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ScienceDirect

Procedia Engineering 70 (2014) 1378 – 1385

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

Multi-stage linear programming optimization for pump scheduling

V. Puleo[a*], M. Morley[b], G. Freni[c], D. Savić[b]

[a]Dip. di Ing. Civile, Ambientale, Aerospaziale e dei Materiali, Università degli Studi di Palermo, Viale delle Scienze, Edificio 8, Palermo 90128, Italy
[b]Centre for Water Systems, Coll. of Eng., Math. and Phys. Sciences, University of Exeter, North Park Road, Exeter, EX4 4QF, UK
[c]Facoltà di Ingegneria ed Architettura, Università "KORE" di Enna, Cittadella Universitaria, Enna 94100, Italy

Abstract

This study presents a methodology based on Linear Programming for determining the optimal pump schedule on a 24-hour basis, considering as decision variables the continuous pump flow rates which are subsequently transformed into a discrete schedule. The methodology was applied on a case study derived from the benchmark Anytown network. To evaluate the LP reliability, a comparison was made with solutions generated by a Hybrid Discrete Dynamically Dimensioned Search (HD-DDS) algorithm. The cost associated with the result derived from the LP initial solution was shown to be lower than that obtained with repeated HD-DDS runs with differing random seeds.

Keywords: Pump scheduling; Optimization; Linear Programming; HD-DDS.

1. Introduction

In recent years, much research has focused on optimizing pump operation schedules; with increasing energy prices, the cost of electricity used for pumping represents the single largest part of the total operational cost in water distribution systems. The scheduling of pumps is frequently undertaken in near-real time, in order to minimize cost and maximize energy savings, however this requires a computationally efficient algorithm that can rapidly identify an acceptable solution.

Several optimization techniques have been applied to obtain solutions to the pump-scheduling problem: linear (Jowitt and Germanopoulos, 1992), non-linear (Yu et al., 1994) and dynamic programming (Lansey and Awumah, 1994), heuristics (Ormsbee and Reddy, 1995) and evolutionary computation (Savić et al., 1997; McCormick and Powell, 2003; van Zyl et al., 2004, Lopez-Ibáñez et al., 2008). Most of them, either greatly simplify the complex water distribution system or require significant time to solve the problem, limiting their real-time capabilities. An interesting literature review on optimal water distribution control models was provided in Price and Ostfeld (2013). According to the number of variables and objectives considered, optimizing the pump-scheduling problem may become very complex, particularly for large networks.

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In the literature several methods have been proposed. Lansey and Awumah (1994) have determined the optimal pump operations considering the energy and the pump maintenance costs using dynamic programming showed good

* Corresponding author. Tel.: +39-091-23896574; fax: +39-091-6657749.
E-mail address: valeria.puleo@unipa.it

doi:10.1016/j.proeng.2014.02.152

results for real-time application. Unfortunately, this method is impractical when there are more than three reservoirs; nevertheless, this limitation can be overcome where large systems consist of a number of small subsystems which are hydraulically independent. The model performs off-line hydraulic simulations in order to develop the functions describing the network hydraulics and the energy consumption into the dynamic programming algorithm.

In water distribution systems (WDSs), characterized by multiple reservoirs, more sophisticated techniques for generating optimized pumping schedules have been applied. Yu et al. (1994) proposed a non-linear programing based method where a generalized, reduced gradient technique was used to calculate optimal strategies for reducing the number of full-network simulations. The method does not require any network simplification and it can be used for near-real time application, even if the simulator efficiency improvement is needed. McCormick and Powell (2003) outlined a hydraulic network linearization for two stage Simulated Annealing (SA) algorithm. Although this technique is able to find a near global optimal solution, it is time consuming and, as a consequence, its application is often limited to off-line optimization problems. Nevertheless, the authors have demonstrated that linear programming can be a viable part of the solution process and that it can accelerate SA optimizations. A similar approach was undertaken by van Zyl et al. (2004), in which they coupled a Genetic Algorithm (GA) to two hill-climbing search algorithms for improving the local GA search once close to an optimal solution. Although these efforts employ evolutionary optimization techniques, operating directly on hydraulic simulation, these cannot cope with near-real time use. Conversely, Linear Programming (LP), for example, has been shown to be an appropriate technique for this application (Jowitt and Germanopoulos, 1992). The advantage of the LP model is that it can be solved quickly but requires that both objective function and constraints be linear. It assumes near-linear operating conditions in pumping stations as well as within the network. The linear model can be used for systems with multiple pumping stations, but the resulting accuracy and reliability can be quite poor. However, in recent literature, particular attention has been paid to the applicability of LP to the pumping scheduling optimization problem.

Pasha and Lansey (2009) formulated the LP optimization problem, linearizing the pumping station relationships by using the relationship between energy, pump flow, user demand and tank water levels. In particular the energy consumed has been approximated as a linear function of the pumping station flow and the initial tank level; the LP model was then tested on a single tank system, although the authors stated that it could be easily extended to more complex systems. Further investigation into the use of LP algorithm has been reported in Giacomello et al. (2013). Here, a fast, hybrid optimization method was developed, coupling LP with a greedy algorithm which was chosen as the local search method. The former solves a "reduced complexity" hydraulic model, then the latter the "full complexity" hydraulic model: the greedy algorithm performing a search starting from the pumping schedule identified by the LP method. They also demonstrated that the hybrid method, when compared to the GA optimization method, is capable of solving the real-life pump scheduling problem in a much more computationally efficient manner.

In this study, a methodology based on LP has been developed for determining the optimal pump schedule. The resulting model does not guarantee the identification of the global optimum solution of the pump scheduling problem, due to the inaccuracies introduced by linearization. However, it can provide a solution of sufficient quality to be applied in practice.

The methodology was applied on a case study derived from the benchmark Anytown network (Walski et al., 1987). In order to evaluate the reliability of the LP, a comparison was made with solutions generated by a Hybrid Discrete Dynamically Dimensioned Search (HD-DDS) algorithm (Tolson et al. (2009)) which is further addressed below.

2. Problem formulation

As mentioned above, the pump scheduling problem can be formulated as optimization problem which aims to minimize the energy costs, while keeping within physical and operational constraints. The optimization period is divided into a number of discrete control intervals which must be such that a meaningful definition of the problem is obtained. The structure of the electricity tariff and the system component characteristics inform this selection: the smaller the interval, the greater the accuracy of the analysis. However, the number of decision variables and constraints increases significantly with the number of control intervals defined, leading to increased computational and memory requirements for the solution (Jowitt and Germanopoulos, 1992). To reduce the total number of variables, a single decision variable for each pump station and time interval, that relates the particular set of pumps in operation during that period, can be developed (Ormsbee and Reddy, 1995).

According to these considerations, in this study, the objective function (Eq. 1) was defined in terms of pump station discharges Q_t, in place of a single pump status, considering both the network hydraulics and the electricity tariff embedded into the coefficients c_t, as described below. The optimization period was divided into intervals of one hour. The maximum and minimum water levels into the tank (Eq. 2), as well as the limit of the pump station duties (Eq. 3), were considered. Further constraints ensure that the tank level at the end of the optimization period is not lower than the level at the beginning of the next period (Eq. 4) and the tank mass balance over each control interval (Eq. 5) is satisfied. The resulting optimization problem can be then formulated as: