Benefit evaluation of pumped storage power station in electricity marketization environment

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Abstract. At present, pumped storage power station based on two-part system electricity price cannot effectively recover the cost in China, so it has become one of the development directions for the pumped storage power station to enter the electricity market and obtain benefits. Combined with the background of electricity marketization, this paper analyses the benefits of pumped storage energy in electricity market from two aspects: the electric energy market and the auxiliary service market, based on the functions of peak load shifting, peak-regulating, frequency modulation and phase modulation provided by pumped storage power stations. Efficiency analysis based on pump storage power station, an economic benefit, environmental benefit and social benefit for the primary index is established under electricity market environment benefit evaluation system of pumped storage power station, based on the G1 - benefit evaluation model of entropy weight method, taking Tongbai pumped storage power station as an example to carry on the comprehensive evaluation, the evaluating model is verified to have been put into production of pump storage power station in power market yield were analysed, and it provides the direction for future development of China pump storage power station is proposed.

1. Introduction

Pumped storage is the most widely used energy storage technology in the power system. The coordinated operation of pumped storage and clean energy units can increase the peak-regulating capacity of the system, and play an important role in reducing wind abandoning, light abandoning and water abandoning in the power grid, and improving the utilization rate of resources [1]. However, pumped storage power station has always been a kind of power grid operation tool in China, and there is little research on its benefit evaluation. Under the electricity market environment, it is an urgent problem to evaluate the efficiency of pumped storage power station effectively.
2. Operation benefit analysis of pumped storage power station

The benefit of pumped storage power station in power market can be obtained from the electric energy market and auxiliary service market. This part analyzes the benefit of pumped storage power station from both electric energy market and auxiliary service market.

2.1. Benefit analysis of pumped storage in the electric energy market

There are many users in the power system, and their working time and demand are different, resulting in unbalanced system load [2]. Generally speaking, the power system has a peak demand in the day and evening, and a trough in the middle of the night. In order to maintain the stable output of the thermal power station, it is necessary to have relevant users to absorb the electric energy in the trough, and the pumped storage power station is the best choice.

Pumped storage power station can produce peak electricity, which is converted from electricity in non-peak load period to electricity in peak load period. Pumped storage power station is an important power source for the construction of a new generation of power system in China. It can adapt to different demands of the power grid and plays the dual role of "power plant" and "power user" in the power system [3]. Pumped storage power station can convert the surplus electric energy into the potential energy of water when the load of the power grid is low, and store the energy by pumping the water up to the top. At the same time, it can also convert the potential energy of water into electricity at the peak of load, generate electricity according to the needs of the power system, so as to realize the effective storage of electricity. At this time, pumped storage power station plays the function of "power plant".

When the power load is at a low ebb, the pumped storage power station absorbs electricity from the power grid under the pumping condition for energy storage. When the load is at a high peak, the power station sends the electricity back to the power grid under the power generation condition. Therefore, an important function of the pumped storage power station in the electric energy market is to cut the peak and fill the valley.

2.2. Benefit analysis of pumped storage in auxiliary service market

Pumped storage power station has good operating characteristics and can provide many auxiliary services for the power system, such as peak and frequency modulation, phase modulation, emergency standby, black start and so on.

(1) Peak and frequency modulation

The most basic function of pumped storage unit is to adjust the peak and frequency, running through the whole process of the power system. It is the foundation of safe and stable operation of power grid and has a critical impact on the overall economy of power market. Considering the operation characteristics and economic dispatching principle of different generating units, the basic services of peak and frequency modulation are mainly provided by pumped storage units, a small number of gas turbine units and other types of units. The pumped storage unit is simple in structure and easy in control. It can effectively respond to the frequent fluctuation of the load, optimize the load curve, and play an important role in ensuring the safe and stable operation of the power system.

(2) Phase modulation

Phase modulation refers to the reactive power in the regulation system. The change of reactive power will cause the system voltage to change, resulting in the voltage deviating from the rating value, affecting the power quality and adversely affecting the safe operation of the system. Now the most common way to solve the reactive power regulation is to build a phase group, adjust the reactive power in the system, and stabilize the system voltage. The advantages of constant speed pumped storage units have special working condition of phase modulation, and can run for a long time to pump storage power plant in synchronous speed, no theory is generating or pumping can adjust reactive power, reactive power during a power grid voltage, pumping in absorbing reactive power grid voltage, the grid provides positive and negative two direction of reactive power regulation.

(3) Emergency standby
As large power units in the grid are put into operation, the failure of a single component will cause more and more frequent impacts on the power grid after the tripping of nuclear power units or more than 1000 mw fire power units, and in severe cases will lead to the collapse or collapse of the power grid. Therefore, in large power grid, load reserve and accident reserve must be set up to cope with unpredictable load increase and sudden accidents. The pumped storage power station can be used as a load or emergency standby, technically it can quickly meet the requirements of sudden load change and emergency, and can save the coal consumption of "hot standby" of thermal power units.

(4) Black-start
In the off-peak period of the grid, when the large power supply trip for some reason, the impact on the grid is more serious than in the peak period. Generally speaking, pumped storage unit operates in pump condition during off-peak period of power grid, which is equivalent to high-power rotary standby for power grid [4]. When it is detected that the power grid frequency drops to a certain value, the low-frequency cutting pump device of the unit running in the working condition of the water pump will operate, the unit will shut down, and the other units will start the power generation load, so that the power grid frequency can be restored to normal in a very short time.

3. Efficiency evaluation system for pumped storage power station

3.1. Efficiency evaluation index system of pumped storage power station
Pumped storage power plant in the electric power market has an important function of peak shaving in valley, the resulting power load in valley of benefits, combined with pump storage FM phase modulation in the ancillary services market, spare power station, and other functions, mutual influence the economic benefits of pumped storage power station, so will the peak shaving in valley, FM phase-modulation spare and power efficiency, capacity, efficiency and other auxiliary services such as the black start of benefits as the economic benefits of pumped storage power station [5].

Considering the technical characteristics of pumped storage units, the benefit of pumped storage power station is taken as the technical benefit index by influencing the technical level of pumped storage power station.

At the same time, as a project that serves the society, pumped storage power station will bring great changes to the people's lives around the power station, the environment of the region where it is located and the consumption level of clean energy in the region. In this paper, the benefits that affect the people's livelihood and the environment are respectively taken as social benefit indicators and environmental benefit indicators.

Figure 1 lists the index system of economic benefit index, technical benefit index, social benefit index and environmental benefit index of pumped storage power station, which is roughly as follows:
3.2. Benefit evaluation model based on G1-entropy weight method

The weight selection will directly affect the final evaluation and judgment of the operation of each pumped storage power station. Currently, among various comprehensive evaluation methods, the weighting method can be generally divided into subjective weighting method and objective weighting method. In order to ensure that the evaluation results can truly reflect the operation status of pumped storage power station, this paper adopts the G1-entropy weighting method, which has the advantages of subjective and objective weighting method [6-7].

(1) G1 weighting method:

1) After a certain number of experts are selected, each expert should sort the index set \{x_1, x_2, \ldots, x_m\} according to the importance of the evaluation index, and a unique ordering relation \(x_1^* \geq x_2^* \geq \cdots \geq x_m^*\) is determined.

2) Determine the relative importance of adjacent indicators:

The ratio of the importance of adjacent indexes \(x_{k-1}\) to \(x_k\) can be expressed in the following expression:

\[
    r_k = \frac{w_k - 1}{w_k}
\]  

(1)

Where \(k = m, m-1, \ldots, 3, 2\), \(w_k\) is the weight of the kth indicator.

3) Calculation of index weight:

If the relation (1) is satisfied by the expert (or decision-maker), then the weight \(w_m\) of indicator \(m\) is:

\[
    w_m = \left(1 + \sum_{k=2}^{m} \prod_{r=2}^{k} r_k\right)^{-1}
\]  

(2)

And \(w_{m+1} = r_{m}w_{m}, k = m, m-1, \ldots, 3, 2\), in this way, we get the weight of all the evaluation indicators.

(2) Entropy weight method

Entropy weight method is an objective weighting method. In the specific use process, the entropy weight method calculates the entropy weight of each index according to the degree of variation of each index, and then corrects the weight of each index through the entropy weight, so as to obtain a more
objective index weight. Entropy weight method is a kind of comprehensive evaluation method which can be used for multi-object and multi-index. The evaluation results are mainly based on objective data, and are hardly affected by subjective factors, which can largely avoid the influence of human factors. The calculation steps are as follows:

1) For each sample, \( x_{ij} \) is the value of the index \( j \) of the sample \( i \), and normalize the index first.

2) Calculate the proportion of the sample value \( i \) of the indicator \( j \) in the index:

\[
p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}
\]  

(3)

Where, \( x_{ij} \) is the measured value \( i \) of the indicator \( j \).

3) Calculate the entropy value of the indicator \( j \).

\[
e_{j} = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ij} \ln p_{ij}, \quad j = 1, \ldots, m
\]  

(4)

4) Calculate information entropy redundancy (difference):

\[
d_{j} = 1 - e_{j}, \quad j = 1, \ldots, m
\]  

(5)

5) Calculate the weight of each indicator:

\[
\omega_{j} = d_{j} / \sum_{i=1}^{m} (1 - e_{j}), \quad j = 1, \ldots, m
\]  

(6)

(3) Determine the combination weight of evaluation indicators

Set \( w_{j} \) as the weight of the index term \( j \) after the combination of G1 method and entropy weight method, \( w_{j} \) is represented as a linear combination of the weight coefficient obtained by G1 method and the weight coefficient \( w_{j}^{f} \) obtained by entropy weight method, namely:

\[
w_{j} = aw_{j}^{f} + (1 - a)w_{j}^{s}
\]  

(7)

Where, \( w_{j} \) is the weight of the fourth index after the combination of G1 method and entropy weight method; \( w_{j}^{f} \) is the weight coefficient obtained by G1 method; \( w_{j}^{s} \) is the weight coefficient obtained by entropy weight method, \( a \) is the subjective coefficient used to adjust the degree to which subjective and objective factors affect the overall weight coefficient. The value range is 0~1, and the value of \( a \) can be selected according to the need

(4) Determine the final score of each evaluation index

Set \( s_{i} \) as the score of the composite index \( i \), the score \( p_{ij} \) of the sub indicator \( j \) of the index \( i \) can be obtained:

\[
s_{i} = \sum_{j=1}^{m} p_{ij} w_{ij} \times 100
\]  

(8)

Where, \( p_{ij} \) is the score of the sub indicator \( j \) of the index \( i \), and \( s_{i} \) is the final score.

4. The example analysis

Tongbai pumped storage power station is equipped with four 300MW vertical single-stage reversible mixed-flow pumped storage units with a total capacity of 1.2GW. It is the third pumped storage power station in China with an installed capacity of more than 100 kw after Guangzhou and Tianhuangping pumped storage power stations. The power station operates on a daily basis with an annual generating capacity of 2.1TWh and an annual pumping capacity of 2.8TWh, with an overall efficiency of 75.3%. In this paper, the operation data of Tongbai in 2018 are selected for example analysis, so as to verify its operating benefits.

(1) Subjective weight of comprehensive benefit index of pumped storage power station

The economic benefit evaluation system is composed of peak-load and valley benefit, frequency modulation benefit, peak-load benefit, phase adjustment benefit, accident standby benefit, black start
benefits, electricity benefit and capacity benefit. The experts give the order relation of the seven, and assign the value of the adjacent indexes. After calculation, the weight coefficient of economic benefits is \( W_{b1} = (0.3107, 0.2219, 0.1849, 0.1541, 0.1284, 0.1673, 0.1742) \).

The technical benefit indexes in this paper include unit availability coefficient, start-up success rate, annual start-up times, and annual frequency pass rate. The order relation of the four was given by the expert, and the adjacent indexes were assigned. After calculation, the weight coefficient of technical benefits is \( W_{b2} = (0.2179, 0.1861, 0.1513, 0.1462) \).

The social benefit index includes two parts: employment effect and influence on related industries. The order relation of the four was given by the expert, and the adjacent indexes were assigned. After calculation, the weight coefficient of social benefits is \( W_{b3} = (0.2322, 0.1955) \).

The environmental benefit indexes include reducing pollutant emissions, impacts on soil and vegetation, and increasing clean energy consumption. The experts give the order relation of the four, and assign the value of the adjacent indexes. After calculation, the weight coefficient of environmental benefits is \( W_{b4} = (0.2456, 0.2047, 0.2411) \).

(2) Objective weight of comprehensive benefit index of Tongbai pumped storage power station

According to the above formula is given and the specific numerical calculation of the indicators, the Tongbai pumped storage power station of each benefit weight: for the economic benefit index of peak shaving in valley, FM, peak shaving, phase modulation, and emergency, black start, power efficiency, capacity, efficiency of various weights respectively (0.281, 0.145, 0.201, 0.149, 0.150, 0.074); The weight of unit availability coefficient, start-up success rate, annual start-up times, and annual frequency pass rate of technical benefit index are respectively (0.224, 0.250, 0.236, 0.290). The employment effect of the social benefit index and its impact on the related industries are respectively (0.470, 0.530). The weights of reducing pollutant emissions, affecting soil and vegetation, and improving clean energy consumption are respectively (0.660, 0.101, 0.239).

(3) Comprehensive score of comprehensive benefit index of Tongbai pumped storage power station

According to formula (7) and (8), the comprehensive score of Tongbai pumped storage power station is 85.16.

5. Conclusion

In this paper, the benefit analysis pumped storage power stations in China is firstly carried out in combination with the background of electricity marketization. It is concluded that in the electric energy market, the pumping and storage power stations can get benefits by cutting peaks and filling valleys, and in the auxiliary service market, the pumping and storage power stations can get benefits by providing auxiliary services such as peak adjustment, frequency modulation and phase adjustment. Secondly, based on the efficiency of pump storage power station in the two markets, to economic benefit, environmental benefit, technical benefit and social benefit four aspects as the primary index pump storage power station benefit evaluation model is established, in addition, the G1 - order relation combination method to each of the indicators in the evaluation system of scores, and concluded a pump storage power plants in electricity market environment comprehensive benefits.

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