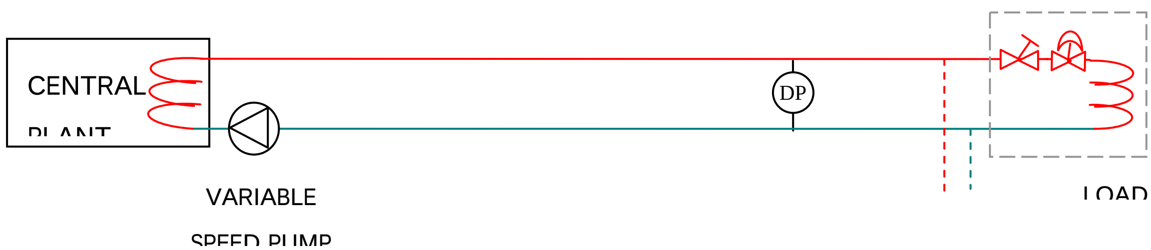
Sensorless Control Basics

Introduction

In an HVAC system with a central heating and/or cooling plant, the thermal energy is sent to the loads (air handlers, radiators, fan-coils, etc) in the form of a hot or cold fluid (usually water, glycol or a mix of both).

Each load has a heat exchanger which takes (or gives) thermal energy from (or to) the fluid. The amount of energy transferred depends, among other factors, on the amount of fluid flow and its temperature.

Each load controls the flow it takes by means of a motorized valve. Adjusting the valve position, and so changing its hydraulic resistance, the flow taken is controlled to match what the load needs.



The actual hydraulic resistance (or valve position) needed to produce a certain flow depends on the differential pressure across the valve. In fact, it's given by the following formula: $Hyd\_Res = Diff\_Press / Flow^2$.

The maximum flow a motorized valve can allow at a given differential pressure happens when it's full open and its resistance is lowest.

The purpose of the distribution pump(s) is to deliver the flow of cooling or heating fluid required by the system loads. To do so, they have to produce enough head, (differential pressure), that the valves at the loads can allow the required flow (at the given fluid temperature) within the range of hydraulic resistances they can produce.

If a valve is full open and the flow is less than what's required, that load demand for heating or cooling is unsatisfied and the load it's said to be *starving* or *in underflow*.

Flow Loss Compensation

One option to avoid starving loads is installing differential pressure sensors close to the loads, and adjusting the distribution pumps speed to maintain the sensors readings at or above certain minimum levels, which would ensure all loads can take the flow they need at all times.

The differential pressure at a sensor location is the head produced by the pump minus the friction losses in the pipes between the pump and the sensor, including those in the central plant heat exchanger (or decoupler, if constant primary – variable secondary).

Since all the elements between the pumps and the sensor have fixed hydraulic resistance, when maintaining the remote pressure constant the friction losses have a quadratic relationship with the flow, as shown in the figure below.

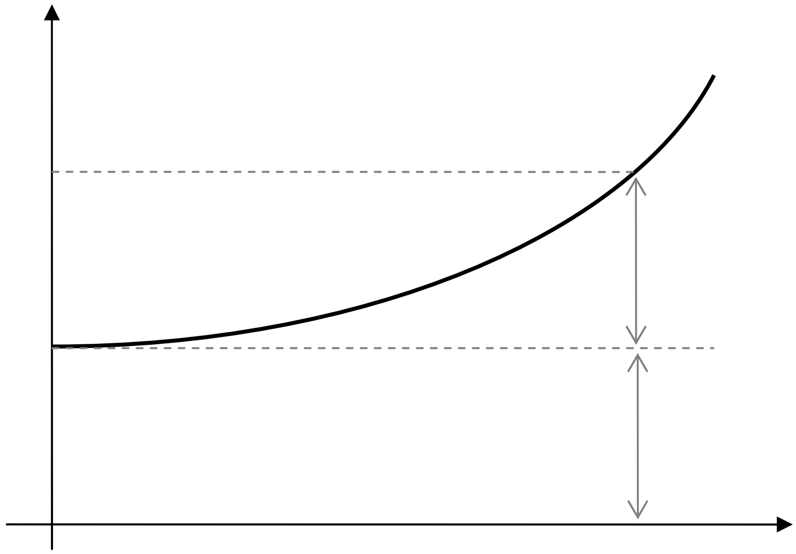


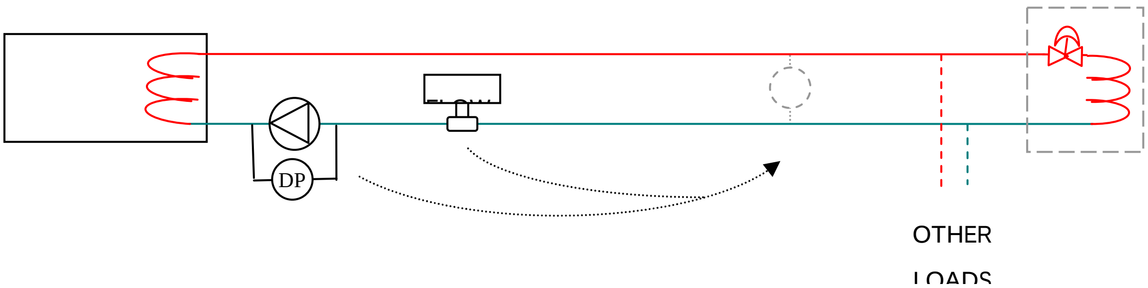
Figure 2

To ensure the flow demand is satisfied at all times, the differential pressure maintained at the sensor location (or pressure setpoint) has to be at least the required to produce the design flow of the loads when their valves are fully open. That is, the pressure across the motorized valve, plus the friction losses between the sensor location and the valve (including the load heat exchanger and balancing valve(s), if present).

Notice that as long as the sensor is located before the flow is split between multiple loads, its reading can be calculated from the pump head and flow if the fixed hydraulic resistance (k) of the piping between the pump and the sensor is known.

Conversely, if that fixed hydraulic resistance is known, the head (H) the pump needs to produce for each given flow (Q) to maintain a certain pressure (H_o) at the sensor location, can be calculated by the formula $H = H_o + k\,Q^2$, as shown in Figure 2 above.

Then using a differential pressure sensor across the pump (to measure its head or differential pressure produced) and a flow meter, the pump speed can be adjusted to maintain a remote differential pressure at a constant value.

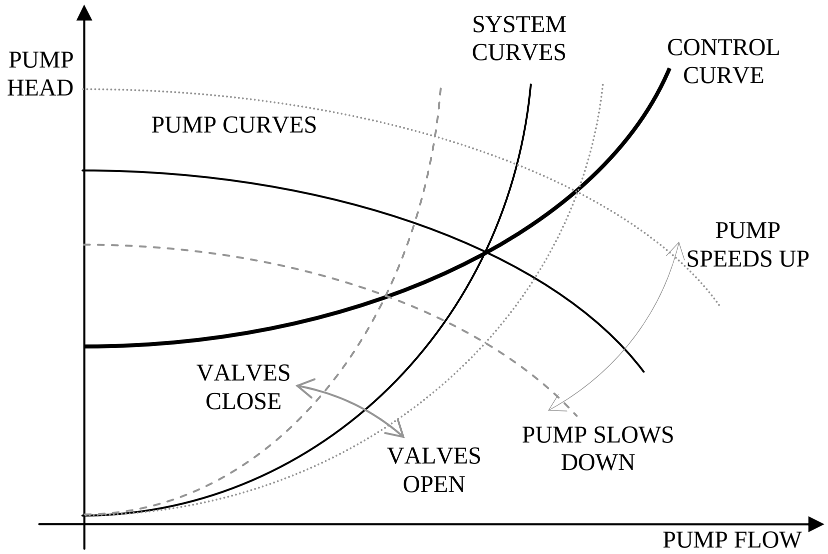


This method for controlling the pump speed is called *Flow Loss Compensation*.

Another way of viewing this control method is noticing that if all the system motorized valves stay at fixed positions or move slowly enough, the pump(s) will, at least temporarily, be working against a fixed system flow & head curve (called the System Curve). Different pump speeds result in flow & head operation points over that curve.

The Flow Loss Compensation control method will adjust the pump speed to make it operate at the intersection of the given System Curve (at that time) and the Control Curve ($H = H_o + k\,Q^2$)

As the valves open or close, the pump speed is adjusted up or down.



Sensorless

The same method can be used if the pump head and flow are *not directly measured*, but calculated from other variables measured by the pump speed drive.

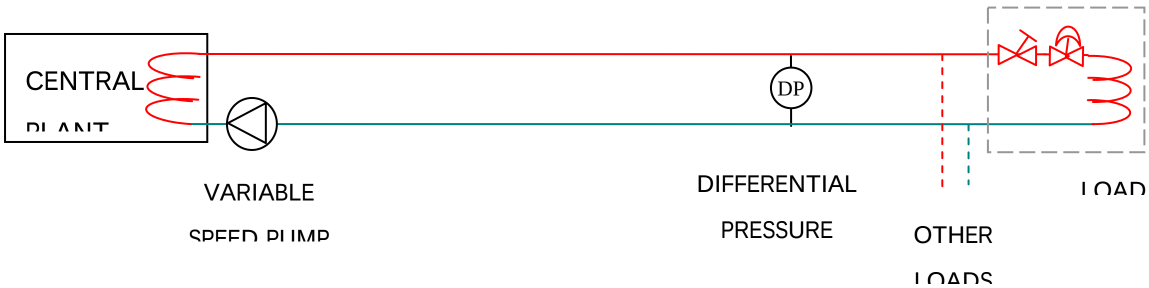
Since no sensors are inserted in the pipes, the calculated pump head and flow are called *Sensorless Readings*.

The application of *Flow Loss Compensation* with *Sensorless Readings* is what we call *Sensorless Control*.

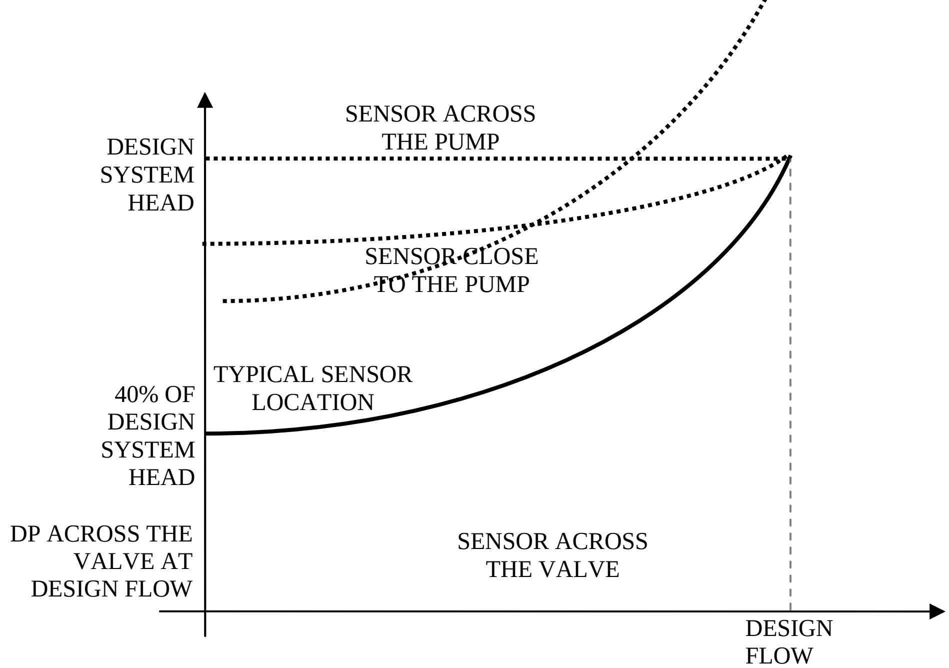
Sensorless Control is a method for adjusting the speed of HVAC distribution pumps, which infers the flow demand by indirectly measuring the hydraulic system resistance, and then calculates a speed that balances satisfying that demand with minimizing the energy used.

Sensorless Control

Sensor location implications



In the figure above, if the pressure sensor is moved closer to the load, the pressure setpoint required to ensure the loads can take their design flow is reduced by the design flow friction losses in the portion of the pipe between the previous and new sensor locations. This will increase the energy savings, as the distribution pump will have to produce less head at partial flows, as shown in the figure below.



In the more extreme case, the sensor would just measure the pressure across one load valve, obtaining maximum savings. This is sometimes recommended by pressure independent valve manufacturers.

However, when moving the sensor close to one load, the pressure across other loads in the system becomes more variable and more prone to falling below the minimum required.

Conversely, if the sensor is moved towards the central plant, the pump will have to produce more head resulting in less energy savings, but better ensuring all loads are satisfied at all times.

When changing the sensor location, increased savings come with increased risk of starving loads, (unless additional pressure sensors are installed), and robustness is achieved at the expense of energy savings.

The same happens when using Sensorless Control. If the control curve point at zero flow is set low, great energy savings are achieved, but there is a risk of starving some loads if their demands are very different. If that point is set high, the system is more robust but the savings are poor.

The factory default for the control curve at zero flow is 40% of the pump design head. In most cases this is the highest value that still achieves the savings required by ASHRAE 90.1

Let's now analyze how well this setting satisfies the loads in different scenarios. To simplify calculations, it's assumed the design pressure for all loads is 40% of the pump design head, so 60% of head is lost as friction in pipes and balancing valves.

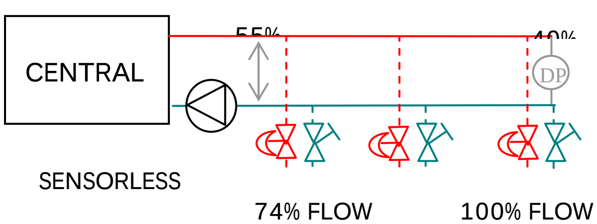
Scenario 1

Let's assume in the system of the figure above there are a high number of loads, and the percent flow demand from any load was at most 50% higher than the average flow demand.

This means when one load demands 100% flow, there should be at least 50% flow through the distribution pump(s). At this point the pump is adjusted to provide a head equal to 55% of design head, and the friction losses, which are related to the square of the flow, are at most 25% of the design losses at any point in the system.

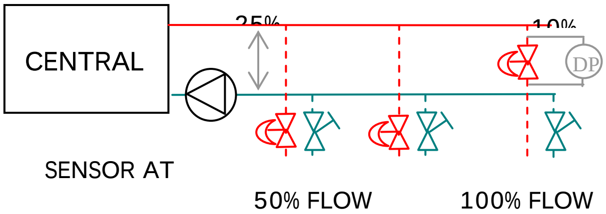
If the load demanding 100% flow is at the end of the line, the differential pressure it receives is 55% - 0.25 x 60% = 40% of the pump head. But if this load is at the end of the line, it should be balanced for 40% or less pressure, so it is able to take all its design flow.

If instead, that load was very close to the pump, it would receive just 55% of the differential pressure it was balanced for: contradicting common knowledge, the starved load is the closest to the pump, not the furthest.



If the pump was controlled based on a DP sensor at the end of the line, it would produce exactly the same situation (design DP at the end of the line, 55% of design DP close to the pumps).

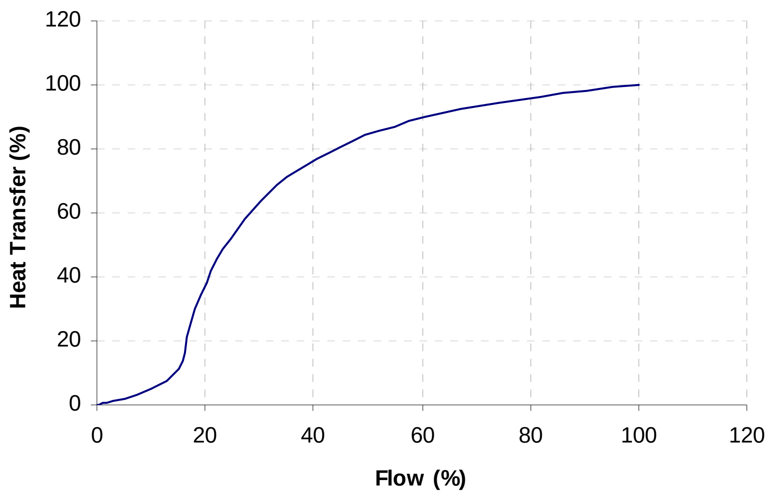
And a DP sensor just across the furthest load valve, whether pressure independent or not, would make it even worse because the portion of the head otherwise taken by the valve is drastically reduced.



In that case, at 50% of its design flow, the drop across the coil on the furthest load would be 25% of it design pressure drop, which is approximately 25% x 40% of the pump head = 10% of the pump head. So the pump would be controlled to produce a head equal to the pressure drop at that load plus the friction losses in the distribution piping. That is 10% + 0.25 x 60% = 25% of the design head, at most. And that's what the load closest to the pump would be receiving.

Let's now analyze how the load receiving 55% of its design head with Sensorless Control performs.

The percent flow it gets is the square root of the percent head, that is, 74% of its design flow. And the heat transferred typically varies with the flow as per the graph below.



At 74% flow, the heat transferred is about 95% of design value. If the distribution fluid is at design temperature, the loss in system performance is almost unnoticeable.

In a system where the fluid temperature was changed based on load, the effect would be cumulative. Typically at 50% load in a chilled water application the temperature would be increased by 2 to 3°F, which would result in an extra 5% loss. The heat transferred would be about 90% of design, which is still acceptable.

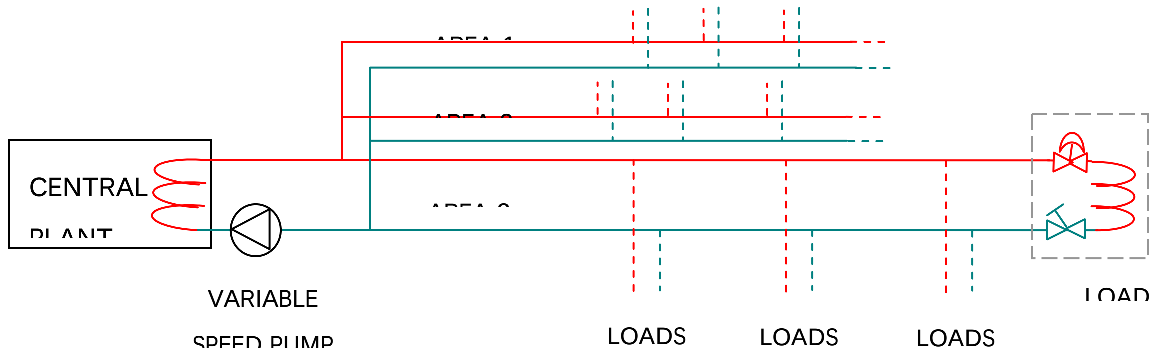
But this problem disappears if the load(s) with demands much higher than average are either equipped with pressure independent valves or balanced for lower pressure (though this last option, at normal pressure may cause them to overflow, make the motorized valve hard to position, and produce low delta T).

Notice that 50% difference in flow demand is just 15% difference in heat transfer demand at the higher flow values. So, let's analyze what happens in systems with bigger heat transfer demand differences.

Scenario 2

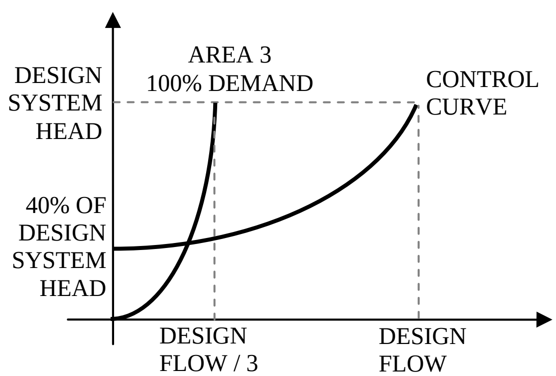
This is the worst case scenario for sensorless control.

The flow is split into several areas right at the outlet of the central plant. This could be a plant serving several buildings or a building with several wings.



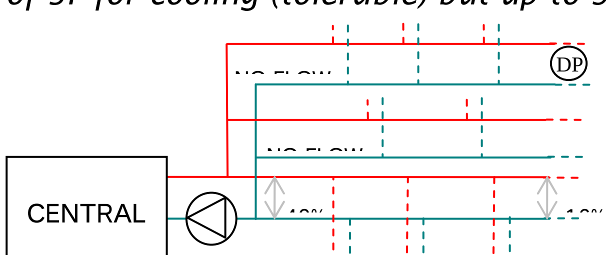
The demand from some areas can be disabled (because they are not rented or shut off for vacation), at the same time other areas are having 100% demand.

The pump(s) control curve is configured for the design demand of the whole system.



If just one area has 100% demand (all the valves full open) while all others are disabled, the maximum demand (minimum hydraulic resistance) that area can produce will make the speed of the pump(s) be adjusted to produce just over 40% of the design head.

All the loads in that occupied area receive 40% of their design differential pressure, with which they get 63% of their design flow and can deliver up to 90% of their design heat transfer, if the fluid temperature is at design value. This would typically cause a room temperature drift from setpoint of 3F for cooling (tolerable) but up to 9F for heating (unacceptable).



In a typical system where the fluid temperature is adjusted based on demand, the heat *transfer will be 80% of design for a cooling application or 70% of design for a heating application.*

Even in this very extreme scenario, the loss of performance could be easily corrected by adjusting the parameters of the control curve to match the design demand of the occupied area(s).

If instead of Sensorless Control one differential pressure sensor in one zone was used, and that zone was disabled, the results would be exactly the same.

A single sensor just across one valve, whether pressure independent or not, in a disabled area, would make the pump head setpoint equal to 5psi, which in most cases would be less than 15% of the pump design head. The pump would spin at minimum speed, producing a very low head, and the heat transfer would be below 50% of design for most loads. This would cause deviations from setpoint greater than 10F.

Having at least one sensor in each area is a solution that doesn't lose performance when areas are disabled, but with the limitations discussed in Scenario 1: big differences in the loads in one area cause the loads closest to the pumps to starve, and adding more sensors in the same area to prevent it reduces the energy savings (unless pressure independent valves are using in the most demanding loads closer to the pumps).

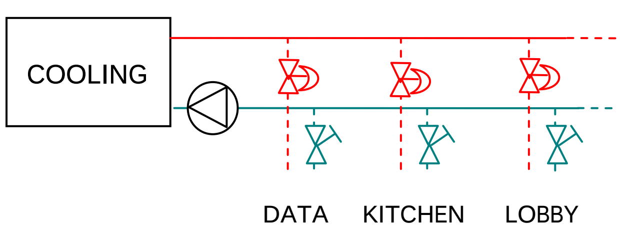
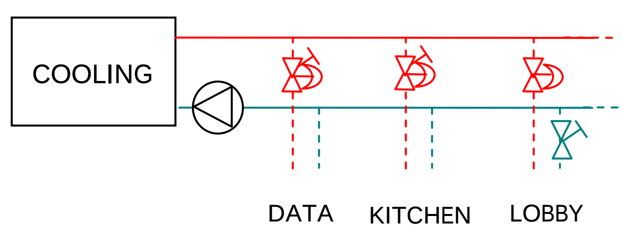
Careful layout of the piping, to prevent having in the same area loads with expected very different demands (south and north sides, lobby and data center, different long term occupancy, etc) improves system performance.

Insights

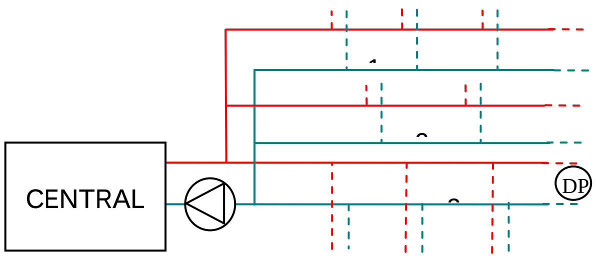
1. Sensorless Control is a distribution pump control method which infers the average HVAC system heating or cooling demand from the hydraulic system resistance, and then adjusts the pump(s) speed to balance satisfying that demand with minimizing the energy used.
2. With factory defaults, it achieves ASHRAE 90.1 in most cases.
3. If the flow through the central plant is variable, it produces an average 18% plant energy savings due to increased chiller and boiler efficiency.
4. Sensorless Control doesn't noticeably starve loads if the percent heat transfer demand of the most demanding load is less than 40% higher than the average
5. In the worst case scenario, the less satisfied load is still able to deliver 90% of the design heat in a constant fluid temperature system, or 80% for cooling and 70% for heating in variable temperature systems.
6. Careful layout of the piping, to prevent having in the same area loads with expected very different demands (south and north sides, lobby and data centre, mixed variable long term occupancy, etc) allows improving savings without loosing system performance.
7. If the mechanical equipment is properly sized, loads are starved not during high system demand, but when the average demand is low.
8. With traditional balancing valves, the loads more prone to starvation are those closest to the distribution pumps.
9. In systems where some loads may have demands much higher than the average, there are 3 possible solutions:
    a. Limit the head reduction on low demand, thus loosing savings
    b. Balance the highest demanding loads for lower pressure, thus risking overflowing them and causing low delta T syndrome

c. Use pressure independent control valves in the highest demanding loads closer to the pumps. In this case, it's better to have these loads closest to the distribution pumps. This is the best solution and arguably the best use for these valves.

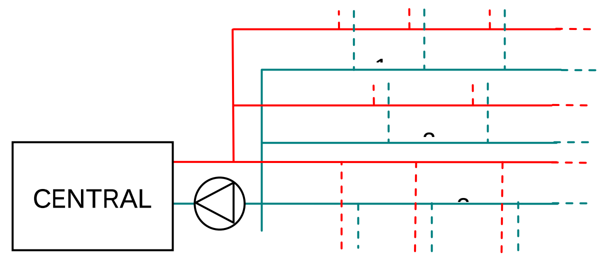
10. At preventing loads starvation, Sensorless Control performs equally or better than using one remote DP sensor.
11. In systems with multiple areas, the pump(s) can be reconfigured (or allowed to auto-adjust) to adapt to changing (occupancy) needs.
12. Sensorless Control can be easily tuned (or allowed to auto adjust) to optimize the balance between energy savings & system performance.
13. Sensorless Control does not require installing and wiring remote sensors. It's a great solution for upgrading constant speed systems.
14. Sensorless Control has less failure points and is easier to reconfigure than solutions using remote sensors.
15. Sensorless Control protects deadheading pump(s).
16. Sensorless Control can maintain a remote pressure constant if it is in a location before the flow splits between loads.

DESIGNS PRONE TO STARVING LOADS	RECOMMENDED DESIGNS
	
-A few loads with demands much higher than the average, are close to the pumps and have traditional balancing -Pump control from a DP sensor or Sensorless	-Most demanding loads have pressure independent valves and are closer to the pumps, or -More than 50% of loads have demand profiles

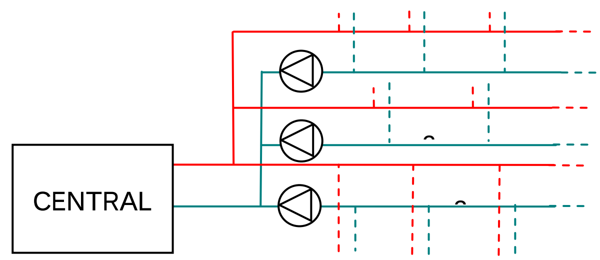
similar to the most demanding



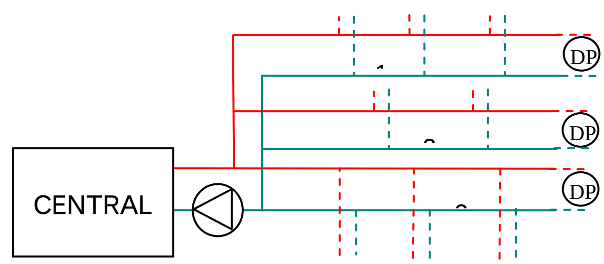
- 1 (set of) pump(s) serving multiple areas
- Potentially one area could have over 70% demand while most areas have little or none
- The pump is controlled from 1 DP sensor which is not in an area known to be always among the most demanding
- Some areas have a few loads with demands much higher than the average, are close to the pumps and have traditional balancing



- The pump(s) sensorless control is adjusted according to the design flow of the occupied areas
- Loads in each area as in the first example above



- Each area has its own distribution pump
- Pump control from DP sensor(s) or Sensorless
- Loads in each area as in the first example above



- Each area has its own sensor
- Loads in each area as in the first example above