Multi-power Combined Optimal Dispatch Operation Model Based on Wind-Nuclear Coordination

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Abstract. Multi-power coordinated operation under the background of promoting renewable energy poses new problems and challenges for grid dispatching, the study of the optimization scheduling of wind turbine (WT)-thermal power generator unit (TPGU)-nuclear power plant (NPP)-pumped storage power station (PSPS) has great significance. We propose a combined mode of WT and NPP, NPP adopts the operation mode of "12-3-6-3". When NPP operates in a fixed manner, WT outputs as much as possible, the task of peak-shaving is mainly completed by TPGU and PSPS. The wind power curtailment condition will only happen in the case of absence of peak shaving capacity. Taking the effects of the uncertainty of wind power, the operation mode of NPP and PSPS into account, and a scheduling model was established which the objective functions are both the maximum capacity of wind power consumption and the minimum system costs. The particle swarm algorithm was used to solve this model. We used the power network dispatching date of Chinese province to verify the effectiveness of the model. The result shows it can reduce the purchase cost of the grid and improve the ability of wind power consumption.

1. Introduction
As the proportion of clean energy in the power system gradually increases, it is more and more difficult for the power grid to complete peak regulation tasks while taking full advantage of the large-scale clean energy. An effective solution is to establish an optimized multi-power scheduling operation mode [1].

Traditional multi-power scheduling research focused on dispatching TPGUs [2, 3], the study of the optimization scheduling of WT-TPGU-NPP-PSPS is immaturity [4-7]. For safety and economy reasons, most NPPs operate at full capacity [8]. Some countries have proposed that NPPs can participate in the daily peak load regulation [9] with the way of "12-3-6-3", its major idea is to match the NPP with the daily load [5, 7, 9]. The integration of large-scale wind power has increased the power system’s load peak-valley difference, and even threatens its safe and stable operation. By increasing reserve capacity, the impact of wind power’s uncertainties can be reduced [10]. NPP has larger peak regulation capacity and peak shaving depth. When the NPP operates in coordination with the WT, it will remedy shortcomings of wind power: In the period of less wind power output, the NPP is running at full capacity to avoid the overturning of the conventional units. In the period of more wind power output, NPP is running at 67% of its nominal power, which can enlarger the ability of wind power consumption.
Based on the existing research results, this paper analyzes the coordinated operation of wind power and nuclear power, and on this basis, established a combined operation scheduling model of wind power, thermal power, nuclear power and pumped storage. Moreover, simulations show that the proposed model can reduce the purchase cost of the grid and improve the ability of wind power consumption.

2. Wind-Nuclear coordination

2.1. Wind power output characteristics

Analysis the Total Output of wind power in a Certain Province in China, it can be seen that wind power output has typical characteristics: intermittency, volatility and randomness [11-14]. As shown in Fig.1, from its typical sunrise power curve in January 2015, the period of less wind power output is from 8:00am to 14:00pm, while the period of more wind power output is from 21:00pm to 3:00am, so wind power has obvious anti-peaking characteristics.

![Figure 1. Typical day output curve of wind power in January.](image)

2.2. The coordinated operation of WT and NPP

It can be seen from Fig.1 that during the day, the wind power has a larger output period and a smaller output period. In the conventional NPP output method of "12-3-6-3", the output power can also be adjusted. If wind-nuclear coordination is running in the power system, the NPPs can make up for the shortcomings of WTs output.

The actual significance of wind-nuclear coordination is the macroscopic plan of the grid under a certain operation cycle. The object of nuclear power output matching is the output trend of wind power in this cycle. As long as the wind-nuclear coordination can improve the system's ability to absorb wind power in a certain period, it will be positive for the operation of the new energy grid.

In a specific scenario of wind power, the steps for obtaining the wind-nuclear coordination method are as follows:

1) Extraction of the maximum forecast output of wind power
   The dispatching department of the grid can read the wind power forecast data directly from the wind farm. In view of the accuracy of the wind power forecasting and the safety and rationality of the schedule, the forecast results of the next 7 days are generally selected.

2) Seeking the typical wind power output curve
   Based on the forecast value of wind power output, the formula for calculating the typical output curve by the weighted average method is as follows [15]:

$$p_i = \frac{1}{7} \sum_{n=1}^{7} P_{ni} (i = 1, 2, \ldots, 96)$$  \hspace{1cm} (1)
Where: $p_i$ denotes wind farm’s typical forecast output value at i moment in 7 days; $p_m$ is the wind farm’s predicted output value at i moment in the first n days i in the n day.

3) Using Pearson coefficient to determine the best match between wind power and nuclear power

The Pearson coefficient is a linear correlation coefficient that reflects the linear correlation between two variables. In this paper, the Pearson coefficient is used to determine the best linear matching method [16] for predicting the typical output of wind power and nuclear power output. The predicted typical wind power output curve obtained in step 2 is a definite time sequence, and the nuclear power can be divided into 96 different time series according to different starting times of full power operation according to the operation mode of "12-3-6-3" (One day divided by 15min intervals). The Pearson correlation coefficient matching the nuclear power sequences (96) respectively is calculated, and the nuclear sequence corresponding to the minimum Pearson correlation coefficient is obtained as the best matching sequence (the larger the Pearson correlation coefficient indicates the positive correlation between two variables, however, the matching method in this paper needs to make two variables negatively correlated, so take the smallest Pearson coefficient.)

Pearson correlation coefficient is calculated as follows:

$$r = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{\sqrt{N \sum x_i^2 - \left(\sum x_i\right)^2} \sqrt{N \sum y_i^2 - \left(\sum y_i\right)^2}}$$ \hspace{1cm} (2)

Where: $r$ is Pearson correlation coefficient; $N$ denotes the number of sequence samples, this paper is 96; $x_i$, $y_i$ are time series sequences, this paper takes the typical output value of wind power and nuclear power output value.

3. Multi-power scheduling operation model

3.1. The objective function

The objective function of multi-power combined optimal scheduling model based on wind-nuclear coordinated operation is composed of two parts: the lowest cost of grid purchase and the largest of wind power consumption.

3.1.1 Purchase the lowest cost. Most of the literature has the lowest operating cost of the system and the least fuel consumption as the optimization objective, while less considering the economics of grid dispatching. In this paper, the least cost of grid dispatching and the maximization of grid income are taken as objective functions.

$$\max F_a = \sum_{t=1}^{T} \tau \left[ k_i \cdot P_{i,t} - \sum_{i=1}^{N_{G}} k_i \cdot P_{i,t} \right]$$ \hspace{1cm} (3)

Where: $\tau$ is the interval that system reads the power unit output(such as the system reads the output per 15min, then $\tau = \frac{1}{4}$ ); $N_{G}$ denotes total number of all generating units in the area, including TPGUs, NPPs, WTs and PSPSs. $k_i$ is the sale price at t moment for the grid, $P_{i,t}$ is the electric power at t moment, $k_i$ denotes the purchase price, $P_{i,t}$ is the output power at t moment.
3.1.2 The largest wind power consumption. Multi-power scheduling considers maximum wind power consumption:

\[
\max F_{\text{wind}} = \sum_{i=1}^{T} \sum_{j=1}^{N_{\text{wind}}} P_{w,j}
\]  

Where \( N_{\text{wind}} \) is the total number of wind turbines in the region, \( P_{w,j} \) is the output that WTs plan to contribute.

3.1.3 Determination of the total objective function. The total objective function of the multi-power scheduling model is as follows:

\[
\max F = \alpha F_a + \beta \cdot \lambda F_{\text{wind}}
\]  

Where: \( \alpha \) and \( \beta \) are weight coefficient for total objective function; \( \lambda \) is multiple order of magnitudes. Due to different dimensions between \( F_a \) (yuan) and \( F_{\text{wind}} \) (MW), in order to deal with a target function in unity, this article needs \( F_{\text{wind}} \) ’s magnitude 100 times, so \( \lambda = 100 \) (When the unit of electricity price is calculated according to Yuan / MW, \( F_a \) ’s magnitude 100 times for \( F_{\text{wind}} \)).

When using weighted method to solve multi-objective optimization problem, in order to overcome the subjective influence of artificial assignment of weights, this paper uses AHP method to calculate the weight of each objective, weighting coefficient \( \alpha \) with \( \beta \), the calculation process is as follows:

1) Establish a hierarchical model, the model shown in Figure 2.

2) Construct ZC judgment matrix
Judgment matrix A can obtain the weight of each factor in criterion C:
Where: $a_{ij}$ indicates the ratio of the judgmental value of the influential factors of the criterion layer ($i$ is 1, 2, and 3, respectively representing economic, energy-saving and policy-oriented); $a_{i2}$ is the economic judgment value is more than the pollution judgment value, and the judgment value is decided according to the important degree of the influencing factors. The matrix $A$ passes the consistency check, and the eigenvector corresponding to the largest eigenvalue is:

$$w_1 = (0.1094, 0.3090, 0.5816)$$

3) Construct the C-P judgment matrix $B$ and find the rank order

The judgment matrix $B$ is constructed in the same way as $A$, namely, the two factors of the measure layer respectively construct the judgment matrix according to the three factors of the criterion layer as follows:

$$B_1 = \begin{bmatrix} 1 & 1 \\ 3 & 1 \\ 5 & 2 \end{bmatrix}, B_2 = \begin{bmatrix} 1 & 1 \\ 3 & 3 \\ 1 & 1 \end{bmatrix}, B_3 = \begin{bmatrix} 1 & 3 \\ 3 & 3 \\ 1 & 1 \end{bmatrix}$$

The matrix $B_1, B_2, B_3$ all pass the consistency check, and the eigenvectors corresponding to the largest eigenvalues of the three matrices are arranged in a column:

$$w_2 = \begin{bmatrix} 0.2499 & 0.7501 & 0.7501 \\ 0.7501 & 0.2499 & 0.2499 \end{bmatrix}$$

Construct ZP matrix and find the total order of hierarchy and decision-making results

$$w = w_2w_1^T = \begin{bmatrix} 0.6954 \\ 0.3046 \end{bmatrix}$$

So the values of $\alpha, \beta$ are 0.6954 and 0.3046.

3.2. Constraints

Constraints include power balance constraints, output constraints, climbing constraints and system reserve constraints.

3.2.1 Power Balance Constraints.

$$\sum_{k=1}^{N_m} P_{H,k} + \sum_{j=1}^{N_d} P_{w,j} + \sum_{l=1}^{N_u} P_{u,l} + \sum_{m=1}^{N_c} P_{c,m} = P_{load}$$

Where: $N_H$, $N_{\text{wind}}$, $N_{\text{unclear}}$, $N_c$ mean the total number of thermal power units, wind power units, nuclear power units and pumped storage units in the region, mean respectively, $P_{H,k}$, $P_{w,j}$, $P_{n,l}$, $P_{c,m}$ denote the thermal power, wind power, nuclear power and pumped storage unit output at $t$ moment, respectively. $P_{\text{load}}$ is the total amount of electrical load required at $t$ moment. Considering the coordination of wind and nuclear operation, the output of nuclear power units is determined by section 2.2.

3.2.2 Output constraints.
1) Wind turbine output constraints
   Wind turbine output constraints consider the following [9]:
   ① The wind power project has to contribute less than the wind farm installed capacity:
   \[
   0 \leq P_{w,j} \leq W_{\text{max}}
   \]  
   Where: $W_{\text{max}}$ is the installed capacity.
   ② Allowed to abandon the wind, but can not exceed the expected average wind power. Abandoned wind volume with the predicted average and actual output value of the difference that:
   \[
   0 \leq \Delta P_{w,j} \leq P_{\text{fore}}
   \]  
   \[
   \Delta P_{w,j} = P_{\text{fore}} - P_{w,j}
   \]
   ③ Due to the uncertainty of wind power output, the introduction of probability constraints:
   \[
   \Pr\{P_{w,j} \leq W_j\} \geq \rho
   \]  
   Where $\Pr\{\}$ denotes occurrence probability of the incident $\{\}$, $\rho$ is the confidence level; $W_j$ is the maximum allowable real power output for wind power, it is a random variable, which is expressed as Beta distribution.
   Beta distribution of the cumulative probability distribution function is:
   \[
   F(x) = \begin{cases} 
   0 & x \leq 0 \\
   \int_0^x u^{-1}(1-u)^{\beta-1} du & 0 < x < 1 \\
   1 & x \geq 1 
   \end{cases}
   \]
   \[
   B(\alpha, \beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1} dx
   \]
   \[
   \alpha = \frac{1 - E(x)}{E(x)D(x)} - E(x)
   \]
\[
\beta = \frac{1-E(x)}{E(x)} \alpha
\]  

(19)

The Beta distribution represents the actual output. According to equation (16) when calculating the actual output, the actual value needs to be converted into a per-unit value. \(E(x)\) and \(D(x)\) are mean and variance respectively. Equation (15) can be derived as:

\[
P_{w,j} \leq W_{\text{max}} \cdot F_{w,j}^{-1}(1-\rho)
\]  

(20)

2) Pumped storage unit output constraints [7]:

\[
\begin{aligned}
\text{electricity generation: } & \quad P_{\text{min}} \leq P_{c,j} \leq P_{\text{max}} \\
\text{pump: } & \quad P'_{\text{min}} \leq P'_{c,j} \leq P'_{\text{max}}
\end{aligned}
\]  

(21)

Where \(P_{\text{min}}\) and \(P_{\text{max}}\) are the minimum and maximum generating power of the pumped storage power station unit; \(P'_{\text{min}}\) and \(P'_{\text{max}}\) are the minimum and maximum pumped storage power station unit.

Upper reservoir water level \(Z\) and water storage \(S\) constraints:

\[
Z_{\text{min}} \leq Z(t) \leq Z_{\text{max}}, t = 1,2, \ldots, T
\]  

(22)

\[
S_{\text{min}} \leq S(t) \leq S_{\text{max}}, t = 1,2, \ldots, T
\]  

(23)

Where: \(Z_{\text{min}}\) and \(Z_{\text{max}}\) are the minimum and maximum water level of the pumped storage power station reservoir; \(S_{\text{min}}\) and \(S_{\text{max}}\) are the minimum and maximum pumped storage power station storage capacity.

Upper reservoir water balance constraint:

\[
S(t) = S(t-1) - \Delta S(P_s(t)), t = 1,2, \ldots, T
\]  

(24)

Where: \(S(t-1)\) and \(S(t)\) are the beginning and the ending of the reservoir storage capacity at \(t\) moment; \(\Delta S(P_s(t))\) is the amount of change of reservoir water storage at \(t\) moment.

3) Thermal power unit output constraints:

\[
P_{\text{H,min}} \leq P_H \leq P_{\text{H,max}}
\]  

(25)

Where: \(P_{\text{H,min}}\) and \(P_{\text{H,max}}\) are the minimum and maximum output of thermal power units.

3.2.3 Climbing constraints. Thermal power unit climbing constraints:

\[
P_{H,\text{down}} \leq \Delta P_H \leq P_{H,\text{up}}
\]  

(26)

Where: \(P_{H,\text{down}}\) and \(P_{H,\text{up}}\) are maximum rate of decline and rise.
3.2.4 System Backup Constraints.

\[
\sum_{k=1}^{N_{s}} P_{H,k,\text{max}} + \sum_{j=1}^{N_{\text{wind}}} P_{w,j,\text{max}} + \sum_{l=1}^{N_{\text{nuclear}}} P_{n,l,\text{max}} + \sum_{m=1}^{N_{\text{c,m}}} P_{c,m,\text{max}} \geq (1+5\%) P_{\text{load}} + 15\% \sum_{j=1}^{N_{\text{wind}}} P_{w,j,\text{max}} \tag{27}
\]

5% and 15% are the load fluctuation standby demand coefficient and the wind power fluctuation standby reserve demand coefficient.

3.3. Model solution method

In this paper, we use the chaos particle swarm optimization algorithm to solve the model [17]. Chaos particle swarm optimization is a combination of chaos optimization and particle swarm optimization. For a given optimization function, the search process corresponds to the chaotic orbit traversal process, which can make the search process avoid the local minimum.

4. Example analysis

In this paper, we design an example to verify multi-power scheduling model based on wind-nuclear coordination mentioned above. It is based on a province of China for seven consecutive days in 2015.

4.1. Example Description

This example extracts wind power data and load data for seven consecutive days in 2015, of which the wind power data includes the predicted output and the actual output data from the wind farm. This example set two kinds of projects. In project 2, NPPs match the load.

4.2. Wind Power Data Analysis

The forecast and actual value of typical output of wind power for 7 consecutive days are shown in the Figure 3:

![Figure 3. The Contrastive data of output power.](image)

As we can see from Figure 3, the forecast curve of the wind farm output for the next 7 days is quite different from the actual curve, however, the wind-nuclear coordination and matching method designed in this paper has a large fault tolerance rate for wind power forecasting. As long as the wind power forecast can describe out of it’s less productive period or contribute to a larger time period to meet the requirements. Obviously, both the predicted curve and the actual curve have smaller wind power output from 6:00 AM to 10:00 AM. A program of nuclear power can be matched according to the wind power forecast.

4.3. Wind power consumption and electricity purchase cost comparison

Wind power consumption comparison results in 7 days for project 1, 2 is shown in Figure 4.
Figure 4. The Contrastive data of wind power consumption.

Table 1. The wind power consumption.

| Total predicted power / (MW * h) | Option One | | Option II |
|----------------------------------|------------|--|------------|
| Consume electricity / (MW*h)    | Consumption ratio% | Consume electricity / (MW*h) | Consumption ratio% |
| 117240                           | 60119      | 51.3 | 57838      | 49.3         |

From Table 1, it can be seen that the wind turbine in project 1 contributes more than it in project 2, about 2%.

For the scheduling costs, Project one save more than Project 2, about 272.8 yuan.

5. Conclusion
This paper designs wind-fire-nuclear-pumped storage operation mode based on wind-nuclear coordination, the main characteristic is wind-nuclear coordination, that NPPs running accordance with the "12-3-6-3" mode, the NPPs’ full power operating period matches wind power less output period, and NPPs’ low-power operation period matches wind power large output period. Wind-nuclear coordination can increase the output of wind turbines, thereby reducing the abandonment of the system. In addition, the model we proposed can reduce the cost of scheduling. Wind-unclarer Coordination will increase the peaking task of TGPUs. This feature may have a potential impact on the safe and stable operation of the power system. This is the follow-up study to be carried out in this paper.

The most important part of multi-power scheduling modeling is wind power output prediction. This paper simplifies the processing. As the research on wind power forecasting achieves progress, the accuracy of the unit combination will also become more and more economically.

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