Torque is achieved because the VFD is increasing the voltage to the motor as it increases the speed. This is displayed by the **Volts/Hz chart** shown above. In this chart, when the VFD sends a signal of 30Hz, it is also sending a 230Vac signal to the motor. When the VFD sends a 60Hz signal, the voltage is at 460Vac. This relationship keeps the current and in turn the torque to the motor relatively constant. The changes seen in the motor current are based on the load. Notice that when the speed reaches 60Hz, base speed, the voltage going to the motor from the VFD can not go higher, it has reached its limit, in the example above 460Vac. If the speed is increased above base speed, to say 90Hz, the voltage from the VFD stays at 460Vac, but the current and torque drop. This Volts/Hz chart is different with motors that use different voltages.

## 1. b) Constant Power (CP)

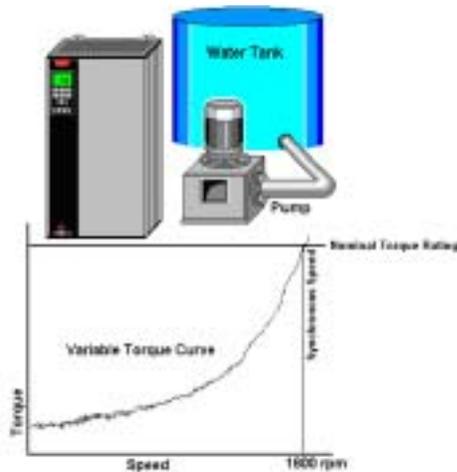


- CP applications are rare for the VFD.
- CP applications are always above base speed.
- Torque drops significantly above base speed (60Hz).

**Constant Power** applications are always run at speeds above base speed, 60Hz and higher. On a Constant Torque Curve, the area above base speed is known as the Constant Power Curve. The few applications that require these high speeds are typically saws, and grinders. A Constant Power setup for a VFD is NOT used in the Water-Wastewater industry.

In the example above, notice that the torque curve drops off above 60Hz (1800rpm). It is at this point that the voltage being sent to the motor can NOT be increased, it has hit its maximum limit. As the drive continues to increase the speed, and with the voltage staying the same, the current to the motor starts to drop off, which means that the torque drops as well.

## 1. c) Variable Torque (VT)



- VT applications save a great deal of energy
- Used with centrifugal pumps and centrifugal fans.

**Variable Torque** (VT) applications almost always involve centrifugal pumps and centrifugal fans. The vast majority of VFD applications in the Water-Wastewater industry are VT. The torque required to operate a pump or fan is very low until it starts to approach its base speed, 60Hz. There are formulas that show the relationship of power to rpm. Ideally, assuming no friction losses, the pump at half the speed only requires 1/8 the power. VFDs on VT applications save a great deal of energy and money. Once above base speed, a fan or pump requires a considerable amount of power, so they are rarely run above 60Hz.

A point of clarification between Synchronous speed and base speed is useful.

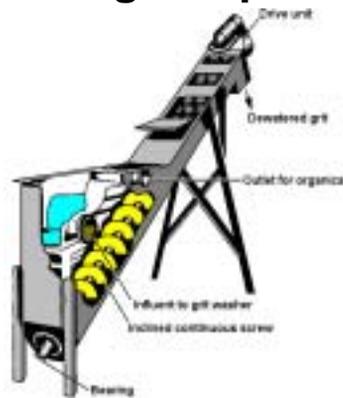
**Synchronous speed**, in an induction motor, is the RPM of the magnetic field when the motor reaches its nameplate voltage and frequency. The formula for synchronous speed is as follows:

$$\text{Synchronous speed} = (\text{Motor frequency}) * 120 / (\# \text{ poles})$$

$$\text{Example: } 60\text{Hz} * 120 / 4 \text{ poles} = 1800\text{RPM}$$

**Base Speed** is the speed in rpm that results when the motor is at its nameplate voltage, frequency and current. Most Asynchronous 4-pole induction motors using 60Hz have a base speed between 1725 to 1770rpm.

## 2. Starting Torque



**Grit Separator**

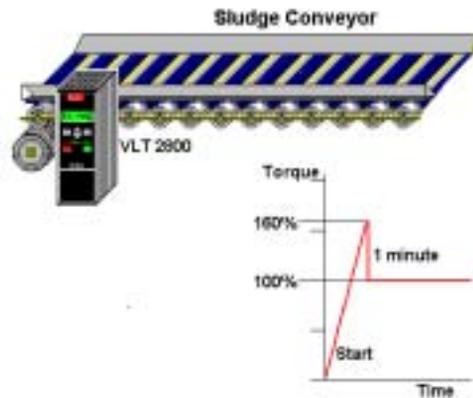
This part of the lesson covers the application terminology associated with starting torque.

### Outline:

#### **VFD Application Terminology**

1. Application Torque Curves
2. **Starting Torque**
  - a) High Overload (HO)
  - b) Breakaway Torque
  - c) Normal Overload (NO)
3. Open or Closed Loop
4. Closed Loop & PID
5. Different Types of VFDs

## 2. a) High Overload (HO)

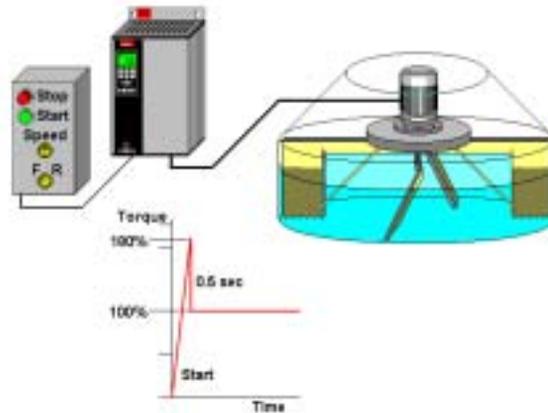


- High Overload allows 160% starting current for 1 min.
- Most CT applications require High Overload.
- If drive exceeds 160% or 1 minute, the VFD trips.

**High Overload (160%)** is used to apply the torque to start a load. The inertia to start a grit separator, or in the example above a sludge conveyor requires a great deal of starting torque. It can be as high as 160% of the current for 1 minute. Once started the torque drops back to 100% or less. If the load does not move and the drive exceeds 160% or exceeds 1 minute, the drive trips, which means that the VFD does not move the motor. This trip gives an Over-current or Torque Limit alarm and for protection sake a reset button must be pressed to clear the alarm and restart the VFD. Some VFDs have a High Overload limit of 150% for 1 minute.

## 2. b) Breakaway Torque

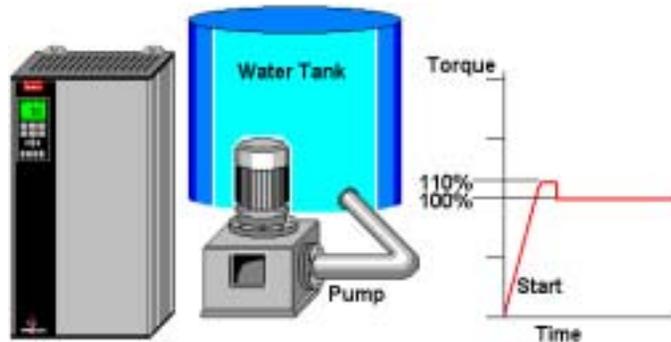
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- High Overload has a breakaway torque that allows 180% starting current for 0.5 seconds.
- If drive exceeds 180% or 0.5 seconds, VFD trips.

**Breakaway Torque (180%)** also known as Starting Torque, usually refers to the first 0.5 seconds after start. In the example, a mixer has a very thick substance, perhaps a batch of adhesive. When the VFD starts to turn the motor the resistance of the substance is very high. The VFD increases the current output up to 180% for half a second to get the mixer started. Once it starts, the VFD continues at the High Overload setting of 160% for 1 minute. If it does not move, the VFD trips for protection of the VFD, motor and mixer.

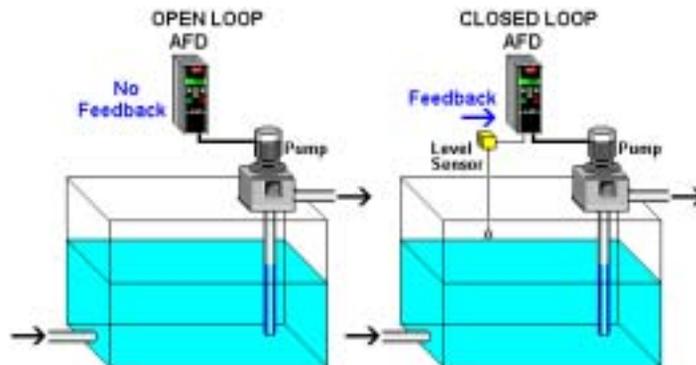
## 2. c) Normal Overload (NO)



- Normal Overload has a starting torque that allows 110% starting current for 1 minute.
- Most VT applications require Normal Overload.
- VT VFDs are sized differently – 200Hp (132kW) for CT; 250Hp (160kW) for VT

**Normal Overload (110%)** is almost always used with VT applications basically with centrifugal fans and pumps. When a centrifugal pump is started it takes very little starting torque to turn the impeller against water, so the 110% limit is adequate. If the 110% for 1 minute is exceeded, again the VFD trips. Since the current output on starting is less for VT applications, smaller VFDs can operate slightly larger motors. If a 200Hp (132kW) VFD which is normally Constant Torque (CT) has a VT setting, the VFD could be used to operate a 250Hp (160kW) motor with little difficulty.

### 3. Open or Closed Loop



- All applications fall into 2 categories, Open Loop or Closed Loop
- Closed loop has additional settings which include controller action, setpoint, and PID settings

#### Outline:

#### VFD Application Terminology

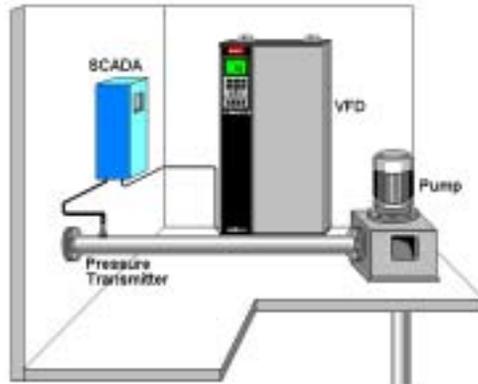
1. Application Torque Curves
2. Starting Torque
3. Open or Closed Loop
  - a) Open Loop
  - b) Closed Loop
4. Closed Loop & PID
5. Different Types of VFDs

A quick definition for Open and Closed Loop is shown here.

Open Loop control does NOT have a direct feedback signal.

Closed Loop has a direct feedback signal coming into the VFD.

### 3. a) Open Loop



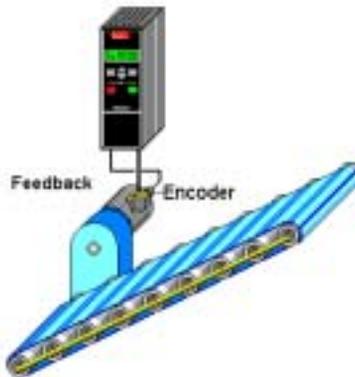
- The VFD is programmed for open loop, because there is NO feedback signal going to the VFD – but the system using the SCADA is a closed loop system.

**Open Loop** does NOT have a direct feedback signal to the VFD.

In the example above, a pressure sensor is wired to a SCADA controller. The closed loop inside SCADA calculates a reference signal. This reference signal is sent to the VFD, which in turn controls the motor and pump. In this example the VFD is programmed for Open Loop. It receives a reference command from SCADA controlling the pressure in the pipe. Because the feedback signal, pressure, goes to the SCADA, a closed loop must be setup inside SCADA to control the pump. SCADA then sends a reference signal to the VFD for proper modulation of the pump. If the pressure sensor were wired directly into the VFD, then the drive would need to be programmed for Closed Loop in order to have proper control of the pump.

The system is a closed loop system because it senses its own action, but the VFD is programmed for open loop.

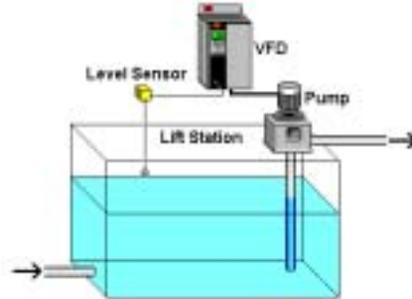
### 3. b) Speed Closed Loop



Speed Closed Loop requires an encoder to feedback the RPM signal to the VFD letting it know the speed of the motor.

**Speed Closed Loop** has feedback coming from an encoder which gives a fixed number of pulses (example: 4096) every time the motor makes one revolution. This rating is known as PPR or pulses per revolution. The speed closed loop configuration for the VFD monitors the encoder to match the speed reference or setpoint, perhaps 950rpm. A proportional gain setting is used for modulation, an integral setting and perhaps a derivative setting. These terms are covered later in this lesson. In some VFDs, the default settings are adequate for proper control of speed. Speed Closed Loop is far more common in Industrial applications.

## 4) Closed Loop



- Sensor monitors the feedback signal.
- Controller, the VFD, gives the sensor a desired value, action and PID settings and calculates a response.
- Controlled Device, the pump, responds to the signal from the controller, increasing or decreasing in speed.

**Closed Loop** is where the controller inside the VFD can be used to modulate the speed of a motor to maintain a process. It is the job of the **sensor** or transmitter to measure a variable, in the example above, this is water level. This sensor sends a signal (usually a 4-20mA) to the controller.

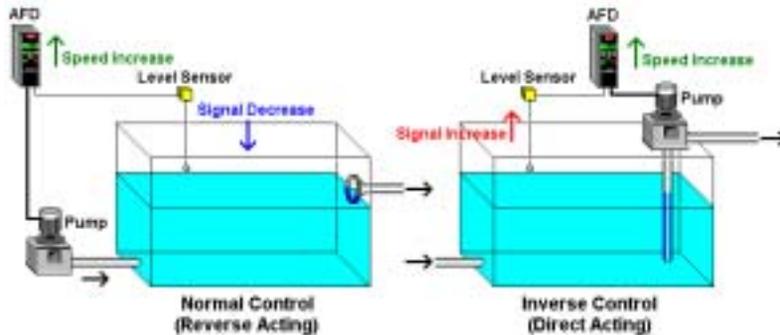
The sensor is wired to the current input of the VFD, the **controller**. This signal is programmed in the VFD as the feedback signal. This feedback signal must be given engineering units, say "feet" or "meters". The feedback signal must also be given a range that matches the sensor. For example, when the sensor sees 4mA it is 0 feet (0 meters) and when the sensor sees 20mA, the reading is 10 feet (3 meters).

The VFD, controller, has a setpoint, action and PID settings (explained later) to calculate the response necessary to maintain the desired value seen at the sensor. The VFD sends a signal to the pump to speed up or slow down to maintain a certain level.

The pump, **controlled device**, responds to match the signal from the VFD, controller. It speeds up when the level of the water increases and slows down when the level of the water drops.

## 4. a) Control Action

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Normal Control – as the incoming signal **decreases** the output speed increases.

Inverse Control – as the incoming signal **increases** the output speed increases

In process closed loop applications, the VFD must always be programmed for the correct action. There are 2 choices:

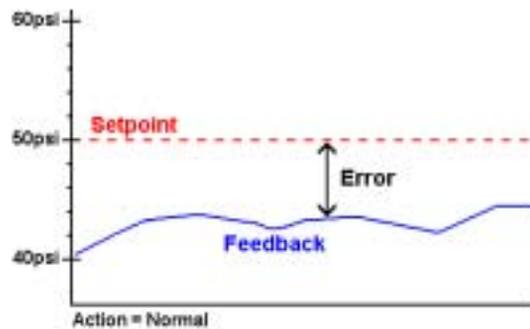
(Note: different controllers use different terms for the same function.)

**Normal Control** (also known as Reverse Acting). As the signal from the sensor increases above the setpoint the output from the VFD decreases. Notice the tank on the left. The action is correct if the sensor is downstream from the controlled device, pump. As the level sensor sees an increase, the signal to the pump decreases, slowing the pump down. As the level sensor sees a drop, the speed of the pump increases.

**Inverse Control** (also known as Direct Acting). As the signal from the sensor increases above the setpoint the output from the VFD increases. This action is correct if the level sensor is upstream from the pump as pictured by the tank on the right.

If the wrong action (Normal) were programmed in the VFD in the tank application on the right, the pump would slow down as the level in the tank rose higher. Eventually the water in the tank would overflow. If the incorrect action is programmed in an application the VFD is locked at minimum or at maximum speed.

## 4. b) Setpoint, Error & Gain



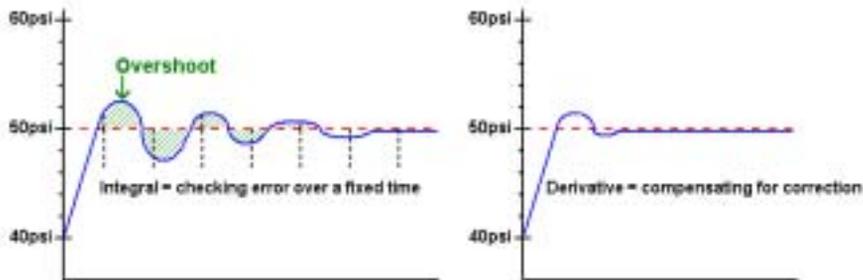
- Setpoint or reference is the desired value for a controlled variable; example: 50psi (345kPa).
- Error (offset) is the amount the feedback is from setpoint at any given time, example: 7psi (45kPa)
- Proportional Gain is a multiplier times the error (offset). Example above the Gain starts at 0.3

**Setpoint** is the desired value or reference of the controlled variable for a process closed-loop application. In the example above, 50psi (345 kPa) is the desired setpoint or reference.

**Error** is a difference between the setpoint, 50psi (345 kPa) and the actual feedback pressure, 43psi (300 kPa) for the system. This difference is also known as Offset (off the setpoint).

**Proportional Gain** is multiplied by the error to create an output. The larger the proportional gain, the larger the output change for a given error. If the proportional gain is too small (0.01) this multiplier times the error has no effect on the speed of the VFD. If the proportional gain is too large (3.00 or higher) the system can become unstable, modulating between minimum speed and maximum speed which is called "hunting". A good starting place for the Proportional Gain is about 1.00 but changes depending on the application. If Proportional Gain is only used, without I or D (explained on the next slide), the output is relatively close to setpoint but there is always an error.

## 4. c) Integral & Derivative

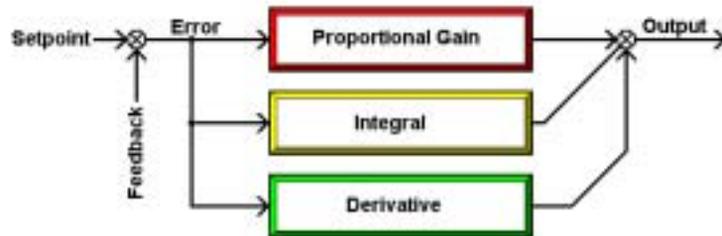


- Integral checks the offset over a period of time and makes corrections.
- Derivative checks the offset and corrects for the speed of the integral correction.

**Integral** Gain is based on the history of the error. The integral function maintains a running total of the error and creates an output based on this total. The lower the number used for the integral gain the more frequently the error is checked and the larger its influence. If the integral time is too low (less than 5 seconds), the system can become unstable and starts to hunt. A good place to start is 10 seconds, but again this can vary based on the application. Integral gain eliminates the steady error inherent to proportional control. As pictured above, integral gain adds overshoot, but eventually settles close to setpoint.

**Derivative** or differential is based on the rate of change of the error. It is used to limit overshoot and dampen system oscillation. The larger the derivative time, the larger the influence. If the derivative time is too large, the system becomes unstable. Derivative is very sensitive to noise on the feedback signal and historically seldom used in process control systems. In speed closed loop applications, derivative is used extensively.

## 4. b) PID



**Summary:** There are many different PID algorithms. All contain these 3 features, Proportional Gain, Integral, and Derivative. The ways these terms are combined may be different.

In some implementations the 3 values operate independently of each other and in others, changing one value effects the others.

**Proportional Gain** contributes to the output in a direct relationship to the error between the feedback and setpoint.

**Integral** contributes to the output based on the history of the error.

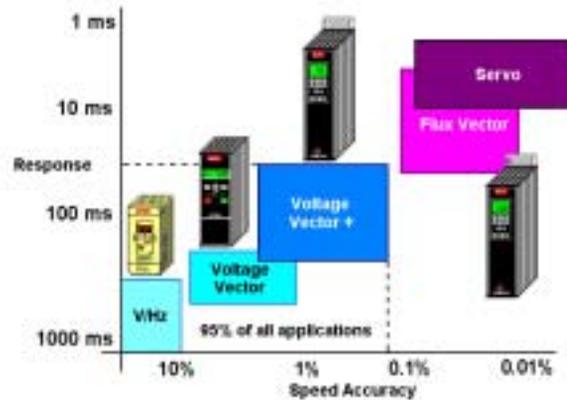
**Derivative** contributes to the output based on the rate of change to the error.

**Setpoint** is the desired value for the variable being controlled.

**Feedback** is the actual value of the variable being controlled.

**Error** (offset) is the difference between the setpoint and feedback

## 5) Different Types of VFDs



There are different types of VFDs, which are briefly covered here. They include Volts/Hz, Voltage Vector, Voltage Vector +, Flux Vector and Servo.

**Volts/Hz** drives also known as a Basic Scalar drives, are the least expensive drive with the least features. This drive is usually setup for CT and Open Loop only.

**Voltage Vector** drives also known as Space Vector drives have more features and may have the ability to do both CT/VT and Open/Closed Loop.

**Voltage Vector Plus** drives have more features than the others and therefore have more cost than previously mentioned drives. They can calculate motor characteristics without spinning the shaft of the motor.

These previous 3 types of VFD account for 95% of all applications. There are a few that need greater accuracy which follow.

**Flux Vector** drives have more calculations which makes them more expensive and more accurate. Some Flux vector drives require special motors.

**Servo** drives are DC and do not operate with AC induction motors. They are expensive in comparison to VFDs. They are the most responsive to dynamic changes.

These drive types are explored in greater detail in a later lesson.

## 5) Different Types of VFDs



### Summary:

<u>Type</u>	<u>Response</u>	<u>Accuracy</u>	<u>Speed Range</u>
V/Hz	500 – 1000ms	10% +	10:1 – 180rpm
Voltage Vector	200 – 700ms	2% - 8%	50:1 – 36rpm
Voltage Vector +	50 – 300ms	0.2%-2%	Open 100:1 – 18rpm Closed 900:1 – 2rpm
Flux Vector	5 – 60ms	0.02% - 0.1%	1400:1 – 1.3rpm
Servo	2 – 8ms	0.007% - 0.08%	1800:1 – 1rpm

As a comparison above, each type of motor control shows,

Response to dynamic changes

Accuracy and

Speed Range.

Speed Range indicates how slow the motor can turn but still have proper operation. Speed Range is always indicated as a ratio. The higher the ratio the better control at slow speeds. The minimum rpm for each type has been calculated, assuming 1800 base speed.

Voltage Vector Plus has 2 values, one for open loop and the other for closed loop.

This completes this lesson.

There are Review Questions in the Post-Test section.