Discussion on joint operation of wind farm and pumped-storage hydroplant

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Abstract. Due to the random fluctuations in wind power, large amounts of grid integration will have a negative impact on grid operation and the consumers. The joint operation with pumped-storage hydroplant with good peak shaving performance can effectively reduce the negative impact on the safety and economic operation of power grid, and improve the utilization of wind power. In addition, joint operation can achieve the optimization of green power and improve the comprehensive economic benefits. Actually, the rational profit distribution of joint operation is the premise of sustainable and stable cooperation. This paper focuses on the profit distribution of joint operation, and applies improved shapely value method, which taking the investments and the contributions of each participant in the cooperation into account, to determine the profit distribution. Moreover, the distribution scheme can provide an effective reference for the actual joint operation of wind farm and pumped-storage hydroplant.

1. Introduction

In recent years, wind power experienced a great leap forward because of its non-polluting, short investment cycle, relatively mature technology and so on [1]. However, due to the strong random fluctuating and strong anti-peaking of wind power, large-scale wind power grid integration has brought great difficulties to the safe dispatching of the grid [2]. Therefore, in order to absorb the wind power and protect the interests of the wind farm as much as possible, the grid should provide adequate capacity of peak shaving and frequency modulation for the wind power. Pumped storage is the ideal peak shaving power. Accordingly, joint operation between wind farm and pumped-storage hydroplant can buffer the fluctuation of the output of large-scale wind farm, and make the uncontrollable wind power into a reliable power, which improves utilization of wind power.

The key technologies in the construction of combined system of wind farm and pumped storage hydroplant were studied in references [3-4]. Taking the combined construction of wind farm and pumped storage hydroplant in Ebinur pluripotent complementary renewable energy base for example, the reference [3] confirms the feasibility of joint operation technically. Additionally, some researches on joint operation [5-7] pay more attention to the optimal scheduling of joint operation by establishing an optimization model with single objective of the minimum coal consumption, the lowest operating cost or the minimum wind curtailment. It verifies the effect of pumped-storage hydroplant on peak clipping and valley filling and balancing wind power fluctuation through the model simulation. A multi-objective optimization model is established in references [1, 8-10] to maximize economic benefits and minimize output volatility in joint operation. In addition, the multi-objective evolutionary algorithm based on plant growth simulation, the genetic algorithm, the fuzzy multi-objective
evolutionary algorithm and etc. are used to optimize the model. Thus, the maximization of the economic benefits under the condition of satisfying the requirements of power quality can realize.

The simulation results of combined system optimal scheduling model show that the joint operation is economically and technically feasible. However, few people have studied the allocation of cooperative revenue in the joint operation \[11\]. In fact, the rational distribution of profits of joint operation is the premise of sustainable and stable development. Reasonable and fair profit distribution can enhance the willingness of member enterprises to cooperate, and thus raise the stability of cooperation. Conversely, unreasonable and unfair distribution may weaken the willingness of member enterprises to invest, and even lead to the collapse of cooperation \[12\]. This paper focuses on the joint operation of wind farm and pumped storage hydroplant and its profit distribution scheme, which provides an effective reference for actual joint operation. Based on Stackelberg, Nash negotiation and etc. \[13-14\], the existing cooperative game methods are relatively complex and impractical. While, the researches about distribution based on the Shapely value method and its improved allocation method are relatively mature. In this paper, the improved Shapely value method is utilized to distribute the profit, which simultaneously considers the investments and contributions. Namely, it not only considers the investment costs of both wind farm and pumped storage hydroplant, but pays more attention to their contributions in the cooperative benefits. Consequently, it takes into account the profit of enterprises with larger investments and dominant positions in the cooperation, and meanwhile can improve the enthusiasm of cooperative enterprises, and thus it is conducive to a long-term stable cooperation.

2. The feasibility of joint operation of wind farm and pumped-storage hydroplant

2.1. Complementary in nature

Because wind power has strong random intermittence and volatility, and the current wind power forecasting technology has a considerable error, the large-scale wind power grid integration will bring great challenges to the safe dispatching of power grid \[6\]. Moreover, wind power has strong anti-peak, that is, the peak period of wind power is the low period of electricity load. Therefore, it is necessary to equip the grid with sufficient capacity of peak shaving and frequency modulation to absorb the wind power and protect the interests of wind farms as much as possible, and ensure the safe operation of grid and the power dispatching between the peaks and valleys. It is important to choose peak shaving and frequency modulation units. If thermal power units were used for peak-shaving, it is unreasonable in economy, and simultaneously increases the emissions of carbon and polluting gas, thus weakening the environmental advantages of the wind power \[3\]. Gas-based peak shaving also is unrealistic because gas resources are not rich in China. At present, a more reasonable solution is energy storage technology, which can provide energy storage system for wind power. The system is equivalent to a power supply with flexible response and large capacity. In this case, there is an “energy buffer” between the wind power and the grid. Thus, both safety and economy of the system are taken into consideration. There are many energy storage technologies now, such as pumped storage, compressed air storage, superconducting energy storage, fluid battery, water electrolysis and so on. Among of them, pumped storage technology is more mature and its unit capacity cost is lower relatively, which can realize large-scale energy storage. In order to cooperate with the wind farm, the pumped-storage hydropower needs to develop the scheduling scheme in advance according to the predicted value of wind power, and adjust its operation conditions according to the time. Thus, it can make uncontrollable wind power into a reliable power supply and effectively reduce its negative effect on the safe and economical operation of grid. The pumped-storage hydropower can take advantage of pumping conditions and power generation conditions to act as both a load and a power supply, thus making the output of wind farm pretty smooth and improving utilization of wind power.

The combined system of wind farm and pumped-storage hydropower can give full play to the function of peak shaving and frequency modulation of pumped storage to improve wind power utilization and achieve peak clipping and valley filling. Additionally, the load regulation ability of
pumped-storage hydroplant can buffer the impact of large-scale wind power grid-integration on the power grid, and smooth the volatility of wind power effectively. Moreover, it can achieve the optimization of green power due to non-pollution of the wind power and hydropower itself. The combined system enhances economic benefits and promotes the coordinated development of power grid and renewable energy.

2.2. Feasible technically and economically
In the condition of combined operation, when the grid load is low, the pumped-storage hydroplant can convert the surplus wind power into the potential energy of the water and store it, and then converts potential energy to electricity at the peak of the load. As a result, it can reduce large-scale wind power curtailment, and bring additional benefits to wind power companies. Conversely, cooperating with wind farm can increase the utilization of pumped-storage hydropower, in the conversion of the "curtailed" wind energy. In addition, under the influence of peak-valley price, using the difference of electricity price can further increase the power generation gains of pumped-storage hydroplant. Therefore, the joint operation can realize a win-win situation between wind power companies and pumped-storage hydropower.

As the data shown in the reference [5], the utilization rate of wind power may begin to decrease when its capacity increases to a certain value. At this time, peaking units are required in order to increase the utilization of wind power. If the thermal power unit is used for peak-shaving, the total coal consumption will be increased, and the economic and environmental benefits will be damaged. While the use of pumped-storage hydropower is conducive to ensuring the safe dispatching of the grid in the condition of large-scale wind power grid-integration. Additionally, it can reduce the reserve capacity for power system accident and improve the ability to absorb wind power of power system. At the same time, the total cost on the condition that the pumped-storage hydropower units are involved in peak-shaving is lower than that only thermal power units are involved in peak-shaving, thus bringing huge economic and social benefits. The combined system of wind farm and pumped storage hydropower plant uses “abandoned” wind power to generate electricity, and makes it possible to bring about large-scale use of wind power. Thus, the proportion of wind energy as a renewable energy source in total energy consumption is increased. Meanwhile, the consumption of coal for thermal power is reduced, and pollution of carbon dioxide, sulfur dioxide, and other pollutant on the environment are reduced accordingly. Therefore, the joint operation has good environmental benefits.

The joint operation can develop the good regulation characteristics of pumped-storage plant under the safety and stability operation constraints to make full use of wind power resources and their environmental advantages. Taking economic benefits and environmental benefits of the joint operation as the optimization objective, the operation benefits of the whole power system has been strengthened, and a win-win situation among wind farms, pumped-storage hydropower units, grid corporations and social environment is achieved. Therefore, the combined development of wind power and hydropower has the realistic economic significance.

3. Profit distribution of joint operation
Reasonable and fair profit distribution can enhance the willingness of member enterprises to cooperate, and thus enhance the stability of cooperation. Conversely, unreasonable and unfair distribution may weaken the willingness of member enterprises to invest, and even lead to the collapse of cooperation. This section will focus on the profit distribution between wind farm and pumped storage hydropower. Taking into account the profit gains of members with larger investments and dominant positions in cooperation, the distribution scheme in this section will consider investment cost to ensure a reasonable return on investment. Meanwhile, the distribution scheme may pay more attention to their contribution to cooperation, considering the profits gains of members with relatively less investments but a larger proportion of contribution. It can not only enhance the enthusiasm of the member enterprises in their work and creation, but also make the distribution more equitable. Therefore, it is conducive to build a long-term stable cooperation.
3.1. The profit distribution method based on investment

J.S. Admas, an American behaviorist, proposes a theory of fairness, which holds that it can achieve fair when the ratio of the participants’ gains to inputs is equal to that of the other participants in cooperation. In view of this fairness theory, the profit gains of each participant should be proportional to their invested cost. In the alliance of joint operation, there are only two participants, namely, wind farm \( w \) and pumped storage hydroplant \( p \). And their gains can be recorded as \( \alpha(w) \) and \( \alpha(p) \), respectively. Therefore, the formulas of their gains are as follows:

\[ \alpha(w) = \frac{l_w}{l_w + l_p} V_{wp} \]  
\[ \alpha(p) = \frac{l_p}{l_w + l_p} V_{wp} \]

Here, \( l_w \) is the invested cost of wind farm in cooperation, and \( l_p \) is the invested cost of pumped-storage hydroplant in cooperation. Moreover, \( V_{wp} \) stands for the total profit gains of the wind farm and pumped storage hydropower.

3.2. The profit distribution method based on investment and contribution

The premise of the joint operation of wind farm and pumped storage hydroplant should be that the whole cooperative profit is greater than that of the individual operation, which is the individual rationality requirement of cooperation. The profit distribution of the joint operation can be studied by means of cooperative game theory. In this section, the investment and contribution of each participant in the cooperation are considered comprehensively to obtain the distribution scheme.

(1) The profit distribution scheme based on investment

Considering the investment cost as a factor and referring to the method of previous section, the investment-based profit distribution scheme for the joint operation of wind farm and pumped storage hydroplant is as follows:

\[ A = (\alpha(w), \alpha(p)) \]  

(2) The profit distribution scheme based on contribution

The distribution scheme considering the contribution to cooperation can be obtained on basis of the Shapley value method. The Shapley method is proposed by Shapley L.S. to solve the multiplayer cooperative game. It assigns each participant a unique and quantifiable value to characterize its contribution margin. According to the contribution margin of each participant to the cooperation, it can define the profit formula as follows:

\[ \beta(i) = \sum_{S \in N, i \notin S} r(S) (v(S) - v(S \setminus i)) \]

\[ r(S) = \frac{|S|-1}{n!} \]

\[ N = \{1, 2, \ldots, n\} \]

where \( N \) is denoted as the set of \( n \) participants, and \( S \) is any subset of \( N \), namely, alliance subset. Moreover, \( v(S) \) represents the cooperative profit of alliance \( S \), and \( v(S \setminus i) \) is the cooperative profit of the alliance after eliminating the \( i \) from \( S \). Thus, \( v(S) - v(S \setminus i) \) is the marginal benefit of \( i \), and \( |S| \) is the number of members in the alliance.

Thus, for wind farm and pumped-storage hydroplant, \( N=\{w, p\} \), the distribution scheme obtained by above shapley value method is as follows:

\[ B = (\beta(w), \beta(p)) \]  

(3) The profit distribution scheme based on investment and contribution

Above, it respectively sets up investment-based and contribution-based distribution strategy for single objective optimization. Whereas, the profit distribution for enterprise alliance is a complicated problem, and thus it needs to comprehensively consider multiple factors for distribution. Here, the AHP method is chosen to assign weight to each single objective distribution scheme \cite{[12]}.

Firstly, a matrix based on the investment and contribution factor needs to be constructed. The importance of these two factors is compared, and the corresponding values, which are usually given by experts in certain field independently, are determined.
Here, $y_{12}$ is the importance value for comparing the investment factor to contribution factor, and $y_{21}$ is the importance for comparing the contribution factor to investment factor. Among them, $y_{ij} = 1/y_{ji}$ ($i \neq j$), $y_{ii} = 1$ ($i = j$). Meanwhile, the importance evaluation is obtained on basis of the following scaling method.

| Importance level                                      | $y_{ij}$ |
|-------------------------------------------------------|-----------|
| When $i$ and $j$ are equally important                | 1         |
| When $i$ is slightly more important than $j$          | 3         |
| When $i$ is more important than $j$                   | 5         |
| When $i$ is much more important than $j$              | 7         |
| When $i$ is extremely more important than $j$        | 9         |

If the importance level is between any two levels above, the value 2, 4, 6 and 8 can be chose. While, the reciprocal exactly means the opposite.

Since the second-order matrix does not need to judge consistency, just the product of each row in the matrix need to be calculated\(^{[12]}\):

$$M_i = \prod_{j=1}^{2} y_{ij}, \quad i = 1, 2$$  

(8)

And the final weight coefficient can be calculated as:

$$w_i = \frac{2/\sum_{i=1}^{2} \sqrt{M_i}}{\sum_{i=1}^{2} \sqrt{M_i}}$$  

(9)

Thus, the profit distribution scheme based on the investment and contribution of the wind farm and pumped storage plant is denoted as follow:

$$\Phi = w_1 A + w_2 B$$  

(10)

4. Analysis of simulation results

4.1. Economic benefit

Based on the data model of joint operation of wind farm and pumped storage hydroplant established in reference \([15]\), it researches on maximizing the economic benefits of wind farm and pumped storage hydroplant. The simulation results are divided into two cases of winter typical day and summer typical day according to the seasonal characteristics of wind power output. And the typical day is divided into two cases: weekday and weekend. Considering the distribution of typical days and assuming that summer and winter occur with equal probability, it can be calculated that the average daily profit of pumped-storage hydroplant run alone is 17919 yuan, the average daily profit of wind farm run alone is 119357 yuan, and the profit of joint operation is 161575 yuan. The data is shown in table 2.

| operation mode          | power station | daily profit / yuan |
|-------------------------|---------------|---------------------|
| independent operation   | wind farm     | 119357              |
|                         | pumped-storage hydroplant | 17919          |
| joint operation         | wind farm and pumped-storage hydroplant | 161575        |

4.2. Investment cost

According to the relevant data and calculation formula of the current power market in reference \([11]\), the daily average investment cost of wind farms and pumped storage hydroplants can be calculated respectively. Based on the model described in last subsection, the capacity of wind farms and pumped
storage plants is 30MW and 32.8MW. The average daily investment cost of each hydroplant are shown in table 3.

| Power station          | Daily investment cost / yuan |
|------------------------|-----------------------------|
| Wind farm              | 69840                       |
| Pumped storage hydroplant | 9512                     |

4.3. Profit distribution

4.3.1. Profit distributed as investment-based method. According to the investment-based profit distribution method in last section, the profit results of wind farm and pumped-storage hydroplant are calculated respectively as follow:

\[ \alpha(w) = \frac{f_w}{f_w + f_p} V_{wp} = \frac{69840}{69840 + 9512} \times 161575 = 142207 \] (11)

\[ \alpha(p) = \frac{f_p}{f_w + f_p} V_{wp} = \frac{9512}{69840 + 9512} \times 161575 = 19368 \] (12)

4.3.2. Profit distributed as investment and contribution-based method. Firstly, according to the calculation above, the investment-based profit distribution result of wind farm and pumped-storage hydroplant is calculated.

\[ A = (\alpha(w), \alpha(p)) = (142207, 19368) \] (13)

Then, the marginal contribution-based profit distribution results and calculation process of wind farm and pumped storage hydroplant are shown in Table 4 and table 5 below.

| S      | Wind farm | Wind farm and pumped-storage hydroplant |
|--------|-----------|-----------------------------------------|
| v(S)   | 119357    | 161575                                  |
| v(S\w) | 0         | 17919                                   |
| v(S)- v(S\w) | 119357 | 143656                                  |
| |S| | 1 | 2 |
| r(S)   | 1/2       | 1/2                                     |
| r(S)(v(S)-v(S\w)) | 59678.5 | 71828                                   |

According to the above calculation process, it can be obtained:

\[ \beta(w) = 59678.5 + 71828 = 131506.5 \] (14)

| S      | Pumped-storage hydroplant | Wind farm and pumped-storage hydroplant |
|--------|----------------------------|-----------------------------------------|
| v(S)   | 17919                      | 161575                                  |
| v(S\p) | 0                          | 119357                                  |
| v(S)- v(S\p) | 17919 | 42218                                  |
| |S| | 1 | 2 |
| r(S)   | 1/2                        | 1/2                                     |
| r(S)(v(S)-v(S\p)) | 8959.5 | 21109                                  |

According to the above calculation process, it can be obtained:

\[ \beta(p) = 8959.5 + 21109 = 30068.5 \] (15)
For the wind farm and pumped storage hydroplant, the profit distribution obtained by the above Shapely value method is as follows.

\[ B = (\beta(w), \beta(p)) = (131506.5, 30068.5) \]  

(16)

It is advisable to assume that the contribution factor in cooperation is slightly more important than investment factor. Hence:

\[ \Gamma = \begin{bmatrix} 1/3 & 1/3 \end{bmatrix} \]  

(17)

The product of each row is \( M_1 = 1/3, M_2 = 3 \), and it can be obtained:

\[ w_1 = \frac{\sqrt[3]{M_1}}{\sqrt[3]{M_1} + \sqrt[3]{M_2}} = 0.25 \]  

(18)

\[ w_2 = \frac{\sqrt[3]{M_2}}{\sqrt[3]{M_1} + \sqrt[3]{M_2}} = 0.75 \]  

(19)

The profit distribution result based on investment and contribution for wind farm and pumped storage hydroplant is:

\[ \Phi = 0.25A + 0.75B = (134182, 27393) \]  

(20)

Combined with the above calculation, the profit returns obtained from the two distribution methods of wind farm and pumped storage plant are shown in Table 6 below.

| Distribution strategy | Wind farm / yuan | Pumped storage hydroplant / yuan |
|-----------------------|------------------|----------------------------------|
| Profit distributed as investment-based method | 72367 | 64342 |
| Profit distributed as investment and contribution-based method | 9856 | 17881 |

Distributing the profit according to the invested cost of each enterprise accords with the basic requirement of the profit distribution. Namely, whoever invests more should correspondingly gain more, and thus a relatively reasonable distribution is achieved. However, if the profits are distributed only according to the amount of investment, it may strike the enthusiasm of cooperative enterprises, especially the enterprises with relatively small scale and investment. Actually, it ignores the value created by labor. The distribution method based on investment and contribution not only considers the impact of investment factors, but also pays more attention to the contribution of the enterprise to cooperation. In fact, in the combined alliance between wind farm and pumped storage hydroplant, the investment of pumped storage hydroplant is relatively small, but the proportion of contribution is greater than that of investment. Considering the two factors can correspondingly increase the profit of pumped storage hydroplant. Actually, it can improve the cooperative willingness of pumped storage hydroplant to smooth wind power fluctuations, help peak load shifting and prevent wind curtailment. Therefore, the distribution method based on investment and contribution is more conducive to cooperation between wind farm and pumped storage hydroplants for long-term and stable development.

5. Conclusion

The joint operation of wind farm and pumped storage hydroplant can improve the wind power utilization and comprehensive benefits. It is necessary to distribute the profits reasonably in order to protect the enthusiasm of cooperative enterprises. The improved shapely value method proposed in this article comprehensively consider the investment and contribution, and can provide useful exploration for effectively solving the cooperative benefit distribution, and promote the long-term sustainable and stable development of cooperation between wind farms and pumped storage hydroplants.
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