Irrigation Pump Variable Frequency Drive (VFD) Energy Savings Calculation Methodology

Public Utility District No. 1 of Chelan County

This paper describes how to calculate energy saved by installing a variable frequency drive (VFD) on a centrifugal or turbine irrigation pump.

James A. White, P.E. and Andy Parks

9/3/2012

Irrigation Pump VFD Energy Savings Calculation Methodology

Executive Summary

This paper is intended to help the reader understand and accurately predict the energy savings of installing variable frequency drives (VFD's) on irrigation and well pumps. Because of the elevation gain that irrigation pumps must overcome before any flow occurs, calculating the energy savings of VFD's on these, and other open-loop pump systems, is more challenging than calculating the savings for a conventional closed-loop pump system. Because of the difficulty in accurately calculating the savings, VFD's installed on irrigation pumps often end up saving little, if any, energy.

To calculate the energy savings it is necessary to know:

1. How the existing pump is controlled (Pressure reducing valve (PRV), bypass valve or none)
2. Desired pressure setpoint of the system (elevation gain + frictional losses + sprinkler operating pressure)
3. Annual operating hours

The last two items, which are typically the most difficult to get, are:

4. The approximate percentage of time spent at different flow rates, and
5. The pump's performance curve.

Installing a VFD on an irrigation pump should only be considered if:

1. The discharge pressure pump is controlled by a bypass valve that dumps excess water
2. There is significant variation of flow during the time that the pump is operating, and/or
3. During low flow operation, the operating pressure of the system with the VFD is significantly lower than the discharge pressure of the pump if it were operating at a fixed speed.

Introduction

Pumping systems consume a significant portion of the electricity in the United States. In Chelan County of Washington State alone there are over 1,100 irrigation pumps which consume more than 10,000 average horsepower from April through October. Although energy savings potential exists for most irrigation pumping systems, accurately calculating these savings can be difficult. Variable frequency drives (VFD's) are often recommended as a way to save pumping energy, but actual energy savings can vary dramatically as shown in Figure 1 – Actual Measured Irrigation Pump VFD Savings below.

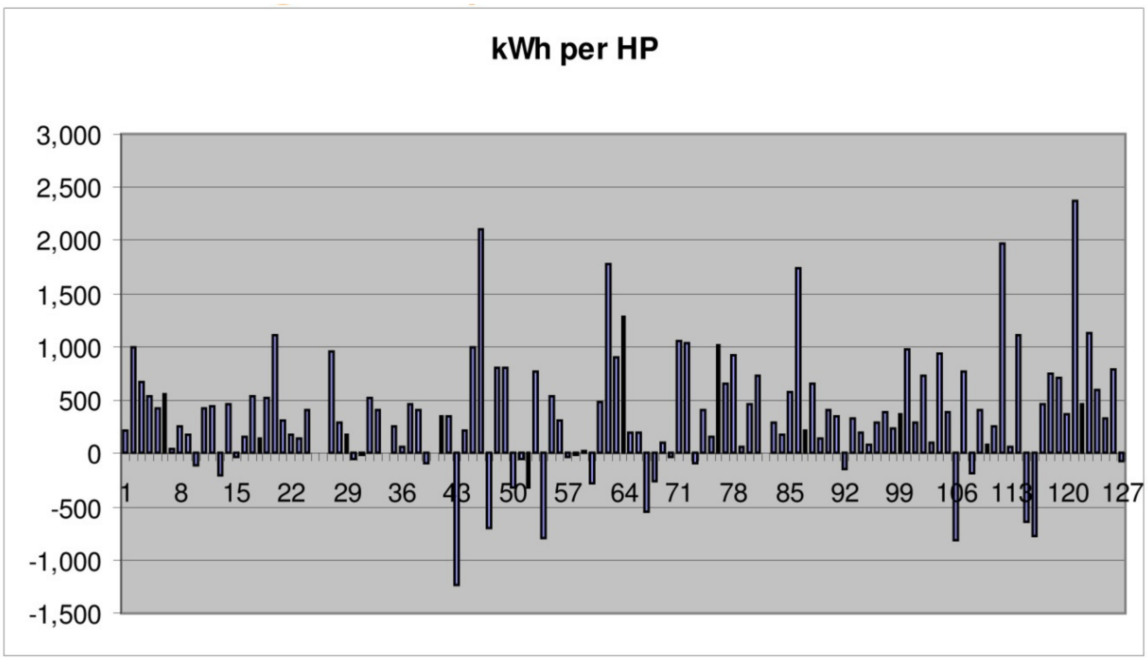


Figure 1 – Actual Measured Irrigation Pump VFD Savings[1]

Actual energy savings will vary greatly depending on how the discharge pressure of the constant speed pump is controlled and how it is operated after the VFD is installed. It takes five variables (pump curve, flow profile of system, annual run time, operating pressure and existing pressure control type) to accurately calculate energy savings, and usually only two or three are readily available. Energy savings are difficult to calculate because critical information is often missing. Energy savings are further complicated by the fact there are few published papers or documents on how changing the speed of a pump modifies its head vs. flow curve. This paper is intended to be a guide to calculating energy savings in pumping systems after a variable frequency drive (VFD) is installed.

[1] BPA 2012 Energy Efficiency Utility Summit, Agriculture Sector Update, Ag Pump VFD Results by Dick Stroh. http://www.bpa.gov/Energy/N/utilities_sharing_ee/Utility_Summit/Workshop2012/Agriculture_Sector_Update.pdf

Pump Curves and Variable Speed Drives

Most pump curves show characteristics of multiple pump diameters that are operated at a constant speed. This is confusing, because the efficiency lines for a fixed diameter pump operating at different speeds are not the same as the efficiency lines shown on a plot of different diameter pumps operating at a fixed speed. After extensive research of existing literature on how varying the speed of irrigation pumps affects its power usage, no conclusive results were found. Occasionally, a pump manufacturer will include information showing the pump running at multiple speeds, such as the one shown in Figure 2. While the multiple speed pump tables provide insight into how the pump performs at different speeds, the plots are complicated in that they show different diameters of pumps on the same plot. This adds unnecessary confusion.

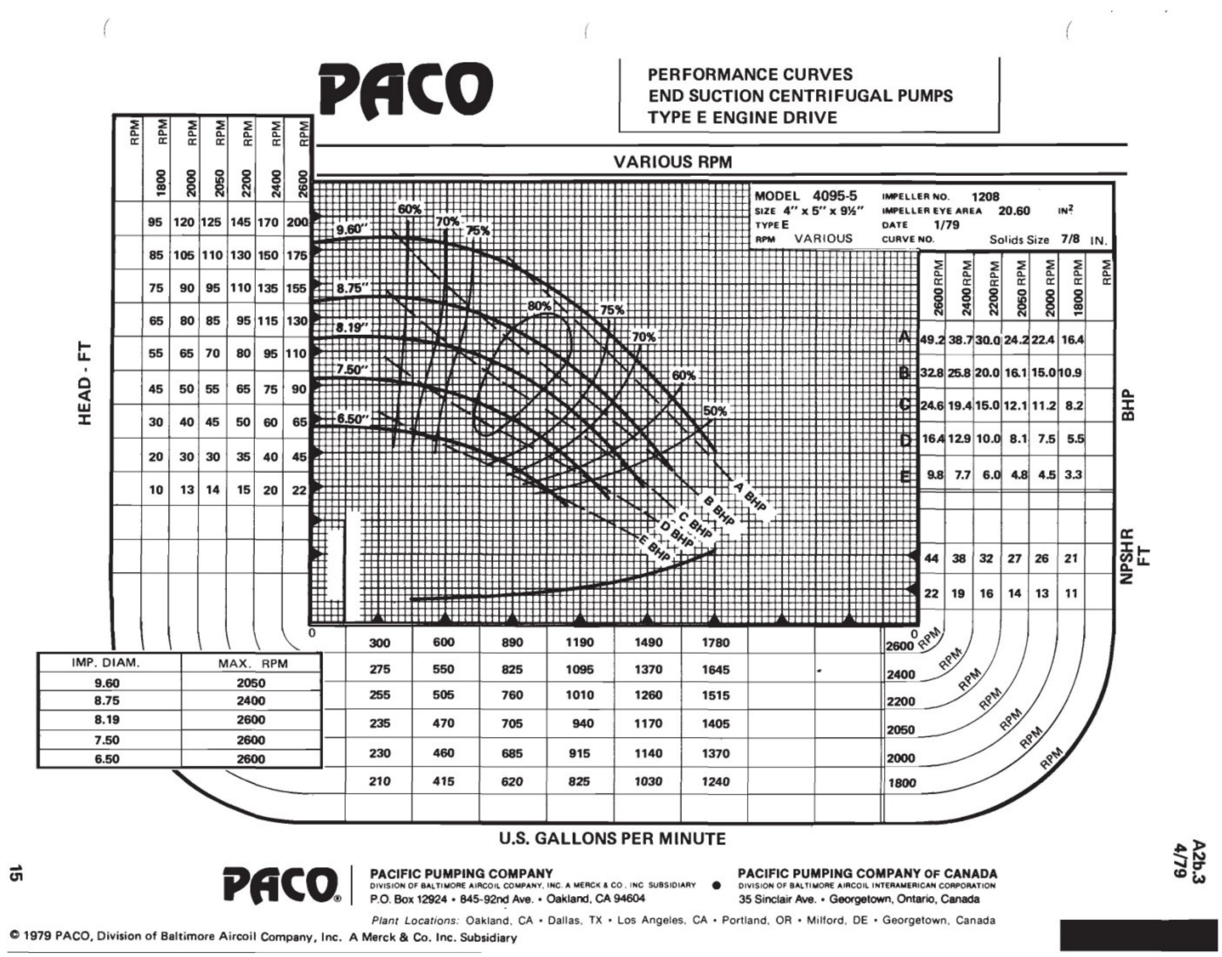


Figure 2: Pump curve for a centrifugal pump.

Applying Affinity Laws to Irrigation Pump VFD's

After close examination of Figure 2, it is important to note that the pumps' efficiency remains constant for flows and pressures that follow the affinity laws. ***<u>The efficiency lines for the variable speed pump are NOT the same as the efficiency lines shown for different diameter pumps</u>***. Knowing that the efficiency lines are constant along affinity law lines is the key to creating variable speed pump curves from a constant speed performance curve.

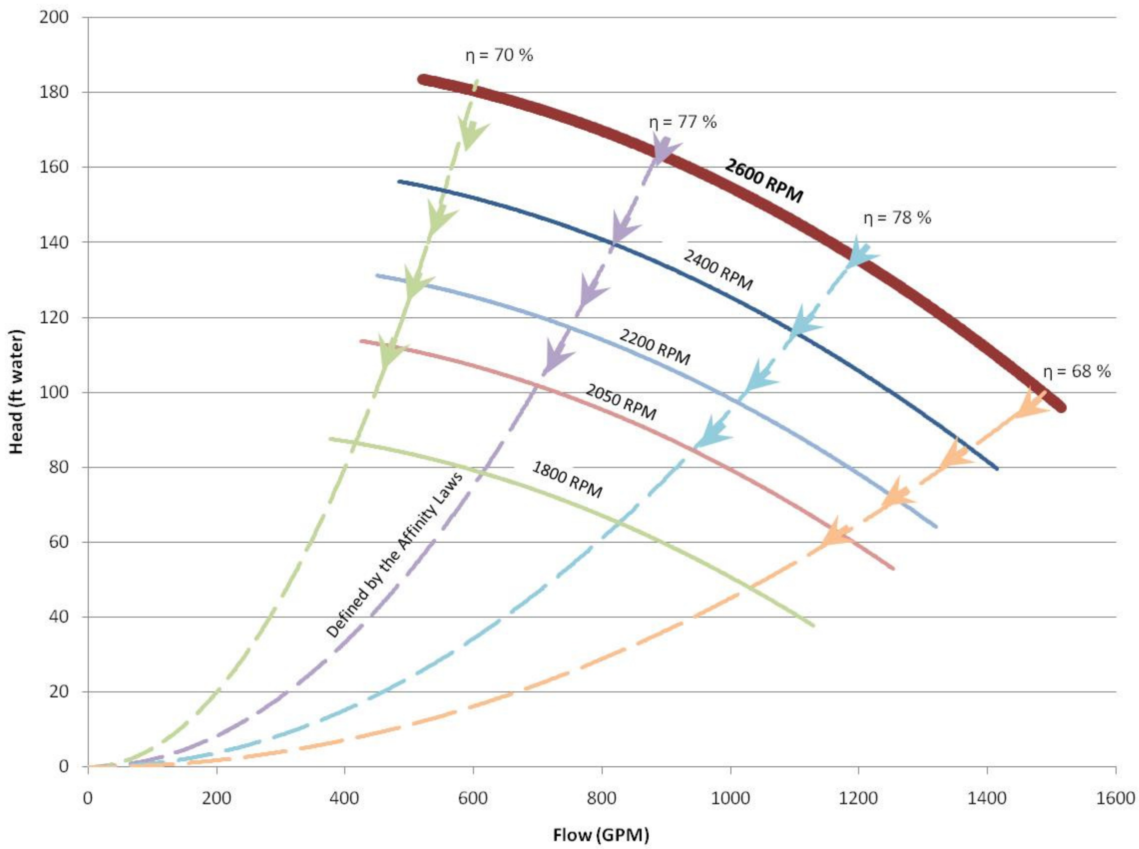


Figure 3 – Constant efficiency lines and performance curves for a variable speed pump.

The flows, pressures and power can be calculated along each constant efficiency line using the affinity laws. The affinity laws are as follows:

$$\frac{Q_1}{Q_2} = \left(\frac{N_1}{N_2}\right)$$

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

$$\frac{Q_1}{Q_2} = \sqrt{\frac{H_1}{H_2}}$$

Where Q is the flow rate (GPM), N is the speed (RPM), H is head (Feet), and P is power (Horsepower).

Once the flows and pressures are known, the pump's horsepower can be determined for a given efficiency (η) using the power equations shown below.

$$P = \frac{QH}{(3960)(\eta)} \qquad\qquad kW = \frac{P * 0.746\ kW/HP}{Motor\ Eff.}$$

Steps to Calculate Irrigation Pump VFD Savings

Use the following steps to calculate the energy saved by installing a variable speed pump.

Step 1. Obtain the flow, pressure and efficiency for at least three points along the pump's constant speed performance curve.

Step 2. Using the constant pressure setpoint for the VFD, determine the flow for each of the variable speed operating points along the constant efficiency lines.

$$\frac{Q_1}{Q_2} = \sqrt{\frac{H_1}{H_2}} \qquad ,Q_1 = Q_2\sqrt{\frac{H_1}{H_2}} \qquad ,Flow\ with\ VFD = Flow\ at\ Constant\ Speed\ \sqrt{\frac{Constant\ Pressure\ Head}{Head\ at\ Constant\ Speed}}$$

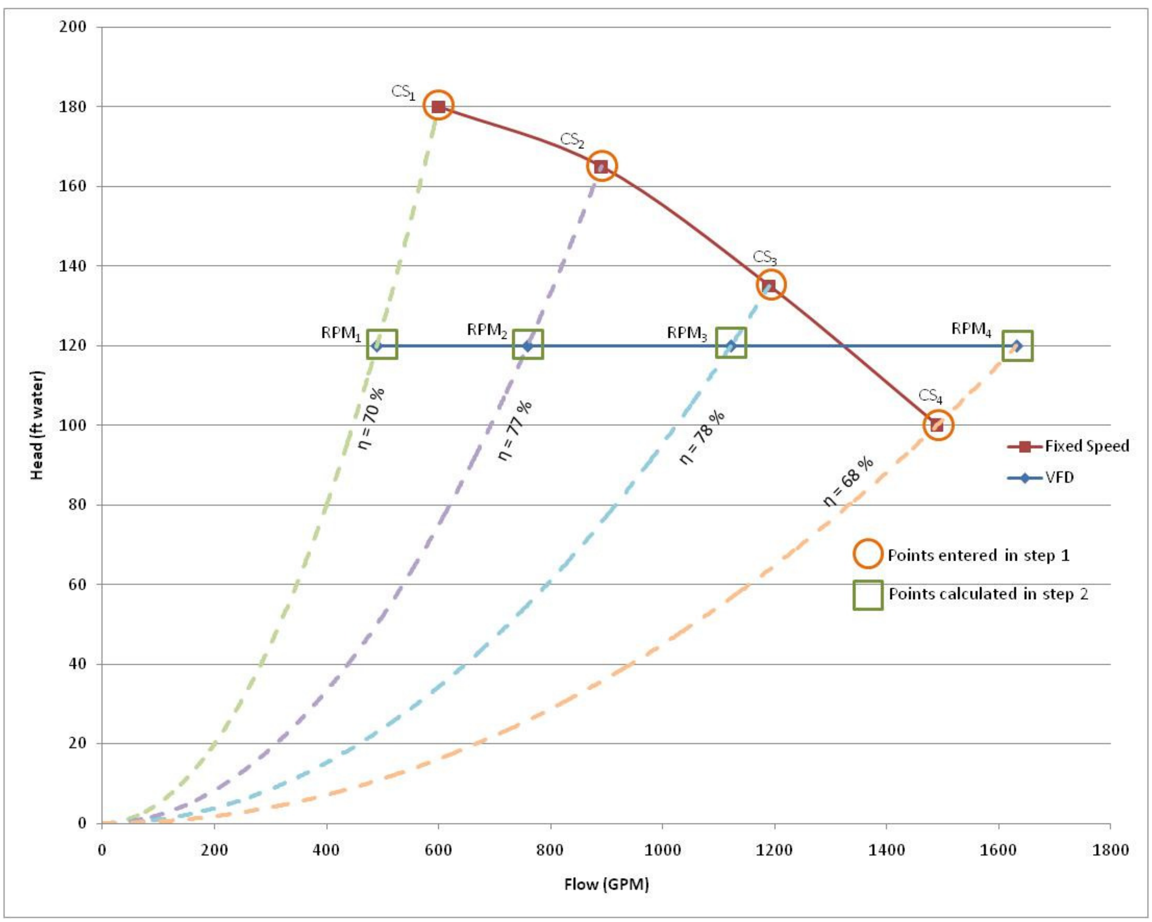


Figure 4 - Flow vs. Pressure Curve w/ Constant Eff. Lines

Step 3. Calculate the power for each of the operating points along the constant speed and variable speed lines using the flow, head and efficiency values found in Steps 1 and 2 using the equation below.

$$P = \frac{QH}{(3960)(\eta)} \qquad\qquad kW = \frac{P * 0.746\ kW/HP}{Motor\ Eff.}$$

Step 4. Determine the coefficients a, b and c that define the horsepower of the constant speed and variable speed pump as a function of the flow rate Q (Gallons per minute). Note that the coefficients a, b and c may be found by plotting the four points on a scatter plot in Excel and then showing the trend line and formula for a second order polynomial that goes through these points. Another option is to use Excel's "LINEST" function to automatically calculate the variables. The LINEST function can calculate the coefficients for up to a third order polynomial. Although LINEST is an obscure function in Excel that is very poorly documented or explained, it proves very useful at describing functions that follow a parabolic pattern.

	A	B	C	D
1	From Pump Curve			Fixed
2	Flow	Head	Efficiency	Speed HP
3	400	460	73%	64.09
4	300	620	72%	65.24
5	200	720	63%	58.18
6	180	740	60%	56.53
7				
8	Fixed Speed HP = (A3*B3)/(3960*C3)			
9				
10	Fixed Speed HP = a GPM^2 + b GPM + c			
11	Coefficients			
12	a	b	c	
13	=LINEST($D$3:$D$3,$A$3:$A$6^{1,2})			

To apply the LINEST function, type "=LINEST($D$3:$D$3,$A$3:$A$6^{1,2})" into cell A13, press "Enter," then select cells A13 through C13 (A13:C13), press the function key F2, and then press Control-Shift-Enter keys at once. Once this is done, the coefficients a, b and c will be shown in cells A13, B13 and C13 respectively and will automatically update as the flows and horsepowers in rows 3 through 4 are changed.

Fixed Speed Following Pump Curve, HP vs. GPM Flow						
Efficiency	Flow	Head	Fixed Speed HP	Fixed Speed HP Fit*	*HP = a GPM ^2 + b GPM + c	
70%	600	180	38.96	39.2	a =	-1.89E-05
77%	890	165	48.16	47.5	b =	0.0566721
78%	1190	135	52.01	52.7	c =	11.993058
66%	1490	96	54.73	54.5		

VFD Pump Following Fixed Discharge Pressure, HP vs. GPM Flow								
Efficiency	VFD Flow	Constant Head Setpoint	Pump RPM	Fixed Head w/ VFD HP	Fixed Head VFD HP Fit	*HP = a GPM ^2 + b GPM + c		
70%	490	120	2123	21.21	21.52	a =	2.01E-05	
77%	759	120	2217	29.87	29.16	b =	0.003281	
78%	1122	120	2451	43.59	44.09	c =	15.08488	
66%	1666	120	2907	76.49	76.38			

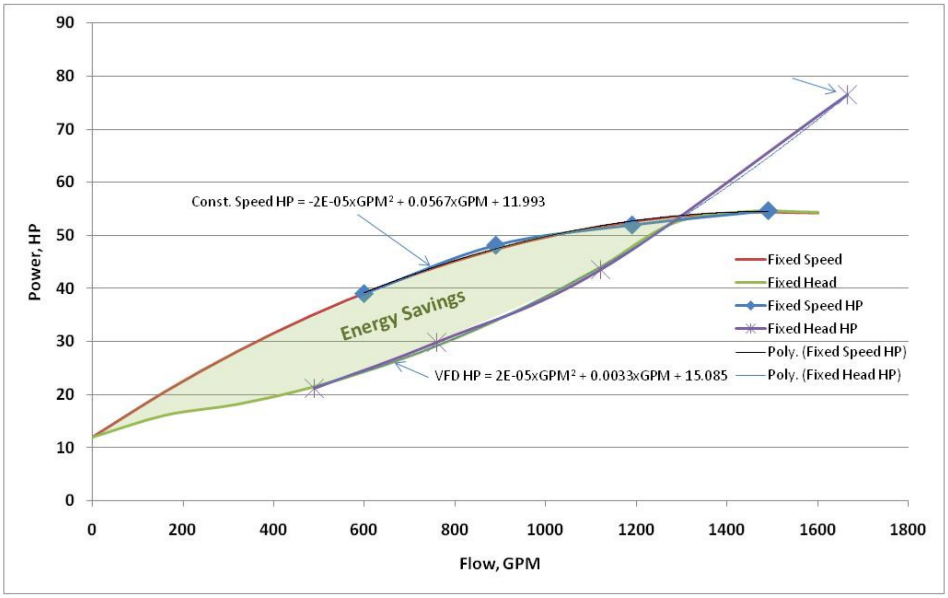


Figure 5 - HP Curves for Constant Speed and Constant Head Pump

Step 5. Use the horsepower formulas from Step 4 to determine the energy savings at each of the flow conditions of the pump, $kW = \frac{P*0.746\ kW/HP}{Motor\ Eff.}$

Case Study

A 60 HP turbine pump is used to pump water from a lake up to a hill to irrigate a golf course and a residential area. The system is capable of pumping up to 400 GPM up the hill, but the existing flow averages around 200 GPM most of the time. The owner is planning to install a variable frequency drive (VFD) on the pump motor to control the supply pressure. Currently the system has no pressure regulation. The system pressure simply follows the 60 HP pump curve shown in Figure 6. Controls on the VFD will limit the maximum pressure to 540 feet of head (234 psi).

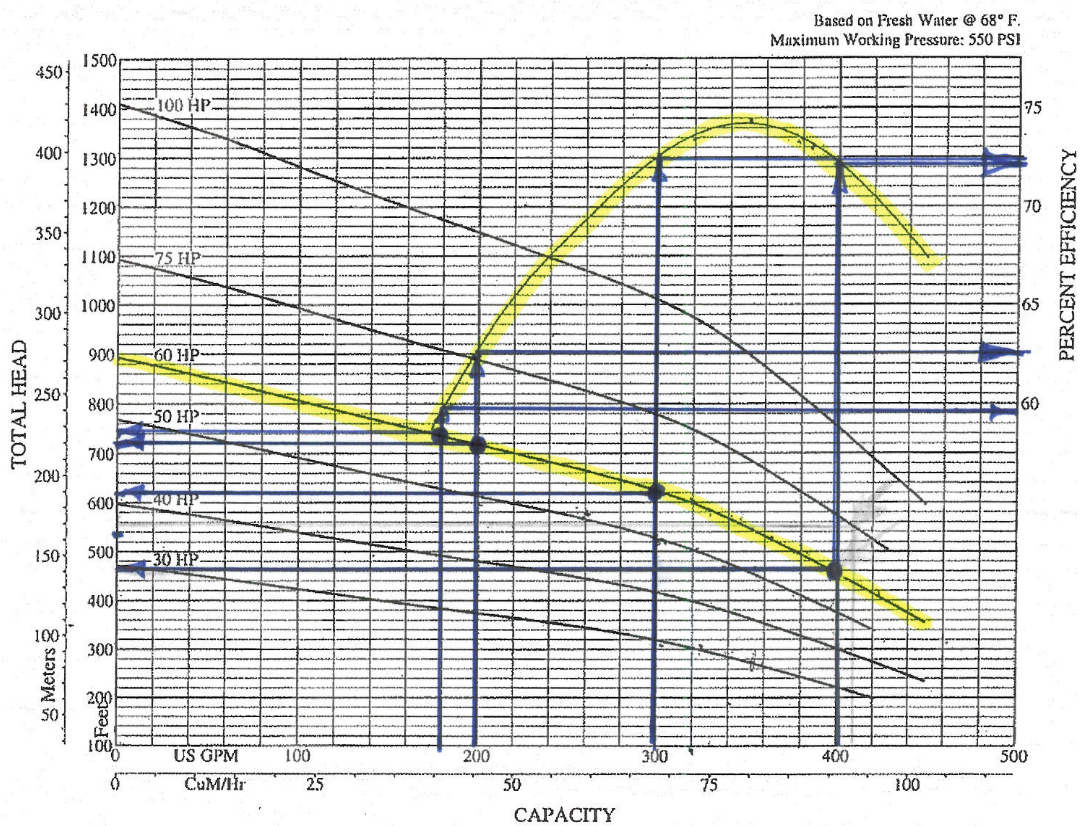


Figure 6: Pump curve for case study with selected performance points

Using points from the pump curve in Figure 6 and the affinity laws, the variable speed pump curves are calculated as shown in Figure 7. Also it is important to notice the pump must maintain a minimum speed in order to supply the pressure as defined by the VFD set point.

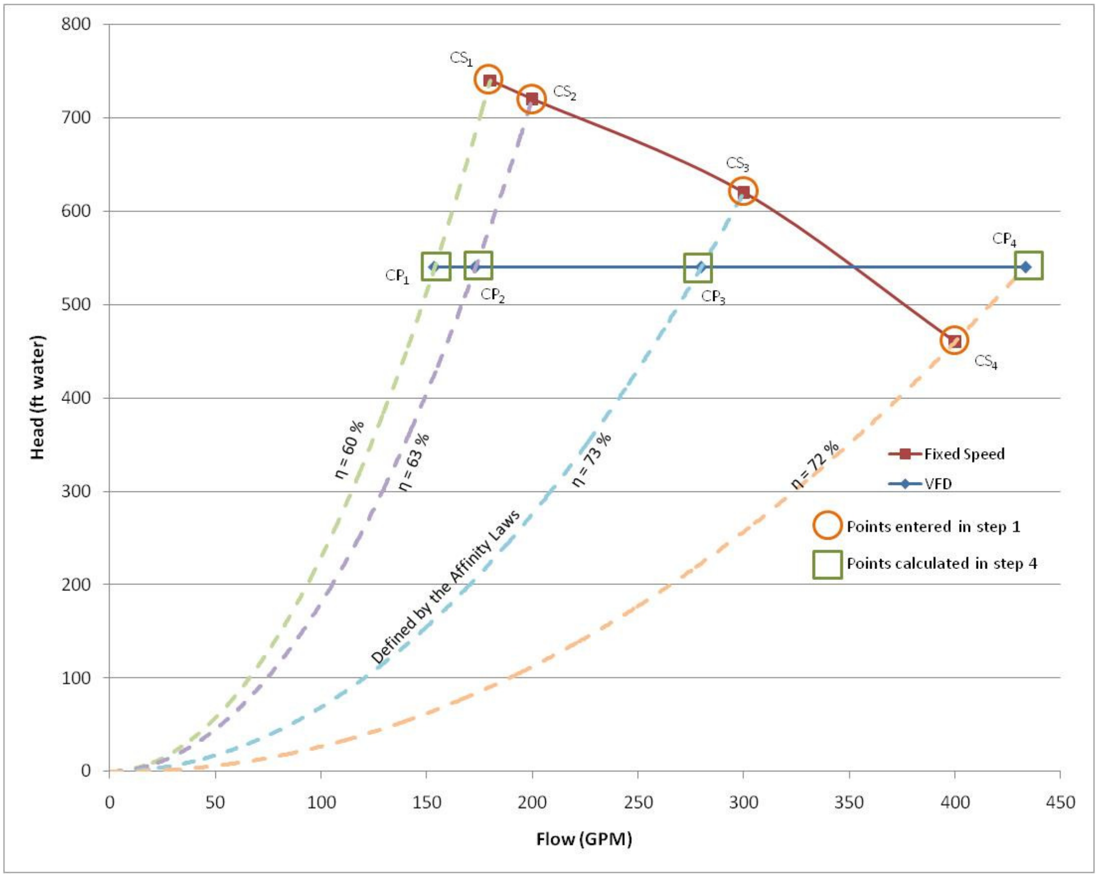


Figure 7: Variable Speed Pump Curve

When the head vs. flow curve for different speeds is known, the following steps can be used to calculate theoretical energy savings when installing a VFD on a pumping system.

Step 1. Determine the flow (Q), head (H) and efficiency (η) for three or more points along the constant speed pump curve.

Fixed Speed Following Pump Curve, HP vs. GPM Flow								
Flow	Head	Efficiency	Fixed Speed HP	Fixed Speed HP Fit	Const. Speed HP = a GPM ^2 + b GPM + c			
400	460	73%	64.09	64.12	a =	-0.000381		
300	620	72%	65.24	65.12	b =	0.2564665		
200	720	63%	58.18	58.51	c =	22.451315		
180	740	60%	56.53	56.28				

Step 2. Use the affinity law $Q_1 = Q_2\sqrt{\frac{H_1}{H_2}}$ and constant efficiency lines to define the flow rates and efficiencies through the variable speed pump running at different speeds to maintain a constant pressure.

$$Flow\ with\ VFD = \ Flow\ at\ Constant\ Speed\ \sqrt{\frac{Constant\ Pressure\ Head}{Head\ at\ Constant\ Speed}}$$

From Pump Curve			Const. Press.
Flow	Head	Efficiency	Flow
400	460	73%	434
300	620	72%	280
200	720	63%	173
180	740	60%	154

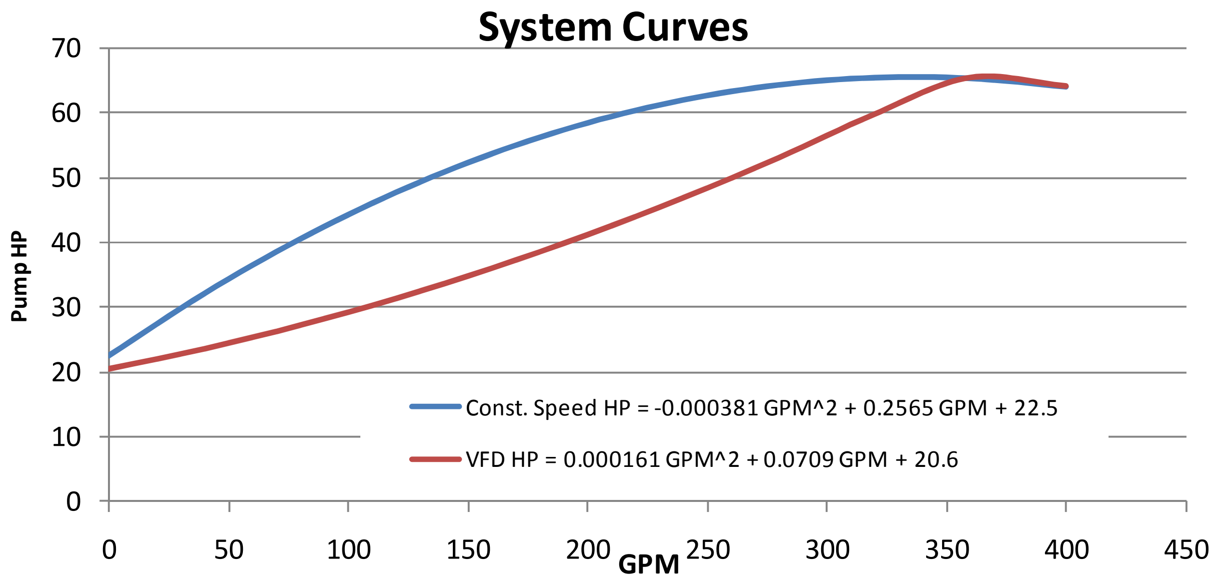
Step 3. Determine the horsepower of the constant speed and variable speed pump for each of the flows and efficiencies found in Steps 1 and 2 using the formula.

$$P = \frac{QH}{(3960)(\eta)}$$

Step 4. Using the process described in Step 3, determine the polynomial coefficients a, b and c that define the variable speed pump's horsepower at different flow rates and a constant discharge pressure.

VFD Pump Following Fixed Discharge Pressure, HP vs. GPM Flow							
Efficiency	Flow	System Head	Pump RPM	Fixed Head w/ VFD HP	VFD HP From Best Fit	VFD HP = a GPM ^2 + b GPM + c	
73%	434	540.54	1951	81.64	81.63	a =	0.000161
72%	280	540.54	1681	53.11	53.13	b =	0.07089
63%	173	540.54	1560	37.85	37.76	c =	20.64609
60%	154	540.54	1538	35.29	35.36		

Note: The maximum speed of the variable speed pump is typically limited to the speed of the constant speed pump, so the actual HP of the variable speed pump may not reach the values shown in the table above. The speed of the variable speed pump is determined using the relationship $\frac{N_1}{N_2} = \left(\frac{Q_1}{Q_2}\right)$.



Step 5. Estimate the percentage of time that the pump operates at various flow rates. Note that there may be a percentage of time when the pump is OFF, which is different than when the pump is running with little or no flow.

% Time	0%	0%	0%	0%	0%	5%	40%	30%	10%	5%	5%	5%	100%
% of Design Flow	OFF	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	Total
Flow Rate	-	-	40	80	120	160	200	240	280	320	360	400	GPM

Step 6. For each of the flow rates identified in Step 5, calculate the horsepower for the constant speed and variable speed pump using the coefficients and formulas found in Steps 4. Then calculate the annual energy savings using the formula:

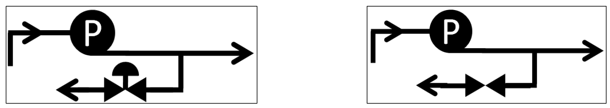
$$kWh_{savings\ per\ bin} = \frac{(HP_{Constant\ speed} - HP_{VFD})(Hrs/Yr\ at\ bin\ flow)(0.745\frac{kW}{HP})}{(\eta_{motor})}$$

% Time	% Design Flow	Design Flow, gpm	Fixed Speed HP	Fixed Head w/ VFD HP	Fixed Head HP Savings	Fixed Head kWh Savings	Baseline kWh	
0%	Pump OFF	-	-	-	-	-	-	
0%	0%	0	22.5	20.6	1.8	-	-	
0%	10%	40	32.1	23.7	8.4	-	-	
0%	20%	80	40.5	27.3	13.2	-	-	
0%	30%	120	47.7	31.5	16.3	-	-	
5%	40%	160	53.7	36.1	17.6	3,188	9,718	
40%	50%	200	58.5	41.3	17.3	24,963	84,651	
30%	60%	240	62.1	46.9	15.1	16,433	67,348	
10%	70%	280	64.4	53.1	11.3	4,088	23,295	
5%	80%	320	65.5	59.8	5.7	1,036	11,850	
5%	90%	360	65.4	65.4	-	-	11,833	
5%	100%	400	64.1	64.1	-	-	11,595	
100%						**49,708**	**220,290**	
						23%	**Savings**	
						828	**kWh/Year/HP**	

Note: Motor efficiency η_{motor} is equal to 88%.

Other Considerations

The type of pressure regulation in place in the system affects the potential for energy savings. Power for a bypass system is constant when the pump is running at a constant speed, because the flow and pressure of the fluid running through the pump does not change. Flow through the pump is always the same because excess water is spilled back into the source if not needed by the system after it passes through the pump. A bypass system is illustrated in Figure 8.



(a) Automatic (b) Manual

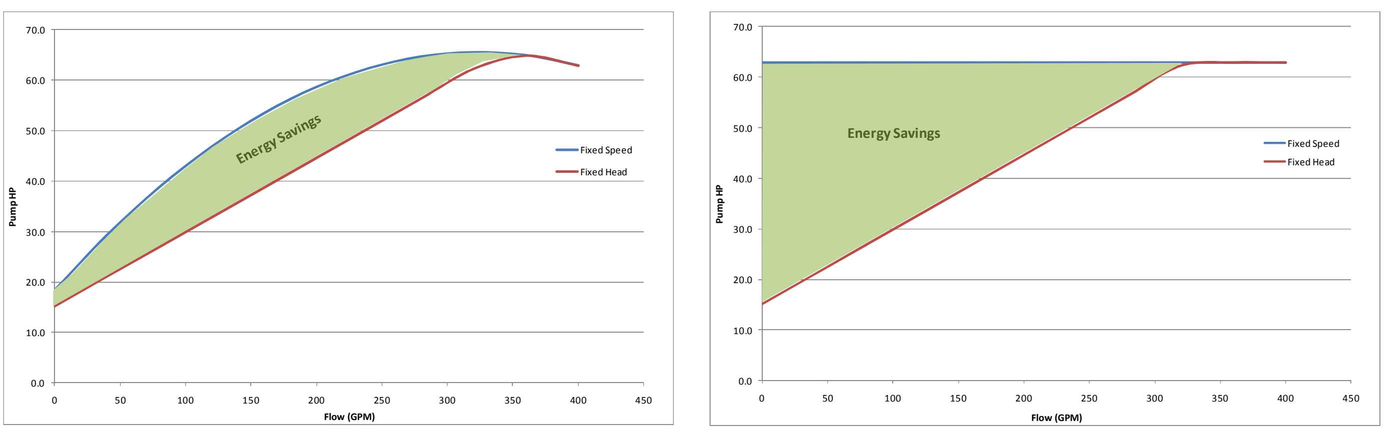
Figure 8: Bypass System Types

The discharge pressure of a constant speed pump will go up and down depending on the amount of flow through the pump and its performance curve. To keep the pressures from getting too high, a pressure reducing valve (Cla-Val) is sometimes installed.

(a) No pressure control (b) Pressure Reducing Valve

Figure 9 – Non-Bypass System

Potential energy savings for bypass and non-bypass systems are illustrated in Figure 10.



(c) Non-Bypass System (a) Bypass Valve

Figure 10: Energy savings for different pressure control types

Measuring Actual Energy Savings

Most irrigation pumping systems have a revenue meter that records the total energy consumed by the pump for each month. The total kWh consumption varies by month depending on the customer's irrigation needs. Average kW is calculated to account for the different number of days in each month's billing period.

Each month's average kW is then plotted in box plot to see if the variation in monthly energy usage and to determine actual energy savings.

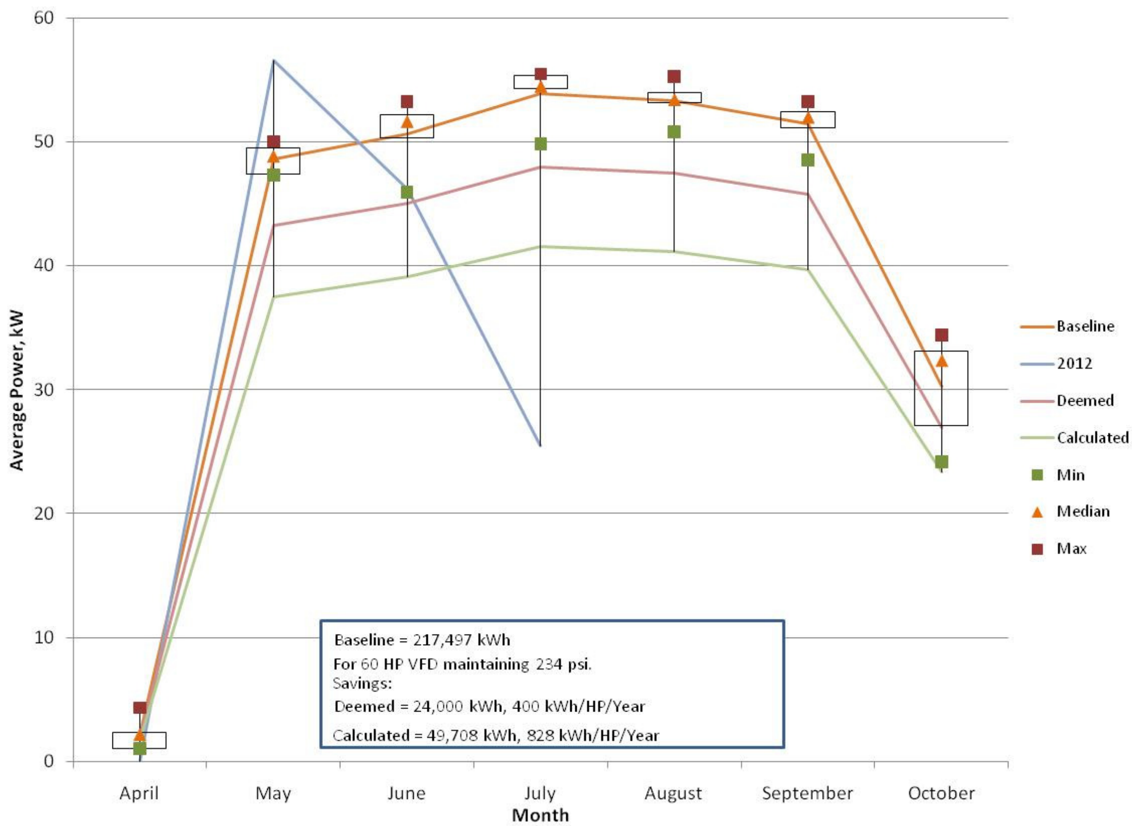


Figure 11 - Box Plot of 60 HP Irrigation Pump