Regulation Model of Suppressing Wind Power Fluctuation Based on Small Hydropower Virtual Power Plant

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Abstract. Using energy storage power station to suppress wind power fluctuation has large investment and low economic effect. According to the condition that Ningde grid has adjustable small hydropower, two construction schemes of virtual power plant based on adjustable small hydropower is proposed to suppress the power fluctuation of the coastal wind power in Ningde. The objective function of the coordination and optimization regulation model is to minimize the generation cost of the small hydropower units. Based on the cascade hydropower model, the water constraints of the reservoir and output constraints of the hydropower, as well as the constraints of stable operation of power system are considered. A double-layer algorithm based on the branch and bound and the checking and adding method of power flow constraint is used to solve the optimal model. The algorithm proves the validity of the optimal scheduling model and proposes the optimal strategies of the small hydropower. The simulation results show that the virtual power plant using small hydropower to suppress wind power fluctuation can effectively realize friendly access of Ningde wind farm, reduce the operation cost of power grid and achieve low carbon and clean electric power without additional construction investment.

1. Introduction
The development of renewable energy such as wind and light is an important way for energy transition and an important requirement for China’s implementation of sustainable development strategies. However, due to the randomness and fluctuation of wind power and photovoltaic output, it is difficult to connect to power grid on a large scale [1-3]. The “Thirteenth Five-Year Plan” for renewable energy development issued by the China’s National Development and Reform Commission (NDRC) in 2016 proposed the policy of using the complementary characteristics of wind, solar and hydropower to promote the construction of Energy complementary pilot demonstration project in water-rich regions.

China has abundant hydropower resources. As an adjustable and clean power source, hydropower has the advantages of strong regulation ability and fast regulation speed, and can quickly respond to wind power fluctuations. A virtual power plant constructed based on an adjustable hydropower station can integrate various distributed power sources through complex control methods and energy management, and output relatively stable power [4], to achieve coordination of multiple distributed energy power sources Optimized control has better economic and environmental benefits than the traditional use of thermal power or batteries to regulate wind power fluctuations. Compared with the
traditional use of thermal power or batteries to regulate wind power fluctuations, it has better economic and environmental benefits.

Ref. [5] introduced the concept and development direction of virtual power plants; Ref. [6] studied the coordination and coordination of multiple distributed power sources in the virtual power plant and the analysis methods of economic benefits; Ref. [7] constructed a two-stage economic dispatch model that takes into account the aggregation characteristics of the virtual power plant. First determine the total output of the virtual power plant including wind power and thermal power units, and then reallocate the output of each unit in the virtual power plant; Ref. [8] constructed a virtual power plant economic optimal dispatching model based on time-of-use electricity price. This model is based on the time-of-use electricity price of a virtual power plant operation strategy, aiming to maximize the profit per unit of time and use particle swarm optimization algorithm to solve the output of various distributed power sources; Ref. [9] considers the water abandonment of cascade hydropower stations. Establishes an optimal dispatching model based on wind, light, and water virtual power plants, and realizes coordinated and optimal dispatching of electric energy from multiple regions and types of clean energy power generation units.

Drawing on the research results mentioned above, this paper proposes to build a virtual power plant based on Ningde’s adjustable small hydropower to calm the power fluctuations of coastal wind farms in order to improve the impact of wind power fluctuations on the power quality of Ningde Power Grid. Ultimately improve the economics and stability of Ningde Power Grid operation.

2. Initially Determine the Construction

There are four wind farms including Fuying, Luxia, Dajing, and Yanting along the eastern coast of Ningde. Small hydropower is mainly distributed in the western mountainous regions, of which more than a dozen have the ability to adjust daily and monthly.

2.1. Principles for Selecting Small Adjustable Hydropower Stations

The principles for selecting small adjustable hydropower stations to build a virtual power plant are as follows:

Principle 1: Economics. The larger the installed capacity of small hydropower, the lower the cost of power generation and the better the economy.

Principle 2: Technicality. Small hydropower with strong regulation ability can reduce the amount of abandoned water to a certain extent, and the control cost is also low.

Principle 3: Security. The shorter the distance between the hydropower station and the load, the easier it is to realize the transmission of electrical energy. It also reduces power grid losses and improves power grid security. Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

2.2. Scheme for Virtual Power Plant Construction

After analysis and comparison, two construction schemes are proposed.

Scheme 1: According to the installed capacity of small hydropower stations and transmission line transmission capacity, the hydropower stations with larger installed capacity and closer to the load are preferentially selected. Scheme 1 builds a virtual power plant with Qinshan, Fengyuan, and Zhouning hydropower stations.

Scheme 2: According to the regulation capacity of the small hydropower station and the transmission capacity of the line, the hydropower station with annual regulation and seasonal regulation capability and close to the load is preferred. Scheme 2 includes five hydropower stations: Huanglanxi, Houlong I, Houlong II, Shangpei, and Wangkeng.
3. Scheme Optimization Model

3.1. Objective Function
The objective function of the virtual power plant regulation is that the cost of small hydropower generation is the smallest, and power generation cost is the sum of the daily power generation costs of all small hydropower stations. The expression is:

\[ \min F = f_{\text{cost}} = \sum_{i=1}^{N} \sum_{t=1}^{24} \left( r_i \cdot P_{G,i,t} \right) \]  

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; \( P_{G,i,t} \) is the output value of small hydropower \( i \) at time \( t \); \( N \) is the total number of hydropower stations.

3.2. Restrictions

3.2.1. Water Constraints. (1) Constraints of Water flow: For the cascade relationship that may exist between hydropower stations, the water balance constraint expression is

\[ V_{i,t+1} = V_i + (Q_{o,i} - Q_{i,t}) \times 3600 \]  

where, \( V_{i,t} \) and \( V_i \) are the storage capacity of reservoir \( i \) at time \( t + 1 \) and time \( t \); \( Q_{o,i} \) and \( Q_{i,t} \) are the inflow and outflow of the hydropower station.

(2) Constraints of hydropower station flow:

\[ Q_{i,t}^{\text{min}} \leq Q_{i,t} \leq Q_{i,t}^{\text{max}} \]  

where, \( Q_{i,t}^{\text{min}} \) is the minimum amount of passing water required by hydropower station \( i \) during the dispatch period, and \( Q_{i,t}^{\text{max}} \) is the maximum amount of passing water required by hydropower station \( i \) during the dispatch period.

(3) Constraints of reservoir storage:

\[ V_{i,t}^{\text{min}} \leq V_{i,t} \leq V_{i,t}^{\text{max}} \]  

where \( V_{i,t}^{\text{min}} \) and \( V_{i,t}^{\text{max}} \) represent the minimum and maximum water storage required by reservoir \( i \) during the operation period.

3.2.2. Operational Constraints. (4) Constraints of node voltage:

\[ V_{i,t}^{\text{min}} \leq V_{i,t} \leq V_{i,t}^{\text{max}} \]  

where, \( V_{i,t}^{\text{min}} \) and \( V_{i,t}^{\text{max}} \) respectively represent the minimum voltage amplitude value and the maximum voltage amplitude value of node \( i \) at time \( t \).

(5) Constraints of branch flow:

\[ |P_{ij,t}| \leq P_{ij,t}^{\text{max}} \]  

where, \( P_{ij,t} \) is the transmission power of the branch between nodes \( i \) and \( j \) at time \( t \); \( P_{ij,t}^{\text{max}} \) is the maximum transmission power of the branch between nodes \( i \) and \( j \) at time \( t \).

The expression of the active branch flow of the line (ignoring the effect of parallel lines) is:
(6) Constraints of system power balance:

\[
P_{ij} = V_i \cdot V_j \cdot \left(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}\right) - V_i^2 G_i
\]  

(7) Hydropower output constraints: The upper and lower limits of the hydropower unit power constraints are:

\[
P_{G,j}^{\text{min}} \leq P_{G,j}^t \leq P_{G,j}^{\text{max}}
\]

\[
Q_{G,j}^{\text{min}} \leq Q_{G,j}^t \leq Q_{G,j}^{\text{max}}
\]

(10)

where, \(P_{G,j}^{\text{min}}\) and \(P_{G,j}^{\text{max}}\) are the lower and upper limits of the active power of the hydropower unit \(i\) at time \(t\), \(Q_{G,j}^{\text{min}}\) and \(Q_{G,j}^{\text{max}}\) is the lower and upper limit of the reactive power of the hydropower unit \(i\) at time \(t\).

(8) Constraints of unit climbing and landslide:

\[
P_{G,j}^{t-1} - P_{G,j}^t \leq \sigma_1 T_{60}
\]

\[
P_{G,j}^t - P_{G,j}^{t-1} \leq \sigma_2 T_{60}
\]

(11)

where, \(\sigma_1\) and \(\sigma_2\) respectively represent the landslide rate and climb rate of unit \(i\), \(T_{60}\) is a continuous operation cycle, this paper takes one hour as a cycle.

4. Scheme Optimization Algorithm

4.1. Branch and Bound Algorithm

The branch and bound algorithm is used to solve the model without considering the branch flow constraints. Specific steps are as follows:

Step 1. Solve the corresponding relaxation problem without considering the integer constraints of the original problem;

Step 2. If the optimal solution is an integer, it is directly output; otherwise, choose a variable \(x\) that does not meet the integer requirements, set its value to \(z\), and discuss the optimal conditions under the constraints of A and B, respectively;

Step 3. If the optimal solution of the sub-problem satisfies the integer condition, an integer solution \(B_2\) of the sub-problem is obtained, and the smallest integer solution \(B_1\) in the branching process is the upper bound \(B_{up}\). If the optimal solution of the sub-problem does not satisfy the integer condition, then the relaxed solution \(B_2\) of the sub-problem is obtained, and the largest relaxed solution \(B_2\) in the branching process is the lower bound \(B_{down}\);
Step 4. When the upper and lower bounds coincide or the relative gap satisfies the convergence accuracy, the result can be output.

4.2. **Power Flow Constraint Check Addition Method**
In order to reduce the complexity of the model and algorithm, this paper uses the “check-add” method to solve network security constraints. Specific steps are as follows:

Step 1. Ignore the line power flow constraints and solve the optimization model to get a set of solutions;

Step 2. For this set of solutions, load flow safety verification is performed, and add the lines that fail the security check as constraints to the optimization model to obtain a new solution;

Step 3. If the new solution fails to meet the security check, then add the new constraints that fail the security check to the optimization model, then solve and perform the power flow security check, and continue to check-add until the obtained solution meets all safety verification stops.

4.3. **Double-layer Algorithm Flowchart**
The flow of the two-layer algorithm based on Branch and Bound Algorithm and Power Flow Constraint Check Addition Method proposed in this paper is shown in figure 1. Although the solution time is slightly longer than the single-layer algorithm, the solution time for small and medium-sized power grids is much lower than the control time, which is suitable for the study of optimal dispatch of virtual power plants.

![Flow chart of the double-layer algorithm.](image)

Figure 1. Flow chart of the double-layer algorithm.

5. **Case Study**
For the two preliminary selection schemes, the optimal scheme is determined by solving the hydropower station’s optimal dispatching scheme and power generation cost and making a comparative analysis. The calculation example is based on a typical scenario of Ningde Power Grid. The basic information of wind power and small hydropower are shown in tables 1 and 2. The output curves of wind power are shown in figure 2.
Figure 2. Wind power output in typical scenario.

Table 1. Basic information of wind power.

| Serial number | Name   | Installed capacity (MW) | Maximum adjustable output (MW) | Maximum adjustable output (MW) | Access system voltage level (kV) | Scheduling relationship     |
|---------------|--------|-------------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------|
| 1             | Dajing | 42                      | 40                              | 2×20                            | 110                             | Provincial dispatching      |
| 2             | Lucia  | 40                      | 35                              | 2×20                            | 110                             | Provincial dispatching      |
| 3             | Fuying | 48                      | 45                              | 2×24                            | 110                             | Provincial dispatching      |
| 4             | Yanting| 66                      | 60                              | 2×33                            | 110                             | Provincial dispatching      |

Table 2. Basic information of hydropower.

| Serial number | Name | Installed capacity (MW) | Maximum adjustable output (MW) |
|---------------|------|-------------------------|--------------------------------|
| 1             | Dajing | 42                      | 40                             |
| 2             | Lucia  | 40                      | 35                             |
| 3             | Fuying | 48                      | 45                             |
| 4             | Yanting| 66                      | 60                             |

5.1. Optimal Scheduling Scheme for Two Construction Schemes

5.1.1. Optimized Scheduling Scheme for Scheme 1. The output curve of scheme 1 obtained by simulation calculation is shown in table 3. The three hydropower stations in Option 1 quickly adjusted the output to respond to wind power fluctuations at 3-5 o’clock and 19-21 o’clock. Because the installed capacity and basic data of the three hydropower stations are similar, with the increase of wind power output, the output of the hydropower station tends to be consistent after 12:00.

Table 3. Strategies of each hydropower in scheme 1.

| Time (h) | Fengyuan (MW) | Zhouning (MW) | Qinshan (MW) |
|----------|---------------|---------------|--------------|
| 1        | 35            | 50            | 31           |
| 2        | 34            | 45            | 30           |
| 3        | 33            | 25            | 24           |
| 4        | 29            | 30            | 26           |
| 5        | 33            | 30            | 30           |
| 6        | 34            | 30            | 30           |
| 7        | 35            | 30            | 31           |
| 8        | 34            | 30            | 30           |
| 9        | 34            | 30            | 30           |
| 10       | 33            | 30            | 30           |
| 11       | 33            | 30            | 30           |
| 12       | 31            | 30            | 28           |

| Time (h) | Fengyuan (MW) | Zhouning (MW) | Qinshan (MW) |
|----------|---------------|---------------|--------------|
| 13       | 15            | 14            | 16           |
| 14       | 15            | 15            | 16           |
| 15       | 12            | 12            | 17           |
| 16       | 14            | 12            | 18           |
| 17       | 16            | 18            | 19           |
| 18       | 9             | 9             | 20           |
| 19       | 6             | 9             | 21           |
| 20       | 6             | 9             | 21           |
| 21       | 17            | 17            | 19           |
| 22       | 18            | 19            | 22           |
| 23       | 18            | 19            | 22           |
| 24       | 19            | 21            | 21           |
5.1.2. Optimized Scheduling Scheme for Scheme 2. The output curve of scheme 2 is shown in table 4. Houlong I, Shangpei, and Wangkeng Hydropower Stations maintained stable output in the early stages and were in full power. After 12 o’clock, the output decreased with the increase of wind power; Houlong II Hydropower Station had more output and a large change; Lanxi Hydropower Station has the smallest output and strong fluctuation. This shows that the Shangpei, Houlong I, and the Wangkeng hydropower stations have the strongest control ability, Houlong II are relatively weak, and the Huanglanxi power station have the weakest control ability.

Table 4. Strategies of each hydropower in scheme 2.

| Time(h) | Huangxilan(MW) | Houlong II (MW) | Houlong I (MW) | Shangpei (MW) | Wangkeng (MW) |
|---------|----------------|-----------------|----------------|---------------|---------------|
| 1       | 10             | 40              | 42             | 44            | 40            |
| 2       | 0              | 45              | 42             | 44            | 40            |
| 3       | 1              | 34              | 42             | 44            | 40            |
| 4       | 2              | 26              | 42             | 44            | 40            |
| 5       | 1              | 25              | 42             | 44            | 40            |
| 6       | 1              | 30              | 42             | 44            | 40            |
| 7       | 8              | 40              | 42             | 44            | 40            |
| 8       | 1              | 49              | 42             | 44            | 40            |
| 9       | 2              | 49              | 42             | 44            | 40            |
| 10      | 0              | 49              | 42             | 44            | 40            |
| 11      | 0              | 49              | 42             | 44            | 40            |
| 12      | 1              | 49              | 42             | 44            | 40            |

5.2. Comparative Analysis of Schemes
The costs of small hydropower generation under the two virtual power plant construction schemes and without the virtual power plant scheme are shown in table 5.

Table 5. Optimization values of the schemes.

| Scheme | Without the virtual power plant | Scheme 1 | Scheme 2 |
|--------|---------------------------------|----------|----------|
| Power generation cost (CNY) | 513720 | 501516 | 485465 |

It can be seen that under the same conditions, the costs of small hydropower generation under the control of two virtual power plant schemes are better than those without virtual power plants. On the premise of ensuring the safe and stable operation of the power grid, the economic efficiency of the operation can be improved.

Comparing the scheduling schemes of the two virtual power plants, the scheduling scheme 2 has the lowest power generation cost and the objective function is optimal. Priority should be given to the hydropower station’s regulation capacity and line transmission capacity to construct a virtual power plant to calm the wind power fluctuations.

6. Conclusion
Based on the Ningde area, this paper proposes a virtual power plant construction scheme and optimized regulation model based on adjustable small hydropower to regulate wind power output fluctuations. An example validates the effectiveness and practicability of the proposed scheme and model. The results show that the virtual power plant can be effective Integrate different types of distributed power sources in multiple regions to achieve coordinated and optimized scheduling of wind power and small hydropower, reduce the cost of power generation in the power grid, and It can be implemented in water-rich regions.
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