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Effects of digitalization of self-acting flow and pressure controllers

Digitalization is unavoidably changing the district energy industry. The benefits of a more detailed insight into processes using connected components & systems and therefore optimization possibilities are wide and not so hard to reach. Industry 4.0 is a tool that will enable effective transition to 4th gen. of DH systems. In Danfoss, we have a long history of developing best-in-class self-acting flow & differential pressure controllers for DH systems, which enable DH operators to control flow & pressure conditions in the primary DH network. But the new digitalized generation of flow & differential pressure controllers creates new opportunities for additional optimization. Flow & differential pressure controllers equipped with new intelligent actuators enable DH operators to remotely control (set) the differential pressure at any point in the network.

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Upgraded with proper control logic, these intelligent controllers can i.e. autonomously work together with the goal of providing information to the control center about the optimal (min. required) pumping station set-point in real time, consequently optimizing the pumping costs and differential temperature. Another example is the use of these intelligent controllers to, by intelligently adapting differential pressure conditions on substation primary side, remove flow-controller authority related oscillations, consequently also secondary side supply temperature oscillations, avoiding over-supply and improving the primary side differential temperature conditions.

Keywords: pressure; optimization; digitalization; district; heating; flow; intelligent; actuators; oscillations

I. Digitalization in District energy

Industry 4.0 has brought a lot of benefits not just in the manufacturing industry, but also outside, including the (district) energy sector. Especially in the process industry, concepts like identification of devices, connectivity of devices into cloud systems, and combining the devices into advanced nervous-like systems offer substantial benefits to utilities as well as to end users, with the goal of improving energy- / cost-efficiency and the quality of supply & service.

The first step in making a classic mechanical products digital is to connect it to the IoT (Internet of things) world, be it just a simple solution with a QR code for identification, or a more sophisticated connectivity and functionality through integrated intelligence and sensors on the product, which are cloud connected. The ultimate digitalization step is a digital twin, where the virtual and the real object are connected in real time and can be analyzed or diagnosed either physically or virtually, and together they can form some level of artificial intelligence. The security of connectivity should not be a question, as only encrypted communication should be used.

When a product is part of this digital world, the next step can be made, and that is interactivity. Interactivity is extremely important when digitalization is introduced into processes, as through it, other devices and computer based optimization systems are getting real time multi-directional data and therefore the ability to interact and influence each other, identically with the function of our nervous system. For example, if we draw a parallel to navigation before, when paper maps were used, and today's ability of a "smart" navigation system, where maps are digitalized and constantly updated, traffic data is connected in real time to our navigation systems and this gives it ability to calculate the optimal travel route. But the final judgement which path to take still involves human decision making.

A properly designed digital device will perform autonomously, and at the same time will or can be a part of a smart system (network) of devices. Device "smartness" is, identically to the human nervous system, preprogrammed in its "brain" (CPU) with algorithms which can be either analytical or based on predictive self-learning. In any case the device becomes smart to some degree and the decision-making process is performed in the device or by other smart devices in its – now smart – network.

Figure 1 graphically depicts the three steps described above.

Another aspect of digitalization and smart devices is also the granularity of data made possible to obtain. Classical control & monitoring systems were too often restricted in the number of connected devices due to engineering efforts and costs needed for their establishment. With limited data, also the decision-making process was limited in extent and quality. With advances in communication technology, this is becoming much easier and cost-effective today. With much more established connected points, the digital "reflection" of systems (networks) can become much more granular and precise. This enables real time optimization of the systems; in other words, continuous commissioning enables systems to always operate in the optimal mode. This is a back bone for the usage of optimization algorithms which, relating to external data (e.g. weather forecast), can significantly optimize the operation of district heating systems.

II. Pressure and flow controller challenges

Mechanical self-acting controllers have long been known and proven in the district energy segment. They enable basic autonomous functionalities for temperature, pressure and flow control and regulation. Though thermostats for temperature control are disappearing from applications, being replaced with PI driven control loops with motorized valves as execution elements, still the response speed is normally unmatched and they are therefore mainly used in small application units with the demand for fast response like for instance domestic hot water service control in flat stations.

Pressure and flow controllers, working on the same physical phenomena, are still very relevant in district heating operations. They represent mainly differential pressure controllers with obvious benefits in:

- improvements of motorized valve (flow control) performance, by keeping valve authority very high (in the vicinity of 1), and
- ability to hydraulically balance the network by allowing subscribers (end users) only a certain limited amount of pressure drop on their connection point, which is precisely controlled.

Those controllers are genuine proportional, thus lacking the integrational part and having a drawback in proportional set point error; however, this is still small enough for the benefits of fast response, stability and compactness to prevail. Combined with simplicity and robustness, these are the reasons why such controllers are standard in hydronic balancing in district heating systems today.

Figure 2 represents a typical substation setup for heating and (instantaneous) domestic hot water service. Both loops

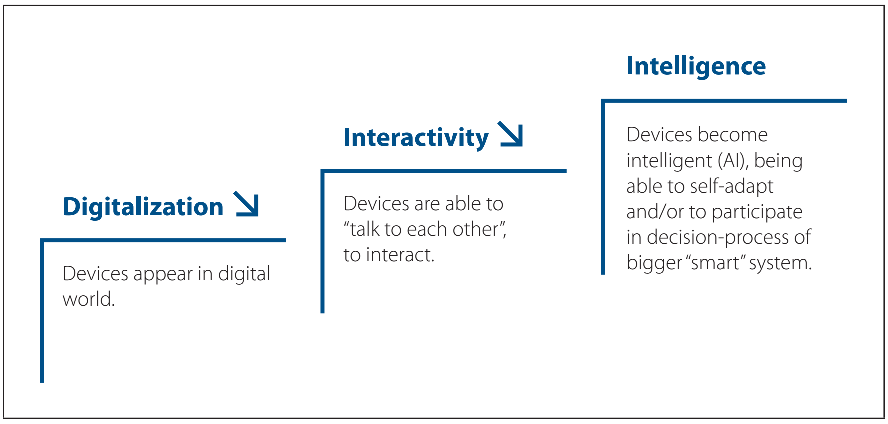

Figure 1: Main steps in digitalization of devices

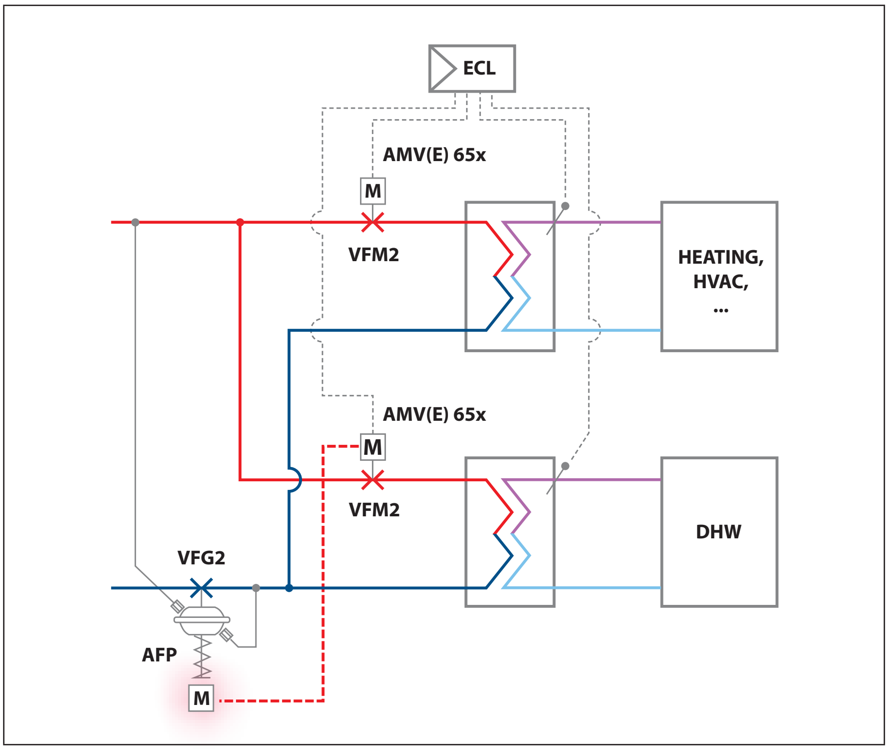

Figure 2: Typical district heating substation with heating and instantaneous domestic hot water service

are controlled by the same electronic controller and executed with two separated motorized control valves. In order to keep the authority high, but not 1, a differential pressure controller is used, which ensures that differential pressure on both motorized control valves is always the same (pre-set), no matter what differential pressure is available at the connection point. The latter is only valid if differential pressure at the connection point is higher than the pre-set differential pressure for motorized control valves, as differential pressure takes the excess or unrequired connection point differential pressure on itself.

A. Motorized control valve (flow) control authority challenge

Differential pressure (and the flow as a result) in a temperature control loop significantly influences temperature stability. In fact, the stability of the temperature control loop depends on the system gain of the control loop. The system gain depends on the following parameters:

- PI setting of electronic controller,
- temperature drop on primary side,
- inverse of mass flow on secondary side,
- square root of differential pressure over motorized valve, and
- shape of characteristics of executional motorized control valve.

And precisely the latter can significantly change with valve opening. Due to mechanical tolerance in machining and the needed gap between valves eat and cone for control, there is an initial opening position area of the control valve which cannot be used for control (low or no-authority). That area is defined with valve rangeability and it results in a very steep relationship between stroke and flow in the first 0,1–0,5 mm of the valve opening. When the valve operates in this area, flow oscillations occur (on / off effect). This kind of unstable operation is inevitable and happens as a result of different situations:

- wrong PI configuration in controller because of poor commissioning,
- intermediate heating periods (e.g. late autumn and early spring),
- when heating demand is low and DHW circulation is active (in heating season),
- over-dimensioned valves because of poor dimensioning or improved energy efficiency (lowered connected power),
- big min. to max. power ratio on connection point (e.g. industry).

Oscillations are very hard to detect (basically real-time data logging would be required), but have a number of negative impacts, such as:

- shorter life span of equipment,
- over-flow as a consequence of operating in non-authority range,
- over-heating (over-supply) as a result of over-flows,
- higher return temperatures as a result of over-flows.

B. Primary network hydraulic balancing challenges

The settings of differential pressure and flow-control valves are normally dimensioned so that the most critical users still receive enough differential pressure for operation, also at peak or near-peak demand. But in reality, operation at maximum load conditions represents only a smart part of overall operation. This results mainly in the fact that minimum differential pressure for critical points in the network can be "over-dimensioned" and therefore the motorized valve would rarely end up in fully open conditions, or in other words, most of the time it would operate close to its low- or no-authority range. However, a valve not fully open and too high differential pressure for a given load at the critical point result in a higher pump head then needed. Another challenge is that the network critical point is not static in the systems with more than one source, with loops in the systems, or in other complex network topologies.

III. Digitalization of differential pressure controllers

Instances of sudden oscillations of pressure in the system caused by too high system gains and the need for remote real-time optimization of differential pressure settings are perfect cases for digitalization of mechanical self-acting flow & pressure controllers. There are of course many ways how to introduce digitalization and at which level. It turns out that the simplest case which does not require extensive sensor and actuation add-ons to the controllers and connection points is the ability to change the set point of the differential pressure controller, by monitoring the behavior of the flow valve.

This is allowed by upgrading the differential pressure controller with a motorized actuator, which can execute the required differential pressure setting by adjusting the differential pressure spring position. This gives us the possibility to remotely or automatically (by algorithm) change the differential pressure on the flow control valve, which enables us to:

- Implement an algorithm with which the differential pressure on the flow control valve is always at a set-point which allows the flow control valve to operate within its high-authority range;
- Implement an algorithm which automatically sets the differential pressure on the flow control valve (on network critical points) in a manner that allows 80–100% of valve opening and gives feedback to the pumping station on pressure-overhead (or pressure too low) at critical network point(s).

Two cases described below are based on iSET and iNET functionalities on the new Danfoss Virtus – intelligent pressure and flow controllers.

A. Eliminating flow and temperature oscillations (iSET)

The most efficient way to resolve oscillatory flow (and consequently temperature) behavior of the control loop is, as mentioned earlier, by adjusting the differential pressure on the control valve. Considering the fact that flow-to-pressure relationship is a function of square root, this means that relatively fast responses can be achieved by setting the differential pressure. Digitalized differential pressure controllers, such as Danfoss Virtus with iSET functionality, already incorporate the intelligence to achieve this kind of differential pressure adjustment.

Oscillatory behavior of flow control valves with split or logarithmic characteristics normally occurs in nearly closed position (Figure 3), especially when valve authority deforms the characteristics.

iSET algorithm works by detecting the position of the flow control valve (by reading the position of the flow control valve actuator) and is triggered when the opening is sufficiently small (below C1 threshold as shown on Figure 4). When triggered, the algorithm monitors the oscillatory behavior of the motorized valve's stroke, and if conditions connected to the size, frequency and duration of the oscillations are met (shown as C2 on Figure 4), the algorithm enters the anti-oscillation functionality and starts to act. It acts by reducing the differential pressure over the motorized flow control valve, which results in a lower-then-required flow and triggers the substation electronic controller to start opening the flow control valve. The algorithm acts until the pressure is so low that the substation electronic controller opens the flow control valve up to its authority range and oscillations are eliminated. When the stroke again rises over the threshold stage, everything is reset on the algorithm to the initial stage, and therefore no relevant interference with the control logic in the temperature control loop controller occurs. The control algorithm logic is depicted in Figure 4.

B. Optimization of primary network differential pressure and pumping costs (iNET)

Another application example of an intelligent differential pressure controller and its possibilities are shown with Danfoss Virtus iNET functionality. In general, iNET functionality allows two main applications:

- Possibility to remotely adjust differential pressure at the substation or branch level (Figure 5);
- Possibility to optimize the network differential pressure diagram and lower pumping costs.

Hydraulic conditions in district energy networks are constantly changing due to:

- Daily changeovers (morning / evening …);
- Seasonal changeovers (winter / summer …).

In addition, hydraulic condition changes are becoming even more frequent in modern networks, which include multiple heat power sources, are based on complex topology and energy-saving measures are implemented on the demand side. So, changes also occur due to:

- Building renovations (reduction in energy consumption);
- Network extensions (increase of energy consumption);
- Decentralization & multiple heat sources dynamics (switch in / out).

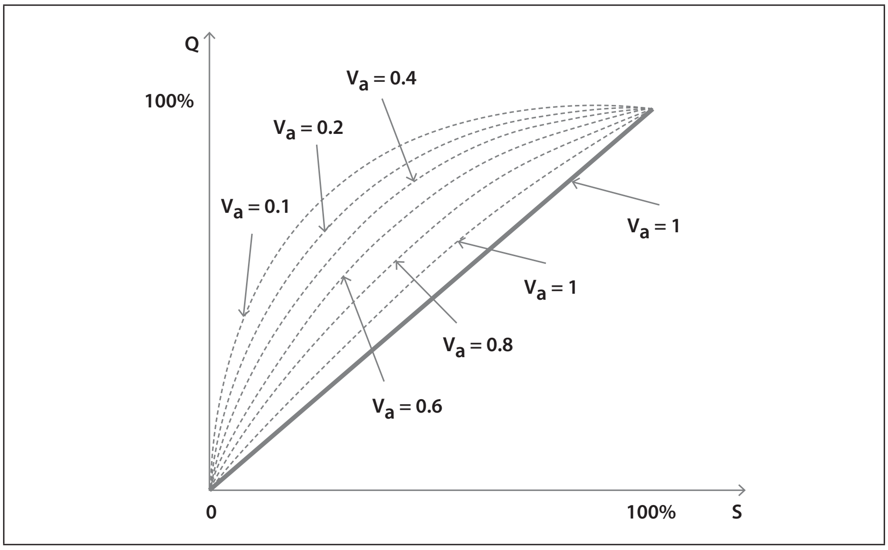

Figure 3: Valve authority

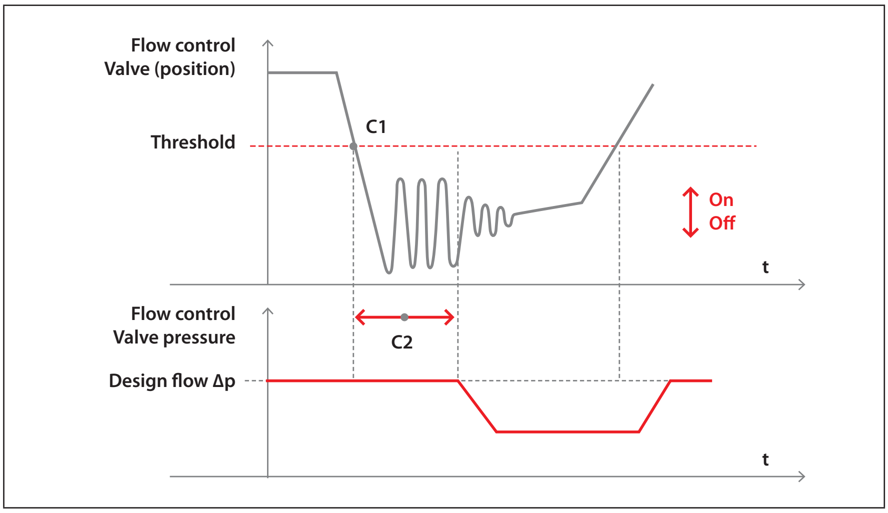

Figure 4: iSET anti-oscillation logic

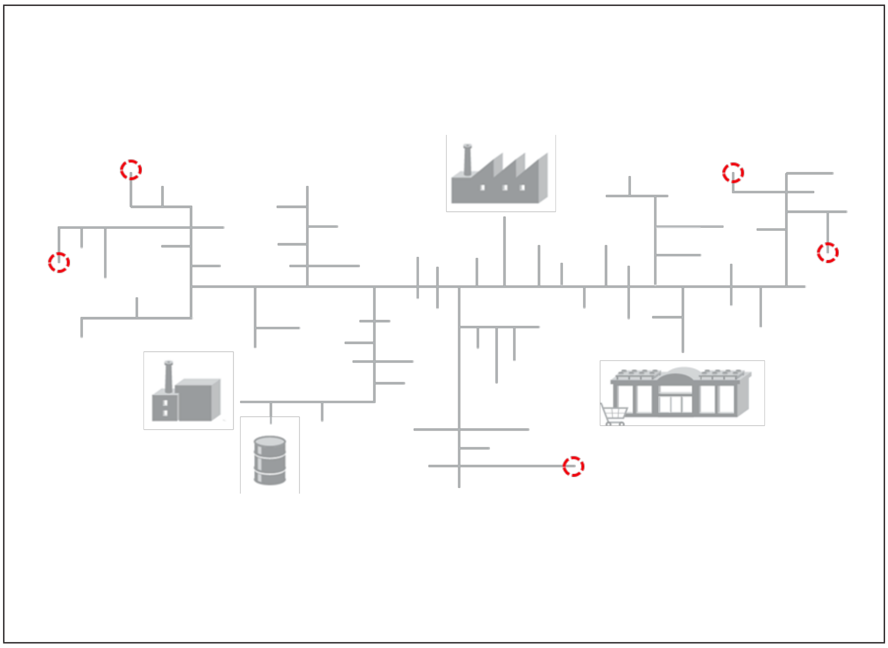

Figure 5: Intelligent differential pressure controllers critical points

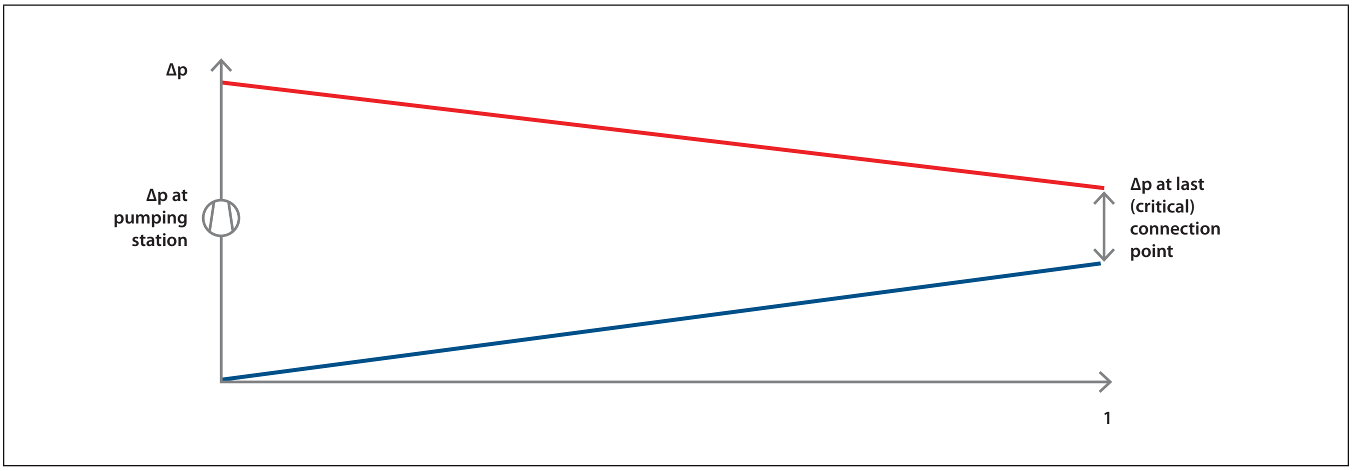

Figure 6: Differential pressure diagram

By installing intelligent differential pressure controllers on substations or branches (Figure 5), the operator has the ability to remotely adjust the differential pressure at substation or branch, independent of the situation on the primary line. Remote adjusting can be done manually (e.g. changes in flow limitations due to energy savings measures on the demand side), or input can be provided by higher-level network intelligence (e.g. real-time optimization software based on a hydraulic model or big data intelligence). One example of this kind of application is the possibility to optimize the flow on the branch level, providing just enough flow to satisfy the demand. Of course, application intelligence of this kind and similar has to be well thought through in order not to interfere with the controls on the demand side or cause supply issues (shortages), but on the other hand it can represent a cost-affordable way for network (Δp, ΔT) optimization especially on older 3G or even 2G type networks with a poorly or even un-automated demand, as they transit to 4G (which happens slowly, as in most cases big investments into infrastructure or new substations are required).

Another application example is the optimization of pumping costs at the network level. For the purpose of simplifying the explanation, this example is based on a simple line-topology network with one critical point (the last connection point) and a linear (fixed) pressure drop per meter of the network (Figure 6).

As shown in the differential pressure diagram, the last (critical) connection point in the network is the "set-point" source for pumping station operation, as it should always provide sufficient differential pressure to satisfy the demand needs of that last (critical) point. It is true that systems with variable speed pumps, proportionally driven towards securing minimum operational pressure in critical points, are improving the situation most of the time, but this does not secure the conditions where only a truly minimum operational pressure is available for the last connection or critical point.

One way of optimizing the network differential pressure would be to utilize a real-time network hydraulic model, which would execute constant calculations based on demand profiles and provide input to the pumping station on a minimum required pumping set-point. This process requires differential pressure measurements on the network (precisely on the critical point), quality demand profiles and a good self-calibrating real-time network hydraulic model. On bigger networks, these calculations can also be time consuming, allowing only a limited optimization frequency.

Another simpler approach is simply starting from the assumption that the differential pressure on a critical connection is optimal at a point where the flow control valve is between 80–100% of openness and the flow is just adequate to fulfill the demand (thus, only a minimal differential pressure is "taken away" by the differential pressure controller). This situation can, by a proper algorithm, be connected in real time to the pumping station, allowing a constant change of the pumping station set-point to achieve the previously described situation.
An example of simple Danfoss iNET logic is:

1. Intelligent differential pressure controller on the critical point lowers the flow control valve differential pressure, until local automation provides input to open the flow control valve up to 80–100%. The optimal set-point is defined by substation type - the need for quick response to demand (e.g. for a substation with instantaneous DHW this set-point can be 80% to allow for quick demand changes and not to limit it with the differential pressure actuator speed; if it is only a heating substation, this set-point can be over 90%, as changes in demand are not so rapid).
2. After the flow control valve has reached an 80–100% openness, it means that the differential pressure controller has "taken away" all the "excess" differential pressure, and consequently we can, by that same amount, lower the differential pressure on the pumping station.
3. Intelligence in the differential pressure controller kicks in, and the "pressure over-head" signal is sent in real-time to the pumping station, where consequently the pumping set-point is gradually lowered until the intelligent differential pressure controller detects that the local automation is trying to open the flow control valve further, even when it has already reached is end-open position. At this point we are just below the optimal differential pressure, and the differential pressure control loop algorithm further precisely sets the required pumping set-point.

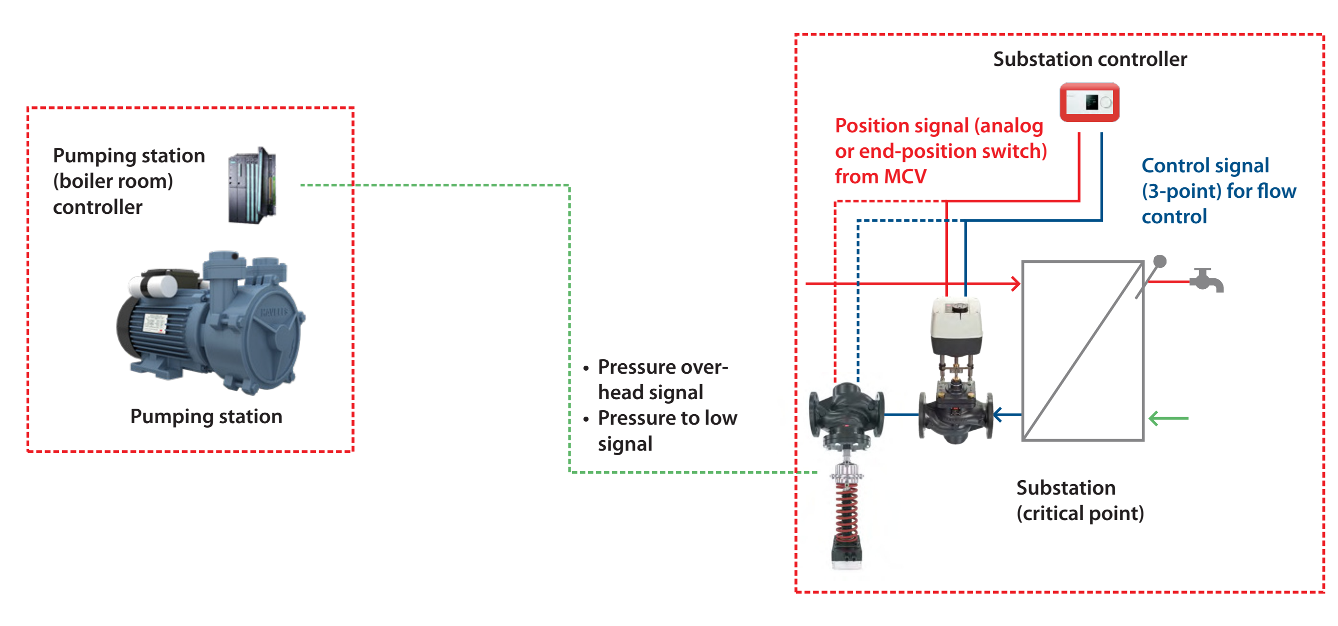

Figure 7: Simple pressure optimization control loop example

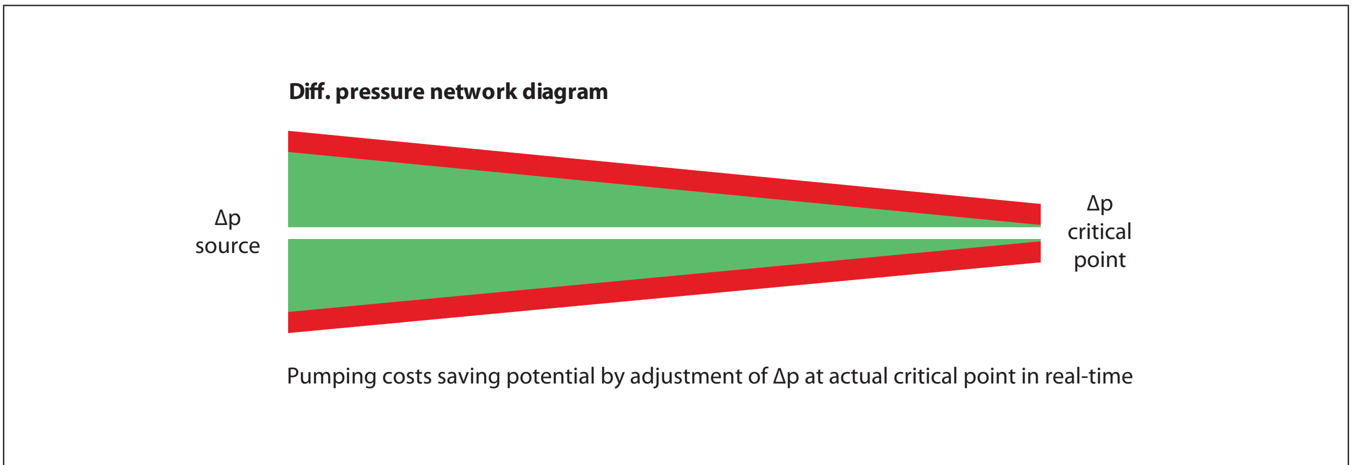

Figure 8: Optimization of differential pressure

This algorithm can be executed in real time each time the intelligent differential pressure controller detects a flow control valve open position under its optimum open position (80–100%), and vice-versa, sending out a "pressure too low" signal each time it detects the local automation trying to open the flow control valve further, even when it has already reached its end-open position.

Assuming that the local automation is properly commissioned, this kind of differential pressure control loop can always provide the minimal required pumping set point, thus allowing significant savings in pumping costs, as shown in Figure 8. Nevertheless, this example is based on a rather simple application, but it can be elevated to support more complex networks (e.g. networks with multiple production units, multiple pumping stations and a shifting critical point).

Upgrading this logic to more complex networks and more real-like conditions where multiple critical points are possible, means that intelligent differential pressure controllers need to be able to communicate directly among themselves, recognizing which is the critical point at any given time. This "real-time" critical point is then used as the pumping station set-point source, while other points retain pressure & flow stabilization functionality (iSET-like functionality as described in III.A).

IV. Conclusion

As described in this article, digitalization of differential pressure controllers can bring substantial benefits to district energy network operators, as well as to end-users. It also showcases how the concept of smart devices can bring additional benefits to systems like district energy, with the goal of lowering operational & investment costs and improving (or maintaining) the quality of supply.

The example of iSET functionality shows how primary side flow oscillations can be avoided, and consequently:

- life span of the equipment improved,
- over-flow avoided,
- over-heating avoided,
- return temperatures lowered,
- quality of end-user supply improved.

The example of iNET functionality shows how differential pressure on the network can be remotely or intelligently managed, and consequently:

- overall supply stability improved,
- return temperatures lowered,
- pumping costs lowered.

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