Benefit-balance model of combined operation of wind power and pumped storage based on Sharply value method

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Abstract. Reasonable benefit distribution is a key issue in the joint operation of wind power pumped storage. Only by ensuring the fairness of the benefit distribution can the cooperation of wind power pumped storage be carried out for a long time, and then the maximum benefit can be guaranteed. This paper analyses the problem of reasonable distribution of profits from the combined operation of wind power pumped storage from the perspective of cooperative game theory, uses the Shapley value method to distribute the profits obtained from cooperation, and improves them. Factors such as value, input resource level, resource utilization rate, etc., introducing a comprehensive correction factor, thereby establishing an improved profit distribution model of the Shapley value method. The result of the example analysis shows that the improved profit distribution model of Shapley value is more in line with the actual situation, and the interests of various partners are guaranteed to the greatest extent, which is helpful for the long-term cooperation of this cooperation, thereby bringing benefits to the dispatch of the power system. Therefore, the improved Shapley value method is an important method of profit distribution for the combined operation of wind power pumped storage.

1. Introduction
The uncertainty of wind power generation makes the dispatch of the power system more difficult. The formulation of traditional power generation plans is carried out based on controllable power supplies, and the uncertainty and volatility of wind power have brought a lot of dispatch Hinders. Due to its advantages of rapid startup, flexibility and reliability, the combined operation of wind farms and pumped storage power plants that can flexibly regulate output has received a lot of research. Reference [1] provides a comprehensive literature review on the coordination of wind power and hydropower. On the issue of joint dispatch optimization: 1) To improve wind farm benefits and smooth power output[2]; 2) Consider cost benefits[3]; 3) To maximize joint operation benefits[4]; 4) Consider Real-time tiered electricity prices and grid transmission capacity limitations[5]; according to the above literature, the coordinated operation of wind power and hydropower can bring greater benefits to both parties. However, in the above literature, there is no proposed profit distribution plan for coordinated...
wind and hydropower. Reference [6] based on stakeholder theory, analyzed the main contradictions and conflicts of stakeholders in the joint operation of wind power and hydropower, and also mentioned the contradictions between the power grid, government and wind power generators, and proposed solutions, but did not propose a reasonable benefit distribution plan.

Reference [7] studied the profit distribution of the joint operation of wind farms and pumped storage power stations, and finally concluded that the use of the Shapley value method is the most reasonable in this profit distribution. However, the reference [8] pointed out that this distribution method has deficiencies, it only focuses on the probability of occurrence of the event, the contribution brought by the participation of the collaborators, does not take into account the contribution of each subject, and does not give different factors the weight of. The Shapley value defaults that the contribution factors among the cooperative members are all equal, which is a vague reflection of the contribution of the collaborators, so they have made corresponding improvements to the Shapley value method, and the main improvement measures are considered each contribution factor and the corresponding factor weight, the introduction of comprehensive correction factors, and case analysis, confirmed that the improved Shapley value is more practical, however, reference [9] does not give a specific method for calculating the weight of factors. Reference [10] from the perspective of the contribution of participating members, using the Analytic Hierarchy Process (AHP) to calculate the weights of evaluation indicators, and an example shows that the improved allocation method is beneficial to the stability of the consortium.

Based on the above analysis, this paper considers that in the cooperation process of actual wind farms and pumped storage power stations, the risk-bearing capacity, the resources invested, and the resource efficiency of the two parties are different. Comprehensively consider the influencing factors of benefit allocation, construct an evaluation index structure system of influencing factors, use fuzzy analytic hierarchy process to quantify the evaluation index, use the improved particle swarm optimization algorithm to solve the evaluation index weight, and introduce a comprehensive correction factor. Therefore, the Shapley Value Method is improved to make the distribution of benefits fairer and more reasonable and more in line with the actual situation, thereby encouraging both parties to carry out long-term cooperation.

### 2. Profit Distribution Model in Joint Operation

#### 2.1. Shapley value distribution model

In order to encourage producers to coordinate their planning and operation, a plan to distribute production costs or profits was proposed. This plan must be transparent and fair; in other words, the additional benefits of each producer’s participation must be evaluated and distributed. According to game theory, these attributes are guaranteed by the concept of Shapley. The Shapley value method is defined as follows:

Suppose the set \( N = \{1, 2, \cdots, n\} \), for any subset corresponds to a real-valued function \( v(s) \), satisfy the following conditions:

\[
\begin{cases}
    v(\emptyset) = 0 \\
    v(s_1 \cup s_2) \geq v(s_1) + v(s_2), s_1 \cap s_2 = \emptyset
\end{cases}
\]  

(1)

Let \([N, v]\) be an \( n \)-player alliance game, and let \( v \) be the feature function of the alliance game.

Let \( x_i \) denote the share that the player \( N \) in the set \( i \) should get from the maximum return \( v(N) \) of the alliance. Based on alliance \( N \), a distribution of each player is denoted by \( x = (x_1, x_2, \cdots x_n) \). The alliance must meet the following conditions:
In the Shapley method, \( \Phi(v) = (\phi_1(v), \phi_2(v), \ldots, \phi_n(v)) \) represents the profit obtained by each player. Where \( \phi_i(v) \) represents the distribution obtained by game party \( i \) under alliance \( N \), and its calculation formula is:

\[
\phi_i(v) = \sum_{s \in \mathcal{S}_i} w(|s|)[v(s) - v(s \setminus i)], i = 1, 2, \ldots, n
\]  

(3)

Where \( s \) is all subsets of the game player \( i \) in the set \( N \), \(|s|\) represents the number of players in the league; \( v(s) \) represents the total profit of the alliance \( s \) in cooperation; \( v(s \setminus i) \) represents the player \( i \) does not join the alliance \( s \) profit; \( v(s) - v(s \setminus i) \) represents the marginal contribution of the player \( i \) to the alliance; the players form the alliance in a random order, and the probability of occurrence of each order is \( w(|s|) \).

The Shapley value is the weighted average of the marginal contributions of the partners to all alliances, that is, the benefits are distributed according to the size of the partners' contribution to the revenue, and the partners who make the most contributions can obtain greater profits. Obviously, this allocation method does not conform to the principle of benefit allocation. In actual situations, not only the contribution of participants, but also the degree of risk faced by each member and the initial investment and other factors must be considered, so this model needs to be Make improvements.

2.2. Improved Shapley value distribution model

Considering the characteristics of the combined operation of wind power pumped storage, based on the existing research results, this paper comprehensively considers factors such as the ability to take risks, the degree of resources invested, and the utilization rate of resources. The improved model is:

\[
\phi_i'(v) = \phi_i(v) + V \cdot \Delta \lambda_i
\]  

(5)

\[
\Delta \lambda_i = \lambda_i - n \lambda_i
\]  

(6)

\[
\lambda_i = (M_{R_i} M_{U_i} M_{P_i}) \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}
\]  

(7)

Where \( \phi_i'(v) \) is the expected return of player \( i \) in the cooperative game \( (N,v) \) after improvement; \( \Delta \lambda_i \) is the difference between the comprehensive evaluation value of player \( i \) in the game and the average level, and \( \sum_{i=1}^n \Delta \lambda_i = 0, \sum_{i=1}^n \lambda_i = 1 \); \( V \) is the total revenue; \( M_{R_i}, M_{U_i}, M_{P_i} \) represent the risk-bearing ability value, resource utilization rate, and resource input level of the person \( i \) in the bureau; \( m_j \) represents the size of the factor weight.

(1) Risk taking ability index ( \( M_{R_i} \))

In order to compensate for the randomness and instability of wind power during the combined operation of wind power pumped storage, the pumped storage power station must always adjust the
output power of the hydropower unit according to the output of the wind farm, so that the combined output power can be as planned output. When evaluating member risks, you can use the relative risk allocation method, covariance risk allocation method, and analytic hierarchy process. After evaluating the risk values of each participant, you must further normalize it to facilitate comparison and subsequent calculation.

The indicators of the partner’s risk-bearing capacity are:

\[
M_{R_i} = \frac{R_i}{\sum_{i=1}^{n} R_i}, n = 1,2
\]  

(8)

Where \( R_i (i = 1,2) \) represents the risk degree rating result of member \( i \); where 1, 2 represent wind farms and pumped storage power stations.

(2) Resource utilization index ( \( M_{U_i} \))

The average annual equipment utilization rate of different power sources is different. Therefore, resource utilization is also an important indicator:

\[
M_{U_i} = \frac{U_i}{\sum_{i=1}^{n} U_i}, n = 1,2
\]  

(9)

Where \( U_i (i = 1,2) \) represents the resource utilization of member \( i \).

(3) Indicators of input resources ( \( M_{P_i} \))

The indicator of the degree of resources invested indicates the amount of resources invested by the participants in the alliance. The resource investment index is:

\[
M_{P_i} = \frac{P_i}{\sum_{i=1}^{n} P_i}, n = 1,2
\]  

(10)

Where \( P_i (i = 1,2) \) represents the resource input of member \( i \).

3. Determination of Evaluation Index Weight

After constructing the benefit allocation model, it is necessary to adopt a reasonable method to obtain the importance of each evaluation index. In the current research, the main methods for determining weights are AHP, Fuzzy Analytical Hierarchy Process (FAHP), expert evaluation method, Delphi survey method, entropy weight method, etc. Because AHP has certain defects in practical applications, such as the consistency test of the judgment matrix is very difficult, the expert evaluation method has a certain subjective tendency, the Delphi survey method is complicated in price comparison, and takes a long time. Decision maker’s subjective intentions. FAHP is a method that combines the advantages of the fuzzy method and the analytic hierarchy process, but in the process of constructing the fuzzy judgment matrix, subjective evaluation has a greater influence, so this paper uses an improved fuzzy analytic hierarchy process to solve the weights of each factor size.

4. Example Application and Analysis

4.1. Calculation of evaluation index weight

According to the wind power-pumped storage combined daily operation optimization scheduling model mentioned in reference [6], the factors such as the start and stop of the pumped storage unit and the limitation of operating conditions are considered, and the start and stop costs of the generator set in the pumped storage power station and the penalty for deviation from the output plan maximizes the
benefits of the combined operation of wind power and pumped storage. According to the 0.1-0.9 five-scale method, the fuzzy judgment matrix $R$ is obtained as:

$$
R = \begin{bmatrix}
0.5 & 0.9 & 0.7 \\
0.1 & 0.5 & 0.3 \\
0.3 & 0.7 & 0.5
\end{bmatrix}
$$

(11)

The FAHP model uses MATLAB 2015b for simulation analysis. The algorithm parameters are set as follows: the population size is $N = 30$, $c_1 = c_2 = 2$, $\omega_{max} = 0.9$, $\omega_{min} = 0.4$, $\alpha = 5$, $\beta = 1$, the number of iterations is 500. After calculation, the results are shown in Table 1.

| Weight calculation method | Fuzzy judgment matrix | Weights $\omega$ | Operation hours (s) |
|---------------------------|-----------------------|-----------------|---------------------|
| formula (24)             | $R$                   | $\omega_1 = 0.4335$, $\omega_2 = 0.2332$, $\omega_3 = 0.3332$ | /                   |
| FAHP                     | $R$                   | $\omega_1 = 0.5298$, $\omega_2 = 0.1366$, $\omega_3 = 0.3335$ | 1.124               |

4.2. Improve the profit distribution of the Shapley Value Method

In order to protect the interests of the participants to the greatest extent, considering the factors such as the ability to take risks, the degree of resources invested, and the utilization rate of resources, the various influencing factors are assigned weights and normalized to obtain $M_M = (0.25, 0.75)$, $M_M = (0.34, 0.66)$, $M_M = (0.85, 0.15)$ When $a = (n-1)/2$, according to the improved Shapley value distribution model:

$$
\lambda_i = (M_M, M_M, M_M) \begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} 0.462 \\ 0.538 \end{bmatrix}
$$

(12)

$$
\Delta \lambda_i = \lambda_i - 1/n = \begin{bmatrix} 0.462 \\ 0.538 \end{bmatrix} - \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix} = \begin{bmatrix} -0.038 \\ 0.038 \end{bmatrix}
$$

(13)

$$
\phi_i = \phi_i + V \cdot \Delta \lambda_i = \begin{bmatrix} \frac{3042}{670} \\ \frac{+3712}{811} \end{bmatrix} = \begin{bmatrix} 2901 \\ 811 \end{bmatrix}
$$

(14)

Perform a statistical analysis on the above results and draw a return curve, as shown in Figure 1, where (0-1) indicates that the basic Shapley value method is used to distribute the benefits of the total profit generated by the joint operation, compared to the separate during operation, the respective increased revenue, (1-2) indicates that after the improved Shapley value method is used to distribute the total profit generated by the joint operation, compared with the separate operation, the respective increased revenue:

Figure 1. Curve of income change.
As can be seen from the graph above, the revenue from wind farms and pumped storage power stations has increased. When the basic Shapley value method is used, the added benefits of the two are the same, and the additional benefits obtained from the joint operation are directly divided equally between wind power and hydropower. Obviously, this is unreasonable, but when decision-makers pay more attention to the difference in the importance of the elements as a result of the improved profit distribution, compared with the stand-alone operation, the increased revenue from wind farms was 1.17 million yuan, and the increased revenue from pumped storage power stations was 3.99 million yuan. This distribution not only considers the contribution of participants, but also the results obtained by considering other important factors, making the distribution more reasonable and fairer.

5. CONCLUSIONS
In this paper, the value of risk-bearing capacity, the degree of resource input, and the utilization rate of resources are taken as indicators into the plan of benefit allocation. The weight of each indicator is determined by introducing a comprehensive correction factor and using EGPSO to solve FAHP. Through comparative analysis, we can see that the improved sand the distribution method of the Pulitzer method is more in line with the actual situation and makes the distribution more equitable. In the joint operation of wind power pumped storage, pumped storage power plants can obtain greater profits through joint operation with wind power. The regulation capability of the company is subject to less punishment and a win-win situation, in order to stimulate the enthusiasm of the two to cooperate and form a longer-term cooperation, which plays a good role in the safety of the power grid and the utilization rate of new energy. The energy storage power plant is used as the wind power's rotating reserve, so it also reduces the cost of the power system's rotating reserve due to the randomness of the wind power.

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