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Variable speed pumping: A guide to successful applications

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Authors

Tutterow, Vestal
McKane, Aimee T.

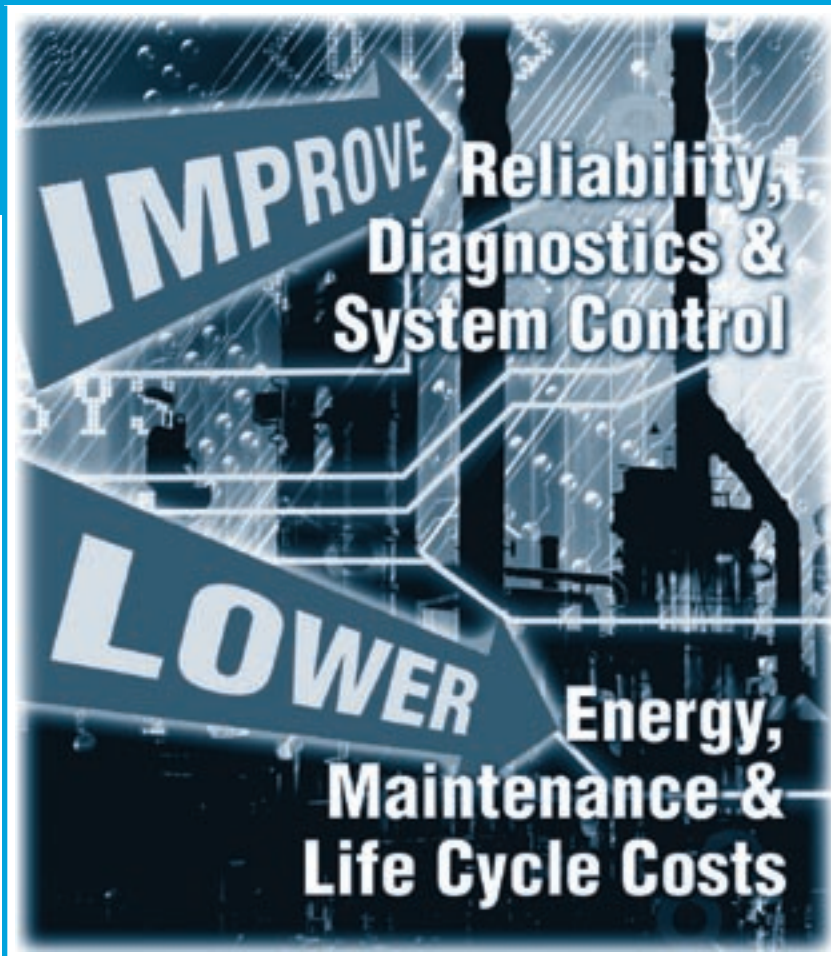
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VARIABLE SPEED PUMPING

A GUIDE TO SUCCESSFUL APPLICATIONS

EXECUTIVE SUMMARY



VARIABLE SPEED DRIVES A WAY TO LOWER LIFE CYCLE COSTS

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Acknowledgment

Variable Speed Pumping — A Guide to Successful Applications, Executive Summary is the result of a collaboration between the Hydraulic Institute, Europump, and the U.S. Department of Energy's (DOE) Industrial Technologies Program.

Introduction

Pumping systems account for nearly 20% of the world's energy used by electric motors and 25% to 50% of the total electrical energy usage in certain industrial facilities. Significant opportunities exist to reduce pumping system energy consumption through smart design, retrofitting, and operating practices. In particular, the many pumping applications with variable-duty requirements offer great potential for savings. The savings often go well beyond energy, and may include improved performance, improved reliability, and reduced life cycle costs.

Most existing systems requiring flow control make use of bypass lines, throttling valves, or pump speed adjustments. The most efficient of these is pump speed control. When a pump's speed is reduced, less energy is imparted to the fluid and less energy needs to be throttled or bypassed. Speed can be controlled in a number of ways, with the most popular type of variable speed drive (VSD) being the variable frequency drive (VFD).

Pump speed adjustment is not appropriate for all pumping systems, however. This overview provides highlights from *Variable Speed Pumping — A Guide To Successful Applications*, which has been developed by Europump and the Hydraulic Institute as a primer and tool to assist plant owners and designers as well as pump, motor, and drive manufacturers and distributors. When the requirements of a pump and system are understood, the user can consult this guide to help determine whether variable speed pumping is the correct choice. The guide is applicable for both new and retrofit installations and contains flowcharts to assist in the selection process.

Pumping Systems

A proper discussion of pumping considers not just the pump, but the entire pumping “system” and how the system components interact. The recommended systems approach to evaluation and analysis includes both the supply and demand sides of the system.

Pumping System Hydraulic Characteristics

In a pumping system, the objective, in most cases, is either to transfer a liquid from a source to a required destination, e.g., filling a high-level reservoir, or to circulate liquid around a system, e.g., as a means of heat transfer. Pressure is needed to make the liquid flow at the required rate and this must overcome losses in the system. Losses are of two types: static and friction head.

Static head, in its most simple form, is the difference in height of the supply and destination of the liquid being moved, or the pressure in a vessel into which the pump is discharging, if it is independent of flow rate. Friction head (sometimes called dynamic head loss), is the friction loss on the liquid being moved, in pipes, valves, and other equipment in the system. This loss is proportional to the square of the flow rate. A closed-loop circulating system, without a surface open to atmospheric pressure, would exhibit only friction losses.

Pumping applications with variable-duty requirements offer great potential for energy savings, improved performance, and reduced life cycle costs.

The ratio of static to friction head over the operating range influences the benefits achievable from VSDs.

Most systems have a combination of static and friction head. The ratio of static to friction head over the operating range influences the benefits achievable from VSDs. Static head is a characteristic of the specific installation. Reducing this head whenever possible generally reduces both the cost of the installation and the cost of pumping the liquid. Friction head losses must be minimized to reduce pumping cost, but after eliminating unnecessary pipe fittings and length, further reduction in friction head will require larger diameter pipes, which adds to installation cost.

Pump Types

Proper selection of pumps, motors, and controls to meet the process requirements is essential to ensure that a pumping system operates effectively, reliably, and efficiently. All pumps are divided into the two major categories of positive displacement (PD) and rotodynamic.

PD pumps can be classified into two main groups: rotary and reciprocating. Rotary pumps typically work at pressures up to 25 Bar (360 pounds per square inch [psi]). These pumps transfer liquid from suction to discharge through the action of rotating screws, lobes, gears, rollers, etc., which operate within a rigid casing. Reciprocating pumps typically work at pressures up to 500 Bar. These pumps discharge liquid by changing the internal volume. Reciprocating pumps can generally be classified as having a piston, plunger, or diaphragm, displacing a discrete volume of liquid between an inlet valve and a discharge valve. The rotary motion of the driver, such as an electric motor, is converted to the reciprocating motion by a crankshaft, camshaft, or swash-plate.

The performance of a pump can be expressed graphically as head against flow rate. The rotodynamic pump has a curve where the head falls gradually with increasing flow. However, for a PD pump, the flow is almost constant whatever the head. It is customary to draw the curve for PD pumps with the axes reversed, but for comparison, a common presentation is used here for the two pump types.

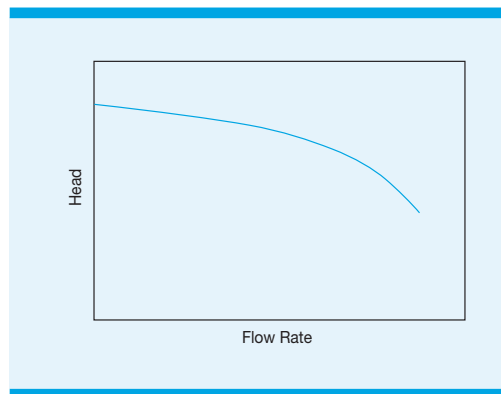


Figure ES-1.
Performance curve for a
rotodynamic pump

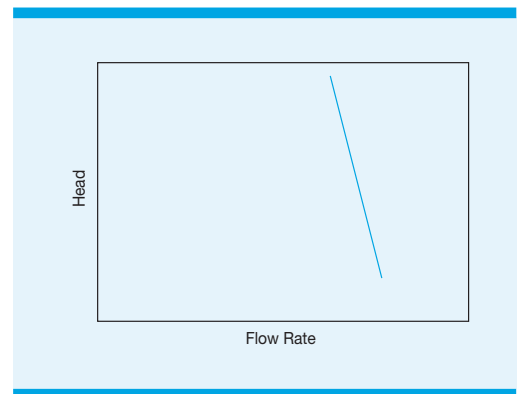


Figure ES-2.
Performance curve for a positive
displacement pump

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Interaction of Pumps and Systems

When a pump is installed in a system, the effect can be illustrated graphically by superimposing pump and system curves. The operating point will always be where the two curves intersect.

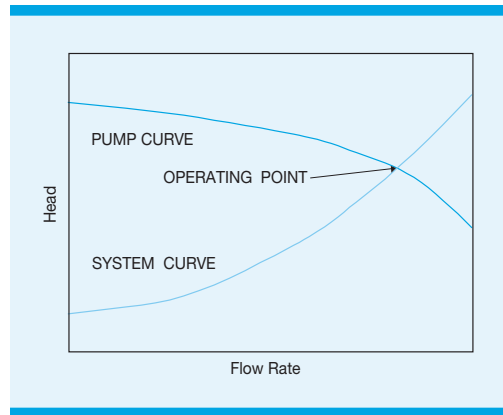


Figure ES-3.
System curve and a
performance curve for a
rotodynamic pump

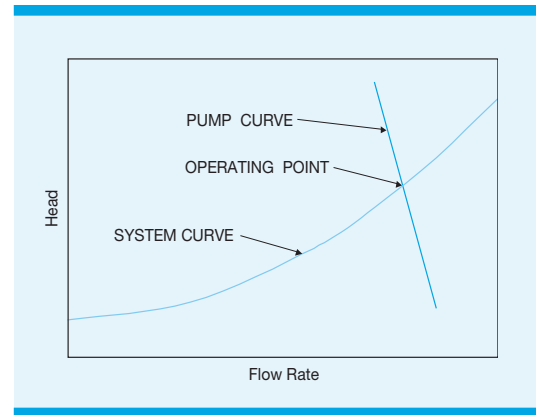


Figure ES-4.
System curve and a per-
formance curve for a positive
displacement pump

**Many pumping systems
require a variable flow or
pressure; variable speed
reduces power dur-
ing periods of reduced
demand.**

For a PD pump, if the system resistance increases, i.e., the system curve is moved upwards, the pump will increase its discharge pressure and maintain a fairly constant flow rate, dependent on viscosity and pump type. Unsafe pressure levels can occur without relief valves. For a rotodynamic pump, an increasing system resistance will reduce the flow, eventually to zero, but the maximum head is limited. Even so, this condition is only acceptable for a short period without causing problems. Adding comfort margins to the calculated system curve to ensure that a sufficiently large pump is selected will generally result in installing an oversized pump. The pump will operate at an excessive flow rate or will need to be throttled, leading to increased energy use and reduced pump life.

Many pumping systems require a variation of flow or pressure. Either the system curve or the pump curve must be changed to get a different operating point. Where a single pump has been installed for a range of duties, it will have been sized to meet the greatest output demand. It will therefore usually be oversized, and will be operating inefficiently for other duties. Consequently, there is an opportunity to achieve an energy cost savings by using control methods, such as variable speed, which reduce the power to drive the pump during the periods of reduced demand.

Varying the rotational speed has a direct effect on the pump's performance.

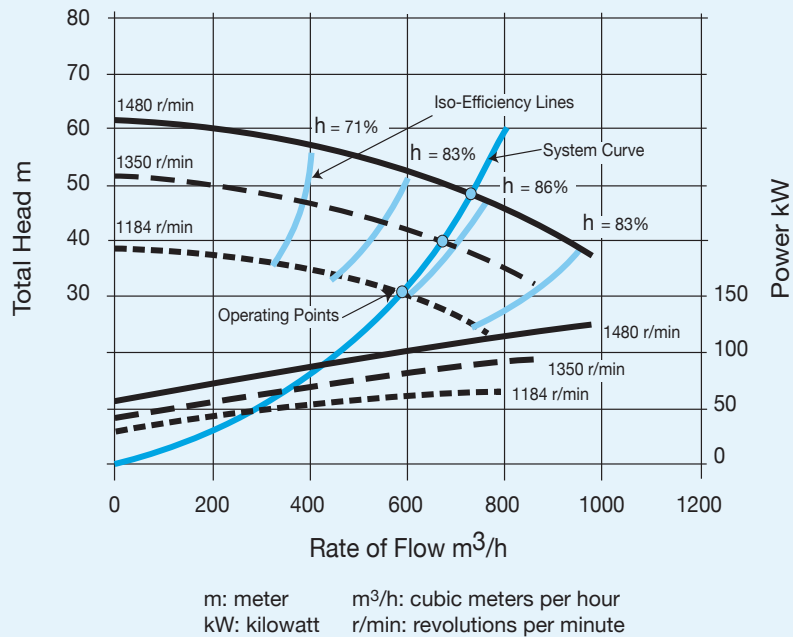
Effects of Speed Variation on Rotodynamic Pumps

A rotodynamic pump is a dynamic device with the head generated by a rotating impeller. Thus, there is a relationship between impeller peripheral velocity and generated head. Peripheral velocity is directly related to shaft rotational speed, for a fixed impeller diameter. Varying the rotational speed therefore has a direct effect on the pump's performance. The equations relating rotodynamic pump performance parameters of flow to speed, and head and power absorbed to speed, are known as the Affinity Laws.

Changing pump impeller diameter also effectively changes the duty point in a given system, and at low cost, but this can be used only for permanent adjustment to the pump curve and is not discussed further as a control method.

For systems where friction loss predominates, reducing pump speed moves the intersection point on the system curve along a line of constant efficiency (see Figure ES-5). The operating point of the pump, relative to its best efficiency point, remains constant and the pump continues to operate in its ideal region. The Affinity Laws are obeyed, which means that there is a substantial reduction in power absorbed accompanying the reduction in flow and head, making variable speed the ideal control method.

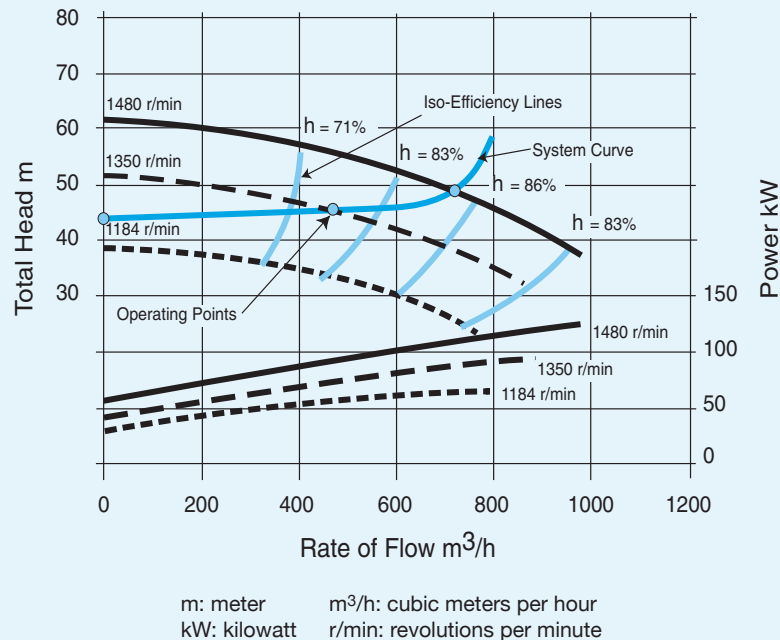
Figure ES-5.
Example of the effect of pump speed change in a system with only friction loss



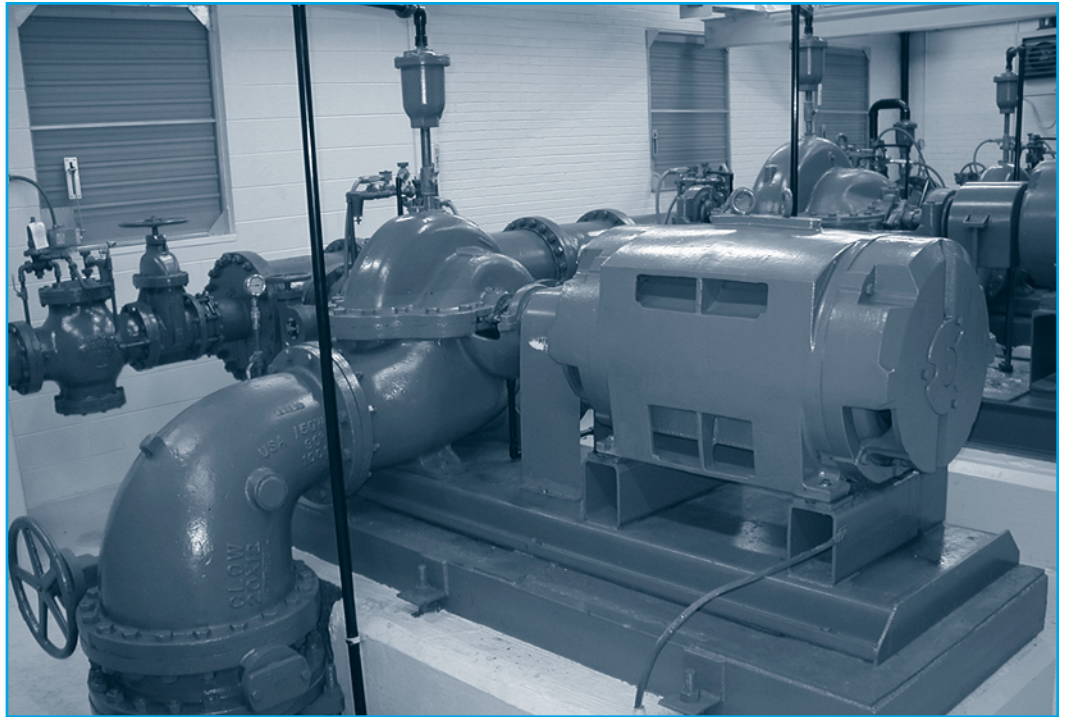
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However, in systems with high static head, the system curve does not start from the origin but at some non-zero value on the y-axis corresponding to the static head. Hence, the system curve does not follow the curves of constant efficiency. Instead, it intersects them (see Figure ES-6). The reduction in flow is no longer proportional to speed; a small turn down in speed greatly reduces flow rate and pump efficiency. A common mistake is to also use the Affinity Laws to calculate energy savings in systems with static head. Although this may be done as an approximation, it can also lead to major errors.

Figure ES-6.
Example of the effect
of pump speed change
in a system with high
static head



It is relevant to note that flow control by speed regulation is always more efficient than by a control valve. In addition to energy savings, there could be other benefits to lower speed. The hydraulic forces on the impeller, created by the pressure profile inside the pump casing, reduce approximately with the square of speed. These forces are carried by the pump bearings, and so reducing speed increases bearing life. It can be shown that for a rotodynamic pump, bearing life is proportional to the seventh power of speed. In addition, vibration and noise are reduced and seal life is increased, provided that the duty point remains within the allowable operating range.



Proper selection of pumps, motors, and controls to meet the process requirements is essential to ensure that a pumping system operates effectively, reliably, and efficiently.

Effect of Speed on Pump Suction Performance

Liquid entering the impeller eye turns and is split into separate streams by the leading edges of the impeller vanes, an action that locally drops the pressure below that in the inlet pipe to the pump. If the incoming liquid is at a pressure with insufficient margin above the vapor pressure, then vapor cavities, or bubbles, appear along the impeller vanes just behind the inlet edges. These collapse further along the impeller vane where the pressure has increased. This phenomenon is known as cavitation, and has undesirable effects on pump life.

Increasing pump speed will negatively affect pump suction performance and should be thoroughly investigated. Conversely, reducing speed will have a positive effect.

Effects of Speed Variation on Positive Displacement Pumps

To control flow in a PD pump, the speed needs to be changed or some of the flow has to be diverted. Throttling is not effective and is potentially dangerous. For many applications, some small flow rate changes need to be made while holding the pressure constant, and this is best achieved with a pressure-regulating valve. Such a valve will spill a small amount of liquid back to the source to maintain a constant system pressure. This will accommodate small amounts of wear in any restricting device; however, the use of such a valve to spill large volumes of liquid will be very inefficient, with the loss of energy manifesting as heat and noise.

A VSD is the preferred option for an application where the flow needs to vary on a regular basis. This is the most efficient method of flow control and it does not waste any of the shaft input energy.

Increasing pump speed will negatively affect pump suction performance, while reducing speed will have a positive effect.

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A VSD provides the most efficient method of flow control for a PD pump and does not waste any of the shaft input energy.

For a PD pump, the flow is proportional to speed, but the pressure can be independent of speed. Consequently, power and energy savings do not fall so quickly when speed is reduced. Sometimes it is necessary to operate PD pumps over a wider speed range than rotodynamic pumps, typically up to 10:1. This large speed range and the characteristics of PD pumps have implications for both the pump and the drive train, including:

- Lower or higher operating speeds may require special consideration with respect to the method or type of lubrication and/or cooling.
- The motor may not be adequately cooled at the lowest speed. A separately driven fan may need to be considered.
- The flow rate may be so low that the valve opening is too small to be sustainable under the different forces, and the valve could flutter.
- The energy from the drive-train inertia becomes too small to smooth the torque ripple and the motor starts to hunt. Two possible solutions are a motor running at a higher speed with a bigger drive-train reduction ratio, or a compensating flywheel.
- At the system design stage, the constant torque characteristic and possible low-speed torque effects must be considered, because they impose demands on electronic VSDs.
- When liquids containing solids with a high settling rate are pumped, excessive solids accumulation can occur in the pump, causing wear. It is paramount, when reducing speed with such liquids, that the velocity be maintained high enough in the pump and in the pumping system to avoid settling out of the solids.
- A change in liquid temperature and viscosity could lead to cavitation.



Photo: Courtesy Don Casada, Diagnostic Solutions

Most existing pumping systems are oversized, many by more than 20%, thus providing substantial opportunity for systems optimization.

Motors

There are many types of pump prime movers available (such as diesel engines and steam turbines) but the majority of pumps are driven by an electric motor. Although this guide is principally about pumps and VSDs, it is important to appreciate that, on a typical industrial site, motor-driven equipment accounts for approximately two-thirds of electricity consumption. Improvements in motor efficiency, by using high-efficiency motors, can offer major energy savings and short payback. Many of the principles outlined in the guide apply to all motors on a site, not just those used as pump prime movers.

Variable Speed Drives

There are several types of VSDs, as shown in Figure ES-7. In applications that require flow or pressure control, particularly in systems with high friction loss, the most energy-efficient option for control is an electronic VSD, commonly referred to as a variable frequency drive (VFD). The most common form of VFD is the voltage-source, pulse-width modulated (PWM) frequency converter (often incorrectly referred to as an inverter). In its simplest form, the converter develops a voltage directly proportional to the frequency, which produces a constant magnetic flux in the motor. This electronic control can match the motor speed to the load requirement. This eliminates a number of costly and energy inefficient ancillaries, such as throttle valves or bypass systems.

Selection Process — New Systems

It is essential to commence the sizing exercise with the hydraulic system, and to work systematically to select the pump, motor, and drive. When the pump maximum duty is known, the peak power and speed for the drive will become clear. It is common to oversize system components (pumps, motors, and drives); however, this practice is not recommended because it leads to higher initial equipment costs and higher life cycle costs.

When selecting a rotodynamic pump in combination with a VSD for a system with some static head, a pump should be chosen such that the maximum flow rate is slightly to the right-hand side of the best efficiency point (BEP). The exception is for a constant flow regulated system, in which case the recommendation is to select a pump that operates to the left of BEP at maximum pressure. This approach optimizes pump operating efficiency.

All operating conditions must be considered when designing the system. Some operating profiles may be satisfied best by installing multiple pumps, which could be fixed or variable speed. On/off control can be used to vary flow rate for systems in which an intermittent flow is acceptable. This can be an energy-efficient solution, but these systems often require a liquid storage facility.

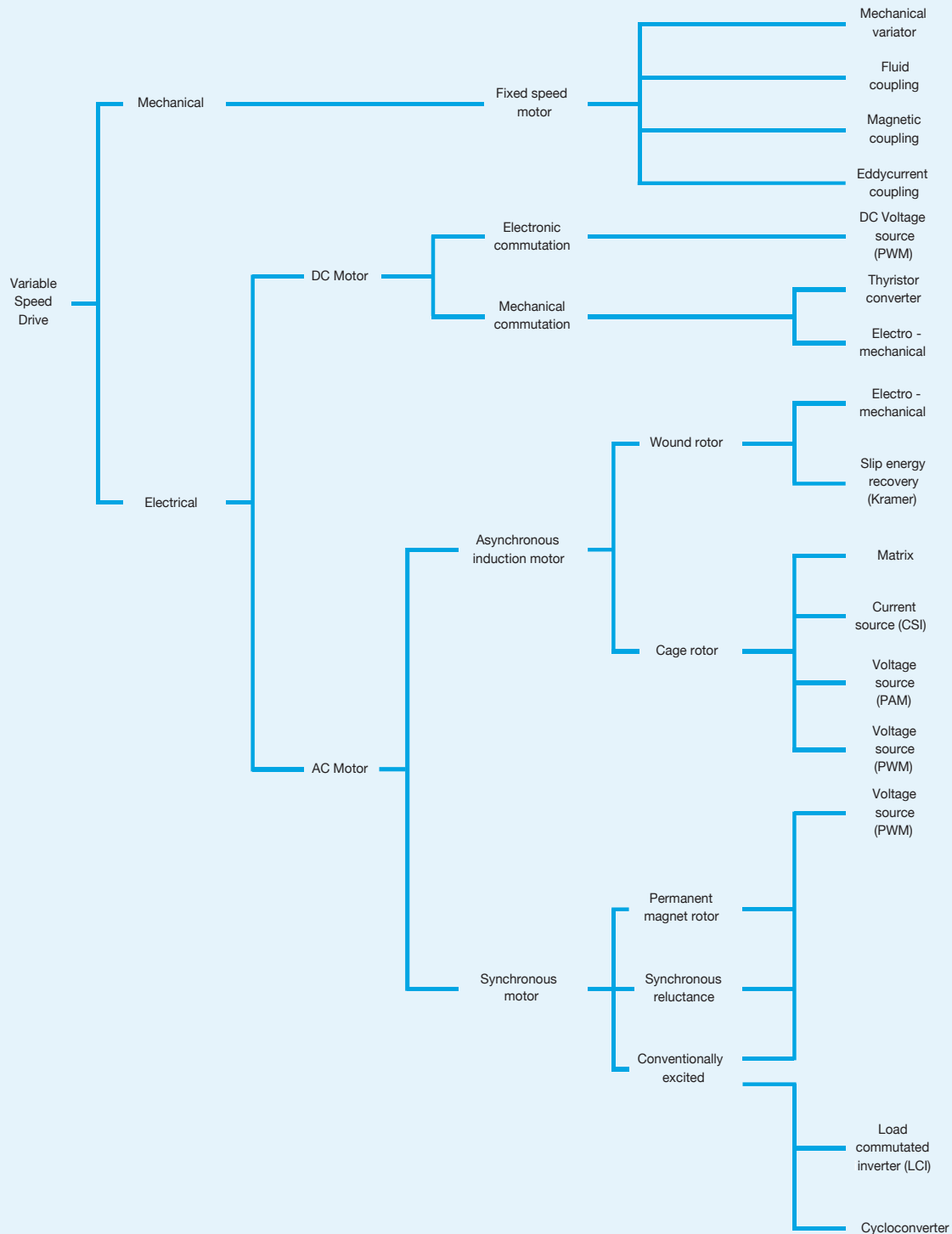


Figure ES-7.
Types of Variable Speed Drives

Selection Process — Retrofitting to Existing Equipment

When sizing the hydraulic system, consider all operating conditions and work systematically to select the pump, motor, and drive.

There are approximately 20 times more pumps in service than are supplied new every year. It is therefore apparent that a major opportunity exists for modifying installed systems to make them more energy efficient. Most system designers allow a contingency on the system head required. It is estimated that 75% of pump systems are oversized, many by more than 20%. It follows that retrofitting with VSDs could match pump systems to actual system requirements more accurately and save considerable amounts of energy.

When considering adding a VSD to an existing motor, care should be taken to match the electrical characteristics of the motor and frequency converter; otherwise, the risk of premature failure is introduced into the system. Early frequency converters produced outputs with a very high harmonic content in the waveform, which caused substantial additional heating of motor windings, and therefore motors were derated for inverter use. A modern inverter output causes relatively small levels of harmonic current distortion in the motor windings, and therefore little derating is normally required. High-efficiency motors are less affected by harmonics than standard efficiency types.

Benefits of VSDs

VSDs offer several benefits, some of which are relatively easy to quantify, and others of which are less tangible, but there are some potential drawbacks, which must be avoided.

Energy Savings

With rotodynamic pump installations, savings of between 30% and 50% have been achieved in many installations by installing VSDs. Where PD pumps are used, energy consumption tends to be directly proportional to the volume pumped and savings are readily quantified.

Improved Process Control

By matching pump output flow or pressure directly to the process requirements, small variations can be corrected more rapidly by a VSD than by other control forms, which improves process performance. There is less likelihood of flow or pressure surges when the control device provides rates of change, which are virtually infinitely variable.

Improved System Reliability

Any reduction in speed achieved by using a VSD has major benefits in reducing pump wear, particularly in bearings and seals. Furthermore, by using reliability indices, the additional time periods between maintenance or breakdowns can be accurately computed.

Potential Drawbacks of VSDs

VSDs also have some potential drawbacks, which can be avoided with appropriate design and application.

Structural Resonance

Resonance conditions can cause excessive vibration levels, which in turn are potentially harmful to equipment and environment. Pumps, their support structure, and

A number of analyses may be performed to predict and avoid potential resonance situations.

piping are subject to a variety of potential structural vibration problems (resonance conditions). Fixed-speed applications often miss these potential resonance situations because the common excitation harmonics due to running speed, vane passing frequency, plunger frequency, etc., do not coincide with the structural natural frequencies. For VSD applications, the excitation frequencies become variable and the likelihood of encountering a resonance condition within the continuous operating speed range is greatly increased. Pump vibration problems typically occur with bearing housings and the support structure (baseplate for horizontal applications, motor and stool for vertical applications).

Pressure pulsations are the common excitation mechanism. These pressure pulsations may be further amplified by acoustic resonance within the pump or the adjacent piping. There are a number of analyses that can be performed to predict and avoid potential resonance situations, including:

- Simple hydraulic resonance calculations
- Passing frequency analysis
- Structural resonance, for example, utilizing Finite Element Analysis
- Modal testing of the actual machine.

Modal testing can supplement the regular vibration test. Very often, a pump intended for variable speed operation will only be tested at one single speed.

Rotor Dynamics

The risk of the rotating element encountering a lateral critical speed increases with the application of a VSD. Lateral critical speeds occur when running speed excitation coincides with one of the rotor's lateral natural frequencies. The resulting rotor vibration may be acceptable or excessive, depending on the modal damping associated with the corresponding mode. Additionally, drive-induced torque harmonics may cause resonance conditions with torsional rotor dynamic modes. However, such conditions are usually correctible or preventable.

Variable speed vertical pumps are more likely than horizontal machines to exhibit operational zones of excessive vibration. This is because such pumps' lower natural frequencies are more likely to coincide with running speed. Small, vertical close-coupled and multistage pumps normally do not present this type of problem.

Additional Considerations for VFDs

The introduction of VFDs requires additional design and application considerations. VFDs can be fitted to most existing motors in Europe and other areas, which use a 400 Volt (V) network. However, this is generally not the case in the United States, and other areas where network voltages exceed 440 V. Hence, reinforced insulation "inverter duty" motors are often needed.

The high rate of switching in the PWM waveform can occasionally lead to problems. For example:

- The rate of the wavefront rise can cause electromagnetic disturbances, requiring adequate electrical screening (screened output cables). Filters in the inverter output can eliminate this problem.
- Older motor insulation systems may deteriorate more rapidly due to the rapid rate of voltage change. Again, filters will eliminate this problem.
- Long cable runs can cause "transmission line" effects, and cause raised voltages at the motor terminals.

Voltages can be induced in the shafts of larger motors, potentially leading to circulating currents, which can destroy bearings. The following corrective measures are required:

- Insulated non-drive-end bearings are recommended on all motors over 100 kilowatt (kW) output rating.
- Common mode filters may additionally be required for higher powers and voltages.

The converter will have losses, and ventilation requirements for the electronics can be an important issue. The life expectancy of the converter is generally directly related to the temperature of the internal components, especially capacitors.

The converter may require installation in a less onerous environment than the motor control gear it replaces. Specifically:

- Electronics are less able to cope with corrosive and damp locations than conventional starters.
- Operating a VFD in a potentially explosive atmosphere is not usually possible.

Estimating Pumping Energy Costs

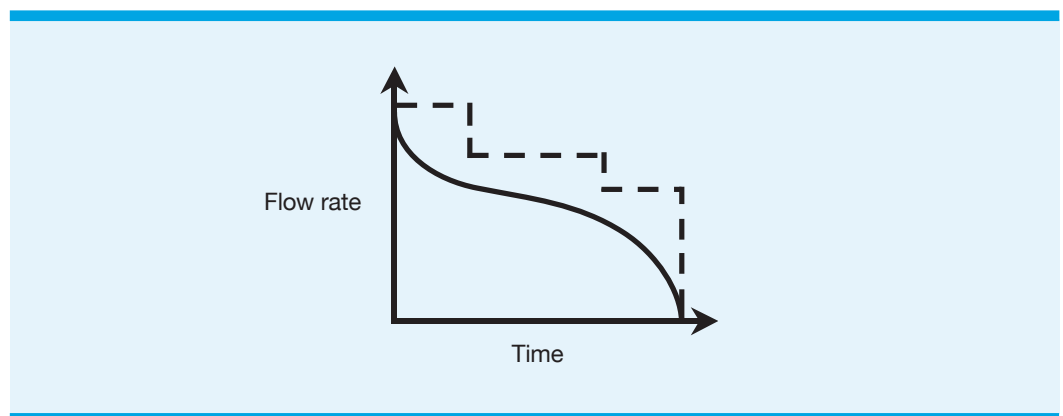
Use a duration diagram to help estimate pumping energy costs.

To compare different system and pumping equipment proposals and make an intelligent choice, some basic facts will need to be established.

- Will the process require varying flow rate, and, if so, must it be continuously variable or can flow rate be varied in steps?
- Can on-off batch pumping be used?
- What is the peak flow rate and how is the flow rate distributed over time?

The answers to these questions will determine if, and how, to regulate the flow. It will also give some guidance regarding the pumping system design. A helpful way of showing the flow demand is to use a duration diagram. A duration diagram in its simplest form (see Figure ES-8) shows how many hours during a year that a given flow rate is needed — the dashed line. The solid curve in the same diagram is interpreted differently. Each point on the solid curve tells how many hours during a year the flow rate exceeds the value on the y-axis.

Figure ES-8.
Example of a duration diagram



This diagram is instrumental in understanding the pumping needs. The system must be able to deliver the peak flow, but, from an economic point of view, it is also important to know at what flow rates the system is going to operate most of the time. To find the total cost of operating the pump, the running cost at each operating condition must be calculated and summated.

Capital Cost Savings

When designing and installing a new pumping system, the capital cost of a VSD can often be offset by eliminating control valves, bypass lines, and conventional starters, as explained below.

Offset the capital cost of a VSD by eliminating control valves, by-pass lines, and conventional starters.

Elimination of Control Valves

Control valves are used to adjust rotodynamic pump output to suit varying system requirements. Usually a constant-speed pump is pumping against a control valve, which is partially closed for most of the time. Even at maximum flow conditions, a control valve is normally designed to be 10% shut, for control purposes. Hence, a considerable frictional resistance is applied. Energy is therefore wasted overcoming the added frictional loss through the valve. Using a VSD to control flow can eliminate the control valve.

Elimination of Bypass Lines

All fixed-speed centrifugal pumps have a minimum flow requirement. If the pump is operated at flow rates below the minimum for extended periods, various mechanical problems can occur. If the flow requirements in a system can drop below this minimum flow capacity, it is necessary to install a constant or switched bypass to protect the pump. The use of a VSD greatly reduces the volume to be bypassed.

Financial Justification

An LCC analysis is a very appropriate way to compare technical alternatives in pump system design to make a financial justification.

The initial cost of pumping equipment is often a very small part of the total life cycle cost (LCC). An LCC analysis is therefore a very appropriate way to compare different technical alternatives in the design of a pumping system and make a financial justification. The components of an LCC analysis typically include initial costs, installation and commissioning costs, energy costs, operation costs, maintenance and repair costs, downtime costs, environmental costs, and decommissioning and disposal costs (see Figure ES-9). The LCC equation can be stated as:

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$

C = cost element

ic = initial cost, purchase price (pump, system, pipes, auxiliaries)

in = installation and commissioning

e = energy costs

o = operating cost (labor cost of normal system supervision)

m = maintenance cost (parts, man-hours)

s = downtime, loss of production

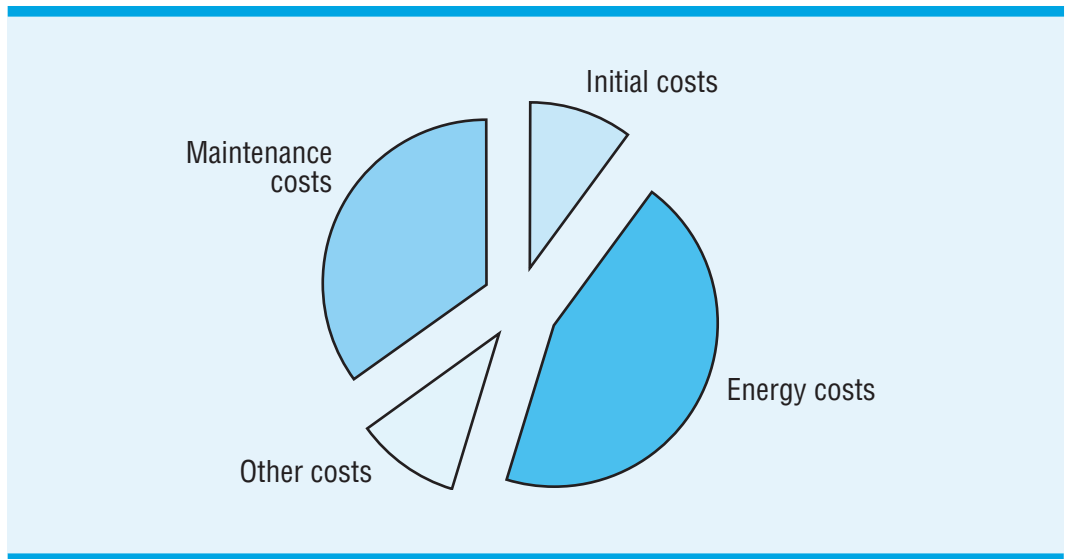
env = environmental costs

d = decommissioning

A very well documented guide, *Pump Life Cycle Costs: LCC Analysis for Pumping Systems*¹, has been published jointly by Hydraulic Institute and Europump. This guide explains how the operating costs of a pumping system are influenced by system design and shows in detail how to use a life cycle cost analysis to make comparative cost assessments. Many case studies have been included in the guide to highlight the value of possible savings in real applications.

¹*Pump Life Cycle Costs: LCC Analysis for Pumping Systems*, 2001, is available through both the Hydraulic Institute (www.pumps.org) and Europump (www.europump.org).

Figure ES-9.
Typical LCC components for a medium-sized industrial pumping system



Example: Variable Speed Drives Fitted on a Primary Feed Pump and Product Transfer Pump in a Refinery

Summary

At a San Francisco refinery, installing a VFD on a product transfer pump saved €/ \$120,000 (euros/U.S. dollars) per year, and on a primary feed pump, saved €/ \$220,000. Vibration was reduced and mechanical seal and bearing failures have been eliminated. There was no investment cost to the refinery, but savings were shared with the contractor, who provided the capital investment.

Other Potential Applications

Suitable applications include any in which the pump is sized for an intermittent maximum flow rate but runs mostly at a reduced (but variable) rate.

Investment Cost

The energy services contractor agreed to install the VFDs and upgrade the equipment at no charge to the refinery, but took a share of the savings. The total investment was €/ \$1.2 million.

Savings Achieved

Over the course of a year, the VFDs saved €/ \$340,000 and the total project saved €/ \$750 000 per year.

Payback Period

Overall payback was about 1.6 years, but this was not applicable to the refinery, which gained immediately with its share of the savings.

Installation and Operation Details

Conversion of the refinery's vacuum gas oil plant to a Diesel Hydro Treater (DHT)

Executive Summary

left the pumps grossly oversized. Several were often operating at 40% of best efficiency point, causing low hydraulic efficiency, excessive vibration, and seal or bearing failure about once a year.

The full range of upgrades consisted of:

- Installing VFDs on the 1,650-kW (2,250-horsepower [hp]) primary feed pump and on the 500-kW (700-hp) product transfer pump
- Replacing the internal elements on the 1,650-kW (2,250-hp) secondary feed pump and on a 400-hp Power Recover Turbine (PRT)
- Changing operating procedures for the main 3,700-kW (5,000-hp) and 3,000-kW (4,000-hp) back-up pumps.

Installing the VFDs on the primary feed pump and product transfer pump saved energy by reducing losses through flow control valves. The energy saved from using VFDs was 500,000 kWh per month. Resizing the PRT and secondary feed pump, along with a more energy-efficient operating procedure for the back-up pumps, saved another 500,000 kWh per month. Cost savings shared by the refinery and contractor were €/\$340,000 from the variable speed pumps and €/\$750,000 overall. The demand charge previously levied on the DHT process was eliminated. Since the upgrade, there have been no seal or bearing failures and process control has improved. It should be noted that a VFD was not considered appropriate for all the oversized pumps. If the flow rate does not vary, then resizing the pump (e.g., replacing the impeller and diffuser element), reduced impeller diameters, or even a new pump will usually give greater lifetime cost savings and better payback than a VSD.

At a San Francisco refinery, installing a VFD on product transfer and primary feed pumps saved energy and money, reduced vibration, and eliminated mechanical seal and bearing failures.

Notes

Notes

Variable Speed Pumping Full Report

Further details and specific guidance are available in the complete *Variable Speed Pumping — A Guide to Successful Applications*. This comprehensive document provides information on the design, specification, and operation of efficient, cost-effective variable speed pumping systems. It covers both the basic principles of pump, motor, and drive technology as well as more advanced, specific, and detailed concepts, and provides step-by-step guidance on using a systems approach to incorporating variable speed drives in pumping system applications.

The guide contains over 150 pages, and is compiled, written, edited, and critiqued by pump, motor, and drive experts from academia and industries worldwide.

The guide is available at a cost of €/\$95 from both the Hydraulic Institute (www.pumps.org, phone: 973-267-9700) and Europump (www.europump.org, phone: +32 2 706 82 30).

For More Information

About the **Hydraulic Institute**

The Hydraulic Institute (HI), established in 1917, is the largest association of pump producers and leading suppliers in North America. HI serves member companies and pump users by providing product standards and forums for the exchange of industry information. HI has been developing pump standards for over 80 years. For information on membership, organization structure, member and user services, and energy and life cycle cost issues, visit www.pumps.org.

About **Europump**

Europump, established in 1960, acts as spokesperson for 15 national pump manufacturing associations in Europe and represents more than 400 manufacturers. Europump serves and promotes the European pump industry. For information on Europump, visit www.europump.org.

About the Office of Energy Efficiency and Renewable Energy

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. By investing in technology breakthroughs today, our nation can look forward to a more resilient economy and secure future.

Far-reaching technology changes will be essential to America's energy future. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies that will:

- Conserve energy in the residential, commercial, industrial, government, and transportation sectors
- Increase and diversify energy supply, with a focus on renewable domestic sources
- Upgrade our national energy infrastructure
- Facilitate the emergence of hydrogen technologies as vital new "energy carriers."

The Opportunities

Biomass Program

Using domestic, plant-derived resources to meet our fuel, power, and chemical needs

Building Technologies Program

Homes, schools, and businesses that use less energy, cost less to operate, and ultimately, generate as much power as they use

Distributed Energy Program

Expanding clean on-site energy choices for greater efficiency, reliability, and security

Federal Energy Management Program

Leading by example, saving energy and taxpayer dollars in federal facilities

FreedomCAR & Vehicle Technologies Program

Less dependence on foreign oil, and eventual transition to an emissions-free, petroleum-free vehicle

Geothermal Technologies Program

Tapping the Earth's energy to meet our heat and power needs

Hydrogen, Fuel Cells & Infrastructure Technologies Program

Paving the way toward a hydrogen economy and net-zero carbon energy future

Industrial Technologies Program

Boosting the productivity and competitiveness of U.S. industry through improvements in energy and environmental performance

Solar Energy Technology Program

Utilizing the sun's natural energy to generate electricity and provide water and space heating

Weatherization & Intergovernmental Program

Accelerating the use of today's best energy-efficient and renewable technologies in homes, communities, and businesses

Wind & Hydropower Technologies Program

Harnessing America's abundant natural resources for clean power generation

To learn more, visit www.eere.energy.gov

Hydraulic Institute
9 Sylvan Way
Parsippany, NJ 07054
Phone: 973-267-9700 Fax: 973-267-9055
www.pumps.org

Europump
Diamant Building, 5th Floor
Blvd. A Reyers 80, B1030
Brussels, Belgium
Phone: +32 2 706 82 30 Fax: +32 2 706 82 50
www.europump.org

U.S. Department of Energy
Industrial Technologies Program
Washington, D.C.
EERE Information Center
Phone: 877-337-3463 (877-EERE-INF)
www.eere.energy.gov/industry

