Smart Pressure Management to Reduce the Spatial and Temporal Pressure Variations in Water Distribution Networks

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ABSTRACT

Water distribution networks are one of the most critical infrastructures in urban systems, the use of which has always been associated with many challenges. These networks are encountered frequent problems such as pipe breaks, water leakages, and non-uniform nodal pressure distribution. In this study, a time-based scheduling approach is presented for the use of pressure control equipment in water networks. Two operational scenarios consisting of simultaneous use of individual pressure reducing valves in the first scenario (individual scenario) and the hybrid use of pressure reducing valves with a variable speed pump in the second scenario (hybrid scenario) are investigated. In this case, operational programs are developed to control nodal pressures in the network for providing minimum temporal and spatial pressure variations, using a Genetic algorithm as an optimization tool. The proposed strategies based on dual scenarios were validated for both theoretical and real networks. The optimal scenario was determined by calculating the hydraulic evaluation indicators of each scenario. The results show that simultaneous use of pressure reducing valves and variable speed pumps (hybrid scenario) was more effective in pressure management, in comparison with the individual scenario.

KEYWORDS

Water distribution networks, Pressure management, Pressure reducing valves, Variable speed pump, Genetic algorithm

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1. Introduction

In recent years, the importance of implementing pressure management (PM) strategies has been highlighted due to various challenges such as high pipe breakage and water leakage rates. In addition, the use of the PM methods can effectively control the insufficient, unequal, and non-uniform pressure distributions among the different nodes of each water network. PM involves a wide range of control measures, including tank water level control, partitioning of water networks into DMAs, using pumps as turbines (PAT), or variable speed pumps (VSPs), and the installation of pressure control valves including pressure-reducing valves (PRVs) [1]. The optimized location and operational schedule of PRVs have been investigated in many studies. Gupta et al. employed a multiobjective genetic algorithm (NSGA-II) to minimize the water leakage rate by determining the number, location, and setting of PRVs [2]. In regard to hybrid approaches, Gupta et al. presented a model, that optimizes both pump speed and PRV schedule in the simple branched network [3]. In the present paper, the performance of two smart PM schemes including individual (using only PRVs) and hybrid (the combined application of PRVs and VSP) scenarios has been investigated.

2. Methodology

In this paper, the proposed methodology consists of three phases including the hydraulic simulation phase, the optimization model, and the calculation of hydraulic evaluation indicators. These three phases are interacting as illustrated in Figure 1.

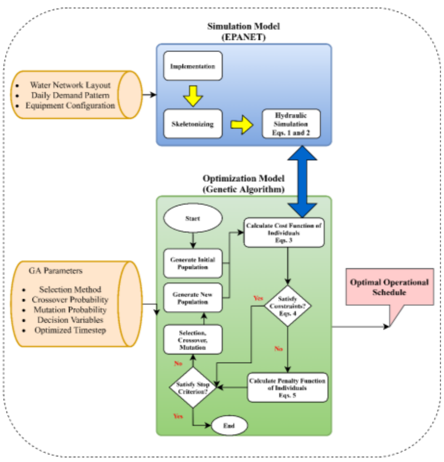

Figure 1. Flowchart of the developed methodology

2.1. Hydraulic simulation phase

The hydraulic simulation model is developed using EPANET software. In the EPANET, two governing equations of flow continuity in nodes and the conservation of energy in closed loops are solved by the GGA[2] method.

2.2. Optimization model

The optimization model consists of determining PRVs settings under both individual and hybrid scenarios. The optimized relative pump speed is calculated in the hybrid scenario as well. The objective function is to minimize the total pressure variations in the water network, which is defined as:

$$Min\ f_1=\sum_{i=1}^{NPN}\sum_{t=1}^{24}\left(H_i^t-H^{Des}\right)^2 *(NPN*24)^{-1} \tag{1}$$

f_1: Objective function, H_i^t: Pressure in node i at time t, H^{Des}: Desirable pressure value to supply water network, NPN: Total number of nodes in the network. Furthermore, the optimization constraints are defined according to the hydraulic performance of the water network, which is denoted as:

$$Subject\ to: \begin{cases} S_{Min} \le S_{Set} \le S_{Max} \\ H_{Min} \le H_i^t \end{cases} \tag{2}$$

S_{Min} and S_{Max}: Minimum and maximum pressure bounds, S_{Set}: Set of all possible values related to each decision variable. It is noteworthy to mention that the influence of pressure violation can be calculated using the penalty theorem. The optimization process was conducted using the single-objective genetic algorithm.

2.3. Hydraulic evaluation indicators

In the third phase, a set of hydraulic evaluation indicators are defined in order to investigate the efficiency of each PM strategy including pressure variation index (PVI), hourly leakage rate, desired pressure coverage percentage (DPCP), and hydraulic failure index.

3. Discussion and Results

The PM schemes were implemented in two case studies, including a well-known benchmark (theoretical) network introduced by [4] and a real network of the I-1 zone in Mashhad city of Iran. To determine the operational schedule of time modulated PRVs and VSP, the optimal time step was determined by calculating the total optimization evaluation parameter (TOEP) according to each time step as:

[2] Global Gradient Algorithm

$$TOEP_{TimeStep} = [\, f_{NFE} * CF(x)]_{TimeStep} \quad (3)$$

$TOEP_{Timestep}$: TOEP parameter related to each time step, f_{NFE}: NFE fraction, $CF(x)$: Minimum cost function. Concerning the fact that low TOEP leads to enhanced solutions optimality, a time step of 6 hours was considered the optimal time step. Based on this, the optimal operational schedules for both pressure control devices in two case studies have been characterized. Figure 7 represents the obtained optimal schedules in the real network of the I-1 zone, under both individual and hybrid scenarios.

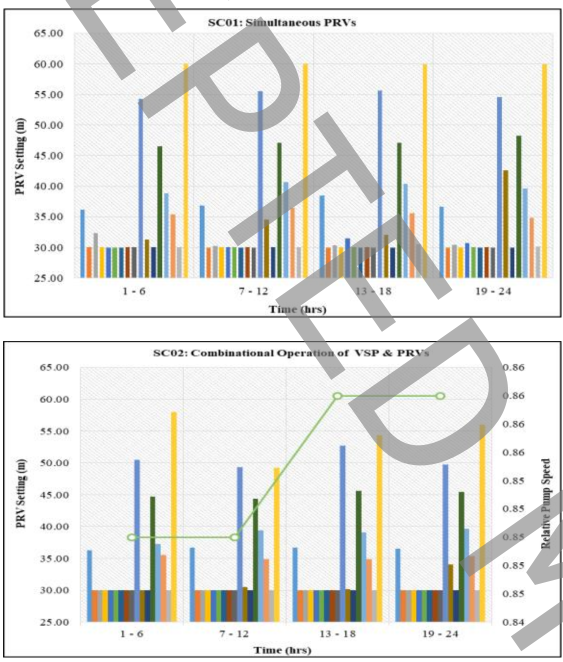

Figure 2. Operational schedules for time modulated PRVs and VSP in the I-1 network

Once all the time modulated PRVs and VSP were scheduled, the hydraulic simulation model was updated to calculate the hydraulic evaluation indicators, which are shown in Table 1.

Table 1. Hydraulic evaluation indicators for time-based pressure management scenarios (Real Network)

PM Scenario	CF	PVI Reduction	DPCP Improvement	Average Hourly Leakage Reduction
SC01: PRVs	306.53	24.30%	7.92%	2.53%
SC02: PRVs & VSP	280.21	36.04%	9.54%	6.67%

According to Table 1, the hybrid scenario has led to the higher value of three parameters including PVI reduction, DPCP improvement, and average hourly leakage reduction rate. In addition, the hydraulic failure rate was calculated equal to 18% in the second scenario.

Therefore, the hybrid scenario was concluded to be a superior approach for applying pressure control in the real network. Figure 3 illustrates the nodal pressures distributions layers before and after implementing the hybrid strategy, conforming to the reduced pressure distributions uniformity after PM implementation.

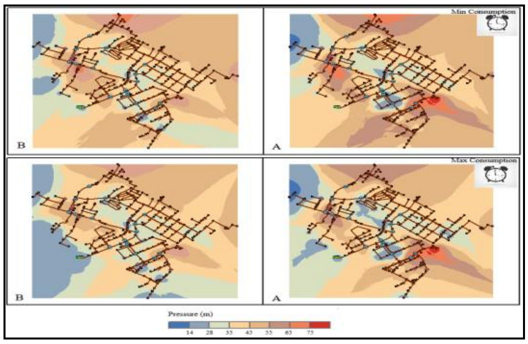

Figure 3. Nodal pressure layers before and after the PM

It is significant to mention that the values of hydraulic indicators that resulted from implementing the dual scenarios in the theoretical network have proven the superiority of the hybrid approach as well.

4. Conclusion

In this paper, two smart pressure management schemes are implemented on both theoretical and real water networks to minimize nodal pressure variations. The obtained results indicate that the hybrid operation of PRVs and VSPs leads to a more impressive reduction in the pressure variation index (75.4% in the theoretical and 36% in the real network), in which both pressure control devices are optimized using time-modulated approaches.

5. References

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