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Efficient operation of the fourth Huaian pumping station in east route of South-to-North Water Diversion Project☆

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ABSTRACT

The fourth Huaian pumping station is one of the second-stage pumping stations on the east route of the south-to-north water diversion project in China. The operation optimization problem of three pumps in the station is formulated to minimize the electricity cost while satisfying the flow demand. After analyzing the characteristics of the problem, a decomposition method is proposed to reduce the dimensionality of the optimization problem and thus the computation time. Simulation shows that the energy cost is reduced by 2.54% compared with the benchmark scheduling based on the proposed method. In comparison with the decomposition/aggregation-dynamic programming method and the dynamic programming with successive approximation method, the proposed algorithm can effectively save electricity costs for Huaian pumping station. The case study shows that the cost efficiency comes from two aspects: demand shift from the time intervals with a high electricity price to those with a low electricity price, and the operation mode with high energy efficiency. The former is subject to the pumps' capacity and the daily demand. The larger the pumps' capacity is, the more demand can be shifted and thus the lower the cost is. The latter is subject to the pumps' characteristics and the pump heads. The larger the head is, the smaller the difference for energy efficiencies with different blade angles are, and the smaller the energy savings with the optimal operation are. When the demand is high for a given pump head, demand shifting is the main reason, while the second aspect is the main reason when the demand is low.

1. Introduction

The water shortage problem in North China and the related eco-environmental issues have become the most significant aspects to be considered in sustainable development. To solve the water scarcity situation in North China, the South-to-North Water Diversion Project (SNDP) was commenced in 2002 to balance the nation's water supply. The SNDP aims to transfer 59 billion m^3 of water from the wet southern region to the dry northern region annually through three routes (east, central and west routes). The east route was scheduled to develop in three stages to progressively improve the amount of water discharge and the extent of the diversion. The first stage is intended to utilize the diversion project in Jiangsu Province, extending its scale northwards and diverting the water from the Yangtze River to Shandong Province. The fourth Huaian pumping station is located in Huaian County and is one of the second-stage pumping stations in the SNDP (east route) in China.

The water is diverted from the Yangtze River, utilizing Beijing-Hangzhou Grand Canal and the river courses approximately parallel to the Canal and Hongze Lake, Luoma Lake, Nansi Lake and Dongping Lake as well as water employing diversions and impounding reservoirs. The difference between the water levels of the Yangtze River and Dongping Lake is about 40 m. The diagrammatic sketch of the water delivery trunk of the east route of the SNDP is shown in Fig. 1. There are 30 pumping stations in east route to pump the water from the Yangtze River to Dongping Lake. The total designed flow rate of the pumps is 10,200 m^3/s and the total rated power of the motors is 1.02 GW. The pump stations have similar characteristics: most heads are small within 2–6 m, the flow rate of one pump is large, within 15–40 m^3/s, and the annual time of pump operation is about 5000 h. Operation scheduling is very important to reduce the operational cost. The fourth Huaian pumping station is one of the pumping stations on the east route of the SNDP and its operation scheduling is studied in this manuscript to show the optimization approaches and results for the operation of the SNDP.

The operation of a pumping station is always important in achieving the tasks of the station. One is to supply the demand in a given period, and the other is to reduce the operational cost [1–3]. With the operational scheduling optimized, a remarkable reduction in the operational

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Nomenclature

i	number of the pump
t	number of the time interval
ρ	water density
$\theta_{i,t}$	blade angle of the ith pump
$Q(i,t,\theta_{i,t})$	flow rate of the ith pump
$H_{i,t}$	head of ith pump
$\eta_{i,t}$	pump efficiency
η_{m}.	motor efficiency
ΔT	length of the time interval
P_t	electricity price
C	electricity cost
Q_D	daily water demand
E_m	rated power of the pump
S	number of blade angle choices
H_{av}	daily average head
Q^M	maximum value of the daily flow of a pump
s_j	blade angle decision of the jth interval
Q_s	water flow
P	energy consumption
E_s	required power
$M(i)$	a decision combination

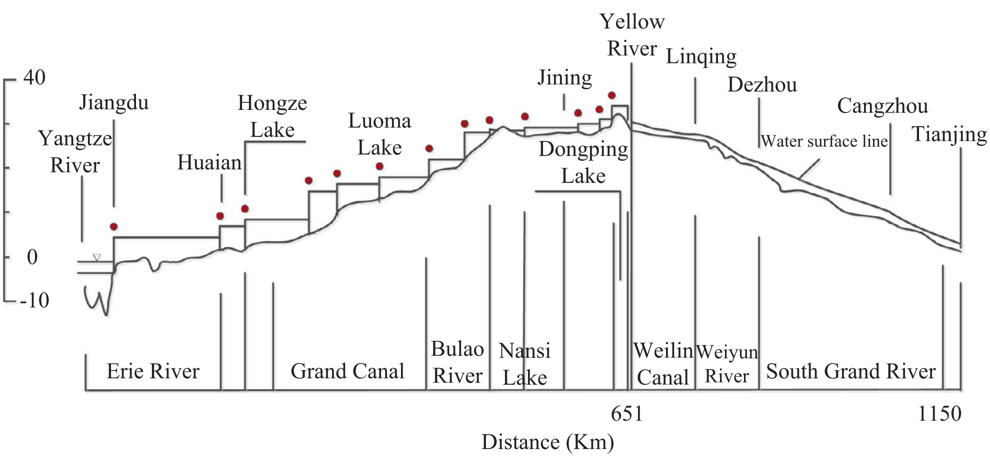

Fig. 1. The diagrammatic sketch of water delivery trunk of the east route of SNDP.

cost could be achieved while no change was needed in the physical elements, such as pumps and civil infrastructure [4–6].

The operational scheduling problem of a water-supplying pumping station can be formulated as a cost optimization problem, of which the objective is to minimize the operational cost while the flow demand is satisfied [7–11]. The on/off states within a time period are scheduled and sometimes the blade angles of the pumps are scheduled, as well as the frequencies of AC power supply.

The problem of the optimal operation scheduling of a pumping station has been studied and the results have been published in many papers in recent years [12–16]. The optimization problem is formulated for different pumping systems. The problem of a pumping station with fixed-speed motor pumps is intrinsically an integer programming problem (linear or nonlinear), depending on the mathematical models of the hydraulic structures, networks, etc. For such a kind of integer programming problem, various techniques have been employed in load shifting for different processes, for example, mixed-integer programming in [17], linear programming (LP) in [18], dynamic programming (DP) in [19] and stochastic DP by McCormick and Powell in [20]. The above methods can theoretically solve the optimal operation scheduling problem, but they are limited in practice when the underlying model is large or complex because of *the curse of dimensionality* of the DP or *interminable branch and bound* of the integer programming.

To search the global optimal solution to a programming problem, some modern optimization methods, such as genetic algorithm [21–24], simulated annealing [25,26], particle swarm optimization [27], ant colony optimization [28] and fuzzy optimization [29], are adopted. The computational time of those approaches is sometimes very long or the algorithms are sometimes too complex, which again limits their application.

The optimal scheduling problem of the fourth Huaian pumping station is intrinsically an integer programming problem, which is studied in [30] using the decomposition dynamic programming aggregation method. The optimal operation problem of multiple pumps is decomposed to several operational sub-problems (each sub-problem corresponds to a pump) and the daily pump flows in the solutions to the sub-problems are coordinated with a DP algorithm to minimize the electricity cost while satisfying the daily demand of the station. In this way, the computation time can be significantly reduced. There are three pumps in the operation scheduling problem and it is assumed that the number of the blade angle values is N_b and the time period is partitioned into N_t time intervals. Then the dimensionality of the operational problem of multiple pumps is $N_b^{3N_t}$ (it is 17^{36} when $N_b = 16$ and $N_t = 12$). With the method proposed in [30], the original problem is decomposed into three sub-problems and a DP problem with three decision variables. The dimensionality of each sub-problem is $N_b^{N_t}$, which is much lower than the original problem. However, the solution to the decomposed problems is an approximation to the real optimum of the original problem and the gap between the approximation and the real optimum depends on the value choices in DP.

In [31,32], a reduced dynamic programming (RDPA) algorithm is developed to address the optimal operational scheduling problem with the capability of fast computation. The scheduling problem is reformulated as a control sequence optimal scheduling problem. This algorithm is a cost-efficient scheduling approach to the pump operation. Incorporated with the model predictive control in [33,34], the RDPA could be applied to develop an on-line closed-loop controller for the pump operation.

The optimal operational scheduling in [31,32] is studied for the pumps with the blade angle fixed. The admitted domain of the control variable of a pump is {0,1}. When more blade-varying pumps' operation is required to be optimized, the method in [31] cannot be directly employed. There are several pumps in the pumping station considered in this paper, and the blade angles of the pumps are adjustable. The approach of RDPA is re-investigated and extended to implement in a pumping station with multiple blade-varying pumps.