Variable Speed Drive (VSD) for Irrigation Pumping

Pumping water for irrigation can be a major expense for irrigated farms. In 2003 more than 500,000 pumps were used for irrigation, and the total estimated energy cost nationwide was over 15.5 billion dollars. Improving the efficiency of irrigation pumps has many benefits, including improving the profitability of the irrigated farm.

When a single pump is required to operate over a range of flow rates and pressures, standard procedure is to design the pump to meet the greatest output demand of both flow and pressure. For this reason, pumps are often oversized and they will be operating inefficiently over a range of duties. This common situation presents an opportunity to reduce energy requirements by using control methods such as a variable speed drive.

Most existing systems requiring a control method use bypass lines, throttling valves, multiple pumps, or pump speed adjustments. Figures 1 through 3 illustrate common control methods including variable speed and the potential energy savings. Often, changing the pump's speed is the most efficient method of control. When a pump's speed is reduced, less energy is used by the pump's power unit and therefore less energy needs to be dissipated or bypassed.

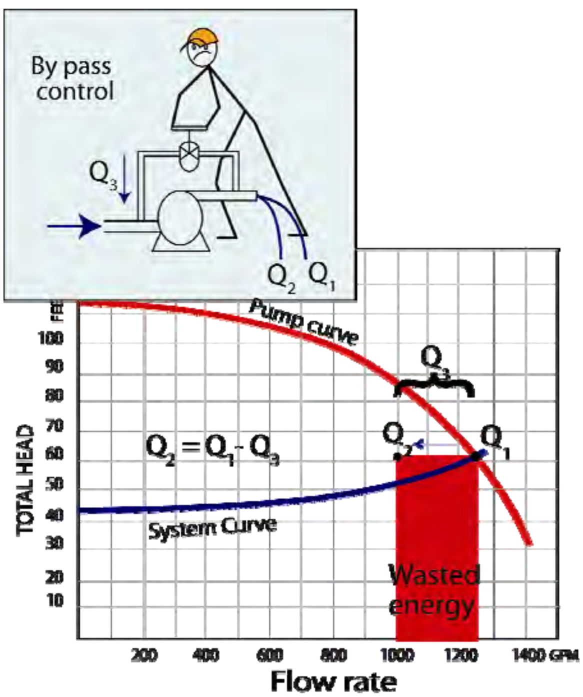

Figure 1 – Bypass control energy use

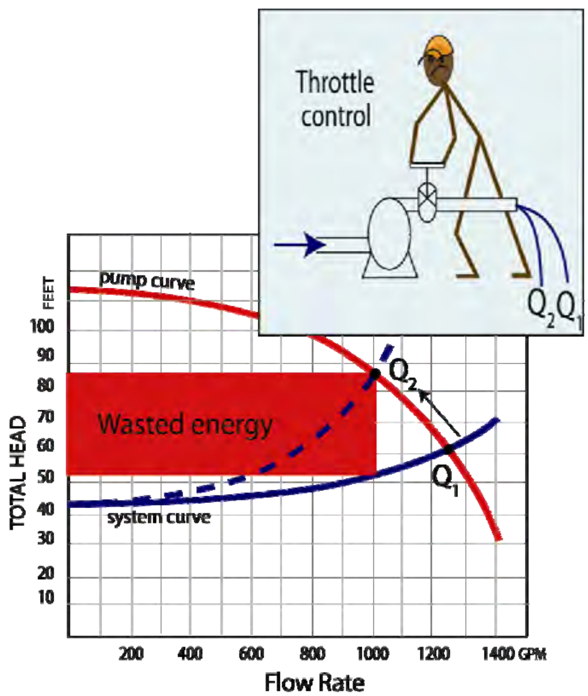

Figure 2 – Throttle control energy use

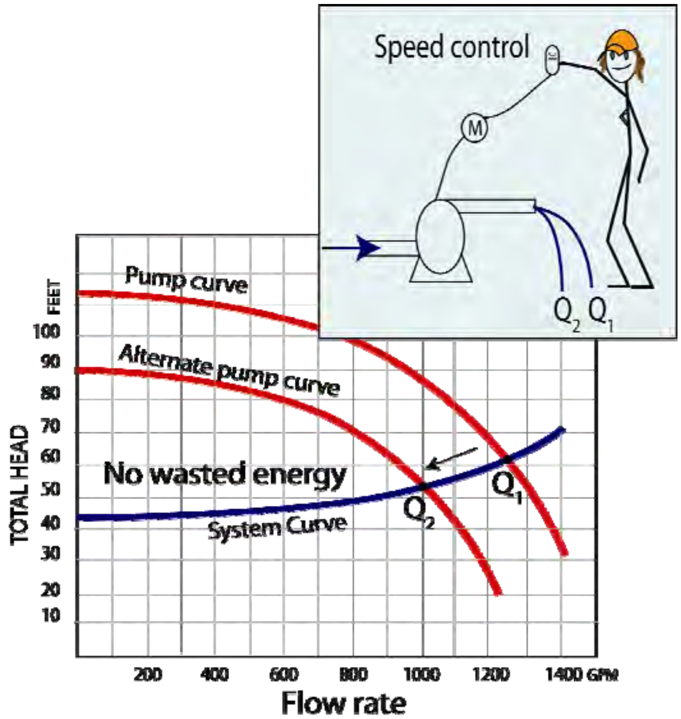

Figure 3 – Speed control energy use

Pump speed refers to the rotational speed of the pump shaft. The shaft is connected to the impeller; the impeller adds energy to the water. Slowing the rotation of the impeller reduces the energy that is transferred to the water and thereby the power requirement of the pump. Pump speed can be controlled in a number of ways:

- Mechanical (drive line directly connected to a variable speed engine)
- Hydraulic (hydraulic coupling)
- Variable-speed pulley arrangements
- Changeable gearbox (constant-speed input with variable-speed output)
- Magnetic coupling (constant-speed input with variable-speed output)
- Electrical (induction motors using a variable frequency drive)

Pumping System Hydraulic Characteristics

Pumps can be placed into several broad categories including positive displacement and rotodynamic. Most pumps used for agricultural irrigation pumping are rotodynamic meaning that they transfer energy to the water by means of a rotating impeller. Pumps add energy to the water by:

- raising the height (elevation) of the water and
- increasing the pressure of the water as it exits the pumps. This pressure is used to move the water through the irrigation system and overcome losses.

When evaluating pumps, a system approach should be used that includes all components, energy inputs (via pumps), pressurization requirements of the irrigation system and energy to overcome friction losses in the system.

The total energy requirement for a pumping system is defined by the static head and the friction head requirements of the system. In pumping systems, total energy is often referred to as total dynamic head. Total dynamic head has two components: static head and friction head.
Static head is the sum of the difference in elevation of the supply and delivery point of the liquid being moved plus pressure head. Static head is independent of flow rate, Figure 4.

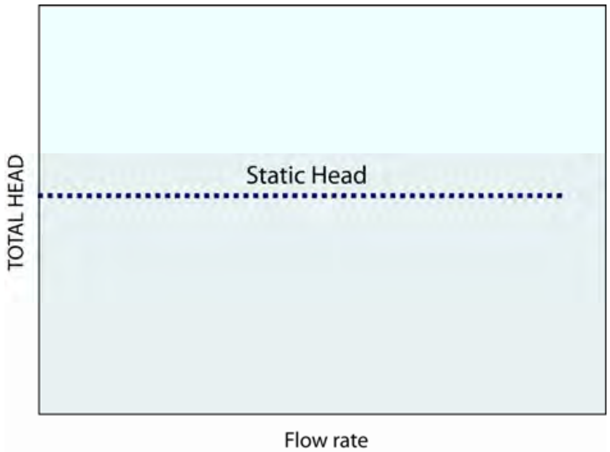

Figure 4 – Static Head Loss

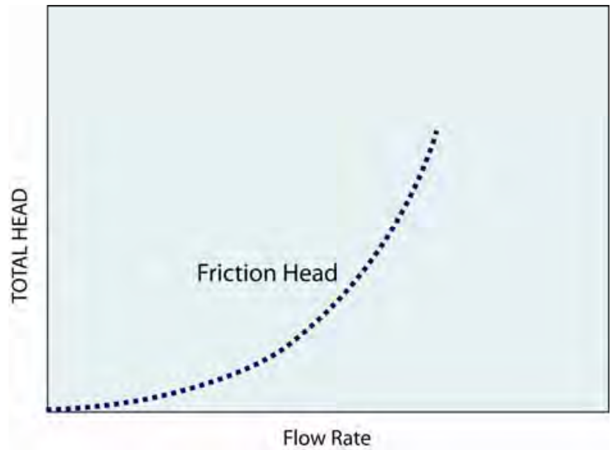

Figure 5 – Friction Head Loss

Friction head is the energy required to overcome friction losses in the system caused by the water being moved in and through pipes, valves, and other components in the system. This loss is proportional to the square of the flow rate as shown in Figure 5.

The third component of total dynamic head is the velocity head. This component is generally small in irrigation systems, and is often ignored because it is normally insignificant in comparison to static and friction head components.

In order to select a proper pump the system operating characteristics need to be known. A system curve relating flow rate to total head needs to be developed. In general the system curve will consist of the sum of the static and friction heads as shown in Figure 6.

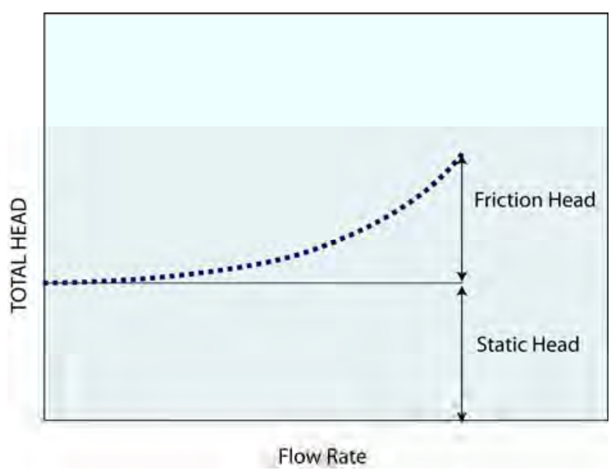

Figure 6 – System curve

The performance of a pump is typically shown graphically in a pump curve. A pump curve shows the relationship between total dynamic head and flow rate. Rotodynamic pumps have curves where the head falls gradually with increasing flow as shown in Figure 7.

When a pump curve and a system curve are combined, the intersection of the pump and system curve is the point where the pump will operate, Figure 8.

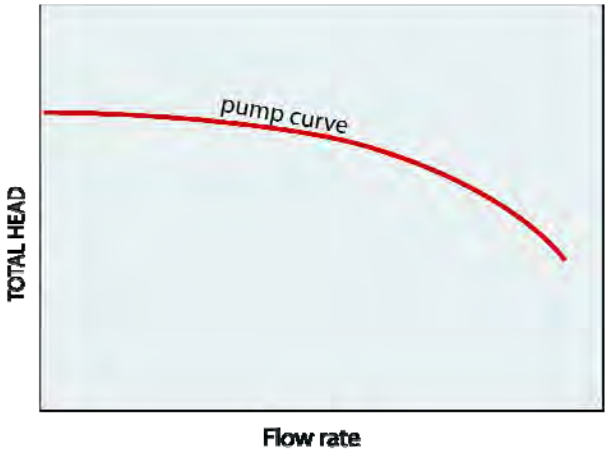

Figure 7 – Pump Curve

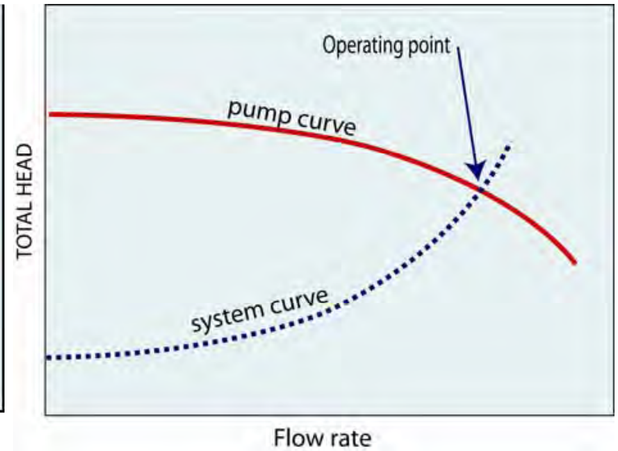

Figure 8 – Pump and system curve intersection

Pump operation characteristics are related to the rotational speed of the pump. The equations relating pump performance parameters to speed are known as the Affinity Laws.

$$\frac{Q_1}{Q_2} = \frac{\omega_1}{\omega_2} \qquad \frac{H_1}{H_2} = \frac{\omega_1^2}{\omega_2^2} \qquad \frac{BHP_1}{BHP_2} = \frac{\omega_1^3}{\omega_2^3}$$

Where:

Q = flow rate
H = head or pressure
BHP = brake horsepower (hp)
ω = rotational shaft speed (rpm).

Figure 9 demonstrates how the pump curve changes with shaft speed. As the rotational shaft speed (and thus the pump impeller) changes, the pump curve shifts accordingly.

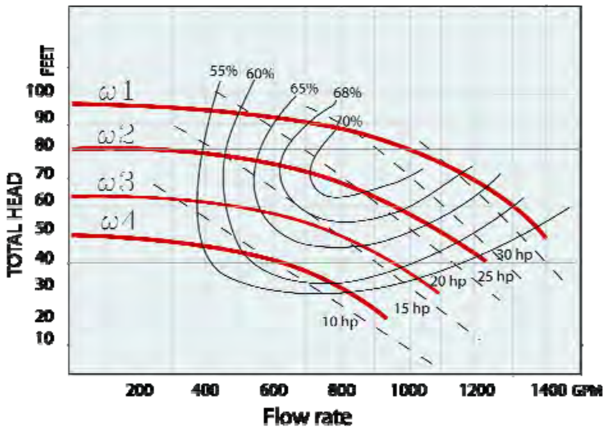

Figure 9 – Pump curve changes with shaft speed

As demonstrated by the Affinity Laws and shown in Figure 9, a change in pump speed greatly affects the power requirements; a slight reduction in speed can result in a significant reduction in input power. The potential energy saved varies depending upon the type of irrigation system supplied and pump selected.

When the pumping head required by a system is mainly friction loss, reducing the speed causes the pump's operating point on the system curve to follow the path of the efficiency curve and allows the system to operate over a range of speeds at or near the Best Efficiency Point (BEP) of the pump. The reduction in flow varies proportionally to speed, and the affinity laws accurately predict flow rate and head changes as well as power savings (see Figure 10).

When the majority of pumping head required by a system is due to static head, (i.e., when most of the work of the pump is used to lift the water to a certain elevation) changing the speed of the pump will cause the system curve to cross through more efficiency lines and not follow the BEP. The flow reduction is no longer directly proportional to speed change. Not only are energy savings not as great but they are more problematic to calculate because of difficulties in determining the change in pump efficiencies (see Figure 11).

The shape of the pump curve also has an effect on the potential energy saved. Pumps with steeper curves have more potential to save more energy. Flat-curved pumps will have less energy savings (see Figures 12 and 13).

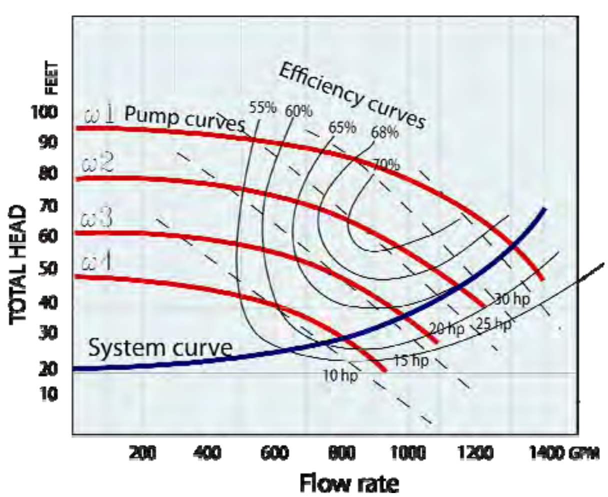

Figure 10 – System curve parallel with efficiency curves

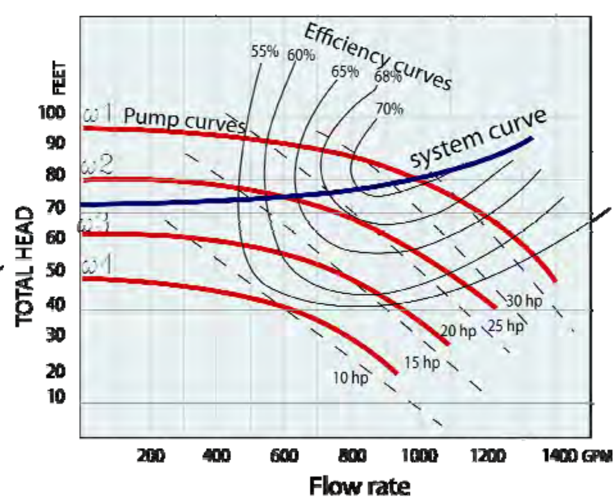

Figure 11 – System curve crosses efficiency curves

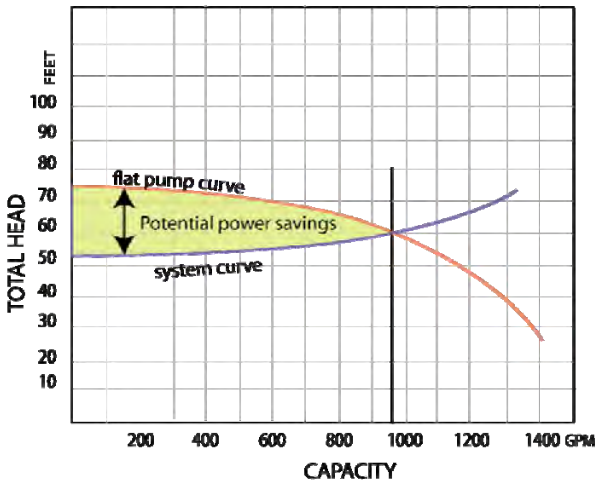

Figure 12 – Potential savings flat pump curve

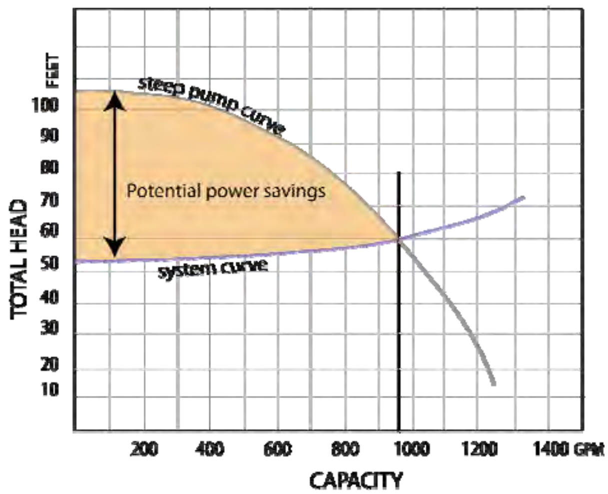

Figure 13 – Potential savings steep pump curve

Variable Speed Electric Motors

Most variable speed applications involving an electric motor generally employ a variable frequency drive (VFD). A brief discussion of electric motors and the major types of VFD's follows.

The speed of an Alternating Current (AC) motor depends on three principle variables:

- The fixed number of winding sets (known as poles) built into the motor, which determines the motor's base speed.
- The frequency of the AC line voltage. Variable speed drives change this frequency to change the speed of the motor.
- The third variable is the amount of torque loading on the motor, which causes slip. Because slippage occurs, the actual motor speed is somewhat lower than the nameplate value for the motor.

The following equation is used for calculating motor speed:

$$Synchronous\ Speed = \frac{120 \times Frequency}{Number\ of\ \ poles}$$

Normal electric power in the United States is supplied at 60 cycles per second, or 60 hertz (Hz). Common motor rotational speeds (rpm) at this frequency are 3,600 rpm, 1,800 rpm, 1,200 rpm, or 900 rpm, depending on how the motors are wound (number of poles). Once the motor is fabricated, the only variable that can change in the synchronous speed equation is the frequency (Hz) of the power supply. The motor speed is directly proportional to the frequency. Rather than supplying the electric motor with a constant frequency of 60 Hz, the VFD takes the electrical supply from the utility and changes the frequency of the electric current which results in a change of motor speed.

Also increasing the frequency above 60 hertz makes the motor run faster but it generates several concerns:

1. Was the motor or load designed for the increase in speed? Some motors are designed to operate at higher than normal speeds at frequencies above 60 hz. However, most motors and devices are not mechanically balanced to operate without vibration and mechanical safety concerns at higher than design speeds.

2. VFD’s control both frequency and voltage simultaneously to keep a constant ratio of volts and hertz so that the motor sees a constant current flow similar to full speed conditions. VFD’s are not capable of increasing voltage so as the frequency increases the torque starts to decrease. At some point as the speed increases there will not be enough torque to drive the load, and the motor will slow even with increased frequency.

Variable Frequency Drives (VFD's)

Since changing the frequency of the power supply is one way of controlling the pump speed, VFD’s are a subset of VSD’s.

VFD’s are electronic systems that convert AC to DC and then simulate AC with a changed frequency thereby changing the speed of the motor. There are three basic designs for variable frequency AC motor controls: Six Step Inverter (variable voltage source), Current Source Inverter, and Pulse Width Modulated Inverter (PWM; constant voltage source). Each type possesses unique electrical characteristics which must be considered in the application for load requirements, motor selection, system operating efficiency, and power factor. Pulse Width Modulated (PWM) is the most prevalent.

The PWM creates a series of pulses of fixed voltage and adjustable time duration (width). The sum of widths of the pulses and intermediate off cycles determine the resultant frequency of the wave. The sum of the pulse areas equals the effective voltage of the true alternating current (AC) sine wave. By varying the width of the pulses different wave lengths of alternating current can be simulated to emulate variable frequencies and the motor speed is controlled. Figure 14 illustrates a wave form generated by a PWM inverter.

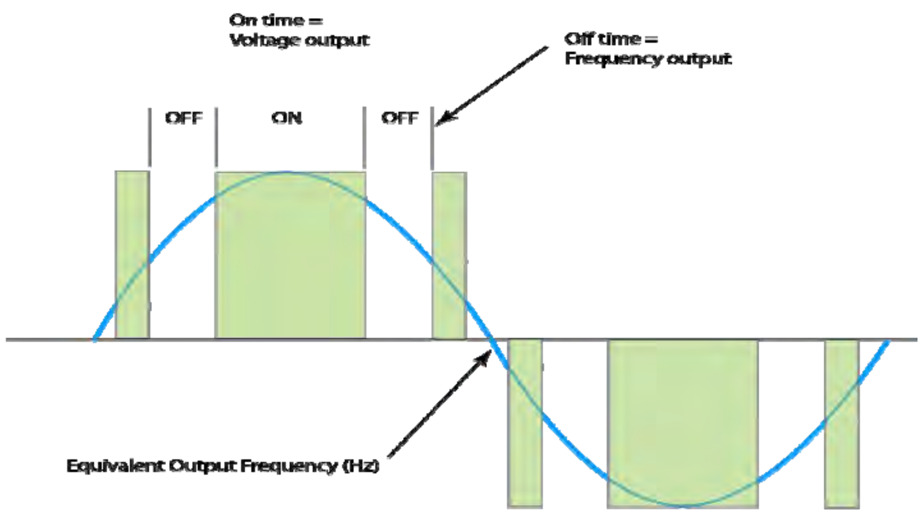

Figure 14 – Pulse Width Modulation generated wave form

Variable Speed Applications

Although there are many uses for variable speed drives associated with pumps, probably the primary reason they are installed is for energy savings. Applications where energy savings might result, can generally be divided into three basic categories:

- Constant pressure/head-variable flow
- Constant flow-variable pressure/head
- Variable flow-variable pressure/head.

Constant pressure head applications—include those where pressure is maintained at some desired point regardless of flow rate. An example would be several center-pivot sprinklers supplied by a pump from a single well. The same pressure would be required regardless of how many pivots were operating. The system would usually include a pressure transducer to control the output of the VSD which, in turn, would change the pump speed in order to maintain a constant pressure. Figure 15 demonstrates the interaction of a variable speed pump and an operation curve for constant pressure.

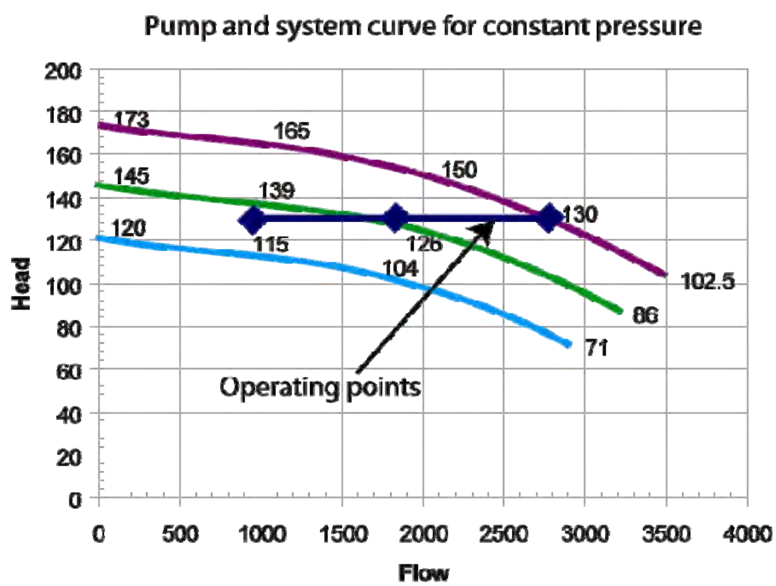

Figure 15 – Constant pressure - variable flow application

Constant flow applications—require flow to remain constant regardless of changes in pumping head and pressure. A flow meter is usually employed to control VFD output and, in turn, motor speed. One example is a well experiencing drawdown over the irrigation season. At the beginning of the season the water level in the well is near the surface, and as the season progresses the water level drops. The pump is sized for the maximum drawdown and thus is over sized for much of the season. By adding a VFD, the total head developed by the pump can be adjusted as the drawdown changes.

Another example would be a center pivot (without pressure regulators) operating on a steep slope. The uphill position would be the most critical design point where the end pressure is the lowest and the pump pressure the highest. (The pump pressure would be highest because of the lower flow rate in the system.) As the pivot moves downhill, the pressures along the pivot lateral increase, causing an increased flow rate. Differences in elevation, required nozzle pressures, and pipeline friction require the pump to provide different pressures to maintain a constant flow. Since the system is typically designed for the highest pressure requirement, the VFD can reduce the motor speed for the lower pressure component and save energy in doing so. Figure 16 displays a pump and operation curve that would provide a constant flow rate.

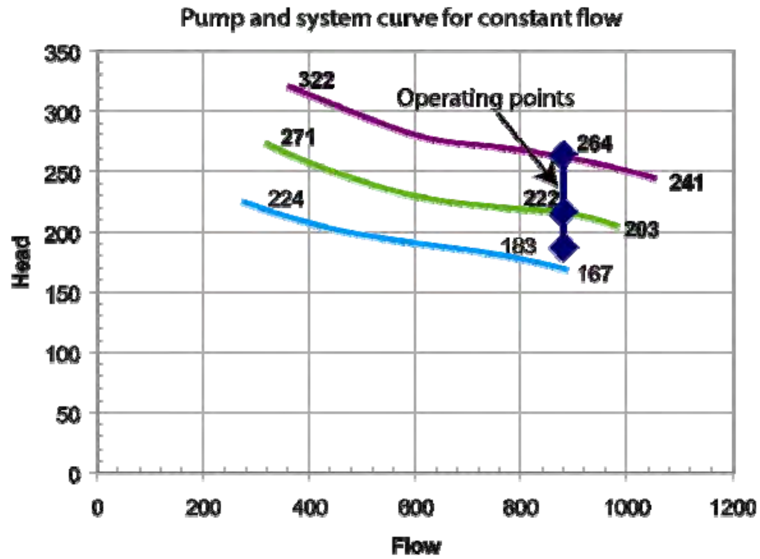

Figure 16 – Constant flow - variable pressure application

Variable flow – variable pressure applications—is where both the flow and pressure change. An example might be a farm with multiple systems of wheel lines and pivots operating off of one or multiple pumps. There could be any combination of systems operating and varying elevation requirements for the different systems. Figure 17 displays pump and operation curves representing this condition.

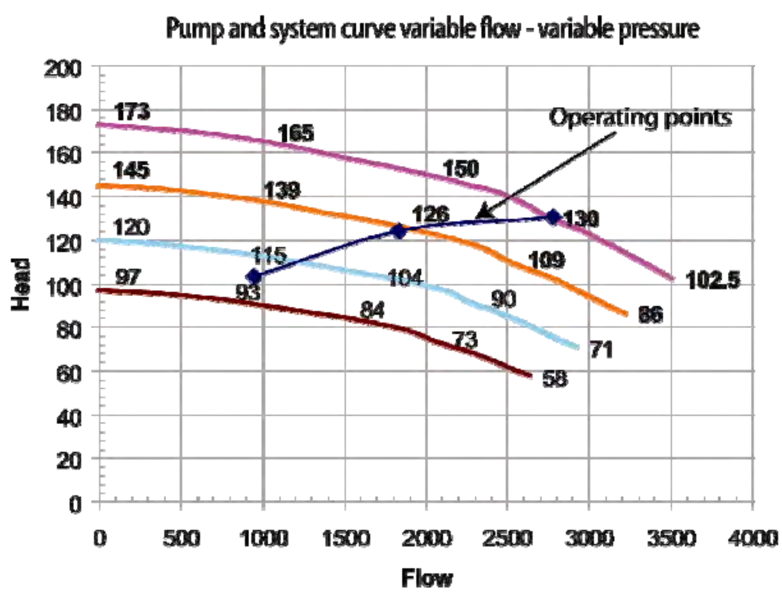

Figure 17 – Variable flow - variable pressure application

VFD Operation

If the purpose of installing a VFD is power savings, several factors need to be considered including motor efficiency and motor loading. Table 1 lists motor efficiencies based on the 1992 National Energy Policy Act. This has become the standard for motors manufactured in the U.S. after 1997. Motor loading can also affect motor efficiency. This factor is generally not a concern in constant speed pump applications. As long as the motor operates in the range of 60 to 100 percent load factor the efficiency curve is relatively flat. When loading drops below 60 percent, motor efficiency begins to drop and will drop rapidly at around 40 percent load. With variable speed drives, the motor may operate in an inefficient range because of the changes in the motor load. Figure 18 displays the efficiency load relationship for various sizes of motors.

Table 1 - National Energy Policy Act Efficiency Values

Full Load Nominal Efficiencies			
Motor Horsepower	Number of poles/ motor RPM		
	6/1200	4/1800	2/3600
1	80.0	82.5	—
1.5	84.0	84.0	82.5
2	85.5	84.0	84.0
3	86.5	86.5	84.0
5	87.5	87.5	85.5
7.5	88.5	88.5	87.5
10	90.2	89.5	88.5
15	90.2	91.0	89.5
20	91.0	91.0	90.2
25	91.7	91.7	91.0
30	92.4	92.4	91.0
40	93.0	93.0	91.7
50	93.0	93.0	92.4
60	93.6	93.6	93.0
75	93.6	94.1	93.0
100	94.1	94.1	93.0
125	94.1	94.5	93.6
150	94.5	95.0	93.6
200	94.5	95.0	94.5

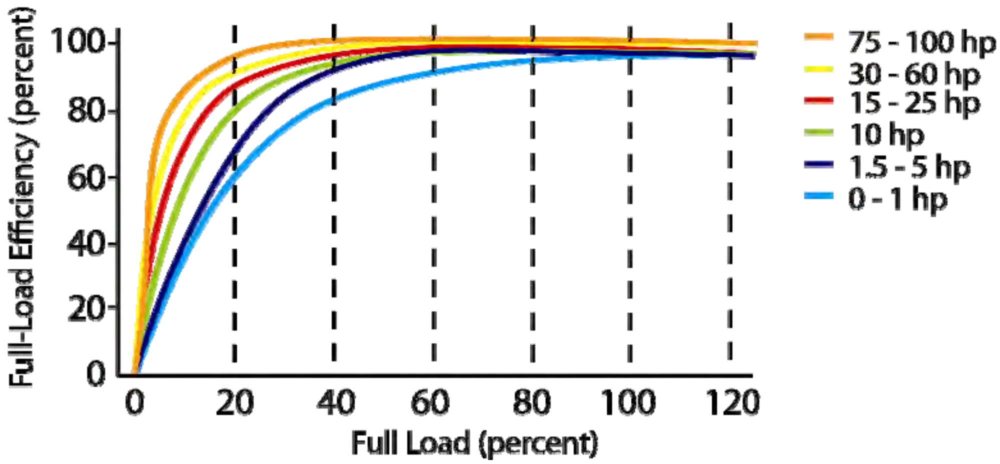

Figure 18 – Induction motor efficiency as a function of load (Energy Innovators Initiative, 2003)

To prevent operating the motor in its inefficient range, a good rule of design is to avoid operating a motor at less than 50% of full load. If the motor is operated at less than 50% load, adjustments in motor and system efficiencies may need to be made in system analysis.

To obtain the results shown in Figure 14, a VFD converts AC to DC then pulses DC to emulate an AC wave form. This process is not 100% efficient. Heat is generated and this is an energy loss. A suggested efficiency range for VFD's is 95-98%. The pulsed nature of the current may also cause harmonic losses in the motor for another drop of about 1% efficiency. For design purposes, an appropriate estimate of efficiency for VFD's is 97%.

Many times VFD's are installed for reasons other than power savings.

Soft start/stop option—Soft start/stop allows the pump and motor to be started at a lower rpm and then "ramped" up to run speed over a longer period time, significantly reducing the starting current required by the motor. Some utilities require that motors over a certain horsepower undergo a soft start. In addition to a lower inrush current, mechanical stress on the motor and pump are also greatly reduced. In a normal start, the motor rotor and pump rotating element go from motionless to the motor's rated RPM in about one second. Also, using soft start/stop greatly reduces the chances of water hammer in almost any pumping system.

Single to Three Phase Conversion—In areas where three phase power is unavailable, a VFD provides an alternative to other forms of power conversion. The VFD converts incoming AC power to DC whether the source is single or three phase. Regardless of the input power, the output will always be three phase. The drive must be capable of rectifying the higher current, single phase source. Therefore, as a rule of thumb, for a drive supplied by single phase input most manufacturers recommend using a drive that is double the motor size to handle the increase in current.

Open Delta Phase Balancing—There are times when utilities will use two transformers, instead of three, to produce three phase power. This open delta connection is often seen in more remote areas where a relatively small amount of three phase power is needed, and lower installation cost is a factor. One of the problems with this lower cost approach is that there is a high potential for phase and voltage imbalance. This will cause current imbalance in a three phase motor which can significantly shorten its life. Since the VFD converts the incoming AC to DC and then generates its own three phase output, voltage output to the motor will be balanced.

Improved process control—VFD's are generally solid state electronic devices that can take control signal inputs for start/stop, speed control and output signals to Distributed Control Systems (DCS), Programmable Logic Controller (PLC) systems, or provide information to other computers, which lends itself to automated process control networks. PLC is more or less a tiny computer with a built-in Operating System (OS). The PLC is primarily used to control machinery. A program is written for the PLC which turns on and off outputs based on input conditions and the internal program. A PLC is designed to be programmed once, and run repeatedly

Disadvantages and Potential Problems

Motor bearing damage—VFD's can generate high frequency current pulses through motor bearings. These pulses may lead to metal being transferred from the bearings into the bearing lubricant. The wear depends on the bearing impedance and is a function of the load, speed, temperature and type of lubricant. Some new drive installations have reported bearing failure only a few months after start-up. This type of damage is typically associated with high voltage/higher horsepower motors but can also be a problem in typical irrigation pumping applications. To avoid damage, motor bearings with high quality insulation need to be selected, and the VFD needs to be properly grounded, have symmetrical motor cables, and/or inverter output filtering.

Harmonics—most variable frequency controllers inject harmonic currents (noise caused by the high switching frequency of a VFD) into the power supply side of the drive and all circuits connected to that supply. The effects of harmonics can range from annoying hums and flickering lights (computer displays) to more serious problems such as the overheating of wiring or causing devices to trip circuit breakers. A "buffer" transformer or filter may be recommended by the inverter manufacturer or may be required by the local power provider, to isolate supply line disturbance created by the VFD. The filters will protect other sensitive electrical in-line equipment such as computers and increase inverter reliability and protection. The current standard for harmonics is IEEE 519.

Motor insulation damage—Insulation damage can result from several factors such as thermal stress and voltage spikes. When motor speed is reduced, the cooling mechanism (i.e., fan) also slows down. Thus, motors have a tendency to overheat at low speeds. High efficiency motors overheat less, but the easiest way to reduce heat induced insulation stress is to use a motor with a higher grade of insulation. The high grade breaks down less easily.

Insulation damage may also occur from voltage spikes. Voltage spikes result from a number of conditions or combinations of conditions. Voltage spikes create several processes that cause insulation to deteriorate over time. The easiest way to eliminate voltage spikes is to follow NEMA cable length guidelines. Here again, a general rule of thumb is, when operating at 230 volts, lengths greater than 200 feet become a significant concern and when operating motors in the 460 volt range cable lengths greater than 25 feet are a concern. In more complex situations load reactors and filters may need to be installed between the drive and motor.

Resonant frequency—the frequency at which an object undergoes natural vibration is generally not a problem with a standard, fixed-speed pump. However, excessive vibrations in the pump system may occur at some rotational speeds that may be encountered over the operational range of a variable-speed pump. This situation can occur at speeds greater than or less than the pump's nominal rated speed.

As a rule of thumb, frame-mounted pumps, multistage pumps and those with elongated shafts tend to be more vulnerable to vibrations. Drives can be programmed to bypass these critical speeds or speed ranges that have been determined to cause vibration. Although the pump speed will still pass through these points, it will not remain there long enough to cause vibration damage.

Variable frequency electronics are subject to environmental factors that may not be a concern for constant-speed units which can contribute toward equipment malfunction. Some of the environmental factors that must be considered are temperature, humidity, and elevation.

Consideration must also be given to VFD reliability, maintenance costs, and skills of available maintenance personnel. Additionally, the completed package must be considered as a unit. A variable speed drive unit can consist of motor by Manufacturer A, inverter by Manufacturer B, and system control hardware and interface to inverter by Manufacturer C. The VFD supplier needs to assume responsibility for the total package; otherwise; interests of the customer may suffer, especially when problems with one of the components interrupts pump operation and water supply.

Effect of Speed on Pump Suction Performance

Cavitation can significantly decrease pump performance and may even damage a pump. Reducing the pump speed can have a positive effect on reducing cavitation, but increasing pump speed will negatively affect pump suction performance and increase the risk of cavitation damage. A thorough investigation should be conducted on the effects of an increase in pump speed beyond normal operating speed.

Design Considerations

Sizing

In the design process, it is not unusual for a VFD to be rated for more horsepower than the nameplate horsepower of motor being driven. Because of the service factor, it is not uncommon for a motor to use 15% or more horsepower than its nameplate rating. Also, the rating of the VFD should include the factor of its operating efficiency. For example, a 100 HP (rated) VFD at 97% efficiency will output 97 HP. However, if the system is adequately analyzed, the rating of the VFD will be no more than the electric motor rated HP. Another reason drives are oversized is to minimize, voltage distortion and interference with other electrical equipment.

Care should also be taken to not select a VFD too large as the VFD output might exceed motor specifications and cause motor failure. The motor and VFD manufacturers need to be consulted to prevent over sizing of the VFD.

Filters

Because incoming power may have irregularities the VFD should not be connected directly to the line voltage. An isolation motor contactor should be used. This will also provide a method of bypassing the VFD in emergency situations.

Line filters may be required for VFD's. The line filters regulate the voltage of the different legs of a three-phase supply and control the voltage of all legs to equal the lowest voltage in any one leg. Imbalance in voltage generates more heat and loss of efficiency in the VFD, motor, and line filters.

Electromagnetic interference (or EMI, also called radio frequency interference or RFI) is a disturbance that affects an electrical circuit due to either electromagnetic conduction or electromagnetic radiation emitted from an external source. The EMI and RFI generated by the installation should be measured. If the interference exceeds limits defined by the current IEEE 519, electric utility may require that filters be installed.

Environmental Control

Most agricultural applications can be considered outdoor installations. Dust, rodent damage, and heat are the leading causes of VFD failure. VFD's also generate significant heat that must be dissipated. Cool, clean electrical components last longer and perform better. VFD's are rated for a specific amperage and voltage at a specified temperature. An increase in temperature will see a dramatic drop in VFD efficiency and may require installation of a cooling mechanism. Ambient air temperature must be between 32° F. and 104° F. Several types of cooling methods exist:

External Heat Sinks

In many cases VFD's with external heat sinks can be effectively used outdoors without additional cooling (but not always). External heat sinks require regular cleaning to remove dust build-up. Clogged filters reduce cooling system effectiveness so maintenance should include regularly changing filters and cleaning and servicing fans.

Higher elevations may require de-rating of the drive due to less dense cooling air flowing over the heat sinks.*

* De-rating is the operation of an electrical or electronic device at less than its rated maximum output. This is generally due to some environmental influence, mainly temperature.

Self-Contained Cooling Systems

Use of outside, filtered air is not an acceptable method of cooling a large VFD in an outdoor application. Larger VFD's require air conditioning or an effective heat exchanger for cooling. Air conditioners (A/C) or heat exchangers must be sized for maximum ambient temperatures, be industrial grade designed for dirty environments and also take into account the elevation of the installation.

The cooling output of the A/C unit must be varied as the heat load from the VFD changes–otherwise over-cooling, compressor short cycling, and freeze-up of the cooling unit can occur. Also water-cooled heat exchangers should not be used outdoors in areas where freezing may occur during early and late season operation.

VFD's cannot tolerate dust or dampness; therefore, they need to be installed in enclosures that meet NEMA 4 standards (dust and watertight). Adequate sunshades or pump houses are required for all installations.

Other Factors

Other factors that may affect VFD efficiency are:

- Radio frequency or stray high frequency signals
- Line voltage variation greater than ± 10%
- Line frequency variation greater than ± 2Hz
- Altitude greater than 3,300 feet (1000 meters).

The VFD manufacturer should be consulted to determine the impacts of site-specific conditions.

Case Studies

Example Case 1 – Center Pivot Sprinkler on a Steeply-Sloped Field

Given:

Water is pumped from a well to supply a center-pivot sprinkler system. The pumping plant consists of an electric motor and vertical turbine pump. Power costs are $0.07 per kWh. The sprinkler irrigation system is a MESA (Mid-Elevation Spray Application) pivot system with 20-psi pressure regulators and nozzles mounted at 6 feet. The estimated pivot flow rate is 877 gpm. The sprinkler irrigates 140 acres of corn with an estimated annual net water requirement of 28 inches (see Figure 19).

The pumping lift is 100 feet, and the pivot is irrigating a field that has a fairly uniform slope 4%. Pump selection is based on delivering the design flow with the pivot oriented uphill on a 4% slope.

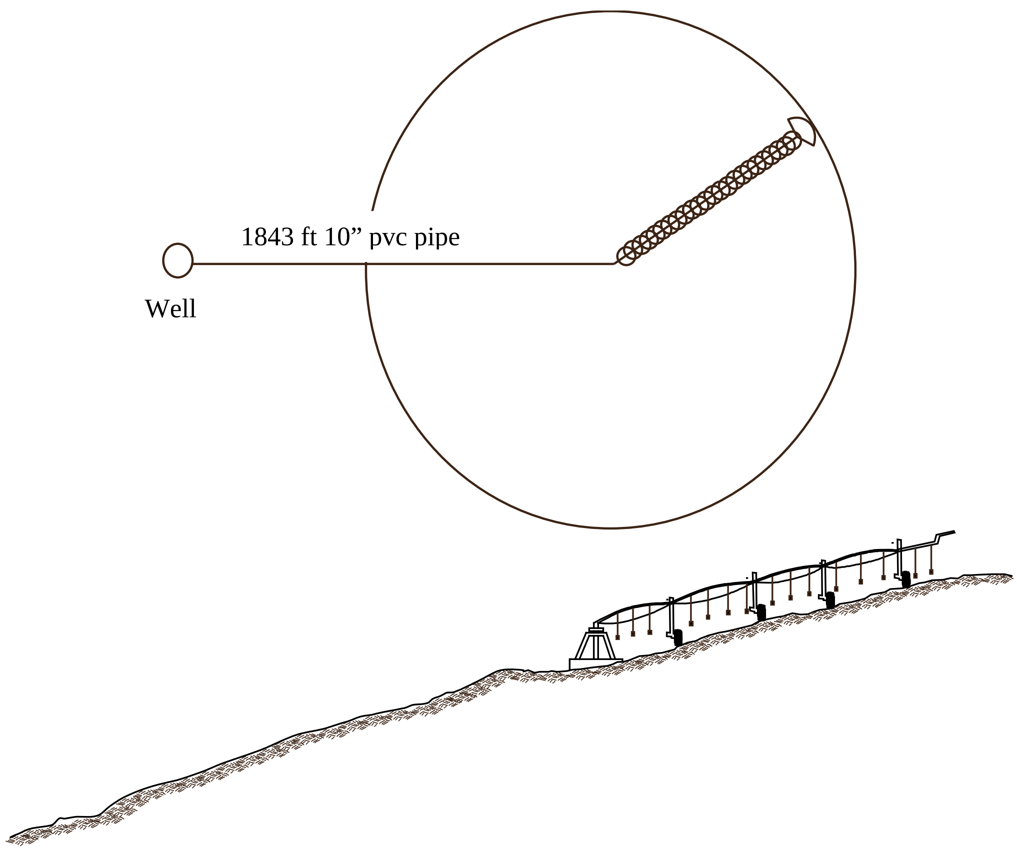

Figure 19 – Case 1 Farm Layout

Due to the use of pressure regulators in the system, the flow rate is assumed to remain essentially constant, but it is necessary to determine the Total Dynamic Head (TDH) for the pivot at different positions. The pressure requirement at the pivot with no elevation change is 40 psi (operating pressure + friction loss + nozzle height).

Because of the field slope, the pressure at the distal end of the pivot lateral is constantly changing. The pressure regulators provide uniform pressure and uniformity to the nozzles but the energy use may be reduced by adjusting the pressure to match the conditions required on the field. This analysis can range from simple to complicated. In most cases a simplified analysis will provide good information on energy and cost savings. To make evaluation easier, the field is divided into three major control sections:

1) pivot operating uphill
2) pivot operating on the level
3) pivot operating downhill.

More field sections could be used if a more detailed analysis is desired.

The head requirements for the three selected conditions a summarized in Table 2.

Table 2 – TDH Requirements

	TDH Uphill Condition	TDH Level Condition	TDH Downhill Condition
Pivot point pressure	40 psi	40 psi	25 psi*****
Elevation gain	+22.9 psi	0 psi	0 psi
Friction loss in mainline	3.16 psi	3.16 psi	3.16 psi
Miscellaneous losses	3 psi	3 psi	3 psi
Pump losses	1.5 psi	1.5 psi	1.5 psi
Pump column lift	43.3 psi	43.3 psi	43.3 psi
TDH	113.7 psi = 262.6 ft	90.8 psi = 209.8 ft	78 psi = 175.5 ft

The pivot applies 1.94 ac-in/hr (877 gal/min***** 60 min/hr / 7.481 gal/cu ft / 43560 sq ft/ac***** 12 in/ft = 1.94 ac-in/hr.)

The pivot applies 877 gpm or 1.94 in/hr on 140 acres gross. At a reasonable application efficiency of 85%, the net application is 1.65 in/hr.

The estimated seasonal operation time is 2376 hr (28 inches with sprinkler on 140 ac: 140 ac***** 28 in = 3920 acin/1.65ac-in/hr)

At worst design condition - a pump would need to provide 877 gpm and a TDH of 262 ft.

Select a Gould 10DHHC with 8 stages operating at 1770 RPM. Points from the manufacturer's pump curve are shown in Table 3.

* When the pivot is in the downhill condition the minimum pressure of 20 psi plus 5 psi for the pressure regulators still need to be supplied. The slope which is steeper than the friction slope will provide the rest of the necessary pressure.

Table 3 – Points from Manufacturer's Pump Curve

Q (gpm)	Head (ft)	Efficiency (%)
352	322	42
528	290	58
704	270	70
880	264	80
1056	241	82

Without VFD

Water horsepower is equal to:

$$WHP = \frac{QxH}{3960} = \frac{877x262}{3960} = 58.02hp$$

With a pump efficiency of 79% the Brake horse power is equal to:

$$BHP = \frac{QxH}{3960xEff_p} = \frac{877x262}{3960x.79} = 73.4hp$$

The power input with an estimated motor efficiency of 94% is:

$$power\ input\ \frac{73.4hp}{.94\,eff_m}\,x\,\frac{.746KW}{hp} = 58.28KW$$

Estimated annual operating cost is:

$$Cost \quad = 58.28KW\ \ x\ 2376\,hrs\ \ x\,\frac{\$0.07}{KW - hr} = \$9695\,/\,season$$

Without a VFD excess pressure is dissipated through the pressure regulators when the pivot is operating in the level and downhill positions so the estimated cost remains at $9695/season.

With VFD

The pivot will operate approximately 25% of the time in the uphill condition 50% of the time in the level condition and 25% of the time downhill.

Use affinity laws to plot new pump curves. Data points for the adjusted speeds are shown in Table 4.

$$\frac{H_2}{H_1} = \left(\frac{RPM_2}{RPM_1}\right)^2$$

Table 4 – **Alternate Pump Curves, Case 1**

RPM					
1770		1584		1451	
Q	H	Q	H	Q	H
352	322	315	258	289	216
528	290	473	232	433	195
704	270	630	216	577	181
880	264	788	211	721	177
1056	241	945	193	866	162

Plot the new pump curves (see Figure 20). Then plot the estimated operating points or system curve and plot the approximated efficiency curves. Pump efficiency can now be estimated at the new speeds. Efficiency curves move down and to the left similar to the pump curves. Chances are that the operating points won't fall on the plotted curves but the new efficiency may still be approximated.

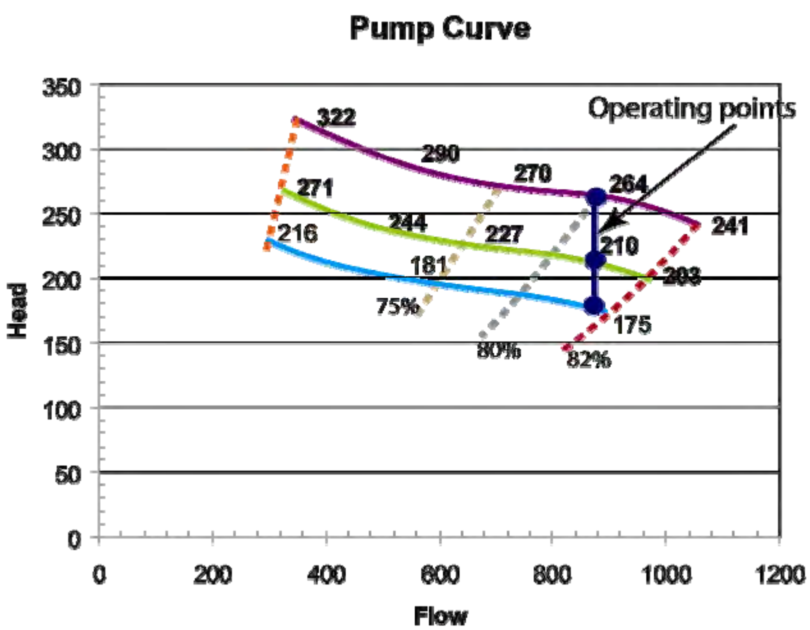

Figure 20 – **Adjusted Pump Curve, Case 1**

The new efficiencies at the various TDH values are:

TDH = 262 ft – efficiency = 79%
TDH = 210 ft – efficiency = 81%
TDH = 175 ft – efficiency = 82%.

The VFD adds another loss in the form of efficiency. The default value for VFD efficiency is approximately 97%. Horsepower and energy input are calculated using the following equation:

$$power\ input = \frac{QxH}{3960x\,eff_p\,x\,eff_m\,x\,eff_{vfd}}$$

The power requirements for the various operating points are 80.6 hp, 62.2 hp, and 52 hp.

The actual energy cost is based upon the percent of the total hours that the system is operated at each condition, in this case 25, 50, and 25%. Using the following equation the seasonal cost is estimated as $7962.

$$hp\,x\frac{0.746KW}{hp}x\,hrs\,x\ \%of\ time\,x\frac{\cos t}{KW-hr}$$

This results in a savings of ($9695 - $7962) = $1733 per season.

Compare this value to the cost of the VFD to calculate the payback period. In this case the savings from power alone are relatively small. Other benefits and associated values from using a VFD are much harder to determine. The power savings are also very dependent on the type of pump that is being retrofitted or selected. A steeper pump curve would generate more savings. The number of hours the system is operated also directly affects the cost. In many agricultural situations the operating hours are too low to justify the cost of a VFD from power savings alone.

Example Case 2 – Center Pivot Sprinkler with a Declining Water Table

Given:

Water is supplied to Pivot from a single well located in the Ogallala Aquifer. The pumping lift from the well ranges from 50 feet at the beginning of the irrigation season to 185 feet at the end of the season. The pumping plant is an electric motor and vertical turbine pump. The sprinkler irrigation system is a LESA pivot system on relatively level ground with the pivot point located 5 feet higher than the well. It is nozzled for 750 gpm at 36 psi (ground level at pivot). Pressure regulators set at 15 psi are used on the system to control flow rate during the season. The sprinkler height is 4 feet above ground. The sprinkler irrigates 122 acres of corn with a net irrigation requirement of 24 inches annually and the power costs are $0.07 per KW-Hr (see Figure 21).

The sprinkler operates close to its design point at the end of the season, but the producer must be careful to avoid air entrainment due to inadequate water depth over the pump inlet.

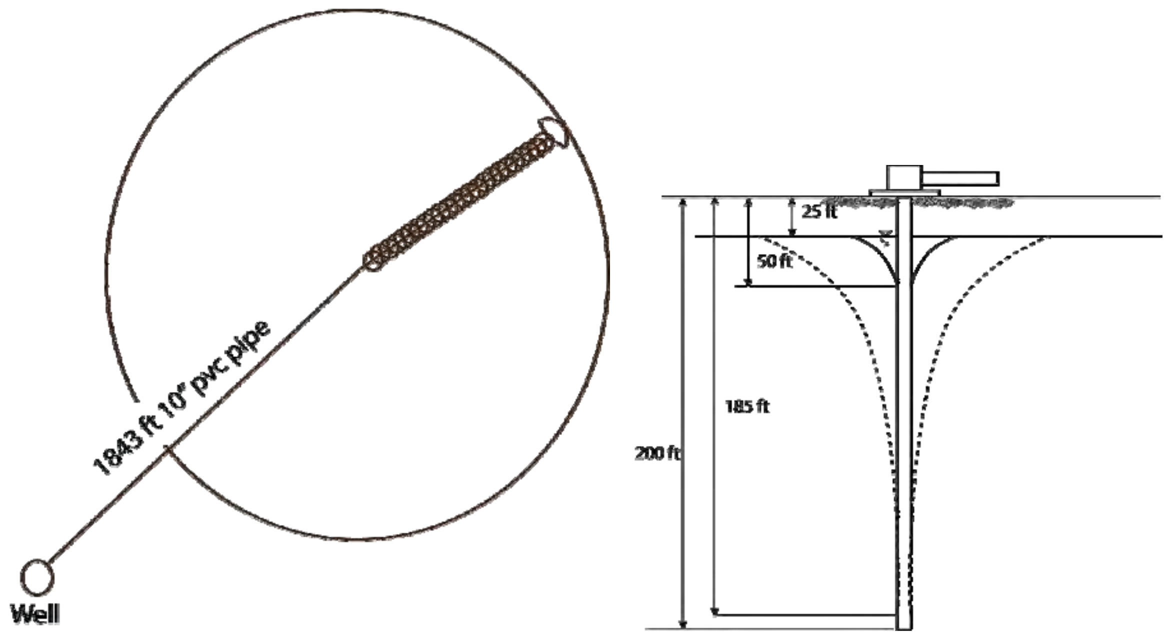

Figure 21 – Farm Layout, Case 2

First calculate TDH at the beginning and end of the season. The results are summarized in Table 5.

Table 5 – TDH Results

	Season Start TDH	End of Season TDH
Static Lift	25 ft	
Drawdown (end of season)	25 ft	160 ft
Pivot Pressure	83.2 ft	83.2 ft
Column and Discharge Friction losses	4.8 ft	4.8 ft
Elevation from well to pivot	5.0 ft	5.0 ft
Mainline Friction losses	17.7 ft	17.7 ft
Total	160.7 use 161	295.7 use 296

The pivot applies 1.66 ac-in/hr (750 gal/min* 60 min/hr / 7.481 gal/cu ft / 43560 sq ft/ac* 12 in/ft = 1.66 ac-in/hr.) here again this is a gross amount. A reasonable efficiency for a LESA system is 92%. The net application is 1.52 ac-in/hr.

The estimated seasonal hours of operation are 1917 hrs.
(24 inches with sprinkler on 122 ac: 122 ac* 24 in = 2928 ac-in/1.52ac-in/hr).

Without VFD

The maximum required TDH is 296 ft and the system would operate at this point year round. Early in season the excess pressure would be dissipated by the pressure regulators. The required water horsepower is:

$$Water\ HP = \frac{750 gpm \times 296\ ft\ (TDH)}{3960} = 56.06 hp$$

Select a Flowserve 10 EGH with 8” column pipe. Operating point 750 gpm at 37 ft head/stage, rpm =>1770 rpm. Number of stages needed - 296 ft /37 ft head/stage = 8 stages.

Impeller efficiency from pump curve = 80.5%:

$$BHP = \frac{Water\ hp}{Efficiency} = \frac{56.06}{.805} = 69.64 BHP$$

Select from table a motor efficiency of 94.1%. The power input for the motor would be:

$$power\ input \frac{69.96 hp}{.94 eff_m} x \frac{.746 KW}{hp} = 55.17 KW$$

Estimated annual operating cost is:

$$Cost \quad = 55.17 KW\ \ x\, 1917 hrs\ \ x \frac{\$0.07}{KW - hr} = \$7403 / season$$

Without VFD excess pressure is burned up through the valve and pressure regulators to maintain proper pressure and flow rate.

With VFD

Use affinity laws to plot new pump curves. The results are summarized in Table 6.

$$\frac{H_2}{H_1} = \left(\frac{RPM_2}{RPM_1}\right)^2 \qquad RPM_2 = \sqrt{\frac{H_2}{H_1}} \times RPM_1 = \sqrt{\frac{161}{296}} \times 1770 = 1305$$

Table 6 – Alternate Pump Curve, Case 2

RPM			
1770		1305	
Q	H	Q	H
460	368	345	200
582	350	437	191
621	340	466	185
700	320	525	174
781	280	586	152
830	256	623	139
880	232	660	126
945	200	709	109

Plot the new pump curves (see Figure 22). Then plot the estimated operating or system curve and estimate the pump efficiency. Efficiency curves move down and to the left similar to the pump curves.

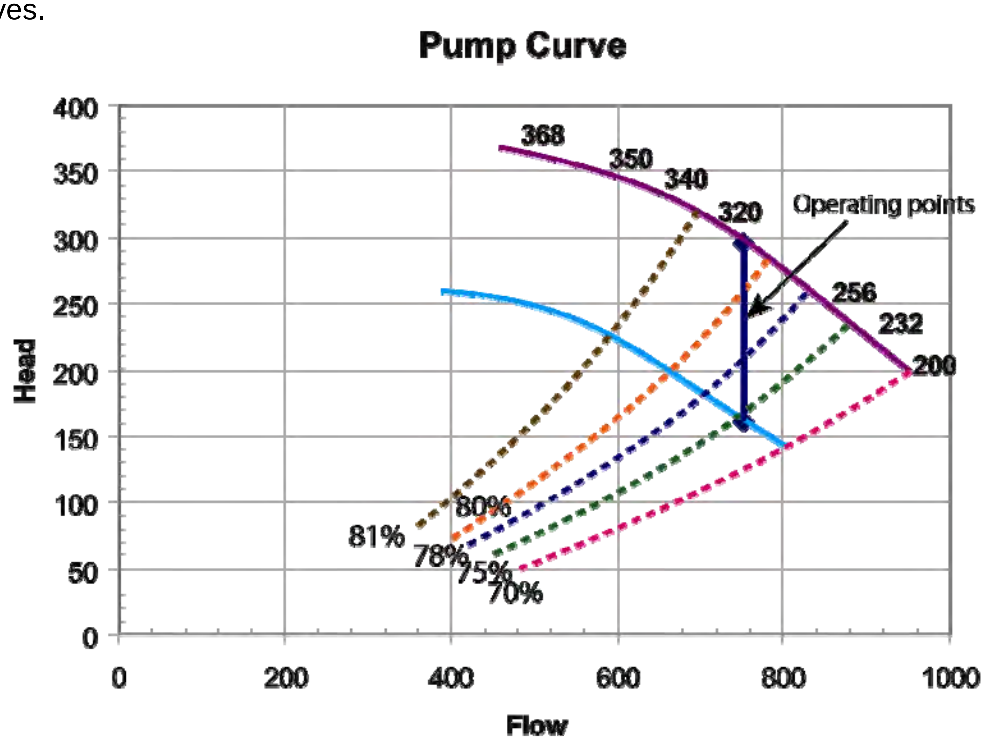

Figure 22 – Alternate Speed Pump Curve, Case 2

The efficiencies at the various TDH's are:

TDH = 296 ft – efficiency = 80.5%
TDH = 161 ft – efficiency = 75%.

The VFD adds another loss in the form of efficiency. The default value for VFD's is approximately 97%. Horsepower and energy input for the two conditions are 76.4 hp and 44.6 hp.

The actual energy cost is based upon the percent of the total hours that the system is operated at each condition, in this case take an average of the two. The seasonal cost would be:

$$76.4hpx\frac{.746KW}{hp}x1917\,hrs\,x\,0.50x\frac{\$0.07}{KW-hr}=\$3824+$$
$$44.6hp\frac{.746KW}{hp}x1917\,hrs\,x\,0.50x\frac{\$0.07}{KW-hr}=\$2232$$
$$=\$6056/\,season$$

This results in a savings of ($7403 - $6056) = $1346 per season.

The annual or seasonal savings is compared to the cost of the VFD to calculate the payback period. Here again it is difficult to justify installing a VFD on power savings alone.

Example Case 3 – Multiple Fields Off of One Pump

Given:

The farm is 360 acres irrigated by three pivots, wheel lines and solid set sprinklers (see Figure 23). Two of the pivots have corner systems. All of the pivots have end guns. The pipe sizes and pressure requirement are shown on Figure 23. The fields are all the same elevation and are planted in a variety of crops; potatoes, alfalfa, small grains, sugar beets, and corn. The water source for the fields is a single well. The power source is electricity at $0.10 per kilowatt-hr and the average pumping season is 1700 hours. The pump is an older vertical turbine operating at 1770 rpm, with 3 stages, each 10.3 inch diameter. The operator would like to install a VFD to facilitate management and save energy.

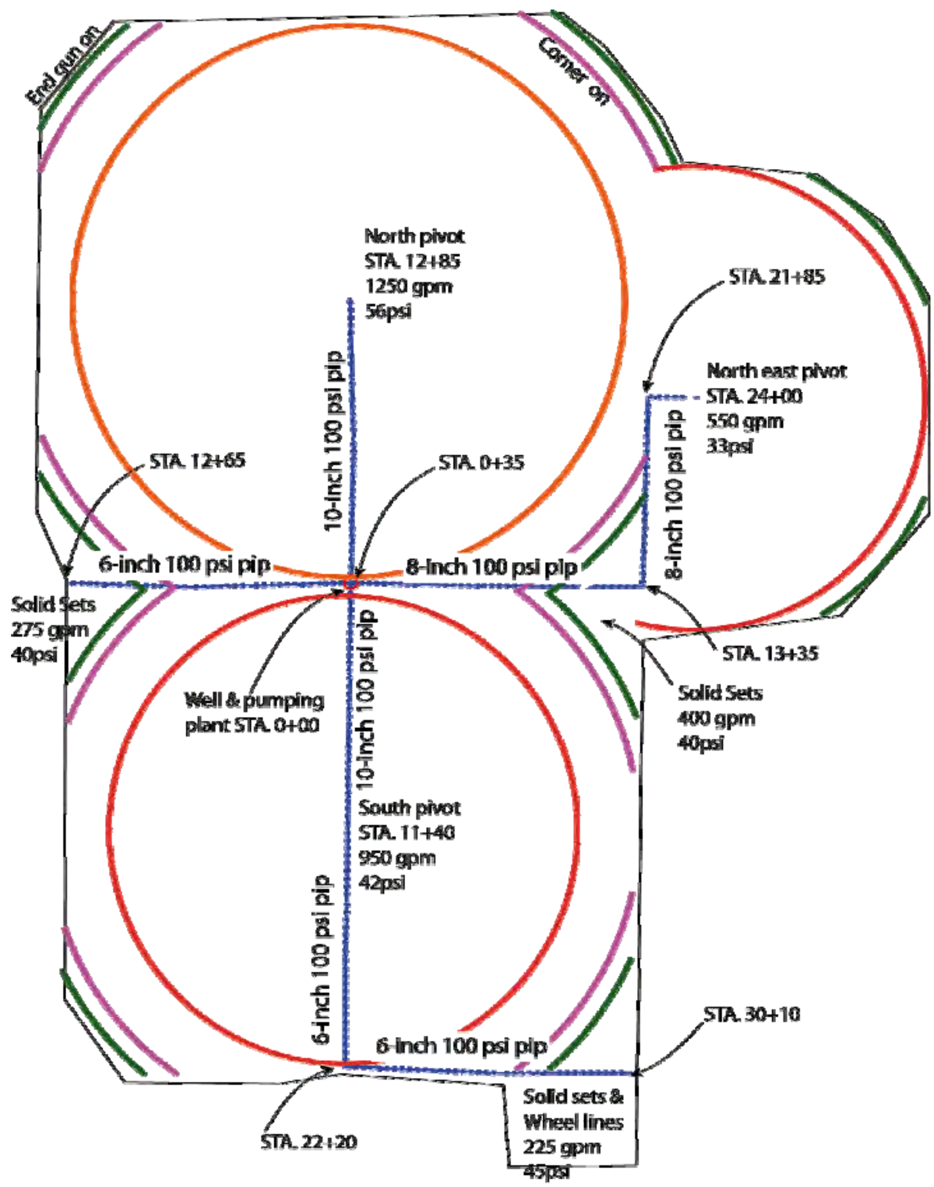

Figure 23 – System Plan Map, Case 3

Some of the possible operating scenarios are as follows:

(1) All 3 pivots; both corner arms fully extended with all 3 end guns operating
(2) All 3 pivots; corner arms mostly extended with 1 or 2 end guns operating
(3) All 3 pivots; various combinations of corner positions with end guns status
(4) All 3 pivots; both corner arms fully retracted with all 3 end guns off
(5) North pivot corner arm fully extended with end gun operating and solid sets operating
(6) North pivot corner arm mostly extended with end gun off and solid sets operating; OR South pivot corner arm fully extended with end gun operating and solid sets operating
(7) Either North or South pivot operating with corner arms fully or partially extended with end guns operating or off; for south pivot, with solid sets operating
(8) North pivot corner arm fully retracted and end gun off; OR South pivot with corner arm partially extended and end gun off; OR Northeast pivot with end gun operating and solid sets operating
(9) Northeast pivot with end gun operating; OR South pivot corner arm mostly retracted with end gun off
(10) Northeast pivot with end gun off.

Even though all scenarios are possible some are more likely than others. Scenarios 1, 2, 4, 6, and 9 were selected as being the most likely and the percent of time for each is 5%, 25%, 50%, 15%, and 5% respectively.

The pump curve information is taken from the manufacturer's chart and shown in Table 7.

Table 7 – Existing Pump Curve, Case 3

Pump curve for existing Johnson pump 14ECII		
Q (gpm)	Pump TDH (ft)	Pump Efficiency %
465		
560	286	29
700	278	35
1000	270	49
1200	264	56
1400	252	63
1770	228	73
2100	219	79
2350	216	82.5
2750	190	81.3

Without VFD

Calculate pressure requirements for the different conditions using operating pressures and friction loss equations. Include column lift of 40 feet and minor losses. The pressure requirements are summarized in Table 8. Motor load is ok (see Figure 18) and from Table 1 the motor efficiency is 95%. The excess head is burned off through pressure regulators and valves.

Table 8 – Head and Flow Summary without VFD

System operation table, no VFD						
Scenario	Q (gpm)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term Operation (%)	Power costs @ $0.10/ kw-hr
1	2750	190	81	171	5	$1084
2	2350	216	82	162	25	$5136
4	1770	228	73	149	50	$9448
6	1200	264	56	148	15	$2815
9	560	286	29	146	5	$926

The estimated seasonal operating cost is $19,409.

With VFD

There are two control scenarios for VFD's: one, select a constant pressure and just vary the flow rate; or two, select a VFD that will vary both flow rate and head. For this example a VFD that can vary both flow rate and head is selected. Determine the flow and head requirements for each control point. Calculate the required RPM's and plot the new pump curves for each control point using the infinity laws. Plot the operating points (see Figure 24). This simulates a system curve but in reality is just a bunch of set points. Estimate the new efficiency and calculate the power requirements and cost. Here again use a motor efficiency of 95% and a VFD efficiency of 97%. The inputs are summarized in Table 9. The "Input HP" column includes both the motor and VFD efficiencies.

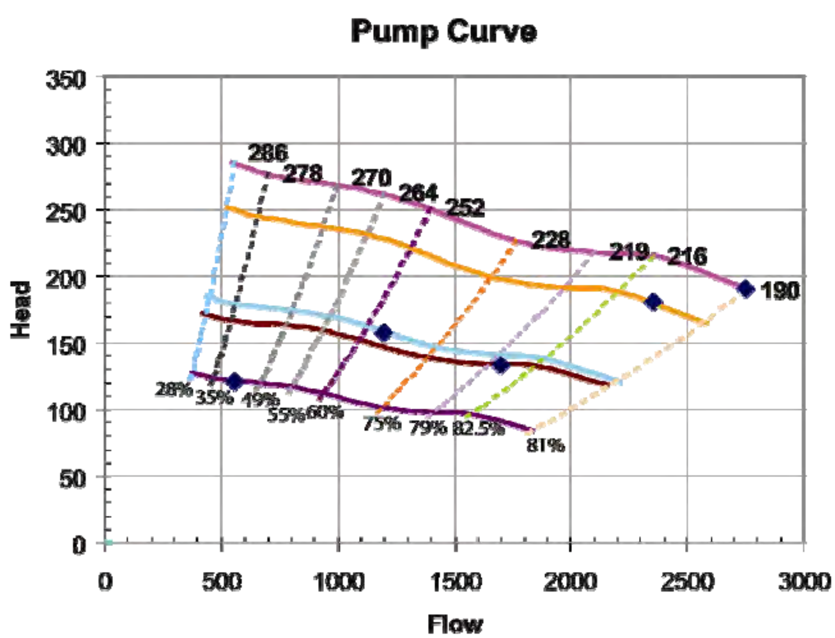

Figure 24 – Alternate Speed Pump Curves, Case 3

Table 9 – Head and Flow Summary with VFD

System operation table, with VFD						
Scenario	Q (gpm)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term Operation (%)	Power costs @ $0.10/ kw-hr
1	2750	190	81	176	5	$1116
2	2350	180	82	141	25	$4470
4	1770	133	81	78	50	$5072
6	1200	157	66	85	15	$1484
9	560	121	42	44	5	$279

The total estimated annual power cost with the VFD is $12,422 with a resulting estimated savings of $6,987 per season.

This information can be used to calculate the payback period. Several other factors need to be considered in the payback calculations including the escalating cost of energy and system management. Being able to manage the system has always proven to save water and energy and thereby money.

Sample Specifications for Construction and Materials – Variable Frequency Drives (VFD)

1. General

1.1 Scope of Work

The contractor shall furnish, and install a pump control system designed to operate one pump using Variable Frequency Drives (VFDs) as described herein. The control system shall be designed utilizing proven technology in control design for constant pressure, constant flow rate, or a combination of flow and pressure ranges to provide the desired operating conditions of the pumping system. The control system shall be operator and maintenance friendly to ensure ease of system set up and to limit down time.

The pump control system shall be capable of operating one electric pump motor as manufactured by ____.

Model ____.

Horsepower ____.

Full-Load Amps (FLA): ______________________________________.

Incoming power shall be?

Vac ___________________________ Phase, 60 Hz _______________________

Line/load reactor required by electric supplier? Yes________ No________

The desired operating ranges for pump output pressures and flow-rates are:

Minimum Pressure (psi): ________________________

Maximum Pressure (psi): ________________________

Minimum Flow (gpm): ________________________

Maximum Flow (gpm): ________________________

The control system shall use a pressure transmitter and/or flow meter connected to the discharge piping of the pump.

The factory assembled system shall include:

- Variable Frequency Drive
- VFD protection package
- Line and load reactor as required
- Lightning arrestors
- Pressure transmitter or flow meter
- Enclosure
- Main disconnect
- Circuit breaker
- Alarm and Communication interface.

2. Products:

2.1 General

2.1.1 Codes

Electrical equipment, materials and workmanship shall comply with all applicable codes, safety and fire law regulations at the location of the work and shall conform to applicable codes and standards of the organizations listed below:

1. National Electric Code (NEC)
2. National Electrical Manufacturers Association (NEMA)
3. American National Standards Institute (ANSI)
4. Underwriters Laboratories (UL 508)
5. International Electrotechnical Commission (IEC)

2.1.2 Component Standards

All equipment and materials shall be new and shall bear the manufacturer's name and trade name. In cases where a standard has been established for the particular material, the material shall be so labeled. The equipment to be furnished shall essentially be the standard product of a manufacturer regularly engaged in the production of the required type of equipment for this type of work and shall be the manufacturer's latest approved design.

2.2 Construction

2.2.1 Enclosure

For Indoor Applications:

Indoor applications are defined as a VFD control panel mounted in a clean, insulated, temperature-controlled environment. In such applications, the described equipment shall be housed in a single NEMA 12 powder-coated steel enclosure of a wall thickness of not less than 0.075 in. The enclosure shall be sized accordingly to allow easy access to components and provide adequate ventilation for VFDs. The enclosure shall also include louvers, filter fans, and/or air conditioning as required from VFD heat loss calculations and average ambient temperatures. All louvers, filter fans, and air conditioning units shall conform to appropriate NEMA and UL standards and must be mounted directly to the VFD control panel. Direct exposure of the VFD unit to un-filtered, outside air is not acceptable. Ventilation or cooling shall be adequate to ensure that the VFD does not operate above its rated ambient temperature rating.

For Outdoor Applications:

Depending on the design of the VFD unit, the described equipment shall be housed in one of two types when installed in outdoor applications.

VFD with external heat sinks

VFD units with external heat sinks that are designed to be flange-mounted on the exterior of a cabinet may be mounted in such a fashion. A dust-tight, flanged-mounted seal shall be maintained, and a NEMA 3R rated rain hood shall protect the external heat sinks. The mounting cabinet shall be a single NEMA 3R or NEMA 4 free standing, power-coated steel enclosure of a wall thickness of not less than 0.075 in. The enclosure shall be sized accordingly to allow easy access to components and provide adequate ventilation for the VFD. The enclosure may also include louvers and filter fans as required from heat loss calculations and average ambient temperatures. All louvers and filter fans shall conform to appropriate NEMA 3R or NEMA 4 or UL Type 3 or UL type 4 standards. Direct exposure of the VFD unit to un-filtered, outside air is not acceptable. Sun shielding of the enclosure shall be provided for on-site.

VFD without external heat sinks

The described equipment shall be housed in a single NEMA 4 free standing, powder-coated steel enclosure of a wall thickness of not less than 0.075 in. The enclosure shall be sized accordingly to allow easy access to components and provide adequate ventilation for the VFD. The enclosure shall include water/air heat exchangers, glycol/water heat exchangers, or air conditioners as required from VFD heat loss calculations and average ambient temperatures. Additional measures such as painting the enclosure white, installing a sun shield, and adding insulation to the inside of the enclosure shall also be considered as to prevent the temperature inside the enclosure from exceeding the acceptable VFD temperature limits. All components used, or modifications made, to the enclosure to aid in cooling must conform to NEMA 4 and applicable UL standards.

Air Conditioning:

Should air conditioning be required to properly cool the VFD control panel, the cooling output of the A/C unit must be controlled to ensure that the following conditions do not occur: overcooling of the VFD panel, freeze-up of the A/C compressor loop or excessive cycling of the A/C compressor. The A/C unit must be sized and rated to accommodate all environmental conditions including high and low temperature extremes, rodents, dust, etc.

2.3 Control Circuit Wiring

Control circuit wiring inside the panel shall be 18 gauge (AWG) minimum, type MTW or THW, rated for 600 volts. All power wiring shall be 12 gauge (AWG) minimum rated for 600 volts. Conductors shall be color-coded using the same colors throughout the entire panel. Control circuit wiring shall be organized in snap-cover raceways. All wires shall be individually numbered or labeled at both ends. All wiring shall be done in a workman-like manner.

2.4 Schematics and Labeling

As per UL and the NEC, all power input and output points of connection shall be clearly labeled. A detailed color schematic showing all control and power circuits shall be affixed to the inside of the panel door. In addition, a label displaying pre-programmed factory settings such as pressure set point shall be affixed to the inside of the panel door.

2.5 Safety

Control panel construction methods shall take into account provisions to ensure operator safety from electrocution. UL508A safety standards shall be observed. In addition, all terminals on power circuits carrying greater than 50V shall be made finger-safe if this provision does not already exist in the original component manufacturer's design. This provision may be accomplished with the addition of appropriate safety shields over exposed terminals.

3. Components

3.1 Variable Frequency Drive

A variable torque Variable Frequency Drive (VFD), of the pulse width modulated type shall be mounted inside the enclosure. The VFD shall monitor the sensor (pressure or flow rate) signal (4-20mA loop powered signal) and control the pump speed using the factory pre-programmed in order to maintain the desired operating condition. The VFD shall also be capable of having an acceleration or deceleration time, adjustable 3 to 1800 seconds with override circuit to prevent nuisance trips if the deceleration time is set too short.

The VFD shall be sized to the pump motor supplied by the Contractor or the existing pump and it shall be compatible with all equipment utilized at the pump station. The VFD's shall meet the following requirements:

<u>Analog input</u>:
The VFD shall come standard with a 4-20mA input channel. The input signal shall be scalable from 0.0 to 999.9 and the displayed unit shall be selectable from: pressure, flow, and/or percent. The controller shall detect invalid sensor readings and open loop circuit and display a fault message. The analog input channel shall have a 0.1% resolution and incorporate noise filtering.

<u>Sizing / Efficiency</u>:

- The VFD shall be sized to the motor Service Factor Amps (SFA) and not the Full Load Amps (FLA) for deep submersible well pumps.
- The efficiency rating shall be of 95% or better across the full operating speed range.
- Each VFD shall account for all motor service factors, have a guaranteed ability to provide continuous output amperage of 15% greater than the maximum amperage required by the motor at a specified input voltage and have an overload current capacity of 120% for 1 minute.

<u>Service Conditions</u>:

<u>The VFD shall be designed to operate within the following service and environmental conditions</u>:

- 100% performance rating in the temperature range 0-40° Celsius. Cooling shall be provided if expected operating temperatures exceed 40° Celsius.
- 0 to 95% relative humidity, non-condensing
- Elevation to _______ feet (_______ meters) without de-rating
- AC line voltage variation, -10% to +10%.

Pump / System protection:

The VFD shall have the following pump and system protection:

- Low Pressure
- High Pressure
- Low Water Input (low suction pressure/low level),
- Broken Pipe
- Loss of Prime
- Dry Well
- Feedback Loss Alarm and Pump over-Cycling.

Motor / Drive protection:

The VFD shall protect the motor and the drive against the following conditions:

- Output Phase Loss
- Ground Fault
- Motor Overload
- Motor over-Temperature and Broken Shaft
- Over Voltage
- Input Phase Imbalance
- Under Voltage
- Phase Imbalance and
- Short Circuit protection.

These faults shall provide an orderly shutdown of the VFD with clear indication of the fault. The history of previous faults shall be stored in memory for future review. For a fault condition other than a ground fault, short circuit or internal fault, an auto restart function shall provide up to 6 programmable restart attempts. The time delay before restart attempts shall be a minimum of 30 seconds. This function permits automatic restarting after the drive controller detects a fault, provided that the other operating functions are correct, a run command is present, and the fault has disappeared. This shall be a function that is field selectable.

Phase conversion:

For installations where 3-phase power is not available, single-phase power shall be supplied to the VFD and the VFD shall convert the power to 3-phase. Extreme care shall be taken to properly size the VFD in phase conversion applications; it shall only be done in accordance with the manufacturer's specifications. In all cases, a 3-phase motor shall be used.

Keypad / operation:

The VFD shall be equipped with an interface keypad with START/STOP buttons and a display for the visualization of process and alarm status. The main screen shall display the set-pressure/flow rate, the actual pressure/flow rate (in psi/gpm), the motor current (in Amps), and the motor speed in (Hz) simultaneously. The keypad shall allow the user to navigate through the configuration menus and adjust set point values via the front keypad. The VFD setup shall be simple and shall not require the use of a laptop computer. The VFD shall be factory configured and tested to minimize field programming and start up time.

The VFD shall be provided with a 12-month standard warranty against defects in workmanship and materials under normal use operation and service from the date of startup.

3.2 Pressure Transmitter

In those systems where pressure is used as the controlling factor, the pressure transmitter shall be industrial grade and have a static accuracy of 1% of full scale or better. The pressure transmitter shall be two-wire loop powered and produce a 4-20mA signal proportional to the discharge pressure and be fully temperature compensated. No calibration of the transducer shall be required in the field. The connection shall be mounted vertically and in such a manner as to minimize the possibility of air accumulation between the transmitter and the discharge pipe.

3.3 Flow Meter

In those systems where flow rate is used as the controlling factor, the flow meter shall be industrial grade and have a static accuracy of 3% of full scale or better. The flow meter shall produce a 4-20mA output signal proportional to the discharge. No calibration of the flow meter shall be required in the field. The flow meter shall be connected to the pump discharge. Flow meter shall have an external power source that provides a consistent power supply.

3.4 Communication

The control panel shall be capable of communicating to a central monitoring system via RS 232 or RS 485 port using MODBUS protocol.

3.5 Circuit Breakers

All electrical circuits shall be protected by molded case circuit breakers. Each pole of the breaker shall provide inverse time delay overload protection and instantaneous short circuit protection by means of a thermal magnetic element.

The breaker shall be operated by a toggle-type or rotary handle and shall have a quick make, quick break switching mechanism that is mechanically trip free from the handle. Tripping due to overload or short circuit shall be clearly indicated by the handle automatically assuming a position midway between the manual “on” and “off” position. Breakers shall be completely enclosed in a molded case and shall bear the UL label. The short circuit interrupt capability shall exceed the fault level (Isc) of the incoming power. The circuit breakers for the VFDs shall be mounted on the sub-panel of the enclosure with the operating handles mounted through the door and capable of being locked in the OFF position. The handles will interlock with the door mechanism, only allowing the door to open when the breakers are in the OFF position.

3.6 Relays

Relay contacts shall be rated for 10 amps at 300VAC. Relay sockets shall have screw terminals with self-lifting clamps and terminal identification numbers located at each connection on the relay socket. A “Motor Running” relay and a “VFD Ready” relay shall be available for user interface.

3.7 VFD Protection Package

The VFD unit shall be protected from line voltage with a line isolation contactor that is interfaced with a digital voltage monitor. The digital voltage monitor shall be capable of detecting phase loss, phase reversal, phase unbalance and over/under voltage. The voltage monitor shall be wired to the line isolation contactor so that when any such conditions are detected the contactor breaks line voltage to the VFD. The line isolation contactor shall be fully rated for across-the-line starting of the motor and shall include appropriately sized overloads for the FLA of the motor.

A lightning/surge arrestor shall be provided at the incoming power terminals to the control panel. The unit shall be of the solid-state type and be able to clamp in five (5) nanoseconds and absorb up to 25KA peak surge current during an occurrence. The unit shall have a surge life expectancy of 10,000 occurrences at 200 amps.

3.8 Line and Load Reactors:

Each VFD shall be equipped with a factory-installed swinging choke capable of reducing total harmonics distortion by up to 25%. For VFD's not equipped with a swinging choke, a 5% impedance line reactor shall be installed ahead of each VFD to reduce the effects of current and voltage harmonics. The VFD shall be sized such that the addition of the 5% line reactor does not reduce drive performance.

The installation shall follow all NEMA cable length guidelines. If NEMA guidelines are exceeded:

1. The motor shall require a load reactor if the pump leads from the VFD exceed the following lengths:

    - 800 ft for 208-240V applications
    - 200 ft for 460V applications
    - 50 ft for 575V applications.

2. The VFD shall require a dV/dt filter if the pump leads from the VFD exceed the following lengths:

    - 1,500 ft for 208-240V applications
    - 500 ft for 460V applications
    - 200 ft for 575V applications.

Individual motor manufacturers may have different standards of protection. All Load Reactors used for motor protection must be designed and implemented via the motor manufacturer's recommendations.

3.9 IEEE-519 Harmonics Mitigation Hardware:

If required by the local power provider, a full IEEE-519 harmonics analysis of the VFD installation must be performed. Utilizing this analysis the VFD panel manufacturer shall determine the harmonics mitigation hardware necessary to fully comply with IEEE-519.

This shall include the use of a line reactor, harmonics kit, phase-shift transformer, or other appropriate hardware approved for this application. Upon request, the VFD panel manufacturer shall make available their IEEE-519 analysis worksheet.

The appropriate harmonics mitigation hardware shall be fully integrated into the VFD control panel package such that it is deliverable to the job site in a single package and shall not require any additional on-site wiring. Additional heat loads and amp losses resulting from harmonics mitigation hardware shall be determined and appropriate steps shall be taken to ensure that the VFD control panel design accommodates these issues.

4. Quality Assurance

4.1 Manufacturer Experience

4.1.1. UL Certification

The manufacturer of the control system shall be certified by Underwriters Laboratories (UL) as being a UL 508A listed manufacturing facility and certified to install a serialized label for quality control and insurance liability considerations.

4.1.2 Experience

The manufacturer of the control system must be able to document experience in successfully designing and manufacturing similar control systems using Variable Frequency Drives in pumping applications.

4.2 Manufacturer Quality Control

The control system shall be functionally tested by the manufacturer and/or supplier and certified as a complete system to assure proper operation per specification.

4.3 Approval

All controls must have the capabilities and functions as outlined in the specifications.