Strategies for the electric regulation of pressure control valves

Orazio Giustolisi, Rita M. Ugarelli, Luigi Berardi, Daniele B. Laucelli and Antonietta Simone

ABSTRACT

In water distribution networks (WDNs), the classic pressure control valves (PCVs) are mechanical/hydraulic devices aimed at maintaining the target pressure just downstream or upstream of the PCV pipe, namely pressure reduction or sustaining valves. From a modelling standpoint, the major drawback of such local control is that classic PCVs may require target pressure varying over time with the pattern of delivered water because the controlled node is not strategic for the optimal WDN pressure control. Current information and communication technology allows transferring streams of pressure data from any WDN node to the PCV. Thus, remotely real-time control (RRTC) permits real-time electric regulation of PCVs to maintain a fixed target pressure value in strategic critical nodes, resulting in optimal control of pressure and background leakages. This paper shows three strategies for the electric regulation of RRTC PCVs, which use as control variables the shutter opening degree (SD), the valve hydraulic resistance (RES) and the valve head loss (HL). The Apulian network is used to compare the three strategies, while the application on the real Oppegård WDN yields further discussions. Results show that HL and RES strategies outperform SD; constraining the maximum shutter displacement helps SD stability although it still needs calibration.

Key words | pressure control valves, remote real-time control, water distribution networks

Orazio Giustolisi
Luigi Berardi (corresponding author)
Daniele B. Laucelli
Antonietta Simone
Department of Civil Engineering and Architecture,
Politecnico di Bari,
via Orabona n.4,
70125 Bari,
Italy
E-mail: *luigi.berardi@poliba.it*

Rita M. Ugarelli
SINTEF Building and Infrastructure,
Forskningsveien 3b,
NO-0314 Oslo,
Norway

Orazio Giustolisi
Rita M. Ugarelli
IDEA – Research Transfer,
via Monsignor J. Nuzzi n.10,
70129 Bari,
Italy

INTRODUCTION

The effective management of water distribution networks (WDNs) with respect to background leakage reduction is today a relevant issue. For instance, data from the Italian Institute of Statistics indicate that the mean value of real water losses increased from about 32% to 37% of total inlet volume in WDNs during the period 2008–2012, which is similar to the European value ranging from 30% to 40%, with a significant trend of increase (1% per year). This situation, quite worrisome for social community and water utilities, strongly affects water resources stressing water scarcity due to socio-economic factors and/or climate changes. Therefore, several planning actions have been proposed, in order to reduce background leakages, spanning from short to long time horizons of investments.

Water utilities recognize that the most important action to achieve reduction of background leakages in a short time horizon is via the optimal pressure control, because it requires investments lower than WDN rehabilitation plans. For this reason, during the last years, several methods have been proposed to plan the optimal location of pressure control valves (PCVs) in WDNs (e.g., Germanopoulos & Jowitt 1989; Jowitt & Xu 1990; Reis *et al.* 1997; Tucciarelli *et al.* 1999; Araujo *et al.* 2006; Nicolini & Zovatto 2009; Creaco & Pezzinga 2014). The purpose of such devices is to reduce the pressure into the hydraulic system thus allowing the decrease of background leakages without diminishing the quality of service for customers (Vairavamoorthy & Lumbers 1998; Ulanicki *et al.* 2000), i.e.,

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without decreasing the pressure below the value required for a correct service (Giustolisi & Walski 2012).

The classic PCVs are mechanical/hydraulic devices allowing the local control of a target pressure (Prescott & Ulanicki 2008; Meguid et al. 2011) 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 limitation causes the main drawback of the classic PCVs: they require a target pressure varying over time with the hydraulic system behaviour and, in particular, with the pattern of the delivered water to customers, because the controlled node is not strategic for the optimal pressure control into the hydraulic system (Giustolisi et al. 2016).

For example, a classic PCV aimed at reducing pressure into the downstream network requires a higher target pressure at the downstream node when the delivered water increases because the network head losses increase with flow rate and vice versa. This circumstance requires setting different target pressure values depending on the predicted delivered water; for this reason, two target values are generally adopted for night and daily functioning conditions. This procedure is neither optimal nor reliable because the selection of the target pressure assumes a fixed and predicted water demand, while in reality the supplied demand varies during the day, the week and the year and the prediction uncertainty is significant (e.g., Buchberger & Wells 1996).

Current information and communication technology (ICT) allows transferring streams of pressure data from nodes internal to the hydraulic system to PCVs in order to maintain the target pressure in any selected node using a real-time electric regulation. Then, the controlling node can also be remote with respect to the device. Therefore, those devices, named remotely real-time controlled (RRTC) PCVs, allow a real-time regulation by means of target pressure values, which are set in strategic points named critical nodes, permitting the optimal pressure control into the hydraulic network. In fact, the critical node is the 'worst' node, hydraulically speaking, i.e., the first node where the pressure falls below the value desired to provide a proper water supply service (Giustolisi & Walski 2012), which can be identified by WDN model runs. Therefore, maintaining the minimum required pressure for a correct/sufficient service in that node guarantees service quality in the entire system.

The position of the critical node does not generally vary over time depending on the local elevation, building height and required residual pressure for supplying sufficient water. Determination of the target value of the pressure at the critical node is then reliable and easy because it depends on the minimum residual pressure for a correct service at the last floor of the highest building whose value is not varying over time (Giustolisi & Walski 2012). In fact, the spatial variation of the demand can move the critical node, although a conservative value of the target pressure can account for it. For example, in the case of pressure reduction valves, the target pressure at the control node should be slightly above the minimum value to guarantee that all nodes in the controlled area are at normal pressure conditions, based on WDN model runs. Furthermore, the variation of the pressure at the critical node integrates the hydraulic system behaviour with respect to water requests, e.g., a decrease of water request increases the pressure and vice versa, allowing the optimal regulation of RRTC devices in terms of optimal opening degree of a PCV.

It is worth noting that each RRTC device controls the pressure into a portion of the network under its influence and the critical node relates to that part of the system. Therefore, for segmentation of the hydraulic system, e.g., by means of district metering areas (DMAs), it is useful to install several RRTC devices in order to achieve the optimal pressure control for avoiding interferences. Therefore, RRTC devices are effective in order to optimize pressure management of WDNs, provided that the critical node is controllable over time, i.e., all water paths feeding the critical node pass through the pipe where the valve is installed.

Since the controlled nodes are generally far from the device, the system status cannot change instantaneously and pressure reading at the critical node differs from the target value, thus the RRTC PCVs are electrically regulated during a control time step. Neglecting this aspect would produce over-control of the device that might result in dangerous oscillations of the flow, causing relevant unsteady flow processes into the network (Meniconi et al. 2015).

The most common way of electrically regulating PCVs is based on the use of PID (proportional–integral–derivative) controllers. A number of papers have been published in recent years on the adoption of PID units for the operational electric regulation of PCVs in WDNs. The application of PID control to a theoretical single input DMA was demonstrated by Prescott & Ulanicki (2003), while Prescott & Ulanicki (2008) studied multi-input DMAs and considered a real water network configuration.

Kumar & Kumar (2009a, 2009b) emphasized the importance of the calibration of PID units for effectiveness and reliability of pressure control in WDNs. Ulanicki & Skworcow (2014) considered the use of PID controllers to identify causes for instabilities of pressure in WDNs. Campisano *et al.* (2010) were the first to introduce the idea of adopting a simple proportional (P) controller to regulation PCVs in WDNs using RRTC devices. Campisano *et al.* (2012) developed a controller calibration simulation-based methodology in order to achieve a reliable and optimal pressure control.

Today, the adoption of embedded programmable logic controllers (PLCs) enables the implementation of regulation algorithms allowing transforming the difference between pressure reading and the target pressure value at the critical (controlling) node into an action of the actuator of the PCV to optimally adjust its opening degree during a control time step. For example, Creaco & Franchini (2013) developed an algorithm based on flow measurements at the PCV, obtaining good performance in simulated pressure control.

At the beginning of 2014, a research project, InnoWatING (Innovation in Water Infrastructure – New Generation) funded by the Norwegian 'Regionale Forskningsfond Hovedstaden' was launched to analyse the potential for exploitation of RRTC PCVs as a novel technology to reduce leakage in WDNs through improved pressure control. The municipality of Oppegård, close to Oslo (Norway), was selected as the bench-case for such an analysis. A portion of the water distribution system characterized by high pressures and leakages was identified as a pilot sub-network in order to explore the benefits of RRTC PCVs by both model simulations and successive field tests.

For the purpose of planning and testing the operational behaviour of the RRTC PCVs, the strategies of regulating such devices were studied in order to develop regulation algorithms to be embedded in PLCs. This paper presents three main strategies for the electric regulation of RRTC PCVs considering three different control variables to drive the shutter opening degree. Each strategy is discussed in a hydraulic consistent and comprehensive framework. The comparison based on the advanced WDN hydraulic modelling intends to support RRTC PCVs' implementation, considering effectiveness in controlling pressure, possible limitations for real-world applications and costs required to install additional flow/pressure meters. This approach follows the idea that the application of new operational methodologies in real systems need to be preceded by thorough theoretical and numerical studies. To this purpose, the Apulian network is used in order to show and discuss the effectiveness of the three electric regulation approaches. Then, the application to the WDN of Oppegård allows further discussion of the electric regulation strategies.

STRATEGIES FOR THE ELECTRIC REGULATION OF RRTC PCVS

As stated in the Introduction, the aim of RRTC PCVs is to maintain the target set-point pressure value at the critical node, generally far from the control device, by means of an electric regulation occurring in real-time. In order to maintain the target pressure, the electric regulation adjusts the opening degree of the PCV. Hydraulically speaking, a RRTC PCV regulates the pressure by increasing/reducing its internal head loss for reducing/increasing the pressure at the critical node in order to reach the target pressure value.

It is possible to model RRTC PCVs as varying local head losses as:

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

where ΔH_{PCV} is the valve head loss; ξ is a variable head loss coefficient; K_{ml} is the resistance; $K_{ml\text{-}min}$ is the minimum 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).

Therefore, the displacement of the internal regulating device (membrane or shutter) modifies RRTC PCV hydraulic resistance (or head loss coefficient) and downstream pressure.

For electrically controllable valves like plunger or needle valves, manufacturers provide mathematical curves allowing calculating the head loss coefficient (ξ) associated with the valve opening degree (α). Irrespective of the valve size, a power law equation allows interpolating such curves as follows (Campisano *et al.* 2012):

$$\xi(\alpha) = 10^{-k_1 \log(\alpha) + k_2} \tag{2}$$

The shutter opening degree, α, is the ratio between the valve opening (shutter position) and the total shutter stroke (valve fully closed means null α and valve fully open means unit α); $K_{ml\text{-}min}$ is obtained for $\xi(\alpha = 1)$. Figure 1 shows the curve $\xi = \xi(\alpha)$ for a needle valve without anti-cavitation basket by PAM-St Gobain and expressed through Equation (2) for the constants k_1 and k_2, respectively, using $k_1 = 2.8$ and $k_2 = 1.5$.

The RRTC PCV can have three states:

1. active when the head loss is set and the target pressure value is maintained;
2. fully closed when the valve closes because the pressure cannot be further reduced to reach the target value (actually it can be constrained to close up to an assigned minimum degree);
3. fully open when the valve opens because the pressure cannot be further increased to reach the target value.

A fourth status related to the inversion of flow exists. In fact, such devices are usually equipped with a non-return (check) valve, i.e., they are directional devices.

The electric regulation of RRTC PCVs consists of adjusting in real time the valve resistance $K_{ml}(t)$ of Equation (1) using a control unit, i.e., a PLC. A PLC allows controlling the valves based on the pressure measurement acquired at the *critical node* at each control time step (Tc) and on the pressure deviation (ΔH_{set}) from the target set-point value. The pressure deviation (ΔH_{set}) allows regulation of the devices during the next control time step (Tc) by varying the valve resistance.

A control transfer function (unit process function) allows the regulation of the next control time step in terms of prediction of the shutter movement. Thus, conceptually, the *control strategies* for the electric regulation of the PCVs analysed in this paper aim at computing the target values of the *control variables* to be reached during each control time step, while the control transfer functions aim at driving the shutter movement in order to reach such target values using the available actuation technologies.

The work of Giustolisi *et al.* (2015) mentioned three main *control strategies* for RRTC PCVs, with the aim of presenting the tool used to perform the analysis of RRTC PCV. They are based on three possible *control variables*: (i) the shutter opening degree, α; (ii) the valve resistance, K_{ml}; and (iii) the valve head loss, ΔH_{PCV}.

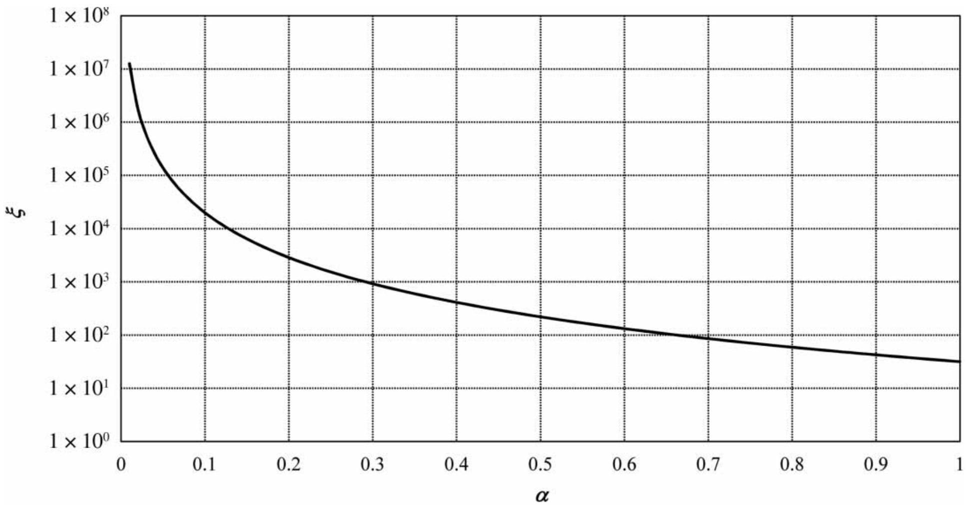

Figure 1 | Head loss coefficient ξ associated with opening degree α using $k_1 = 2.8$ and $k_2 = 1.5$ in Equation (2).

For RRTC PCVs, the formulations of the three unit process functions of pressure deviation (ΔH_{set}) are:

$$\begin{array}{ll} \alpha(t, t+Tc) = -k_c \Delta H_{set}(t-Tc, t) + \alpha(t) & \text{valve shutter opening degree control (SD)} \\ K_{ml}(t, t+Tc) = -\Delta H_{set}(t-Tc, t)/Q^2_{PCV}(t-Tc, t) + K_{ml}(t) & \text{valve resistance control (RES)} \\ \Delta H_{PCV}(t, t+Tc) = \Delta H_{set}(t-Tc, t) + \Delta H_{PCV}(t) & \text{valve head loss control (HL)} \end{array} \tag{3}$$

The argument $(t-Tc, t)$ represents the average values of readings (usually sampled with higher frequency by flow meters) from $t-Tc$ to t, while the argument $(t, t+Tc)$ of the control variables indicates that the new value will be reached during the next time step Tc starting from the initial value at time t.

The last two control strategies of PCVs are related to hydraulic variables (K_{ml} or ΔH_{PCV}), while the first is related to the mechanical variable (α) modifying the hydraulic resistance of the valve.

The SD strategy relates to the direct prediction of the shutter opening degree α based on ΔH_{set}. This approach requires the calibration of k_c that is the proportional gain of the control function in order to transform the degree into pressure variation at the control nodes (e.g., Campisano et al. 2012). The calibration of k_c should aim at minimizing the mismatching between the target pressure and the pressure simulated by the WDN hydraulic model at the control node. Nonetheless, the main drawback of the SD strategy is that k_c is not dimensionless and depends on the current WDN hydraulic behaviour. In fact, k_c should be proportional to $Q_{PCV}{}^{-2}$, as can be obtained by comparing the first and second Equations (3), although it is kept constant over time.

In order to overcome such drawback, the second control strategy named 'RES' in Equation (3) accounts for the variation of valve hydraulic resistance K_{ml} in Tc that is computed by means of ΔH_{set} and a flow measurement at valve (Q_{PCV}). Indeed, the measurement of the flow rate through the PCV allows transforming ΔH_{set} in a hydraulic resistance value. $\Delta H_{set}(t-Tc, t)$ and $Q_{PCV}(t-Tc, t)$ represent the average values of readings from $t-Tc$ to t, while the control variable K_{ml} $(t, t+Tc)$ indicates the new resistance to be reached during the next time step Tc starting from $K_{ml}(t)$. Depending on the peculiar valve curve, the target value $K_{ml}(t, t+Tc)$ permits achieving the target opening degree (α).

As mentioned above, Creaco & Franchini (2013) also proposed a control algorithm that uses the water discharge in the pipe fitted with the PCV. In that work, a correction factor of the valve head loss coefficient ξ was introduced in order to overcome the main hypotheses that the discharge through the PCV is uniform, constant in time and independent of pressure head at the downstream network. Nonetheless, that factor still needs calibration depending on the average daily demand. Actually, the second Equation (3) does not require such a correction factor because ΔH_{set} and Q_{PCV} represent the average of readings from $t-Tc$ to t, thus integrating actual WDN hydraulic behaviour over the last time step Tc accounting for actual water demand of the controlled areas, including also pressure-dependent background leakages. Accordingly, the RES control strategy is more robust in the face of all uncertainties surrounding the WDN model and demand patterns that are used for calibrating other correction factors.

For the sake of completeness, Equation (4) reports the control transfer functions to modulate the valve opening degree α based on the target valve hydraulic resistance K_{ml} $(t, t+Tc)$, as can be obtained considering the general Equation (1) and the power law in Equation (2):

$$\alpha(t, t+Tc) = 10^{\frac{k_2 - \log[2gA^2_{\max}(K_{ml}(t,t+Tc)+K_{ml-min})]}{2+k_1}} \tag{4}$$

It can be derived from Equations (1) and (2), assuming that the current cross-sectional area of the valve is $A = \alpha A_{max}$, with A_{max} the cross-sectional area of the fully open valve.

The third case (HL) assumes the PCV head loss (ΔH_{PCV}) as a control variable based on the idea of regulating from t to $t+Tc$ the PCV head loss according to the readings of ΔH_{set}, from $t-Tc$ to t, starting from $\Delta H_{set}(t)$, e.g., using the measurement of the PCV head loss by means of a differential pressure measurement.

In HL strategy, the simulation model imposes during the next Tc the predicted head loss (see third Equation (3)), instead of the valve resistance for the predicted α (see first Equation (3)) in the case of SD or directly the valve resistance (see second Equation (3)) in the case of RES. In this case, it is not possible to use the valve curve (e.g., Equation (2) or Figure 1) because no flow measurement is assumed to be available to compute the valve hydraulic resistance. However, if an estimate or a measurement of Q_{PCV} is available, the estimate of the shutter degree α_e can be computed from Equation (4):

$$\alpha_e = 10^{\frac{k_2 - \log\left[2gA_{\max}^2\left(\Delta H_{PCV}(t, t+Tc)/Q_e^2 + K_{ml-min}\right)\right]}{2+k_1}} \quad (5)$$

where Q_e is the flow estimate that might descend from flow data recorded in the previous days at the same time, bearing in mind that the control variable remains the PCV head loss ΔH_{PCV}. In fact, the HL strategy does not require any calibration and the shutter degree α_e in Equation (5) allows estimating the initial shutter velocity, although it is not strictly required, as discussed in the following.

Major companies producing PCVs agree that the needle valves are likely to be the most appropriate for fine regulation. In fact, they are conceived to avoid cavitation, fast mechanical wearing and/or need of periodical recalibration. These valves generally have a proper shutter profile that helps minimize flow turbulence. However, it is worth noting that these conditions are assumed under steady flow conditions, while little knowledge exists on valves operating under unsteady flow conditions (Brunone & Morelli 1999; Prescott & Ulanicki 2008; Meniconi *et al.* 2015) generated by frequent shutter opening–closing cycles. The adjustment of valve shutter degree is achieved accounting for a mechanical constraint related to the maximum velocity of the shutter, $v_{max\text{-}\alpha}$, $[\Delta\alpha \cdot s^{-1}]$ (Creaco & Franchini 2013). This fact is very important when modelling the actual behaviour of the RRTC PCVs because it might modify the valve performance with respect to pressure control capability, as will be shown in the case studies. In addition, the constraint on maximum shutter velocity avoids unsteady flow instabilities thus limiting the adjustment of the valve when sudden variations of pressure at the *critical node* occur. The product of Tc and $v_{max\text{-}\alpha}$, gives the maximum displacement, $\Delta\alpha$, of the shutter opening degree during the regulation time step.

Such remarks hint that the easiest algorithm to drive the shutter movement in HL control strategy consists of moving the shutter with the maximum velocity allowed to avoid unsteady flow conditions (i.e., $v_{max\text{-}\alpha}$) or considering the estimate of Equation (5) to get an estimate of the shutter velocity, until the target value of ΔH_{PCV} is observed across the valve. Indeed, pressure data loggers have sampling rates of a few samples per second, allowing differential pressure measurement during the shutter adjustment.

If the target ΔH_{PCV} is reached before $(t + Tc)$, the shutter stops and the new target value of ΔH_{PCV} is estimated in the next regulation time step. If the target ΔH_{PCV} is not reached at $(t + Tc)$, the target value of ΔH_{PCV} in the next control time step is estimated based on current ΔH_{PCV} $(t + Tc)$ (as obtained from the maximum allowed shutter movement) and ΔH_{set}, according to the last Equation (3).

It is worth noting that all strategies in Equation (3) account for actual WDN hydraulic behaviour in terms of readings of ΔH_{set} and/or Q_{PCV} from $t - Tc$ to t, which are likely affected measurement errors. Thus, in field applications, the stream of data coming from sensors has to be pre-processed using a data-modelling technique aimed at returning the most representative value of the average system behaviour over the last step Tc.

REMARKS ON RELIABILITY AND STABILITY OF THE SD, RES AND HL STRATEGIES

As stated, the SD, RES and HL strategies differ for control variables and required measurements at the valve, as reported in Table 1.

The SD case is not reliable nor optimal independently on the selection Tc because the variation of Q_{PCV} in Tc asks for a

Table 1 | Summary of control variables and measurements required for each strategy

Strategy	Control variable	Measurement
SD	Valve shutter degree	Not required
RES	Valve shutter degree	Flow at the valve
HL	Head loss at the valve	Differential pressure at the valve

varying gain parameter k_c, which is not dimensionless and depends on $Q_{PCV}{}^{-2}$, as theoretically demonstrated above. In other words, the adjustment of α, the control variable of SD, produces a head loss variation at the valve ΔH_{PCV} $(t+Tc) - \Delta H_{PCV}$ (t) due to Q_{PCV} $(t+Tc) - Q_{PCV}$ (t) which is not well predicted. In fact, bearing in mind that k_c is kept constant (although it should depend on $Q_{PCV}{}^{-2}$) and that its prediction is based on ΔH_{PCV} $(t+Tc) - \Delta H_{PCV}$ (t) only, an over control or under control generally occurs depending on the value of k_c. A value of k_c higher or lower than the optimal one depending on $Q_{PRV}{}^{-2}$ $(t+Tc)$ causes the over or under control, meaning that the adjustment of α will cause a larger or lower value of ΔH_{PCV} $(t+Tc) - \Delta H_{PCV}$ (t) with respect to that predicted with the first formulation in Equation (3) and this can produce instabilities.

This fact does not occur for the RES method because the measure of Q_{PCV} (t) allows predicting a sort of varying k_c. In fact, Q_{PCV} (t) surrogates Q_{PCV} $(t+Tc)$ because they are generally close if Tc is selected properly considering the specific hydraulic system.

The HL method is also stable because the prediction of the head loss variation at the valve ΔH_{PCV} $(t+Tc) - \Delta H_{PCV}$ (t), which is equal to the pressure variation with respect to the target value at the critical node, is directly controlled during Tc. In fact, the control variable is the head loss at the valve, measuring the differential pressure during the adjustment while moving the shutter at the maximum velocity allowed, i.e., reaching the new valve head loss that is required by the prediction.

The analyses of the following case studies will clearly demonstrate such remarks about the stability of the three methodologies.

It is worth noting that the non-linear relationship between ξ and α in Equation (2) is expected to have a larger impact on the stability of the SD method than on the other two methods. In fact, the SD method directly estimates the control variable α using a linearized approach, although the corresponding minor head loss (and ξ) is non-linear in α; this fact likely results in oscillations of pressure at the controlled node. On the contrary, the RES method effectively reduces the impacts of such non-linearity by translating the desired value of K_{ml} into the appropriate value of α, accounting for $Q_{PCV}{}^{-2}$. In the HL approach, α derives from either applying the maximum allowed shutter velocity (i.e., $v_{max\text{-}\alpha}$) until the desired value of ΔH_{PCV} is reached or from using Equation (5) (if the estimate Q_e is available) which follows the non-linear expression of $\xi(\alpha)$.

Considering now an abnormal variation of Q_{PCV} during Tc, the adjustment α of the RES method cannot detect the consequent abnormal variation of the head loss at the valve, which will propagate into the hydraulic system. In contrast, since the control variable for the head loss method is the head loss at the valve, abnormal variations of Q_{PCV} over Tc will be detected during the adjustment. Therefore, HL will guarantee that the adjustment predicted by the differential pressure with respect to the target at the critical node will not change also if an abnormal variation of flow should occur during Tc. Furthermore, controlling the head loss allows controlling any oscillation of pressure at the valve and allows constraining the maximum head loss variation in Tc, which are important features for practical applications in order to avoid the propagation of abnormal pressure oscillations into the hydraulic system.

Reliability under unsteady flow conditions

Unsteady flow conditions across the PCV are generated by the shutter movement (the basis of the pressure control) or can reach the PCV from other parts of the WDN. It has to be remarked that the propagation of unsteady flow conditions in pressurized networks serving real urban areas is limited by pipeline discontinuities like pipe joints, junctions, connections to private properties, each entailing a coefficient of transmission of the pressure wave fairly lower than 1. Accordingly, the shutter movement mostly generates the unsteady conditions at the PCV for any strategy (SD, RES and HL).

It can be argued that the strategy HL is more robust than SD and RES. In fact, in both SD and RES methods, the control variable is the valve shutter degree to be reached during the control time step Tc. The shutter movement continues over Tc irrespective of possible unsteady flow perturbations generating from the shutter movement and high variation of flow driven by customer water demands and leakages. In fact, it should be remembered that the valve adjustment does not affect directly the flow through it, but controls pressure in the WDN which generally does not affect customer water demands but only leakages in feedback.

The common expedient to limit unsteady flow conditions due to the shutter movement in SD, RES and HL strategies is to set the value of the maximum shutter velocity $v_{max\text{-}\alpha}$.

It is worth noting that shutter corrections span over minutes, constrained by $v_{max\text{-}\alpha}$, thus being far from an abrupt movement that is described in unsteady flow theory; moreover, the same theory allows calculation of the theoretical over-pressure or under-pressure assuming no wave reflection from the network.

HL strategy allows controlling the effect of a high variation of flow across the valve due to a high variation of customer water demands and/or leakages, although this kind of phenomenon does not occur at the scale of a few minutes or seconds even for pipe bursts events. In fact, the high variation of the flow across the valve generates anomalies in the differential head loss (the control variable of HL), which can be faced in HL strategies, for example, stopping the control.

WDN SIMULATION MODEL

In order to simulate the operational behaviour of the RRTC PCVs, the above-mentioned regulation strategies have been integrated within the WDN extended period simulation (EPS) model within the WDNetXL system (Giustolisi et al. 2011). In particular, the generalized WDN (G-WDN) modelling was used here (Giustolisi et al. 2012):

$$\begin{cases} \mathbf{A}_{pp}(t)\mathbf{Q}_p(t) + \bar{\mathbf{A}}_{pn}\begin{bmatrix} \mathbf{H}_n(t) \\ \cdots \\ \Delta\mathbf{H}_0(t) \end{bmatrix} = -\mathbf{A}_{p0}\mathbf{H}_0(t-\Delta T) + \mathbf{H}_p^{pump}(t) \\ \bar{\mathbf{A}}_{np}\mathbf{Q}_p(t) - \begin{bmatrix} \dfrac{\mathbf{V}_n(\mathbf{H}_n(t), t)}{\Delta T} \\ \cdots \\ \dfrac{\mathbf{V}_0(\mathbf{H}_n(t), t)}{\Delta T} + \dfrac{\mathbf{\Omega}_0\Delta\mathbf{H}_0(t)}{\Delta T} \end{bmatrix} = \begin{bmatrix} \mathbf{0}_n \\ \cdots \\ \dfrac{\mathbf{V}_0^{ext}(t)}{\Delta T} \end{bmatrix} \end{cases} \tag{6}$$

where t is the time reference of each EPS snapshot; ΔT is the time window of each snapshot; $\mathbf{Q}_p$ is the $[n_p, 1]$ column vector of unknown pipe flow rates; $\mathbf{H}_n$ is the $[n_n, 1]$ column vector of unknown nodal heads; $\Delta\mathbf{H}_0$ is the $[n_0, 1]$ column vector of unknown tank level variations; $\mathbf{H}_0^{ini}(t) = \mathbf{H}_0(t-\Delta T) = [n_0, 1]$ column vector of initial tank heads; $\mathbf{H}_p^{pump}$ is the $[n_p, 1]$ column vector of static heads of pump systems installed along pipes (if any) varying over time t in variable speed factor cases or when pumps are controlled by states or by tank levels; $\mathbf{V}_n$ is the $[n_n, 1]$ column vector of outlet volumes of each snapshot lumped in the nodes; $\mathbf{V}_0$ is the $[n_0, 1]$ column vector of volumes lumped in the tank nodes; $\mathbf{\Omega}_0$ is the $[n_0, 1]$ column vector of cross-sectional area of tanks (generally assumed constant); $\mathbf{V}_0^{ext}$ is the $[n_0, 1]$ column vector of volumes feeding tanks from external pipes to the hydraulic system; ΔT is the time interval of the real hydraulic system snapshot; $\bar{\mathbf{A}}_{pn} = [\mathbf{A}_{pn} \,\vdots\, \mathbf{A}_{p0}]$ is the general topological matrix of size $[n_p, n_n + n_0]$; $\mathbf{A}_{pp}\mathbf{Q}_p$ is the $[n_p, 1]$ column vector of pipe head losses containing the terms related to internal head loss of pump systems, minor head losses and evenly distributed head losses. $\mathbf{V}_n$ is null for demand-driven analysis (Giustolisi & Walski 2012; Giustolisi et al. 2012), while for the pressure-driven analysis (PDA) performed in the presented case studies, the component of nodal demands related to background leakages and customers (Giustolisi & Walski 2012) is used.

Inside the G-WDN model, background leakages' modelling is performed as in Giustolisi et al. (2008), while the customer demands are modelled as in Wagner et al. (1988).

It is worth noting that from a technical standpoint the assessment of leakages is relevant and mandatory for the analysis of scenarios involving pressure control by means of PCVs (Giustolisi et al. 2015). In fact, the behaviour of the valves is influenced by the pressure-dependent background leakages as they represent a surplus flow through the valve, which was furthermore demonstrated to be beneficial for the stability of valve control (Ulanicki & Skworcow 2014).

In addition, the assessment of the total volume of leakages over time allows actually calculating the effect of various scenarios of PCV locations. The benefit of leakage reduction could be wrongly assessed if based on approaches that surrogate the actual WDN behaviour, e.g., based on demand-driven analysis and assessment of pressures reduction.

Each snapshot at time t in Equation (6) has been arranged to have one mass balance equation for each tank, i.e., variable level water storage node along with the unknowns, $\Delta\mathbf{H}_0(t) = \mathbf{H}_0(t) - \mathbf{H}_0^{ini}(t) = \mathbf{H}_0(t) - \mathbf{H}_0(t-\Delta T)$, representing the variation of tank heads (levels) during ΔT.

The reason for using the G-WDN model for EPS relates to the effectiveness of the mass balance simulation at tank nodes (as in Oppegård WDN) in order to predict the level variations, i.e., the local mass balance (Giustolisi *et al.* 2012).

The above-mentioned WDN model is of primary importance for planning RRTC PCVs as well as for supporting their real-time operation. Planning a RRTC PCV encompasses its location, the identification of the control node and the delimitation of the controlled area (i.e., by closing gate valves). Such analysis exploits the assumption that the pressure set point at the control node is reached instantaneously because its main objective is to achieve the highest leakage reduction comparing alternative PCV locations, irrespective of the real-time control strategy.

Once the optimal location of the PCV is identified, the operational simulation of RRTC PCVs, which is undertaken in this work, analyses alternative real-time control strategies and is performed subdividing the simulation intervals ΔT into time steps equal to Tc. To this end, the customer-required demand is linearized over each ΔT and PCV resistances or head loss to be included into the model are predicted by means of Equation (3). In more detail, the vector $\mathbf{A}_{pp}\mathbf{Q}_p$ includes also the head losses at PCVs computed at each time step equal to Tc.

APULIAN CASE STUDY

The EPS of 1 day (24 hours) of the Apulian WDN is performed here. The Apulian network is composed of 34 pipes, 24 nodes and one reservoir (Giustolisi *et al.* 2015) (Figure 2). A PCV is added on pipe P34 close to the reservoir and the target pressure values is 13m at node N13.

The parameters of a background leakage model (Giustolisi *et al.* 2008) were estimated to get a leakage rate of about 26% of total inlet volume, under the above-mentioned pressure control configuration.

The EPS was performed using PDA, $Tc = 5$ min and a daily nodal demand pattern, i.e., a sequence of 24 snapshots corresponding to each hour of the daily demand pattern (see Giustolisi *et al.* 2015). Then, the EPS generates a sequence of 12 snapshots in each hour corresponding to Tc. For the PCV, the three control functions listed in Equation (3) were used: resistance (RES), head loss (HL) and shutter

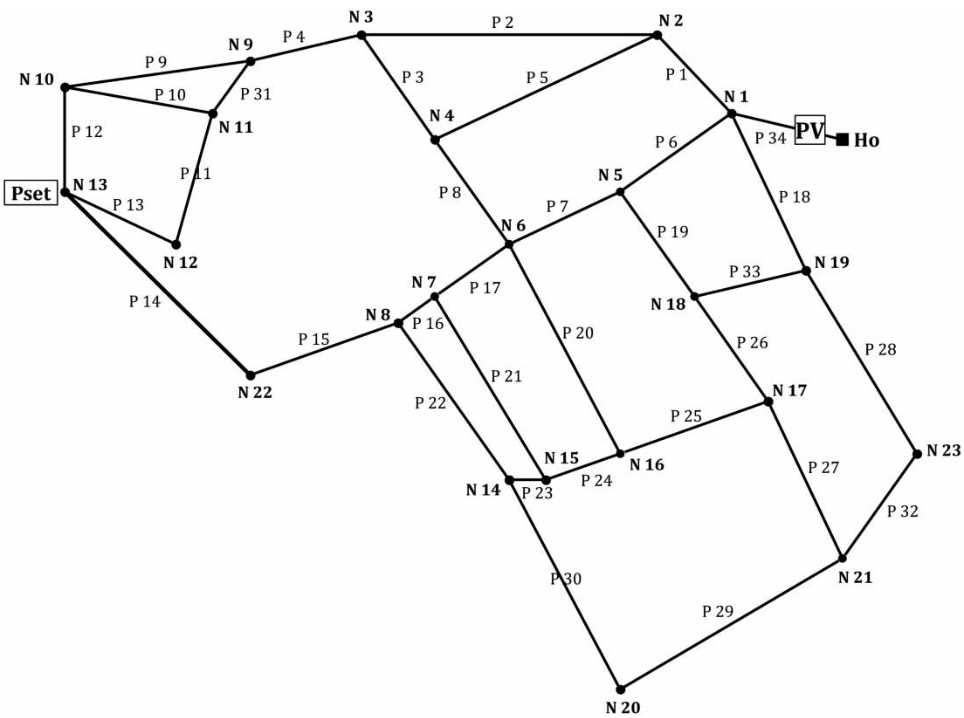

Figure 2 | Layout of Apulian WDN with PCV in P34 and control node N13.

opening degree (SD). When using the SD control strategy k_c is set equal to {0.05, 0.01 and 0.1} in order to show the effect of the gain factor. Finally, the effect of the maximum displacement of the shutter in Tc was investigated. Therefore, $\Delta\alpha$ was not used during the first set of simulations and it was set equal to 0.03 during the second set of simulations, i.e., corresponding to a shutter velocity $v_{max\text{-}\alpha} = 0.0001\text{s}^{-1}$ which is assumed to be conservative to avoid possible unsteady flow conditions.

Figures 3 and 4 report the five simulations using RES, HL and SD using $k_c = \{0.01; 0.1; 0.05\}$ in the case of unconstrained $\Delta\alpha$. Figure 3 shows the instability of the PCV through the abrupt opening of the shutter in the case of $k_c = \{0.1; 0.05\}$, while for $k_c = 0.01$ the instability does not occur. This fact demonstrates the need for calibrating k_c, which is a critical task because a too high value of k_c could generate over-controlling of some hydraulic conditions (i.e., high variation of the hydraulic network behaviour, for instance, due to high demand variation), while a low value of k_c makes the pressure control inefficient, although more stable. Furthermore, it is arguable that in complex situations with several RRTC PCVs and a variable behaviour of the hydraulic system, the calibration of k_c is a difficult, if not impossible, task. This is related to the fact that k_c is a dimensional variable depending on flow rate of the PCV, as evident from comparing the first and third Equations (3).

Figure 4 shows the above-mentioned instabilities through the abrupt change of pressure over time and, in addition, it shows that RES and HL strategies outperform

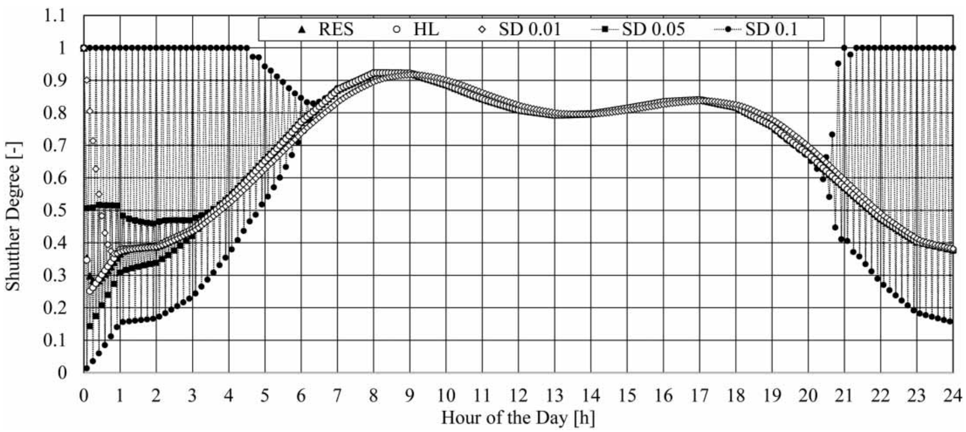

Figure 3 | Shutter degree (α) over time, $\alpha = 1$ for $t = 0$. Unconstrained maximum displacement $\Delta\alpha$.

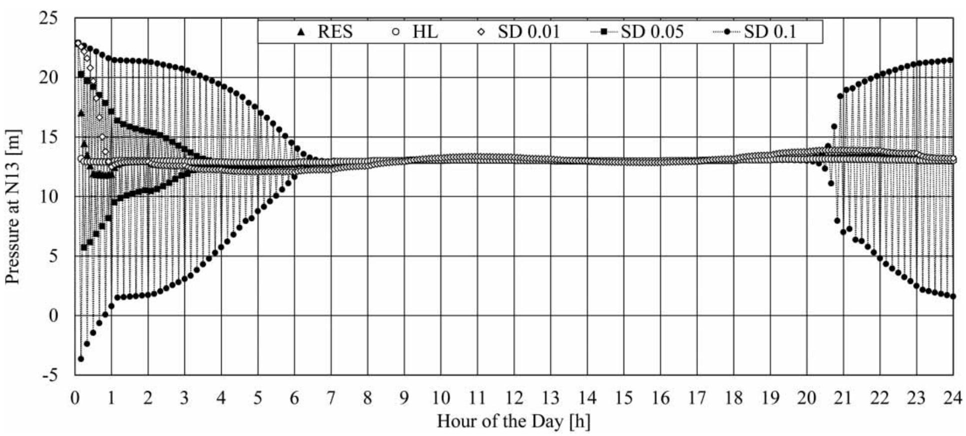

Figure 4 | Pressure over time at the controlling node (N13), target pressure 13m. Unconstrained maximum displacement $\Delta\alpha$.

the SD strategy. In fact, for $k_c = 0.01$, the pressure slightly oscillates around the target value of 13m. Finally, the HL strategy seems to outperform the RES strategy looking at the pressures in the first hour in Figure 4, where in the RES case a small oscillation of the pressure before reaching the target value is shown.

Figures 5 and 6 report the five simulations using RES, HL and SD using $kc = \{0.01; 0.1; 0.05\}$ in the case of $\Delta\alpha = 0.03$. Figure 5 shows again the instability of the PCV through a slight oscillation of the shutter in the case of $k_c = \{0.1; 0.05\}$, while for $k_c = 0.01$ the instability does not occur. The instability is lower than in the previous simulations because the constraint on the maximum displacement in Tc, $\Delta\alpha = 0.03$, allows the limitation of the over-controlling as discussed above. In any case, the selection of $\Delta\alpha$ reduces the instabilities of the valve without removing the need of calibrating kc. In fact, Figure 6 shows the pressure oscillation that can be increased by the local unsteady flow due to the shutter instability. For the sake of clarity, in the middle of Figure 6 is reported a zoom of the larger-diagram which is relative to the pressure range from 12 to 14 m.

Finally, the comparison between Figures 3 and 5 demonstrates that RES is slightly influenced by the constraint on $\Delta\alpha$ in Tc (showing no oscillation of the shutter degree in the first 2 hours), while HL is not at all influenced by $\Delta\alpha$ because it is already effective as a control strategy.

Table 2 compares the above-mentioned control strategies in terms of average absolute deviation from the target pressure at control node N13. Time steps from 2.00 to 23.55 are considered only in order to neglect the effect of initially open valve.

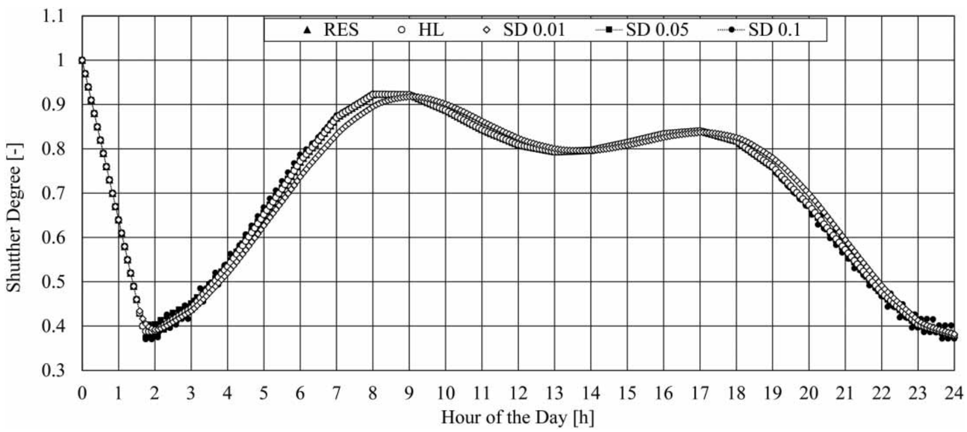

Figure 5 | Shutter degree (α) over time, $\alpha = 1$ for $t = 0$. Maximum displacement $\Delta\alpha(Tc) = 0.03$.

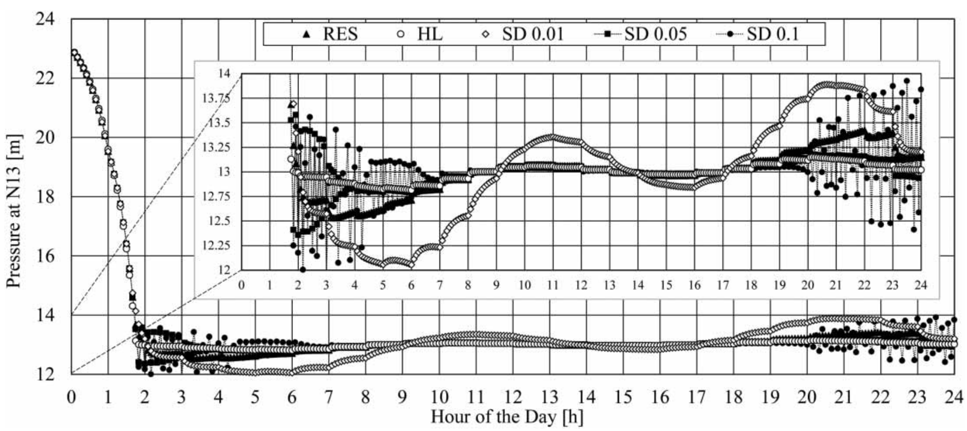

Figure 6 | Pressure over time at the controlling node (N13), target pressure 13m. Maximum displacement $\Delta\alpha(Tc) = 0.03$.

Table 2 | Absolute average deviation [m] from the target pressure set at node N13 in the Apulian case study

	RES	HL	SD ($k_c = 0.01$)	SD ($k_c = 0.05$)	SD ($k_c = 0.1$)
Maximum displacement $\Delta\alpha(Tc) = 0.03$	0.16	0.07	0.43	0.11	0.15
Unconstrained maximum displacement $\Delta\alpha$	0.16	0.07	0.43	0.19	2.45

OPPEGÅRD CASE STUDY

The second case study refers to a portion of the WDN serving the northwest area of Oppegård municipality (Norway). Oppegård is characterized by remarkable changes in elevation ranging from 40 m to 180 m a.s.l. (Figure 7). Due to firefighting requirements, a minimum pressure of 30 m has to be guaranteed everywhere in the system and, for this reason, diameters are oversized with respect to normal water supply scenario. This, in turn, results in roughly invariant pressure regime over the day, irrespective of customers' water demand pattern. Pumping stations are operated to guarantee sufficient pressure in high elevation areas, while classic PCVs are installed in order to limit pressure excess in lower zones. The northwest area of Oppegård in the dashed box in Figure 7 is actually one such low elevation zone where nine PCVs control local pressure (indicated as white triangles in the same figure). Due to the negligible effect of customers' demand on pressure regime, the target pressure values at downstream nodes of such PCVs do not change over an operating cycle, and the water utility set such values between 35 m and 70 m depending on valve location.

As part of the InnoWatING project, Oppegård municipality was interested in improving such pressure control, mainly aimed at reducing leakages. Thus, a hydraulic model for Oppegård WDN was preliminarily built and calibrated using the WDNetXL system. The parameters of a background leakage model (Giustolisi *et al.* 2008) were estimated to get a leakage rate of about 28% of total inlet volume in Oppegård, which resulted in about 900 m^3 of water lost per day in the northwest (Berardi *et al.* 2015). This model was used to plan alternative pressure control scenarios involving both some of the existing PCVs and new RRTC PCVs. Figure 8 reports one of such planning scenarios consisting of seven PCVs, thus two less than the nine currently installed; three are new RRTC-PCVs (black triangles) and four are classic PCVs already installed (white triangles). Both locations and P_{target} values of the existing classic PCVs remain unchanged with respect to the original WDN configuration. The P_{target} of the RRTC PCVs were set as 35 m where the location of the critical node in the controlled area possibly changes over time (i.e., at nodes N2186 and N2028), otherwise P_{target} equals 30 m (i.e., node N1849).

In Figure 8, 'P_{set}' nodes are the critical nodes controlled by the relevant RRTC PCVs. The controllability of such

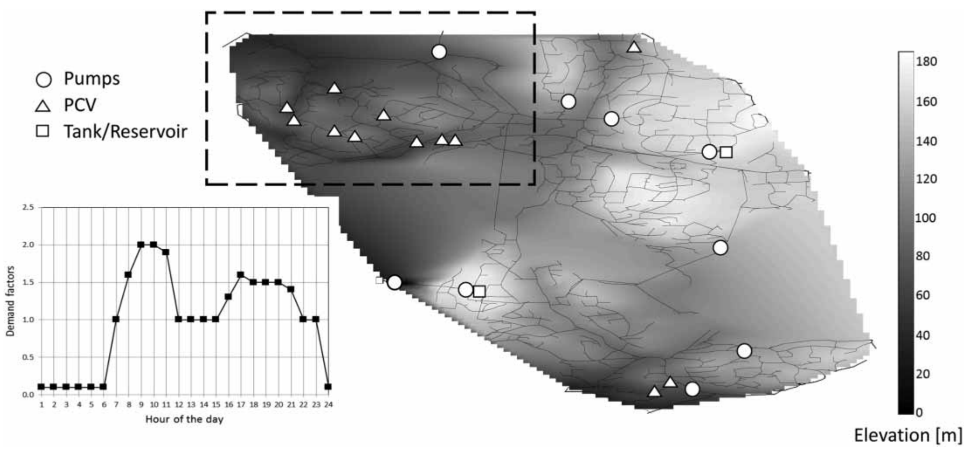

Figure 7 | Oppegård WDN layout, elevation and demand pattern for the analysed district.

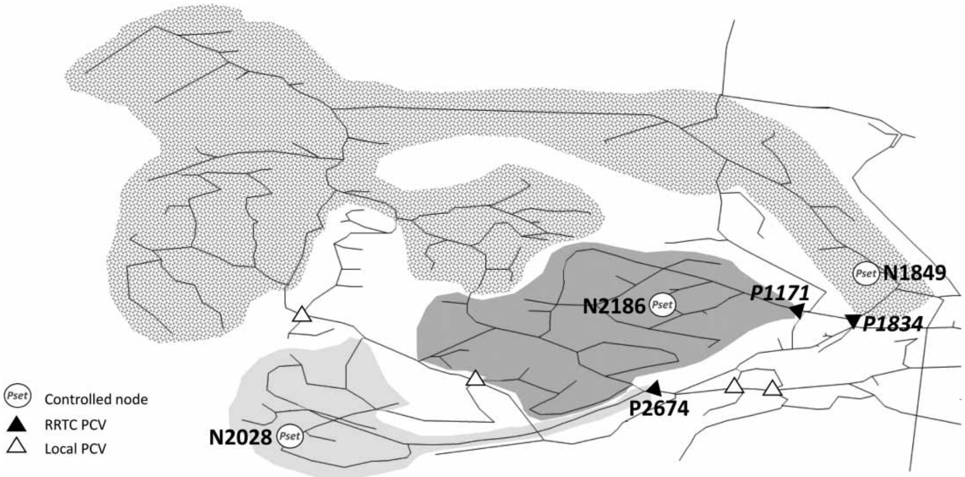

Figure 8 | Planning scenario with four classic PCV and three RRTC PCVs.

nodes from the RRTC PCVs location is guaranteed by closing some existing gate valves, resulting in three pressure control areas (shaded in Figure 8). From a WDN management perspective, this solution permits reduction of current leakages by 27% of the water volume lost from northwest Oppegård (Berardi *et al.* 2015). It is worth noting that the hydraulic simulation for planning purposes in Berardi *et al.* (2015) assumed the instantaneous reaching of the P_{target} values, thus neglecting the PCV behaviour within each simulation step, which is analysed herein.

Similarly to the Apulian case study, the PDA EPS was performed here with $Tc = 5$ minutes and daily patterns as reported in Figure 7. Therefore, two sets of five simulations using RES, HL and SD with $k_c = \{0.001; 0.0028; 0.0036\}$ were performed, i.e., not constraining the maximum displacement or using $\Delta\alpha = 0.03$. Characteristics of the PCVs do not change among all simulations.

Figure 9 reports the shutter opening degree diagrams over time of the three RRTC PCVs with unconstrained maximum displacement; the diagrams confirm that a

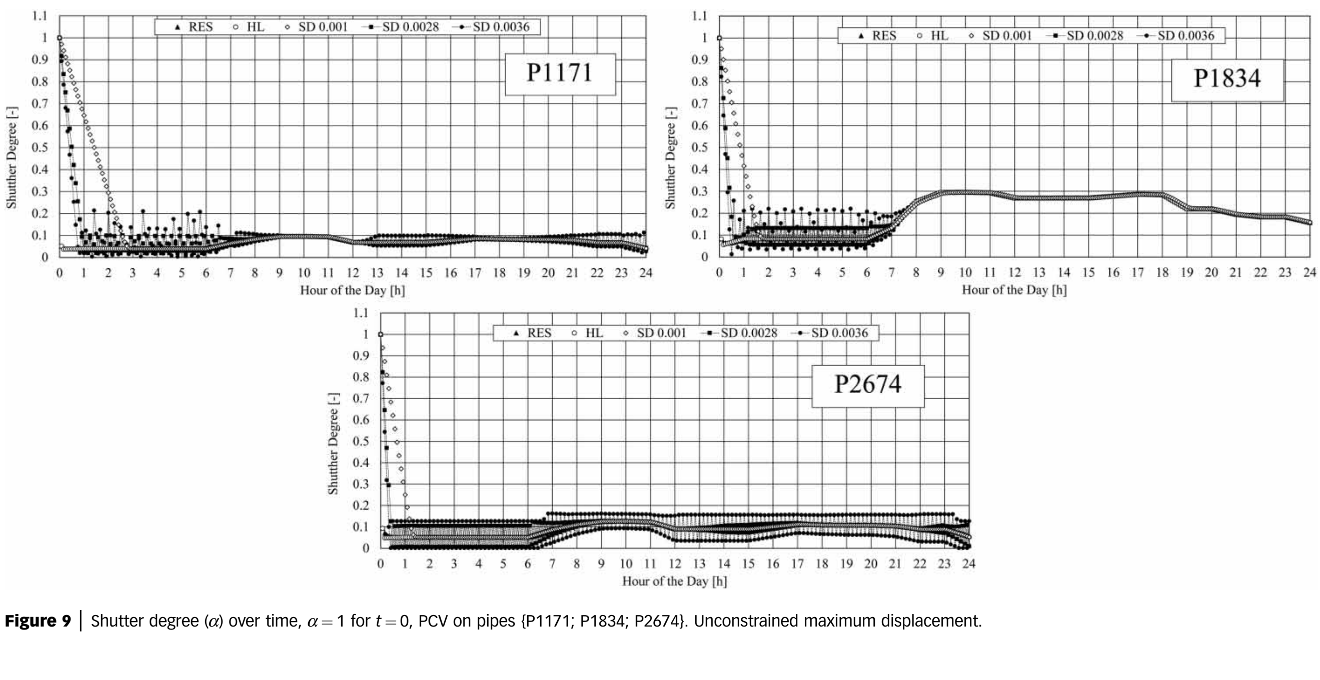

Figure 9 | Shutter degree (α) over time, $\alpha = 1$ for $t = 0$, PCV on pipes {P1171; P1834; P2674}. Unconstrained maximum displacement.

wrong choice of the factor k_c causes the instability of the control due to the over-controlling during Tc, while the RES and HL strategies outperform the SD strategy, similarly to the Apulian case study. Figure 10 shows the pressure diagrams at controlling nodes of the three RRTC PCVs (on the left) and a zoom in those three pressure diagrams (on the right) in order to compare the effectiveness of the three regulation strategies. The left-side three diagrams confirm the information of Figure 9. SD using $k_c = \{0.0028;\ 0.0036\}$ is not stable, while $k_c = 0.001$ seems to be effective. It is worth noting that in the case of the Apulian network the value to avoid instabilities was one order of magnitude larger ($k_c = 0.01$).

This fact clarifies that the calibration value depends on the specific network through the hydraulic state variables because the gain factor is not dimensionless. The right-side three diagrams show that the HL strategy always outperforms the others and that the SD strategy (with $k_c = 0.001$) slightly outperforms the RES strategy. In particular, from 6:00 to 12:00 a.m., the occurrence of demand pattern changes (see Figure 7), asking for a significant regulation of RRTC PCVs, highlights the different performance of the regulation strategies in adjusting the valves without over-controlling.

Figure 11 reports the shutter opening degree diagrams over time of the three RRTC PCVs assuming a maximum displacement $\Delta\alpha(Tc) = 0.03$; also in this case, the diagrams confirm that a wrong choice of the factor k_c causes the instability of the regulation due to the over-controlling, although the constraint on the maximum displacement $\Delta\alpha$ in Tc significantly limits the oscillations. RES and HL strategies outperform the SD strategy similarly to the Apulian

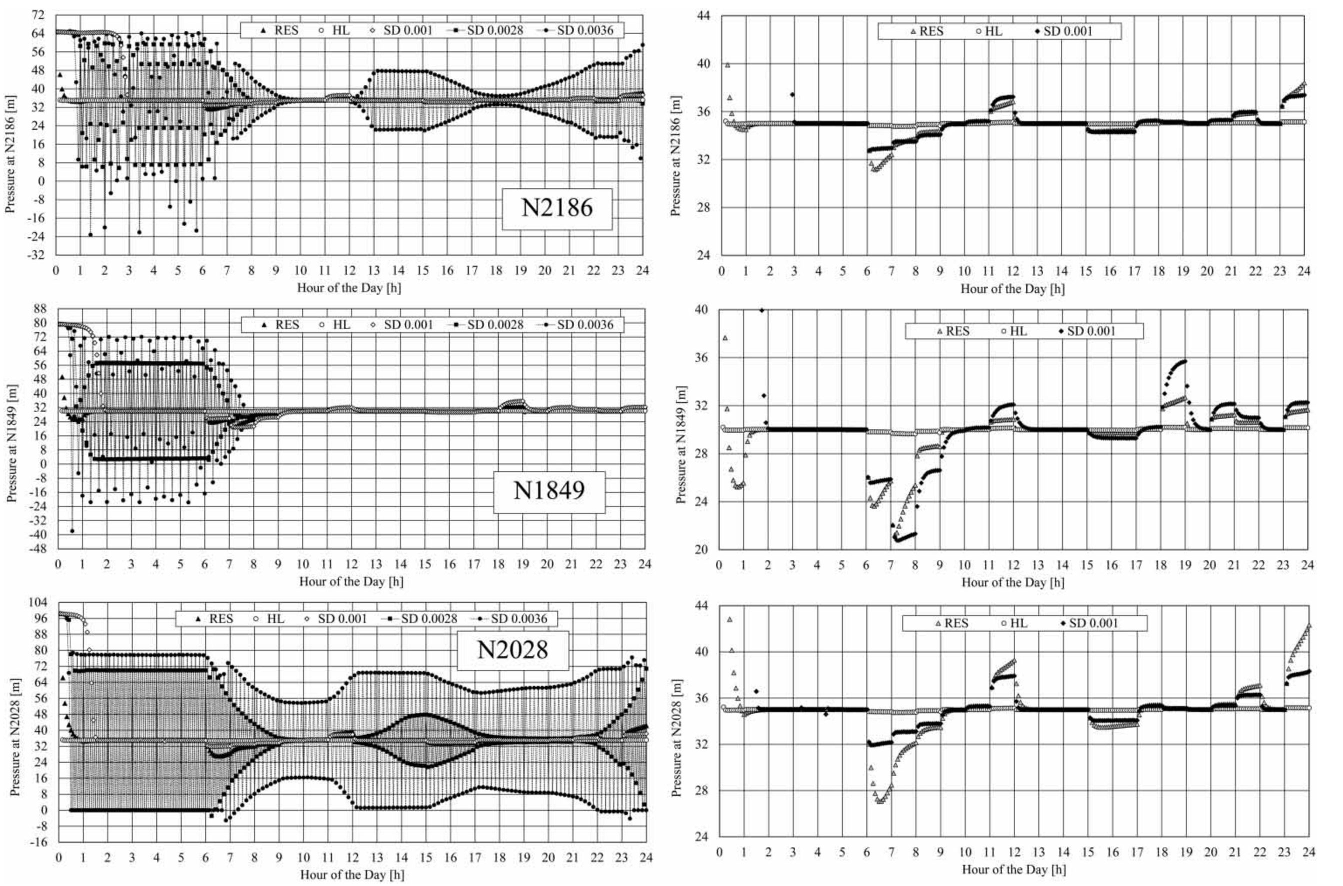

Figure 10 | Pressure over time at the controlling nodes {N2186; N1849; N2028}, target pressure {35, 30, 35} m and zooming of pressure over time. Unconstrained maximum displacement.

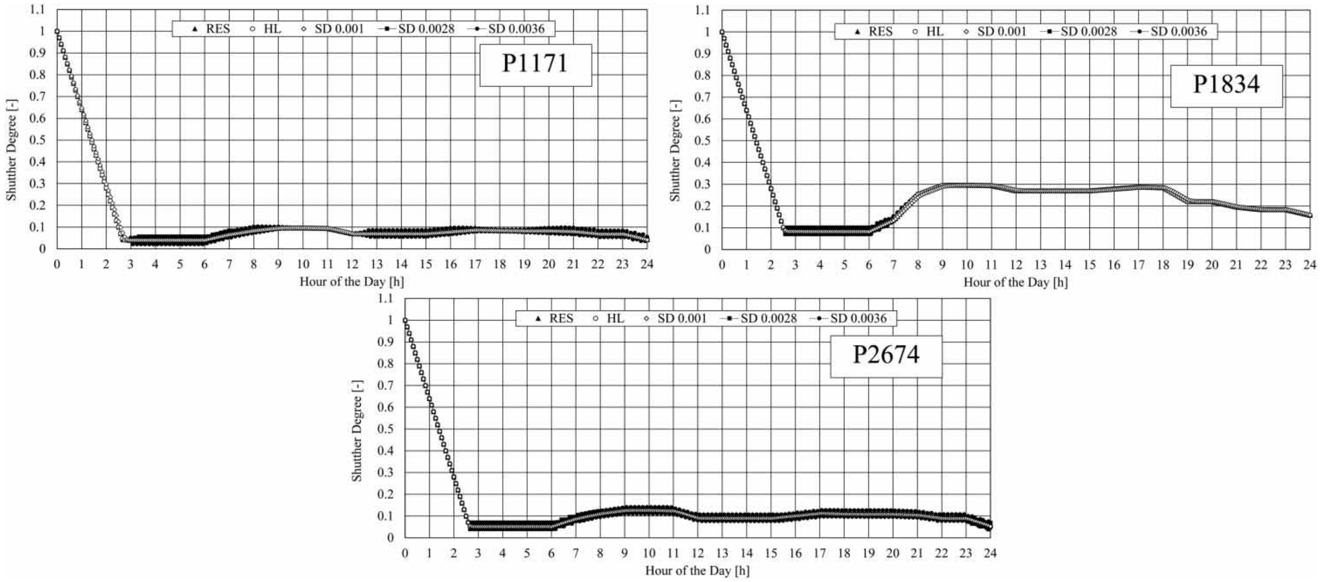

Figure 11 | Shutter degree (α) over time, $\alpha = 1$ for $t = 0$, PCV on pipes {P1171; P1834; P2674}. Maximum displacement $\Delta\alpha(Tc) = 0.03$.

case study and seem not to be influenced by the maximum displacement because their regulation is already efficient to avoid over-controlling.

Figure 12 shows the pressure diagrams of the three RRTC PCVs (on the left) and a zooming in those three pressure diagrams (on the right) when the constraint on maximum displacement $\Delta\alpha$ in Tc is set to 0.03. The left-side three diagrams confirm the information of Figure 11. SD using $k_c = \{0.0028;\ 0.0036\}$ is not stable, while $k_c = 0.001$ is effective. The right-side three diagrams shows that the HL strategy always outperforms the others and that the SD strategy (with $k_c = 0.001$) slightly outperforms the RES strategy.

Finally, the diagrams of Figure 12 demonstrate that the constraint on maximum displacement $\Delta\alpha = 0.03$ does not influence the RES, HL and SD (with calibrated gain factor) strategies. Therefore, it is useful to limit the oscillation of pressures in the case of SD with $k_c = \{0.0028;\ 0.0036\}$, i.e., the maximum displacement acts as a limit to the over-controlling but it is not a way to 'calibrate' or 'increase' the performance of the regulation strategy.

Table 3 compares the above-mentioned control strategies in terms of average absolute deviation from the target pressure at all control nodes. Time steps from 3.00 to 23.55 are considered only in order to neglect the effect of initially open valves.

For the sake of completeness, Figure 13 also shows that results obtained for 1-day EPS are consistent with those expected for 1-week EPS even for the unconstraint maximum displacement case. In more detail, due to the lack of real 1-week-long data in Oppegård, hourly demand patterns used to get results in Figure 13 are sampled from a uniform random distribution in the range of ±10% across the values of the first day.

OVERALL DISCUSSION ON REGULATION STRATEGIES

The two cases studies, Apulian and Oppegård, are very different and, for this reason, allow drawing some general conclusions about the three proposed regulation strategies.

First, it is possible to state that the shutter degree (SD) strategy is not very effective because the need to calibrate k_c makes it not reliable for significant changes of the hydraulic system behaviour. Indeed, the value of k_c depends on the network hydraulic status because it is not dimensionless, i.e., it depends on flow at the valve Q_{PCV}, which in turn depends

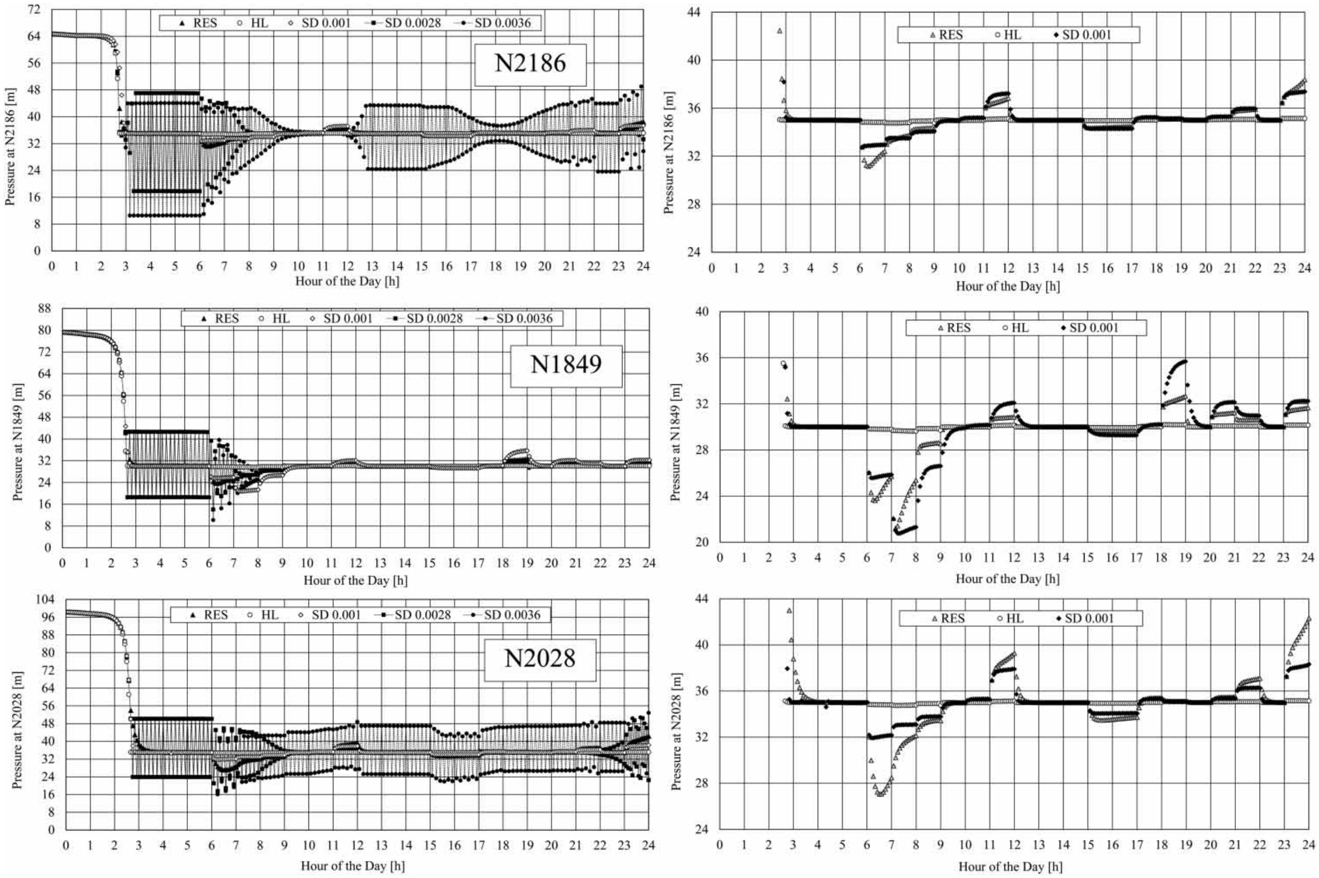

Figure 12 | Pressure over time at the controlling nodes {N2186; N1849; N2028}, target pressure {35, 30, 35} m and zooming of pressure over time. Maximum displacement $\Delta\alpha(Tc) = 0.03$.

Table 3 | Absolute average deviation [m] from the target pressure set at control nodes in the Oppegård case study

		RES	HL	SD ($k_c = 0.001$)	SD ($k_c = 0.0028$)	SD ($k_c = 0.0036$)
N2186	Maximum displacement $\Delta\alpha(Tc) = 0.03$	0.59	0.05	0.58	2.97	7.93
	Unconstrained maximum displacement $\Delta\alpha$	0.58	0.05	0.58	4.17	10.48
N1849	Maximum displacement $\Delta\alpha(Tc) = 0.03$	0.98	0.07	1.52	2.61	2.62
	Unconstrained maximum displacement $\Delta\alpha$	0.98	0.07	1.52	5.20	7.07
N2028	Maximum displacement $\Delta\alpha(Tc) = 0.03$	1.36	0.06	0.77	3.88	10.64
	Unconstrained maximum displacement $\Delta\alpha$	1.31	0.06	0.77	11.05	30.26

on delivered water, generally pressure-dependent leakages and required customer demand. In fact, the first and second Equations (3) show that k_c is proportional to $(Q_{PCV})^{-2}$. Clearly, the shutter degree strategy is cheaper because it does not require flow/pressure measurements at the valve.

The second statement is that the HL strategy outperforms all the other strategies and, in particular, the resistance (RES) strategy. The difference between the two strategies relates to the fact that, for HL the HL of the PCV needs to be adjusted during Tc using a differential pressure measurement across the valve (i.e., ΔH_{PCV}). While in the case of RES, the new shutter degree is computed after calculating the valve resistance to be reached during the next Tc based on the measurement of Q_{PCV} at the previous Tc. In both cases, a measurement of flow or differential pressure at the PCV is necessary; therefore, both strategies are more expensive

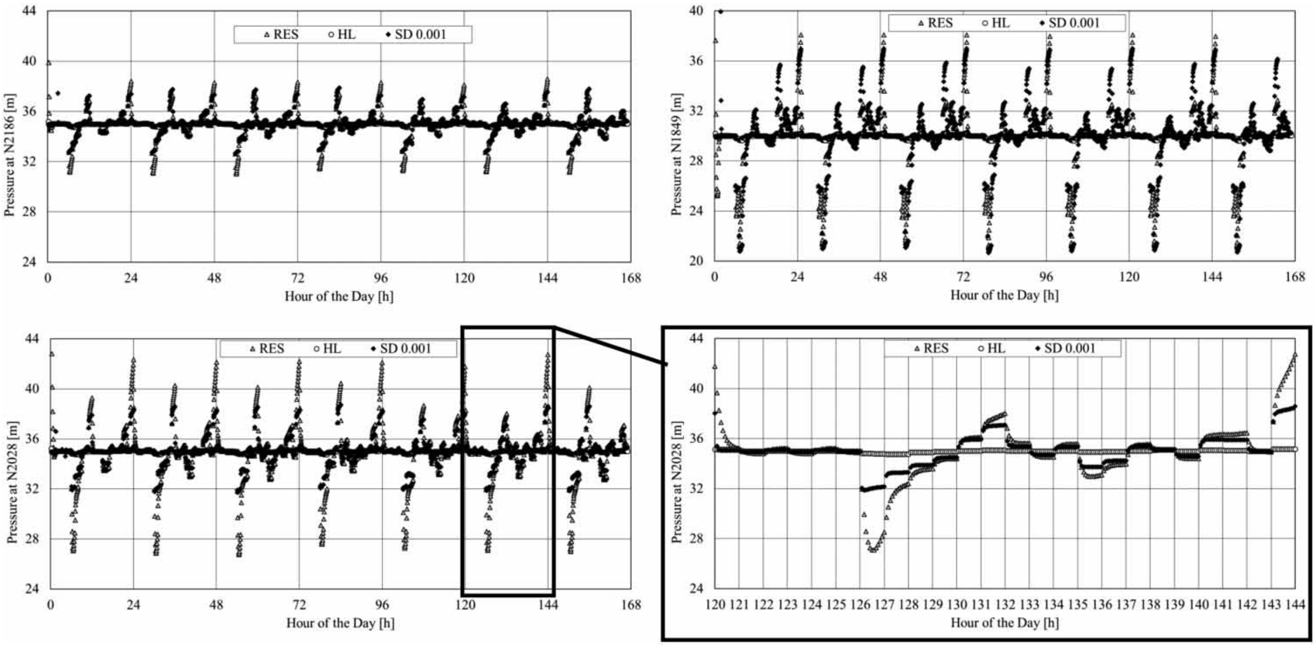

Figure 13 | Pressure over time at the controlling nodes {N2186; N1849; N2028}, target pressure {35, 30, 35} m. Unconstrained maximum displacement.

than the SD strategy. However, the extra cost of one more measurement should be justified by a much more reliable and effective control of pressures.

Furthermore, the HL outperforms RES because it involves one variable only at the previous Tc, i.e., the difference of pressure with respect to the target pressure at the controlling node, while RES involves also the flow rate at the valve raised at power two. Therefore, the RES prediction is influenced by two variables changing from $t - Tc$ to $t + Tc$, and one (i.e., Q_{PCV}) is quadratic and at the denominator, while the HL strategy prediction is influenced by one variable only (i.e., ΔH_{set}) at the previous Tc.

Finally, the tests performed using or not the constraint on the maximum shutter displacement ($\Delta\alpha$) in Tc, clarify that it acts as a constraint to over-controlling only, i.e., it makes more reliable the regulation, without a significant effect on the performance of the control. This fact excludes the possibility of using $\Delta\alpha$ in order to better calibrate the SD strategy.

It can be argued that it is possible to add gain factors very close to 1 also in the RES and HL strategies to further improve their performances, although they were not reported herein for the sake of clarity.

CONCLUDING REMARKS

The control of pressure in WDNs by means of PCVs is traditionally performed using mechanically regulated devices, controlling pressure at valve outlet nodes only. Nowadays, ICT permits such limitation to be overcome, allowing the real-time control of PCVs based on pressure metering at critical control nodes, even remote from PCV location. This, in turn, poses the need for effective and reliable strategies for electric regulation of pressure control devices to be implemented in PLC units that drive valve opening, in both locally and remotely real-time controlled PCVs. This contribution discusses and compares three main strategies related to the three regulation variables, namely, (RES) the valve resistance, K_{ml}; (HL) the valve head loss, ΔH_{PCV} and (SD) the shutter opening degree, α. The analysis also investigates the effects of constraining the maximum shutter displacements $\Delta\alpha$ on pressure control. RES and HL strategies outperform the SD strategy and seem not to be influenced by the maximum displacement because their regulation is already efficient to avoid over-controlling. Constraint on maximum shutter displacement helps the stability of the SD strategy although the calibration of the gain factor

k_c still remains a challenging (if not impossible) task since it is not dimensionless and depends on WDN hydraulic status.

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