Study on optimal operation of reservoir in the electricity market transaction model

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Abstract. Electric power market transaction is one of the important measures for the reform of the electric power system in China. In this paper, the optimal operation model of the reservoir was established. Based on the standard particle swarm optimization, the improved particle swarm optimization algorithm was proposed. Taking a hydropower station as an example, the Time of Use (TOU) price annual profits calculated in dry years, flat and humid years than the single price increased by 1.42%, 19.49% and 15.85%. The results show that the annual benefit price of hydropower station was significantly higher than the annual benefit of one price system when taking TOU price into account, can be used to solve the reservoir optimal scheduling strategy in the electricity market transaction model.

1. Introduction

Under the background of electricity market, the center of hydropower will shift from plan to market, the Hydropower Station Dispatching whose goal is maximum power generation benefit as can adapt to the development requirements, the reservoir time price and bidding policy has become an inevitable trend, so it is very important to study the market trading mode of reservoir optimal scheduling.

Foreign electricity market is mainly to adapt to political reform and the reform of the energy industry, the electric power market reform in Britain's success made countries around the world saw the huge potential of the market system, after entering in 2000, the Latin American countries, the United States, European Union, Asian countries are trying to reform of the electricity market. Some achievements have been made in the research of hydropower station scheduling in power market: In 2008, Vicuna took into account the impact of peak and valley electricity price on reservoir scheduling. In 2009, Madani and Lund discussed the effect of different price per hour on the monthly hydropower generation [1]. In China, some achievements have been made in the study of reservoir scheduling under the environment of electricity market: In 2012, Feng and Zhang put forward the Hydropower Station Reservoir long-term optimal scheduling model in the condition of flood and dry power price, achieved remarkable results in the practical application, and laid the foundation for the dispatching of hydropower station under Time of Use (TOU) price. In 2014, Li, Wang, and others studied the problem of the annual power generation planning in the electricity market environment [2].

With the scale of power system and the reform of power market is growing, China's electric power industry is gradually implementing the market mechanism, hydropower will also move toward the market, in accordance with the "fair and open" principle to participate in the competition [3,4]. Because of the market competition, electricity price and electricity were uncertain, electricity trading center made the market clearing calculation according to the power generating capacity and price and announced the
market clearing price and the capacity. The hydropower station no longer accept only passive power dispatching command and participate in market transactions, with the implementation of "bidding" policy and the change of load demand of hydropower station, how to build up the power grid operation rules and the reservoir operation rules in the electricity market environment of hydropower station which follows the new mode of power market and makes the benefit maximum is a new subject worthwhile to research, the scheduling research based on TOU price has become a new the direction of research on optimization operation of hydropower station [5-8].

In this paper, the influence factors of price are added to the basic reservoir scheduling model, and some constraints are taken into consideration, and the optimal dispatching model of hydropower station is constructed under the TOU price system. The dynamic programming, genetic algorithm and ant colony algorithm have been proposed to solve the reservoir optimal scheduling model, but these algorithms have many problems, such as curse of dimensionality, long calculation time, and complex processing constraints and so on. Particle swarm optimization (PSO) algorithm has many advantages, such as simple principle, fast convergence speed and high universality. It has been widely used in reservoir operation [9-11]. However, the PSO algorithm is easy to fall into local optimal solution, so the basic particle swarm optimization algorithm is improved in this paper and the calculation accuracy and convergence speed are improved. Finally, an example is used to solve the optimal annual dispatch model which takes the maximum generating revenue as the goal.

2. Optimal reservoir operation model in electricity market

In one price system, the price is fixed, so the yield of power plant is the product of electricity generation and electricity price, that is to say, the biggest benefit is the largest power generation, but in TOU price system, because there is a price difference, the maximum power output does not mean the maximum benefit. At present, many of the reservoir optimal operation taking the maximum power generation as the goal did not solve the above-mentioned maximum benefit problem, so the reservoir optimal operation considering TOU price factor is a new research subject of reservoir operation [12-16].

● Objective function

In the case of water has been set, according to the maximum power output as a criterion, the optimization goal of the hydropower station’s power generation is:

\[ F = \text{Max} \sum_i^T (A \cdot Q_i \cdot H_i \cdot T_i) \]  

(1)

Under the premise of the time-sharing electricity price, the annual income of the hydropower station is determined by the sum of the production of the electricity price and the electricity consumption during all periods of the year, so the optimal goal is:

\[ M = \text{Max} \sum_i (A \cdot Q_i \cdot H_i \cdot T_i \cdot B_i) \]  

(2)

In this formula, \( A \) is hydropower station output power coefficient; \( Q_i \) is the power station’s diversion discharge in time interval \( i \), \( m^3/s \); \( H_i \) is the power station’s average net water head in time interval \( i \), \( m \); \( T \) is the total time period of hydropower station scheduling (In this paper, the calculation period is one month, \( T = 12 \)); \( T_i \) is the power station’s generation hours in time interval \( i \); \( B_i \) is time-sharing electricity price; \( M \) is the total power generation efficiency in \( T \) time intervals.

● Constraint condition

① Water balance constraint

\[ V_i = V_{i-1} + Q_{pi} - Q_{di} - ZF_i - L_i \]  

(3)
In this formula, $V_i$ is the reservoir water storage at the end of time interval $i$, $m^3$; $V_{i-1}$ is the reservoir water storage at the beginning of time interval $i$, $m^3$; $Q_{di}$ is the reservoir discharge in interval $i$, $m^3$; $ZF_i$ is the evaporated water in interval $i$, $m^3$; $L_i$ is the leakage loss in interval $i$, $m^3$.

3. Capacity limit

$$V_{i,\text{min}} \leq V_i \leq V_{i,\text{max}}$$ (4)

In this formula, $V_{i,\text{min}}$ is the allowable minimum reservoir storage in interval $i$, $m^3$; $V_{i,\text{max}}$ is the allowable maximum reservoir storage in interval $i$, $m^3$.

3. Diversion discharge limit

$$Q_{i,\text{min}} \leq Q_i \leq Q_{i,\text{max}}$$ (5)

In this formula, $Q_{i,\text{min}}$ is the reservoir guaranteed minimum diversion discharge in time interval $i$, $m^3/s$; $Q_{i,\text{max}}$ the reservoir maximum allowable diversion discharge in time interval $i$, $m^3/s$.

4. Power output constraint

$$N_{i,\text{min}} \leq AQ_iH_i \leq N_{i,\text{max}}$$ (6)

In this formula, $N_{i,\text{min}}$ is the allowable minimum output limit of hydropower station, it is firm power generally, $kw$; $N_{i,\text{max}}$ is the maximum permissible output, it is installed capacity generally, $kw$.

5. Power price constraint

$$B_i = \begin{cases} B_{f_i} \\ B_{p_i} \\ B_{k_i} \end{cases}$$ (7)

In this formula, $B_{f_i}$ is the power price of time interval $i$ in abundant water period, yuan/kW·h; $B_{p_i}$ is the power price of time interval $i$ in normal water period, yuan/kW·h; $B_{k_i}$ is the power price of time interval $i$ in low water period, yuan/kW·h.

6. All parameters are nonnegative.

### 3. Improved particle swarm optimization algorithm

#### 3.1. The principle of particle swarm optimization

PSO algorithm is a kind of swarm intelligence optimization algorithm which is based on the study of bird flight, there is a group of $N$ particles in the $D$ dimensional target space, the location of the particle $i$ is $x_i = (x_{i1}, x_{i2}, \cdots, x_{id})$, the flight speed is $v_i = (v_{i1}, v_{i2}, \cdots, v_{id})$, its optimal location when iterated to $h$ times is $P_i = (P_{i1}, P_{i2}, \cdots, P_{id})$, the entire particle swarm’s optimal location when iterated to $h$ times is $P_{gd} = (P_{gd1}, P_{gd2}, \cdots, P_{gdi})$, the basic formula is as follows:

$$v_{id}^{(k+1)} = \alpha v_{id}^{(k)} + c_{1i}^{(k)} (P_{id}^{(k)} - x_{id}^{(k)}) + c_{2i}^{(k)} (P_{gd}^{(k)} - x_{id}^{(k)})$$ (8)
In this formula, \( c_1, c_2 \) is acceleration coefficient, \( r_1, r_2 \) is random numbers between 0-1, \( \omega \) is the inertia factor, and is the weight of the control speed.

### 3.2. Improved particle swarm optimization algorithm

- Clerc and Kennedy proposed a PSO algorithm with compression factor, which can ensure the convergence of the PSO algorithm by selecting appropriate parameters [17].

\[
\begin{align*}
\mathbf{v}_{id}^{(k+1)} &= \chi \left( \omega \mathbf{v}_{id}^{(k)} + c_1 r_1^{(k)} \left( \mathbf{P}_{id}^{(k)} - \mathbf{x}_{id}^{(k)} \right) + c_2 r_2^{(k)} \left[ \mathbf{P}_{gd}^{(k)} - \mathbf{x}_{id}^{(k)} \right] \right) \\
\mathbf{x}_{id}^{(k+1)} &= \mathbf{x}_{id}^{(k)} + \mathbf{v}_{id}^{(k+1)}
\end{align*}
\]

(9)

In this formula, \( \chi \) is the compressibility factor.

In general, the initial value of \( \omega \) is 0.9, and it decreases with the increase of the number of iterations to 0.4, the choice of the inertia factor \( \omega \) is first to focus on the global search so that the search space converges rapidly to a specific region, and then the local fine search is used to obtain a higher accuracy solution [18], the evolution factor \( f \) is used to adjust the weight change. The specific formula is as follows:

\[
\omega(f) = \frac{1}{1 + 1.5e^{-2.5f}} \in [0.4, 0.9], \forall f \in [0, 1]
\]

(10)

In order to ensure the smooth solution of the algorithm, \( c_1 + c_2 \) must be more than 4. In this paper, the formula (12) is used to calculate.

\[
c_i = \frac{c_i}{c_1 + c_2} \ast 4.0, i = 1, 2, c_1, c_2 \in [1.5, 2.5]
\]

(12)

- The particle swarm optimization algorithm based on natural selection can be obtained by combining the particle swarm optimization and the natural selection principle of genetic algorithm. In the iterative process, the whole particle swarm is sorted according to the fitness value, and the position and the speed of the half particles with poor fitness value is replaced by the half particles with good fitness value and keep the optimal value of each individual [19].

Combined with the improved method, the specific steps of the improved particle swarm optimization algorithm are shown in figure 1:
Begin
Initialize the population position and velocity
Evaluate the fitness of population. The optimal individual is stored in pbest, and the optimal population is stored in gbest.
Update the velocity and displacement of the particle according to the formula (8), (9), (12)
Update weights according to formula (10)
According to the fitness value, update the optimal value of each particle
Update gbest by comparing pbest and gbest
Fitness value sorting, the half particles with worst velocity are replaced by another half, keep pbest and gbest unchanged
Whether reach the number of iterations?
Yes
No
End

Figure 1. Improved particle swarm optimization algorithm.

Set the parameters according to the calculation steps of the improved particle swarm optimization algorithm: \( \omega = 0.9 \), \( c_1 = c_2 = 2 \), the number of population is 50, and the number of iterations is 2000, take the average value of 20 times, and test the common test function of PSO algorithm: Rastrigin, DeJong, Sphere, Griewank and Rosenbrock [20]. The results are shown in table 1:

| Algorithm             | Rastrigin | DeJong  | Sphere  | Griewank | Rosenbrock |
|-----------------------|-----------|---------|---------|----------|------------|
| Basic PSO algorithm   | 1.07E+02  | 4.35E+02| 3.70E+02| 2.61E+07 | 1.39E+01  |
| Kalman                | 5.33E+01  | 4.61E+00| 4.72E+00| 3.28E+03 | 9.96E-01  |
| Improved PSO algorithm| 7.91E+00  | 1.29E-02| 1.90E-01| 1.75E-01 | 6.88E-01  |

As can be seen from table 1, the results of the improved PSO algorithm are closer to the extreme point, the search precision is higher, and the superiority of the algorithm is proved.

4. Case study
A hydropower station: the installed capacity is 144 MW; the guaranteed output is 11.91 MW; the normal water level is 73.0 m; the corresponding storage capacity is 60.08 million m³; the dead water level is 69.0 m; the corresponding storage capacity is 42.8 million m³; the average annual runoff is 8 billion and 740 million m³; the average annual rainfall is 1600 mm; the average annual inflow is 277 m³/s; the main
function of this project is electric power generation, it doesn’t undertake the downstream flood control, and it is a daily regulating reservoir.

According to the 62 years’ natural runoff and annual runoff calculation results from April 1951 to March 2012, select the wet years (P=25%), normal year (P=50%) and dry years (P=75%) as the typical year, respectively in 2010, 2005, 2003, the natural runoff flow of the selected typical hydrological years is shown in figure 2.

![Figure 2. Typical hydrological year natural runoff.](image)

The one price system in this paper does not consider the impact of the power price factor on reservoir operation that price is a constant, and in the TOU price system, subject to market fluctuations and changes of its hydropower station operation load, price change, spot price is most likely to maximize the benefits, but at present our country does not have real time price conditions, due to price changes in different periods are various and the calculation is so complicated, in order to facilitate the calculation, the price is simplified in this paper, take the electricity price in one price system as the price of normal water period, that is 0.35 yuan /kW· H, the price of wet period fall 25%, that is 0.26 yuan /kW· h, the price of low water period go up 50%, that is 0.53 yuan /kW· H.

For the on-grid energy of the same year, annual incomes of power plants have significant differences due to the different price in abundant water year and low water year. Take this power plant as the example, annual incomes comparison data between the improved particle swarm optimization algorithm and the basic particle swarm algorithm are shown in table 2, the annual generating incomes are calculated by the improved particle swarm optimization algorithm under different pricing systems. The specific data are shown in table 3.

| Month | Power generation ($10^4$MW·h) | One price system (hundred million yuan) | TOU price system (hundred million yuan) |
|-------|--------------------------------|----------------------------------------|----------------------------------------|
|       |                                | Dry year | Normal year | Wet year | Dry year | Normal year | Wet year |
| 1     |                                | 2.803    | 2.756       | 3.280    | 2.838    | 3.301       | 3.793    |
| 2     |                                | 2.814    | 2.766       | 3.284    | 2.855    | 3.312       | 3.799    |
| 3     |                                |          |             |          |          |             |          |
| 4     |                                |          |             |          |          |             |          |
| 5     |                                |          |             |          |          |             |          |
| 6     |                                |          |             |          |          |             |          |
| 7     |                                |          |             |          |          |             |          |
| 8     |                                |          |             |          |          |             |          |
| 9     |                                |          |             |          |          |             |          |
| 10    |                                |          |             |          |          |             |          |
| 11    |                                |          |             |          |          |             |          |
| 12    |                                |          |             |          |          |             |          |

The improved particle swarm optimization algorithm and the basic particle swarm algorithm are shown in table 2, the annual generating incomes are calculated by the improved particle swarm optimization algorithm under different pricing systems. The specific data are shown in table 3.

| Table 2. Annual income comparison table of different algorithms. |
|---------------------------------------------------------------|
| computing method    | One price system (hundred million yuan) | TOU price system (hundred million yuan) |
|--------------------|----------------------------------------|----------------------------------------|
| Dry year | Normal year | Wet year | Dry year | Normal year | Wet year |
| Basic PSO algorithm | 2.803    | 2.756       | 3.280    | 2.838    | 3.301       | 3.793    |
| Improved PSO algorithm | 2.814    | 2.766       | 3.284    | 2.855    | 3.312       | 3.799    |

| Table 3. Typical annual hydrological generating efficiency. |
|-----------------------------------------------------------|
| Month | Power generation ($10^4$MW·h) | One price system (hundred million yuan) | TOU price system (hundred million yuan) |
|-------|--------------------------------|----------------------------------------|----------------------------------------|
The goal is according to the actual situation the income for optimal dispatching of hydropower station in the electricity market transaction model provides an idea of optimal scheduling for significantly higher than that algorithm, of electric power market in China hydropower station power output as the objective for the optimal

This paper collects investment in peak regulating units in dry season. So that the power load is evenly distributed in a certain period of time, the effect avoid period, so that the power load is evenly distributed in a certain period of time, the

In TOU price system the low price in wet year is not entirely based on power generation, this system, the low price in wet year and high price in dry year is conducive to the promote users to make full use of the electricity of wet period, so that the power load is evenly distributed in a certain period of time, the TOU price can effectively avoid a large number of abandoned water consumption in wet season and reduce the investment in peak regulating units in dry season.

### 5. Conclusions

This paper collected the latest research results of reservoir optimal operation at home and abroad on the electric power market transaction mode, analyzed the optimal objective function taking the maximum power output as the objective for the optimal operation of reservoir. The optimal dispatching model of hydropower station considering in TOU price system was established according to the actual situation of electric power market in China, and achieved good results by using the improved particle swarm algorithm, the calculation results show that the power generation benefit in TOU price system was significantly higher than that in one price system, and achieved the goal that improving the economic benefits of hydropower station and the optimal allocation of water resources, hydropower station provides an idea of optimal scheduling for power market transaction mode. This paper provides an idea for optimal dispatching of hydropower station in the electricity market transaction model. There are also

| Dry year | Normal year | Wet year | Dry year | Normal year | Wet year | Dry year | Normal year | Wet year |
|----------|-------------|----------|----------|-------------|----------|----------|-------------|----------|
| 4        | 8.64        | 8.69     | 8.69     | 0.30        | 0.30     | 0.30     | 0.22        | 0.23     |
| 5        | 8.69        | 8.69     | 8.69     | 0.30        | 0.30     | 0.30     | 0.23        | 0.23     |
| 6        | 8.69        | 8.69     | 8.69     | 0.30        | 0.30     | 0.30     | 0.23        | 0.23     |
| 7        | 8.69        | 8.69     | 8.69     | 0.30        | 0.30     | 0.30     | 0.23        | 0.46     |
| 8        | 3.90        | 8.69     | 8.69     | 0.14        | 0.30     | 0.30     | 0.21        | 0.46     |
| 9        | 7.31        | 8.69     | 8.69     | 0.26        | 0.30     | 0.30     | 0.39        | 0.46     |
| 10       | 2.64        | 8.69     | 7.13     | 0.09        | 0.30     | 0.25     | 0.14        | 0.46     |
| 11       | 3.62        | 3.28     | 6.94     | 0.13        | 0.11     | 0.24     | 0.19        | 0.17     |
| 12       | 2.14        | 5.28     | 7.63     | 0.07        | 0.18     | 0.27     | 0.11        | 0.28     |
| 1        | 8.69        | 4.60     | 3.76     | 0.30        | 0.16     | 0.13     | 0.30        | 0.16     |
| 2        | 8.69        | 1.38     | 7.51     | 0.30        | 0.05     | 0.26     | 0.30        | 0.05     |
| 3        | 8.69        | 3.65     | 8.69     | 0.30        | 0.13     | 0.30     | 0.13        | 0.46     |
| Total    | 80.41       | 79.04    | 93.83    | 2.81        | 2.77     | 3.28     | 2.85        | 3.31     | 3.80     |

Table 2 shows that for different typical hydrological years, the annual incomes calculated by the improved particle swarm optimization algorithm, both in single price system or in the TOU price system, are higher than the basic particle swarm optimization algorithm, which further proves that the improved particle swarm algorithm in this paper has advantages in solving the model.

In table 3, three cases were analyzed, in TOU price system, the annual income of dry year is 285 million yuan, normal year is 331 million yuan and wet year is 380 million yuan, in one price system, the annual income of dry year is 281 million yuan, normal year is 277 million yuan and wet year is 328 million yuan, the power generation benefit in TOU price system is significantly higher than that of one price system, the power generation efficiency of dry years increased by 1.42%, the power generation efficiency of normal years increased by 19.49%, the power generation efficiency of wet years increased by 15.85%. The above analysis shows that the calculation results of reservoir optimization scheduling considering TOU electricity price are entirely different from that not considering the electricity price factors, the annual power generation benefit when considering TOU electricity price are significantly better than that the goal is only to maximize power generation. Therefore, in the power market transaction mode, we can’t only consider the factors of water, but also we need to consider the price factor, the reservoir operation should be in accordance with the TOU price floating policy to obtain greater economic benefits.

Analyze the data of each typical year according to figure 2 and table 3, the income is only relevant with the power generation, the income of wet year is high while the dry year is low, and the generation in TOU price system is not entirely based on power generation, in this system, the low price in wet year and high price in dry year is conducive to the promote to users to make full use of the electricity of wet period, so that the power load is evenly distributed in a certain period of time, the TOU price can effectively avoid a large number of abandoned water consumption in wet season and reduce the investment in peak regulating units in dry season.

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many deficiencies in this paper, in the future research, it is also possible to explore the problems such as how to minimize the output power and how to run the plant in the power system to make the optimal dispatching of hydropower station in the electricity market transaction model more detailed and more suitable for the actual operation of the scheduling to save the cost of power generation.

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