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PRVS WORKING IN PARALLEL CONFIGURATIONS – ANALYSIS OF DYNAMICS

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Abstract

Société wallonne des eaux (SWDE) is the most important water production and distribution company in Wallonia, one of the regions in Belgium. Its distribution network stretches over 40,000 km. It covers nearly 200 municipalities and has more than one million connections. SWDE supplies drinking water to nearly 2.4 million people, constituting over 70 % of the Walloon population. Recently, SWDE has launched a major multimillion-Euro project to improve security of the water supply in Wallonia. The project involves a 500/800 mm extension of a 1000-mm wide, over 100 km long pipeline as a backbone of the distribution network, starting from the Eupen and Gileppe reservoirs. The project created a number of engineering challenges and one of them is considered in this paper. The work represents a design of a pressure control station which provides efficient operation over a wide range of flows from 40 m3/h to 1500 m3/h. Additionally, the pressure control scheme needs to work in a stable manner with the downstream flow control system. It is proposed to use two identical hydraulically controlled PRVs connected in parallel without any external PLC control loop. To make sure that such a configuration can be installed in practice it was necessary to carry out extensive simulations to understand the system dynamic behavior for different scenarios.

Keywords
Pressure control, PRV parallel connection, Rigid Water Column model, Dynamics, Stability.

1 INTRODUCTION – CASESTUDY DESCRIPTION

A schematic of the system fragment with the PRV chamber with two PRVs connected in parallel is pictured in Figure 1.

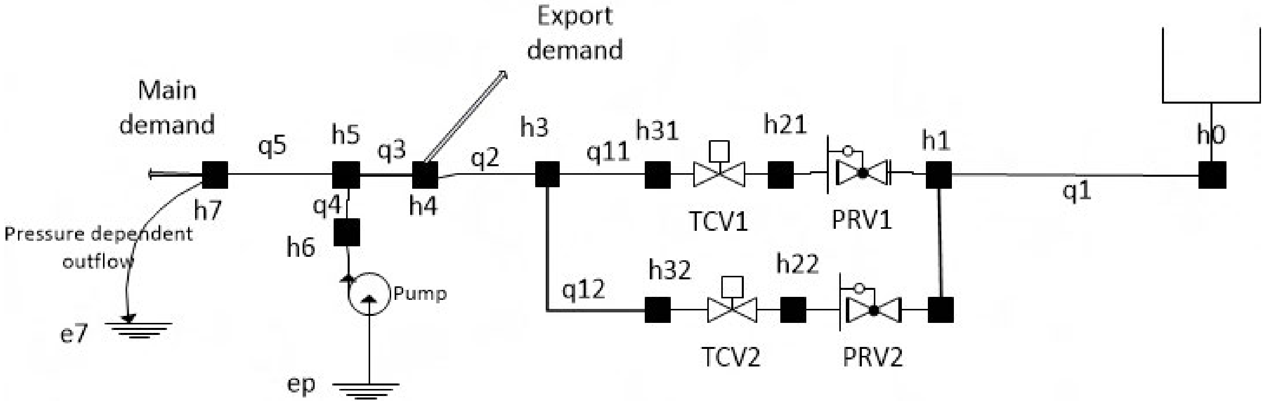


Figure 1. Schematic of the water distribution system

The source flow comes from the Eupen reservoir with capacity of 50,000 m^3. In order to reduce the required pressure in the downstream part of the water system a PRV station with the two valves connected in parallel with the outlet head of 254 m (pressure 28 m) is planned to be installed. There is a significant water demand at node h4 where the water is exported to another water company. At node h5 the Eupen water is mixed with the water imported from another water company through a pumping station. It is necessary to maintain a constant ratio of 0.6 between the $q_4$and q_5 flows due to water quality requirements, and at same time to maintain feasible positive pressure at node h7 in order to maintain the required pressure at a critical point downstream of the system not shown in Figure 1. The design of the flow ratio control system was considered in an associated paper [2] presented also at this conference. An important conclusion was that it was necessary to introduce additional head losses in order to prevent strong interactions between the flow control system and the PRVs. These additional head losses are represented by TCV1 and TCV2 in Figure 1. The focus of this paper is on dynamics of the two hydraulically controlled PRVs connected in parallel for different setting scenarios summarized in Table 1. If there is a need to connect two PRVs in parallel some manufacturers, for instance Bermad, [1] recommends setting the main valve 1m-2m above the second valve. In this way the main valve operates all the time and the second valve with the lower settings becomes active only for peak flows when the main valve is fully open (saturated). However, in this study because of the presence on the TCVs the situation is more involving and all four scenarios given in Table 1 for different PRV and TCV settings are investigated.

Table 1. Valve setting scenarios

Id	PRV1 head setpoint [m]	PRV2 head setpoint [m]	TCV1 head loss [m]	TCV2 head loss2 [m]
a	264	264	10	10
b	264	262	10	8
c	264	260	10	6
d	264	260	10	10

The description of the scenarios is provided below:

a) The two PRVs has the same set-point of 264 m and the two TCVs are adjusted to have the same head loss of 10m, the situation is symmetrical for the two PRV branches.

b) PRV2 has a lower set-point of 262 m and TCV2 is adjusted to have 8 m head loss to make sure that the target head value at the connection node h3 is consistent for the two branches and equal to 254 m.

c) PRV2 has a lower set-point of 260 m and TCV2 is adjusted to have 6 m head loss to make sure that the target head at the connection node h3 is consistent for the two branches and equal to 254 m.

d) PRV2 has a lower set-point of 260 m and TCV2 is adjusted to have 10 m head loss in order to create a conflict between the two PRV branches. The target head at h3 is still 254 m for Branch 1 but it is 250 m for Branch 2.

The TCV settings are corrected at 15 minutes intervals when the flow and subsequently head loss changed significantly. The PRVs operate continuously controlled by hydraulic pilot loops.

Pipes q1, q2, q3 and q5 in Figure 1 are transport pipes connecting important sites along the main pipeline and their data are displayed in Table 2. Remaining pipes, q11, q12 and q4 are short connection pipes in the PRV chamber and the pump chamber respectively.

Table 2. Pipe data of main pipes

Pipe id	Length [m]	Diameter [mm]	D-W friction factor
q1	46212	800	0.0175
q2	9749	800	0.015
q3	10	800	0.015
q5	21179	800	0.015

The node data are included in Table 3.

Table 3. Node data]

Node id	Elevation [m]	Demand [m^3/d]	Comment
h0	322.5	-	Fixed Head Source
h1, h21, h31, h31, h32, h3	226	-	Valve connection nodes
h4	129.5	5000	Demand pattern is in Figure 2
h5	129.5	-	Connection node
h6	120	-	Destination node of the pump station
h7	180	7218	Main demand+ outflow area =10^{-7} m^2

The node h0 represents a fixed head source and the node h7 is a boundary node representing the whole downstream part of the system with Main demand equal to $7218\, {m^3}/{d}$ and an additional pressure dependent outflow with the equivalent area of $10^{-7} m^2$.

The selected PRVs for this study are 200mm Cla-Val valves with the « Low Flow system » option. The PRV capacity characteristic in original units, i.e.. flow expressed in l/s and pressure in bar is displayed in Fig.2.

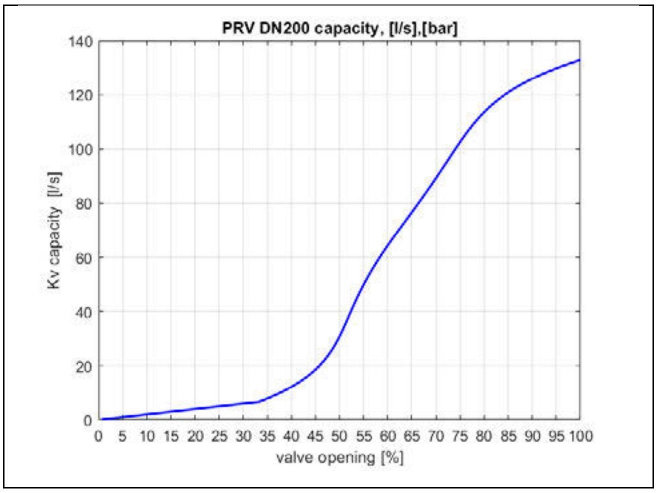


Figure 2. PRV DN200 capacity characteristic in original units

It was suggested to try the same 200mm Cla-Val valves but without control pilot loops as the TCVs. The characteristic was approximated by a piece-linear function in the Simulink model to preserve accuracy of the original data from the catalogue.

The pump model was derived from the manufacturer data for the KSB pump, type W12-200/T14 and is displayed in Figure 3.

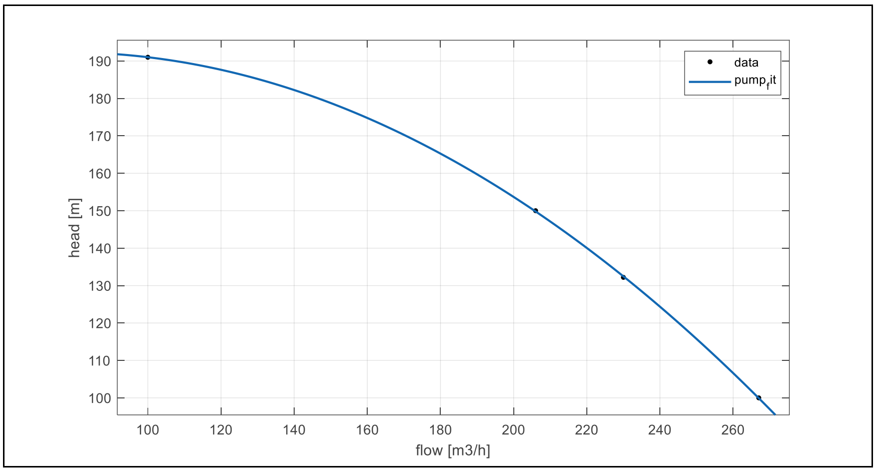


Figure 3. KSB pump characteristic

Analytically the model was represented by a second order polynomial given in Equation 1,

$$\Delta h = -0.0026 * q^2 + 0.3974 * q * s + 177s^2 \qquad (1)$$

where q is the pump flow in $[{m^3}/{h}]$, Δh is the head increase across the pump in $[m]$ and finally s the relative pump speed, where value 1 corresponds to the nominal speed.

The overall objective was to investigate dynamics of the PRVs connected in parallel for different setting scenarios given in Table 1 over the range of flows from 300 ${m^3}/{h}$ up to 1450 ${m^3}/{h}$., i.e., which represents the high flow situation

The reminder of the paper is organised as follows. The Methodology section describes an approach adopted in this study. The simulation results for the high flow conditions which represents the most interesting case are described in the Results section. The paper finishes with conclusions from the modelling study.

2 METHODOLOGY

The methodology is based on the theory provided in [3]. A mathematical model is formulated in the form of differential-algebraic equations (DAEs) and the model is simulated using the Matlab/Simulink environment.

The rigid water column (RWC) model given in Equation 2 is used for pipes,

$$\dot{q} = -Rq|q| + M\Delta h \tag{2}$$

where $q =$ pipe flow; $\Delta h =$head loss along the pipe; $R = f_D({}^{1}/_{2DA})$; $M = {}^{gA}/_{L}$; $f_D =$Darcy friction factor; $D =$pipe hydraulic diameter; $A =$pipe cross section area; $L =$pipe length; and $g =$ gravitational acceleration.

The RWC model can be used for analysis of slow transients, [4] or for analysis of control problems in a WDS, [3].

The PRVs are represented by a behavioural model from [5] and is given in Equations 3 and 4 (differential part) and in Equation 5 (algebraic part),

$$\dot{x}_m = \alpha_{open}(h_{set} - h_d) \tag{3}$$

$$\dot{x}_m = \alpha_{close}(h_{set} - h_d) \tag{4}$$

where x_m =valve opening in percent; and α_{open} and α_{close}=rates of the valve opening and closing, respectively; h_{set} =PRV setpoint and h_d = PRV outlet head. The algebraic part is given by a standard valve equation, Equation 5,

$$q = K_v(x_m)\sqrt{\Delta h} \tag{5}$$

where $K_v(x_m)$=valve capacity, which depends on the valve opening x_m, the $K(x_m)$ is a characteristic provided by the manufacturer and is shown in Figur2.

The TCV is a static element represented only by an algebraic equation of the same form as Equation 5 and with the capacity characteristic displayed in Figure 2.

The pump is represented by the two equations. The first equation, Equation 6

$$\dot{s} = -\frac{1}{T}s + \frac{1}{T}v \tag{6}$$

is a differential equation that describes the pump inertia, where s =pump speed, v = speed set-point, and T = time constant. The second is an algebraic equation that describes the head increase along the pump scaled by the pump speed s, [6],

$$\Delta hh_o = Aq^2 + Bqs + Cs^2 \tag{7}$$

where the specific values for the coefficients A, B, C are given in Equation 1.

According to theory presented in [3] it is necessary to select pipe independent flows, in this case they are q_1, q_{11} and q_4 while the dependent flows can be evaluated from the mass balance at the connection nodes as follow:

$$\begin{aligned} q_{11}+q_{12} &= q_1 \\ q_2 &= q_{11}+q_{12} \\ q_3 &= q_2 - d_{export} \\ q_5 &= q_3 + q_4 \end{aligned} \tag{8}$$

$$q_{out} = q_5 - d_{main}$$

where d_{export} is the water export to another water company at node h4 in Figure 1, $q_{out} = c_{out}(h_7 - e_7)^{0.5}$ represents pressure dependent outflow in the downstream system and d_{main} is the main flow of the downstream system, c_{out} is the outflow coefficient and e_7 is the elevation of the h_7 node.

The independent pipe flows, q_1, q_{11} and q_4 are explicitly represented by the differential Equation 2. To make sure that the dependent flows in other pipes, i.e., q_{12}, q_2, q_3, q_5 obey the RWC model it is necessary, according to [3], to introduce the 'differential mass balance' equations for the connection nodes with pipes as follow,

$$\dot{q}_{11} + \dot{q}_{12} = \dot{q}_1$$
$$\dot{q}_2 = \dot{q}_{11} + \dot{q}_{12}$$
$$\dot{q}_3 = \dot{q}_2 - \dot{d}_{export}$$
$$\dot{q}_5 = \dot{q}_3 + \dot{q}_4$$

which are subsequently are transformed into Equations 9 with the help of the relationship from

Equation 2.

$$-R_{11}q_{11}|q_{11}| + M_{11}\Delta h_{11} - R_{12}q_{12}|q_{12}| + M_{12}\Delta h_{12} = -R_1q_1|q_1| + M_1\Delta h_1$$
$$-R_2q_2|q_2| + M_2\Delta h_2 = -R_{11}q_{11}|q_{11}| + M_{11}\Delta h_{11} - R_{12}q_{12}|q_{12}| + M_{12}\Delta h_{12}$$
$$-R_3q_3|q_3| + M_3\Delta h_3 = -R_2q_2|q_2| + M_2\Delta h_2 - \dot{d}_{export} \quad (9)$$
$$-R_5q_5|q_5| + M_5\Delta h_5 = -R_3q_3|q_3| + M_3\Delta h_3 - -R_4q_4|q_4| + M_4\Delta h_4$$

The mass balance equations need to be complemented by the energy balance equations for one proper loop and the two pseudo-loops. The proper loop involves all components in the PRV chamber as depicted in Equation 10.

$$\Delta h_{11} + \Delta h_{TCV1} + \Delta h_{PRV1} - \Delta h_{PRV2} - \Delta h_{TCV1} - \Delta h_{12} = 0 \quad (10)$$

The first pseudo-loop is between the source h_0 to the ground level of the pump branch e_p and the second between the source and the ground level of the outflow branch e_7. Starting from the pump branch and following the clockwise direction yields,

$$e_p + \Delta h_{pump} - \Delta h_4 + \Delta h_3 + \Delta h_2 + \Delta h_{11} + \Delta h_{TCV1} + \Delta h_{PRV1} - h_0 = 0 \quad (11)$$

and then starting from the outflow branch provides the third energy balance equation,

$$e_7 + \Delta h_{leak} + \Delta h_5 + \Delta h_3 + \Delta h_2 + \Delta h_{11} + \Delta h_{TCV1} + \Delta h_{PRV1} - h_0 = 0 \quad (12)$$

The differential part of the DAE model is represented by Equation 2 for the independent flows q_1, q_{11} and q_4, Equations 3 and 4 for the valve openings, x_{m1} and x_{m2} and Equation 6 for the pump speed, s; altogether six differential equations.

Consequently, the state vector of the model $\boldsymbol{x}$ is made of the six variables listed in Equation (13).

$$\boldsymbol{x} = [q_1 \quad q_{11} \quad q_4 \quad x_{m1} \quad x_{m2} \quad s]^T \quad (13)$$

The algebraic part of the model is represented by Equations 5, 7, 8, 9, 10, 11 and 12 and the vector of the algebraic variables $\boldsymbol{y}$ is composed of the dependent flows and head losses/gains on all components. Altogether seventeen variables displayed in Equation 14.

$$\boldsymbol{y} = [q_{12} \quad q_2 \quad q_3 \quad q_5 \quad \Delta h_{PRV1} \quad \Delta h_{TCV1} \quad \Delta h_{PRV2} \quad \Delta h_{TCV2} \quad \Delta h_{pump} \quad \Delta h_{leak} \quad \Delta h_1 \quad \dots$$
$$\Delta h_{11} \quad \Delta h_{12} \quad \Delta h_2 \, \Delta h_3 \quad \Delta h_5 \quad \Delta h_6]^T. \quad (14)$$

The considered DAE system has index 1as indicated in [3], which means that for a given value of the vector $\boldsymbol{x}$, the vector $\mathbf{y}$ can be evaluated in a unique way by solving equations of the algebraic part of the model. In this case, the solution of the algebraic part can progress in the following steps: 1) calculate the dependent flows from Equations 8; 2) calculate the head losses/gains on the control elements from Equations 5 and 7; 3) calculate the head losses on the pipes $\Delta h_1, \Delta h_{11}$, Δh_{12}, $\Delta h_2, \Delta h_3, \Delta h_4, \Delta h_5$ from the system of linear simultaneous equations composed of Equations 9, 10, 11 and 12.

The Simulink model is depicted in Figure 4.

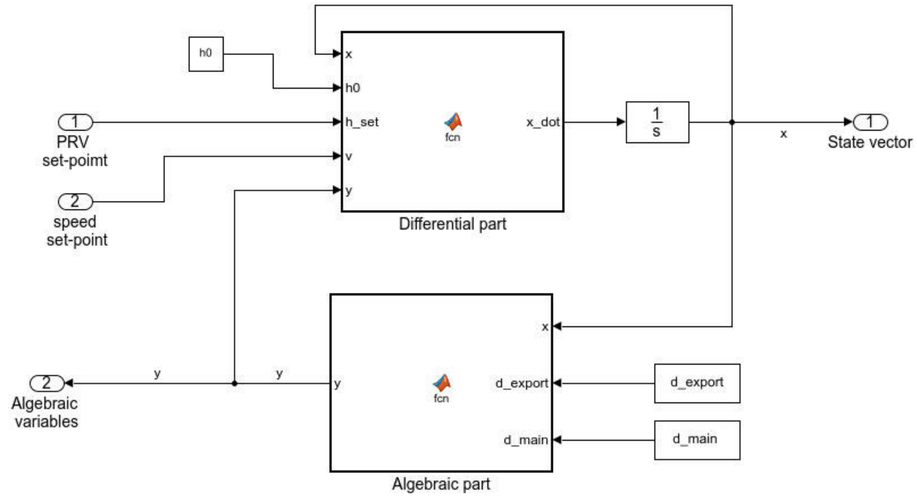


Figure 4. Simulink model of the physical WDS from Figure 1.

The Simulink model comprises the two major Matlab functions, 'Differential part' and 'Algebraic part'. Differential part calculates derivatives of the state variables, i.e., right sides of Equations 2,3, 4and 6. The input variables and the input parameters to this block are: the state vector $\boldsymbol{x}$**;** the head of the source h_0;the vector of the PRV set-points $\boldsymbol{hset}$; the pump speed set-point v ; and the vector of algebraic variables $\mathbf{y}$. These signals are used to calculate the mentioned derivatives, the commands inside the block are written in the Matlab language. The block with symbol $\frac{1}{s}$ contains integrators which calculate the state vector elements from its derivatives. Algebraic part calculates the current value of algebraic vector $\mathbf{y}$ for given values of the state vector $\boldsymbol{x}$ and the demand data, including the Export demand d_{export} and the downstream demands d_{main}.Note, that in order to calculate the head losses along the pipes it is necessary to sole the system of seven linear algebraic equations, Equations 9, 10, 11 and 12.

3 RESULTS

The simulation results are presented for the high flow conditions. The high demand conditions are more interesting than normal or low flow conditions as they show how the two valves interact during the whole day when the flow vary widely from 300 $m^3/_h$ up to its maximum value of 1450 $m^3/_h$. In the low flow conditions, for instance it is sufficient to use one PRV branch over the entire day. There are limits imposed on the PRV opening, the maximum opening is 89% (recommended by the manufacturer) and the minimum opening is 1%, if these limits are violated during simulations the PRVs act like fixed valves with the constant opening of 89% or 1%, respectively. The lower limit of 1% was assumed for the modelling purposes, in the physical system the valve would be completely closed.

The simulations were carried out for all four scenarios defined in Table 1. Scenario a) is symmetrical for the two PRV branches with identical settings for PRV1 and PRV2 and also for TCV1 and TCV2. Scenarios b) and c) are not symmetrical with respect to the PRV set-points and the TCV head losses but are consistent with respect to the target head at the node h_3 of $254m$

which is the same for the both branches. A PRV with a higher set-point, in this case PRV1 will be called a leader and the PRV with a lower set-point, i.e., PRV2, a follower. Scenario d) is not symmetrical and is not consistent with respect to the target head at h_3, Branch 1 tries to impose the head of $254m$ whilst Branch 2, $250m$., in such a conflict situation the two PRVs cannot be active at the same time. The behaviour of the two branches is investigated in details in this section.

The high flow conditions were mimicked by multiplying the normal profile of Export demand by factor of 3.45. Main demand and the modified Export demand are depicted in Figure 5.

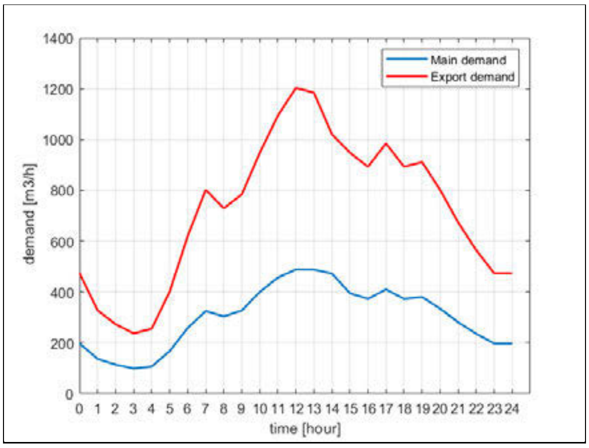
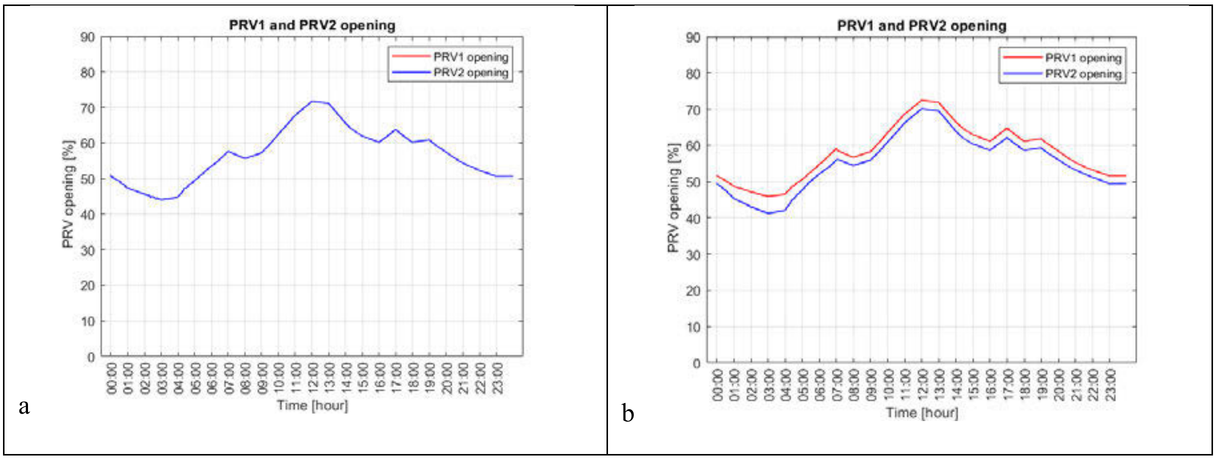


Figure 5. Main demand and Export demand

The value of the demand factor has been adjusted by trial and error to achieve the maximum q_1 flow of 1450 $m^3/_h$ see Figure 8. The valve opening signals for different scenarios are displayed in Figure 6.



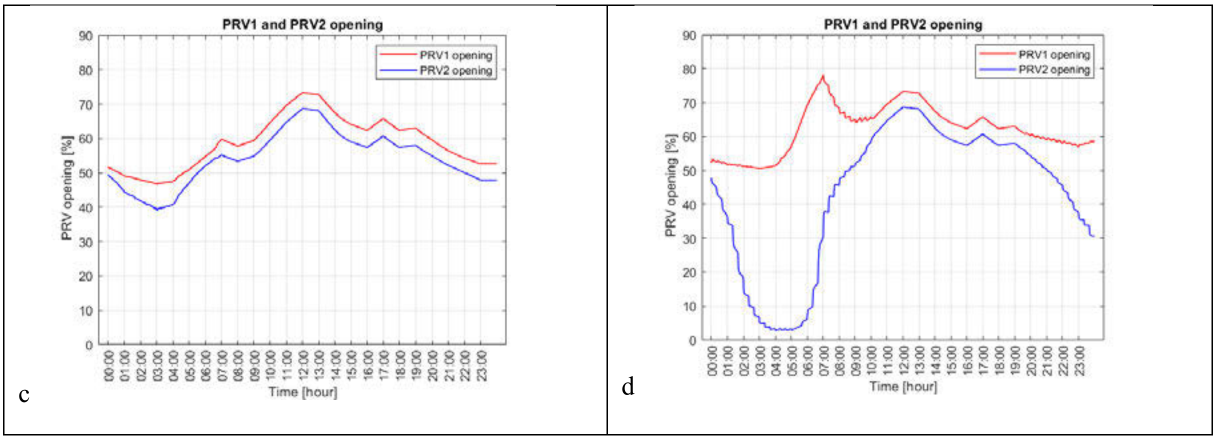


Figure 6a, 6b, 6c, 6d. PRV1 and PRV2 opening signals for different scenarios

The PRV opening signals are consistent with engineering intuition, the behaviour of the valves for each scenario are summarised in the bullet points below:

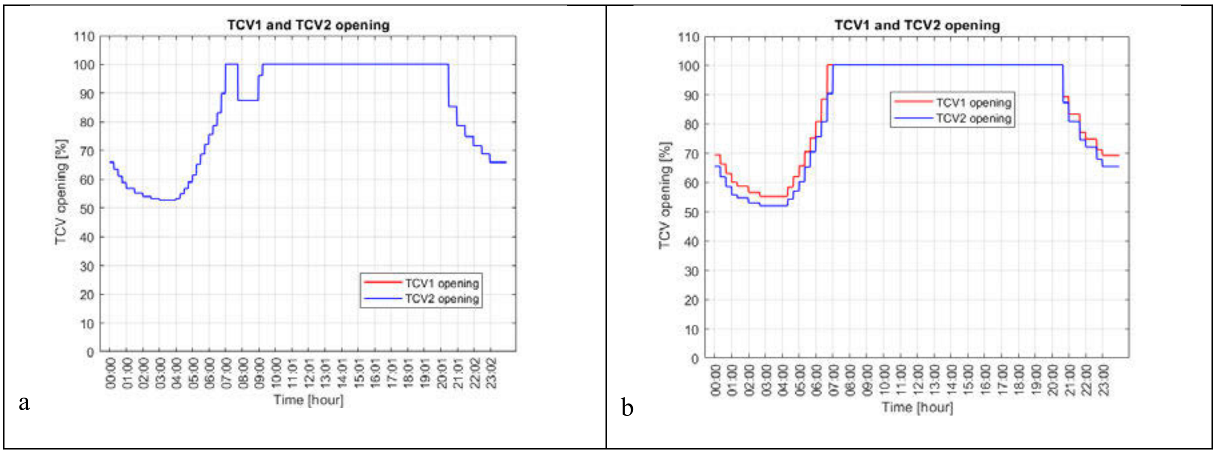
a) The opening signals from the two PRVs are overlapping due to the symmetry and identical initial conditions assumed in the both valves.

b) The symmetry has been broken with PRV2 (follower) having lower set-point of $hset(2) = 262m$. The PRV2 opening is slightly smaller than for PRV1 (leader) however both branches aim the same head of 254 m at the connection node h_3.

c) Ditto but effects are even stronger than in point b).

d) PRV2 closes at night in the enforced conflict situation between the PRV branches, PRV1 has enough capacity at that time to convey the entire flow. However, during the day when the flow increases and TCV1 fully opens, PRV2 opens gradually and then during the peak hours the two PRVs convey almost equal flow.

The corresponding TCV opening signals are presented in Figure 7.



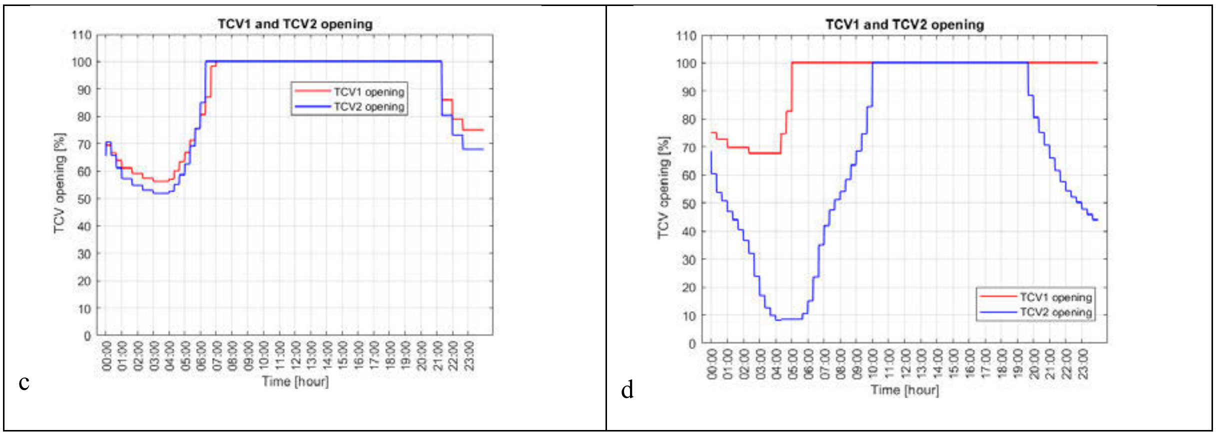


Figure 7a, 7b, 7c, 7d. TCV1 and TCV2 opening signals for different scenarios

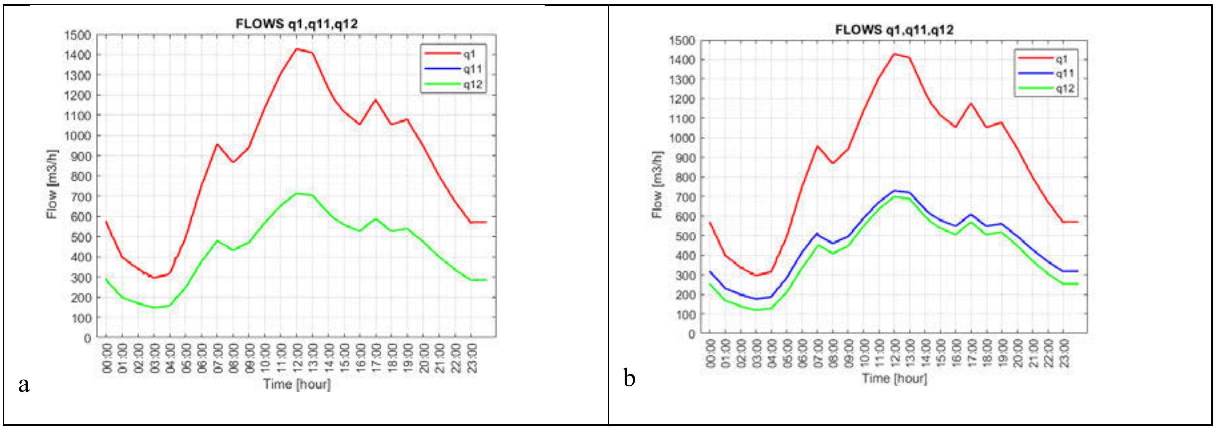
The behaviour of the valves for each scenario are summarised in the bullet points below.

a) b) c) The TCV s are fully open (100%) over the high flow period but even so the head loss on the valves is higher than the desired 10m and their outputs drop to 240m as it is shown in Figures 9a, 9b and 9c.

d) In the conflict situation TCV2 follows the same pattern as PRV2. It closes at night and then opens gradually during the day. TCV1 fully opens at 06.00am and stays fully open (100%) over the rest of the day.

Clearly, the TCVs are undersized and even fully opened generate a head loss higher than 10 m for peak flows. These valves are adapted for low flows and here they should be replaced by valves with different capacity characteristic and possibly bigger diameter.

The main Eupen flow and the two PRV branch flows are shown in Figure 8.



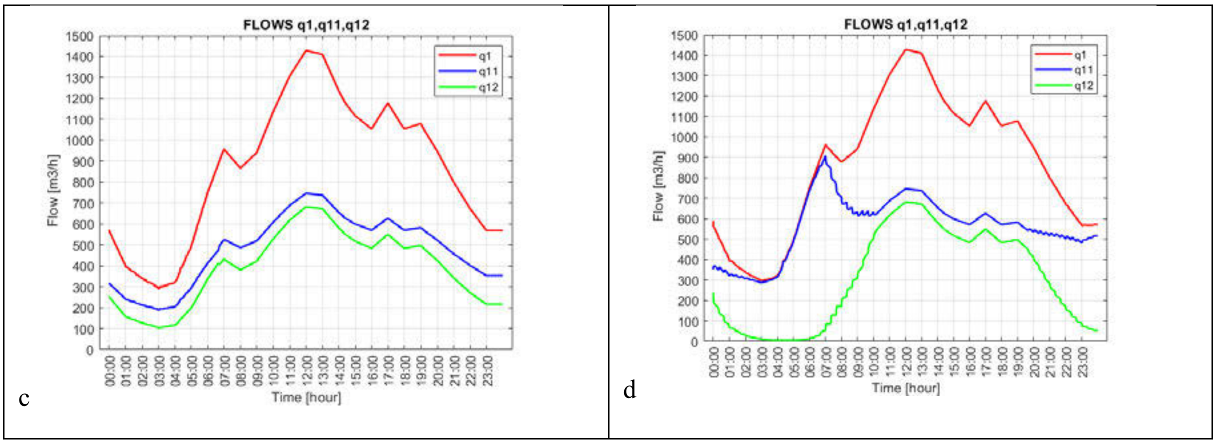


Figure 8a,8b,8c,8d. Flows q1, q11 and q12 for different scenarios

The Eupen (q_1) flow is in the red line, PRV1 (q_{11}) flow is in the blue line and the PRV2 (q_{12}) flow is in the green line. The behaviour of the flows for each scenario are described below

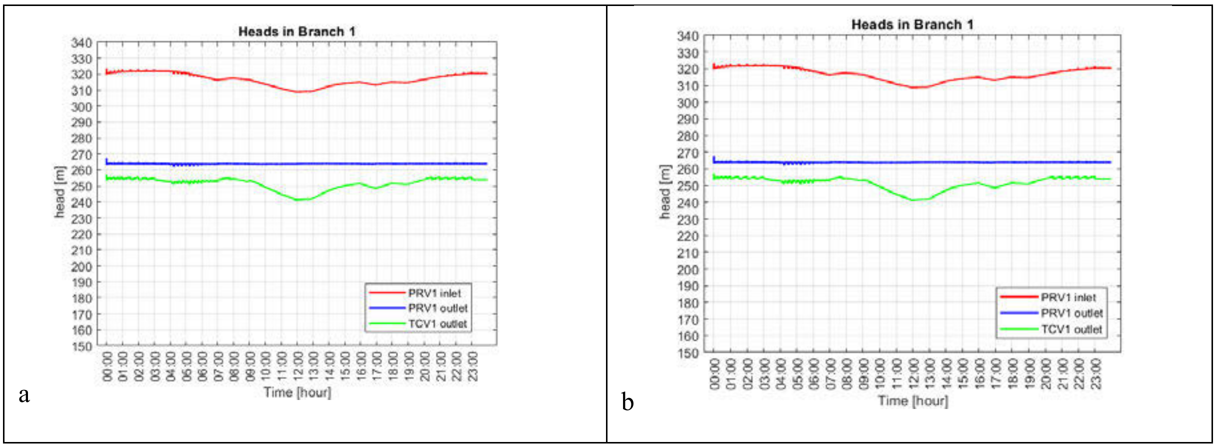
a) The flows through both valves are identical due to symmetry of the arrangement.

b) The flow through PRV1 (leader) has slightly increased compared to a) and the flow through PRV2 (follower) has slightly decreased. This difference can be explained by the flow selecting a path with a lower resistance.

c) The phenomenon is more visible in Figure 8c. for $hset(2) = 260m$, the flow in PRV1 increased even more and subsequently the PRV2 flow has decreased.

d) For lower flows at night PRV1 is open and PRV2 is closed, PRV1 is sufficient to convey the required flow. However, when the flow increases to a significant value during the peak hours PRV2 opens (see Figure 6) and the main flow is distributed evenly between the both valves. This happens when TCV1 saturates at 100% opening (see Figure 7) and cannot be adjusted any more. Branch 1 cannot enforce the required head of 254m at the TCV1 output.

Figure 9. depicts the three important heads in Branch 1, the PRV1 input, the PRV1 output and the TCV1 output



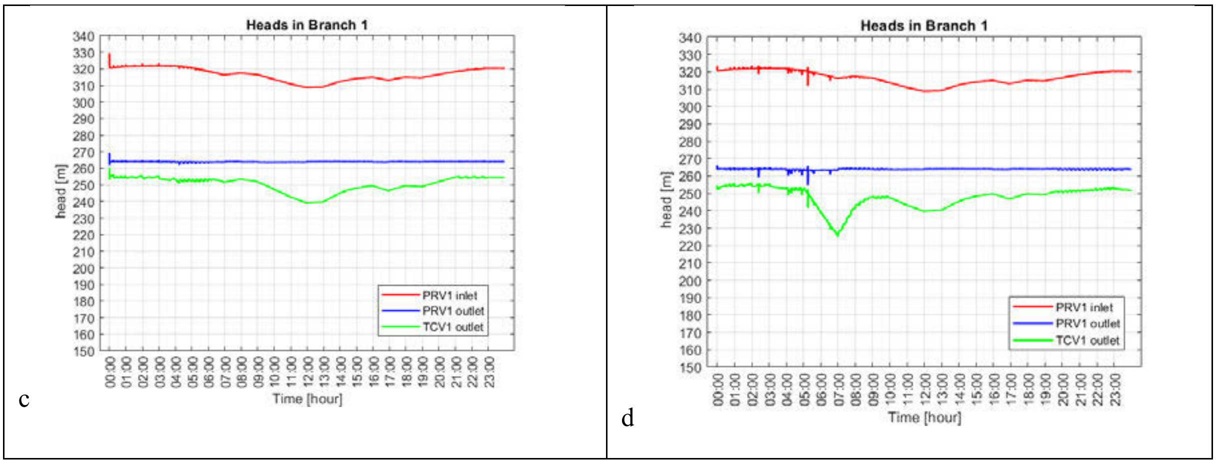


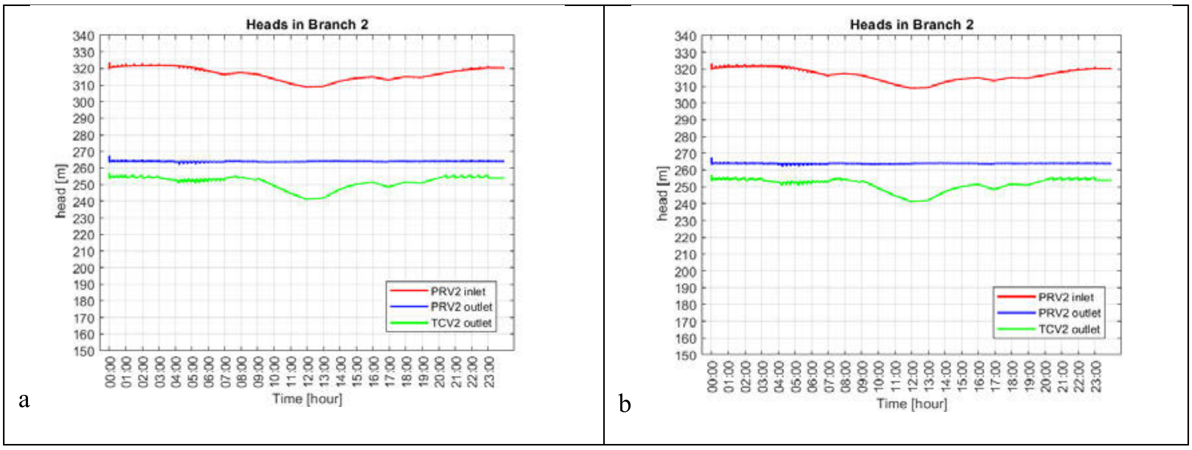
Figure 9a, 9b, 9c, 9d. Head signals in Branch 1 for different scenarios

The PRV1 inlet head is represented by the red line, the PRV1 outlet head by the blue line and the TCV1 output by the green line. The following can be observed for each scenario.

a) b) c) Independently of the PRV2 settings PRV1 maintains constant head of 264m following its set-point. The TCV1 output drops to 240m due to very high flow which gives the head loss higher than the desired 10m even for the fully open TCV valve.

d) PRV1 maintains the 264m set-point however the output from TCV1 drops to 225m at 06.00am during the transition period when PRV2 is slowly opening. PRV1 conveys the substantial flow of 950 $m^3/_h$ which causes big head loss on TCV1 despite the valve being fully open. TCV1 acts as a fixed valve and consequently the conflict situation ceases to exist.

The head signals from Branch 2 are given in Figure 10.



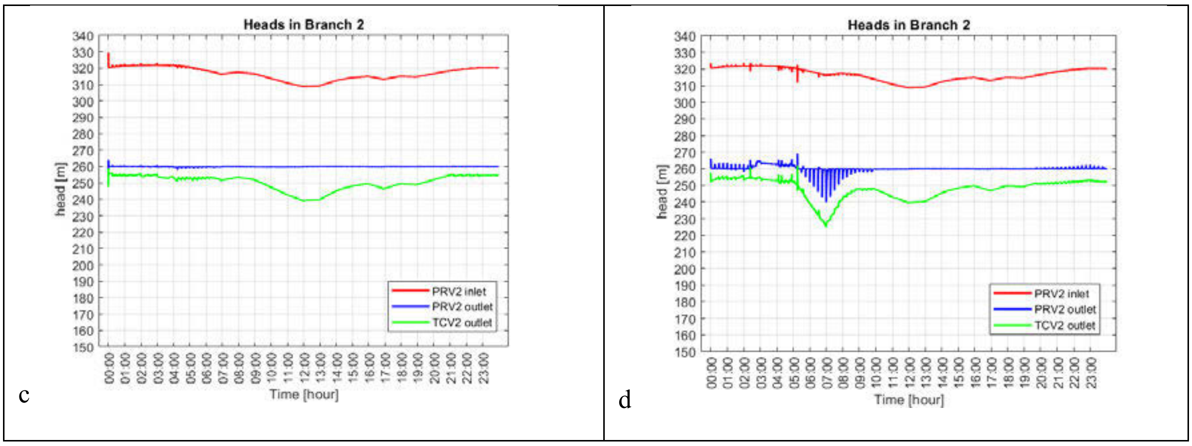


Figure 10a, 10b, 10c, 10d. Head signals in Branch 2 for different scenarios

The figure presents the head signals in the PRV2 branch, PRV2 input (red line), PRV2 output head (blue line) and the TCV2 output (green line). The observations for each scenario are as follow:

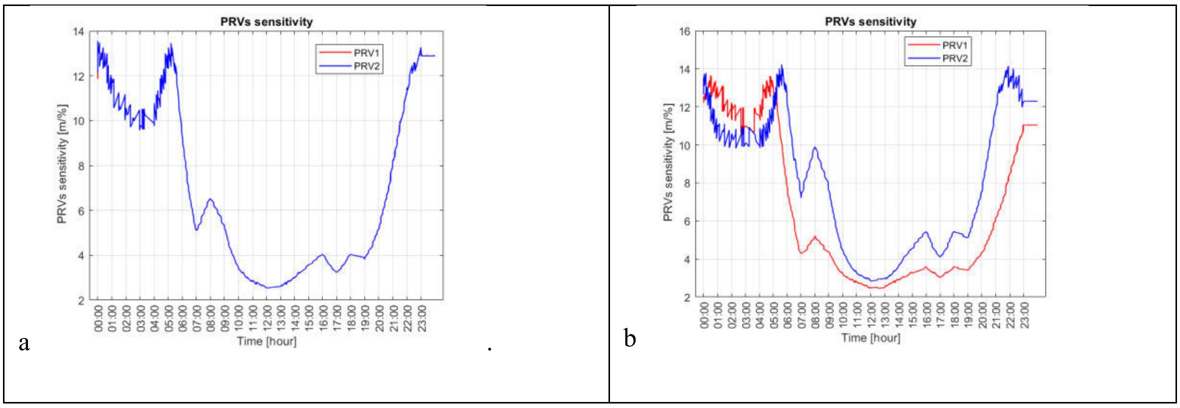
a) PRV2 maintains its 264 m set-point, the TCV2 output drops to 240 m despite the valve being fully open for peak hours

b) PRV2 maintains its 262 m set-point, the TCV2 output drops to 240 m despite the valve being fully open for peak hours

c) PRV2 maintains its 260 m set-point, the TCV2 output drops to 240 m despite the valve being fully open for peak hours

d) PRV2 is closed at night and does not control its output. It starts opening at 06.00am and during this transition period correcting the TCV2 settings result in significant jumps in the PRV2 output. The TCV2 output is the same a TCV1 output and drops to 225m at the peak hours. After 10 am when the both TCVs are fully open the TCVs output is similar to scenarios a), b) and c).

Finally, the sensitivity signals for the PRVs for different scenarios are displayed in Figure 11.



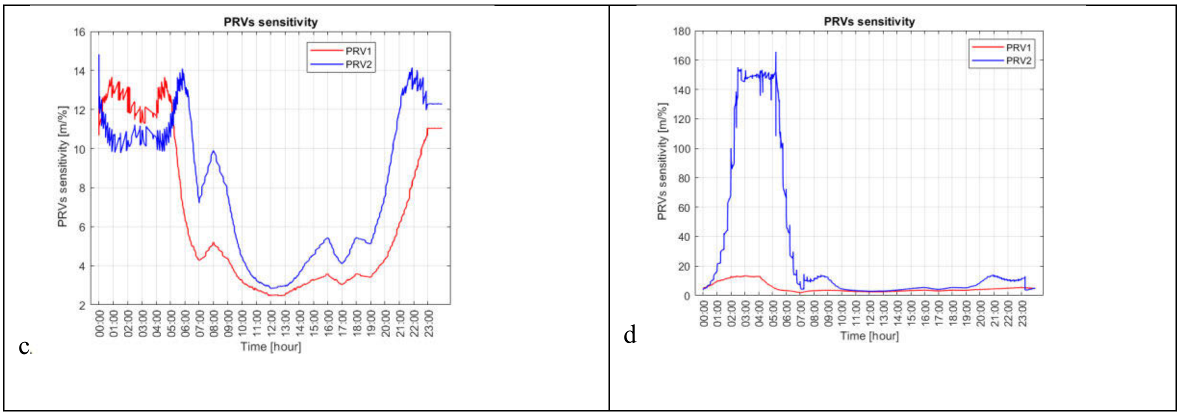


Figure 11a, 11b, 11c, 11d. PRV1 and PRV2 sensitivity signals for different scenarios

The sensitivity signal is an indicator of how stable is operation of the PRVs. The following observations can be made for each scenario.

a) b) c) The sensitivity is higher for the low flows, up to 14 $^{m}/_{\%}$ and lower for the peak flows, down to 2 $^{m}/_{\%}$. These are upper bond estimates and the real values are lower due to damping effects of the pressure dependent outflow in the WDS as it is explained in [7].

d) The PRV1 sensitivity is in normal range. The PRV2 sensitivity jumps to 120 $^{m}/_{\%}$ but it is practically closed at night and the notion of the sensitivity does not then applies. During the day the both PRVs have acceptable level of sensitivity.

The sensitivity values for lower the flows are not only higher but also noisier compared to the period with higher flows.

4 CONCLUSIONS

A need for parallel connection of two PRVs arises when the range of flows is very wide and one PRV cannot cope with the range. Normally it is recommended setting the main valve to higher set-point which results in the main valve being active most of the time and the second valve opens only for peak flow when the main valve is already saturated. In this case-study an additional feature was the presence of the TCVs. The PRVs operated continuously controlled by hydraulic pilot loops. The TCVs were adjusted periodically at 15 minutes intervals to maintain constant head loss following the changing flows. The TCVs were introduced to reduce the interactions between the PRVs and the downstream flow ratio control system. In such a situation behaviour of the entire system depends on both the PRV settings and the TCV settings. The detailed observations for scenarios a), b) c) and separately for scenario d) are summarised in the two paragraphs below.

Observations for scenarios a), b) and c) PRV2 settings affects flow distributions among PRVs. If the two set-points are equal $hset(1) = hset(2) = 264m$ there is a symmetrical situation and the valve openings and the valve flows are identical. For $hset(2) = 262m$ and $hset(2) = 260m$ the PRV1 opening is bigger than the PRV2 opening and also flow through PRV1 is higher than through PRV2. The both PRVs maintain their respective set-points well, $hset(1) = 264m$ and $hset(2) = 262m, 262m\ and\ 260m$ respectively. The both TCVs fully open for the high flows but even so the head loss on the valves is much higher than expected 10 m. At node h3 where the both PRV branches merge the head varies from 240 m to 255 m. The outlet head from TCVs of 240 m is well below the required value of 254 m. The two PRVs for all PRV2 settings work in a stable manner because the target head at h3 for the two branches is the same and equal to 254 m. The downstream part of the system after the pump connection is affected by the low head of 240 m at node h3 nevertheless, the flow mixing ratio is relatively stable.

Observations for Scenario d). This scenario corresponds to the enforced conflict situation where Branch1 tries to enforce head 254 m at the node h3 whilst Branch 2 tries to enforce the head equal to 250 m. In this situation Branch 2 with the lower PRV2 settings of 260 m closes and water is conveyed only by PRV1 at night when the main flow is low. However, during the day around 06.00am when the main flow increases and saturates TCV1, PRV2 regains control and starts to open. The main flow is now split between the two valves. The flow in PRV2 gradually increases until the both flows are almost identical and both TCVs are fully open. The lowest head at node h_3 is at 07.00am and is equal to 225 m. This impacts the pump operating point down to 100m head increase nevertheless, the flow mixing ratio is maintained at the required level in relatively stable fashion.

In scenarios a), b), c) in which the target head at node h3 is the same, both PRV branches are active all the time. In scenario a) the two PRV flows were identical while in scenarios b) and c) the PRV with the higher setting conveyed slightly higher flow. If the intention is to use mainly one PRV branch and open another only for the peak flow then scenario d) is recommended. For normal and low flow situations not presented in this case-study the valve with lower setting closes immediately and remained closed over the entire 24 hour period.

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