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LOCAL CONTROL SCHEMES FOR REAL-TIME OPTIMIZATION OF VARIABLE SPEED PUMPS

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Abstract

In this work, we have developed local control schemes for optimal operation of a pumping station that includes multiple variable speed pumps. The pumping station must maintain a target pressure for a closed supply network that usually does not contain storage facilities. The control loop includes repeatedly reading the control feedback (pressure) from the control system and then adjusting the operation of the pumps in the station as needed: changing the pumps' speed and on\off status. Firstly, we formulated a control algorithm that simulates the current practice. Next, an optimization algorithm was developed to achieve minimum energy operation considering the efficiency curves of the pumps. The algorithm utilizes the pumps' characteristics curves for ensuring hydraulic feasibility while sustaining the required pressure setpoint. The optimization problem incorporates bound constraints on the speeds, time gap constraints to prevent frequent pump changes, and physical constraints that quantify the operation point in the flow-head domain and the flow-efficiency domain. We considered two operation strategies. The first is the "free strategy", in which each pump can operate with a different speed inside a predetermined speed range, while in the "equal strategy", all active pumps must share the same speed. The methodology was demonstrated using a realistic case study. Our preliminary results indicate potential energy reduction compared to the current practice.

Keywords
Variable speed pumps, real-time control, water distribution systems, optimization.

1 BACKGROUND

Variable speed pumps (VSP) are used to maintain a desired flow or pressure. VSPs are common because they provide several advantages [1], including a) the pump flow can change gradually and give the upstream process (e.g., treatment plant) time to adjust; b) no water storage is required on the demand side, as the pump can adjust to changing demands while maintaining the required pressure in the demand zone; c) the flow can be changed gradually to reduce water hammer, and d) motor life can be extended since fewer starts and stops are needed [2].

On the other hand, Gottliebson et al. [1] argue that VSPs also have disadvantages as compared to fixed speed pumps (FSPs): a) they are more expensive in both installation and maintenance; b) they may be less efficient; c) controlling a VSP is more complex, and d) a VSP may not be suitable for flat H-Q system curves as high efficiency is difficult to maintain over the entire flow range. Despite these disadvantages, VSPs are most popular in systems with no water storage. In these systems, there is a need to regulate the flow using a demand following mechanism.

With the VSPs gaining popularity in practice, they have been modeled in most simulation software, such as EPANET [3], and their modeling and simulation continue to be an active research topic [4–6]. Many studies of VSPs address the operation of WDSs and optimization of pumps scheduling [7–11]. In a recent review, Wu et al. [12], report improved system efficiency due to VSPs and other benefits of increased flexibility in controlling WDSs in real-time. Lima et al. [13] suggested using

VSPs to recover energy and reduce leakage in WDSs. Wu et al. [14] incorporated VSPs in the design stage of water networks and transmission lines. Huo et al. [15] explored using VSPs in deep injection well systems.

The operation of variable speed pumps for pressure control in a closed pipe system is a well-known problem [16–24]. However, a simple and practical methodology is still required for optimal operation of an entire pumping station to utilize the VSPs better and reduce energy costs. One of the most common controllers used is the proportional–integral–derivative (PID) controller [25]. A PID controller continuously calculates the difference (error) between the desired setpoint and the measured variable. Then it applies a correction based on proportional, integral, and derivative terms of the error.

2 METHODOLOGY

2.1 Current controller

In the traditional control loop of the VSP based pumping station, for each time step t, the current state of the system is obtained from the SCADA, which includes the on\off state of the pumps, I, their speed, n, and the last update time of these values, τ_I and τ_n respectively. The reference pressure (setpoint), H_{ref}, and the measured pressure, H are also obtained. The difference (error) between these values is calculated, e, and fed to the proportional control algorithm (PCA). Some parameters for the PCA are predetermined: the minimum and maximum allowed speeds of the pumps, n_{min} and n_{max} respectively, the maximum allowed change in the pump's speed, Δn_{max}, the proportional coefficient, α, which is the change in the pump's speed relative to the calculated error (e). A minimum time, t_{min}, is also set to limit the time between major changes in pumps operations (e.g., start, stop, reduce the pump's speed from n_{max}). The output of the PCA is the adjusted values for I and n, denoted as $\hat{I}$ and $\hat{n}$ respectively. When these new settings are applied to the system, the system will respond with new values of the pressure and the flow, H_{t+1} and Q_{t+1} respectively. At this stage, the control loop is repeated for the next time step.

The above algorithm is traditional in control applications, and it is implemented in many control system use cases. However, it is not uniquely tailored for pumping systems. The control employs control rules to keep the feedback signal at the desired setpoint regardless of the energy efficiency and hydraulics. Relying on a physical model of the pumps' hydraulics and efficiencies, we propose a model-based approach tailored explicitly for pumping stations that work against closed networks without storage. Unlike the traditional approach, we propose optimizing energy cost as a primary objective, while satisfying the setpoint constraints.

2.2 Proposed Controller

The proposed model-based controller solves an optimization problem to minimize energy consumption. The pump curves (i.e., efficiency and flow-head characteristic curves) are used to choose the lowest energy consumptions that meet the target pressure setpoint. The decision variables are the on/off status of the pumps and their speed. The objective is minimization of instantaneous power consumption. The optimization problem incorporates bound constraints on the pumps' speeds, time gap constraints to prevent frequent pump state changes, and physical constraints that place the operation point in the flow-head and flow-efficiency domains. To formulate the constraints, the water demand must be estimated. For the estimation, we use the known operational conditions from the previous time step to estimate the future water demand in the next time step. The model-based controller follows three modules, as detailed below.

Module 1: Demand estimation based on the current system state and all pumps' known flow-head characteristic curves. Figure 1 provides a schematic demonstration of this process, which, algebraically, involves solving a nonlinear equation.

The figure shows two flow-head characteristic curves for two active pumps (green pump and blue pump) at time step t. These are the active pumps (i.e., ON pumps) out of a set of available pumps in the station. The orange curve represents their combined curve, which is the flow-head relationship of the pumping station at time t. Using the pressure measurement at time t, one can estimate the water demand (i.e., flow) at time t using Eq. (1).

$$Q_{est,t} = \sum_{p \in P} I_{p,t-1} \cdot \sqrt{\frac{\left(\frac{n_{p,t-1}}{n_{\max}}\right)^2 \cdot a_p - H_{t-1}}{b_p}} \tag{1}$$

where a_p and b_p are the coefficients of the Q-H pump characteristic curve of pump p.

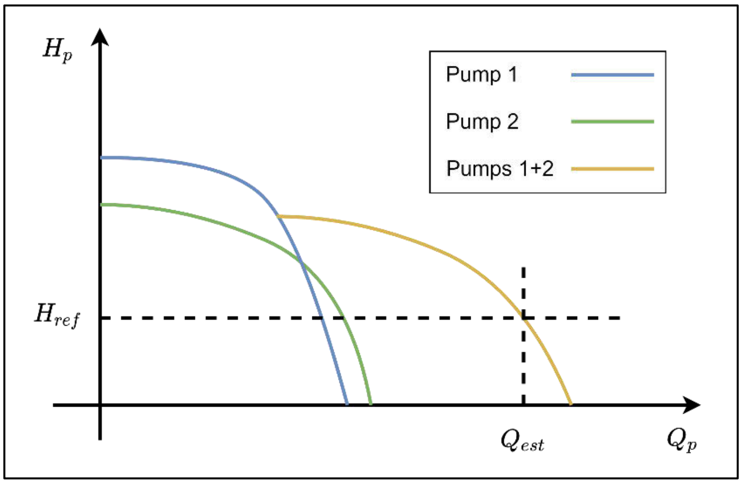

Figure 1: demonstration of flow estimation for two active pumps

Module 2: Determining the feasible speeds for given pumps combinations. Given the estimated flow and a potential pump combination, we seek the set of feasible speeds that reach the operation point of the required pressure setpoint and the estimated flow. While this problem is highly nonlinear, we can rely on a direct search of feasible speeds since the problem dimension is small. That is, we can discretize the allowed speed range and check for the feasibility of each option. Nonetheless, to reach the operation point accurately, we allowed one of the pumps to have continuous speed while the other pumps could have discretized speeds.

Module 3: Direct search for the optimal active pumps combination. In this module, we enumerate all pump combinations in the pumping station. For example, in a pump station with four pumps, there are $2^4 - 1 = 15$ possible combinations of active pumps, C. For each combination module 2 is called, and its output is saved. Two families (i.e., set of sets) are obtained after looping over all the combinations. The first is $N^c_{feas} \quad \forall c \in C$ which contains all the feasible speeds for each combination, and the second is $E^c_{feas} \quad \forall c \in C$, which contains the electric energy. Constraints can be imposed on some of the combinations. For example, some combinations can be ruled out to prevent frequent changes in active pumps. That is, if pump 1 started on time t, we could only consider combinations that have active pump 1 for a predetermined time window $t:t+w$. Similarly, one can filter out combinations with unavailable pumps at any period (e.g., malfunctioned pumps). After ruling out unwanted combinations, the module outputs the option (i.e., combination and speeds) with the lowest electric power from $c^* \in C$, $n^* \in N^c_{feas}$ and $E^* \in E^c_{feas}$.

The modules above can be easily modified to account for additional operational constraints. To demonstrate this flexibility, we consider two operation strategies. The first is the "free strategy", in which each pump can operate with a different speeds inside a predetermined speed range (presented in modules 1-3). The second is the "equal strategy", in which all active pumps must share the same speed.

3 TEST CASE AND RESULTS

We consider the pressure zone 330P in Mey-Sheva, a water utility in Southern Israel, as a test case. The utilitiy's entire system contains 6 pumping stations, 11 water tanks, and serves a population of 143,000. The total waterpipes' length is 670 km, of which about 100 km are part of the selected pressure zone. The WDS layout of this zone is shown in Figure 2.

Figure 2: Water Lines- GIS layer for pressure zone 330P

A single pumping station supplies zone 330P without storage tanks. The pumping station has eight pumps, of which four supply water to zone 330P: pumps 1-4 (labeled 11, 21, 31, and 41). The four pumps are variable speed pumps, each operating at a different frequency. SCADA measurements are available at 30-second intervals for the suction and discharge pressures, total flow through the station, and individual pumps frequencies. These frequencies are recorded in percentage [0, 100] for the range of 35-50 Hz. When the value is 0%, it means that the pump may be working at the minimum frequency or it is turned off. We assume the latter. There are no individual pump flow data and no power data, not even for the entire station. There are power meters (SATECs) in the station, but unfortunately, they are not connected to the newly installed SCADA system.

The pumps are operated to maintain the discharge pressure of the station. As demand in the zone increases, this pressure decreases, and the speed of the operating pump is increased to meet the required pressure. First, the speed of one pump is raised to the maximum speed, and then another pump is added at its lowest speed, which can be increased if the pressure continues to drop. The controlled pressure is set to ~47m during day hours (06:30-23:00) and to ~42m during night hours (23:00-0:630), as shown in Figure 3. The pump curves were derived by analyzing the SCADA data of the pump performance, using the methodology in [26].

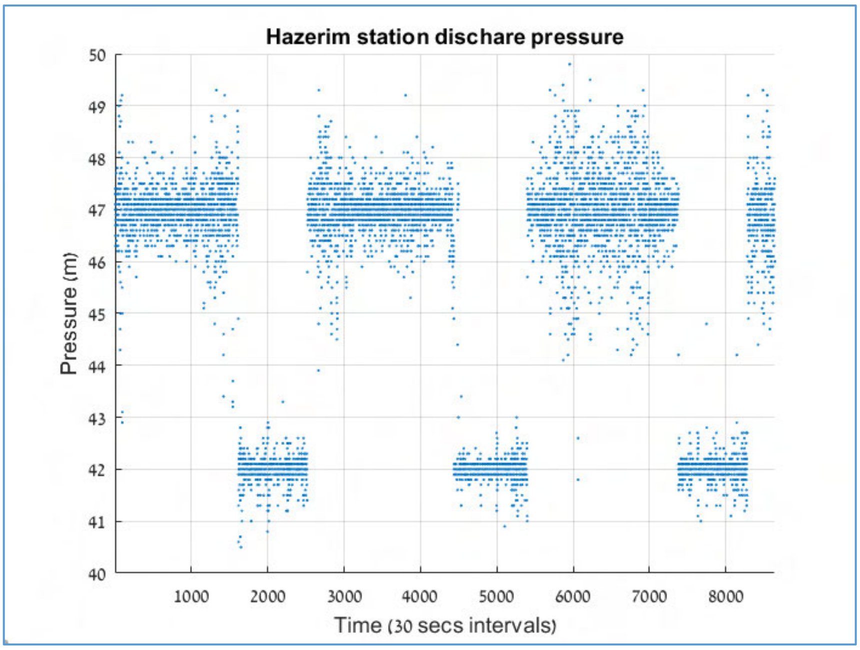

Figure 3: Discharge pressure of Hazerim pumping station

By utilizing the proportional control algorithms presented previously, the current operation of the Hazerim pumping station was simulated. Initial results are shown in Figure 4, in which the simulated pressure is shown in the top figure while the measured pressure is on the bottom. The similarity between the measured and simulated pressure can be easily observed. However, in some time steps, the simulated pressure spikes below the reference pressure, possibly due to the system's (plant) simulations. Further investigation of this issue is required.

The optimization results for two days (out of a representative week) are shown in Figure 5. The results show that the free strategy outperforms the current strategy and the equal speed strategy since it reduced the power consumption in specific periods. This good performance is still achieved while meeting the target pressure, as demonstrated in Figure 6. The figure shows the cumulative probability density function of the three strategies' absolute pressure deviation from the set pressure. The overlapping of the curves indicates that all strategies sustain the required pressure.

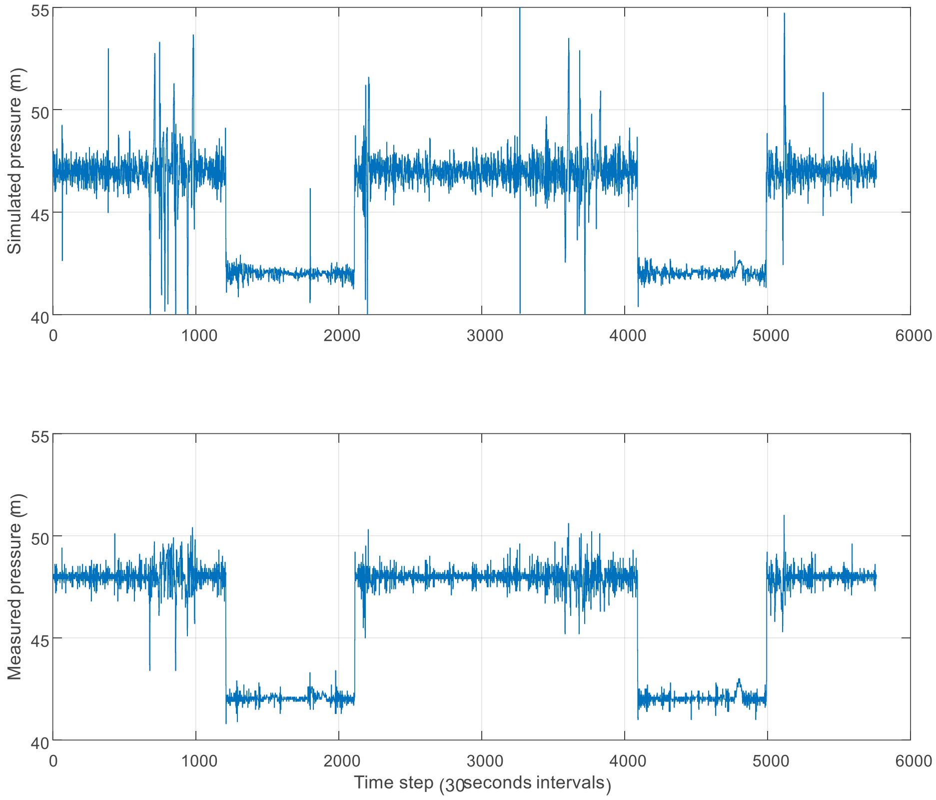

Figure 4: Measured and simulated pressures

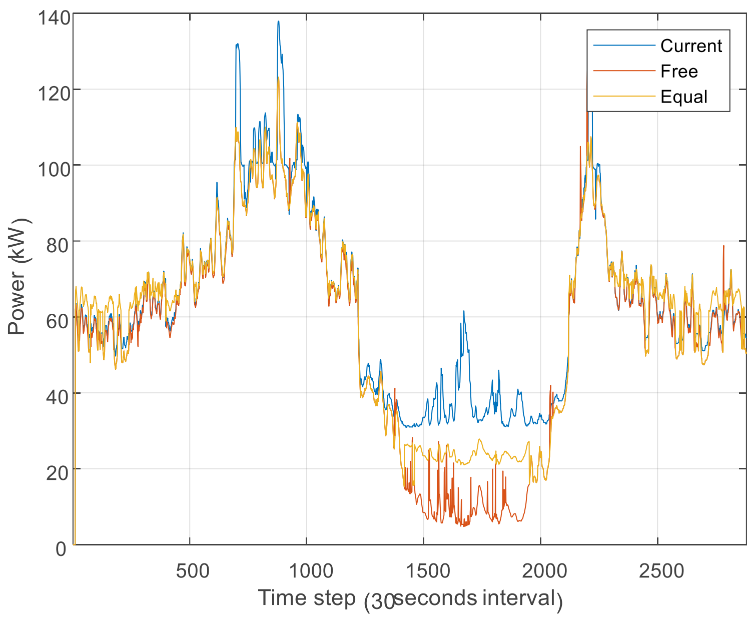

Figure 5: Power consumption for different operational strategies

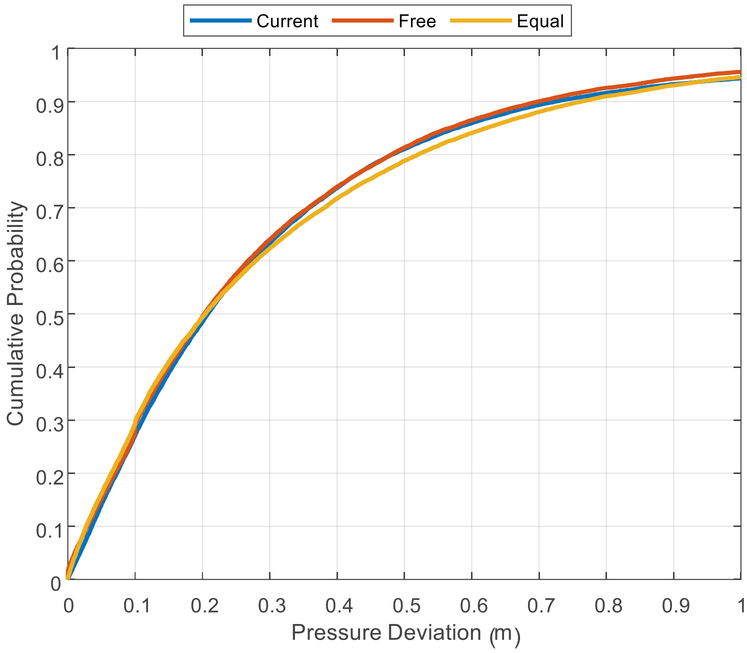

Figure 6: Cumulative probability density function of the absolute pressure deviation from the set pressure for the three strategies

Figure 7 shows that both optimization strategies (free and equal) achieve better balanced operation. Namely, they allocate balanced operation hours for the pumps.

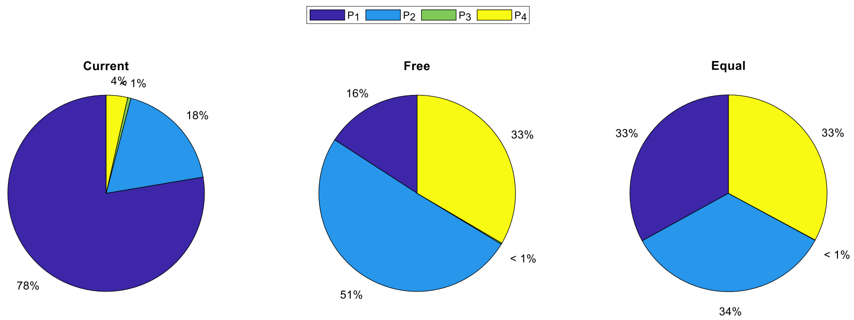

Figure 7: Operation hours for the three strategies

Finally, the energy saving, as compared to the current operation, is 10% for the 'free-strategy' and 5% for the 'equal-strategy'.

4 CONCLUSIONS

This paper presents a new methodology for optimal operation of VSPs. Unlike the traditional approach, in which the physical properties of the pumps are not taken into account, the proposed algorithm uses the pumps' curve to select the optimal pump combinations. The methodology is presented in two variations: a) "free strategy", in which each pump may have a different operating speed, and b) "equal strategy", in which all operating pumps share the same speed. The methodology is demonstrated in a real test case, and the results show a smoother and cost-effective operation compared to the traditional approach. The developed algorithm is planned to be utilized in the pumping station control unit for further testing.

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