Optimal pump scheduling with pressure control aspects: case studies

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ABSTRACT: In this paper a method for combined energy and pressure management via integration of pump scheduling with pressure control aspects is described and applied to a medium scale water supply network. The method is based on formulating and solving an optimisation problem and involves utilisation of an hydraulic model of the network with pressure dependent leakage and inclusion of a PRV model with the PRV set-points included in a set of decision variables. Such problem formulation led to the optimizer attempting to reduce both energy usage and leakage. Case study considered revealed potential for substantial saving in electrical energy cost using the proposed method. This research is sponsored by and is a part of EPSRC Neptune project (www.neptune.ac.uk). The authors are grateful to Ridwan Patel of Yorkshire Water Services for providing the data used in this paper.

1 INTRODUCTION

Water distribution systems, despite operational improvements introduced over the last 10-15 years, still lose a considerable amount of potable water from their networks due to leakage, whilst using a significant amount of energy for water treatment and pumping. Reduction of leakage, hence savings of clean water, can be achieved by introducing pressure control algorithms (Ulanicki, Bounds, Rance, and Reynolds 2000). Amount of energy used for pumping can be decreased through optimisation of pumps operation (pump scheduling) (Ormsbee and Lansey 2007; Bounds, Kahler, and Ulanicki 2006).

Optimisation of pump schedules and algorithms for control of pressure are traditionally considered separately. However, if the pressure reducing valve (PRV) inlet pressure is higher than required, in many networks it could be reduced by adjusting pumping schedules in the upstream part of the network. Modern pumps are often equipped with variable speed drives, therefore, the pressure could be controlled by manipulating pump speed, thus reduce leakage and energy use. Furthermore, taking into account the presence of pressure-dependent leakage whilst optimising pumps operation is likely to influence the obtained schedules. In this paper development and application of a new method for combined energy and pressure management via coordination of pumps operation with pressure control aspects is presented. Developed methodology is demonstrated on a medium scale water supply system.

2 METHODOLOGY OVERVIEW

The proposed method for combined energy and pressure management, based on formulating and solving an optimisation problem, is an extension of the pump scheduling algorithms described in (Ulanicki, Bounds, and Rance 1999; Bounds, Kahler, and Ulanicki 2006). The method involves utilisation of an hydraulic model of the network with pressure dependent leakage and inclusion of a PRV model with the PRV set-points included in a set of decision variables. The cost function represents the total cost of water treatment and pumping. Figure 1 illustrates that with such approach an excessive pumping contributes to a high total cost in two ways. Firstly, it leads to high energy usage. Secondly, it induces high pressure, hence increased leakage, which means that more water needs to be pumped and taken from sources. Therefore the optimizer, by minimising the total cost, attempts to reduce both energy usage and leakage.

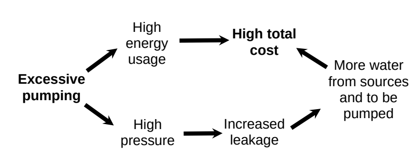

Figure 1: Illustrating how excessive pumping contributes to high total cost when network model with pressure dependent leakage is used.

In the optimisation problem considered some of the decision variables are continuous (e.g. water production, pump speed, and valve position) and some are integer (e.g. number of pumps switched on). Problems containing both continuous and integer variables are called mixed-integer problems and are hard to solve numerically. Continuous relaxation of integer variables (e.g. allowing 2.5 pumps on) enables network scheduling to be treated initially as a continuous optimisation problem solved by a non-linear programming algorithm. Subsequently, the continuous solution can be transformed into an integer solution by manual post-processing, or by further optimisation, see (Bounds, Kahler, and Ulanicki 2006).

Remark 1 *An experienced network operator is able to manually transform continuous pump schedules into equivalent discrete schedules (Ulanicki, Kahler, and See 2007).*

Optimisation methods described in this paper are model-based and, as such, require hydraulic model of the network to be optimised. Such hydraulic model consists of three main components: boundary conditions (sources and exports), a hydraulic nonlinear network made up of pipes, pumps, valves, and reservoir dynamics. In order to reduce the size of the optimisation problem the full hydraulic model is simplified using module reduction algorithm (Ulanicki, Zehnpfund, and Martinez 1996).

3 OPTIMAL NETWORK SCHEDULING PROBLEM

Network scheduling calculates least-cost operational schedules for pumps, valves and treatment works for a given period of time, typically 24 hours. The decision variables are the operational schedules for control components, such as pumps, valves (including PRVs) and water works outputs. The problem has the following three elements: (i) objective function, (ii) hydraulic model of the network and (iii) constraints.

The scheduling problem is succinctly expressed as: minimise (pumping cost + treatment cost), subject to the network equations and operational constraints. The three elements of the problem are discussed in the following subsections. The problem is expressed in discrete-time, as in (Ulanicki, Bounds, and Rance 1999; Bounds, Kahler, and Ulanicki 2006)

3.1 Objective function

The objective function to be minimised is the total energy cost for water treatment and pumping. Pumping cost depends on the efficiency of the pumps used and the electricity power tariff over the pumping duration. The tariff is usually a function of time with cheaper and more expensive periods. For given time step τ_c, the objective function considered over a given time horizon $[k_0, k_f]$ is given by the following equation:

$$\phi = \Big(\sum_{j \in J_p} \sum_{k=k_0}^{k_f} \gamma_p^j(k) f_j\left(q^j(k), c^j(k)\right) + \sum_{j \in J_s} \sum_{k=k_0}^{k_f} \gamma_s^j(k) q_s^j(k) \Big) \tau_c \tag{1}$$

where J_p is the set of indices for pump stations and J_s is the set of indices for treatment works. The vector $c^j(k)$ represents the number of pumps on, denoted $u^j(k)$, and pump speed (for variable speed pumps) denoted $s^j(k)$. The function $\gamma_p^j(k)$ represents the electrical tariff. The treatment cost for each treatment works is proportional to the flow output with the unit price of $\gamma_s^j(k)$. The term $f_j\left(q^j(k), c^j(k)\right)$ represents the electrical power consumed by pump station j.

The mechanical power of water is obtained by multiplying the flow $q^j(k)$ and the head increase $\Delta h^j(k)$ across the pump station. The head increase $\Delta h^j(k)$ can be expressed in terms of flow in the pump hydraulic equation, so that the cost term depends only on the pump station flow $q^j(k)$ and the control variable $c^j(k)$. Finally, the electrical power consumed by the pump station can be calculated using pump power characteristics and the following formula (Ulanicki, Kahler, and Coulbeck 2008):

$$P(q,u,s) = us^3 \left(e \left(\frac{q}{us}\right)^3 + f \left(\frac{q}{us}\right)^2 + g\frac{q}{us} + h \right) \tag{2}$$

where e, f, g, h are power coefficients constant for given pump. Note that, for simplicity of notation, in equation 2 the time-indices k and superscripts j for terms q, u, s were omitted.

3.2 Model of water distribution system

Each network component has a hydraulic equation. The fundamental requirement in an optimal scheduling problem is that all calculated variables satisfy the hydraulic model equations. The network equations are non-linear and play the role of equality constraints in the optimisation problem. The network equations used to describe reservoir dynamics, components hydraulics and mass balance at reservoirs are those described in (Ulanicki, Kahler, and See 2007). Since leakage is assumed to be at connection nodes, the equation to describe mass balance at connection nodes was modified to include the leakage term:

$$\Lambda_c \mathbf{q}(k) + \mathbf{d}_c(k) + \mathbf{l}_c(k) = 0 \tag{3}$$

where Λ_c is node branch incidence matrix, $\mathbf{q}$ is vector of branch flows, $\mathbf{d}_c$ denotes vector of demands and $\mathbf{l}_c$ denotes vector of leakages calculated as:

$$\mathbf{l}_c(k) = \mathbf{p}^{\alpha}(k)\kappa \tag{4}$$

with $\mathbf{p}$ denoting vector of node pressures, $\alpha \in \langle 0.5, 1.5 \rangle$ denoting leakage exponent and κ denoting vector of leakage coefficients, see (Ulanicki, Bounds, Rance, and Reynolds 2000). Note that $\mathbf{p}^{\alpha}$ denotes each element of vector $\mathbf{p}$ raised to the power of α.

3.3 Constraints

In addition to equality constraints described by the hydraulic model equations, operational constraints are applied to keep the system-state within its feasible range. Practical requirements are translated from the linguistic statements into mathematical inequalities. The typical requirements of network scheduling are concerned with reservoir levels in order to prevent emptying or overflowing, and to maintain adequate storage for emergency purposes:

$$h_f^{\min}(k) \leq h_f(k) \leq h_f^{\max}(k) \quad \text{for} \quad k \in [k_0, k_f]$$

Similar constraints must be applied to the heads at critical connection nodes in order to maintain required pressures throughout the water network. Another constraint is on the final water level of reservoirs, such that the final level is not smaller than the initial level. The control variables such as the number of pumps switched on, pump speeds or valve positions, are also constrained by lower and upper constraints determined by the features of the control components.

4 DISCRETISATION OF CONTINUOUS SCHEDULES

In this section a method of transforming the continuous pump schedules obtained by non-linear programming into discrete schedules is described. Let us first introduce some nomenclature and state the assumptions. Let τ_c (introduced in Section 3) denote time step for continuous pump schedules and τ_d denote time step for discrete pump schedules. Define $tp_{i,j}$ as electrical tariff period number i for pump station $j \in J_p$, i.e. i^{th} period over which tariff $\gamma_p^j(k)$ is constant. Let $TPF_c(tp_{i,j})$ and $TPF_d(tp_{i,j})$ denote total flow through pump station j during tariff period $tp_{i,j}$, obtained for continuous and discrete schedule, respectively. In addition to time index k we introduce k_d which denotes time index for discrete schedules; note that time$(k+1) -$ time$(k) = \tau_c$ and time$(k_d+1) -$ time$(k_d) = \tau_d$.

Continuous schedules, i.e. solution of continuous optimisation problem, consist of a set of pump station control vectors $c^j(k)$, each consisting of number of pumps on $u^j(k)$ and pump speed $s^j(k)$, where $u^j(k), s^j(k) \in \mathbb{R};\ u^j(k), s^j(k) \geq 0$. The goal of schedules discretisation process is to produce a set of equivalent control vectors denoted $c_d^j(k_d)$, each consisting of number of pumps on $u_d^j(k_d)$ and pump speed $s_d^j(k_d)$, where $s_d^j(k_d) \in \mathbb{R};\ s_d^j(k_d) \geq 0$ and $u_d^j(k_d) \in \mathbb{N}$.

Proposed schedules discretisation approach is based on concept of matching pump flows resulting from discrete schedule to pump flows resulting from continuous schedule, for each pump and each tariff period. Formally, the approach attempts to generate such discrete schedules that satisfy:

$$\forall j \in J_p\ \forall tp_{i,j}\ \ TPF_c(tp_{i,j}) \approx TPF_d(tp_{i,j}) \tag{5}$$

Assumptions for the considered approach are stated as follows: (i) time steps for continuous and discrete pump schedules are such that $\tau_d \cdot n = \tau_c,\ n \geq 2, n \in \mathbb{N}$, (ii) pump speeds $s_d^j(k_d)$ and $s^j(k)$ are the same during corresponding periods.

Note that second assumption imposes that condition given by Equation 5 needs to be achieved by manipulating number of pumps on in a given pump station, rather than by manipulating their speed. The reason for such assumption is that power consumption increases significantly when the pump speed is increased, see Equation 2. Description of the proposed schedules discretisation process follows.

For given pump station and given time step k, maximum and minimum number of pumps on for all discrete schedule periods k_d corresponding to k are calculated as ceil$\left(u^j(k)\right)$ and integer$\left(u^j(k)\right)$, respectively, where ceil$\left(u^j(k)\right)$ denotes $u^j(k)$ rounded up and integer$\left(u^j(k)\right)$ denotes integer part of $u^j(k)$. Such maximum and minimum are imposed so that the discrete schedules are 'close' to the continuous schedules. Note that the decision variable describing number of pumps on for given pump station, during each k_d corresponding to k, is thus binary, i.e. knowing that at least integer$\left(u^j(k)\right)$ pumps are on, we need to decide whether an additional pump should be on, that is whether $u_d^j(k_d) =$ integer$\left(u^j(k)\right)$ or $u_d^j(k_d) =$ ceil$\left(u^j(k)\right)$. Define $\eta(k)$ as the number of discrete schedule periods k_d corresponding to k when an additional pump is on. Value of $\eta(k)$ is calculated as follows:

$$\eta(k) = \text{round}\left(\text{frac}\left(u^j(k)\right) \cdot \frac{\tau_c}{\tau_d}\right) \tag{6}$$

where frac$\left(u^j(k)\right)$ denotes fractional part of $u^j(k)$.

To illustrate the above description consider the following example. Let $\tau_c = 60$ min, $\tau_d = 15$ min, $u^j(k) = 2.2$ for given pump station and given k. For such τ_c and τ_d we have four discrete schedule periods k_d corresponding to a single k. Maximum and minimum number of pumps on for all k_d corresponding to

k are $\text{ceil}(2.2) = 3$ and $\text{integer}(2.2) = 2$. Using Equation 6 we obtain $\eta(k) = \text{round}\left(\text{frac}\,(2.2) \cdot \frac{60}{15}\right) = 1$, therefore one out of four $u_d^j(k_d)$ is equal 3, while remaining three $u_d^j(k_d)$ are equal 2.

Having $\eta(k)$, it needs to be decided to which k_d an additional pump on is assigned. Using the above example, discrete schedule corresponding to $u^j(k) = 2.2$ could be implemented as $\{2,2,2,3\}$, $\{2,2,3,2\}$, $\{2,3,2,2\}$ or $\{3,2,2,2\}$. Due to remark 1, it was decided to allow the user (operator) to interact with the discretisation process. After $\eta(k)$ is calculated for each k, an initial discrete schedule is automatically generated. Subsequently, the user can alter the discrete schedule by manipulating when an additional pump is on/off for each pump station. By manipulating the discrete schedule the user is therefore able to e.g. reduce the amount of switching on/off, and also to minimise the discrepancy between $TPF_c(tp_{i,j})$ and $TPF_d(tp_{i,j})$, whilst ensuring that the constraints are not violated, or such violation is minimal. To compare $TPF_c(tp_{i,j})$ and $TPF_d(tp_{i,j})$ network simulator is utilised. Note that operator involvement is not essential during schedules discretisation process, but is likely to improve the quality of the obtained discrete schedules. Further details on implementation of the proposed pump schedules discretisation are given in Section 5.

5 IMPLEMENTATION

Developed energy and pressure management continuous scheduler was integrated into a modelling environment, called Finesse. Using model of a network Finesse automatically generates optimal network scheduling problem written in a mathematical modelling language called GAMS (Brooke, Kendrick, Meeraus, and Raman 1998), which calls up a non-linear programming solver called CONOPT (Drud 1985) to calculate a continuous optimisation solution. CONOPT is a non-linear programming solver, which uses a generalised reduced gradient algorithm (Drud 1985). An optimal solution is fed back from CONOPT into Finesse for analysis and/or further processing. For further details on using GAMS and CONOPT for optimal network scheduling see (Ulanicki, Bounds, and Rance 1999).

Proposed interactive schedules discretisation method was implemented in Matlab environment. Developed user interface allows the user to: manipulate the discrete schedule proposed by the algorithm for each pump, export the schedule back to Finesse, load simulation results from Finesse, evaluate $TPF_c(tp_{i,j})$ and $TPF_d(tp_{i,j})$ for each pump and each tariff period. The discretisation software utilises Finesse hydraulic simulator called Ginas to calculate the flows resulting from a given discrete schedule.

6 CASE STUDY

6.1 Network description

The case study selected is medium scale water supply network, being part of Yorkshire Water Services (YWS). The network is fed by two major sources where the first source is modelled as imposed pressure corresponding to the reservoir level, whilst the second is modelled as forced boundary flow into the system. There are two major exports and one import/export where direction of flow changes during one day. The network model provided in Aquis format consists of 2074 nodes, 2212 pipes, 4 reservoirs, 12 pumps and 56 valves (including 7 valves controlled by water-level and one PRV) with a total average demand of 400 l/s. However, 4 out of 12 pumps are in standby mode and it was assumed they should not be used unless in an emergency situation such as failure of other pumps; also 46 out of 56 valves are to remain fully closed during normal operation. Schematic of the case study network is illustrated in Figure 2. Average total demand including exports is approximately 400 l/s. Description of current operation of the network follows in the next subsection.

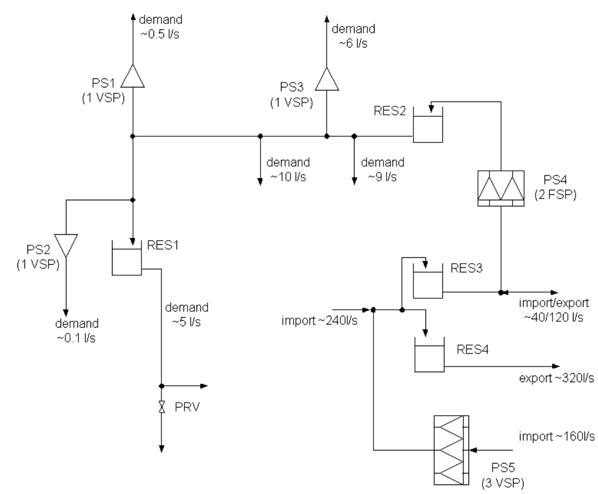

Figure 2: Structure of the YWS case study network. Abbreviations denote: PS - pumping station, FSP - fixed speed pump, VSP - variable speed pump, RES - reservoir. Demands and average import/exports are also depicted.

The booster pumps (PS3, PS3 and PS2) are small pumps that operate such that required outlet pressure is maintained. Their speed, therefore, changes together with demand. PS4 is controlled by water level in reservoir RES2 (on/off control with 20 cm water level margin); typically only one pump is used. Due to tight margin (20 cm) the pump in PS4 is switched on/off frequently, every 7 to 30 minutes. PS5 consists of three large pumps with variable speed drives. They operate to number of preset flow bands; typically only one or two pumps are on.

Provided electricity tariffs are the same for all pumps in the considered network. Only the costs associated with KWh usage are taken into account, i.e. standing charges etc are ignored. Furthermore, it was assumed that winter period week-day tariffs will be used in order to make the 'pattern' of tariff periods more complex than for summer tariffs. Based on these assumptions, the electricity tariffs used in this case study are given in Table 1. Note that due to the confidentiality agreement the actual cost of KWh cannot be disclosed in this paper; cheap tariff is approximately 0.8 of the standard tariff, whilst expensive tariff is approximately twice the standard tariff.

Table 1: Electricity tariffs used.

Time	Cost (p/KWh)
00.00 - 07.00	cheap
07.00 - 16.00	standard
16.00 - 18.00	expensive
18.00 - 00.00	standard

6.2 Modelling

A model of the network was provided in Aquis format. Structure of nodes and pipes was automatically converted into Epanet format and subsequently imported into Finesse. Other network elements, i.e. reservoirs, pumps and valves, were added manually to the Finesse model.

Pumps, valves and reservoirs parameters were described in Finesse using data from Aquis model. Local control rules were removed for PS4. Instead, time-series describing pumps operation, taken from results of Aquis simulation, were fed into the Finesse model. It was found that in Aquis model, which allows variable simulation step, the pump in PS4 was switching at intervals as small as 7 minutes, due to tight margin (20 cm). To represent such irregular switching and model similar operation of this pump in Finesse, where minimal time step is 15 minutes, it was assumed that e.g. 0.5 pump is on during a single time step.

Once the Finesse model was completed, it was simplified using Finesse model reduction module (Ulanicki, Zehnpfund, and Martinez 1996) to reduce the size of the optimisation problem. In the simplified model all control elements remained unchanged, but the number of pipes and nodes was reduced to 45 and 43, respectively. Subsequently, both full and simplified Finesse models were simulated and compared, with respect to pump flow and reservoir trajectories, against the reference Aquis model. Since the reservoirs RES4 and RES3 are directly connected, it is considered sufficient to compare average levels for these two reservoirs. Both Finesse models showed satisfactory agreement, see reservoir trajectories illustrated in Figure 3.

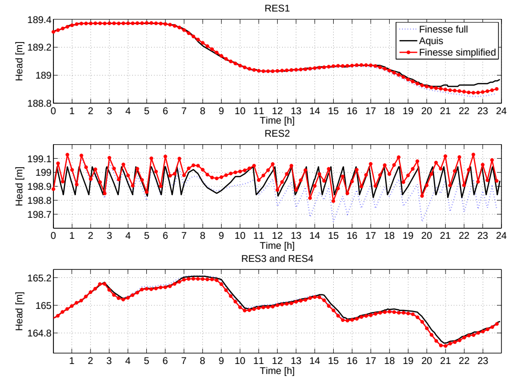

Figure 3: Illustrating reservoir level trajectories for full Finesse model, simplified Finesse model and reference Aquis model

6.3 Network scheduling

For the purpose of network scheduling 1 hour time step for the continuous optimisation problem was used ($\tau_c = 60$ min) and 15 minutes time step for the schedules discretiser ($\tau_d = 15$ min). Only limited information about leakage in the considered network was available at the time this work was carried out. According to YWS there is a considerable leakage on the connection between PS5 and reservoirs RES4 and RES3, due to significant distance and elevation difference which require high pressure at PS5 outlet. Therefore, in the study described in next subsections the leakage was assumed to be on this connection. Leakage coefficient α in Equation 4 was chosen to be 1.1.

6.3.1 Comparison of energy cost: current and optimised operation

In this subsection a comparison, in terms of energy cost, between current and optimised operation is considered. To be able to compare the cost a case with no pressure-dependent leakage was considered, i.e. κ in Equation 4 was zero for all nodes. Initial reservoir levels were assumed to be in the middle of their bounds to allow more flexibility for optimisation. The continuous optimisation ran for 2 minutes on a Pentium 4 3GHz PC. Continuous solution was transformed into an integer solution using the discretiser. Obtained pump schedules for PS4 and PS5 are illustrated in Figure 4 and Figure 5, respectively.

It can be observed in Figure 4 that due to operational constraints, particularly small size of RES2, current and optimal schedules are similar, i.e. both exhibit frequent switching throughout the 24h period. In Figure 5 it can be observed that optimal schedules for PS5 cause an intensive pumping during the cheap tariff period to fill RES4 and RES3, which subsequently supply water during the expensive tariff period. The operational speed of PS5 pumps is lower, compared to current operation, particularly during the expensive

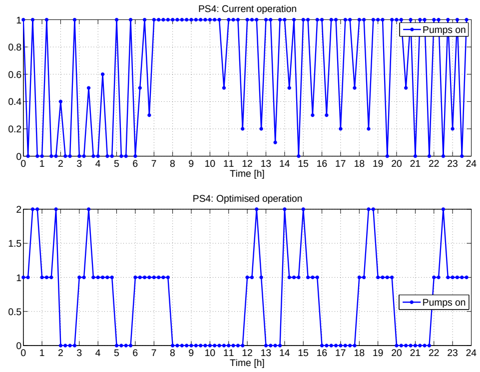

Figure 4: Comparison of current and optimised network operation for PS4

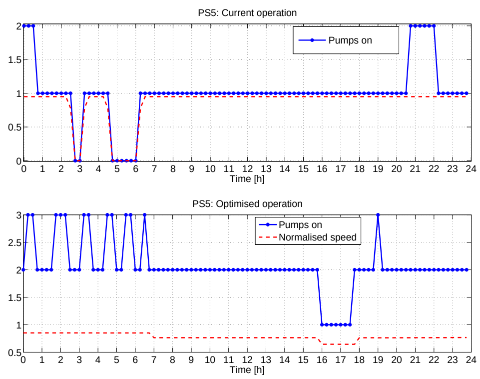

Figure 5: Comparison of current and optimised network operation for PS5

tariff period, which also contributes to reduced cost.

Calculated daily cost of electrical energy for PS4 and PS5 was as follows: £402 for current network operation, £264 for optimised continuous solution and £266 for integer solution. As expected, significant savings (35%) result from optimising the operation of PS5, whilst optimising the operation of PS4 reduced its energy cost only by 15%. This is due to: (i) PS5 consisting of variable-speed pumps and (ii) large size of reservoirs RES4 and RES3 giving more flexibility than RES2. The results also indicate that the schedule discretisation process did not increase the cost significantly compared to continuous schedules.

6.3.2 Different leakage levels

The network optimiser was run for several scenarios, assuming different leakages levels. Information about the electrical tariffs in the considered water network was not available at the time this particular part of study was carried out. For this reason the tariffs were assumed to represent a typical scheme of cheap at night and expensive during day. Assumed tariffs were: 0.1 unit/kWh between 22:00 - 07:00 and 0.2 unit/kWh between 07:00 - 22:00. Three scenarios were considered for different leakage levels. Parameter κ in Equation 4 was chosen such that the leakage at a node close to the outlet of PS5 was approximately 10%, 20% or 30% of the flow for scenarios 1, 2 and 3, respectively. Leakage was assumed to be zero at other nodes. The continuous optimisation ran for 2 minutes on a Pentium 4 3GHz PC. Obtained pump schedules for PS5 for different scenarios are illustrated in Figure 6; only continuous solutions are illustrated for simplicity. Daily cost of electrical energy was 534, 547 and 562 units for scenarios 1, 2 and 3, respectively.

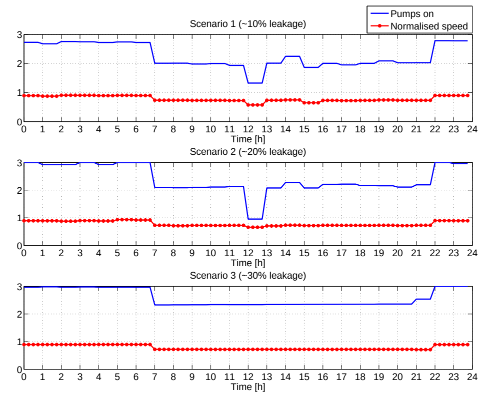

Figure 6: Comparison of PS5 pump schedules for three different leakage levels using assumed tariffs.

It was found that increased leakage coefficient, not surprisingly, led to increased cost, since harder pumping is required due to increased pump flow, as can be seen in Figure 6. The patterns of pump schedules for all cases exhibit intensive pumping during the cheap tariff period to fill reservoirs RES4 and RES3, which subsequently supply water during the expensive tariff period.

6.3.3 Different demand levels and initial conditions

This subsection considers network scheduling for different demand levels and different initial conditions, i.e. initial water levels in reservoirs. Actual electricity tariffs, summarised in Section 6.1, were utilised in this study. Parameter κ in Equation 4 was chosen such that the leakage at a node close to the outlet of PS5 was approximately 15% of the flow.

All nominal (from Aquis model) demands and import/export flows were multiplied by 0.75 and 1.25 for ‘low demands’ and ‘high demands’ scenarios, respectively. Demands for ‘medium demands’ scenarios remain unchanged. Initial reservoir water levels, chosen independently for each reservoir, were at 25%, 50% and 75% of the maximum level. In total 27 scenarios were scheduled; generated library of schedules will be utilised as a basis to develop an expert system for rule-based pump control. Three example schedules of PS5, obtained for initial reservoir water levels at 50% and three different demand levels, are illustrated in Figure 7.

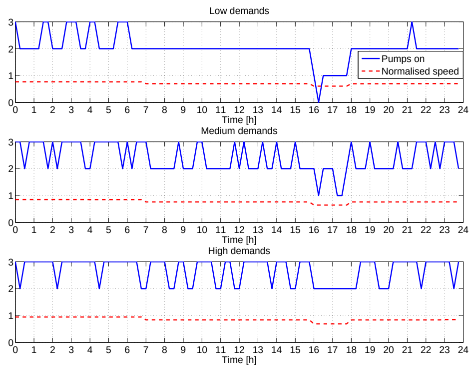

Figure 7: Comparison of schedules of PS5 for 3 demand levels

It can be observed in Figure 7 that increased demands, not surprisingly, required more intensive pumping in terms of both speed and number of pumps on. The cost, taking into account only PS5, was £164, £255 and £388 for low, medium and high demands, respectively. Note that increase in demands by a factor of 1.25 (for high demands scenario) resulted in increase of cost by a factor of 1.5, compared to medium demands. Similarly, decrease in demands by a factor of 0.75 (for low demands scenario) resulted in decrease of cost by a factor of 0.65. This indicates that the pumping cost increases exponentially with demand levels.

7 CONCLUSIONS

In this paper a method was described for combined energy and pressure management via integration and coordination of pump scheduling with pressure control aspects. The method is based on formulating and solving an optimisation problem and involves utilisation of an hydraulic model of the network with pressure dependent leakage and inclusion of a PRV model with the PRV set-points included in a set of decision variables. The cost function of the optimisation problem represents the total cost of water treatment and pumping.

The case study selected was a medium scale water supply network, being part of Yorkshire Water Services (YWS). Developed models, both full and simplified, showed good agreement with the reference Aquis model provided by YWS. Network scheduling studies considered different leakage levels, initial reservoir levels and demand levels. A comparison has been made between the cost of the current network operation and the optimised operation. Taking into account only the costs associated with KWh usage of scheduled pumping stations and assuming winter tariff the optimised operation reduced the daily electricity cost from £402 to £266. A library of 27 schedules for different scenarios was generated for the purpose of developing an expert system for rule-based pump control. Results obtained for different demand levels indicate that the pumping cost increases exponentially with demand levels.

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