Constant Pressure Boosters

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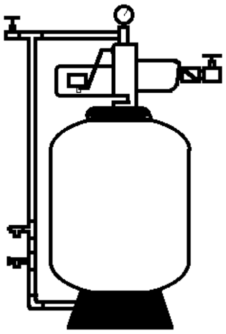
Introduction

Although there are many different water pumping applications, most tend to fall into three basic categories -- constant pressure, constant flow, and variable flow. This tutorial is the first in a series that will investigate each of the three.

Because design philosophies differ, some booster system designers may not agree with some of the contents of this tutorial. I, however, believe them to be valid as they are based on my almost twenty years experience in packaged, booster system design and fabrication.

All booster pumps and booster systems take advantage of the "additive" pressure rule that applies to series pump operation, regardless of whether their source is another pump, a municipal water line, or and elevated tank. And, as its name implies, the **constant pressure booster** not only adds pressure to the incoming water (boosts), but also provides constant (or nearly constant) pressure at its discharge. These systems can be as simple as a jet pump boosting the domestic water supply to a home or as complex as a quadraplex (four pump) system servicing a manufacturing plant, high rise building, or a subdivision. But, regardless of the application they all operate in much the same way with the single exception that complexity tends to increase with the number of pumps in the system.

In the past, booster systems relied on hydraulic valves and electromechanical devices to maintain constant pressure. Today we see a mix of those older technologies and the variable frequency drive (VFD), a device that can electronically vary the speed of an electric motor and, thus, achieve the same result. (If you are not familiar with the VFD, I suggest that you download "Variable Frequency 101" before proceeding any further. A basic understanding of the VFD is required for the second part of this tutorial.) Since both technologies are in use today we will investigate how each achieves its goal of providing constant pressure at varying flows.

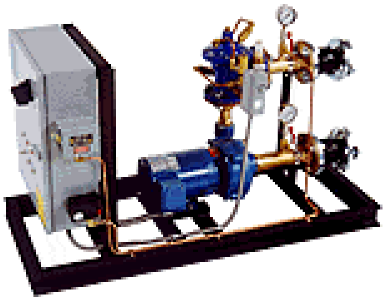


Before we enter the realm of constant pressure, lets take a look at a typical booster that utilizes a hydropneumatic tank to store water, under pressure, for use during periods of low or no demand. In this system (seen to the right) demand causes the tank to initiate flow and a pressure switch starts the pump when pressure drops to some minimum. When demand disappears, the tank is repressurized and the switch turns the pump off when pressure reaches some predetermined maximum. In between, it provides some intermediate pressure that is dependent upon demand and the capability of the pump. A check valve prevents the higher pressure water from returning to the source when the pump is not operating.

Now, this type of booster operates exactly like a domestic water well system except that, in this example, it is used to boost the existing pressure of some water source rather than drawing water from a well. It is known as a **differential pressure** booster because the pressure switch is set to start the pump at a certain pressure (say 50 PSI) and then stop it at a higher pressure (say 65 PSI). This differential allows a properly sized tank to accumulate pumpage and provide some, predetermined, minimum run time for the pump. As you can see, it is not a constant pressure system as the pressure of the flowing water ranges between the on and off points. These booster systems can be perfectly adequate in many applications but in others a constant discharge pressure is more desirable.

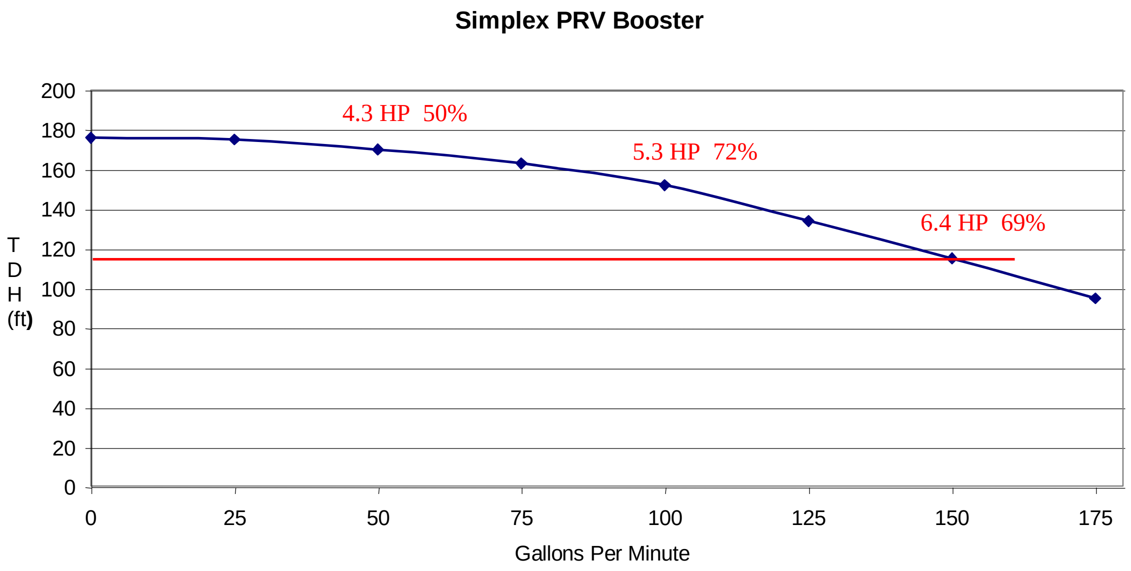
I might mention here that only centrifugal pumps can be used to **boost** the pressure of an existing pressurized water source. The centrifugal can do this because it converts velocity into pressure. Positive displacement pumps (inelastic ones anyway) cannot. They can boost the pressure of gases because gases are compressible, but not water, as it is nearly noncompressible. See "The Corrupted Curve Puzzler" for more on the operational characteristics of positive displacement pumps. They have their own, very special, affinity laws!

PRV Controlled Constant Pressure Systems



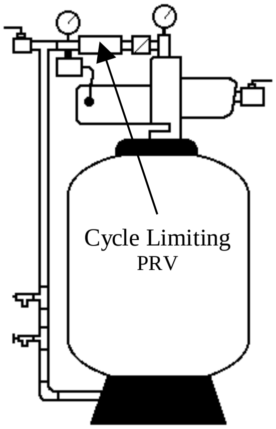
The figure to the left is that of a simple, **simplex** (one pump) constant pressure booster. It consists of pump that runs continuously, a check valve mounted on its suction (or discharge), a pressure reducing valve (PRV) mounted on its discharge, and a control panel. Often a low volume bypass line is installed between the discharge and the suction so that some water will flow through the pump during periods of zero demand. If the pump must withstand long periods of operation at or very near shut off head, the water temperature within the pump case can rise to an unacceptable level. When this possibility arises a solenoid valve, controlled by a temperature sensor, can be used to purge water to a drain when the temperature reaches a certain level. As fresh water enters the pump case, temperature drops and the valve closes. The PRV maintains a constant down stream pressure by continuously varying its discharge orifice via a preset spring or a small control valve. The latter provides more precise control at higher flows. The orifice closes completely when demand is zero and downstream pressure is maintained. The check valve simply protects the source supply from contamination by the higher pressure system water when the source is shut down for maintenance.

The figure below shows this booster pump's head / capacity curve (blue) and the system curve (red) produced by the PRV. As you can see pump pressure increases as demand decreases but system pressure, down stream of the PRV, remains the same (115'). The power required by the system decreases as demand decreases and can be calculated, fairly accurately, by: BHP = (GPM x Head) / (3960 x Pump Efficiency). BHP is shown at several points across the curve. A little later, you will see that the use of a VFD in a constant pressure application can reduce power consumption substantially over that of a PRV regulated system. Pump size varies by application and they can be quite large if the application has few periods of low demand. In applications where low or no demand is frequent, the simplex system is usually limited to smaller pumps. Applications with large variations in demand are often better serviced by a multi-pump booster (VFD controlled simplex boosters can be an exception to this rule) .



If a simplex booster is placed in an application that will see long periods, or many short periods, of zero demand, a hydropneumatic tank can be incorporated in the system thus allowing the pump to be cycled on and off. Since the tank must be installed on the high pressure side of the PRV, it must be rated to withstand the shut off pressure of the pump. In many cases an ASTM rated tank will be required and, although expensive, the power savings alone can often justify its installation. A constant pressure booster that incorporates a tank is usually controlled by a pressure switch in conjunction with a delay-off timer. The timer prevents short cycling of the pump during low demand periods by establishing some minimum run time. Usually the tank is not sized to provide flow during periods of low demand because of the storage volume required and its reduced capacity due to higher pressures . It is there simply to maintain pressure on the pump side of the PRV during periods of no demand. An exception to this rule applies to low volume, lower pressure boosters. With these systems hydropneumatic tanks can be used to store water for use during periods of very low demand.

There are also several “cycle limiting” control valves on the market that allow use of a small tank to limit pump cycling in booster systems. These differ from standard tank based boosters because the tank and pressure switch are installed on the low pressure side of the valve. These units reduce cycling by forcing water into the tank through an extremely small orifice after demand has ceased. In order to shut the pump off the system pressure must increase above its normal operating pressure (+10-20 PSI). Except for this higher shut off pressure, they operate in the same manner as a standard PRV. An example of a domestic, cycle limiting booster is seen to the right.



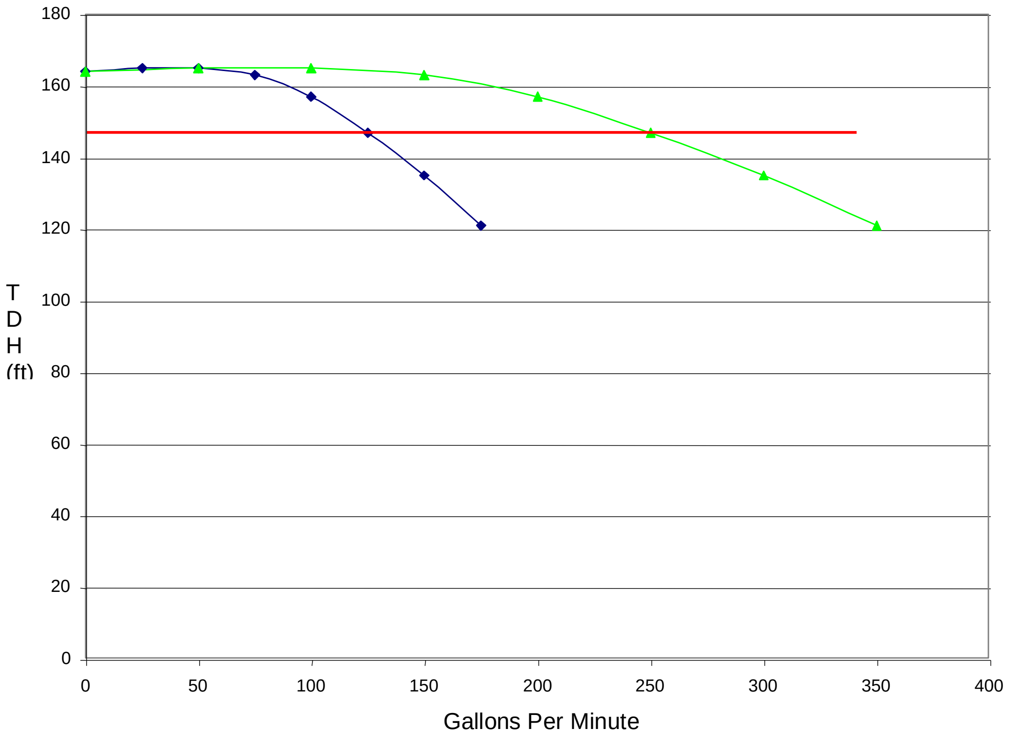
In some applications, the desired flow range may be too great for a simplex booster. In these applications a **duplex** (two pump), **triplex** (three pump), or even a **quadraplex** (four pump) system can be employed. These designs are often referred to as lead / lag systems because the additional pumps (lag pump(s)) are brought on line as demand exceeds the capacity of the lead or primary pump. Multi-pump boosters take advantage of series operation to boost pressure and also benefit from the rules of parallel pump operation to increase flow.

Duplex systems will utilize either two pumps of the same size or a small, continuous run “jockey” pump and a main pump. The configuration depends upon the flow range required. The purpose of the duplex design is to reduce power consumption during periods of varying demand as compared to a simplex system of the same capacity. When two pumps of the same size are used, a

hydropneumatic tank may be incorporated if periods of no demand are anticipated. Such a system is seen to the left. In this case, the lead pump is controlled in the same manner as the tank based, simplex system we saw before. The lag pump is controlled by a flow switch or a pressure switch that is set at a slightly lower pressure than that of the primary pump. Either will bring the second pump on line just as the primary pump approaches its maxim flow (or minimum pressure). Depending upon the flow rate of the pumps a single, discharge header mounted, PRV or individual pump mounted PRV's may be used. In some cases a single PRV, capable of handling the flow of both pumps, may not be able to maintain constant pressure at lower flows. Depending upon the sophistication of the controls, the lag pump may always be the same physical pump or, it can be alternated to the lead pump position after each stop cycle thus evening out usage. Delay timers are also usually employed to protect both pumps from short cycling. A bypass may also be required depending upon the pump design.

The figure below shows the head / capacity curves and the system curve for a duplex system that employs two pumps of the same size. The blue curve is that of the lead pump and the green curve is that of the lead and lag pumps running in parallel. As illustrated by the system curve (red) the second pump will start when flow approaches 125 GPM or pressure drops to 147'. In parallel booster operation,

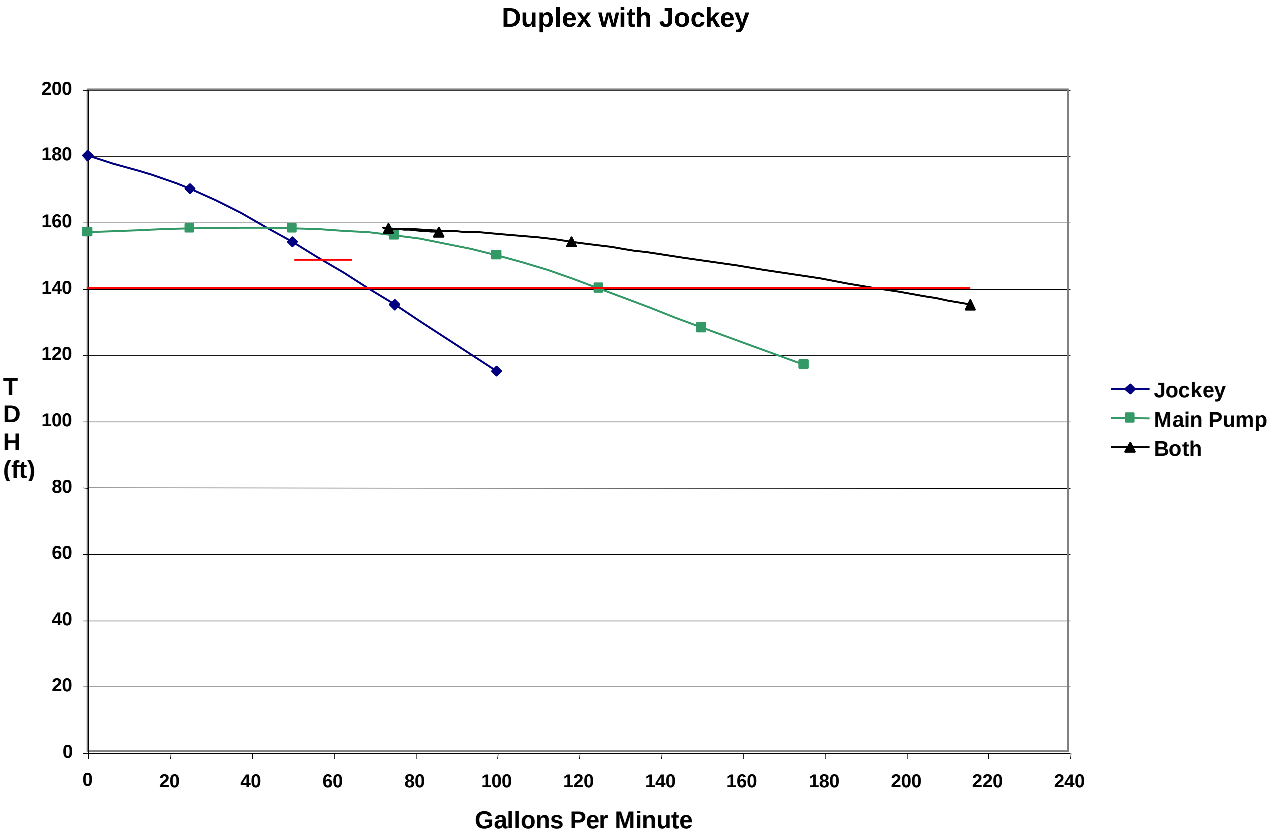
Parallel Booster Operation (Identical Pumps)



the flows of the two pumps are additive at each point on their head / capacity curves. In the example above, note where the system curve intersects each head / capacity curve. When one pump is running, the maximum flow is 125 GPM at 147'. When both pumps are running the maximum flow is 250 GPM at 147'. The PRV maintains constant down stream pressure regardless of the actual head of the two pumps.

In duplex systems utilizing a continuous run jockey pump, hydropneumatic tanks are usually not employed. The jockey is sized to handle "off hours" periods of low demand and a pressure switch brings the main pump on line as demand increases. A bypass and thermal purge are usually installed on the jockey pump and a delay-off timer protects the main pump from short cycling. In this configuration, the pumps cannot be alternated from a lag to a lead position due to their differing capacities.

The figure below shows this booster system's head / capacity curve and the system curve produced by the PRV. The blue curve is that of the jockey and the green curve is that of the lag pump. The black curve is that of the two running in parallel and the system curve is in red. As illustrated by the system curve the jockey pump will carry the load until flow approaches 60 GPM or pressure drops to about 150' . At that point the lag pump is brought on line and both, operating in parallel, will



produce a maximum flow of about 200 GPM. The reason the lag pump is brought on line at 150′ rather than at system pressure is to avoid the possibility of a pressure drop that could be followed by a surge from the higher capacity lag pump. Either a flow or pressure switch can accomplish this task.

Triplex systems (shown to the right) consist of three pumps of the same capacity or a jockey and two lag pumps, depending upon the flow required. Jockey based systems usually do not incorporate a tank since the jockey is sized to handle low demand. As with the duplex booster, the triplex design is used to provide a broad capacity range and, at the same time, use electrical power effectively. They are sequenced by pressure switches (or flow switches) that bring the next pump (Pump 2 or Pump 3) on line just as the previous pump approaches its maximum flow. Pumps 2 and 3 are shut down in a reverse order and are protected from short cycling by delay-off timers. The parallel flow characteristics of the triplex are similar to that of the duplex booster except that there is the potential for three pumps operating at the same time. Once again, a thermal purge system protects the jockey from over heating and delay timers protect the main pumps from short cycling.

Some triplex systems incorporate more sophisticated sequencing controls and will shut down the jockey when pump 2 comes on line. If additional flow is needed, the jockey is brought back on line. If pump 3 comes on line, the jockey is again shut down and pumps 2 and 3 provide flow. (During extreme flow conditions, all three pumps will be on line.) When demand decreases, pump 3 shuts down and the jockey is brought back on line. Pump 2 is then shut down and the jockey, once again, carries the load. Can you imagine the number of relays required for this type of sequencing prior to the advent of programmable logic controller (PLC)? I can, because I used to design them! The advent of VFD control has replaced many triplex applications with duplex systems and we will discuss these a little later. We will not get into **quadraplex** systems but, after reviewing the triplex system, I suspect that you can appreciate the opportunity to mix various pump sizes and the potential complexity of the logic required to sequence them.

Pump Selection (PRV Operation)

Depending upon its design, a pump will produce a flat, moderate, or steep head / capacity curve. All are used in PRV controlled, constant pressure booster systems, however, a "flatter" curve is often preferred. Why? Because the flat curve offers the greatest potential for power savings as demand declines and the pump progresses towards shut off. The power required at any point on the head / capacity curve is function of both flow and head (see the HP equation we stated earlier). Flat curves exhibit a much lower head rise at shut off and therefore consume less power than steeper ones. In duplex and triplex boosters incorporating identical pumps, these flat curves can be accommodated by use of a flow switch to control the lag pump(s).

When a hydropneumatic tank is installed in a constant pressure booster system, a pressure switch is normally used to control the pump(s) and a slightly steeper curve will be required to assure accurate on / off control. Although more sensitive pressure switches are available, many flat curves do not offer the differential pressure necessary to pressurize the tank to a level that will provide even a few seconds of flow during periods when the pump(s) are off line.

Duplex systems that incorporate a continuous run jockey pump typically use a pressure switch to control the lag pump. Again, it is desirable for the lag pump to produce a flat curve, however, the jockey is usually chosen with a steeper curve so that the pressure switch can, consistently, bring the main pump on and off line. In triplex systems, flow switches can be used to control lag pumps that produce flat curves or those pumps can be sized with slightly steeper curves for pressure switch operation.

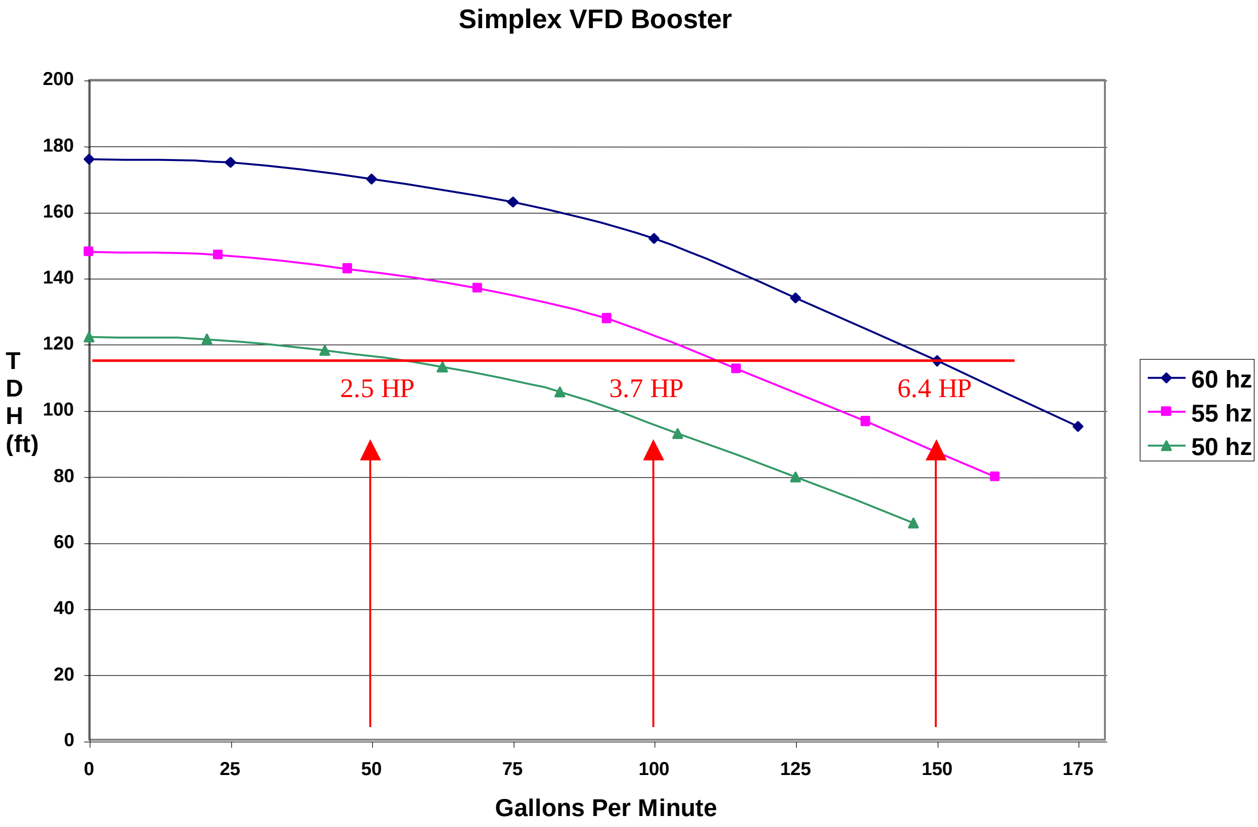
VFD Controlled Constant Pressure Systems

The variable frequency drive (VFD) changes a motor's rotational speed by increasing or decreasing the frequency of the AC current that supplies it. The beauty of the VFD is, that by changing a motor's speed and therefore that of the pump, the system takes full advantage of the laws of affinity. These laws state that flow varies directly with the rotational speed, head varies as the square of a change in speed, and power varies as the cube of that speed change. For example, if you reduce pump rotational speed by one half -- flow is halved, head is reduced by three quarters, and power is reduced by seven eighths.

Instead of a pressure or flow switch, a pressure transducer is used to control the drive and, ultimately, the output of the pump. The transducer is an electronic device that converts pressure into a small current (4-20 ma) that can be used by the VFD to monitor system pressure. Depending upon the "feed back" from the transducer, the drive will either increase or decrease frequency, in 0.1 hz increments, to maintain constant pressure regardless of the flow (a little later you will see that a one hz change can make quite a difference!). Just how well such a system can maintain constant pressure depends upon the drive itself, the accuracy of the transducer, and rate of change in flow demand. Huge dips or increases in demand may require a few seconds for the drive to restabilize pressure (the same is true for PRV controlled systems).

I would show you a picture of a VFD operated pressure booster but it would be redundant because, on the exterior, they look just like the boosters we have seen earlier. The only exception is a PRV is not required. They may be continuous run systems or their controls may incorporate the logic necessary to accommodate a small hydropneumatic tank for periods of no demand. Often their controls will include a "bypass starter" so that the pump(s) can be operated manually if the drive malfunctions. Although simplex systems are quite straight forward, the logic required to sequence multipump systems can get a little complex. Fortunately the PLC (programmable logic controller) has reduced this complexity substantially. We will take a look at duplex and triplex systems a little later.

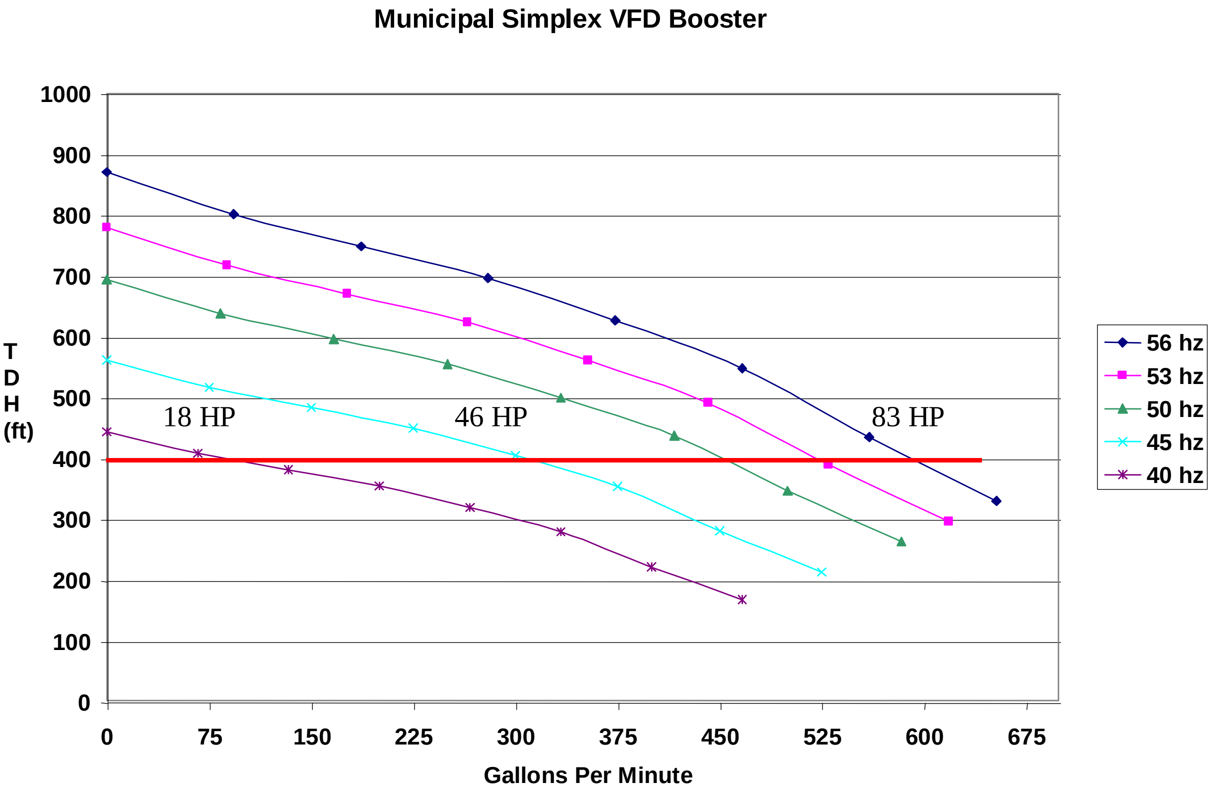
Below are the head / capacity curves for the PRV controlled simplex booster we saw earlier under VFD control at 60, 55, and 50 hz. The system curve (red) is at 115'.



Remember that, even though they are not shown, the VFD will produce a head / capacity curve for each individual and fractional hz in between and, any point on the system curve, will operate at the lowest frequency that will meet system head at that point. This particular application will utilize a frequency range of 49 – 60 hz and maintain a system pressure of 115′ from shut off to maximum flow.

The striking difference between this illustration and that of the PRV controlled simplex system is the lower power required at intermediate flow points. Both the VFD and PRV controlled units require the same power at maxim flow. But, at 100 GPM the power required drops from 5.3 to 3.7 HP and at 50 GPM, it is reduced from 4.3 to 2.5 HP. A similar reduction would be seen at every point on the system curve.

I mentioned earlier that VFD controlled simplex boosters have been able to replace many duplex applications and still control flow and pressure while often reducing power consumption below that of the duplex. The reason they can do this is because the laws of affinity and the steeper head / capacity curves produced by some pump designs. The illustration below is just such an example.



Here we see a 100 HP submersible turbine servicing a small municipal application designed to provide constant pressure to a subdivision. The system design calls for a flow of 75 to 600 GPM at a constant pressure of 400′ as measured at the pump discharge. Now, this application would not be feasible via a PRV because the head rise from maximum flow to shut off is over 500′ (at 60 hz) and the power consumed at low flows would be extremely high. Also, damage to the pump and motor is assured if one were to actually try this. Before the advent of the VFD, the pump would have been sized to fill a holding tank and a duplex, constant pressure booster would be installed at the well head. A duplex booster is required because a simplex unit would exhibit inefficient use of power across the broad range of flow required.

As you can see the pump selected meets the system curve throughout the flow range and does so over a frequency range of approximately 39 – 56 hz. Power consumption is shown at 75, 300, and 600 GPM. Now, the minimum recommended flow across an 8″ motor in an 10″ casing is 55 GPM but, that is at full load (in this case 100 HP). In this application the load is greatly reduced and a substantially lower flow rate can provide proper cooling (contact the manufacturer for minimum flows at low loadings). In applications such as these a bypass (back to the well) is usually installed in order to assure some minimum flow past the motor. Also a small hydropneumatic tank can be used to accommodate long periods of no flow.

This application illustrates another property of VFD control that is often over looked. The system curve requires a maximum frequency of just 56 hz to meet its maximum flow requirement. If the application does not require it, there is no need to operate the pump at 60 hz. In this example, the power required, at full flow, is reduced by 17% compared to that required by PRV control. If additional capacity is required in the future, pump speed can be increased to its 60hz value. In fact, pumps are often sized to meet current requirements at just 50 hz. This allows quite a bit of growth capability over the life of the system.

Duplex and **Triplex** VFD controlled booster systems can be controlled in two very different ways -- **individual** pump control and **lag** pump control. A single VFD can be sized to control many pumps at once, however, it cannot control them individually. Any change in frequency affects all of the pumps connected to that single VFD. Therefore, multipump, systems must have individual VFD's if they are to operate independently. Manual control of such systems is next to impossible so, once again, the PLC comes into the picture.

The VFD's used to control **individual** pumps in a multipump booster are usually limited in their capability. Their single purpose is to ramp the frequency up or down depending upon what they are "told" to do. The device that tells them what to do is the PLC. It is the brains of the system and digests the pressure and flow information it receives and makes decisions as to how to best apply the pumps available to it. Duplex and triplex systems are sequenced in much the same way, so lets take a look at the simpler duplex PLC control.

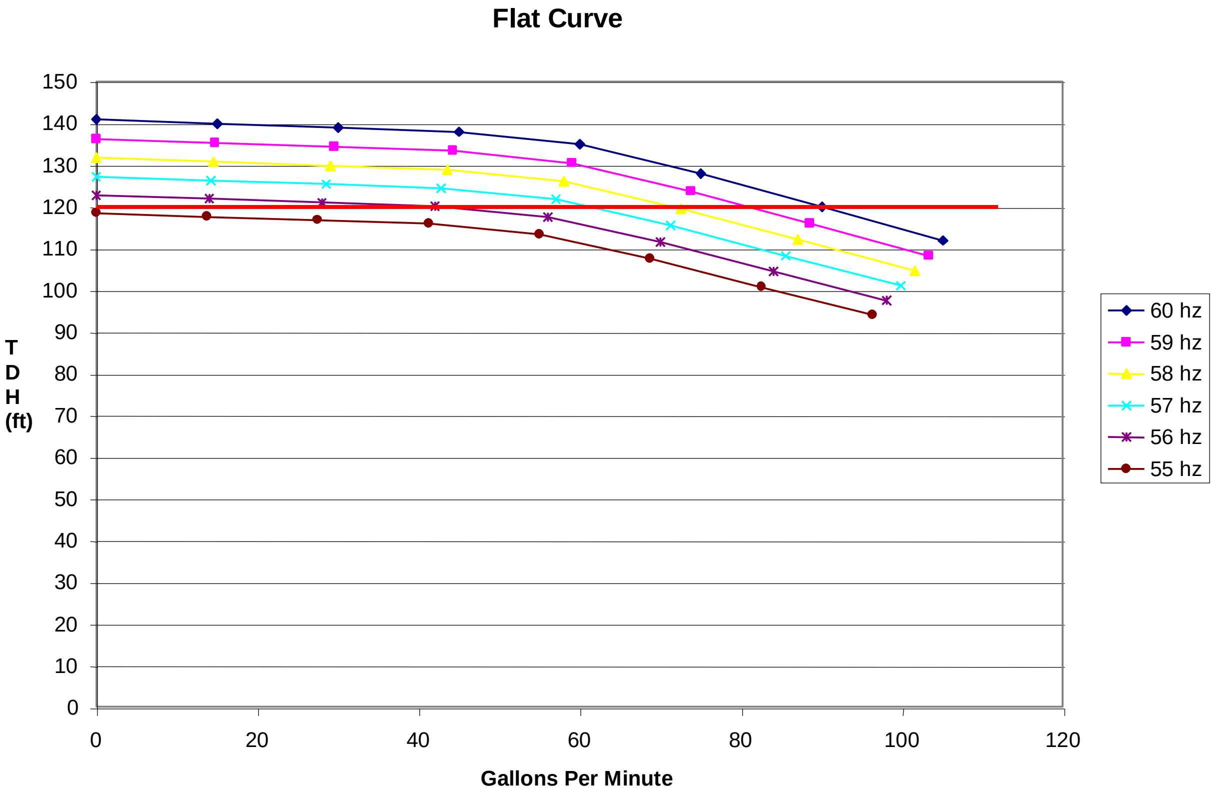
Duplex systems with pumps of the same size are pretty straight forward. The PLC uses pressure or flow information to send a signal to the lead pump VFD that causes it to increase or decrease frequency in order to maintain constant pressure, just as we saw in the simplex system. If flow decreases or increases, frequency will be reduced or increased accordingly. When the flow (frequency) of the lead pump reaches its maximum, it is "locked" in at full speed and the PLC brings the lag pump on line and adjusts its frequency to meet demand. As demand declines the frequency of the lag pump is decreased until it reaches a point the lead pump can handle the load. At that point the lag pump is brought off line and the PLC once again controls the frequency of the main pump. In some systems the PLC will alternate the lead and lag pumps in order to even out the use of each.

In a duplex system that uses pumps of different sizes the PLC sequences the pumps in much the same way as a PVC controlled booster. It varies the frequency of the smaller pump to meet the constant pressure requirement but, once it reaches its maximum flow and the larger pump is brought on line, the smaller pump is removed from the system. The larger pump's frequency is then varied but if demand exceeds its capacity, the smaller pump is brought back on line and its frequency is again varied to meet demand. As demand decreases, the larger pump is removed from the system and the PLC again controls the output of the smaller pump. I realize that this may seem somewhat complex but, if you read through it a couple of times, I think it will become clearer.

There is a simpler way to control multipump systems and, in many applications, it will be just as effective. **Lag** pump control may not require the use of a PLC as it is built into the control software of some VFD's (ABB for example). In these systems the VFD controls the frequency of the lead pump to meet demand. If demand exceeds its capability, the VFD energizes a relay that activates a separate "across the line" controller which brings the lag pump on line at full speed. The VFD then reduces or increases the frequency of the lead pump to meet any additional changes in demand. When demand decreases to that of the lead pump's capability, the relay drops the lag pump and the VFD continues to control the lead pump.

Pump Selection (VFD Operation)

As I mentioned earlier various pump head / capacity designs are used in constant pressure booster systems, however, some flat curve models are not well suited for VFD operation. An example of a flat curve is seen at the top of the next page. The system curve shows a constant pressure of 120′. Notice that, as flow decreases from 90 GPM to shut off, the head produced by the 60 hz curve increases by less than 25′.



This leaves very little room for variable frequency control and, as you can see, the 55 hz curve does not meet the system curve at any point. Therefore the usable frequency range is just 5 hz - - an example of a poor VFD application.

In VFD controlled booster systems, the curve must be steep enough to allow a reasonable frequency reduction and still maintain the desired pressure at several points across the flow curve. The number of points depends upon the flow rate of the pump and the accuracy of control desired. For example, if a booster system designed for 0 to 600 GPM has a head / capacity curve capable of producing system pressure from 60 to 48 hz, the BHP required at 48 hz will be about 50% of that of that required at 60 hz - - a major energy savings. If the curve were a straight line, each one hz change would result in a flow change of about 50 GPM. Although flow can be regulated and power saved over a smaller frequency range, 10 – 12 hz tends to be a desired minimum. Remember that the VFD varies frequency by both whole and fractional units. It maintains constant pressure by continuously varying the frequency it supplies (many times each second) which results in some "average" frequency per time increment. If the distance between frequency points on the system curve is too great, the accuracy of pressure regulation will suffer.

For a more detailed discussion of pump sizing for VFD operation download "VFD Pump Selection – Constant Pressure".

Joe Evans July 2003