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Real-time optimal control of water distribution systems

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Abstract

This study attempts to develop a real-time optimal control model for water distribution network. The model aims to minimize operation cost by optimal control of pump system, while satisfying various operational constraints under demand fluctuations and energy tariff variations throughout operation period. The real-time control is realized using SCADA system, by which monitoring data is collected and the obtained control decisions are implemented. Optimal pump scheduling model is developed by combining demand forecasting, hydraulic simulation, and optimization models. Decision variables include pump on/off (binary code of 0/1) schedules for fixed-rate pumps for each time-step over pre-defined operation time horizon. Various operational constraints are applied such as, 1) maintaining system pressure near allowable minimum pressure avoiding excessive pressure to reduce energy consumption and non-revenue water, 2) maintaining tank water level within an appropriate range, and 3) peak energy consumption limit for each pump station. The proposed model follows four steps; step1) demand forecasting, step 2) system update based on SCADA monitoring data, step 3) optimizing pump/valve control decision, and 4) implementing current time control settings.

Keywords: Optimization; Real-time pump operation; Water distribution system

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1. Introduction

Optimal water distribution system (WDS) operation is to adjust the control components, such as pumps and valves to minimize pumping costs while ensuring customer demands with required delivery pressure. Since WDS is a large and complex network, the optimal operation is a quite difficult task. The operation was conventionally managed by skilled staff based on a pre-defined pump-scheduling rules and, recently, limited information was

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provided for decision making process with aid of SCADA (Supervisory Control and Data Acquisition) facilities. Bearing in mind the uncertainties associated with demands, the current operation scheme is not efficient for reducing energy cost and maintaining system-wide operation pressure. Given the uncertainty in system demands and network status, there is an inevitable tendency for the operators to maintain a higher pressure than required in traditional operation strategy. Since system leakage is a function of pressure, this approach induces leakage losses and is unfavorable for sustainable water supply practice. It is always advantage to maintain the system pressure as low as possible while still comply with the required pressure requirement. Recently notable studies for optimal WDS operation have been published including Alvisi et al. (2007), Jamieson et al. (2007), Martinez et al. (2007), Rao and Alvarruiz (2007), Rao and Salomons (2007), and Salomons et al. (2007). Note these studies were published as companion papers and they presented the real-time WDS operation approaches in a project called potable water distribution management (POWADIMA). Referring to these remarkable studies, here, an optimization approach is suggested for real-time, on-line control of system, which proactively responds to short-term demand variations and minimizes long-term system operation costs. The proposed model combines three computational modules of (1) demand forecasting, (2) hydraulic simulation, and (3) system control optimization modules.

2. Methodology

2.1. Model overview

Optimizing the operation of a water distribution network is a discrete non-linear, non-smooth combinatorial problem. The decision variables comprise each pump's status (on/off) at each time step up to the operating horizon. A real-time operation is a dynamic process that regularly rolls forward with each update of the SCADA monitoring and incorporates demand forecasts over the next operating time horizon. In this application, a genetic algorithm (GA) optimizer and a hydraulic simulator, EPANET, have been combined. The hydraulic simulation model is to determine the feasibility of each potential solution proposed by the GA and estimate any penalties on constraint violations. In addition, a demand forecasting model is embedded in the optimization framework. After optimizing the control settings for the current condition and each time-step up to the operating horizon, only the decision for the current time-step would be sent via the SCADA facilities for implementation. Then the model waits till the next time-step before receiving the monitoring data from the SCADA facilities to establish the revised state of the network and repeating the whole process as demand is continuously varied. Consequently, the previously EPANET simulated tank water levels at the next time step are revised as the monitored values from the SCADA facilities to minimize any errors occurred. In searching for the optimal control of pumps, it is necessary to calculate control settings for not only current time step but also those up to the operating horizon, in order to select the least-cost pumping strategy. To do this, the model should incorporate the demand forecasts. Again, only the optimal control settings for the current time step are implemented since there is no reason to implement the decisions of the future that has not realized. The objective is to meet the current and forecast demands on the network at minimal operating cost, without violating any operational constraints. Following the next update of the SCADA facilities, which defines the current state of the network, the whole process is repeated to accommodate any amendments to the demand forecasts. Rolling the process forward at short, regular time intervals gives an approximation to optimal system control. Fig 1. illustrates model flowchart.

2.2. Decision variables

The decision variables of the model are the operational settings of the pumps for each time step up to the operating horizon. For fixed-rate pumps, the decision variable is confined to pump status which can be either off or on (0/1 binary decision). Urban water distribution networks generally operate on a daily cycle, thus the typical operating horizon is 24 h. In some networks where the storage facility is large, it may be appropriate to consider a longer operating time horizon to fully explore the energy tariff structure. Here a 48-h operating horizon was selected. The choice of the time step is also a profound impact on the computational time. Here, a fairly conservative time step of 1 h was selected.

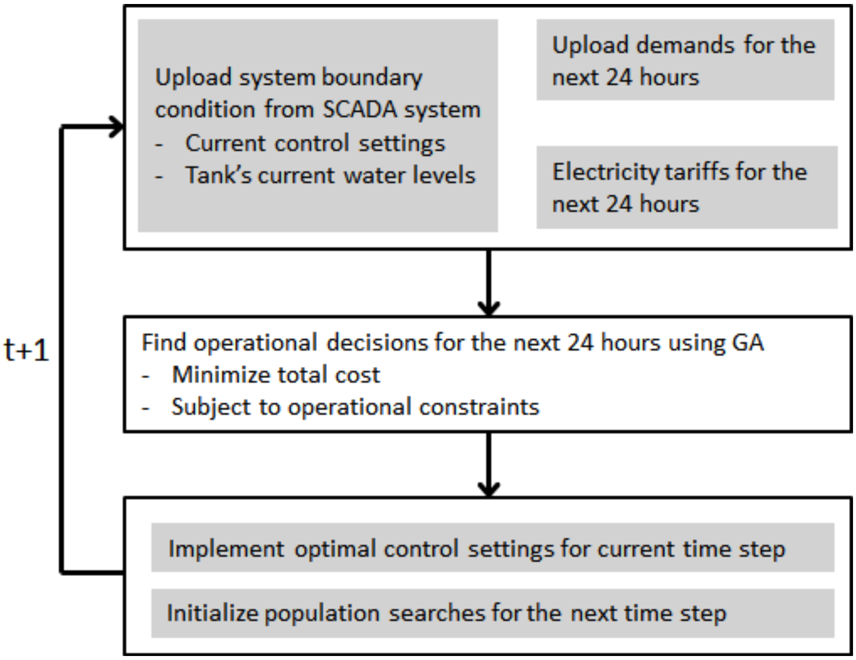

Fig. 1. Schematic diagram of the proposed optimization model

2.3. Objective function and constraints

The basic objective function of real-time, near-optimal control of water distribution networks is to minimize the overall cost of delivering the required amount of water to customers, subject to maintaining a specified delivery pressure and other operational constraints. Here the objective function is to minimize the energy costs of meeting the current and future demands up to the operating horizon, while satisfying various operational constraints. The following constraints have been included in the optimization framework:
(1) A minimum pressure has to be maintained at all demand nodes;
(2) Each storage tank water level should be maintained between a maximum and minimum range, defining the normal operating range;
(3) The water level in each storage tank has to be at or above a prescribed value at a fixed time in the early morning; that is, the operators eager to have the tank water surface above a certain level before the demand increases.

2.4. Warm initial population

Normally, initialization of the decision variables in GA is random. However, the repetitive nature of real-time decisions offers the potential to reduce the number of generations to find the new control settings in GA process. That is, since the operating decisions at the current time-step is not expected to be radically different from the next, rather than randomly initializing the decision variables at the next update, the contemporaneous portion of current GA decisions can be used as initial starting conditions for the next GA runs. As a result, it is expected the number of generations required to find the optimal settings for the next time-step can be reduced significantly. The proposed approach is illustrated in Fig. 2.

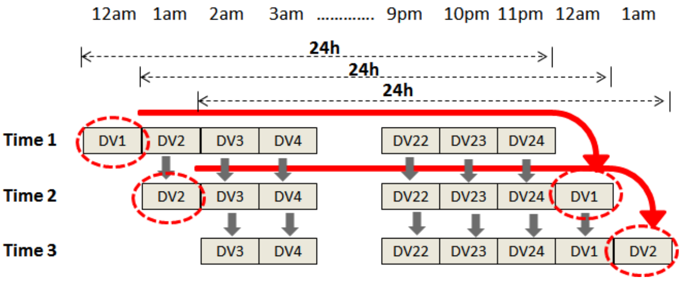

Fig. 2. A scheme for generating warm initial population in GA

3. Application results

3.1. Study network

The study network is a pilot plant system composed of 1 reservoir (T103), 3 pumps (P101, P102, and P103), 2 tanks (T101 and T102), 169 nodes, and 213 pipes as shown in Fig. 3. SCADA facilities are located in the reservoir and tanks to monitor water level, and flow rates and pressures are monitored at the outlet of each pump station. The electricity tariff has a daily pattern with three discrete periods, each having a different charge as listed in Table 1.

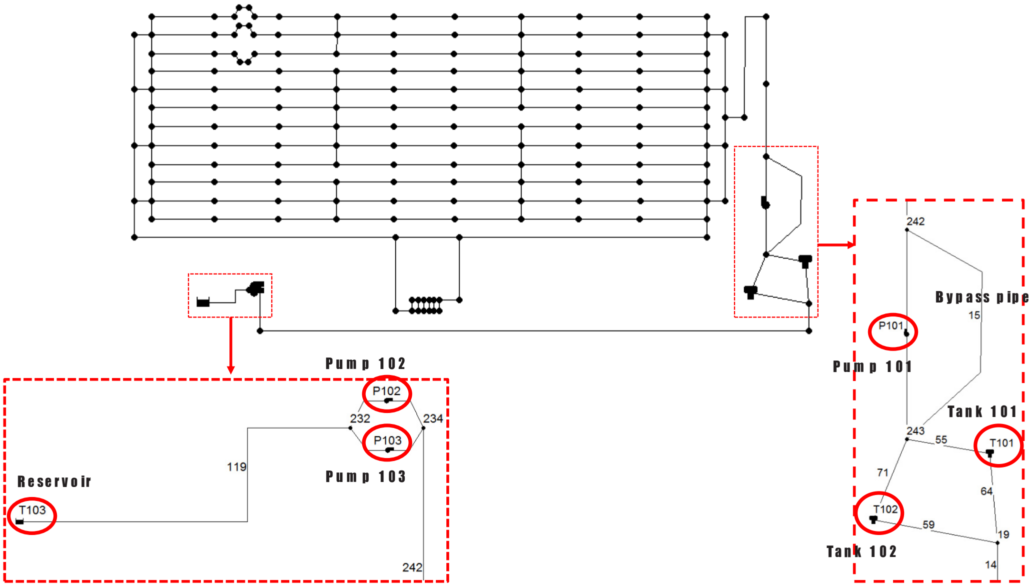

Fig. 3. Pilot plant study network

Table 1. Energy tariff structure

Time	Energy cost (USD/kWh)
0:00~06:00	0.087
06:00~15:00	0.284
15:00~21:00	0.186
21:00~24:00	0.087

3.2. Results

For illustration purposes, two operating schemes were simulated. Firstly, conventional operating scheme (i.e., utility's rule-based operation) is simulated, in which the pump control decisions are dependent upon the storage tank water levels. More specifically, each pumping unit is assigned water levels for each tank, one at which the pumps are switched on, the other for them to be switched off. Therefore, it can be inferred that energy consumption is not considered to be a high priority, with no special attention being given to the electricity tariff and demand variation. Although this approach is accepted by the utilities because the approach is simple and guarantees supply reliability, it is likely to be inefficient for minimizing energy costs and maintaining system pressure at the desired level. The pumping units are assumed to be operated following the pre-determined rules listed in Table 2 to maintain the storage tank water levels within a defined range. Second simulation was done using the proposed real-time optimal model, in which the pump on/off status was controlled in real-time based on the forecasted demands and monitored tank water levels. The 48-hr pump operating schedules by the two applied schemes are depicted in Fig. 4. As seen, by the rule-based controls, P103 is frequently operating to maintain the water level at the downstream tanks. On the contrary, for optimal operating scheme, P101 (smallest in size) is more often operating to satisfy the minimum pressure requirement throughout the system. P103 for optimal simulation operates less frequently that allows tank water level fluctuations, while still satisfying the minimum allowable tank water levels.

Table 2. Pump/pipe control rules

Pump	P101	Close	when	Tank	T102	water level is above 3.0
Pump	P102	Close	when	Tank	T102	water level is above 3.0
Pump	P103	OPEN	when	Tank	T102	water level is above 3.0
Pipe	15	OPEN	when	Tank	T102	water level is above 3.0
Pump	P101	OPEN	when	Tank	T102	water level is below 2.5
Pump	P102	OPEN	when	Tank	T102	water level is below 2.5
Pump	P103	Close	when	Tank	T102	water level is below 2.5
Pipe	15	Close	when	Tank	T102	water level is below 2.5

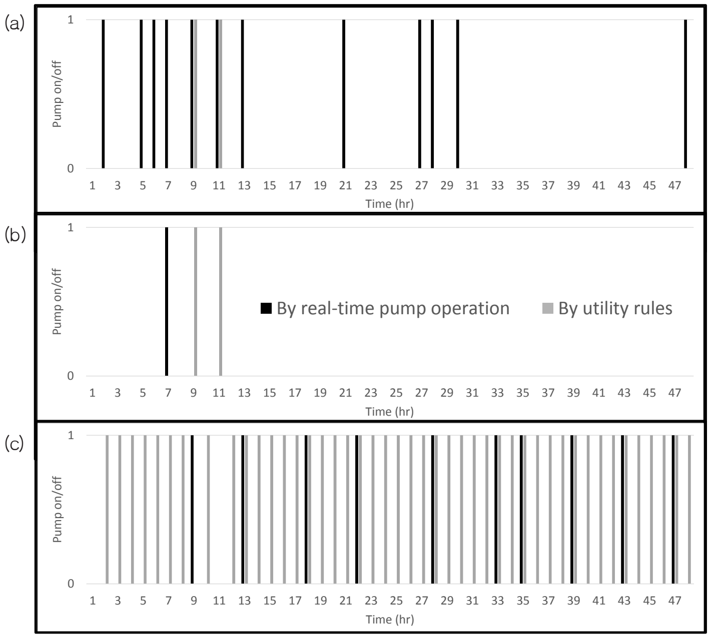

Fig. 4. Pump operating results by conventional rules and real-time optimal operation: (a) P101, (b) P102, and (c) P103

Fig. 5 depicts the water level changes at the storage tanks. As expected, the patterns are quite different; by the rule-based controls, the water levels are maintained within narrow boundary (2.5 ~ 2.9m), while periodic fluctuations are observed for the real-time optimal simulations. The energy cost of each pump for 48-hr durations are summarized in Table 3. By optimal operations, the total energy cost was reduces as 1/5 of the rule-based operation. Among three pumps, largest saving was obtained for P103.

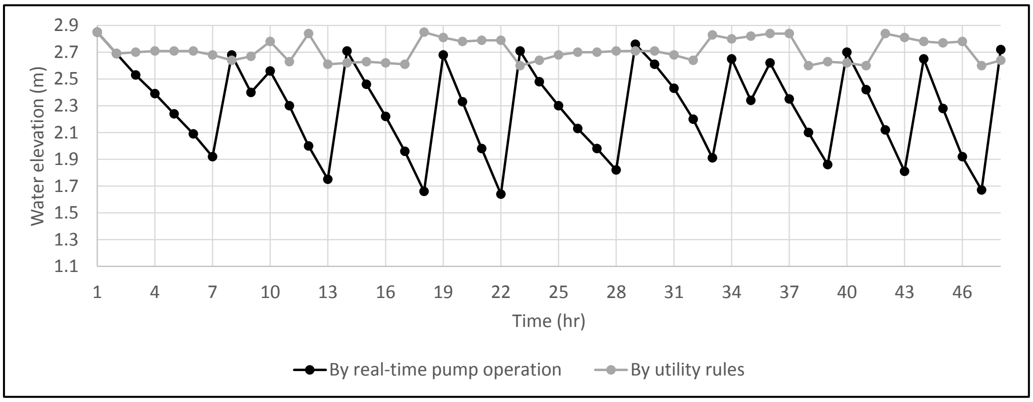

Fig. 5. Water level changes at T101 and T102

Table 3. Energy costs for two operating schemes (Cost in $USD)

	P101	P102	P103	Total
Optimal operation	0.35	2.16	12.24	14.75
Rule-based operation	0.14	14.93	56.78	71.86

4. Discussion

It was possible to find the optimal, or at least near-optimal, pump control settings for the present time step as well as those up to a selected operating horizon, taking account of demand forecasting, the electricity tariff structure and operational constraints such as minimum delivery pressures, etc. The obtained control settings for the present time are implemented using SCADA system. Having grounded any discrepancies between the previously predicted and the measured storage water levels at current update of the monitoring facilities, the whole process is repeated on a rolling basis and a new control decisions are made as time moves on. From the simple network applications, it was found that the proposed real-time operation approach reduces energy cost significantly compared to the rule-based operations while maintaining various operational constraints. Given the high variability of demands and the need to adjust the control apparatus frequently, the time available between successive system updates is a critical factor in judging the availability of the proposed model. For the applied simple network, it took 22mins to run one time-step optimization simulation. Since most urban water distribution networks are large and complex, the simulation time would be troublesome to apply the proposed model to real networks. Therefore, the question arises how the optimal-control strategy can be derived in a short period of time. Efforts to mitigate the simulation time will be pursued as future study.

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