An Optimal Regulation Method for Parallel Water-Intake Pump Group of Drinking Water Treatment Process

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ABSTRACT
Electricity consumption of pump group accounts for a significant proportion of cost in water distribution system (WDS). This paper discusses the optimal regulation method for parallel water-intake pump group consisting of fixed-frequency pumps and variable-frequency pumps. For this purpose, the regulation strategy for the water level of clean water tank is designed, and then the intake water flow of parallel pump group is calculated. For overall optimizing operation of parallel water-intake pump group, the minimization of electricity consumption is performed within the constraints of limited pressure fluctuations of WDS and required flow of water supply. Dynamic programming algorithm and particle swarm optimization algorithm are employed to solve the optimization problem with constraints. Experimental studies have been conducted and the results show that 4.20% electricity-saving can be achieved by using the proposed optimal regulation method.

INDEX TERMS Water distribution system, clean water tank, water-intake pump group, optimal regulation.

I. INTRODUCTION

Water distribution system (WDS) is a critical infrastructure in urban areas [1]. Its operational management is a subject of increasing interest, taking into account the economic and environmental factors [2]. Its optimization involves many aspects, such as layout of pipe network, water consumption, types of pump group, clean water tank, and electricity charges [3], [4]. The optimal regulation of pump group has been proved to be a practical and effective method for reducing operation costs of the whole WDS system [5]–[7]. According to the number of variables and optimization objectives, optimal regulation problem of pump group may become very complex, especially in large systems. Some literature have studied this problem, introducing different approaches [8], [9].

The optimal regulation of pump group for achieving maximum efficiency is of great research interest [10]. This paper shows a method of electricity-saving through optimizing the pump regulation in the first time [11]. Setting up the water level of clean water tank can adjust the load in high or low peak period. The main operational goal is electricity-saving, while guaranteeing the flow requirements of water-supply and stable pressure fluctuations.

In view of the different operational conditions of facilities and their influence on the WDS, the optimal operation models of WDS can be divided into two classes [12]. The first one is the static optimization problem without considering clean water tank in the WDS. The second one is the dynamic optimization problem with considering clean water tank in the WDS. The first one has been studied in detail [13]. The second one is much more complicated than the first one for the existence of many important influence factors such as flow of water supply, pressure of WDS, inflow and outflow of clean water tank, etc. [14]–[16]. It is a large-scale nonlinear dynamic optimization problem with temporal correlation [17].

Single pump operation problems are recognized very well at a fundamental level [18]–[20]. Pump optimization research has been thoroughly explored in the areas of...
design, construction, and operational characteristics [21]. If the pumps are fixed-frequency, it usually focuses on the different operational combination of pumps [22]. However, many researchers have turned their attention to the using of variable-frequency pumps for constructing pump group [23], [24]. When the variable-frequency pumps are applied in the pump group, a wider range of variable-flow features and better operating efficiency can be obtained. However, the physical models are also difficult to build up accurately [25], and conventional optimization methods are difficult to be customized. Fundamental heuristic algorithm provides an effective resolution for these problems.

In this paper, the optimization problem can be described as follows: giving the required water flow, seeking the parallel operation combination of water pumps, controlling speed regulation ratio of each parallel frequency conversion pump, so as to minimize the total electricity of water-intake pump group. To date, this work has been experimented successfully in a water-intake pump group of water treatment plant of Suzhou, China. This paper’s experimental environment includes four fixed-frequency pumps and two variable-frequency pumps.

The major contribution of this work is the development of dynamic electricity prediction model. Through analysis of system construction, pump characteristics and pump working state, a dynamic electricity prediction model is proposed in Section 2. The regulation methods of water level of clean water tank is to adjust the difference between the system and the water delivery system, the main function of clean water tank is to adjust the difference between the water-intake and the water-supply. It is based on the principle of replenishing water at peak and storing water at low peak.

II. ELECTRICITY MODEL
A. SYSTEM CONSTRUCTION
The switch status and frequency regulation of water pump group is affected by some facilities in urban water supply. For example, the urban water supply system is made up of water supply pipes, which are connected in a specific combination. Therefore, it is important to understand the construction of entire urban water supply system for establishing an optimization model.

All the water supply system runs in a cycle of 24 hours. Because the running environment is different, and it is affected by different town topography, size and user water, etc. The system construction is very different. In addition, the operation of some components in the system, such as reservoirs and pressurized pump group, will also affect the operation of system. The construction of entire urban water supply system leads to different systems with different optimal regulating models. In this paper, the clean water tank includes four water storage building, and the height is less than three meters. The total volume is 40000m$^3$. Due to the variation of water level, this kind of system is a large-scale nonlinear dynamic optimization problem. Figure 1. shows the whole water supply system.

Stage-1 is the water-intake of water system. Water-intake pump group pumps water from water source in Lake Taihu, China. The water delivery system pumps water from stage-2 (water treatment plant). And the water supply network is constituted by DN1200 and DN1400 muddy water pipe. Each muddy water pipe equips one pressure gage to monitors the pressure in the water supply network. Stage-2 includes water treatment process and water storage system (such as clean water tank). The workflow of water-intake system is generally as follows:

Firstly, water is pumped from rivers, lakes or other water sources by water-intake pump group. And is fed into the water storage building through water supply network. However, sometimes, the amount of water cannot meet the urban water supply dispatching task. Water treatment plant needs opening the standby water pipe. And it supplies water from other water-intake pump group to borrows water.

Secondly, the water treatment process is proceeding, and the treated water quality should meet the safety standards. After that the clean water flows into the clean water tank, which is finally transferred to the water distribution pipe network through the water-supply pump group.

As the connection part between the water-intake of water system and the water delivery system, the main function of clean water tank is to adjust the difference between the water-intake and the water-supply. It is based on the principle of replenishing water at peak and storing water at low peak.

B. PUMP CHARACTERISTICS AND WORKING STATE
Usually the performance of pump refers to a certain speed, the pump flow and head(Q-H), flow and power (Q-P), flow and efficiency (Q-$\eta$), flow and vacuum suction height or cavitation allowance. The Q-H curves of fixed-frequency pump can be formulated as:

$$H = H_s - Q^2$$ (1)

where $Q$ is fixed-frequency pump’s flow, and $H$ is fixed-frequency pump’s head. $H_s$ and $d$ are data fitting parameters, which are measured by actual production conditions.

The $Q$-$N$ curves of fixed-frequency pump can be formulated as:

$$N = a + bQ + cQ^2$$ (2)

where $Q$ is variable-frequency pump’s flow, and $N$ is variable-frequency pump’s power. The $a$, $b$, $c$ are data fitting parameters. In this paper, six different coefficients are fitted, which are shown in Section 3.
According to the law of pump similitude, the following formula is obtained:
\[
\frac{Q}{Q_N} = s
\]  
(3)
\[
\frac{H}{H_N} = s^2
\]  
(4)
\[
\frac{N}{N_N} = S^3
\]  
(5)
where \(s\) is the ratio of speed governing. In this paper, the optimal value is set from 0.7 to 1. It indirectly reflects the regulating frequency of inverter pump. \(Q_N, H_N\) and \(N_N\) are flow, head and power of variable-frequency pump under rated speed. The parameters are determined by the factory sets. Performance curve of variable-frequency pump is given by:
\[
H = s^2H_s - Q^2
\]  
(6)
\[N = aS^3 + bS^2Q + cSQ^2\]  
(7)
When the pump is running, its working condition not only depends on the characteristics of pump itself, but also depends on the pipe system of pump and the change of water level or other factors. The H-Q curves includes pipeline characteristic is as follow:
\[
H = H_{st} + s'Q^2
\]  
(8)
where \(H_{st}\) is terrain elevation difference, \(s'\) is resistance parameters of piping system.

The purpose of optimal regulation is to make full use of the variable-frequency pump to minimize the electricity consumption, under the premise of meeting the required water flow. Therefore, this paper realizes the minimum power of water pump group as one objective function.

In this paper, water-intake pump group is composed by four fixed-frequency pumps and two variable-frequency pumps. All pumps are marked. 1#, 2#, 4#, 5# are variable-frequency pumps. 3#, 6# are variable-frequency pumps. The state factor is defined as \(W\).

\[
W = [w_1, w_2, w_3, w_4, w_5, w_6]
\]  
(9)
where \(w_i\) is the working state of pump \(i\). 1 is on, and 0 is off.

According to formula 3, \(S_3, S_4\) is defined as the 3#, 6# variable-frequency pump’s ratio of speed governing. And the water-intake pump group’s model can be given as:
\[
\min J = \sum_{i=1,2,4,5} w_i \left( a_i + b_iQ_i + c_iQ_i^2 \right)
\]  
(10)
\[
+ \sum_{i=3,6} w_i \left( a_iS_i^3 + b_iS_i^2Q_i + c_iS_iQ_i^2 \right)
\]
Some other influence factors are considered as constraints:
\[
\sum_{i=1}^{6} Q_i = Q_p
\]  
(11)
\[
S_i \in \{S_{min}, 1\}, = 3, 4
\]  
(12)
\[
W_i \in \{0, 1\}, = 1, 2, \ldots 6
\]  
(13)
where \(Q_p\) is the required water of total regional water supply. The \(Q_p\) is the historical user’s requirement. \(S_{min}\) is minimum ratio of speed governing. The model is an existing discrete variable (combination of pumps in parallel), and has a continuous variable (ratio of speed governing). Moreover, it is a complex optimization problem with constraints. The research shows that the range of flow regulation of variable-frequency pump should be 0.7 ∼ 1. And \(S_{min}\) is usually defined 0.7. Because the pump is set for parallel, also need to consider the parallel pump head and flow relationship.

The head need meets the formula as follow:
\[
H_1 = H_2 = \cdots = H_n = H_0
\]  
(14)
The objective function adds a correction term to steady the water pressure of pipeline:
\[
\min J' = \sum_{i=1,2,5,6} \left[ w_i \left( a_i + b_iQ_i + c_iQ_i^2 \right) \right]
\]  
(15)
\[
+ \sum_{i=3,4} \left[ w_i \left( a_iS_i^3 + b_iS_i^2Q_i + c_iS_iQ_i^2 \right) \right]
\]
\[
+ \sigma \left| p_p - \sum_{i=1}^{6} p_i \right|
\]
where \(\sigma\) is penalty factor. The difference between actual and expected stress is greate, and the penalty is stronger. It can fully balance the pressure fluctuations in 0.02 MPa.

### III. METHOD

#### A. CLEAN WATER TANK REGULATION

The percentage of volume of clean water tank in the maximum daily water consumption is a factor that affects the operation of water-intake pump group. Figure 2. shows the practical usage of clean water tank in S water treatment plant.

![FIGURE 2. Water level trend.](image-url)

Figure 2. reflects the basic situation of water level curve of clean water tank all year round. The clean water tank in the water treatment plant needs to satisfy two working condition requirements.

1) Clean water tank volume constraint. 1#, 2# clean water tank volume are 10000m³. 3#, 4# clean water tank volume are 7200m³.
2) Clean water tank level difference constraint. All four tanks are 3 m high. The total volume is 34400 m³. There is
a difference in elevation. The minimum for no.2 is not less than 0.95 m. The maximum for 3# is no more than 2.95 m. Therefore, the other water clean tanks are same to 2# and 3#.

The four parts are described as follows:
1) One hour before the peak time (5:00~6:00 and 17:00~18:00). This time needs keeping the clean water tank as full as possible.
2) Peak time (6:00~12:00 and 18:00~22:00). In the case of considering the maximum range of water-making process, the demand of supply needs to be meet.
3) Off-peak time (12:00~17:00). During this time, it meets normal water demand and prepares for peak times.
4) Nocturnal low flow period (22:00~5:00 next day).

All four parts should satisfy the requirements of two working conditions.
The clear water tank regulation adopts the dynamic programming algorithm. It takes 24 hours as the whole process of optimization problem, and each hour is seen as a period. The whole process can be divided into three stages. The diagrammatic graphics is shown as Figure 3.

Phase 1: In the first hour, the task of this stage is to determine the initial water level for clean water tank $H_s$. Between the maximum allowable water level $H_{\max}$ and the minimum allowable water level $H_{\min}$, it divides the water level of clean water tank into n equal parts. Every part is $(H_{\max} - H_{\min})/n$. So the water level of one clean water tank is probably: $H_s + (H_{\max} - H_{\min})/(k \times n)$, $k = 0 \sim n$. Operating power consumption corresponding to $n + 1$ water levels is calculated. It is recorded on the corresponding node.

Phase 2: In the 2~23 hours. The Phase 1’s node all have corresponding operating power. At the end of the second period in the clean water tank of $n + 1$ water level (any one of water level) H is taken. It is assumed that the water level of clean water tank changes from $n + 1$ possible water level at the beginning of the second period become to the assumed water level $H_s$. Operating power consumption corresponding to $n + 1$ water level is calculated. It is recorded on the corresponding node. In the second period, a certain water level was selected one by one among the $n + 1$ water level, and the above process was repeated. The power consumption is figured out from the initial water level changing to the end of the second period.

Phase 3: In the final 24 hour. The water level of clean water tank should be restored to a smaller value. This paper adopts the idea of dynamic programming, so when the final stage is reached, the water level of clean water tank returns to the initial water level $H_s$.

B. WATER-INTAKE PUMP GROUP REGULATION
The regulation of water-intake pump group includes determining the pump combination and variable-frequency pump speed. In the experimental water treatment plant, the water-intake pump group is constituted by fours fixed-frequency pumps and two variable-frequency pumps. By studying the characteristics of pump group, setting up reasonable water pump matching scheme and running time, it can reduces the time of phenomenon in water hammer and pipe burst accidents.
The regulation of water-intake pump group is set out by the existing pump combination scheme and pump characteristic curve of water treatment plant.
The model of 1# fixed-frequency pump is RDL500-640A1, and the Q-H and Q-$\eta$ fitted curve is measured by field test data. The formula 16 is the Q-H curve of 1# fixed-frequency pump, and the formula 17 is the Q-$\eta$ curve of 1# fixed-frequency pump.

\[
y = 0.0095x^3 - 2.7023x^2 + 84.942x + 3449 \quad (16)
\]

\[
y = -0.0012x^3 + 0.0836x^2 - 1.1436x + 78.113 \quad (17)
\]

Figure 4. shows the Q-H curve of 1# fixed-frequency pump, and the coefficient of association is 0.999. The figure 5. shows the Q-$\eta$ curve of 1# fixed-frequency pump, and the coefficient of association is 0.993.

All fitting data is listed in Table. 1. The head, flow, simulated flow, efficiency simulated efficiency are considered.
The model of 2# fixed-frequency pump is 32SH-19. The model of 4# fixed-frequency pump is RDL500-640A1. The model of 5# fixed-frequency pump is RDLO/RDLO V600-705A. The model of 3# variable-frequency pump is RDL/RDL V700-820A. The model of 6# variable-frequency pump is RD/RDL V600-620A. And the Q-H curve and Q-$\eta$ curve are also measured by the same method.
TABLE 1. Fitting data of 1# power frequency pump.

| Head (m) | Flow (m³/h) | Simulated flow (m³/h) | efficiency (%) |
|----------|-------------|-----------------------|---------------|
| 25.0     | 4032        | 4033                  | 83.0          |
| 31.5     | 3744        | 3741                  | 88.0          |
| 36.0     | 3456        | 3449                  | 89.0          |
| 38.5     | 3251        | 3257                  | 90.4          |
| 39.5     | 3168        | 3174                  | 89.2          |
| 42.9     | 2880        | 2870                  | 88.2          |
| 45.7     | 2592        | 2595                  | 86.5          |
| 48.5     | 2304        | 2297                  | 83.5          |
| 51.0     | 2016        | 2013                  | 78.0          |
| 53.4     | 1728        | 1726                  | 73.5          |

According to the above design objective function, through the following steps, to generate a more scientific, reasonable, electricity-saving pump group optimal regulating scheme. The regulation of water-intake pump group is shown in Figure 6. As can be seen from the trend chart, there are two peak periods during the day in the task of water transportation and dispatching. At night, the level fluctuates more gently. The dispatching task changes regularly, with the maximum water level not exceeding 2.89m and the minimum water level not lower than 1.24m. It contains follow steps.

1) Firstly, the regulation of water-intake pump group needs to calculate the total required flow in water supply network. The required flow is set as the next hour variable. It is calculated by the history data about the hourly demand for water supply. The trendline of hourly demand for water supply is shown in Figure 7.

2) Secondly, water treatment plant has a standard for water making process. In this paper, the regulation of water-intake pump group is based on existing technical standard to adjust the state of each pump.

3) Thirdly, electricity model is updated by matching scheme of flow, pump running state.

4) Fourthly, the objective function and constraint conditions are substituted into particle swarm optimization (PSO) algorithm.

However, some basic PSO key parameters are as follows: Referring to the actual production conditions of water treatment plant, there are 8 unknown solutions for each group of particle (including flow of pump and frequency of variable-frequency pump). In this paper, 40 groups of particle is trained. Due to the limited performance of device, relevant regulation need to be given in limited time. The iterative weight can be given by the following formula:

$$h^{(k)} = (h_1 - h_2) \frac{k_{max} - k}{k_{max}} - h_2$$

The $h_1$ is set 0.9, and the $h_2$ is set 0.4, which are the initial iteration weight and the final iteration weight respectively. In order to make the particle swarm have better global search ability at the initial search stage and better local search ability at the later stage.

The particle updates its speed and position according to 2 extremum (individual extremum $p_i$ and global extremum $p_g$). The speed amendment equations is shown as formula 19 and the location amendment equations is shown as formula 20. The $k$ is the number of iterations. In this paper, $k$ is set 30. $r_1$, $r_2$ are randomly set in 0~1.

$$v_i^{(k+1)} = h^{(k)} v_i^{(k)} + c_1 r_1 (p_i^{(k)} - x_i^{(k)}) + c_2 r_2 (p_g^{(k)} - x_i^{(k)})$$

$$x_i^{(k+1)} = x_i^{(k)} + v_i^{(k)}$$

We test 3 years history data about the hourly demand for water supply, and set its value as reference parameters $y_i$. The training output data is set as $y_t$. The fitness function of training set is shown as formula 21.

$$E = \frac{1}{N} \sum_{i=1}^{N} (y_i - y_t)^2$$

Because the water-intake pump group’s operation is affected by the factors including siphon mud discharge, conventional mud discharge and the factory self-use water etc, there will be some loss after the water reaches the clean water tank. The turbidity of water source of Taihu lake is not controllable, so the loss ratio between the muddy water amount and the clean water amount of other day is calculated.
After completing the above steps, the plan is iteratively calculated for the next 2~24 hour.

IV. RESULTS AND DISCUSSION
Optimal operation of water-intake pump group is an important link in the water treatment process of water treatment plant. The effect of optimal operation of water-intake pump group in present period and long-term are the main parameters to measure the automatic control system of a water treatment plant. Because of the interference of many factors (e.g. maintenance of equipment, special holiday, etc.), it is very difficult to realize the optimal pump group of drinking water treatment process.

The regulation and storage function of clean water tank plays a key role in the regulation of pump group. According to the fluctuation rule of water level in the water treatment plant, the range of water level is properly adjusted based on the existing technology, so that the water supply and pipe network pressure are within the production standard and the electricity consumption is obviously lower. Water level optimization curve is shown in Figure 8. The water level goes from 1.31 m to 2.73 m in gentle trend. The regulation considers peak time in 6:00∼8:00 and off-peak time in 22:00∼4:00.

![FIGURE 8. Water level optimization curve.](image)

Furthermore, when it realizes the optimal operation of water-intake pump group, which compared with manual operation (e.g. switching the state of pump group, regulation of variable-frequency pump), the operation frequency of pump is not only set reasonably to make the pump running in the efficient area, but also to achieve the purpose of electricity saving.

The application of variable-frequency control system is mainly to adjust the pump speed to change the water pump head to meet the requirements. The frequency optimization was carried out by considering the water supply index and the high efficiency area of water pump as the constraint conditions. The experiment through different index combination of pump group to test their pressure and efficiency of each condition of water supply. And the optimization strategy of water-intake pump group is given in Table 2.

Compared the regulating scheme with manual adjustment at 10:00 a.m for three consecutive days, the experimental results are given in Table 3.

From the data of continuous operation for 3 days, it can be seen that the electricity-saving of water-intake pump group is about 4.20% when adopting the proposed optimal regulation method. The operation conditions of experiments refer to table 2 in different time, pressure and water-supply task.

V. CONCLUSION
This paper focuses on the water level of clean water tank and the combinatorial optimization of water-intake pump group. The method adopts the dynamic programming to predict the production tendency in the next 24 hours. The experimental results show that 4.20% electricity-saving can be achieved. However, actual production condition is relatively harsh, and electricity-savings may be reduced. In future, the research will focus on two aspect. One is the forecast of water demand. Forecast of water demand will indirectly affect the electricity consumption. The other is that single objective trans to multi-objective optimization. Optimal regulation objectives of pump group not only consider the electricity, but also consider other production factors.

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