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OPTIMAL PUMP OPERATION FOR RESIDENTIAL WATER SUPPLY SYSTEM

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ABSTRACT

The pump-storage system is used to improve the reliability of water supply, particularly in locations where water supply is unreliable. However, the drawbacks of this system are excessive pumping and water loss to tank overflow. Therefore, an operational optimisation is proposed to address these challenges. This paper presents a linear programming model to minimise the operating cost of the proposed system under the time-of-use (TOU) electricity tariff. The model is applied to a practical case study and solved by the solving constraint integer programming (SCIP) solver in MATLAB's OPTI toolbox. Simulation results show that the proposed approach eliminates water loss to tank overflow and improving energy savings by up to 18.3%.

Keywords: operation optimisation, energy-water nexus, water supply system, pump scheduling.

1. INTRODUCTION

Energy and water insecurities are global challenges caused by increasing demands relative to supplies. The United Nations reports that global energy and water demand will increase by 50% and 40% in 2030, this will be due to population growth, urbanisation, commercialisation and industrialisation [1, 2]. In developed nations, these resources are often provided by utility providers, therefore, reduced production and transmission capacities will cause widespread resource scarcities or crises, in extreme situation. Building accounts for 8% and 14% of the world's water consumption [3] and energy consumption [4], respectively. Energy-water nexus, a concept that defines the mutual relationship between energy and water, shows that water savings produce energy savings and vice versa [5]. Hence, this study proposes an optimal pumping operation for residential water supply system to maximise water, energy and financial savings.

Optimisation of pumping operation in multi-product pipeline are solved using a mixed integer linear programming (MILP) model using flowrate database [6] and hybrid time MILP [7]. A hybrid time genetic algorithm is used to optimise pump operation in [8]. Pump-storage and optimisation of pump operation are used to maximise operating cost savings and energy efficiency in coal beneficiation plant [9]. The performance of the open loop optimal control and closed loop model predictive control (MPC) strategies on pump operation in the residential water supply system are investigated in [10, 11]. These studies show that the performances of both control strategies are the same without disturbances, however, the closed loop MPC performs better with disturbances because of its robustness.

Unlike [10, 11] that compare the performance of the open-loop optimal control and the closed loop MPC strategies on the municipal water supply system and integrated rainwater-greywater recycling system respectively, this study formulates a linear programming problem to optimally schedule the pumps subject to the TOU tariff to maximise water, energy and financial savings subject to the physical, operational and boundary constraints of the system. The simulation is carried out for a sampling time of 15 mins, operating time of $24h$ leading to a total sampling interval of 96. This optimisation problem is solved by the solving constraints integer programming (SCIP) solver in MATLAB's OPTI toolbox.

The remainder of this paper is organised as follows: Section 2 presents the mathematical model formulation, Section 3 contains the case study, while Section 4 discussed the simulation results and discussion. The Conclusion is presented in section 5.

2. MATHEMATICAL MODEL FORMULATION

2.1 Schematic layout

Figure 1 shows the schematic diagram of the proposed residential water supply system. The water supplied from the utility provider is pumped into the rooftop tank for storage and later use. Water flows by gravity to the various use-points. Operational optimisation of this system is proposed to improve the energy efficiency, water savings and the operating cost of the water supply system. The mathematical model of the sub-system is given in the following:

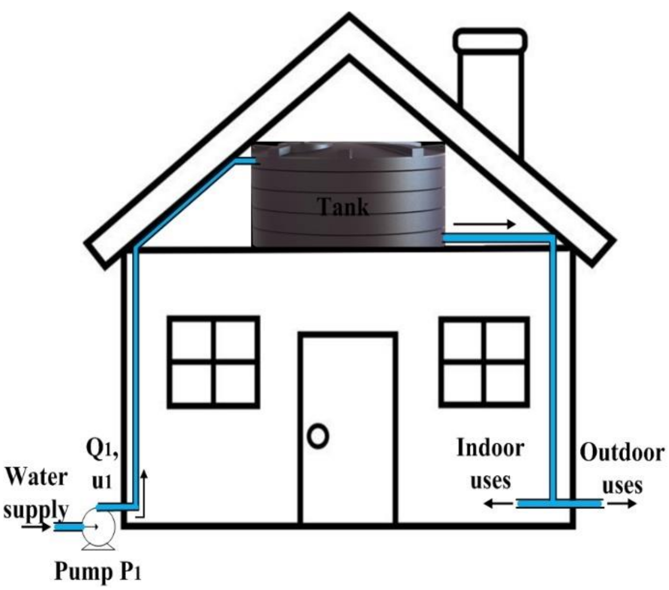

Fig. 1. Schematic diagram for residential water supply

2.2 Rooftop tank

This is a cylindrical, uniform cross-sectional area tank that collects, stores and releases water to use-points. The volume of water in the tank is modelled as the accumulated difference between the water demands and supplies. This is expressed in the discrete time domain, in terms of water level, as [10]:

$$h_1(j) = h_1(0) + \frac{1}{A_1}\sum_{i=0}^{j-1}\left[t_s Q_1 u_1(i) - D_{total}(i)\right], \tag{1}$$

where A_1 is the cross-sectional area of the tank, $h_1(j)$ is instantaneous water level at time instant (*j*), Q_1 is pump flow rate, $u_1(j)$ is the binary decision variable and D_{total} is the total water demand. t_s is sampling time within the sampling interval $j = 1, 2, 3, ..., N$ and N is the total number of intervals within the 24h operating cycle.

2.3 Optimisation model

The objective of the study is to minimize the electricity cost subject to the time-of-use electricity tariff. The objective function of the optimization problem is formulated as:

$$\min\ J = \sum_{j=1}^{N} t_s \rho_e P_1 u_1(j), \tag{2}$$

subject to the following constraints:

$$h_1^{\min} \le h_1(0) + \frac{1}{A_1}\sum_{j=1}^{N}[t_s Q_1 u_1(j) - D_{total}(j)] \le h_1^{\max}, \tag{3}$$

$$u_1(j) \in \{0,\ 1\}. \tag{4}$$

where ρ_e is the cost of electricity, P_1 is the power rating of the pump (W). With a uniform cross-sectional area, $h_1^{\min}$ and $h_1^{\max}$ represent the lower and upper bounds of the tank.

3. CASE STUDY

The case study is based on a residential building in Durban, KwaZulu Natal province of South Africa, whose municipal water supply is unreliable. Figure 2 shows the water demand profile of the residence. The pump is manually operated by the occupants, hence this energy demand and water demand profile of the residents are used as a baseline for this study. However, the drawbacks of the baseline are water loss to tank overflow and energy inefficiency due to excess pumping. Therefore, an operation optimisation is proposed to solve these problems.

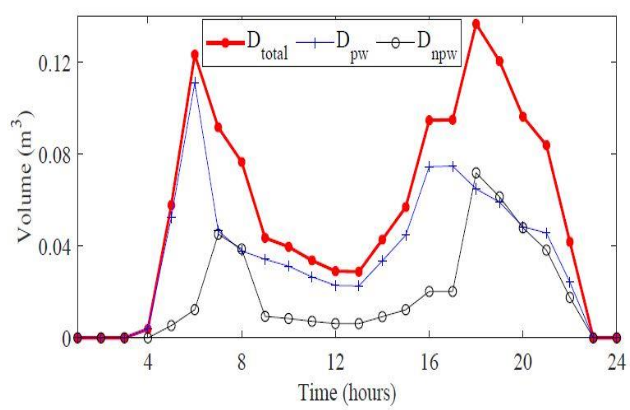

Fig. 2. Residential water demand profile

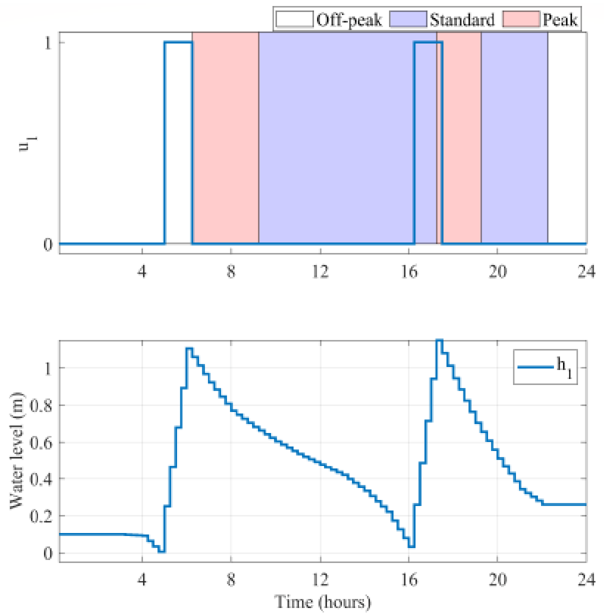

Fig. 3. Switching and variation in water level of the baseline system

The pump has a power rating of 0.7kW and a flowrate of 0.55 m^3/h. The tank has a cross-sectional area of the tank of $0.5m^2$, while its lower and upper bounds in terms of water level are $0.1m$ and $1.0m$, respectively.

3.1 Electricity tariff

Eskom is South Africa's electricity utility provider. The residential TOU tariff used in this study is given as:

$$\rho_e(t) = \begin{cases} 0.5732\ R/kWh, & \text{if } t \in [0,6] \cup [22,24], \\ 1.0504\ R/kWh, & \text{if } t \in [9,17] \cup [19,22], \\ 3.452\ R/kWh, & \text{if } t \in [6,9] \cup [17,19]. \end{cases} \quad (5)$$

where ρ_e is the cost of electricity at off-peak, standard and peak periods, respectively. t is the time of the day in hours.

3.2 Water tariff

The incremental block water tariff for residential customers in Durban used in this study is seen in Table 1.

Table 1. Water tariff

Vol (m^3)	0-6	7-25	26-30	31-45	≥ 45
PW rate (R)	0	17.2	23.59	51.99	57.18
WW rate (R)	0	6.01	8.25	18.14	19.99

where WW is the volume of wastewater disposed and R is the currency of South Africa, Rand.

4. SIMULATION RESULTS AND DISCUSSION

A linear optimization problem is formulated and solved by the solving constraint integer programming solver (SCIP) in MATLAB's OPTI toolbox. The simulation is carried out for sampling time of 15 $mins$ within a $24h$ operating cycle, leading to a sampling interval of 96. The optimisation model can be expressed as: $\min f^T X$ subject to $AX \leq b, A_{eq}X = b_{eq}$ and $L_b \leq X \leq U_b$. $f^T$is the vector of the objective function, X is the decision variable. A and A_{eq} are the coefficient matrices of the inequality and equality constraints, while b and b_{eq} are the corresponding vectors of the constraints. L_b and U_b are the lower and upper bounds of the decision variable.

4.1 Optimal operation of the proposed system

Figure 3 shows the switching operation and the corresponding water level of the baseline, while Figure 4 shows the switching operation and the corresponding water level of the proposed system. In Figure 3, the pump is operated continuously until the tank is full, while for the tank emptying cycle the water demand is continuous until the tank is empty.

The objective of the proposed model is to satisfy the demand in the most economical manner. Hence, the pump is switched on at 01:45 and 05:45 for 45 mins and 15 mins each, to provide water to meet the morning peak

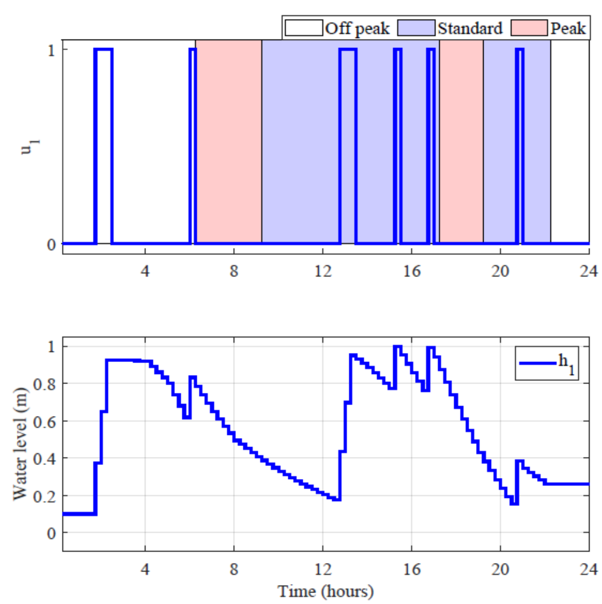

Fig. 4. Switching and variation in water level of the proposed system

water demand. Next, the pump is switched on at 12:45 for 45 mins and at 15:15, 16:45 and 20:45 for 15 mins each to provide enough water to meet the remaining water demand. Unlike the baseline, the proposed system does not operate the pump at peak period, thus minimizing the operating cost of the system.

The simulation result shows that both systems consume the same amount of energy, but the baseline pays more because of the pumping operation at peak period. Both systems consume 52.5 kWh of energy per month, but the baseline system pays R55.23, while the proposed system pays R45.12 leading to an energy cost savings of 18.29%. Also, the baseline loses water to tank overflow because it is manually controlled, and its performance depends on the knowledge of the occupants. Therefore, the baseline system loses 12.69 m^3 of water per month to tank overflow and this cost R115.32, while the proposed system does not lose water to tank overflow because its operation is bounded by the boundaries of the tank. Therefore, the simulation results show that the proposed system achieves its objective without violating any constraints.

5 CONCLUSION

Optimal pump operation has the potential of improving energy efficiency, water savings and the associated operating cost savings of the system. This study presented a linear programming model to minimise energy cost by optimal scheduling the pump subject to the time-of-use tariff, physical, operation and boundary constraints of the system. The application of the model to a practical case study shows the potential of the model to improve water and energy savings while minimising the operating cost of the system.

The operating cost of the system can be further improved with cost-reflective water and energy tariffs.

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