Pressure management in water distribution systems in order to reduce energy consumption and background leakage

H. Monsef, M. Naghashzadegan, R. Farmani and A. Jamali

ABSTRACT

Due to the seriousness of the water shortage crisis over the past decades, the need to manage water use has become more and more important. Pressure management in urban water distribution networks is one of the options that can significantly reduce water loss. The pressure reducing valve (PRV) and the variable speed pump (VSP) are two devices that are most used in water distribution system (WDS) pressure management. In the present study, an optimization code was first proposed to estimate the instantaneous water demand based on the reported network pressures. According to the estimated instantaneous water demand, another optimization code is presented based on the DE algorithm to control the installed PRVs and VSPs. This results in the uniform distribution of the pressure and reduction of the excessive pressure on the water network for all hours of the day, reducing the water leakage and energy consumption accordingly. The provided method has been applied to a real water distribution network in northern Iran. The results showed that by applying this method, the network background leakage and the energy consumption have been reduced by 41.72% and 28.4%, respectively, compared to a non-management mode.

Key words | background leakage, energy consumption, pressure management, pressure reducing valve, variable speed pump, water distribution system

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INTRODUCTION

Due to increasing water demand in urban communities as well as reducing water resources, water loss management is one of the major challenges engineers face these days. Reports indicate that about 30%, or even more, of the total water entering the distribution network is wasted (Araujo *et al.* 2006). There are many factors that are effective in leakage quantity in water distribution systems (WDSs) such as the water pressure, the pipe age, the quality of fittings, the characteristics of the soil around the pipe, etc. Due to the direct relationship between pressure and leakage, pressure management is one of the effective methods to reduce leakage in WDSs.

The WDS is designed to deliver adequate water to consumers with the minimum acceptable pressure throughout the operation time, especially during the peak hours of peak days. In other operation time in 'which water demand is lower', the network's nodal pressure is more than minimum the acceptable pressure. This causes an increase in the background leakage, the pipe failure, and also energy losses (in order to create surplus pressure on the WDS). Therefore, pressure management of WDSs can play an important role in decreasing the water and energy losses, which has an effect on the sustainability of consumption and the protection of the environment. The pressure reducing valve (PRV) and variable speed pump (VSP) are most used for WDS pressure management. PRVs, regardless of changing the inlet pressure or flow rate, can reduce inlet pressure to a steady lower set

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pressure. PRVs can be controlled with different approaches such as hydraulic or electronic controllers (Vicente 2016). PRVs with electronic controller can be used perfectly in supervisory control and data acquisition (SCADA) systems according to the momentary operation conditions. VSPs are pumps with variable speed drive (VSD). The VSD regulates the rotational speed of the pump's electric motor by changing the frequency of the input power. Changing the speed of the electric motor can change the hydraulic performance of the pump (such as power consumption, outlet flow, and pressure).

Many articles have been presented about pressure management methods in WDSs. Germanopoulos & Jowitt (1989) described the relationship between network pressures and leakage losses and evaluated the effect of pressure control on water network leakage. They presented a linear theory method to find the optimal control valve settings to minimize the nodal excess pressure and also water leakage. The set point of the control valve should be adjusted so that the pressure at the critical point (junction with the highest elevation or at the far end of the water network) remains within the allowable range.

Araujo *et al.* (2006) presented a model to specify the optimal number, the location, and the output pressure of the control valves in order to minimize the pressures and, consequently, leakage of WDSs. They used genetic algorithms to find roughness coefficients of pipelines in order to minimize surplus nodal head. The pipes with higher roughness coefficient are potential points for installation of the control valve. They optimized the set point of control valves to reduce the network leakage.

In a case study, Marunga *et al.* (2006) reduced the WDS's background leakage of Mutare city in Zimbabwe using pressure management. They reduced the minimum night flow (MNF) by about 25% with nodal pressure reduction from 77 m to 50 m by controlling the outlet pressure of PRV.

Nicolini & Zovatto (2009) proposed a multi-objective optimization method to find the optimal number, location, and also set point of installed PRVs. The first objective function in their study was to minimize the total number of installed PRVs while the second objective function was to minimize the total leakage in the WDS. They achieved a Pareto front that shows the total leakage versus the number of installed PRVs.

Skworcow *et al.* (2009) provided a method for energy and pressure management in WDSs in order to minimize the operation cost. They changed pump scheduling (determining the number of fixed speed pumps in the operation state) and the speed of VSPs and also the PRV set points to reduce the excess pressure and dependent leakage. Their method has been applied to a medium scale WDS and it was shown that the daily electricity cost was reduced by about 34%.

Bakker *et al.* (2013) presented an active pressure control model to manage the outlet pressure of a pump station according to off-line pressure loss prediction in transmission pipelines. The model is a combination of a predictive and a feedback controller. Their results showed a decrease of 31% in pump energy consumption and a decrease of 20% in water losses by applying the model on a water treatment plant pump station in midwest Poland.

Tricarico *et al.* (2014) suggested a novel methodology for the pressure management of WDSs. They used turbines instead of conventional PRVs to reduce network pressure and to generate electricity simultaneously. Minimization of the pump operation cost by reducing the surplus pressures in the water network and also maximization of the generated electricity with turbines at the same time were also objectives of their study.

Pecci *et al.* (2015) surveyed a mathematical programming method to find the optimal place of PRVs and their operation control in order to reduce excess pressure in WDSs under multiple demand scenarios.

In all of the previously mentioned literature, the demand profile should be known to decide on the status of pumps and valves settings for pressure management and leakage control. Due to the influence of ambient temperature, date, residents' culture, and other parameters on instantaneous water consumption, using a fixed daily or seasonal demand profile may not correspond to the reality on many occasions. In this paper, a feedback control leakage management method is presented in order to minimize the background leakage and energy consumption in WDSs by controlling the outlet pressure of PRVs and speed of VSPs, individually or together.

In this method, the amount of instantaneous demand is estimated by an optimization code, which was based on the transmitted data from the installed sensors on the WDS. To analyze the effect of the control device (PRV/VSP) on leakage and energy reduction in a case study, the method has been run three times: (1) control with PRVs, (2) control with VSPs, and (3) control with PRVs and VSPs simultaneously.

METHODOLOGY

In this study, the measured pressure of one or more points of the WDS, where the pressure gauges have been installed, has been applied as an input for a demand estimator code to find the instantaneous demand multiplier. The estimated instantaneous multiplier is then used as an input parameter of another optimization procedure to reduce the excess nodal pressure in the WDS in order to reduce the background leakage and energy consumption. For this purpose, the optimization code should find the optimal set points of installed PRVs and optimal speed of VSPs, respectively. Figure 1 shows the flow diagram of this methodology.

In the above method, the following assumptions are considered:

1. The hydraulic model is calibrated.
2. The pressure sensor error is ignored.
3. The demand pattern of all consumption nodes is the same.

In the first part of this study, to estimate the instantaneous demand multiplier, an optimization code was developed using differential evolution (DE) algorithm in MATLAB software based on the provided algorithm by Storn & Price (1997). The EPANET 2.0 hydraulic solver (Rossman 2000) was used as the hydraulic solver and linked to the optimization code. The nodal pressure of one or more points of WDS (according to the complexity of the network) via the current settings of PRVs and VSPs are used as the inputs of the optimization code. The demand multiplier has been considered as the design variable in the optimization procedure. Also, minimizing the difference between measured and calculated nodal pressure 'in nodes where the pressure sensors installed' was considered as the objective function. The code can find the actual demand multiplier with minimum error due to transferred data from WDSs.

In the next part, another optimization code was presented using DE algorithm in order to find the optimal set point of installed PRVs (outlet pressure) and VSPs (pump speed). The purpose of this section is the pressure management of the WDS to reduce the background leaks and energy consumption. In the presented code, the estimated demand multiplier is used as the model input, the outlet pressure of PRVs and/or speed of VSPs are the design variables, and minimizing the mathematical sum of the total nodal leakage and energy consumption (in the same order of magnitude) is the objective function.

Due to the inverse relationship between water consumption and network pressure, the pressure on WDSs in the non-maximum peak hours is more than minimum acceptable pressure and more surplus pressure increases the leakage in WDSs. The relation between leakage and pressure has often been described by Equation (1) (Thornton & Lambert 2005):

$$L_i = k_i \times P_i^n \tag{1}$$

where L_i is leakage flow in node i, k_i is constant leakage coefficient of node i which depends on the length and number of the connected pipes to the node, P_i is the nodal pressure of node i, and n is a fixed parameter between 0.5 and 2.5 which depends on the type of leak.

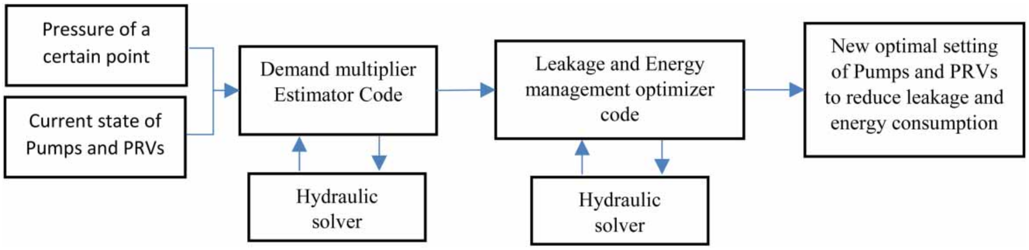


Figure 1 | Flow diagram of the optimization process.

CASE STUDY

A real WDS has been selected to apply the above methodology in order to reduce water leakage and energy consumption. The Mehr water distribution system (MWDS) is located in the north of Iran in Rasht city and serves up to 44,000 people. The area covered by this network is 144 acres and its daily average demand is 366 m^3 per hour. The altitude difference of MWDS is about 4 meters and it has 371 pipes with a length of 33 kilometers, 366 junctions, one reservoir, two PRVs and a pump station with three pumps. This network is made up of eight commercially available pipe sizes (90 to 500 mm). Due to the existence of a household water tank and a pumping system in the apartments of that area, the minimum acceptable pressure of all nodes was considered as 20 meters. The pipe configuration and elevation of MWDS are shown in Figure 2.

According to the demand profile of MWDS, in the absence of control equipment such as PRVs or VSPs, the minimum and maximum of nodal pressure at maximum demand time (21:00) is 23 and 49 meters, respectively, and the minimum and maximum pressure at the minimum demand time (3:00) is 45 and 55 meters, respectively. According to Equation (1), the calculated leakage in maximum and minimum peak time is 83.36 m^3/h (22.77% of average hourly demand) and 115.41 m^3/h (31.53% of average hourly demand). Also, the consumed power in the pump station at peak and non-peak times is 135.16 kW and 158.82 kW, respectively. The purpose of this case study is to minimize the background leakage and electrical energy consumption of the MWDS at all hours of the day, by using the transferred data from the installed pressure sensor in the network.

To validate the demand multiplier estimator code, more than 100 random multipliers have been generated in the range of 0.4 to 1.4. The hydraulic model runs to analyze the nodal pressure of network after applying each generated multiplier. The calculated pressure in the middle point of the city (the point where the pressure gauge is installed) was used as the input parameter of estimator code instead of the transferred data from the installed pressure gauge. Comparing the input and the estimated demand multiplier shows an acceptable accuracy. Selecting an initial population of 10 and generation number of 40 for the estimation procedure leads to an accuracy of 99.9% within 6 seconds for each multiplier in a PC with 8 GB of RAM and Intel i7 2.4 GHz CPU. This result guarantees that the amount of consumption for any given moment will be presented correctly to the pressure management optimization code. For pressure management of the MWDS, three different states were implemented as follows:

- State 1: Finding the optimal set points of PRVs (outlet pressures) individually.
- State 2: Finding the optimal set points of VSPs (fraction of speed in percent) individually.
- State 3: Finding the optimal set points of PRVs and VSPs together.

In state 1, set points of two installed PRVs have been used as design variables. In state 2, regardless of the PRVs,

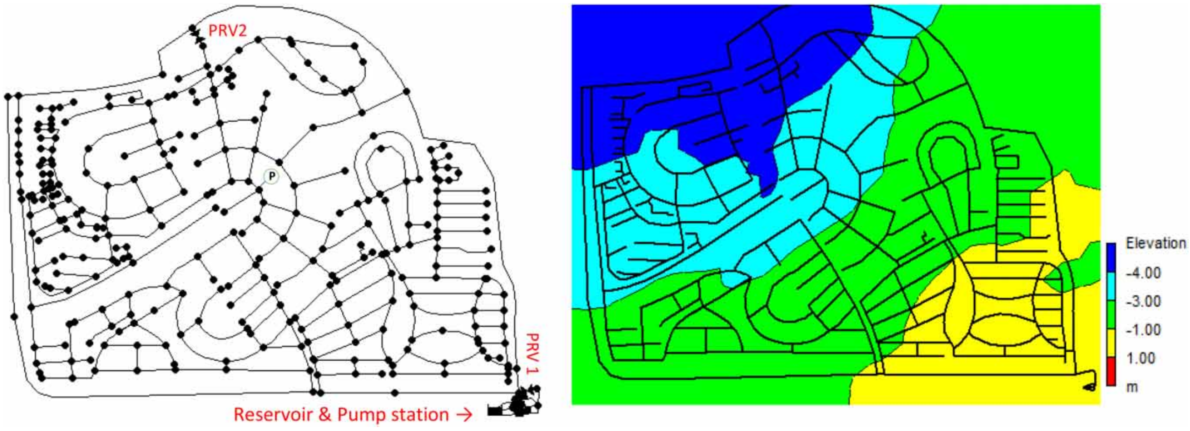


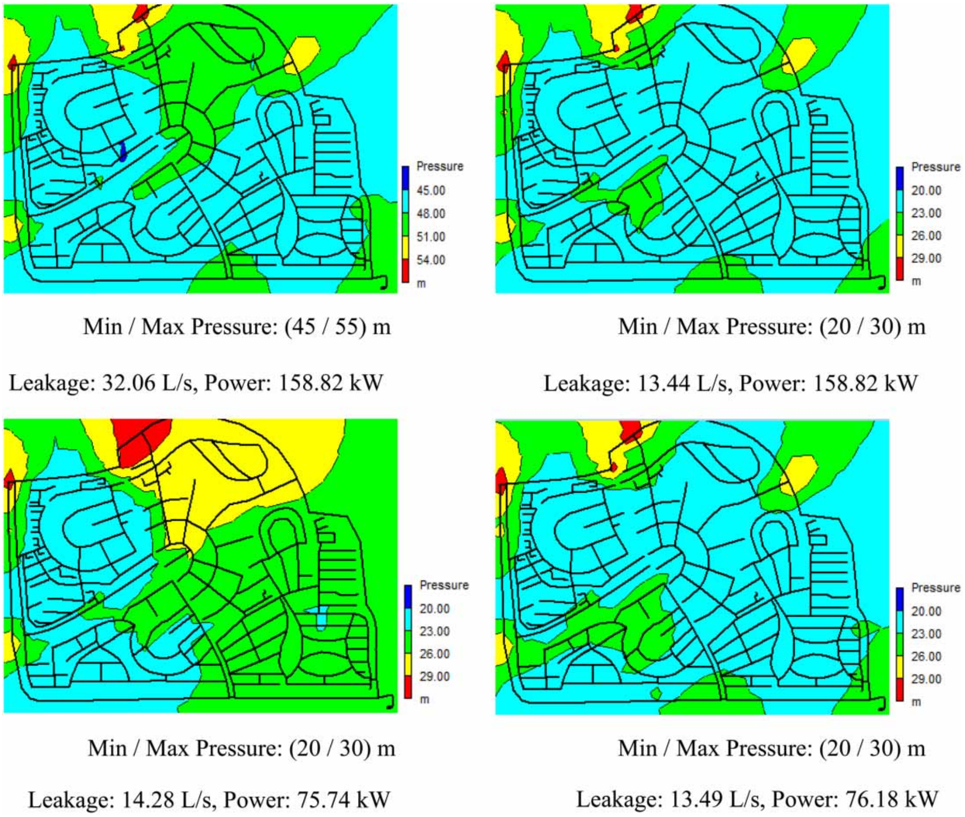
Figure 2 | Pipe configuration (left) and ground elevation (right) of MWDS.

set points of three VSPs have been used as design variables. In state 3, the set point of PRVs and VSPs have been used as design variables together. In all of the above states, the objective functions of the optimization have minimized the mathematical sum of total nodal leakage and energy consumption in the WDS. The initial population and also the generation number of the DE optimization procedure considered 100 and 150, respectively. Figure 3 shows the counterplot of optimal pressure distribution for MWDS in different states in demand non-peak time (3:00 a.m.) alongside the pressure distribution graph of uncontrolled mode.

Results show that using PRVs to control pressure management of the WDS (state 1) can reduce the background leakage significantly, but it cannot reduce the pump station electricity consumption. Using VSPs for pressure controlling of the WDS (state 2) shows better results because of the simultaneous reduction of leakage and electricity consumption. Using PRVs and VSPs together in network pressure controlling (state 3) achieves the best result.

To investigate the effect of the mentioned method for a full day pressure management, the reported demand multiplier (Figure 4) has been applied to the optimization code. This information may be sent by the SCADA, telemetry system or demand multiplier estimator code to the central control unit. Figure 5 shows the leakage, energy consumption, min/max nodal pressure, and PRV/VSP set point in different states versus time.

The results shown in Figure 5 show that reducing water consumption during the night will increase pressure, leakage, and energy consumption in non-controlling mode. In state 1, the best PRV's set point has been shown at different times in order to reduce minimum nodal pressure and remove excess pressure. During the night, the PRVs (especially PRV2) experienced the lowest output pressure.



Min / Max Pressure: (45 / 55) m

Leakage: 32.06 L/s, Power: 158.82 kW

Min / Max Pressure: (20 / 30) m

Leakage: 13.44 L/s, Power: 158.82 kW

Min / Max Pressure: (20 / 30) m

Leakage: 14.28 L/s, Power: 75.74 kW

Min / Max Pressure: (20 / 30) m

Leakage: 13.49 L/s, Power: 76.18 kW

Figure 3 | Pressure distribution of MWDS at 3:00 a.m. (non-peak time): without pressure controlling (upper left), with PRVs controlling (upper right), with VSPs controlling (lower left), and with simultaneous PRVs and VSPs controlling (lower right).

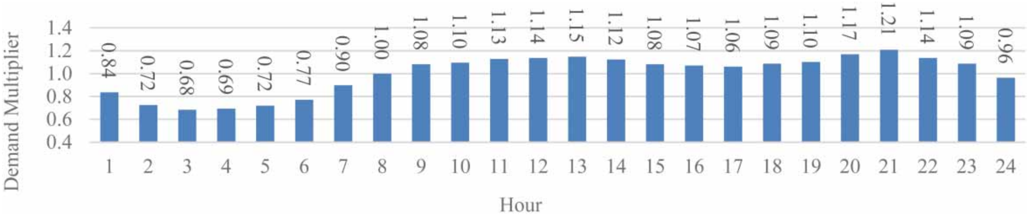


Figure 4 | Demand multiplier versus time in MWDS.

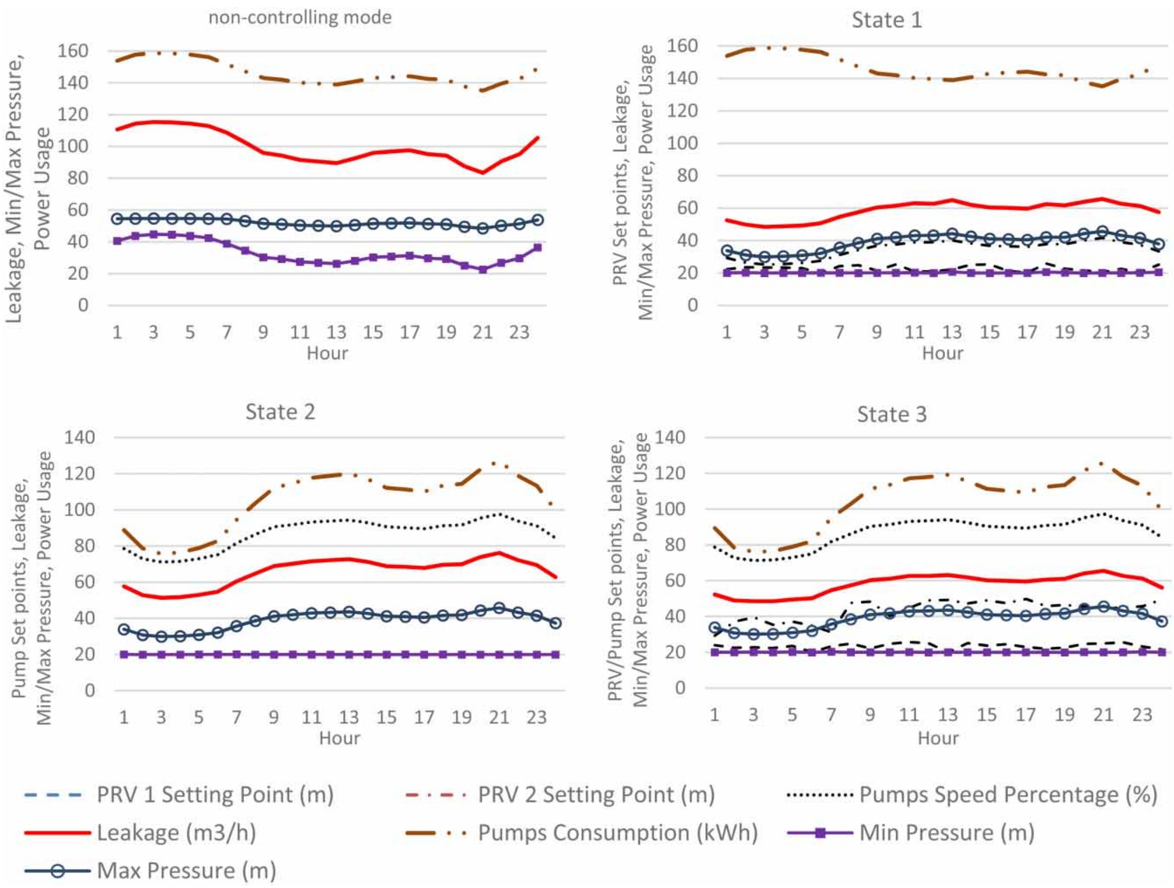


Figure 5 | Background leakage, energy consumption, min/max nodal pressure, and PRV/VSP set point in different states versus time.

In this state, the background leakage has a significant reduction but the energy consumed by the pumps was not reduced. In state 2, the VSPs set point (percentage of pump's speed) calculated with optimization code at different times, by applying the mentioned set point on the hydraulic model caused reduction of minimum nodal pressure to the minimum acceptable pressure. As a result, leakage and pump energy consumption decreased simultaneously. In state 3, the set points of PRVs and VSPs are shown at different times. Results showed that the background leakage and energy consumption have a greater reduction than the two previous states.

Also, the results show that, unlike the uncontrolled state, the nodal pressure and leakage at non-peak times of states 1, 2, and 3 is less than the nodal pressure and leakage at peak times. The reason for this phenomenon is the reduction of network surplus pressure during non-peak hours by PRVs and VSPs, which reduces the pressure and background leakage in the WDS. It should be noted that the reduction of surplus pressure does not increase the quality of service to customers.

Table 1 | Leakage and energy consumption reduction in a full day for MWDS with different states

	Total leakage (M^3/day)	Leak reduction (%)	Energy consumption (Kwh)	Energy cons. reduction (%)
Without pressure man.	2,390	–	3,507	–
State 1	1,403	41/30	3,506	0/03
State 2	1,573	34/18	2,524	28/03
State 3	1,393	41/72	2,511	28/40

Therefore, the simultaneous use of the PRVs and VSPs for pressure management of WDSs will achieve the best results in reducing background leakage and energy consumption. In this state, the calculated leakage at maximum and minimum demand peak times are 65.51 m^3/h (17.9% of average hourly demand) and 48.56 m^3/h (13.27% of average hourly demand). Also, the consumed power in the pump station at maximum and minimum demand peak times is 126.09 kW and 76.18 kW, respectively. These values are significantly better than the uncontrolled state. The summarized results of a full day are shown in Table 1.

CONCLUSION

In this study, a momentary demand multiplier estimator code was presented to estimate the water demand according to the reported nodal pressure from the installed pressure meter in the WDS. The estimated demand multiplier used as input parameter another optimization code in order to achieve pressure management of WDS. The presented code has been written with DE optimization algorithm and can find optimal set points of installed PRVs and VSPs in WDSs. Reducing the background leakage and pump energy consumption is the objective function of the optimization code. The methodology was applied to a real WDS in the north of Iran. The results showed that using PRVs and VSPs simultaneously can improve the pressure management process and achieve the highest reduction in leakage and energy consumption versus the single use of one of these. In the case study, controlling the PRVs and VSPs by the provided optimization code causes the reduction of background leakage and power consumption by 41.72% and 28.4%, respectively, compared to uncontrolled mode.

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