The wind-PV-hydro-thermal multi-source cleaning dispatch with the influence of super-power thermal storage boiler

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Abstract. Aiming at the problem of serious waste of clean energy caused by the randomness and volatility of clean energy output during the winter heating period in Northeast China, this paper proposes a dispatching scheme of super-large power regenerative electric boiler, which fully combines the different physical characteristics and respective advantages of power systems and thermal systems. To maximize the economic and environmental benefits of wind-PV-hydro-thermal and other multi-energy joint dispatching, an optimal dispatch model is constructed with the lowest overall power generation cost as the dispatch target considering the power generation operating cost of the thermal power unit, the cost of abandoned light, the cost of abandoned water, the cost of abandoned wind, and the heating income of super-large power storage boilers combined together. The improved PSO algorithm based on multi-agent is used to solve the model. The results of the calculation example show that, after considering the absorption capacity of the super-large power regenerative electric boiler, the operating cost of the system is reduced by about 10%, and under the premise of ensuring the safe and stable operation of the system, the utilization rate of clean energy utilization and the system operation economy is improved.

1. Introduction

At present, China's installed capacity of wind, hydro, PV, and other clean energy power generation ranks first in the world. However, with the relative surplus of power supply, the use of clean energy is increasing, resulting in the problem of insufficient absorption capacity [1]. Due to the imperfect multi-energy dispatching system, thermal power units still occupy the dominant position in power generation [2], which limits the utilization of clean energy and is not conducive to economic benefits and environmental improvement.

In recent years there have been many relevant studies aiming at the problem of insufficient utilization of clean energy in multi-energy integrated scheduling. In literature [3], a cost-based mixed-integer linear programming model is proposed for the short term planning and obtaining the optimum solution for the production and load dispatch in a distribution network containing energy hubs. In literature [4], a multi-time-scale active power coordinated operation method, consisting of day-ahead scheduling, hour-level rolling corrective scheduling, and real-time corrective scheduling, is proposed...
for the combined operation of wind-photovoltaic-thermal-hydro power and battery (WPTHB) to handle renewable power fluctuations. Decomposition based multiobjective evolutionary algorithm and summation based multiobjective differential evolution algorithm are proposed in the literature [5] and the simulation results of both the algorithms are summarized, analyzed, and compared. Literature [6] builds a multi-objective function. NSGA-II is used to optimize the objective function and improve wind power consumption capacity. Literature [7] uses CPLEX to solve the 24 points scheduling scheme by establishing an objective function that considers the operating costs of thermal power units and the costs of wind, light, and water. The results show that this scheduling method can not only reduce the cost of power generation but also reduce clean energy. Literature [8] established the optimized operation mode of cascade hydropower stations. This method can absorb large-scale wind and light energy while providing a relatively continuous and stable power supply for the power grid. Literature [9] adopts the multi-energy scheduling method of wind power priority and full grid connection to establish a multi-objective function and achieves multi-objectives such as minimizing the system operating cost, minimizing the output fluctuation of thermal power units, and minimizing the amount of wastewater.

In this paper, based on the existing research results and from the three aspects of the economy, environmental protection and maximization of absorption of clean energy, a combined optimization objective function of wind-PV-hydro-thermal power considering the absorption capacity of thermoelectric storage boilers are established. A particle swarm optimization (PSO) algorithm based on multi-agent is used to solve the optimal value of the model. The results show that when heating in winter, the method is conducive to the utilization of clean energy, and the overall operation economy of the system is better.

2. A new model of multi-energy optimal dispatch considering thermal storage electric boiler

When considering the absorbing capacity of clean energy, the absorbing capacity of the regenerative electric boiler is considered based on the objective function of the original wind-PV-hydro-thermal power combined optimization dispatch model. Under the constraints of the original wind-PV-hydro-thermal power scheduling model, the depth adjustment capability of the thermal power unit, and the relevant constraints of the regenerative electric boiler were added. In the existing research, the rated power of the regenerative boiler is mostly around 30MW. In this paper, the rated power of the regenerative boiler is 80MW, and it is named as the super-large power regenerative boiler.

2.1. Objective function

To establish an economic dispatch model to preferentially consume clean energy, this paper adds the benefits of regenerative thermoelectric boilers undertaking into the objective function of the lowest combined operating cost account. The objective function is the overall operating cost of the system, and the goal is the minimum operating cost. Ignores the operating cost of the thermal storage boiler, so the objective function is:

\[
\min F = C_h + C_s + C_f + C_g + C_{nl} - E_{reb} \\
C_h = \sum_{i=1}^{N_h} \sum_{t=1}^{T} u_{it} (a_i P_{git}^2 + b_i P_{git} + c_i) + \sum_{i=1}^{T} \sum_{t=1}^{N_h} u_{it} (1 - u_{i(t-1)}) s_i \\
C_s = K_s \sum_{t=1}^{T} (P_{Hst} - P_{st}) \Delta t \\
C_f = K_f \sum_{t=1}^{T} \sum_{i=1}^{N_h} (P_{max_{ft}} - P_{ft}) \Delta t \\
C_g = K_g \sum_{t=1}^{T} \sum_{g=1}^{N_g} (1 - r_{gt}) P_{g_{max}} \Delta t \\
C_{nl} = E_p \sum_{t=1}^{T} P_{nl} \Delta t \\
E_{reb} = Z (C_{reb})^2 \eta P_{reb} \Delta t + \frac{\Delta t^2}{2} a \eta P_{reb} \Delta t \\
\]

In the formula: \( T \) is the total number of daily dispatching periods; \( N_h \) is the number of thermal power units; \( P_{git} \) is the average output power; \( a_i, b_i, c_i \) are the power generation cost coefficient; \( s_i \) is the starting cost; \( u_{it} \) is the state of thermal power unit \( i \) starts and stops [10]. \( K_c \) is the penalty coefficient for abandoning water; \( \Delta t \) is the number of hours in a period; \( P_{Hst} \) is the actual grid power; and \( P_{Hst} \) is the total power. \( K_f \) is the penalty factor for wind abandonment; \( F \) is the number of wind
power plants; $P_{\text{max}}$ is the total generating power; $P_F$ is the grid power. $P_{\text{gt max}}$ is the maximum output; $r_{gt} \in [0,1]$ is the dispatch interval coefficient; $G$ is the number of PV power plants; $K_g$ is the transaction cost penalty coefficient. $P_{\text{nit}}$ is the network loss power at time $t$; $E_p$ is the local electricity price. $P_{\text{Rebt}}$ is the operating power; $\eta$ is the thermal efficiency, 85%; $\alpha$ is the calorific value of electricity, 3600KJ/kWh; $\Delta t=900$s; $Z$ is the heating cost.

2.2. System constraints

$$P_{\text{Git min}} - P_{\text{downmax}} \leq P_{\text{Git}} \leq P_{\text{Git max}}$$

$$\sum_{i=1}^{N_h} (P_{\text{Gmax i}} - P_{\text{Git}}) + P_{\text{max s}} - P_{\text{st}} \geq k_d P_{\text{dt}} + k_w \sum_{f=1}^{E} P_f + k_l \sum_{g=1}^{G} r_{gt} P_{gt}$$

$$-r_d \Delta t \leq P_{\text{Git}} - P_{\text{Git (t-1)}} \leq r_u \Delta t$$

$$P_{\text{Hmin s}} \leq P_{\text{Hst}} \leq P_{\text{Hmax s}}$$

$$P_{\text{Hst}} = A_g \eta_s Q_{st} h_{st}$$

In the formula: $P_{\text{upmax}}$ and $P_{\text{downmax}}$ are the lower and upper limit of thermal power depth adjustment capability. $P_{\text{Gmax i}}$ is the max output of unit $i$; $P_{\text{max s}}$ is the max output of the hydropower station; $k_d, k_w, k_l$ are the load, wind power, and PV fluctuation coefficient [11]. $r_{dt}$ and $r_{ui}$ are the speed limit of unit $i$ deloading and upload in dispatch period $t$. $P_{\text{Hmin s}}$ is the minimum technical output of the hydropower station. $A_g$ is the conversion constant; $\eta_s$ is efficiency; $h_{st}$ is the height of Waterhead.

2.3. Constraints of regenerative electric boiler

$$0 \leq P_{\text{Rebt}} \leq P_{\text{Rebmax}}$$

$$Q_{\text{Rebt}} \leq Q_{\text{Rebmax}}$$

$$Q_{\text{Rebt}} = \sum_{t=1}^{T} P_{\text{Rebt}} \Delta t$$

$$\Delta P_{\text{Reb}}^{+} \leq P_{\text{Reb}} - P_{\text{Reb (t-1)}} \leq \Delta P_{\text{Reb}}^{-}$$

In the formula: $P_{\text{Rebmax}}$ is the upper limit of the power of the regenerative electric boiler. $Q_{\text{Rebmax}}$ is the heat storage capacity of the regenerative electric boiler; $Q_{\text{Rebmax}}$ is the maximum heat storage capacity of the regenerator. $\Delta P_{\text{Reb}}^{+}$ and $\Delta P_{\text{Reb}}^{-}$ are the response speed limit of power increase and decrease.

3. The model solution of improved PSO algorithm based on multi-agent

3.1. Particle swarm optimization

The PSO algorithm obtains the quality of the solution by evaluating the adaptability. Its advantages are large storage and a few parameters. In the multi-agent algorithm, after each agent corrects its action, it exchanges information with the optimal agent which increases a single agent’s information transmission efficiency to improve the convergence speed [12].

The $n$ elements in the objective function are abstracted as the position of the particle $i$ in space $X_i = (x_{i,1}, ..., x_{i,n})$, giving velocity $V_i = (v_{i,1}, ..., v_{i,n})$. The particle iteration speed and position update information are determined by the following equation:

$$v_i(j)(m+1) = w v_i(j)(m) + c_1 r_1 [p_{i,j} - x_i(j)(m)] + c_2 r_2 [P_{\text{g, j}} - x_i(j)(m)]$$

$$x_i(j)(m+1) = x_i(j)(m) + v_i(j)(m+1)$$

$$p_{k+1}^{p_{\text{best, i}}} = \begin{cases} f(X_i^{k+1}) & \text{if } f(X_i^{k+1}) < p_{k}^{p_{\text{best, i}}} \\ p_{k}^{p_{\text{best, i}}} & \text{if } f(X_i^{k+1}) \geq p_{k}^{p_{\text{best, i}}} \end{cases}$$

$$p_{m}^{g_{\text{best, i}}} = \min\{p_{m}^{g_{\text{best, 1}}}, p_{m}^{g_{\text{best, 2}}}, ..., p_{m}^{g_{\text{best, i}}}, ..., p_{m}^{g_{\text{best, n}}}\}$$

In the formula: $j=1,2, ..., n$; $r_1, r_2$ are uniform random numbers in the range of $[0,1]$; $w$ is the inertial weight; $c_1, c_2$ are non-negative constant, called learning factors. $p_{k}^{p_{\text{best, i}}}$ and $p_{k}^{p_{\text{best, i}}}$ are the local optimal values of the $m$ and $m+1$ generations respectively; $f$ is the objective function; $p_{m}^{g_{\text{best, i}}}$ is the global optimal value.

In the experiment, the algorithm proposed in this paper uses the following parameters. In the particle swarm, the inertial weight $\omega = 1$, the learning factor $c_1 = c_2 = 1.5$; 20 particles are used for
iterative optimization. Each particle retains up to 5 local Pareto optima, while all particles retain a total of 20 global Pareto optima. Among them, the number of allocation schemes is a key parameter. The smaller allocation scheme will make the algorithm end faster, while the larger allocation scheme increases the number of iterations of each scheme, to improve the optimal solution under the scheme probability [13]. In this paper, the number of distribution plans is 50. When the number of iterations \( n = 20 \), the algorithm jumps and eventually converges to the optimal solution.

3.2. Multi-agent particle swarm optimization
The algorithm flow is shown in Figure 1.

3.2.1. Initialize the network environment
3.2.2. Initialize the position and velocity of the agent
3.2.3. Calculate the position of 8 neighbor agents in each agent
3.2.4. Calculate the fitness value in each agent
3.2.5. Compete and cooperate in the field according to equations (17)-(18)
3.2.6. Network power flow calculation based on the updated power value
3.2.7. Check the voltage and power of the node
3.2.8. Update the individual and global extremum of each particle
3.2.9. Self-learning of the current global extremum agent
3.2.10. Set the number of iterations to \( T = T + 1 \)
3.2.11. Output result

Figure 1. An improved PSO algorithm flow based on Multi-Agent.

4. Example analysis
4.1. Introduction of simulation system
The IEEE 24 node test system forms a wind-PV-hydro-thermal power system containing a thermal storage boiler as shown in Figure 2.

This article specifies extreme cold weather conditions (minimum temperature is below -22°C) and normal heating conditions (minimum temperature is greater than or equal to -22°C). The data in this article adopts the temperature in a region in northeast China in 2017 and selects 2017.12.23 as the extremely cold weather day and 2017.1.2 as the general weather day. The improved PSO algorithm based on multi-agent is used to solve the optimal scheduling scheme that maximizes the utilization of clean energy.
4.2. Analysis and comparison of multi-scenario scheduling results
To verify the advantages of the model in this article, the following four scenarios are set for comparative experiments.

Scenario 1: Operation of wind-PV-hydro-thermal combined system without heat storage electric boiler in extremely cold weather (Figure 3)

Scenario 2: The wind-PV-hydro-thermal combined system operation of a thermal storage electric boiler with extreme cold weather (Figure 4)

Scenario 3: Operation of wind-PV-hydro-thermal combined system without a regenerative electric boiler in normal weather (Figure 5)

Scenario 4: Wind-PV-hydro-thermal combined system operation of a thermal storage electric boiler in normal weather (Figure 6)
In extremely cold weather, 2017.12.23 is selected as a typical load day, and the amount of hydropower generation is 0. The power generation cost of Scenario 1 is 2273355 yuan, and the cost of Scenario 2 is 2054765 yuan, which saves 9.6% of the cost compared with not considering the regenerative electric boiler. The power generation cost of scenario 3 is 199244 yuan, and the cost of scenario 4 is 1782405 yuan, which saves 10.5% of the cost compared with not considering the regenerative electric boiler. Before considering the regenerative electric boiler, due to the strong randomness and volatility of clean energy output, there is a phenomenon of clean energy waste when scheduling the dispatching unit output. In the winter heating period, consider the heating demand of the super-power regenerative electric boiler. Since the super-power regenerative electric boiler is a controllable load, during the period of clean energy waste, by increasing the power of the regenerative electric boiler, the utilization rate of clean energy is increased. Among them, the ultra-high power regenerative electric boiler further improves the utilization of clean energy. The analysis of the calculation examples shows that it is verified that the ultra-high power regenerative electric boiler is used to improve the utilization rate of clean energy in extremely cold weather or general weather, which not only improves the environmental friendliness of dispatching but also improves the economic operation [14].

5. Conclusions
To solve the problem of inadequate clean energy utilization, this paper establishes a wind-PV-hydro-thermal multi-energy clean optimization objective function that considers regenerative electric boilers. The improved PSO algorithm based on multi-agent is used to solve the optimal value of the model. The new method is suitable for the heating season in winter, which requires residential and commercial heating in winter. Considering the capacity of the super-power regenerative electric boiler, the electrical energy generated by clean energy power generation is stored in the form of heat energy when the load is low. Thermal energy provides heating for residents and businesses, ensuring the safe and stable operation of the system. It not only meets the heating needs in winter but also uses clean energy on a deeper level. The overall operating cost of the system is lower. When the output of clean energy is large and there is waste, the utilization of clean energy can be improved by adjusting the power of the regenerative electric boiler. Therefore, the wind-PV-hydro-thermal scheduling model of thermal storage boilers proposed in this paper can fully improve the utilization rate of clean energy and reduce the operating cost of the system when the clean energy output is large.

Acknowledgment
Thanks to Professor Huang Nantian, from the topic selection of the thesis to the mid-term to the completion of the manuscript, you have coagulated your hard work. Thanks to the authors of the literature cited in this article, your research results inspired my ideas, and guide the direction of the formation of the paper.
This work was supported by the Science and Technology Development Plan Program of Liaoning Power Grid Co. LTD (SGLNASOOFZJS1801223).

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