Research on the optimal strategy of pumped storage power station to provide multiple time-scale reserves

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Abstract—In the background of peak carbon emissions and carbon neutrality, renewable energy generation (REG) will become the main generation form in the future power system. Simultaneously, the randomness and volatility increase the reserve requirement in the different time scale. Increasing importance has been attached to energy storage in the aspect of reserve, as energy storage has the advantages of power flexibility and relatively low reserve cost. Trading off the benefits of energy storage in the energy market and the reserve market to maximize its benefits is of great significance to the economic operation and investment of energy storage. In this regard, taking the pumped storage power station (PSPS) as an example, this paper establishes an optimal decision-making model for PSPS to participate in the energy market and to provide reserve services. In addition, an optimal decision model for PSPS to provide multiple reserve services is established. The analysis finds that the power reserve capacity provided by PSPS at different time scales have little impact on each other, but their storage capacity requirements are mutually restricted. Case studies show that the total revenue of the PSPS is significantly increased through providing reserve service. The PSPS may even bid all its capacity to provide reserve service when the compensation price reserve reaches a certain level. In addition, the total revenue of PSPS when providing multiple time-scale reserves is higher than that when providing reserve service at single time scale.

1. Introduction
Under the goals of peak carbon emissions and carbon neutrality, The generation structure and grid operation characteristics in China will undergo profound changes. The proportion of renewable energy generation (REG) in generation side will continue to increase and add difficulty to the power balance in power systems. It also increases the demand for ancillary services such as reserve at different time scales. Therefore, the literature [1] proposes a new structure of power system reserve at multiple time scales. The development of energy storage technology will provide reserve support to the power system at different time scales. However, the economy and market strategy of energy storage participating in various ancillary services and electric energy market need to be further studied.

Energy storage is an important support to the development of REG and the construction of new power system. From the perspective of power grid, an ultra high voltage (UHV) AC and DC interconnection network structure has been constructed between regional power grids in China. However, UHV DC block will cause serious power imbalance to the power system operation, posing a huge challenge to the rapid reserve demand at second to minute level in regional grids. Due to the high level of REG access, its intermittency and volatility calls for more and more reserve demands at minute level, hour level, and
hours level. It indicates that under the construction of new power system, the reserve at various time scale need to be strengthened.

From the perspective of response time and duration, various national power grids defined and categorized various reserve related ancillary services. Europe continental power grid classifies power system reserve into primary reserve, secondary reserve and tertiary reserve corresponding to different time scales [2] and [3]. The reserve capacity in UK includes primary frequency response capacity, secondary frequency response capacity, rapid reserve and short-term operating reserve capacity [4]. California power grid in the United States divides reserve resources into frequency regulation reserve, spinning reserve, non-spinning reserve and alternative reserve [5]. In the early stage, reserve services in the power system are mainly provided by various power plants. However, with the increasing demand of reserve services, the reserve resources only from the generation side can hardly meet the reserve demand in future power systems. Therefore, more and more attentions have been paid to energy storages and demand-side reserve.

Energy storages have the characteristics of fast power regulation speed and low reserve cost. Their potential in the new power system will be gradually found. Relevant literatures have studied the operation and benefits of energy storages and flexible loads in ancillary services market, such as in frequency regulation (FR) and reserve market [6]-[9]. Literature [10] studied the peak regulation market model considering the participation of energy storage aggregators. Literature [11] studied the operation strategy of energy storage power stations and electric vehicles participating in the FR market in the background of California market rules. Literature [12] proposed a distributed autonomous control method to realize the application of battery storage in FR service. Literature [13] studied a cooperative control method of wind power and compressed air energy storage system. Compressed air energy storage is used for FR in charging and discharging mode, so as to alleviate the influence of wind power uncertainty on system frequency. In order to improve the AGC response performance of the power system, a dual-objective optimization control model with energy storage participating in FR was established in reference [14], aiming at minimizing the total power deviation and frequency modulation cost.

Literature [15] builds a market model in which multi-types of power supply i.e. wind, PV, water, coal-fired generation and energy storage participate in frequency modulation. The sequential bidding model marginal price clearing model is adopted. This paper analyzed the improvement effect of multi-types of power supply on the system FR performance. Literature [16] compares the FR performance of thermal power units and energy storages. It concludes that energy storage has the advantages of fast response speed and high stability.

In addition to the FR, the role of energy storage in reserve ancillary services and the corresponding price strategy also gain great attention. A lot of researches have been done regarding the problem of power grid reserve. Literature [2] puts forward systematic suggestions for power grid reserve services. Literature [17] puts forward the management idea of "fine emergency re" and the idea of "special time standby" to deal with new energy power generation. Based on robust optimization, Literature [18] proposed the bidding strategy of wind power and pumping storage joint participation in the day-ahead and real-time market.

With the deepening of research on energy storage to provide ancillary services, the advantages of flexibility and rapidity of energy storage are gradually highlighted. More and more attentions are paid to the potential of energy storage to provide ancillary services. Battery storage and pumped storage stations, as representative batteries, have the characteristic of rapid power regulation. Their main ways to make profits are arbitraging the price spread and providing ancillary services [19]. The cost of energy storage participating in the electricity market comes from the degradation cost and maintenance costs. When it participates in the reserve service market, it needs to reserve certain reserve capacity. Therefore, the reserve cost comes from the opportunity cost in the energy market.

This study takes pumped storage power station as an example to deal with the decision making problem for energy storage between energy market and reserve market, especially considering its providing reserve services at different time scales. The decision making model of energy storage
participating in the electricity market and reserve market is constructed. The optimal strategy is also discussed considering the uncertain price of electricity and compensation prices of different reserve services.

2. The Profit Analysis of Pumped Storage in Electricity Market

2.1. Pumped storage operation mode
To satisfy the operation requirement of the pumped storage power station, it is necessary to consider its operation constraints in the actual dispatching stage.

Power generation constraint of pumped storage power stations:

\[ 0 \leq p_{\text{dch},t} \leq b_{\text{dch},t}P_{\text{dch, max}} \]  

(1)

where \( p_{\text{dch},t} \) is the generation power of pumped storage; \( P_{\text{dch, max}} \) is the maximum generating power of pumping storage; \( b_{\text{dch},t} \) is a 0-1 variable denoting the discharging state of the pumped storage.

Constraints on pumping power of pumped storage power station:

\[ 0 \leq p_{\text{ch},t} \leq b_{\text{ch},t}P_{\text{ch, max}} \]  

(2)

where \( p_{\text{ch},t} \) is the pumping power of the pumped storage station; \( P_{\text{ch, max}} \) is the maximum pumping power of the pumped storage; \( b_{\text{ch},t} \) is a 0-1 variable denoting the pumping state of the pumped storage station.

Mutual exclusion constraints of pumping and discharging states of the pumped storage station:

\[ b_{\text{ch},t} + b_{\text{dch},t} \leq 1 \]  

(3)

Constraint of reservoir capacity of pumped storage station:

\[ 0 \leq e_t \leq E_{\text{max}} \]  

(4)

where \( e_t \) is the current state of the reservoir; \( \eta_{\text{dch}} \) is generation efficiency, \( T \) is time length of a step; \( E_{\text{max}} \) is the maximum reservoir capacity of the pumped storage station; \( \eta_{\text{ch}} \) is the pumping efficiency.

Correlation constraints between the storage state and the pumping/generation power:

\[ e_t = e_{t-1} + p_{\text{ch},t}\eta_{\text{ch}} - p_{\text{dch},t}/\eta_{\text{dch}} \]  

(5)

The periodic constraint of pumped storage capacity: namely, the storage state at the end of each day is equal to the state at the beginning:

\[ e_t = e_N \]  

(6)

2.2. Benefit analysis of pumping storage in energy market
Pumped storage makes profits by arbitraging the peak-valley price difference in the energy market. In the day-ahead energy market, pumped storage participates in the market as an independent player. Its income is closely depends on the day-ahead clearing prices. In this study, a profit analysis model for energy storage was established considering the uncertainty of the energy prices. The modeling process is shown in Figure 1.
Obtain historical electricity price data of in the energy market

The probabilistic prediction results of day-ahead energy price are obtained based on the probabilistic prediction method

Generation and reduction of day-ahead energy price scenario

The profit model of pumped storage power station participating in energy market is established

Fig. 1 Steps of the revenue calculation for pumped storage power station under uncertainty of day-ahead energy price.

The modeling process includes:
1) Obtain the historical electricity price data in the energy market and use it for the energy price prediction of the next day;
2) Obtain system information of the next day, combined with the historical data and using the probabilistic prediction method; then, obtain the probabilistic prediction result of the day-ahead energy price;
3) Construct price samples of the day-ahead energy prices based on the probability prediction results; obtain certain number scenario curves acceptable for the actual solution through scenario reduction technology;
4) Construct the profit model of pumped storage stations participation in the energy market;

Since this study mainly analyzes the income situation and market strategy of the pumped storage power station, it is assumed that the scenario data of energy price is known. The profit model of pumped storage power station established in this paper is as follows.

The objective function is:

$$\max f_1 = \sum_{s=1}^{n_s} \sum_{t=1}^{N} \lambda_{s,t} (p_{dch,t,s} - p_{ch,t,s}) T$$

Where $n_s$ is the number of scenarios; $\lambda_{s,t}$ is the energy price at time $t$ in scenario $S$. In each scenario, there are a set of variables of pumping power, generation power and storage state [$p_{ch,t,s}, p_{dch,t,s}, e_b, t = 1,2,...,N$], which need to satisfy constraints (1-6).

3. Revenue Modeling of Pumped Storage Power Station under Multi-time Scale Reserve

3.1. Operational modeling of the pumped storage station when providing a single reserve

Literature [1] defines four types of reserve resources and defines their responding time and continuous supply duration $\tau_j, j = 1,2,3,4$. In this study, four alternative operational models and optimization strategies for pumped storage will be investigated.

When pumping storage provides reserve service, it is necessary to reserve certain power capacity and inventory capacity to be invoked. Therefore, its operating boundary in the energy market will change. In this study, the reserve resources are composed of upward and downward parts. It is assumed that the compensation price of reserve in each time scale is known.

Considering the reserve capacity from pumped storage, its declared upward and downward reserve capacity is denoted by $r_{j,up}$ and $r_{j,down}$. Pumped storage power stations declare its reserve capacity after
comprehensively considering the income in all scenarios. Therefore, in the multi-scenario model, there is only one set of reserve capacity variables. The sum of generation power and declared reserve capacity in each scenario should be less than its maximum generating power, and the sum of pumping power and declared reserve capacity should be less than its maximum pumping power, namely:

\[ 0 \leq P_{dch,t,s} + \eta_{up} \leq P_{dch,max} \]  
(8)

\[ 0 \leq P_{ch,t,s} + \eta_{dn} \leq P_{ch,max} \]  
(9)

Reserved capacity constraints:

\[ 0 \leq r_{j,up} \leq R_{j,upmax} \]  
(10)

\[ 0 \leq r_{j,dn} \leq R_{j,dnmax} \]  
(11)

Pumped storage has flexible adjustment characteristics and can change its pumping and generation status within a day. Therefore, different operating state variables are used for each scenario. However, in a specific scenario, the pumped storage power station still needs to meet the mutually exclusive constraint of pumping and generation states, namely:

\[ b_{ch,t,s} + b_{dch,t,s} \leq 1 \]  
(12)

When pumped storage provides reserve capacity, a certain amount of water storage and storage capacity needs to be reserved for invoking. Therefore, the upper and lower limits of the storage capacity of the pumped storage station should be updated as follows:

\[ r_{j,up} \tau_j \leq e_{t,s} \leq E_{max} - r_{j,dn} \tau_j \]  
(13)

Equation (13) indicates that a pumped storage station should reserve a certain amount of storage capacity for generation or pumping when playing a reserve role.

The correlation constraints between the storage state and the pumping/generation power is updated as (14). The periodic constraints of the storage capacity in each scenario is expressed as (15):

\[ e_{t,s} = e_{t-i,s} + p_{ch,t,s} \eta_{ch} - p_{dch,t,s} / \eta_{dch} \]  
(14)

\[ e_{t,s} = e_{N,s} \]  
(15)

The total revenue of the pumped storage station participating in the energy market and providing the \( j \)th type of reserve service, namely, the objective function of the optimization model is:

\[ (P2) \ max f_2 = \sum_{s=1}^{n_s} \pi_s \sum_{t=1}^{N} \lambda_{t,s} (p_{dch,t,s} - p_{dch,t,s})T + (\rho_{j,up} r_{j,up} + \rho_{j,dn} r_{j,dn})NT \]  
(16)

where, \( \rho_{j,up}, \rho_{j,dn} \) is the compensation price of the \( j \)th type of reserve service, including upward and downward reserve.

The above objective function should satisfy constraints (1~2) and (8~15). By solving Model P2, the optimal declaration strategy for pumped storage to provide the \( j \)th type of reserve service can be obtained.

3.2. Operation modeling of pumped storage power station in multiple reserve situations

When the reserve services at multiple time scales is provided by energy storage, considering the correlation relationship of all types of reserve in the time horizon, the declared capacity of all types of reserve needs to satisfy constraint (1-2) and (8-11). Different from the power constraint, its water storage and storage capacity need to meet the reserve demand at each time scale at the same time. Therefore, the upper and lower limits of the storage state of the pumped storage station should be updated as:

\[ \sum_{j=1}^{4} r_{j,up} \tau_j \leq e_{t,s} \leq E_{max} - \sum_{j=1}^{4} r_{j,dn} \tau_j \]  
(17)

The total revenue of the pumped storage station when it participates in the energy market and provides various reserve services, namely, the objective function of the optimization model is:
(P3) \[
\max f_3 = \sum_{s=1}^{N_s} \pi_s \sum_{t=1}^{N_t} \lambda_{s,t} (p_{dch,t,s} - p_{ch,t,s}) T + \sum_{j=1}^{4} (\rho_{j,up} r_{j,up} + \rho_{j,down} r_{j,down}) \]  
(18)

The above objective function should satisfy constraints (1~2), (8~12), (14), (15) and (17).

By solving Model P3, the optimal declaration strategy for pumped storage station to provide multiple reserve services can be obtained.

4. The Example Analysis

4.1. Introduction of tested case
Parameters of a pumped storage power station are as follows: the maximum generation power and the maximum pumping power are 20MW, and the storage capacity is 100 MWh. Its efficiency in a cycle is 75%. The multi-scenario energy price curve adopted in this study is shown in Figure 2. Energy prices at night are relatively low, while energy prices at noon and evening are relatively high.

![Electricity price curves in 20 scenarios.](image)

Fig.2  Electricity price curves in 20 scenarios.

4.2. Operation results participating in the of the energy market
When not providing reserve service, the pumping and generation power under different energy price scenarios are shown in figure 3. Positive values represent generation power and negative values represent pumping power. The pumped storage station pumps mainly at night, and generates at noon and evening when energy prices are high. It makes profit from the energy price spread. The total expected revenue is 8357 yuan in a day. The maximum pumping and generation power of are 20MW. The maximum and minimum storage state are 100 and 0 MWh, respectively, indicating that the capacity of the pumped storage station has been fully utilized.

![Operation results of pumped station s in energy market.](image)

Fig.3  Operation results of pumped station s in energy market.
4.3. Operation strategy when providing reserve

When only considering one type of reserve, for example, primary frequency regulation reserve is provided. The duration is not less than one minute, and the upper limit of reserve capacity is set as 3 MW. The declared reserve capacity and income of the pumping and storage station are shown in Table 1 under different reserve compensation prices. When the reserve compensation price is low, the capacity of pumped storage power station is fully used to participate in the energy market. When the reserve compensation price is higher than 0.012 yuan/hour, the capacity of pumped storage station will be used to provide reserve service as far as possible, so as to obtain more profits. Under this price, the total revenue of pumped storage station is 8835 yuan, higher than the total expected revenue in the energy market, namely 8,357 yuan.

Table 1. The decision result of PSPS under different compensation prices of reserve type 1.

| compensation price (Yuan/hour) | declare spare capacity (MW) | total revenue (Yuan) | maximum pumping power (MW) | maximum discharge power (MW) | minimum storage capacity state (MWh) | maximum storage capacity state (MWh) |
|--------------------------------|------------------------------|----------------------|---------------------------|-----------------------------|--------------------------------------|-------------------------------------|
| 0.002                          | 0                             | 8357                 | 20                        | 20                          | 0.00                                 | 100                                 |
| 0.004                          | 0                             | 8357                 | 20                        | 20                          | 0.00                                 | 100                                 |
| 0.006                          | 0.8                           | 8360                 | 19.15                     | 20                          | 0.01                                 | 100                                 |
| 0.008                          | 3                             | 8479                 | 17                        | 20                          | 0.05                                 | 100                                 |
| 0.01                           | 3                             | 8623                 | 17                        | 20                          | 0.05                                 | 100                                 |
| 0.012                          | 3                             | 8835                 | 17                        | 17                          | 0.05                                 | 99.95                               |
| 0.014                          | 3                             | 9123                 | 17                        | 17                          | 0.05                                 | 99.95                               |
| 0.016                          | 3                             | 9411                 | 17                        | 17                          | 0.05                                 | 99.95                               |
| 0.018                          | 3                             | 9699                 | 17                        | 17                          | 0.05                                 | 99.95                               |
| 0.02                           | 3                             | 9987                 | 17                        | 17                          | 0.05                                 | 99.95                               |

When the minute-level reserve, the duration of 10 minutes, and the upper limit of reserve capacity of 10MW are considered, the declared reserve capacity and income of the pumping and storage station under different reserve compensation prices are shown in Table 2. When the reserve compensation price is higher than 0.0064 yuan/hour, the pumping and storage stations begin to gain more profits by providing reserve. When the reserve compensation price is 0.016 yuan/hour, the declared capacity of the pumping and storage station is 10MW, that is, the maximum declared reserve capacity. At this time, the maximum available capacity in the electricity energy market is 10MW. At this time, the operating state of the pumping and storage station in each scenario in the electricity energy market is shown in Figure 4. In addition, under the reserve compensation price, the total income of the pumping and storage station can reach 10,860 yuan, the minimum storage capacity is 1.67MWh, and the maximum storage capacity is 98.33MWh.

Table 2. The decision result of PSPS under different compensation prices of reserve type 2.

| compensation price (Yuan/hour) | declare spare capacity (MW) | total revenue (Yuan) | maximum pumping power (MW) | maximum discharge power (MW) | minimum storage capacity state (MWh) | maximum storage capacity state (MWh) |
|--------------------------------|------------------------------|----------------------|---------------------------|-----------------------------|--------------------------------------|-------------------------------------|
| 0.0016                         | 0                             | 8357                 | 20                        | 20                          | 0                                   | 100                                 |
| 0.0032                         | 0                             | 8357                 | 20                        | 20                          | 0                                   | 100                                 |
| 0.0048                         | 0                             | 8357                 | 20                        | 20                          | 0                                   | 100                                 |
| 0.0064                         | 2.4                           | 8376                 | 18                        | 20                          | 0.40                                | 100                                 |
| 0.008                          | 4.9                           | 8510                 | 15                        | 20                          | 0.82                                | 100                                 |
| 0.0096                         | 10                            | 8873                 | 10                        | 13                          | 1.67                                | 98.87                               |
| 0.0112                         | 10                            | 9559                 | 10                        | 11                          | 1.67                                | 98.56                               |
| 0.0128                         | 10                            | 10324                | 10                        | 10                          | 1.67                                | 98.33                               |
| 0.0144                         | 10                            | 11092                | 10                        | 10                          | 1.67                                | 98.33                               |
| 0.016                          | 10                            | 11860                | 10                        | 10                          | 1.67                                | 98.33                               |
Fig. 4 Operation results of PSPS in the electric energy market after providing reserve service.

When the pumped storage station provides 10 minutes of reserve, the duration is required to be 2 hours, and the limit of reserve capacity is set as 20 MW. The declared reserve capacity and income of the pumped storage station under different reserve compensation prices are shown in Table 3. When the reserve compensation price is lower than 0.0048 yuan/h, the pumped storage station will not participate in the reserve service market. When the reserve compensation price is higher than 0.096 yuan/h, all the capacity of the pumped storage station is used to provide reserve, namely 20MW, and more benefits can be obtained. In this condition, the minimum storage capacity is 40 MWh, and the maximum storage capacity is 60MWh.

| compensation price (Yuan/hour) | declared reserve capacity (MW) | total revenue (Yuan) | maximum pumping power (MW) | maximum generation power (MW) | minimum storage capacity state (MWh) | maximum storage capacity state (MWh) |
|-------------------------------|-------------------------------|----------------------|-----------------------------|-------------------------------|--------------------------------------|--------------------------------------|
| 0.0012                        | 0                             | 8357                 | 20                          | 20                            | 0                                    | 100                                  |
| 0.0024                        | 0                             | 8357                 | 20                          | 20                            | 0                                    | 100                                  |
| 0.0036                        | 0                             | 8357                 | 20                          | 20                            | 0                                    | 100                                  |
| 0.0048                        | 0                             | 8357                 | 20                          | 20                            | 0                                    | 100                                  |
| 0.006                         | 0.9                           | 8359                 | 19                          | 20                            | 1.71                                 | 100                                  |
| 0.0072                        | 2.4                           | 8420                 | 18                          | 20                            | 4.77                                 | 100                                  |
| 0.0084                        | 5.3                           | 8558                 | 18                          | 20                            | 10.66                                | 100                                  |
| 0.0096                        | 20                            | 9216                 | 0                           | 0                             | 40                                   | 60                                   |
| 0.0108                        | 20                            | 10368                | 0                           | 0                             | 40                                   | 60                                   |
| 0.012                         | 20                            | 11520                | 0                           | 0                             | 40                                   | 60                                   |

When the pumped storage station provides 30 minutes of reserve, the duration is required to be 2 hours. The limit of reserve capacity is set at 20MW. The declared reserve capacity and income of the pumped storage station under different reserve compensation prices are shown in Table 4. When the pumped storage station provides reserve, the factors that affect its profit in the energy market are the reserve capacity and duration of reserve. Therefore, the market strategy under this type of reserve is the same as that under the reserve of "10-minute response and duration of 2 hours" (see Table 3). When the reserve compensation price is 0.006 yuan/h, the pumped storage station starts to provide reserve service, thus increasing the total revenue.
Table 4. The decision result of PSPS under different compensation prices of the 4th type of reserve.

| compensation price (Yuan/hour) | declare spare capacity (MW) | total revenue (Yuan) | maximum pumping power (MW) | maximum discharge power (MW) | minimum storage capacity state (MWh) | maximum storage capacity state (MWh) |
|-------------------------------|-----------------------------|----------------------|-----------------------------|-----------------------------|-------------------------------------|-------------------------------------|
| 0.001                         | 0                           | 8357                 | 20                          | 20                          | 0                                   | 100                                 |
| 0.002                         | 0                           | 8357                 | 20                          | 20                          | 0                                   | 100                                 |
| 0.003                         | 0                           | 8357                 | 20                          | 20                          | 0                                   | 100                                 |
| 0.004                         | 0                           | 8357                 | 20                          | 20                          | 0                                   | 100                                 |
| 0.005                         | 0                           | 8357                 | 20                          | 20                          | 0                                   | 100                                 |
| **0.006**                     | **0.9**                     | **8359**             | 19                          | 20                          | 1.71                                | 100                                 |
| 0.007                         | 2.4                         | 8409                 | 18                          | 20                          | 4.77                                | 100                                 |
| 0.008                         | 4.9                         | 8508                 | 15                          | 20                          | 9.80                                | 100                                 |
| 0.009                         | 6.8                         | 8653                 | 13                          | 20                          | 13.58                               | 100                                 |
| 0.01                          | 20                          | 9600                 | 0                           | 0                           | 40                                  | 60                                  |

When considering that pumped storage station can simultaneously provide four types of reserve services, the optimal market strategy is shown in Table 5. The compensation prices of four types of reserve are set as 0.01, 0.008, 0.006 and 0.005 yuan/h, respectively. At this time, the optimal declaration strategy of pumped storage station is that: primary frequency regulation is 3MW, reserve capacity of 1-minute is 10MW, and reserve capacity of 30-minute is 10MW. The operation results in the energy market is shown in Figure 5. In this case, the total revenue of pumped storage station is 12,340 yuan. At the corresponding prices, the revenues under conditions of providing single reserve are 8,632, 8,510, 8,359 and 8,357 yuan, respectively. It indicates that when the pumped storage station provides reserve services at different time scales its storage capacity and power capacity will be fully utilized, and the total revenue will be significantly increased.

Fig.5 Operation results of PSPS in the electric energy market after providing multiple reserve services.

Table 5. Comparison of the operational decision and profit when providing different reserve services.

| compensation price (Yuan/hour) | Reserve 1 | Reserve 2 | Reserve 3 | Reserve 4 | All Reserve |
|-------------------------------|-----------|-----------|-----------|-----------|-------------|
| compensation price (Yuan/hour) | 0.01      | 0.008     | 0.006     | 0.005     | /           |
| maximum pumping power (MW)    | 17        | 15        | 19        | 20        | 10          |
| maximum discharge power (MW)  | 20        | 20        | 20        | 20        | 10          |
| minimum storage capacity state (MWh) | 0.005 | 0.82     | 1.71      | 0         | 21.72       |
| maximum storage capacity state (MWh) | 99.95 | 100      | 100       | 100       | 78.28       |
| total revenue                 | 8623      | 8510      | 8359      | 8357      | 12340       |
5. Conclusions
This paper studies the optimization problem of pumped storage power station participating in energy market and reserve services market. Considering the uncertainty of energy prices, a scenario-based optimization model is established for the decision making. In the model, a variety of reserve services are considered. The power capacities provided by reserve services at different time scales does not affect each other. But the reserved storage capacity for various types of reserve are mutually restricted.

In the energy market, the pumped storage stations arbitrage the price spread to make profits. When providing reserve services, the pumped storage station needs to reserve certain power capacity and storage capacity. When the compensation price of reserve service is higher than a certain level, the pumped storage stations can get more profits through participating in the reserve service market, or even use all of its capacity to provide reserve services.

Simulation analysis is made about the optimal decisions and revenues considering pumped storage power station providing multiple types of reserve service. Even though the compensation price of each type of reserve is relatively low, the pumped storage power station can increase its revenue by providing multiple reserves. The total revenue of the pumped storage power station when providing multiple types of reserve services is obviously higher than that when providing single type of reserve service.

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