Scheduling Analysis of Coordinated Operation of Wind and Hydro Power Considering Electricity Price

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Abstract. Due to the randomness and intermittency of wind power, the accurate planning and dispatching of power generation is hindered. Hydro power has a certain ability to regulate, the coordination between wind farms and hydro power plants may be mutually beneficial. Wind power and hydro power collaborative optimization operation model considering the ladder electricity price is established, and the chaotic particle swarm optimization (CPSO) algorithm is used to solve the model. A case study is used to verify the reliability of the model and the feasibility of coordination strategy.

Introduction

The coordinated operation of wind power and hydro power has been studied in different aspects. Literature [1] provided a comprehensive literature review of coordinated operation of wind power and hydro power. On the joint scheduling optimization problem: 1)To improve the efficiency of the wind farm and smooth the output power[2]; 2)Consider cost effectiveness[3]; 3)For the purpose of maximizing the benefits of joint operation[4]; These scheduling schemes were based on the optimization purpose, established an optimization model, and created a new algorithm or used commercial software to solve. In the above literature or other literature, there is no proposed that scheduling analysis considering real-time ladder price for the coordinated operation of wind power and hydro power.

This paper aims to maximize the joint profit of wind power and hydro power, proposed an optimization model for the coordinated operation of wind power and hydro power, considering the ladder price, smoothing the output power curve according to the electricity price curve, using chaotic particle swarm optimization algorithm (CPSO), used the Visual Studio 2010 simulation platform to design the interface and solved the optimization model.

Wind Power and Hydro Power Collaborative Optimization Model

Since the operating costs of wind power and hydro power are very low during actual operation, the operating costs of wind power and hydro power are ignored in this paper.

A. Cooperative Operation Strategy

The goal of the coordination strategy is to enable the active output power from the wind farm and the hydro power plant to be controlled, thereby, converts a stochastic power source that is difficult to control into a power source that can be output as planned and reduces the difficulty of dispatching power systems with random power supplies, increases the on-grid price of random power, therefore, it will obtain greater profits and maximize the overall profit of the combined production of hydro power farms and wind farms. In order to respond to the country's requirements for new energy development, reduce the waste of wind resources, and integrate wind power into the grid as much as possible:

\[
\max E_{WH} = E_{WB.net} - F_P - F_{WA}
\]  

(1)
\[ E_{wh.net} = \sum_{i=1}^{96} C'(P'_W + P'_H) \]  

(2)

\[ F_{WA} = \sum_{i=1}^{96} \sum_{j=1}^{m} \omega_j R_{WA} P'_{W,j} \]  

(3)

\[ F_p = \lambda \sum_{i=1}^{96} \left( P'_W + P'_H - \overline{P'_{wh}} \right)^2 \]  

(4)

s.t. \[ P_{\text{min}} \leq P'_W + P'_H \leq P_{\text{max}} \]  

(5)

\[ P'_{H_{\text{min}},j} \leq P'_{H,j} \leq P'_{H_{\text{max}},j} \]  

(6)

\[ Q_{\text{min},i} \leq \sum_{i=1}^{96} Q'_j \leq Q_{\text{max},i} \]  

(7)

\[ 0 \leq P'_W \leq P'_W \]  

(8)

Where, \( E_{wh} \) is the benefits from the coordinated operation of wind power and hydro power; \( F_p \) is the punish for smooth power output; \( \lambda \) is the fluctuation penalty coefficient; \( l \) represents the segments under different price; \( F_{WA} \) is abandoned wind regulation; \( F_{wh.net} \) is electricity sales income for the coordinated operation of wind power and hydro power; \( C' \) is on-grid price at time \( t \); \( P'_W \) is the output of wind power; \( P'_H \) is the output of hydro power; \( \omega_j \) is the proportion of abandoned wind for wind farm \( j \); \( R_{WA} \) is the abandonment wind adjustment factor; \( \overline{P'_{wh}} \) indicates the average power of wind power and hydro power complementary at different electricity prices; \( Q_{\text{max},i}, Q_{\text{min},i} \) are the maximum and minimum water consumption of hydro power station \( i \); \( P_{\text{max}}, P_{\text{min}} \) are determined by the power generators and grid operators by considering various factors, such as wind farm capacity and hydro farm capacity constraints; \( P'_W \) is wind farm installed capacity.

B. Other Constraints

1) Power balance constraint

\[ P_{W,j} + P_{H,j} = P_{D,j} \]  

(9)

\( P_{W,j} \) is the output power of hydro power plant; \( P_{H,j} \) is the regulated power of hydro power plant; \( P_{D,j} \) is the power inputted to the grid.

2) Rotational reserve constraint for complementary systems

To solve the problem of wind forecasting error, hydro power unit commits rotation reserve for the system.

\[ \sum_{i=1}^{n} P_{U,i} \geq \beta (P_{W_{\text{max}}} - P'_{W}) \]  

(10)

\[ \sum_{i=1}^{n} P_{D,i} \geq \gamma (P_{W} - P_{W_{\text{min}}}) \]

Where, \( P_{U,i}, P_{D,i} \) are the positive and negative rotating reserve capacity that hydro power units can provide; \( \beta, \gamma \) are the demand coefficient for positive and negative rotation reserve of wind farm;
$P_{W_{\max}}$, $P_{W_{\min}}$ indicate the maximum and minimum wind outputs under a certain confidence probability; $P_{Wi}$ is wind farm output prediction;

3) Power fluctuation limits for combined operating units

GB/T 19963-2011 Wind Farm Access to Power System Technical Regulations explains that the maximum limit active power change for a wind power with installed capacity greater than 150MW in 10 minutes. In order to make the wind power and hydro power coordinated operation system meets the national standard, this paper stipulates that the active power fluctuation is less than 50MW within 15 minutes.

$$-50 \leq \{(P_{W_{t}}^{i} + P_{H_{t}}^{i}) - (P_{W_{t-1}}^{i} - P_{H_{t-1}}^{i})\} \leq 50$$ (11)

Optimization Solution

In order to solve the problem that PSO is easy to fall into local optimum, the chaos optimization algorithm is introduced into the initial stage of the algorithm and the later stage of the search. Chaotic motion has the characteristics of randomness, ergodicity and "regularity", therefore, chaotic variables can traverse all the states according to their own "rules" and not repeat within a certain range, the search is forced to jump out of the local minimum, and finally achieve the global best.

In the chaotic particle swarm optimization algorithm, a cubic mapping is used to generate chaotic sequences, as follows:

$$z(t+1) = 4z(t)^3 - 3z(t) \quad -1 < z(0) < 1, t = 0,1,2,...$$ (12)

This mapping has a zero point in the interval $[-1,1]$, as long as the initial value of iteration is not zero, chaos will occur.

Performs chaotic operations on the initial generated particle swarm to randomly generate an n-dimensional chaotic vector $Z = (z_1, z_2, ..., z_n)$, $Z_1$ is the initial value, from equation (11), we get $N$ vectors $Z_1, Z_2, ..., Z_N$, iterative search is performed using chaotic variables, according to the objective function equation (1), the fitness value corresponding to each vector is calculated, according to the results, the first $m$ particles are used as the initial particle group, and $m$ initial velocities are randomly generated within the range of power output of each unit. Chaos operation is carried out for particles that are about to fall into the local optimum, the fitness variance is introduced to determine when the particle group is about to fall into a local optimal solution $\sigma^2$:

$$\sigma^2 = \frac{1}{m} \sum_{i=1}^{m} \left( \frac{f_i - f_{avg}}{f} \right)^2$$ (13)

Where, $f = \max_i \max_j |f_i - f_{avg}| \quad i = 1,2,...,m, f$ is normalized scaling factor. When the particle swarm is about to fall into local optimum or global optimal, $\sigma^2$ will tend to 0, but when it converges to local optimal, the change of $\sigma^2$ in continuous iteration is not much different. Therefore, it can be judged that the difference of $\sigma^2$ between two adjacent iterations is less than a given value, whether the particles are going to fall into local optimum. The chaotic sequence is generated by equation (11), and the resulting chaotic particle swarm is transformed into variable space, and sorted and optimized according to its fitness value.

The implementation steps of the optimization algorithm are shown in figure 1.
The Case Analysis of Coordinated Operation

In order to verify the correctness of the reporting strategy and the feasibility of the algorithm with the goal of maximizing the expected revenue of the coordinated operation of wind power and hydro power under the ladder price, as well as the advantages of cooperative operation compared to the independent operation of the power station, this paper analyzes the example based on the actual data, and obtains the optimization result through Visual Studio 2010 programming.

In this paper, the day is the research period. In order to make the calculation result more accurate, the day is divided into 96 periods, and one of which is 15 minutes.

A. The Basic Study of Joint Operation

Assuming that the smooth power coefficient $\lambda$ is 1500, the optimization result of the coordinated operation of the wind farm and the hydro power plant under the ladder price is shown in Figure 2.
Figure 2 shows the optimal declaration plan and joint declaration plan for each power plant when coordinated operation under the ladder price. It can be seen from the figure that at different electricity price levels, the combined output power curve can basically follow the ladder price curve, met the demand law of the load and improved the benefits of the joint operation system, made up for the shortcomings of wind power output fluctuations. At the same time, this is also conducive to the safe and stable operation of the power system. Through the real-time adjustment of the output of the hydro power unit to reduce the deviation between the actual output of the combined power station and its planned output, the system is more stable.

B. Change the Smoothing Power Penalty Coefficient

Assuming that the smooth power coefficient $\lambda$ is 1200, the optimization result of coordinated operation of wind farms and hydro power plants under the ladder price is shown in figure 3:

Compared with figure 2 and figure 3, it is obvious that when the smooth power coefficient is large, the combined output curve is smoother, the fluctuation is smaller, and it is closer to the ladder curve. The results of the calculation of the benefit of the electric field after cooperative operation are shown in table 1:
Table 1. Comparison of optimization results under different penalty coefficients.

<table>
<thead>
<tr>
<th>Smooth coefficient</th>
<th>1200</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind power alone earns revenue $E_w$</td>
<td>9.9427million RMB</td>
<td>7.8562million RMB</td>
</tr>
<tr>
<td>Penalty for wind power operation alone $F_w$</td>
<td>4.397million RMB</td>
<td>6.4835million RMB</td>
</tr>
<tr>
<td>Gain for hydro power operation alone $E_H$</td>
<td>17.1723million RMB</td>
<td>17.1723million RMB</td>
</tr>
<tr>
<td>Gain for coordinated operation $E_{WH}$</td>
<td>30.2308million RMB</td>
<td>29.3188million RMB</td>
</tr>
<tr>
<td>Increased revenue after coordinated operation $E$</td>
<td>3.1158million RMB</td>
<td>4.2903million RMB</td>
</tr>
<tr>
<td>Reduced penalty charges after coordinated operation $F$</td>
<td>2.4117million RMB</td>
<td>3.9844million RMB</td>
</tr>
<tr>
<td>The actual output of wind power $W_w$</td>
<td>20018MWh</td>
<td>20018MWh</td>
</tr>
<tr>
<td>The actual output of hydro power $W_H$</td>
<td>21228.4MWh</td>
<td>20739.03MWh</td>
</tr>
<tr>
<td>Hydro power remaining $W_{sH}$</td>
<td>1514.69MWh</td>
<td>1837.74MWh</td>
</tr>
<tr>
<td>Hydro power resource utilization $L_H$</td>
<td>93.34%</td>
<td>91.86%</td>
</tr>
</tbody>
</table>

The following conclusions can be drawn from the table above: when the smooth power penalty coefficient is large, the income gained from wind power operation alone decreases and the penalty cost increases. Since the hydro power can flexibly adjust the output power of the unit, the gains obtained have not changed. Although the total revenue obtained after the joint operation has decreased, the gains from the joint operation are higher than the total revenues from the independent operation. The reduction in the penalty brought by joint operation is more and more obvious, and less water can be used to make up for wind power to make the output smoother and increase revenue.

**Conclusion**

This paper proposes a coordinated operation strategy for wind power and hydro power based on the ladder price in the electricity market environment, an optimized operation model is established, and finally the optimized scheduling results of the power station in the power market are obtained through calculation. The results of the example show that the joint operation can reduce the fluctuation of output and increase the income of the power plant, it plays an important role in the safe and stable operation of the power system. Both the smooth power penalty factor and the wind power prediction curve will have an impact on the optimal operation results. Hydro power can achieve greater profits through coordinated operation with wind power. Wind power is also gaining more profits due to the adjustment ability of hydro power, achieving a win-win situation, in order to stimulate the enthusiasm of the two cooperation and form a longer-term cooperation. This plays a very good role in the safety of the grid and the use of new energy.

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References


