Variable Frequency 101

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The rotational speed of an AC induction motor depends upon two components - - the number of poles (windings) in its stator and the frequency of the AC power source. Increase the number of poles and the rotational speed decreases. The opposite occurs with a change in frequency. Increase the frequency and rotational speed increases - - decrease frequency and rotational speed decreases. The nice thing about frequency is that it can be easily changed. This is not the case for the number of motor poles because, once a motor is built it stays that way for life. Variable Frequency Drives (VFD's) take advantage of both when controlling motor speed. If you gain an understanding of frequency and how a motor is wound you will find that understanding the VFD will be quite straight forward. Lets start our discussion by taking a look at the component known as frequency or cycles per second .

Frequency (The AC Wave Form)

Exactly what do we mean when we refer to the frequency of AC power? Well, we probably all know that AC stands for "alternating current". Unlike direct current (DC), where voltage remains the same with respect to time, alternating current moves back and forth (or up and down) from some positive voltage or current to some negative voltage or current. Because of these oscillations, AC is more complex and, it is for this reason that DC almost became the standard in the US. Fortunately Mr. Edison lost this battle because, even though it is more complex, AC is the better solution to our general electrical needs.

The illustration below compares a DC "wave", produced by a battery or generator, with that of a single phase AC sine wave produced by a power utility. The DC "wave" remains flat (or at the same voltage) from beginning to end. If it were generated at 12V it will remain at 12V as long the power is on. Not true for AC - - notice that it begins at zero volts and rises to some maximum positive voltage and then falls again to zero volts. It continues falling to some maximum negative voltage and then begins rising to zero volts. This progression is known as one AC cycle. In the US one complete AC cycle occurs 60 times each second and its frequency is referred to as 60 cycles per second or 60 Hz (Hertz).

12V DC

60 HZ AC
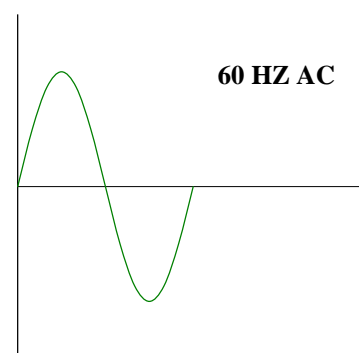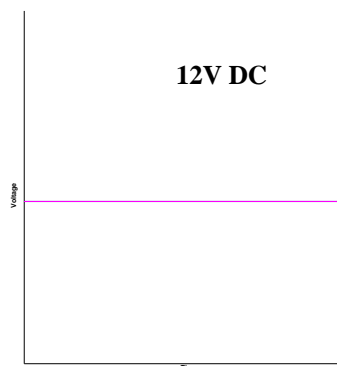
Now, don't get confused when I tend to alternate (pun intended) the usage of current and voltage when referring to AC. Both are components of AC power and produce similar curves. For a detailed look at voltage and current or, for that matter, all of the components of AC download my AC Power tutorial.

Why 60 Hz - - why not 30 Hz ? Well, it really doesn't matter all that much if the power is being used by a resistive circuit (incandescent lights, heaters, etc). As long as its 30 Hz and above, incandescent lights will not flicker and power, in watts, is still volts times amps regardless of the frequency. There are several reasons why higher frequencies are better suited for inductive devices (motors and transformers) but we will not address them here. Tesla, the inventor of the AC induction motor and generator, decided upon 60 Hz but it was some years later that his became the standard in the US. Early on, generators with outputs as low as 25 Hz were common. For some reason, (one which I have yet to find the answer) Europe standardized on 50 Hz. I suspect that it had something to do with the French or possibly the Germans but, I digress as this is purely a political hypothesis. The figures below compare the AC wave form seen in the previous illustration to those generated at a lower and higher frequency.
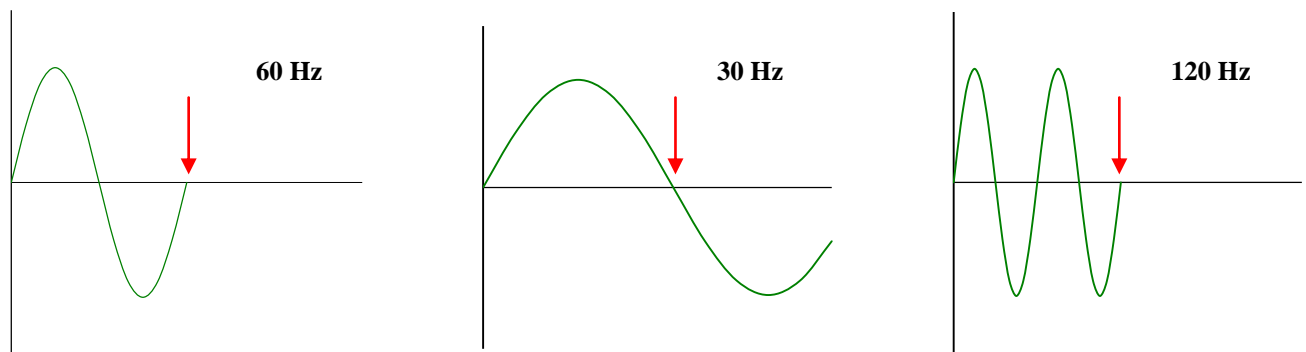
As you can see, the amplitudes are the same. Only the number of up and down motions per unit time differ. During the same period of time, the 30 Hz wave completes just half a cycle compared to a full cycle for the 60 Hz wave while the 120 Hz wave completes two. In the examples above, frequency is dependent upon the rotational speed of the generator. Increase generator speed and frequency increases, lower its speed and frequency decreases. It is as simple as that! And, the frequency of the AC wave has a direct relationship with the rotational speed of the electric motor it powers.

Motor Windings (Poles or Pole Pairs)

Hopefully the previous section has given you a basic understanding of the definition of frequency as it applies to alternating current and the wave form a generator produces. Lets take this information and apply it to the AC induction motor and the rotational speed it can attain based upon the frequency of the power applied and the manner in which it is wound.

The illustration to the right is that of a two pole, single phase motor stator. It contains two windings (poles), wired in series, and separated by 180 degrees. As the AC wave form rises from zero to its maximum positive voltage, the upper pole has a north (N) polarity while the lower pole has a south (S) polarity. When the wave form changes direction and begins to fall, the poles change polarity and then change yet again when the wave begins another upward rise. These polarity changes in the stator poles induce magnetic fields in the motor rotor which oppose those in the poles. And, it is this opposition to one another that causes the rotor to rotate. One complete AC wave cycle (regardless of its frequency) will cause the rotor of the two pole motor to complete a single rotation. If the AC frequency is 60 Hz the motor will rotate at 3600 RPM (60 rotations per second times 60 seconds). At 50 Hz the rotational speed will be 3000 RPM and at 30 Hz it will rotate at 1800 RPM.
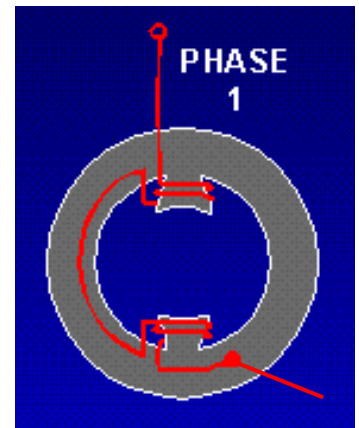
If we were to increase the number of poles in the stator to four, the rotational speed would be halved. Why? Because the poles are, once again, wired in series and it takes two AC cycles to circumnavigate the stator. Therefore it takes twice as long to produce a single rotation of the rotor. In the case of the four pole motor, two complete AC wave cycles will cause the rotor to complete a single rotation and do so regardless of the frequency. At 60 Hz the rotational speed will be 1800 RPM. At 50 Hz it will rotate at 1500 RPM and at 30 Hz its rotational speed will be 900 RPM. A six pole motor operated at 60 Hz will rotate at 1200 RPM while an eight pole unit will at the same frequency will do 900 RPM. The following equation will allow you to compute rotational speed of any motor if you know the frequency and the number of motor poles. RPM = (frequency X 120) / # poles

For a more detailed discussion of AC motor components and rotational fields, download The Single Phase Induction Motor and The AC Induction Motor tutorials at Pump Ed 101.

By now you should have a pretty good understanding of the relationship between AC frequency and the number of motor poles as they pertain to the rotational speed of an electric motor. Lets move on to the VFD and how it controls motor speed.

Variable Speed Operation

Variable frequency operation has been around, in the form of the AC generator, since the advent of the induction motor. Change the rotational speed of a generator and you change its output frequency. Before the advent of high speed transistors, this was one of the few options available to vary motor speed, however, frequency changes were limited because generator speed reduction lowered the output frequency but not the voltage. We will see why this is important a little later. In our industry, variable speed pumping applications were far more complex in the past than they are today. One of the simpler methods was to employ a multi

pole motor that was wound in such a way that allowed a switch (or switches) to vary the number of stator poles that were active at any given time. Rotational speed could be changed manually or by a sensor connected to the switches. Many variable flow pumping applications still employ this method. Examples include hot & chilled water circulators, pool pumps, and cooling tower fans & pumps. Some domestic booster pumps used fluid drive or variable belt drive systems (an automatic transmission of sorts) to vary pump speed based on feedback from a pressure diaphragm valve. And, several others were even more complex.

Based upon the hoops we had to jump through in the past, it becomes pretty apparent why the advent of the modern AC Variable Frequency Drive revolutionized (yet another pun) the variable speed pumping environment. All you have to do today is install a relatively simple electronic box (that often replaces more complex starting equipment) at the application site and, suddenly you can, either manually or automatically, change pump speed to your heart's desire.

So, lets take a look at the components of an AC Drive and see how they actually function together to vary frequency and thus motor speed. I think you will be amazed at the simplicity of the process. All it took was the maturing of the solid state device we know as the transistor.

VFD Components

The Rectifier

Because it is difficult to change the frequency of an AC sine wave while in the AC mode, the first job of a VFD is to convert the wave to DC. As you will see a little later, it is relatively easy to manipulate DC in order to make it look like AC. The first component of all VFD's is a device known as a rectifier or converter and it is shown to the left of the figure below.
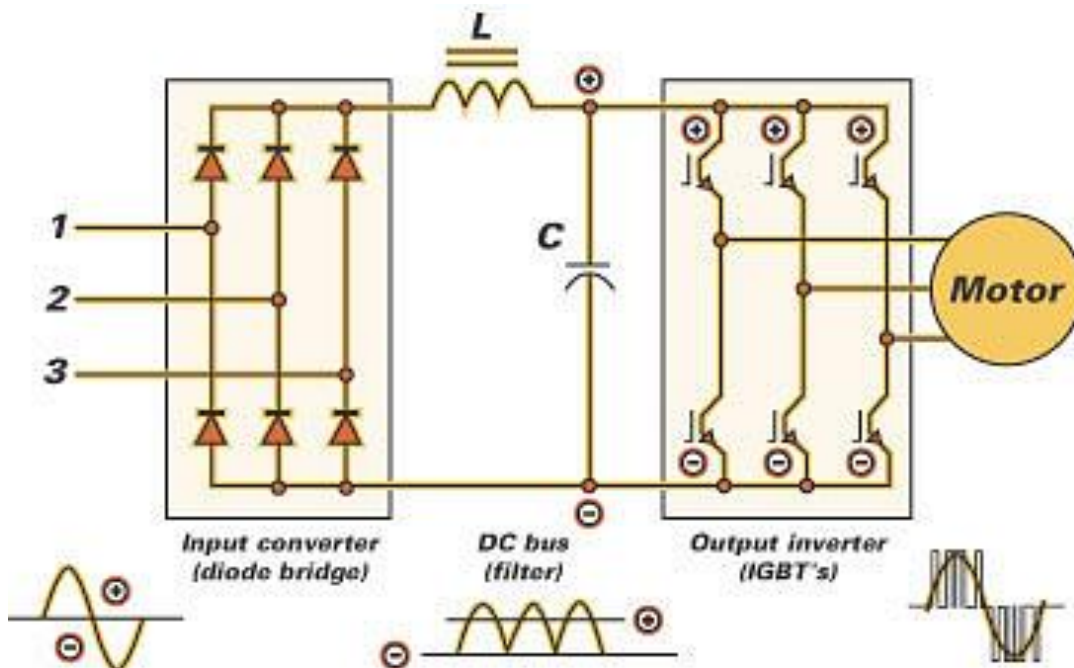
The rectifier circuit converts AC to DC and does so in much the same manner as those of a battery charger or arc welder. It uses a diode bridge to limit the travel of the AC sine wave to one direction only. The result is a fully rectified AC wave form that is interpreted by a DC circuit as a native DC wave form. Three phase drives accept three separate AC input phases and convert them to a single DC output. Most three phase drives can also accept single phase (230V or 460V) power but, since there are only two incoming legs, the drive's output (HP) must be derated because the DC current produced is reduced proportionally. On the other hand, true single phase VFD's (those that control single phase motors) utilize a single phase input and produce a DC output that is proportional to the input.

There are two reasons why three phase motors are more popular than their single phase counter parts when it comes to variable speed operation. First they offer a much wider power range. But, equally as important is their ability to begin rotation on their own. A single phase motor, on the other hand, often requires some outside intervention to begin rotation. In this case, we will limit our discussion to three phase motors used on three phase drives.

The DC Bus

The second component, known as the DC Bus (shown in the center of the illustration) is not seen and in all VFD's because it does not contribute directly to variable frequency operation. But, it will always be there in high quality, general purpose drives (those manufactured by dedicated drive manufacturers). Without getting into a lot of detail, the DC Bus uses capacitors and an inductor to filter the AC "ripple" voltage from the converted DC before it enters the inverter section. It can also include filters which impede harmonic distortion that can feed back into the power source supplying the VFD. Older VFD's and some pump specific drives require separate line filters to accomplish this task. (See the "Distorted Wave Puzzler" for more information on this subject)
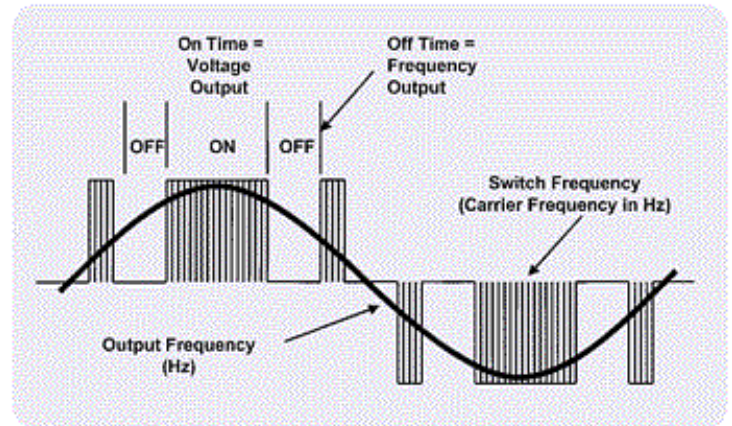
The Inverter

To the right of the illustration is the "guts" of the VFD. The inverter uses three sets of high speed switching transistors to create DC "pulses" that emulate all three phases of the AC sine wave. These pulses not only dictate the voltage of the wave but also its frequency. The term inverter or inversion means "reversal" and simply refers to the up and down motion of the generated wave form. The modern VFD inverter uses a technique known as "Pulse Width Modulation" (PWM) to regulate voltage and frequency. We will cover this in more detail when we look at the output of the inverter.

Another term you have probably run across when reading VFD literature or advertisements is "IGBT". IGBT refers to the "Insulated Gate, Bipolar Transistor" which is the switching (or pulsing) component of the inverter. The transistor (which replaced the vacuum tube) serves two functions in our electronic world. It can act as an amplifier and increase a signal as it does

in a radio or stereo or, it can act as a switch and simply turn a signal on and off. The IGBT is simply a modern version that provides higher switching speeds (3000 – 16000 Hz) and reduced heat generation. The higher switching speed results in increased accuracy of AC wave emulation and reduced audible motor noise. A reduction in generated heat means smaller heat sinks and thus a smaller drive footprint.

Inverter Output

The illustration to the right shows the wave form generated by the inverter of a PWM variable frequency drive compared with that of a true AC sine wave. The inverter output consists of a series of rectangular pulses with a fixed height and adjustable width.   In this particular case there are three sets of pulses -- a wide set in the middle and a narrow set at the beginning and end of both the positive and negative portions of the AC cycle. The sum of the areas of the pulses equals the effective voltage of a true AC wave (we will discuss effective voltage in a few minutes). If you were to chop off the portions of the pulses above (or below) the true AC wave and use them to fill in the blank spaces under the curve, you would find that they match almost perfectly. It is in this manner that a VFD controls the voltage going to the motor.

The sum of the width of the pulses and the blank spaces between them determines the frequency of the wave (hence PWM or pulse width modulation) seen by the motor. If the pulse was continuous (i.e. no blank spaces), the frequency would still be correct but the voltage would be much greater than that of the true AC sine wave. Depending upon the desired voltage and frequency, the VFD will vary the height and width of the pulse and the width of the blank spaces in between. Although the internals that accomplish this are relatively complex, the result is elegantly simple!
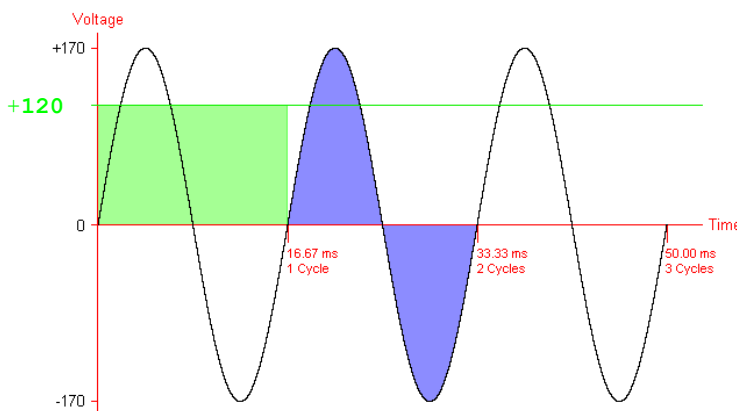
Now, some of you are probably wondering how this "fake" AC (actually DC) can run an AC induction motor. After all, doesn't it take an alternating current to "induce" a current and its corresponding magnetic field in the motor's rotor? Well, AC causes induction naturally because it is continuously changing direction. DC, on the other hand, does not because it is normally motionless once a circuit is activated. But, DC can induce a current if it is switched on and off. For those of you old enough to remember, automobile ignition systems (prior to the advent of the solid state ignition) used to have a set of points in the distributor. The purpose of the points was to "pulse" power from the battery into the coil (a transformer). This induced a charge in the coil which then increased the voltage to a level that would allow the spark plugs to fire. The wide DC pulses seen in the previous illustration are actually made

up of hundreds of individual pulses and, it is this on and off motion of the inverter output that allows induction via DC to occur.

Effective Voltage

AC power is a rather complex quantity and it is no wonder that Edison almost won the battle to make DC the standard in the US. Fortunately, for us, all of its complexities have been explained and all we have to do is follow the rules those before us have laid out.

One of the attributes that makes AC complex is that it changes voltage continuously, going from zero to some maximum positive voltage, then back to zero, then to some maximum negative voltage, and then back to zero again. How is one to determine the actual voltage applied to a circuit? The illustration on the left is that of a 60 Hz, 120V sine wave. Notice, however, that its peak voltage is 170V. How can we possibly call this a 120V wave if its actual voltage is 170V? During one cycle it starts at 0V and rises to 170V then falls again to 0. It continues falling to –170 and then rises again to 0. It turns out that the area of the green rectangle, whose top border is at 120V, is equal to the sum of the areas under the positive and negative portions of the curve. Could 120V then be the average? Well, if you were to average all of the voltage values at each point across the cycle, the result would be approximately 108V so that must not be the answer. Why then is the value, as measured by a VOM, 120V? It has to do with something we call "effective voltage".

If you were to measure the heat produced by a DC current flowing through a resistance, you would find that it is greater than that produced by an equivalent AC current. This is due to the fact that AC does not maintain a constant value throughout its cycle. If you did this in the laboratory, under controlled conditions, and found that a particular DC current generated a heat rise of 100 deg, its AC equivalent would produce a 70.7 deg rise or just 70.7% of the DC value. Therefore the effective value of AC is 70.7% of that of DC. It also turns out that the effective value of an AC voltage is equal to the square root of the sum of the squares of the voltage across the first half of the curve. If the peak voltage is 1 and you were to measure each of the individual voltages from 0 deg to 180 deg, the effective voltage would be 0.707 of the peak voltage. 0.707 times the peak voltage of 170 seen in the illustration equals 120V. This effective voltage is also known as the root mean square or RMS voltage. It follows that the peak voltage will always be 1.414 that of the effective voltage. 230V AC current has a peak

voltage of 325V while 460 has a peak voltage of 650V. We will see the effects of peak voltage a little later.

Well, I have probably gone on about this longer than necessary but, I wanted you to gain an understanding of effective voltage so that you will understand the illustration below. In addition to varying frequency, a VFD must also vary voltage even though voltage has nothing to do with the speed at which an AC motor operates.
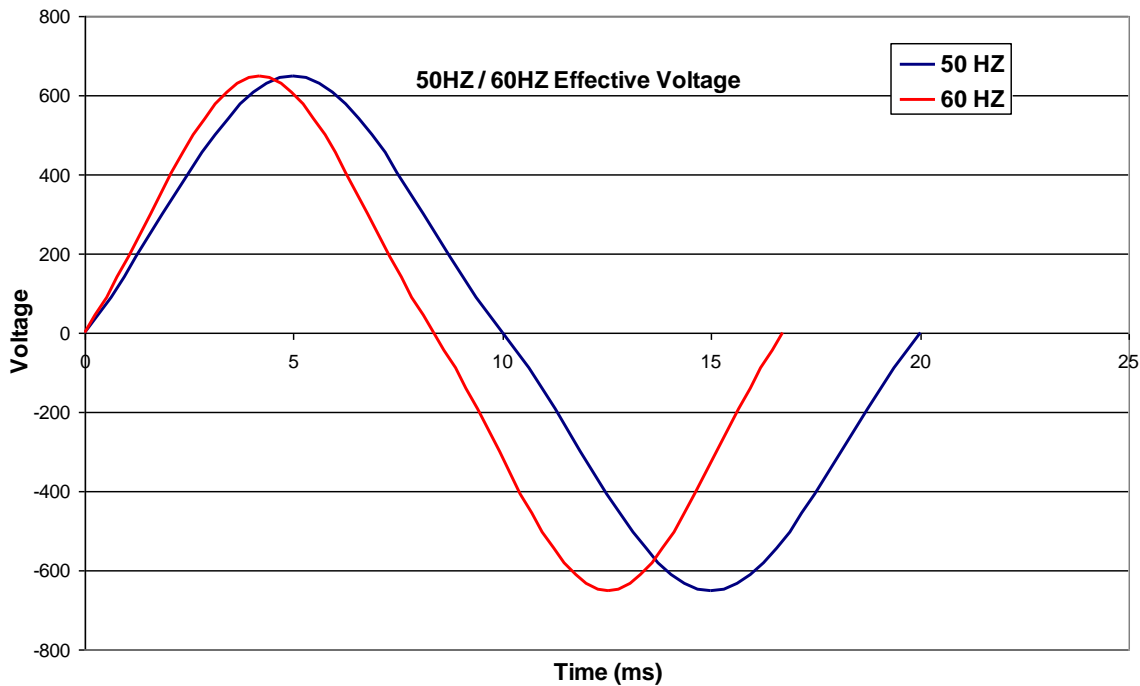
The illustration shows two 460V AC sine waves. The red one is a 60hz curve while the blue one is 50hz. Both have a peak voltage of 650V but, the 50hz is much broader. You can easily see that the area under the first half (0 – 10 ms) of the 50hz curve is greater than that of the first half (0 – 8.3 ms) of the 60hz curve. And, since the area under the curve is proportional to effective voltage, its effective voltage is higher. This increase in effective voltage becomes even more dramatic as frequency decreases. If a 460V motor were allowed to operate at these higher voltages, its life could be decreased substantially. Therefore, the VFD must constantly vary "peak" voltage, with respect to frequency, in order to maintain a constant effective voltage. The lower the operating frequency, the lower the peak voltage and vice versa. It is for this reason that 50hz motors, used in Europe and parts of Canada, are rated for 380V. See, I told you that AC can be a bit complex!

You should now have a pretty good understanding of the workings of a VFD and how it controls the speed of a motor. Most VFD's offer the user the ability to set motor speed manually via a multi-position switch or key pad, or use sensors (pressure, flow, temperature, level etc) to automate the process. We will cover a few examples of the latter in the final section of this introduction.

Potential Problems

Someone once said that "there is no such thing as a free lunch" and, this is certainly the case with the VFD. Problems can and often will arise. They are not yet fool proof (I like to use the term "fool resistant" because nothing can be truly "fool proof") so caution is advised when applying a VFD to a pumping application. There are four major categories of problems that can occur in a VFD installation -- **motor bearing damage, the production of harmonics, motor insulation damage, and resonant frequency**. I will mention the first two briefly and go into detail on the last two.

Motor Bearing Damage

Bearing currents have been around since the advent of the electric motor but the incidence of damage they cause has increased with the growth of VFD usage.

It seems reasonable that if a moving charge in the motor's stator can induce a charge in its rotor, it might induce them elsewhere also. Although low frequency bearing currents have all but been eliminated by modern motor manufacturing techniques, the high switching frequency of AC VFD's can generate high frequency current pulses through the bearings. If the energy of these pulses is high enough, metal can transfer from the balls and race to the lubricant (EDM or Electrical Discharge Machining) and cause bearing fluting (a rhythmic pattern on the bearing's race). The illustration to the right shows a typical EDM wear pattern. EDM wear depends upon the bearing impedance and is a function of load, speed, temperature, and the lubricant used. Impedance is a non-linear function and varies greatly from case to case. High frequency bearing current damage is generally associated with higher voltage / higher HP motors and is not usually a problem in typical variable speed pumping applications.
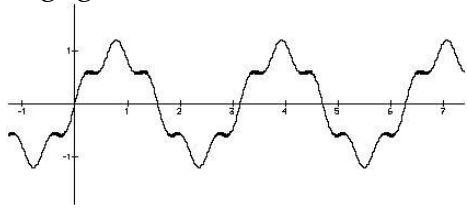
If you ever need to know more about this phenomenon, go to the ABB web site www.abb.com/motors&drives and download Technical Guide # 5 (Bearing Currents in Modern AC Drive Systems).

I might also mention that VFD operation can cause bearing damage in another way. Bearings (ball, roller, & sleeve) are designed to float on a microscopic film of grease or oil while in operation (much like the faces of a mechanical seal that float on a thin film of water). In some cases, low rotational speeds will allow the balls and the race to

come into contact during operation and accelerate bearing wear. This is even more of a problem when the motor has a high radial load (belt drive etc).

Harmonics

Harmonics (noise caused by the high switching frequency of a VFD) affect the power supply side of the drive and all circuits connected to that supply. Its effect can range from annoying hums and flickering lights (& computer displays) to more serious problems such as the overheating of wiring and its connected devices to tripped circuit breakers. Usually a single PWM drive, that incorporates a DC Bus section, is a negligible contributor to harmonic distortion. But when many of these drives are attached to a circuit (refinery, manufacturing plant, etc) their contribution is additive. The illustration on the left shows an AC sine wave that has been contaminated with a fifth order harmonic. The simplest method of removing these unwanted waves is to use line reactors or harmonic traps on the low voltage side of the site's power transformer. For more information on this subject see the "Distorted Wave Puzzler" or you can go to the ABB web site and download "Technical Guide # 6" (Guide to Harmonics with AC Drives).

Insulation Stress and Damage

Insulation stress, and the damage that results from that stress, can be broken down into two general categories -- **thermal stress and voltage spikes**. Excess heat (thermal stress) can be generated by several conditions including voltage spikes. There are several ways to eliminate or reduce the intensity of voltage spikes and we will cover them in detail shortly. But, there can be another cause of excess heat. Sometimes, low speed applications can cause a motor to overheat because the normal heat removal process (i.e. fan) is limited by the motor speed. This is not usually a consideration in centrifugal pump applications because a centrifugal pump requires less power at lower speeds (i.e. variable torque) and heat tends to be a function of the power generated by the motor and its electrical efficiency. Still, under adverse conditions (high ambient temperatures etc) heat build up can be a problem at frequencies under 60 Hz. The easiest way to reduce or eliminate insulation stress due to heat, regardless of its cause, is to utilize a motor with a higher grade of insulation. Some motor manufacturers use Class B insulation in their standard motors while others standardize on Class F. Class B can withstand temperatures of 266 degrees F while Class F is rated at 311 degrees F. An even higher grade, Class H, can handle temperatures up to 356 degrees F. If heat is a concern, upgrade to a higher grade of insulation.

Voltage spikes present quite a different problem. Although they may cause an overall rise in operating temperature, their main contribution to insulation stress is their ability to cause a small breakdown (known as a partial discharge PD) in the air filled voids that occur in any insulation system. Repeated PD breakdowns will eventually destroy the insulation. Another phenomenon caused by voltage spikes is known as a corona discharge (usually a slice of lime will fix this one). A corona discharge ionizes the air between the windings and the highly reactive ions that are formed can cause insulation to deteriorate over time. This type of discharge occurs more often in hot, humid environments.

What exactly causes these voltage spikes to occur during VFD operation. Well, they can be due one or any combination of three different conditions:

Overshoot occurs when the DC pulse "over shoots" the maximum peak voltage required by the motor. At the beginning of the pulse, voltage rises rapidly and typically exceeds peak voltage before it settles down. Voltage overshoot can be 10-20% greater than peak voltage but usually does not cause a problem by itself because standard motor insulation is designed to handle up to 600V continuously.

Reflected Voltage occurs when a wave travels down a transmission line and is reflected back and combines with the incoming wave (similar to ripples traveling across a pond that strike a barrier). This reflection is caused by the difference between the line and load (motor) impedance. If they are the same there is no reflection. If there is a large difference, the amplitude of the reflected wave will approach that of the original wave. Under certain conditions (rise time and travel time are not discussed here) the reflected wave will combine with the original wave resulting in a much higher voltage at the motor.

Ringing is the result of the capacitance and inductance of the cable, motor, and the output circuit of the VFD. Together they can create a resonant circuit that can cause the edges of the voltage circuit to assume an undampened ringing waveform. When combined with reflection, ringing can result in voltage peaks at the motor of **two to three** times the normal peak voltage.

The illustration to the right shows an oscilloscope tracing of the output of a VFD at 460V. The darker blue spikes peak around 650V (460V peak voltage) but some of the light blue spikes peak close to 1500V. In this illustration the larger spikes are due to a combination of overshoot, reflection, and ringing. Were this a 230V output the effect
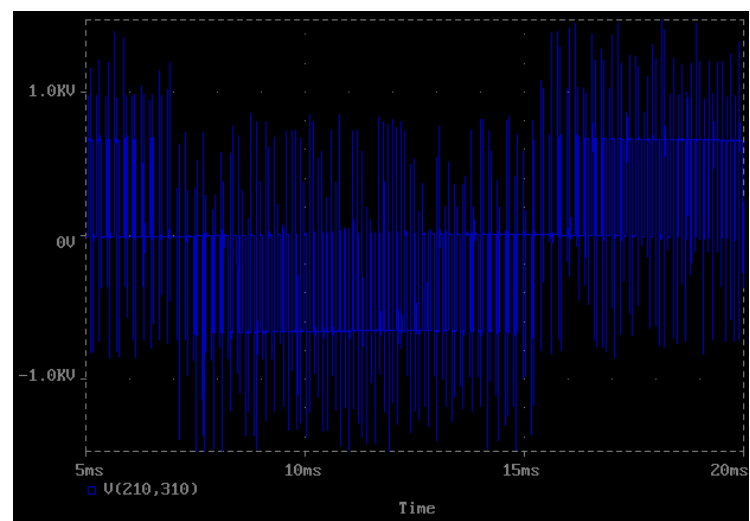
would be the same but, the peak voltage of the spikes probably would not exceed 900V. The statement is important because, as you will see a little later, voltage spikes are not usually a problem in 230V applications if certain rules are followed.
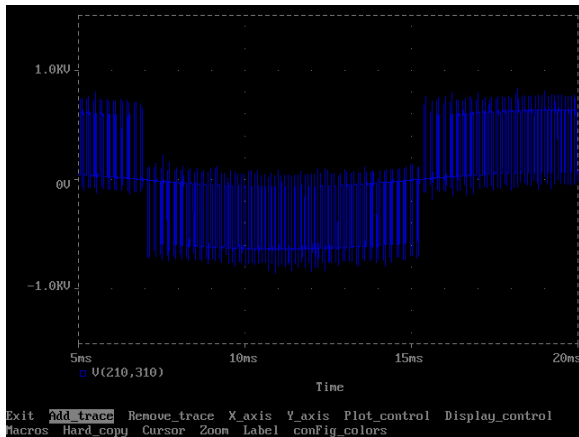
Eliminating the voltage spikes seen in the previous illustration can be as easy as following NEMA cable length guide lines or it could be more complex and require the installation of load reactors or dv/dt filters between the motor and the drive. The illustration to the left shows the same 460V VFD output after appropriate corrective action (cable length, filters etc) was taken. As you can see the 1500V spikes have been reduced to nearly that of the 650V pulses.

The application of line reactors and dv/dt filters is a topic for a future discussion. In most cases, they will not be required if we select the proper motor and follow the recommended cable length guidelines. For more information on the application of reactors and filters, see the "Mumbo-Jumbo Puzzler" or go to the ABB website and download Technical Guide # 102 (Effects of AC Drives on Motor Insulation).

Resonant Frequency

The resonant frequency or, the frequency at which an object undergoes natural vibration, is often overlooked when applying a VFD to a pumping application. In the VFD environment this is often referred to as the critical speed or critical frequency.

You have probably witnessed this phenomenon many times. Vehicles with manual transmissions often exhibit greater vibration at certain engine speeds. Certain musical tones, especially lower ones, will cause objects on a table to rattle even when the volume is low. And, some of us are familiar with the vibrating wine glass that breaks due to the pitch of the singers voice. (If you would like to see this in action click on the Quick Time movie "Resonate Frequency" in the VFD section of my web site.)

The same is true of a rotating machine - - at some rotational speed or speeds, one or more of its components will begin to vibrate. This is not a problem when a standard, fixed speed pump is employed. If resonance occurred at its design speed, it would have been detected and eliminated during the testing phase. When that same pump is used in a variable speed application, however, it could, very well, exhibit vibration at speeds above or below its nominal fixed speed.

It is difficult to predict whether a particular pump will exhibit resonance over the speed range it encounters during variable frequency operation. As a rule of thumb, frame mounted pumps are more likely to exhibit this form of vibration than are close coupled units. Likewise, multistage pumps and those with elongated shafts also tend to be more vulnerable. There is, however, a simple way of testing for resonance and avoiding it, if it occurs. With the VFD in manual mode, simply scroll through each frequency value from the lowest to the highest (for example 30 through 60 hertz). Let the pump run at each frequency for five seconds or so. If a resonate frequency is encountered, noticeable vibration will occur. You might also find that vibration may not be limited to a single hertz, but occurs over a range (say 33 to 35 hertz). Once these critical speeds or speed ranges have been determined, the drive can be programmed to bypass them. Although the pump will still pass through these points, it will not remain there long enough to cause vibration.

AC Motor Selection and Cabling

I mentioned earlier that voltage spikes do not usually present a problem in 230V VFD applications. The reason this is true is that all NEMA standard motors use an insulation that is designed to operate at 600V continuously and withstand intermittent voltage spikes of 1000V (a new motor can often withstand spikes to 1200V). Even if a spike were three times normal peak voltage (325V), it would still be within the 1000V limit. The net result is that standard motors are well suited for operation in 230V VFD applications as long as the drive and motor manufacturer's cable length guidelines are followed. Always consult the manufacturer if the cable between the drive and motor will exceed 200 feet. If higher than normal ambient temperatures exist, you may want to upgrade to a motor that uses Class F insulation but, "special" inverter duty insulation is not required.

Unfortunately this is not always the case for 460V applications. Due to the high peak voltage (650V), even relatively small spikes can exceed the 1000V limit of standard motors. If the cable length between the VFD and a standard motor exceeds 25 feet, a load reactor or dv/dt filter is always recommended. Always follow the manufacturers cable length guidelines closely when using standard motors in 460V VFD applications.

One way to get around the use of a reactor or filter in many 460V applications is to use a motor specifically designed for VFD applications. Special **inverter duty** motors utilize insulation that is designed to accommodate spikes up to 1600V and has a temperature rating of Class F or H. In some cases, these motors can be up to 300 feet downstream of the drive and still not require reactors or filters. Again, always follow the manufacturers cable length guide lines.

I will end this section with one final cautionary note. Avoid 460V operation when using **standard** motors with a frame size of 180 or smaller (180 = 5 to 7.5 HP, 56 = 2 to 3 HP). The reason I say this is that these motors tend to be manufactured with price as the major objective. The insulation system is not as robust as that of larger frame motors and they have an inherently high impedance. Since these motors are usually wound for 230/460V operation and therefore utilize 600V insulation they can be used, safely in 230V VFD applications.


Variable Speed Applications

We will end our discussion of VFD's with several pumping application examples. Although there are many uses for VFD's in the pumping environment, they usually fall into three basic categories -- **constant pressure, constant flow, and variable flow**. There are, of course, other ways to maintain these conditions (control valves for example) but the VFD offers an extra bonus -- a significant reduction in power consumption.

Constant pressure applications include those where pressure is maintained at some desired point regardless of flow. Domestic and commercial booster systems are a good example and usually employ a pressure transducer that controls the output frequency of the VFD which, in turn, changes pump speed in order to keep pressure constant.

The illustration at the top of the following page shows a simplex booster in a constant pressure application. The 60 HZ design point is 150 GPM @ 120 ' TDH and requires 6.4 BHP. The two other curves represent 55 and 50 Hz operation. The red horizontal line indicates the constant pressure required at various flow rates. At about 53 Hz the pump can provide 100 gpm at the design head and at 50 Hz it can provide about 50 gpm. Therefore over a relatively small frequency range of 50 to 60 Hz the pump will provide 50 to 150 gpm at 120'. Remember that the VFD provduces not only 50, 55, and 60 Hz pulses, but also each individual (and fractional) Hz in between. The result is a significant savings in the power required at flows lower than design flow. The brake BHP requirement at 53 Hz (100 gpm) drops to 3.7 or 58% of design point HP. And, at 50 Hz (50 gpm) it drops to 2.5 HP or just 39% of that at the design point .

Now, we could use a pressure reducing valve (PRV) to maintain a constant pressure of 120 feet as demand decreases and take advantage of the centrifugal pump's reduced power consumption as its flow moves towards the left of the capacity curve. But, at the 100 gpm point on the 60 Hz curve the required BHP is 5.3. Even though flow is reduced, the power required by a PRV application is 5.3 HP compared to 3.7 HP for VFD control. At 50 gpm PRV control requires 4.3 HP or 72% more than the VFD. In a

constant pressure application, the VFD offers precise and flexible control plus an increased power savings over mechanical constant pressure devices. Because centrifugal pumps follow the laws of affinity, a relatively small change in frequency (speed) can result in a substantial reduction in power.

Simplex VFD Constant Pressure Booster
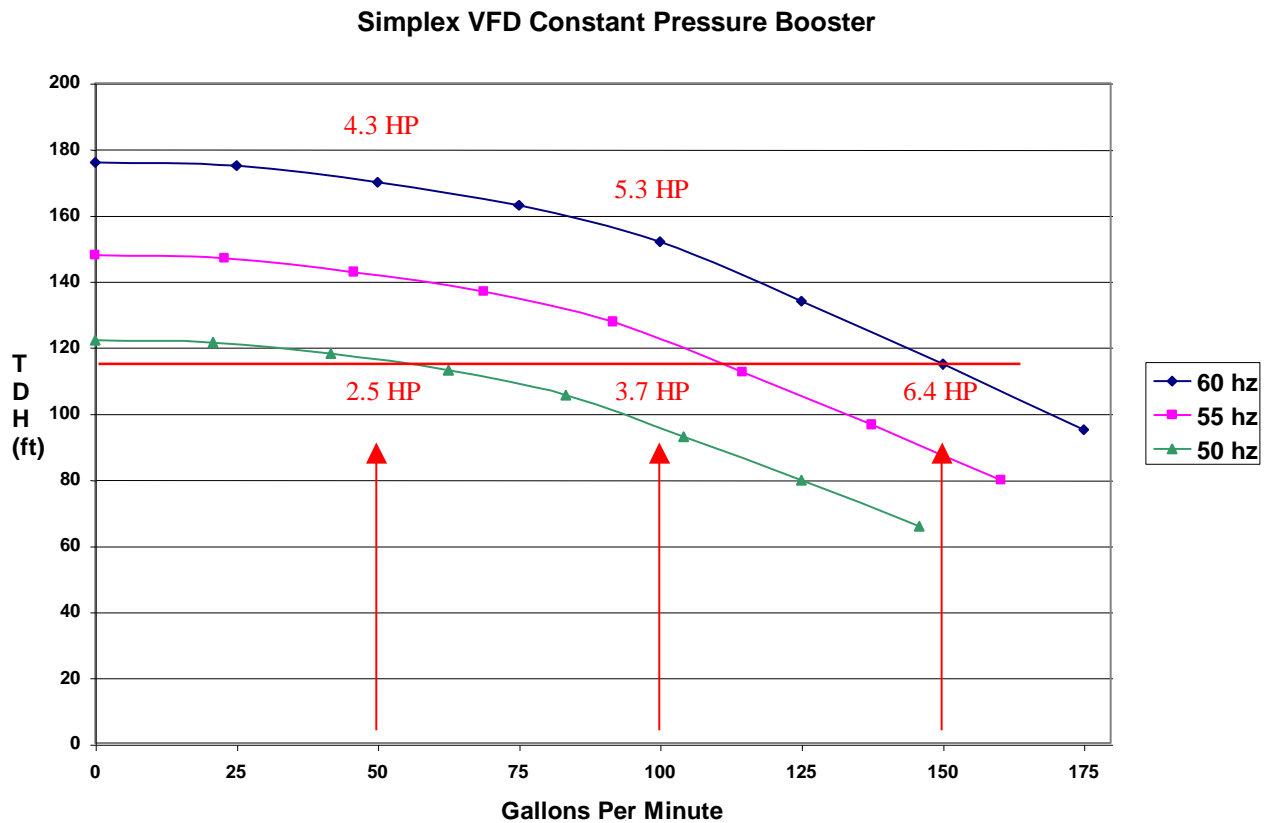
The illustration at the top of the following page is that of a **Constant flow** application. These applications require flow to remain constant regardless of the back pressure the system may encounter. A flow meter is usually employed to control VFD output and, in turn, motor speed. Examples include maintaining levels in tanks at various elevations, manufacturing processes, and the operation of nearby and remote irrigation zones. Each of the multiple components served by these applications require similar flows but, differences in elevation, back pressure, and pipe line friction may require different pressures to maintain those flows. The system is designed for the highest pressure component of the application so that the VFD can reduce motor speed for the lower pressure component and save energy in doing so.

BVM8-160 @ VARIOUS SPEEDS
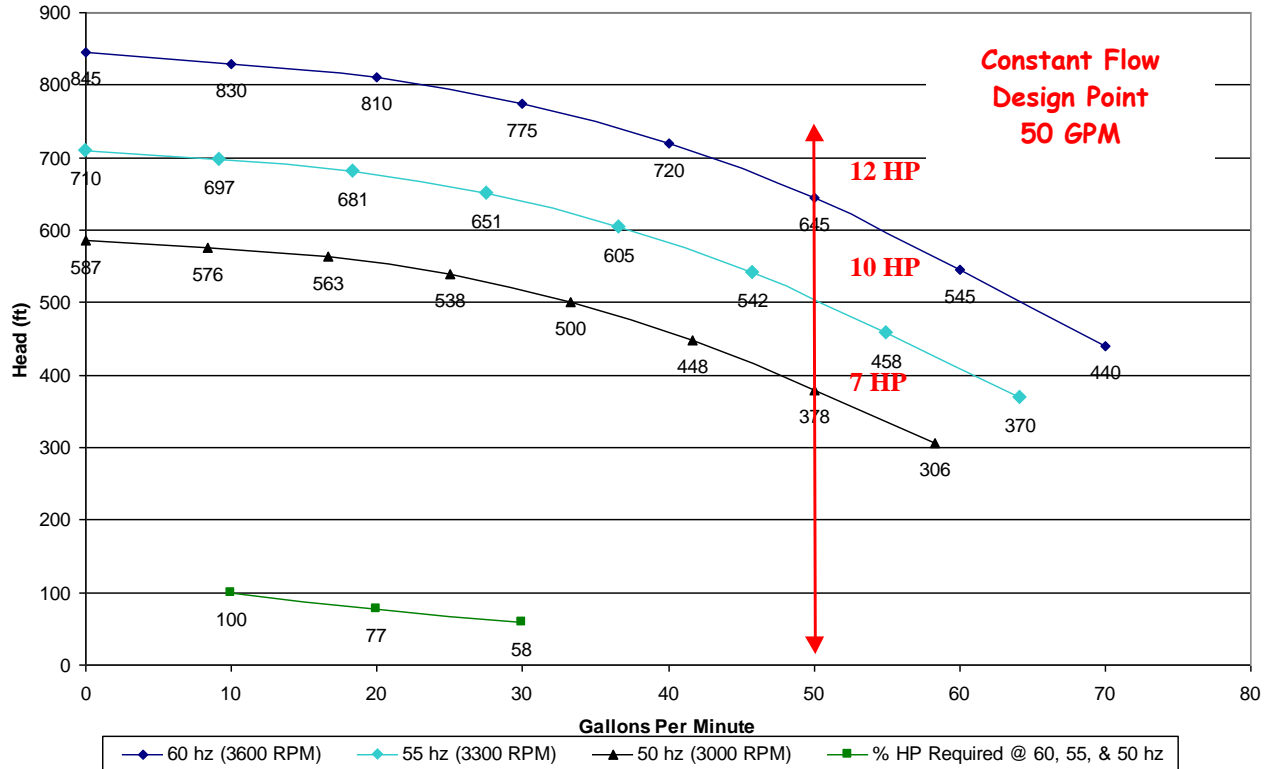
Variable Flow applications might also be termed variable flow / variable pressure because neither remains constant. Most are circulation applications and deal only with pipe line friction as flow changes. A major application area is that of chilled water circulation in large air conditioning systems (HVAC) where cooling demand is always changing. Since the chilled water flows in a circulation loop, the only pressure component that changes is that due the friction caused by the flowing water (see the "Hot and Cold Puzzler" for more information on circulation loops and pipe line friction). VFD output is controlled by a flow meter, temperature transmitter, or directly by the chiller controls. The cooling tower pump is often controlled by the same circuit. The illustration at the top of the following page is that of a variable flow, chilled water application.

The diagonal arrow shows flow points on the various frequency curves and the additional pressure required to over come friction as flow increases. Please note that the arrow may not necessarily be a straight line. Since friction is not a linear function, it could be curved and would be based upon the calculated friction in the circulation loop. In the past, multi speed motors were used for this application. Large swimming pools also use a similar design for

circulation through a filter. Again, power savings is achieved as the flow is decreased by the VFD.

B3ZPMS @ Various Speeds
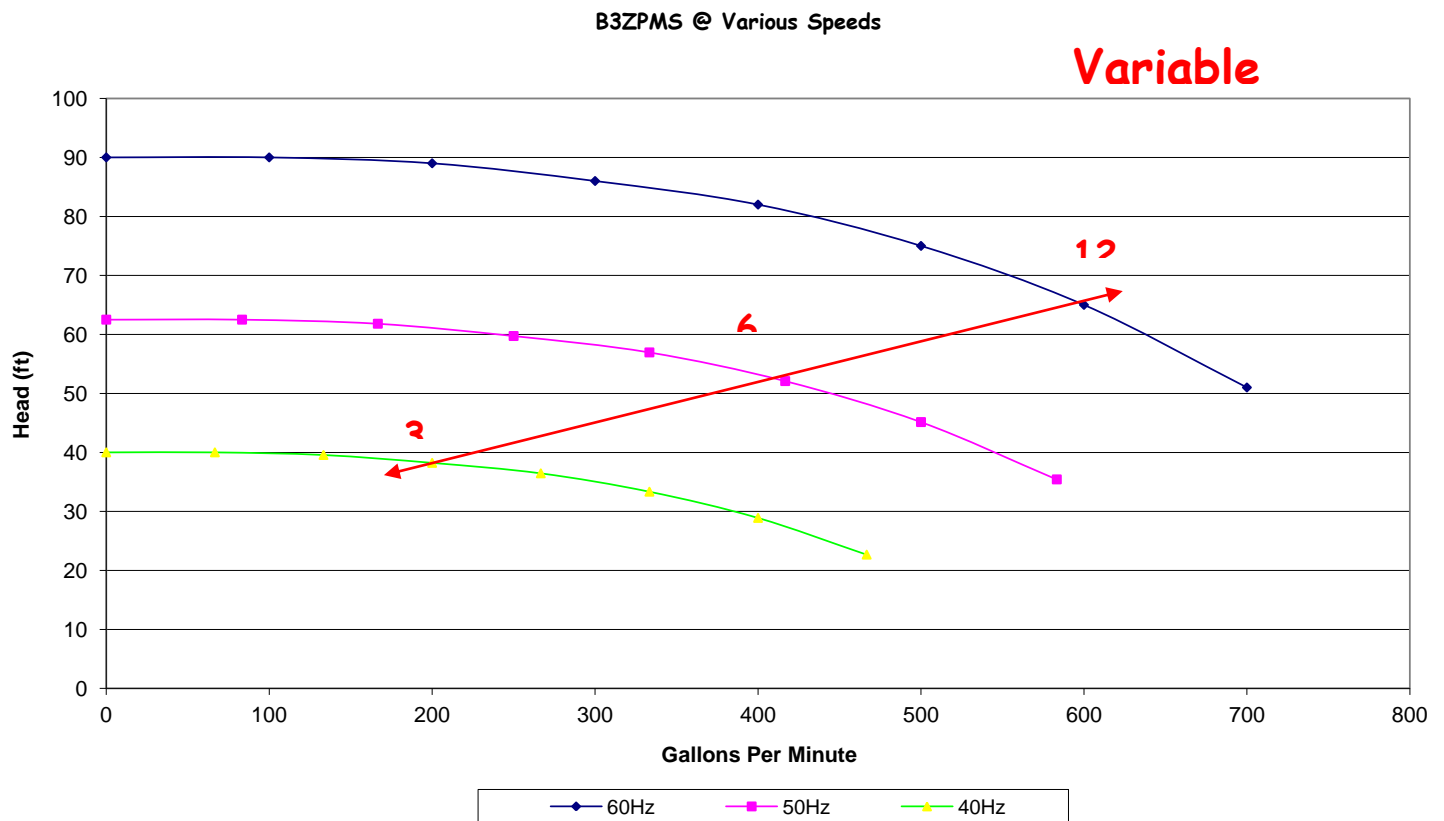
A final advantage, available to any VFD application, is the **Soft Start/Stop** option. This option allows the pump and motor to be started at a lower frequency (say 30 HZ) and then "ramped" up to run speed over a period of a second or more. The result is a significant reduction in the starting current required by the motor. Some utilities require that motors over a certain HP undergo a soft start. With the VFD, its just part of the package. In addition to a lower inrush current, mechanical stress on the motor and pump are also greatly reduced. In a normal "across the line" start, the motor rotor and pump rotating element go from motionless to the motor's rated RPM in about one second! And, soft start/stop virtually eliminates water hammer in almost any pumping system.

I hope that this short introduction has given you a better understanding of the Variable Frequency Drive, its operation, and its application to centrifugal pumps. If you decide that you would like to learn more, I suggest that you go to the ABB web site www.abb.com/motors&drives and download the technical publications located there. They are extremely well written and cover many areas of VFD operation and application (including a cable length guide) . All are in PDF format. If you have questions or suggestions email me at joeeevans@gmail.com .

Joe Evans
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