EFFICIENCY PARAMETERS FOR VARIABLE FREQUENCY DRIVES ON PUMPS IN OPEN SYSTEMS

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ABSTRACT

Variable speed, variable frequency drives are a common "no-brainer" application to improve energy efficiency. However, on pumps in open systems with a significant static head, the energy savings can be much less than a shortcut application of the affinity laws would indicate. Indeed, in some cases in the authors' experience, VFDs have been found to actually use more energy.

This paper discusses energy-saving applications for two methods of control: on/off and throttled. In most cases, on/off control is more efficient than variable speed operation.

For pumps in throttled systems, we present a parametric series of curves which enable the reader to make a quick judgement of the cost-effectiveness of an application. The charts are arranged by motor size and hours of use with payback lines for various combinations of static pressure and flow.

Background

In HVAC applications and recirculating systems VFDs typically save a great deal of energy. In our energy engineering practice we are often asked to calculate energy savings to be expected from installing VFDs on various systems. While VFDs usually save energy, the savings are often less than shortcut applications of the affinity laws would indicate and occasionally are negative.

In throttled systems with relatively high static head, energy savings may be considerably less than predicted by such shortcuts.

In systems that operate on/off, VFDs are seldom cost-effective and may actually use more energy. Over the years, we have often explained to a disappointed facility operator why a VFD does not save energy compared to on/off control.

This paper was developed to explore when VFD savings may be considerably less than predicted by commonly employed rules of thumb, particularly in open systems where the static head is a significant component of the total head.

Scope

In this paper, we explore the cost-effectiveness of variable frequency drives (VFDs) in open systems. We conducted a parametric analysis based on various conditions of static head and flow. Both flow and head are normalized for general application. Static head is expressed as a percent of total design head. Flow is expressed as a percent of design flow. The graphical results in this paper indicate the expected payback period as a function of flow and static head.

Note: although the terms are often used interchangeably, we use the term variable frequency drive (VFD) to distinguish from other older and less-efficient variable speed drive (VSD) technologies.

Open Systems

In an open system, in contrast to a recirculation system, each gallon goes through the pump only once. An open system typically pumps either to or from a vessel which is open to the atmosphere. Open systems are common in industry, notably the water and wastewater industries. Examples of pumps in open systems and their typical method of control are listed in Table 1.

Table 1. Examples of Pumps in Open Systems and Common Control Methods

Application	**Typical method of control**
Industrial transfer pump	on/off, throttled
Well water pumps	on/off
High-lift pumps providing drinking water to standpipes	on/off
Wastewater pumping stations	on/off
Wetwell pumps	on/off, VSD
Return sludge pumps	throttled
Waste sludge pumps	throttled
Effluent pumps	on/off, VSD
Plant water pumps	throttled at point of use
Condensate return pumps	on/off

As shown in the table, pumps in open systems are often controlled on/off. Typically on/off control is appropriate and efficient.

On/off Control - Why a VFD Usually Does not Save Energy

We have investigated several applications of VFDs to pumps that would otherwise operate on/off. Thus far, we have not found one that is cost effective. Often facility managers are surprised to find that on/off control can be more efficient than VFD control. The misunderstanding comes from industries where recirculating systems are common, such as in HVAC. The affinity laws state that power is proportional to the cube of speed. Therefore, one may reason, that a pump operating at 80% speed would draw 51% power (0.8^3). This is a misapplication of the affinity laws.

The affinity laws indicate what happens to a pump as its speed is changed. Graphically each point on the pump curve follows a parabola that goes through the origin. In a recirculating system the system curve also goes through the origin, so the affinity law “shortcut” works and is correct. In an open system, the system curve does not go through the origin, so the shortcut doesn’t work.

On/off control is commonly used with level control to intermittently fill or empty a tank. Examples are listed in Table 1. Typically, when a pump is controlled on/off, it operates near its best efficiency point (BEP) when it is operating.

Adding a VFD to the system slows the pump down so that flow is balanced into and out of a tank with a controlled level. As the flow is reduced, the dynamic head is reduced. Since power is a function of head and flow, one would expect that reduced head would lead to reduced power. However, in on/off control situations, the pump is typically operating in a system with comparatively low dynamic head, i.e. the static head represents a significant percentage of the total head. Since slowing down the pump only reduces the dynamic component of the head, very little savings in total pump head are achieved. So the pressure savings and therefore the power savings are less than might be expected.

Reduced flow does not save energy in most on/off control systems. In an open system with on/off control, the purpose of the pump is to move fluid from one location to another. Installation of a VFD will change the instantaneous flow at the pump but will not reduce the total flow on an annual or daily basis. Reductions in flow are necessarily offset by increases in operating hours.

A VFD may make it possible to minimize pressure by constantly maintaining the minimum static head (by maximizing the level in a suction tank and/or minimizing the level in a discharge tank). Typically operators are reluctant to make significant changes and we have not found VFDs to be cost effective in these applications.

But even if the pressure is reduced only slightly and the flow reduction is not a factor, one might expect some saving from installing a VFD on an on/off control system. However, pump efficiency decreases significantly at low flows, minimizing the energy savings opportunity from VFDs. The reduction in pump efficiency, combined with the energy required to operate the VFD itself, often offset the reduction in total head, resulting in little or no savings. If there are substantial hours at very low flows, an additional small pump which is efficient at the low flow may be cost effective and should be analyzed.

Throttled Control

When compared to throttled control, a VFD will usually save energy. A throttled pump delivers the flow desired by the end-use. As flow varies, the pump "travels along its pump curve," providing greater pressure than required by the end-use. Throttling valves reduce the pressure. In some cases flow may be throttled at the pump. In other cases, it may be throttled at the point of use.

By installing a VFD and adjusting the speed of the VFD to control supply pressure, the head developed by the pump, and therefore pump power is reduced. The heart of this paper explores the cost-effectiveness of retrofitting a VFD to various throttled pumps. In the retrofit, the throttling valve would be locked open and the VFD used to control system pressure.

This paper will give a rough idea of cost-effectiveness. If the payback determined from use of this paper is promising or borderline, we recommend that the reader undertake a more detailed analysis. To conduct a more detailed analysis, the reader will first need a specific pump curve. For assistance in conducting a more detailed analysis, the reader may use engineering principles, use software provided by pump vendors or by EPRI (ASDMaster), or refer to "Understanding the economics of variable speed pumping," Plant Services, October 1998.

Factors Affecting Cost Effectiveness

Energy savings from variable speed drives on pumps depend on several factors. The first column in Table 2 lists the factors which have a significant impact on the cost-effectiveness of VFD installations. The second column in Table 2 lists the value(s) used in this paper.

Table 2. Parameters Used in this Analysis which Affect VFD Cost-effectiveness

Parameter	Value(s)
Cost of electricity	$0.06/kWh
Horsepower of motor	10, 50, and 100 hp
Installation cost of VFD	$8,200; $12,800; and $18,400 for 10, 50, and 100 hp, respectively
Pump curve	Cornell 6H – 14"
System curve	static head as a percent of design, 0 to 80%
Operating point	flow as a percent of design, 10 to 80%
Annual hours of operation	2000, 4000, 8000 hr/yr
Method of control	Throttled

In this analysis motor efficiency is the same for both the VFD and throttled system; if the installation includes a new more efficient motor, both cost and savings would increase. Any impact of the VFD on motor efficiency is not included in this analysis. Motor efficiency used in this analysis is shown in Figure 1.

For drive efficiency we use a constant drive burden of 3% of nameplate horsepower. The equivalent drive efficiency is shown in Figure 1.

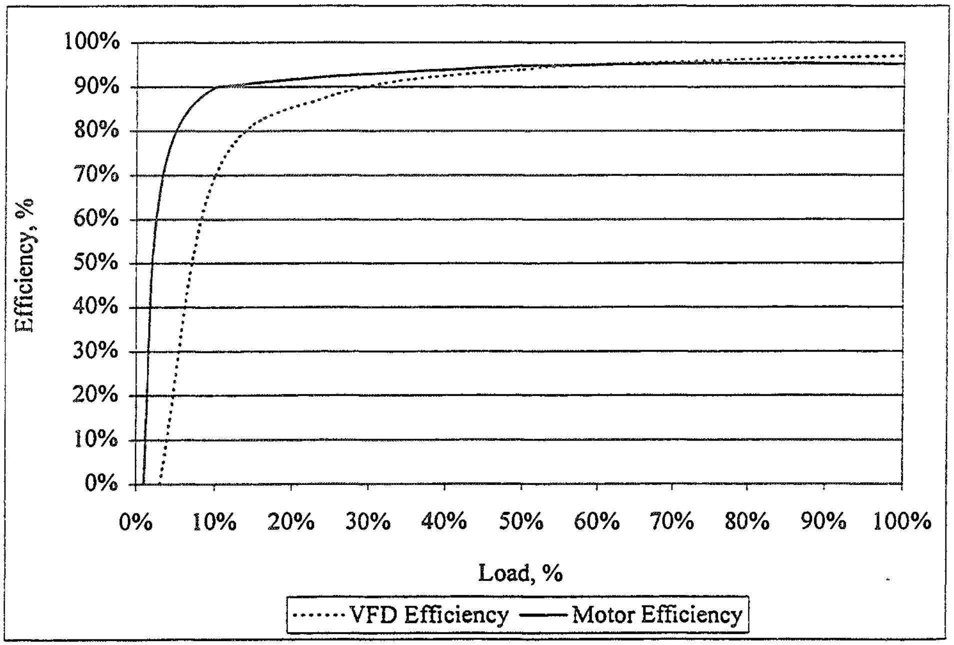

Figure 1. Motor and Drive Efficiency Used in this Analysis

Methodology

The reader will notice that both motor and drive efficiency reduce with load. Pump efficiency also generally decreases with load, so the combined overall pumping efficiency (pump efficiency * motor efficiency * drive efficiency) may decrease dramatically with load.

How Example Was Selected

The throttled pump with a specific speed of 1769 is a plant water pump at a large wastewater treatment plant. This 100-hp pump is a Cornell model 6H - 14" with a best efficiency point of 2000 gpm and 160 ft at 1780 rpm. From a sampling of recent projects in our energy engineering consulting practice, we chose this recent actual example as representative of pumps being analyzed for installation of VFDs.

To check of the general applicability of results using this pump, we conducted the same analysis on a 125-hp Allis-Chalmers NSY 16 x16 x 20 return sludge pump with a rotational speed of 858 rpm and a specific speed of 5048. We found that the results were generally consistent for flows above 50% and that the payback period for flows under 50% was generally faster than indicated by the charts included in this paper. We expect that pumps with higher specific speeds will have faster payback periods.

The 100-hp pump curves represent the Cornell pump directly. Because installed cost is not proportional to horsepower, we also developed charts for 10-hp and 50-hp pumps. We used the pump affinity laws to develop the pump curves for the 10-hp and 50-hp pumps based on the same pump geometry operating at a slower speed. The full speed pump performance curve is shown in Figure 2 below.

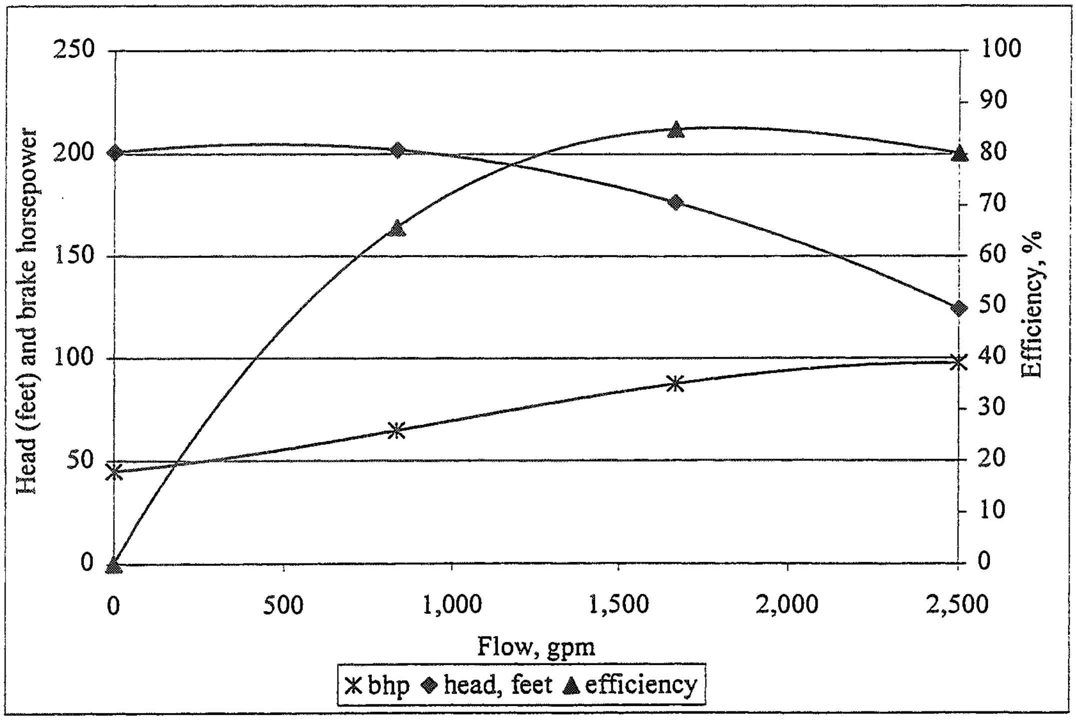

Figure 2: Full-speed Pump Performance Curve

How Charts Were Developed

In actual systems, the system curve may intersect the pump curve anywhere along its length. However, designers attempt to choose a pump to operate near its best efficiency point (BEP). For simplicity, we assume that the system curve intersects the pump curve at the best efficiency point (BEP). When employing the charts given in this paper, if the reader does not know the BEP, he should use the design point. As long as the design point is near the BEP, we feel that the analysis presented here is valid for a first estimate. The further the design point is from the BEP, the lower the accuracy of results obtained from the charts presented here. Note: If the design point is to the right of the BEP then pump efficiency will initially increase with decreasing speed, making the results shown here conservative.

In our analysis flow does not exceed BEP. If the reader's flow exceeds BEP flow then we recommend that the reader employ the design point when using these charts.

Basis of and How to Correct for Electric Cost

The charts in this paper use $0.06/kWh for electrical costs. This cost was chosen to represent the median cost of electricity including demand charges and all other ancillary charges. To correct the results for your cost of electricity, simply multiply the resulting payback period by 0.06 and divide by your cost per kWh.

Basis of and How to Correct for VFD Cost

The VFD costs are meant to be reasonable estimates of the total cost to retrofit a VFD on an existing pump. Based on our experience, we estimate the total installed cost including all parts and labor required to purchase, install, and interface the VFD with an existing energy management or process control system. Our cost estimate also assumes that the VFD is being installed as a stand-alone project. If your costs are known to be different from those given here, the payback can easily be adjusted for installation cost; simply multiply the resulting payback by your known cost and divide by the cost given in Table 2.

Basis of and How to Correct for Operating Hours

We provide charts with three examples of operating hours. 2000 hours represents one-shift operation. 8000 hours is approximately full-time operation to represent pumps which operate continuously. 4000 hours is approximately half of the year and is common for situations where a pump runs continuously but two pumps exist and are alternated into service.

Results

How to Use Charts

In this section we present graphical results for use by the reader. The purpose of these charts is to allow the reader to quickly estimate the potential payback for installing a

VFD on a pump which is currently throttled. To use the charts the reader needs the following information about the candidate system:

- horsepower of motor
- annual hours of operation
- information on pump
  - head at BEP or design point, ft
  - flow at BEP or design point, gpm
- static head as a percent of BEP or design point
- typical flow as a percent of BEP or design point

If BEP is not known, use the design point. First, knowing the horsepower and annual operating hours, identify the chart that most closely matches your situation. If your motor size does not exactly match one of the given charts, using the chart for a smaller motor will provide a more conservative (i.e. longer) payback period.

Second, move along the x-axis to the flow calculated as a percent of design flow.

Third, move up on the chart to the line that most closely matches the static head as a percent of design head.

Last, move to the left to read payback period in years.

Graphical Results

Figure 3 shows our results for a 100-hp pump operating 8000 hours per year. The curved lines on the chart represent various conditions of static head as a percent of total BEP (or design) head. As an example, suppose we know the following information:

- horsepower of motor: 100
- annual hours of operation: typically two of three pumps operate; 5840 hours/yr
- information on pump
  - head at BEP: 160 ft
  - flow at BEP: 2000 gpm
- static head as a percent of BEP: 128/160 = 80%
- typical flow as a percent of design point: 1200/2000 = 60%

Using this information and the chart in Figure 1, we see that at 60% flow and 80% static head, a payback period of 2.5 years can be expected if the pump operates 8000 hours per year. Since the pumps actually operate only 5840 hr/yr, we adjust the results by the ratio of 8000/5840 or 1.37, resulting in a payback period estimate of 2.5*1.37 = 3.4 years.

Figures 3 through 11 show our results of payback period for installing a VFD on a throttled pump. Figures 3, 4, and 5 show a 100-hp pump operating for 2000, 4000, and 8000 hours per year, respectively. Figures 6, 7, and 8 show a 50-hp pump operating for 2000, 4000, and 8000 hours per year, respectively. Figures 9, 10, and 11 show a 10-hp pump operating for 2000, 4000, and 8000 hours per year, respectively.

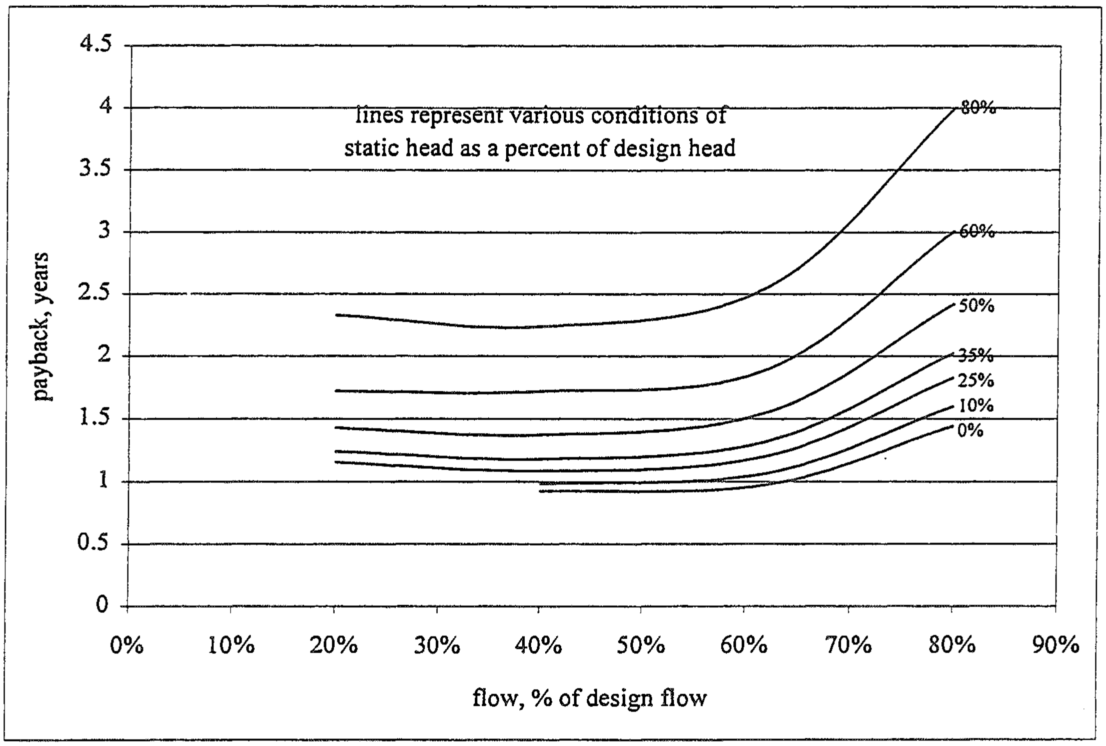

Figure 3. 100-hp Throttled Pump Operating 8000 Hours/year

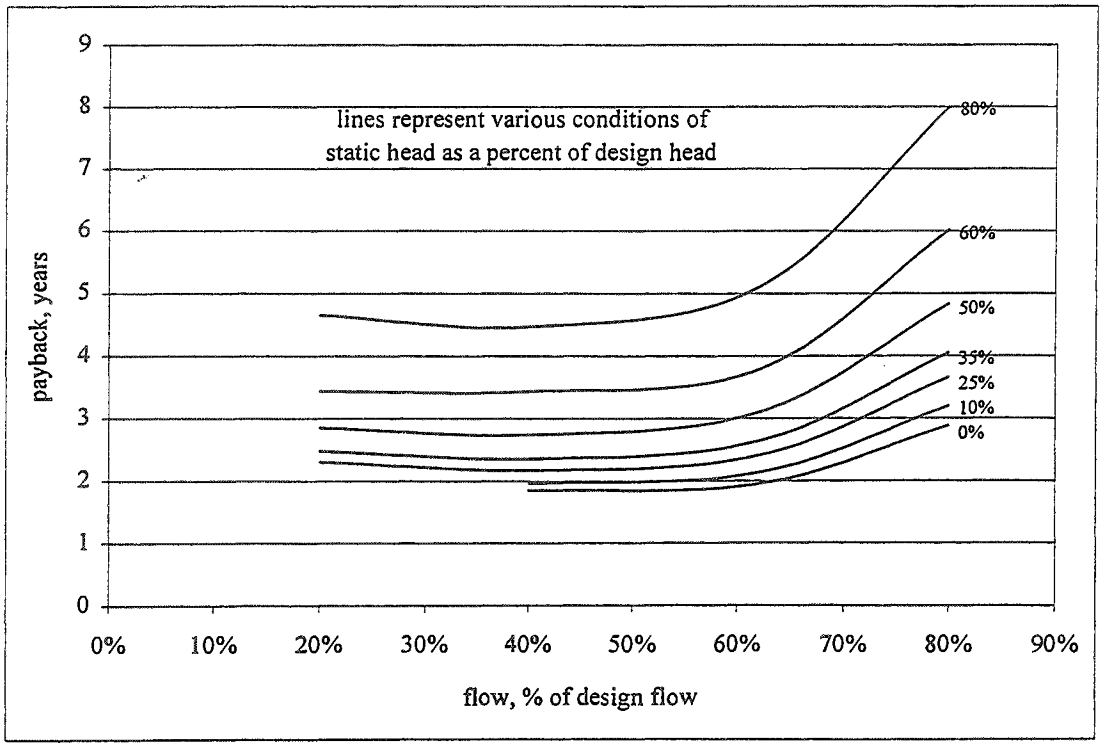

Figure 4. 100-hp Throttled Pump Operating 4000 Hours/year

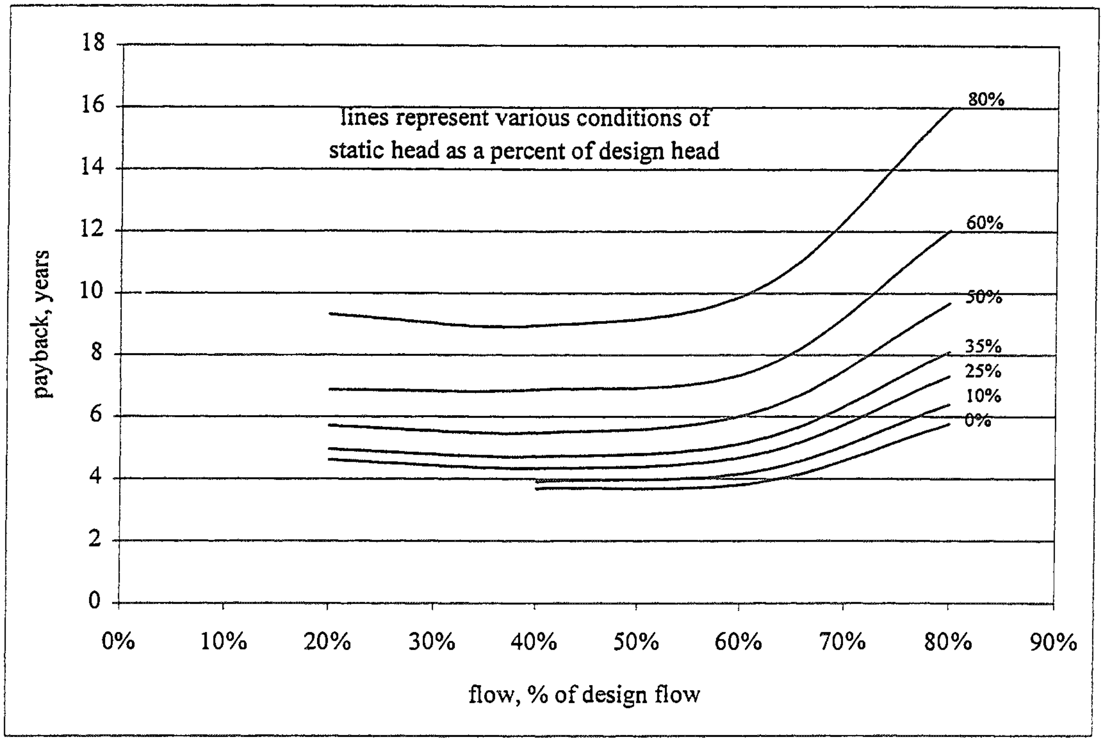

Figure 5. 100-hp Throttled Pump Operating 2000 Hours/year

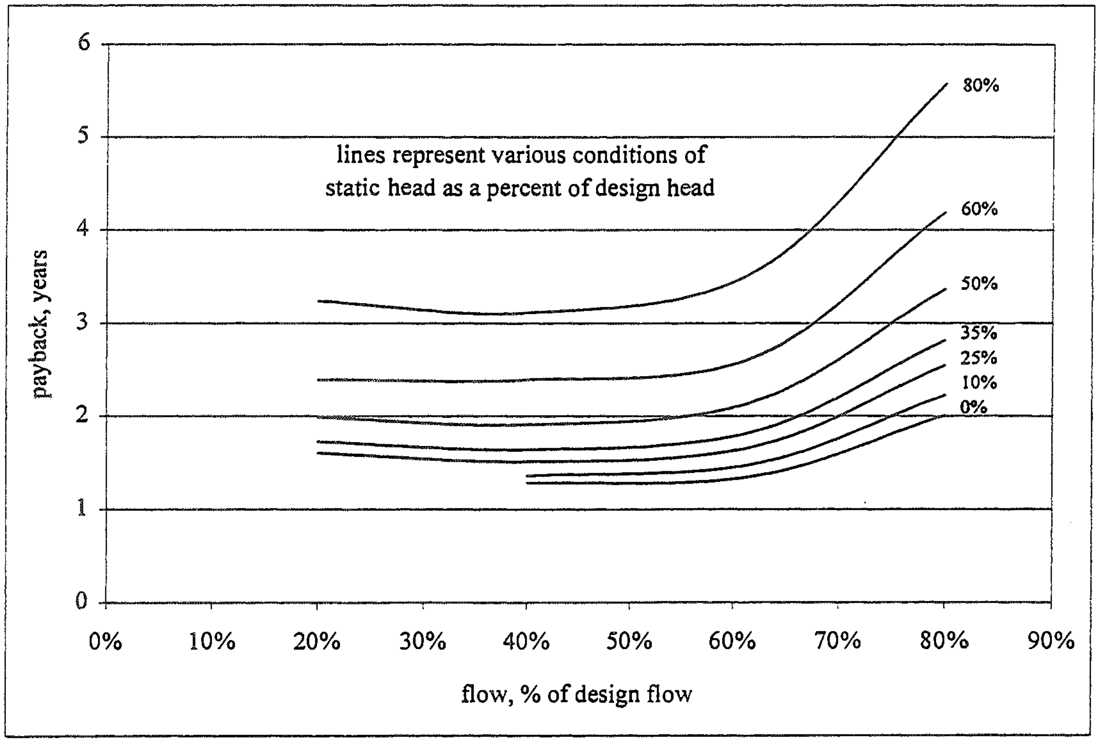

Figure 6. 50-hp Throttled Pump Operating 8000 Hours/year

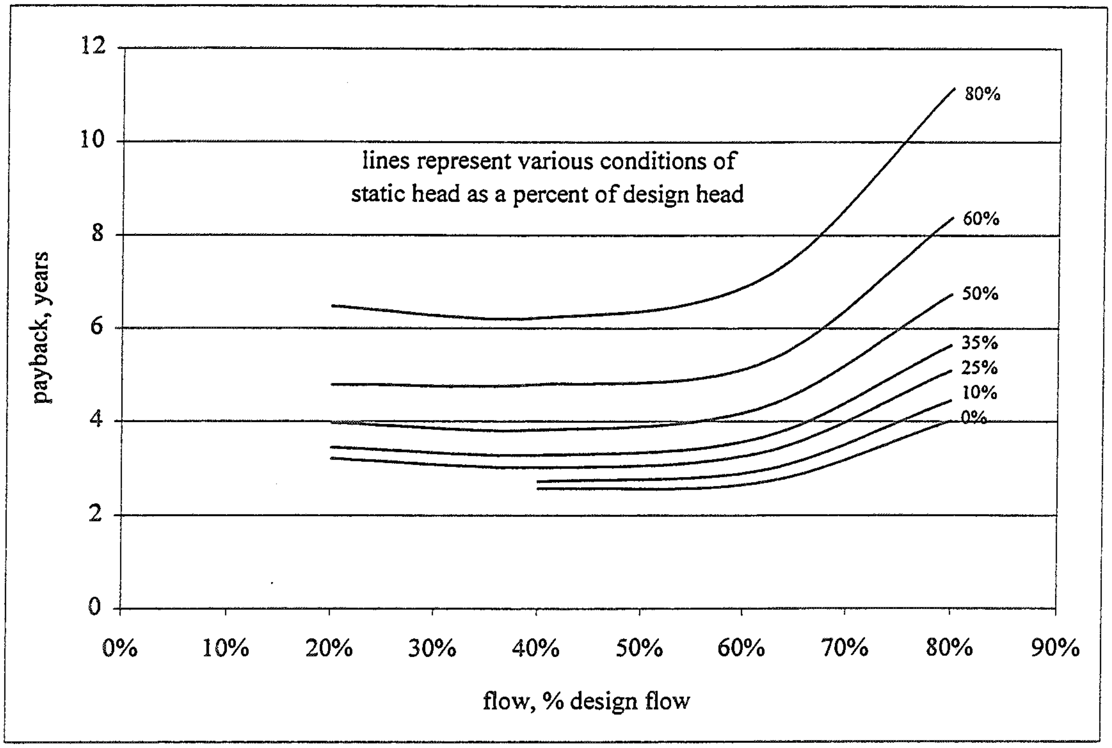

Figure 7. 50-hp Throttled Pump Operating 4000 Hours/year

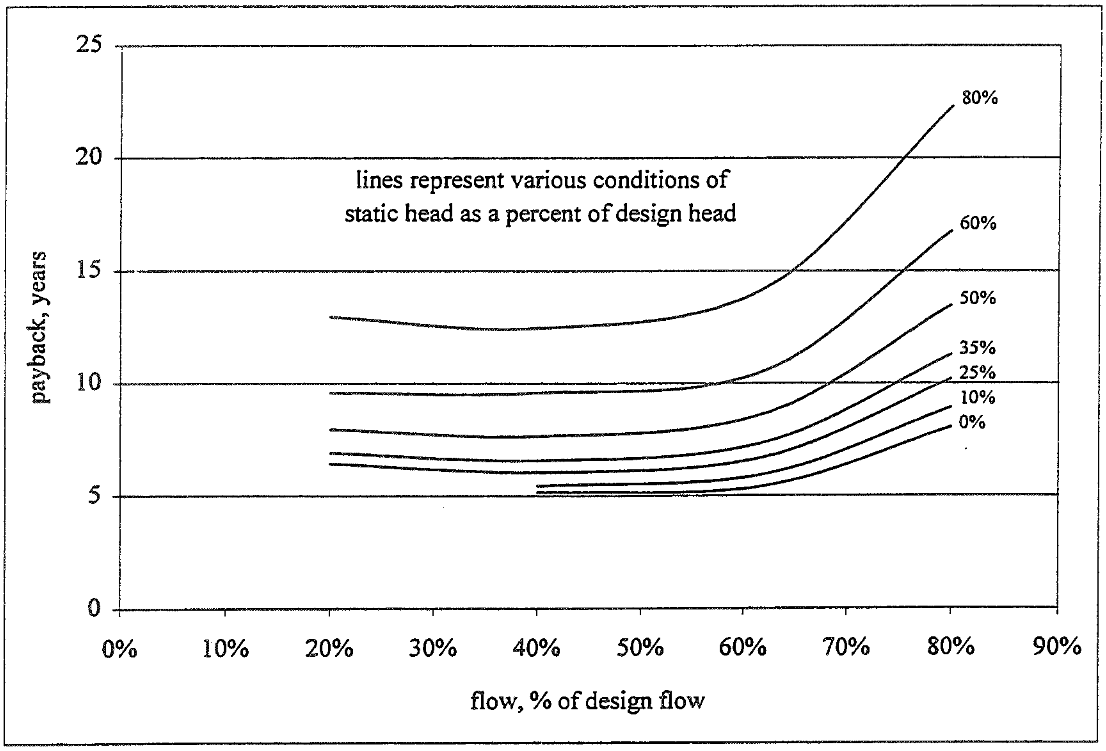

Figure 8. 50-hp Throttled Pump Operating 2000 Hours/year

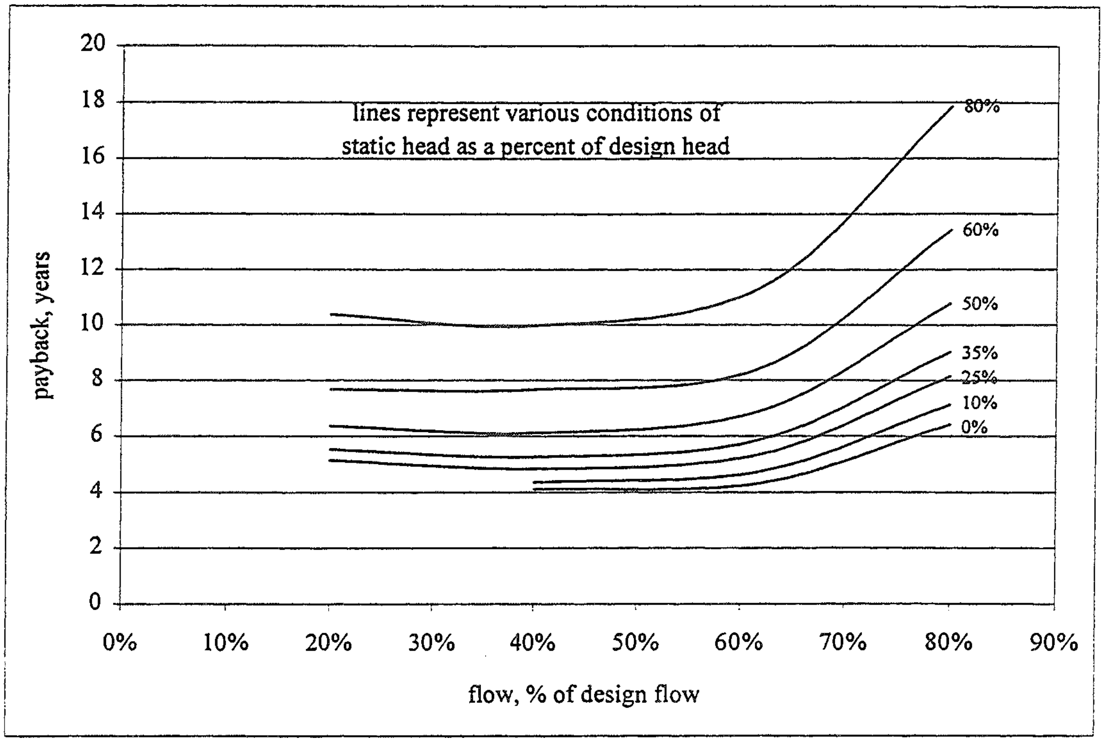

Figure 9. 10-hp Throttled Pump Operating 8000 Hours/year

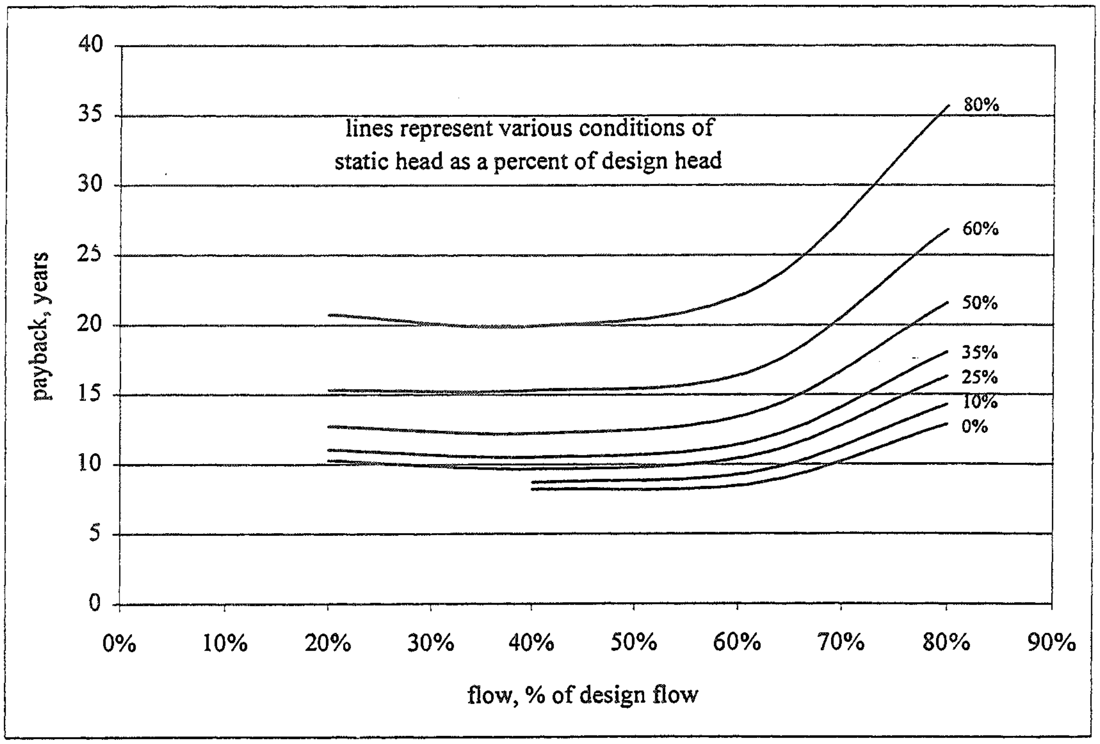

Figure 10. 10-hp Throttled Pump Operating 4000 Hours/year

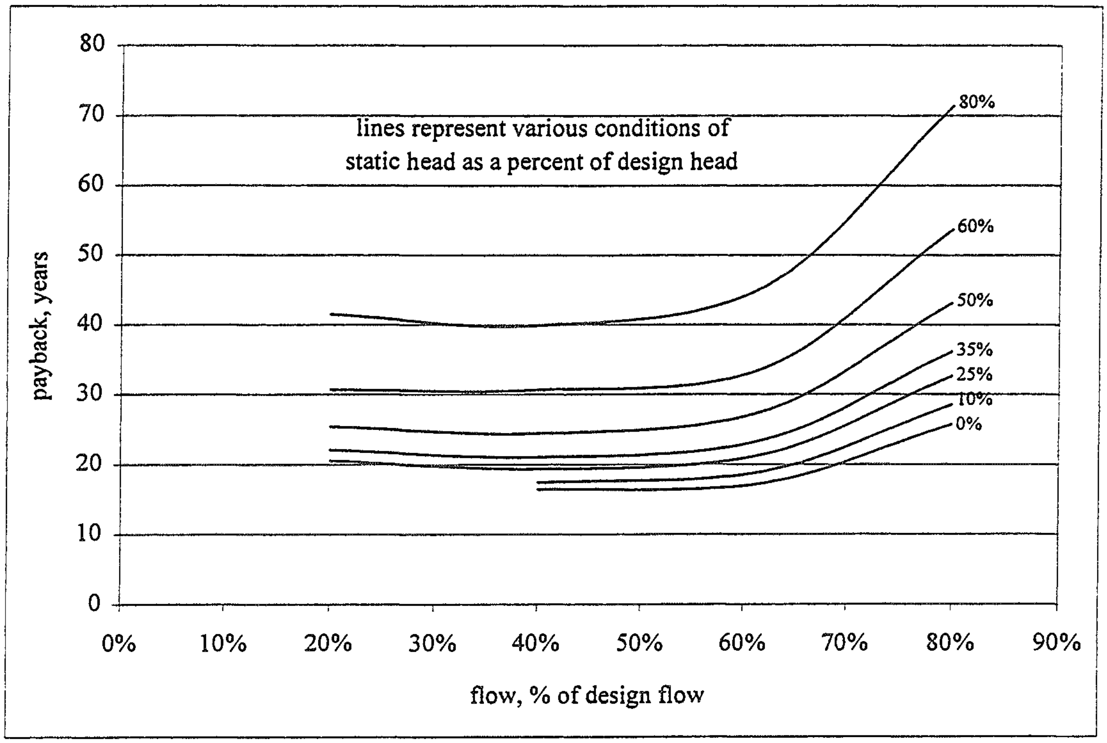

Figure 11. 10-hp Throttled Pump Operating 2000 Hours/year

Conclusions

VFDs can save energy in many applications. VFDs on recirculating systems are generally known to save considerable energy. Shortcut application of the affinity laws that are correct and appropriate for recirculating systems can greatly overstate the energy savings for VFDs on open systems.

VFDs on throttled pumps in open systems can be cost-effective, particularly on pumps with high horsepower, low static head, and/or high hours of use.

VFDs seldom save energy compared to on/off control.