Optimum Simulation and Control of Fixed-Speed Pumping Stations

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Abstract: Traditional set point control and operation of a pumping station using fixed speed pumps usually amplify both the frequency and magnitude of variations in the influent flow rate. The purpose of the present study is to develop a control strategy to minimize these unwanted hydraulic surges. To realize this, an optimum control model was developed using computer simulation. The model is suitable for both separate and combined pumping installations. It is superior to conventional set point control techniques and reduces the frequency of starting and stopping pumps as well as energy consumption. The model uses energy saving and outflow smoothing factors to provide the improved control. Appropriate values of the two factors will depend on specific site conditions, such as pump lift height, wet-well depth, number of pumps and their sizes.

INTRODUCTION

The design and operation of a pumping station, as well as the selection of an appropriate control strategy, are difficult problems. The main reasons are large variations in flow rate and the comparatively small storage capacity provided by wet wells (Andrews 1984). The small storage volume is due to the high capital cost, the inability to use the collection system for storage, and the maximum hydraulic residence time that wastewater can be stored without sedimentation of solids and generation of odors. For fixed speed pumping installations, these limitations can result in too-frequent starting and stopping of the pumps, which create man-made hydraulic shocks (Olsson 1985). The problem is also complicated by the need for high reliability of pumping stations in order to avoid sewer overflow and surcharge. This frequently results in use of oversized pumps which will further increase the number of on-off cycles, and cause even larger hydraulic shocks to the downstream treatment processes.

Pumping stations are the major consumers of energy in wastewater collection systems. Common characteristics of most wastewater pumping stations are high ratios of static head to friction head. Keeping water level in the wet well as high as possible, thus decreasing the static head, can substantially reduce power requirements.

Several investigators have reported techniques to minimize hydraulic shocks caused by operation of fixed speed pumps using set point control in a feedback loop (Pincince 1970; Vitasovic et al. 1985). Bouck and Webb (1980) used different sizes of pumps that produce as many as 17 various flow rates to match the influent flow rate pattern of the diurnal variation. This approach requires a large number of spare pumps, and the different combinations of pumps make the operation complicated. The approach does not optimize the combination of pumps and does not address energy savings. A similar approach has been taken by Goldschmidt (1978); however, his method can only be applied to pumping systems where each pump has its own suction pipings and discharges into a common header. Robinson et al. (1991) used a group of fixed speed and variable speed pumps to obtain a smoother outflow profile. In their study the system also has equalization tanks that provide damping capacity to smooth out the hydraulic surges.

In the present study, two typical pumping installations are investigated. One is a pumping station where each pump has its own suction and discharge pipes, and the other is a pumping station where the pumps discharge into a common header. An optimum control model was developed to minimize both the number of pump on-off cycles and power consumption. The trade-off between the two objectives was obtained using two weighting factors: an energy saving factor and an outflow smoothing factor. The technique was mathematically modeled and simulated and the results have shown that the optimum control model with a feedback loop is superior to the conventional high-low set point control scheme. This study used actual flow rate data as the model input, and the results of the study should be useful as a semiquantitative aid for pumping station design.

The influent flow rate data were collected from the Interbay Pumping Station in Seattle, Wash. (Vitasovic 1990). A typical pump curve was selected for the system. The modeling and simulation were performed using an integration of the software packages Statgraphics (Statistical 1987), Simnon (Elmqvist 1990), and EBL Plus (Seaware 1990).

MODEL DEVELOPMENT

The design of a pumping station consists of four major items: determination of influent flow rate patterns, wet-well volume, pump number and sizes, and control system. Actual data for a 24-h period were used as the inputs to the simulation. A more advanced approach would be to use ARIMA models (Box and Jenkins 1976; Pankratz 1983) to model the influent flow rate patterns (Yin 1991), and is the subject of our future work. Models for the rest of the three components were established separately.

Wet Well

Based on a material balance, the differential equation describing the relationship between influent flow rate, outflow rate and wet-well volume is

$$dV/dt = Q_i - Q_o \quad (1)$$

Eq. (1) can be written in the form of a finite difference equation

$$V_t = V_{t-1} + (Q_i - Q_o)\Delta t \quad (2)$$

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where V_t and V_{t-1} = tank volume at t and $t - 1$, respectively; Q_i, Q_o = influent and effluent flow rate, respectively; and Δt = time interval between two samples. In traditional pump control techniques, the water level in the wet well is usually maintained at a set point or range around a set point. Eq. (2) can be written in terms of water level in the wet well as follows:

$$H_t = H_{t-1} + (Q_i - Q_o)\Delta t/A \quad (3)$$

where H_t and H_{t-1} = water level in wet well at t and $t - 1$, respectively; and A = wet-well surface area.

Characteristic Curves of Pumping Systems

There are three functions (curves) that represent the characteristics of a pumping system: pump head-capacity, pump efficiency, and system head-capacity. The first two curves are intrinsic to the pumps and can be measured or obtained from the pump manufacturer. The third is obtained by calculating head losses at different flow rates for the piping system. Once the construction of the pumping station is accomplished, the shape of the system curve is fixed.

Vitasovic (1986) proposed a polynomial equation to mathematically describe the curves. In fact, for pump specific speeds less than 80, a parabolic equation adequately describes the characteristic curves of fixed speed pumps. In the present study, the researchers used the following polynomial equations for the pump head-capacity, efficiency, and system head-capacity curves, respectively:

$$H_P = A_1 + B_1 Q + C_1 Q^2 \quad (4)$$

$$E_f = A_3 + B_3 Q + C_3 Q^2 + D_3 Q^3 \quad (5)$$

$$H_s = A_2 + B_2 Q + C_2 Q^2 \quad (6)$$

where As, Bs and Cs = parameters identified from curves using least-square regressions; H_p = pump lift head; H_s = system head; E_f = pump efficiency; and Q = pump flow rate at the operating point (Fig. 1).

There are two common types of fixed speed pump installations: one is the system in which each pump has its own suction and discharge piping, the other is where all pumps discharge to a common header or force main. In the following sections, we abbreviate the former as installation type 1 and the latter as installation type 2. The modeling and calculation of the operation points of each pump for the two configurations are different. Fig. 1 shows a typical curve for a fixed speed pump working individually. The intersection between the pump head-capacity curve and system curve is the pump operating point. The operating point corresponding to the range of the highest pump efficiency is called the best efficiency point (BEP). Since the authors did not have information on the pump head and efficiency curves for the Interbay Pumping Station, typical curves for a radial-flow pump were selected as a basis for pump station modeling and simulation.

For installation 1, since the pump works individually, the pump characteristic curves can be directly applied to each pump working in parallel, and (4), (5), and (6) were employed to fit the curves. For installation 2, the curves can not be directly used since each pump delivers certain amount of water to a common force main. The basic pump curves in Fig. 1 were modified to address the effect of the head losses. For this installation a total system curve is needed. Fig. 2 shows the pump head-capacity and system head-capacity curves for four pumps working in parallel and using a common header. The amount of water each pump delivers is additive and the static head of each pump is the same, but the total dynamic head for each pump is different. Eqs. (4), (5), and (6) can also be applied to these curves. The intersections between the pump and system head-capacity curves are the operation points for the system where all pumps share a common header.

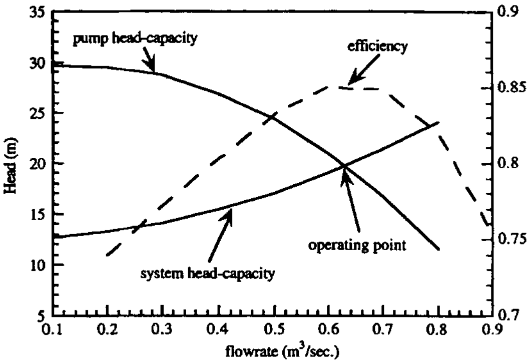

FIG. 1. Pump Head, Efficiency, and Pumping System Characteristic Curves

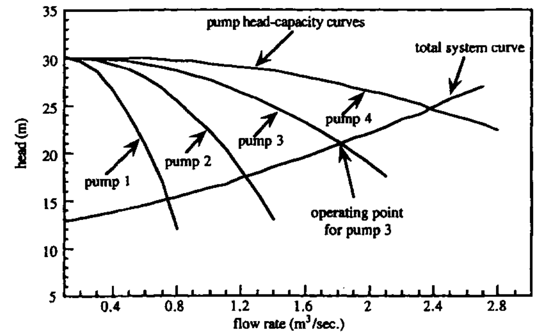

FIG. 2. System Curves for Four Pumps Working in Parallel and Discharging to One Common Header

The operating point varies dynamically for both pumping systems because of changes in the flow rate of pumps and water level in the wet well (changes of system static head). To accommodate operating points for each pump at every sampling time, Newton's interpolation method was applied to obtain the solutions using polynomial equations (4), (5), and (6).

Optimum Control Model

The goals of the optimum control model presented herein are to reduce pump cycling frequency, thus minimizing hydraulic surfaces and maximizing pump life, and minimizing energy consumption. To realize the first objective, we expect to minimize the deviations of the pump outflow rates between samples $t - 1$ and t, as follows:

$$\min Z_{1t} = (F_{t-1} - F_t)^2 \quad (7)$$

where F_{t-1} and F_t = pump outflow rates at $t - 1$ and t, respectively. To realize the energy consumption objective, the water level in the wet well at time t should be maintained as high as possible to reduce lift head, as follows:

$$\min Z_{2t} = (H_{up} - H_t)^2 \quad (8)$$

where H_{up} = top limit of water level in wet well; and H_t = water level at time t. For fixed-speed pumps the outflow rate at time t can be written in the form of a summation of pump capacities

$$F_t = \sum_{j=1}^{K} Q_{j,t} X_{j,t} \quad (9)$$

where j = pump number, $j = 1, \ldots, K$; $Q_{j,t}$ = average outflow rate of jth pump over time interval $t - 1$ to t, and can be obtained from flow-rate axis corresponding to operating point in Fig. 1. It varies since the operation point is changing with time. $X_{j,t}$ = state variable of the jth pump over the time interval $t - 1$ to t. For fixed speed pumps $X_{j,t}$ equals one when the pump is on and zero when the pump is off. Based on (3) we can express the dynamic water level in the wet well as

$$H_t = H_{t-1} + \left[\left(Q_{\text{in}_t} - \sum_{j=1}^{K} Q_{j,t}X_{j,t}\right)\Delta t\right] \Big/ A \qquad (10)$$

where $Q_{i,t}$ = influent flow rate; A = cross-section area of wet well; and Δt = sampling interval (using 1 min for all simulations). In order to combine the two different objective functions into a single function, an energy weighting factor α and a flow smoothing weighting factor β are introduced ($\alpha + \beta = 1$). Substituting (9) and (10) into the objective functions and combining the two objective functions (Z_{1t}, Z_{2t}) into a single function (Z_t), we obtain

$$\min Z_t = \alpha \left\{ H_{\text{up}} - \left[H_{t-1} + \left(\frac{Q_{\text{in}_t} - \sum_{j=1}^{K} Q_{j,t}X_{j,t}}{A} \right) \Delta t \right] \right\}^2 + \beta \left(F_{t-1} - \sum_{j=1}^{K} Q_{j,t}X_{j,t} \right)^2 \qquad (11)$$

This function is subject to the following constraints at any sampling interval

$$H_{t-1} + \frac{\left(Q_{\text{in}_t} - \sum_{j=1}^{K} Q_{j,t}X_{j,t}\right)\Delta t}{A} \le H_{\text{up}} \text{ for all } j \qquad (12)$$

$$H_{t-1} + \frac{\left(Q_{\text{in}_t} - \sum_{j=1}^{K} Q_{j,t}X_{j,t}\right)\Delta t}{A} \ge H_{\text{down}} \text{ for all } j \qquad (13)$$

$$\sum_{k=t+1}^{t+pj} X_{j,k} = 0 \text{ for all } j \qquad (14)$$

$$X_{j,t} = 0,\ 1 \text{ for all } j \qquad (15)$$

$$Q_{i,t},\ H_t, \text{ and } F_t \ge 0 \text{ for all } j \qquad (16)$$

where $(t + p_j)$th time interval is defined such that the total time between time t and time $t + p_j \ge M_j$; M_j = minimum off time for jth pump, which is function of cooling rate for pump motor; and H_{down} = lower limit of water level in wet well. The p_j can be defined as $M_j/\Delta t$. Since Δt is 1 min for all the simulation, then $p_j = M_j$. It should be noted that (14) does not apply when the jth pump is on and the minimum pump cycling time is satisfied. The constraint (14) is applied only when the jth pump is turned off and the cooling time is not satisfied. This logic was included in the program's FORTRAN code.

The constraints given in equations 12 and 13 require that the water level in the wet well at any sampling time not exceed the upper and lower limits. Eq. 14 states that each pump, once it stops, must remain stopped until the minimum time for cooling (M_j) has elapsed. This constraint is applied whenever the jth pump is turned off. The minimum cooling time (M_j) required for motors depends on their size. For larger motors, longer cooling times are required. For traditional set point control it is difficult to satisfy this constraint, especially when the variations of influent are large and unknown. Therefore, (14) is frequently violated in practice. M_j was assigned 20 min in the simulation. The optimal controller satisfies this constraint for all cases, except in the Sensitivity Analysis section, in which the constraint was removed to observe the maximum energy conservation.

Eqs. (11) through (16) comprise a nonlinear mixed integer programming problem (MIP). The combination of the solutions is 2^K, where K = number of pumps. In the present study we used four identical pumps in simulation. Eq. 11 along with constraint equations is solved at each sampling time to determine the optimum combination of pump states ($X_{j,t}$). There are a number of methods available to solve these kinds of discrete equations (Ignizio 1982). In the present study, a cutting plane method, which is a modified simplex method for integer programming, was used to obtain the optimum states of each pump. The complexity of solving the MIP greatly depends on the size of the problem, which is largely determined by the numbers and the sizes of pumps.

The results presented later for the various control strategies are optimized at each time interval in the simulation. An alternative strategy, which is capable of determining the optimal pumping schedule over an interval of time, has been developed for a limited number of cases. For this alternative, one must know or predict future flow rates. All the cases presented in the present paper use only the flow rate at the current time for optimization.

RESULTS AND ANALYSIS

In the following sections, the writers present simulations for four fixed speed pumps working in parallel for a typical day for the two types of pumping station installations. First, we show the simulation results and comparison between conventional two point control and optimum control for the system in which each pump has its own suction and discharge pipes (installation 1). Next, the effects of the wet-well volume on conventional and optimum controls for this system are analyzed. Comparisons of the two control schemes for the system where a common header is used (installation 2) are then presented. Finally, a sensitivity analysis for use in choosing numerical values for the two weighting factors is performed.

Two Point On-Off Control for Installation 1

Two point on-off controllers are frequently used for the control of fixed speed pumps in wastewater collection systems (IAWPRC 1989). Two typical strategies (modes A and B) are presented here for comparison with the optimal control techniques. Fig. 3 shows the two control schemes for four pumps working in parallel in a closed feedback loop. The major measurement is the water level in the wet well.

For mode A, when the water level exceeds set point L_2, pump 1 will start; if the water level increases continuously and is higher than set point M, pump 2 will start; the same procedures are applied to pump 3 and 4 to start at set points H_2 and H_1, respectively. When the water level is lower than set point M both pumps 3 and 4 stop, and pumps 1 and 2 stop at set point L_1. For mode B, the starting procedure is the same as in mode A, but the stopping processes are different. Pumps 4, 3, 2, and 1 stop working whenever the water level is lower than the set points H_2, M, L_2, and L_1, respectively. In this

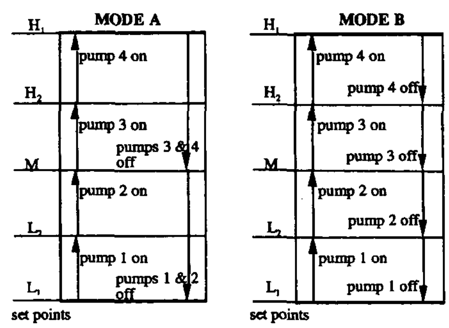

FIG. 3. Two Setpoint Control Modes for Four Pumps Working in Parallel

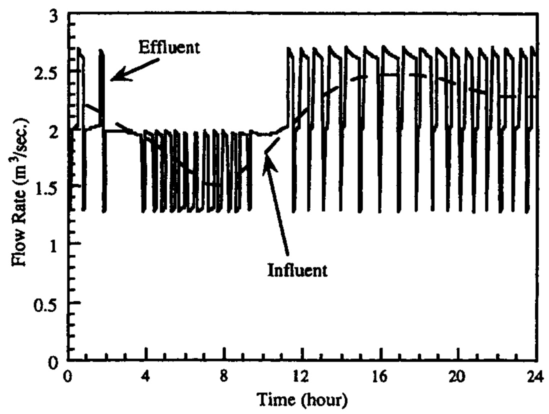

FIG. 4. Outflow-Rate Profile Generated by Control Mode A for Installation 1

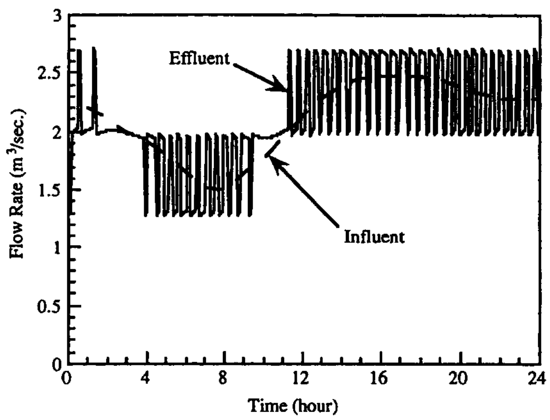

FIG. 5. Outflow-Rate Profile Generated by Control Mode B for Installation 1

scheme, each pump is responsible for a certain volume of water in the wet-well.

Using equations (3), (4), (6) and these control schemes, we obtained the outflow profiles for control modes A and B, which are presented in Figs. 4 and 5, respectively. The dashed line in the figures is the influent flow rate in a 24-h period (April 5, 1990), and the solid line represents the pump station outflows to the downstream processes. Pumps 1 and 2 were always on while pumps 3 and 4 were either on or off depending upon the flow rate. Clearly, the operation of the fixed speed pumps amplifies both the magnitude and the frequency of the variation in influent flow rate. The reason for this is that the on-off status of each pump is bounded by the upper and lower set points. These set points are not dynamically changed in operation.

Comparing control mode A and B, we can not decide which mode is better. In control mode A, the minimum pump cycling time is comparatively longer than that of control mode B. However, this advantage is offset by the larger magnitude of

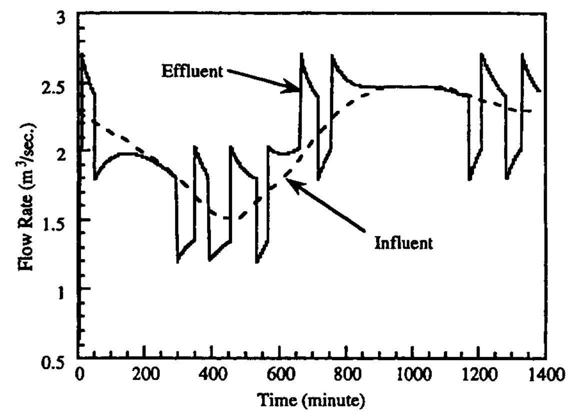

FIG. 6. Outflow Rate Profile Generated by Optimum Control for Installation 1 (Feedback Only)

hydraulic surges. Pump control mode B produces smaller hydraulic surges, but with a shorter pump cycle time.

Optimum Control for Installation 1

In order to compare the two control techniques, the optimum controller was simulated for the same conditions as the two-point controller. The energy saving and flow smoothing factors in (11) were assigned values of 0 and 1, respectively. Therefore, only hydraulic surges and pump on-off times were minimized.

Fig. 6 shows the outflow profile obtained using the optimum controller in a feedback loop along with constraint equations (12) through (15). The dashed line is the influent flow and the solid line is the outflow. As compared to control techniques A and B in Figs. 4 and 5, both the magnitude and frequency of hydraulic surges are substantially reduced. The outflow generated by the optimum control scheme conforms more closely to the influent profile. Tables 1 and 2 summarize quantitative indications of the improved performance. The on-off cycles of pumps 3 and 4 are reduced 86% and 69%, respectively as compared to control mode A, and 67% and 81.5% for control mode B. Another significant improvement is the increase of the minimum pump cycle time. The minimum cycle time (MCT) is defined as the minimum time interval over which the pump goes through a complete cycle (from off state to on state, and then to off state again). The maximum MCTs for modes A and B are 40 min and 32 min, respectively. The minimum MCT for the optimum control is 97 min. A two-fold increase in MCT is achieved by the optimum control scheme. The significance of minimizing the cycling of the pumps and maximizing the MCT time are extension of the pump and motor life and reduced maintenance, as well as reductions of the frequency of hydraulic surges. The simulation demonstrates that the optimum control model has the potential to significantly reduce cycling and hydraulic disturbances to downstream treatment, as well as to increase the MCT of the pumps.

TABLE 1. Simulation Results of Conventional Control Schemes for Installation 1

Control mode	Mode A[a]					Mode B[a]				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Pump setpoint	L_1	L_2	M	H_2	H_1	L_1	L_2	M	H_2	H_1
Liquid level (m)	0.5	1.75	3.0	4.25	5.5	0.5	1.75	3.0	4.25	5.5
Pump Number	1	2	3	4	—	1	2	3	4	—
On-off cycles/day	C	C	28	16	—	C	C	12	27	—
Minimum cycle time (minute)	N/A	N/A	28	40	—	N/A	N/A	32	27	—

Note: The sign C indicates that a pump is operated continuously; N/A indicates "not applicable."
[a]The power required is 0.028 kW·h/m³.

TABLE 2. Simulation Results of Optimum Control for Installation 1 with Different Weighting Factors

Optimum control	Energy-Saving Strategy 1[a] (α = 0.0, β = 1.0)				Energy-Saving Strategy 2[b] (α = 0.3, β = 0.7)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Pump number	1	2	3	4	1	2	3	4
On-off cycles/d	C	1	4	5	C	1	4	8
Minimum cycle time (min)	—	—	121	97	—	—	121	74

[a]The power required is 0.029 kW·h/m³.
[b]The power required is 0.027 kW·h/m³.

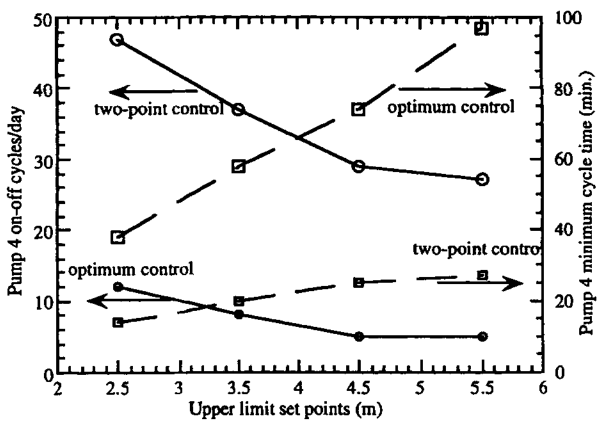

FIG. 7. Effects of Reducing Wet-Well Volume on Pump On-Off Cycles and Minimum Cycle Time

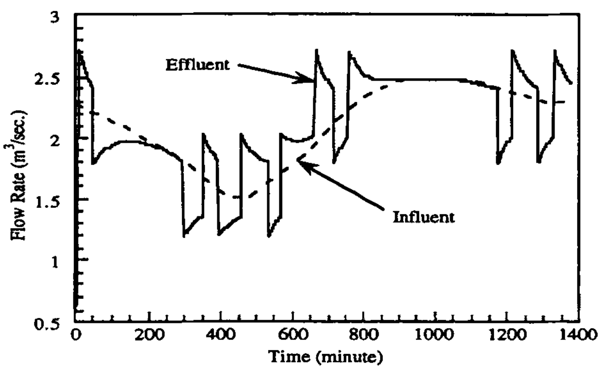

FIG. 8. Outflow Rate Profile Obtained by Optimum Control for Installation 2 (Feedback Only)

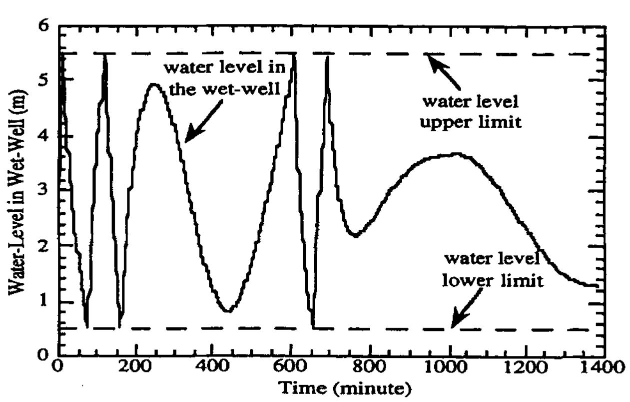

FIG. 9. Water Level Changes versus Time for Installation 2

To address energy savings, different weight values of α and β (α = 0.3 and β = 0.7) were assigned to the model. This results in a 7% power reduction over the optimum control result which did not consider the energy savings (α = 0.0 and β = 1.0), as indicated in Table 2.

Effects of Reducing Wet-Well Volume for Installation 1

The wet-well volume plays an important role for both the conventional and optimum control systems. In the previous simulations, the wet-well volume was determined based on the requirement that the detention time should be 30 min or less at the minimum daily flow rate. The upper set point for this volume was 5.5 m. To investigate the effects of changing the wet well volume on pumping station performance, the upper set point was changed from 5.5 to 2.5 m, while the area of the wet well remained the same. This has two effects on the system: one is a smaller damping capacity and the other is an increase of pump static head.

Fig. 7 shows the effect of reducing the wet-well volume by lowering the upper set point on the on-off cycles and minimum cycle time (MTC) for pump 4 for two-point and optimum controls. As expected, reducing the wet-well volume increases the on-off cycles for both control schemes. However, the increased number of on-off cycles for two-point control is greater than that of the optimum control. For example, when the upper set point of the wet-well is lowered from 5.5 to 2.5 m, the corresponding on-off cycles of pump 4 increase from 27 to 47 for the conventional control, which there is only a 7-cycle increase for the optimum control (from 5 to 12). In contrast to the on-off cycles, the decreases of MCT for optimum control are higher than for the two-point control. The reduction of MCT for optimum control is 59 min (from 97 to 38 min) when the upper set point is reduced from 5.5 to 2.5 m, while only a 13 min reduction of MCT resulted for the two-point control (from 27 to 14 min).

Lowering the upper limit set points in the wet-well results in more power consumption for both control schemes. For conventional two-point control (mode B), the average power required is increased from 0.028 to 0.032 kWh/m³, a 14.3% increase, while for optimum control the power increase is only 4.4% (from 0.0294 to 0.0307 kWh/m³).

Optimum Control for Installation 2

To investigate the performance of different piping systems for the two-point and optimum controls, a piping system with discharge to a common header was simulated. The simulation conditions, such as influent flow rate, pump lift, upper and lower set point in the wet well, are the same as for installation 1. The pump curves presented in Fig. 2 were used for modeling pump performance. For conventional control, only operation mode B (Fig. 3) was simulated and compared with the optimum control method.

Fig. 8 shows the performance of the optimum controller, and Fig. 9 shows the water level changing with respect to time under this control scheme. Comparing this plot with Fig. 6 (optimum control for installation 1), a better outflow profile is obtained. However, for two-point control the performance of installation 2 is somewhat inferior to installation 1. For example, the MCT of pump 3 is 32 min for installation 1 and 25 minutes for installation 2. Tables 3 and 4 give a numerical comparison of the results.

The major difference between the two types of installation is the increase in power consumption for installation 2. This is true for both conventional and optimum controls. Referring to Tables 3 and 4, the power required by installation 2 for two-point control is 0.038 kWh/m³ which is 34.6% greater than for installation 1 (0.028 kWh/m³). For optimum control, installation 2 requires 0.041 kWh/m³, which is 40% greater than for installation 1 (0.029 kWh/m³). The reason for this is that more energy is required to overcome the resistance in the common header. The point can be clearly seen by comparing Figs. 1 and 2. The working head for each pump in the separate

TABLE 3. Simulation Results of Conventional Control Scheme (Mode B) for Two Pumping Station Installations

Two-point control (for mode B)	Installation 1[a]					Installation 2[b]				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Pump setpoint	L_1	L_2	M	H_2	H_1	L_1	L_2	M	H_2	H_1
Liquid level (m)	0.5	1.75	3.0	4.25	5.5	0.5	1.75	3.0	4.25	5.5
Pump Number	1	2	3	4	—	1	2	3	4	—
On-off cycles/d	C	C	12	27	—	C	C	11	25	—
Minimum cycle time (min)	N/A	N/A	32	27	—	N/A	N/A	25	28	—

[a]The power required is 0.028 kW·h/m³.
[b]The power required is 0.038 kW·h/m³.

TABLE 4. Simulation Results of Optimum Control for Two Pumping Station Installations

Optimum control (weighting factors)	Installation 1[a] (α = 0.0, β = 1.0)				Installation 2[b] (α = 0.0, β = 1.0)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Pump number	1	2	3	4	1	2	3	4
On-off cycles/d	0	1	4	5	1	1	1	4
Minimum cycle time (min)	N/A	N/A	121	97	N/A	N/A	N/A	84

[a]The power required is 0.029 kW·h/m³.
[b]The power required is 0.041 kW·h/m³.

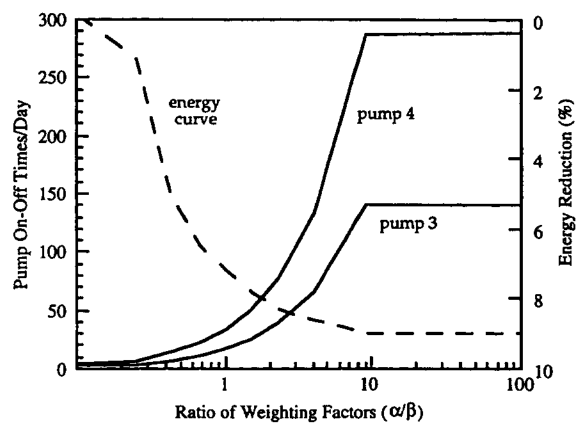

FIG. 10. Sensitivity Analysis for Selection of Two Weighting Factors

piping system is lower than that in the common header. This is especially true for pumps 3 and 4.

In the previously described simulations, we emphasized weighing of the objective function to reduce pump cycling. For some situations, the energy saving can also be significant, especially when the ratio of the lift head to the wet-well depth is small. The ability to separately consider energy consumption and flow smoothing can be an important advantage of the optimum control model. A sensitivity analysis of the effects of varying the two weighting factors is given in the next section.

Sensitivity Analysis of Weighting Factors

Intuitively, the energy reduction objective is in conflict with the objective of minimizing pump on-off times. If the energy required by the pumps is to be minimized, the number of pump on-off times will increase in order to keep the water level in the wet well as high as possible. The purpose of this analysis is to show how sensitive the energy utilization and pump cycling frequency are to variations in the energy saving and outflow smoothing factors.

The analysis was carried out by simultaneously varying the energy weighting factor from 0 to 1 and outflow weighting factor from 1 to 0; the ratio of the two factors (energy consumption/flow smoothing) is plotted versus energy reduction and pump on-off times during a day. Fig. 10 shows the relationship among the energy reduction, pump on-off times and the ratio of weighting factors. At low ratios (0 to 0.11; α = 0.1, β = 0.9), the energy required is not reduced, as would be expected. Significant energy reduction occurs in the range of 0.25 (α = 0.2, β = 0.8) to 0.667 (α = 0.4, β = 0.6). For ratios greater than 1 (α = 0.5, β = 0.5), energy reduction becomes less sensitive to a change in the ratio. The pump on-off times are not sensitive at low ratios (from 0 to 1; α = 0, β = 1 to α = 0.5, β = 0.5, respectively), which means the on-off times during a day do not increase significantly. Therefore the best combined values for α and β are within this range. If the ratio is higher than 0.667, the minimum pump off time for motor cooling cannot be guaranteed.

It is interesting to observe the limits of energy reduction and pump on-off times by allowing a high value of the ratio. Even at elevated values of the energy saving factor, the energy reduction curve improves only slightly and also reaches its limit of 9%, while the pump on-off time curve increases significantly and also reaches a limit. If the best ratio value is chosen as 0.42 (α = 0.3, β = 0.7), the energy reduction is about 5%, and the number of operating cycles for pumps 3 and 4 are 4 and 8 cycles, respectively. Referring to Tables 1 and 2, in addition to the 5% energy savings, the numbers of the pump on-off cycles for the optimum control with α = 0.3 and β = 0.7 are still much less than those of control modes A and B. Comparing the optimum control with and without considering energy saving, the numbers of the pump on-off cycles do not increase significantly (an increase from 5 to 8 for pump 4, and no increase for pump 3).

As expected, the energy-saving objective conflicts with the pump-cycling objective. If energy reduction is stressed we will increase pump on-off cycling, and vice versa. The best combinations are in the range where the energy reduction is sensitive to the ratio and pump on-off times are insensitive. In practice, the selection of weighting factors will depend on factors such as the pump lift head, wet-well depth, number of pumps and their size.

The effects of pump number and size on the optimum control scheme were also investigated. The simulation results have shown that better performance can be obtained with more pumps. If only two pumps are used in a system, the optimum control is only marginally better than the traditional two point control. Increasing the number of pumps and reducing their size decreases the time required for pump cooling. Relaxing the constraint imposed in (14) (minimum cooling time) allows a better combination of pumps and a smoother flow profile. However, using a greater number of small pumps may lower the overall system efficiency, and this effect has not been investigated.

CONCLUSIONS AND SUGGESTIONS

The optimum control technique developed is superior to conventional control methods for fixed-speed pumping stations (both separate and combined piping installations). It can reduce both the frequency and magnitude of hydraulic surges. Optimum control maximizes the minimum cycling time (MCT) of pumps, reduces maintenance cost, and extends the life of pumps and motors. The reason for these improvements is that the optimum control system removes the upper and lower bounds that are imposed on the conventional two point control method. This allows the system to maximally utilize the limited storage capacity of the wet well such that an optimum state can be reached.

The technique also provides operational flexibility by using energy saving and outflow smoothing weighting factors. The selection of the two factors can be obtained by performing a sensitivity analysis. The best range of the two factors will vary based on the specific site conditions, such as the number, size, and efficiency of pumps. A large value of the energy saving factor may be used in wastewater collecting system where the depth of the wet well is large. To minimize the hydraulic surges a large value of outflow smoothing factor is usually required.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A = cross-section area of wet well;
A_1, A_2, A_3 = parameter for pump head-capacity polynomial equation;
B_1, B_2, B_3 = parameter for efficiency polynomial equation;
C_1, C_2, C_3 = parameter for system head-capacity polynomial equation;
E_f = pump efficiency (%);
F_t, F_{t-1} = outflow rates at time t and $t - 1$, respectively (m^3/s);
H_p = pump total dynamic head (m);
$H(S)$ = system head (m);
H_t, H_{t-1} = water levels in wet well at time t and $t - 1$, respectively (m);
H_{up}, H_{down} = upper and lower limits of water levels in wet well, respectively (m);
K = total number of pumps;
M_j = minimum cooling time for jth pump at off state (min);
p_j = pump cooling time for jth pump ($p_j = M_j$ if $\Delta t = 1$ min).
Q_{in_t} = influent flow rate at time t (m^3/s);
$Q_{j,t}$ = jth pump discharge rate at time t (m^3/s);
$X_{j,t}$ = state of jth pump at time t (0, 1); and
Δt = sampling interval (min).

Subscripts

j = pump number;
k = counter to count time during pump cooling; and
t = time index.