



# VFD 101

## Lesson 4

### Application Terminology for a VFD



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:** Other names are used for this device, such as Adjustable Frequency Drive (AFD), Variable Speed Drive (ASD), Frequency Converter and Inverter, but Variable Frequency Drive (VFD) or just Drive is used throughout this lesson.



## Outline

### Application Terminology

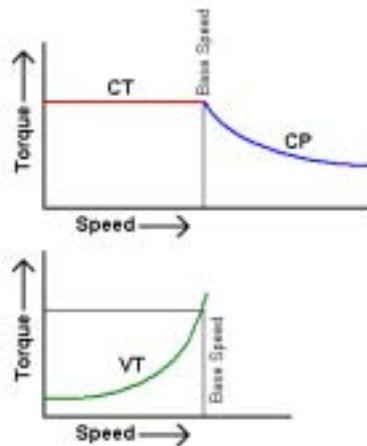
1. Application Curves – CT, CP, VT
2. Starting Torque – HO, Breakaway, NO
3. Open or Closed Loops
4. Closed Loop & PID – Action, Setpoint, Offset, Proportional, Integral, Derivative
5. Different Types of VFDs

This module covers some of the application terminology used with VFDs. 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 open loop and closed loop are also covered. Terms in 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

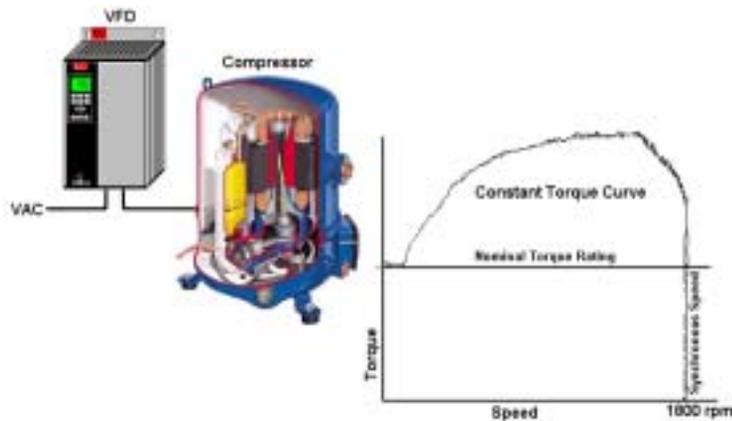


This part of the lesson covers the application terminology associated with a VFD, starting with application torque curves.

## 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)



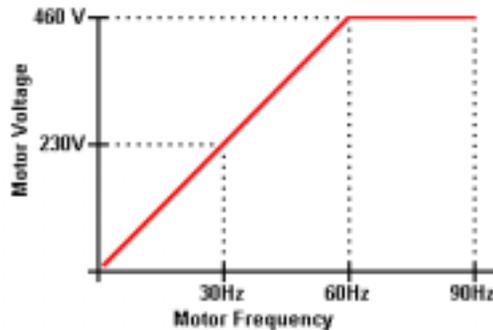
- CT used on Reciprocating Compressors
- Torque stays relatively constant from 5Hz to 60Hz.
- AC motors have low torque at slow speeds.

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. Please be aware that this particular CT application, reciprocating compressor, should never run less than 30Hz.

**Constant Torque** applications require a constant level of torque throughout a process regardless of different speeds. The vast majority of constant torque applications are for industry, which involve conveyors, mixers, elevators, feeders, hoists, and bottling machines. In HVAC reciprocating compressors, and positive displacement pumps might be encountered which require CT. Some VFD manufacturers attempt to apply a CT drive to fans and pumps used in HVAC, because they do not make a specific VFD for variable torque applications. More information is given in the pages that follow.

On most CT applications, constant torque must be maintained from 1 to 60Hz. Notice that the torque curve drops when the speed is reduce below a minimum of 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. In HVAC, "Motor tuning" is only a slight advantage for fans and pumps, saving only a small portion of energy. Because of motor cooling, most fans and pumps have a minimum speed of 10Hz or greater.

## Volts per Hertz Chart

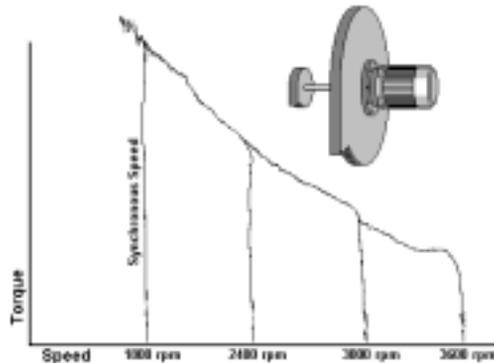


- Voltage increases as speed increases
- CT – linear relationship between volts and hertz
- 30Hz = 230V; 60Hz = 460V on 460VAC motor

VFDs attempt to generate the correct level of torque needed for its application. Torque is directly related to current. In CT applications, voltage going from the VFD to the motor is increased in a linear manner 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 and higher.

The chart above displays the **Volts/Hz** relationship for a CT application. Constant Torque is achieved because the VFD is increasing the voltage to the motor as it increases the speed. In this chart, when the VFD sends a signal of 30Hz, it is also sending a 230V signal to the motor. When the VFD sends a 60Hz signal, the voltage is at 460V. 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, 460V. If the speed is increased above base speed, to say 90Hz, the voltage from the VFD stays at 460V, but the current and torque drop. This Volts/Hz chart is different for motors that use different voltages.

## 1. b) Constant Power (CP)



- CP applications are rare for the VFD, none in HVAC.
- CP applications are always above base speed.
- Torque drops significantly above base speed (60Hz).

**Constant Power** applications are run at synchronous speed, 60Hz and higher. On a CT Curve, the area above synchronous speed is known as the Constant Power Curve. As speed continues above 60Hz, torque continues to drop. The few applications that require these high speeds are typically saws, and grinders, and no applications in HVAC.

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

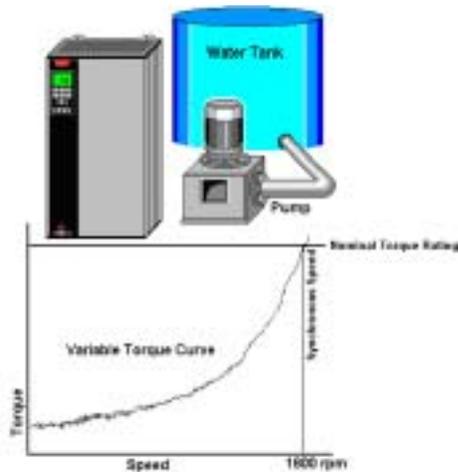
**Synchronous speed**, in an induction motor, is the RPM of the magnetic field when the motor reaches its nameplate voltage and frequency. The formula for synchronous speed is as follows:

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

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

**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.

## 1. c) Variable Torque (VT)

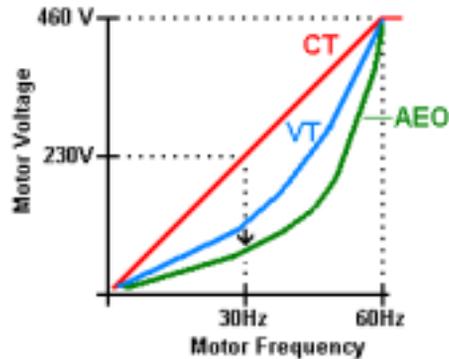


- VT applications save a great deal of energy
- Used with centrifugal pumps and centrifugal fans.

**Variable Torque** (VT) applications almost always involve centrifugal pumps and centrifugal fans. If a VFD manufacturer has an HVAC drive, it is most likely designed and programmed for VT applications only, such as the VLT 6000 from Danfoss. The torque required to operate a pump or fan is very low until it starts to approach its base speed, say 1750rpm at 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.



## Automatic Energy Optimization (AEO)



- VT – voltage lower at speeds than CT
- AEO - Reduces voltage until speed is effected
- 30Hz = 160V straight VT; 90V with AEO

A couple of VFD manufacturers, such as Danfoss, offer Automatic Energy Optimization (AEO). This is used in all VT applications. This function automatically and continuously monitors and adjusts the output voltage to maximize energy savings. After the motor reaches the set speed, say 30Hz, the AEO function reduces the output voltage to the motor, if the load allows. When the load is light, the voltage is reduced perhaps from 160V to 90V. This reduced voltage not only saves energy, but reduces motor heating, motor noise, and increases efficiency.

## 2. Starting Torque



Centrifuge

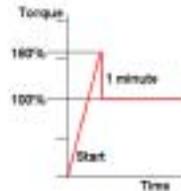
This part of the lesson covers the application terminology associated with starting torque.

### 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)

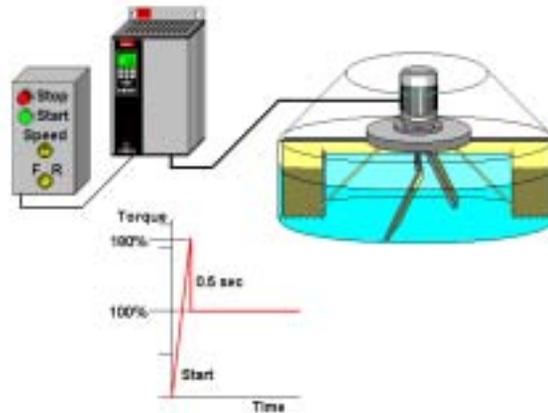


- High Overload allows 160% starting current for 1 min.
- Most CT applications require High Overload.
- If drive exceeds 160% or 1 minute, VFD trips.

**High Overload (160%)** is used to apply the torque to start a load. The inertia to start a reciprocating compressor, a positive displacement pump or in the example above a hoist 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. It is possible to use a High Overload or CT Start to get a fan or pump moving, but most HVAC applications do not require High Overload.

## 2. b) Breakaway Torque

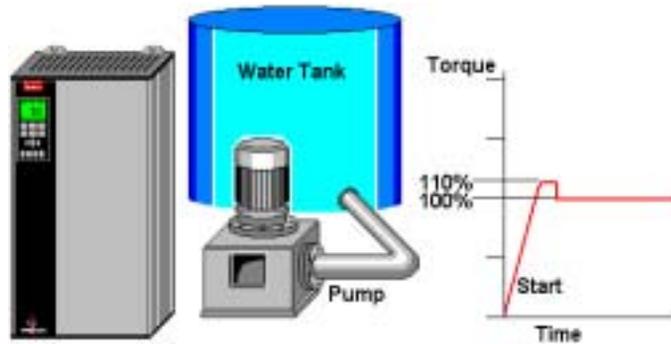
*Danfoss*



- 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. This is rarely needed for HVAC applications.

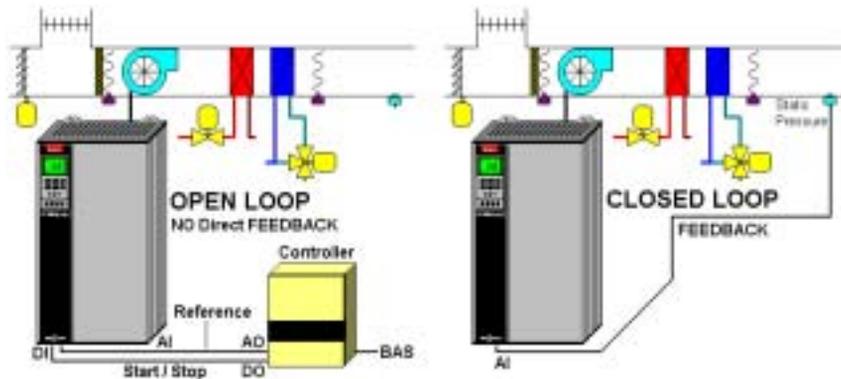
## 2. c) Normal Overload (NO)



- 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 for CT; 250Hp for VT

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

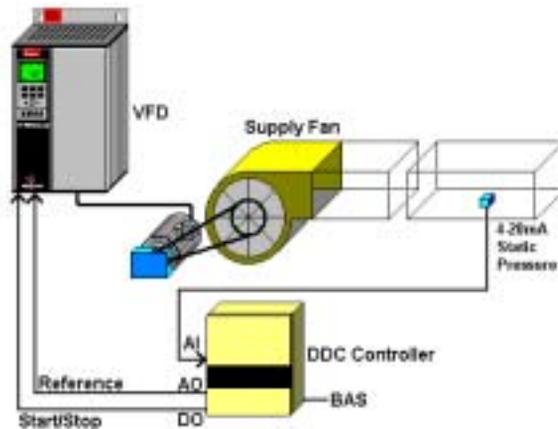
1. Application Torque Curves
2. Starting Torque
3. Open or Closed Loop
  - a) Open Loop
  - b) Closed Loop
4. Closed Loop & PID
5. Different Types of VFDs

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 is closed loop.

**Open Loop** control does NOT have a direct feedback signal.

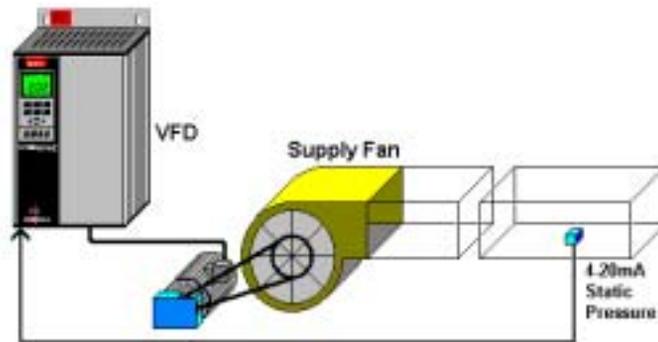
In the example above, a static pressure sensor is wired to a Direct Digital Controller (DDC). Because the feedback signal, pressure, goes to the Controller, a closed loop must be setup in it to control the static pressure. This closed loop inside the Controller monitors the pressure comparing it against a setpoint and then calculates a reference signal. The Controller then sends this reference signal to the VFD for proper modulation of the fan.

The reference signal is sent to the VFD, which in turn controls the motor and fan. In this example, the VFD is programmed for Open Loop and it receives a reference command from the Controller. 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 fan.

The system is a closed loop system because it senses its own action, its feedback, but because the feedback signal does not go directly to it, the VFD is programmed for open loop.

## 4) Closed Loop

*Danfoss*



- 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 fan, responds to the signal from the controller, increasing or decreasing in speed.

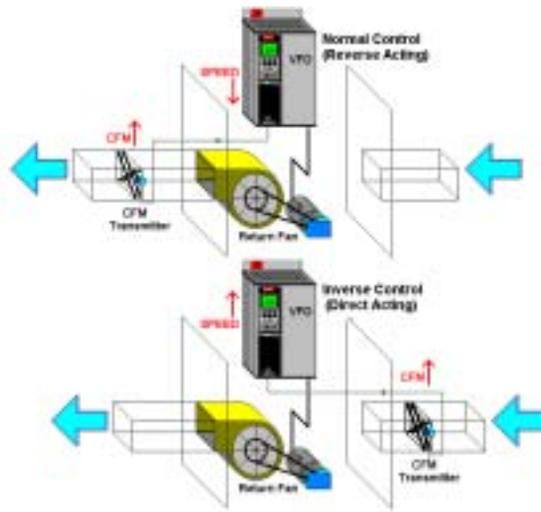
**Closed Loop** is where the controller inside the VFD can be used to modulate the speed of a motor to maintain a process. It is the job of the **sensor** or transmitter to measure a variable, in the example above, this is static pressure. This sensor sends a signal (usually a 4-20mA) to the controller over a particular range, in this example from 0" to 5"wc.

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, from our example, "inches of water column ("wc)" or "Pascals". Inside the VFD the feedback signal must also be given the range that matches the sensor. When the sensor sees 4mA it is 0"wc (0 Pascals) and when the sensor sees 20mA, the reading is 5"wc (1250 Pascals).

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 fan to speed up or slow down to maintain a certain level.

The fan, **controlled device**, responds to match the signal from the VFD, controller. It speeds up when the level of the static pressure decreases and slows down when the level of the static pressure is too high.

## 4. a) Control Action



Normal Control – incoming signal **increases**; VFD speed **decreases**.

Inverse Control – incoming signal **increases**; VFD speed **increases**.

In closed loop applications, such as controlling pressure by monitoring the volume of return air, shown above, the VFD must always be programmed for the correct action. There are 2 choices:

**Normal Control** (also known as Reverse Acting). In the top return fan example, when the CFM Transmitter sends a signal that indicates it is above the setpoint, the output from the VFD decreases. The action is correct if the sensor is downstream from the controlled device, the return fan. As the CFM sees an increase, the signal to the fan decreases, slowing the fan down. As the CFM transmitter sees a drop, the speed of the fan increases.

**Inverse Control** (also known as Direct Acting). In the bottom return fan example, when the signal from the CFM Transmitter increases above the setpoint, the output from the VFD increases. This action is correct if the CFM transmitter is upstream from the return fan.

If the wrong action (Inverse) were programmed in the VFD on the top return fan, it would speed up as the CFM in the duct rose higher. Eventually the speed of the return fan would go to its maximum. This could put a major stress on the ductwork. If the incorrect action is programmed in an application the VFD ends up locked at minimum or at maximum speed.

## 4. b) Setpoint, Error & Gain



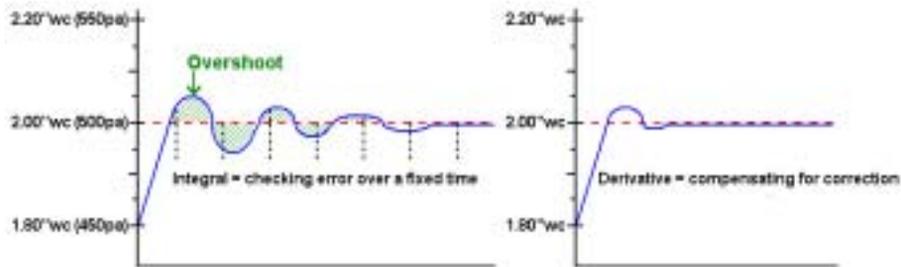
- Setpoint or reference is the desired value for a controlled variable; example: 2.00"wc (500pa).
- Error (offset) is the amount the feedback is from setpoint at any given time, example: 0.15"wc (38pa)
- Proportional Gain is a multiplier times the error (offset). Example above the Gain starts at 0.3

**Setpoint** is the desired value or reference of the controlled variable for a closed loop application. In controlling static pressure, shown above, 2.00"wc (500pa) is the desired setpoint or reference.

**Error** is a difference between the setpoint, 2.00"wc (500pa) and the actual feedback pressure, 1.85"wc (462pa) for this system. This difference is also known as Offset (or 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

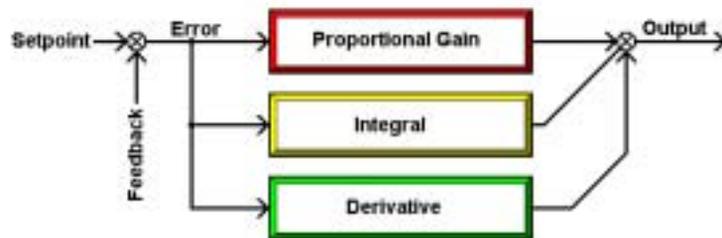


- Integral checks the offset over a period of time and makes corrections.
- Derivative checks the offset and corrects for the speed of the integral correction.

**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 every time the load changes, but eventually settles close to setpoint. Integral is used frequently in HVAC applications.

**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 HVAC closed loop systems.

## 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.

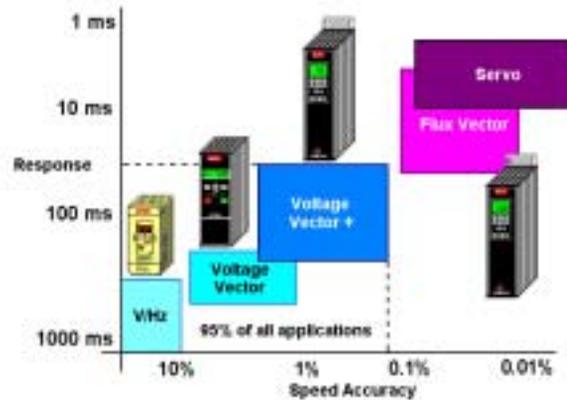
**Setpoint** is the desired value for the variable being controlled.

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

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

**Hunting** is an unstable condition which causes the speed of the motor to continuously vary from maximum to minimum.

## 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 last 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.