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Variable Frequency Drive Control Methods

Setting VFDs for the Correct Control Method Can Make or Break an Application

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Control Methods and PWM

A typical variable frequency drive (VFD) can have anywhere from a few hundred to well over a thousand parameters. Knowing which ones to adjust and to what setting can be intimidating. Which parameters are important and which ones not so much? Arguably, one of the most important, and sometimes misunderstood, VFD parameters is the one which determines the “Control Method”. Setting a VFD for the correct control method can make or break an application. Once an understanding of the advantages, disadvantages, and particular specifications for each control method is established, choosing the right one for your application is simple.

First of all, what is a “Control Method?” Many people in the industry think a control method is the sequencing method used to control a VFD; as in a 2-wire or 3-wire setup. A 2-wire or 3-wire setup will set the VFDs input control terminals to interface to either maintained contacts or momentary push buttons to start and stop the VFD. The control method which this article is focusing on actually determines how the VFD controls motor operation. You can call it a motor control method to further distinguish it. With this bit of knowledge, it should now be obvious why this is of huge importance for all applications.

There are 4 primary types of motor control methods used to control induction motors connected to a VFD. They are: V/f (volts-per-hertz), V/f with encoder, Open Loop Vector, and Closed Loop Vector.

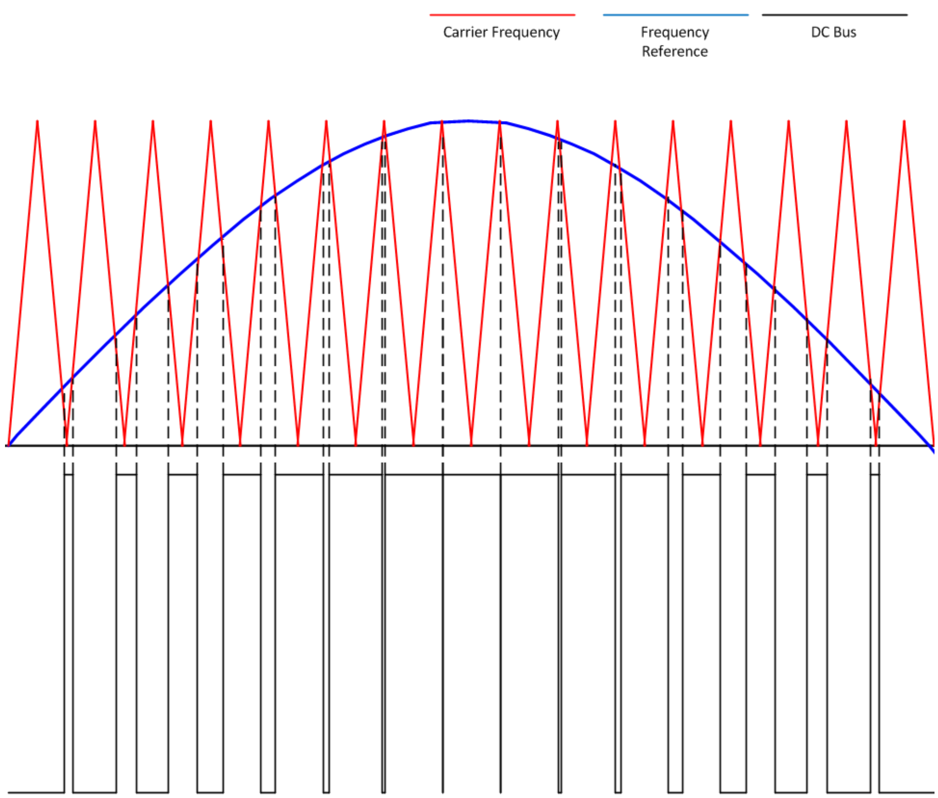

Figure 1: Pulse Width Modulation is used to Control an AC Motor

Before defining these motor control methods and deciphering what makes each one unique, there is one commonality shared by all four. That commonality is Pulse-Width Modulation (PWM). PWM is a technique which varies the width of a fixed signal by modulating pulse duration to represent a variable analog signal. PWM is applied to VFD’s by using the fixed DC voltage from the VFD’s DC bus capacitors. A set of Insulated Gate Bi-polar Transistors (IGBT’s) on the output rapidly open and close to produce pulses. By varying the width of the output pulses in the output voltage waveform, a simulated AC sine wave is constructed (See **Figure 1**). Even though the drives output voltage waveform consists of square waves due to DC pulsing, the current waveform will be sinusoidal since the motor is inductive. All motor control methods use a PWM voltage waveform to control the motor. The difference between the control methods lies in the process used to calculate what voltage the motor needs at any given moment.

V/f

Volts-per hertz, commonly called V/f, can be deemed as the simplest motor control method. This method is often preferred due to its "plug-n-play" simplicity. This method is considered plug-n-play since very little motor data is needed by the drive. Tuning the VFD to the connected motor is not required (but still recommended). No motor encoder is required. A motor encoder is a simple electro-mechanical device usually mounted on the rear of a motor enclosure and coupled to the motor shaft. Motor shaft rotation will generate a series of electrical pulses per revolution(PPR). These pulses are relayed back to the VFD and used as speed feedback. The V/f control method does not utilize an encoder. This results in lower cost and less wiring. The V/f control method is often used when there is a demand for high frequency operation which could easily exceed 1000 Hz. Most machine tool and spindle applications use the V/f control method for this advantage.

Another advantage is that V/f is the only control method which allows for multiple motors to be run off of a single VFD. When running multiple motors, all motors will start and stop at the same time, as well as follow the same speed reference.

Some limitations are, the VFD has no guarantee that the motor shaft actually is rotating. Additionally, starting torque of the motor is limited to 150% @ 3 Hz. Though this starting torque specification can be categorized as a disadvantage, this will be more than enough starting torque for most variable torque applications. In fact, just about every variable torque fan and pump application in the field today is running the V/f control method.

Since V/f is a relatively simple control method it also has some "looser" specifications. Speed regulation is typically +/- 2 to 3 % of maximum frequency. Speed response is rated at 3 Hz. Speed response is defined as how well the VFD can respond to a change in the frequency reference. An increase in speed response results in a faster motor response when the frequency reference is changed.

Each control method also has a speed control range expressed as a ratio. V/f's speed control range is 1:40. If we multiply this ratio by maximum frequency we can determine the minimum speed which the VFD can run and still maintain control of the motor. For example, with a 60 Hz maximum frequency and 1:40 control range, a drive using the V/f control method can control a motor all the way down to 1.5 Hz.

What sets V/f control apart from other control methods is how the output voltage sent to the motor is determined. This control method uses what is called a V/f pattern. A V/f pattern defines a ratio of voltage to frequency for the motor to follow. At a given speed reference a corresponding voltage will be output to the motor. This ratio is often optimized with a custom set profile or a preset for the application and motor being used. Applications such as fans and pumps are variable torque loads. A variable torque V/f pattern should be used to prevent faults and increase performance and efficiency. The same goes for constant torque applications such as conveyors, extruders, hoists, etc. A constant torque V/f pattern should be chosen for a constant torque application.

A V/f pattern for a variable torque load calls for a reduced magnetizing current at lower speeds in order to achieve higher efficiency. To attain this, motor voltage is simply reduced on the lower end of the profile. Contrarily, a constant torque load requires full magnetizing current at all speeds. A straight slope is constructed and followed throughout the entire speed range for a constant torque load (**Figure 2**).

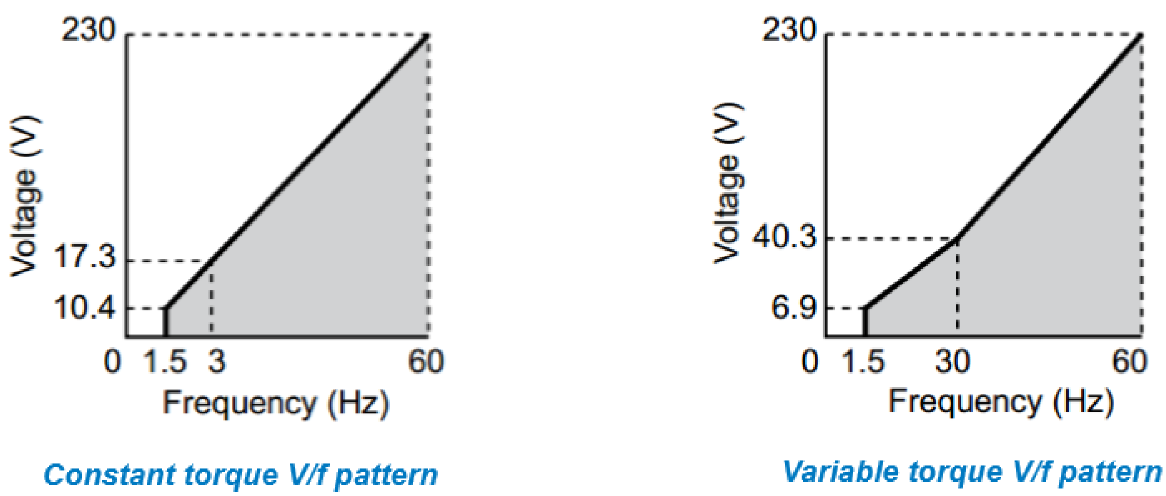

Figure 2: Figure 2: Different V/f patterns allow a VFD to control a multitude of different applications while maintaining optimal performance

V/f with Encoder

If slightly better speed regulation is desired along with the ability to run at a higher frequency reference, the V/f control method can be setup to run with an encoder. Adding encoder feedback to the V/f control method tightens the speed regulation down to +/- 0.03% of maximum frequency.

Output voltage is still determined by the selected V/f pattern. This allows for high speed control without high dynamic response since the voltage and frequency are predetermined. This control method is not too common since an encoder and feedback card must be purchased and the resultant advantages over the standard V/f control method are minimal. Starting torque, speed response, and speed control range are all identical to the aforementioned V/f control method. Higher operating frequency is limited by the encoder's PPR.

Open Loop Vector

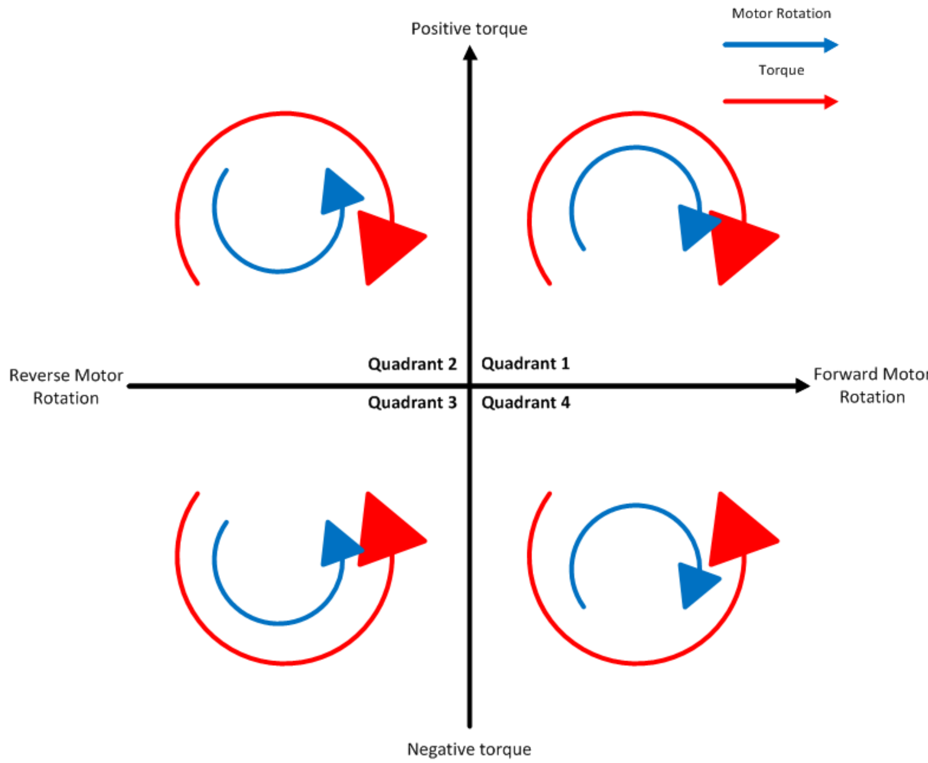

Figure 3: The Open loop vector control method allows for 4 quadrant torque limits

Open Loop Vector (OLV), sometimes called sensor-less vector, is quite different than the V/f control method. As the name describes, the "open loop" designator means there is no encoder being used. The grand goal of the OLV control method is to achieve greater and more dynamic motor control. Vector control is used to achieve independent control of motor speed and motor torque, similar to how a DC motor is controlled.

When running OLV, the motor can produce 200% rated torque @ 0.3 Hz. The higher starting torque at lower speeds opens the door for a variety of applications. This control method also allows for setup of four-quadrant torque limits. Torque limits are primarily used to limit motor torque to prevent damage to equipment, machinery, or product. Torque limits are broken into four different quadrants (**Figure 3**) dependent on the motor direction (Forward or Reverse) and whether the motor is motoring or regenerating. A bottle capper which requires a torque limit to prevent over-torquing the bottle caps would require a torque limit set-up for Quadrant 1. Alternatively, an unwinding application would have forward motor rotation to feed the line but a negative torque limit due to regeneration caused by the line being pulled to create tension. This application would require a torque limit set in Quadrant 4.

In addition to torque limits, the OLV control method has a higher speed response of 10 Hz which allows for a more dynamic response to impact loads. An example of an application which can have impact loads would be a rock crusher. The load is constantly changing dependent on the size and quantity of rocks being processed through the crusher.

What makes vector control special and allows for high performance operation is how the VFD determines output voltage to the motor. There have been many books, theses, courses, and other types of research and documentation produced to explain vector control over the years. This article will just touch on the most basic concepts of vector control. Instead of a fixed V/f pattern, OLV uses a vector algorithm to find the best output voltage necessary to run the motor. Vector control accomplishes this by using current feedback from the motor. Basic vector math is utilized by breaking up the motors magnetizing current and the torque producing current into vectors (**Figure 4**). Since this control method depends heavily on the motor dynamics, some type of auto-tune of the motor must be performed to ensure the VFD has as much motor data as possible.

After auto-tuning the VFD for the connected motor, vector control is now possible. With the help of reliable motor data/parameters, the VFD can now calculate the magnetizing current (*Id)* and the torque producing current (*Iq*). These values are vectors. For maximum efficiency and torque, the VFD must keep these two vectors at 90 degrees of separation. This 90 degrees is significant since sin (90) =1. The value 1, represents the maximum motor torque. See **Figure 5**.

Overall, tighter control specifications result by utilizing a vector algorithm for this control method. Speed regulation is +/- 0.2% of maximum frequency. The speed control range jumps to 1:200, allowing for low speed operation without sacrificing torque production.

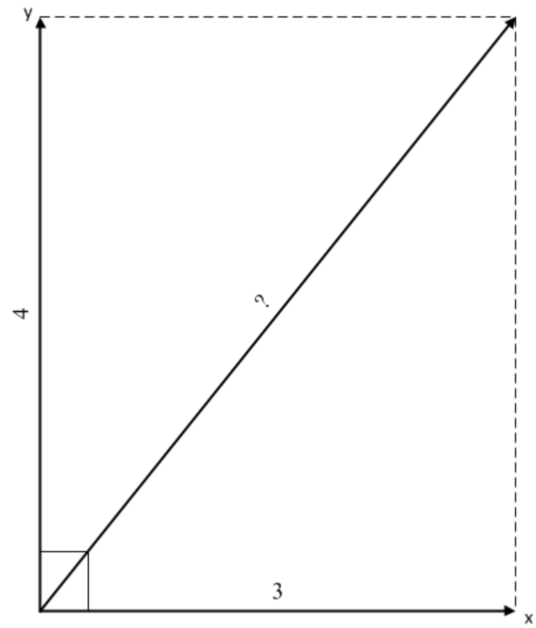

Figure 4: An example of basic vector math:

$$? = \sqrt{3^2 + 4^2}$$
$$? = \mathbf{5}$$

Basic Vector math is key for separation of the torque producing and magnetizing currents of an AC motor.

Closed Loop Vector

The last control method we will discuss is also the highest performing. The Closed Loop Vector (CLV) motor control method uses a vector algorithm to determine output voltage just like the OLV method. The key difference is now an encoder is incorporated. Encoder feedback paired with the vector control method allows for 200% motor starting torque at 0 rpm. This feature is a selling point for applications which require holding a load and not moving. Applications can include elevators, cranes, and hoists.

The encoder feedback allows for the highest speed response, over 50 Hz, and also the highest speed control range 1:1500. In addition to these high performance operating specs, the CLV method also has the ability to run the motor in torque control mode. Torque control mode allows for the VFD to directly control motor torque instead of motor speed. This is necessary for any application where torque takes priority over speed. Winder, rewinders, capping, and web applications are some good examples of when torque control is utilized.

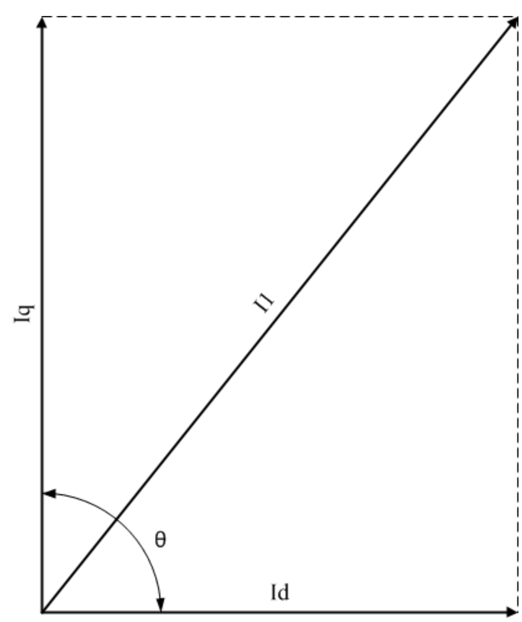

Figure 5: Vector control optimizes maximum torque per amp by keeping torque producing current (Iq) and magnetizing current (Id) at 90°.

- **If θ = more than 90°, then sin θ<1**
- **If θ = less than 90°, then sin θ<1**
- **When θ =90°, then sin θ=1. This results in maximum torque**

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Summary

It is estimated that motors account for at least 50% of the United States total energy consumption. Selecting the proper control method for an application will allow the motor to run most efficiently while maximizing torque production and *overall* performance. A more efficiently run motor will result in less energy consumption, less application downtime, and higher overall savings.

V/F

Advantages

Auto-Tuning not required (but recommended)
Very high frequency References possible(>400Hz)
Multiple motors controlled from one Drive
Simple Closed Loop performance possible
No encoder required
Good for motors with unknown data

Disadvantages

No feedback means no guarantee motor shaft is responding
Starting torque = 150% @ 3.0Hz

Specifications

Speed Regulation: +/- 2 to 3% of max frequency
Speed Response: 3Hz
Speed Control Range: 1:40
Output voltage determined by: V/F Pattern

V/F w/PG

Advantages

Auto-Tuning not required (but recommended)
Very high frequency References possible
(>400Hz limited by the encoder PPR)
Better speed regulation than V/F mode

Disadvantages

Encoder and feedback card required
Starting torque = 150% @ 3.0Hz

Specifications

Speed Regulation: +/- 0.03% of max frequency
Speed Response: 3Hz
Speed Control Range: 1:40
Output voltage determined by: V/F Pattern

Open Loop Vector

Advantages

No encoder required
Good starting torque (200% of rated torque @ 0.3Hz)
Four-quadrent torque limits possible
Good on impact loads

Disadvantages

Auto-Tuning required for optimum performance
No feedback means no guarantee motor shaft is responding

Specifications

Speed Regulation: +/- 0.2% of max frequency
Speed Response: 10Hz
Speed Control Range: 1:200
Output voltage determined by: Vector algorithm

Closed Loop Vector

Advantages

Able to operate in torque control mode
Excellent starting torque (200% of rated torque @ 0 rpm)
Four-quadrent torque limits possible
Best for impact loads
Zero speed operation capability

Disadvantages

Auto-Tuning required for optimum performance
Encoder and feedback card required

Specifications

Speed Regulation: +/- 0.02% of max frequency
Speed Response: Over 50Hz
Speed Control Range: 1:1500
Output voltage determined by: Vector algorithm