Study on three-part pricing method of pumped storage power station in China considering peak load regulation auxiliary service

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Abstract. The existing operation mode of pumped storage power station in China has the problems of low profit and unable to fully reflect the value of various auxiliary services. In this regard, this paper puts forward a more reasonable and more suitable price mechanism of pumped storage power station in China. Firstly, this paper studies the pricing method considering dynamic depreciation. Then, on the basis of the feed-in tariff of thermal power units, the avoidable cost method is used to study the pricing method of grid price for pumped storage power station. Finally, based on the efficiency loss cost, generation opportunity loss cost and unit start-up and shut-down cost of pumped storage power station participating in peak load regulation auxiliary service market, a three-part electricity price mechanism is proposed. The electricity price mechanism proposed in this paper is helpful to correctly evaluate the benefit of pumped storage power station and promote the construction and development of pumped storage power station.

1. Introduction

As the largest economic and clean energy storage mode, pumped storage power station has become the “stabilizer” and “regulator” for safe and stable operation of power grid, large-scale optimal allocation of energy and effective absorption of clean energy, which provides an important guarantee for effectively solving energy security problems. At present, the installed capacity of pumped storage power stations in the world has reached $1.5 \times 10^8$ kW. The installed capacity of China's pumped storage power stations has ranked first in the world. The scale in operation is $2.9 \times 10^7$ kW, and the scale under construction is $3.8 \times 10^7$ kW. By 2020, the installed capacity will reach $4 \times 10^7$ kW [1]. However, China's power market is still in its infancy, and pumped storage power stations in many areas cannot participate in the market. Therefore, it is worth studying how to determine the price of pumped storage power stations in power grid.

Experts all over the world have carried out in-depth research on the price of pumped storage. In the countries with relatively developed power market, pumped storage can obtain profits by recovering costs in the power market. According to the bidding strategy of pumped storage, in reference [2], a novel risk management method, downside risk constraint (DRC), is proposed to obtain the optimal bidding strategy for pumped storage power stations. Reference [3] puts forward the optimal bidding strategy of pumped storage power station in a pool-based power market. When the market clearing price is high, the pumped storage power station operates as a generator, and when the price is low, the pumped storage power station operates as a load. Reference [4] presents a cooperative optimal bidding
strategy for pumped storage generators in a competitive power market and the validity of the proposed quotation strategy is verified by numerical simulation. However, China's power market is not perfect. In most areas, the profit of pumped storage power station is completely determined by the grid company's grid price.

This paper formulates the grid price of pumped storage power station in the transitional stage of power market in China. Based on the avoidable cost method, taking the on grid electricity price of thermal power units as reference, the method of making the on grid price of pumped storage power station is studied, and the compensation price of pumped storage power station participating in peak load regulation auxiliary service market is formulated to form the three-part electricity price. The pricing method proposed in this paper provides a reference for China power grid corporation to formulate electricity price.

2. Research on pricing method of two-part feed-in tariff for pumped storage power station

The feed-in tariff refers to the metering price of the power grid purchasing the electric power of the power generation enterprise at the point of connecting to the main grid. It is generally determined by the unit cost of power generation plus the average unit cost profit of power generation in the grid, and considering other factors. In order to better evaluate the comprehensive benefits of pumped storage power station to the whole power system and the whole society, in this paper, the avoidable cost method is used to set the electricity price. Assuming that the system power supply consists of thermal power station and pumped storage power station, the alternative power station in avoidable cost method is thermal power station. Therefore, the calculation method of feed-in tariff of thermal power unit is discussed first [5]. In addition, considering the price rise and other factors, this paper uses the dynamic depreciation method and the investment profit rate to calculate the construction cost of the power station, so as to calculate the capacity price.

2.1. Dynamic depreciation method and investment profit rate

Considering the dynamic characteristics of the calculation method of feed-in tariff, the fixed cost, fuel cost and water fee increase year by year according to the set price rising rate. The time value of capital and assets should be considered in the depreciation cost and enterprise profit. In the calculation of the capacity cost of the feed-in tariff, the incremental dynamic depreciation method is used to calculate the depreciation cost of the power station year by year [6]. The calculation formula is as follows:

\[ D_t = D_{t-1}(1+y) \quad (t=1,2,\ldots,T) \quad \text{(yuan)} \]  

\[ D_t = P(1-r)(1+y)^T \frac{x-y}{(1+x)^T-(1+y)^T} \quad (x \neq y) \quad \text{(yuan)} \]  

\[ D_t = TP(1-r)(1+y)^T \frac{x}{1+x}^{T-1} \quad (x = y) \quad \text{(yuan)} \]  

In the formula, \( D_t \) is the depreciation cost in the \( t \)-th year; \( y \) is the average annual growth rate of the assets, which can be used as the average price rise rate; \( P \) is the original value of the fixed assets of the power plant at the end of the construction period; \( r \) is the ratio between the net residual value and the original value of the fixed assets; \( x \) is the average annual growth rate of the fund; \( T \) is the depreciation period.

Enterprise profit is calculated by the index of investment profit rate. Assume that the total dynamic investment at the end of the construction period of the power plant project is \( I_0 \) and the investment profit rate of each year within the service life of the project is \( \rho \), then the annual profit of the \( t \)-th year is as follows:

\[ RP_t = \rho \cdot I_t = \rho \cdot (1+y)^{t-1} \cdot I_0 \quad \text{(yuan)} \]  

Using formula (4) to calculate the annual profit can keep the investment profit rate unchanged throughout the service period, but the annual profit increases with the annual increase of the initial
investment. The investment profit rate remains unchanged, which is convenient to judge the investment effect of the project.

In all loans of the project, find out the one with the shortest repayment period as the control loan. If there are several loans with the shortest repayment period at the same time, the one with the largest loan amount shall be taken as the control loan. Therefore, we can get the formula of investment profit rate which is necessary to meet the loan repayment requirements as follows:

\[
\rho = \frac{L_1 (1 + x_1)^n + \sum_{i=1}^{n} (SL_i - D_i - PT_i) (1 + x_i)^{-i}}{(1 - \varepsilon) I_0 \sum_{i=1}^{n} A_i (1 + y)^{t-i} (1 + x_i)^{n-i}}
\]

(5)

In the formula, \(L_1\), \(x_1\) and \(n\) are respectively the amount and interest rate of the control loan converted to the end of the construction period and the number of years from the first year of production to the full repayment of its principal and interest; \(SL_i\) is the principal and interest of all the remaining loans in the \(t\)-th year (\(t=1\) corresponding to the first year of production); \(D_i\) is the loan repayment depreciation in the \(t\)-th year, calculated by formula (1); \(PT_i\) is the other loan repayment funds in the \(t\)-th year; \(\varepsilon\) is the proportion of retained profits of the enterprise, which is taken according to the regulations; \(A_i\) is the ratio of the production capacity to the installed capacity in the \(t\)-th year.

2.2. Calculation method of feed-in tariff of alternative power station

The feed-in tariff of thermal power station adopts two-part electricity price system, which consists of five parts: fixed cost (including repair cost, wage and employee welfare fee, management fee, financial expense, etc.), depreciation cost, fuel cost and water fee, sales tax and surtax, and enterprise profit.

2.2.1. Capacity price. During the loan repayment period, the profit required for loan repayment is included in the capacity price, and the payment of principal and interest is ensured through a fixed capacity price, so as to reduce the uncertain risk caused by electricity competition. The capital profit is included in the electricity price to promote the investors to continuously improve the management level and actively participate in the market competition.

The capacity price for the \(t\)-th year of thermal power station is composed of fixed operation cost \(O_1\), depreciation cost \(D_1\), pretax profit \(RP_{1t}\), required for loan repayment, sales tax and additional tax \(TAX_{1t}\). The capacity price in the \(t\)-th year is as follows:

\[
PT_{1t} = \frac{O_1 + D_1 + RP_{1t} + TAX_{1t}}{NT (1-\eta_1)(1-\eta_2)} \quad \text{(yuan/kW.a)}
\]

(6)

In the formula, \(NT\) is the installed capacity of thermal power station; \(\eta_1\) is the power consumption rate of thermal power station itself; \(\eta_2\) is the loss rate of supporting power transmission and transformation.

2.2.2. Electricity price. The electricity price for the \(t\)-th year of thermal power station is composed of fuel charge \(C_1\), water charge \(W_1\), sales tax \(TAX_{2t}\) related to power generation, and capital profit \(RP_{2t}\). The electricity price in the \(t\)-th year is as follows:

\[
PT_{2t} = \frac{C_1 + W_1 + RP_{2t} + TAX_{2t}}{ET_t (1-\eta_1)(1-\eta_2)} \quad \text{(yuan/kW.h)}
\]

(7)

In the formula, \(ET_t\) is the power generation of thermal power station in the \(t\)-th year; other variables have the same meaning.

2.3. Dynamic estimation method for two-part feed-in tariff of pumped storage power station

The avoidable cost method is used to calculate the feed-in tariff of pumped storage power station. According to the marginal theory, avoidable cost is the economic index of the worst project in the
selected project, or the economic index of the best project in the unselected project. In the two-part electricity price system, the avoidable cost is divided into capacity cost and electricity cost.

The calculation steps are as follows:
(1) Based on the same requirement of power quantity and peak load regulation capacity, the optimal power structure with the design scheme of pumped storage power station and the alternative scheme without pumped storage power station is determined;
(2) The operation optimization of the two schemes is carried out, and the capacity cost and electricity cost are calculated by accounting cost method, and the operation benefits of the two schemes are quantified from two aspects of economic benefits and environmental benefits. As shown in Figure 1, calculating avoidable capacity cost and electricity cost, capacity price and electricity price.

Figure 1. Composition of system operation benefit.

The feed-in tariff of pumped storage power station determined by avoidable cost method includes not only the capacity cost and electricity cost of the alternative power station, but also the difference between the fixed operation cost and the variable operation cost of other power stations in the scheme. The benefits such as reducing coal consumption and pollutant emission, absorbing wind power and emergency reserve and other benefits due to the input of pumped storage power station are included in the electricity price. Therefore, the pumped storage power station obtains a higher electricity price to compensate its capacity and electricity efficiency, which is conducive to the development of pumped storage power station and the comprehensive benefit evaluation of pumped storage power station.

3. Study on compensation electricity price of peak load regulation auxiliary service
For the pumped storage power station to participate in peak load regulation auxiliary service, the cost of efficiency loss, generation opportunity loss cost and unit start-up and shut-down cost should be considered to formulate the compensation price mechanism [7]. This study paves the way for proposing the cost compensation mechanism of auxiliary services and the power station operation mode considering auxiliary services.

3.1. Lost cost of generating efficiency
When pumped storage units participate in peak load regulation, their output needs to be output according to dispatching instructions, which is likely to be unable to operate in its economic optimum, thus generating efficiency loss cost will be generated. The efficiency loss of a pumped storage power station during peak shaving is calculated as follows:
In the formula, $N$ is the number of units in the power station; $P_n$ is the optimal power generation condition of the $n$-th unit, and the actual output of $P_{n,t}$ participates in the peak adjustment of $t$ time length; $c$ is the feed-in tariff of the power station; $k_{PLR}$ is the unit working condition, the value of 1 is taken under the generating condition and 0 is taken under other working conditions; function $F$ represents the generation efficiency function of the unit under different outputs; $M$ is the number of peak shaving sections with reduced power under the condition of peak load regulation on that day; $t$ is the length of the peak-regulating period.

3.2. Lost cost of generating opportunity

The financial accounting of a power station is based on the planned output of the power station. If the average daily output of the power station is less than the planned daily output due to peak regulation, the power generation benefit of the power station will be directly lost, which is the generation opportunity loss cost of peak regulation. Under the power generation condition, if the power generation is reduced due to peak load adjustment, the opportunity of generating benefits will be directly reduced. Under the pumping condition, if the pumping volume is reduced due to peak regulation demand, the reduced pumping capacity cannot obtain electricity revenue through subsequent peak generation, so the unit loses the opportunity to generate benefits. Both of the above situations have the output opportunity loss cost due to peak regulation.

When a pumped storage power station participates in peak regulation operation, according to the peak regulation output curve, the daily total generating capacity and total pumping water can be calculated. If it is equivalent to the full power output, the calculation is as follows:

3.2.1. Generator operation mode. Based on the annual planned power generation of the power station, the daily equivalent minimum full-power generation time $T_{g, min}$ of the power station is obtained as follows:

$$T_{g, min} = \frac{W_g}{(365 \times N \times P_t)} \text{ (h)}$$  \hspace{1cm} (9)

If the equivalent full-power generation time $t_g$ of a certain day of the power station satisfies equation (10), no power generation opportunities will be lost in the case of peak adjustment, and no compensation is required. On the contrary, the power station should compensate for the loss of generating opportunities due to peak regulation.

$$t_g \geq T_{g, min} \quad \text{(10)}$$

3.2.2. Pumping operation mode. If $t_g$ is the equivalent full-power pumping time of the power station on a certain day, then under the pumping condition, the upper and lower reservoir capacity balance is mainly considered, which is satisfied as follows:

$$\left(\frac{t_g}{\eta}\right) = t_p$$  \hspace{1cm} (11)

If the following equation (12) exists, it indicates that the upper reservoir capacity supplemented by pumping is less than the upper reservoir capacity already consumed by the power generation, and the benefits brought by this part of water pumped back to the upper reservoir to participate in subsequent power generation are also lost.

$$\left(\frac{t_g}{\eta}\right) > t_p \quad \text{(12)}$$

Therefore, the opportunity loss cost of power station peak regulation $C_{PLR, op}$ is:

$$C_{PLR, op} = N \cdot P_t \cdot \left[ k_{PLR, g} \cdot \left( T_{g, min} - t_g \right) \cdot c + k_{PLR, p} \cdot \left( \frac{t_g}{\eta} - t_p \right) \cdot \left(c - c_g\right) \right] \text{ (yuan)}$$  \hspace{1cm} (13)

where, $k_{PLR, g} = \begin{cases} 1 & \text{if } t_g < T_{g, min} \\ 0 & \text{else} \end{cases}$, $k_{PLR, p} = \begin{cases} 1 & \text{if } \left(\frac{t_g}{\eta}\right) < t_p \\ 0 & \text{else} \end{cases}$
In the formula, \( P_r \) is the rated maximum generating power of a single unit; \( c \) is the feed-in tariff of the power station; \( c_p \) represents the pumping price of the power station; \( k_{PLR,g} \) represents whether generating opportunity loss occurs, and a value of 1 means a loss of generating opportunity; \( k_{PLR,p} \) represents whether pumping opportunity loss occurs, and a value of 1 indicates a loss of pumping opportunity.

### 3.3. Cost of unit start-up and shut-down

The start-up and shut-down costs of pumped storage units include water consumption costs during start-up and shut-down, additional maintenance costs of units, and costs of shortening unit life due to equipment wear, etc., which are generally determined according to test or operation experience. Generally, once the unit starts and stops, the operation life of the unit will be reduced by about 10-15 hours. If the unit starts and stops 150 times a year, the unit life will be shortened by 20%. Based on this, we can calculate the start-up and shut-down cost \( C_{PLR_{ss}} \) in a certain day under the condition of peak load regulation is:

\[
C_{PLR_{ss}} = \sum_{n=1}^{N} N_{ss} \times c_{ss} \text{ (yuan)}
\]

In the formula, \( N_{ss} \) is the number of start and stop adjustment of the \( n \)-th unit; \( c_{ss} \) is the cost of each start and stop of a single unit, calculated by the cost of life loss.

The compensation price of the pumped storage power station participating in peak regulation auxiliary service is obtained by the above three cost calculations according to the actual situation.

### 4. Discussion on the three-part electricity price based on the cost compensation mechanism of peak load regulation auxiliary service

In this paper, the two-part electricity price model and its price mechanism which are widely used in China are expanded. According to the cost charging compensation mechanism of peak load regulation auxiliary service, the economic compensation for auxiliary service is carried out, and a three-part electricity price operation mode including capacity price, electricity price and peak shaving auxiliary service cost compensation is proposed.

This three-part tariff operation mode not only recognizes the benefits of auxiliary services, greatly improves the initiative of power stations to participate in auxiliary services for peak adjustment of the grid, but also improves the traditional two-part tariff pricing method. The avoidable cost method is adopted to more accurately analyze the capacity price and electricity price of pumped storage power station, so as to help the pumped storage power station to maximize its own value and benefit income and meet the requirements of the current utilization rate of pumped storage power station to be improved.

### 5. Conclusions

Combined with China's electric power system and its own operation characteristics, this paper puts forward a pricing method for pumped storage power station, which is suitable for the current situation of China's power market-oriented reform. This paper refines the calculation methods of the capacity price and electricity price of the existing two-part system and compensates them for their participation in auxiliary services. It helps to correctly evaluate the benefits of pumped storage power stations, reasonably determine the development scale of pumped storage power stations, optimize the power source structure, and improve the competitiveness of pumped storage power stations in the power market. Promote the further independence of power station operation and give full play to the service capacity of pumped storage power station. This paper puts forward the cost recovery mechanism of pumped storage from the perspective of China's existing operation mode and power grid company. However, with the acceleration of China's power system reform process, how to better play the role of pumped storage units in the power market, through the market price to fully reflect its price, and to effectively compensate them, so as to achieve system cost reduction and efficiency improvement, it is urgent to further study.
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