

Getting it Right, Applying a Systems Approach to Variable Speed Pumping

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Abstract

It is fairly common that variable speed pumping is misunderstood and that variable speed drives are at times applied in situations where they should not be used. This paper gives a review of proper and improper use of variable speed drives and explains how the operating point of the pump and hence the possible energy savings depend on system parameters not connected to the pump, *but the system*.

A review of the concept of specific energy for a pump system, the cost of pumping as a function of speed, static head, motor-, pump-, drive-efficiencies and the duration curve is made. It is shown how a systems approach has to be used in order to achieve the best possible result from an energy point of view.

The paper compares energy uses for different control methods such as on-off regulation, throttling, and by using variable speed drives

The presentation includes examples of a good and a bad application for variable speed drives.

1 Introduction

Many times, variable speed pumping can save a tremendous amount of energy and sometimes actually increase the energy consumption. It is therefore important to understand when to use them and when not to use them.

A common reason for using variable speed drives (VSDs) is to correct for over-sizing. That most pump systems are oversized should not be a surprise to anyone. Accurately calculating the required head and rate of flow to be delivered by pumps is difficult. Safety margins are therefore usually added during the design phase. In addition, flow resistance often increases with time and flow requirements often are set to accommodate possible future increases. When all of these factors are considered, it is easy to understand why most systems are oversized and capable of providing more flow than needed.

A systems approach to evaluating pumping systems starts at the process demand. When a system is designed, many different solutions will usually be able to fulfill the process demands. The task of the designer will then be to choose the most cost effective of these solutions. This paper will discuss some tools and methods that can be used when comparing different system solutions.

2 System Flow Demand/Variations

There are a number of alternative solutions, such as throttling, speed regulation or bypass control, which can be used to control the rate of flow.

The process demands will generally dictate the type of control system needed. For example: Do the system rate of flow/head requirements change with time? Is it necessary to be able to accurately control the rate of flow? Are the changes in flow requirements continuously variable and spread over a relatively broad range, or at a few discrete flow rates? How large is the desired rate of flow and how does it vary in time? The answer to these questions will give guidance to the design of the system and also to the size and maybe numbers of pumps that have to be used. It may seem like the above questions are obvious. However, it is surprising how often these issues are overlooked.

The flow demand in a system and its variation in time can easily be presented using a duration curve, which shows how many hours a certain rate of flow is exceeded. The highest demand will thus be shown to the far left in the diagram. See Figure 1.

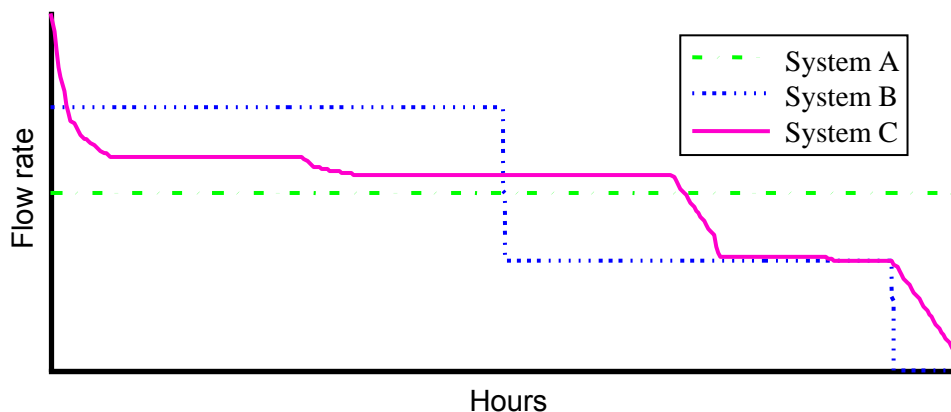


Figure 1: Example flow duration curves

Examples of duration curves for three different systems are shown. The total flow required (i.e., the area under each curve) is the same for the three systems, but the distribution is obviously quite different. This type of curve is a good starting point for overall system analysis.

Further consideration, such as the relationship between system flow and head requirements, is needed to fully understand system requirements and optimize design. But even a casual review of the three duration curves shown in Figure 1 reveals that the kind of pumping configuration that is suitable for System A (a single-size pump, selected to operate efficiently at the constant flow requirement) would be less than optimal for either System B or C.

3 Flow Control

The two basic methods for flow control are to change 1) the system curve by throttling, or 2) the pump curve, by using a VSD. The most common option is to use a throttling valve. VSDs are almost always more efficient than throttling valves, and they will usually be more economical to use than valve regulation, especially on a life cycle cost comparison. Controlling rate of flow by by-passing some of the pumped liquid is also used in many applications, in spite of its being uneconomical.

In systems where precise control is *not* needed, other solutions besides throttling valves or VSDs, may prove to be more efficient. For example, properly sized pumps running on-off can be a very efficient solution in many systems.

3.1 Flow Regulation by Throttling

When the flow is regulated using a throttling valve, the system curve is changed. The duty point moves to the left on the pump curve, (see Figure 2) when the flow is throttled. The vertical lines in Figure 2 represent the throttling loss in the valve.

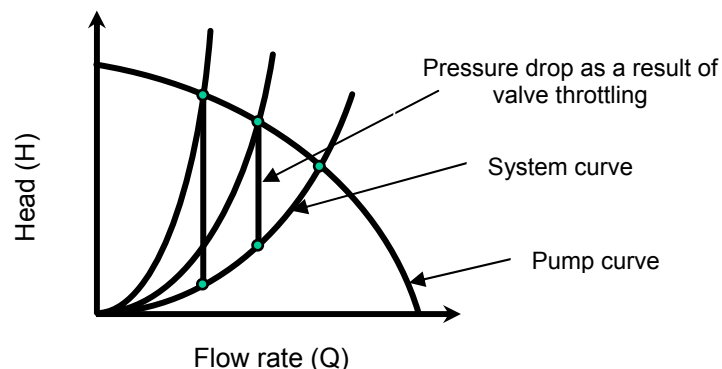


Figure 2: Throttling a valve changes the flow rate by adding pressure drop in the valve. The operating point moves along the pump curve.

The specific energy (E_s), as discussed in section 4.1, can be calculated for each such operating point by dividing the input power to the motor by the flow rate. E_s usually increases rapidly as the flow is reduced.

3.2 Flow Regulation by Using Variable Speed Drives

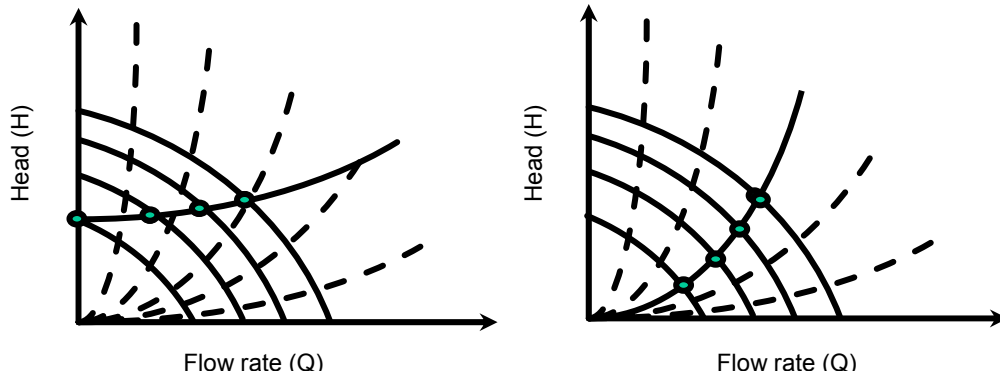


Figure 3: With a VSD, the operating point moves along the system curve. The graphs show two different system curves, one with and one without static head.

Figure 3 shows two system curves and reduced pump curves (solid lines), along with lines of constant efficiency (dashed lines), the middle one having the highest efficiency. The curves demonstrate what happens in a speed-regulated system. New pump curves are obtained as the speed is decreased. New operating points will be determined by the intersection of the system curve and a reduced pump curve. It is important to separate systems with static head from systems without static head, since they react quite differently to speed changes. In a system with static head the pump efficiency will change as the speed is changed, see the left part of Figure 3.

A variable speed drive makes it possible to adjust the output to the demand without throttling. The impact of an oversized pump can therefore often be neutralized, resulting in significant energy and cost savings. In the case of systems exhibiting a large amount of static head, however, special care has to be taken. When the speed is reduced in such a system the operating point moves higher and higher on the reduced pump curves, until the pump finally is dead-headed. It should be stressed that long before that happens, the pump leaves the preferred operating range and can experience severe damage if operated under such conditions for an extended period of time. It is therefore necessary to take a broad view of the system before deciding on what kind of control to use.

In systems without static head, however, the new operating points obtained when the speed is reduced will remain at the original efficiency as shown on the right side of Figure 3.

Variable speed drives will give good control of the flow rate except when the static head is high and the pump curve has a flat upper portion. In those situations very small changes in speed can result in very large changes in the rate of flow.

VSDs generally greatly reduce the operating cost in systems when compared to throttling valves, and in systems with little or no static head without throttling valves. In sys-

tems with high relative static head, extra care has to be taken when using variable speed drives to avoid the pitfalls of low pumping efficiency and operation in harmful flow regimes. The allowable speed range thus becomes restricted both from an operational and economical point of view. A common mistake is to use the affinity laws to calculate savings using variable speed systems. These laws cannot be used to calculate new operating points, and hence energy usage, when static head is present in the system.

3.3 Drive Efficiency

Of course, like any other active component, the drive efficiency is not 100%. Figure 4 shows motor, drive, and combined efficiency for a modern pulse width modulated drive (the most common type of drive) operated at rated speed conditions (on a two-pole, 37.5 kW motor) (see Casada, et al. 1998). The motor efficiency alone, when driven directly from the power supply (i.e., without the drive) is also shown for comparison. As can be seen, the drive efficiency is in the upper 90-percent range. The drive also causes the motor to operate at a slightly lower efficiency than when the motor is driven directly across the line. Figure 5 shows the same motor efficiency curve as Figure 4, but for the combined drive and motor curve, and uses data that represent the torque variation of a typical centrifugal load.

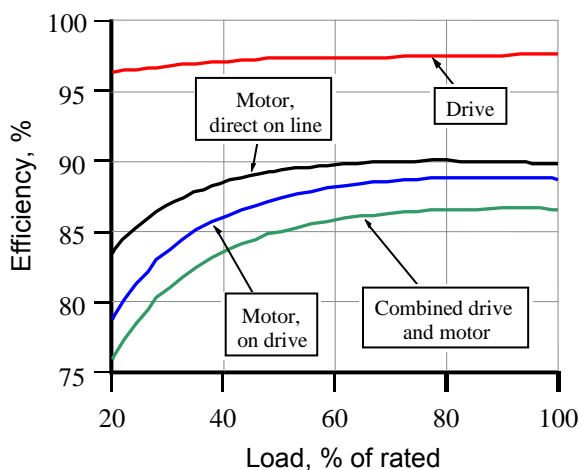


Figure 4: Motor and adjustable speed drive efficiencies at rated speed (See Casada, et al. 1998)

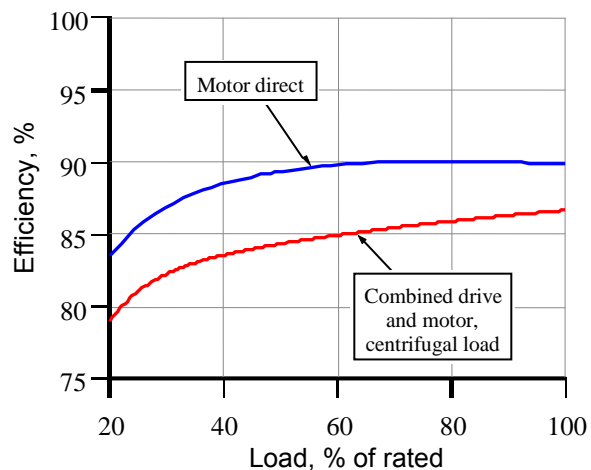


Figure 5: Motor (rated speed) and adjustable speed drive (centrifugal-type load speeds) efficiencies (see Casada, et al. 1998)

However, simply considering efficiency alone doesn't capture the essence of variable speed drives. The real saving derives from the drop in power that accompanies speed

reduction. Figure 6 contrasts the difference in shaft power between fixed and variable speed in a system *without static head*, where the shaft power is approximately proportional to the cube of the speed.

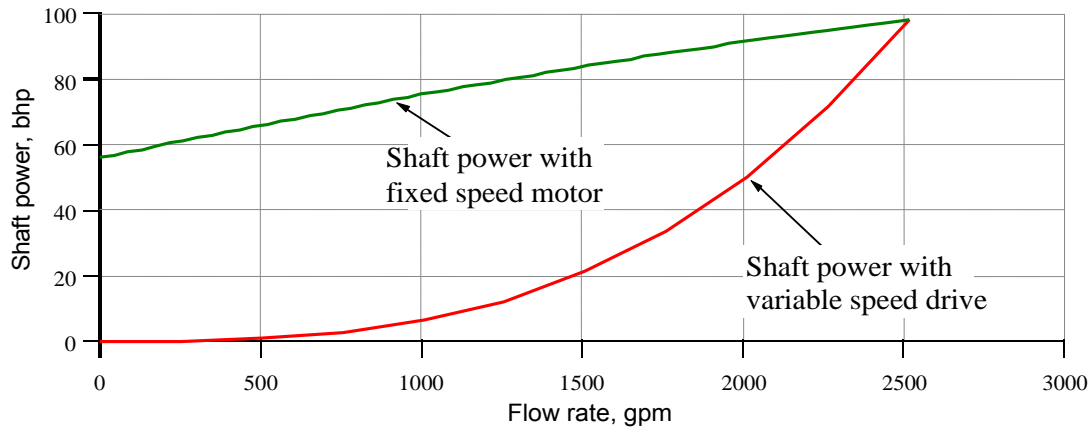


Figure 6: Shaft power requirements for a fixed and variable speed driven pump (See Casada, et al. 1998)

4 Calculating Energy Use

4.1 Specific Energy

When comparing different solutions for a pump system it is helpful to be able to easily identify the system effectiveness and to compare different solutions. A useful entity for this comparison is the specific energy:

$$(1) \quad \frac{\text{Energy used}}{\text{Pumped Volume}} = \text{Specific Energy}$$

$$(2) \quad E_s = \frac{P_{in} \cdot \text{Time}}{V} = \frac{P_{in}}{Q}$$

P_{in} = input power to the driver

In systems without static head, this is rather straightforward using the equations above. In systems with static head the energy usage can be calculated the following way. The head needed from the pump can be separated into static and dynamic (friction losses). Substituting $H_s + H_f$ for the total head in the expression for specific energy will generate the following expressions:

$$(3) \quad P_{in} = \frac{Q \cdot (H_s + H_f) \cdot \rho \cdot g}{\eta_{motor} \cdot \eta_{drive} \cdot \eta_{pump}}$$

where ρ = density, g = the gravitational const. and η = efficiency

$$(4) \quad E_s = \frac{H_s + H_f}{H_s} \cdot \frac{\rho \cdot g \cdot H_s}{\eta_{motor} \cdot \eta_{drive} \cdot \eta_{pump}}$$

$$(5) \quad \frac{H_s}{H_s + H_f} = f_{HS}$$

$$(6) \quad E_s = \frac{H_s \cdot \rho \cdot g}{\eta_{drive} \cdot \eta_{motor} \cdot \eta_{pump} \cdot f_{HS}}$$

The “Hydraulic System factor”, f_{HS} , indicates the relative amount of static head in the system. E_s now has a minimum value: $H_s \cdot \rho \cdot g$, which would occur if all efficiencies were equal to 100% and there were no friction losses. If there is no variable speed drive in the system, then η_{drive} is = 1. The different factors are all functions of the flow rate and will vary with the duty point. If a variable speed drive is used, they will vary with speed as the duty point moves along the system curve.

Motor efficiency will generally slightly decrease as the speed is lowered and the motor goes below 50% of full load. The drop in combined motor – drive efficiency can be substantial if the motor load drops below 30% of full load. The denominator: $\eta_{drive} \cdot \eta_m \cdot \eta_p \cdot f_{HS}$ can also be seen as the overall efficiency η_{gr} .

The Hydraulic System factor will increase when the friction losses go towards zero, which happens when the duty point approaches the shut off head. The specific energy will always increase drastically as the duty point moves towards shut off head in systems with static head due to reduced pump, motor and drive efficiencies. In systems with high static head, this can happen even at a relatively moderate decrease in speed. In such systems, the area of usefulness of a variable speed drive can be somewhat improved by making sure that the system curve and the full speed pump curve intersect to the right of the pump’s best efficiency point.

As illustrated in Figure 7, the savings potential is very large in systems with low static head, whereas care has to be taken in high static head situations. When the speed is low enough to cause the pump to operate at, or close to, shut-off head, the specific energy goes towards infinity. When operating below the horizontal line D, energy savings will be realized compared to on-off operation.

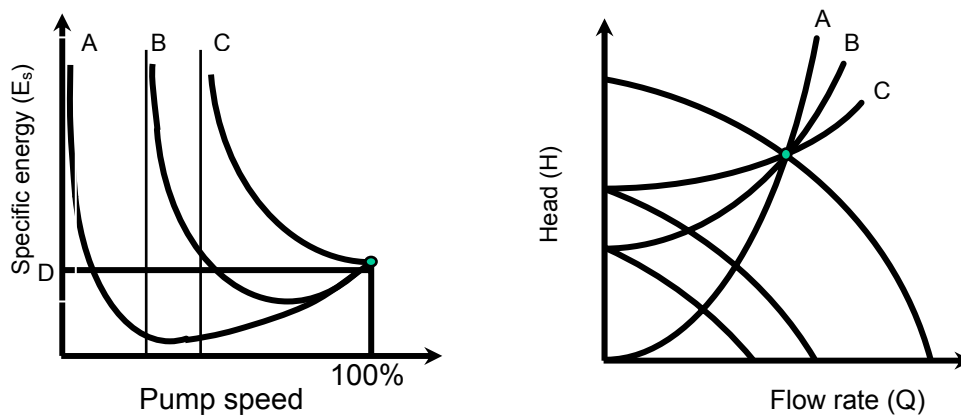


Figure 7: Specific energy as a function of pump speed for three different system curves. (Hovstadius Consulting, LLC)

4.2 Comparing Throttling and Variable Speed Drives

In a throttled system, the specific energy will increase rapidly as the flow is decreased. The specific energy for a speed regulated pump system can be higher than for an on-off regulated system, but will usually be lower and save energy compared to a throttled system. It has to be remembered though, that the ability to continuously regulate the flow is a common demand in many industrial applications and on-off regulation therefore is not always an alternative.

5 Examples

5.1 Incorrect Application of a Variable Speed Drive

A U.S. municipality uses multiple deep wells for their potable water supply. One of their deep wells installed in 1997 is approximately 500 m deep and uses a 10 stage vertical turbine pump with a 450 kW submersible motor controlled by a variable speed drive.

A recent preliminary evaluation revealed that the pump was operated between 100% and 83% speed, varying flow from 238 m³/hr to 103 m³/hr. Based on discussions with operators, three average flow intervals were used to evaluate system efficiency. Flow, head and power were measured at each interval. The results are shown in Table 1.

Table 1: Data for Flow Intervals (Process Energy Services, LLC)

Hours	Flow (m ³ /hr)	Head (m)	Pump Speed (%)	Power (kW)	Overall Eff. (%)
1800	238	451	100	488	60
1500	191	442	92	441	52
1500	103	430	83	345	35

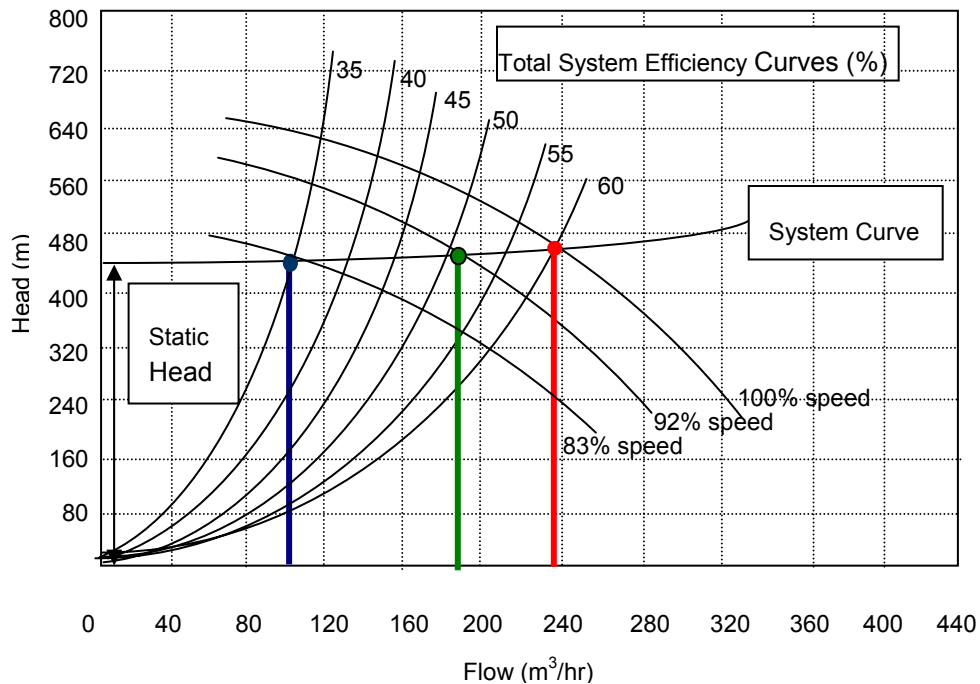


Figure 8: System Curve and Pump Performance at different speeds (Process Energy Services, LLC)

The pump system provides a total of 870 455 m³ of water annually. An overview of the pump, head curves and total system efficiency curves is shown in Figure 8. Consumption data were calculated as shown in Table 2.

Table 2: Total System kWh (Process Energy Services, LLC)

Hours	Flow (m ³ /hr)	Power (kW)	Consumption (kWh)
1800	238	488	878 400
1500	191	441	661 500
1500	103	345	517 500
		Total	2 057 400

At an average cost of \$0.13/kWh, annual energy costs with the drive installed are approximately \$267 000.

After a review of system operation, it was determined that the existing variable speed drive could be *removed* and replaced with a soft start motor control to reduce system energy costs. The new pump operating strategy would allow the pump to cycle on and off a limited number of times each day to satisfy system requirements.

Estimated energy savings from this modification is calculated as follows:

Operating the pump at full speed (after removing the variable speed drive) to provide

the same flow annually (870 455 m³) can be calculated as follows, assuming a full speed motor efficiency of 87.6% and pump efficiency of 76%:

$$\text{kW} = \text{Flow} * \text{Total Head} / 367 * \text{Total System Efficiency}$$

$$\text{kW} = 238 * 451 * / 367 * .66 = 444 \text{ kW}$$

At a flow rate of 238 m³/hr, the pump would need to operate 3657 hours annually to satisfy flow requirements. This corresponds to 1 623 874 kWh/year or 211 103 USD in annual energy costs, saving approximately 57 000 USD.

5.2 A Better Application of a Variable Speed Drive

There are many examples of how variable speed drives have saved a tremendous amount of energy. A typical result from retrofitting pump systems with VSD units at the SINOPEC Yangtze Petrochemical Company in Jiangsu Province, China gave the following results: The project included installation of 34 VSDs on existing pump systems which were generally oversized with rates of flow controlled by throttling valves (see Jiangsu Energy Conservation Center 2005). After the project was completed, the specific energy consumption of the pumps was reduced from 8.016 kWh to 5.766 kWh per ton of crude oil. 6.26 million tons of crude oil was refined in 2003. The plant thus achieved electricity savings of 14.08 million kWh/a (with 11 270 tons of CO₂ emissions reduction), amounting to 6.62 million Yuan RMB (approx. 660 000 USD). The payback period of the project was 0.48 years.

6 Summary

To understand a pumping system it must be realized that all of its components are interdependent. Sub-optimization on the component level can easily be deceptive.

If the system curve exhibits substantial static head, problems with VSD applications can occur. VSDs generally reduce the operating cost in systems when compared to throttling valves, and in systems with little or no static head without throttling valves. In systems with high relative static head, extra care has to be taken when using variable speed drives to avoid the pitfalls of low pumping efficiency and operation in harmful flow regimes. The allowable speed range thus becomes restricted both from an operational and economical point of view.

7 References

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