Optimal dispatch of wind power- photovoltaic- concentrating solar power combined power generation system based on improved PSO

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Abstract. The output power of wind power and photovoltaic is randomness and uncertainty, which brings severe challenges to power generation planning and scheduling of power system. The concentrating solar power (CSP) station with heat storage has the same scheduling as the traditional unit. Through reasonable scheduling of CSP stations, the uncertainty of wind power and photovoltaic power generation can be effectively suppressed, and new energy consumption can be promoted. This paper comprehensively considers the market power sales benefits, grid-connected environmental benefits and system operation and maintenance costs of the wind power-photovoltaic-CSP combined system, a dispatching model is established with the objective of optimizing the grid connected benefits of the combined system. Aiming at the shortcomings of particle swarm optimization (PSO) that is easy to be premature, an improved particle swarm optimization (IPSO) algorithm is formed by adding convergence factor and improving inertia weight to optimize the scheduling model. The results show that the grid connection benefit of the combined system increases by 237784 yuan per day after adding CSP. The convergence speed of the IPSO used in this paper has been greatly improved.

1. Introduction
In recent years, with the rapid development of the global economy and the increasing demand for electricity, the energy crisis and environmental pollution are becoming more and more serious. According to the 13th Five-Year Plan of national power development, in 2020, the installed capacity of wind power in China will reach more than 210 million kilowatts [1]. However, due to the randomness and uncertainty of wind power and photovoltaic, a series of challenges have been brought to the safe and stable operation of power grid, which makes the wind and light abandoned seriously. How to combine wind power, photovoltaic and flexible power generation has become a research hotspot [2-4]. How to make use of the time-shifting characteristics of CSP station to integrate wind power, photovoltaic and CSP joint operation has become one of the research hotspots. Literature [5] established a joint optimal dispatching model for wind power and CSP, and used the good dispatchability and controllability of CSP stations to improve the uncertainty of wind power; Literature [6] established a wind-CSP-thermal-hydropower combined system optimization dispatching model, and suppressed the uncertainty of wind power output by introducing CSP stations; Literature [7] comprehensively considered the power generation cost of thermal power plants, the environmental benefits and operation and maintenance costs of grid-connected CSP stations, and the cost of system...
spinning reserve, and established an economically optimal scheduling model for the combined system; Literature [8], starting from the operating mechanism of the photovoltaic and CSP, a photovoltaic thermal two-stage optimal scheduling model based on improved particle swarm optimization was established. The above literatures mainly focus on the joint scheduling of wind power and photovoltaic, wind power and CSP, as well as photovoltaic and CSP. For the research on the scheduling of wind power-photovoltaic-CSP combined power generation system, Reference [9] constructed a stochastic unit combination optimal scheduling model of multi-source power system based on the flexible output scheduling of photovoltaic thermal power station, the demand response mechanism is introduced into the model to deal with the uncertainty caused by the prediction error and volatility of photovoltaic and wind power in the high penetration renewable energy power system. In Reference [10], firstly, the wind solar power station and the thermal storage system of the concentrated solar power plant are combined through the electric to heat link, and the framework and principle of the wind solar photovoltaic thermal combined power generation system are given. Secondly, the price type demand response is introduced. Considering the optimal comprehensive cost and considering the uncertainty of the system, the day ahead optimal scheduling model of wind solar thermal combined power generation system considering the price demand response is constructed. In Reference [11] an economic load dispatch model developed for both wind turbines and thermal generators is presented in this paper. In the model, the wind power is considered as a constraint due to random nature of wind speed. This optimization problem is solved to obtain optimal power outputs of thermal generators, while taking into account of given constraints. In Reference [12] In this paper, aiming to readjust from the reference schedule as little as possible, the mean-tracking model is proposed for the first time to search for optimal dispatch solutions with the minimal expectation of generation cost and the minimal tracking errors, among which the tracking errors is implemented to each generator unit in terms of minimizing the deviation in generation cost between the trial solution and the pre-schedule. The above literatures all take thermal power generation into account, but there are few researches on joint generation scheduling of wind power-photovoltaic-CSP new energy base without thermal power generation, which is also the case at home and abroad.

This paper comprehensively considers the benefits of joint system market power sales, grid-connected environmental benefits, and system operation and maintenance costs, and establishes a dispatch model that aims to optimize the grid-connected benefits of wind power-photovoltaic-CSP generation systems. Through reasonable scheduling of CSP stations, the uncertainty of wind power and photovoltaic power generation can be effectively suppressed, and new energy consumption can be promoted. An IPSO is formed by adding the convergence factor and improving the inertia weight. The simulation analysis of the built model is performed on the MATLAB software platform to verify the correctness and effectiveness of the scheduling strategy.

2. Optimal scheduling model of wind power-photovoltaic-CSP combined power generation system

In this paper, a scheduling model of wind power-photovoltaic-CSP combined power generation system with optimal grid connected benefits is established by considering the market power sales benefits, grid connected environmental benefits and system operation and maintenance costs.

2.1. Objective function of combined generation system

Objective function: the benefit of wind power–photovoltaic-CSP combined system is the best, namely:

\[
\max F = F_1 + F_2 - F_3 \tag{1}
\]

Where: F indicates the grid-connected benefits of wind power-photovoltaic-CSP combined system, \( F_1 \) indicates the benefit of system electricity sales, \( F_2 \) indicates the environmental benefits of system integration, \( F_3 \) indicates system operation and maintenance costs, the specific formula is as follows:

\[
F_1 = \sum_{t=1}^{T} (C_{\text{wind}} P_{\text{wt}} + C_{\text{pv}} P_{\text{pvt}} + C_{\text{csp}} P_{\text{csp}}) \tag{2}
\]

\[
F_2 = \sum_{t=1}^{T} (K_F P_{\text{wt}} + K_G P_{\text{pvt}} + K_C P_{\text{csp}}) \tag{3}
\]
\[ F_3 = \sum_{t=1}^{T} (C_{\text{wind}} P_{\text{wt}}' + C_{\text{pv}} P_{\text{pvt}}' + C_{\text{csp}} P_{\text{csp}}' ) \]  

Where: \( T \) represents the scheduling period, which is 24h; \( P_{\text{wt}}' \) represents the actual dispatch output of wind power at time \( t \); \( P_{\text{pvt}}' \) indicates the actual dispatch output of photovoltaic at time \( t \); \( P_{\text{csp}}' \) represents the actual dispatch output of CSP at time \( t \); \( C_{\text{wind}}, C_{\text{pv}}, C_{\text{csp}} \) indicates the on-grid price of wind power, photovoltaic, and CSP respectively; \( K_{\text{f}}, K_{\text{G}}, K_{\text{c}} \) respectively indicate the environmental benefit coefficient of wind power, photovoltaic, CSP grid connection; \( C_{\text{w}}, C_{\text{pv}}, C_{\text{csp}} \) indicates the operation and maintenance cost coefficients of wind power, photovoltaic, and CSP respectively.

### 2.2. Constraints

1. **System power balance constraint**
   \[ P_{\text{wt}}' + P_{\text{pvt}}' + P_{\text{csp}}' = P_L \]  
   Where: \( P_L \) represents the predicted value of load at time \( t \).

2. **Wind power output constraints**
   \[ 0 \leq P_{\text{wt}}' \leq P_{\text{wt}}^* \]  
   Where: \( P_{\text{wt}}^* \) respectively represent the forecasted output of wind power at time \( t \).

3. **Constraints on photovoltaic power generation output**
   \[ 0 \leq P_{\text{pvt}}' \leq P_{\text{pvt}}^* \]  
   Where: \( P_{\text{pvt}}^* \) respectively represent the forecasted output of wind power and photovoltaic power at time \( t \).

4. **Constraints of heat storage system**
   \[ -P_{\text{max}} \leq P_{TS,\text{cf}} \leq P_{\text{max}} \]  
   \[ E_{\text{min}} \leq E_b \leq E_{\text{max}} \]  
   \[ A_b \cdot B_b = 0 \]  
   Where: \( P_{TS,\text{cf}} \) indicates the heat storage and heat release of the heat storage device at time \( t \), where the heat release is expressed as a negative number, and the heat storage is a positive number; \( P_{\text{max}} \) indicates the upper limit of heat storage of heat storage device; \( E_{\text{max}}, E_{\text{min}} \) respectively indicate the upper and lower limits of the heat storage capacity of the heat storage system; \( E_b \) represents the heat storage capacity of the heat storage device at time \( t \); \( A_b, B_b \) respectively indicate the heat storage and heat release state of the heat storage device, \( A_b, B_b \) is 0 or 1.

### 3. Model solving

#### 3.1. Basic particle swarm algorithm

In the PSO algorithm, the solution of each optimization problem is regarded as a "particle", and the initial value is a set of random solutions [13]. The initial state of the particles is random, and the optimal solution is sought through iteration. In each iteration, the particle updates its position according to its own individual extreme value \( p_{\text{best}} \) and the entire group extreme value \( g_{\text{best}} \). The update method is [14]:

\[ v_{n+1} = \omega v_n + r_1 c_1 (p_{\text{best}_n} - x_n) + r_2 c_2 (g_{\text{best}_n} - x_n) \]  
\[ x_{n+1} = x_n + v_{n+1} \]

Where: \( v_n \) is the velocity of the particle at the number of iterations \( n \); \( x_n \) is the current position of the particle; \( p_{\text{best}_n}, g_{\text{best}_n} \) are the optimal solution of the particle itself and the current optimal solution of the entire population; \( c_1, c_2 \) learning factors, generally take the constant 2; \( r_1, r_2 \) are two independent random numbers with a value between [0,1]; \( \omega \) is the inertia weight, used to modify its original flight speed.
3.2. Improved particle swarm algorithm

By adding a fixed inertia weight to solve the problem that the basic PSO algorithm is easy to fall into
the local optimum, but the fixed inertia weight will affect the convergence speed of the particle swarm
algorithm. In view of the above defects, this paper uses an IPSO algorithm.

3.2.1. Adjust the weight of particle swarm algorithm. In the PSO algorithm, the value of the inertia
weight \( \omega \) affects the optimization ability of the algorithm. When the value of \( \omega \) is \([0.9, 1.2]\), the
particles can quickly find the global optimal region, but the convergence speed is very slow when it
reaches the optimal value; when \( \omega < 0.8 \), the convergence speed is very fast near the optimal value but
the global search ability is poor. Therefore, this article proposes linearly decreasing adjustment
weights [15].

\[
\omega = \omega_{\text{end}} + (\omega_{\text{start}} - \omega_{\text{end}})(1 - \frac{K}{T})
\] (13)

Where: \( \omega_{\text{start}} \) represents the maximum initial weight, \( \omega_{\text{end}} \) represents the minimum final weight; \( K \)
represents the current number of iterations; and \( T \) represents the maximum number of iterations.

3.2.2. Adjust the learning factor of particle swarm algorithm. The convergence factor is added to the
particle swarm algorithm to ensure that the particle swarm optimization algorithm can converge [16].
Equation (14) is the new formula after adding the shrinkage factor.

\[
v_{n+1} = \gamma(\omega v_n + r_1 c_1 (p_{\text{best}} - x_n) + r_2 c_2 (g_{\text{best}} - x_n))
\] (14)

\[
x_{n+1} = x_n + v_{n+1}
\] (15)

The convergence factor \( \gamma \) can be expressed as:

\[
\gamma = \frac{2}{\sqrt{\phi^2 - 4\phi}} \quad \phi = c_1 + c_2, \phi > 4
\] (16)

Where: \( \gamma \) is a function of \( c_1, c_2 \), generally take \( \phi = 4.1 \).

4. Simulation analysis

4.1. Parameter setting

In this paper, a system consisting of a 200MW wind farm, a 150MW photovoltaic power station and a
100MW CSP station is used for simulation analysis. The parameters of the CSP station are shown in
Table 1, the parameters are taken from Reference [17]. Typical daily wind power, photovoltaic, solar
thermal, and load forecast data are shown in Figure 1. The wind power, photovoltaic, and CSP grid-
connected environmental benefit coefficient \( K_{fp} = K_G = K_C = 230 \text{ yuan/MW} \); wind power, photovoltaic,
CSP operation and maintenance cost coefficients \( C_w, C_{pv}, C_{csp} \) respectively take 20 \text{ yuan/MW}, 30 \text{ yuan/MW},
and 40 \text{ yuan/MW}. The on grid electricity prices of wind power, photovoltaic power and CSP are
\( C_{\text{wind}} = 0.54 \text{ yuan/kW h} \), \( C_{pv} = 0.6 \text{ yuan/kW h} \) and \( C_{csp} = 1.15 \text{ yuan/kW h} \), respectively.

| Parameter                              | Value    |
|----------------------------------------|----------|
| CSP rated output power/MW              | 100      |
| CSP Minimum output power/MW            | 10       |
| CSP Maximum climbing rate/(MW·h)       | 40       |
| TES exothermic loss efficiency/%       | 3.1      |
| Heat and power conversion efficiency of CSP power station/% | 0.4     |
| Daily maximum heat storage capacity/(MW·h) | 1000    |
| TES lower limit of heat storage/(MW·h)  | 100      |
4.2. Analysis of optimization results

In this paper, MATLAB is used for simulation analysis, and the IPSO is used to solve the wind power-photovoltaic-CSP combined system scheduling model. The system has a scheduling period of one day, a time interval of 1h, and a total scheduling period of T=24. IPSO parameters of the algorithm are set as follows: the number of populations P=500, and the maximum number of iterations is 2000.

4.2.1. Analysis of algorithm improvement effect.

Figure 2 shows the comparison of the fitness values of the basic particle swarm optimization (PSO) and the improved dynamic learning factor and inertial weighting particle swarm optimization (IPSO) proposed in this paper in the simulation of the concentrated solar power plant system. It can be seen from the figure that the algorithm only converges around 1000 generations when it is not improved, and it has reached convergence only after 700 generations after the algorithm is improved, and the convergence speed is significantly improved.

4.2.2. Dispatching output of each part of the system after joining CSP.

Figure 3 shows the optimal dispatching output of each power source of the system after adding a CSP station. It can be seen from the figure that after adding a CSP station with energy storage devices, during the peak load period, the power imbalance caused by insufficient wind power output, By joining the CSP station, it can effectively compensate for the random fluctuation of wind power, reduce the peak-to-valley difference, and enhance the power system's ability to absorb wind and light.
4.2.3. Daily economic benefit analysis with or without CSP stations. Table 2 shows the comparison of daily economic benefits with or without CSP stations in the combined system. It can be seen from Table 2 that after joining the CSP power station, the grid-connected benefit of the combined system has increased by 237784yuan per day, and the grid-connected benefit has been significantly improved.

Table 2. Comparison of economic benefits of the combined system with or without CSP station.

|                      | With CSP station | Without CSP station |
|----------------------|------------------|---------------------|
| Grid-connected Benefits | 5974917yuan      | 5737113yuan         |

5. Conclusions

Due to the inherent randomness, volatility, and non-adjustability of wind power and photovoltaic, it is inevitable to abandon wind and solar when they are connected to the grid, which seriously hinders the development of wind power and photovoltaic. To solve this problem, this article Taking into account the power sales benefits of the joint system market, the grid-connected environmental benefits, and the system operation and maintenance costs, a dispatch model with the goal of optimal grid-connected benefits of the wind power-photovoltaic-CSP combined power generation system is established. PSO algorithm is easy to be premature, an IPSO algorithm is formed by improving the dynamic learning factor and inertia weight, and the model built is simulated and verified on the MATLAB software platform, the results show that the wind power-photovoltaic- CSP generation dispatching strategy proposed in this paper can improve the efficiency of the system. Dynamic learning factors and inertia weights form an IPSO algorithm that can improve the convergence speed and accuracy of the algorithm.

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