Comprehensive Evaluation Method of Virtual Power Plant Based on Hydropower Suppressing Wind Power Fluctuation

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Abstract. In order to assess the effects of the virtual power plants (VPP) participating in power grid regulation, this paper constructs a comprehensive evaluation index system of virtual power plants based on hydropower suppressing wind power fluctuations from three aspects: hydropower regulation ability, grid operation and dispatching, and economy of VPPs. The weight of each index is determined by the combination weighting method based on the entropy weight method (EW) and the analytic hierarchy process (AHP). To verify the rationality and scientificity of the index and the weighting method in this paper, a regional power grid in Fujian has been taken as an example. Three VPP construction schemes including wind farms and small hydropower stations are selected and then the score of each index and total score of each scheme are calculated to determine the optimal scheme. The conclusion indicates that the evaluation index system and method is applied to the VPPs composed of wind power and hydropower and provides a theoretical reference for the construction and planning of VPPs in areas rich in wind and water resources.

1. Introduction
Renewable power sources such as wind and light have become more and more important in China’s energy transition and sustainable development [1]. However, there are still many technical difficulties in large-scale grid connection of renewable energy in China, and the problems of abandoning water, wind and light are serious [2]. The VPP [3-4] integrates various distributed power sources through sophisticated control methods and energy management, and solves the problem of peak shaving and accommodation problems of the power grid caused by the large amount of renewable energy access [5]. Therefore, in order to measure the effect of VPPs participating in grid dispatching, it is necessary to conduct a reasonable and effective comprehensive evaluation of the construction plan of VPPs based on renewable energy.

The current research on the evaluation of VPPs is mainly aimed at using traditional power plants to stabilize wind power fluctuations, and the research on the evaluation indexes of VPPs that are coordinated and complementary to wind and water is imperfect. Ref. [6] established a corresponding index system for the system’s peak and frequency modulation capability from multiple time scales. Ref. [7] constructs an evaluation index system from three aspects of reliability, economy and schedulability, and proposes a method of calculating reliability by constructing a three-state transition
model and state-time sampling simulation. Ref. [8] constructed light-water complementary evaluation indexes including peak regulation insufficient coefficient.

According to the characteristics of VPP resource distribution, this paper proposes an adjustable small water level to suppress wind power fluctuation evaluation method. The rationality of the index system and evaluation method in this paper is verified by an example of a real power grid in Fujian Province. It plays a guiding role in the construction of VPP based on renewable energy.

2. Evaluation Index System of VPP
Based on the influence factors of VPP participating in grid dispatching to suppress wind power fluctuation, evaluation indexes are constructed from three aspects: Hydropower regulation ability, grid operation dispatching and VPP economy. Under the data and index quantitative calculation method, a comprehensive evaluation index system of VPP is proposed, which is shown in figure 1.

![Comprehensive evaluation index system](image1)

**Figure 1.** Comprehensive evaluation index system of VPP.

2.1. Index of Small Hydropower Regulation Capacity

Index 1: regulation coefficient of small hydropower capacity.

The regulation capacity of small hydropower is determined by the regulation coefficient of its storage capacity, which is equal to the regulation capacity of the hydropower station divided by the average annual runoff of the reservoir. The regulation capacity is the reservoir volume between the normal water level and the dead water level, and its expression is as follows:

$$\beta = \frac{V_i}{Q_{av}}$$  \hspace{1cm} (1)

where $V_i$ is the regulating capacity of hydropower station $i$, and $Q_{av}$ is the average annual runoff of the reservoir for many years. According to the reservoir capacity coefficient, the adjustable hydropower station can be classified according to the length of time. The larger the capacity regulation coefficient is, the stronger the regulation capacity is.

Index 2: maximum output of hydropower unit.

The output value of hydropower unit can be calculated according to the optimal regulation model of VPP. The larger the value is, the stronger the regulation ability is.

Indicator 3: Hydropower output time.

In the regulation process, the small hydropower with good regulation performance often requires more output and long regulation time, so the length of hydropower output time is also an index to evaluate the power of hydropower regulation, and the hydropower output time can be obtained according to the hydropower output curve.

Index 4: smoothness of hydropower output curve.

The output smoothness of the hydropower unit can be reflected by the output change of the adjacent time of the hydropower unit, which needs to meet the climbing constraint of the hydropower unit. The smaller the value is, the smoother the hydropower output is and the stronger the regulation and control ability is.
\[
\delta = |P_{G,i}^{-1} - P_{G,i}|
\]  
(2)

where \( P_{G,i} \) and \( P_{G,i}^{-1} \) are the output power of hydropower station \( i \) at time \( t \) and time \( t-1 \) respectively.

Indicator 5: reservoir energy storage rate.

The reservoir energy storage rate is positively related to the adjustable storage capacity of the reservoir in a specific period of time. The larger the value is, the better the hydropower regulation ability is. The reservoir energy storage rate of cascade hydropower stations is expressed as

\[
f_r = \frac{V_i}{V_i^{\text{max}}}
\]  
(3)

where \( V_i \) and \( V_i^{\text{max}} \) are the storage capacity of reservoir \( i \) at time \( t \) and the maximum storage capacity of reservoir \( i \) respectively.

2.2. Index of Grid Operation and Dispatching

Indicator 6: reguleakating p valley difference.

\[
E_{\text{PD}} = \max P_i - \min P_i
\]

\[
P_i = P_{w,i} + P_{h,i}
\]  
(4)

where \( P_{w,i} \) and \( P_{h,i} \) are wind power output and hydropower output at time \( t \), \( P_i \) is VPP output at time \( t \), \( \max P_i \) and \( \min P_i \) are VPP output at peak load and low load respectively.

Indicator 7: wind power absorption rate.

\[
D_{w} = \frac{\sum_{i=1}^{24} P_{w}}{\sum_{i=1}^{24} P_{w} + \sum_{i=1}^{24} P_{h}} \times 100\%
\]  
(5)

The denominator part is the total output of the VPP, and the numerator part is the wind power consumption value.

2.3. Economic Index of VPP

Indicator 8: generation costs of small hydropower stations.

The generation cost \( f_G \) of VPP is the sum of the generation cost of all adjustable small hydropower stations in 24 hours. The expression is as follows:

\[
f_G = \sum_{i=1}^{N} \left( r_i \cdot P_{G,i}^{h} \right)
\]  
(6)

where \( r_i \) is the generation cost of small hydropower unit \( i \) at time \( t \), and it is considered that the generation cost of the same unit at different times is the same, \( P_{G,i}^{h} \) is the output value of small hydropower \( i \) at time \( t \); \( n \) is the total number of hydropower stations.

Indicator 9: network loss cost.

Power grid loss is an important part of power flow calculation, which can directly reflect the economy of power grid operation. The state has clear regulations on the grid loss rate. The construction of VPP can be used as an important evaluation index for the optimization of grid loss. The expression of system loss cost is as follows:
\[ f_{CL} = \sum_{i=1}^{N} C_i \cdot P_{\text{Loss},i} \]
\[ P_{\text{Loss},t} = \sum_{j=1}^{N} V_{i,t} V_{j,t} \left( G_{ij} \cos \theta_{ij,t} + B_{ij} \sin \theta_{ij,t} \right) \]  

(7)

where \( P_{\text{Loss},t} \) is the system network loss corresponding to time \( t \), \( V_{i,t} \) and \( V_{j,t} \) is the voltage of node \( i \) and node \( j \) at time \( t \), \( G_{ij} \) is the conductance of branch \( ij \), \( B_{ij} \) is the reactance of branch \( ij \), and \( \theta_{ij,t} \) is the phase angle difference between voltage of node \( i \) and \( j \) at time \( t \).

3. Virtual Plant Evaluation Methods

Based on the 9 indexes proposed in the previous chapter, the active power optimal scheduling of VPP is evaluated. First, according to the actual operation data of VPP and power grid, the index value is calculated by the index quantitative calculation formula; then, the objective and subjective weights of each index are determined by AHP and EWM respectively; finally, the comprehensive weights of each index are determined.

3.1. EWM

The fundamental idea of EWM to determine the objective weight of an index is: if the data sequence of an attribute has greater variation, the corresponding weight coefficient will be larger [9-10]. The steps of empowerment are as follows:

The first step is to calculate the index output information entropy

\[ E_j = -\frac{1}{\ln n} \sum_{i=1}^{n} Z_{ij} \ln Z_{ij} \]  

(8)

where \( Z_{ij} \) is the contribution of index \( j \) of the project \( i \), and \( n \) is the number of indexes. When \( Z_{ij}=0 \), \( Z_{ij}\ln Z_{ij}=0 \) is specified.

The second step is to calculate the index weight vector \( w=(w_1, w_2, \ldots, w_n) \)

\[ w_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)} \]  

(9)

The calculated entropy weight is the objective weight of the evaluation index got by EWM. Compared with subjective weighting method, entropy weighting method has higher accuracy, stronger objectivity and better adaptability, which can be used together with other weighting methods.

3.2. AHP

AHP is a multi-criteria decision-making method combining qualitative and quantitative analysis, which decomposes relevant elements of decision-making problem into objective, criterion and scheme levels [11]. The steps of weighting are as follows:

The first step is to build a hierarchical analysis structure, which divides the decision-making problem into objective level, index level and criterion level.

The second step is to establish a judgment matrix to judge and compare the relative importance of each index.

The third step is to check the consistency of the judgment matrix

\[ CI = \frac{\lambda_{\max} - n}{n-1} \]  

(10)

where \( \lambda_{\max} \) is the maximum eigenvalue of judgment matrix and \( n \) is the number of eigenvalues of judgment matrix.
When the following formula is satisfied, the judgment matrix is considered to have qualified consistency

\[ CR = \frac{CI}{RI} < 0.1 \]  

(11)

where \( RI \) is the average random consistency index, which can be got by looking up the table, and \( CR \) is the random consistency ratio.

The fourth step is to sort in a single hierarchy. The purpose of hierarchical single ranking is to count the relative importance of each index in the judgment matrix. First, each row element of the judgment matrix is normalized, and then each normalized column is added and divided by \( n \) to get the final weight.

\[ w_u = \frac{1}{n} \sum_{i=1}^{n} C_{uv}, u = 1,2,\ldots,n \]  

(12)

where \( C_{uv} \) is the element in row \( u \) and column \( v \) of the judgment matrix, and \( w_u \) is the weight of the indicator \( u \).

3.3. Combination Weight

In this paper, the decision-making indexes are combined and weighted by the method of multiplication synthesis, that is, firstly, the weight coefficients resolved by the above subjective and objective weighting methods are multiplied correspondingly, and finally, the product is normalized. The specific weighting formula is:

\[ \omega_j = \frac{\alpha_j \times \beta_j}{\sum_{j=1}^{n} \alpha_j \times \beta_j}, \; j = 1,2,\ldots,n \]  

(13)

where \( \omega_j \) is the combined weight of index \( J \), \( \alpha_j \) and \( \beta_j \) are the objective weight and subjective weight of index \( J \) respectively.

3.4. Calculation Flow Chart of Evaluation Index Weight of VPP

The calculation process of VPP evaluation index weights is shown in figure 2.

\[ \text{Figure 2. Weight calculation flow chart.} \]

4. Case Study

In order to verify the scientificity and rationality of the proposed indexes and methods, according to the geographical conditions of Ningde area and the installed situation of wind power (table 1) and
hydropower (table 2), this paper selects the construction scheme of VPP in advance as follows, including four wind farms, namely, Fuying, lvxia, Dajing and Yanting.

In scheme 1, Qinshan, Fengyuan and Zhouning Hydropower Stations are used to build VPPs. In scheme 2, huanglanxi, Houlong primary, Houlong secondary, Shangpei and Wangkeng hydropower stations are selected. In scheme 3, five hydropower stations are selected, i.e. Sangyuan, Houlong class I, Houlong class II, Shangpei and Wangkeng.

| Table 1. Basic information of wind power. |
|------------------------------------------|
| Name | Installed capacity (MW) | Maximum adjustable output (MW) | voltage level (MW) |
| Dajing | 42 | 40 | 110 kV |
| Lucia | 40 | 35 | 110 kV |
| Fuying | 48 | 45 | 110 kV |
| Yanting | 66 | 60 | 110 kV |

| Table 2. Basic information of hydropower. |
|------------------------------------------|
| Serial number | Name | Adjustable capacity (MW) | Installed capacity (MW) |
| 1 | Fengyuan | 10-80 | 80 |
| 2 | ZhouNing | 10-250 | 250 |
| 3 | Qinshan | 10-70 | 70 |
| 4 | Houlong class I | 10-48 | 48 |
| 5 | Houlong class II | 10-40 | 40 |
| 6 | Sangyuan | 8-37 | 37 |
| 7 | Huangxilan | 5-30 | 30 |
| 8 | Wangkeng | 10-40 | 40 |
| 9 | Shangpei | 10-44 | 44 |

In this paper, the form of scoring system is adopted, each index gets a full score of 10 points, according to the results of the index system, and the corresponding index scores are obtained (table 3); combined with the combination of AHP and EWM to solve the total score of the scheme.

| Table 3. Scores of comprehensive evaluation indexes of each scheme. |
|------------------------------------------|
| Hydropower regulation capacity | Power operation and dispatching | grid and economy | Total score |
| Index | Index 1 | Index 2 | Index 3 | Index 4 | Index 5 | Index 6 | Index 7 | Index 8 | Index 9 | |
| Scheme 1 | 4 | 8.7 | 4 | 5 | 8 | 8.1 | 6.9 | 5 | 5 | 5.823 |
| Scheme 2 | 8 | 8 | 6 | 5.4 | 5 | 9.6 | 7.1 | 8 | 5 | 7.129 |
| Scheme 3 | 8.4 | 8 | 6.6 | 7.4 | 5 | 9.5 | 7.6 | 10 | 8 | 8.075 |
| Combination weight | 0.148 | 0.078 | 0.106 | 0.112 | 0.088 | 0.092 | 0.126 | 0.204 | 0.046 | 0.532 | 0.218 | 0.25 |
From the perspective of index weight, hydropower regulation ability index has the largest weight and relatively strong importance, while power grid operation and dispatching and economic index have relatively weak importance. From the point of view of the scheme score, the number of adjustable hydropower stations selected in scheme 1 is small and the regulation capacity of hydropower stations is not considered, so the scores of various indicators are the lowest. The score of hydropower regulation capacity and economic index of VPP construction in scheme 3 is higher than that in schemes 1 and 2. And the score of operation and dispatching index in scheme 3 is almost the same as that in scheme 2, which is caused by the similarity of the results of hydropower station selection in scheme 3 and scheme 2. According to the total score of comprehensive evaluation, scheme 3 is the best, and the VPP should be constructed in accordance with scheme 3 to achieve the coordination and complementarity of wind power and hydropower.

5. Conclusion

In this paper, considering the regulation ability of hydropower, the operation and dispatching ability of power grid, and the economy of VPP, a comprehensive evaluation index system of VPP is proposed. The evaluation index system can comprehensively reflect the construction of VPP and the dispatching effect of power grid. The weight of each index is determined through combination weight method. The case study verifies the scientificity and rationality of the index and method. The results can provide theoretical basis and guidance for the planning and construction of VPPs in water-rich areas.

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