Research on the key techniques of the Miyun reservoir regulation and storage engineering’s integrated scheduling

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Abstract. The middle route of the south-to-north water diversion project greatly ease the conflict between supply and demand of water resources in Beijing. As an important supporting engineering of this, the integrated scheduling of the Miyun reservoir regulation and storage engineering is of great significance. In order to strengthen the scheduling management of the engineering and realize the safety and economic operation of the project, using state space analysis, mathematical optimization, automatic control technology and other technologies to establish a "simulation, scheduling and control" technology system, which includes the multi-process simulation technology, multi-dimensional optimal scheduling technology and operation control technology of free-surface-pressureized flow and ice-water coupling in the water delivery system of cascade pumping stations. Research results applied to the Tundian pumping station and intelligent scheduling system platform, which have strong applicability, can provide technical support for the scheduling management of the Miyun reservoir regulation and storage engineering and realize the goal of engineering safety and economic operation.

1. Introduction

Beijing is an international metropolis and a serious water shortage city. Beijing’s per capita water resources is less than 200m³, which is less than 1/30 of the world per capita, far below the internationally recognized per capita water crisis line [1]. At the same time, the rapid development of economic forms and relatively weak water resources has exacerbated the competition between water and ecology, which constitutes the main contradiction of Beijing’s sustainable development. However, with the official running of the South-to-North Water Diversion Project, Beijing accepts 1 billion m³ of southern water every year, which greatly eases the contradiction between water supply and demand.

The Miyun reservoir regulation and storage engineering is an important part of Beijing South-to-North Water Diversion Project, which plays an important role in eliminating the water resources deficit. The engineering is a complex water transfer system consisting of pumping stations, inverted siphon, sluice and so on. The pipeline along the route includes open channels and pressurized pipes. Its biggest feature is that it involves the reverse water of open channel and it also has other features, such as small available storage capacity, the high power consumption of the cascade pumping stations and the operating cost and so on. And they all make it very difficult to integrated dispatch and
control the water diversion project in the cascade pumping station.

On efficient and economical operation of cascade pumping stations, many scholars have done researches. Moradi-Jalal et al. [2] established a new management model based on genetic algorithm. da Costa Bortoni et al. [3] proposed an optimization algorithm framework based on dynamic programming. Ostfeld A et al. [4] extended the design and operation of multi-stage pumping station water distribution system based on ant colony optimization algorithm. Bene J G et al. [5] studied the short-term operation of the pump based on a hypothetical water allocation system with the total energy dissipation as the objective function, the water storage volume, the pump boundary condition, the node mass conservation and the energy demand as the constraints. Theocharis ME et al. [6] compared the minimum cost of pipeline operation and the running cost of pumping stations, compared the advantages and disadvantages of several traditional optimization algorithms, and proposed a simple nonlinear optimization method. Feng Xiaoli et al. [7] established an optimal mathematical model with the goal of minimizing the total input power of the system, considering the pumping station, power transmission equipment, water transport channel as a whole system.

The development of digital simulation and dispatching of water conveyance project has important economic, scientific and social benefits for the safe operation of water conveyance system. The study focuses on the integrated scheduling of the water conveyance system of the Miyun Reservoir, and carries out a complete set of technical system research including simulation, dispatching and control.

2. Overview of the Miyun Reservoir Regulation and Storage Engineering
The Miyun reservoir regulation and storage engineering takes water from the Tuancheng lake and reverses the flow by using the original Jingmi channel. The water is lifted to Huairou reservoir by the six new pumping stations, which were built near the Tundian sluice, the Qianliulin inverted siphon, the Niantou inverted siphon, the Xingshou inverted siphon, the Lishishan sluice and the Xitaishang sluice, respectively. The water flow is 20m³/s. Through the adjustment of the Huairou reservoir, part of the water returns to the water source area, and the other part of the water is fed into the Miyun reservoir. The water flow is 10m³/s.

3. Technical Framework for Integrated Scheduling and Operation of Water Conveyance Systems
In order to realize the safety and economic operation of the Miyun reservoir regulation and storage engineering, research on the optimal operation and control of the cascade pumping station is carried out. The state space analysis, mathematical optimization, automatic control and other technologies are used to coordinate all parts of the system scientifically to establish a safe and economical integrated scheduling strategy, so that the system can effectively reduce the cost of operation and achieve its economic and social benefits on the basis of meeting the needs of various working conditions and ensuring the safe operation. A closed-loop control technology system of "simulation-dispatching-control" is established and its technical system is shown in Figure 1.
3.1. The Multi-Process Simulation Technology of Mixed Free-Surface-Pressurized Flow and Ice-Water Coupling

The pipeline of cascade pumping stations is the coexistence of open channel and pressurized pipe. Besides, during winter operation, open channels is in a variety of conditions, such as ice-free water transfer, ice-flowing water transfer and ice sheet water transfer. Therefore, the establishment of mixed free-surface-pressurized flow and ice-water coupling multi-process simulation model can accurately simulate the alternation of mixed free-surface-pressurized flow in space and the multi-process of ice water coupling in time, providing technical support for safe water transmission.

3.1.1 Simulation of hydraulic process in open channel. A one-dimensional hydraulics model is constructed to generalize the complex internal structures such as pumping stations, inverted siphons, and graded sections, then the generalized internal structures are coupled with the Saint-Venant equations. At the same time, the equations are discretized by using Preissmann four-point spatiotemporal eccentricity scheme and solved by double sweep method.

3.1.2 Water hammer simulation of pipe. The basic differential equation of water hammer consists of two equations: the motion equation and the continuous equation. The theoretical basis is the mechanical rule and continuous principle of water flow. It is a mathematical expression that comprehensively reflects the law of unsteady flow in a pressurized pipe, including the change of water flow velocity and head. The basic differential equation of water hammer is the basis for studying the hydraulic transition process.

3.1.3 Simulation of water conveyance process in winter. The models, which involved in the numerical simulation of ice conditions, include water flow model, heat exchange model, flow temperature field model, floating ice-ice in water-shore ice model, ice sheet dynamic mode. And the difference between this study and the calculation of the general channel unsteady flow is that the established water flow model can not only get the flow rate and water level process under the conditions of open water, but also can get the flow rate and water level under the condition of ice cover. Besides, the model can solve the prismatic channel and the non-prismatic channel.

3.2. Multi-Dimensional Optimal Scheduling Technology of Cascade Pumping Stations

Mainly considering the time-varying electricity price rules and the distribution of buildings in space,
multi-dimensional optimal scheduling adopts mathematical optimization technology to optimize the allocation of water flow rate and head in time and space, so as to formulate the project scheduling scheme and achieve the goal of efficient and economic operation of the project.

3.2.1 Intelligent energy saving technology of cascade pumping station based on technology of dumped station. The operation condition, namely, dumped station is to open the certain sluice at a pumping station (which is not working), so that the water directly flows to the next pumping station. When the \(i\)-th pumping station is dumped, according to the water level of the inlet of the \((i+1)\)-th pumping station, the water level of the outlet of the \((i-1)\)-th pumping station and the water level of the inlet of the \(i\)-th pumping station can be calculated by hydraulics model. Then \(\Delta V_1\) and \(\Delta V_2\) can be calculated according to the flow rate and the initial water level and the water level after \(i\)-th pumping station dumped. \(\Delta V_1\) and \(\Delta V_2\) are the variations of water storage volume of the channels before and after the \(i\)-th pumping station, respectively. If \(\Delta V_1 > \Delta V_2\), the flow rate of the \((i-1)\)-th pumping station increased to \(Q_1\), the \(i\)-th pumping station stopped working. The duration time is calculated by equation (3.1). Then, the flow rate of the \((i+1)\)-th pumping station becomes \(Q_2\). Otherwise, the duration time is calculated by \(Q_2\) and \(\Delta V_2\), the flow rate of the \((i-1)\)-th pumping station becomes \(Q_1\), which is calculated by \(\Delta V_1\) and duration time.

\[
\begin{align*}
T_1 &= \frac{\Delta V_1}{Q_1} \\
Q_2 &= \frac{\Delta V_2}{T_1}
\end{align*}
\]

3.2.2 Time-Dimensional Optimal allocation model of water flow rate. The time-dimension optimal allocation model of water flow rate includes the annual/monthly/ten days/day scale optimal allocation model. The daily scale optimal allocation model is described as an example. Under the condition of satisfying the constraints of the reservoir regulation and storage engineering, the optimal allocation of water flow rate considering the peak and valley time price is carried out.

1. The objective function:

\[
\min F = \sum_{i=1}^{t} \sum_{j=1}^{m} \sum_{k=1}^{n} \rho g Q_{k,j,i} H_{k,j} \times \Delta t_k \times c_k
\]

where \(t\) is the total number of time period; \(m\) is the number of pumping stations; \(n\) is the maximum number of units that can be put into operation; \(Q_{k,j,i}\) is the flow rate of the \(i\)-th unit of the \(j\)-th pumping station in \(k\)-th period; \(H_{k,j}\) is the head of the \(j\)-th pumping station in \(k\)-th period; \(\Delta t_k\) is the duration of the \(k\)-th time period; \(c_k\) is the price of the \(k\)-th period.

2. Constraints: The constraints include the constraints of the Tuancheng lake storage capacity, the constraint of the total flow rate, the constraints of the head and the constraints of the total diversion water quantity.

3.2.3 Spatial dimension optimal head distribution model of cascade pumping stations. On the premise of meeting the hydraulic connection of each channel section and the water level constraints of the inlet and outlet of each pumping stations, the head distribution of the cascade pumping stations is carried out to minimize the energy consumption. The model is as follows:

1. Objective function:

\[
\min F = \sum_{j=1}^{m} \sum_{i=1}^{n} \frac{\rho g q_{i,j} H_{j}}{\eta_{i,j}(i,j)} \times \Delta t \times c
\]

where \(q_{i,j}\) is the water rate of the \(i\)-th unit of the \(j\)-th pumping station; \(\eta_{i,j}(i,j)\) is the efficiency of the \(i\)-th unit of the \(j\)-th pumping station.

2. Constraints: The constraints include the constraint of the total head, the head constraint of each
pumping station, the water level constraints of the inlet and outlet of each pumping station.

3.3. Operation Control Technology of Water Conveyance System of Cascade Pumping Stations

Control is to achieve the required hydraulic running state through a series of controlled operation. It is the means to realize the safe and economic operation of the engineering. The steps are as follows:

(1) Water level forecast: The water level can be forecasted by hydraulic model.

(2) Determining whether control is necessary: If \( Q_{i-1} > Q_i \), then

\[
\begin{align*}
\Delta V &= V_{\text{max}} - V_0 \\
\Delta T &= \Delta V / (Q_{i-1} - Q_i)
\end{align*}
\]

(3.4)

where \( V_{\text{max}} \) are the storage volumes corresponding to the highest controlled water level, \( \Delta T \) is the time it takes to reach the highest or lowest controlled water level.

Otherwise, according to the lowest controlled water level, \( \Delta V \) and \( \Delta T \) are calculated. After calculating all the \( \Delta T \) in the cascade pumping stations, the minimum \( \min(\Delta T) \) and its corresponding pumping station are found.

(3) To determine the advance time of control: The calculation method of the ideal advance control time is as follows:

\[
\Delta t = \frac{L_i}{(v + |c|)} \left( \frac{K \cdot L_i}{(v - |c|)} \right)
\]

(3.5)

Where \( L_i \) is the length of the \( i \)-th channel; \( K \) is the weight coefficient; \( v \) and \( c \) are the average velocity and wave velocity of the channel at the initial time, respectively.

(4) The method of control: The control measures are determined by the relationship between \( Q_{i-1} \), \( Q_i \) and \( Q_{i+1} \), and the flow rate of cascade pumping station is gradually balanced.

4. Application Example

4.1. Study on Intelligent Energy Saving Scheme

The hydraulic model is used to calculate the head loss. In order to ensure the inlet water level of the pumping station is not too low to avoid cavitation and the outlet water level of the pumping station is not too low to avoid excessive pump vibration, it needs to calculated whether the inlet and outlet water level of each pumping station are meeting the working range in the condition of dumped station. And through the measured data to check the model, the results demonstrate that the Tundian, Xingshou and Lishishan three pumping stations can be dumped when a single unit is working, and the Tundian pumping station also can be dumped when two units are working.

Taking the Tundian pumping station as an example, the water flow is 6.67 m³/s, the inlet water level of the Tundian pumping station is 48.60 m and the inlet water level of the Qinliulin pumping station is 49.16 m before the Tundian pumping station dumped. After the Tundian pumping station dumped, the water flow is 6.67 m³/s, the inlet water level of the Tundian pumping station is 48.80 m, which are calculated by the hydraulic model. In order to achieve the target storage volume when the Tundian pumping station is dumped, it is necessary to adjust the flow rate at all channels before opening the control sluice. In order to achieve the condition of the Tundian pumping station dumped as soon as possible, the flow rate of the Qinliulin pumping station needs to increase to 13.34 m³/s, thus it needs 2.52 hours to achieve the required storage volume of the channel, which is after the Tundian pumping station. In the corresponding period of time, in order to achieve the target storage volume of the channel before the Tuanbian pumping station, the flow rate of the Tuancheng lake should be reduced to 3.34 m³/s. After 2.52 hours, the sluice of the Tundian pumping station is opened, and the flow rate of the cascade pumping stations are adjusted to 6.67 m³/s. Similarly, according to the actual operation, the control time and flow rate of other pumping stations are calculated when the pumping station is dumped.
4.2. Intelligent Scheduling System Platform
The integrated scheduling system of the Miyun reservoir regulation and storage engineering is a friendly interface and convenient software system. The system is developed with GIS, database, and component technology, based on the data analysis and perfecting, simulation model and economic optimization scheduling model of the Miyun reservoir regulation and storage engineering. In the process of system calculation, the required datum of each model are read in automatically, and the function of scheduling simulation and optimization is provided. Meanwhile, the management and result display of the scheme can be realized. The system is modular in design. The specific structural mode is not limited to B/S or C/S, and the network structure with redundant configuration of network backbone and key nodes is adopted to ensure high reliability of the system. System has a safe and reliable backup measures, including data backup, system backup, application system backup, to ensure that system can quickly return to normal operation and ensure the integrity of the historical data.

5. Conclusion
For the Miyun reservoir regulation and storage engineering, the integrated scheduling system of the complex water conveyance system is established, which contains the process of "simulation-scheduling-control". Based on the principle of hydraulics, the simulation model is the basis of engineering scheduling and control research, which can simulate the flow state of open channel and pipe, as well as the coupled multiple process of ice water. Based on the time-varying price rules and the distribution of buildings in space, the multi-dimensional optimization of cascade pumping stations uses mathematical optimization technology to optimize the allocation of the water flow rate and head, and then plans the scheduling scheme, which can achieve efficient and economic operation. And the intelligent scheduling system platform integrates various models and manages schemes to provide support to the final decision.

The research results are applied to the demonstration engineering and system platform, which is of great practical significance and urgency to the integrated scheduling of the complex water conveyance system, and can guarantee the safety and economic operation of the Miyun Reservoir.

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