Water supply control system for smarter electricity power usage adopting demand-response scheme

H. Tadokoro, H. Koibuchi, S. Takahashi, S. Kakudou, Y. Takata, D. Moriya and M. Sasakawa

ABSTRACT

Demand-response is a scheme in which electricity suppliers and consumers collaborate for smarter usage of electricity aiming to mitigate the gap between supply and demand. It makes electricity consumers receive incentives through curtailing or increasing power demand during a certain period subject to request from the power infrastructure. Water utilities, as heavy electricity consumers, could participate in the scheme through shifting power demand by modifying pump operation schedule, utilizing reservoirs’ buffering stock capability. We developed a conveyance/transmission pump scheduling algorithm to be applied in the scheme that requires a quick modification of pumping schedule to respond to a request. In addition, we made test bedding through a simulation approach utilizing actual data from Osaka Water Supply Authority to show the scheme’s potential for waterworks and the effectiveness of the algorithm.

Key words | demand-response, mathematical programming, pumps operation scheduling

INTRODUCTION

According to the Japan Water Works Association, water utilities are heavy consumers of electricity that use close to 1% of the total energy consumption in Japan, and reducing electricity charges is one of the key issues. Conveyance/transmission pumps especially account for much of it. On the other hand, electric power companies have been required to manage electric supply and demand balance, which is getting less controllable due to the increase of renewable energy. As a means to mitigate gaps between electricity supply and demand, the demand-response (hereinafter called ‘DR’) scheme is under consideration. It makes electricity consumers receive incentives through curtailing or increasing power demand during a certain period subject to request from the power infrastructure. That is beneficial not only for the electric power companies but also for electricity consumers. Water utilities, which consume a great amount of electricity, could contribute to the DR scheme by making conveyance/transmission pump operation schedules utilize reservoirs' buffering stock capability without increasing reservoirs' capacity.

The water utilities make daily pump operation schedules to fulfill a water demand that varies according to the time of the day, day of the week, weather etc. In addition, for a better operation schedule, stable water supply and lower energy consumption are to be considered. To make the daily schedule automatic, various mathematical programming
techniques have been adopted (Ulanicki et al. 2007; Puig et al. 2012) such as multi-objective optimization (Kurek & Ostfeld 2014; Odan et al. 2015). This kind of scheduling problem is formulated as mixed-integer programming (MIP) (Bunn & Reynolds 2009), which is known to be time-consuming. Bioinspired algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO) (Kang 2014; Bohórquez et al. 2015; Castro-Gama et al. 2017; Brentan et al. 2018; Khatakar & Mays 2018) have been utilized to overcome this, but still require much time to obtain near-optimal solutions. An AI approach such as neural network has also been made (Wu & Behandish 2015), which uses a large amount of data to reach a practical solution. To solve the problems above, we have developed a scheduling algorithm, which is an approximate optimization method combining linear programming (LP) and a heuristic method (Tadokoro et al. 2013).

When water utilities participate in the DR scheme, they need to consider curtailing or increasing pumping during the requested period from the power infrastructure, which makes the scheduling problem more complicated. Moreover, the request could come at a short period in advance (e.g. 15 minutes). Accordingly, it is key to develop a new scheduling algorithm to handle curtailing or increasing power demand during requested timeslots as well as criteria such as meeting varying water demand, stable water supply and lowering energy consumption within limited computation time. We enhanced our scheduling algorithm by introducing minimum—maximum optimization, so as to meet the requirements above in the demand-curtailment case (Takahashi et al. 2017).

This paper describes the developed method improved to be utilized also in the demand-increasing case, and shows test bedding results applied to a large water utility.

WATER SUPPLY CONTROL SYSTEM AND DEMAND-RESPONSE SCHEME

Water supply control system overview

A water supply control system, which is configured as a sub-system of supervisory control and data acquisition (SCADA) system, manages the daily schedule of water production, conveyance/transmission and distribution in a water utility. The system remotely monitors and controls geographically dispersed facilities in a water supply network such as purification plants, reservoirs and pumping stations (Figure 1). The system has two main functions, which are water demand forecasting and pumping operation scheduling. The first function forecasts daily water demand in each distribution area in a time series (e.g. every 30 minutes) by multiple regression analysis using weather, temperature, and daily water demand as explanatory variables. The second function plans the optimal daily conveyance/transmission schedule that minimizes objective functions including power consumption and fluctuation in flow rates, while fulfilling water demand under constraints of the facilities such as production capacity of purification plants, pumping capacity in pumping stations and water level of reservoirs. The schedule describes a time series of water flow rate and water level for every time step in a scheduling period, for example, every 30 minutes in 24 hours. It is drafted basically once a day, and modified on an ad hoc basis to countermeasure a situation such as trouble in the facilities.

Demand-response scheme

The USA’s Federal Energy Regulatory Commission defines DR as, ‘Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market price or when system reliability is
jeopardized. In the DR scheme that is under consideration in Japan, an electricity power company communicates with electricity consumers via aggregators to ask for curtailment or increase of power demand during a certain period, and consumers get incentives by responding to the requests (Figure 2). The aggregators accumulate responses from consumers and deal with electricity power companies. In introducing a DR scheme that shifts or cuts power demand in a timely way, power infrastructure can not only manage its peak demand periods without setting up or up-scaling facilities, but also utilize renewable energy efficiently in case the generated electricity exceeds the demand, without installing batteries.

Water utilities that are heavy electricity consumers can participate in the scheme through modifying the daily water supply operation schedule utilizing reservoirs' buffering capability. They can shift power demand in response to the requests from aggregators and contribute to the smarter energy usage of their community. However, the following issues are to be discussed for them to participate.

(1) Primarily for water utilities, stable and reliable water supply is a must, and reservoirs’ capacity is designed in preparation for abnormalities such as trouble at water supply facilities or sudden electricity outage, and accordingly they are required to consider risks in responding to DR requests.

(2) Since DR requests might be sent on an ad hoc basis, 15 to 30 minutes in advance in the least case, water utilities are required to modify their schedule in near real-time.

**SCHEDULING ALGORITHM**

To solve the issues, we developed a scheduling algorithm for water supply control systems. It was designed to solve the computation time problem based on the heuristic approach narrowing down the MIP search space, and we enhanced the algorithm so as to be utilized in the DR scheme as follows.

(1) Making the whole time pumping schedule without a considered DR request. It is an optimal schedule without the DR scheme. This schedule is made by multi-objective programming (MOP) and quasi-optimal routing system (QRS) (Tadokoro et al. 2015). MOP solves the problem using linear programming (LP) to make the computation time short and selects the most satisfactory schedule. QRS is based on heuristic rules. It discretizes the schedule of the fixed pumps that is not well modified in LP.

(2) Modifying the schedule during the DR requested period, MIP is used to minimize maximum demand power in demand curtailment, and maximize minimum demand power in demand increase. The problem of planning an optimal pump operation schedule during the time period of DR is formulated as follows.

\[
\min \max_{X} E_t(X)
\]

\[
E_t(X) = \frac{1}{2} \cdot (e_{t-1}(x_{2t-1}) + e_{t}(x_{2t})) \quad (1 \leq t \leq T)
\]

\[
e_t(x_t) = a \cdot x_t + b \cdot 1 \quad (1 \leq t' \leq 2T)
\]

\[
X = [x_1, x_2, \ldots, x_{2T}]
\]

\[
x_t = \begin{bmatrix}
x_{1,t} \\
x_{2,t} \\
\vdots \\
x_{n,t}
\end{bmatrix}
\]

Equation (1) is the objective function. \( E_t(X) \) is demand power for every 30 minutes by which the power company evaluates it as a time step. \( X \), described in Equation (4), denotes a matrix of the numbers of driving pumps at each pump station and \( t \) denotes time with a time step of 30 minutes. The objective function is set for determining \( X \) to minimize maximum demand
power at \( t \). Equation (2) is a formula to calculate every 50 minutes of demand power by averaging 15 minutes of it. Equation (3) is a formula to calculate every 15 minutes of demand power, where \( e_x(x_x) \) denotes demand power at time \( t \) and \( x_x \), which is described in Equation (5), denotes a vector of the numbers of driving pumps at pump station \( n \) at time \( t' \), and \( t' \) denotes a time step of 15 minutes. We used a short time step of 15 minutes for scheduling to reduce or increase peak power as much as possible. Symbols \( a \) and \( b \) denote constant vectors. The numbers of driving pumps \( X \) are determined under some constraints below.

\[
l_{i,t} = l_{i,t-1} + \frac{\Delta t}{S_i} \cdot (c_{i,t} \cdot f_t + c_{2i} \cdot f_{0r} - d_{i,t}) \quad (1 \leq t' \leq 2T + T_0)
\]

\[
l_{\text{min},i,t} \leq l_{i,t} \leq l_{\text{max},i,t} \quad (1 \leq t' \leq 2T + T_0)
\]

\[
l_{\text{min},i,t} = \frac{\Delta t \sum_{t'=t+1}^{t+48} d_{i,t}}{S_i}
\]

\[
f_t = a_1 \cdot x_t + b_1 \quad (1 \leq t' \leq 2T)
\]

\[
f_{i,t} = f_{\text{max},i,t} \quad (2T + 1 \leq t' \leq 2T + T_0)
\]

\[
f_t = \begin{bmatrix} f_{1,t} \\ f_{2,t} \\ \vdots \\ f_{n,t} \end{bmatrix}, \quad f_{0r} = \begin{bmatrix} f_{0,1,t} \\ f_{0,2,t} \\ \vdots \\ f_{0,m,t} \end{bmatrix}
\]

Equation (6) is a formula to calculate water level during the DR period and until a certain time period \( T_0 \) after the DR, and \( l_{i,t} \) denotes the water level at distribution reservoir \( i \) at time \( t' \). \( \Delta t \) denotes a time step of scheduling that is 15 minutes and \( S_i \) denotes the cross-sectional area of reservoir \( i \). Symbols \( c_{1i} \) and \( c_{2i} \) denote constant vectors, \( f_t \) denotes a vector of flow rates under DR operations at pump station \( n \) at time \( t' \), \( f_{0r} \) denotes a vector of flow rates under normal operations at pump station \( m \) at time \( t' \), which are described in Equation (12), and \( d_{i,t} \) denotes the flow rate of water distributed from reservoir \( i \). The water level needs to satisfy the constraints described in Equations (7) and (8), where \( l_{\text{min},i,t} \) denotes the lower limit of the water level at reservoir \( i \) at time \( t' \), and \( l_{\text{max},i,t} \) denotes its upper limit. The lower limit of the water level during the DR and after the DR is described in Equation (9). It guarantees the water level is kept for water demand for 12 hours. Equations (10) and (11) are formulas to calculate the flow rate, and \( a_1 \) and \( b_1 \) denote constant vectors. The flow rate is set by the number of driving pumps during the DR period and maximum flow rate \( f_{\text{max},i,t} \) at each pump station after the DR period. Initial conditions, water level and flow rates at the start of the DR period, are given from the schedule set out in (1).

(3) Re-schedule the whole time operation by applying the same method as in (1). The pumping schedules during DR periods are given as additional constraints.

By using this developed algorithm, the schedules during DR periods are optimized for DR and in the other periods are optimized for conventional objectives (energy savings, balance of intakes, etc.). The problem of computation time can be solved by applying MIP only to the DR period.

**FEASIBILITY STUDY**

To investigate the potential of the DR scheme in waterworks and verify the effectiveness of the developed scheduling algorithm, we made a case study in the water conveyance network. This study was performed as part of a subsidy project by the New Energy Promotion Council and conducted with Osaka Water Supply Authority as a test bedding field. The authority is the bulk water supplier to 42 municipalities in the prefecture, and its daily supply capacity is 2,330,000 m³. The studied conveyance network consists of three purification plants, six reservoirs, and 15 pumping facilities (Figure 3). A total of 116 connection points to the municipalities are grouped in 21 demand points. We evaluated eight cases of DR potential (four cases in summer, four cases in winter). DR requested periods are two or three consecutive hours between 15:00 and 18:00 in summer and between 17:00 and 20:00 in winter, which are peak times of electricity demand so it is very likely to be requested demand curtailment. There are the same consecutive hours are between 12:00 and 15:00, which are hours when renewable energy supply possibly exceeds demand so it is very likely to be a requested demand increase.
Figure 3 | Conveyance network of Osaka Water Supply Authority (‘P’ represents pumping facility).
Each simulation makes a 30 minute time series schedule for 48 hours. The schedule in the DR case is required to comply with the following conditions, the same as the usual operation to ensure secure and stable water supply. Although the authority has applied time-of-use (TOU) electricity pricing that is similar to the DR, we did not consider TOU to estimate DR potential properly.

- Flow rates in water purification plants are considered to be as constant as possible in purification process operation.
- Each conveyance line has its upper and lower limit in flow rate.
- Each reservoir has an upper and lower limit in water level for keeping a safety stock of water, and the water level recovers close to the upper limit at 7:00 enabling it to cope with sharp water demand increase in the morning.
- The supplying flow rate to each municipality is equal to the usual operation case.

RESULTS

Demand curtailment simulation results are shown in Table 1. The DR potential is the total curtailment of power demand in the conveyance network. To evaluate the DR potential, the DR operation schedule is compared with the usual operation schedule. The DR potential is evaluated at a time step of 30 minutes but the average value during the DR period is shown in the table. It shows that the water supply system can reduce power demand by 2,221 to 3,592 kW during the DR period. In case 1, the usual power demand during the DR period was 32,080 kW (not shown), accordingly the power demand can be reduced by 11.2%. The computation time of the simulation by PC (CPU: Intel Core i5-4590 3.30 GHz, RAM: 4GB) was approximately 1 minute. It shows the computation time is reasonable even if the developed algorithm is applied to a large water network.

As an example, schedules of Banpaku Pumping Station (Banpaku) and Senri Reservoir Station (Senri), whose location is the dotted area in Figure 3, in case 1 are shown in Figure 4(a) and 4(b). Senri receives water from Banpaku and Onohara Pumping Station (Onohara). The schedule of Onohara during the DR period is same as the usual (not shown). The usual flow rate of Banpaku during the DR period is 6,085 m³/h (17:00 to 18:00) and 6,213 m³/h (18:00 to 19:00), which is equal to a large pump operation. The simulation shows that flow rate can be reduced to 2,750 m³/h (a small pump operation) in that period. The change of pump operation corresponds to 1,053 kW. The water level at Senri does not fall below the lower limit during the DR period and after the DR. So it can be said that Banpaku has 1,053 kW DR potential. In evaluating other facilities, four facilities (Murano, Niwakubo, Fujiidera, and Sayama) also have DR potential.

Table 2 shows the demand increase simulation results. The DR operation schedule can increase power demand by 7,304 to 8,624 kW. In case 5, the usual power demand during the DR period was 31,823 kW (not shown), accordingly there can be an increase of 27.1% of power demand. Computation time of all the simulations was less than 1 minute.

As an example, schedules of Banpaku and Senri in case 5 are shown in Figure 5(a) and 5(b). The usual flow rate of Banpaku during the DR period is 6,284 m³/h (12:00 to 13:00) and 6,054 m³/h (13:00 to 14:00), which is equal to a large pump operation. And the flow rates can be increased to 10,800 m³/h (two large pump operations) in that period. The change of pump operation corresponds to 1,444 kW. In evaluating other facilities, all of them except two pumping facilities (Onohara and Fujiidera) have DR potential.

Table 1: Demand curtailment potential and computation time at Osaka Water Supply Authority

<table>
<thead>
<tr>
<th>Season</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR period</td>
<td>Winter</td>
<td>Winter</td>
<td>Summer</td>
<td>Summer</td>
</tr>
<tr>
<td>DR potential (kW)</td>
<td>3,592</td>
<td>2,221</td>
<td>3,185</td>
<td>3,511</td>
</tr>
<tr>
<td>Computation time (sec)</td>
<td>43.162</td>
<td>38.366</td>
<td>68.293</td>
<td>53.972</td>
</tr>
</tbody>
</table>

aAverage value during the DR period.
CONCLUSIONS

The feasibility study shows that Osaka Water Supply Authority has potential to be a resource provider through modifying their pumping schedule and utilizing reservoirs’ buffering stock capability. There are many water utilities that have similar conveyance/transmission systems to the authority that can also apply the DR scheme.

In participating in the DR scheme, water utilities might need to modify their schedules in near real-time while sustaining secure and stable water supply. The proposed scheduling algorithm made daily pumping schedules under...
the DR scheme in around 1 minute even in the case of a large water utility. In addition, the schedules did not violate operational conditions such as water demand and control ranges of water level. It shows that the algorithm can strongly support water utilities in joining the DR scheme.

REFERENCES

Bohórquez, J., Saldarriaga, J. & Vallejo, G. 2015 Pumping pattern optimization in order to reduce WDS operation costs. 
Procedia Engineering 119, 1069–1077.
Journal of Water Resources Planning and Management 144 (9), 04018055.
Bunn, S. M. & Reynolds, L. 2009 The energy-efficiency benefits of pump-scheduling optimization for potable water supplies. 
Procedia Engineering 186, 436–443.
Kang, D. 2014 Real-time optimal control of water distribution systems. 
Procedia Engineering 70, 917–923.
Khatavkar, P. & Mays, L. W. 2018 Model for real-time operations of water distribution systems under limited electrical power availability with consideration of water quality. 
Journal of Water Resources Planning and Management 144 (11), 04018071.
Kurek, W. & Ostfeld, A. 2014 Multiobjective water distribution systems control of pumping cost, water quality, and storage-reliability constraints. 
Journal of Water Resources Planning and Management 141 (9), 04015011.
Procedia Engineering 186, 327–332.
Journal of Water Resources Planning and Management 133 (1), 23–32.

First received 7 November 2018; accepted in revised form 24 September 2019. Available online 11 October 2019