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Supporting real-time pressure control in Oppegård municipality with WDNetXL

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Abstract

The Pressure Control module in the WDNetXL system [1] was recently developed to support planning and real-time operation of classic and remotely real-time controlled (RRTC) pressure control valves (PCVs). These devices allow pressure regulation by setting target pressure values in strategic (even remote) points in the network named critical nodes. Transferring pressure readings in real-time from remote nodes to PCVs is technically feasible, so that they can be modulated according to pressure variation at critical nodes. Pressure control strategy by RRTC PCV was demonstrated to allow effective background leakage reduction into the network. In this paper, the WDNetXL *Pressure Control* module is used to analyse real-time operation of RRTC PCVs aimed at leakages reduction in the Oppegård municipal network (Norway), while considering three main strategies for the electric regulation of PCVs, which are discussed into a hydraulically consistent framework.

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Keywords: Pressure control; Background leakage reduction; Remote Real-Time Control; Pressure control valves; WDNetXL.

1. Introduction

The background leakage reduction is today a relevant issue worldwide; for instance, the mean value of real water losses observed in European water distribution networks (WDNs) during the period 2008-2012 ranges from 30% to

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40% total inlet volume, with a significant trend of increase (1% per year). Water utilities consider pressure control in WDNs as an effective action in a short-medium period to reduce water leakages, being less expensive than asset rehabilitation/replacement. Consequently, several methods have been recently developed to plan the optimal location of PCVs in WDNs in order to decrease background leakages without impairing the quality of the water delivery service to customers (i.e., without decreasing pressure below the minimum required for a correct service), e.g., [2][3][4][5][6].

Classic PCVs permits to control the node right downstream the valve (e.g. [7]) corresponding, from a modelling standpoint, to maintain a target pressure to one of the ending nodes of the pipe where the device is installed. This is the main drawback of classic PCVs, since they need a target pressure varying over time with the WDN behaviour due to variation of customers' demand (e.g., higher target pressure at the downstream node is needed when customers demand increases, since the head losses increases with flow rate, and *vice versa*). This requires setting different target pressure values over time according to predicted delivered water. This process is neither optimal nor reliable because of the uncertainty of water demand prediction [8].

Recently developed remote real-time control (RRTC) strategies allows transferring streams of pressure data from strategic (even remote) nodes into the WDN to PCVs to maintain a target pressure value using a real-time electric regulation. This permits to modulate the PCV by an actuator driven by a programmable local control (PLC) unit, based on pressure measured at *critical* nodes in the network. From a hydraulic standpoint, the *critical* node is the "worst" node, i.e., the first node with the pressure under the value needed for a proper water supply service [9]. Therefore, getting the minimum required pressure for a correct service in the critical node guarantees service quality in the entire system or in a portion of it. Furthermore, the pressure variation at the critical node integrates the actual hydraulic system behaviour, e.g., due to changing water requests over time, allowing the optimal and robust regulation of RRTC PCV. In fact, the critical node can be associated to a part of the system, and thus there can be a number of RRTC devices controlling the pressure into the different WDN portions, each characterized by its critical node. Therefore, the preliminary identification of such pressure control areas of the hydraulic system is useful to locate RRTC devices in order to achieve the effective pressure control while avoiding interferences among different control devices. The target pressure value to be set at the critical node can be defined reliably and does not change over time because it depends on the minimum residual pressure for a correct service (e.g., at the last floor of the highest building) [9].

RRTC PCVs can be electrically regulated during a control time step, because critical nodes are commonly far from the device and the system status cannot change instantly with the pressure readings (when it differs from the target value). Otherwise, an over-controlling of the device might results into an unsafe flow oscillation causing relevant unsteady processes into the network [10]. The most common way to regulate electrically a PCV is based on the use of proportional-integral-derivative (PID) controllers. The application of PID control to a theoretical single input DMA was demonstrated by [11], while [7], studied multi-input DMAs and considered a real water network configuration. Most recently, researchers have analysed the PID units for the operational electric regulation of PCVs in WDNs [12][13]. Today, the adoption of embedded programmable logic controllers (PLCs) enables to implement regulation algorithms allowing transforming the difference between pressure reading and target pressure value at the critical node into a movement of the PCV actuator to adjust its opening degree during a control time step [14]. From a hydraulic standpoint, analysing these control strategies by simulating real-time operation is very important in order to understand the consequences of the pressure control process of RRTC PCVs over the considered operating cycle.

The present contribution presents the application of WDNetXL *Pressure Control* module [15] in supporting real-time operation of RRTC PCVs in order to control pressure and reduce leakages in the Oppegård municipal network (Norway), starting from the work of Berardi et al. [16]. The presented control scenarios are analysed considering three main strategies for the electric regulation of PCVs, accounting for the PCV shutter behaviour at each simulation step.

2. Simulation of electric regulation of RRTC PCVs

RRTC PCVs aim at reaching the target pressure value at the critical node in a WDN (or a portion of it) by means of electric regulation, which modifies the opening degree of the PCV according to pressure reading at the critical node. The variation of the PCV opening degree results into increasing/reducing of its internal head loss in order to reducing/increasing the pressure at the critical node to reach the target pressure value. This variable local head loss of each RRTC PCV can be modeled using the following expression:

$$\Delta H_{PCV}(t) = \frac{\xi(t)}{2g} v(t)^2 = \frac{\xi(t)}{2gA(t)^2} Q(t)^2 = \left(K_{ml}(t) + K_{ml-min}\right) Q(t)^2 \quad (1)$$

where ΔH_{PCV} is the valve head loss; ξ is a variable head loss coefficient; K_{ml} is the hydraulic resistance due to minor head loss; $K_{ml\text{-}min}$ is the minimum hydraulic resistance of fully open valve; v is the average water velocity into the pipe; Q is the pipe flow rate; A is the cross-sectional area of the pipe; and g is the gravitational acceleration (9.808 m/s^2). The displacement of the internal regulating membrane/shutter modifies the RRTC PCV head loss coefficient and downstream pressure. More details can be found in [15]. The RRTC PCV can have three states: (i) active when ΔH_{PCV} is set and the target pressure value is kept at critical node; (ii) fully closed when the valve closes because the pressure cannot be further reduced to reach the target value (in real situations it is constrained to an assigned minimum opening degree); and (iii) fully open when the valve opens because the pressure cannot be further increased to reach the target value. A fourth status can exist and is related to the inversion of flow; but usually such devices are equipped with a non-return (check) valve.

The electric RRTC regulation of PCVs involves the real time setting of the valve head loss $K_{ml}(t)$ of Eq. (1) using a control unit. For example, a PLC control unit regulates the valve based on pressure measurements acquired at the critical node at each control time step (T_c) and using the pressure deviation (ΔH_{set}) from the target value. A control transfer function (unit process function) allows the regulation of the next control time step in terms of the shutter movement (i.e., valve head loss). Three main strategies of the control transfer functions are analyzed in this work, as they are implemented in the WDNetXL Pressure Control module [15]. They are based on assuming three possible control variables: (i) the valve hydraulic resistance, K_{ml}; (ii) the head loss across the valve, ΔH_{PCV}; and (iii) the shutter closure degree, α, according to the following formulations,

$$\begin{aligned} &K_{ml}(t, t+Tc) = -\Delta H_{set}(t-Tc, t) / Q_{PCV}^2(t-Tc, t) + K_{ml}(t) && \text{valve resistance control (RES)} \\ &\Delta H_{PCV}(t, t+Tc) = \Delta H_{set}(t-Tc, t) + \Delta H_{PCV}(t) && \text{valve head loss control (HL)} \\ &\alpha(t, t+Tc) = -k_c \Delta H_{set}(t-Tc, t) + \alpha(t) && \text{valve shutter degree control (SD)} \end{aligned} \quad (2)$$

The first two control strategies of PCVs are related to hydraulic variables (K_{ml} or ΔH_{PCV}), while the third is related to the mechanical variable (α) that modify the valve head loss. In the latter case, the direct prediction of the shutter opening degree α is based on ΔH_{set}, and this requires the calibration of k_c that is the proportional gain of the control function to transform the opening degree in pressure variation at the critical node, thus k_c is not dimensionless.

The modification of the shutter degree is subject to a mechanical constraint to the maximum shutter velocity, $v_{max\text{-}\alpha}$ [$\Delta\alpha \cdot s^{-1}$], where $\Delta\alpha$ is the product of Tc and $v_{max\text{-}\alpha}$ and is the maximum displacement of the shutter opening degree during the regulation time step. This constraint can limit the shutter movement when sudden variations of critical node pressure occur, thus avoiding consequences of related unsteady flow conditions.

3. RRTC modelling using WDNetXL Pressure Control module

The Pressure Control module in the WDNetXL system [1] was recently developed to support planning and real-time operation of PCVs, accounting for both classic and RRTC-PCVs [15]. This new module exploits WDNetXL-Analysis module features [17], therefore it contains functions to perform the standard hydraulic and topological analyses of WDNetXL considering pressure-driven simulation and background leakages [18], and also different components of demand [9] and failure events, i.e., hydraulic analysis considering valve shutdowns to isolate a district of the WDN for planned and unplanned works. Actually, this tool for the analysis is mainly useful for planning purposes including the location of RRTC devices, the selection of the critical node, as well as the identification of pressure control areas in order to avoid mutual interference among various devices. Such analysis assumes that, when the RRTC-PCV controls the critical node, the target pressure is reached instantaneously.

Nonetheless, the operational functioning of RRTC PCVs needs to be analyzed considering the actual functioning over *Tc*, the implemented control function, the specific valve curve, the shutter maximum degree, etc. Accordingly, the *Pressure Control* module allows the analysis of real-time operation of RRTC-PCVs since it includes the hydraulic simulation of various alternative strategies for electric regulation of the PCVs, as reported in Eq. (2), selecting also the adjustment time step (few minutes) and/or the maximum velocity of the valve shutter.

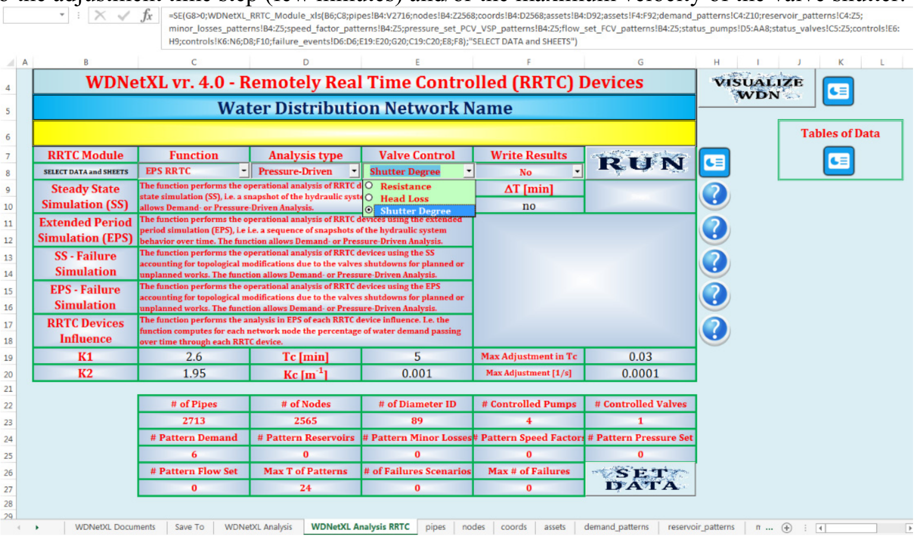

Fig. 1. User Interface in WDNetXL for RRTC device analysis.

The hydraulic analysis is performed at each control step *Tc* assuming a linear variation of the demand pattern, since the time steps used for defining the demand patterns (generally 1 hour) might include multiple time steps for RRTC control (*Tc* of few minutes). Fig. 1 reports the user interface of WDNetXL - Pressure Control module. Note that it is possible to define *Tc*, the control strategy, the gain factor k_c (working only when the “shutter degree” strategy is used), and the power law constants K1 and K2 for electrically controllable valves like plunger or needle valves [15]. The functions in Fig. 1 consist in five analysis functions allowing steady state simulation and extended period simulation (EPS) under normal and pipe failure conditions (i.e., requiring the gate valves shutdown to isolate WDN portions), and the analysis in EPS of each RRTC device influence (i.e., computing for each network node the percentage of water demand passing over time through each RRTC device).

4. Oppegård Case Study

The present application follows the study reported in Berardi et al. [16], which planned different scenarios of the location of classical and RRTC PCVs in Oppegård WDN in order to control pressure and thus reduce leakages. In their work, Berardi et al. [16] assumed the instantaneous reaching of the pressure target values, thus neglected the PCV behavior within each simulation step. This case study demonstrates the analysis of RRTC PCVs operation using the WDNetXL - *Leakage Control* Module by analyzing some of the planned scenarios proposed in [16] accounting for the three strategies for the electric regulation of RRTC PCVs in Eqs. (2).

The test network is the municipal network of Oppegård (see Fig. 2), a town located at south of Oslo (Norway), extended for about 129 km of pipelines and suppling an area with significant changes in elevation, ranging from 40 to 180 a.s.l.. Due to firefighting requirements, a minimum pressure of 30 m has to be guaranteed everywhere in the system and, therefore, diameters are oversized with respect to normal water supply functioning. Therefore, the pressure regime is substantially invariant over the day, without regards for water demand pattern. Pumping stations guarantee sufficient pressure in high elevation areas (dark-red in Fig. 2), while classic PCVs are currently installed to limit pressure in lower zones (light green-blue in Fig. 2). Of particular interest for this case study is the North-West area of Oppegård WDN, which is the most critical low-elevation zone. The window on the right of Fig. 2 shows that there are nine classic PCVs (black triangles in Fig. 2) controlling local pressure. The target pressure in this area ranges from 35 m to 70 m right downstream of the valves. Such pressure regime currently results into a leakages level that the water utility quantifies of about 28% of the total inlet water volume for the entire WDN. Therefore, the problem of Oppegård network is to control pressure and reduce leakages, possibly finding alternative PCV location scenarios.

This application exploits the same hydraulic model for Oppegård WDN built in the WDNetXL system as in [16]. This model was used within the WDNetXL Pressure Control module for an extended period simulation (EPS) of the Oppegård WDN over 24 hours, using the customer nodal demand pattern in right lower corner of Fig. 2 (provided by the water utility), and assuming the background leakage model parameters [18] that allow matching the leakage rate calculated by the water utility.

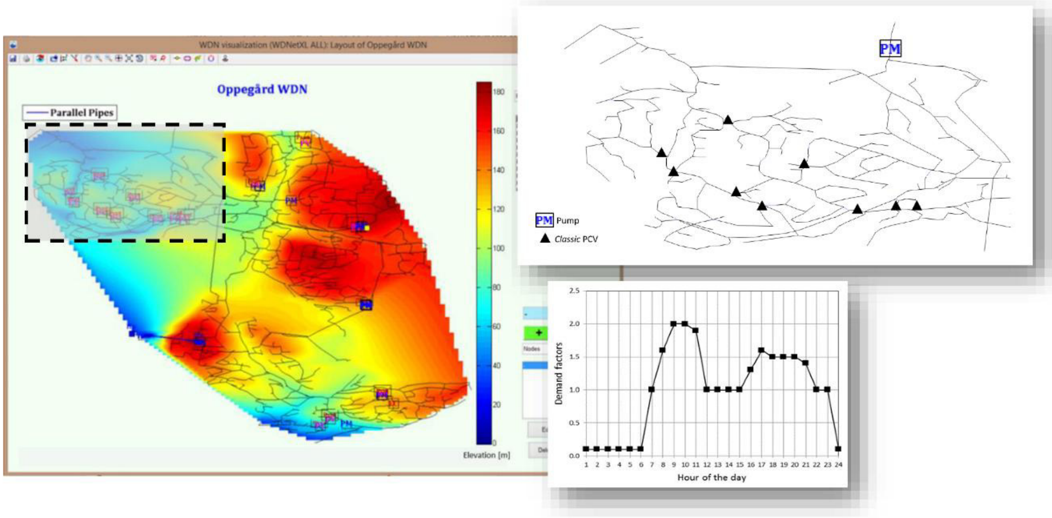

Fig. 2. Oppegård WDN with elevations. On the right, there is a zoom of the analysed sub-WDN with locations of pumps and PCVs and the demand pattern adopted for network simulation.

Within the planning scenarios defined by Berardi et al. [16], the WDNetXL Pressure Control module allows to analyze the PCV shutter behavior at each control step by comparing the three strategies for the electric regulation of RRTC PCVs in Eqs. (2). It is to remark, here, that in Berardi et al. [16] the location of new PCVs was selected manually considering the changes in elevation and the need to reach the desired service pressure (i.e. 30 m) at critical nodes, while reducing pressure as much as possible along the pipeline in order to decrease water losses. In that work, the PCV locations scenarios was defined considering the following technical alternatives: (i) the elimination of existing classic PCVs; (ii) the installation of new RRTC PCVs; (iii) possible closure/opening of gate valves to define the controlled areas. All discussions of this case study refers only to the circled North –West Oppegård area in Fig. 2.

5. Results discussion

Starting from current network condition (i.e., 9 PCVs, with no RRTC), all analyzed scenarios result into lower water leakages than current configuration [16]. For the sake of brevity, among the eight alternative plans for PCVs installation, entailing both classical and RRTC schemes, the two scenarios showed in Fig. 3 are here discussed in more details. Fig. 3 reports the location of classical and RRTC PCVs for the North-West part of Oppegård WDN, and indicates the influence area for each RRTC PCV and relevant critical nodes. Scenario A has seven PCVs in total (out of the current nine), three of them are new RRTC-PCVs (white triangles) and four are the classic PCVs already installed (black triangles). Locations and target values of the existing classic PCVs are unchanged, while the target values of the RRTC PCVs were set = 35 m where the location of the critical node possibly changes over time, otherwise it equals 30 m. Closing gate valves (red crosses in Fig. 3) allows controlling critical nodes from RRTC PCVs location, and thus the relevant pressure control areas colored in the Fig. 3-left. This scenario reduce the current leakages by about 27% of the water volume lost from the North-West Oppegård in its original configuration (i.e., 244 m^3/day less).

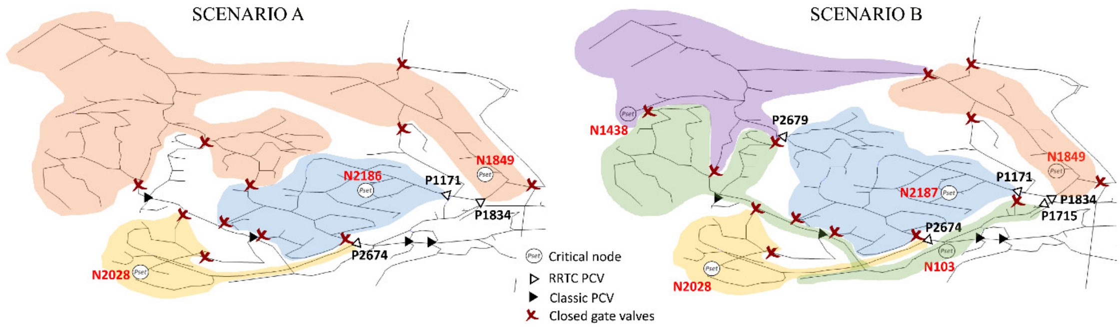

Fig. 3. Two selected scenarios of operative location of classical and RRTC PCV for the North-West part of Oppegård WDN, with indication of influence area for each RRTC PCV and closed gate valves.

Scenario B includes the same number of devices with respect to the original configuration, while having five RRTC PCVs (white triangles) and four classic PCVs already installed (black triangles) as indicated in Fig. 3-right. This scenario achieves a decrease of the background leakage volume of about (41% of the water volume lost from the North-West Oppegård, i.e., 375 m^3/day less). Fig. 3-right shows the 5 pressure control areas obtained for the new RRTC-PCVs by closing some existing gate valves.

5.1. Comparison of strategies for electric regulation of RRTC PCVs

The operational simulation of RRTC PCVs has been performed subdividing the simulation intervals ΔT into time steps equal to Tc, by linearizing the customer-required demand varying over each ΔT and predicting the PCV resistances or head losses to be included into the model according to Eqs. (2). Here, the EPS was performed using Tc = 5 min, thus generating a sequence of 12 snapshots into each hour (ΔT= 60 min). For the PCV, the three control functions listed in Eqs. (2) have been used, and the effect of the maximum displacement of the shutter in Tc was also investigated. Therefore, two sets of five simulations using RES, HL and SD with k_c = {0.001; 0.0028; 0.0036} were performed, with ($\Delta\alpha$ = 0.03) and without constraining the maximum shutter displacement.

For the sake of brevity, the results of Scenario A refers only to the RRTC PCV placed on pipe P1171 that controls the critical node N2186. Fig. 4-left reports the five simulations using RES, HL and SD using k_c = {0.001; 0.0028; 0.0036} in the case of unconstrained $\Delta\alpha$, for pipe P1171 in terms shutter degree (upper diagram) and for node N2186 in terms of pressure value (lower diagram). Note that the shutter degree axis is reported in a logarithmic scale. The upper diagram in Fig. 4-left shows the instability of the PCV through the abrupt opening of the shutter in the case of k_c = {0.0028; 0.0036}, while for k_c = 0.001 the instability is very limited. This fact demonstrates the need for calibrating k_c, which is a critical task because too high values of k_c could generate over-controlling of some hydraulic conditions (i.e., high variation of the hydraulic network behavior, for instance due to high demand variation), while a low value of k_c makes the pressure control inefficient, although more stable. It is arguable that in complex situations with several RRTC PCVs and a variable behavior of the hydraulic system, the calibration of k_c is a problematic task, mainly because k_c is a dimensional variable depending on flow rate through of the PCV, see the first and third Eqs. (2). Also the lower diagram of Fig. 4-left shows that RES and HL strategies outperform the SD strategy, and confirms the above mentioned instabilities through the abrupt change of pressure over time. Fig. 4-right reports the five simulations using RES, HL and SD using k_c = {0.001; 0.0028; 0.0036} in the case of Δα = 0.03. Both diagrams in Fig. 4-right shows again the instability of the PCV through a slight oscillation of the shutter and pressure in the case of k_c = {0.0028; 0.0036}, while for k_c = 0.001 there is lower instability. However, the instabilities are lower than in the previous simulations because of the constraint Δα = 0.03, which allows the limitation of the over-controlling during Tc. In any case, the use of Δα does not remove the need of calibrating k_c, as arguable by the lower diagram of Fig. 4-right showing the pressure oscillation increased by the local unsteady flow due to the shutter instability.

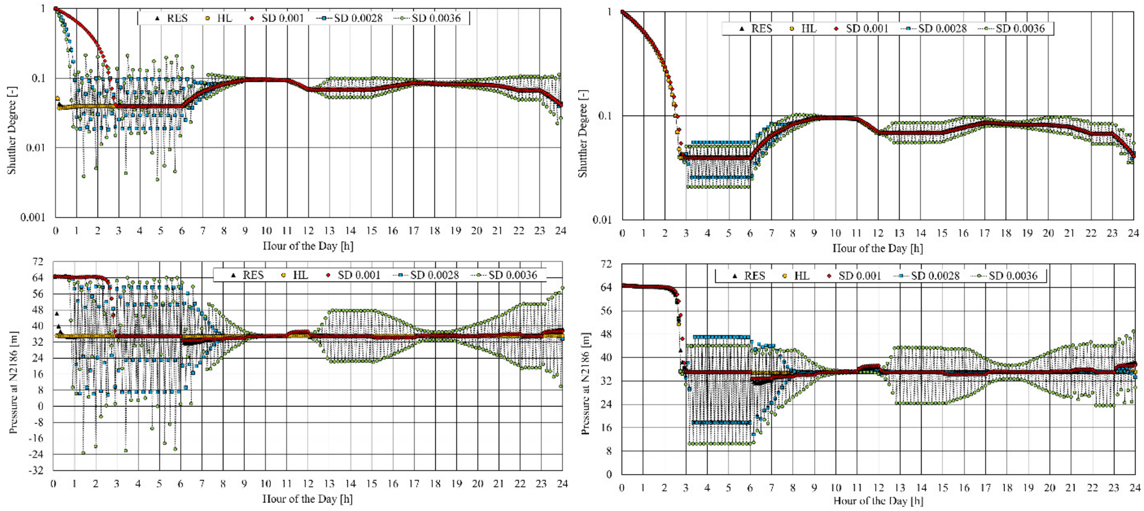

Fig. 4. Scenario A: behavior over 24 hours of the RRTC PCV installed on pipe P1171 in terms of shutter degree, and target pressure value at the controlled node N2186. The behaviors are simulated with (on the right) and without (on the left) constraint on the maximum displacement Δα.

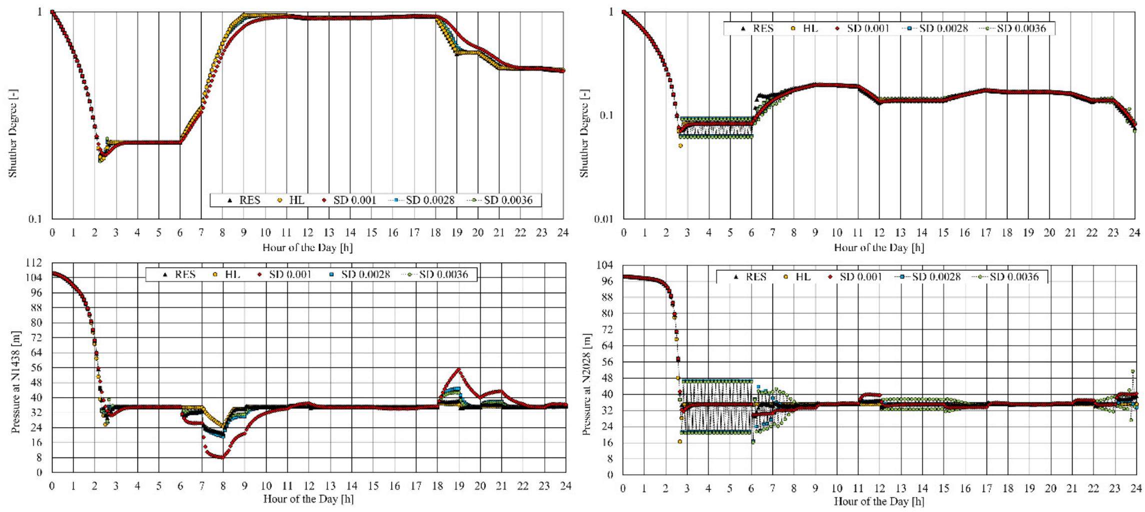

Fig. 5. Scenario B: behavior over 24 hours of the RRTC PCV installed on pipe P2679 (on the left) and on pipe P2674 (on the right) in terms of shutter degree, and target pressure value at the controlled node N1438 (on the left) and N2028 (on the right).

The results showed in Fig. 4 obtained using or not the constraint on the maximum shutter displacement (Δα) in *Tc*, clarify that it acts as a constraint to over-controlling, making more reliable the regulation, without a significant effect on the performance of the control, while excluding the possibility of using Δα to better calibrate k_c. For this reason, the analysis of Scenario B was performed only using Δα = 0.03. For the sake of brevity, Fig. 5 shows only to the RRTC PCV placed on pipe P2679 that controls the critical node N1438 (on the left), and the RRTC PCV placed on pipe P2674 that controls the critical node N2028 (on the right). Both diagrams in Fig. 5 confirm that the RES and HL strategies generally outperform the SD strategy similarly to the Scenario A, even if for pipe P2679 both strategies perform similarly. In particular, from 6:00 to 18:00, the demand variation, see Fig. 2, asks for a significant regulation of the shutter degree, to which all strategies respond in a similar way. The effect on the target pressure (lower diagram of Fig. 5-left), however, evidences that the HL strategy outperform the others. Diagrams in Fig. 5-right (referring to the PCV on P2674) confirms also that SD using k_c = {0.0028; 0.0036} is not stable, while k_c = 0.001 seems effective.

6. Conclusions

The present contribution analyze some strategies for real-time operation of RRTC PCVs aimed at leakages reduction in the real Oppegård municipal network (Norway) simulating the PCV shutter behavior at each simulation step accounting for the proposed three strategies for the electric regulation of RRTC PCVs, related to the three regulation variables, namely (RES) the valve resistance, K_{ml}; (HL) the head loss across the valve, ΔH_{PCV} and (SD) the shutter degree, α. The effects of constraining the maximum shutter displacements $\Delta\alpha$ on pressure control is also investigated. RES and HL strategies outperform the SD strategy and seem to be not influenced by the maximum displacement, since their regulation is already efficient to avoid over-controlling. Constraint on maximum shutter displacement helps the stability of SD strategy although the calibration of the gain factor k_c seems to be a challenging task, due to its dimensionality and dependence on the WDN hydraulic status.

Acknowledgements

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