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Variable Speed Drive (VSD) for Irrigation Pumping

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Cover photo: Example of pump station

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Introduction

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 more than $15.5 billion. 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 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 power unit and, therefore, less energy needs to be dissipated or bypassed.

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:

Figure 1 Bypass control energy use

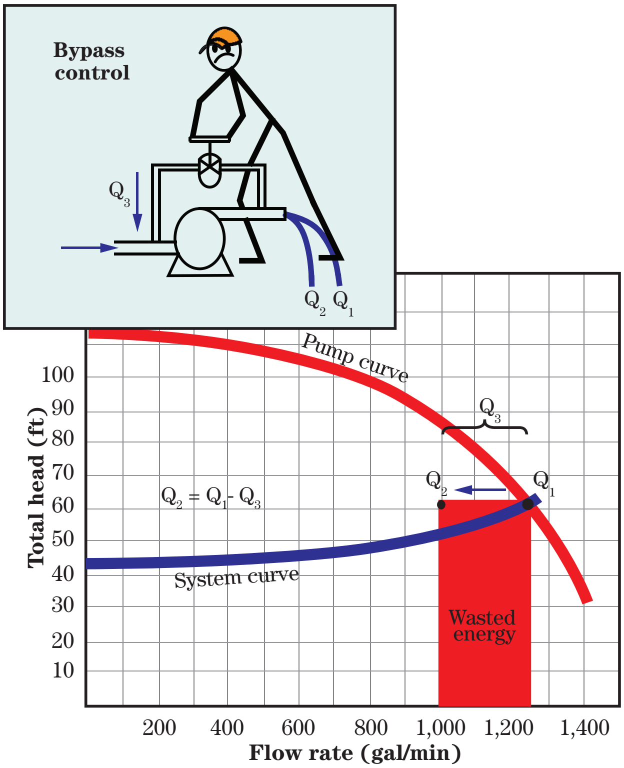
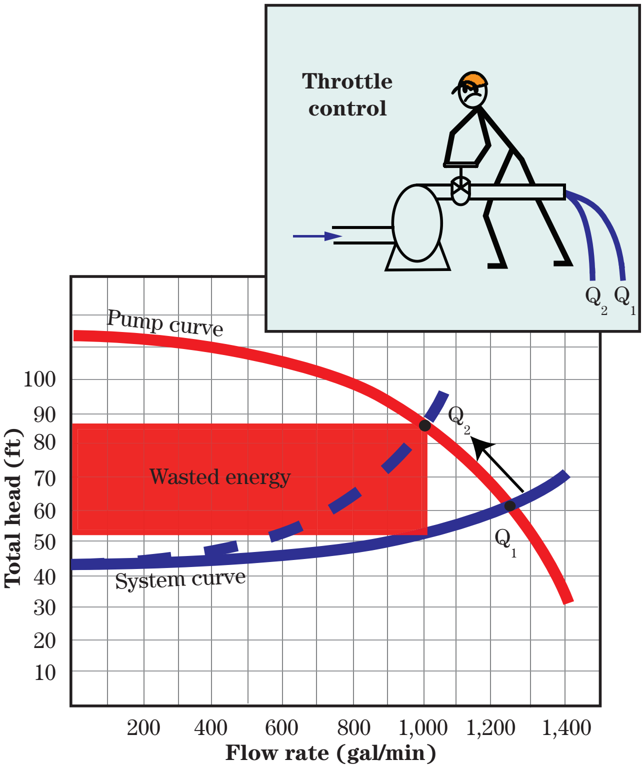
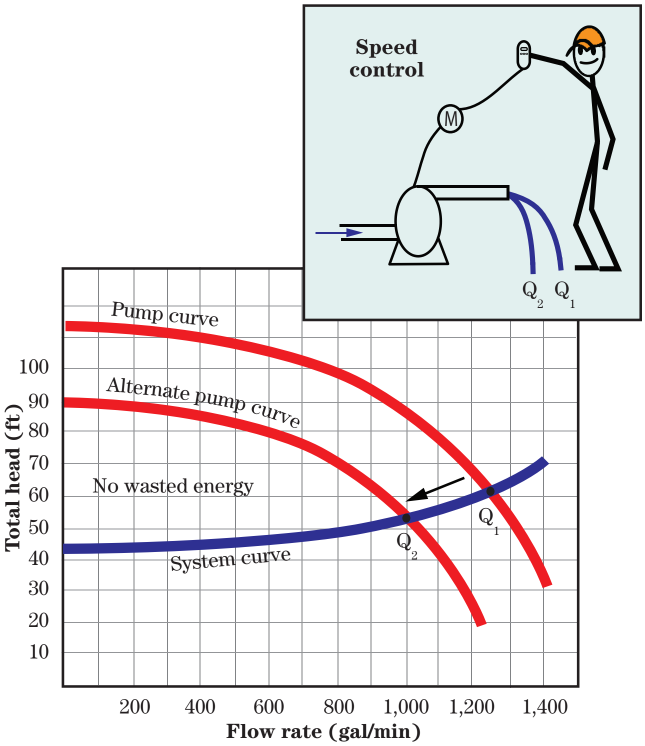


Figure 2 Throttle control energy use



- mechanical (driveline 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)

Figure 3 Speed control energy use



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 energy is transferred to the water by means of a rotating impeller. Pumps add energy to the water by:

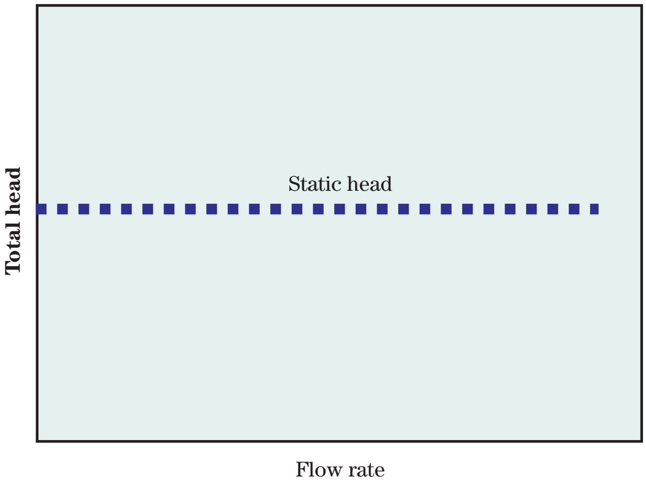
- raising the height (elevation) of the water
- increasing the pressure of the water as it exits the pumps; this pressure is used to move the water through the irrigation system and overcome losses

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 as the sum of static head, friction head, pressure head, and velocity head. In pumping systems, total energy is often referred to as total dynamic head.

Static head is the difference in elevation of the supply and delivery point of the liquid being moved. Static head is independent of flow rate (fig. 4).

Figure 4 Static 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.

Pressure head is the head necessary to operate a piece of equipment (e.g., sprinkler). This can vary during the operation of the pump (e.g., normal operation pressure may be low, but a higher pressure may be required to flush the system or clean a filter).

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

To select a proper pump, the system operating characteristics must be known. A system curve relating flow rate to total head should be developed. In general, the system curve will consist of the sum of the static, friction, and pressure heads as shown in figure 6.

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 (fig. 8).

Figure 5 Friction head loss

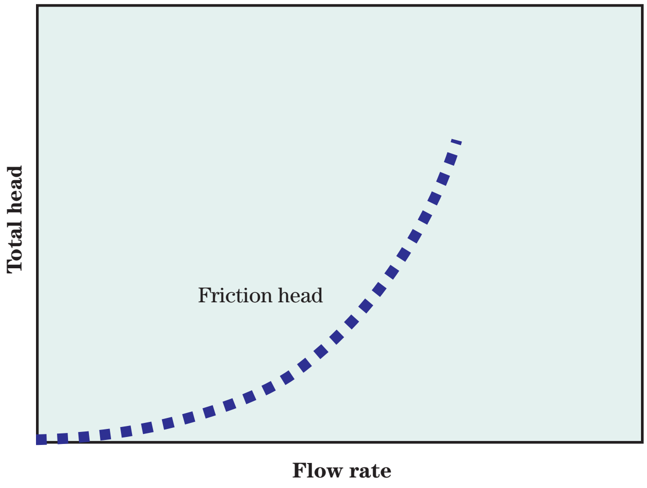


Figure 6 System curve

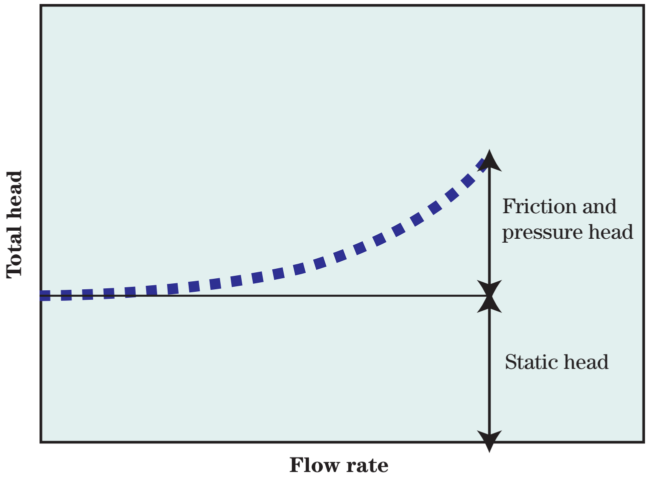


Figure 7 Pump curve

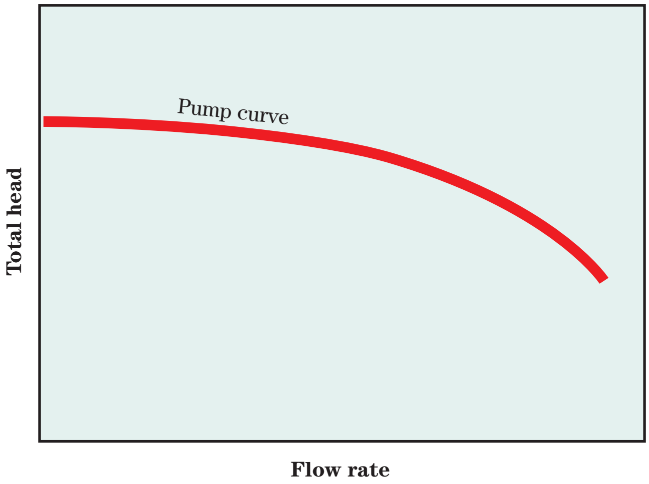
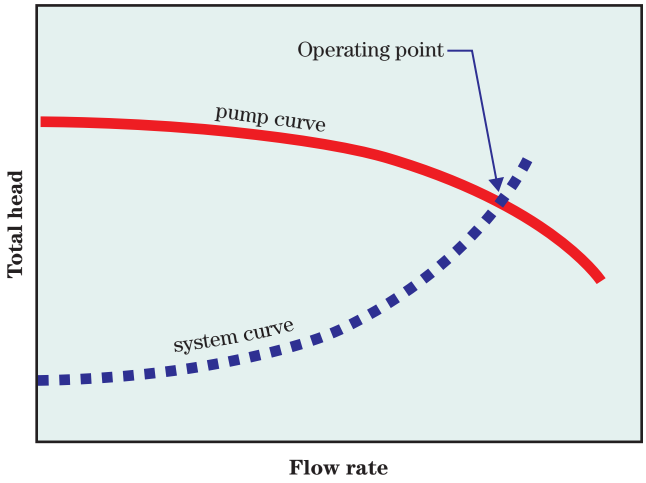


Figure 8 Pump and system curve intersection



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:

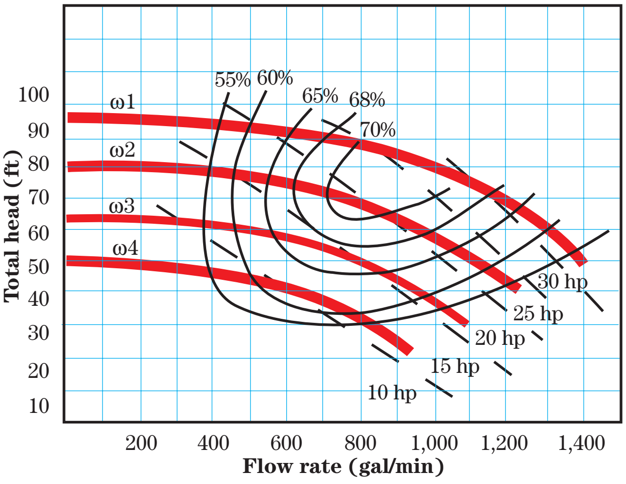
Q = flow rate
H = head or pressure
BHP = brake horsepower (hp)
ω = rotational shaft speed (rpm)

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

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 at near-constant pump efficiency over a range of speeds. The reduction in flow varies proportionally to speed, and the Affinity Laws accurately predict flow rate and head changes as well as power savings (fig. 10).

Figure 9 Pump curve changes with shaft speed



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 curves. Energy savings in this case are not as great and are more problematic to calculate because of difficulties in determining the change in pump efficiencies (fig. 11).

Figure 10 System curve parallel with efficiency curves

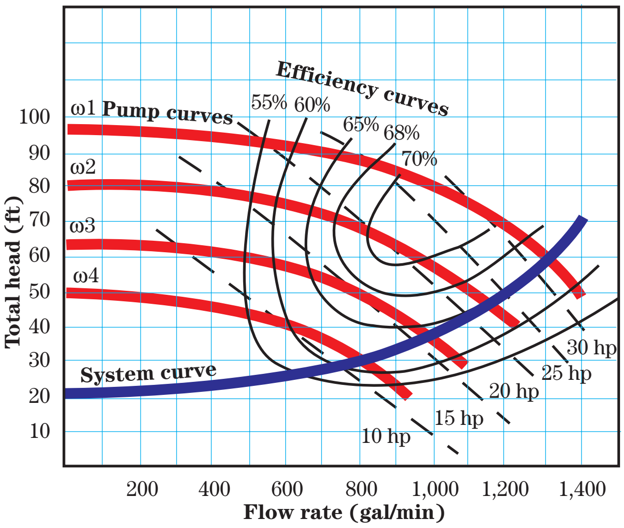
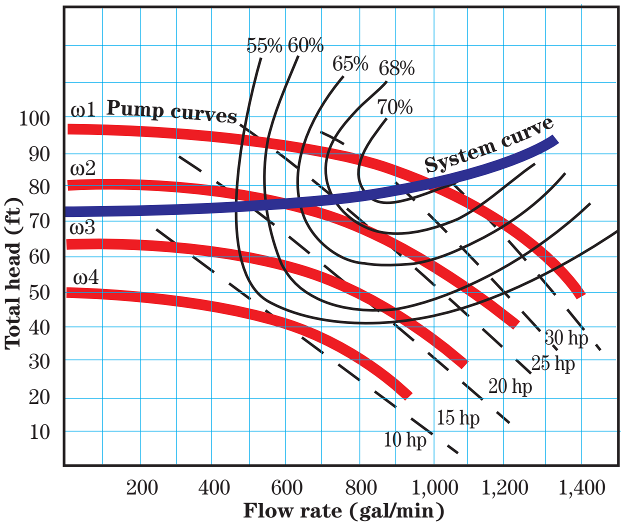


Figure 11 System curve crosses efficiency curves



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 (figs. 12 and 13).

The typical pumps used in agriculture are the vertical turbine, submersible, and end suction centrifugals (fig. 14). The vertical and submersible turbines (well pumps) have steeper curves than end suction centrifugals. For constant pressure and variable flow situations, the vertical and submersible turbines usually have a much higher energy savings potential. End suction centrifugals usually have flatter curves with less energy savings potentials.

Variable speed electric motors

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

The speed of an alternating current (AC) motor depends on three principal 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 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.

Figure 12 Potential savings flat pump curve

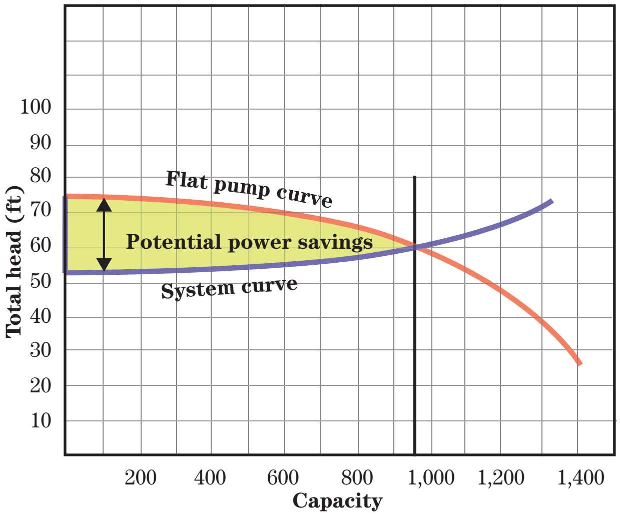


Figure 13 Potential savings steep pump curve

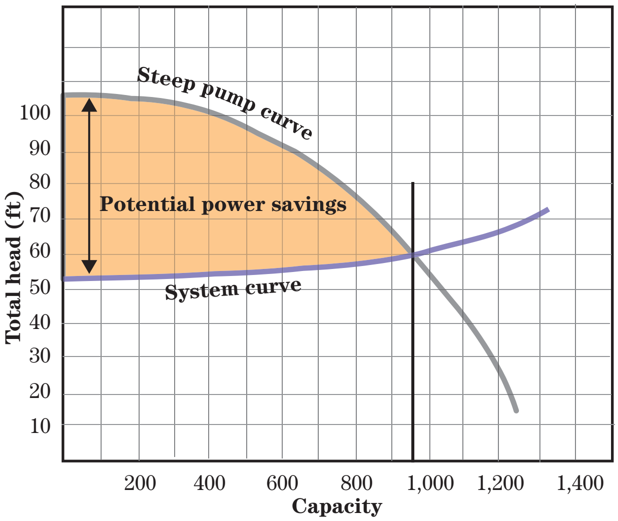
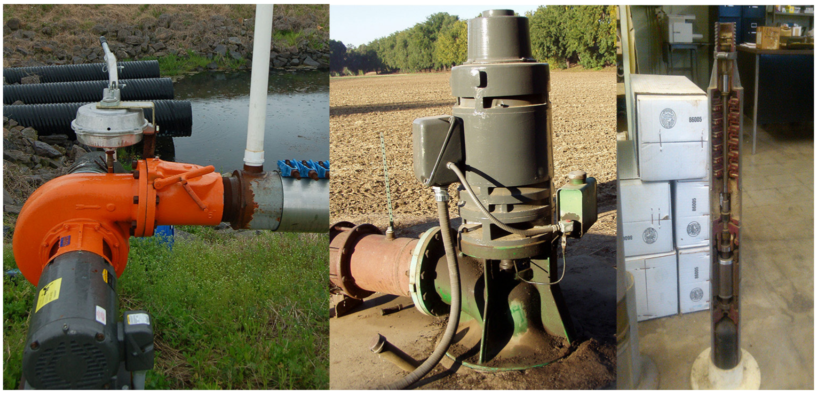


Figure 14 Centrifugal, vertical turbine, and submersible turbine pumps



The following equation is used for calculating motor speed.

$$\text{Synchronous speed} = \frac{120 \times \text{frequency}}{\text{number of poles}}$$

Normal electric power in the United States is supplied at 60 cycles per second, or 60 hertz (Hz). Common rpm at this frequency are 3,600, 1,800, 1,200, or 900, 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 Hz makes the motor run faster, but it generates several concerns:

- 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.
- VFDs control both frequency and the peak voltage simultaneously to keep a constant effective voltage so that the motor sees a constant current flow similar to full speed conditions. VFDs are not capable of producing voltage above the original input 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.

VFDs

Since changing the frequency of the power supply is one way of controlling the pump speed, VFDs are a subset of VSDs.

VFDs 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. 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 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 15 illustrates a wave form generated by a PWM inverter.

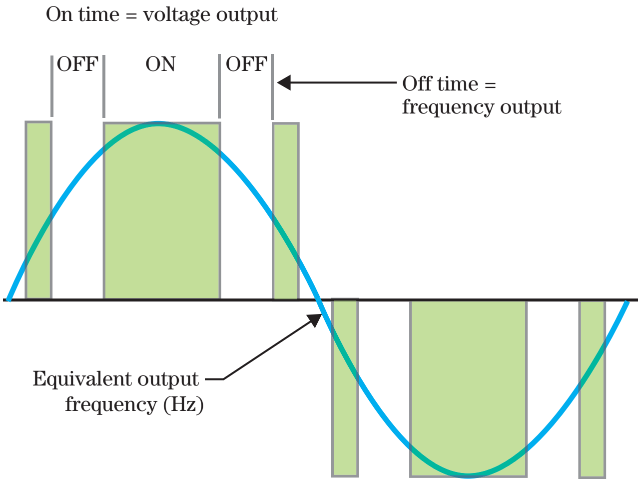
Variable speed applications

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—Applications 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 sin-

Figure 15 Pulse width modulation generated wave form



gle 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 that, in turn, would change the pump speed in order to maintain a constant pressure. Figure 16 demonstrates the interaction of a variable-speed pump and an operation curve for constant pressure. In general, for these situations flatter head/flow pump curves are desirable.

Constant-flow applications—Applications that 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. In general, steeper head/flow pump curves are desirable for this situation. The pump is sized for the maximum drawdown and is oversized 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 slope. The uphill (upslope) position would be the most critical design point, where the end pressure is the lowest and the pump pressure the highest. (The system flow rate would be lowest because the pump pressure is its highest.) As the pivot moves downhill, pressures along the pivot lateral increase and pressure on the pump decreases, 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. Figure 17 illustrates how a typical pump curve might look in this situation.

Variable flow—variable pressure applications—Applications 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 18 displays pump and operation curves representing this condition.

Figure 17 Constant flow – variable pressure application

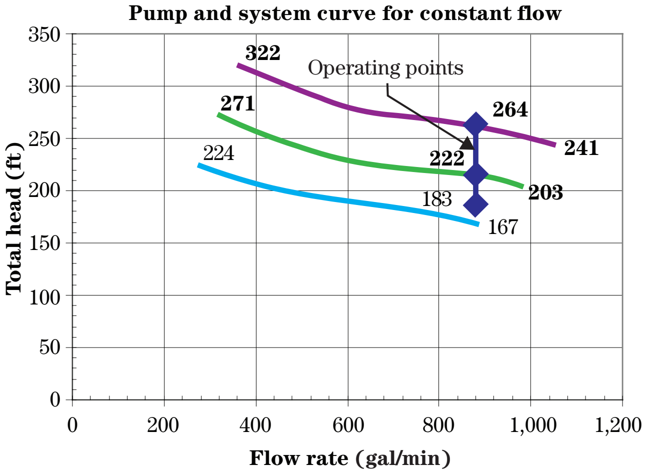


Figure 16 Constant pressure—variable flow application

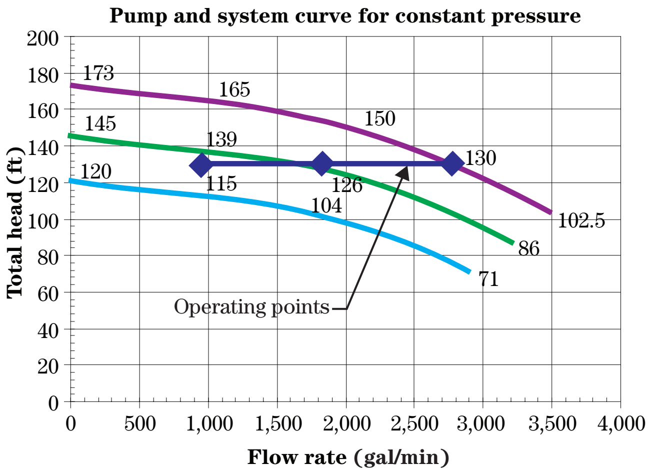
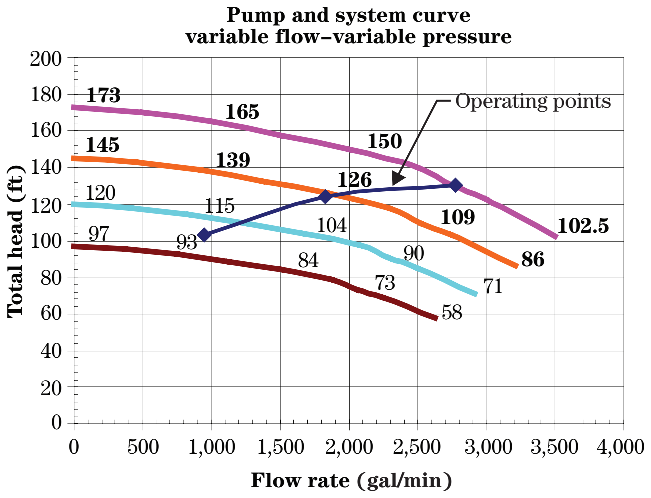


Figure 18 Variable flow – variable pressure application



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 United States 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 19 displays the efficiency load relationship for various sizes of motors.

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

Table 1 National Energy Policy Act efficiency values

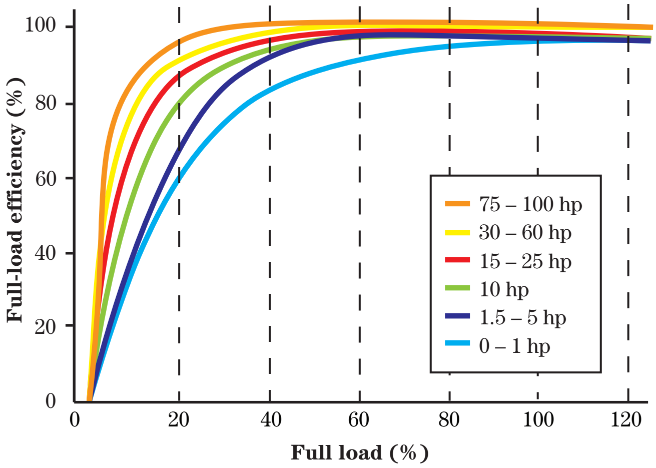
Full Load Nominal Efficiencies			
Motor horsepower	**Number of poles/motor rpm**		
	6/1,200	**4/1,800**	**2/3,600**
1	80.0	82.5	—
1.5	84.0	84.0	82.5
2	85.5	84.0	84.0
3	86.5	86.5	84.0
5	87.5	87.5	85.5
7.5	88.5	88.5	87.5
10	90.2	89.5	88.5
15	90.2	91.0	89.5
20	91.0	91.0	90.2
25	91.7	91.7	91.0
30	92.4	92.4	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

To obtain the results shown in figure 15, a VFD converts AC to DC then pulses DC to emulate an AC wave form. This process is not 100-percent efficient. Heat is generated, and this is an energy loss. A suggested efficiency range for VFDs is 95 to 98 percent. The pulsed nature of the current may also cause harmonic losses in the motor for another drop of about 1-percent efficiency. For design purposes, an appropriate estimate of efficiency for VFDs is 97 percent.

Many times VFDs 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 1 second. Also, using soft start/stop greatly reduces the chances of water hammer in almost any pumping system.

Figure 19 Induction motor efficiency as a function of load (*Energy Innovators Initiative 2003*)



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—Sometimes when three-phase power is needed, utilities will install two transformers, instead of the usual three. This type of installation is known as an open-delta connection and is used because of the lower cost of installation in remote areas where the need for three-phase power is less. With this type of installation, there is a high probability for phase and voltage imbalance. This will cause a three-phase motor to see a current imbalance, which may significantly lessen its lifespan. But with a VFD, the motor's input voltage will be balanced, because the VFD converts the incoming AC to DC and then generates its own three-phase output.

Improved process control—VFDs are generally solid-state electronic devices that can accept control signal inputs for start, stop, and speed control, then provide output signals to distributed control systems (DCS), programmable logic controller (PLC) systems, or provide information to other computers. This ability lends itself to automated process control networks. PLCs are more or less tiny computers with a built-in operating system (OS). A PLC is primarily used to control machinery. A program is written for the PLC that turns on and off outputs based on input conditions and an internal program. A PLC is designed to be programmed once and run repeatedly.

Disadvantages and potential problems

Motor bearing damage—VFDs 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 startup. This type of damage is typically associated with high-voltage and 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, have inverter output filtering, or some combination of these.

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 required by the local power provider to isolate supply line disturbance created by the VFD. The filters will protect other sensitive electrical inline equipment, such as computers, and increase inverter reliability and protection. The current standard for harmonics is from the Institute of Electrical and Electronics Engineers Standard, IEEE Std. 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 insulation 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 460V 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.

The drives most vulnerable to vibrations tend to be frame-mounted pumps, multistage pumps, and those with elongated shafts. The speed ranges that have been shown to cause vibrate can be bypassed by programming the drives. The pump will not remain long enough at these speeds as it changes up or down to cause vibration damage. More information about critical speed can be obtained from the manufacturer.

Variable-frequency electronics are subject to environmental factors that can contribute to equipment malfunction. These factors may not be a concern for constant-speed units. 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, the 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, which is the sudden formation and collapse of low-pressure bubbles in liquids by means of mechanical forces, 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—It is not uncommon for a motor to deliver 15 percent or more horsepower than its nameplate rating. This relates to the service factor of the motor. In the design process, the size of the VFD needs to account for all inherent drive inefficiencies as well as the motor load including service factor. Drive size may also be increased 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. When using the VFD to convert single-phase to three-phase power, many times the VFD will need to be double the size of the motor.

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 VFDs. 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 Std. 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. VFDs also generate significant heat that must be dissipated. Cool, clean electrical components last longer and perform better. VFDs 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° and 104° Farenheit. Several types of cooling methods exist.

External heat sinks

In many cases (but not always), VFDs with external heat sinks can be effectively used outdoors without additional cooling. External heat sinks require regular cleaning to remove dust buildup. Clogged filters reduce cooling system effectiveness, so maintenance should include regularly changing filters and cleaning and servicing fans. Higher elevations may require derating of the drive due to less dense cooling air flowing over the heat sinks. (Derating 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 filtered outside air is not an acceptable method of cooling a large VFD in an outdoor application. Larger VFDs 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, overcooling, 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

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

Minimum continuous stable flow (MCSF) for pumps/VFDs—Many people think that if a VFDis placed on a pump, it will provide constant pressure and an unlimited flow range along the pump curve. Most VFD failures result from the VFD slowing down the pump motor with the pump operating to the left of the MCSF near the shutoff head. The pump will vibrate and shake, or the shutoff head will be reached, and a pump saver device will shut down the system. As a rule of thumb, the motor/pump should not operated at less than half the original frequency; so, for a 60 Hz motor, this would be around 30 Hz

Other factors—Other factors that may affect VFD efficiency are:

- radio frequency or stray high frequency signals
- line voltage variation greater than ±10 percent
- line frequency variation greater than ±2Hz
- altitude greater than 3,300 feet (1,000 meters)

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

Case studies

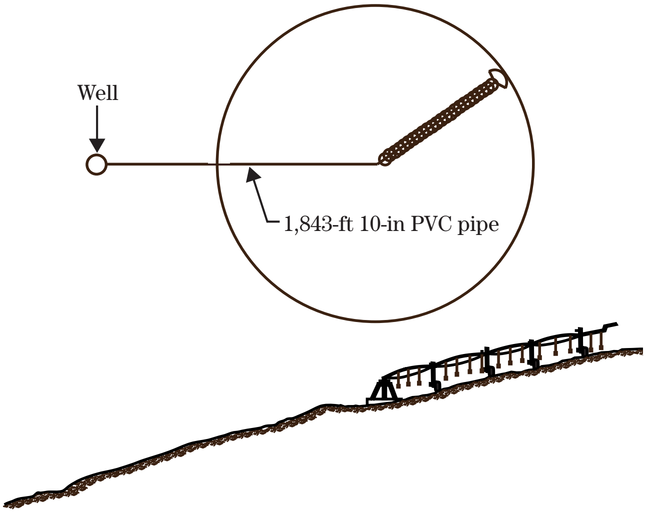
Example: Case 1—Center-pivot sprinkler on a steeply sloped field

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 gallons per minute. The sprinkler irrigates 140 acres of corn with an estimated annual net water requirement of 28 inches (fig. 20).

The pumping lift is 100 feet from the water level in the well to the pivot point, and the pivot is irrigating a field that has a fairly uniform slope of 4 percent. Pump selection is based on delivering the design flow with the pivot oriented uphill on a 4-percent slope.

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 pounds per square inch (operating pressure+ friction loss+ nozzle height).

Figure 20 Case 1—farm layout



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:

- Pivot operating uphill
- Pivot operating on the level
- Pivot operating downhill

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

The head requirements for the three selected conditions are summarized in table 2.

The pivot applies (877 gal/min × 60 min/h ÷ 7.481 gal/ft^3 ÷ 43,560 ft^2/acre × 12 in/ft) = 1.94 acre-in/h).

The pivot applies 877 gallons per minute or 1.94 inches per hour on 140 acres gross. At a reasonable application efficiency of 85 percent, the net application is 1.65 inches per hour.

The estimated seasonal operation time is 2,376 hours (28 in with sprinkler on 140 acres: 140 acres × 28 in = 3,920 acre-in. 3,920 acre-in ÷1.65 acre-in/h= 2,376 h)

At the design condition with the highest TDH, a pump would need to provide 877 gallons per minute and a TDH of 263 feet.

Select a Gould 10DHHC with eight stages operating at 1,770 rpm.

Points from the manufacture's pump curve for an impeller diameter of 6.062 inches are shown in table 3.

Table 3 Points from manufacturer's pump curve

Q (gal/min)	Head (ft)	Efficiency (%)
352	322	42
528	290	58
704	270	70
880	264	80
1,056	241	82
1,325	168	70

Without VFD

Water horsepower is equal to:

$$\text{WHP} = \frac{Q \times H}{3{,}960} - \frac{877 \times 262}{3{,}960} = 58.02\,\text{hp}$$

With a pump efficiency of 79 percent the brake horsepower is equal to:

$$\text{BHP} = \frac{Q \times H}{3{,}960 \times \text{Eff}_p} - \frac{877 \times 262}{3{,}960 \times .79} = 73.45\,\text{hp}$$

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

$$\text{Power input} = \frac{73.4\,\text{hp}}{.94\,\text{Eff}_m} \times \frac{.746\,\text{KW}}{\text{hp}} = 58.29\,\text{KW}$$

Table 2 TDH requirements

	TDH uphill condition (lb/in^2)	TDH level condition (lb/in^2)	TDH downhill condition (lb/in^2)
Pivot point pressure	40	40	25 1/
Elevation gain	+22.9	0	0
Friction loss in mainline	3.16	3.16	3.16
Miscellaneous losses	3	3	3
Pump losses	1.5	1.5	1.5
Pump column lift	43.3	43.3	43.3
TDH	**113.7 lb/in^2 = 262.6 ft**	**90.8 lb/in^2 = 209.8 ft**	**76.0 lb/in^2 = 175.5 ft**

1/ When the pivot is in the downhill condition, the minimum pressure of 20 pounds per square inch plus 5 pounds per square inch needs to be supplied for the pressure regulators. The slope, which is steeper than the friction slope, will provide the rest of the necessary pressure.

Estimated annual operating cost is:

$$\text{Cost} = 58.29\,\text{KW} \times 2{,}376\ \text{h} \times \frac{\$0.07}{\text{KW}-\text{h}} = \$9{,}695\ \text{per season}$$

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 $9,695 per season.

With VFD

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

Use the affinity laws to plot new pump curves. Merely plugging a new value

$$\frac{H_2}{H_1} = \left(\frac{RPM_2}{RPM_1}\right)^2 \qquad \frac{Q_2}{Q_1} = \frac{RPM_2}{RPM_1}$$

for rpm into the affinity law formula will not work because the new pump curve must pass through the two points, the new head and new Q; the affinity law will give a curve that passes through one point. The solution is iterative, and it can take a little bit of time to find the right combination. To demonstrate the process, use the new head of 209.8 feet (the "pivot operating on the level" condition) to calculate the new rpm of 1,582. Use the ratio of 0.8937 (1,582/1,770) calculate the new Q for each point on the original curve. Then find the new head for each point on the original curve by multiplying the head by the square of 0.8937. Plot the new curve: this is the lower limit (fig. 21).

The solution lies somewhere between the two curves. Select a new rpm somewhere in between the original and the lower limit. Determine the new Q and H values then plot the curve. Make adjustments until the correct rpm and operating point is found. It will take several iterations. A spreadsheet can help streamline the process.

The adjusted data points and speeds for this example are shown table 4.

Plot the new pump curves (fig. 22). 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

Table 4 Alternate pump curves Case 1

Rpm					
1770		**1610**		**1496**	
Q	**H**	**Q**	**H**	**Q**	**H**
352	322	320	266	298	230
528	290	480	240	446	207
704	270	640	223	595	193
881	264	800	218	744	189
1,057	241	960	199	893	172
1,326	168	1,205	139	1,120	120

Figure 21 Example of original curve and lower limit

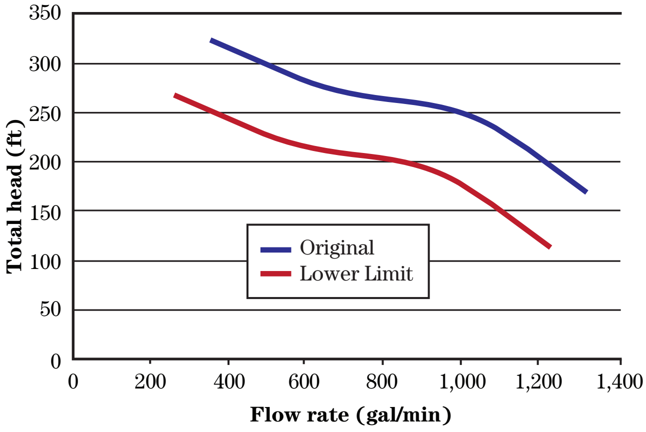
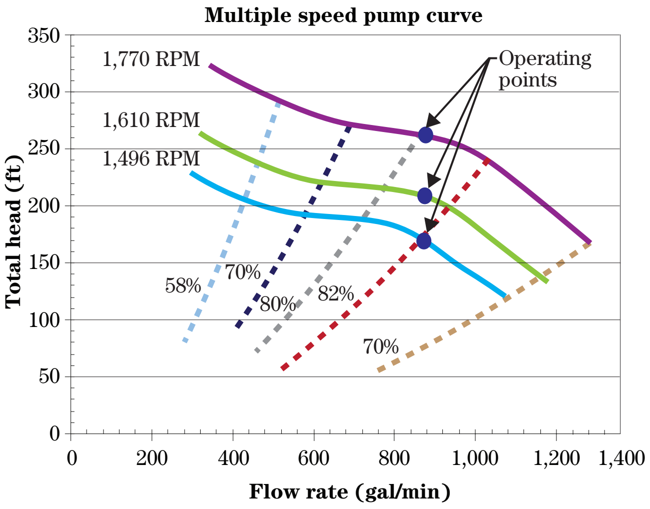


Figure 22 Adjusted pump curve case 1



curves move down and to the left similar to the pump curves. In other words, the efficiency for a give flow on the 60Hz curve follows the new flow rate for the lower speed. For example, the efficiency and Q at 1,770 rpm were 80 percent and 790 gallons per minute, respectively. At the new rpm of 1,500, the Q would be 669 gallons per minute, and the efficiency would be 80 percent. In most instances, the operating points will not fall on the plotted curves, and the new efficiency will need to be approximated.

The new efficiencies at the various TDH values are

TDH = 263 feet, efficiency = 79 percent

TDH = 210 feet, efficiency = 81 percent

TDH = 175 feet, efficiency = 82 percent

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

$$\text{Power input} = \frac{Q \times H}{3{,}960 \times \text{eff}_p \times \text{eff}_m \times \text{eff}_{vfd}}$$

The power requirements for the various operating points are 80.55 hp, 62.97 hp, and 51.83 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 percent. Using the following equation, the seasonal cost is estimated as \$2,499 + \$3,907 + \$1,608 = \$8,014.

$$\text{hp} \times \frac{0.746\,\text{KW}}{\text{hp}} \times \text{h} \times \%\text{ of time} \times \frac{\text{cost}}{\text{KW} - \text{h}}$$

This results in a savings of (\$9,695–8,014) \$1,681 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, a Flowserve 10EGH operating at 1,770 rpm. The sprinkler irrigation system is a LESA pivot system and is on relatively level ground with the pivot point located 5 feet higher than the well. It is nozzled for 750 gallons per minute at 36 pounds per square inch (ground level at pivot). Pressure regulators set at 15 pounds per square inch 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 (fig. 23).

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.

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

The pivot applies 1.66 acre-in/h (750 gal/min × 60 min/h/ 7.481 gal/ft^3 / 43,560 ft^2/acre × 12 in/ft = 1.66 acre-in/h).

The estimated seasonal hours of operation are 1,764 hours (24 in with sprinkler on 122 acre: 122 acre × 24 in = 2,928 acre-in/1.66 acre-in/h = 1,764 h).

Without VFD

The maximum required TDH is 296 feet, 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 horse power is

$$\text{Water HP} = \frac{750\text{ gal/min} \times 296\text{ ft (TDH)}}{3{,}960} = 56.06\,\text{hp}$$

Select a Flowserve 10 EGH with 8-inch column pipe. Operating point 750 gallons per minute at 37 feet head/stage, rpm =>1,770 rpm. Number of stages needed - 296 ft/37 ft head/stage = 8 stages with the 7.72-inch impellor curve.

Figure 23 Case 2 farm layout

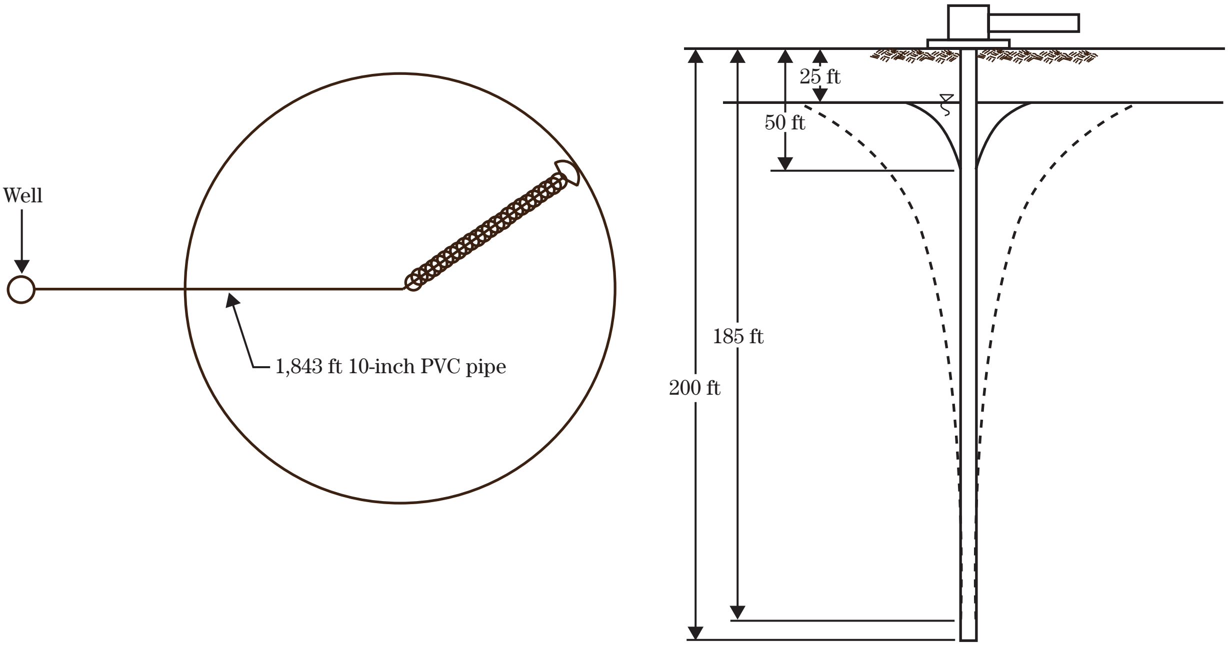


Table 5 TDH results

	Season start TDH	End of season TDH
Static lift (ft)	25	25
Drawdown (ft)	25	160
Pivot pressure (ft)	83.2	83.2
Column losses (ft)	4.8	4.8
Elevation from well to pivot (ft)	5.0	5.0
Mainline friction losses (ft)	17.7	17.7
Total (ft)	160.7 use 161	295.7 use 296

Impeller efficiency from pump curve = 80.5 percent

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

Select a motor efficiency from a source similar to table 1, in this case 94.1 percent is selected. The power input for the motor would be

$$\text{Power input } \frac{69.96 \text{ HP}}{.94 \, \text{Eff}_m} \times \frac{.746 \text{ kW}}{\text{HP}} = 55.17 \text{ kW}$$

Estimated annual operating cost is

$$\text{Cost} = 55.17 \text{ kW} \times 1{,}764 \text{ h} \times \frac{\$0.07}{\text{kW} - \text{h}} = \$6{,}812 \text{ per season}$$

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

With VFD

Use the affinity laws to plot a series of new pump curves. Merely plugging a new value

$$\frac{H_2}{H_1} = \left(\frac{\text{RPM}_2}{\text{RPM}_1}\right)^2 \qquad \frac{Q_2}{Q_1} = \frac{\text{RPM}_2}{\text{RPM}_1}$$

for rpm into the affinity law formula will not work because the new pump curve must pass through the two points, the new head and new Q; the affinity law will give a curve that passes through one point. The solution is iterative, and can take a little bit of time to find the right combination. A spreadsheet can help streamline the process. The results for the new curve are summarized in table 6.

Plot the new pump curves (fig. 24). 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.

The efficiencies at the various TDHs 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 VFDs is approximately 97 percent. Horsepower and energy input for the two conditions are 76.4 and 44.6 horsepower.

The actual energy cost is based upon the percent of the total hours that the system is operated at a particular operating condition. In this case, we could assume the operating condition transitions linearly from operating point 1 at season startup to point 2 at shutdown, the seasonal pumping cost could be estimated by averaging the horsepower use of operating points 1 and 2 over the entire pumping season:

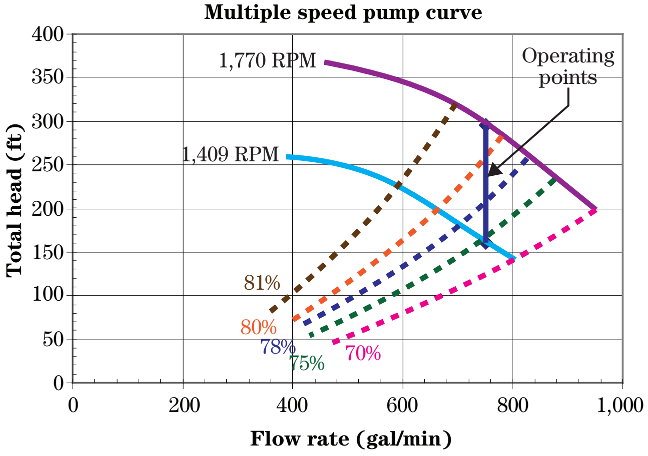
$$(76.4 \, \text{hp} + 44.6 \, \text{hp}) \times 0.50 \times \frac{746 \, \text{KW}}{\text{hp}} \times 1{,}7\,64 \text{h} \times \frac{\$0.07}{\text{kW} - \text{h}}$$
$$= \$5{,}573 \text{ per season}$$

This results in a savings of ($6,812–5,573) = $1,239 per season.

Table 6 Alternate pump curve case 2

Rpm			
1,770 (original)		**1,409 (alternate)**	
Q	**H**	**Q**	**H**
460	368	387	261
582	350	490	248
621	340	523	241
700	320	589	227
781	280	658	198
830	256	699	181
880	232	741	164
945	200	796	142

Figure 24 Case 2 alternate speed pump curve



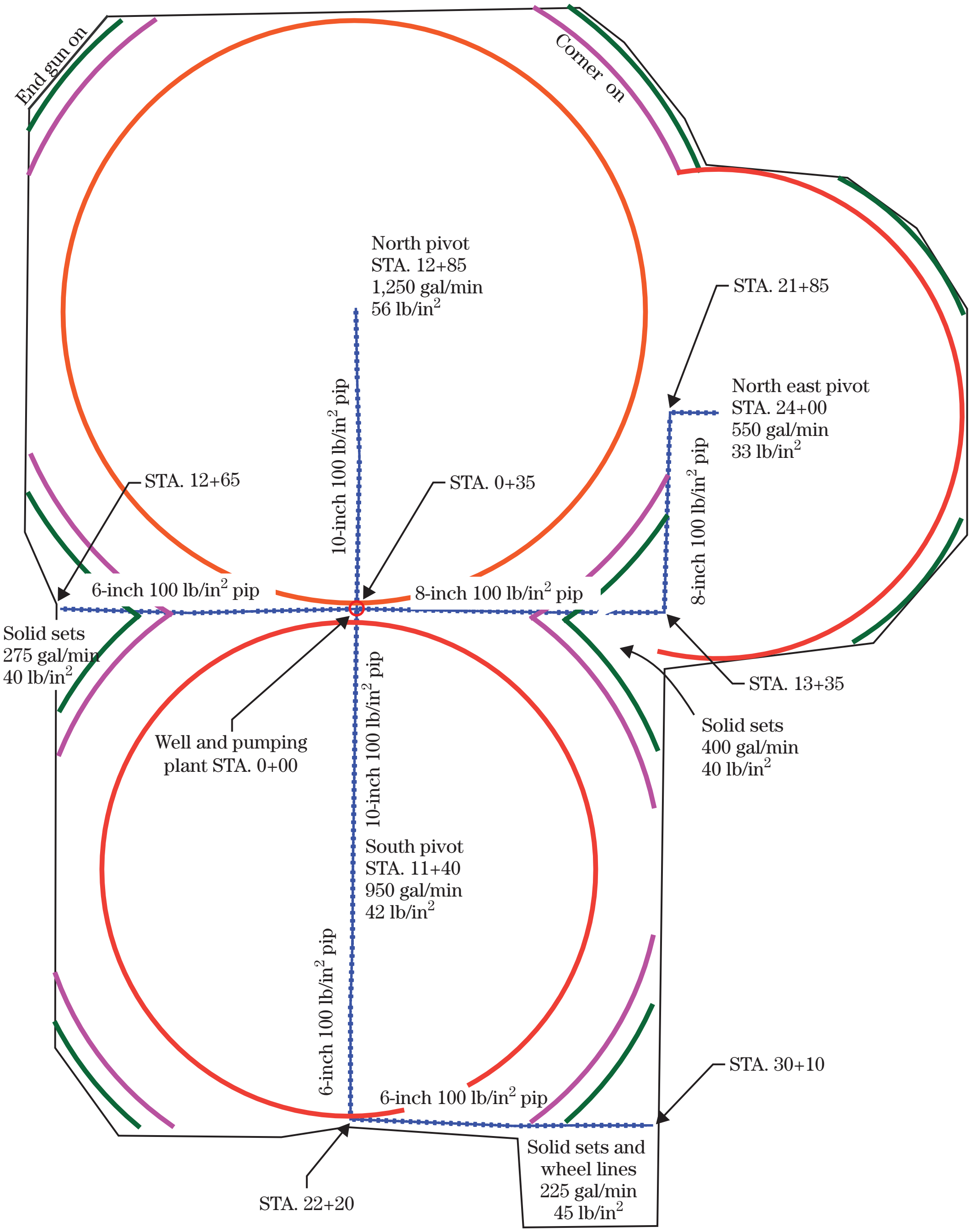
The annual or seasonal savings is compared to the cost of the VFD to calculate the payback period. Here again it is difficult to justify installing a VFD on power savings alone.

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 (fig. 23). Two of the pivots have corner systems. All of the pivots have end guns. The pipe sizes and pressure requirement are

Figure 25 Case 3 system plan map



shown on figure 25. 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-hour and the average pumping season is 1,700 hours. The pump is an older vertical turbine operating at 1,770 rpm, with three stages, each 10.3 inches in diameter. The operator would like to install a VFD to facilitate management and save energy.

Some of the possible operating scenarios are as follows:

(1) all three pivots; both corner arms fully extended with all three end guns operating

(2) all three pivots; corner arms mostly extended with one or two end guns operating

(3) all three pivots; various combinations of corner positions with end guns status

(4) all three pivots; both corner arms fully retracted with all three 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 percent, 25 percent, 50 percent, 15 percent, and 5 percent, respectively.

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

Without VFD

Table 7 Existing pump curve for case 3

Pump curve for existing Johnson pump 14ECII		
Q (gal/min)	Pump TDH (ft)	Pump efficiency (%)
560	286	29
700	278	35
1,000	270	49
1,200	264	56
1,400	252	63
1,770	228	73
2,100	219	79
2,350	216	82.5
2,750	190	81.3

Table 8 Head and flow summary without VFD

System operation table, no VFD						
Scenario	Q (gal/min)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term operation (%)	Power costs ($0.10/kW-h)
1	2,750	192	81.5	172	5	1,091
2	2,350	213	81.8	162	25	5,136
4	1,770	232	73.3	149	50	9,448
6	1,200	261	56.1	148	15	2,815
9	560	283	28.9	146	5	926

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 okay (fig. 18), and from table 1, the motor efficiency is 95 percent. The excess head is dissipated through pressure regulators and valves. The estimated seasonal operating cost is $19,416.

With VFD

There are two control scenarios for VFDs: select a constant pressure and just vary the flow rate, or 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 and plot the new pump curves for each control point using the Affinity Laws. Merely plugging a new value for rpm into the Affinity Law formula will not work because the new pump curve must pass through the two points, H and Q; the Affinity Law will give you a curve that passes through one point. The solution is iterative. Once the new curves are plotted, plot the operating points (fig. 26). 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 percent and a VFD efficiency of 97 percent. The inputs are summarized in table 9. The "Input HP" column includes both the motor and VFD efficiencies.

Figure 26 Case 3 alternate speed pump curves

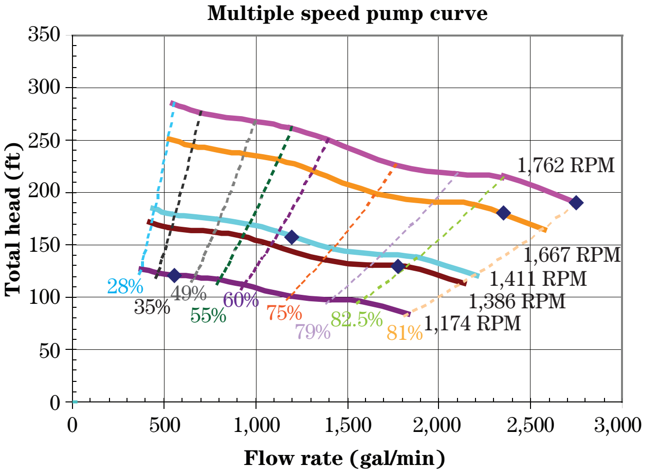


Table 9 Head and flow summary with VFD

System operation table, with VFD

Scenario	Q (gal/min)	Pump TDH (ft)	Efficiency (%)	Input HP (hp)	Long-term operation (%)	Power costs ($0.10/kW-h)
1	2,750	190	81.4	176	5	1,116
2	2,350	180	82	141	25	4,470
4	1,770	133	81	80	50	5,072
6	1,200	157	66	78	15	1,484
9	560	121	42	44	5	279

The total estimated annual power cost with the VFD is $12,421, with a resulting estimated savings of $6,995 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.

Example: Case 4—VSD stock water example

Given:
The rancher runs a cow-calf operation with 600 head and grazes the cows from May to October (~153 days). He uses only one tank at a time and rotates from pasture to pasture every 45 days. Average water requirement is 20 gallons per day per head. The profile is shown in figure 27.

Well elevation 2,400
Static water elevation 2,315
Depth of well 212 feet
Pump set at elevation 2,200
All pipes are 2-inch diameter HDPE, 200 pounds per square inch
Design flow rate 20 gallons per minute

The tanks are supplied by a Red Jacket Big-Flo 28GPM Series “dc” pump, 3,560 rpm.

1st tank, Sta. 45+00, elevation 2,550
2nd tank, Sta 52+50, elevation 2,575
3rd tank, Sta 59+15, elevation 2,610
4th tank, Sta. 67+00, elevation 2,630

Cost for kWh based on BPH hours per fuel unit (National Irrigation Guide):

Electric $0.08
Diesel $0.21
Gas $0.33

Solution:

$$600\ \text{head} \times \frac{\frac{20\ \text{gal}}{\text{d}}}{\text{head}} \times 153\ \text{d}$$

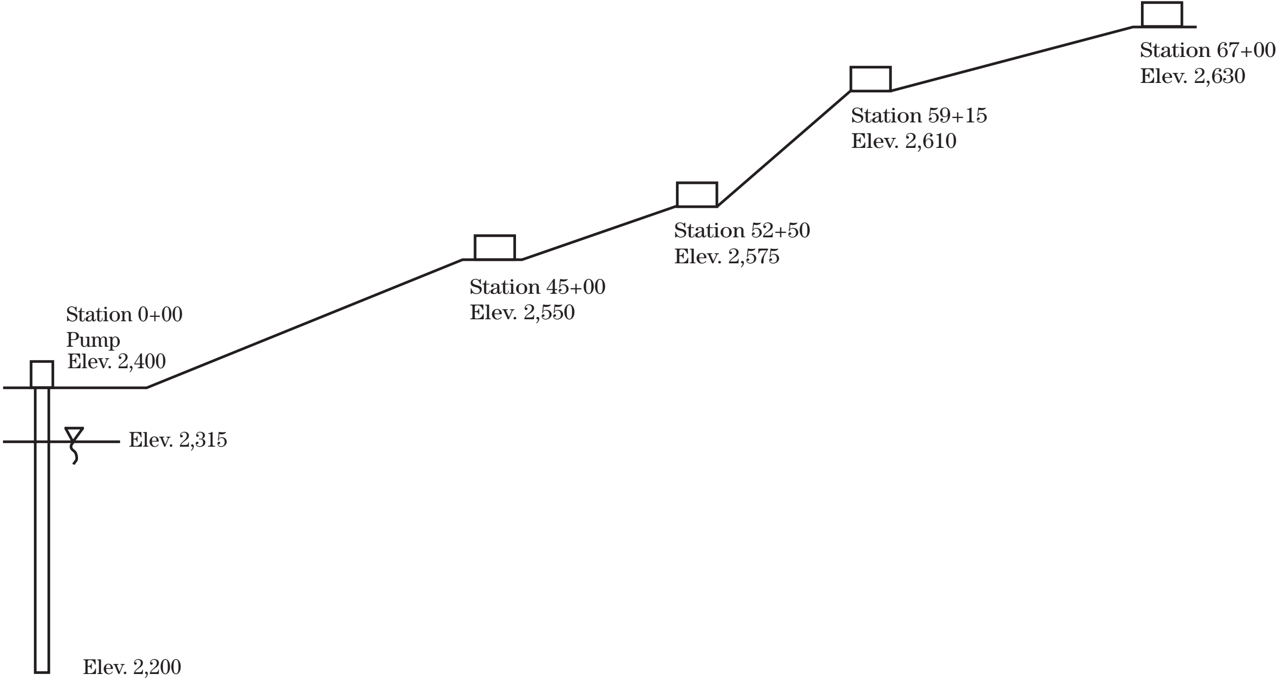
$$= 1{,}863{,}000\ \text{gal/season}$$

$$\text{Total hours of operation} = \frac{1{,}836{,}000\ \text{gal}}{20\ \text{gal/min} \times \frac{60\ \text{min}}{\text{h}}}$$

$$= 1{,}530\ \text{h}$$

Calculate friction loss and total TDH requirements. The results are shown in table 10.

Figure 27 Case 4 system profile map



Without VFD

Plot points from manufactures pump curve. Because of the low efficiency use the 5HP–17DC curve (see fig. 34).

Based on pump curve, the pump will supply 20 gallons per minute at 504 feet of head instead of the 398 feet needed. The extra head is burned off and wasted. Water horsepower is equal to:

$$\text{WHP} = \frac{\text{Q} \times \text{H}}{3{,}960} = \frac{20 \times 504}{3{,}960} = 2.5 \text{ hp}$$

With a pump efficiency of 54 percent, the brake horse power is equal to

$$\text{BHP} = \frac{\text{Q} \times \text{H}}{3{,}960 \times \text{Eff}_\text{p}} = \frac{20 \times 504}{3{,}960 \times .54} = 4.71 \text{ hp}$$

The power input for an electric motor with an estimated motor efficiency of 84 percent is

$$\text{Power input} = \frac{\text{Q} \times \text{TDH}}{3{,}960 \times \text{Eff}_\text{m} \times \text{Eff}_\text{VFD}} \times .746 \text{ kW/hp}$$

Estimated annual operating cost is

$$\text{Electric cost} = 4.2\,\text{kW} \times 1{,}530\,\text{h} \times \frac{\$0.08}{\text{kWh}} = \$512 \text{ per year}$$

If gas or diesel is used, the respective cost would be $1,854 and $1,179.88.

$$\text{Gas cost} = 4.2\,\text{kW} \times 1{,}530\,\text{h} \times (\$0.33 / \text{kWh}) = \$2{,}114 \text{ /yr}$$

$$\text{Diesel cost} = 4.2\,\text{kW} \times 1{,}530\,\text{h} \times (\$0.21/\text{kWh}) = \$1{,}345\text{/yr}$$

Table 10 Total dynamic head requirements at each station

Station	Friction plus elevation requirements (ft)	Total dynamic head (ft) friction plus well lift
45+00	209.65	296.37
52+50	241.11	327.83
59+15	284.91	371.63
67+00	311.66	398.38

In this example, the motor efficiency was not adjusted for the gas or diesel motors. In a real example, the motors' efficiencies would need to be adjusted to represent the respective motors.

With VSD

Water would be supplied to each pasture approximately 25 percent of the time. The VSD would be constant flow- variable pressure and would be controlled with a flow meter or sensor of some kind.

Use the affinity laws to plot a series of new pump curves based off of the original pump curve (table 11). Merely plugging a new value for rpm into the affinity law formula will not work because the new pump curve must pass through the two points; the affinity law will give you a curve that passes through one point. The solution is iterative, and the NRCS VFD economic calculator spreadsheet can help solve this without spending too much time. The spreadsheet can be obtained from the water management engineers SharePoint site. Data points for the adjusted speeds are shown in table 12.

$$\frac{\text{H}_2}{\text{H}_1} = \left(\frac{\text{RPM}_2}{\text{RPM}_1}\right)^2 \qquad \frac{\text{Q}_2}{\text{Q}_1} = \frac{\text{RPM}_2}{\text{RPM}_1}$$

Plot the new pump curves (fig. 28). Then plot the estimated operating points or system curve and plot the

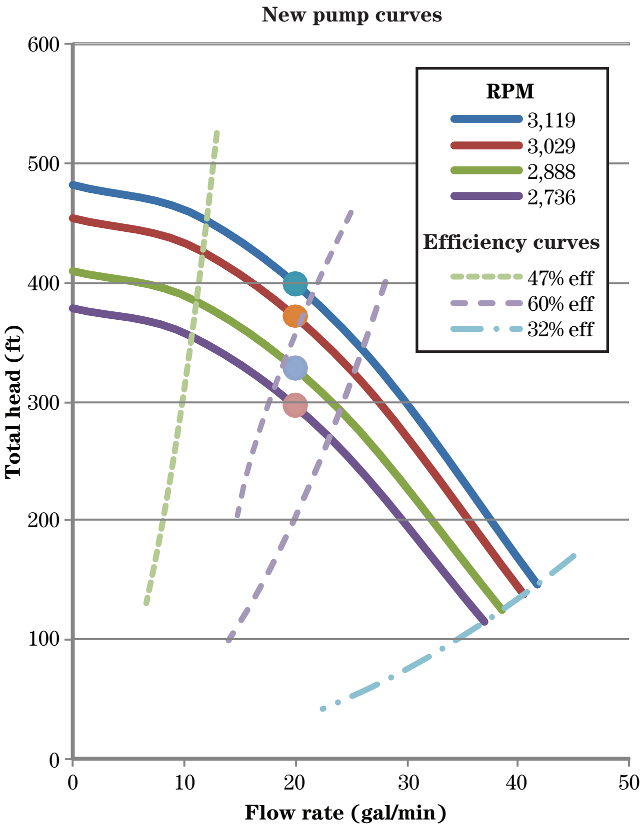
Table 11 Pump curve

Q (gal/min)	Head (ft)	Efficiency (%)
0	570	0
13	545	42
28	430	58
41	170	32

Table 12 Alternate pump curves

Rpm							
3,119		3,029		2,888		2,736	
Q	H	Q	H	Q	H	Q	H
0	466	0	439	0	397	0	366
12	445	11	420	11	380	11	350
25	351	25	331	23	300	22	276
41	139	41	131	39	118	36	109

Figure 28 Case 4 alternative pump curves



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.

The VFD adds another loss in the form of efficiency. The default value for VFD efficiency is approximately 96 percent. Horsepower and energy input are calculated using the following equation:

$$\text{Power input} = \frac{Q \times TDH}{3{,}960 \times Eff_m \times Eff_{VFD}} \times .746 \text{ kW/hp}$$

The actual energy cost is based upon the percent of the total hours that the system is operated at each condition; in this case, each pasture is operated 25 percent time. Seasonal cost is estimated using the following equation:

$$\text{Power cost} = \text{Power input (kW)} \times \text{hours of operation (hr)} \times \frac{\$}{\text{kW} - \text{h}}$$

The power requirements are summarized in table 13.

The seasonal cost for operating an electric motor would be $352.

The net savings would be $512–$352 = $160 per season. The respective cost savings for gas and diesel are as follows (once again not adjusting for the different motor efficiencies): $663 and $422.

Table 13 Energy requirements

TDH	**Efficiency**	**Power input**	**Hours of operation**	**kW-h**
296	58	3.2	383	919
328	57	3.6	383	1,027
371	56	4.1	383	1,177
398	56	4.5	383	1,274

Compare this value to the cost of the VSD 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 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 5—VSD stock water example

Given:

The rancher runs a cow-calf operation with 600 head and uses any two pastures at one time as he rotates his heifers and cows. The pipeline runs through the landowner's corral, where there is a 12-foot-diameter tank, and is used all the time. From May to October (~153 days), 500 head are split between the two rotating pastures and 100 head are rotated through the corral. From October through April, all 600 head are at the home corral. The tanks are supplied by a Red Jacket Big-Flo 28GPM Series "DC" pump, 3,450 rpm. The profile is shown in figure 29.

Average water requirement: 20 gal/d/head
Well elevation: 2,400
Static water elevation: 2,315
Depth of well: 212 feet
Pump set at elevation: 2,200
All pipe is 2-inch diameter HDPE, 200 lb/in^2
Design flow rate: 20 gal/min

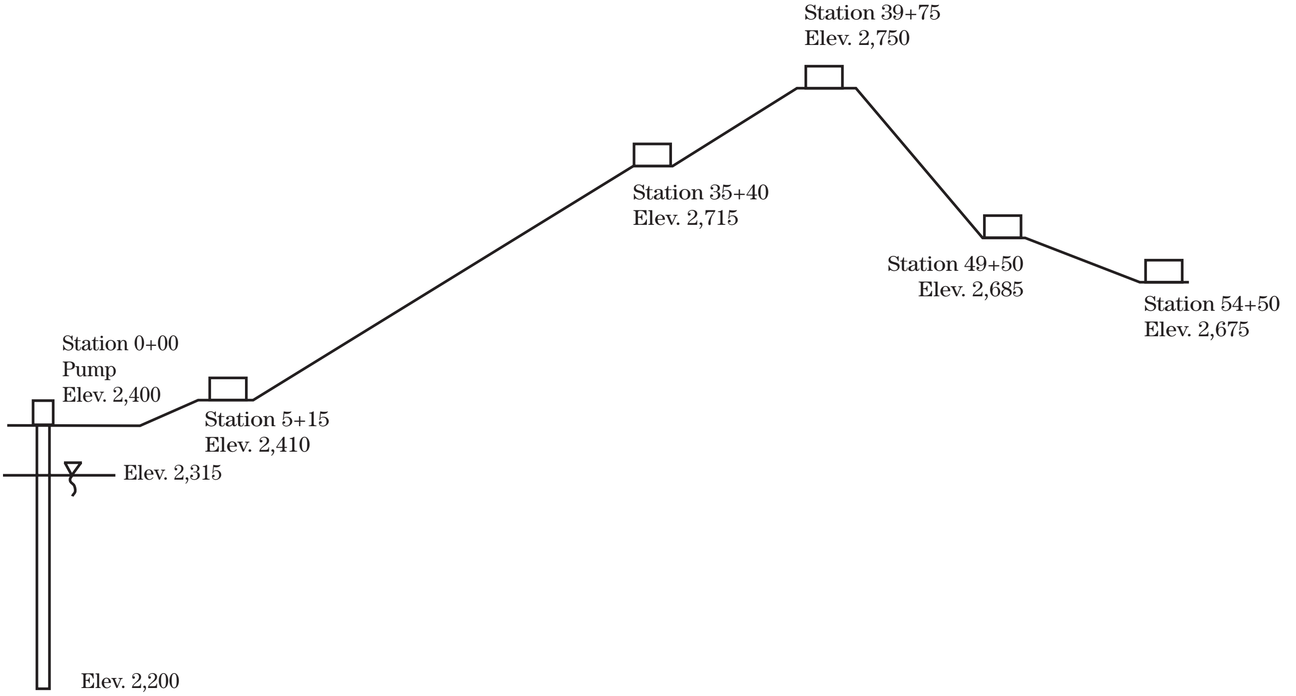
Corral tank, sta. 5+15, elevation 2,410
1st tank, sta. 35+40, elevation 2,715
2nd tank, sta 39+75, elevation 2,770
3rd tank, sta. 49+50, elevation 2,685
4th tank, sta. 54+50, elevation 2,675

Cost for kWh based on BPH h/fuel unit
Electric: $0.08
Diesel: $0.21
Gas: $0.33

Solution:

$$\begin{aligned}&600\text{ head}\times 20\text{ gal/d/head}\times 365\text{ d}\\&\quad = 4,380,000\text{ gallons per season}\end{aligned}$$

Figure 29 Case 5 system profile map



Calculate friction loss and total TDH requirement. Results are summarized in table 14.

Without VSD

Plot points from manufactures pump curve. Because of the low efficiency, use the 5HP–17-curve (fig. 34).

Without a VSD, the pump should be designed based on the maximum TDH of 504 feet. The pump will supply 498 feet of head; any extra head is burned off and wasted.

Water horsepower is equal to:

$$\begin{aligned}\text{WHP} &= \frac{Q \times H}{3{,}960} \\ &= \frac{20 \times 504}{3{,}960} \\ &= 2.5 \text{ hp}\end{aligned}$$

With a pump efficiency of 54 percent the brake-horse power is equal to:

$$\begin{aligned}\text{BHP} &= \frac{Q \times H}{3{,}960 \times \text{Eff}_p} \\ &= \frac{20 \times 504}{3{,}960 \times .54} \\ &= 4.71 \text{ hp}\end{aligned}$$

The power input for an electric motor with an estimated motor efficiency of 84 percent is:

$$\begin{aligned}\text{Power input} &= \frac{4.71 \text{ hp}}{.84 \times \text{Eff}_m} \times .746/\text{kW/hp} \\ &= 4.2 \text{ kW}\end{aligned}$$

Estimated annual operating cost is:

$$\text{Cost} = 4.2\,\text{kW} \times 3{,}650\,\text{h} \times \frac{\$0.08}{\text{kWh}} = \$1{,}222 \text{ per year}$$

If gas or diesel is used, the costs would be 15,280 kWh multiplied by $0.33 and $0.21 or $5,042 and $3,209, respectively.

In this example, the motor efficiency was not adjusted for the gas or diesel motors. In a real example, the motors' efficiencies would need to be adjusted to represent the respective motors.

With VSD

The VSD would be constant flow, variable pressure, and would be controlled with a flow meter or sensor of some kind.

Determine what percentage of the time each TDH will be needed. Because the last two stations are so close, use the same TDH. That will give four different TDH conditions that can occur: three for the pastures and one for the corral.

The four main pastures are used equal amounts of time for the spring and summer grazing.

$$\begin{aligned}\frac{500 \text{ head} \times 20 \text{ gal/d}}{20 \text{ gal/min} \times 60 \text{ min/h}} &= 8.33 \text{ h/d} \times 153 \text{ d} \\ &= \frac{1{,}275 \text{ h}}{4 \text{ pastures}} \\ &= 318.75 \text{ h/pasture}\end{aligned}$$

Since all of the water for tanks 3 and 4 have to pass by tank 2, that leaves three operating conditions: the corral and two tanks, one of which will always require the maximum head. That is two TDH possibilities for the pastures with 319 hours and 956 hours.

Table 14 Friction and TDH requirements

Station	Friction plus elevation requirements (ft)	Total dynamic head (ft) friction plus well lift
5+15	16.82	103.54
35+40	347.83	434.55
39+75	388.61	475.33
49+50	331.99	418.71
54+50	328.62	415.34

Table 15 Pump curve

Q (gal/min)	Head (ft)	Efficiency (%)
0	570	0
13	545	42
28	430	58
45	170	32

Corral—May to October

$$\frac{100\text{ head}\times\frac{20\text{ gal}}{\text{d}}\text{ per head}}{20\text{ gal/min}\times\frac{60\text{ min}}{\text{h}}}=\frac{1.67\text{ h}}{\text{d}}\times 153\text{ d}=255\text{ h}$$

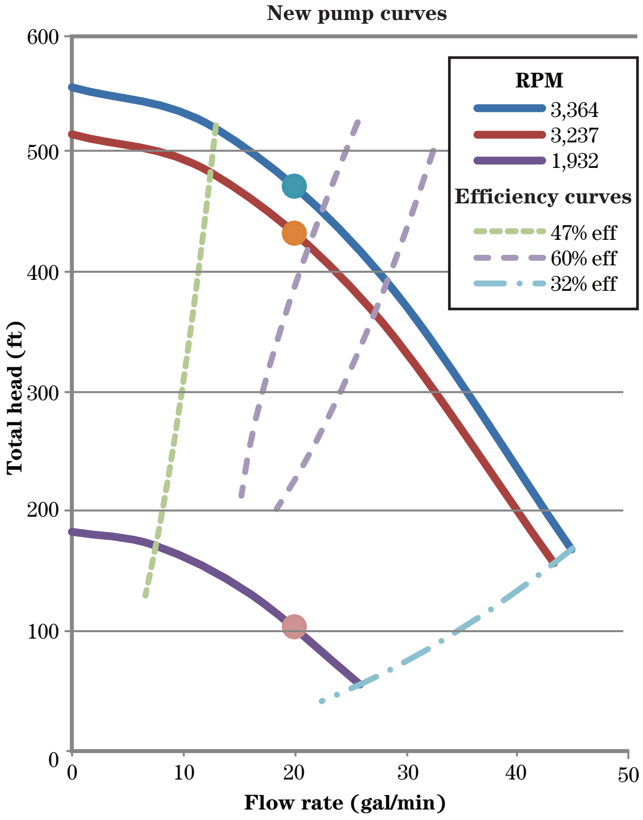
Corral—October thru April

$$\frac{600\text{ head}\times\frac{20\text{ gal}}{\text{d}}\text{ per head}}{20\text{ gal/min}\times\frac{60\text{ min}}{\text{h}}}=\frac{10\text{ h}}{\text{d}}\times 212\text{ d}=2{,}120\text{ h}$$

Table 16 Alternate pump curves

Rpm					
3,364		**3,237**		**1,932**	
Q	**H**	**Q**	**H**	**Q**	**H**
0	542	0	502	0	179
13	518	12	480	7	171
27	409	26	378	16	135
445	162	42	150	25	53

Figure 30 Alternate pump curves



Total hours for the coral are 2,120 + 255 = 2,375.

Use the affinity laws to plot a series of new pump curves.

$$\frac{H_2}{H_1}=\left(\frac{RPM_2}{RPM_1}\right)^2 \qquad \frac{Q_2}{Q_1}=\frac{RPM_2}{RPM_1}$$

Merely plugging a new value for rpm into the affinity law formula will not work because the new pump curve must pass through the two points; the affinity law will give you a curve that passes through one point. The solution is iterative, and the NRCS VFD economic calculator spreadsheet can help solve this without spending too much time. Data points for the adjusted speeds are shown in table 16.

Plot the new pump curves (fig. 30), 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.

The VFD adds another loss in the form of efficiency. The default value for VFD efficiency is approximately 96 percent. Horsepower and energy input are calculated using the following equation:

$$\text{Power input}=\frac{Q\times H}{3{,}950\times \text{Eff}_p\times \text{Eff}_m\times \text{Eff}_{VFD}}$$

The actual energy cost is based upon the percent of the total hours that the system is operated at each condition. Seasonal cost is estimated using:

$$\text{Energy cost}=\text{HP}\times\frac{0.746\text{ kW}}{\text{HP}}\times \text{h}\times\%\text{ of time}\times\frac{\text{cost}}{\text{kWh}}$$

The results are summarized in table 17.

Table 17 Energy requirements

TDH	Efficiency	Power input	Hours of operation	kWh
475	54	5.5	955	3,882
435	55	4.9	319	1,210
104	52	1.2	2,375	2,193

The seasonal cost of an electric motor would be $583.

The net savings would be $1,222–$583 = $639 per season. The respective cost savings for gas and diesel are (once again not adjusting for the different motor efficiencies): $2,638 and $1,680.

Compare this value to the cost of the VSD to calculate the payback period. The price for VFD (electric) controls ranges from $100 to $200 per horsepower depending on the options required. In this case with a 5 hp motor that is between $500 to $1,000 or roughly 1- to 3-year payback. 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.

The following is a sample of a specification that might be used for specifying a VFD. In no way is this to be considered all inclusive or that everything in this sample would need to be included. This is just an example of how a VFD might be specified.

Figure 31 Gould's Model 10DHHC pump curve

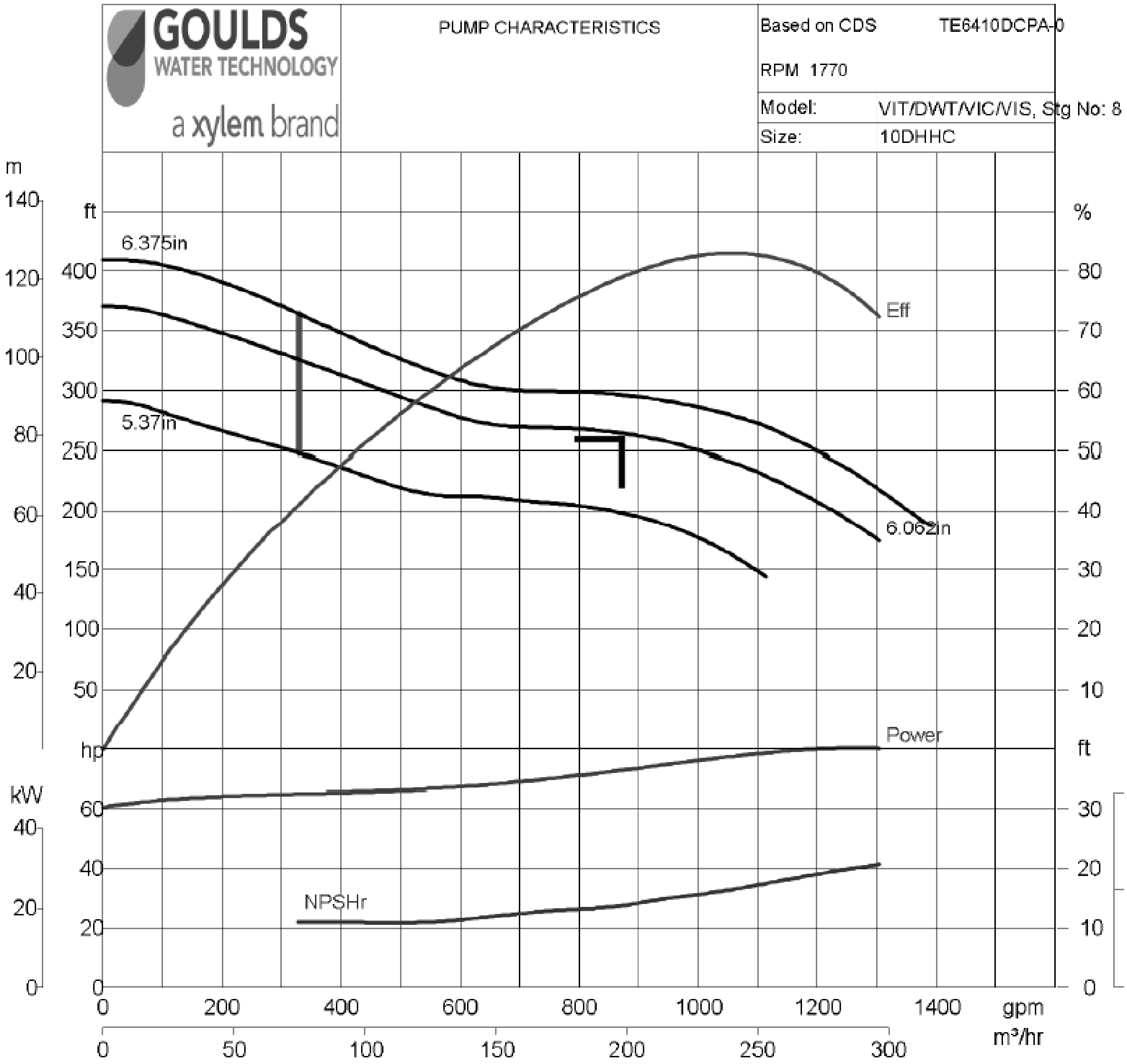


Figure 32 Flowserve Model 10EGH/10LKH pump curve

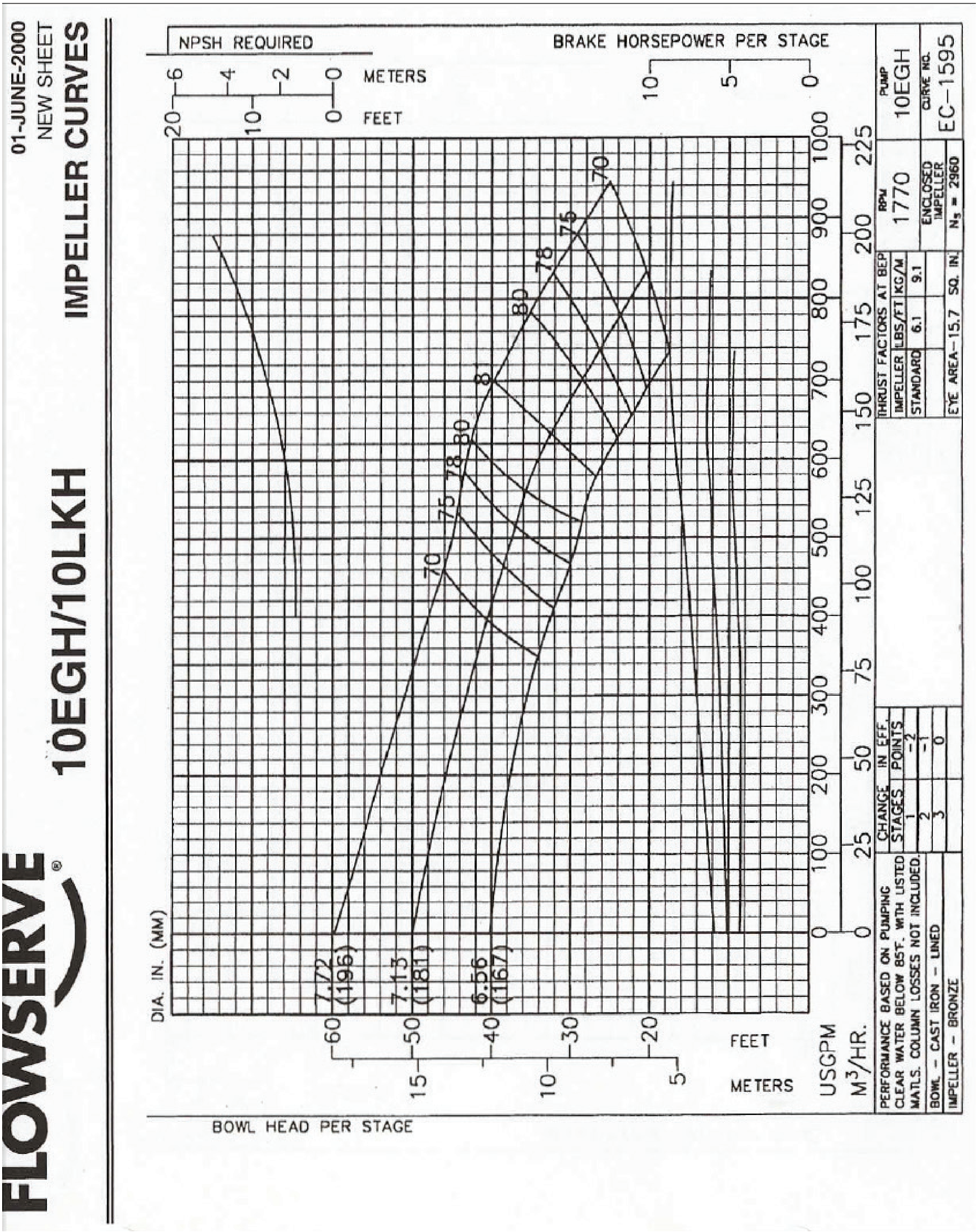


Figure 33 Johnston Model 14ECII pump curve

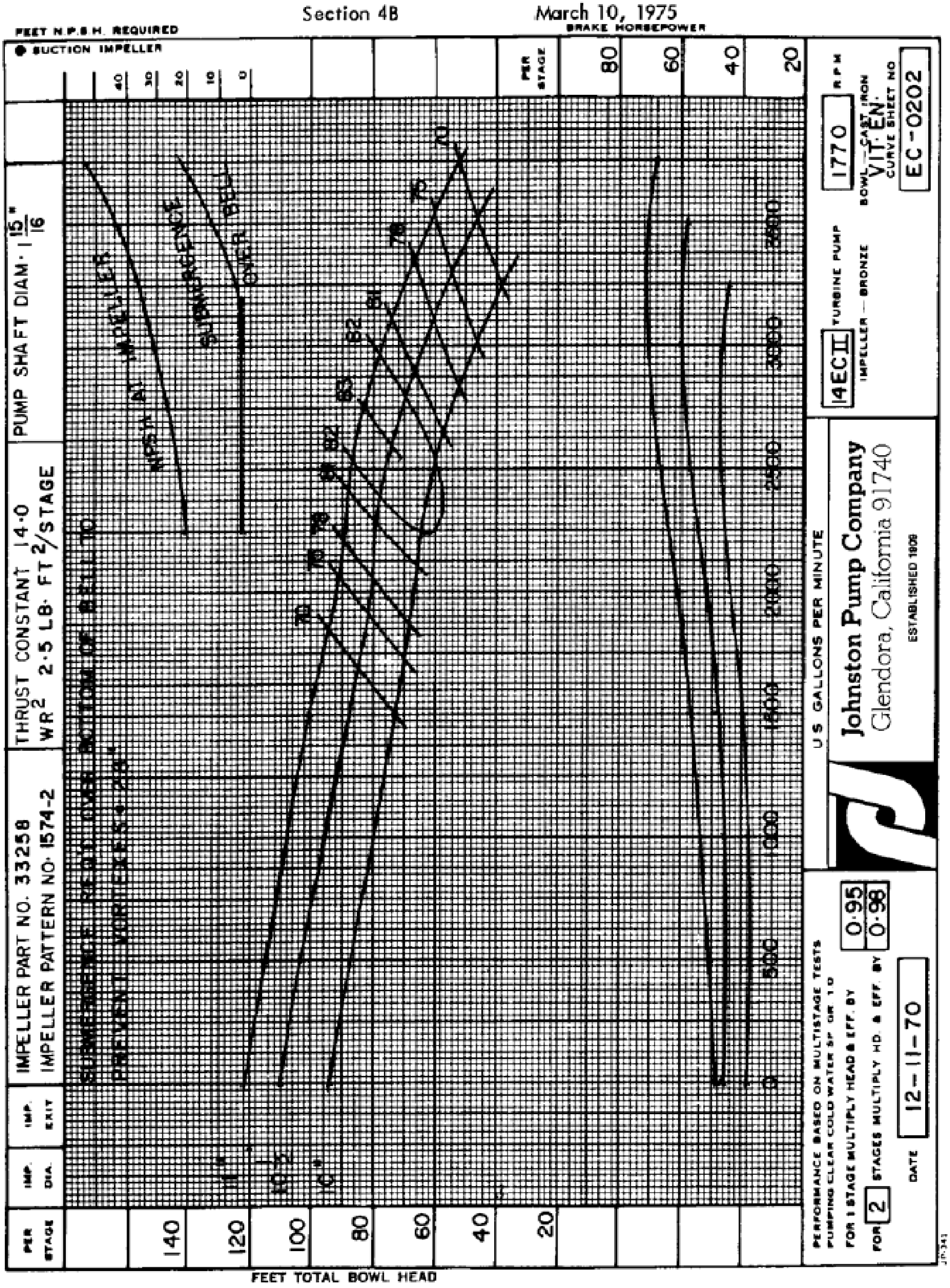
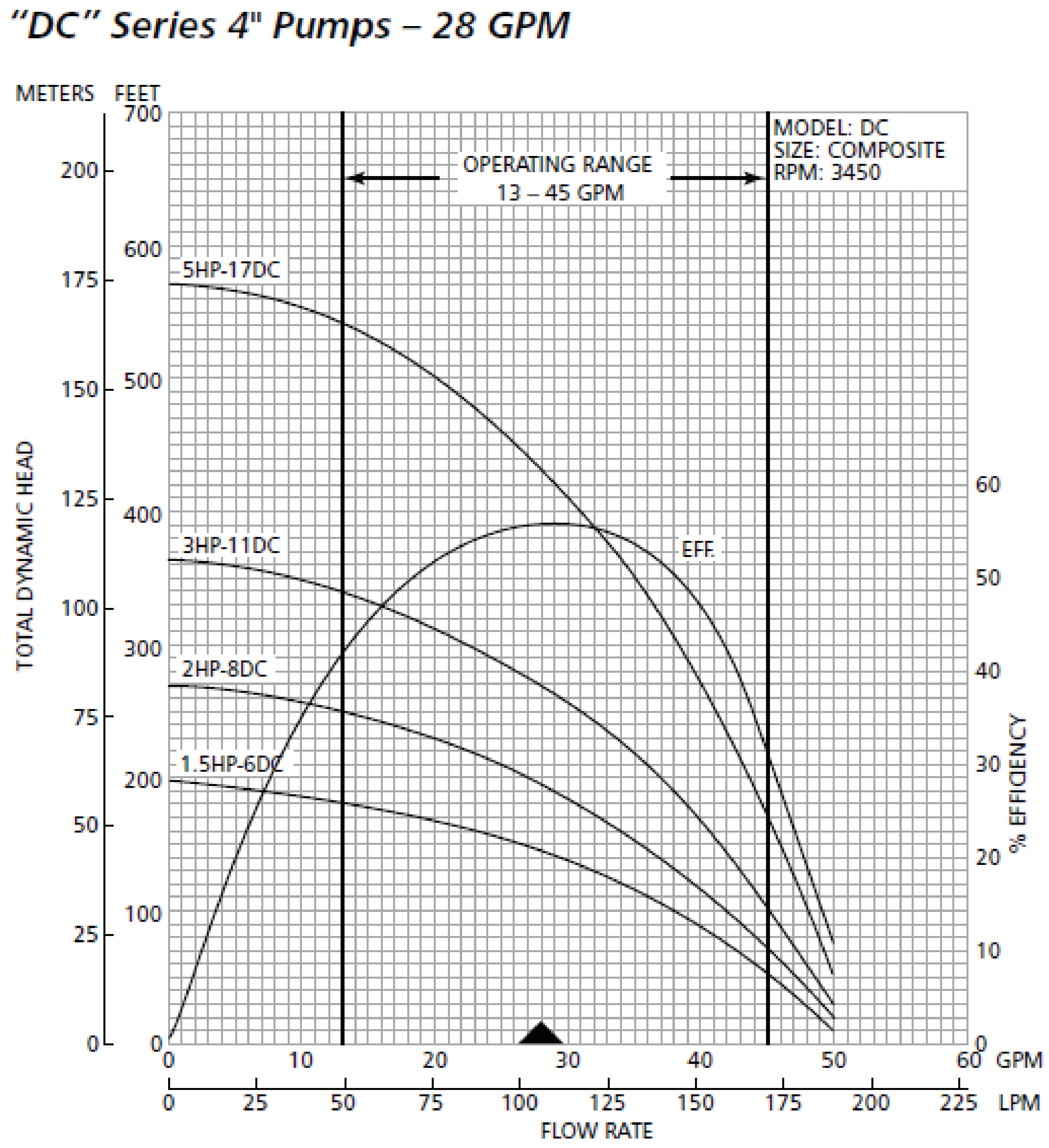


Figure 34 Pump curve for 28GPM Series "DC" pump



▲ ***Rated Flow at Best Efficiency***

"DC" Series, 28 GPM

Guaranteed as minimum performance only if certified.

Minimum Well Size: 4" I.D.

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

(Adapted from specifications provided by and with permission of Precision Pump Systems, Boise, ID)

1. General

1.1 Scope of Work

The contractor will furnish and install a pump control system designed to operate one pump using Variable-Frequency Drives (VFDs) as described herein. The control system must 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 must be operator and maintenance friendly to ensure ease of system setup and to limit down time.

The pump control system must be capable of operating one electric pump motor as manufactured by

Model:				
Horsepower:				
Full-load amps (FLA):				
Incoming power must 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 (lb/in^2):	
Maximum pressure (lb/in^2):	
Minimum flow (gal/min):	
Maximum flow (gal/min):	

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

The factory assembled system must 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 must comply with all applicable codes, safety, and fire law regulations at the location of the work and must conform to applicable codes and standards of the organizations listed:

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 must be new and must bear the manufacturer's name and trade name. In cases where a standard has been established for the particular material, the material must be so labeled. The equipment to be furnished must 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 must be the manufacturers 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 must be housed in a single NEMA 12 powder-coated steel enclosure of a wall thickness of not less than 0.075 inches. The enclosure must be sized to allow easy access to components and provide adequate ventilation for VFDs. The enclosure must 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 must conform to appropriate NEMA and UL standards and must be mounted directly to the VFD control panel. Direct exposure of the VFD unit to unfiltered outside air is not acceptable. Ventilation or cooling must 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 must 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 must be maintained, and a NEMA 3R rated rain hood must protect the external heat sinks. The mounting cabinet must be a single NEMA 3R or NEMA 4 free standing, power-coated steel enclosure of a wall thickness of not less than 0.075 inches. The enclosure must be sized 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 must conform to appropriate NEMA 3R or NEMA 4 or UL type 3 or UL type 4 standards.

Direct exposure of the VFD unit to unfiltered outside air is not acceptable. Sun shielding of the enclosure must be provided for onsite.

VFD without external heat sinks

The described equipment must be housed in a single NEMA 4 free standing, powder-coated steel enclosure of a wall thickness of not less than 0.075 inches. The enclosure must be sized to allow easy access to components and provide adequate ventilation for the VFD. The enclosure must 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, must 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 must be 18 gauge (AWG) minimum, type MTW or THW, rated for 600 volts. All power wiring must be 12 gauge (AWG) minimum rated for 600 volts. Conductors must be color-coded using the same colors throughout the entire panel. Control circuit wiring must be organized in snap-cover raceways. All wires must be individually numbered or labeled at both ends. All wiring must be done in a workmanlike manner.

2.4 Schematics and Labeling

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

2.5 Safety

Control panel construction methods must take into account provisions to ensure operator safety from electrocution. UL508A safety standards must be observed. In addition, all terminals on power circuits carrying greater than 50V must 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, must be mounted inside the enclosure. The VFD must monitor the sensor (pressure or flow rate) signal (4-20mA loop powered signal) and control the pump speed using the factory preprogrammed control points in order to maintain the desired operating condition. The VFD must also be capable of having an acceleration or deceleration time, adjustable 3 to 1,800 seconds, with override circuit to prevent nuisance trips if the deceleration time is set too short.

The VFD must be sized to the pump motor supplied by the Contractor or the existing pump and it must be compatible with all equipment utilized at the pump station. The VFDs must meet these requirements:

Analog input

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

Sizing/efficiency

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

Service conditions

The VFD must be designed to operate within the following service and environmental conditions:

- 100-percent performance rating in the temperature range 0–40 degrees Celsius. Cooling must be provided if expected operating temperatures exceed 40 degrees Celsius.
- 0 to 95 percent relative humidity, noncondensing
- Elevation to _______ feet (_______ meters) without derating
- AC line voltage variation, –10 percent to +10 percent

Pump/system protection:

The VFD must have these 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 overcycling

Motor/drive protection:

The VFD must 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
- Short circuit protection

These faults must provide an orderly shutdown of the VFD with clear indication of the fault. The history of previous faults must be stored in memory for future review. An automatic restart option must be provided, with a minimum 30-second time delay. 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 must be a function that is field selectable.

Phase conversion:

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

Keypad/operation:

The VFD must be equipped with an interface keypad with START/STOP buttons and a display for the visualization of process and alarm status. The main screen must display the set pressure/flow rate, the actual pressure/flow rate (in lb/in^2/gal/min), the motor current (in Amps), and the motor speed in (Hz) simultaneously. The keypad must allow the user to navigate through the configuration menus and adjust set point values via the front keypad. The VFD setup must be simple and must not require the use of a laptop computer. The VFD must be factory configured and tested to minimize field programming and startup time.

The VFD must 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 must be industrial grade and have a static accuracy of 1 percent of full scale or better. The pressure transmitter must 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 may be required in the field. The connection must 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 must be industrial grade and have a static accuracy of 3 percent of full scale or better. The flow meter must produce a 4-20mA output signal proportional to the discharge. No calibration of the flow meter may be required in the field. The flow meter must be connected to the pump discharge. Flow meter must have an external power source that provides a consistent power supply.

3.4 Communication

The control panel must 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 must be protected by molded case circuit breakers. Each pole of the breaker must provide inverse time delay overload protection and instantaneous short circuit protection by means of a thermal magnetic element.

The breaker must be operated by a toggle-type or rotary handle and must have a quick-make, quick-break switching mechanism that is mechanically trip free from the handle. Tripping due to overload or short circuit must be clearly indicated by the handle automatically assuming a position midway between the manual "on" and "off" position. Breakers must be completely enclosed in a molded case and must bear the UL label. The short-circuit interrupt capability must exceed the fault level (Isc) of the incoming power. The circuit breakers for the VFDs must be mounted on the subpanel 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 must be rated for 10 amps at 300VAC. Relay sockets must 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 must be available for user interface.

3.7 VFD Protection Package

The VFD unit must be protected from line voltage with a line isolation contactor that is interfaced with a digital voltage monitor. The digital voltage monitor must be capable of detecting phase loss, phase reversal, phase unbalance, and over/under voltage. The voltage monitor must 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 must be fully rated for across-the-line starting of the motor and must include appropriately sized overloads for the FLA of the motor.

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

3.8 Line and Load Reactors

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

The installation must follow all NEMA cable length guidelines. If NEMA guidelines are exceeded—

1. The motor must require a load reactor if the pump leads from the VFD exceed the following lengths:
   - 800 feet for 208–240V applications
   - 200 feet for 460V applications
   - 50 feet for 575V applications
2. The VFD must require a dV/dt filter if the pump leads from the VFD exceed the following lengths:
   - 1,500 feet for 208–240V applications
   - 500 feet for 460V applications
   - 200 feet 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 Std. 519 Harmonics Mitigation Hardware

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

The appropriate harmonics mitigation hardware must be fully integrated into the VFD control panel package such that it is deliverable to the job site in a single package and must not require any additional onsite wiring. Additional heat loads and amp losses resulting from harmonics mitigation hardware must be determined and appropriate steps must 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 must 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 must be functionally tested by the manufacturer, supplier, or both 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.

References

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