Dynamic topology in water distribution networks

R. Wright\textsuperscript{a}, I. Stoianov\textsuperscript{a*}, P. Parpas\textsuperscript{b}

\textsuperscript{a}Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, United Kingdom
\textsuperscript{b}Department of Computing, Imperial College London, SW7 2AZ, United Kingdom

Abstract

A new approach for the operational management of water distribution networks is herein presented, which introduces district metered areas (DMAs) with dynamic topology. The approach facilitates the operation of an open and adaptive network that reverts back to the original DMA structure only at night for leakage detection purposes, therefore eliminating the disadvantages of a closed topology such as reduced resilience to failure and suboptimal pressure management. The concept and technology is currently being implemented on a water distribution network in the UK, and a novel optimization method used for its control has been derived that is fast and reliable.

© 2013 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of the CCWI2013 Committee

Keywords: District metered area; optimization; resilience; pressure management; valve control

1. Introduction

District metered areas (DMAs) are a popular and cost-effective method for identifying and reducing leakage. The concept of the DMA is simple; by closing valves in a looped distribution network, discrete areas can be formed and the flow into each area monitored in order to assess leakage, particularly at night when customer demand is low. This helps water companies to identify bursts quickly and facilitates reporting and efficient planning of asset management programs by comparing background leakage amongst DMAs. Since its first implementation in the early 1980s, the DMA has been successful in reducing leakage in the UK where it fell by a third between 1994/5 and 2006/7 (Ofwat, 2007).

* Corresponding author. Tel.: +44 2075946035
E-mail address:ivan.stoianov@imperial.ac.uk

© 2013 The Authors. Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
Selection and peer-review under responsibility of the CCWI2013 Committee

doi:10.1016/j.proeng.2014.02.191
In addition to night flow monitoring, DMAs also facilitate pressure reduction to reduce leakage by installing pressure reducing valves (PRV) at inlets. The concept of DMAs is gradually being adopted in many countries that are committed to reducing non-revenue water, and as a result many technologies now exist on the market for improving the efficiency of pressure management. At its most basic and conventional form, a PRV aims to keep a constant outlet pressure regardless of variations in upstream pressure, generally using a hydraulically operated pilot controller. Whilst this approach is simple, the diurnal pattern of customer demand results in pressure often being too high, particularly at night when demand is low. A good compromise between simplicity and efficiency is a time controlled PRV, which allows diurnal variations in the pressure profiles based on historical demand data to be programmed into the valve. This ensures that the network pressure and consequently leakage can be reduced at times of low demand. However, this form of valve control can constrain the system response to bursts or fire flow, particularly at night. More recently, flow modulation has become popular as it addresses the shortcomings of time controlled PRVs. A flow modulation PRV measures flow locally and adjusts its outlet pressure accordingly using a lookup table that is typically based on historical data and modeling. Flow modulation settings can also be updated automatically by intermittently measuring the pressure at a critical point to remotely update the flow modulation curves (i2O Water Ltd, 2010; Palmer Environmental, 2010; Technolog, 2010).

Although DMAs have been successful in reducing leakage in the UK, their implementation has not been without drawbacks. By extensively closing boundary valves in order to discretize the network, the natural redundancy in connectivity of these large looped pipeline systems is severely reduced and this gives rise to a number of problems.

- Reduced redundancy in network connectivity significantly reduces the network’s resilience to failure and the security of supply. Consequently, manual intervention in failure situations is required so that alternative supply routes can be used, especially in commonly found single-feed DMAs. This passive approach is time consuming and therefore has higher consequences both for customers and water utilities.
- A manual approach to failure can also cause water quality incidents, for example through the opening of closed boundary valves where stagnant water and sediments have accumulated.
- It is not uncommon for valves to be left incorrectly open or closed and this leads to errors in monitoring, modeling and decision making.
- Higher average zone pressure and leakage than an equivalent open network. This is because frictional energy losses are smaller in a network that makes use of its inherent redundancy, a phenomenon that can be seen by examining the concave shape of a flow-head loss relationship. Therefore valves in a multi-feed DMA do not need to provide the network with as much pressure as an equivalent single-feed DMA configuration.
- Since energy losses are greater in single-feed DMAs, the diurnal pressure variability due to demand patterns will also be higher. This can lead to pipe fatigue and more long-term network failures, a phenomenon that has been observed in the oil and gas industry (Hrabovs’kyi, 2009).

All of these outcomes ultimately impact on the service levels. It is of the utmost importance that water companies provide a consistent and good level of service and security of supply. Failing to do so can not only have serious consequences for their customers, especially critical ones such as hospitals, but also results in the water company itself being penalized by the regulator (Ofwat, 2012). The motivation of this paper is to demonstrate a novel approach to leakage management that addresses these problems.

2. Dynamic topology in water distribution networks

2.1. Concept

The variable DMA topology of water distribution systems is enabled by replacing closed boundary valves and retrofitting existing PRVs with novel self-powered multi-function network controllers that adjust the network topology and continuously monitor the hydraulic conditions. These multi-function network controllers integrate modulation and position control, flow measurement and energy harvesting technologies (Cla-Val Ltd, 2013, Series
99-51) and technologies for continuous high-frequency time-synchronized pressure monitoring (Stoianov and Hoskin, 2012), (Fig. 1).

Using the multifunction network controller, an open and adaptive network topology can be implemented that reverts back to the original DMA structure for a few hours each night for minimum night flow analysis and leakage detection (Fig. 2). Therefore, the disadvantages associated with DMAs such as sub-optimal pressure management, reduced resilience to failure, manual response to failure, and water quality concerns can be successfully eliminated whilst its original purpose and success in leakage management is retained. Furthermore, the smallest DMAs possible can be created without compromising on the quality and security of service during peak hours, which will further drive reductions in leakage as water companies gain more insight into their networks. Finally, the continuous monitoring of the hydraulic conditions guarantees the implementation of robust control as it promptly captures hydraulic instabilities thus minimizing the risk for bursts and discoloration complaints.

---

Fig. 1. A self-powered multifunction network controller for dynamically reconfigurable DMAs: (a). The Cal-Val 99-51 which includes an energy harvester (e-Power), a vortex flow meter (e-FlowMeter) and an actuator for position control (CVP-33) is integrated with (b). InfraSense TS for continuous high-speed (128S/s) time-synchronized (5ms) sampling; (c). Retrofitting a PRV with the developed network controller.

Fig. 2. Adaptive water distribution networks with dynamically reconfigurable topology: (a). Original DMA structure (2am-4am) for leakage detection purposes; (b). Aggregating DMAs into larger pressure zones for improved pressure management and redundancy (4am-2am).
2.2. Case Study

The presented concept for DMAs with reconfigurable topology is currently being implemented on a water distribution network in the UK in order to test the technology and assess the performance and scalability. The case study initially consisted of two single-feed DMAs that were separated by three closed boundary valves as shown in Fig. 3a. The installation included the replacement of two boundary valves with self-powered network controllers, and the upgrade and installation of two more internal DMA network controllers as shown in Fig. 3b. A number of critical customers are located in this area, including two hospitals and industrial customers. In addition to the water company’s intention to improve pressure management in these zones, it was also desirable to improve the reliability of supply for these critical customers.

3. Optimization

Each of the control valves will be programmed with an optimal outlet pressure profile. Optimal valve settings are calculated by solving a series of nonlinear programs (NLP) that represent steady-state hydraulic simulations in an extended-period simulation. Typical customer demand and piezometric heads are used as the boundary conditions in the model, which are kept up-to-date using the water company’s telemetry system and the control valves’ monitoring technology.

3.1. Problem formulation

The general structure of the NLP can be stated mathematically as follows:
\begin{align}
\min \ f(H) \\
\text{s.t.} \ g(Q, H, V) &= 0 \\
\text{and} \ h(Q, H, V) &\geq 0
\end{align}

where the decision variables \( Q, H, \) and \( V \) are vectors of link flow rates, nodal piezometric heads, and control valve head losses respectively. The set of all nodes is denoted \( NN \), where \( |NN| = nn \), and the set of all links is denoted \( NP \), where \( |NP| = np \). Control valves are positioned within links, and the set of all control valves is denoted \( NV \), where \( |NV| = nv \) and \( NV \subseteq NP \). The network model consists of some 2,300 nodes, 2,400 links and 4 control valves.

The objective function in Eq. (1) is selected to minimize pressure throughout the network:

\[ F = \sum_{j}^{nn} H_j \]  

The equality constraints in Eq. (2) represent the hydraulic model consisting of \( nn \) linear mass conservation equations at each node:

\[ A21_j Q - q_j = 0 \quad \forall \ j \in NN \]  

and \( np \) nonlinear energy conservation equations for each link:

\[ \Delta H_i + A12_i H + A13_i V + A10_i H0 = 0 \quad \forall \ i \in NP \]  

where \( A21_j \) is the \( j^{th} \) row of a node-branch incidence matrix, \( q \) is a vector of nodal customer demands, \( \Delta H \) is a vector of head losses in each link, \( A12_i \) is the \( i^{th} \) row of a branch-node incidence matrix, \( A13_i \) is the \( i^{th} \) row of a branch-valve incidence matrix, \( A10_i \) is the \( i^{th} \) row of a branch-fixed head node incidence matrix, and \( H0 \) is a vector of fixed piezometric heads. In order to aid convergence of the optimization method, the Hazen-Williams equation is used to calculate the head loss \( \Delta H \), since it does not contain any discontinuities that are found in other head loss equations. The general form of the Hazen-Williams formula is as follows:

\[ \Delta H_i = K_i Q_i^{1.85} \quad \forall \ i \in NP \]  

where \( K \) is a vector of constants calculated as follows:

\[ K_i = \frac{10.67}{C_i^{1.85} D_i^{4.87}} \quad \forall \ i \in NP \]  

where \( C \) is a vector of Hazen-Williams coefficients and \( D \) is a vector of pipe diameters for each link.

The inequality constraints in Eq. (3) represent both valve characteristics and operational limits. Firstly, \( Q \) and \( V \) are bounded in order to ensure control valve \( i \) only removes energy from the flow:
As shown in Eq. (7), each control valve has a resistance coefficient in addition to the independent valve head loss term $V_i$, which ensures that a flow-dependent pressure differential across the valves can be modeled when fully open. This approach simplifies the NLP and therefore aids convergence, as opposed to introducing a valve opening term that is a product of the valve flow as found in the literature (Jowitt and Xu, 1990; Vairavamoorthy and Lumbers, 1998).

Finally, the following inequality constraints ensure that the pressure at all nodes in the network does not fall below a minimum allowable pressure:

$$H_j \geq P_{\text{min}} - \tilde{\lambda}_j + z_j \quad \forall \ j \in NN$$

where $P_{\text{min}}$ is the minimum allowable pressure which has been set to 20mH2O, $z$ is a vector of node elevations, and $\tilde{\lambda}$ is a vector of pressure violation. As suggested by Vairavamoorthy and Lumbers (1998), minor violations in the pressure constraints at certain non-critical nodes are permitted in order to ensure critical nodes in the network reach the target pressure.

3.2. Discussion

The major difficulty in solving the optimization problem defined by Eq. (1) - (3) stems from the fact that there are a high number of nonlinear constraints due to energy conservation defined in Eq. (7). In previous work on valve control (Jowitt and Xu, 1990; Vairavamoorthy and Lumbers, 1998; Ulanicki et al., 2000) the optimization problem has been smaller in size because hypothetical networks have often been used to demonstrate the proposed method, or model skeletonization has been undertaken to reduce the computation burden. Genetic algorithms have also been proposed for pressure management design and operation (Nicolini and Zovatto, 2009) which are capable of solving larger networks, however this approach is generally acknowledged as being unsuitable for near real-time control due to the computational time required to find a solution (Ulanicki et al., 2007; Giacomello et al., 2013).

For this project, an optimization method that does not rely on model skeletonization was sought for the following reasons:

- to facilitate scalability of the scheme;
- to accommodate future modes of operation and objective functions that may be sensitive to the placement of customer demand;
- to retain as much information about the network as possible which helps ensure that the implementation of optimal control does not result in a suboptimal response of the network.

The problem was therefore reformulated with three objectives in mind that to the authors’ knowledge have not all been satisfied by any single approach in previous research on the optimization of valve control:

- reliable convergence of a solution with minimal susceptibility to starting point;
- rapid convergence of a solution for very large networks without the use of network skeletonization;
- a search space with hydraulically feasible iterations to facilitate early termination in critical failure situations.

In order to achieve these objectives, the following observations are made:

- linear programming is generally considered to be a fast, scalable and reliable form of optimization;
• the use of a hydraulic solver at each iteration in the optimization produces hydraulically feasible iterations.

These observations led to the construction of an optimization method that is known as a sequential convex programming method.

3.3. Sequential convex programming

The approach developed in this paper decomposes the main optimization problem into two subsystems, both of which are convex and solved iteratively until convergence is achieved. When both subsystems are convex, the method is known as a sequential convex programming (SCP) method. Although SCP has been acknowledged as a suitable and efficient method for very large scale optimization and control problems (Zillober et al., 2004), it has not previously been applied to the control of water distribution networks.

The method starts with a static hydraulic simulation in order to find $Q$ and $H$ when $V$ is fixed. For this study, the valves are initially set to be fully open, therefore:

$$V_i = 0 \; \forall \; i \in NV$$

(11)

In order to solve the system of partly linear and partly nonlinear equations describing water flow in a water distribution network, the nodal Newton-Raphson method is used due to its speed and efficiency, which is equivalent to solving a convex problem (Todini and Pilati, 1988). This iterative method for calculating nodal hydraulic heads and pipe flows is modified in order to take into account the control valves’ head loss terms:

$$H_{s}^{k+1} = - (A21.N^{-1}.A11^{-1}.A12)^{-1} ...$$

$$... \{A21.N^{-1}.(Q_{s}^{k} + A11^{-1}.(A10.H0 + A13.V)) + (q - A21.Q_{s}^{k})\}$$

$$Q_{s}^{k+1} = (I - N^{-1})Q_{s}^{k} - N^{-1}A11^{-1}(A12.H_{s}^{k+1} + A10.H0 + A13.V)$$

(13)

where $H_s$ is a vector of simulation piezometric heads, $Q_s$ is a vector of simulation flow rates, $N$ is a diagonal matrix containing the head loss formula exponents, $A11$ is a diagonal matrix defined as $K_i|Q_i|^{0.85}$ for $i \in NP$, $I$ is the identity matrix, and $k$ indicates the hydraulic simulation iteration number. Once a set of hydraulically consistent flows and heads have been calculated, a linear program is solved with the following decision variables:

$$x = \{Q, H, V\}^T$$

(14)

A linear approximation of the hydraulic model is constructed at the solution $Q_s$ in order to form the linear program. The only nonlinear term is the head loss formula in Eq. (7) and the linear approximation of this takes the general form:

$$F(Q_i) = A_iQ_i + b_i \; \forall \; i \in NP$$

(15)

with the following boundary conditions:

$$F(0) = 0$$

$$F(Q_{s,i}) = K_iQ_i^{1.85} \; \forall \; i \in NP$$

(16)
These boundary conditions ensure that the linear head loss equation is representative of energy conservation, i.e. that energy losses always occur in the direction of flow. Solving Eq. (15) with Eq. (16) gives:

\[ A_i = K_{i}Q_{s,i}^{0.85} \quad \forall \ i \in NP \]
\[ b_i = 0 \]

(17)

In matrix form, the linearization of energy conservation in Eq. (6) combined with flow continuity in Eq. (5) is therefore as follows:

\[
\begin{bmatrix}
A & A12 & A13 \\
A21 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
Q \\
H \\
V \\
\end{bmatrix}
= 
\begin{bmatrix}
-A10.H0 \\
q \\
\end{bmatrix}
\]

(18)

This system of equations forms the constraints of the convex linear program which can be solved efficiently using a modern program solver. The linear program outputs new valve settings and these are once again used in a nonlinear hydraulic simulation in order to construct another convex approximation that is closer to a local or global NLP optimum. Further iterations are carried until the difference between the linear program and the nonlinear hydraulic solver is sufficiently small. The termination criterion is as follows:

\[
|Q_i - Q_{s,i}| \leq \varepsilon_{tol} \quad \forall \ i \in NP
\]

(19)

where \( \varepsilon_{tol} \) is the termination tolerance equal to \( 10^{-3} \) l/s, which is considered a negligible difference between the flow vectors of the hydraulic solver and its linear approximation. Therefore at this iteration, the solution to the linear program is equivalent to solving the original nonlinear program described in Eq. (1) - (3).

4. Results

The valve settings obtained from the SCP method are used in a commercial hydraulic simulation package in order to validate the hydraulic modeling undertaken in the optimization as well as to compare the performance in pressure management between different configurations of the network. The three configurations to be compared are as follows:

- Case 1: Constant outlet PRVs (valve position one and three in Fig. 3) and closed boundary valves. The valve settings are chosen to ensure the critical point pressure does not fall below 20mH2O, which is most likely to happen during peak demand hours;
- Case 2: Flow modulation PRVs (valve position one and three in Fig. 3) and closed boundary valves. The valve settings are chosen to keep pressure at the critical point at 20mH2O;
- Case 3: Valve settings based on the results of the optimization solver (dynamic DMA topology).

The valve settings calculated using the SCP method for case three are shown in Fig. 4. On average a single NLP took 12 iterations to converge, and did so in every instance. From the optimization solution, the valve settings for valve two showed a very small flow, therefore the valve was set to fully open in order to avoid valve hunting and instabilities.
4.1. Pressure Management

Fig. 5 shows a pressure comparison using the hydraulic model for the three cases. The average zone pressure (AZP) for case three (dynamic topology) is on average 17.6% lower than case one (constant outlet PRVs with a closed DMA structure) and 8.4% lower than case two (flow modulation PRVs with a closed DMA structure). In addition, the diurnal pressure variability is also smaller in case three, with 98% of nodes having pressure variability below 10mH2O. These improvements in pressure management are achieved because energy losses are smaller in an open network that makes use of its inherent redundancy in connectivity.
4.2. Resilience to failure

In order to demonstrate the improvements in resilience, a burst of 5 l/s is simulated in a steady state hydraulic simulation for an open network configuration (valves two and four fully open) and a closed network configuration. For both configurations in normal operation, settings for valves one and three are chosen so that pressure at the critical point is 20mH20. After simulating the burst, pressures drop below 20mH2O in 13.4% of nodes in the closed configuration, whereas only 4.3% of nodes experience pressure below 20mH2O in the open configuration.

5. Conclusion

This paper has demonstrated a novel concept for the management of water distribution networks. By combining advancements in energy harvesting, monitoring, control, modeling and optimization, a new mode of operation can be achieved that makes water networks smarter and more adaptive in response to operational changes and incidents. The concept has been demonstrated in a case study, where the technology has been installed on a water distribution network in the UK identified as needing improved pressure management and security of supply. This trial is currently being extensively monitored in order to assess the benefits of DMAs with dynamic topology and the scalability of the proposed approach. An optimization method based on sequential convex programming has been developed as a fast and reliable method of controlling the valves and dynamic topology, and preliminary results show reduced average zone pressure and diurnal pressure variability, and improvements in the network’s resilience to failure.

Acknowledgements

The authors would like to acknowledge Cla-Val Ltd, Bristol Water Ltd and the Engineering and Physical Sciences Research Council for their financial and technical support.

References