Water Resources Management (2022) 36:2639–2652
https://doi.org/10.1007/s11269-022-03166-5

Performances of Pressure Reducing Valves in Variable Demand Conditions: Experimental Analysis and New Performance Parameters

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Received: 12 January 2022 / Accepted: 28 April 2022 / Published online: 23 May 2022

Abstract

Pressure Reducing Valves (PRV) play a critical role in Water Distribution Networks (WDN): they regulate pressure ensuring an efficient service to users and preventing damage to pipelines. In recent years, the attention of water utilities towards pressure management and leakage control led to the necessity of more flexible and responsive technologies that can guarantee a higher level of pressure control accuracy. Because of this the common performance parameters based on steady state conditions are no longer satisfactory to evaluate the effective behaviour of the devices when used in situations where demand can change. In the present paper the pressure control effectiveness of different types of PRV (electric actuated, pilot operated and direct acting) in variable demand conditions is discussed. The data used are from experimental tests, literature and field application. To assess valves' pressure control performance, the use of new parameters, which consider the peak of pressure reached during control operations and the accuracy of target pressure regulation, has been proposed. The use of these parameters allows the comparison between different type of valves giving to WDN managers a direct overview on the valves ability to regulate pressure under variable demand conditions.

Keywords PRV · Green Valve · DMA · Pressure Management · Variable demand

1 Introduction

Pressure management in water distribution networks is a crucial process that has drawn the attention of researchers in recent years. Complete reviews of the argument can be found in the work of Vicente et al. (2015) and in the more recent work of Doghri et al. (2020) where different modes of pressure regulation are compared in terms of leakage reduction and pressure oscillations. The main scope of pressure management is the optimization of the network to reduce leakages (Abd Rahman et al. 2018), reduce energy consumption (Mambretti and Orsi 2011; Pérez-Sánchez et al. 2017), increase plant resilience (Pagano

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et al. 2019) and improve the service for users. To follow these objectives, pressure reducing valves (PRV) are going to play a very critical role as explained in Dini and Asadi (2020) where the advantages of using installed valves regulation to improve network function is investigated. Generally control valves in WDN are used to modulate the pressure and flow rate on the basis of a target parameter that is usually a pressure upstream or downstream of the valve.

The use of PRV at the entrance of District Metered Areas (DMA) has been one of the preferred strategies adopted by water utility managers to effectively reduce water leakages and improve control and monitoring in the network (Alvisi and Franchini 2014; Gomes et al. 2012; Di Nardo and Di Natale 2011). The DMA approach proved to save a considerable amount of water in most applications. Nevertheless, the isolation of a branch of the network causes the loss of adaptability of the network. The use of remotely-operated devices can address the problem by creating a framework for dynamic DMA (Wright et al. 2014; Giudicianni et al. 2020) that can modulate the topology of the network on the basis of the real-time or quasi real-time working conditions monitored in the WDN. In this context, static set-point PRV are likely to be substituted with dynamic and tuneable devices that can answer to the new WDN performance requirements for pressure management (e.g. Remote Real Time Control (Adedeji et al. 2018 and Page et al. 2017) or District Metered Area (Giudicianni et al. 2020)). PRV are intended not simply as devices for the control of hydraulic parameters, but also as tools for the realization of improved plant management strategies able to enhance water security (Su et al. 2020 and Bajany et al. 2021) and equity (Gullotta et al. 2021).

Despite the fact that PRV are one of the main actors in water distribution network optimization and development, in the literature there is a lack of knowledge about their effective pressure regulation performance in operative conditions, i.e. with variable demand. Up to now the performances of PRV are usually based on parameters that consider the behaviour of the valve in steady state conditions. The present paper investigates the performances of different type of PRV focusing on their behaviour during demand variations.

Two new performance parameters are proposed to evaluate the accuracy of pressure regulation and they are used to compare the different models of PRV. In particular, the performances of the GreenValveSystem (GVS), an electric actuated control valve, and of direct acting and pilot operated PRV are considered and compared.

After the devices under consideration have been presented a discussion about the pressure control performances is shown. Then the experimental campaign is described and the results presented. In the end, an example of field application, in which the GVS and a pilot operated PRV are installed alternatively in the same node of a network is shown.

2 Material and Methods

Usually commercial control valves are characterized only by parameters based on steady flow states not considering the transient conditions that occur in real environments. Two performance parameters to characterize their behaviour in variable demand conditions are proposed in the present paper to improve the knowledge about different types of automatic control valves.

The study is based on experimental analyses that in part are taken from literature references (Prescott and Ulanicki 2003; Meniconi et al. 2017) and in part are performed by the authors. In the section *experimental setup*, the procedures of the tests performed are described.

In the following paragraphs the GVS and the standard PRV that are used in the study are briefly described, then the main parameters used in the discussion are introduced.

2.1 The GVS

The GVS is a new concept of electric actuated control valve, patented by the Politecnico di Milano (Malavasi 2013), that is able to recover part of the energy dissipated in the throttling process and reuse it to feed the actuator, the integrated system of sensors, the electronics, and the data transmission system. In this way, the device can work as a stand-alone monitoring and control station. The device is of interest in the context of water-distribution network revamping and optimization as described in (Ferrarese and Malavasi 2020). The valve was developed to assure pressure regulation with the addition of certain enabling functions that can help the transition towards smart WDN. Examples of these functions are: remote control of the valve position; real-time adjustment of the control parameters; real-time monitoring of pressure and flow rate; local energy supply. These characteristics allow the use of a single integrated device instead of a series of different devices that must be arranged to work together (e.g. pressure sensors, flow meter, communication system). Thanks to its functions and to the energy recovery capability, the GVS is an Internet of Things (IoT) system that can work without an electrical grid connection. Where an IoT system is intended as a network of physical objects embedded with sensors and connected to the internet to exchange data.

In the following the pressure control mechanism is described. The actuator, a Valpes VR with quarter turn operating time of 15 s, is controlled by a Programmable Logic Controller (PLC) installed in a control box. The logic of control is based on the pressure recorded by the pressure transducers integrated in the GVS. The control is a closed-loop in which the pressure is the control variable. The principal parameters that are used to define the control behaviour are:

- the dead-band, *db*, that defines the tolerance on the pressure; in the tests this parameter is kept equal to 0.15 bar in the laboratory experiments and to 0.2 in field.
- the target pressure, P_t, that is the pressure that the valve must regulate.

The following graph shows the valve's behaviour during a transient between two stable conditions. In Fig. 1 the main phases of valve operation are schematically indicated. An abrupt decrease of the downstream pressure is induced by increasing the demand downstream of the valve. After a short time, the valve begins to open increasing the downstream pressure until the target pressure (continuous line in Fig. 1) is again achieved.

Generally, PRV can show two states as defined in Prescott and Ulanicki (2003): a steady state when the valve does not move and pressure and flow rate are stable, and a transient state when the control valve moves and pressure and flow rate change. The transient state of the GVS is subdivided into four phases (Fig. 1):

Phase 1: the pressure begins changing but still remains inside the dead-band. The valve does not move. No command is sent to the actuator.

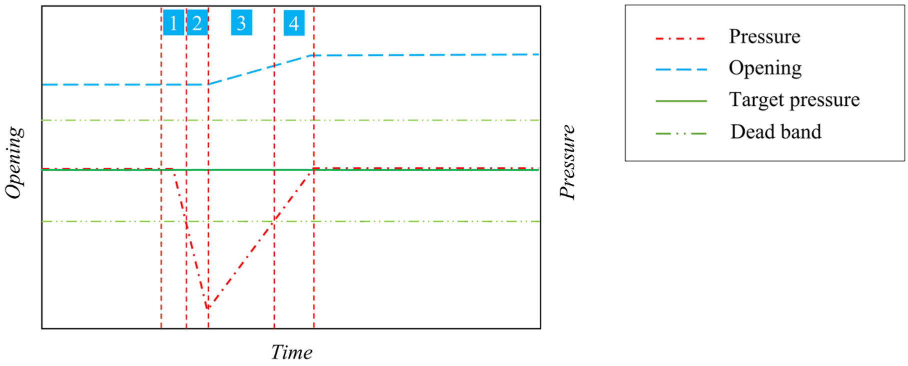

Fig. 1 Phases of downstream pressure control operation of GVS

Phase 2: the pressure exits the dead-band. The system shows a dead-time in which the valve is still not moving even though the pressure is out of the dead-band.
Phase 3: after a dead-time of the electronics' response, the system reacts by moving the valve until the pressure is restored to a value inside the dead-band.
Phase 4: the pressure achieves the set point and the actuator stops moving.

2.2 Pilot Operated PRV

Pilot operated PRV, otherwise referred to as Clayton type valves, are membrane pilot operated hydraulically-actuated valves. A description of the functioning of the device can be found in Khezzar et al. (1999) and Meniconi et al. (2017). The data shown in this paper is about a Cla-Val NGE 9001 DN100 from Prescott and Ulanicki (2003) and about a Cla-Val ECO 90–35 DN80 from Meniconi et al. (2017). Pilot operated valves assure an automatic behaviour based on the pressure balance between the pressure in the main valve chamber and the pressure imposed regulating the pilot valve that is installed in the control loop. The pressure to be controlled is manually set by changing the regulation of the pilot. The controlled pressure can be maintained constant in a certain range of flow rates.

2.3 Direct Acting PRV

Both pilot operated and direct acting PRV are hydraulically actuated and automatic control valves, but the latter are simpler and less expensive. The functioning mechanism is based on the balance between a spring whose compression can be tuned manually to set the target pressure, and the direct action of the flow on the valve trim. This kind of valve shows some limitations due to the limited capacity. The model shown in the present work is a CSA VRCD DN50.

2.4 Parameters of Interest

The flow coefficient *KV* is one of the most important performance parameters of a valve. It is a dimensional parameter that has been derived from the valve loss coefficient introduced in (Idelchik 1986) and widely used in valve sizing procedures both in European and

American standards (International Society for Automation 2007; The International Electrotechnical Commission 2011). In the field of regulation, in addition to the maximum flow coefficient that expresses the maximum capacity of the valve, the characteristic curve is also of crucial importance. It expresses the flow coefficient as a function of valve opening rate. The flow coefficient is defined by international standards as the discharge that passes through the valve for a pressure drop equal to 1 bar, at a certain opening rate. In the following the flow coefficient is defined with units $\frac{m^3}{hbar^{0.5}}$, thus referred to as KV and calculated as follow:

$$KV = \frac{Q}{N_1}\sqrt{\frac{\frac{\rho_1}{\rho_0}}{\Delta P}} \tag{1}$$

where $\rho_1\left[Kg/m^3\right]$ is the density of the used fluid, $\rho_0\left[Kg/m^3\right]$ is the reference density in standard condition (water at 15 °C and 1 atm) and ΔP $[bar]$ is the difference between the pressure HU_S measured in standard position upstream of the valve and pressure HD_S measured in standard position downstream of the valve. N_1 is a constant that depends on the unit used for Q and ΔP. In the following N_1 is equal to 1 with Q expressed in $\frac{m^3}{h}$ and ΔP in bar.

To allow the comparison between different valve sizes, the flow coefficient is divided by the nominal diameter of the valve to the square:

$$KV^* = \frac{KV}{D^2} \tag{2}$$

where KV^* $[\frac{m}{hbar^{0.5}}]$ is referred to as the flow coefficient index, D [m] is the nominal diameter of the valve. The flow coefficient index KV^* is a dimensional parameter that is widely used in industrial-valve sizing procedures to express the head loss coefficient (Idelchik 1986) of a generic size valve at certain opening rate.

The derivative of the characteristic curve is a very important index that indicates the inherent valve gain. The gain G_I is defined as the ratio between the change in flow coefficient ΔKV and the change in travel $\Delta\delta$.

$$G_I = \frac{\Delta KV}{\Delta\delta} \tag{3}$$

A large gain value means that the flow rate changes abruptly for a small change of the opening of the valve. In some cases a very high value of gain can indicate the possible occurrence of instability (Ulanicki and Skworcow 2014). Instability is addressed in the GVS system by an automatic parameter that regulates the motion velocity of the shutter. Some solutions to limit instability for electronically regulated valves are discussed in (Giustolisi et al. 2017; Janus and Ulanicki 2018; Galuppini et al. 2020).

When the condition of discharge changes during the test, the valve tested needs some time to react and restore the target pressure. During that time the regulated pressure reaches a peak. The difference ΔH_P between the peak and the regulated pressure before the transient HD_{V1} is referred to as the *pressure peak index* and used as a comparison term in this work to differentiate the behaviour of the different kind of valves. The subscript 1 indicates the period before the transient and subscript 2 indicates the period after the transient.

$$\Delta H_P = HD_{VP} - HD_{V1} \tag{4}$$

After the transient, the pressure is regulated near the target within a certain accuracy. To evaluate this accuracy another comparison parameter ΔH_t is introduced in the present work, which is defined as the difference between the target pressure imposed and the pressure effectively regulated after a transient by the valve. It is referred to as the *pressure accuracy index* and defined as:

$$\Delta H_t = HD_{V2} - P_t \tag{5}$$

where P_t is the target pressure and HD_{V2} is the stabilized pressure after the transient.

2.5 Experimental Set-up

Tests at the hydraulic laboratory of the Politecnico di Milano have been performed on the direct acting PRV and on the GVS. A scheme of the test plant is shown in Fig. 2b. The plant is fed by a multi-stage pump that is supplied by a free surface tank. The test section, that contains the valve under test, is delimited by two control valves that are used to set the boundary condition of pressure and flow rate during the tests. The variables recorded during the tests are:

- pressures measured on the pressure taps placed in the standard positions as defined in (The International Electrotechnical Commission 2011) respectively 2 diameters upstream HU_S and 6 diameters downstream HD_S with relative pressure transducers by Lektra model KPT with full scale 10 bar;
- pressures measured upstream on the tested valve body HU_V [*bar*] and downstream on the tested valve body HD_V [*bar*] with relative pressure transducers by Lektra model KPT with full scale 10 bar.
- flow rate measured 20 diameters upstream of the test section, with an ultrasonic flowmeter VALCOM UPF-01;
- water temperature.

All the data are recorded simultaneously with a data acquisition system at the frequency of 100 Hz. In addition to the above-mentioned acquisition system a monitoring system integrated on the valve has been used for tests performed on the GVS. The integrated system is able to acquire data at a frequency of 10 Hz. The two systems are synchronized through a manual trigger. The additional data of interest for this study, recorded by the GVS built-in monitoring system, is the valve position δ [%].

2.6 Test Procedures

The test procedures explained in the following were developed to investigate the downstream pressure control ability of the direct acting PRV and of the GVS. A preliminary series of tests was performed to define the characteristic curve of the valve under study as a function of the valve travel rate. The tests follow the procedure described in (The International Electrotechnical Commission 1997). A second series of tests was finalized to evaluate the control effectiveness of the device. A test procedure was developed to highlight how the valve behaves in the transient between two conditions of stable pressure, with particular interest to the pressure peaks generated on the regulated pressure and on the accuracy of pressure regulation. The tests consisted in a series of abrupt changes of discharge by changing the opening of a valve downstream of the test section (valve VD in Fig. 2b). The change in discharge simulates the change in water demand in field applications. In

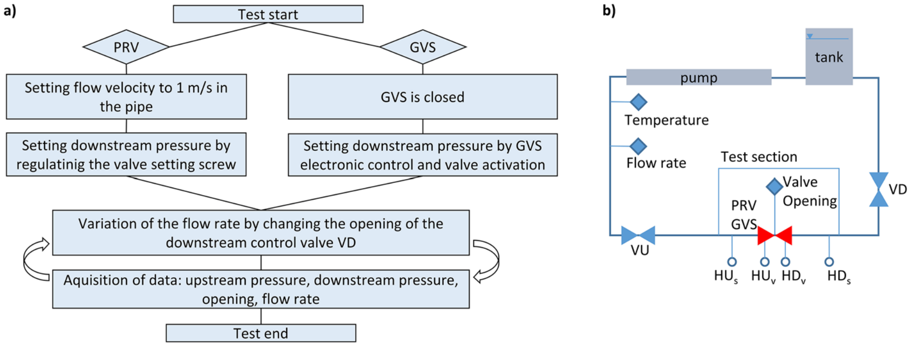

Fig. 2 Scheme of the test procedure (**a**) and sketch of the test plant (**b**)

particular, if the discharge increases the valve under test partially opens to achieve the target pressure. Instead, if the discharge decreases the valve under test partially closes again to restore the target pressure. Figure 2a shows the main phases of the test procedure used for the tests on the GVS and for the test on the direct acting PRV.

2.6.1 GVS Test

The built-in electronic control of the GVS can be set to keep a certain target pressure upstream or downstream of the valve. For this series of tests, the valve was set to control the downstream pressure in order to compare the behaviour with that of other standard PRV that have this function. The test begins with the valve completely closed, then the valve is activated. After the valve is activated it reaches a certain opening rate to achieve the target pressure. Then the flow rate is changed abruptly several times by changing the opening of a control valve placed downstream of the valve under test. The GVS reacts to the variation of discharge by opening or closing the shutter until the target pressure is reached. The test ends with the valve closed.

Several tests of this kind have been performed to explore the functioning of the valve for a total of 35 transients that are considered in the discussion.

2.6.2 Direct Acting PRV Test

Initially the target pressure is set for a velocity of the flow in the pipe equal to 1 m/s, as suggested by the constructor. After the setting, the opening of the valve VD placed downstream of the test section is changed to vary the discharge. The variation causes the valve under test to open or close stabilizing the pressure to the target value.

Several tests of this kind have been performed to explore the functioning of the valve for a total of 36 transients, all of which are considered in the discussion.

3 Results and Discussion

The following section investigates the pressure regulation ability of the valves considered. Firstly, the characteristic curves of the valves are compared. The characteristic curve is the plot of the flow coefficient as a function of the opening rate of the valve, representing a common performance indicator of control valves. The flow coefficient index is used in place of the flow coefficient to allow the comparison between valves of different sizes. Figure 3a shows the characteristic curves of the GVS and of the other pressure reducing valves considered in the study. The GVS shows a maximum flow coefficient index 9.7% larger than that of the other valves, guaranteeing a larger maximum capacity.

Looking at Fig. 3a, it can be seen that the maximum flow coefficient of the direct acting PRV is quite different from that of a pilot operated PRV. In particular, the direct acting PRV (ACMO VRCD) shows a discrepancy of about 80% compared to the valve used in (Prescott and Ulanicki 2003), a Cla-val NGE9001, and about 35% of that used in (Meniconi et al. 2017), a Cla-val ECO9035. This difference highlights the inherent discrepancy in terms of capacity between direct acting PRV and pilot operated PRV, due to the different operating principles that the two devices are based on. In one case the shutter is directly balanced by the pressure of the fluid flowing in the valve, instead in the case of pilot operated valves the backside of the shutter is balanced by the pressure regulated by the pilot valve.

Figure 3b shows the behaviour of the gain G_I for the valves considered. The gain can be considered as an indicator of the ability of the valve to increase the capacity due to a change in travel. The difference between the two pilot operated valves is due principally to different trim geometries. The geometry of the trim of this kind of valve can have a strong effect on the characteristic curve and consequently on the gain. For example, a linear trim like that of the tested direct acting PRV indicates a linear trend of the characteristic curve and consequently a constant trend of the gain. In the cases of the two pilot operated PRV it can be seen that the trend of the characteristic curve is very similar even if the two models show different maximum flow coefficients. The two are different in that the gain of the valve used in (Meniconi et al. 2017) is almost linear while the gain of the valve used in (Prescott and Ulanicki 2003) is more variable with the opening. The gain of the GVS is in the same range of values of the pilot operated PRV considered but with a slightly different trend. In particular, the GVS shows very low values of gain at a high opening rate. This behaviour can help to handle high flow rate conditions when the valve should work at high opening rates. Instead, at average openings (30%-55%), the gain of the GVS is in the same range of the valve used by (Prescott and Ulanicki 2003), i.e. a Cla-val NGE9001.

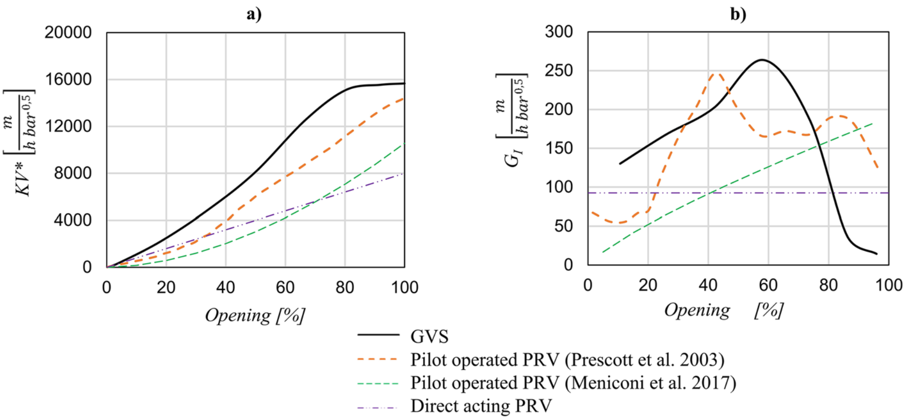

Fig. 3 Flow coefficient index KV* (**a**) and gain G_I (**b**) of the valves as a function of opening rate

After the main parameters that characterize the steady functioning of the valves under study have been presented, their pressure regulation performances are discussed based on variable demand conditions.

Figure 4 shows the ΔH_t resulted from the tests as a function of the opening (Fig. 4a) and of the Reynolds number (Fig. 4b) calculated using pipe mean velocity and nominal diameter. A first consideration appears clearly: there is a large difference between the direct acting PRV and the other types of valves. The accuracy of pressure regulation of the GVS is very similar to that of pilot operated PRV, with ΔH_t always below 0.1 bar for both of them. The GVS maintain the limit until Reynolds number 200′000.

In the case of direct acting PRV, after the pressure is set at velocity 1 m/s (Reynolds number of 70′000), the pressure is regulated but with a low accuracy. At worst, the ΔH_t of direct acting PRV overcomes -1.2 bar. The direct acting PRV moreover shows hysteresis. In particular, the regulated pressure depends not only on the velocity of the fluid, but also on the direction of motion of the shutter: if the valve is closing the pressure regulated is lower; if the valve is opening the pressure is greater. The two trends can be seen easily in Fig. 4 between opening 10 and 60%. Instead GVS and pilot operated valves do not show hysteresis. The dead-band *db* set for the GVS during tests is equal to 0.15 bar.

Figure 5 shows the term ΔH_P as a function of the difference between the flow coefficient index and the Reynolds number before and after each transient. The quantities used in the abscissa of Fig. 5 are chosen to express the dependency of the peak size on the change in discharge imposed by the operation. GVS shows an effective reaction to pressure solicitation when the demand of the plant increases or decreases by large amounts (extremes of x axis of Fig. 5). In these cases, the pressure peaks are successfully limited by the GVS action, showing a stable trend of ΔH_P. The ΔH_P is always lower than 0.6 bar for GVS. For low values of demand variation (nearby the origin of x axis of Fig. 5), the GVS seems to be less reactive;ΔH_P in this region does not decrease as it occurs for other PRV. A lack of data nearby the origin can also be noted. This behaviour is due to the intrinsic functioning of the GVS and in particular to the parameter *db*. The valve is programmed to react when pressure solicitation is greater than a certain threshold, which, in this particular case, is regulated by the parameter *db* (Fig. 1). Whereas hydraulically acted valves show a continuous behaviour

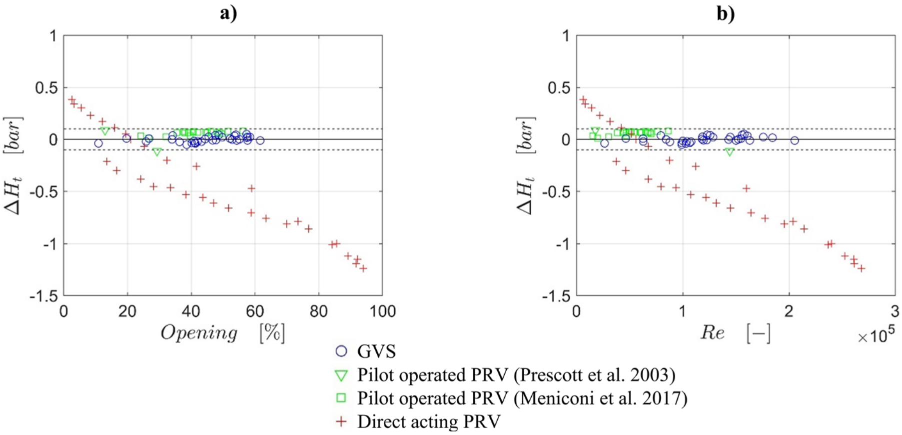

Fig. 4 ΔH_t of GVS, direct acting PRV and pilot operated PRV as a function of the percentage opening of the valve (**a**) and of the Reynolds number (**b**). Dotted lines indicate at ΔH_t equal to 0.1

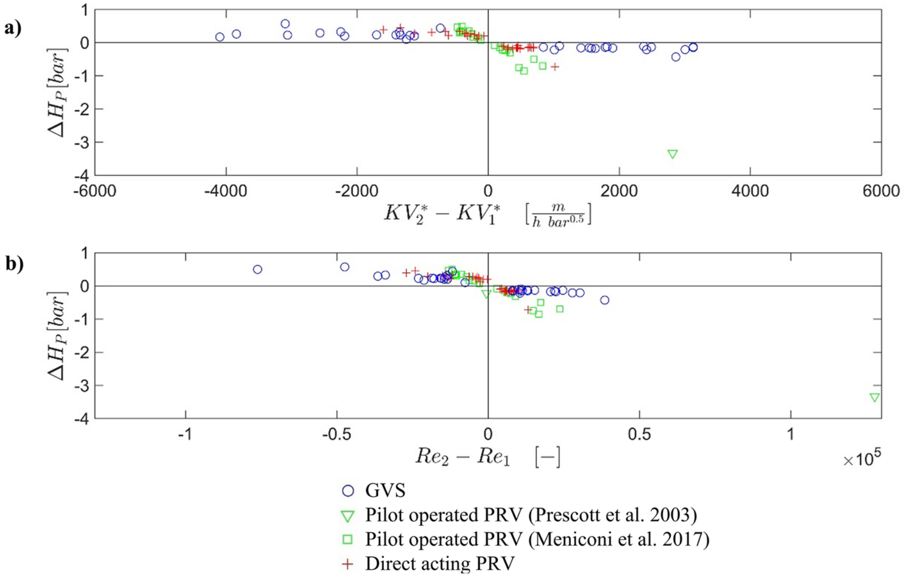

Fig. 5 ΔH_P as a function of the difference between the flow coefficient index before and after the transient (**a**) and as a function of the difference between the Reynolds number before and after the transient (**b**)

even near the origin, but when the change in discharge increases the pilot operated PRV seems to fail in the limitation of the peaks, especially when the peaks are negative, namely when the valve is opening. Comparing direct acting and pilot operated PRV: pilot operated PRV show an increase of ΔH_P with the increase of the change in the discharge. Instead, the direct acting PRV is able to limit the peaks even when the changes of discharge to handle are high (extremes of x axis). Direct acting PRV reacts faster than other PRV thanks to the simple functioning mechanism. The behaviour can be verified by the experimental result of Fig. 5 where the direct acting PRV is the one that succeeds better in limiting the pressure oscillations during transients. Nevertheless, the ‘direct’ mechanism appears to be less efficient to maintain the regulated pressure close to the target, as can be seen in Fig. 4, and it limits the maximum capacity of the valve (Fig. 3).

It is worth saying that for an effective and safe functioning of a water distribution plant, the precision in pressure regulation is a basic necessity, often required by water utilities Key Performance Indicators (KPI). Nevertheless, in order to reduce the occurrence of burst the ability of the valve to limit overpressures and in general large oscillations of pressure during a transient is also a parameter of interest for water utilities (Gomes et al. 2011). The parameters ΔH_t and ΔH_P have been proposed to express these abilities of automatic control valves, which for the reason explained in the introduction, will be object of study in the coming years.

3.1 Field Test

In this paragraph a field application of a pilot operated PRV and of the GVS is shown. Using a local monitoring system, the pressure regulated is recorded for both the valves. The pressure sensor used is placed at a distance of about 5 m from the valve.

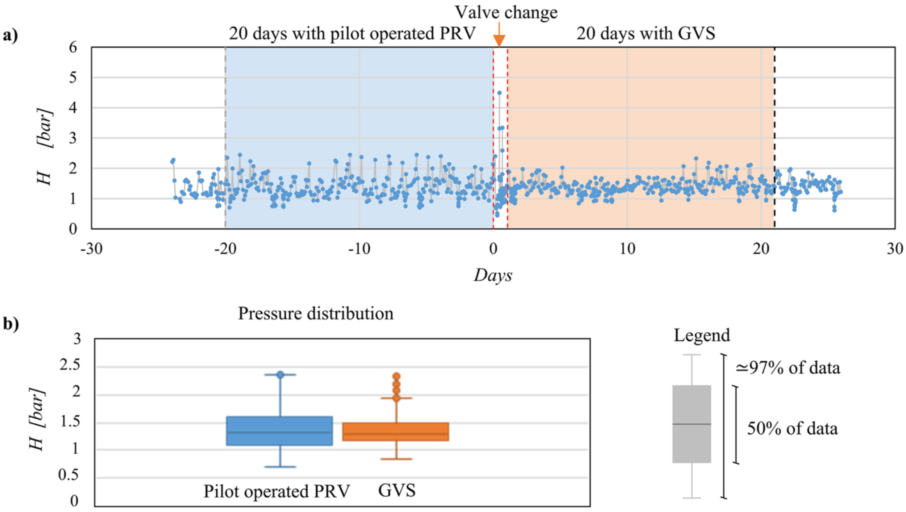

Fig. 6 Regulated pressure (**a**) and its statistics (**b**) in the 20 days of pilot operated PRV use and 20 days of GVS use

Figure 6a shows the pressure measurements made by the monitoring system during 20 days of pilot operated PRV use (highlighted blue area) and 20 days of GVS use (highlighted orange area). The peak recorded during the valve change is due to the work on the line required for the installation.

The data acquired in the two periods of reference, are used to create two datasets whose statistics are shown in Fig. 6b. This Figure shows a bar and whisker plot that represents the dataset medians, quartiles and the outliers. The medians of the two datasets show a small discrepancy (1.2%) i.e. the pressure regulated with the GVS and with the pilot operated PRV are very similar. The boxes show that the GVS is able to reduce the interquartile range (IQR) by 38 percent, guaranteeing that the pressure regulated with the GVS is more stable. The whisker for both datasets is extended to 1.5 times the interquartile ranges. Data out of the whisker range are considered outliers.

GVS system achieves better regulation of the pressure compared to the pilot operated PRV, limiting overpressures and guaranteeing the required regulated pressure with a reduced confidence interval.

4 Conclusions

The objective of the paper is to evaluate the pressure-control effectiveness of different types of automatic control valves for WDN application in variable discharge conditions. In particular, the performance of an innovative control valve, the GVS, is compared to that of common PRV (i.e. pilot operated PRV and direct acting PRV). Two parameters ΔH_t and ΔH_P are proposed to assess pressure regulation performances of PRV in variable discharge conditions. The parameters can be calculated both for hydraulically actuated and electronically controlled valves. The parameters are calculated in a series of experimental tests in significant flow conditions with the following results:

(i) The GVS and the pilot operated PRV show a ΔH_t almost constant for a large range of Reynolds numbers and always below 0.1 bar. The direct acting PRV shows a progressive collapse of performance since the discharge changes from the setting value. In the worst case a value of ΔH_t equal to 1.25 bar was shown, moreover a hysteretic behaviour is shown depending on the direction of motion of the valve stem.

(ii) The GVS was able to effectively limit the occurrence of large pressure peaks keeping ΔH_P always below 0.6 bar even for large discharge change (extremes of x axis in Fig. 5). Direct acting PRV shows very low ΔH_P implying that the velocity of reaction of the valve is high enough to limit the pressure peaks even for large discharge changes. The pilot operated PRV shows a very good performance for low discharge changes, but loses efficiency for high discharge changes where ΔH_P reaches -1 bar and in the worst case -3.3 bar.

In the end, the data from a field application, in which first a pilot operted PRV and then a GVS have been installed, are used to compare their behaviour in a real environment. The GVS shows reduced pressure peaks with respect to the pilot operated PRV and a regulated pressure statistically closer to the target. The GVS demonstrated to have promising pressure regulation characteristics both in laboratory tests and in field, proving to be a viable alternative to the type of PRV considered in the present work. Electric actuated control valves enable the development of remote, automated and smart water management strategies that are not achievable with standard PRV representing an opportunity for WDNs optimization.

To conclude, the parameters introduced in the present work can be used to compare the behaviour of different types of automatic control valves in variable discharge conditions. They give a direct overview on two aspects of PRV functioning that are of interest for WDN management namely: the ability of maintaining the pressure close to the target after a demand change (low values of ΔH_t) and the ability of limiting pressure peaks during demand change (low values of ΔH_P).

Acknowledgements The authors would like to acknowledge A2A Ciclo Idrico Brescia for the support in the field tests. The authors would also like to acknowledge InterApp AG, s&h srl and Appflue srl for the support in the valve prototype production. The Authors wish to thank Silvia Meniconi and Bruno Brunone, Università degli studi di Perugia, for sharing their experimental data.

Authors' Contributions All authors contributed to the study conceptualization and methodology development. Data collection and analysis were performed by GF with the supervision of SM. All authors commented and reviewed the manuscript.

Funding Open access funding provided by Politecnico di Milano within the CRUI-CARE Agreement. No funding was received for conducting this study.

Availability of Data and Material (Data Transparency) Materials and data used in the present paper are available under request to the corresponding author.

Declarations

Ethical Approval This material is the authors' own original work, which has not been previously published elsewhere. The paper reflects the authors' own research and analysis in a truthful and complete manner.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Conflicts of Interest The Authors declare no conflict of interest. It is highlighted that Prof. Stefano Malavasi is the inventor of the patent of the GreenValve owned by the Politecnico di Milano.

References

Abd Rahman N, Muhammad NS, Wan Mohtar WHM (2018) Evolution of research on water leakage control strategies: where are we now? Urban Water J 15:812–826. https://doi.org/10.1080/1573062X.2018.1547773

Adedeji KB, Hamam Y, Abe BT, Abu-Mahfouz AM (2018) Pressure management strategies for water loss reduction in large-scale water piping networks: a review. In: Gourbesville P, Cunge J, Caignaert G (eds) Advances in Hydroinformatics. Springer, Singapore, pp 465–480

Alvisi S, Franchini M (2014) A procedure for the design of district metered areas in water distribution systems. Procedia Eng 70:41–50. https://doi.org/10.1016/j.proeng.2014.02.006

Bajany DM, Zhang L, Xu Y, Xia X (2021) Optimisation approach toward water management and energy security in Arid/Semiarid Regions. Environ Process 1455–1480

Di Nardo A, Di Natale M (2011) A heuristic design support methodology based on graph theory for district metering of water supply networks. Eng Optim 43:193–211. https://doi.org/10.1080/03052151003789858

Dini M, Asadi A (2020) Optimal operational scheduling of available partially closed valves for pressure management in water distribution networks. Water Resour Manag 34:2571–2583. https://doi.org/10.1007/s11269-020-02579-4

Doghri M, Duchesne S, Poulin A, Villeneuve JP (2020) Comparative study of pressure control modes impact on water distribution system performance. Water Resour Manag 34:231–244. https://doi.org/10.1007/s11269-019-02436-z

Ferrarese G, Malavasi S (2020) Perspectives of water distribution networks with the GreenValveSystem. Water. https://doi.org/10.3390/w12061579

Galuppini G, Magni L, Creaco E (2020) Stability and robustness of real-time pressure control in water distribution systems. J Hydraul Eng 146:1–17. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001722

Giudicianni C, Herrera M, di Nardo A et al (2020) Zero-net energy management for the monitoring and control of dynamically-partitioned smart water systems. J Clean Prod. https://doi.org/10.1016/j.jclepro.2019.119745

Giustolisi O, Ugarelli RM, Berardi L et al (2017) Strategies for the electric regulation of pressure control valves. J Hydroinformatics 19:621–639. https://doi.org/10.2166/hydro.2017.101

Gomes R, Marques AS, Sousa J (2011) Estimation of the benefits yielded by pressure management in water distribution systems. Urban Water J 8:65–77. https://doi.org/10.1080/1573062X.2010.542820

Gomes R, Sá Marques A, Sousa J (2012) Identification of the optimal entry points at District Metered Areas and implementation of pressure management. Urban Water J 9:365–384. https://doi.org/10.1080/1573062X.2012.682589

Gullotta A, Campisano A, Creaco E, Modica C (2021) A simplified methodology for optimal location and setting of valves to improve equity in intermittent water distribution systems. Water Resour Manag 35:4477–4494. https://doi.org/10.1007/s11269-021-02962-9

Idel'chik IE, (1986) Handbook of hydraulic resistance: Second edition, United States

International Society for Automation (2007) ISA75.01, Flow equations for sizing control valves. International Society for Automation, Research Triangle Park, North Carolina USA

Janus T, Ulanicki B (2018) Improving stability of electronically controlled pressure-reducing valves through gain compensation. J Hydraul Eng 144:1–13. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001498

Khezzar L, Harous S, Benayoune M (1999) Modeling of pressure reducing valves revisited. WRPMD'99. American Society of Civil Engineers, Reston, VA, pp 1–10

Malavasi S (2013) Energy recovering flow control valve. Patent number PCT/IB2013/051202

Mambretti S, Orsi E (2011) Genetic algorithms for leak detection in water supply networks. WIT Trans Built Environ 122:63–71. https://doi.org/10.2495/UW120061

Meniconi S, Brunone B, Mazzetti E et al (2017) Hydraulic characterization and transient response of pressure reducing valves: Laboratory experiments. J Hydroinformatics 19:798–810. https://doi.org/10.2166/hydro.2017.158

Pagano A, Sweetapple C, Farmani R et al (2019) Water distribution networks resilience analysis: a comparison between graph theory-based approaches and global resilience analysis. Water Resour Manag 33:2925–2940. https://doi.org/10.1007/s11269-019-02276-x

Page PR, Abu-Mahfouz AM, Yoyo S (2017) Parameter-less remote real-time control for the adjustment of pressure in water distribution systems. J Water Resour Plan Manag 143:1–12. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000805

Pérez-Sánchez M, Sánchez-Romero FJ, Ramos HM, López-Jiménez PA (2017) Energy recovery in existing water networks: Towards greater sustainability. Water (switzerland) 9:1–20. https://doi.org/10.3390/w9020097

Prescott SL, Ulanicki B (2003) Dynamic modeling of pressure reducing valves. J Hydraul Eng 129:1–10. https://doi.org/10.1061/0733-9429(2003)129

Su Y, Gao W, Guan D, Zuo T (2020) Achieving urban water security: a review of water management approach from technology perspective. Water Resour Manag 34:4163–4179. https://doi.org/10.1007/s11269-020-02663-9

The International Electrotechnical Commission (2011) IEC 60534.2.1 Industrial process control valves - Part 2.1 flow capacity - Sizing equations for fluid flow under installed conditions, Geneva, Switzerland

The International Electrotechnical Commission (1997) IEC 60534–2–3 Industrial process control valves - Part 2.3 flow capacity - Test procedures, Geneva, Switzerland

Ulanicki B, Skworcow P (2014) Why PRVs tend to oscillate at low flows. Procedia Eng 89:378–385. https://doi.org/10.1016/j.proeng.2014.11.202

Vicente DJ, Garrote L, Sánchez R, Santillán D (2015) Pressure management in water distribution systems: current status, proposals, and future trends. J Water Resour Plan Manag 142:04015061. https://doi.org/10.1061/(asce)wr.1943-5452.0000589

Wright R, Stoianov I, Parpas P et al (2014) Adaptive water distribution networks with dynamically reconfigurable topology. J Hydroinformatics 16:1280–1301. https://doi.org/10.2166/hydro.2014.086