Energy saving and safe operation of Tidal Pumping Stations

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Abstract. Tidal pumping station pumps would consume lots of energy for pumping massive water. This paper provides an effective method to optimize operating schedules of the tidal pumping stations. A multi-objective model was proposed to minimize the total switching times and energy power. In the model, sub-periods are divided according to heads. A classical tidal pumping station, which mainly serves for the China's South to North Water Transfer Project, is performed as a case. As the energy consumption per unit pumped decreases, the switching times increases, and the operational reliability of the T-PS decreases. The optimal operation scheme reduces the switching times by about 58.824% and saves the energy consumption per unit pumped by about 3.803%, respectively. Therefore, the optimal operation scheme not only has excellent safety but also effectively reduces the operation energy consumption. Thus, this paper could provide effective optimized operation schedules for tidal-pumping stations.

1. Introduction

In China, water resources decrease gradually from the southeast coast to the northwest inland due to precipitation [1]. To release water scarcity in the north, China has implemented the South-to-North Water Transfer Project, which transfers water from the lower reaches of the Yangtze River. The water level of Yangtze River is impacted by tides significantly. Therefore, the energy-saving of operation schemes for tidal pumping station (T-PS) are worth studying.

Recent years, the problem of energy waste caused by the operation mode [2] in many water pumping systems has attracted extensive attention. Among them, Hyung et al. [3] proposed a model of an optimal water pumping system that taking seasonal and hourly differential electricity rates in consideration, and they found that the cost of 7 days could be saved 4.5% and 5.1% in winter and summer, respectively, respectively. Gong and Zou [4] proposed dividing periods based on the variation of electricity prices. Their research showed that optimal schemes of urban tidal-drainage pumping stations could save 15.34% and 4.40% costs compared to conventional operation. Ye [5] establishes an optimization model for the operation of intake pump stations considering electricity tariffs, and compared with the method using fixed tariffs, the tariff scheme with the coefficient of different start-stop weights reduces the daily operating cost by an average of about 14.81% at the high-tide, typical-tide and low-tide water levels, and the switching times is within an acceptable range. In same year, Horvath et al. proposed to control the speeds and switching times of the pumping unit, which saves about 10% to 13% energy. Sara et al. [6] aimed to minimize energy of urban water supply systems. They proposed to switch status of each pump and their findings indicate a reduction in energy consumption of 15-20% approximately. Studies above show that controlling of switching times according to the demands of different service object or different operating conditions can effectively save the operating energy consumption.

This paper proposes dividing the sub-periods based on the variation of tides and a multi-objective optimal model is established with both minimizing the energy consumption and the switching times. Applying the multi-objective optimization model to the classic T-PS system, which mainly serves the South-to-North Water diversion project in China, pumping water from typical tidal reaches. This model takes energy saving and safety into account to provide an optimal operation scheme for the T-PS.

2. Model and Methods

2.1 General Information of a tidal pumping station

T-PS pumps water from the ocean or tidally influenced tidal areas to areas of water scarcity as shown in Figure 1. The energy consumption and flow rate of T-PS varies with tidal levels.

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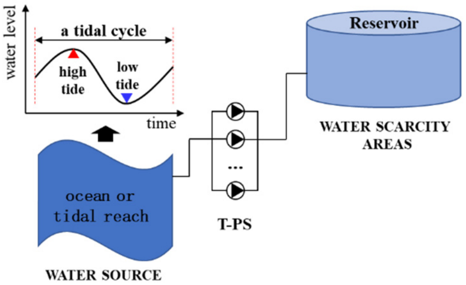


Fig. 1 A general figure of a typical tidal pumping station system.

2.1.1 Objective Function

The multi-objective optimization model based on energy saving and safety for the T-PS is established in Eq.1.

$$\min f = \min\{f_1, f_2\} \tag{1}$$

where f_1, f_2 represent Energy consumption per unit of water pumped (10^3 kW•h/m^3) and switching times. The optimisation model is a multi-objective nonlinear optimisation model with objective f_1 as the energy saving objective that minimize energy consumption per unit pumped of the T-PS, and objective f_2 as the safe operation objective that minimize the loss of wearable parts of each unit.

The energy consumption per unit pumped f_1 is defined as,

$$f_1 = \min \frac{\sum_{i=1}^{m} \int_{t_{s\,i}}^{t_{e\,i}} \left(P_{ps\,i}\right) \mathrm{d}t}{V} \tag{2}$$

where t_e and t_s are the final and initial moments of i-th sub-period. P_{ps} is the power(kW) of units. m is the number of sub-periods.

The number of status switched during a day (switching times) f_2 is defined as:

$$f_2 = \min \sum_{i=1}^{m} \left| n_i - n_{i-1} \right| \tag{3}$$

where n_i is the number of operating units in i-th sub-period.

2.1.2 Main Constraints

The blade angle is constrained as,

$$\alpha_{\min} \le \alpha_i \le \alpha_{\max} \tag{4}$$

where α is blade angle (°), $\alpha_{\max}$ and $\alpha_{\min}$ are the maximum and minimum angle.

The allowed number of running units is defined as,

$$0 \le n_i \le n_{\max} \tag{5}$$

where n is the number of operating units, $n_{\max}$ is the maximum number.

Constraint for water volume is defined as,

$$V_r \ge V_x \tag{6}$$

where V_r and V_x are actual water supply quantity(10^6m^3) and upstream water demand.

2.2 Methods

2.2.1 Discretization of water level

The downstream water level of the system is affected by tides, including two high tides and two low tides in a day. The upstream water level of the system on a typical day is steady all the day. figure.2 is the discretization of the difference of water level downstream and upstream the system, and the ΔH of each microsegment is 0.01m.

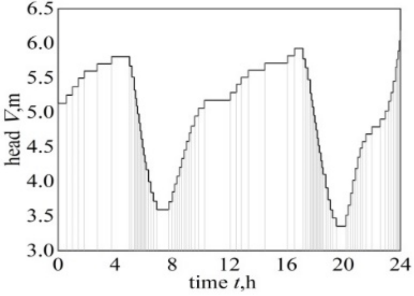


Fig. 2 shows the discretization of water level.

2.2.2 Solution of Multi-Objective Optimization Problems

Multi-objective optimisation problems involve conflicting objectives and goals, which can make the solution process more challenging. Currently, there are two main approaches for solving multi-objective optimisation problems: ① Conversion of a multi-objective optimization problem into a single-objective optimization problem by methods such as weighted summation [7], TOPSIS analysis [8], and then applying single-objective problem-solving methods. ②Solving the multi-objective optimal problems based on the Pareto optimality that makes one or several of the objectives better without making any one of them worse. Wang et al [9] used a multi-objective particle swarm algorithm (MPSO) based on the Pareto optimal solution to solve the optimal water resources scheduling model, and the results show that the optimal equilibrium solution can take into account the social and economic benefits, and provide the decision maker with a multi-attribute decision-making scheme.

Therefore, the crossover and mutation strategies of genetic algorithm (GA) and Pareto Optimality are applied to the multi-objective particle swarm algorithm and the model of the T-PS is solved with the hybrid particle swarm algorithm (HMPSO).

2.2.3 Principles of the hybrid multi-objective particle swarm algorithm(MPSO)

The elementary particle swarm algorithm is a population intelligence algorithm inspired by the regularity of the foraging behavior of flocks of birds, proposed by Shi Y and Eberhart R C in 1995 [10]. Genetic Algorithm (GA) is a search algorithm inspired by the theory of Darwinian evolutionary. Hybrid multi-objective particle swarm algorithm (HMPSO) is constructed on the basis of basic particle swarm algorithm by mixing crossover and mutation operations of genetic algorithm.

2.2.4 Pareto Optimality

Since multiple objectives are in conflict, a solution that is optimal for one objective may be worst for others; these solutions that improve any one objective while weakening at least one other objective are called non-dominant or Pareto solutions.

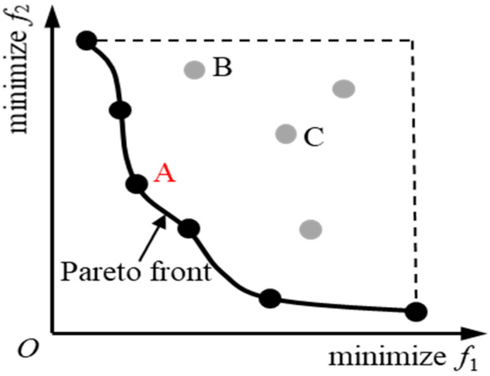


Fig. 3 Pareto optimality.

If the values of both objective 1 and objective 2 at point A in figure 3 are less than at points B and C, then point A dominates B and C and A is a dominant solution to B and C. If no solution dominates point A, then point A is a Pareto solution. A set of non-dominated solutions constitutes a set of Pareto solutions, and a straight line connecting these non-dominated solutions is called a Pareto front.

3. Case Study

3.1 Data of the T-PS

The T-PS in this paper is 330 kilometres away from the estuary of the Yangtze River. And it is the first-stage pumping station of the South-to-North Water Diversion East Route Project in China. 7 sets fully adjustable axial flow pumping units (type: 2900ZLQ30-7.8.) are equipped in the system. And head of the system for a typical day is shown in figure 4.

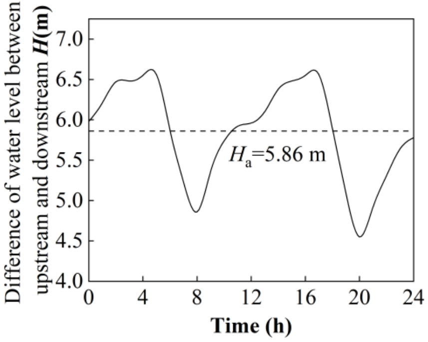
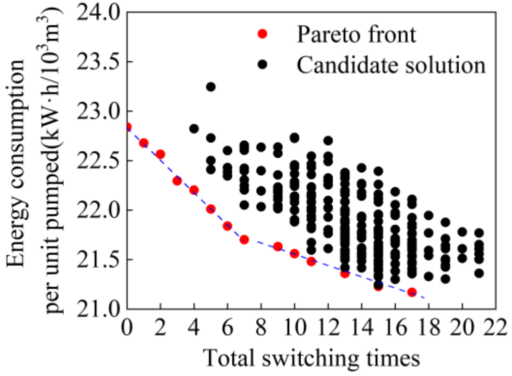


Fig. 4 Head of the system for a typical day

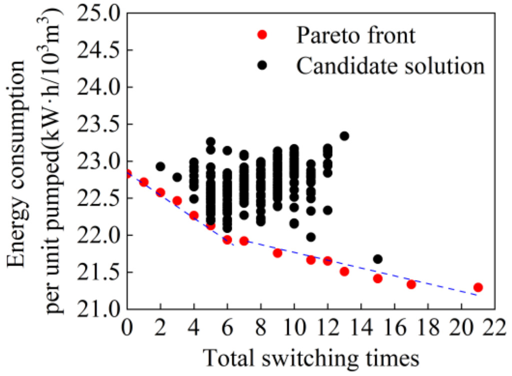
3.2 Results and analysis

The method proposed above is applied to solve the multi-objective model, and Pareto front for different water demand V_x (from 8000×10^{3}m^3 to 10000×10^{3}m^3) are shown in figure 5.

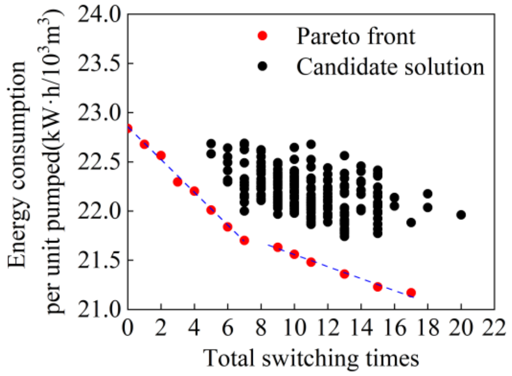
As can be seen in figure 5, the Pareto solution is uniformly distributed over the range of the solution space. Due to the requirement of the total daily lifting constraint, the unit pumping energy consumption of the Pareto front decreases with the increase of the switching times. The results for different water requirements show that the unit pumping energy consumption is linearly and negatively correlated with the switching times.



(a) 8000×10^{3}m^3



(b) 9000×10^{3}m^3



(c) 10000×10^{3}m^3

Fig. 5 Pareto front for different V_x from 8000×10^{3}m^3 to 10000×10^{3}m^3

When the switching times is 0, the pumping station unit lifting operation energy consumption is the highest, respectively, 22.828 kW·h/1000 m^3 ~22.851 kW·h/1000 m^3. Therefore, in the Pareto front, the ideal solution should be the point that minimizes the switching times and the operating cost at the same time, but obviously the two are contradictory and cannot be obtained at the same time.

Compared with the point with the least number of start-stop in the Pareto frontiers (figure 5(c) f_1=22.833 kW·h/1000 m^3, f_2=0), the unit pumping energy consumption is reduced by 0.868 kW·h/1000 m3, which is about 3.803%, in the optimal operation (f_1=21.965 kW·h/1000 m^3, with the number of start-stop as f_2=7) The switching times increases from 0 to 7. Compared with the minimum point of energy consumption per unit of pumping (f_1=21.497 kW·h/1000 m^3, and the switching times of f_2=17), the energy consumption per unit of pumping of the optimal operation scheme increases by 0.467 kW·h/1000 m^3, but the switching times increases to 17, which is about 58.824%.

4. Conclusion

Applying the model constructed in this paper to a typical tidal pumping station, the results show that the energy consumption in the Pareto front is segmentally and linearly negatively correlated with the total switching times.

Comparing the optimal operation scheme with the scheme which the switching times is least in the Pareto front, the energy consumption per unit is reduced by about 3.803%, and the switching times is increased from 0 to 7, which is within a reasonable range.

The results show that the optimal operation scheme determined by the multi-objective optimization model proposed in this paper can effectively reduce energy consumption and reasonably control the total number of switching times.

For different requirements, the decision maker could evaluate the individual Pareto front and select the most suitable operation scheme according to the relevant operation and management regulations of pumping station. The optimization scheme proposed in this paper could provide a reasonable and optimal scheme for the T-PS.

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