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Variable Speed Drives in Electrical Energy Management

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Course Content

Introduction & Overview

The basic equation for a 3 phase electric motor is:

$$N = \frac{120f}{P}$$

N = rotational speed of stator magnetic field in RPM (synchronous speed)

f = frequency of the stator current flow in Hz

P = number of motor magnetic poles

Therefore, in a 60-Hz system, the synchronous speed of a four--pole motor is 1800 rpm and that of a two-pole motor is 3600 rpm.

Thus speed of an AC motor is determined by two factors: the applied frequency and the number of poles. We can conveniently adjust the speed of a motor by changing the frequency applied to the motor. You could adjust motor speed by adjusting the number of poles, but this is a physical change to the motor. It would require rewinding, and result in a step change to the speed. So, for convenience, cost-efficiency, and precision, we change the frequency.

Variable Speed Drives (VSD) or Variable Frequency Drives (VFD) is electronic motor speed controllers that allow the speed (RPM) of any three-phase electric motor to be varied from 0 to 120% of normal (rated RPM). VSD increase efficiency by allowing motors to be operated at the ideal speed for every load condition. In many applications VSD reduce motor electricity consumption by 30-60%.

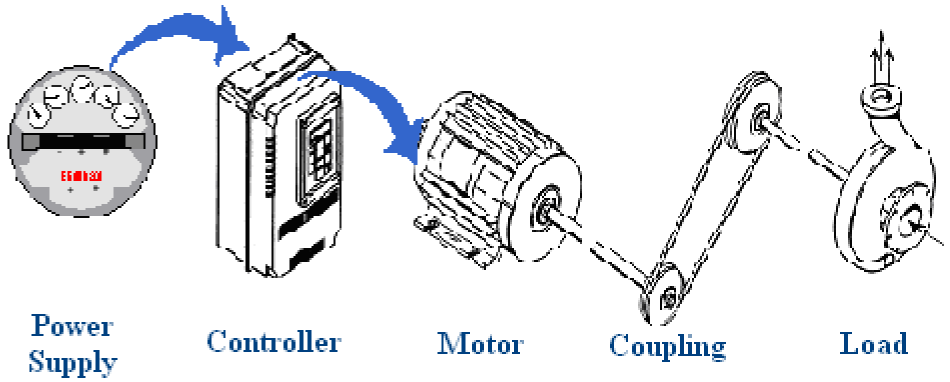
Concept of Variable Speed (Variable Frequency) Drives

Any variable speed electrical drive systems comprises of the following three main components:

1) An electronic actuator – the controller

2) A driving electrical machine – Motor

3) A driven machine – Pumps, Fans, Blowers, compressors



In a conventional system the controller is just a starter. While in variable speed drive applications, the controller is an electronic actuator, which works on the principle of varying the frequency. The controllers are connected to mains supply and the electrical machines. Not every type of load qualifies for the variable speed. We will check the suitability in the following sections.

Note: *The terms variable speed drive (VSD) and variable frequency drive (VFD) have been used interchangeably through out the text in this paper.*

Torque, Speed and Horsepower

A drive controls two main elements of induction motor: “Speed” and “Torque”.

The motor torque refers to how much force the motor shaft exerts as it rotates. Torque is dependent on the strength of the magnetic fields in the motor—a stronger magnetic field will exert a stronger pull on the rotor, creating more torque. The force of the magnetic field, and thus torque, is determined by the amount of voltage and frequency supplied to the motor. The horsepower of a motor refers to how much work the motor can do, or how much torque it can deliver over time. The relationship between torque and horsepower is:

HP = Torque * Speed / 5250

Where:

Torque is measured in Lb-Ft

Speed is measured in RPM

The speed at which the AC motor rotor rotates depends on how many poles are in the stator and the frequency of applied power.

Torque is dependent on the strength of the magnetic fields in the motor —a stronger magnetic field will exert a stronger pull on the rotor, creating more torque.

Type of Loads

Motors are used to rotate other mechanical machines. The equipment being driven by the motor is called a load. The load dictates what type of motor is needed and how the motor needs to be controlled. Some load characteristics that need to be considered are speed, torque, weight, tension, and inertia.

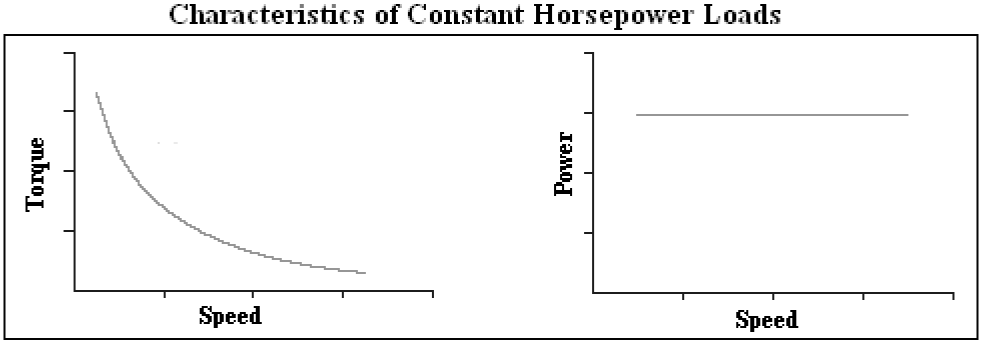
Whether or not these characteristics are constant or vary over time also needs to be considered. In a simple load, only one of these characteristics affects the load at one time. In a complex load, multiple characteristics may change over time. Load characteristics also determine whether or not the load can be classified as constant horsepower, constant torque, or variable torque.

There are 3 distinct types of loads, based on the torque-speed requirement of the driven equipment:

Constant horsepower loads are those in applications where the amount of work to be done is independent of speed and torque. Loads that require constant tension require constant horsepower. An example of a constant horsepower application is a winder. A winder is a roller onto which processed material, such as paper, is wound. As the process of making paper continues, more and more paper is wound around the winder. The diameter of the roll increases, as does the weight of the load. As the diameter of the roll increases, the speed of the winder must slow down to maintain constant tension (otherwise the paper would tear or sag). However, the amount of work that needs to be done doesn't change.

Other applications involving constant horsepower loads are: Drills, grinders, lathes, milling machines, wire drawing machines, and cutting machines.

Characteristics of Constant Horsepower Loads

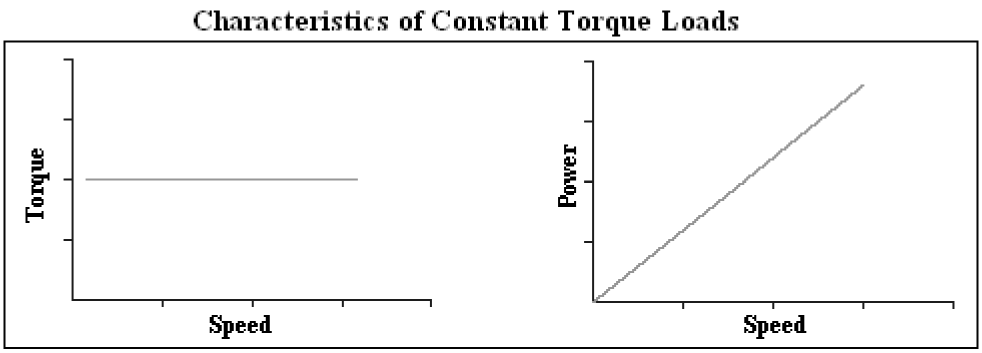


Constant torque loads are the most common in industrial applications. The amount of force needed is independent of speed. An example of a constant torque application is a conveyor belt.

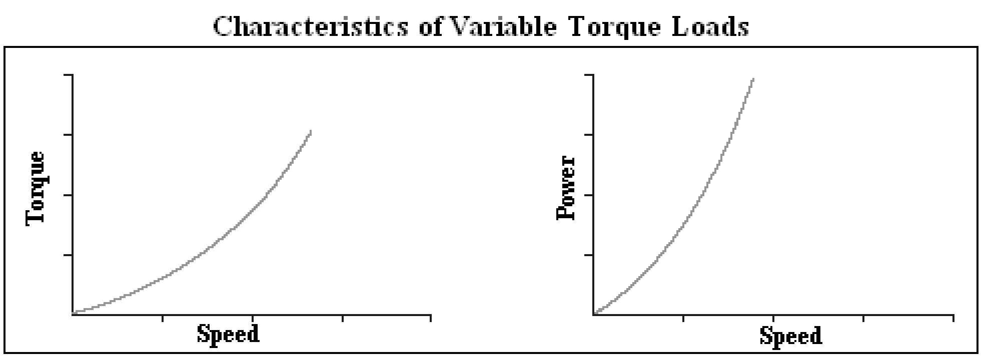
No matter how fast the conveyor belt is going, or how much is loaded onto it, the conveyor must exhibit the same force so that the conveyor runs smoothly without throwing off the load.

Other applications with a constant torque load include: Coaters, cranes, elevators, forming mills, galvanizing lines, planers, and textile spinners.

Typically, drives that are built to handle constant torque loads are capable of handling up to 150% of rated current for 60 seconds. Rated current is the amount of current flowing through the drive/motor when under full load.



Variable torque loads exhibit both an increase in torque and horsepower as speed increases. An example of a variable torque load is a fan. The load includes the fan blades, as well as the centrifugal force felt by the fan. As the fan spins faster, there is more air resistance and centrifugal force to deal with. Pumps are another example of variable torque loads.



It is to be noted that for loads in category # 1, the power drawn remains constant irrespective of the speed, for loads in category# 2, the power drawn is directly proportional to the speed, whereas for loads in category # 3, the power drawn varies as cube of speed i.e. $P \propto N^3$. If the nature of the load is not obvious, it must be determined by a field test.

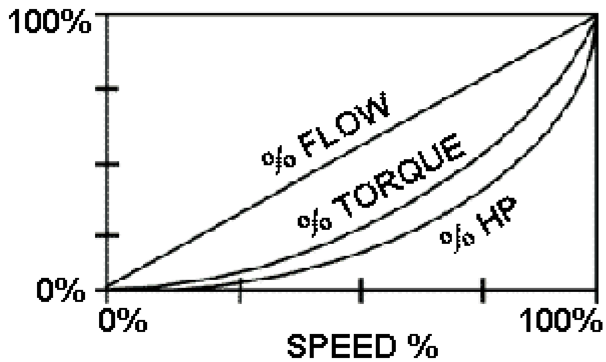
The nature of the load dictates what type of motor is needed and how it needs to be controlled.

This third category – variable torque loads make majority of applications in almost all industrial, commercial and domestic applications and are benefited the most with variable speed drive.

Why Variable Torque Loads offer Greatest Energy Savings

In variable torque applications, the torque required varies with the square of the speed, and the horsepower required varies with the cube of the speed, resulting in a large reduction of horsepower for even a small reduction in speed. The motor will consume only 25% as much energy at 50% speed than it will at 100% speed. This is referred to as the “Affinity Laws”, which define the relationships between speed, flow, torque, and horsepower.

The following diagram illustrates these relationships:



For example, a fan needs less torque when running at 50% speed than it does when running at full speed. Variable torque operation allows the motor to apply on conveyors, positive displacement pumps, punch presses, extruders, and other similar type applications require constant level of torque at all speeds. In which case, constant torque variable frequency drives would be more appropriate for the job. A constant torque drive should have an overload current capacity of 150% or more for one minute.

Drives built to handle variable torque loads need only an overload current capacity of 110-120% of rated current for 60 seconds since centrifugal applications rarely exceed the rated current.

Variable torque loads application for pumps is discussed in detail later in this course.

METHODS OF SPEED CONTROL

The speed of a driven load often needs to run at a speed that varies according to the operation it is performing. The speed in some cases such as pumping may need to change dynamically to suit the conditions, and in other cases may only change with a change in process. Electric motors and coupling combinations used for altering the speed will behave as either a "Speed Source" or a "Torque Source". The "Speed Source" is one where the driven load is driven at a constant speed independent of load torque. A "Torque Source" is one where the driven load is driven by a constant torque, and the speed alters to the point where the torque of the driven load equals the torque delivered by the motor. Closed loop controllers employ a feedback loop to convert a "Torque Source" into a "Speed Source" controller.

Mechanical

There are a number of methods of mechanically varying the speed of the driven load when the driving motor is operating at a constant speed. These are typically:

1) Belt Drive
2) Chain Drive
3) Gear Box
4) Idler wheel Drive

All of these methods exhibit similar characteristics whereby the motor operates at a constant speed and the coupling ratio alters the speed of the driven load. Increasing the torque load on the output of the coupling device, will increase the torque load on the motor. As the motor is operating at full voltage and rated frequency, it is capable of delivering rated output power.
There is some power loss in the coupling device resulting in a reduction of overall efficiency. The maximum achievable efficiency is dependant on the design of the coupling device and sometimes the way it is set up (for example: belt tension, no of belts, type of belts etc.)
Most mechanical coupling devices are constant ratio devices and consequently the load can only be run at one or more predetermined speeds. There are some mechanical methods that do allow for a dynamic speed variation but these are less common and more expensive.
Mechanical speed change methods obey the 'Constant Power Law' where the total power input is equal to the total power output. As the motor is capable of delivering rated power output, the output power capacity of the combination of motor and coupling device (provided the coupling device is appropriately rated) is the rated motor output power minus the loss power of the coupling device.
Torque 'T' is a Constant 'K' times the Power 'P' divided by the speed 'N'.

T = K x P / N

Therefore for an ideal lossless system, the torque at the output of the coupling device is increased by the coupling ration for a reduced speed, or reduced by the coupling ratio for an increased speed.

Magnetic

There are two main methods of magnetically varying the speed of the driven load when the driving motor is operating at a constant speed. These are:

1) Eddy Current Drive

2) Magnetic Coupling

These methods use a coupling method between the motor and the driven load which operates on induced magnetic forces. The eddy current coupling is quite commonly employed, and is easily controlled by varying the bias on one of the windings. In operation, it is not unlike an induction motor, with one set of poles driven by the driving motor, hence operating at the speed of the driving motor. The second set of poles are coupled to the driven load, and rotates at the same speed as the driven load. One set of poles comprises a shorted winding in the same manner as the rotor of an induction motor, while the other set of poles is connected to a controlled D.C. current source. When the machine is in operation, there is a difference in speed between the two sets of poles, and consequently there is a current induced in the shorted winding. This current establishes a rotating field and torque is developed in the same way as an induction motor. The coupling torque is controlled by the DC excitation current. This method of coupling is essentially a torque coupling with slip power losses in the coupling.

Hydraulic

There are two main methods of hydraulically varying the speed of the driven load when the driving motor is operating at a constant speed. These are:

1) Hydraulic pump and motor

2) Fluid Coupling

The fluid coupling is a torque coupling whereby the input torque is equal to the output torque. This type of coupling suffers from very high slip losses, and is used primarily as a torque limited coupling during start with a typical slip during run of 5%. The constant power law still applies, but the power in the driven load reduces with speed. The difference between the input power and the output power is loss power dissipated in the coupling.
In an extreme case, if the load is locked (stationary) and the motor is delivering full torque to the

load via a fluid coupling, the load will be doing no work and hence absorbing no power, with the motor operating at full speed and full torque, the full output power of the motor is dissipated in the coupling. In most applications, the torque requirement of the load at reduced speed is much reduced, so the power dissipation is much less than the motor rating.

In the case of a hydraulic pump and motor, the induction motor operates at a fixed speed, and drives a hydraulic pump which in turn drives a hydraulic motor. In many respects, this behaves in a manner similar to a gear box in that the hydraulic system transfers power to the load. The torque will be higher at the load than at the motor for a load running slower than the motor.

Electrical

There are a number of methods of electrically varying the speed of the driven load and driving motor.

These are:

1) DC Motor
2) Universal Motor
3) High Slip Motor (fan motor)
4) Slip Ring Motor
5) Variable Frequency Drive and Induction Motor

The DC motor: DC motors are based on a stationary magnetic field. The stator of a DC motor consists of windings that are made of coiled wire to form a magnetic pole: when current flows through the windings, they produce a magnetic field.

The DC Motor is traditionally a very common means of controlling process speed. It is essentially a "Torque Source" controller and is usually used with a tacho-generator feedback to control the speed of the driven load. The DC motor consists of a field winding and an armature. The armature is fed via brushes on a commutator. The DC motor is available in two main formats, series wound and shunt wound.

- Small DC Motors are often series wound giving the advantage of improved starting torque. With a series wound DC motor, speed control is achieved by regulating the voltage applied to the motor. The entire motor current passes through the voltage regulator.
- A shunt wound motor has separated field and armature windings. The torque output of the motor is varied by controlling the excitation on the armature winding while maintaining full

voltage D.C. on the field. The voltage regulator only passes the current to the field winding, dissipating much less power than in the case of the shunt wound motor.

DC motors are a torque source, and so are able to operate well under high transient load conditions. At low speed, the DC motor is able to deliver a high torque. The DC drive however needs special consideration in some applications. For example in hazardous atmosphere, vibrations and higher speeds the usage of AC motor with squirrel-Cage rotor is advantageous.

The universal motor: The Universal Motor is a motor with a wound armature and a wound stator. The armature is fed via brushes on a commutator, and is essentially the same as a DC motor. The universal motor will operate off a single phase AC supply and accelerates until the load torque equals the output torque. Domestic appliances, such as vacuum cleaners, and small hand tools such as electric drills use this technology. The speed is changed by reducing the voltage applied to the motor. This is often a *triac* based voltage controller similar to a domestic light dimmer.

High Slip Induction Motor: An induction motor with a high rotor resistance is a high slip motor and is often referred to as a fan motor or a type F motor. The torque capacity of this motor is high at low speeds and low at synchronous speed. By reducing the voltage applied to the type F motor, the available torque is reduced and consequently, when coupled to a fan load, the speed reduces. A type F motor has high power dissipation in the rotor and is only useful for smaller single phase and three phase machines. The actual speed is dependant on the stator voltage, motor characteristics and load torque. Voltage controllers are either transformers, variacs or SCR based solid state controllers.

Slip ring motors: Slip Ring Motors are induction motors with a wound rotor with the rotor winding accessible via slip rings. Changing the value of external resistance connected in series with the rotor windings, will vary the torque curve of the motor. With a high value of resistance in the rotor circuit, the slip ring motor will behave like a type F motor. With the slip ring motor, the stator voltage is held constant at line voltage, and the rotor resistance is varied to alter the torque capacity of the motor and hence the speed. This type of speed control is used on large machines because the rotor power dissipated is external to the motor. Typical applications are in hoisting and dragline type machines associated with dredging machines.

Variable frequency drives: The speed of standard induction motors can be controlled by variation of the frequency of the voltage applied to the motor. Due to flux saturation problems with induction motors, the voltage applied to the motor must alter with the frequency. The induction motor is a pseudo synchronous machine and so behaves as a speed source. The running speed is set by the frequency applied to it and is independent of load torque provided the motor is not over loaded.

Mechanism of Speed Control in DC Drives vs. AC Drives

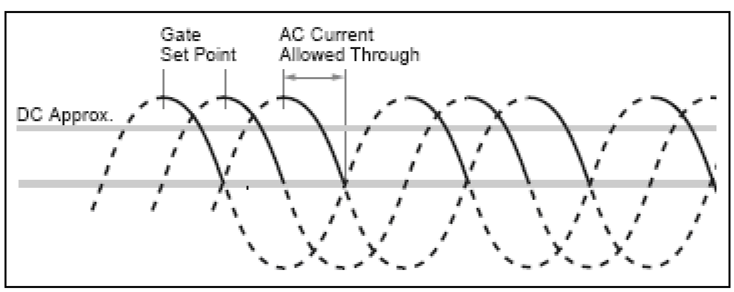
A basic distinction of DC motors vs. AC motors is that the DC motors are based on a stationary magnetic field, while the AC motors utilize a rotating magnetic field within the stator. A basic speed control mechanism of these drives is discussed below.

DC drives can control motor speed in two ways —by controlling the voltage supplied to the armature to obtain speeds below the base speed of the motor, or by reducing the current supplied to the field to obtain speeds above the motor's base speed.

DC drives have two main components: A converter and a regulator.

A converter is an electrical circuit that converts AC power to DC power. DC drive converters typically use a device called a silicon control rectifier (SCR) for this conversion process. SCRs transform AC current into a tightly controlled form of DC current.

An SCR is a gated transistor that only allows current to pass through it when the current reaches a certain value (the point at which the gate is set), which turns on the SCR. SCRs are only "on" when power is applied to its gate. When SCRs are on, they have the effect of chopping the sine wave of an AC power supply into fragments that approximate a DC power supply.



Sine Wave & DC Approximation

A regulator is the control portion of the drive. The regulator is the "smarts" or processing logic that determines what voltage and current is supplied to the motor. The voltage output from the drive can manipulate the speed or the torque of the motor (thus, the tension of a process load can also be controlled). The changes to the power supplied to the motor depend on the logic in the regulator and the type of feedback from the motor. Feedback devices, such as encoders or load cells, are sensors on the motor or on a process line that monitor actual process performance. An example of a feedback device is a tachometer (tach), a device that monitors the actual speed of the motor. A tach can send a signal back to the drive telling it how fast the motor is actually running. The drive regulator can compare that signal to a set number programmed into the drive, and determine if more or less voltage is needed at the motor to get the actual speed of the motor equal to the programmed speed. Because DC drives manipulate the voltage supplied to the motor, they are deemed variable voltage control. A drive using feedback sensors is said to have closed loop control.

AC Drives

AC drives have three main components: A converter, a regulator, and an inverter. The converter in an AC drive is similar to that in the DC drive— it is used to convert AC power into DC power.

Also while some AC drives use an SCR, most use a diode rectifier rather than an SCR. Diodes are similar to SCRs, but they do not have a gate and thus cannot be turned on or off. Hence, diode rectifiers are less expensive, but do not provide as tight of voltage control as an SCR.

Diodes only allow the positive portion of AC power to be transmitted through the circuit. In an AC drive, the DC power will be converted back into a form of AC power, so the DC approximation does not need to be as accurate, the level of DC voltage does not need to be controlled to control the motor speed.

AC drives also have regulators, which control the DC power before it is further transmitted. AC motors may have their speed and torque controlled as well, depending on the type of regulator.

(Details on “Speed regulation of AC motors” is provided in next section)

VSD FUNDAMENTALS

Principle of Operation

Induction motors are wound to match supply voltage and frequency. When it is desired to operate an induction motor at variable speed, it is necessary to consider the effect of voltage of frequency on flux and torque.

Operation of induction motor depends on the rotating field created by the balanced three phase current in the stator winding. The magnitude of the field is controlled not by the strength of the current but by the voltage induces in the field winding by the supply. This induced voltage can be expressed as:

$E = k\,\varphi\,n\,f$

Where E= induced emf

φ = flux per pole

n = no. of turns per pole

f = supply frequency

k = constant related to the winding design

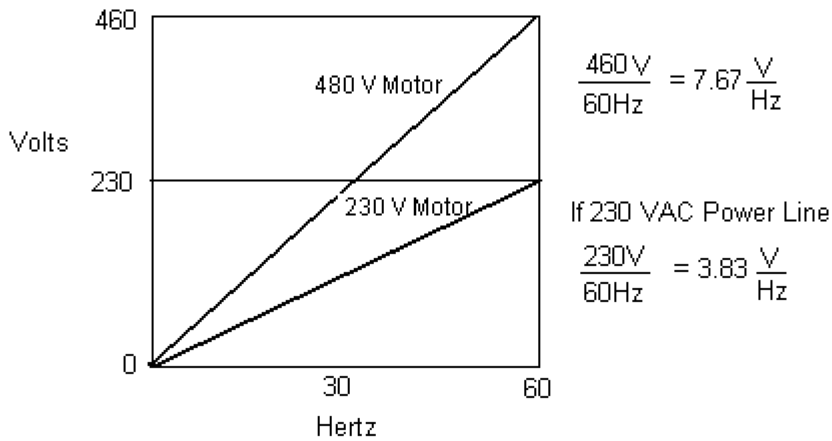
For economy of material, the magnetic circuit of standard motors is designed to operate very close to saturation at rated voltage and frequency. This is the optimum production of torque. At rated frequency any further increase in voltage leads to increase in current and subsequently increase in losses.

From the above $\varphi = 1/kn \times E/f$

This shows that since n is fixed and k is a constant, a linear relationship must be maintained between emf and frequency, if flux is to remain constant at different speed.

This linear relationship is known as constant volt to frequency, (V/ Hz) ratio. With constant volts per hertz, iron losses and magnetizing current are kept within bounds for satisfactory operation of the motor.

Figure below shows the torque-developing characteristic of every motor: the volts per hertz ratio (V/Hz). We change this ratio to change motor torque. An induction motor connected to a 460V, 60 Hz source has a ratio of 7.67.



Volts / Hertz Ratio

As long as this ratio stays in proportion i.e. the volts per hertz ratio is constant from minimum speed to rated speed, the motor will develop rated torque. This is done to maintain rated magnetic flux density in the motor. A drive provides many different frequency outputs. At any given frequency output of the drive, you get a new torque curve. This is the principle of operation of variable frequency drive (VFD).

Operating Conditions

There are two operating condition in VFD…

1. Above “base” speed

2. Below “base” speed

The speed of motor at full rated voltage and normal V/f ratio is called ‘base’ speed.

Since voltage is constant above base speed, the flux falls as the frequency increases. Ability of the motor to produce torque is correspondingly reduced, keeping the power output remain constant.

Second operating condition where departure from constant V/f ratio is beneficial is at low speed and where the voltage drop arising from stator resistance becomes significantly large. This voltage drop is at the expense of flux. As the applied frequency approaches zero, optimum voltage is equal to drop across the stator resistance. To maintain the constant flux in the motor at low speed, the voltage must be increased to compensate the drop. This act of compensation is called as “Voltage Boost”. Most VFD offers some form of adjustment, so that degree of boost can be matched with the winding resistance to reduce the loss, for high starting torque load.

Above rated speed, frequency is increased voltage is held constant and the magnetic flux density is reduced. This is done to limit motor voltage to its design value.

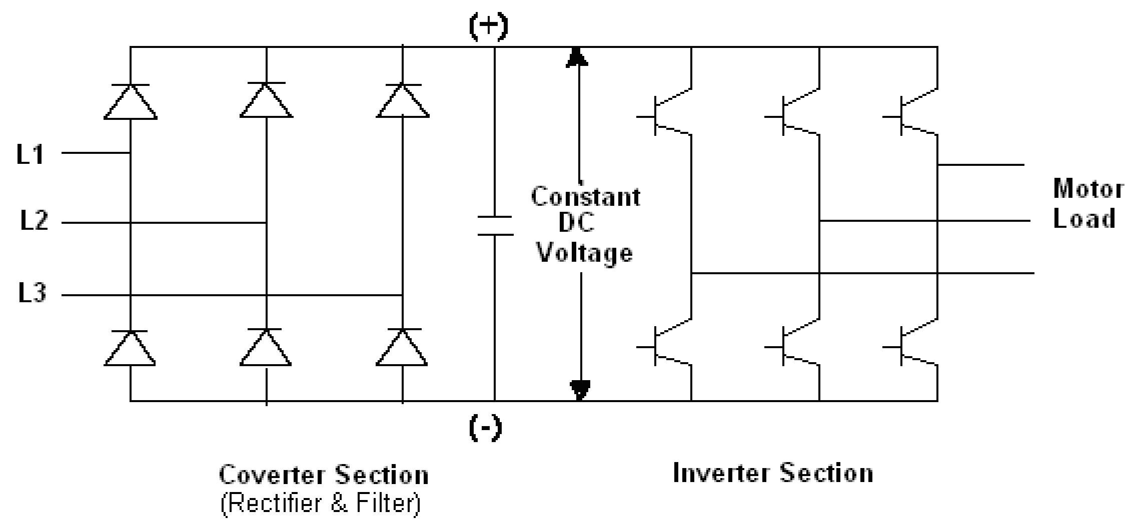
Drive Configuration

Just how does a drive provide the frequency and voltage output necessary to change the speed of a motor? That's what we'll look at next.

To operate an induction motor in all verities of industrial application, a drive must at least be capable of varying voltage and frequency, for which it is necessary to separate the input from the output. This is most conveniently done by rectifying the supply in the converter section and inverting the DC-output at inverter. Variable output voltage can be obtained by varying the DC-link voltage.

AC drives typically utilize an Insulated Gate Bipolar Transistor (IGBT) to invert power through a control strategy called Pulse Width Modulation (PWM). Pulse Width Modulation (PWM), IGBT inverter is capable of providing any voltage from zero to input line voltage, over frequency range from zero to sum practical maximum considerably above the rated frequency of standard induction motor. The control function is also capable of enabling the voltage to be raised at low frequencies to increase torque at low speed.

Figure below shows a simplified circuit of a “Pulse Width Modulated” (PWM) drive.



Pulse Width is a control strategy which uses Insulated Gate Modulation (PWM) Bipolar Transistors to approximate an AC power supply by allowing variable amounts of DC voltage across the line. All PWM drives contain these main parts, with subtle differences in hardware and software components.

1) ***Converter:*** This converts 3-phase AC voltage electrical supply into DC voltage with a slight ripple. The converter (rectifier circuit) as shown in figure above, contains six diodes, arranged in an electrical bridge. For a 600 VAC supply, the DC voltage would approximately be 850 VDC, known as the DC link.

2) ***DC Link of Bus:*** The DC link section filters and removes the ripples in the waveform using a capacitor filter. The diodes actually reconstruct the negative halves of the waveform onto the positive half. The smoother the DC waveform, the cleaner shall be the output waveform from the drive. The average DC voltage is higher than the RMS value of incoming voltage and you can calculate this as line voltage times 1.414. In a 460V unit, you'd measure an average DC bus voltage of about 650V to 680V.

3) ***Inverter:*** *The inverter is a component of an AC drive that takes the regulated DC power and changes it back into a form of regulated (controlled) AC.* The inverter converts the DC bus voltage by pulsing it through a transistor network to a variable voltage and variable frequency supply for a 3-phase electric motor. But, it does so in a variable voltage and frequency output. How does it do this? That depends on what kind of power devices your drive uses. Insulated-Gate Bi-Polar Transistor (IGBT) is widely used in ASDs for AC motor in the range of 5 hp to 400 hp. (discussed further later)

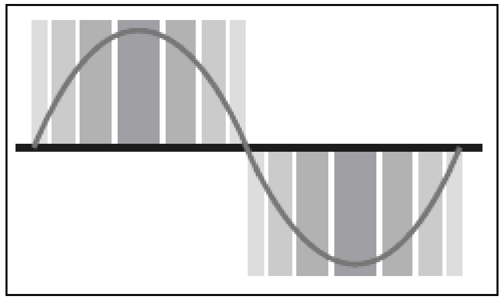
The control section (regulator) of the AFD accepts external inputs which are used to determine the inverter output. The inputs are used in conjunction with the installed software package and a microprocessor. The control board sends signals to the driver circuit which is used to fire the inverter. There are three types of regulators:

1) A volt per hertz regulator controls the ratio of voltage to frequency of AC power output to the motor. The speed of an AC motor depends on the frequency; thus the speed is controlled. A volt per hertz regulator does not use feedback devices.

2) An open loop vector regulator also controls motor speed without feedback devices. However, it regulates the current output to the motor, and controls the rotor/shaft speed by controlling the frequency of the magnetic flux in the stator. This type of regulator may also be used to control the torque of a motor.

3) A closed loop vector regulator (also called flux vector) is similar to an open loop vector drive, but differs in that it uses feedback devices. The third component of an AC drive, the inverter, takes the regulated DC power and changes it back into a form of regulated (controlled) AC power.

IGBTs are capable of turning on and off very fast, allowing pulses of DC voltage to pass through to the motor. These pulses approximate an AC power supply.



PWM Power Approximating AC Power

By adjusting the frequency and voltage of the power entering the motor, the speed and torque may be controlled. The actual speed of the motor, as previously indicated, is determined as: Ns = ((120 x f) / P) x (1 - S) where: N = Motor speed; f = Frequency

(Hz); P = Number of Poles; and S = Slip.

There are various types and combinations of converter and inverter circuits, which are briefly discussed next.

Types of Converters

The converter section of an adjustable frequency controller is sometimes called the front end. It consists of power switching devices and logic controls. The converter is used to control the voltage to the inverter section to maintain the constant volts-per-hertz ratio from the inverter.

There are three popular methods of converting AC power into DC power for adjustable frequency controls:

1) Rectifiers with diode converter

2) Rectifiers with a DC chopper

3) Silicon Controlled Rectifiers (SCR's)

Diode Rectifier circuit is a three phase full wave bridge rectifier using diodes to produce a constant voltage in the DC link.

With this type converter, in order to maintain a constant volts-per-hertz ratio to the motor, the voltage is changed in the inverter section along with the frequency. Hence, this type converter can be used only with a constant voltage, voltage source inverter (PWM) or modified with dc chopper.

Diode Rectifier is similar to SCRs, but diodes do not have a gate and thus cannot be controlled. Diodes only allow the positive portion of AC power to pass through the converter. Most AC drives use diodes.

Rectifier with a DC Chopper circuit is a three phase full wave bridge rectifier using diodes to produce a constant DC voltage, as explained previously. However, with this type converter, an additional power switching device is used, which may be an SCR, a power transistor, or other type switching device. This device will control the magnitude of DC voltage to the inverter section. This circuit is commonly referred to as a DC chopper.

The chopper acts as a switch to permit the DC voltage to rise to a predetermined value. The chopper is then de-energized and the voltage will decrease. By controlling the rate at which the chopper is switched on and off, the DC output voltage can be varied from minimum to maximum.

In this manner, the converter can control the voltage to the inverter section as the frequency is changed, to maintain a constant volts-per-hertz ratio to the motor.

For the larger horsepower motors, this type converter, having a rectifier with a DC chopper, is slightly more complex and costly than the other two types of converters.

Silicon Controlled Rectifier circuit is a three-phase full-wave bridge rectifier using SCR's to control the magnitude of dc voltage to the inverter section. This is accomplished by controlling the conduction time of certain SCR's in the circuit. Logic circuits will control the output voltage from minimum to maximum. In this manner, the converter can control the voltage to the inverter section, as the frequency is changed, to maintain a constant volts-per-hertz ratio to the motor.

An SCR (originally referred to as a thyristor) contains a control element called a gate. The gate acts as the "turn-on" switch that allows the device to fully conduct voltage. The device conducts voltage until the polarity of the device reverses-and then it automatically "turns off." Special circuitry, usually requiring another circuit board and associated wiring, controls this switching. The SCR's output depends on how soon in the control cycle that gate turns on.

With this type converter, the power factor will decrease with the frequency. This may be a disadvantage, depending on the particular installation. In addition, the converter is more sensitive to line disturbances, and may create additional line disturbances, unless special protective circuits are included. However, the significance of these disadvantages will be determined by a manufacture's specific design and specific application conditions.

The advantage of this type converter is its ability to regenerate power back into the AC line.

Types of Inverters

The inverter section of an ASD consists of power switching devices, and logic controls that are considerably more complicated than those required for the converter. Although there are numerous variations in inverter designs, there are basically three types that are most popular:

1) Variable Voltage, Voltage Source Inverters - sometimes called six-step or voltage source

2) Current Source Inverters

3) Constant Voltage, Voltage Source Inverters - usually called pulse width modulation or PWM

Each of these basic designs has variations which manufacturers emphasize for their particular market and application objectives. There are various combinations of converter designs that may be used with each inverter section also. The basic inverter designs are discussed next.

Six-Step Inverter (Variable Voltage, Voltage Source): This inverter section has six power switching devices and 6 diodes. The six power switching devices, performing as switches, are switched on and off in a predetermined sequence to produce a six-step, three-phase voltage wave for the motor.

The distorted current wave contains harmonics which are usually not detrimental when the inverter and motor are correctly applied. To change the frequency to the motor, the conducting time of the power switching devices is either increased or decreased for each of the six steps. This will result in a cycle time that is either longer or shorter. The DC voltage from the converter is changed accordingly also to maintain the constant volts-per-hertz ratio to the motor as the frequency is changed.

The circuit for the six-step inverter is characterized by the use of capacitors in the DC link. When SCRs are used for the inverter, relatively complex "*commutating circuit"* is required. To perform the predetermined sequencing, the SCR's are switched on by the logic controls for the inverter. The SCRs however, require additional power circuits in order to be switched off. These additional circuits are called commutating circuits, and may include capacitors, reactors, diodes, and additional SCR's. These add to the complexity and cost of the inverter.

Newer state of the art devices such as power transistors (IGBT's) do not require commutating circuits. These are being used instead of SCR's for many designs as they become available with higher ratings.

Current Source Inverter: This inverter section has six power switching devices. Unlike the six-step inverter, the current source inverter use SCR's most of the time and will usually be applied for larger horsepower sizes only. There is little advantage in using power transistors for current source inverters. The six SCR's acting as switches, are switched on and off in a predetermined sequence to produce a six-step, three-phase current wave for the motor. Like the voltage source inverter, the distorted current wave contains harmonics which are usually not detrimental when the inverter and motor are correctly applied. The voltage wave, however, is unlike that of the six-step inverter and is generated by the counter emf of the motor. It contains voltage spikes that are caused by commutating the SCR's off.

The distorted current wave contains harmonics which are usually not detrimental when the inverter and motor are correctly applied. To change the frequency to the motor, the conducting time of the power switching devices is either increased or decreased for each of the six steps. This will result in a cycle time that is either longer or shorter. The DC voltage from the converter is changed accordingly also to maintain the constant volts-per-hertz ratio to the motor as the frequency is changed.

The circuit for the current source inverter is characterized by the use of a large reactor in the DC link, the use of series diodes with the SCRs and relatively simple commutating circuits with capacitors for the inverter. To perform the predetermined sequencing, the SCR's are switched on by the logic controls, and switched off by commutating circuits. Unlike the numerous additional devices and circuits required to commutate SCR's for the six-step inverter, the current source inverter requires only simple capacitor circuits and the diodes.

Inverter Comparisons

Because of the many variables, it is not practical to state specific efficiencies for the three basic types. The efficiency for each type should be determined for a specific manufacturer's design for specific conditions. The following comparison parameters should be noted:

1) **Inverter Commutation Circuits for SCR's:** With the six-step and the PWM inverters that use SCR's, the commutation circuits will be considerably more complex than those for current-source inverters. This is one of the current-source inverter advantages. However, when power transistors are used with six-step or voltage-source PWM inverters, there are no commutation circuits and the inverter power circuits are the simplest.

2) **Inverter Short Circuit Protection**: The current-source inverter will inherently limit short circuit currents, thereby minimizing the number of fuses required in the controller. Voltage-source six-step and PWM inverters usually require fuses or additional electronic protection circuits.

3) **Inverter Open Circuit Condition**: With a current-source inverter, an open circuit condition such as disconnecting the load will result in an excessive voltage rise in the inverter circuits, because of the large amount of stored magnetic energy in the dc link reactor. Unless special circuits (sometimes called "crowbar") are employed to discharge this energy, an open circuit condition could cause inverter failures.

4) **Inverter Reactor:** The current-source inverter requires a relatively large and heavy reactor.

5) **Inverter Noise:** All three types of inverters may generate some noise in the controller because of resonance in the power switching devices. With the current source inverter, additional noise can be generated in the large dc reactor, depending on its construction. Also additional noise is generated when rectifiers with a dc chopper are used for the front end.

6) **Inverter Efficiency**: In comparing the efficiency of the three types of inverters, there are many variables involved that will influence the efficiency ratings, such as horsepower sizes, speed ranges, power switching devices and types of loads. As an example, the use of power transistors instead of SCR's will eliminate commutating losses and provide a higher efficiency in voltage-source six-step and PWM inverter.

7) **ASD Power Factor**: With the six-step and current source inverters, the power factor will be determined by the type of front end used. When SCR's are used, the power factor will be relatively poor at reduced speeds. When diodes with a dc chopper are used, the power factor will be the same as a PWM inverter, which is relatively high at all speeds. For low power factor ASDs, observe auxiliary transformer loading.

8) **Load Low Speed Requirements**: With six-step and current source inverters, cogging will be noticeable at speeds below approximately 10 Hertz. Cogging is a jerky motion of the shaft from the badly distorted current wave at these speeds. With a PWM inverter having an optimized design, the current wave at speeds below 10 Hertz is less distorted and smoother shaft rotation is possible. However, not all PWM inverter designs are optimized, and some will produce cogging at low speeds.

9) **Load Breakaway Torque Requirements:** With an optimized design PWM inverter, the torque (per amp) capabilities of the motor will be greater than that with a six-step or current source inverter. This results from the capabilities of the PWM inverter to produce a truer (less distorted) sine wave at the very low frequencies.

10) **Load Regeneration Requirements**: When it is to regenerate motor power back into the AC line to brake the motor, the current source inverter with an SCR front-end can inherently provide this if called for. This feature, however, is not possible with a current source inverter having a DC chopper front end. With six-step or PWM inverter, an additional SCR front end is required to regenerate power back into the ac line. In some cases, to avoid the necessity of

an additional converter, dynamic braking is achieved within the dc link by using a chopper and resistors. Also, to a limited degree, by virtue of the capacitance in the dc link and the motor losses, some small amount of braking is provided. This type of braking is frequently called regeneration also, although technically it is not correct.

Choice of Variable Speed Drives for Squirrel Cage Induction Motors

Up to 350 hp Voltage-Source PWM Power Transistor Type: Induction motors are highly standardized in the NEMA designs up to the 250 hp size. Also, VSDs in this horsepower range have become nearly standardized because of the availability of the power transistor for VSD ratings of up to 400 hp. The power transistor allows the design of a voltage-source, pulse-width modulated (PWM) inverter with a diode rectifier. The voltage-source concept is important for these VSDs because it eliminates the need to match the motor to the inverter allowing these VSDs to be sold without regard to motor characteristics. The power transistor provides an economical inverter capable of PWM control.

To achieve higher horsepower VSDs with power transistors, paralleled Darlington transistors are employed to obtain 500 hp constant torque and 700 hp variable torque.

The voltage-source ASD requires built-in fuse protection for the inverter. With the stored energy in the dc link capacitor, fuses are needed to protect inverter components for internal and external short circuits.

200 hp to 1500 hp Voltage-Source GTO PWM Type: For VSDs rated above the current carrying capacity limit of the power transistor, the gate-turn-off thyristor (GTO) is used in voltage-source PWM type inverters, allowing this concept of off-the-shelf type VSDs with reasonable harmonics to the motor to be extended up to 1500 hp.

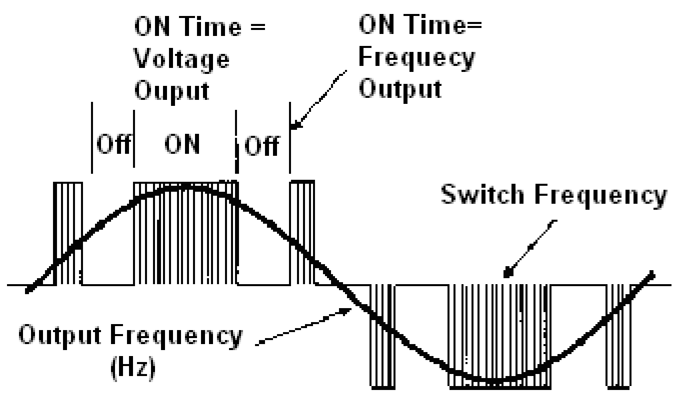
300 - 1500 hp Voltage-Source Inverter Type (six-step): Before the development of the highly reliable power transistor voltage-source PWM inverters and the voltage-source GTO PWM inverters, the principle of the voltage-source inverter was used with the six-step design using thyristors. Most manufacturers have converted their ASD design to the newer turn-on, turn-off devices such as IGBTS and GTO's.

Switching Bus with Insulated-Gate Bi-Polar Transistors (IGBT)

Insulated Gate Bipolar (IGBT) is a transistor used in AC drives to generate AC power from DC power through a control strategy called Pulse Width Modulation (PWM).

Insulated-Gate Bi-Polar Transistor is widely used in ASDs for AC motor in the range of 5 hp to 400 hp. The insulated-gate bi-polar transistor (IGBT) switches the DC bus on and off at specific intervals. In doing so, the inverter actually creates a variable AC voltage and frequency output. The output of the drive doesn't provide an exact replica of the AC input sine waveform. Instead, it provides voltage pulses that are at a constant magnitude.

The drive's control board signals the power device's control circuits to turn "on" the waveform positive half or negative half of the power device. This alternating of positive and negative switches recreates the 3 phase output. The longer the power device remains on, the higher the output voltage. The less time the power device is on, the lower the output voltage (shown in figure below). Conversely, the longer the power device is off, the lower the output frequency.



Drive Output Waveform Components

The speed at which power devices switch on and off is the carrier frequency, also known as the *"switch frequency".* Typical switch frequencies are 3,000 to 4,000 times per second (3 KHz to 4 KHz). With an older, SCR-based drive, switch frequencies are 250 to 500 times per second. *Higher the switch frequency, the smoother shall be the output waveform and the higher the resolution.* However, higher switch frequencies decrease the efficiency of the drive because of increased heat in the power devices.

IGBTs combine the best characteristics of the power MOSFET and the bipolar transistor in a single transistor device. In horsepower ranges up to 400 hp, it is used instead of the thyristor because parts count is reduced from over 1000 to about 10 by using the IGBT, resulting in high reliability and low cost.

STANDARD MOTOR- VSD DESIGN COMPATIBILITY ISSUES

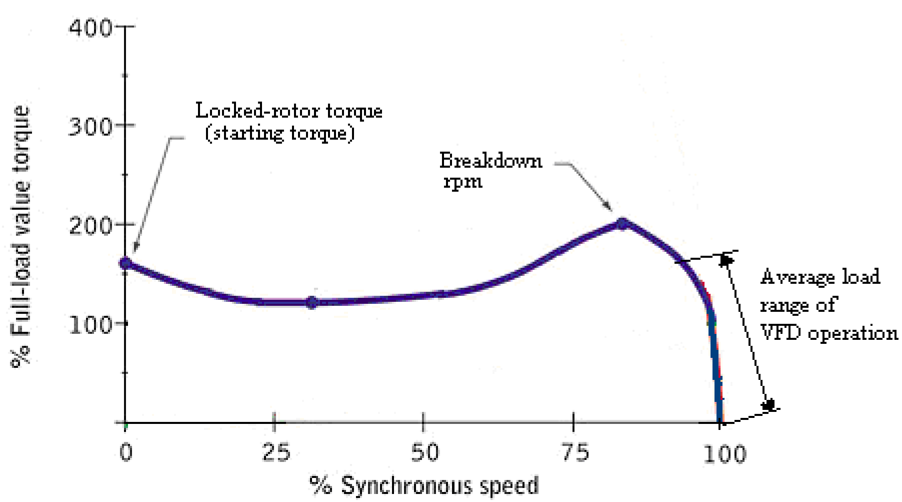
In applying variable frequency controllers attempts are often made to use either "in place" AC motors, or standard sinewave power designs. Many standard efficient, fixed frequency design motors will not achieve their nameplate rating when operated on an adjustable frequency control at 60 Hz. Ideally the motor design must match with the requirements of the variable frequency controller.

Sometime to operate across a speed range, the motor is often oversized relative to the rating required by the application. This can sometimes be done successfully, but there are a number of potential pitfalls. Whenever load speeds are varied, there are many considerations which must be taken into account. These concerns are both electrical and mechanical in nature.

The following paragraphs will discuss issues that are commonly raised in discussions of variable frequency applications.

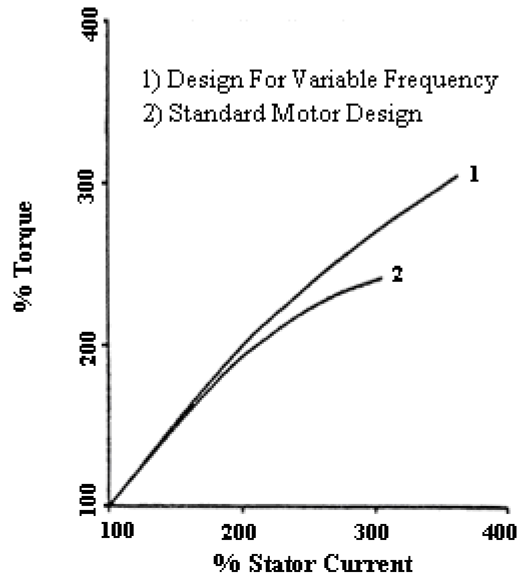
Starting Characteristics

Since adjustable frequency controllers typically accelerate a motor and load by slewing the motor voltage and frequency in such a way as to remain in a region of operation above "breakdown RPM" (as illustrated in figure below), the usual constraints of fixed voltage, fixed frequency starting and acceleration do not apply. Starting torque and current are no longer functions of the 1.0 per unit slip characteristics of the motor but are limited by the overload capability of the control. Thus, the controller can be matched to the motor in such a manner as to produce the appropriate starting torque based on a torque/amp ratio equal to that under full load conditions.



Fixed Voltage and Frequency Speed Torque Curve

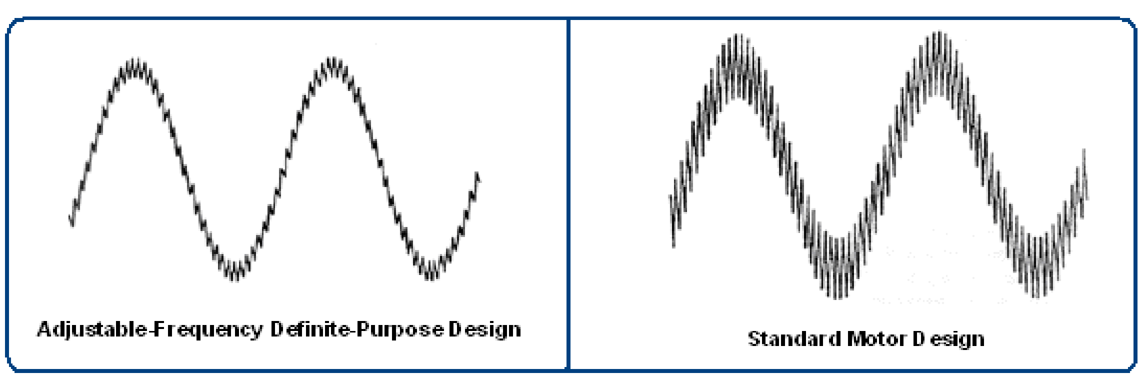
By evaluating the drive as a motor and control "package", the motor designer can take advantage of this to enhance the level of starting torque as well as overload torque per amp as shown in figure below:



Overload Torque per Ampere

Peak Currents

In addition to the RMS current level, an important rating point for a transistor (typically used in adjustable frequency controllers) is the peak current capability. *The high frequency transient current which results from the electronic switching of the control output voltage is inversely proportional to the leakage inductance of the motor.* The leakage inductances can be increased by altering the design of the windings and the magnetic cores in the motor. The use of an electromagnetic design specifically for adjustable frequency power can significantly reduce the peak current required for a given level of power output (see figure below). This will not only improve the reliability of the drive, but often can prevent costly over sizing of the AC controller and provide the most cost effective solution.



Typical PWM Current Waveforms

Definite-purpose, adjustable frequency design reduces peak as well as RMS current required from the controller for a given horsepower.

Variations in Current and Voltage Waveforms

The variable speed drive shall result in the voltage and current waveforms deviating from ideal sinusoidal wave shapes. This creates additional losses without contributing to steady state torque production. The higher frequency components in the voltage waveform do not increase the fundamental air gap flux rotating at synchronous speed. They do, however, create secondary "hysteresis loops" in the magnetic steel, which along with high frequency eddy currents produce additional core losses and raise the effective saturation level in the lamination material. As another consequence of these higher frequency flux variations there are higher frequency currents induced in the rotor bars which generate additional losses. Appropriate electromagnetic design, including rotor bar shape can minimize these added losses.

Power Quality (Line Considerations)

Both AC and DC drives create electrical noise that can affect the reliability and performance of the drive, motor, and AC power supply. The magnetic and electrical forces created within the drive cables can induce forces on other electrical devices in close proximity. The resulting disruptions in the power supply are referred to as noise. Noise disrupts the power in nearby cables, which can cause overheating, reduced power factors, circuit breakers to trip, and malfunctions of other devices operating on the power supply.

Voltage spikes are a type of noise caused by power surges when drives start up and shut off. Large quantities of voltage can suddenly be transmitted across the line when drives are used.

Harmonics are a special type of noise resulting from AC drives. Harmonics are sinusoidal waves with higher frequencies than the main power supply, and are transmitted back to the AC line.

Power Quality (Harmonics):

Harmonics and electrical noise are potential problems when power electronics are utilized. It means a 60Hz voltage source can also produce current flows at frequencies other than 60Hz and these currents are real. These nonlinear loads introduce harmonic voltages, which affect the entire power supply system. When the harmonic content exceeds these limits, we may encounter power quality problems such as low / high RMS voltages, voltage sags, voltage swells, voltage impulses (transients) etc., which can affect the remaining loads on the power system. To counter these problems installing suitable compensating devices such as harmonic filters or isolation transformers may become necessary.

The standard IEEE Std. 519 - 1992; is written to attend to this issue. The standard has been written to limit the harmonic content introduced into the system by either the utilities or the customer. (Note: The limits are, generally, 5% voltage distortion and 3% current distortion at the “Point of Common Connection” (PCC) or the point at which the utility power enters the customer plant.)

Harmonic content has attracted quite a bit of attention when discussing power quality and power electronics. Harmonics, created by the load, generally come from feedback into the line from electronic power supplies. Voltage and current harmonics tend to create alternate fields within motors and rotors, cause transformers to overheat, and interfere with other electronic systems. Odd harmonics of the fundamental frequency are generally found in power electronic systems.

In motor systems the following fundamentals of 60 Hz can be recognized:

Harmonic	1st	3rd	5^{th}	7th	etc
Rotation	Positive	Zero	Negative	Positive	etc

Positive harmonics rotate in the direction of the rotor. Negative rotating harmonics rotate against the rotor causing overheating of the rotor and reducing torque. Zero rotating harmonics generally cause system neutrals to overheat. In the case of electronic drives, in general, the predominant harmonics are the 5th and 7th.

Drives may be built with special devices to reduce the amount of noise and harmonics created or transmitted. *Devices that filter out noise are: Reactors, transformers, harmonic filters, isolation transformers, and 12 or 18 pulse drives.*

Drives can be classified as 6, 12, or 18 pulse. The number of pulses is a reference to the number of conduction sequences available in the converter. Twelve and 18 pulse drives produce fewer harmonics than a 6 pulse drive, and the harmonics are at higher frequencies.

Simple hand held instruments are available at reasonable price, to check harmonic contents or ‘power line” analyzers may be used for conducting detailed study.

Motor Heating

The distorted current wave produced by all type of inverters contains harmonics. These harmonics will not develop productive torque, but will cause additional motor heating. The amount of additional motor heating produced with six-step and current source inverters is predictable and will vary over the speed range from approximately 3% to 15% additional heating. This should be considered when applying motors with inverters. The additional heating with voltage-source PWM inverters may be approximately the same as six-step, depending on a manufacturer's specific design. Newer designs with high carrier frequency produce less than 5% additional heating.

With NEMA frame motors, motor heating is usually not a problem unless the speed range is greater than 4:1. In applying NEMA frame motors for greater than 4:1 speed range use one or two larger frame sizes to accommodate the loss of cooling air at low speed.

Insulation Failures

Because of the type of output generated by the inverter, there is great stress placed upon the insulation and the temperature rise of the windings may increase. In other cases, the motor may be run below its minimum self-cooling speed. The main trouble is that for every 10°C, the insulation life of the windings is reduced by half. If the temperature rise is allowed to climb too high, the motor will overload and burn-up in a very short time. An additional problem, which is rare, is inverter resonance. It is essential to rewind or replace the motor – either rewind with higher insulation class or replace it with a new energy efficient or inverter duty type.

Motor Cooling

As has been well documented in the literature, when AC motors are run across a wide speed range their heat transfer effectiveness will vary a great deal. Cooling fans whose rotation is directly supplied by the motor are subject to high windage losses and noise at high speeds. Modern AC controllers are capable of operating across a very wide frequency range, often up to several hundred hertz. While this provides great flexibility in the control, it places the motor cooling fan well above its fixed frequency design operating point which often leads to inefficient air flow and objectionable noise. In low speed operation the fan's effectiveness falls off with the motor's speed.

In variable torque applications this reduction in cooling air often stays in balance with the reduction in motor losses as the load is reduced with speed. However, in constant torque applications the motor's temperature limits will likely be exceeded. An independently powered blower can provide an essentially constant heat transfer rate. Although not a standard fixed frequency motor feature, depending on the load/speed profile required by the application, this can be a very effective choice and is often specified for high performance applications.

Motor Flux Level

The fundamental frequency component of the voltage output of a variable frequency controller can be as high as the AC input to the controller. However, this is often not achieved. In order to maintain PWM modulation for example, the output voltage may be limited to 90-95% of the incoming AC voltage. As long as this situation is recognized, and appropriate design choices made, it does not usually present a problem. When an existing motor design (expecting 460 V at 60 Hz, for example) is applied to a controller which delivers only 420V, there can be problems.

While NEMA standards for fixed speed AC motors allow for a 10% voltage variation from nominal, it is important to recognize that at 10% lower than nominal flux, performance including the nominal HP rating will vary. For example, it may require 10% more current than nominal to deliver rated HP. While this additional current is almost always available from the incoming line it may not be available from the variable frequency controller.

Operation of an AC motor at lower than nominal flux levels will result in increased slip and rotor heating which is self compounding and may lead to a thermal runaway condition. High efficiency AC motors designed for sinewave operation are often particularly susceptible to poor performance when the controller output voltage is low, since they usually employ low flux density designs at nominal terminal conditions.

Special Cable: When DC bus voltage is inverted to AC output power, switching in the inverter creates current spikes. A non-sinusoidal current waveform permits voltage spikes, reflections, and other non-linear electrical distortions. Resulting corona discharge ionizes the oxygen in the air naturally surrounding the copper conductor, creating an environment suitable for the formation of ozone. Ozone (03) attacks all insulation types, including XLPE, FEP, PE and EP. Evaluate this aspect carefully with the suppliers.

Mechanical Flexibility

Mechanical considerations include "*mechanical resonance"* and "*driven load incompatibility"*. Mechanical resonance can be defined as the speed of the driven load that matches its natural frequency. If this speed is found and maintained, the equipment will develop extremely high levels of vibration and may shake itself apart. While all elements of a high speed motor system (bearings, rotor balance and strength, etc.) must be evaluated for suitability, a motor designed for operation on a high performance variable frequency drive must have considerable flexibility inherent in its construction to accomplish the variety of tasks it will be called upon to perform.

Load incompatibility can be defined as loads which may not be operated at speeds lower than their design speed. For instance, many gearboxes have a minimum speed at which the lubricating oil may not be properly moved over the contacting parts. Load incompatibility can only be avoided by not allowing the drive to operate below a minimum speed.

Motor Noise

With the voltage-source PWM inverter, the motor sometimes will produce higher noise typically in the range of 7 to 10 db more than normal. This is primarily because of the acoustic noise of air caused by running shaft driven fans above their design speed to achieve a wider speed range and the second source is the magnetic noise from flux harmonics which are driving the magnetic core steel into a saturated condition. The newer designs with high switching frequencies greatly reduce the noise levels.

The concerns above can be avoided through the following means:

1) A definite purpose AC motor is used for VSD application, which is essentially a square laminated-frame configuration with integral feet on the end brackets and adaptable electromagnetic designs.

2) The motor insulation system must be capable of withstanding the increased thermal stress as well as the capacitively coupled currents and voltage stresses.

3) Provide external cooling - This is especially important in cases where the self-cooling ability of the motor is compromised.

4) Re-set the parameters - inverter resonance is found in cases where the drive parameters are not properly set. If this is not the case, the drive should be programmed to by-pass those frequencies where the problems are found.

5) Mechanical resonance can be avoided by programming the drive to avoid the appropriate frequency(s). The resonance levels may be determined by using a vibration analyzer and operating the machine through the entire speed range.

6) The VFD should be considered with protective circuits for an orderly shutdown. The motor overload for instantaneous trip, motor over current, over voltage, under voltage, over temperature, ground fault control or microprocessor fault protection must be included.

In summary, the motor and controller must be considered as a system to insure the desired results. Since high performance variable frequency drives will typically be used in "DC like" applications, it can be assumed that more DC like construction will be required in definite purpose AC motors. The motors technically known as “Inverter Duty Motors” shall be used that are essentially compatible with the drive controller.

Inverter Duty Motors

Inverter duty motors are specially designed to withstand the new challenges presented by the use of inverters. There are a number of ways to designate motors "inverter duty," however; several things must exist as a minimum:

1) Class F insulation - to withstand the higher heat generated by non-sinusoidal current from the drive
2) Phase insulation - Insulation between phases is a must to avoid "flashover" between phases from current surges.
3) Layered Conductors - To reduce turn to turn potential between conductors
4) Solid varnish system - to reduce partial discharge and corona damage
5) Tight machine tolerances and good air gap concentricity - to reduce shaft currents and resulting bearing damage.

A proper inverter duty motor will have special rotor bar construction designed to withstand variations in air gap flux densities and rotor harmonics. Additionally, the first few turns of wire may be insulated to better withstand standing waves which occur due to the faster rise times in modern inverter technology.

Caution: Some manufacturers may only de-rate motors. This is done by reducing the motor by (about) 25%. Therefore, a 10 hp motor may be rated as a 7.5 hp motor.

It should be noted, also, that an inverter application does not always require an inverter duty motor. The old motor or an energy efficient motor may be sufficient for the application.

Braking of Motor

Drives not only vary the speed at which motors operate, they also offer a means of “braking” a motor. If a motor is not connected to a drive or equipped with a mechanical brake, it will coast to a stop when the motor is shut off. *Braking provides for a controlled form of stopping, whether it is coasting, gradual braking, or quickly halting the motor.*

There are two means of braking with the use of drives: Injection braking and dynamic braking. **Injection braking** is only applicable with AC drives and motors. To stop the motor, the drive sends DC current to the motor. Without the varying voltage and frequency in various phases, the magnetic field in the stator stops rotating. The rotor is attracted to the halted field and stops. **Dynamic braking** is used when the motor acts as a generator. Changes in the load may cause the motor to act as a generator rather than a motor. An example would be a conveyor belt that is sloped downward—as the weight is added to the belt, the load may pull the motor faster than it would normally operate. In dynamic braking, contactors, or other switching devices, create a circuit in the drive that directs power flow from the motor to resistors. Resistors dissipate power by converting it to heat. This form of controlling power flow slows down or stops the motor. Regenerative braking is a form of dynamic braking in which the power is dissipated back into the main AC line, rather than through resistors.

This eliminates the wasting of power and also reduces the amount of heat created in the resistors.

Benefits of variable drives

Single-speed starting methods start motors abruptly, subjecting the motor to a high starting torque and to current surges that are up to 10 times the full-load current. This heavy current then drops off gradually as the load breaks loose, and the motor comes up to speed, but causes unacceptable voltage sag on the power system, adversely affecting other loads. Variable speed drives, on the other hand, gradually ramp the motor up to operating speed to lessen mechanical and electrical stress, reducing maintenance and repair costs, and extending the life of the motor and the driven equipment.

1) By reducing the output terminal voltage at motor under part load, it is possible to reduce the magnetic core saturation, hysterisis losses and copper winding losses. Thereby it increases the overall efficiency of the system.
2) At below 50% load, where motor efficiency falls down, VFD improves efficiency by reducing losses and giving energy savings @ 30 – 40 %. This saving depends upon the duration of running time at under part load.
3) By progressive ramping up the voltage, motor can be started smoothly to reduce….
    a. Starting current
    b. Mechanical shock to drive mechanism
    c. Variation in power factor

In addition to the energy savings offered by the variable speed drives, other advantages that go with them are –

1) Increased motor life
2) Lesser strain on the drive equipments and lesser breakdowns

3) Lesser strain on power transmission devices like couplings, pulleys, gear boxes and hence improved life

4) Reduced maintenance cost

5) Quieter operation at low load

6) Precise speed variation like in DC drives but are less costly compared to DC drives

7) Soft start facility is built in and well suited for high starting torque applications

8) Every standard AC motor can be fitted with a variable speed drive using a frequency inverter.

Variable speed drives can also run a motor in specialized patterns to further minimize mechanical and electrical stress. For example, an S-curve pattern can be applied to a conveyor application for smoother, which reduces the backlash that can occur when a conveyor is accelerating or decelerating.

When to Opt for Variable Speed Drives

While going in for AC variable speed drives for any application, it is very essential to analyze and verify whether there is justification to go in for these drives. Following points have to be considered to avoid any misjudgment.

1) Confirm whether the production process itself requires variation in speed drives irrespective of whether energy saving potential exists or not.

2) In case of pumps and fans, verify whether the required flow rates for the process does or does not vary much.

   Case #1: If the flow rate requirement does not vary much, check whether the required flow rate is achieved by throttling the valves or dampers permanently. In this case there is no justification for going in for variable speed drives. Any one of the following steps may save energy.

   a) Change the speed of fan / pump by replacing pulley / gearbox / coupling etc. to suit the required flow rate.

   b) Change the impeller or trim the impeller to suit the required flow rate.

   c) Change the pump / fan itself to suit the required flow rate.

   In all these cases if the loading on the motor reduces to less than 50 % (in case of energy efficient motors), replace the motor also with smaller one. Normally the cost benefit in all these cases will be substantial. However this can be calculated before taking a decision.

Case# 2: If the flow rate required varies substantially because of the normal process variations, then it becomes necessary to think of variable speed drives, as there will be high potential for saving energy. The amount of saving can be calculated by finding out the difference in energy consumed by throttling / re-circulating / venting etc. and energy consumed by varying the speed of the equipment using variable speed drive.

3) Check whether a closed loop control can be adopted to regulate the flow rates continuously and adopt the same along with installation of drives. In fact control strategy for temperature and level can also be utilized to save energy.

4) *Efficiency and Power Factor:* A drive should have an efficiency rating of 95% or better at full load. Variable frequency drives should also offer a true system power factor of 95% or better across the operational speed range, to avoid penalties from the power utility, save on energy bills, and to protect you equipment (especially motors).

Where "No" to Variable Speed Drives

Although centrifugal pumps and fans provide the best applications for VSD retrofits, speed controls are not necessarily cost-effective for all pumps and fans. The best way to determine the cost-effectiveness of a proposed VSD installation is to look at the power needed at each operating condition with and without a VSD. The energy savings can then be calculated by taking the reduction in power at each condition and estimating the savings based on the actual (or expected) operating time at that condition.

Following are the few reasons where VFD installation is not recommended.

- The process systems requiring constant pressure regardless of flow should not be retrofitted with VSD drive. The VSD drive shall reduce the pressure at the outlet of the fan or pump at lower flow.
- If the overall utilization of motor is above 70% of designed capacity. At this load motor performance is best and effective benefits of VFD cannot be achieved.
- If the overall utilization of motor below 40% of designed capacity. Such lower utilization indicates the mechanical change (down sizing of equipment) of the system and to go for lower capacity of motor.
- If overall energy conservation is not more than 10 – 12 %, as it adds installation cost.
- If VFD is affecting the final quality and quantity of product.

Selection Considerations for Variable Speed Drives

The following motor information is required for selecting the proper variable frequency drive:

1) Full Load Amp Rating- Using a motor's horsepower is an inaccurate way to size variable frequency drives.
2) Voltage Rating
3) Speed Range

Generally speaking, a motor should not be run at any less than 20% its specified maximum speed allowed. If it is run at a speed less than this without auxiliary motor cooling, the motor will overheat. Auxiliary motor cooling should be used, if the motor must be operated at slow speeds.

If continuous operation is a must, then the following should be specified:

1) 10% voltage fluctuation
2) 3% frequency variation
3) Voltage sag ride-through for the following:

- 0% voltage for 1 cycle
- 60% voltage for 10 cycles
- 87% voltage continuous

If you need to supply a 3-phase drive with single-phase power, then the drive must be derated by 25% to 50% of its current-handling ability, which may require you to specify a larger-sized drive.

Theoretical calculation methods for selecting rating of variable frequency drive are as follows:

Method no - 1

VFDs are typically classified by horsepower. However, the size of VFD necessary is probably larger than the size of the motor being controlled by the VFD. This is for two reasons:

First, a motor can produce more than its rated horsepower. It is not unusual for a motor to produce up to 15% over the rated shaft horsepower by utilizing the motor’s service factor.

Second, the VFD is rated by its output horsepower, which is the input horsepower to the motor. The input horsepower is the motor’s shaft horsepower divided by the motor efficiency. For example, a motor with a 100 horsepower output rating and a motor efficiency of 93% that is being used at the limit of a 1.15 service factor would require a VFD with an output of 124 horsepower. This is 24%over the nominal motor horsepower rating. A 125 HP VFD would be marginal in this case, for the 100 HP motor. For VFD retrofits to existing motors, the best way to determine the required size of a VFD is to measure the electrical current and voltage supplied to the existing motor under actual working conditions that include the condition of maximum load. (For a centrifugal pump, maximum load is usually the maximum flow rate/minimum TDH condition. For an axial flow pump (propeller pump), maximum load is usually the zero flow/maximum head condition. Consult the pump's curve to determine the actual maximum loading condition.)

Method no - 2

Before ordering of VFD, say for pump or fan application, first refer to the speed v/s power curve and flow rate v/s shaft power curve. Find out the maximum power at top almost reaches to achieve full flow rate. For example consider a fan take 125 kW at full flow rate, considering 90% efficiency of AC motor and 95% efficiency of VFD, the input power required would be Shaft power / motor efficiency / VFD efficiency i.e. 125/0.9/. 95= 146kW. Considering further deration of VFD due to ambient temperature, the VFD should be at least 160 KW rating (with 150% for 60 seconds overload capability) for fan application.

Installation Aspects

The variable speed controller can be installed in a open loop or closed loop. In both the cases the controller is put in series to the application motor.

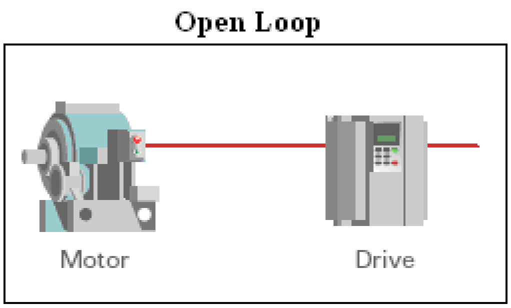
Open Loop Installation: A type of AC regulation that controls motor speed without feedback devices and regulates the current output to the motor, and controls the rotor/shaft speed by controlling the frequency of the magnetic flux in the stator.

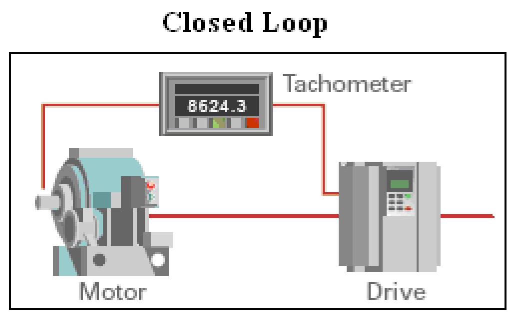
Most drives used in the field utilize volts/ hertz type control, which means they provide open-loop operation. These drives are unable to retrieve feedback from the process, but are sufficient for the majority of variable speed drive applications. Many open-loop variable speed drives do offer slip compensation though, which enables the drive to measure its output current and estimate the difference in actual speed and the setpoint (the programmed input value). The drive will then automatically adjust itself towards the setpoint based on this estimation.

The feed back for variable frequency will be by manual intervention as per requirement. Such installation of VFD is operator dependent, thus result in inconsistence of VFD.

Close Loop Installation: The feed back for variable frequency will be taken through proper set of instrumentation and most variable torque drives have PID capability for fan and pump applications, which allow the drive to hold the setpoint based on actual feedback from the process, rather than relying on estimation. A transducer or transmitter is used to detect process variables such as pressure levels, liquid flow rate, air flow rate, or liquid level. Then the signal is sent to a PLC, which communicates the feedback from the process to the drive. The variable speed drive uses this continual feedback to adjust itself to hold the setpoint.

Such installation of VFD is not operator dependent and high levels of accuracy can be achieved through drives that offer closed-loop operation.





Other Issues

1) Most damaging environments for electronic equipments are excessive heat, excessive moisture and presence of corrosive vapor in the atmosphere. When installing a VFD, we must consider the ambient surroundings. The room must clean, dry, warm, and a maintained circulating air flow. Ideally an electrical room should be used. If there is not an ideal environment available, adjustments should be made i.e. heaters, air conditioners, and NEMA 4 enclosures.

2) The motor age must also be considered. If the motor is over 5 years old, the use of an output filter may be required. This will dampen the voltage spikes coming from the VFD and protect the motor insulation.

If the system voltage is 600 VAC, an output filter should also be used. Even with new motors, the insulation may be damaged from the VFD voltage spikes.

User-Operator Interface

A drive's user interface allows an operator to program control references to the drive/motor system, and to monitor motor and drive operating conditions.

Interfaces include start/stop pushbuttons, keypads situated directly on the drive or in a remote location, PCs with drive compatible software, and programmable logic controllers (PLCs). PCs and PLCs are useful when multiple drive systems will be used at one time. They allow for multiple drives to be programmed quickly with the same control references, and also reduce the amount of wiring needed to link the systems together.

They operate on a communications link or industrial network, which allows for high speed and quality process control. In most applications, drives are used to control motors in conjunction with other electrical equipment. For example, one motor may be used with a series of other motors in a continual process—the speed of one motor might be dependent upon another motor. If a sensor goes off, the motor might need to stop or slow down.

1) *Drives provide a means for developing a control logic based on the status of other devices.*

2) *Drives also display the status of the motor and drive parameters, such as current and speed.*

These functions require input and output (I/O) connections within a drive. There are two types of I/Os: Digital and Analog.

Digital I/Os can be either on or off. Examples of digital I/Os would be a start button, fault signal, light, or photosensor. Analog I/Os may have a value within a set range. Examples of analog I/Os would be current level or current operating speed.

VSD Failures & Troubleshooting

It has been documented that some electric motors fail in inverter applications. This has often been attributed to inverter voltage "spikes." While this is relatively correct, it misses some important aspects to the mode of failure.

The number of pulses that a PWM drive fires in order to control the current waveform to the drive is known as the "carrier frequency". The carrier frequency tends to run from 2 to 18 kHz in most modern PWM drive. In addition, each voltage pulse is not a square waveform. They have a tendency to overshoot on startup, causing a "ringing" effect at the peak voltage of the pulse. Insulation systems are designed, not only for temperature, but also for "rise time," i.e. how fast the voltage increases over time.

Initially, it was thought that inverter duty failures occurred only on the first few turns of the electric motor winding. It was later found that this was not correct for all cases.

Instead, it was discovered, a phenomenon normally seen in electric motors rated at 6,000 VAC, and above, known as "partial discharge", was now occurring in motors rated as low as 460VAC. This phenomenon is similar to a lightning storm within the windings themselves. Within voids in the winding insulation, a charge builds up and then discharges (much like a capacitor). The end result is ozone, which begins to break down the insulation on the wires, eventually causing a current path, or short.

The mode of failure for motors in this environment is as follows:

1) The motor and drive are placed a distance apart and the carrier frequency is set high (i.e.: above 8 kHz) in order to keep the motor quiet. The lower the carrier frequency the louder the motor noise. No filtering is put in place.

2) The pulses from the drive travel out to the motor. Based upon the impedance of the cable and motor, a reflection of the pulse travels back to the drive. This cycle through the "free-wheeling" diodes of the inverter and travel back out with the normal pulses. This adds on to the peak voltage, causing a greater peak (as much as 2 to 4 times, usually 2) with an extremely fast rise time. (i.e. less than .1 u-secs per 500V versus the 1 u-sec per 500 V recommended by NEMA).

3) In some cases, the voltage spikes will cause the weakest part of the winding insulation to fail and the motor shorts.

4) In other cases, small voids in the insulation begin to have partial discharge problems, the ozone eats away at the insulation, until, finally, the insulation becomes weak enough for the spikes to break through.

It should be pointed out that this tends to be a rare problem. Following are measures to avoid the chance of this problem occurring to you:

1) Check with the motor manufacturer to ensure that the motor can operate in an inverter environment.

2) Use filters in the inverter system (i.e.: from line reactors to spike arrestors, designed for inverter use).

3) Read the VFD operators manual. It will often state the minimum distances and frequency settings.

4) Use proper wire sizes.

The table below provides generic troubleshooting points:

Common Problems:

Problem	Possible Cause	Solutions
The motor will not run	No line power; drive output too low; stop command present; no run or enable command; faulty drive	Check circuit breakers and drive programming. Check for other permissions
Overcurrent or sustained overload	Incorrect overload setting; motor is overloaded	Check overload settings and check to ensure motor is not overloaded
Motor stalls or transistor trip occurs	Acceleration time may be too short. High inertia load.	Lengthen acceleration time. Readjust the V/Hz pattern
Overvoltage	The DC bus voltage has reached too high a level	Deceleration time too short or the supply voltage is too high; motor overhauled by load.
Speed at motor is not correct; speed is fluctuating	Speed reference is not correct; speed reference might be carrying interference	Ensure that the reference is correct and clean.

Bypassing Drive

Bypassing the drive means that control of the motor is switched from the drive to a starter.

Some applications require the motor to continue running when the drive has failed. Drives may be bypassed in these applications, or when they need to be maintained. Bypassing the drive means that control of the motor is switched from the drive to a starter. This switching is accomplished through contactors—one between the drive and the motor, and one between the motor and the starter. The electrical circuit has now been reconfigured so that power flows through the starter rather than through the drive. Drives can be bypassed manually (an operator can open and close the contacts), as in the case of maintenance, or automatically if the drive fails.

APPLICATION OF VARIABLE SPEED DRIVES

When selecting a VSD, the basic torque-speed characteristic of the load should be known so that the VSD supplier can be advised. Generally equipment can be classified into one of the following load type:

1) Constant Torque is characteristic of conveyors, extruders and positive displacement pumps. Here, torque is constant for all speeds and horsepower is proportional to speed. With the VSD application to a constant torque load, horsepower, voltage and frequency are proportional to speed. Motor torque and flux density are constant with speed. Since the torque is given by B x I (flux density times stator current), for constant torque, both B and I are constant.

2) Variable horsepower, variable torque load characteristic applies to fans, blowers, centrifugal pumps and low compressors. These require maximum power at maximum speed. Torque varies at the square of speed and horsepower as the cube of speed.

VSD can be installed on any electric motor, but these achieve the maximum energy savings when applied to variable torque load characteristic equipments. The energy efficiency of almost any pump or fan system can be substantially increased by the addition of a VSD motor controller because these systems are either oversized or must respond to widely varying load conditions.

In many systems excess capacity is still handled by mechanically throttling flow with valves or dampers. This is extremely inefficient because the motor continues to work hard to deliver at its full capacity. By changing the speed of the electric motors powering these fans and pump systems, VSD allow them to follow system loads while at the same time capturing the energy efficiency benefits offered by the so-called “Affinity Laws”.

The affinity laws state that the power required by centrifugal equipment varies with the cube of speed but that output varies directly with speed. For example, if a fan load is 50% of its total capacity during some periods of its operation, the fan’s speed can be reduced to 50% to exactly meet that load, while the fan power is reduced by = $(1 – (0.5)^3) \times 100 = 85$ %. A seemingly minor 20 rpm increase in a motor’s rotational speed—from 1740 to 1760 rpm—can result in a 3.5% increase in the load placed upon a motor driving a pump or fan. In contrast, the quantity of air or water delivered varies linearly with speed. Variable speed drives can typically save 14 to 50% of energy.

Below we will discuss the energy conservation benefits on VSD pumps in detail.

PUMPS

Water pumping systems are designed to supply the maximum demand of the system in which they are installed. However, quite often the demand for water can vary and be much less then the system is designed for in capacity. For example, on a conventional pump system, a throttling valve in the system piping normally handles these conditions. The pressure drops across a control valve and other factors cause an energy loss.

A Variable Frequency Drive eliminates the need for a control valve because speed and output of the pump are electrically controlled to match the water demand. Whenever the flow requirement varies, speed of the pump can be increased / decreased automatically.

Principle of operation & control of pumps

The variation of the flow, pressure developed and the power consumption of a pump with speed is as below: -

Flow = K (Speed)

Head = K $(\text{Speed})^2$

Power consumption = K $(\text{Speed})^3$

Varying the speed of the pump achieves considerable energy savings because of the laws, which govern the operation of all pumps, in particular that the power of the motor varies by the cube of the speed. This is the critical factor in understanding the electrical energy savings that can be made by using variable-speed pumps.

Methods of control & energy efficiency

There are various methods of capacity control:

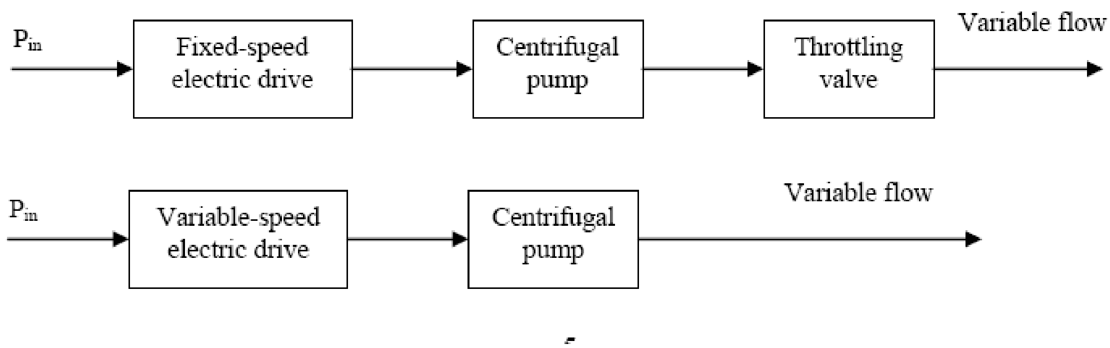
1) Recirculation: - This is a popular method in which part of the liquid is recirculated to the suction tank/suction of the pump to regulate the flow to the system. This type of control is the most inefficient one since only a part of the energy utilized is useful and the rest is lost in recirculation. Irrespective of the capacity utilized, the power consumption is constant.

2) Valve throttling: In this method the valve in the delivery line of the pump is throttled to regulate the flow to the system. This is also energy inefficient as part of the energy supplied (pressure developed) by the pump is lost across the throttle valve.

3) Variable speed devices: The speed of the pump is varied to achieve different capacities. The most efficient way of controlling the capacity is through variable speed drives (especially) VFD, as it is the closest to the ideal theoretical curve.

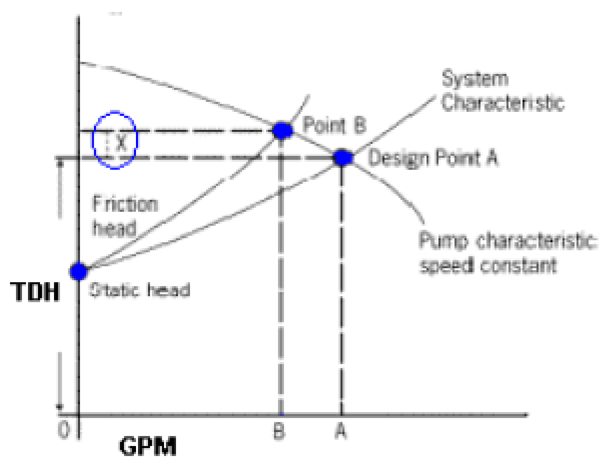
COMPARISON – THROTTLING V/s SPEED CONTROL

Two alternative are illustrated in accompanying block diagram



Block diagram of continuous speed and VSD

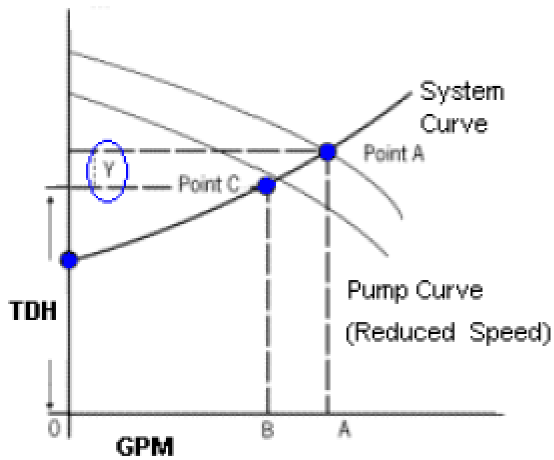
The most important difference of flow control by throttling compared to VFD is that the throttling alters the system curve while the VFD alters the pump curve. It is relevant to note that flow control by speed regulation is always more efficient than by control valve, which can be seen in the discussion below.



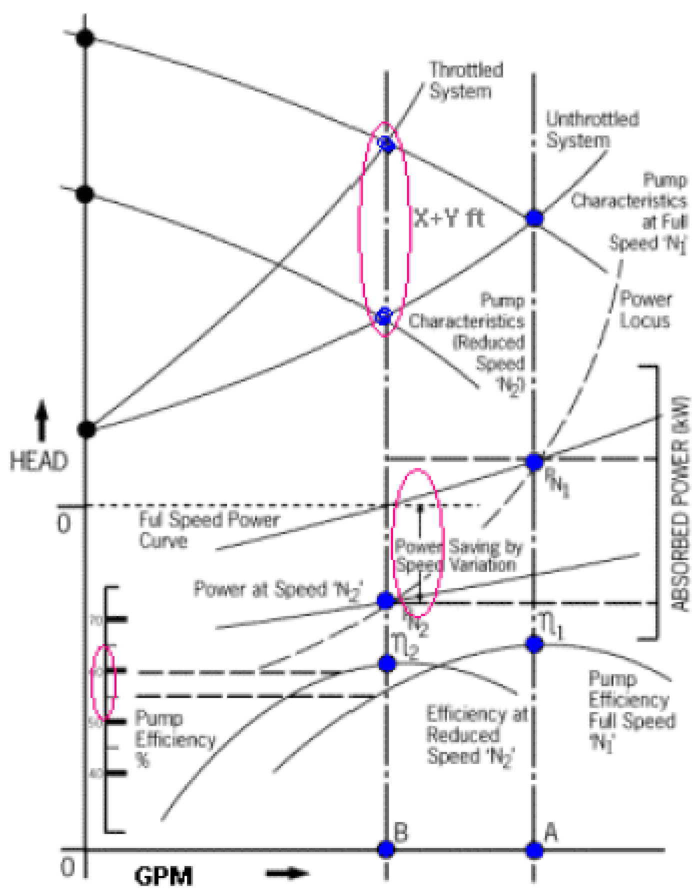
To understand the impact of throttling on the system, refer the figure above. With the valve fully open, the pump operates at design point A. When the reduced flow is required, the discharge valve is throttled, which changes the system curve to operating point B. In this case, the reduced throughput of the system "B" GPM is achieved with a net TDH of X ft. The throttling introduces an additional friction loss in the system, which is proportional to flow squared. The head difference between the two curves is the pressure drop across the valve.

In figure below, the alternative is demonstrated, reducing the speed of the pump. In this case, the reduced throughput of the system "B" GPM is achieved with a net reduction in TDH of Yft.

Therefore, by using variable speed instead of throttling, the saving is the difference in THD of (X+Y) ft.



The combined set of typical pump characteristics is shown in Figure below, illustrating the effect of speed variation verses throttling on both pump efficiency and absorbed power. The most notable points illustrated are that throttling the system does not reduce throughput at the cost of increasing absorbed power as popularly believed; the power absorbed does reduce as the throttle is closed.



The absorbed power locus which passes through points PN1 and PN2, indicates that even at zero flow, some power is still absorbed, and this constant component of absorbed power is necessary to overcome the static head, which is constant in many pump systems. The power locus has a ‘cube law’ characteristic for speed/flow against power, and this enables a calculation of the energy savings.

In the figure, the efficiency characteristics are also shown. The pump is selected to operate at peak efficiency, but throttling the system defeats that objective, and results in the pump operating at efficiency well below its peak value. From the efficiency curves, it is clear that from approximately 70% to 100% throughput, varying the speed loses little efficiency.

Consequently, it is clear that significant energy, and therefore cost, savings are available by using a variable speed system employing inverter drives instead of throttling the pump.

Flow control by speed regulation of pumps, is one of today’s best methods of varying the output and in addition to energy savings there could be other benefits of lower speed. The hydraulic forces on the impeller, created by the pressure profile inside the pump casing, reduce approximately with the square of speed. These forces are carried by the pump bearings and so reducing speed increases bearing life. In addition, vibration and noise are reduced and seal life is increased providing the duty point remains within the allowable operating range.

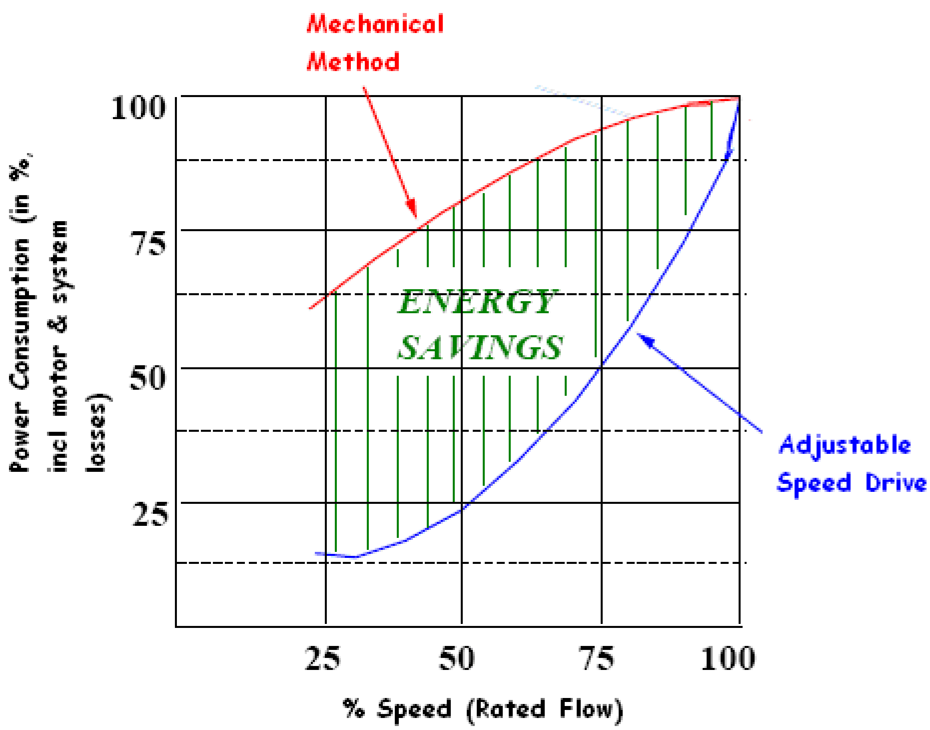
The corollary to this is that small increases in the speed of a pump significantly increase power absorbed, shaft stress and bearing loads. It should be remembered that the pump and motor must be sized for the maximum speed at which the pump set will operate. At higher speed the noise and vibration from both pump and motor will increase, although for small increases the change will be small. If the liquid contains abrasive particles, increasing speed will give a corresponding increase in surface wear in the pump and pipe work.

However speed change can be used over a wider range without seriously reducing efficiency. For example reducing the speed by 50% typically results in a reduction of efficiency by 1 or 2 percentage points. The reason for the small loss of efficiency with the lower speed is that mechanical losses in seals and bearings, which generally represent <5% of total power, are proportional to speed, rather than speed cubed.

In summary the “Affinity Laws” show that the Horsepower, HP, required varies with the Speed cubed. When you have a system where the control valve is wide open, the speed of the motor is 100%, the flow is 100% and the HP required is 100%. As soon as you start to close the valve, the motor is still 100%, flow is 70% and HP required is approx. 90%. If the flow goes to 5 0%, motor is still 100% and the HP required is about 60%. If you install a VFD in this application and remove the control valve, and the flow required is 70%, the motor will be 70% speed, and the HP required will be 34%. If the flow required is 50%, the motor will be at 50% speed, and the HP required is

12.5%. As you can see, there is less HP required with the VFD installed: 34% vs. 90% and 12.5% vs. 60%. These HP differences translate directly into energy savings. This law also works for dampers and vanes in air flow applications. If you consider the increasing cost of power, and that most systems operate between 50% and 80%, the payback time of installing a VFD can soon be realized.

The figure below shows the energy savings potential of a centrifugal pump, when the flow control is made with VSD instead of mechanical throttling.



In general, good applications for variable-speed flow control or VSD control are those:

- Systems which are designed for higher flow than actually required by the load
- Where mechanical throttling (by valves or dampers) provides the variation and where the majority of the operation is below the design flow
- Systems which use flow diversion or bypassing (typically via a pressure-reducing valve)
- System which are greatly oversized for the flow required

This situation can occur where successive safety factors were added to the design and where a process changed so that the equipment now serves a load less than the original design, and where a system was over designed for possible future expansion.

VSD Control Strategy for Pumps

A pump with variable speed capability will need to be controlled to unlock all the benefits available from variable speed operation. VSD can be programmed to adjust motor speed based on a variety of load inputs including: temperature, pressure, flow rates, or time of day set points.

The effect of varying speed with a centrifugal pump is to vary both head and flow. Variation of speed with a positive displacement pump will vary only the flow rate.

The table below shows the most commonly applied control-sensing configuration to vary the performance of pump through variable speed drive.

Process	Controlled Parameter	External influence
Heating system	Temperature	Ambient
Tank filling	Level	Outflow
Pipeline	Flow	Level
Distribution	Pressure	Draw-off

Control by fixing pressure

The most common form of control is by use of a discharge pressure sensor, which sends a signal to the VFD, which in turn varies the speed allowing the pump to increase or decrease the flow required by the system.

This form of control is common in water supply schemes where a constant pressure is required but water is required at different flows dependant on the number of users at any given time.

Capacity changes at constant pressure are also common on centralized cooling and distribution systems and in irrigation where a varying number of spray heads or irrigation sections are involved.

Cooling and Heating System Control

In heating and cooling systems there is a requirement for flow to vary based on temperature?

In this instance the VFD is controlled both by a temperature sensor and differential pressure. The temperature controller actuates the control valve that regulates chilled water or hot water supply to the heat exchanger and the pressure changes in a system as a result of opening and closing of control valve provides control signal to the VFD. Sometime in process applications the temperature controller directly controls the VFD to allow flow of hot or cold liquid in the system to increase or decrease based on the actual temperature required by the process.

This is similar in operation to pressure control, where the flow is also the variable entity, but a constant temperature requirement from a temperature sensor replaces that from a pressure sensor.

Control by fixing flow but varying pressure

In irrigation and water supply systems constant flow is often required, even though the water levels both upstream and downstream of the pumping station vary.

Also many cooling, chiller, spraying and washing applications require a specific volume of water to be supplied even if the suction and delivery conditions vary. Typically suction conditions vary when the height of a suction reservoir or tank drops and delivery pressure can change if filters blind or if system resistance increases occur through blockages etc.

The VFD system is usually the optimum choice to keep constant the flow rate in the system using a control signal from a flow meter, which can be, installed in the suction, but more commonly the discharge line.

Implementation

In many cases there will be an external control system, such as a PLC or PC, which will provide the start/stop control and an analogue speed reference to the drive or will pass this information to the drive by a serial communications link. In other cases the drive may have adequate on board intelligence.

All modern drive systems rely on microprocessor control, and this allows the manufacturer to integrate the basic signal processing functions into the drive.

As every case has its own specific requirements, it is important that the control requirements are understood in order to achieve the optimum system performance.

VSD – Best Applications

Though the variable flow options are many viz. constant-volumes with bypass, multi-speed motor, outlet damper or valve control, variable-inlet vanes etc, the VSD drive offers the maximum energy savings. Some of the best VSD applications include:

- Variable loads – long run hours – larger motors
- Loads where torque varies with speed

- Long run time at lower loads
- Generally over 10-hp can be cost effective
- Centrifugal pumps and fans
- Chilled water pumps
- Condenser water pumps
- Air handling units VAV system fans
- Centrifugal chiller and air compressors

VSD – Choice of Motors

Application	Services	VSD Choice
Maintaining Constant Pressure	Domestic Water Supply Chilled Water Systems Boiler Feed Service Hot Water Systems Municipal Water Booster Systems Water Seal Systems Irrigation Systems Differential Chilled and Hot Water Systems	VSD with Standard Motor
Maintaining Constant level	Sewage Lift Stations Industrial Waste Services Sewage Treatment Plants Condensate Return Systems Container Filling Systems	VSD with Efficiency Motor
Maintaining Constant Temperatures	Incinerator and Furnace Cooling Cooling and Heating Systems Heat Exchanger Supply Bearing Frame Cooling Differential Temperature System Condenser Water Circulation	VSD with premium efficiency motors

Application	Services	VSD Choice
Maintaining Constant Flow	Sludge return Systems Process Recirculation Services	VSD with inverter duty motor

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