Understanding Variable Speed Drives

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When applied properly, the variable frequency drive (VFD) is the most effective motor controller in the industry today. Modern VFDs are affordable and reliable, have flexibility of control, and offer significant electrical energy savings through greatly reduced electric bills.

They are used in a wide variety of applications for various reasons. For example, they are the most effective energy savers in pump and fan applications; they enhance process operations, particularly where flow control is involved. VFDs provide soft-start capabilities, which decrease electrical stresses and line voltage sags associated with full voltage motor start-ups, especially when driving high-inertia loads.

To obtain a clear understanding of the proper and most effective application of VFDs, you first should gain a working knowledge of VFD basic theory as well as a strong familiarity with practical know-how.

Basic VFD Theory

Applying a VFD to a specific application is no mystery when you understand the requirements of the load. Simply put, the VFD must have ample current capability for the motor so that the motor can produce the required torque for the load. You must remember that machine torque is independent of motor speed and that load horsepower increases linearly with rpm.

VFD applications can be divided into the following individual load types.

**Constant torque loads.** These loads represent 90% of all general industrial machines (other than pumps and fans). Examples of these load types include general machinery, hoists, conveyors, printing presses, positive displacement pumps, some mixers and extruders, reciprocating compressors, as well as rotary compressors.

**Constant horsepower loads.** These loads are most often found in the machine-tool industry and center driven winder applications. Examples of constant horsepower loads include winders, core-driven reels, wheel grinders, large driller machines, lathes, planers, boring machines, and core extruders.

Traditionally, these loads were considered DC drive applications only. With high-performance flux vector VFD’s now available, many DC drive applications of this type can be now handled by VFDs.

**Variable torque loads.** Variable torque loads are most often found in variable flow applications, such as fans and pumps. Examples of applications include fans, centrifugal blowers, centrifugal pumps, propeller pumps, turbine pumps, agitators, and axial compressors. VFDs offer the greatest opportunity for energy savings when driving these loads because horsepower varies as the cube of speed and torque varies as square of speed for these loads. For example, if the motor speed is reduced 20%, motor horsepower is reduced by a cubic relationship (.8 X .8 X .8), or 51%. As such, utilities often offer subsidies to customers investing in VFD technology for their applications. Many VFD manufacturers have free software programs available for customers to calculate and document potential energy savings by using VFDs.
**Sizing VFDs For The Load**

How do you size a VFD drive for an application and feel confident it's going to work? First, you must understand the requirements of the load. It helps also if you understand the difference between horsepower and torque. As electrical people, we tend to think of loads in horsepower ratings instead of torque ratings. When was the last time you sized something based on torque? Thus, both torque and horsepower must be carefully examined.

**Torque.** Torque is an applied force that tends to produce rotation and is measured in lb-ft or lb-in. All loads have a torque requirement that must be met by the motor. The purpose of the motor is to develop enough torque to meet the requirements of the load.

Actually, torque can be thought of as "OOUMPH". The motor has to develop enough "OOUMPH" to get the load moving and keep it moving under all the conditions that may apply.

**Horsepower.** Horsepower (hp) is the time rate at which work is being done. One hp is the force required to lift 33,000 lbs 1 ft in 1 min. If you want to get the work done in less time, get yourself more horses!

Here are some basic equations that will help you understand the relationship between hp, torque, and speed.

\[
\text{hp} = \frac{(\text{Torque} \times \text{Speed})}{5250} \quad (\text{eq. 1})
\]

\[
\text{Torque} = \frac{(\text{hp} \times 5250)}{\text{Speed}} \quad (\text{eq. 2})
\]

As an example, a 1-hp motor operating at 1800 rpm will develop 2.92 lb-ft of torque.

Know your load torque requirements Every load has distinct torque requirements that vary with the load's operation; these torques must be supplied by the motor via the VFD. You should have a clear understanding of these torques.

* **Break-away torque:** torque required to start a load in motion (typically greater than the torque required to maintain motion).

* **Accelerating torque:** torque required to bring the load to operating speed within a given time.

* **Running torque:** torque required to keep the load moving at all speeds.

* **Peak torque:** occasional peak torque required by the load, such as a load being dropped on a conveyor.

* **Holding torque:** torque required by the motor when operating as a brake, such as down hill loads and high inertia machines.

**Practical Knowhow Guidelines**

The following guidelines will help ensure a correct match of VFD and motor.

1. **Define the operating profile of the load to which the VFD is to be applied.** Include any or all of the "torques" discussed above. Using a recording true rms ammeter to record the motor's current draw under all operating conditions will help in doing this. Obtain the highest "peak" current...
readings under the worst conditions. Also, see if the motor has been working in an overloaded condition by checking the motor full-load amps (FLA). An overloaded motor operating at reduced speeds may not survive the increased temperatures as a result of the reduced cooling effects of the motor at these lower speeds.

2. Determine why the load operation needs to be changed. Very often VFDs have been applied to applications where all that was required was a "soft start" reduced voltage controller. The need for the VFD should be based on the ability to change the load's speed as required. In those applications where only one speed change is required, a VFD may not be necessary or practical.

3. Size the VFD to the motor based on the maximum current requirements under peak torque demands. Do not size the VFD based on horsepower ratings. Many applications have failed because of this. Remember, the maximum demands placed on the motor by the load must also be met by the VFD.

4. Evaluate the possibility of required oversizing of the VFD. Be aware that motor performance (break-away torque, for example) is based upon the capability of the VFD used and the amount of current it can produce. Depending on the type of load and duty cycle expected, oversizing of the VFD may be required.

**Key VFD Specifications**

While there are many specifications associated with drives, the following are the most important.

* **Continuous run current rating.** This is the maximum rms current the VFD can safely handle under all operating conditions at a fixed ambient temperature (usually 40 [degrees] C). Motor ball load sine wave currents must be equal to or less than this rating.

* **Overload current rating.** This is an inverse time/current rating that is the maximum current the VFD can produce for a given time frame. Typical ratings are 110% to 150% overcurrent for 1 min, depending on the manufacturer. Higher current ratings can be obtained by oversizing the VFD. This rating is very important when sizing the VFD for the currents needed by the motor for break-away torque.

* **Line voltage.** As with any motor controller, an operating voltage must be specified. VFDs are designed to operate at some nominal voltage such as 240VAC or 480VAC, with an allowable voltage variation of plus or minus 10%. Most motor starters will operate beyond this 10% variation, but VFDs will not and will go into a protective trip. A recorded voltage reading of line power deviations is highly recommended for each application.

**Applications To Watch Out For**

If you answer any of the following questions with YES, be extra careful in your VFD selection and setup parameters of the VFD.

* **Will the VFD operate more than one motor?** The total peak currents of all motor loads under worst operating conditions must be calculated. The VFD must be sized based on this maximum current requirement. Additionally, individual motor protection must be provided here for each motor.

* **Will the load be spinning or coasting when the VFD is started?** This is very often the case with fan applications. When a VFD is first started, it begins to operate at a low frequency and voltage and gradually ramps up to a preset speed. If the load is already in motion, it will be out of sync
with the VFD. The VFD will attempt to pull the motor down to the lower frequency, which may require high current levels, usually causing an overcurrent trip. Because of this, VFD manufacturers offer drives with an option for synchronization with a spinning load; this VFD ramps at a different frequency.

* Will the power supply source be switched while the VFD is running? This occurs in many buildings, such as hospitals, where loads are switched to standby generators in the event of a power outage. Some drives will ride through a brief power outage while others may not. If your application is of this type, it must be reviewed with the drive manufacturer for a final determination of drive capability.

* Is the load considered hard to start? These are the motors that dim the lights in the building when you hit the start button. Remember, the VFD is limited in the amount of overcurrent it can produce for a given period of time. These applications may require oversizing of the VFD for higher current demands.

* Are starting or stopping times critical? Some applications may require quick starting or emergency stopping of the load. In either case, high currents will be required of the drive. Again, oversizing of the VFD maybe required.

* Are external motor disconnects required between the motor and the VFD? Service disconnects at motor loads are very often used for maintenance purposes. Normally, removing a load from a VFD while operating does not pose a problem for the VFD. On the other hand, introducing a load to a VFD by closing a motor disconnect while the VFD is operational can be fatal to the VFD. When a motor is Started at full voltage, as would happen in this case, high currents are generated, usually about six times the full load amps of the motor current. The VFD would see these high currents as being well beyond its capabilities and would go into a protective trip or fail altogether. A simple solution for this condition is to interlock the VFD run permissive circuit with the service disconnects via an auxiliary contact at the service disconnect. When the disconnect is closed, a permissive run signal restarts the VFD at low voltage and frequency.

* Are there power factor correction capacitors being switched or existing on the intended motor loads? Switching of power factor capacitors usually generates power disturbances in the distribution system. Many VFDs can and will be affected by this. Isolation transformers or line reactors may be required for these applications.

Power factor correction at VFD-powered motor loads is not necessary as the VFD itself does this by using DC internally and then inverting it into an AC output to the motor. All VFD manufacturers warn against installing capacitors at the VFD output.

**Variable Frequency Drive Technologies**

Three basic types of variable frequency drives offer certain advantages as well as disadvantages depending on your motor application. The new flux vector drive is also discussed.

While all variable frequency drives (VFDs) control the speed of an AC induction motor by varying the motor's supplied voltage and frequency of power, they all do not use the same designs in doing so. There are three major VFD designs commonly used today: pulse width modulation (PWM), current source inverter (CSI), and voltage source inverter (VSI). Recently, the flux vector drive also has become popular.

Let's compare these technologies.
### PWM Design

The PWM drive has become the most commonly used drive controller because it works well with motors ranging in size from about 1/2 hp to 500 hp. A significant reason for its popularity is that it's highly reliable, affordable and reflects the least amount of harmonics back into its power source. Most units are rated either 230V or 460V, 3-phase, and provide output frequencies from about 2 Hz to 400 Hz. Nearly 100 manufacturers market the PWM controller. A typical controller is shown in the photo.

An AC line supply voltage is brought into the input section. From here, the AC voltage passes into a converter section that uses a diode bridge converter and large DC capacitors to create and maintain a stable, fixed DC bus voltage. The DC voltage passes into the inverter section usually furnished with insulated gate bipolar transistors (IGBTs), which regulate both voltage and frequency to the motor to produce a near sine wave like output.

The term "pulse width modulation" explains how each transition of the alternating voltage output is actually a series of short pulses of varying widths. By varying the width of the pulses in each half cycle, the average power produced has a sine-like output. The number of transitions from positive to negative per second determines the actual frequency to the motor.

Switching speeds of the IGBTs in a PWM drive can range from 2 KHz to 15 KHz. Today's newer PWM designs use power IGBTs, which operate at these higher frequencies. By having more pulses in every half cycle, the motor whine associated with VFD applications is reduced because the motor windings are now oscillating at a frequency beyond the spectrum of human hearing. Also, the current wave shape to the motor is smoothed out as current spikes are removed.

PWMs have the following advantages.

* Excellent input power factor due to fixed DC bus voltage.
* No motor cogging normally found with six-step inverters.
* Highest efficiencies: 92% to 96%.
* Compatibility with multi-motor applications.
* Ability to ride through a 3 to 5 Hz power loss.
* Lower initial cost.

The following are disadvantages, however, that you should also consider.

* Motor heating and insulation breakdown in some applications due to high frequency switching of transistors.
* Non-regenerative operation.
* Line-side power harmonics (depending on the application and size of the drive).

### CSI Design
The incoming power source to the CSI design is converted to DC voltage in an SCR converter section, which regulates the incoming power and produces a variable DC bus voltage. This voltage is regulated by the firing of the SCRs as needed to maintain the proper volt/hertz ratio. SCRs are also used in the inverter section to produce the variable frequency output to the motor. CSI drives are inherently current regulating and require a large internal inductor to operate, as well as a motor load.

CSI drives have the following advantages.

* Reliability due to inherent current limiting operation.
* Regenerative power capability.
* Simple circuitry.

The following are disadvantages, however, in the use of CSI technology.

* Large power harmonic generation back into power source.
* Cogging below 6 Hz due to square wave output.
* Use of large and costly inductor.
* HV spikes to motor windings.
* Load dependent; poor for multimotor applications.
* Poor input power factor due to SCR converter section.

**VSI Design**

The VSI drive is very similar to a CSI drive in that it also uses an SCR converter section to regulate DC bus voltage. Its inverter section produces a six-step output, but is not a current regulator like the CSI drive. This drive is considered a voltage regulator and uses transistors, SCRs or gate turn off thyristors (GTOs) to generate an adjustable frequency output to the motor.

VSIs have the following advantages.

* Basic simplicity in design.
* Applicable to multimotor operations.
* Operation not load dependent.

As with the other types of drives, there are disadvantages.

* Large power harmonic generation back into the power source.
* Poor input power factor due to SCR converter section.
* Cogging below 6 Hz due to square wave output.
* Non-regenerative operation.

**Flux Vector PWM Drives**

PWM drive technology is still considered new and is continuously being refined with new power switching devices and smart 32-bit microprocessors. AC drives have always been limited to "normal torque" applications while high torque, low rpm applications have been the domain of DC drives. This has changed recently with the introduction of a new breed of PWM drive, the flux vector drive.

Flux vector drives use a method of controlling torque similar to that of DC drive systems, including wide speed control range with quick response. Flux vector drives have the same power section as all PWM drives, but use a sophisticated closed loop control from the motor to the drive's microprocessor. The motor's rotor position and speed is monitored in real time via a resolver or digital encoder to determine and control the motor's actual speed, torque, and power produced.

By controlling the inverter section in response to actual load conditions at the motor in a real time mode, superior torque control can be obtained. The personality of the motor must be programmed into or learned by the drive in order for it to run the vector control algorithms. In most cases, special motors are required due to the torque demands expected of the motor.

The following are advantages of this new drive technology.

* Excellent control of motor speed, torque, and power.

* Quick response to changes in load, speed, and torque commands.

* Ability to provide 100% rated torque at 0 speed.

* Lower maintenance cost as compared to DC motors and drives.

As usual, there are disadvantages.

* Higher initial cost as compared to standard PWM drives.

* Requires special motor in most cases.

* Drive setup parameters are complex.

While flux vector technology offers superior performance for certain special applications, it would be considered "over-kill" for most applications well served by standard PWM drives.

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