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VFDs for Variable Flow Hydronic Systems

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Contents

1. Introduction

This technical note focuses on hydronic systems used for chilled and hot water distribution in buildings, although the affinity laws apply to both pumps and fans. Most HVAC equipment is designed to perform during peak loads. These loads typically occur infrequently over the course of a year. Pumps and fans, therefore, are also sized to meet the maximum flow of the system. In older legacy systems, the control of flow during partial-load conditions was accomplished using mechanical flow-control devices such as dampers, valves and bypass systems. These mechanical *throttling devices* are not energy efficient since the fan or pump motor is running at 100% speed regardless of load demand. Using a *Variable Frequency Drives (VSD)* to vary the speed of the fans and pumps, in lieu of mechanical means to control flow, minimizes energy usage and increases the life of the motors.

2. Fan and Pump Affinity Laws

Pressure for pumps is frequently measured in feet of head (in the U.S.A.) where one foot of head is equal to 0.433 pounds per square inch. The relationship between head, flow, pressure and power is given below [1].

$$\begin{aligned} &HP = (GPM \times PSI) \div (1{,}714 \times Eff_P), \\ &HP = Head(ft) \times GPM \div 3960 \\ &BHP = HP \div Eff_P \\ &Head(ft) = PSI \times 2.31 \end{aligned} \qquad \text{2-1}$$

The scaling properties of fans and pumps are referred to as the *Affinity Laws* [2].

$$\left\{ Q_2 = Q_1\left(\frac{N_2}{N_1}\right) \qquad H_2 = H_1\left(\frac{N_2}{N_1}\right)^2 \qquad HP_2 = HP_1\left(\frac{N_2}{N_1}\right)^3 \right\} \qquad \text{2-2}$$

Where Q = Flow (GPM, CFM), H = Head (ft), N = speed (Hz, RPM) and P = Power (HP, BHP).

- Flow = linearly proportional to speed.
- The head is proportional to the square of speed.
- Power is proportional to the cube of speed.

If flow Q_2 is reduced by a fraction k with respect to Q_1 then

$$Q_2 = k\,Q_1 \;\rightarrow\; HP_2 = HP_1\,k^3 \qquad \text{2-3}$$

EXAMPLE: Reducing flow Q by a factor of 2 (50%) gives a reduction in power of 8 (87.5%)

$$Q_2 = \frac{1}{2}Q_1 \;\rightarrow\; HP_1 = \frac{HP_1}{2^3} = \frac{HP_1}{8}$$

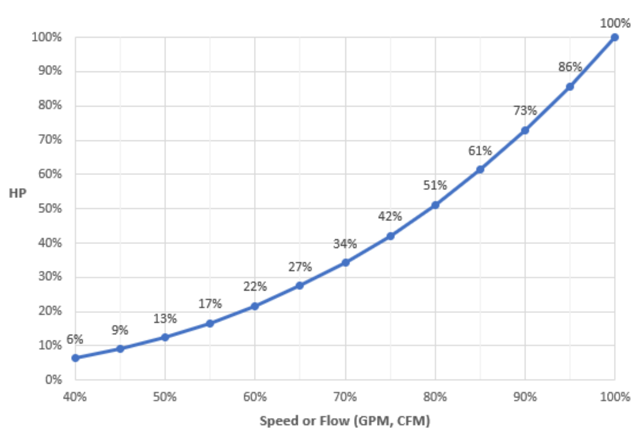


Figure 2-1 Fan or Pump - Power vs. Speed

3. 2-Way Valve and 3-Way Valve Systems

Hydronic systems used for chilled and hot water distribution in buildings typically are one of two types, either with 2-way valves (Figure 3-1) or with 3-way valves (Figure 3-2).

Balancing Valves (BV) and Circuit Setter (CS):

The water flowing through the pipes must overcome frictional resistance that is proportional to the distance the water flows. The circuit nearest to the pump has less frictional resistance than the farthest circuit. Since water seeks the path of least resistance, the more water will flow through the circuit the closer it is to the pump. In order to provide the same flow through all circuits, extra resistance is added to the circuits by the balancing valves. After the system has been balanced, the overall flow of the system is set by the circuit setter (CS) to adjust the system operating point on the pump curve to optimal (see section 0).

Minimum Flow Valve (FV):

The 2-Way valve system when used for a chiller system may be required to provide a minimum flow through the chiller. If minimum flow is required, it is usually provided by a bypass loop fitted with a Balancing Valve (FV) adjusted to provide the minimum flow when all loads (CV) are off. For the 3-Way valve system, flow is constant and there is no need for a minimum flow balancing valve.

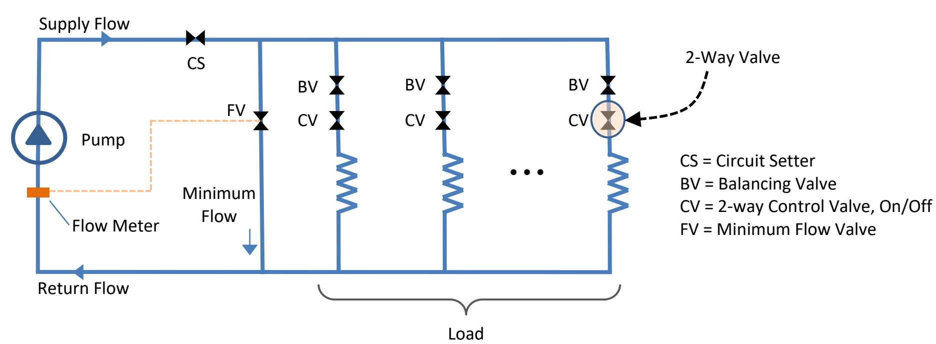


Figure 3-1 System with 2-Way of/off Valves and Constant Speed Pumps

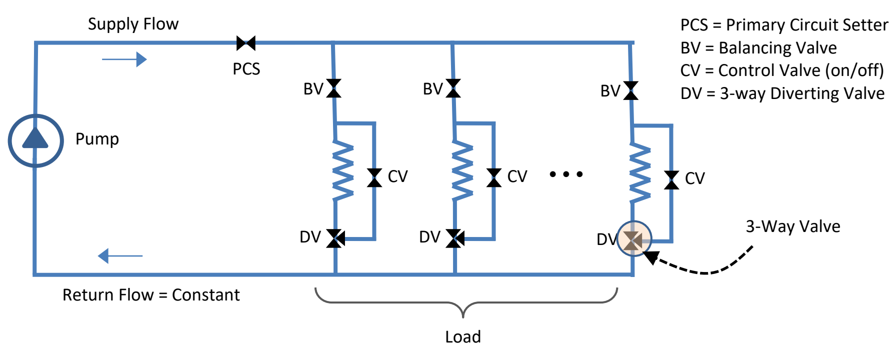


Figure 3-2 System with 3-Way Diverting Valvesand Constant Speed Pumps

4. Primary and Primary-Secondary Systems

When designing a variable volume chilled water system, there are two main types of distribution systems to choose from: a variable-primary system or a primary-secondary system [3] [4].

4.1. Primary Systems

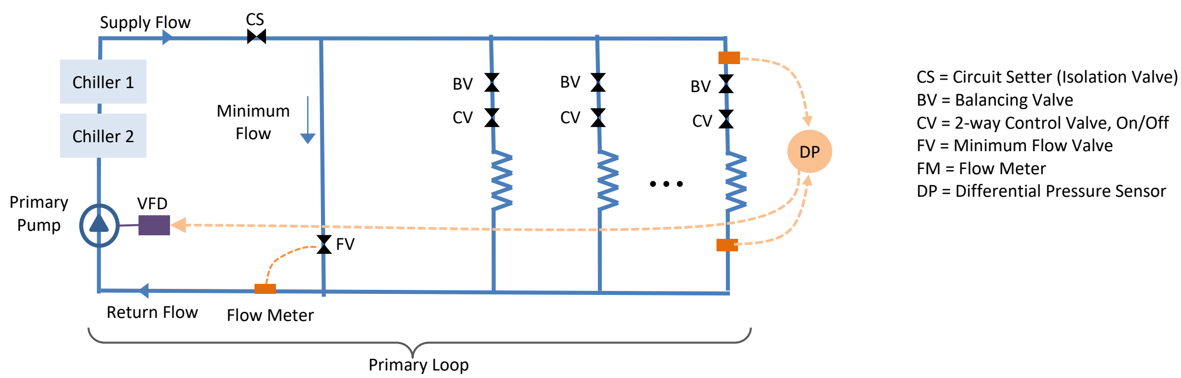


Figure 4-1 Primary System

The advantages [3]:

- Lower first costs e.g., no secondary pumps and their associated piping, fittings, controls.
- Less space required in the central plant due to less pumps.
- Adjustable chiller flow: able to increase the flow through the chiller maximizes the output for the chiller efficiency resulting in lower operating costs.

The disadvantages [3]:

- A means of measuring the flow at the chiller is required to control the bypass valve (BV) to ensure minimum flow is maintained.
- Higher complexity controls (for bypass valve, minimum flows and chiller staging)
- Larger pump motor sizes.

4.2. Primary-Secondary Systems

A primary-secondary system consists of two hydronic loops connected by a de-coupler. The primary loop utilizes constant volume pumps to maintain constant flow through the chillers while the secondary loop utilizes variable volume pumps to pull the chilled water from the 2/4 primary loop and distribute it to the system. A differential pressure sensor located near the end of the system piping will direct the pump(s) to increase or decrease the flow to satisfy the system [3].

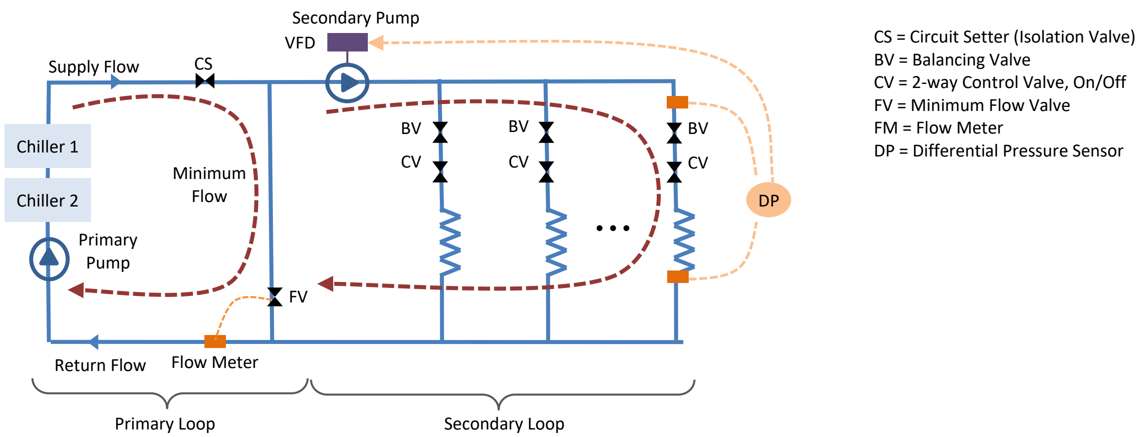


Figure 4-2 Primary-Secondary System

The advantages [3]:

- Simplified controls
- Constant flow through the chiller (better chiller performance)
- Smaller pump motor sizes

The disadvantages [3]:

- Larger first costs (more pumps and piping, fittings, etc.)
- A larger central plant is required to house the additional pumps.
- Higher energy use which equals higher operating costs
- Low ΔT Syndrome: With constant volume primary pumps not allowing an increase of flow through the chiller, the chiller cannot adjust to return chilled water temperatures less than design.

4.3. Pump and System Curves

The *head (pressure)* required at zero flow is called *static head* and is the amount of feet of elevation the pump must lift the water regardless of flow due to gravity. The *friction head* is the pressure needed to overcome the resistance to flow provided by the physical components e.g., pipe, valves, elbows. The *system curve* includes both static and friction "head" necessary for the specified building design. The *pump curve* shows the performance of a pump head vs. flow and is device specific. These curves can be obtained from the pump manufacturer. The *operating point* OP_1 occurs where the system curve and pump curve intersect. The system curve is typically designed for worst-case conditions for loads occurring rarely during the year. The nominal operating point is generally much lower.

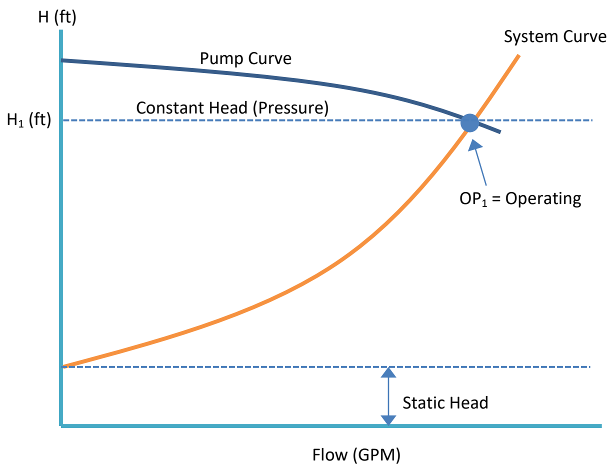


Figure 4-3 Pump and System Curves [2] [5]

2-Way Control Valves: A system using 2-Way Control Valves (CV) to vary the flow by modulating the valve positions. Closing the valve reduces flow and increases friction. A typical operating point for a 2-Pipe system is shown at OP_2 in Figure 4-4. This point occurs for a particular partial-load flow obtained by adjusted the control valve. The flow at this point decreases as desired but at an increased system head, so the operating point rides up the pump curve from OP_1 to OP_2.

3-Way Control Valves: A system using 3-Way Diverting Valves (DV) maintains constant pressure by bypassing flow from the pump discharge to the pump suction (return). In this case, *both constant flow and pressure are maintained* even during partial load conditions. That is, the pump is forced to stay at OP_1 regardless of flow demand.

In either the 2-Pipe or 3-Pipe cases, a circuit setter is used to balance the flow and pressure based on existing system head and load. This mechanically restricts flow, while the pump is still running at 100%. This places undue stress on the pump and valves and wastes energy.

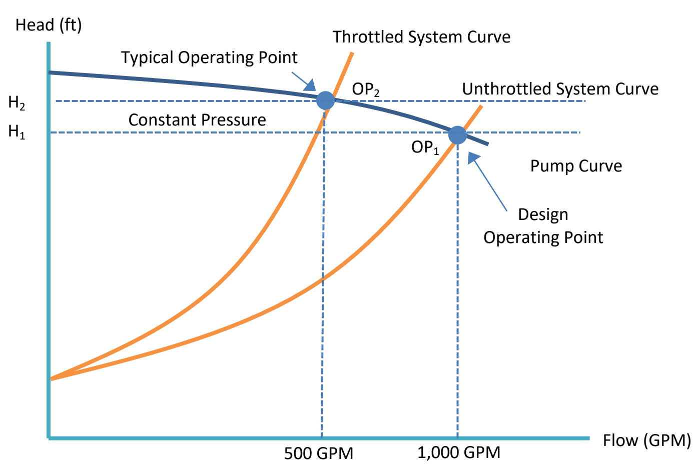


Figure 4-4 Pump and System Curves

4.4. HP = Pressure x Flow

In order to understand *Power*, you must first understand *Energy* and *Work*. Energy is defined as the capacity of a body to do work, by virtue of the position or condition of the body. Assume you apply a force of 100 lb to an object and move it for 1 minute over a distance of 165 feet. The energy or work expended is 100 x 150 = 1,500 ft-lb. Power is the *rate* at which you expend work i.e., energy/time. So, the power in this example is 1,5000 ft-lb/min. In hydronic systems, the unit of power is HP = 33,000 ft-lb per min [6].

$$HP = 33,000\ \frac{ft\text{-}lb}{\min} \qquad (4\text{-}1)$$

We sometimes prefer to work with pressure (psi) instead of head. A square foot of area contains 144 square inches; a cubic foot of ambient-temperature water weighs 62.4 pounds per cubic foot at 70°F at sea level. If you poured 1 pound of water into a tall, narrow vessel that occupies 1 square inch of floor space, I would fill that vessel to 2.31 feet of elevation.

$$\mathrm{P(PSI)} = Head\left(\cancel{ft}\right) \times 62\left(\frac{lb}{\cancel{ft^3}}\right) \times \frac{1}{144}\left(\frac{\cancel{ft^2}}{in^2}\right) = \frac{H}{2.31}\left(\frac{lb}{in^2}\right) \ \Rightarrow\ \mathrm{P(PSI)} = \frac{H(ft)}{2.31} \qquad (4\text{-}2)$$

From which pressure is related to head by the following:

$$H(ft) = 2.31PSI \qquad (4\text{-}3)$$

Example

> Given an elevated tank of ambient water that supplies water pressure to the communities below the tank. If the water in the tank is 150 feet above a faucet in one of the homes, what is the water pressure at the faucet (assuming no other influences on pressure)?
>
> Answer: 150 ÷ 2.31 = 65.8 psi.

4.5. Hydraulic HP

The Pressure vs Flow curve blow allows us to visualize the energy savings provided by a VSD.

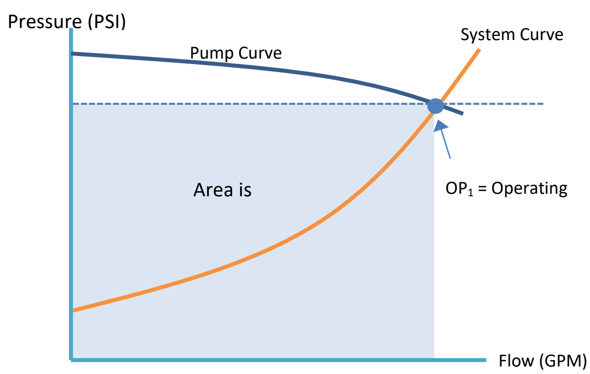


Figure 4-5 PSI vs GPM and System Curves

The blue shaded area = pressure × flow and is proportional to HP as shown below.

$$\text{pressure} \times \text{flow} = \frac{\text{force}}{\text{area}} \times \frac{\text{volume}}{\text{time}} = \left(\frac{lb}{ft^2}\right)\left(\frac{ft^3}{\min}\right) = \left(\frac{ft\text{-}lb}{\min}\right) = \frac{\text{energy}}{\text{time}} = \text{power} \qquad \text{4-4}$$

It is typical to use PSI and GPM, so the appropriate conversions are shown below [6]

$$GPM \times PSI = \underbrace{\left(\frac{\cancel{gal}}{\min}\right)\left(\frac{231\,\cancel{in^3}}{\cancel{gal}}\right)}_{\text{flow}}\underbrace{\left(\frac{lb}{\cancel{in^2}}\right)\left(\frac{ft}{12\,\cancel{in}}\right)}_{\text{pressure}} = \frac{231}{12}\left(\frac{\cancel{ft-lb}}{\cancel{\min}}\right) \times \frac{HP}{33,000}\left(\frac{\cancel{\min}}{\cancel{ft-lb}}\right) = \underbrace{1,714\,HP}_{\text{power}} \qquad \text{4-5}$$

From which the *hydraulic HP* including pump efficiency is given by

$$HP = \frac{GPM \times PSI}{1,714 \times EFF_p} \qquad \text{(Pump input power)} \qquad \text{4-6}$$

4.6. Using VSDs for Hydronic Pump Systems

In the previous cases, it was assumed that the pumps were constant speed pumps running at 100% all the time. Significant energy savings can be achieved by using a *Variable Speed Drive (VSD)* for the pump. A VSD is also referred to as a *Variable Frequency Drive (VFD)*.

Consider the simplified system in Figure 4-6. This system has a design flow of 1,000 GPM and 80 feet (40' + 40') of variable piping head loss, plus 10 feet of control head [7]. The control head is the minimum pump head needed at all times even at zero flow, the system must be delivering this amount head. A differential pressure sensor measures the pressure across the coil and two-way valve, ideally in the farthest branch. As demand drops, the control valve starts to close causing the system flow to drop. The DPS senses increased differential pressure across the coil and control valve. This increase in differential pressure informs the VSD controller to slow the pump speed until the differential pressure of 10' is restored.

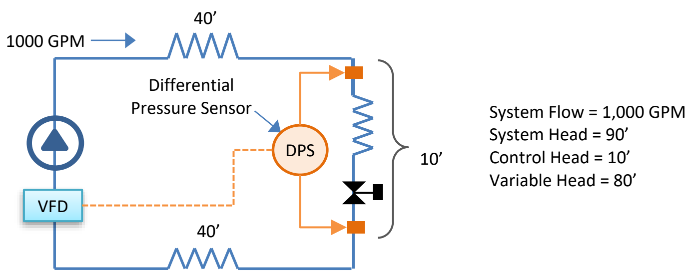


Figure 4-6 Simplified hydronic loop for VSD Controlled Pump and Differential Pressure Sensor (DPS) [7]

Note that the system curve represents the locus of points where the control head is satisfied. The effect of applying a VSD to a pump is to reduce speed and therefore the flow, which effectively causes the pump curve to shift down to OP3 as shown in Figure 4-7. The operating point at OP3 produces the same reduced flow, e.g., 500 GPM, as with a valve configuration at OP2. However, it allows the pump to operate at a lower head at H3 i.e., to satisfy the same partial-load conditions.

Observe that shifting the pump curve downward allows the pump to save power in two ways. First it lowers the load head (pressure) which reduces load horsepower (HP). Secondly, it shifts the OP back to the right-side of the pump curve, increasing efficiency and reducing input power.

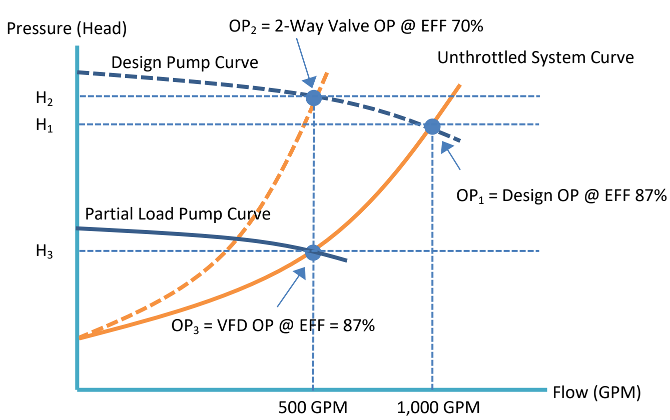


Figure 4-7 Variable Speed Pumps

Example:

The power can be identified as the shaded area under the pump curve below the operating points. The HP for the partial load system with a VSD is proportional to area A1 while the HP for the system with no VSD is proportional to areas A1 + A2. Therefore, the HP savings are proportional to area A2.

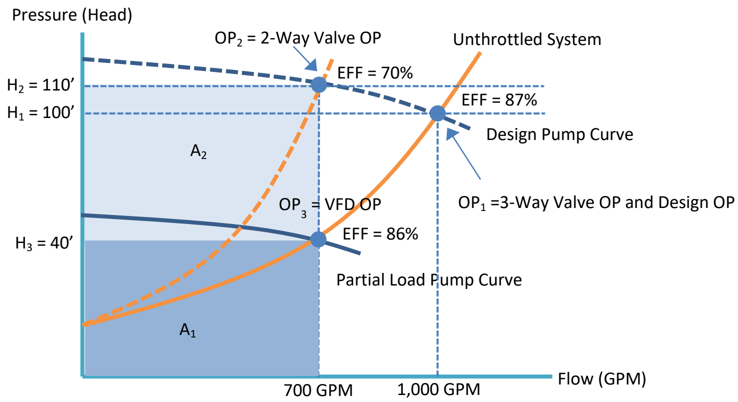


Figure 4-8 Variable Speed Pumps

Example:

Use the configuration in Figure 4-6. The control head = 10, friction head = 80' and flow = 1,000 GPM. We want to reduce flow to 500 GPM. Assume EFF_1 = 87%, EFF_2 = 70% and EFF_3 = 87%. From equation 2-2, if flow drops by ½, the frictional head drops by ¼. So, in this case, the head is 80/4 + 10 = 30. The HP for the three operating points is:

HP1 := (1,000 × 80) ÷ (3960 × .87) = 23.22 `HP

HP2 := (1,100 × 85) ÷ (3960 × .70) = 33.73 `HP

HP2 := (500 × 30) ÷ (3960 × .87) = 4.35 `HP

This results in a BHP savings from OP_3 to OP_2 of 87%

HP_Saved := 1- (4.35) ÷ (33.73) = 0.87 `HP

To summarize, the benefits of VSD operation are:

- Operating at reduced pressures can result in longer pump seal life, reduced impeller wear and less system vibration and noise.
- Converting a 3-Pipe constant flow system to a variable flow system enables the controller and VSD-pump to self-balance the loads as well as deliver capacity were needed thus overcoming deficiencies in the piping system.
- Due to the affinity laws, power is greatly reduced at reduced flows thus offering significant savings.

5. Retrofitting 2-Way for VSDs

To retrofit an existing 2-Way Valve system with a VSD do the following [8]:

Step (1) Add a variable speed drive (VSD) to the hot or chilled water pumps.

Step (2) Add a differential pressure sensor to tract the differential pressure across the load closest to the end branch. Typically, 75% of the way towards the end is acceptable.

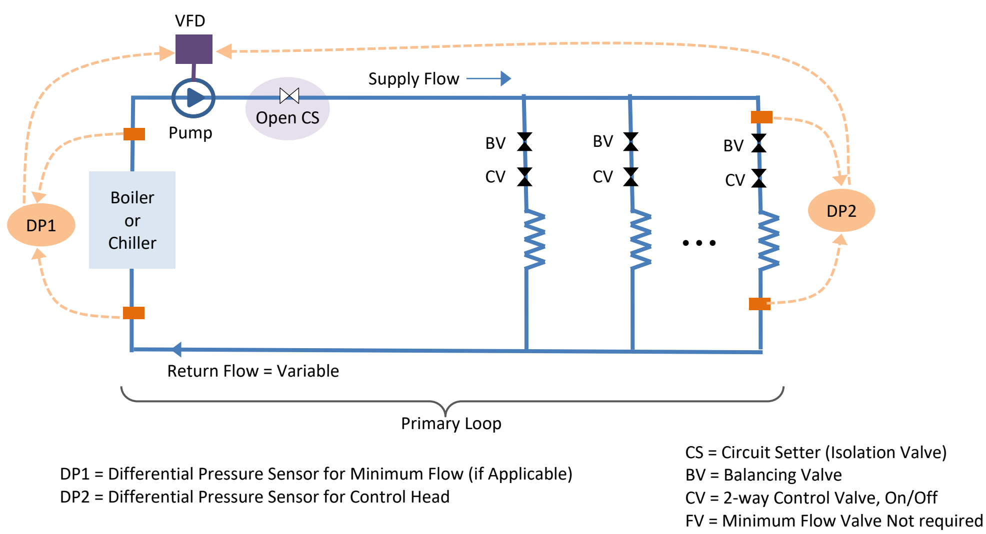
Step (3) Open the main circuit setter (100% open)

Step (4) Set the system to full load condition with all heating and or cooling valves 100% open and measure the differential pressure. This is the differential set point.

Step (5) Program the variable speed drive to operate at the system differential set point.

Step (6) If Minimum flow is required add an additional pressure sensor across the Boiler/Chiller and monitor pressure to ensure minimum flow is maintained.

Step (7) Once you have the system operating at the differential set point you can commission the system.



6. Retrofitting 3-Way for VSDs

One easy method for bypass control that Armstrong recommends is that, when converting a 3-way valve system to 2-way configuration, simply leave the most remote 3-way valve bypass line open on each riser. If there are only few loads in the zone, close the most remote 3-way valve bypass regulating valve 50% so that energy is not wasted with too much conditioned water being returned unused to the chiller or boiler [8].

- Step (1) Add a variable speed drive (VSD) to the hot or chilled water pumps.
- Step (2) Add a differential pressure sensor to tract the differential pressure across the load closest to the end branch. Typically, 75% of the way towards the end is acceptable.
- Step (3) Open the main circuit setter (100% open)
- Step (4) Set the system to full load condition with all heating and or cooling valves 100% open and measure the differential pressure. This is the differential set point.
- Step (5) Program the variable speed drive to operate at the system differential set point.
- Step (6) If Minimum flow is required, the controller is programmed to monitor pressure to ensure minimum flow is maintained.
- Step (7) Once you have the system operating at the differential set point you can commission the system.

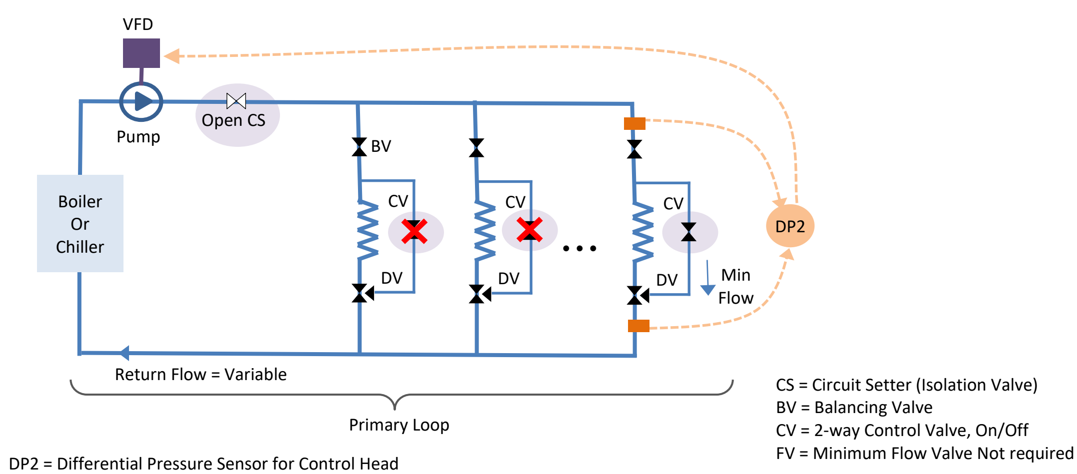


Figure 6-1 Retrofitting a 3-Way Valve System for VSDs [8]

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